The Standard Models

of

Particle Physics & Cosmology

and

Beyond

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Preface

Lecture 1: The uniqueness of the standard model of particle physics and Beyond

Lecture 2: Dark Matter and Cosmic Ray Anomalies

Lecture 3: Understanding Dark Energy beyond the LCDM: Modified Theories of Gravity

Conclusions

Future prospects

- Preface

Science AAAS

American Association for the Advancement of Science (AAAS)

July 1, 2005

Science Magazine

125th anniversary

THE QUESTIONS
The Top 25

Essays by our news staff on 25 big questions facing science over the next quarter-century

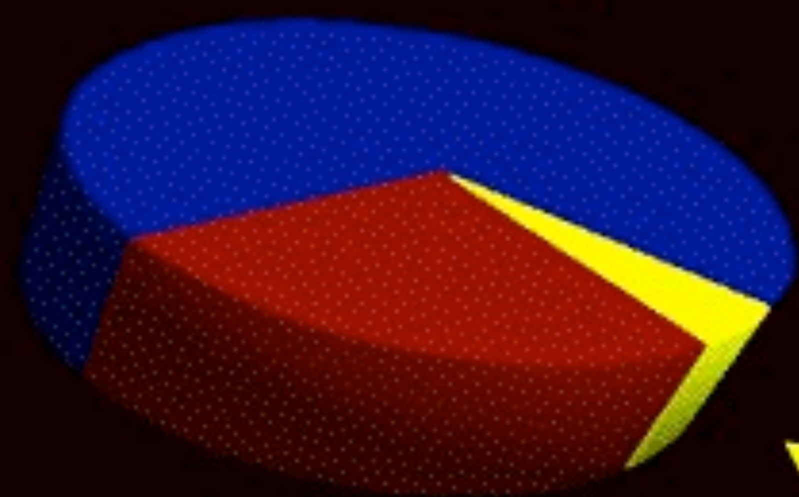
What is the Universe made of ? #1

- What Is the Biological Basis of Consciousness?
- Why Do Humans Have So Few Genes?
- To What Extent Are Genetic Variation and Personal Health Linked?
- Can the Laws of Physics Be Unified?
- How Much Can Human Life Span Be Extended?
- What Controls Organ Regeneration?
- How Can a Skin Cell Become a Nerve Cell?
- How Does a Single Somatic Cell Become a Whole Plant?
- How Does Earth's Interior Work?
- Are We Alone in the Universe?
- How and Where Did Life on Earth Arise?
- What Determines Species Diversity?
- What Genetic Changes Made Us Uniquely Human?
- How Are Memories Stored and Retrieved?
- How Did Cooperative Behavior Evolve?
- How Will Big Pictures Emerge from a Sea of Biological Data?

We know much, we understand very little.

95% of the cosmic matter/energy is a mystery. It has never been observed even in our best laboratories

70% of the universe:
the energy of empty space
(dark energy)

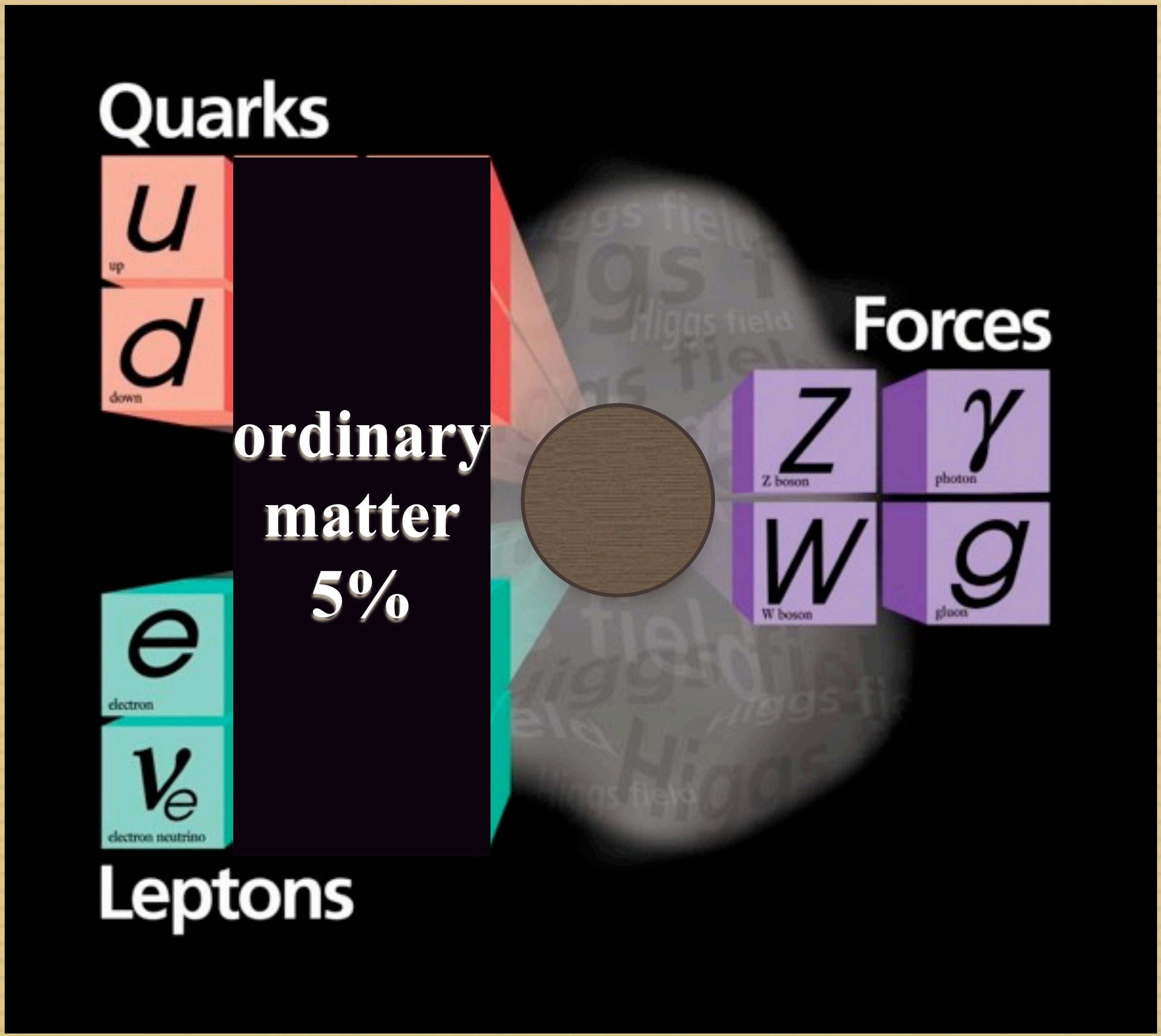


5% of the universe:
ordinary matter

25% of the universe:
a mysterious new particle
(dark matter)

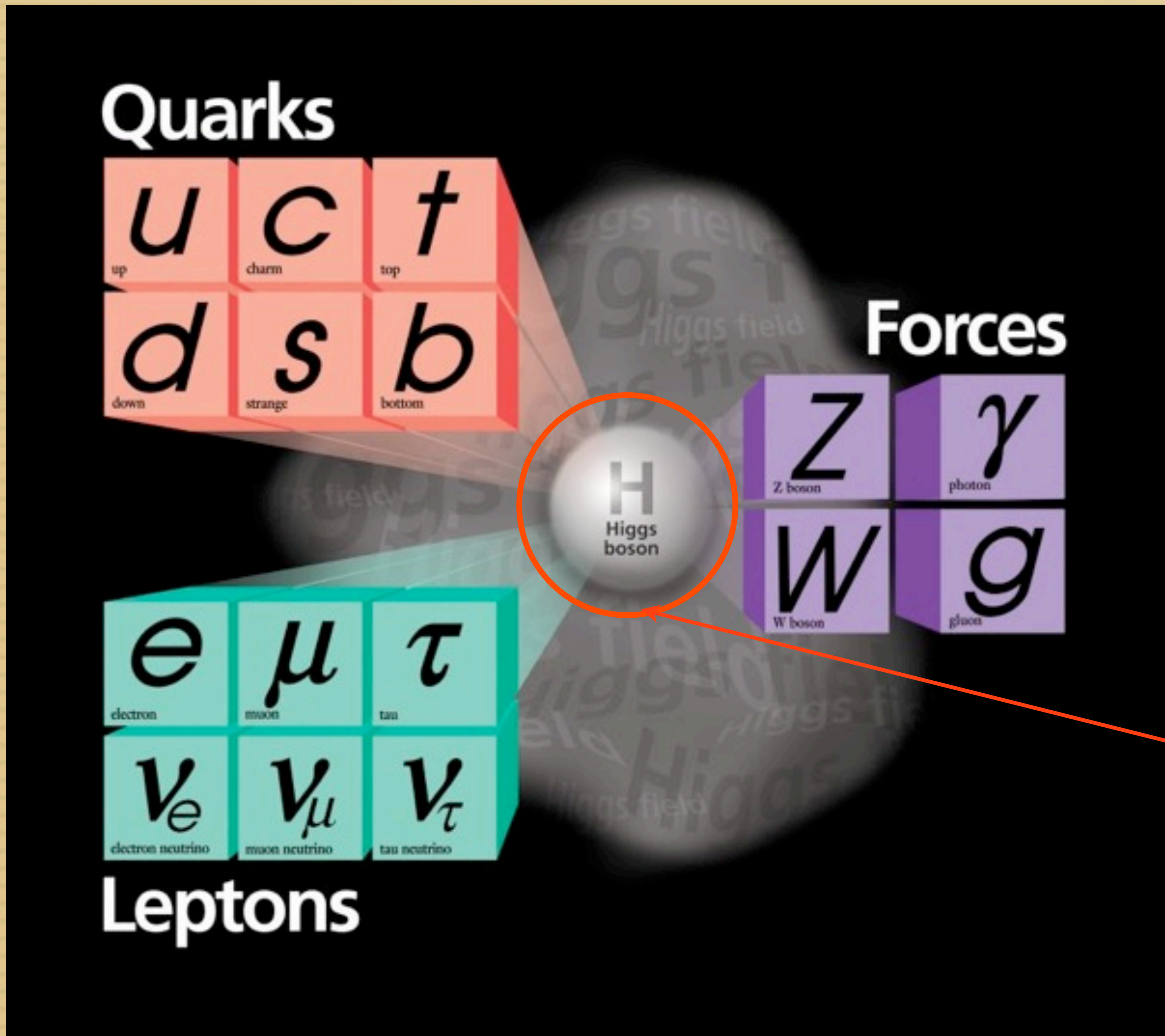
The Standard Model in Particle Physics

Matter **Force**



The Standard Model in Particle Physics

Matter   Higgs   Force

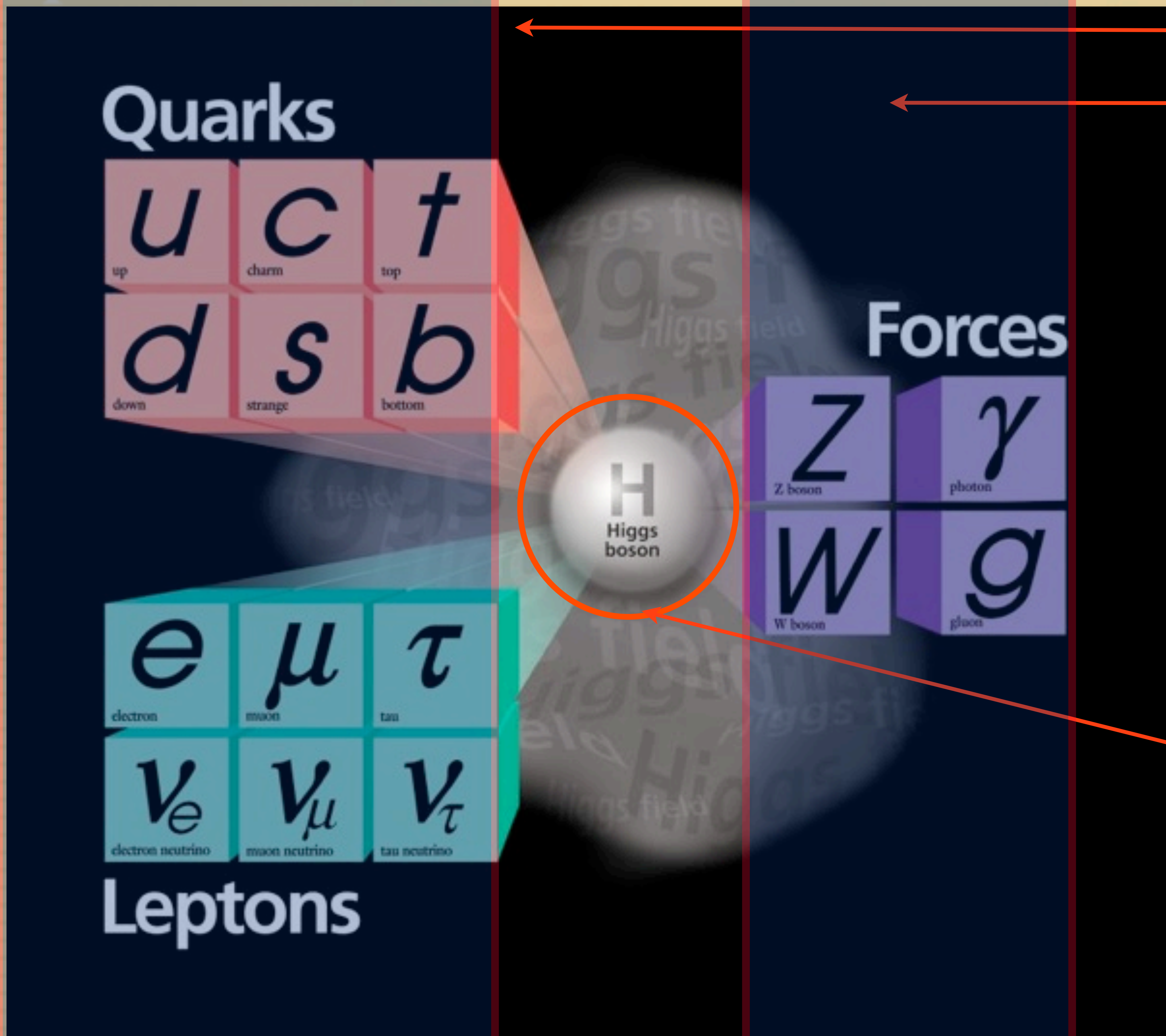


Higgs Boson: observed at LHC !

The Standard Model in Particle Physics

	Fermion	Boson	
	Matter	Higgs	Force
spin	1/2	0	1

$SU(3)_c \times SU(2)_L \times U(1)_Y$

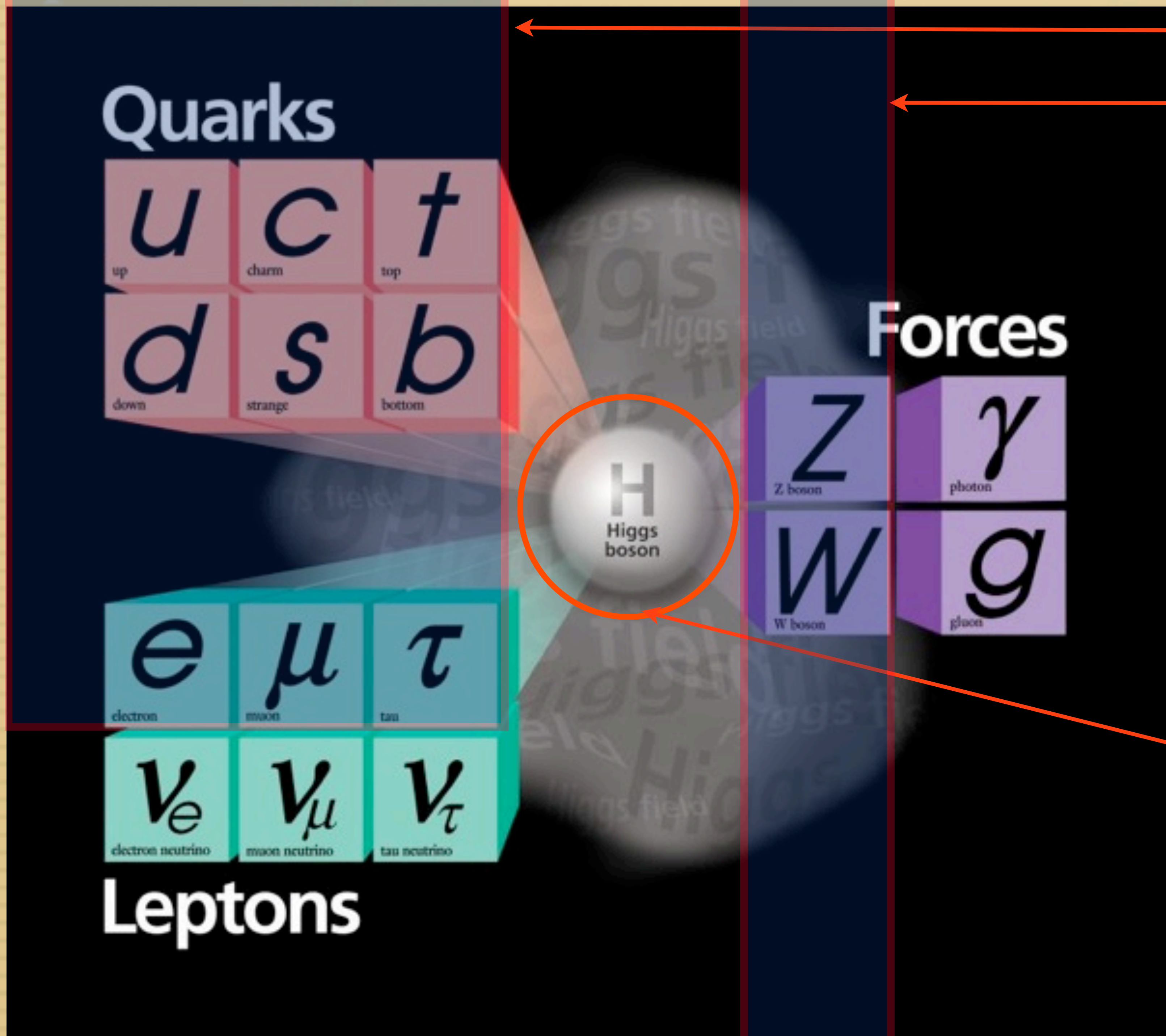


massless

Higgs Boson: observed at LHC !

The Standard Model in Particle Physics

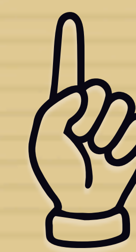
Fermion		Boson	
	Matter	Higgs	Force
spin	1/2	0	1



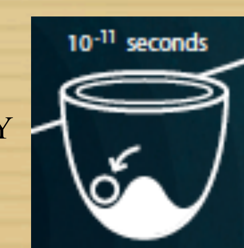
masses

$SU(3)_c \times U(1)_{EM}$

Higgs Mechanism



$SU(3)_c \times SU(2)_L \times U(1)_Y$



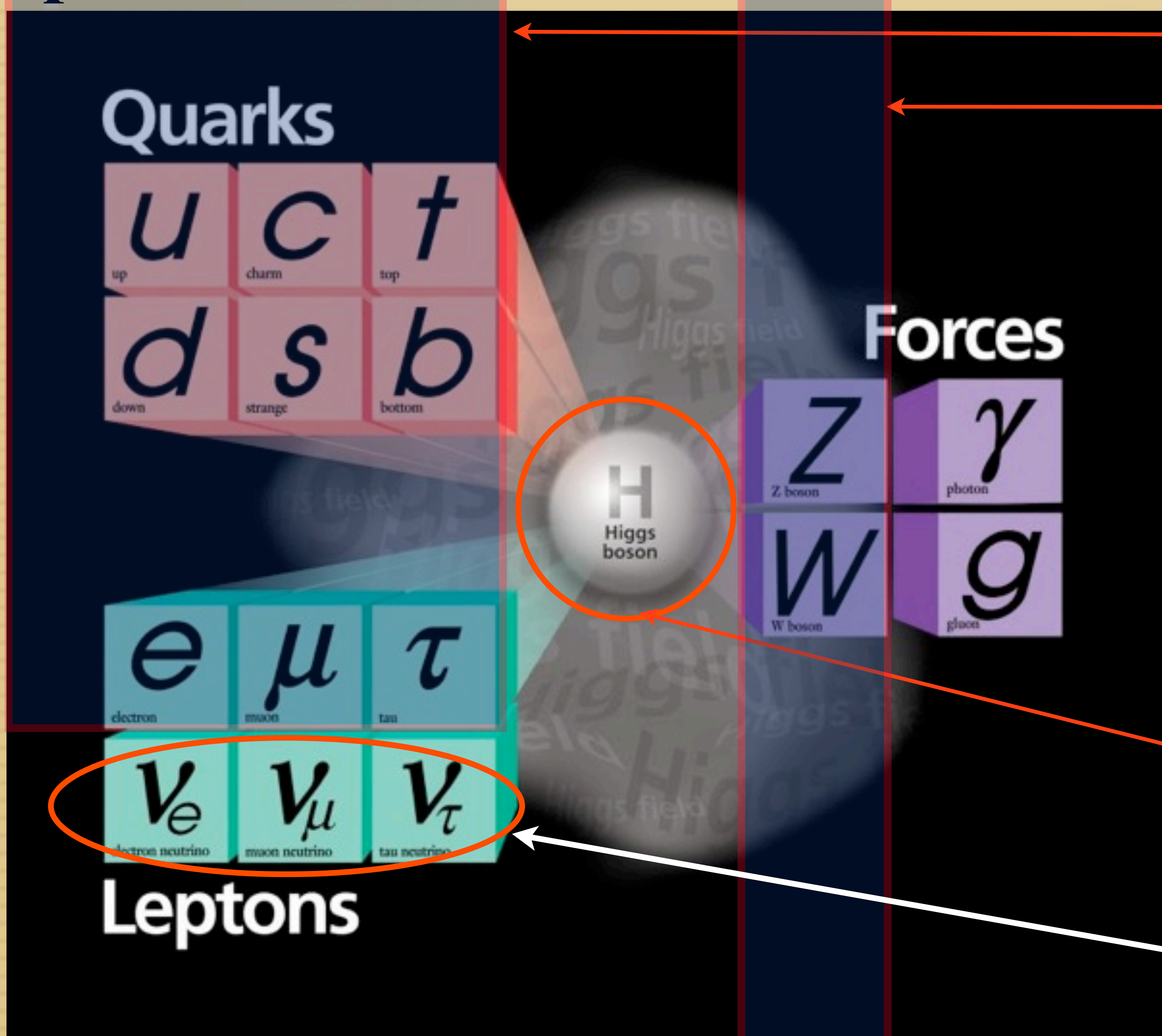
Higgs Boson: observed at LHC !

The Standard Model in Particle Physics

Fermion | Boson

Matter | Higgs | Force

spin 1/2 | 0 | 1

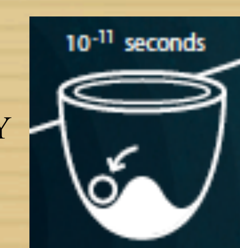


masses

$SU(3)_c \times U(1)_{EM}$

Higgs Mechanism

$SU(3)_c \times SU(2)_L \times U(1)_Y$



Higgs Boson: observed at LHC !

only unknown: m_ν

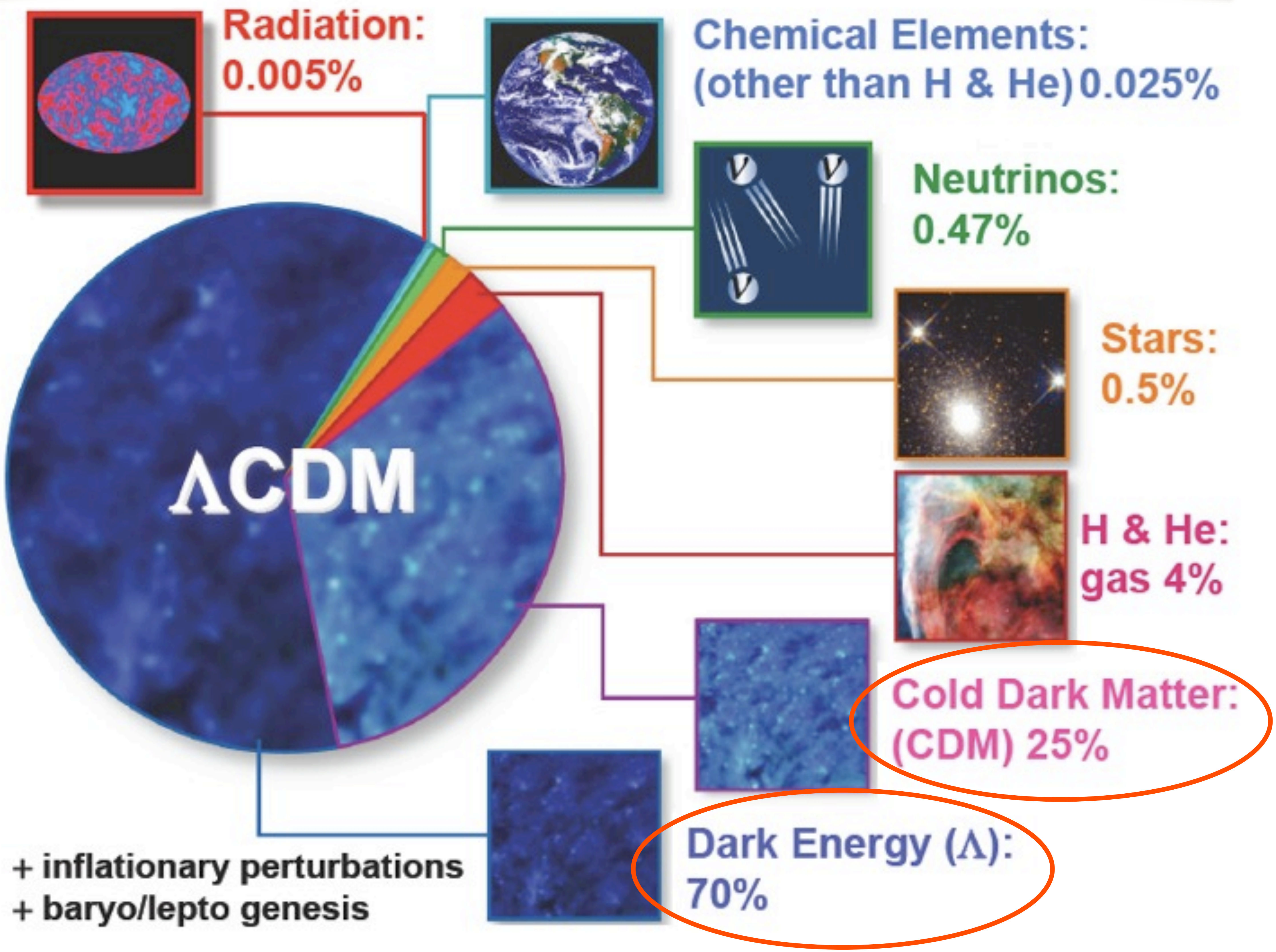
The Standard Model in Particle Physics

$$\underbrace{SU(3)_C}_{\text{Strong Interaction}} \times \underbrace{SU(2)_L \times U(1)_Y}_{\text{Electroweak Interaction}}$$

Particles $(i = 1, 2, 3)$	$SU(3)_C$	$\times$	$SU(2)_L$	$\times$	$U(1)_Y$
$\begin{pmatrix} u \\ d \end{pmatrix}_L^i$	3		2		$\frac{1}{3}$
$u_L^{c\,i}$	$\overline{3}$		1		$-\frac{4}{3}$
$d_L^{c\,i}$	$\overline{3}$		1		$\frac{2}{3}$
$\begin{pmatrix} \nu \\ e \end{pmatrix}_L^i$	1		2		-1
$e_L^{c\,i}$	1		1		2

The Standard Model is a good theory. Experiments have verified its predictions to incredible precisions.

“The Standard Model” in Cosmology



ΛCDM model

- Action

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}(R - 2\Lambda) + S_m$$

- Einstein equation

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = 8\pi G T_{\mu\nu} - \Lambda g_{\mu\nu}$$

$$= 8\pi G\left(T_{\mu\nu} + T_{\mu\nu}^{\mathrm{DE}}\right)$$

Friedmann–Lemaître–Robertson–Walker (FLRW) spacetime

$$ds^2 = -dt^2 + a^2(t)\left[\frac{dr^2}{1-\kappa r^2} + r^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)\right]$$

expansion rate

total energy

curvature

$$H^2 = 8\pi G\,(\rho_M + \rho_{DE})\,/\,3 - k\,/\,a^2$$

$$1 = \Omega_M + \Omega_{DE} - k\,/\,(a^2H^2)$$

G		Newton's constant
a		scale factor or radius
$H \equiv$	$\dot{a}/a$	Hubble parameter
ρ		energy density
p		pressure
k=1, 0, -1		closed, flat, open

$\Omega \equiv 8\pi G\rho/\,3H^2$

For the flat universe of k=0:

$\Omega_M \sim (25+5)=30\%$ and $\Omega_{DE} \sim 70\%$

Lecture 1
The uniqueness of the standard model of particle physics and Beyond

Outline

- Introduction
- Anomalies in four-dimension
- Uniqueness of fermion representations and charges in the SM
- Family problem
- Concluding remarks

- Introduction

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

Standard groups

Strong Interaction — Electroweak Interaction

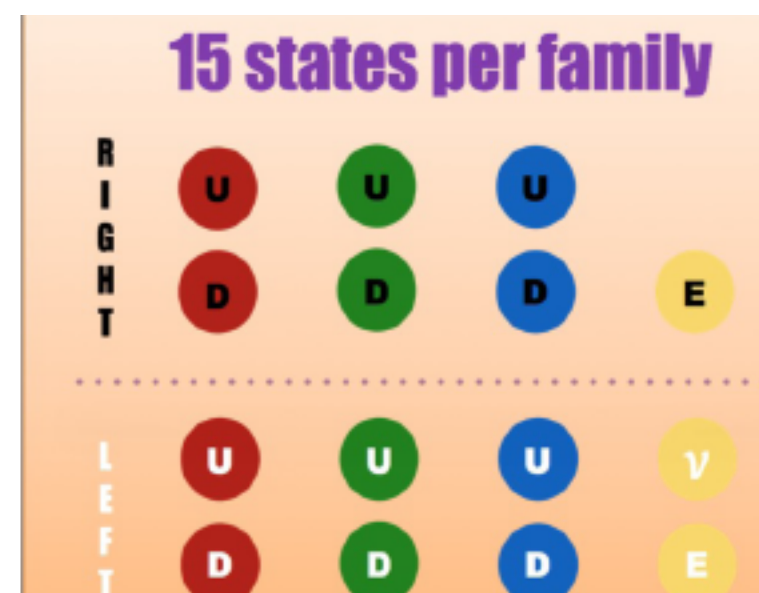
$$Q = T_{3L} + \frac{Y}{2}$$

$SU(3)_C \times SU(2)_L \times U(1)_Y$ $\xrightarrow{\langle H \rangle}$ $SU(3)_C \times U(1)_{EM}$

Higgs Mechanism

				$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$SU(3)_C$	$U(1)_{EM}$
Q_L :	$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$\begin{pmatrix} c \\ s \end{pmatrix}_L$	$\begin{pmatrix} t \\ b \end{pmatrix}_L$	3	2	$\frac{1}{3}$	$\begin{pmatrix} 3 \\ 3 \end{pmatrix}$	$\begin{pmatrix} \frac{2}{3} \\ -\frac{1}{3} \end{pmatrix}$
U_R :	u_R	c_R	t_R	3	1	$\frac{4}{3}$	3	$\frac{2}{3}$
D_R :	d_R	s_R	b_R	3	1	$-\frac{2}{3}$	3	$-\frac{1}{3}$
L_L :	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	1	2	-1	$\begin{pmatrix} 1 \\ 1 \end{pmatrix}$	$\begin{pmatrix} 0 \\ -1 \end{pmatrix}$
E_R :	e_R	μ_R	τ_R	1	1	-2	1	-1

H	1	2	1



Questions:

1. Why are there 15 states of quarks and leptons?
2. Why are the electric charges of particles quantized?
3. Why are there three fermion generations?
4. Are these quantum numbers unique?

- Anomalies in four-dimension

The triangular anomaly

In QED with one Dirac field:
$$\mathcal{L} = i\bar{\psi}\not{D}\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} + m\bar{\psi}\psi \quad (1)$$

$$F^{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu\,, \quad D_\mu = \partial_\mu - ieA_\mu$$

$$(1) \quad \Longrightarrow \quad U(1)_{\text{vector}} \;:\; \psi \longrightarrow e^{i\alpha}\psi$$

$$m \longrightarrow 0 \quad \Longrightarrow \quad U(1)_{\text{axial vector}} \;:\; \psi \longrightarrow e^{i\beta\gamma_5}\psi$$

Using $\psi_L = \frac{1}{2}(1-\gamma_5)\psi\,, \quad \psi_R = \frac{1}{2}(1+\gamma_5)\psi$ notations:

$$(1) \quad \Longrightarrow \quad \mathcal{L} = i\bar{\psi}_L\not{D}\psi_L + \bar{\psi}_R\not{D}\psi_R + m(\bar{\psi}_L\psi_R + \bar{\psi}_L\psi_R) - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

$$m \longrightarrow 0 \quad U(1)_L \;:\; \psi_L \longrightarrow e^{ia}\psi_L \qquad U(1)_R \;:\; \psi_R \longrightarrow e^{ib}\psi_R$$

☜ **Chiral symmetries**

$$U(1)_V = U(1)_{L+R}\,, \quad U(1)_A = U(1)_{L-R}$$

According to *Noether's Theorem*, gauge invariants imply the existence of conserved currents:

$$J_\mu = \bar{\psi}\gamma_\mu\psi\,, \quad \partial_\mu J^\mu = 0\,,$$

$$J_{5\mu} = \bar{\psi}\gamma_\mu\gamma_5\psi$$
$$\partial_\mu J_5^\mu = 2mJ_5 \xrightarrow{m \longrightarrow 0} 0$$

where $J_5 = i\bar{\psi}\gamma_5\psi$

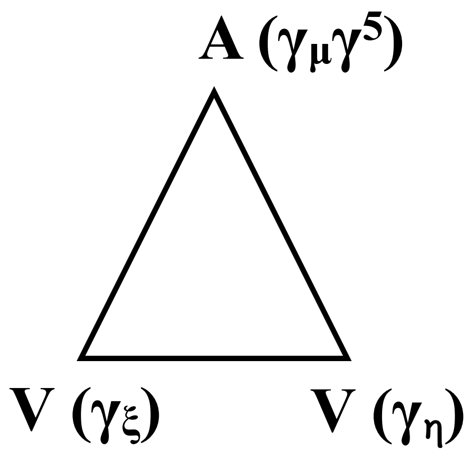
The anomaly phenomenon is that

S.Adler,PR177,2426(1969);
J.S.Bell,R.Jackiw,Nuovo Cimen A60,47 (1969)

$$
\begin{aligned}
\partial_\mu J_5^\mu &= \partial_\mu(\bar{\psi}\gamma_\mu\gamma_5\psi) \\
&= 2mJ_5 + \frac{\alpha_0}{2\pi}\tilde{F}^{\mu\nu}F_{\mu\nu} \\
\boxed{m \longrightarrow 0} \quad &\longrightarrow \frac{\alpha_0}{2\pi}\tilde{F}^{\mu\nu}F_{\mu\nu}
\end{aligned}
$$

$(\tilde{F}_{\mu\nu} = \epsilon_{\mu\nu\alpha\beta}F^{\alpha\beta})$

— Adler-Bell-Jackiw (ABJ) or axial *Anomaly*



— *Triangle Anomaly*

This anomalous result $\Longrightarrow$ an understanding of $\pi \to 2\gamma$

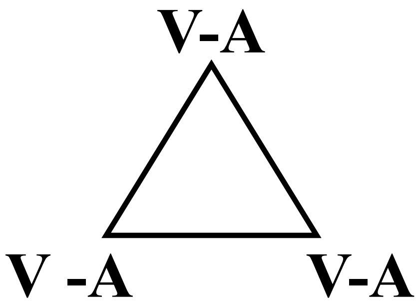
$U(1)$ problem in QCD

No problem in QED the axial-vector current doesn't couple to the photon (γ).

If we introduce a gauge boson which couples to the axial-vector current, such a theory will not be *renormalizable* since the gauge invariance – a necessary requirement for renormalizability — is lost due to $\partial_\mu J_5^\mu \neq 0$.

Electroweak theory: $V-A$ gauge coupling

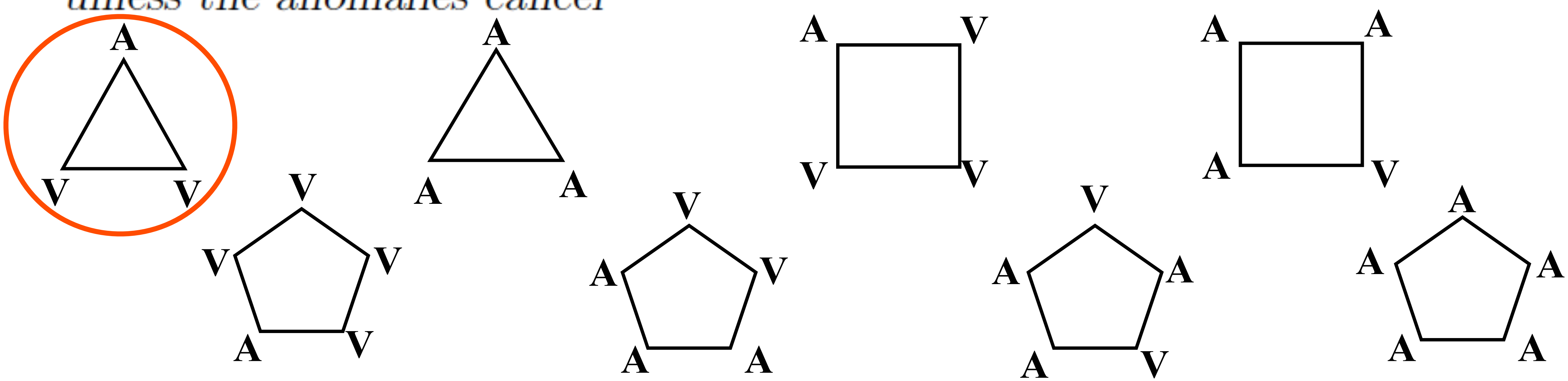
One must consider a fermion triangle with a $V-A$ current at each vertex.



This diagram is again anomalous.

Unless it cancels when summing over the fermion species running around the loop, the anomaly spoils conservation of the $V-A$ current.

- *Any gauge theory with non-vectorlike gauge coupling is inconsistent unless the anomalies cancel*



<u>Two useful theorems:</u>

- Once the AVV triangle anomaly is cancelled, then so are all the others.
- Radiative corrections do not renormalize the anomaly.

$\Longrightarrow$ *Only AVV triangle graph is needed to consider.*

For example: any gauge theory

$$\begin{aligned} J_a^\mu &= \bar\psi \gamma^\mu t_a \psi \\ &= \frac{1}{2}\bar\psi\gamma^\mu t_a^L (1-\gamma_5)\psi + \frac{1}{2}\bar\psi\gamma^\mu t_a^R(1+\gamma_5)\psi \end{aligned}$$

where t_a $(a = 1, 2, \cdots, N)$ are the generators of the gauge group.

$$\begin{aligned} Anomaly - free \Longleftrightarrow \mathcal{A} &\equiv Tr\left[\{t_a^L, t_b^L\}, t_c^L\right] - Tr\left[\{t_a^R, t_b^R\}, t_c^R\right] \\ &= 0 \end{aligned}$$

△ Real representations are <u>*safe*</u>.

△ $SU(2)$, $SO(2k+1)$ $(k > 2)$, $SO(4k)$ $(k > 2)$, $Sp(2k)$, G_2, F_4, E_7, E_8 have only real reps. — <u>*safe*</u>.

△ $SO(4k+2)$ $(k > 2)$, E_6 have complex reps. — <u>*safe*</u>.

△ $SU(N)$ $(N > 2)$ are not <u>*safe*</u>.

For ($\square$, Y) under SU(N)×U(1)$_Y$:
or ($\bar\square$, Y)

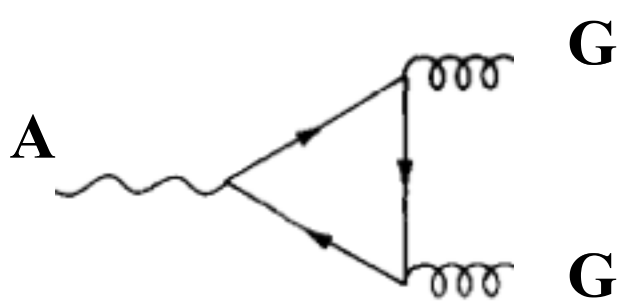
$$\begin{aligned} [SU(N)]^3 &: \mathcal{A}(\square) = 1\,, \quad \mathcal{A}(\bar\square) = -1 \\ [SU(N)]^2\, U(1)_Y &: \mathcal{A}(\square) = Y\,, \quad \mathcal{A}(\bar\square) = Y \\ [U(1)_Y]^3 &: \mathcal{A} = Y^3 \end{aligned}$$

Particles $(i = 1, 2, 3)$	$SU(3)_C$ $\times$	$SU(2)_L$ $\times$	$U(1)_Y$
$\begin{pmatrix} u \\ d \end{pmatrix}_L^i$	3	2	$\frac{1}{3}$
$u_L^{c\,i}$	$\overline{3}$	1	$-\frac{4}{3}$
$d_L^{c\,i}$	$\overline{3}$	1	$\frac{2}{3}$
$\begin{pmatrix} \nu \\ e \end{pmatrix}_L^i$	1	2	-1
$e_L^{c\,i}$	1	1	2

Triangle anomalies in the standard model:

$$\begin{aligned}
[SU(3)_C]^3 &= 2 - 1 - 1 = 0 \\
[SU(3)_C]^2\, U(1)_Y &= 2 \cdot \frac{1}{3} + 1 \cdot (-\frac{4}{3}) + 1 \cdot \frac{2}{3} = 0 \\
[SU(2)_L]^3 &\equiv 0 \\
[SU(2)_L]^2\, U(1)_Y &= 3 \cdot \frac{1}{3} - 1 = 0 \\
[U(1)_Y]^3 &= TrY^3 \\
&= 3 \cdot 2 \cdot (\frac{1}{3})^3 + 3 \cdot 1 \cdot (-\frac{4}{3})^3 + 3 \cdot 1 \cdot (\frac{1}{3})^3 \\
&\quad +2 \cdot (-1)^3 + 1 \cdot (2)^3 = 0
\end{aligned}$$

- The mixed gauge-gravitational anomaly



The triangle with one axial-current and two energy-momentum tensors is anomalous

$$D_\mu J_5^\mu = -\frac{1}{384\pi^2}(TrQ)\, R_{\mu\nu\sigma\tau}\tilde{R}^{\mu\nu\sigma\tau}$$

R.Delbourgo,A.Salam,PLB40,381(72); T.Eguchi,P.Freund,PRL37,1251(76)

$R_{\mu\nu\sigma\tau}$ is the Riemann curvature tensor and $\tilde{R}^{\mu\nu\sigma\tau} = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}R^{\sigma\tau}_{\alpha\beta}$.

In four dimensions, the standard $SU(2)_L \times U(1)_Y$ theory can be coupled to gravity unless the sum of hypercharges (Y) of the Weyl fermions vanishes:

$$Tr\, Y = 0$$

L.Alvarez-Gaume, E.Witten, NPB234 (1983) 269

In the SM: $TrY = 3\cdot 2\cdot(\frac{1}{3}) + 3\cdot 1\cdot(-\frac{4}{3}) + 3\cdot 1\cdot(\frac{2}{3}) + 1\cdot 2\cdot(-1) + 1\cdot 1\cdot 2 = 0.$

Remarks:

- $U(1)$ — *unsafe*, unless $TrQ = 0$.
- G — *safe*. $\quad G \longrightarrow U(1)\times g\,, \qquad TrQ \equiv 0$

Example:

$SU(3)_C$	$\times SU(2)_L$	$\times U(1)_Y$
3	2	$1/3$
$\overline{3}$	1	$-4/3$
$\overline{3}$	1	$2/3$
1	2	-1
1	1	2
1	1	y_i

$i = 1, \cdots, n$

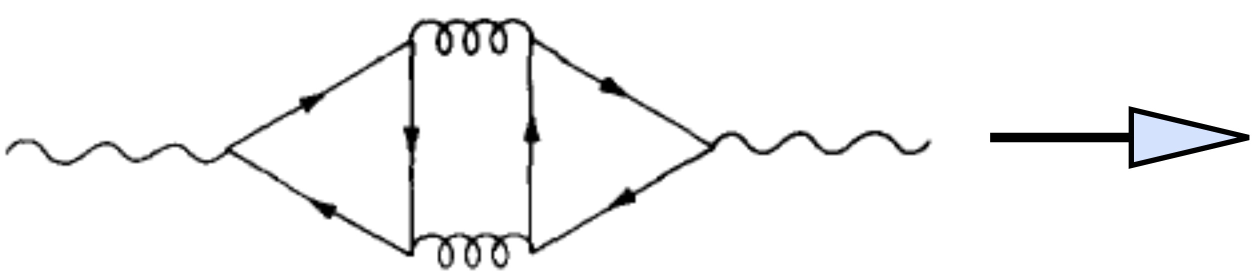
$$\Sigma_{i=1}^{n} y_i^3 = 0$$

$$\Sigma_{i=1}^{n} y_i \neq 0$$

$$\boxed{Q = T_{3L} + \frac{Y}{2} \implies Tr\, Q \neq 0}$$

Existing massless electrically charged fermions:

L.Alvarez-Gaume, E.Witten, NPB234 (1983) 269



$$\boxed{m_\gamma^2 \sim \alpha G_N^2 \Lambda^6 (Tr\, Q)^2}$$

G_N — Newton's constant

Λ — an ultraviolet cut off

$$m_\gamma \leq (10^6\ km)^{-1} \sim 10^{-25}\ GeV \implies \Lambda \leq 10^5\ GeV$$

- The global Witten $SU(2)$ anomaly

E.Witten,PLB117(1982)324

Any $SU(2)$ gauge theory with an odd number of left-handed fermion doublets is mathematically inconsistent.

The fermion integration for N massless Weyl fermion doublets, ψ:

$$\begin{aligned}\int(\mathcal{D}\psi\mathcal{D}\bar{\psi})_{\text{Weyl}}\, e^{\bar{\psi}iD\psi} &= det^{N/2} iD(A) \\ &\longrightarrow (-1)^N det^{N/2} iD(A^U)\end{aligned}$$

a topologically nontrivial gauge transformation U

where $A^U_\mu = U^{-1}A_\mu U - iU^{-1}\partial_\mu U$.

The number of the doublets, N, has to be *even*, otherwise the theory is ill-defined.

In the SM, for each family, $N = 3$ (quark) $+$ 1 (lepton) $= 4$ — even.

Remarks:

- $\Pi_4(G) = Z_2$, $G = Sp(2N), SU(2) = Sp(2)$ — *unsafe*.
- $\Pi_4(G) = 0$, G: all the simple compact Lie groups except $Sp(2N)$ — *safe*.

Π_4(G) is the 4th homotopy group

Question: For $G \longrightarrow SU(2) \times g$, is Witten $SU(2)$ anomaly free?

Triangle Anomaly-free of G $\Longrightarrow$ Witten $SU(2)$ Anomaly-free

CQG, Zhao,Marshak,OKubo PRD36(1987)1953

(a) $SO(10)$ →	$SU(4)_C$ ×	$SU(2)_L$ ×	$SU(2)_R$
16	4	2	1
	$\bar{4}$	1	2

N= even

(b) $SU(3)$ →	$SU(2)$ ×	$U(1)$
3	2	1
	1	-2

N= odd

- Uniqueness of fermion representations and charges in the SM

$SU(3)$	$\times$	$SU(2)$	$\times$	$U(1)$
3		2		$Q_i\,,\ i=1,\cdots,j$
3		1		$Q'_i\,,\ i=1,\cdots,k$
$\overline{3}$		1		$\overline{Q}_i\,,\ i=1,\cdots,l$
$\overline{3}$		2		$\overline{Q}'_i\,,\ i=1,\cdots,m$
1		2		$q_i\,,\ i=1,\cdots,n$
1		1		$\overline{q}_i\,,\ i=1,\cdots,p$
$\cdots$		$\cdots$		$\cdots$

☜ ***arbitrary***

The triangular anomaly-free conditions:

$$[SU(3)]^3 \ :\ \sum_{i=1}^{j} 2 + \sum_{i=1}^{k} 2 - \sum_{i=1}^{l} 1 - \sum_{i=1}^{m} 2 = 0\ , \tag{1}$$

$$[SU(3)]^2 U(1) \ :\ 2\sum_{i=1}^{j} Q_i + \sum_{i=1}^{k} Q'_i + \sum_{i=1}^{l} \overline{Q}'_i + 2\sum_{i=1}^{m} \overline{Q}'_i = 0\ , \tag{2}$$

$$[SU(2)]^2 U(1) \ :\ 3\sum_{i=1}^{j} Q_i + 3\sum_{i=1}^{m} \overline{Q}'_i + \sum_{i=1}^{n} q_i = 0\ , \tag{3}$$

$$[U(1)]^3 \ :\ 6\sum_{i=1}^{j} Q_i^3 + 3\sum_{i=1}^{k} Q_i'^3 + 3\sum_{i=1}^{l} \overline{Q}_i^3 + 6\sum_{i=1}^{m} \overline{Q}_i'^3 + 2\sum_{i=1}^{n} q_i^3 + \sum_{i=1}^{p} \overline{q}_i^3 = 0. \tag{4}$$

The global Witten $SU(2)$ anomaly-free condition: $3j + 3m + n = 0 \mod 2$ (5)

The mixed anomaly-free condition:

$$[U(1)] : 6\sum_{i=1}^{j} Q_i + 3\sum_{i=1}^{k} Q'_i + 3\sum_{i=1}^{l} \overline{Q}_i + 6\sum_{i=1}^{m} \overline{Q}'_i + 2\sum_{i=1}^{n} q_i + \sum_{i=1}^{p} \overline{q}_i = 0\ . \tag{6}$$

The minimal solusions are: ☜ ***Minimality Condition with Chiral Fermions!***

CQG&R.Marshak, PRD39(1989)693

- $j=k=l=m=n=p=0$ NO *fermions*
- $j=1\,,\ k=0\,,\ l=2\,,\ m=0\,,\ n=1\,,\ p=1$

(a) $Q_1=0\,,\quad \bar{Q}_1=-\bar{Q}_2\,,\quad q_1=\bar{q}_1=0$ No *electroweak forces!*

(b) $Q_1=-\frac{q_1}{3}\,,\ \bar{Q}_1=\frac{4q_1}{3}\,,\ \bar{Q}_2=-\frac{2q_1}{3}\,,\ \bar{q}_1=-2q_1$

$SU(3)_C$	$\times$ $SU(2)_L$	$\times$ $U(1)_Y$
3	2	Q_1
$\overline{3}$	1	$\bar{Q}_1$
$\overline{3}$	1	$\bar{Q}_2$
1	2	q_1
1	1	$\bar{q}_1$

Minimality Condition with Chiral Fermions!

CQG&R.Marshak, PRD39(1989)693

The minimal solusions are:

- $j = k = l = m = n = p = 0$ NO *fermions*
- $j = 1\,,\ k = 0\,,\ l = 2\,,\ m = 0\,,\ n = 1\,,\ p = 1$

(a) $Q_1 = 0\,,\quad \bar{Q}_1 = -\bar{Q}_2\,,\quad q_1 = \bar{q}_1 = 0$ No *electroweak forces!*

(b) $Q_1 = -\frac{q_1}{3}\,,\ \bar{Q}_1 = \frac{4q_1}{3}\,,\ \bar{Q}_2 = -\frac{2q_1}{3}\,,\ \bar{q}_1 = -2q_1$

$q_1 = -1$ in unit of e $\longrightarrow$ The *standard model* with *one family*

Table 1. The quantum numbers of quark and lepton representations under $SU(3)_C \times SU(2)_L \times U(1)_Y$ and $SU(3)_C \times U(1)_{EM}$

Particles $(i = 1, 2, 3)$	$SU(3)_C$	$\times$	$SU(2)_L$	$\times$	$U(1)_Y$	$\rightarrow$	$SU(3)_C$	$\times$	$U(1)_{EM}$
$\begin{pmatrix} u \\ d \end{pmatrix}^i_L$	3		2		$\frac{1}{3}$		$\begin{pmatrix} 3 & 2/3 \\ 3 & -1/3 \end{pmatrix}$		
$u^{c\,i}_L$	$\overline{3}$		1		$-\frac{4}{3}$		$\overline{3}$		$-2/3$
$d^{c\,i}_L$	$\overline{3}$		1		$\frac{2}{3}$		$\overline{3}$		$1/3$
$\begin{pmatrix} \nu \\ e \end{pmatrix}^i_L$	1		2		-1		$\begin{pmatrix} 1 & 0 \\ 1 & -1 \end{pmatrix}$		
$e^{c\,i}_L$	1		1		2		1		1

Why the three anomaly cancellations, especially the global Witten $SU(2)$ and mixed gauge-gravitational ones, should be satisfied?

$\longrightarrow$ New Physics!

Unified Theory: G — Triangle $\mathcal{A}$nomaly free

$\Downarrow$

No global Witten $SU(2)$ and mixed gauge-gravitational anomalies when G breaks down $SU(3)_C \times SU(2)_L \times U(1)_Y$

It is very natural to think that the standard model comes from some form of New Physics unless the $\mathcal{A}$nomaly Cancellations are ACCIDENTS.

- Family problem

1. **Family Symmetry (gauged)?**

$$SU(3) \times SU(2) \times U(1) \times SU(2)$$

$$\Downarrow$$

Anomaly free + minimality

Left-right symmetric model

$SU(3)_C$	$\times$	$SU(2)_L$	$\times$	$SU(2)_R$	$\times$	$U(1)$
3		2		1		$\frac{1}{3}$
$\bar{3}$		1		2		$-\frac{1}{3}$
1		2		1		-1
1		1		2		1

1 family: quarks & leptons

CQG,PRD39(1989)2402

$$SU(3) \times SU(2) \times U(1) \times SU(3)$$

$$\Downarrow$$

Anomaly free + minimality

Chiral-color model

P.Frampton,S.Glashow, PRL58(1987)2168

$SU(3)_L$	$\times$	$SU(3)_R$	$\times$	$SU(2)_L$	$\times$	$U(1)$
3		1		2		$\frac{1}{3}$
1		$\bar{3}$		1		$-\frac{4}{3}$
1		$\bar{3}$		1		$\frac{2}{3}$
1		1		2		-1
1		1		1		2
$\bar{3}$		1		1		q
1		3		1		$-q$
$\bar{3}$		1		1		$-q-\frac{2}{3}$
1		3		1		$q+\frac{2}{3}$

one family of quarks and leptons

exotic fermions

2. Preon models

	$SU(N)_{MC}$	$\times$	$SU(N+4)_F$	$\times$	$U(1)_F$
F^{ia}	$\Box$		$\Box$		$(N+2)$
$\bar{S}_{ij}$	$\overline{\Box\Box}$		1		$-(N+4)$

CQG&R.Marshak, PRD35(1987)2278

In the Higgs phase: the most attractive channel (MAC)

$$F^{ia}\bar{S}_{ij}=(\Box;\Box,(N+2))\times(\overline{\Box\Box};1,-(N+4))\rightarrow(\bar{\Box};\Box,-2)$$

$$SU(N)_{MC}\times SU(N+4)_F\times U(1)_F\rightarrow \widetilde{SU}(N)_F\times SU(4)_F\times\tilde{U}(1)_F$$

$$\left(\begin{smallmatrix}\Box\\\Box\end{smallmatrix},1,2(N+4)\right),\ (\Box,\Box,N+4)$$

complementarity

In the confining phase: the t'Hooft anomaly-free conditions

	Preons	$SU(N)_{MC}$	$\times$	$SU(N)_F$	$\times$	$SU(4)_F$	$\times$	$\tilde{U}(1)_F$
$F^{ia}\rightarrow$	p_1'	$\Box$		$\Box$		1		$2(N+4)$
	p_1''	$\Box$		1		$\Box$		$N+4$
$\bar{S}_{ij}\rightarrow$	p_2	$\overline{\Box\Box}$		1		1		$-2(N+4)$

Composites					Indices	
$p_1'p_1''p_2$	1	$\Box$	$\Box$	$N+4$	l_1	$l_1=1$
$p_1'p_1'p_2$	1	$\Box\Box,\begin{smallmatrix}\Box\\\Box\end{smallmatrix}$	1	$2(N+4)$	l_2,l_2'	$l_2=0,\ l_2'=1$
$p_1''p_1''p_2$	1	1	$\Box\Box,\begin{smallmatrix}\Box\\\Box\end{smallmatrix}$	0	l_3,l_3'	$l_3=l_2'=0$

For N=15, $\left(\begin{smallmatrix}\Box\\\Box\end{smallmatrix},1,38\right)$ and $(\Box,\Box,19)$ under $SU(15)_F\times SU(4)_F\times\tilde{U}(1)_F$.

Gauging the subgroup SU(5) of $SU(15)_F$:

$\Box\rightarrow\bar{5}+10$,

$\begin{smallmatrix}\Box\\\Box\end{smallmatrix}\rightarrow 5+\overline{10}+\overline{45}+45$

☞

$N_g=3$ of chiral fermions

$\bar{5}+10$

3. High-dimensional spacetime

In an extra dimensional theory, there are many types of chiral anomalies

M.Bershadsky, C.Vafa hep-th/9703167

For D spacetime dimensions:

$$\Pi_D(G)=Z_n \rightarrow c_D[N(p_{L_D})-N(p_{R_D}) = 0 \bmod n_D$$

where $\Pi_D(G)$ is the D-th homotopy group, similar to the Witten SU(2) global anomaly in D=4:

$\Pi_4(SU(2))=Z_2$; $N(2_{L4})-N(2_{R4})=0 \bmod 2$ $(c_4=1)$

For D=6: **Global gauge anomalies**

$$\Pi_6(SU(3))=Z_6 \rightarrow N(3_{L6})-N(3_{R6}) = 0 \bmod 6\ (c_6=1)$$

$$\Pi_6(SU(2))=Z_{12} \rightarrow N(2_{L6})-N(2_{R6}) = 0 \bmod 6\ (c_6=2)$$

In the SM: $N(3_{L6})=N(3_{R6})$; $N(2_{L6})=4$, $N(2_{R6})=0$

B.A.Dobrescu, E.Poppitz, PRL87(2001)031801

$\rightarrow N_g = 0 \bmod 3$ ☞ $N_g = 3$ (minimal value)

4. CP violation in the SM

M. Kobayahsi, K. Maskawa, Progr. Theor. Phys. **49** (1973) 652.

Gauge couplings $W^{\pm}$: $\boxed{\sum_i \bar{U}_{Li}\gamma_\lambda D_{Li}} \longrightarrow \boxed{\sum_{ij} \bar{U}'_{Lj}\gamma_\lambda V_{ji} D'_{Li}}$

See Xing's lectures

$V = (V^u_L)^+ V^d_L$, $(V^+V = 1)$

Unitary matrix: $V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$

Counting the parameters:

$n \times n$ complex matrix : $2n^2$

$n \times n$ unitary matrix : n^2

rot. angles : $\frac{n(n-1)}{2}$

phases : $n^2 - \frac{n(n-1)}{2} = \frac{n(n+1)}{2}$

Some of the phases in V can be removed by choosing the $(2n-1)$ phase differences $\theta_j - \phi_i$ appropriately.

$$u^i_L \to e^{i\phi_i}\, u^i_L\,, \quad d^i_L \to e^{i\theta_i}\, d^i_L \quad \longrightarrow \quad V_{ij} \to V_{ij}\, e^{i(\theta_j - \phi_i)}$$

$\Rightarrow$ observable or physical phases : $\frac{n(n+1)}{2} - (2n-1) = \frac{(n-1)(n-2)}{2}$

For two generations $(n=2)$ $\Rightarrow$ **no phase** $+$ 1 angle

For three generations $(n=3)$ $\Rightarrow$ one phase $+$ 3 angles

CP Violation in the standard model

5. A toy model

$\mathcal{A}$-free + $\mathcal{M}$inimality: $SU(N) \times SU(2) \times U(1)$

$N = 2k$

$SU(N)$	$SU(2)$	$U(1)$
N	2	0
$\overline{N}$	1	-1
$\overline{N}$	1	1

$N = 2k + 1$

$SU(N)$	$SU(2)$	$U(1)$
N	2	$1/N$
$\overline{N}$	1	$-1/N - 1$
$\overline{N}$	1	$-1/N + 1$
1	2	-1
1	1	2

$SU(N)_C$	$SU(2)_L$	$SU(2)_R$
N	2	1
$\overline{N}$	1	2

N=12 →

$SU(12)_C$	$SU(2)_L$	$SU(2)_R$
12	2	1
$\overline{12}$	1	2

CQG,hep-ph/0101329

$$\downarrow$$

$$SU(12)_C \times SU(2)_L \times SU(2)_R$$

$$\downarrow$$

$$SU(8)_C \times SU(4)_{C1} \times SU(2)_L \times SU(2)_R \times U(1)$$

$$\downarrow$$

$$SU(4)_{C3} \times SU(4)_{C2} \times SU(4)_{C1} \times SU(2)_L \times SU(2)_R \times U(1) \times U(1)$$

$$\downarrow$$

$$\downarrow$$

$$SU(4)_C \times SU(2)_L \times SU(2)_R$$

$$\downarrow$$

$$\downarrow$$

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

three quark and lepton families

with right-handed neutrinos

A note on the color number: N_c

Particles	$SU(N)_C$	$\times SU(2)_L$	$\times U(1)_Y$	$\rightarrow$ $SU(N)_C$	$\times U(1)_{EM}$
$(i = 1, 2, 3)$					
$\begin{pmatrix} u \\ d \end{pmatrix}_L^i$	N	2	$\frac{1}{N}$	$\begin{pmatrix} N \\ N \end{pmatrix}$	$\begin{pmatrix} \frac{N+1}{2N} \\ -\frac{N-1}{2N} \end{pmatrix}$
$u_L^{c\,i}$	$\overline{N}$	1	$-\frac{N+1}{N}$	$\overline{N}$	$-\frac{N+1}{2N}$
$d_L^{c\,i}$	$\overline{N}$	1	$\frac{N-1}{N}$	$\overline{N}$	$\frac{N-1}{2N}$
$\begin{pmatrix} \nu \\ e \end{pmatrix}_L^i$	1	2	-1	$\begin{pmatrix} 1 \\ 1 \end{pmatrix}$	$\begin{pmatrix} 0 \\ -1 \end{pmatrix}$
$e_L^{c\,i}$	1	1	2	1	1

← $Q_u = e(N+1)/(2N)$

← $Q_d = -e(N-1)/(2N)$

C.Chow, T.M.Yan, PRD53, 5105(1996); R.Shrock, PRD53, 6465(1996)

V.A.Kovalchuk, JETP Lett. 48 (1988) 11

R.Marshak, "Conceptual foundations of modern particle physics," Singapore, WS (1993)

For $\pi^0 \rightarrow \gamma\gamma$, the decay width:

$$\Gamma_{\pi^0\rightarrow\gamma\gamma} \propto N(Q_u^2 - Q_d^2) \xrightarrow{Q_u^2 - Q_d^2 = e^2/N} e^2$$ ☞ independent on the color number N!

The result is true for any anomalous process.

BUT: $\boldsymbol{R} \equiv \sigma(e^+e^- \rightarrow \text{hadron})/\sigma(e^+e^- \rightarrow \mu^+\mu^-) = N\,\Sigma Q_u^2 \propto N$ ☞ dependent on the color number N!

- Concluding remarks

1. Three anomaly-free conditions $\longrightarrow$ the quark and lepton representations and their charges under the standard $SU(3)_C \times SU(2)_L \times U(1)_Y$ group.

2. The determination of the uniqueness of the standard model due to the *Anomaly Cancellations* argues strongly for new physics beyond the standard model, especially some form of quark-lepton unification.

3. Family problem:

$\triangle$ some as-yet-unidentified anomaly?

$\diamondsuit$ larger symmetries?

$\heartsuit$ higher dimensions?

$\spadesuit$ Preons?

$\clubsuit$ Others?

4. Neutrino masses

In the SM:

- A $SU(2)$ doublet fundamental scalar Higgs field is employed to give masses to **BOTH** the $SU(2) \times U(1)$ gauge bosons and fermions.

$$H = \begin{pmatrix} 0 \\ \frac{v+h^0}{\sqrt{2}} \end{pmatrix}, \quad v = 247\mathrm{GeV}$$

- Higgs fermion interaction

$$y_e \left(\overline{\nu_{eL}} \quad \overline{e_L}\right) \begin{pmatrix} 0 \\ \frac{v+h^0}{\sqrt{2}} \end{pmatrix} e_R + h.c. \to \frac{y_e\, v}{\sqrt{2}} \bar{e} e + \frac{y_e v}{\sqrt{2}} \bar{e}\, e h^0$$

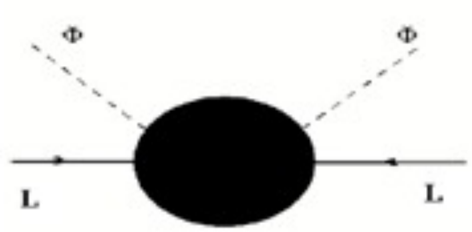
- Fermion mass $m_f = \frac{y_f v}{\sqrt{2}}$ and $\bar{f} f H$ coupling is proportional to fermion mass
- What about neutrinos?
- Do they get their masses like other fermions?

See Petcov's lectures

■ No Dirac mass term (no right-handed neutrino).

■ No Majorana mass term either (ν_L is an SU(2) doublet).

S. Weinberg, Phys. Rev. D22, 1694 (1980).



Dimension five operator responsible for neutrino mass

Effective Dim-5 operator:

$$O = (\lambda_0 / M_X) LHLH$$

$\downarrow$ ***SSB***

$$m_\nu = \lambda_0 \frac{\langle H \rangle^2}{M_X}, \qquad \text{(Majorana)}$$

For $\lambda_0 \sim 1$, $\langle H \rangle \sim 100$ GeV, $M_X \sim M_P \;\to\; m_\nu \sim 10^{-6}$ eV (too small)

(a) If the right handed neutrinos ν_R exist:

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

ν_R	1	1	0

No anomaly, not a chiral field

#s are arbitrary + ~~minimality~~

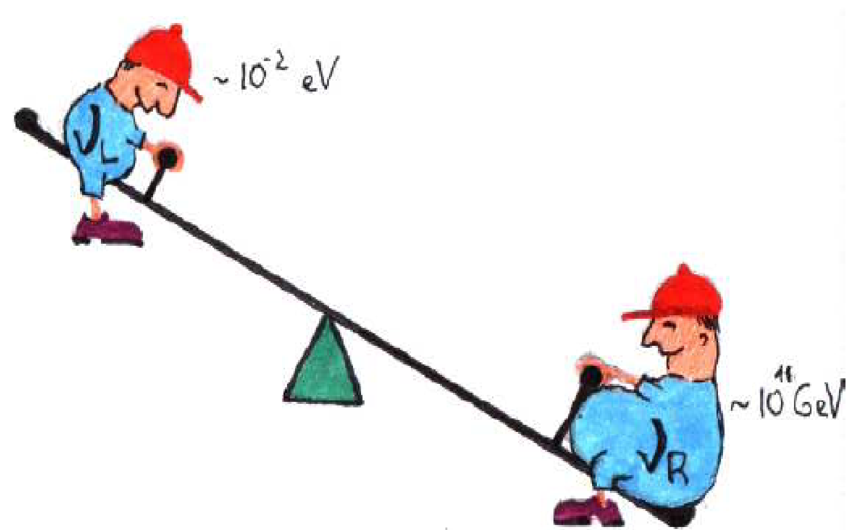
☞ $$\mathcal{L}_Y = Y_\nu \bar{L} \mathrm{H} \nu_R + h.c. \Rightarrow m_\nu^D = Y_\nu < \mathrm{H} >$$

Dirac masses like others

The observed neutrino masses would require $Y_\nu \leq 10^{-13} - 10^{-12}$ (unnatural)

Note that without minimality, *vectorlike particles* can be added arbitrarily.

(b) Majorana mass for ν_R: $M_R \nu_R^T C^{-1} \nu_R + h.c.$



See-saw mechanism:

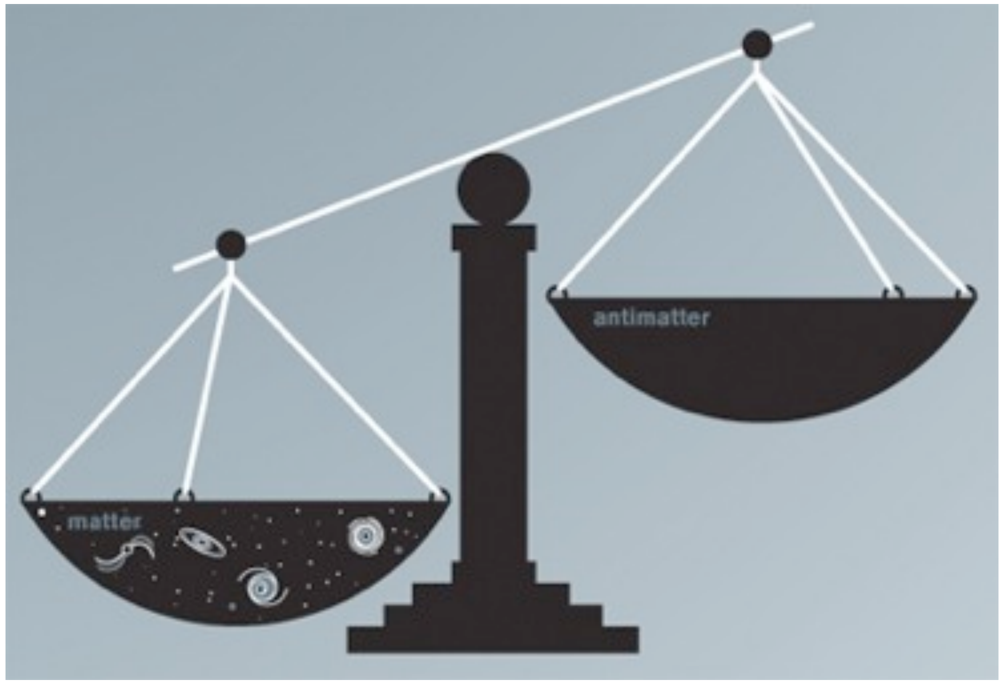
$$\mathcal{M}_\nu = -m_D^T M_R^{-1} m_D.$$

(naturally small?+Majorana)

☞ International Conference on Massive Neutrinos

Feb. 9-13, 2015, NTU, Singapore

5. Matter-antimatter asymmetry



1. *Baryon number violation*
2. *C and CP violation*
3. *A departure from thermal equilibrium*

1967: Sakharov

See Xing's lectures

The CP violating mechanism in the SM, i.e. the phase in the CKM, cannot account for the matter-antimatter asymmetry in the universe.

☞ New Physics beyond the SM!

Preface

Lecture 1: The uniqueness of the standard model of particle physics and Beyond

Lecture 2: Dark Matter and Cosmic Ray Anomalies

Lecture 3: Understanding Dark Energy beyond the LCDM: Modified Theories of Gravity

Conclusions

Future prospects

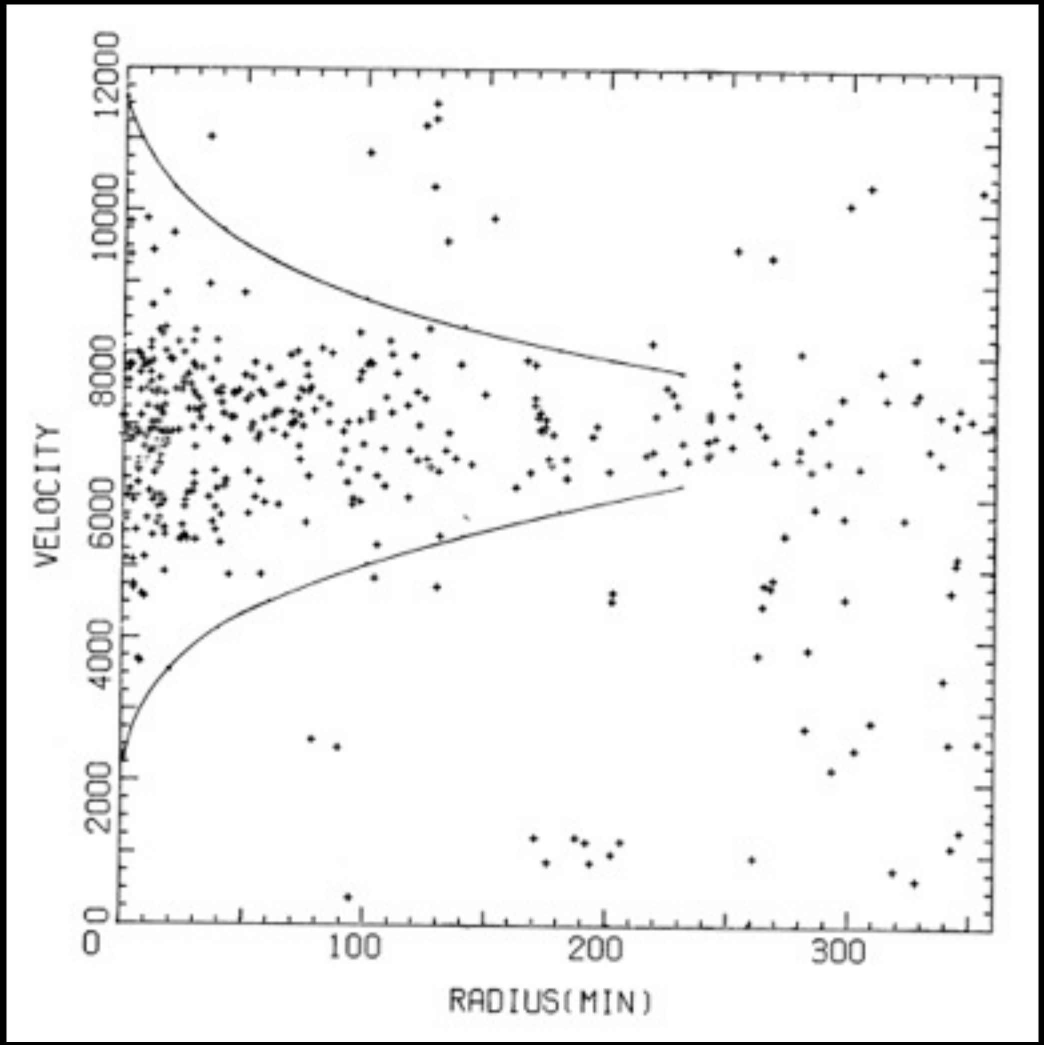
Lecture 2
Dark Matter and Cosmic Ray Anomalies

Outline

- ***Evidences for Dark Matter***
- ***Cosmic Ray Anomalies***
- ***Dark Matter Interpretation***
- ***Open Questions***

• *Evidences Dark Matter*

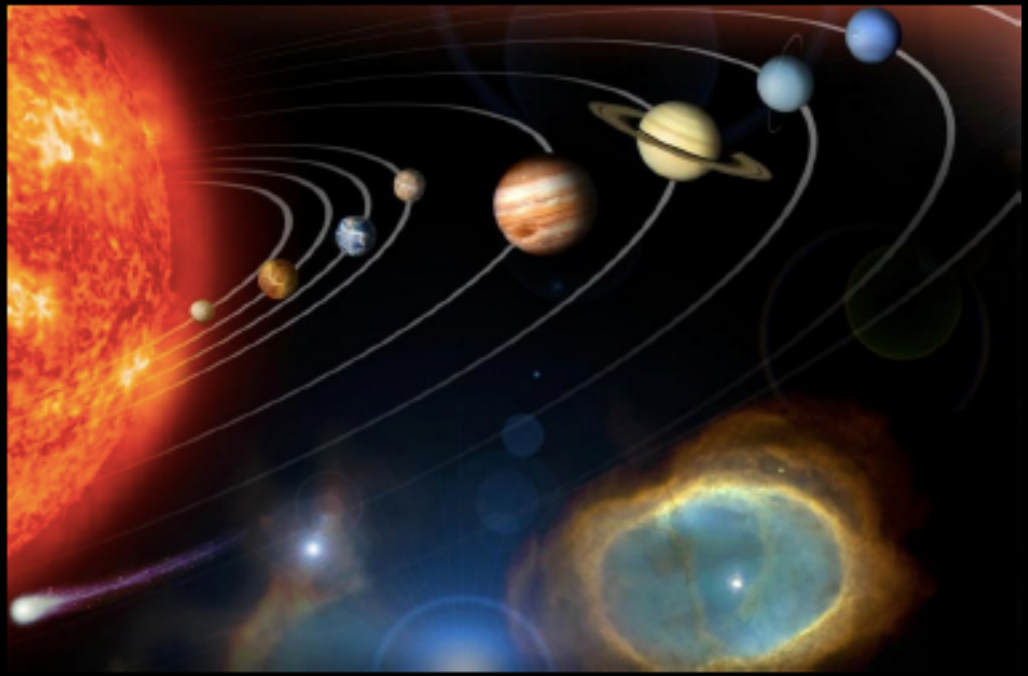
Zwicky (1933) used the radial velocity dispersion in the Coma cluster to conclude that the mass of luminous matter = 10% Gravitational mass .



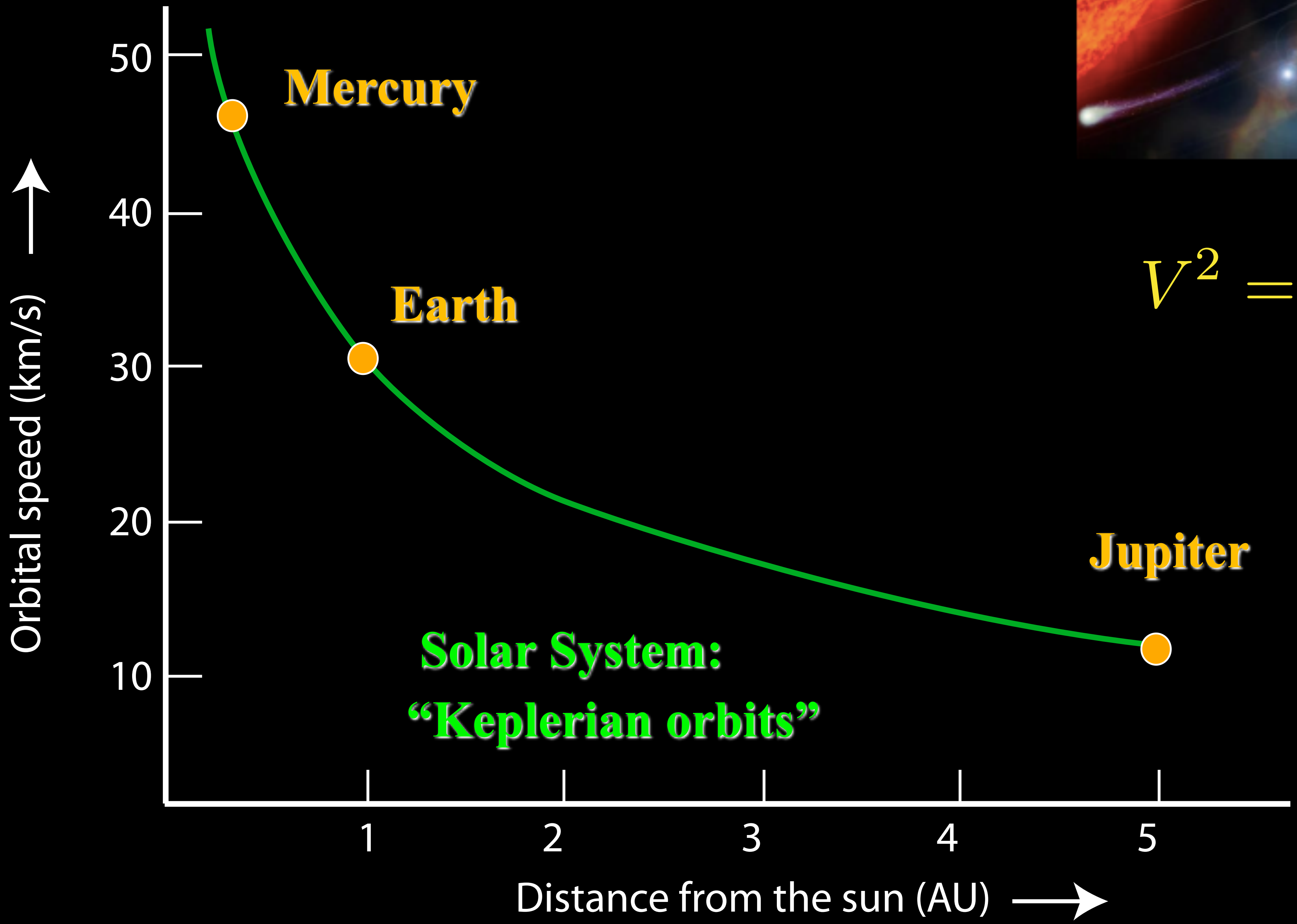
COMA cluster

F. Zwicky 1933

Solar System:



$$V^2 = \frac{GM(<r)}{r}$$



1970 ApJ 159, 379

ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

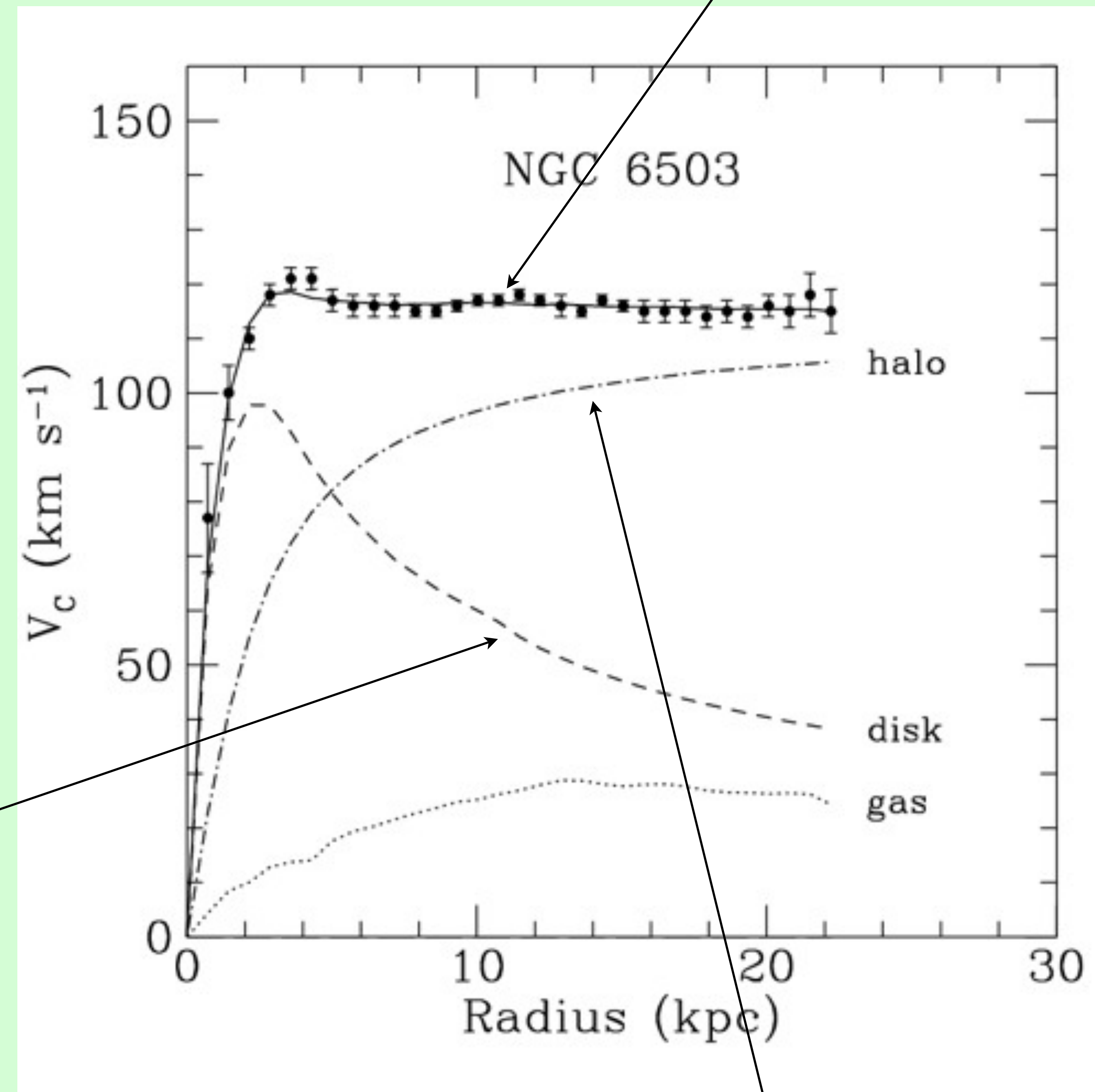
VERA C. RUBIN† AND W. KENT FORD, JR.†

Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory‡

See Sola's lectures

v~constant

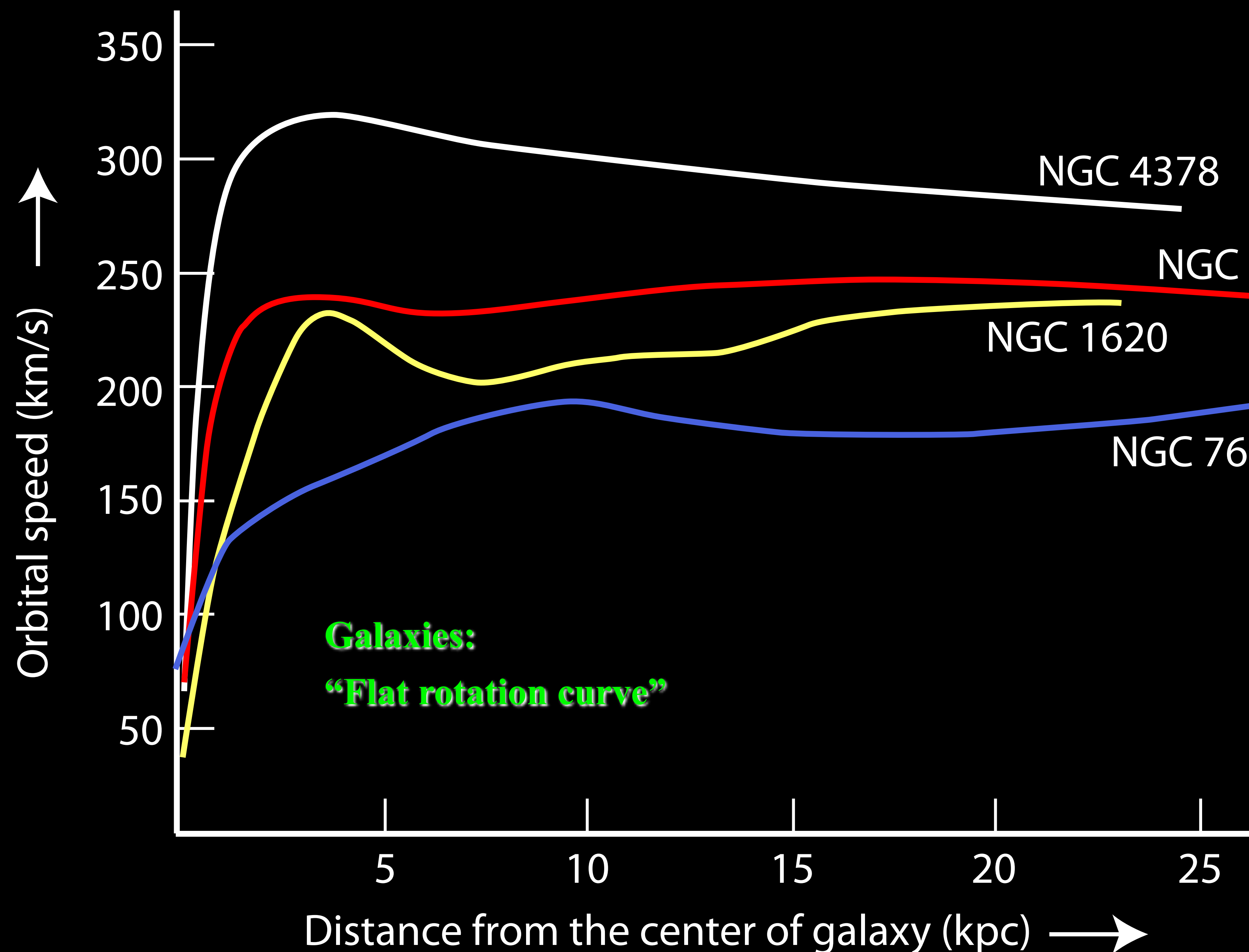
Spiral galaxy

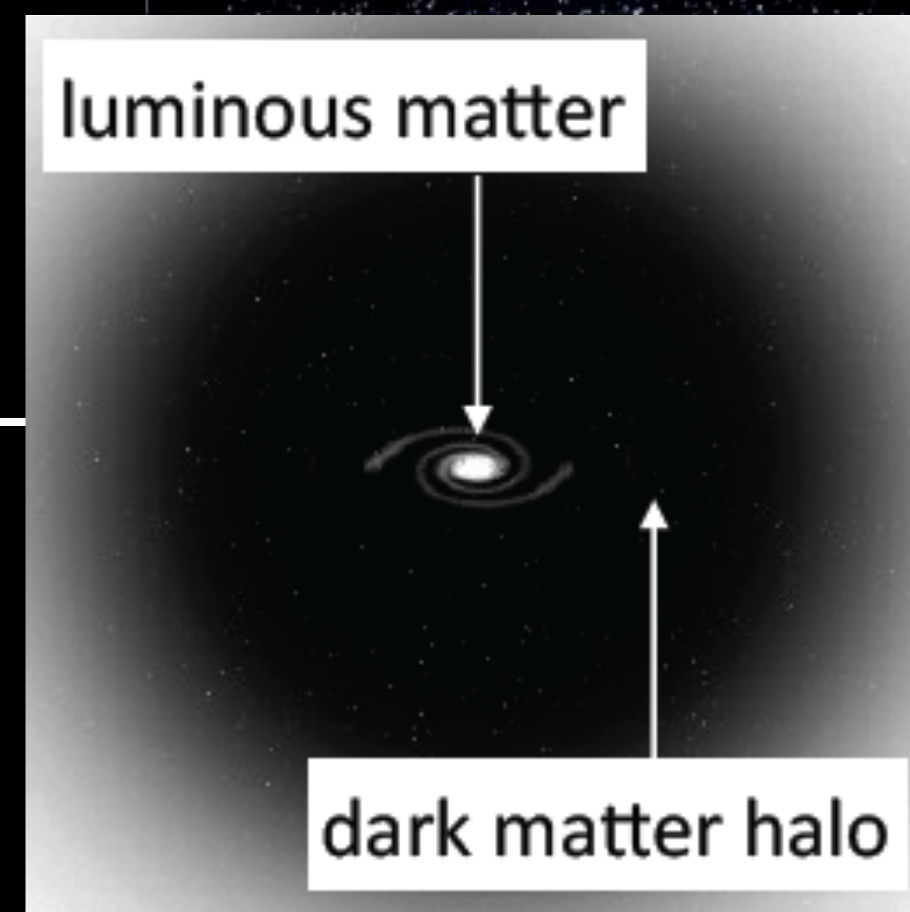


$$\frac{GM(<r)}{r^2} = \frac{v^2}{r}$$

Stars would be moving too fast if there were only luminous matters

A spherical dark matter halo

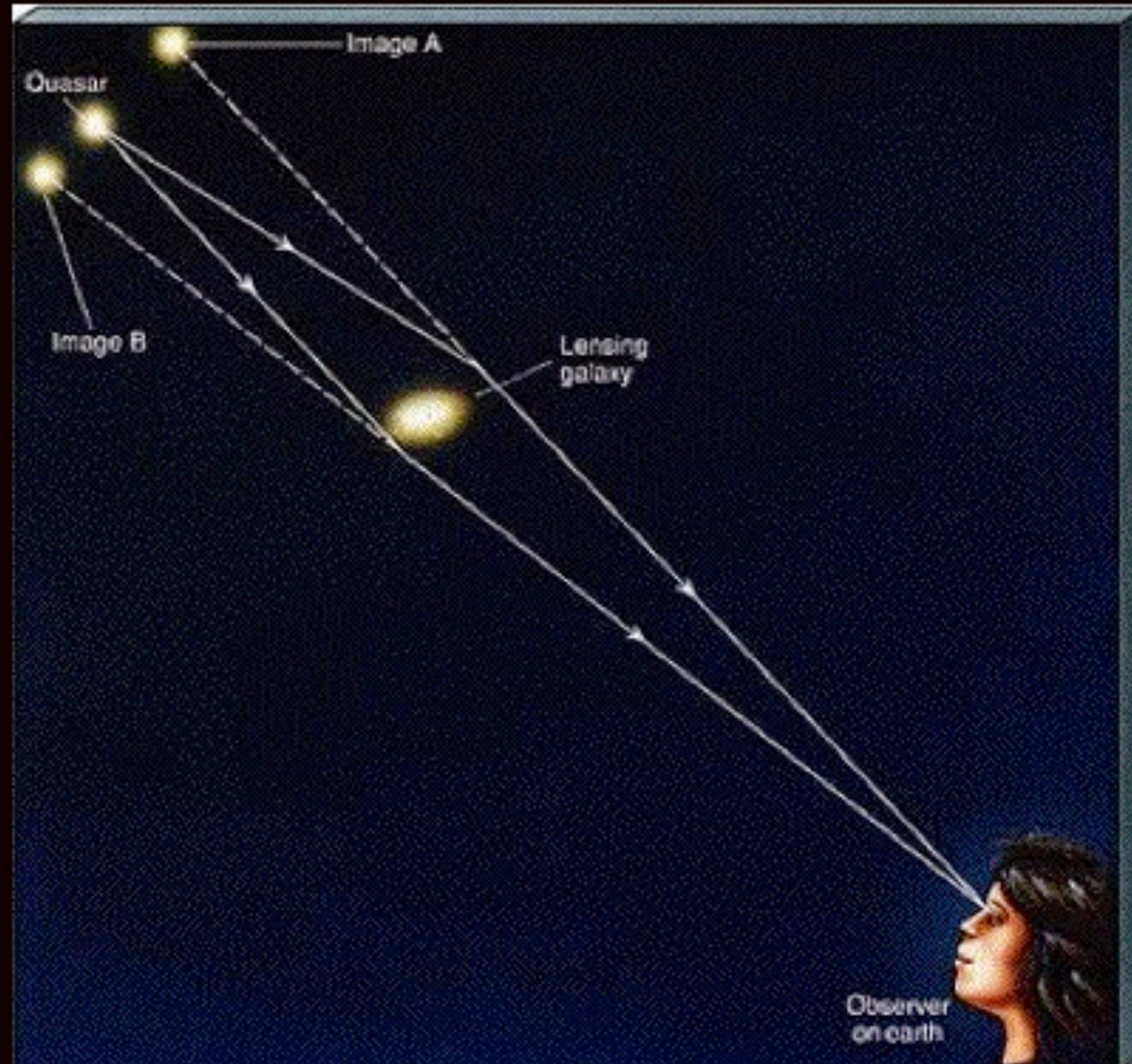

350
300
250
200
150
100
50
Orbital speed (km/s)
5
10
15
20
25
Distance from the center of galaxy (kpc)
NGC 4378
NGC 3145
NGC 1620
NGC 7664
Galaxies:
“Flat rotation curve”


luminous matter
dark matter halo

Most -72%- large galaxies have spiral structures

One way to "weigh" things in the universe:

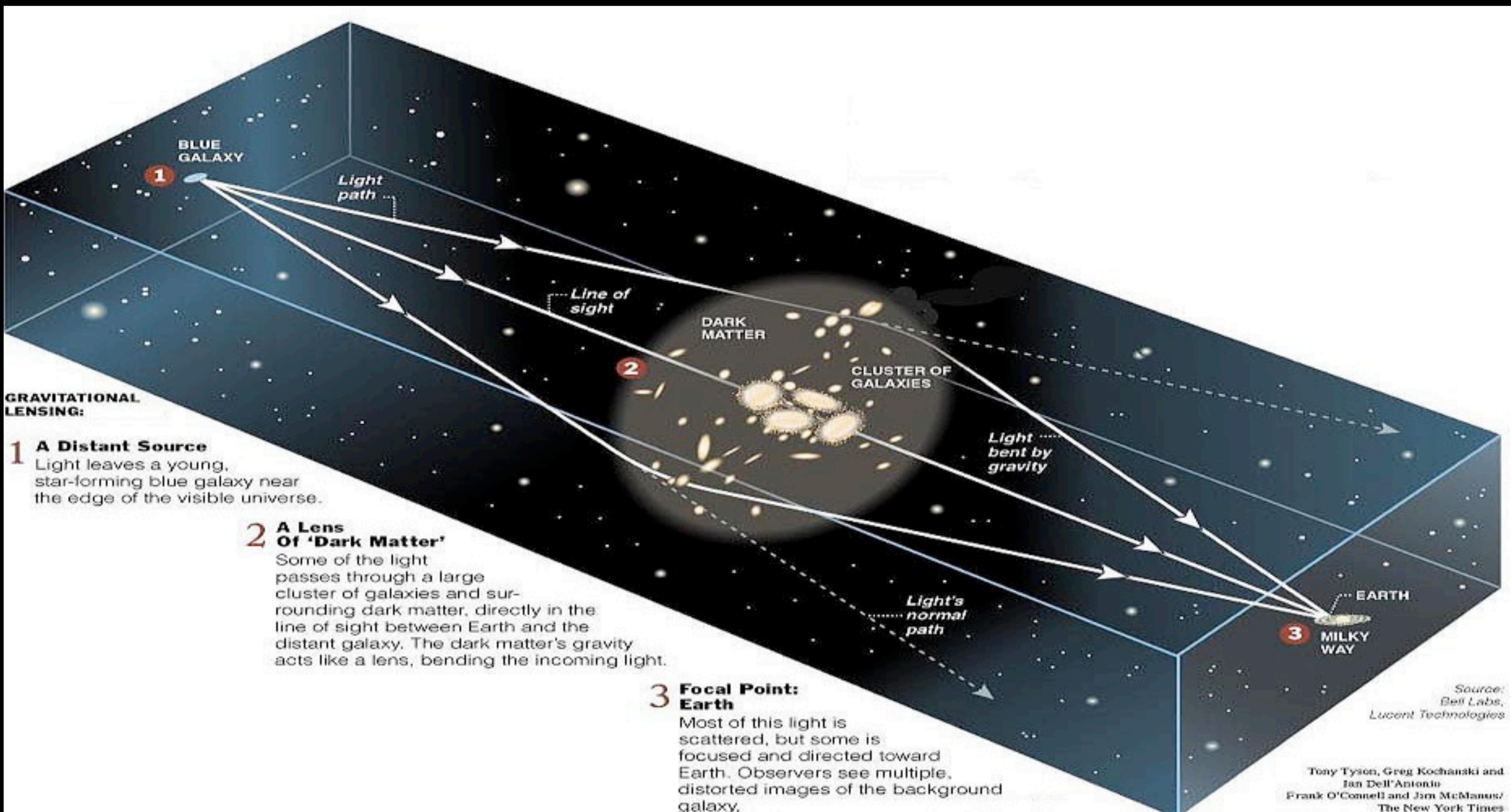
Gravitational lensing.



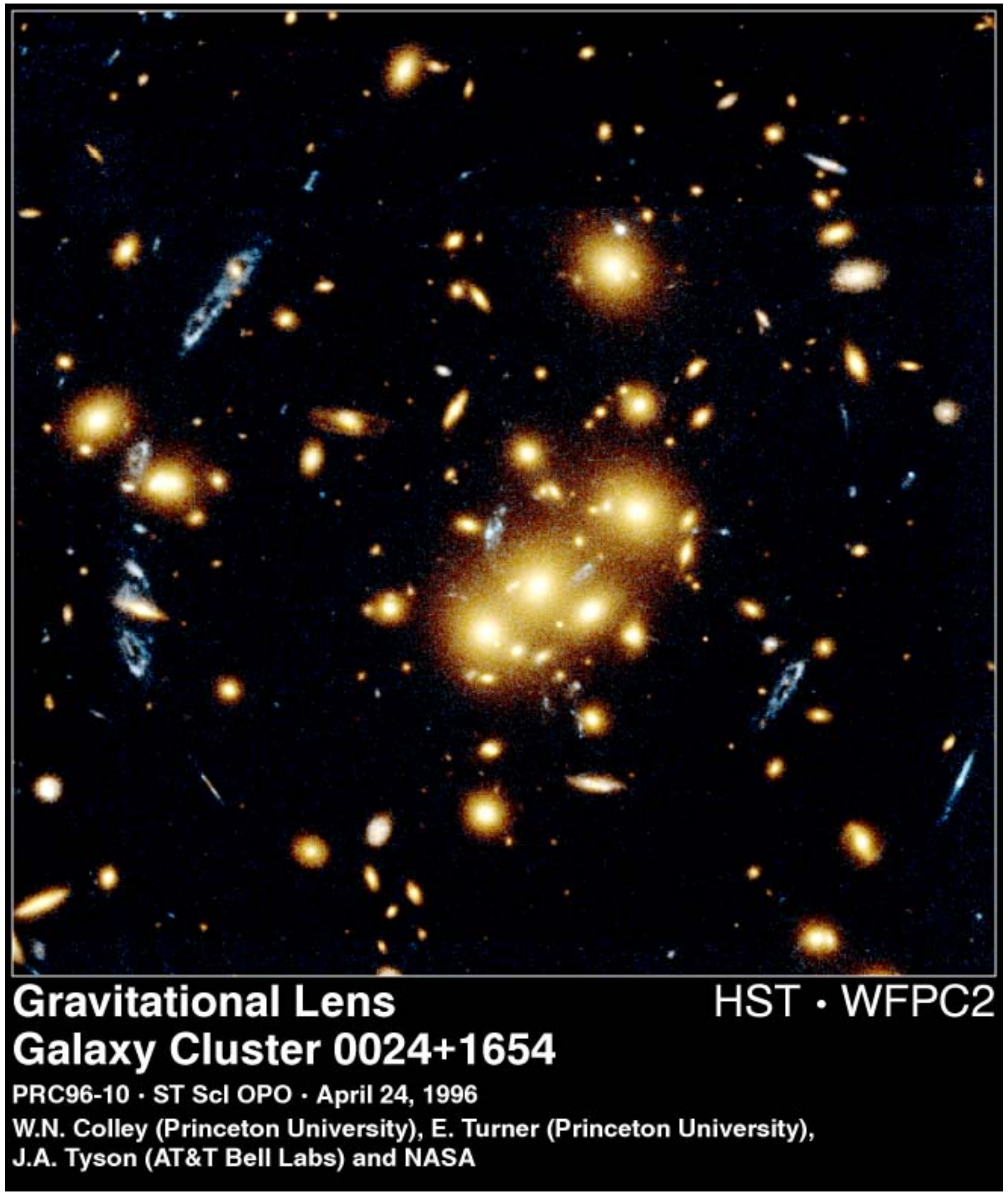
The gravitational field of a galaxy (or cluster of galaxies) deflects passing light; the more mass, the greater deflection.

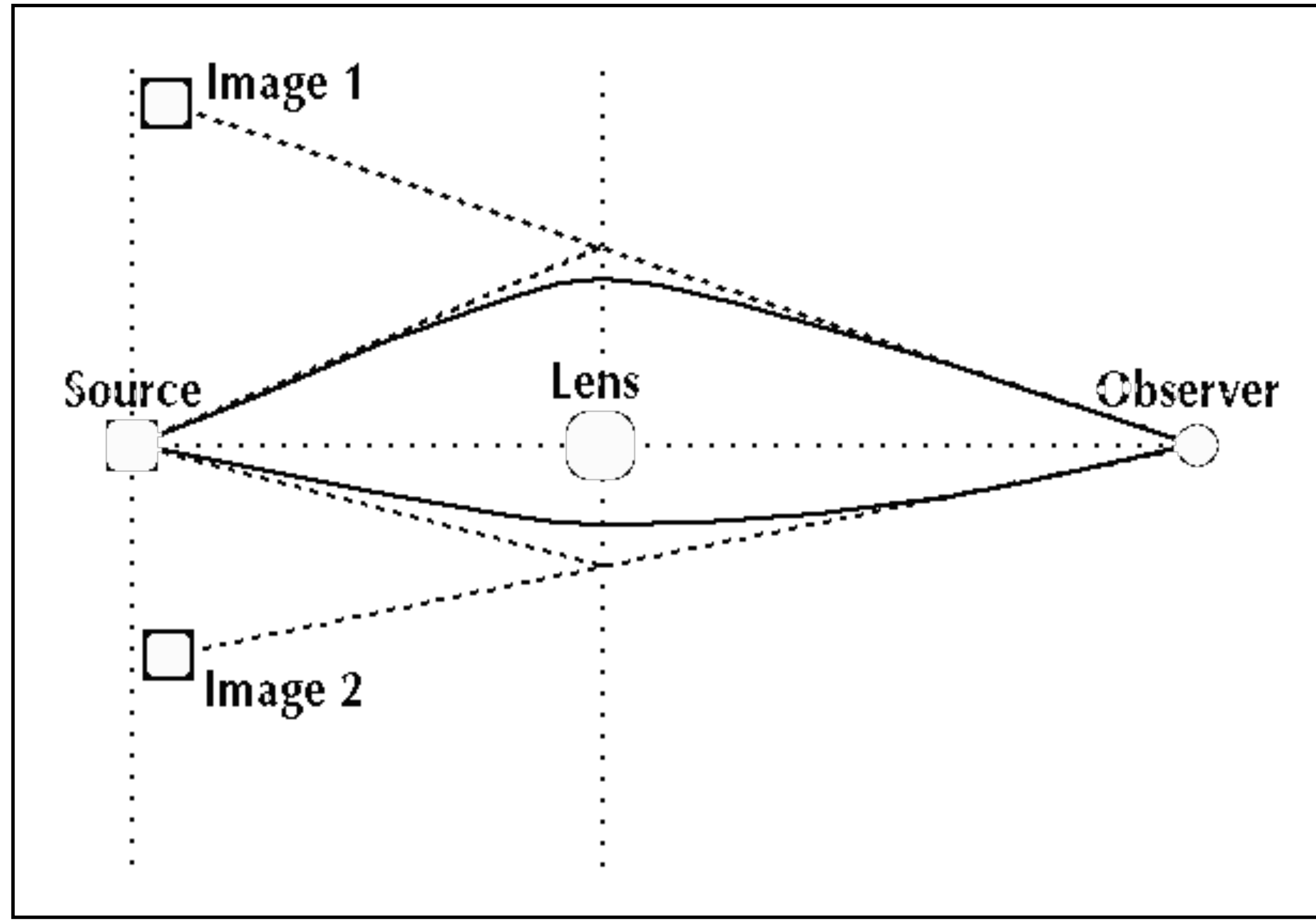
So we can infer the existence of matter even if we can't see it.

Gravitational Lensing



Gravitational Lensing

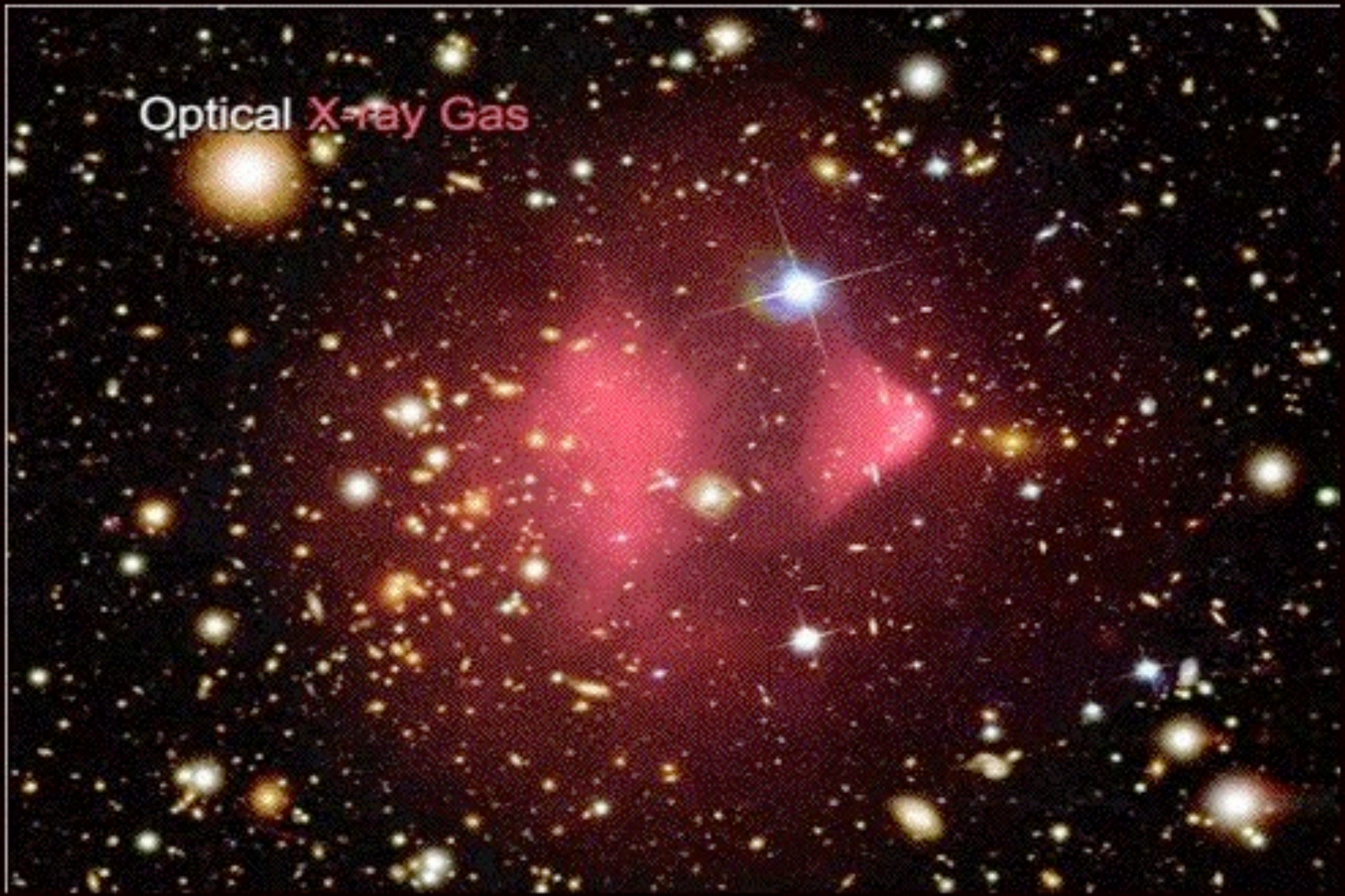




- **Clusters & Superclusters**
  - ↳ **Gravitational Lensing**
    - ⇒**Grav. Mass > Lum. Mass**

☞ Dark Matter

Bullet Cluster

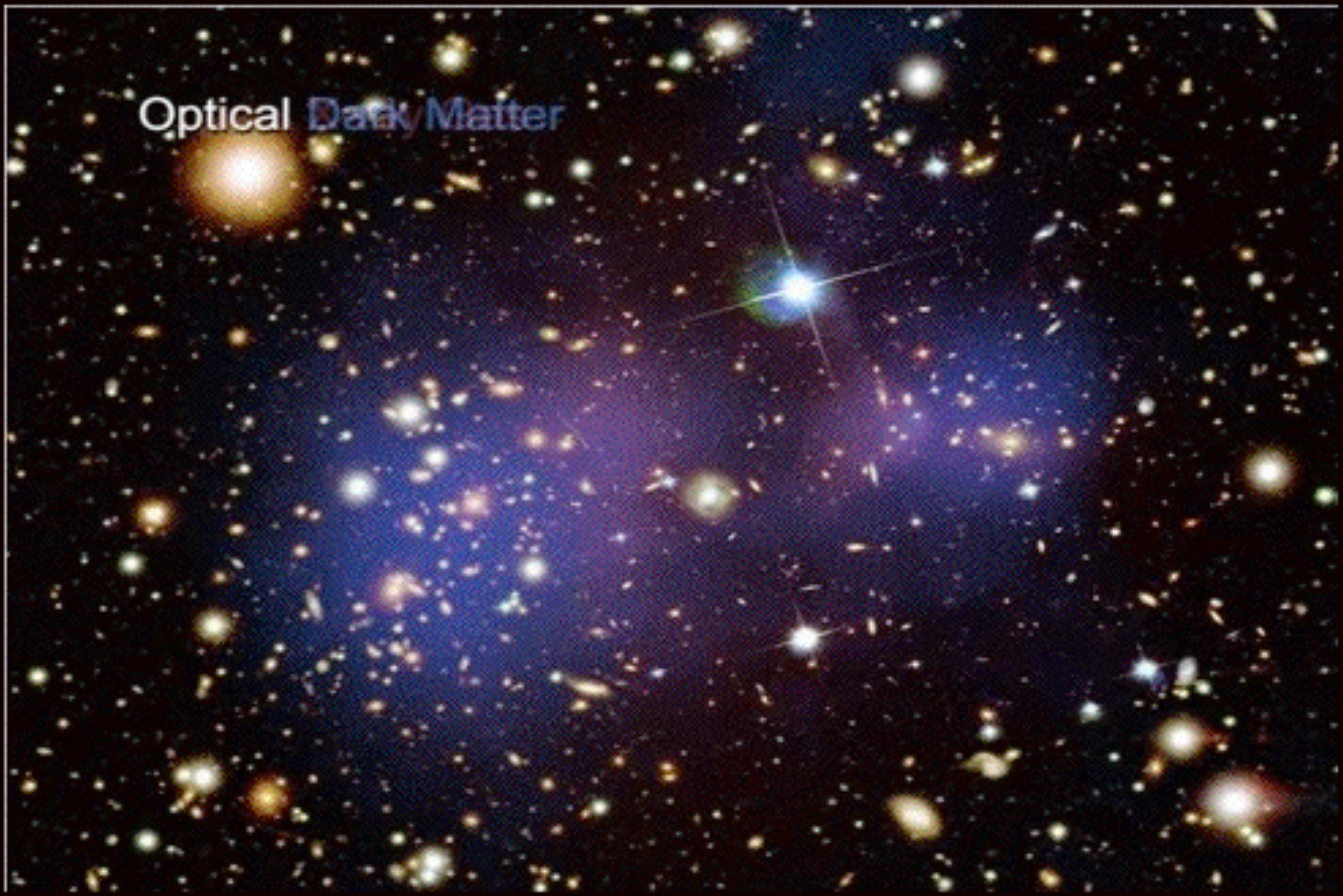


[Clowe et al.]

Bullet Cluster

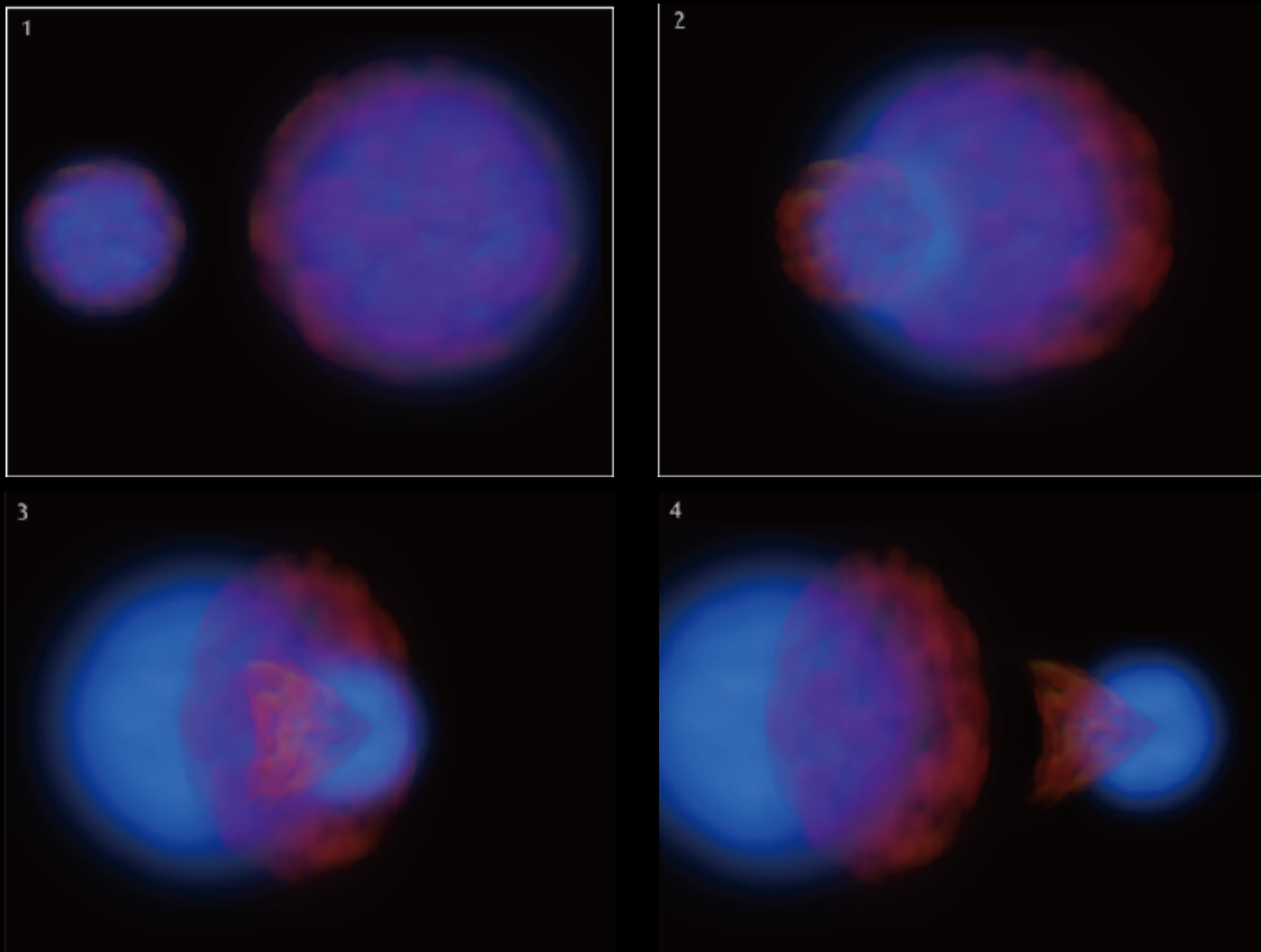
[Clowe et al.]

Bullet Cluster

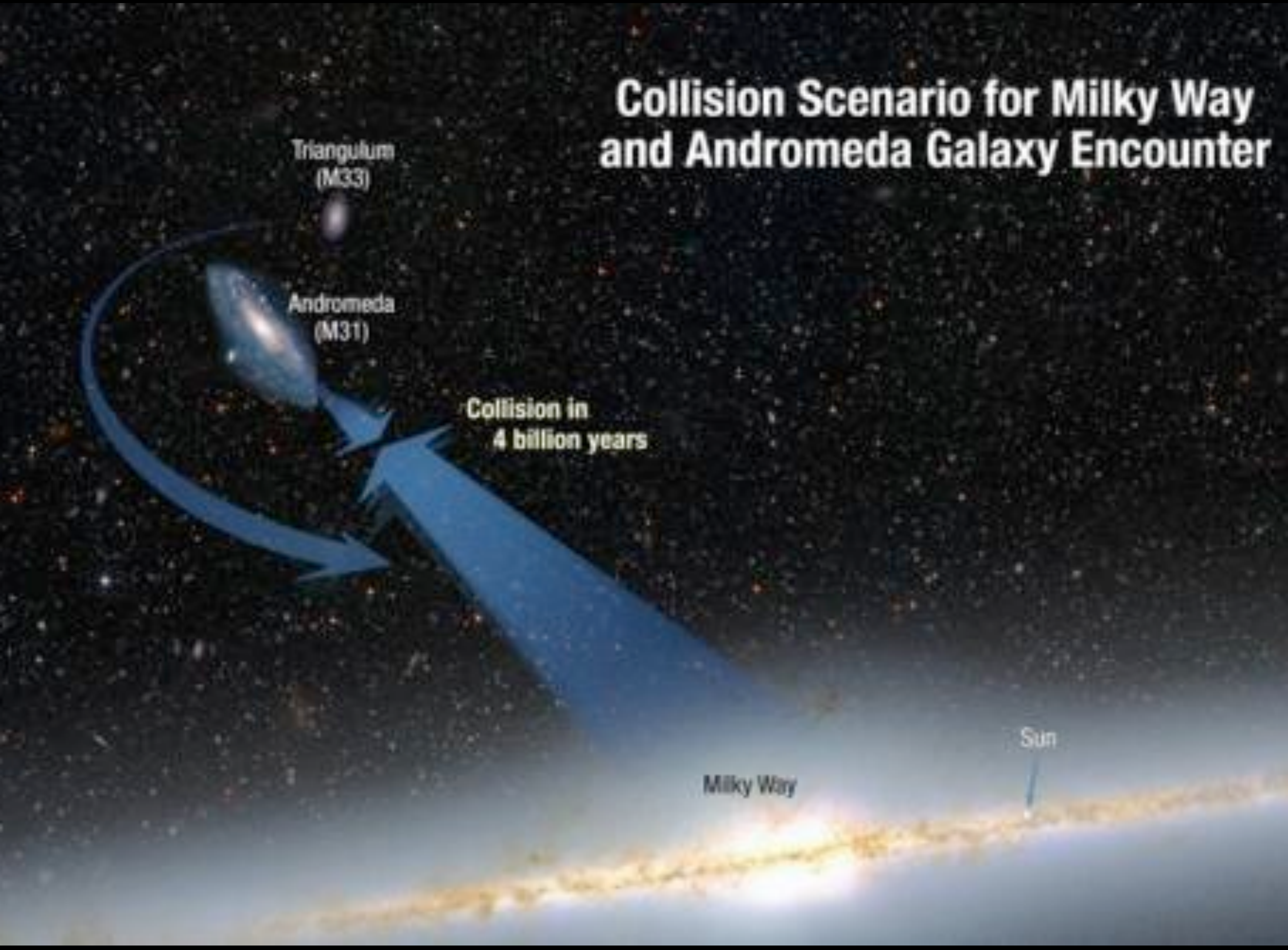


[Clowe et al.]

Merging Clusters artists' rendition

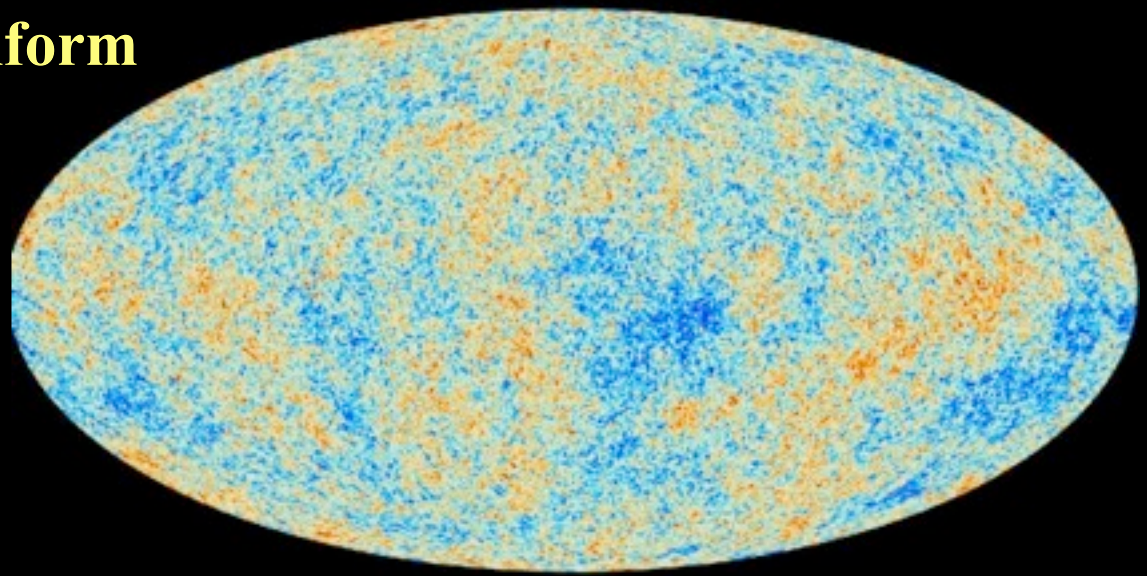



Andromeda
M31
Our Galaxy

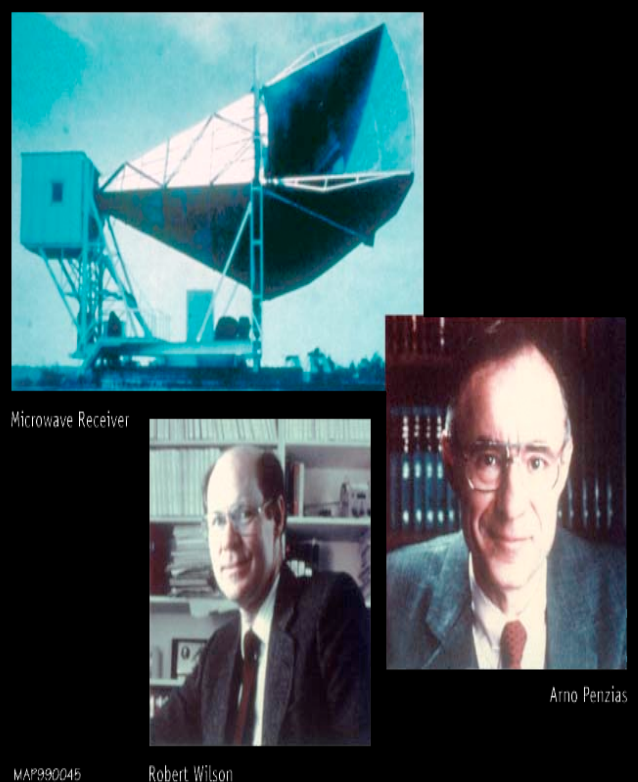

Collision Scenario for Milky Way
and Andromeda Galaxy Encounter
Triangulum
(M33)
Andromeda
(M31)
Collision in
4 billion years
Sun
Milky Way

Cosmic Microwave Background (CMB)

very cold (-270.275 C, 2.725 K) and nearly uniform relic radiation left over from the hot big bang

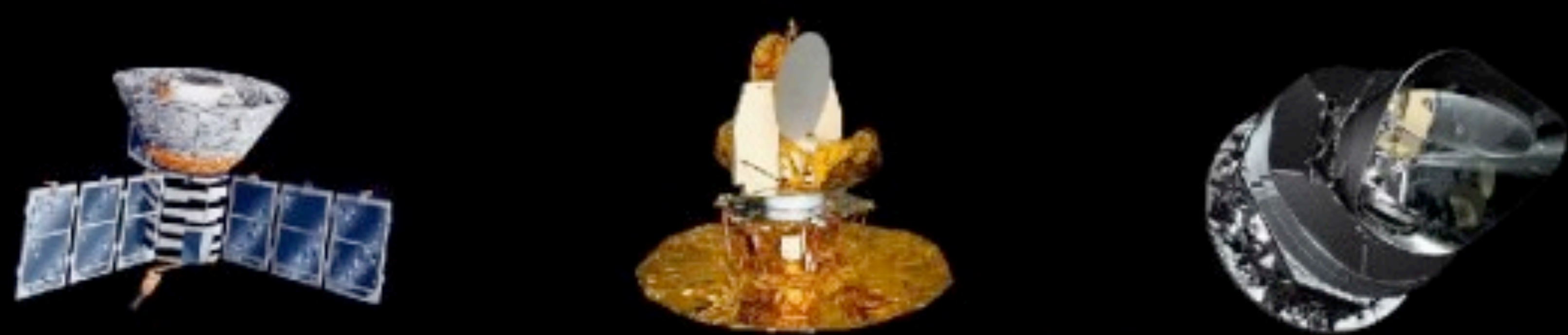


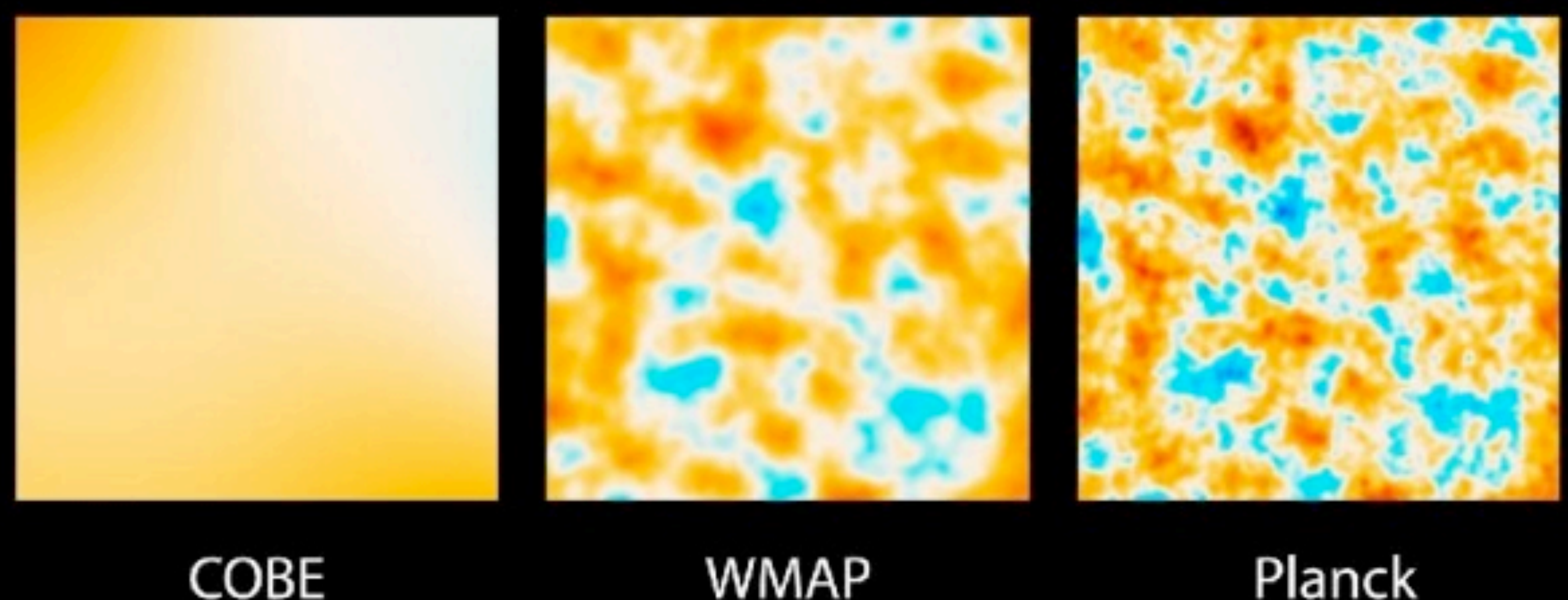
Discovery of Cosmic Background



1965

Nobel Prize 1978

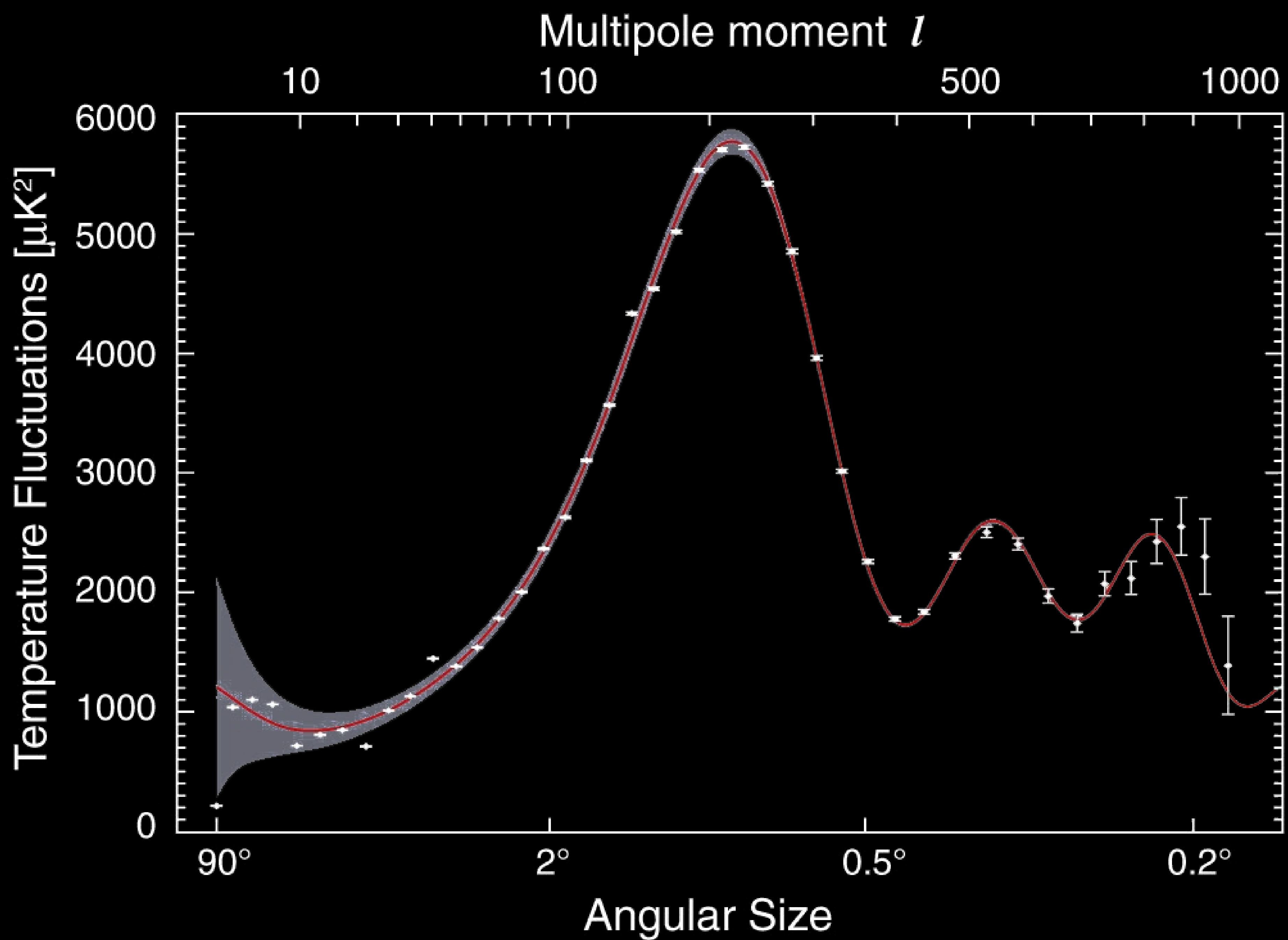




1992 **Nobel Prize 2006**

2001-2010

2009-2013

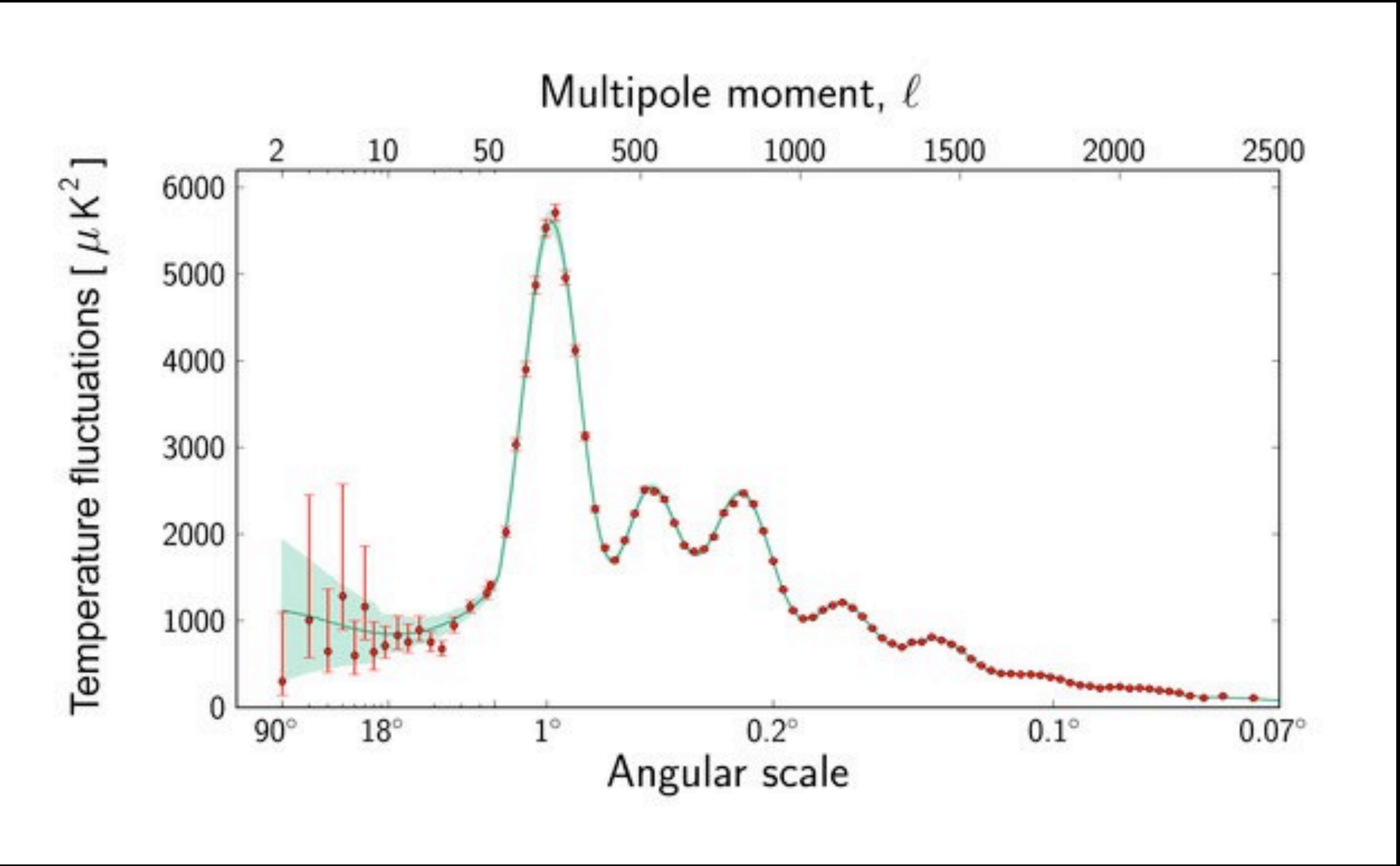


White points:
WMAP (2010)
7-year data

Red curve: Theoretical prediction for a universe made of

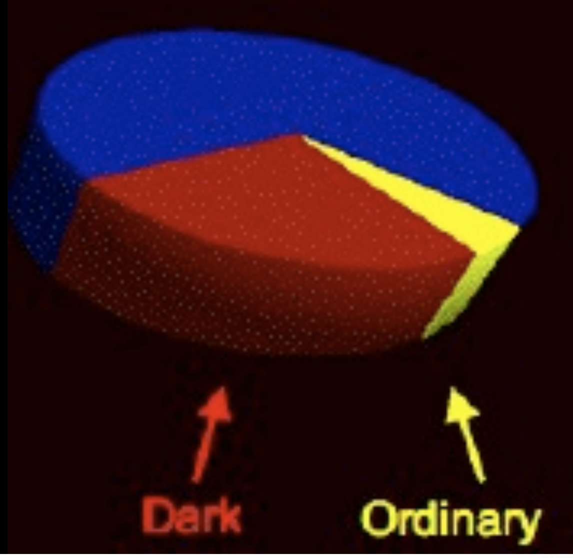
70% dark energy, 25% dark matter, 5% atoms

Planck 2013



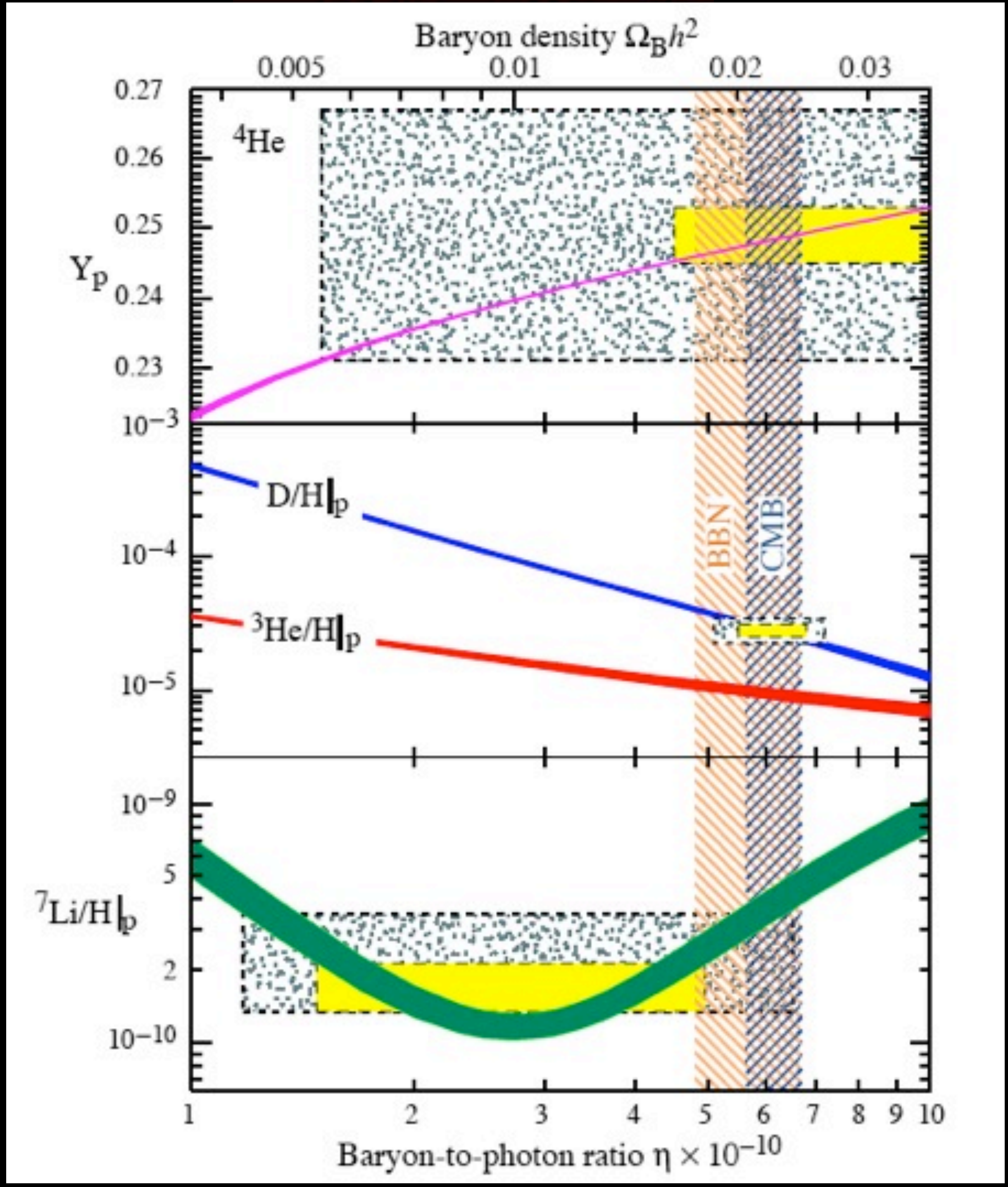
68.3% dark energy, 26.8% dark matter, 4.9% atoms

Dark Matter: 26.8%



See Xing's lectures

Independent methods (using primordial nucleosynthesis & the microwave background) convince us that the dark matter is a completely new kind of particle.



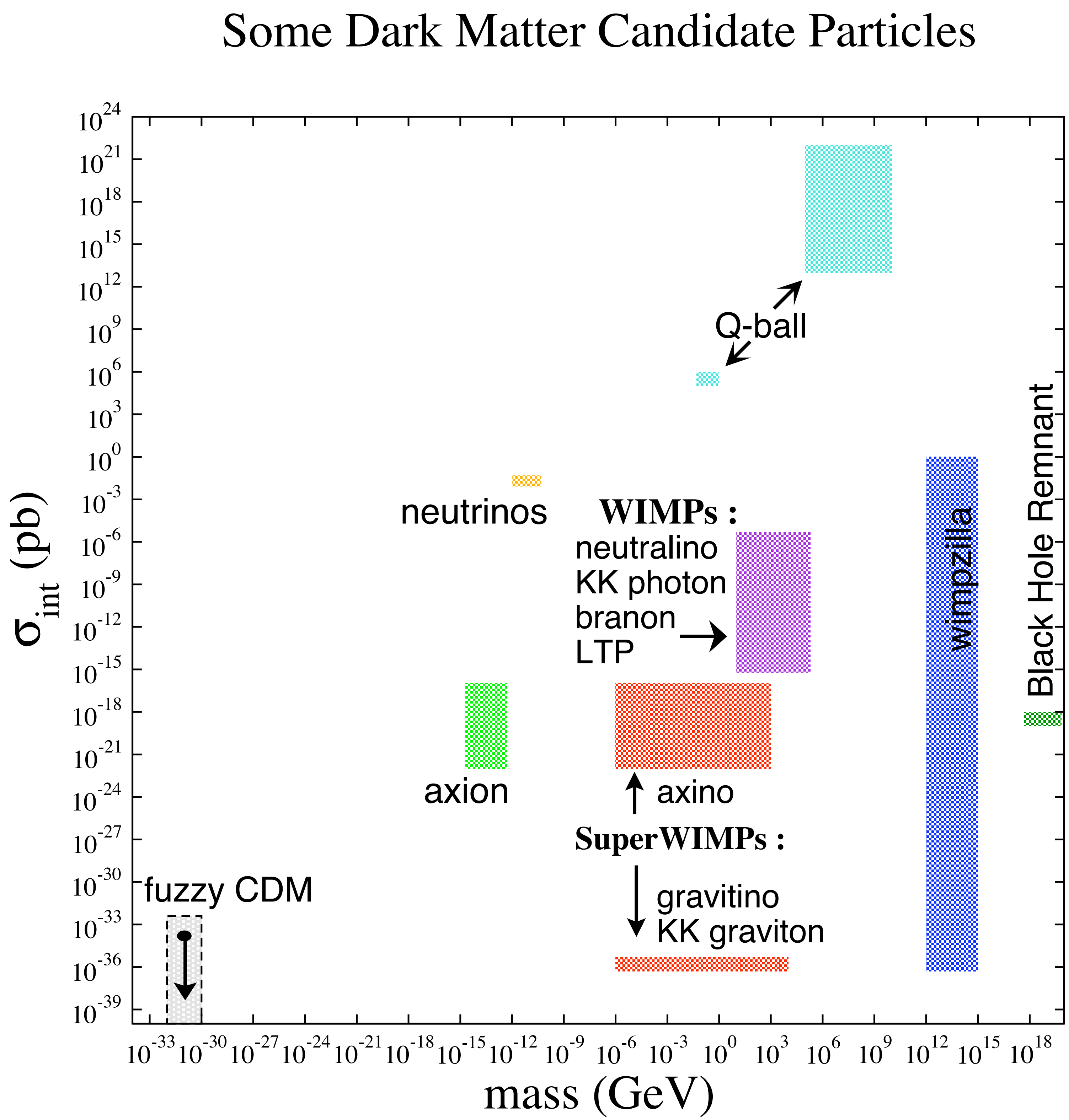
Dark matter cannot be the particle in the standard model, which has to be WIMP

Weakly Interacting Massive Particles

Particle Dark Matter

- Properties of Dark Matter
  - old (long lived)
  - slow (non-relativistic)
  - not charged (electric or colour)
  - interacts very weakly with SM
  - feels the effects of gravity

- Many candidates for Dark Matter
  - *Warm:* sterile neutrinos, gravitinos
  - *Cold:* Lightest SUSY particle (neutralino, gravitino), Lightest Kaluza-Klein particle
  - *Nonthermal relics:* Bose-Einstein Condensate, axions, axion clusters, solitons, supermassive wimpzillas



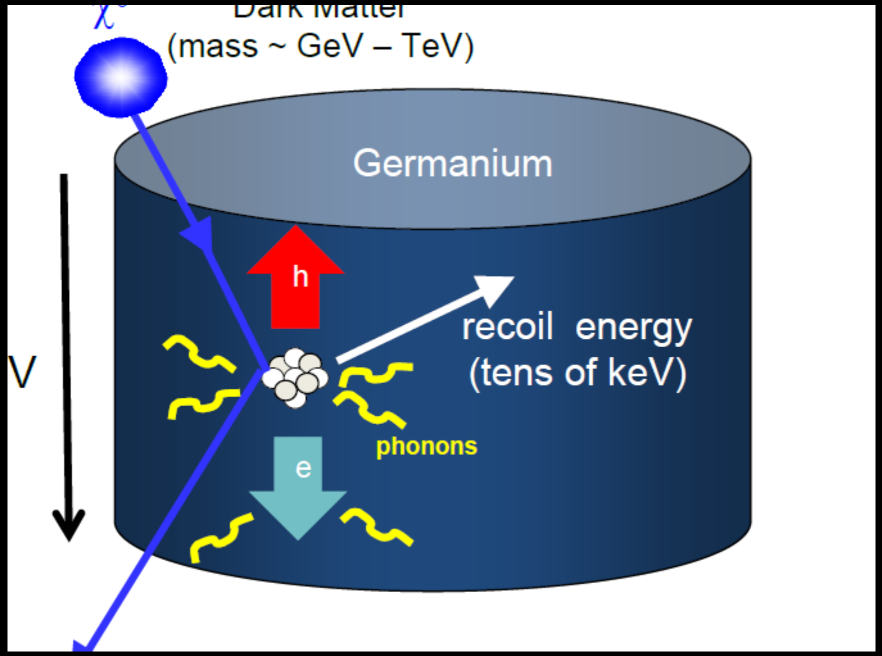
- neutrino ν – hot DM
- neutralino χ
- “generic” WIMP
- axion a
- axino $\tilde{a}$
- gravitino $\tilde{G}$
- wimpzilla,. . .

How to observe dark matter?

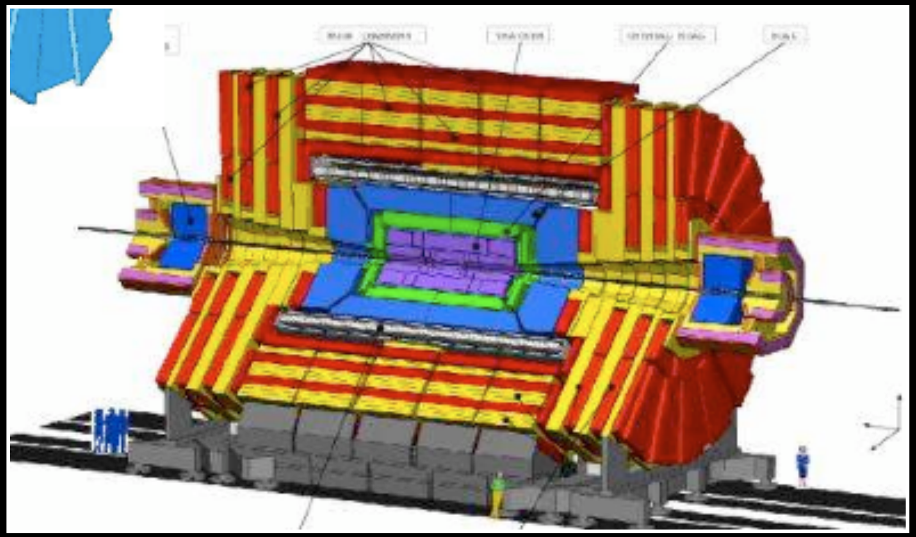
Search for Dark Matter:

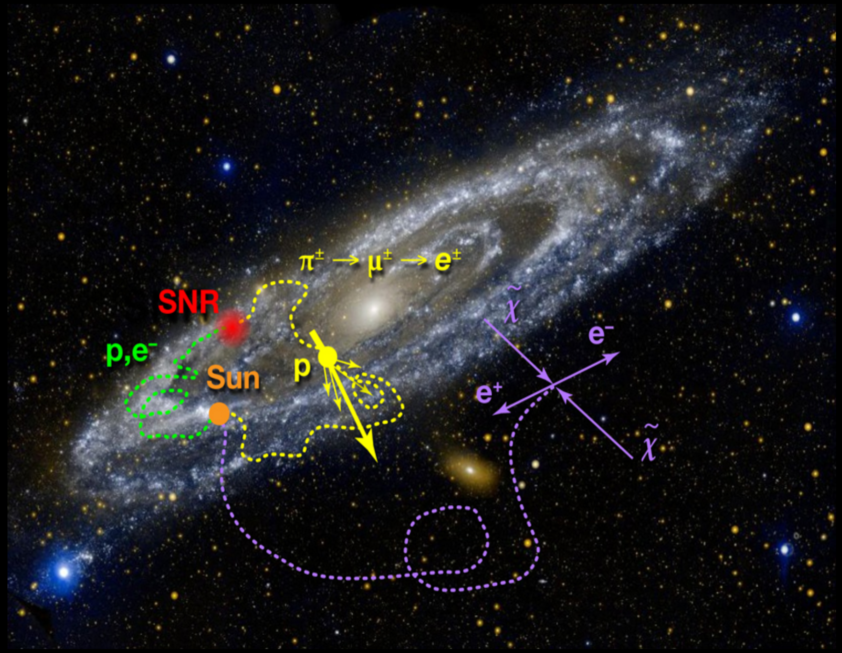
Indirect detection:
(cosmic-ray experiments)

Direct detection:
(underground experiments)



Collider searches: (LHC)



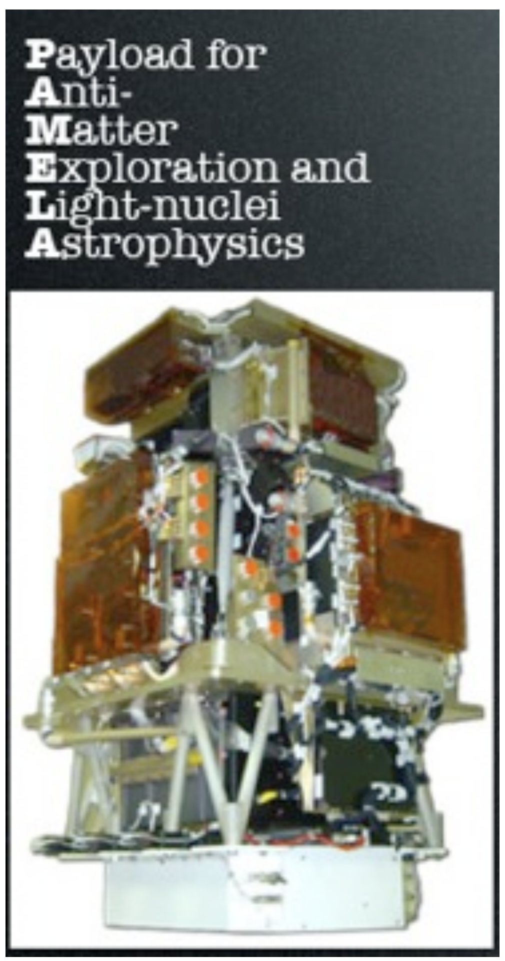


- ***Cosmic Ray Anomalies***

Space Station AMS-02

Satellite

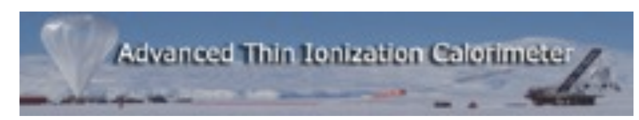
PAMELA



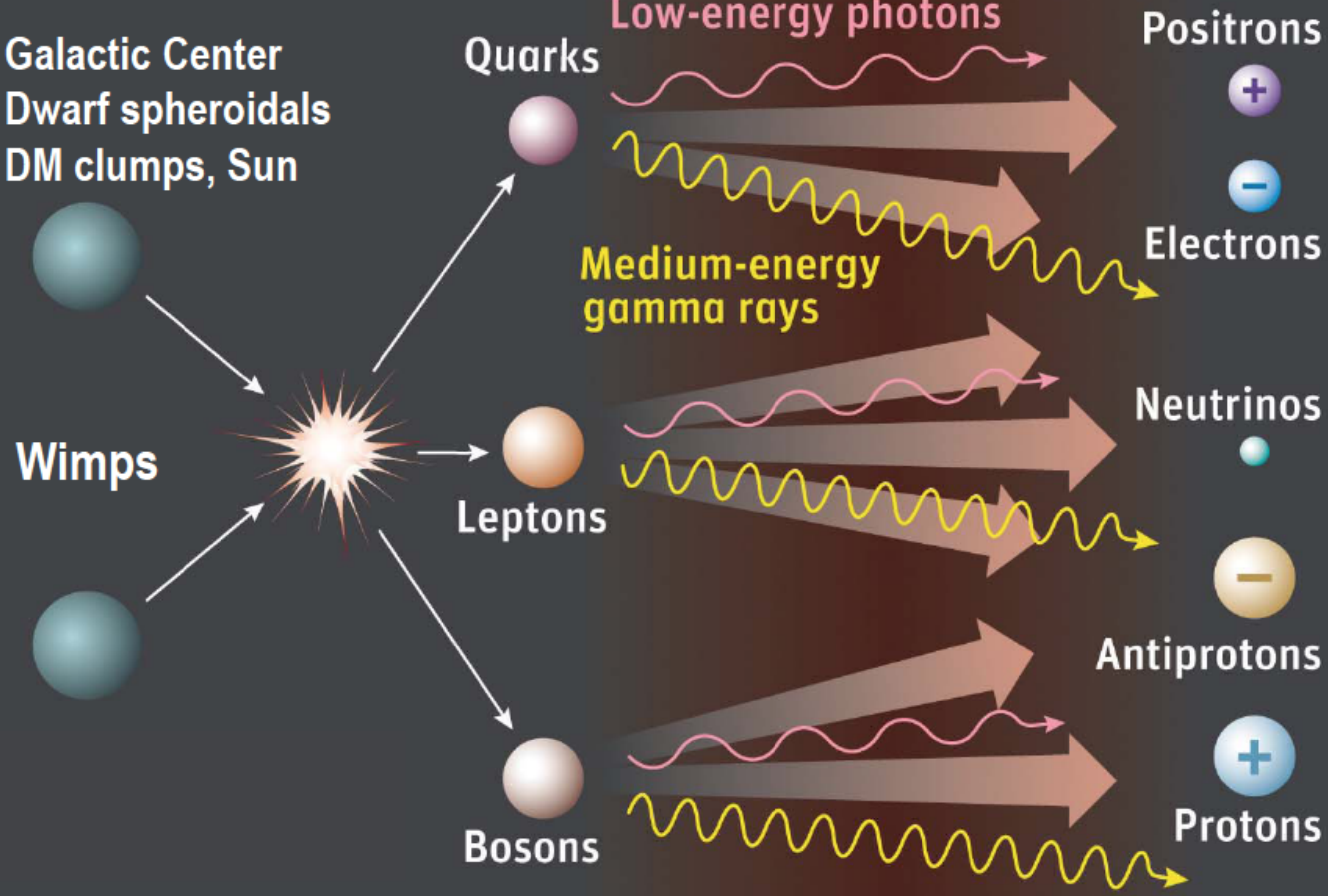
Fermi

Balloon →

ATIC



Indirect Detection



PAMELA/ATIC/Fermi Cosmic-ray anomalies

Fermi: Phys.Rev.Lett. 102 (2009) 181101
Online on May 4, 2009
arXiv:0905.0025 [astro-ph.HE]

ATIC: Nature 456 (2008) 362

PAMELA: Nature 458 (2009) 607
arXiv:0810.4995 [astro-ph]

	Cited 11/16/09	7/31/10	4/19/13	9/26/14	2/2/15
Fermi	181	323	642	744	769
ATIC	258	345	556	627	657
PAMELA	386	564	1040	1298	1372

☞ **Anomalies** → **Pulsars ...?** **Dark Matter ?**

New theory of DM on arXiv every day!

		7/31/10	4/19/13	9/26/14	2/2/15
Theoretical papers:	> 200	300	500	550	570

2011/5/19 (Endeavour) **published on April 3, 2013**

AMS-2: Phys.Rev.Lett. 110 (2013) 141102 → 12 (4/19/13), 240 (9/26/14), 316 (2/2/15)

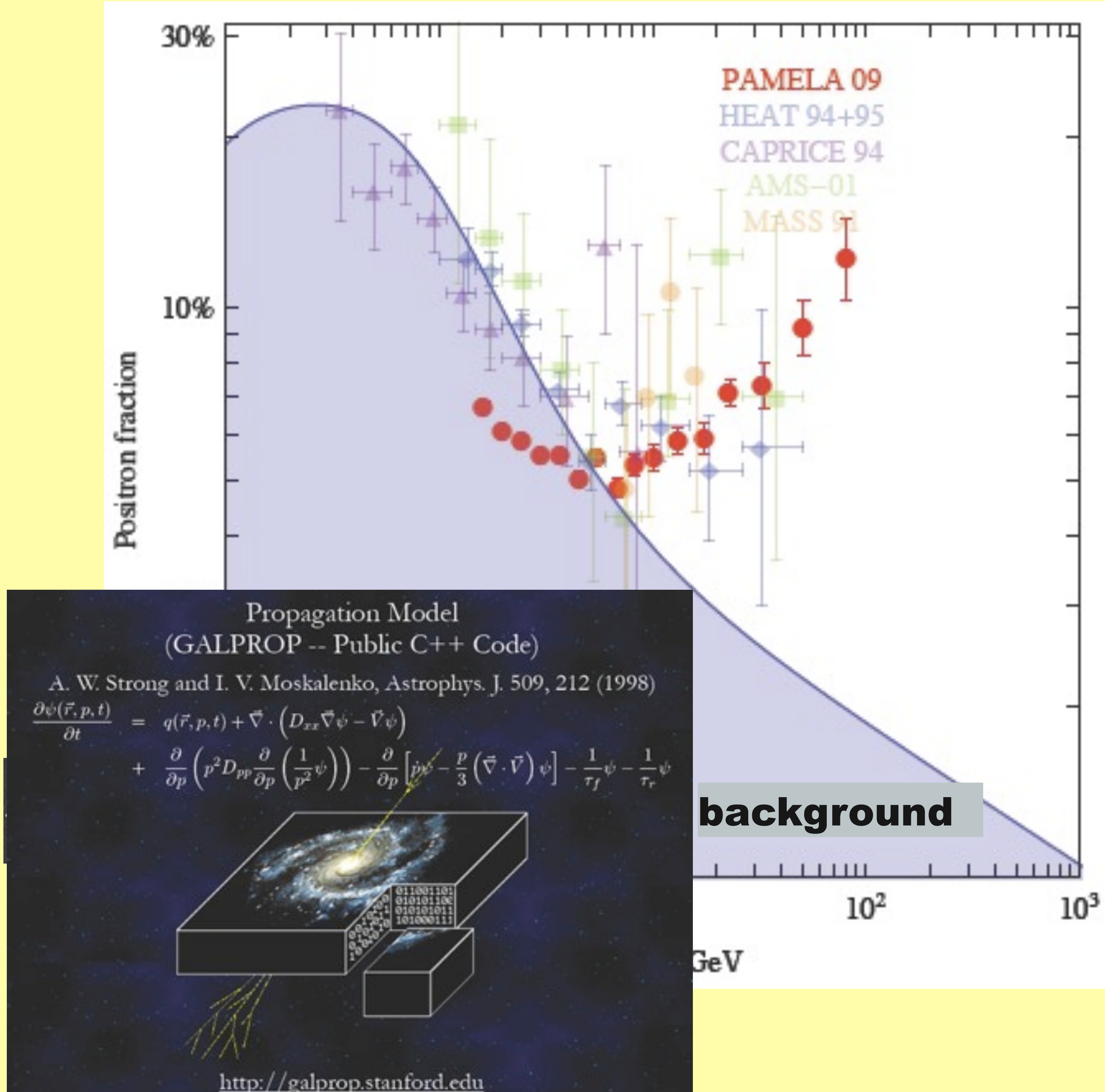
Two new PRLs published on Sept. 19, 2014 → 0 (9/26/14), 35 / 22 (2/2/15)

Positrons from PAMELA:

It can discriminate

$e^+, e^-, p, \bar{p}, \ldots$

(9430 e^+ collected)



Positrons from PAMELA:

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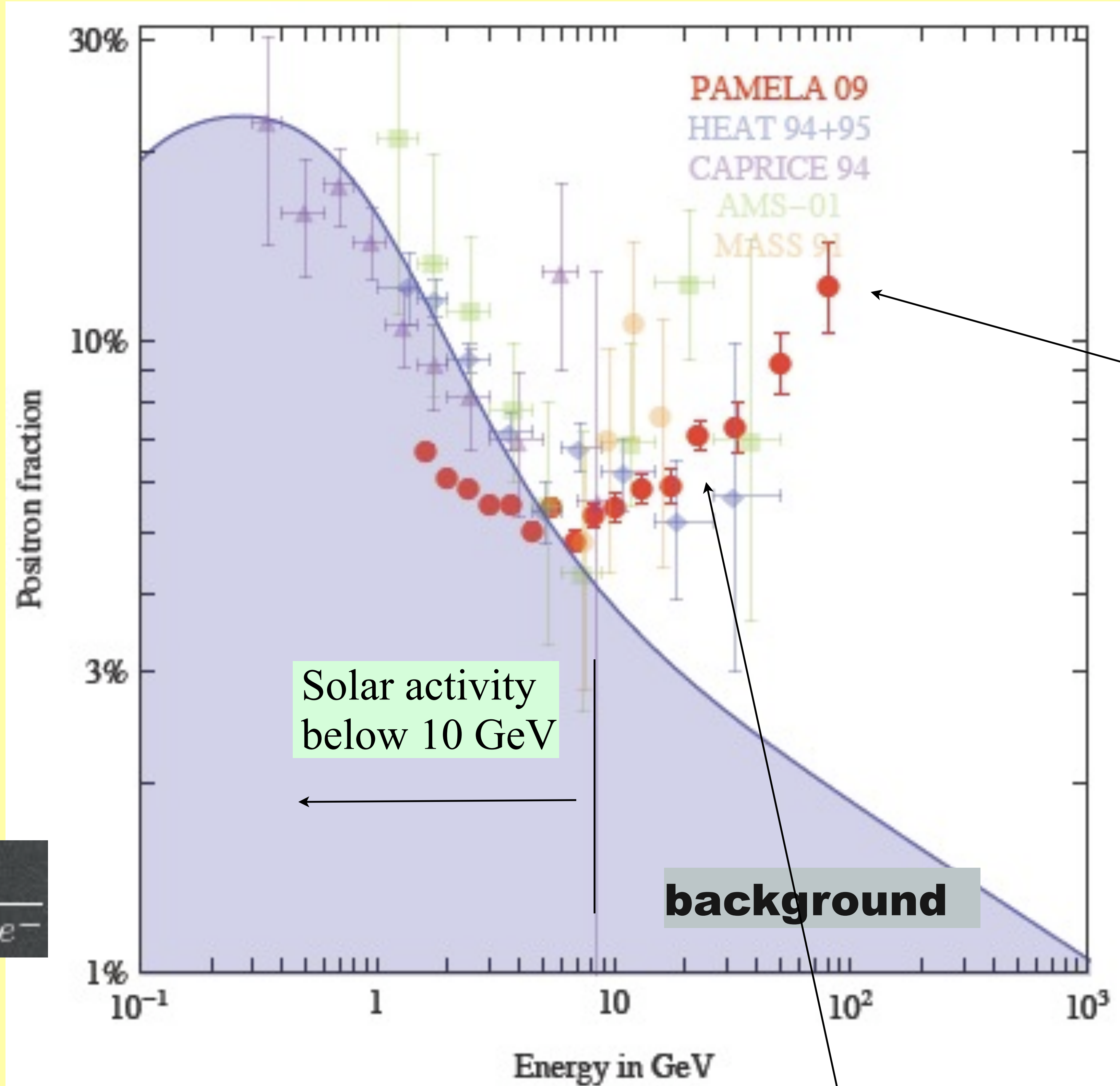
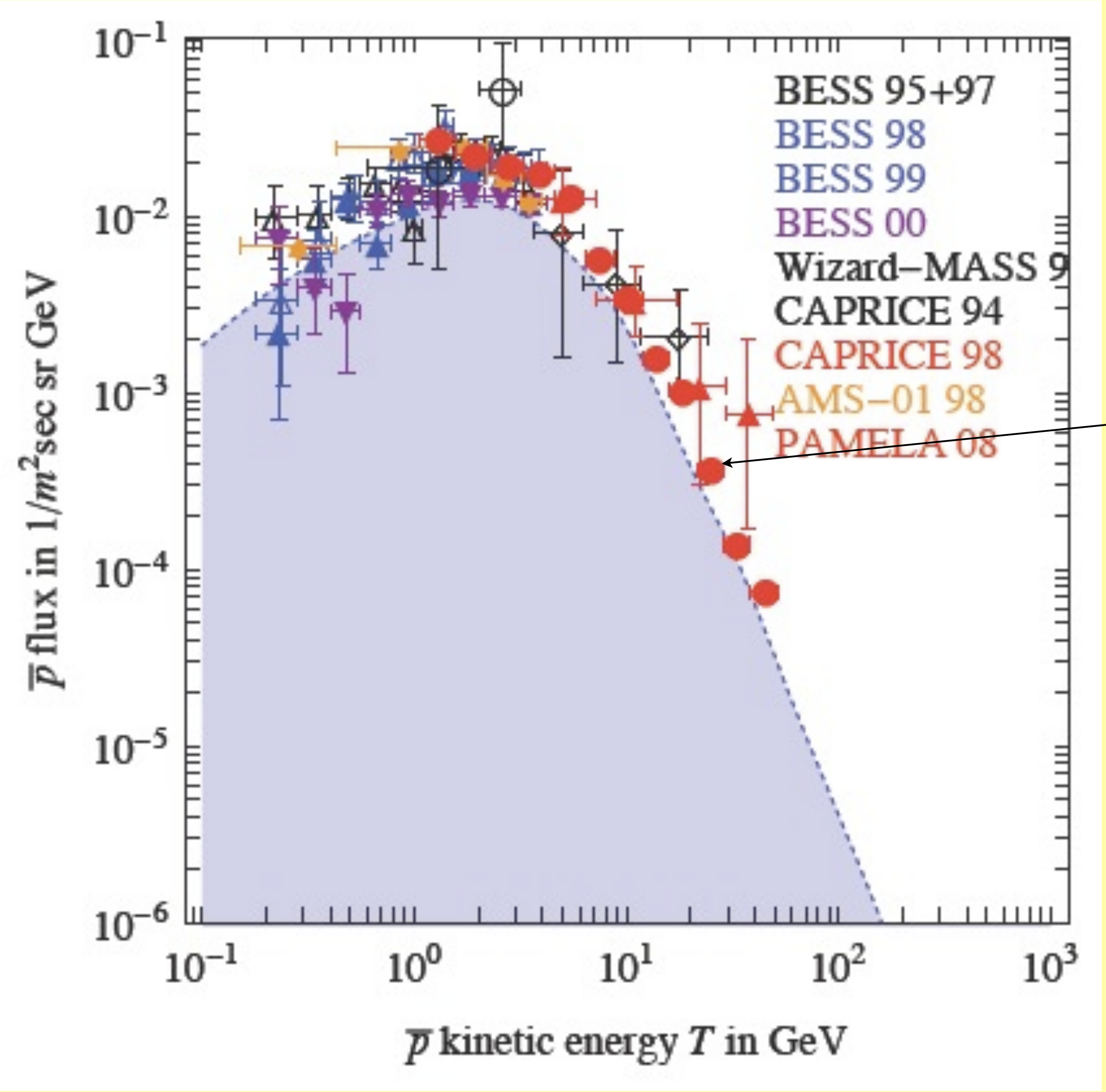


(errors statistical only, larger at high energy)

$$\frac{e^+}{e^+ + e^-}$$

☞ Steep e+ excess above 10 GeV with very large flux

Antiprotons from PAMELA:

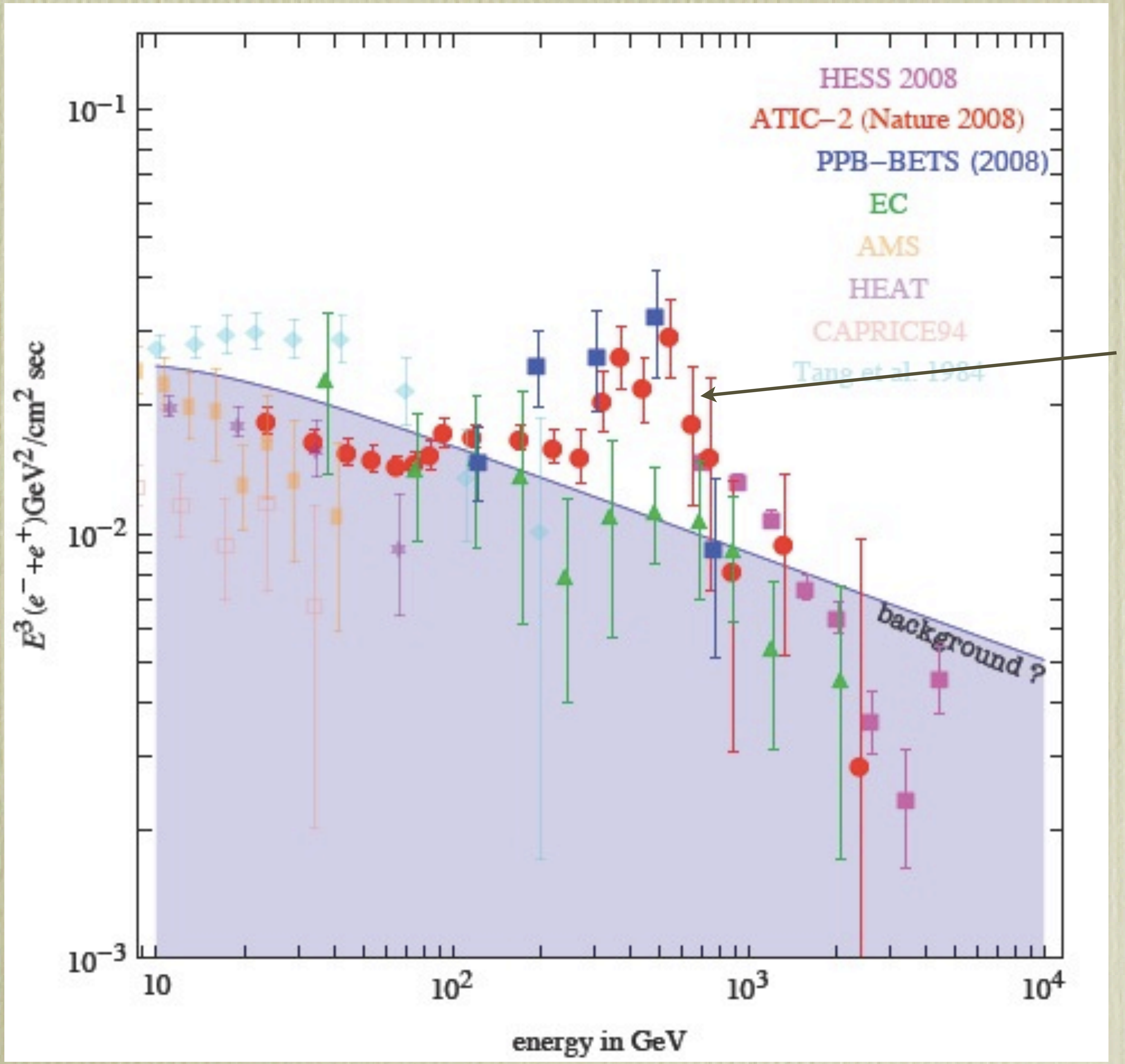


Consistent with the background

(about 1000 $\bar{p}$ collected)

Electrons + positrons from ATIC

It cannot discriminate e^+ and e^-

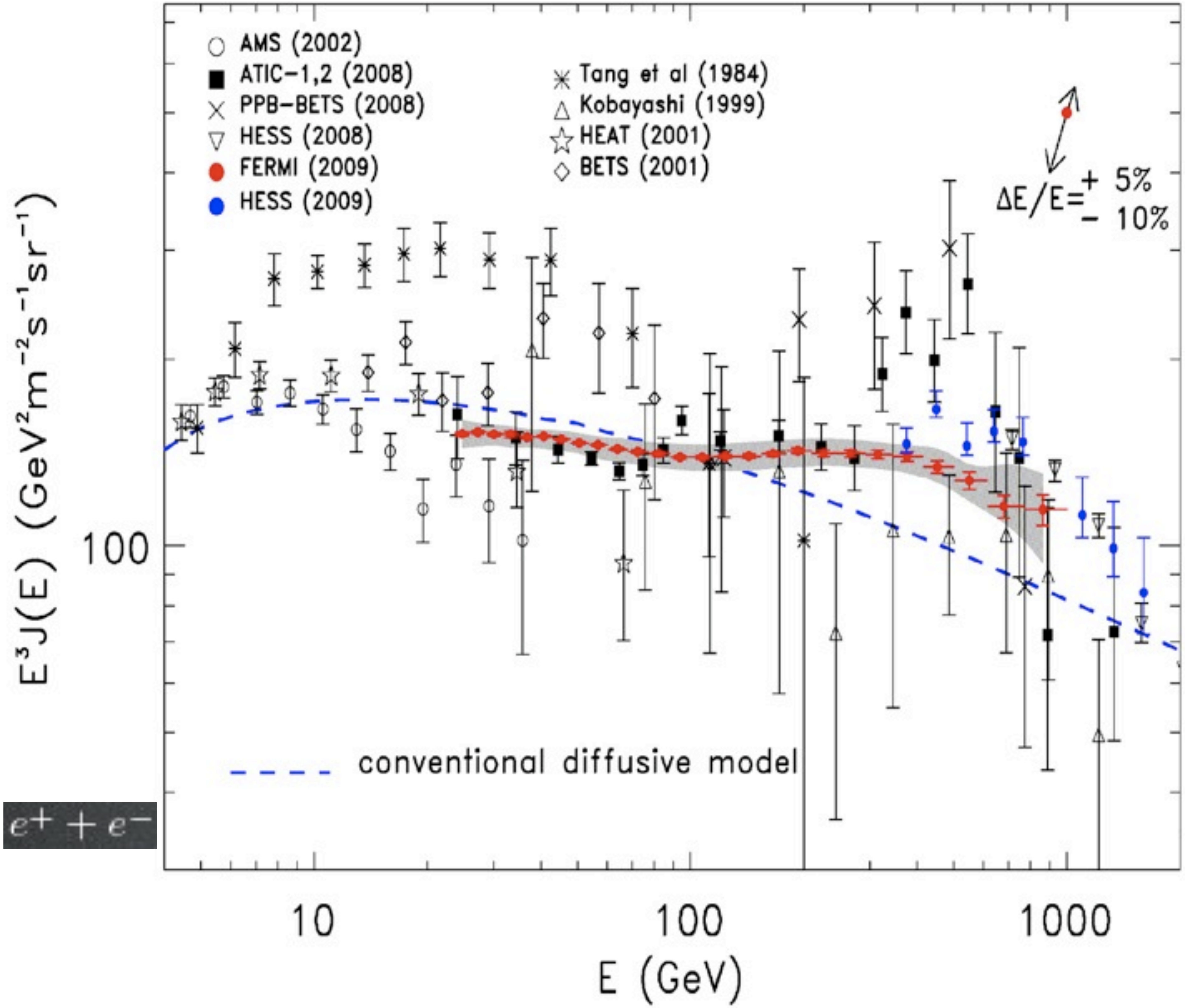


An e^++e^- excess 300-800 GeV

Fermi's result: PRL102(09)181101

It cannot discriminate
e^+ and e^-

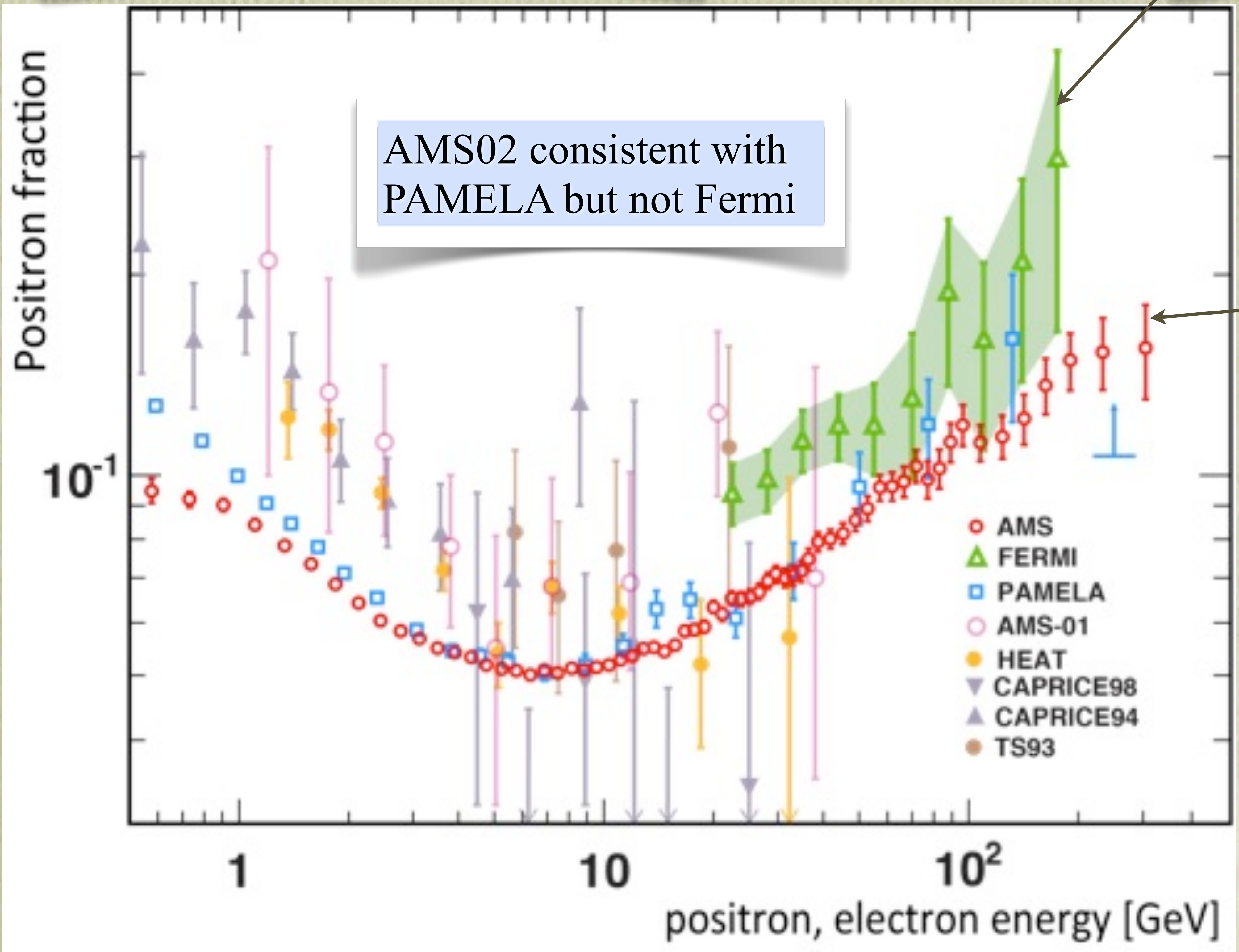
arXiv:0905.0025 [astro-ph.HE]



Fermi Data
4 million events
conflict with
ATIC

AMS-02:PRL110,141102(2013)

Fermi with earth Mag.F.
PRL108,011103(2002)

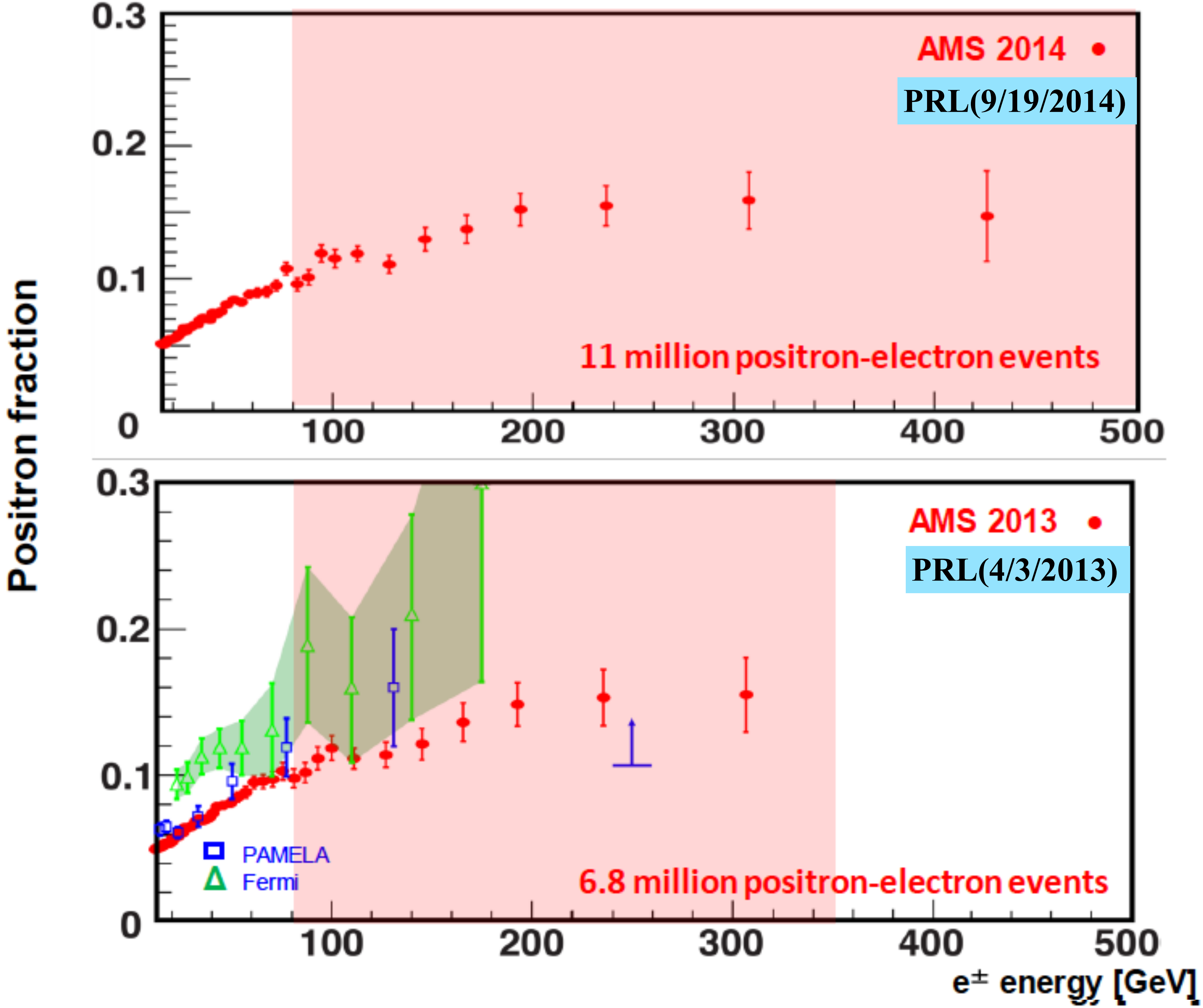


AMS02 consistent with
PAMELA but not Fermi

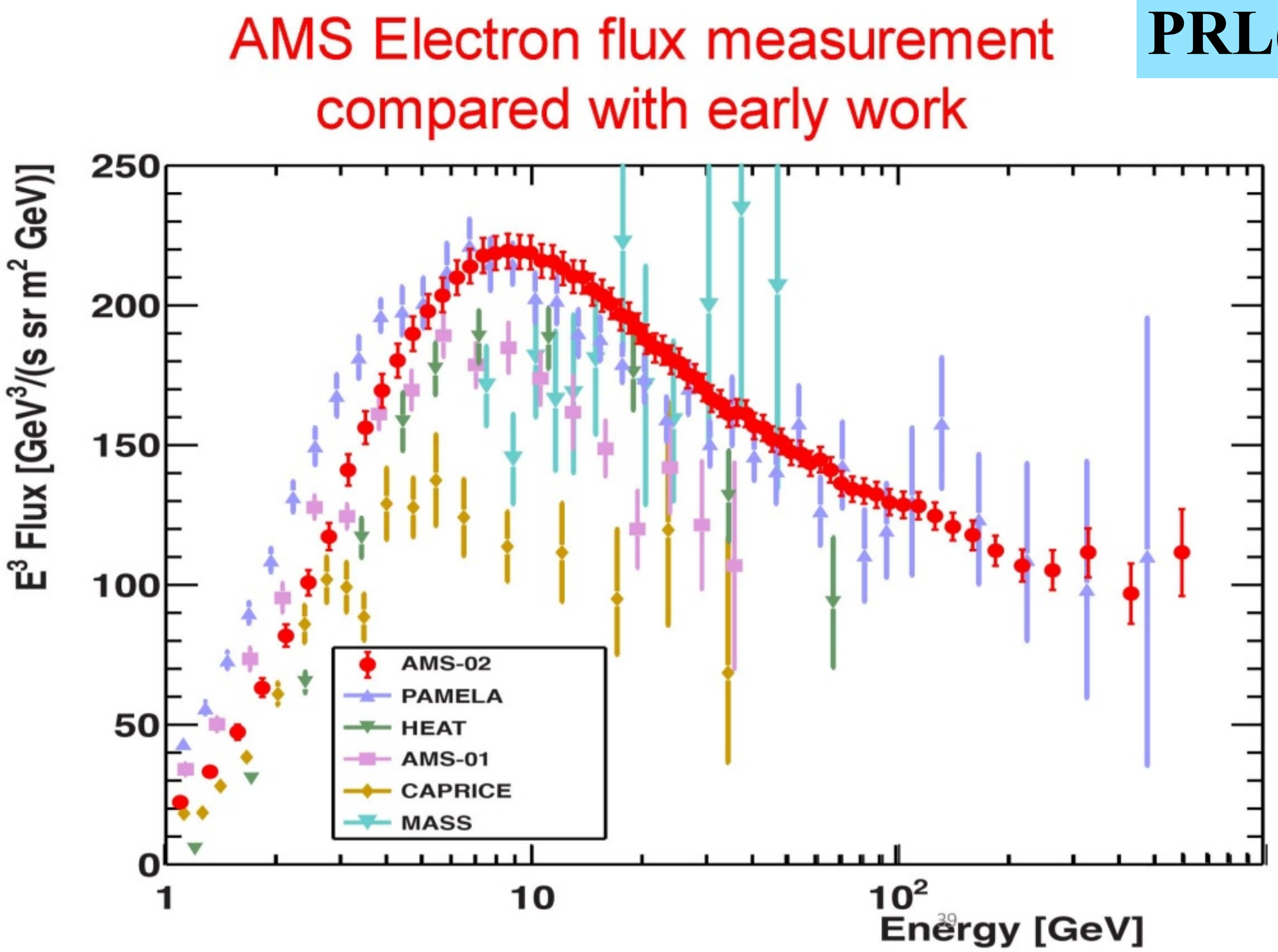
AMS02
4/3/2013

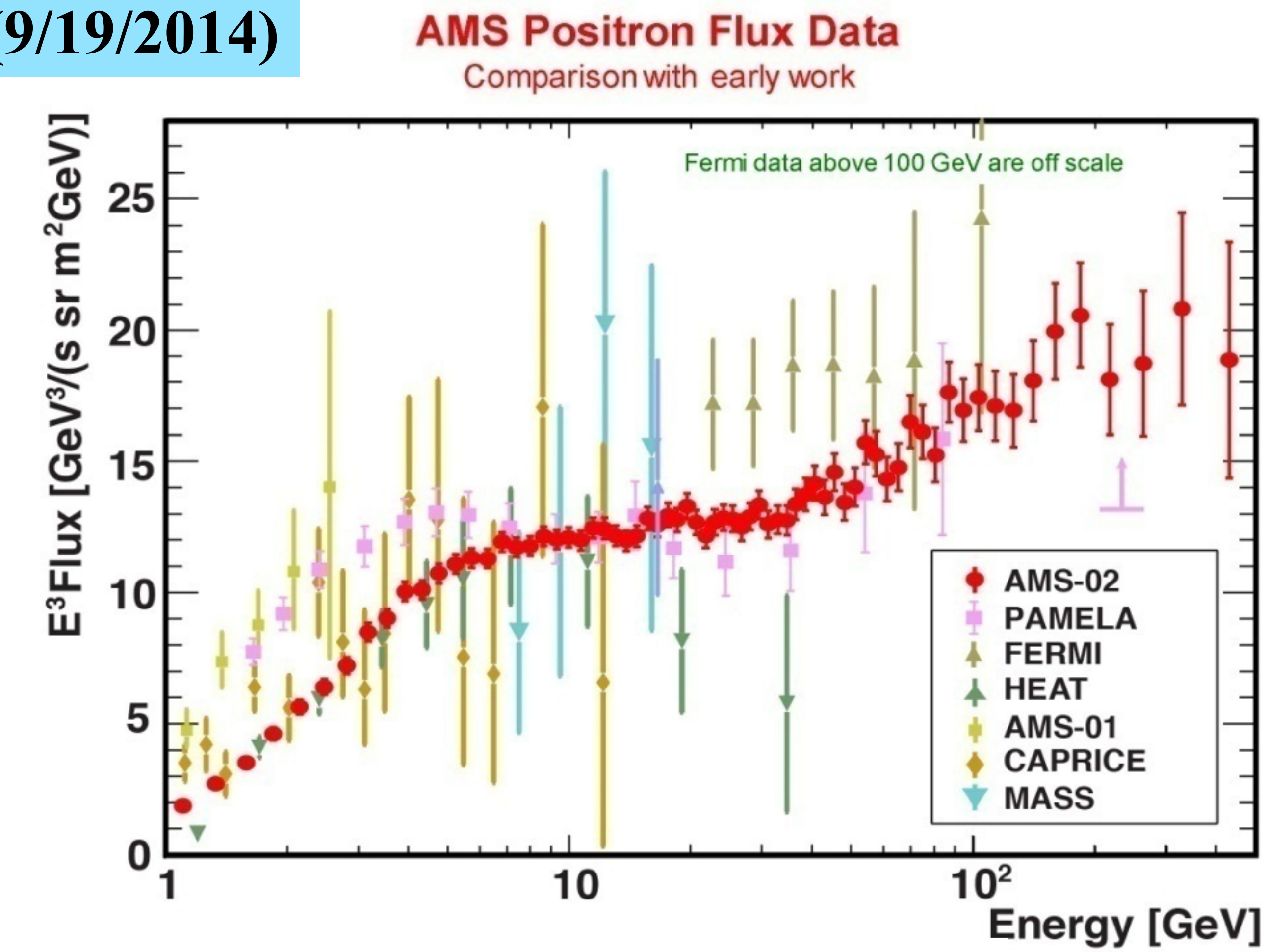
$4\text{x}10^5$ e^+ collected

2. With much higher statistics



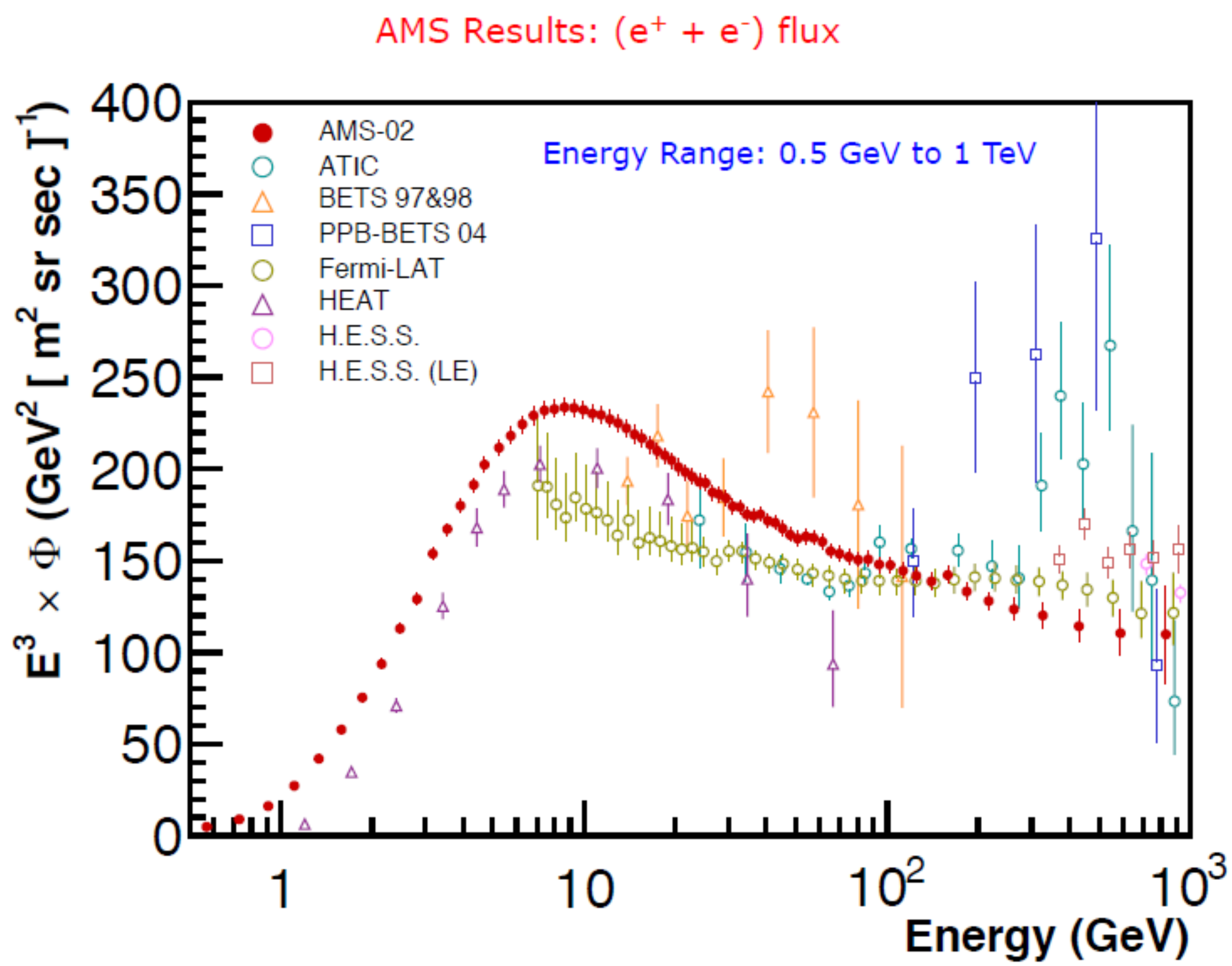
PRL(9/19/2014)





Recent Development

(unpublished)



Possible interpretations

Astrophysics: nearby pulsars ......

Particle physics: Dark Matter (DM)

- General Pulsar Prediction: Anisotropy
- However, current expts. do not see any anisotropy

⇓

Not Support Pulsar Explanation

- DM Prediction: Isotropic Spectrum

- ***Dark Matter Interpretation***

Dark matter annihilation: DM DM $\longrightarrow$ SM SM

See Sola's lectures

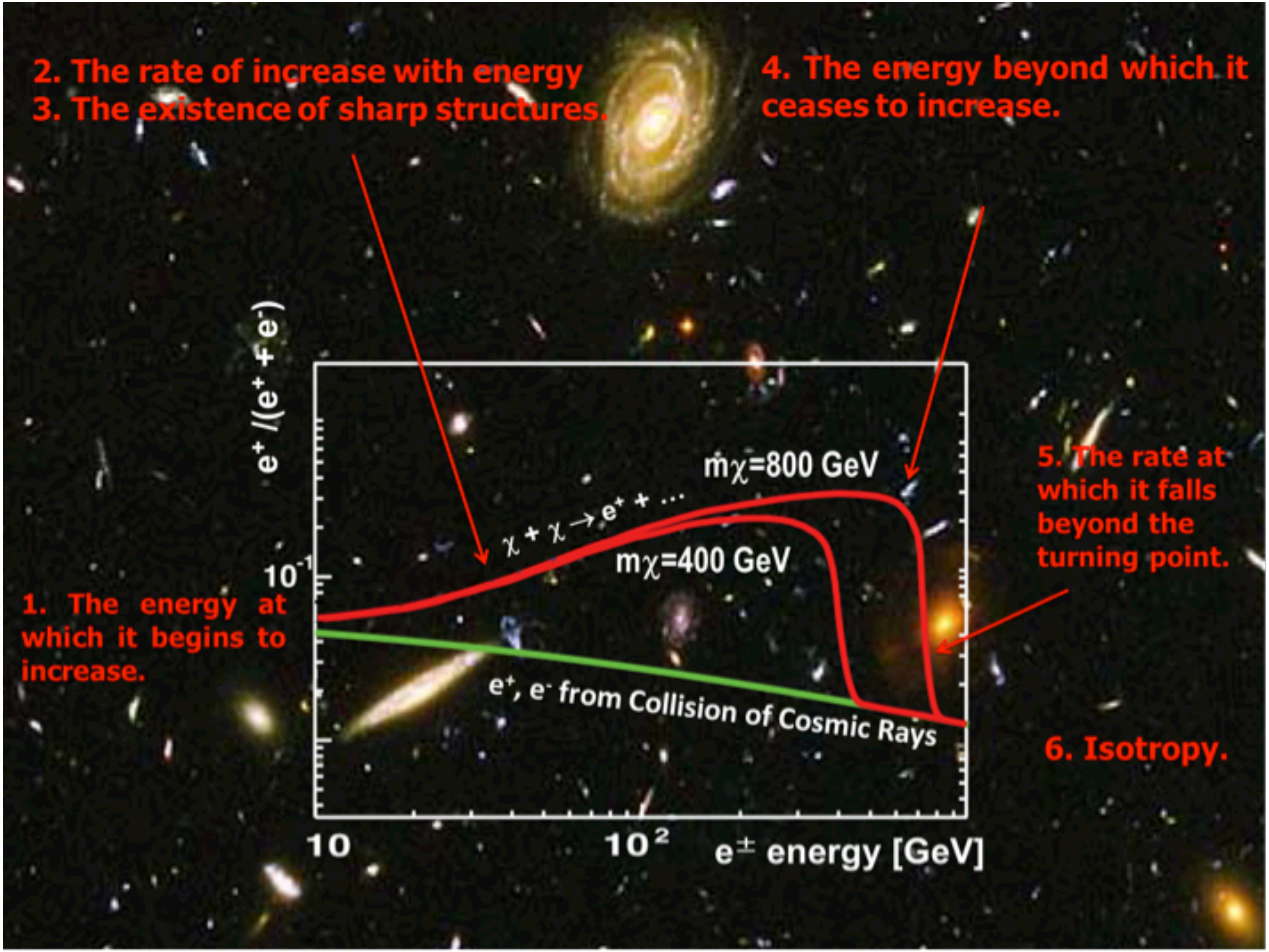
- 0.5 TeV < M < 1 TeV
- $<\sigma v> \sim 10^{-26}\ \mathrm{cm^3 s^{-1}} \sim 10^{-9}\ \mathrm{GeV^{-2}}$
- BF ~ 10^2 - 10^4

Dark matter decay: DM $\longrightarrow$ 2 or 3 SMs

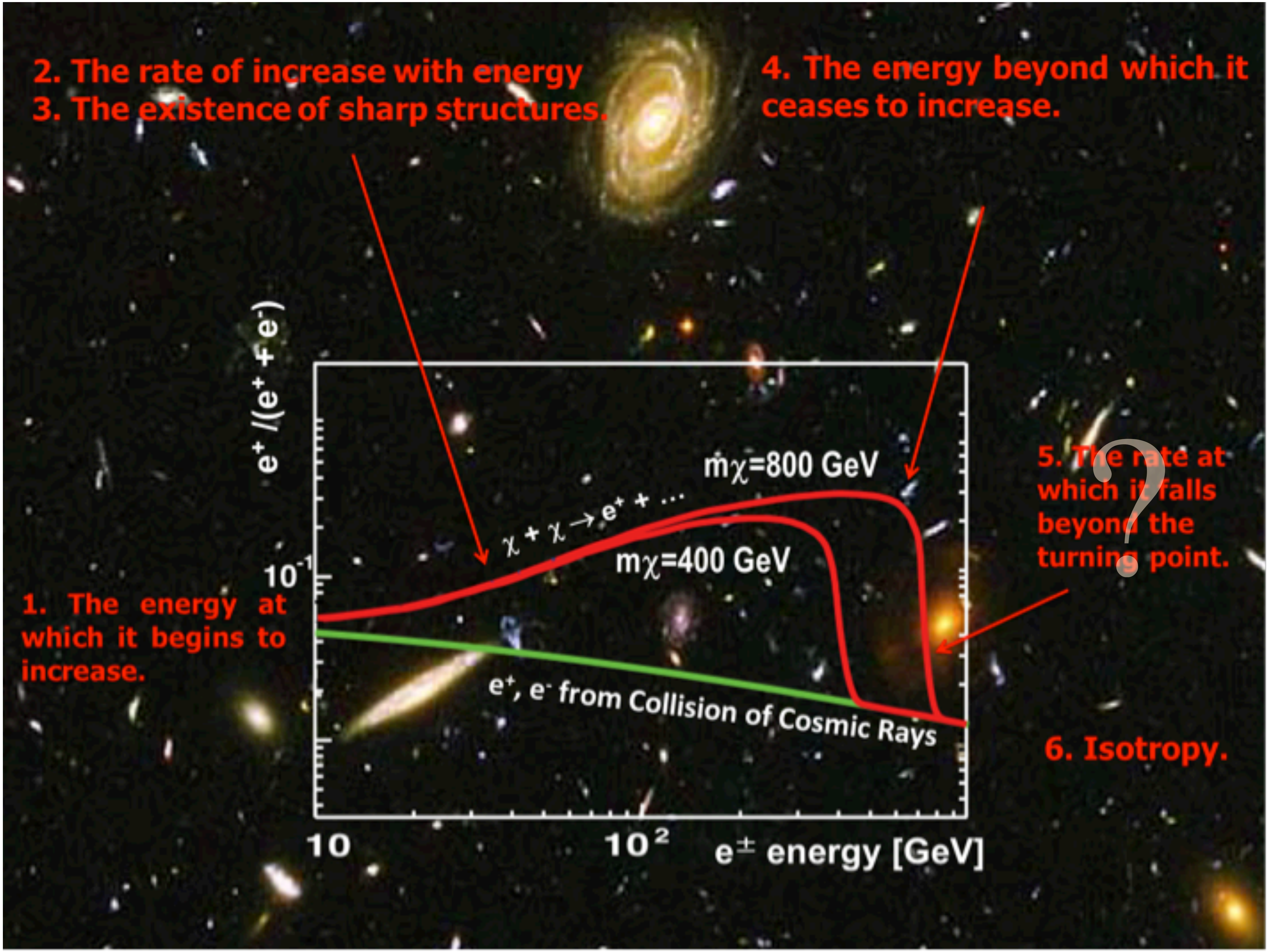
$M \geq 1$ TeV, $\tau \geq 10^{26}$ s

Note: the age of the universe (4.3×10^{17} s).

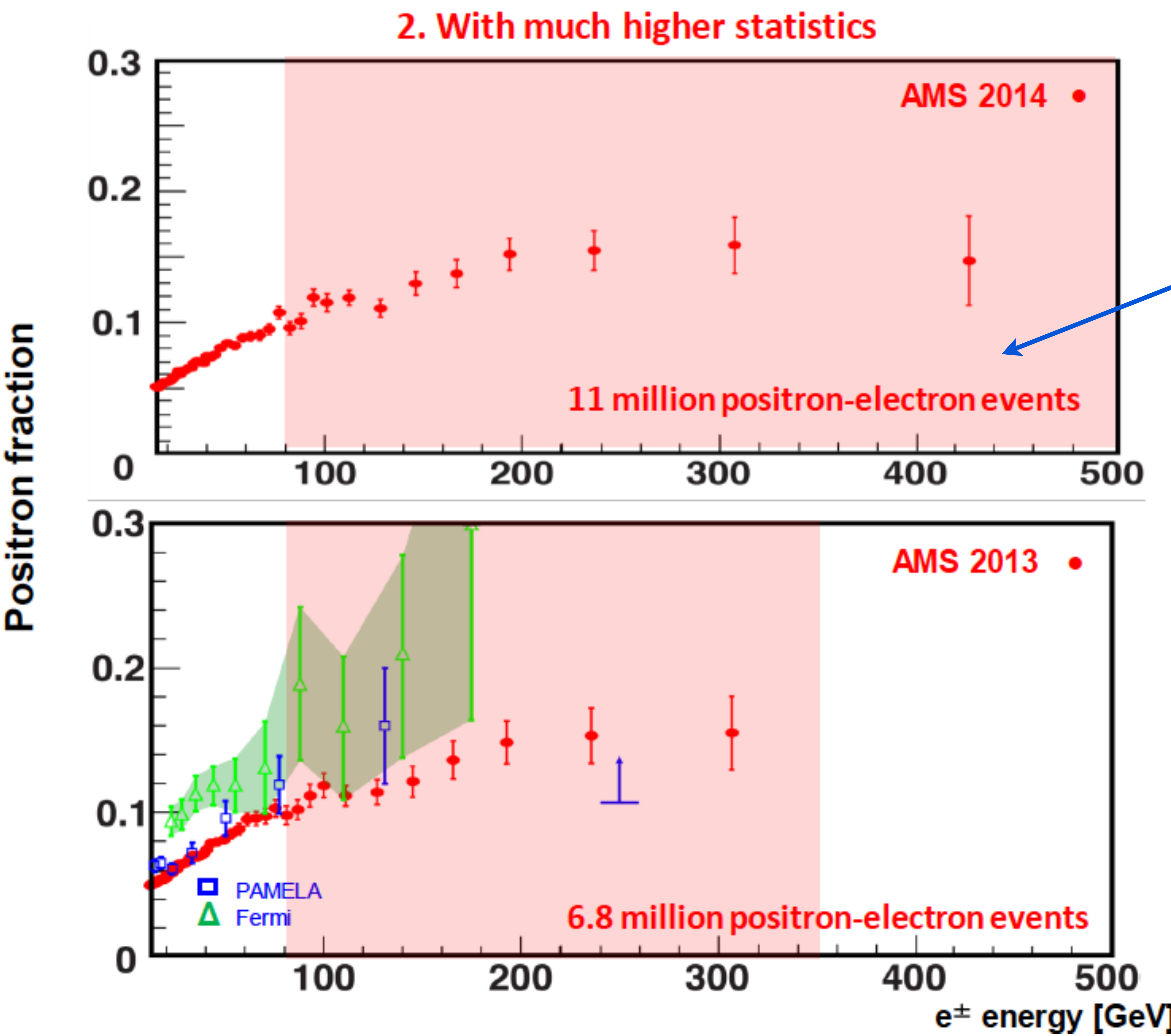
Six conditions for the evidence of Dark Matter!

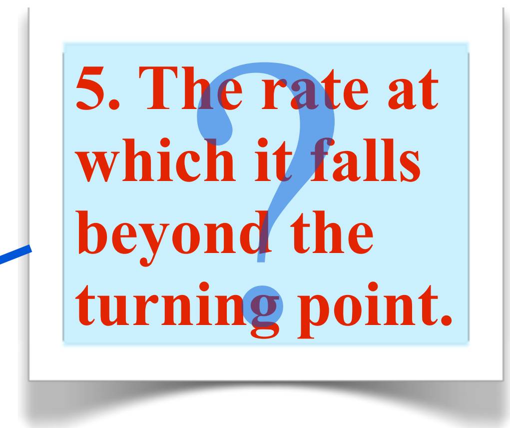


AMS-2: six conditions for Dark Matter with five seen!



AMS-2: six conditions for Dark Matter with five seen!





ATIC Energy Spectrum vs. KK Dark Matter

[Nature 07477 (2008)]

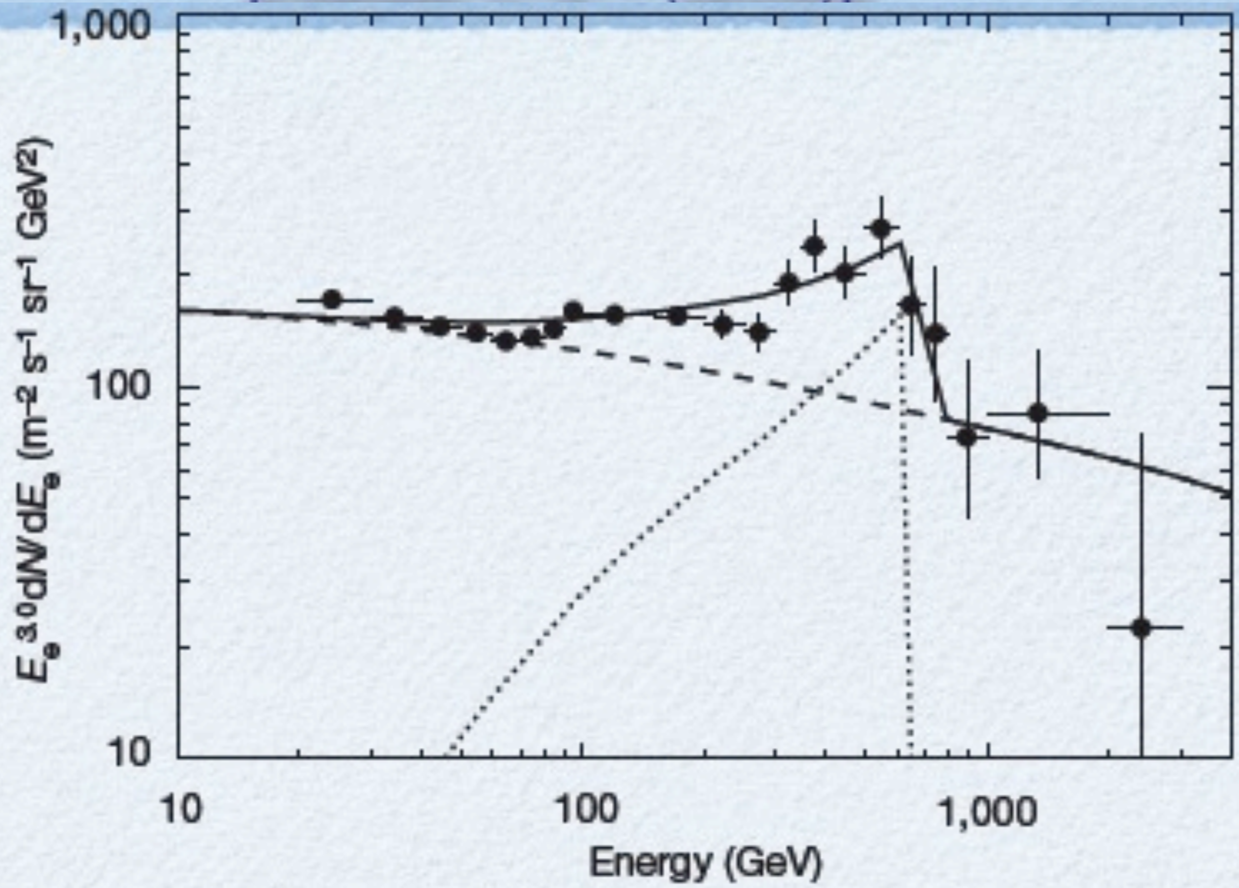


Figure 4 | Assuming an annihilation signature of Kaluza–Klein dark matter, all the data can be reproduced. The GALPROP general electron spectrum resulting from sources across the galaxy is shown as the dashed line. The dotted curve represents the propagated electrons from the annihilation of a Kaluza–Klein particle. The dotted curve assumes an isothermal dark matter halo of 4-kpc scale height, a local dark matter density of 0.3 GeV cm^{-3}, a Kaluza–Klein mass of 620 GeV, and an annihilation cross section rate of 1×10^{-23} cm^3 s^{-1}, which implies a boost factor of ~200. The sum of these signals is the solid curve. Here the spectrum is multiplied by $E^{3.0}$ for clarity. The solid curve provides a good fit to both the magnetic spectrometer data[30,31] and calorimeter data[16,32] and reproduces all of the measurements from 20 GeV to 2 TeV, including the cut-off in the observed excess. All error bars are one standard deviation.

a Kaluza-Klein mass of 620 GeV

Which DM can fit the data?

M.Pospelov and A.Ritz, 0810.1502: Secluded DM - A.Nelson and C.Spitzer, 0810.5167: Slightly Non-Minimal DM - Y.Nomura and J.Thaler, 0810.5397: DM through the Axion Portal - R.Harnik and G.Kribs, 0810.5557: Dirac DM - D.Feldman, Z.Liu, P.Nath, 0810.5762: Hidden Sector - T.Hambye, 0811.0172: Hidden Vector - Yin, Yuan, Liu, Zhang, Bi, Zhu, 0811.0176: Leptonically decaying DM - K.Ishiwata, S.Matsumoto, T.Moroi, 0811.0250: Superparticle DM - Y.Bai and Z.Han, 0811.0387: sUED DM - P.Fox, E.Poppitz, 0811.0399: Leptophilic DM - C.Chen, F.Takahashi, T.T.Yanagida, 0811.0477: Hidden-Gauge-Boson DM - K.Hamaguchi, E.Nakamura, S.Shirai, T.T.Yanagida, 0811.0737: Decaying DM in Composite Messenger - E.Ponton, L.Randall, 0811.1029: Singlet DM - A.Ibarra, D.Tran, 0811.1555: Decaying DM - S.Baek, P.Ko, 0811.1646: U(1) Lmu-Ltau DM - C.Chen, F.Takahashi, T.T.Yanagida, 0811.3357: Decaying Hidden-Gauge-Boson DM - I.Cholis, G.Dobler, D.Finkbeiner, L.Goodenough, N.Weiner, 0811.3641: 700+ GeV WIMP - E.Nardi, F.Sannino, A.Strumia, 0811.4153: Decaying DM in TechniColor - K.Zurek, 0811.4429: Multicomponent DM - M.Ibe, H.Murayama, T.T.Yanagida, 0812.0072: Breit-Wigner enhancement of DM annihilation - E.Chun, J.-C.Park, 0812.0308: sub-GeV hidden U(1) in GMSB - M.Lattanzi, J.Silk, 0812.0360: Sommerfeld enhancement in cold substructures - M.Pospelov, M.Trott, 0812.0432: super-WIMPs decays DM - Zhang, Bi, Liu, Liu, Yin, Yuan, Zhu, 0812.0522: Discrimination with SR and IC - Liu, Yin, Zhu, 0812.0964: DMnu from GC - M.Pohl, 0812.1174: electrons from DM - J.Hisano, M.Kawasaki, K.Kohri, K.Nakayama, 0812.0219: DMnu from GC - A.Arvanitaki, S.Dimopoulos, S.Dubovsky, P.Graham, R.Harnik, S.Rajendran, 0812.2075: Decaying DM in GUTs - R.Allahverdi, B.Dutta, K.Richardson-McDaniel, Y.Santoso, 0812.2196: SuSy B-L DM- S.Hamaguchi, K.Shirai, T.T.Yanagida, 0812.2374: Hidden-Fermion DM decays - D.Hooper, A.Stebbins, K.Zurek, 0812.3202: Nearby DM clump - C.Delaunay, P.Fox, G.Perez, 0812.3331: DMnu from Earth - Park, Shu, 0901.0720: Split-UED DM - .Gogoladze, R.Khalid, Q.Shafi, H.Yuksel, 0901.0923: cMSSM DM with additions - Q.H.Cao, E.Ma, G.Shaughnessy, 0901.1334: Dark Matter: the leptonic connection - E.Nezri, M.Tytgat, G.Vertongen, 0901.2556: Inert Doublet DM - C.-H.Chen, C.-Q.Geng, D.Zhuridov, 0901.2681: Fermionic decaying DM - J.Mardon, Y.Nomura, D.Stolarski, J.Thaler, 0901.2926: Cascade annihilations (light non-abelian new bosons) - P.Meade, M.Papucci, T.Volansky, 0901.2925: DM sees the light - D.Phalen, A.Pierce, N.Weiner, 0901.3165: New Heavy Lepton - T.Banks, J.-F.Fortin, 0901.3578: Pyrma baryons - Goh, Hall, Kumar, 0902.0814: Leptonic Higgs - K.Bae, J.-H. Huh, J.Kim, B.Kyae, R.Viollier, 0812.3511: electrophilic axion from flipped-SU(5) with extra spontaneously broken symmetries and a two component DM with Z_2 parity - ...

Which DM can fit the data?

C.-H.Chen, C.-Q.Geng, D.Zhuridov, 0901.2681: Fermionic decaying DM

Phys.Lett.B675, 77 (2009)

C.H.Chen, C.Q.Geng, D.Zhuridov, JCAP0910(09)001, 0906.1646 [hep-ph],
Neutrino Masses, Leptogenesis and Decaying Dark Matter

C.Q.Geng, D.Huang, L.H.Tsai, PRD89, 055021(2014), 1312.0366 [hep-ph],
Imprint of Multicomponent Dark Matter on AMS-02

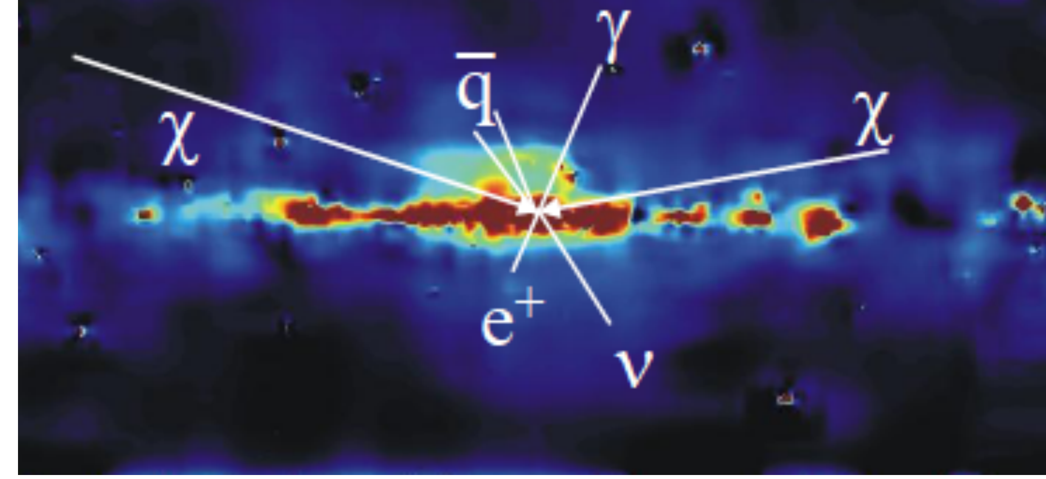
C.Q.Geng, D.Huang, C.Lai, 1411.3813 [astro-ph],
Revisiting Multicomponent Dark Matter with New AMS-02 Data

The total e^- and e^+ fluxes are:

$$\Phi_{e-} = \xi \Phi_{e-}^{prim} + \boxed{\Phi_{e-}^{DM}} + \Phi_{e-}^{sec}$$

$$\Phi_{e+} = \boxed{\Phi_{e+}^{DM}} + \Phi_{e+}^{sec},$$

ξ: the uncertainty in primary e^- normalization



Background:

Supernova shock and diffuse outward (primary)

$$\Phi_{e-}^{prim}(E) = \frac{0.16E^{-1.1}}{1 + 11E^{0.9} + 3.2E^{2.15}} \quad [\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}]$$

collisions among cosmic ray nuclei and intersellar medium (secondary)

$$\Phi_{e-}^{sec} = \Phi_{e+}^{sec}$$

Secondary e^-(e^+) produced in propagation, modeled by GALPROP

Two-Component Decaying DM

e^- (e^+) diffusion eq. and solved numerically by GALPROP

DM source terms:

$$Q(\mathrm{x}) = \frac{\rho(\mathrm{x})}{2}\left[\frac{1}{\tau_1 M_1}\left(\frac{dN}{dE}\right)_1 + \frac{1}{\tau_1 M_2}\left(\frac{dN}{dE}\right)_2\right]$$

Half Density

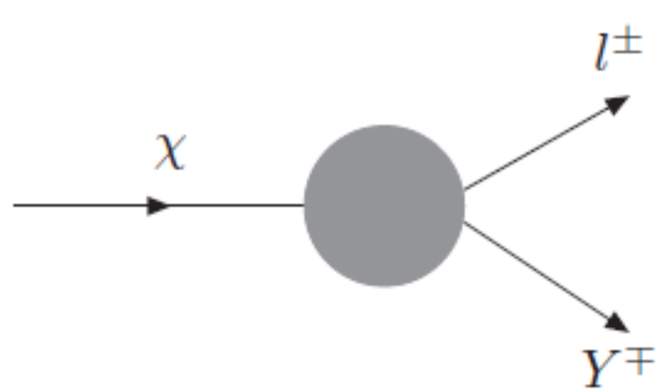
$\rho(\mathrm{x})$: DM density distribution, here we use isothermal profile

τ_i: DM lifetime

M_i: DM Mass

DM decay processes:

model-dependent



Fermionic Decaying DM model:

C.H.Chen, C.Q.Geng, D.Zhuridov, PLB675(09)77 [0901.2681 [hep-ph]]

New Particles: 1 scalar doublet η; 2 neutral leptons N_k + SM ← A minimal model

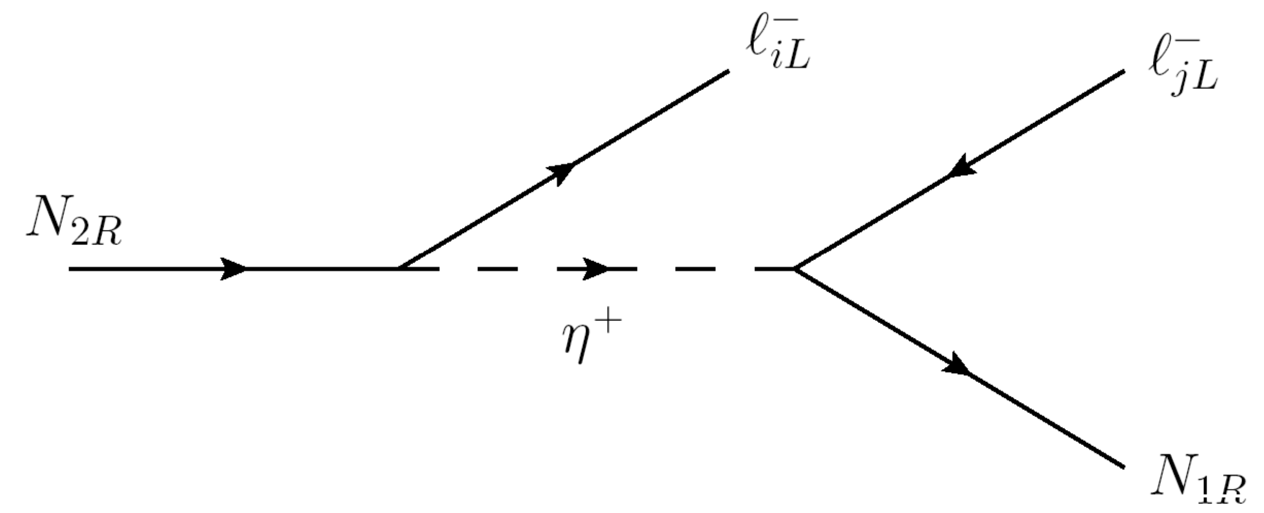
New particles are odd under Z_2 symmetry

The new Majorana mass term and Yukawa couplings can be written as

$$\boxed{M_k N_k N_k + y_{ik} \bar{L}_i \eta N_k + \text{H.c.},}$$

where L is the lepton doublet and i, k are the flavor indexes. We consider the mass spectrum $M_1 < M_2 < M_\eta$.

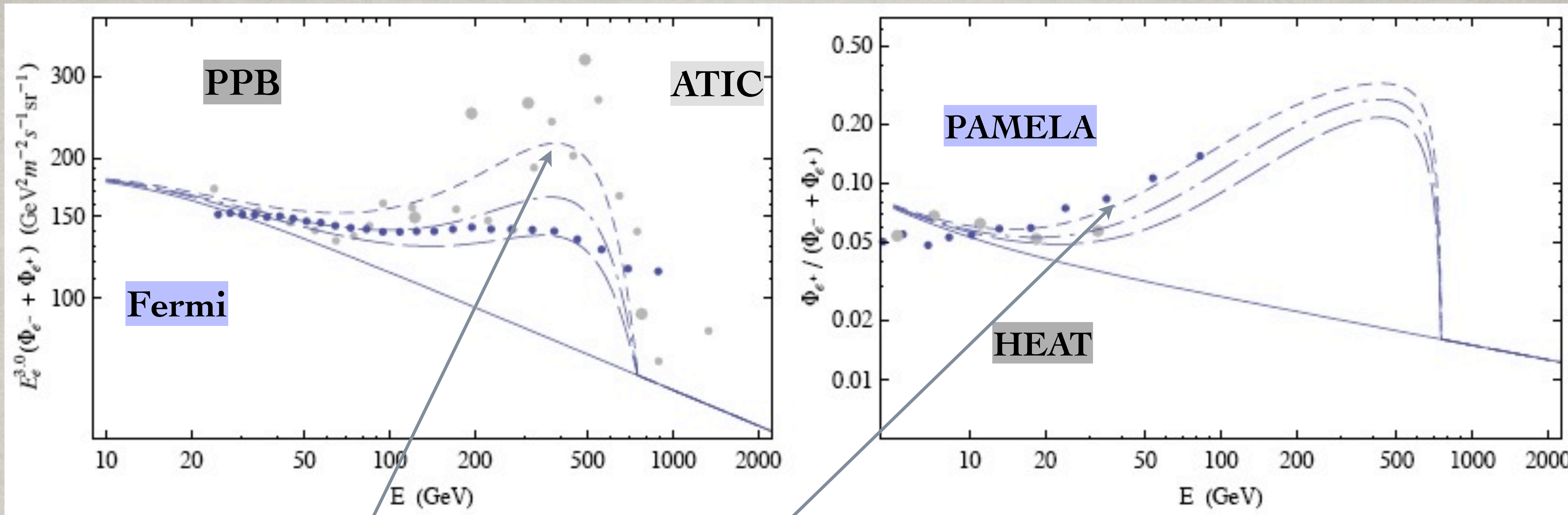
3-body DM decays:



$$\tau_{N_2} \simeq \frac{1}{\Gamma(N_2 \to N_1 \ell_i^\pm \ell_j^\mp)} = \frac{512(2\pi)^3}{5} \frac{M^4 M_2^3}{(M_{21}^2)^4},$$

where $M_{21}^2 = M_2^2 - M_1^2$ is the DM lepton mass splitting and $M \equiv M_\eta / y$ with $y \equiv |y_{ik}|$.

$$\frac{dN_e}{dE} = \frac{96 M_2^3}{(M_{21}^2)^4} \left[(M_{21}^2) E^2 - 2 M_2 E^3 \right]$$



$\tau_2 \sim 10^{26}\mathrm{s},\ M_1 = 10\ \mathrm{GeV},\ M_2 = 1.5\ \mathrm{TeV}$

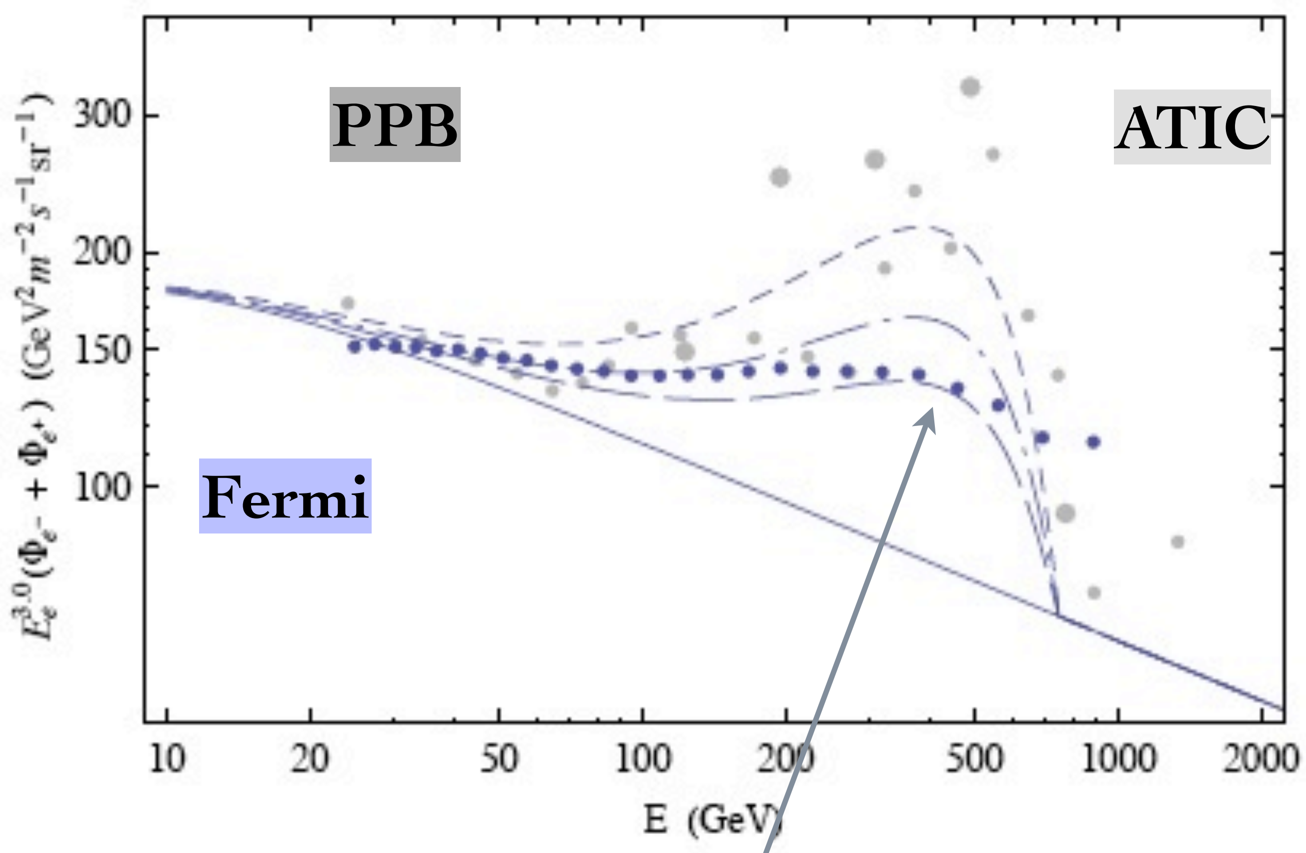
MED propagation

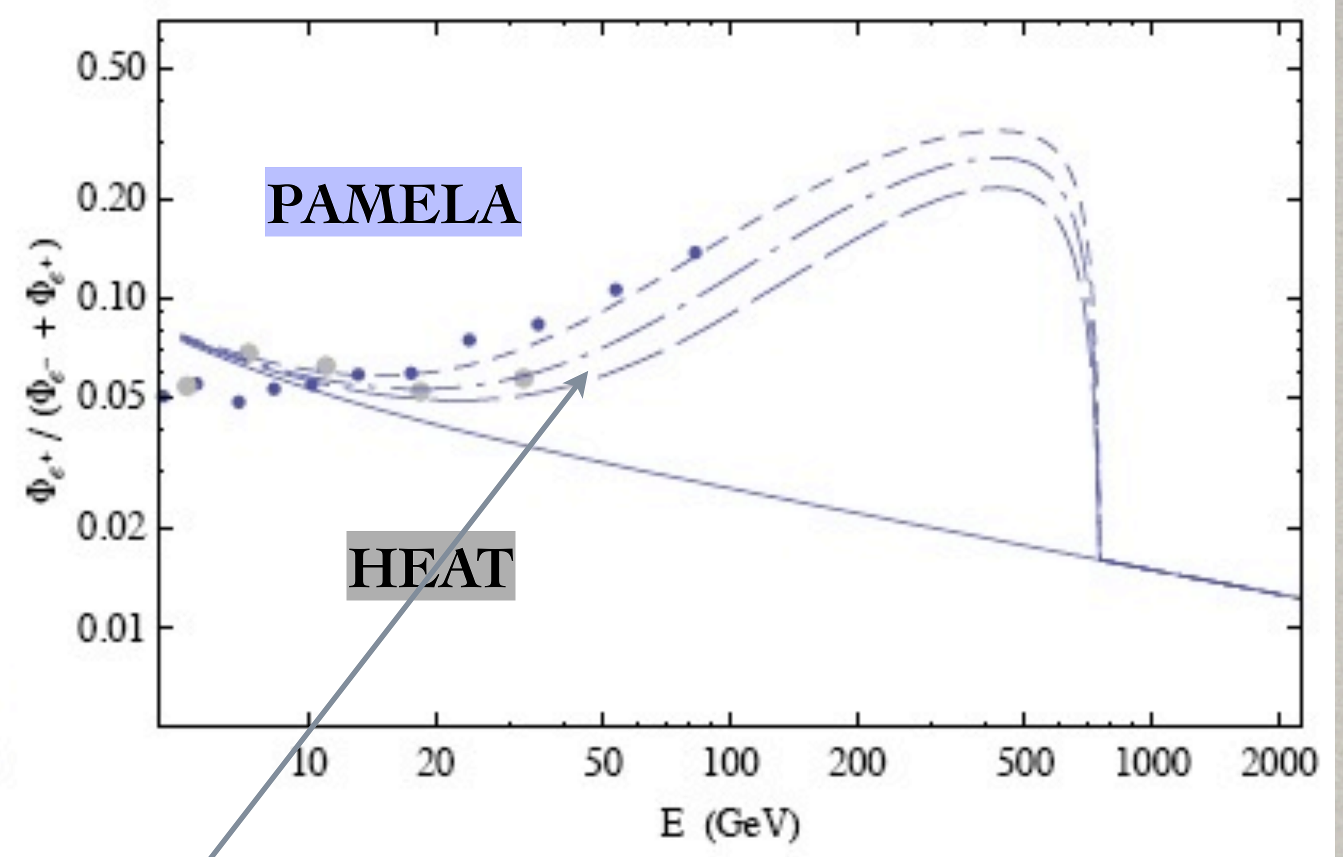
$M = 4 \times 10^{15}$ GeV

$M = 4.5 \times 10^{15}$ GeV

$M = 5 \times 10^{15}$ GeV

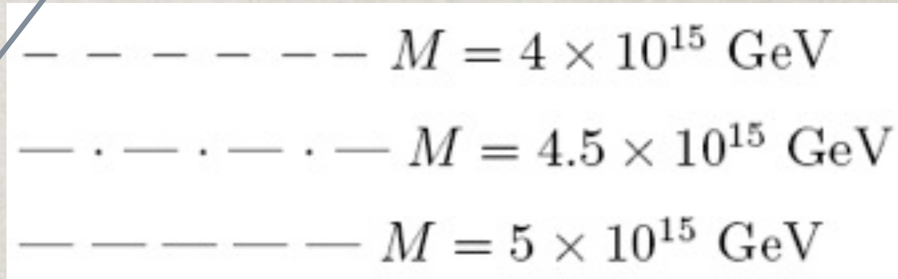
☞ **ATIC and PAMELA can be fitted well simultaneously**





$\tau_2 \sim 10^{26}$s, $M_1 = 10$ GeV, $M_2 = 1.5$ TeV

MED propagation



☞ **ATIC and PAMELA can be fitted well simultaneously**

BUT Fermi and PAMELA canNOT

A dark matter model with realistic neutrino masses and leptogenesis:

Particle	ζ	η	N_i	N
Z_2	$-$	$+$	$-$	$+$
Z_2'	$+$	$-$	$+$	$-$

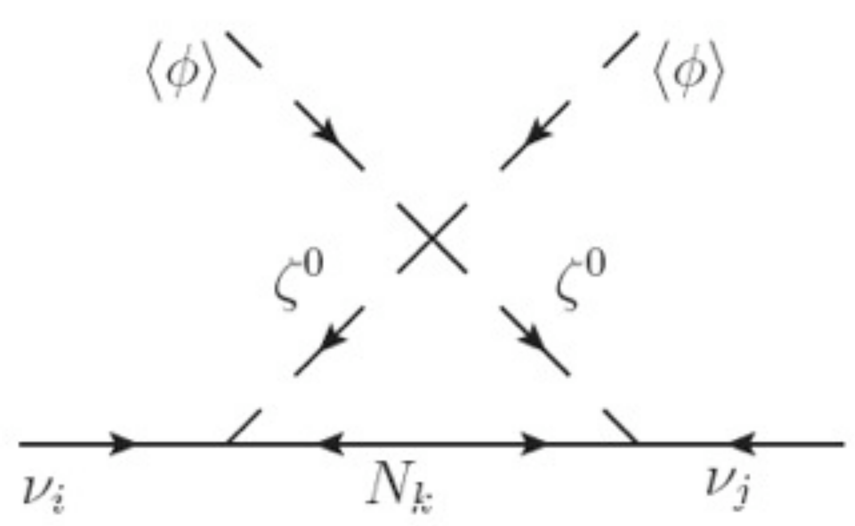
+ SM

Chen, CQG and Zhuridov, JCAP 10, 001 (2009)

$$\frac{M_{ij}}{2} N_i^T C N_j + \frac{M}{2} N^T C N + y_{ij} \bar{L}_i \zeta N_j + y_i' \bar{L}_i \eta N + \mu^2 \eta^\dagger \zeta + \frac{\lambda}{2} (\phi^\dagger \zeta)^2 + \text{H.c.}\,,$$

Neutrino masses:

$$(m_\nu)_{ij} = \frac{\mathcal{O}(\lambda)}{16\pi^2} \sum_{k=1}^{2} \frac{y_{ik} y_{jk}}{M_k} v^2$$



$$m_\nu = \mathcal{O}(0.01 - 0.1 \text{ eV}) \text{ if } \lambda = \mathcal{O}(10^{-4}),\ y_{ij} = \mathcal{O}(10^{-3})$$
$$M_i = \mathcal{O}(100 \text{ GeV} - 10 \text{ TeV}).$$

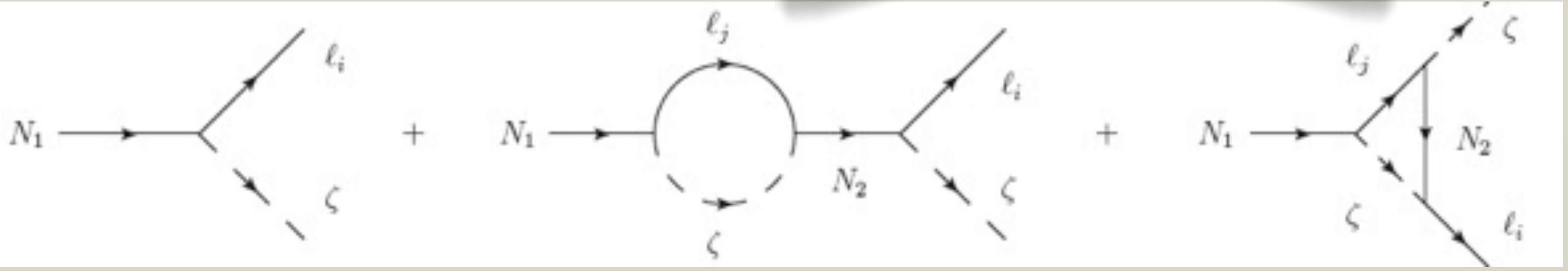
Leptogenesis:

$$\varepsilon \simeq -\frac{3}{16\pi} \frac{1}{(y^\dagger y)_{11}} \text{Im}\left[(y^\dagger y)_{12}^2\right] \frac{M_1}{M_2}.$$

$$\frac{n_B}{s} \simeq -\frac{1}{15} \frac{\varepsilon}{g_*} \simeq 10^{-10}$$

$$g_* \simeq 100$$

See Xing's lectures



DM decays:

$$\Gamma_i = \frac{|y_i'|^2}{4\pi}\left(\frac{|\mu|}{M_\eta}\right)^4 \frac{M_-^2}{M},$$

$$\tau_N = \frac{1}{4\sum_i \Gamma_i} = \frac{\pi A^4 M}{M_-^2}$$

$$A = \frac{M_\eta}{|\mu|(\sum_i |y_i'|^2)^{1/4}},$$

$$M_\pm = \frac{M^2 \pm M_\zeta^2}{2M}$$

$$\varepsilon = |y_\mu'|^2/|y_e'|^2$$

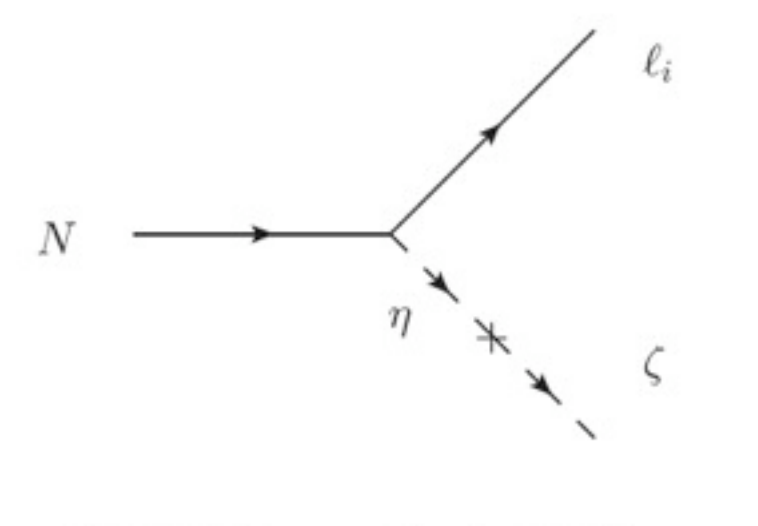
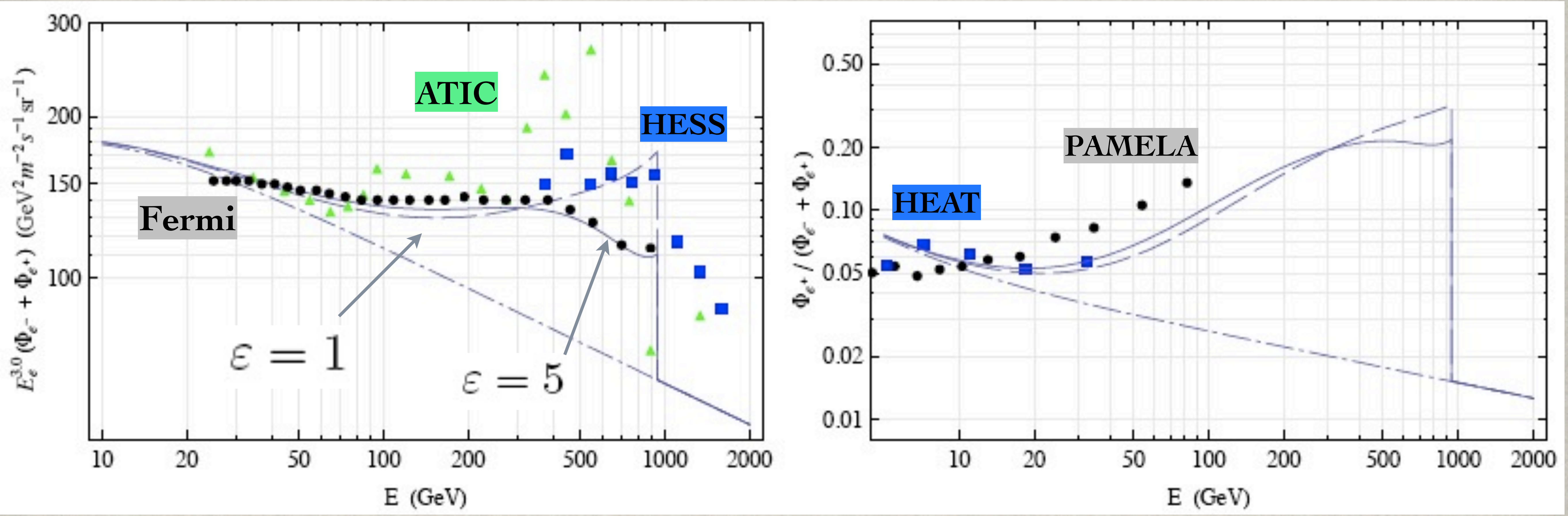


FIG. 3: Diagram for the DM decay.

$$\tau_N = 2.5 \times 10^{26}\ \text{s},\ M = 2\ \text{TeV},\ M_\zeta = 500\ \text{GeV}$$

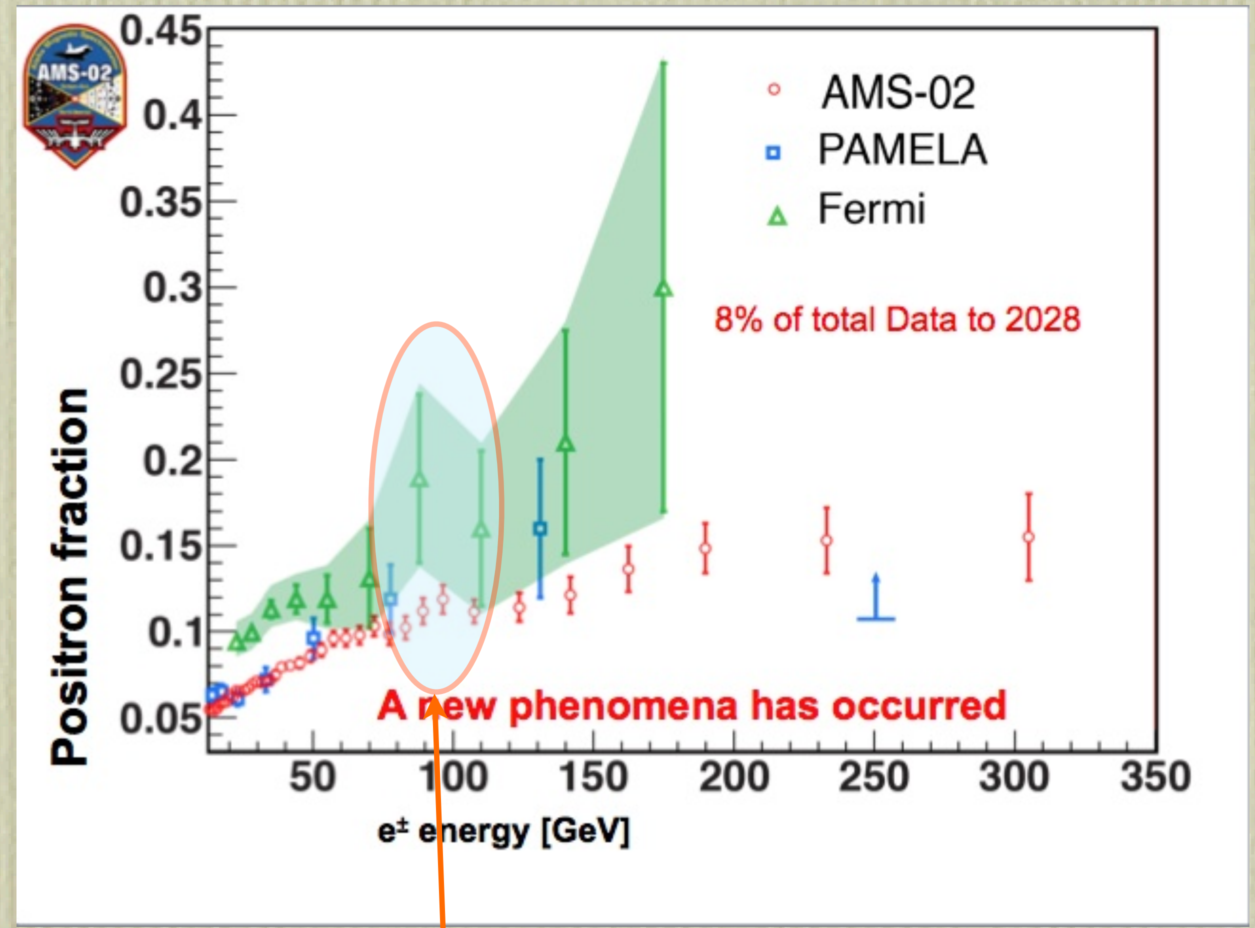


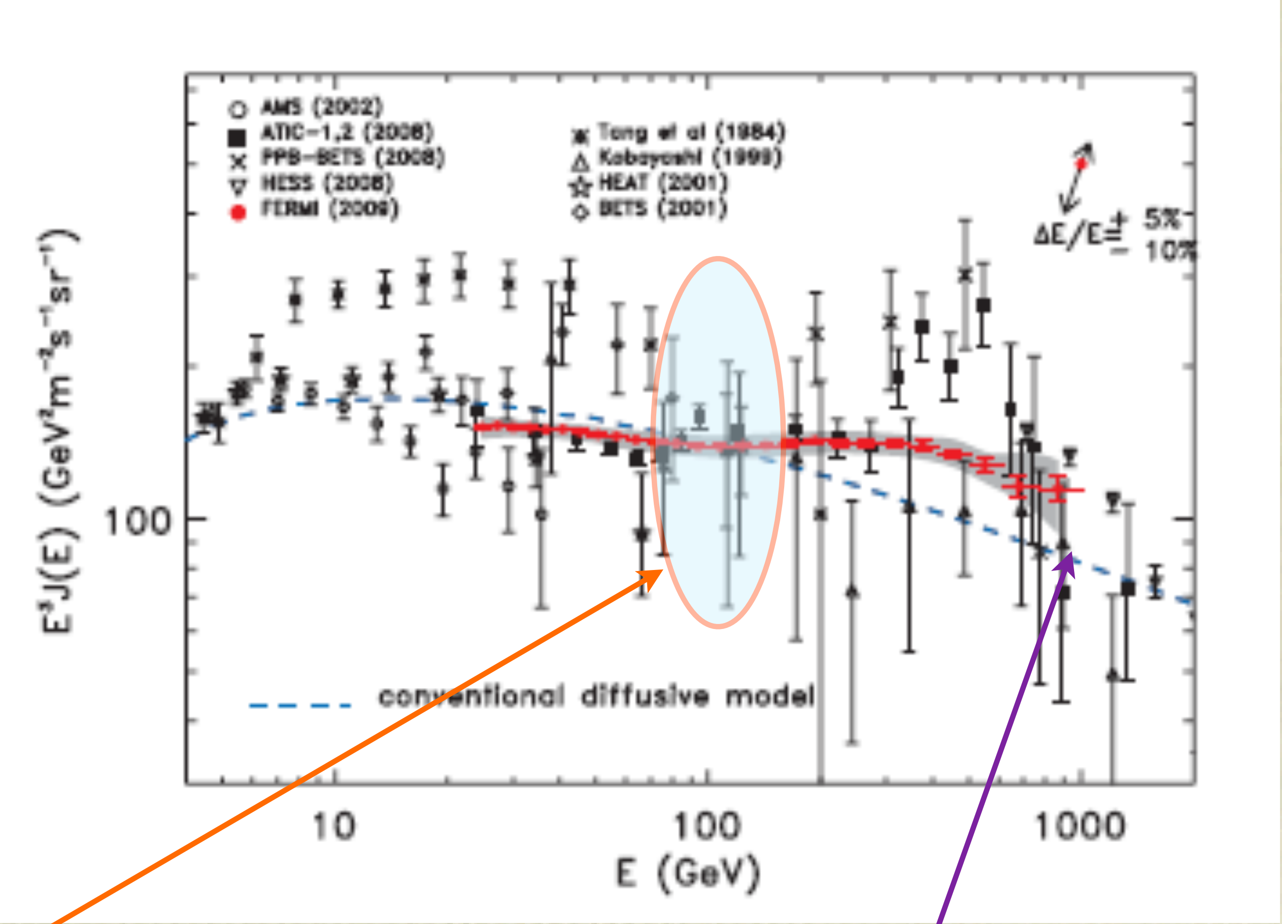
☞ **Fit Fermi and PAMELA well if the muon effect is large**

• *Multi-component Dark Matter*

CQG,Huang,Tsai,PRD89(2014)055021

AMS-02 Positron Fraction Spectrum **Femi-LAT $e^{+}+e^{-}$ Spectrum**





Observations:

1. The excess of total $e^{+}+e^{-}$ flux by Fermi-LAT extends to 1 TeV, at least one DM cutoff should be larger than 1 TeV;

2. The substructure at around 100 GeV could result from some additional lighter DM.

DM with two-body decaying into $e^{\pm}$

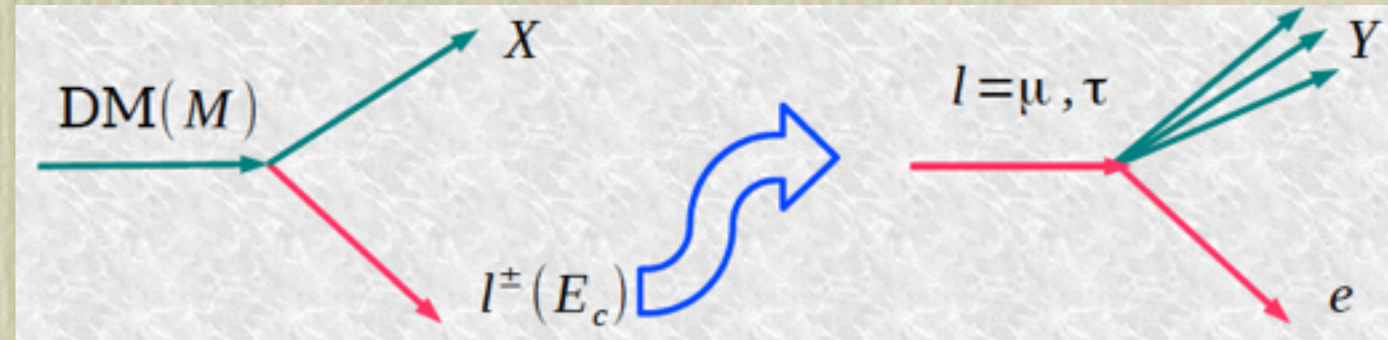
CQG,Huang,Tsai,PRD89(2014)055021

DM $\rightarrow l^-(l^+) + X$ with a specific charged leton energy E_c

The total flux of electron/positron

$$\Phi_e^{tot} = \kappa\, \Phi_e^{primary} + \Phi_e^{secondary} + \Phi_e^{DM}$$

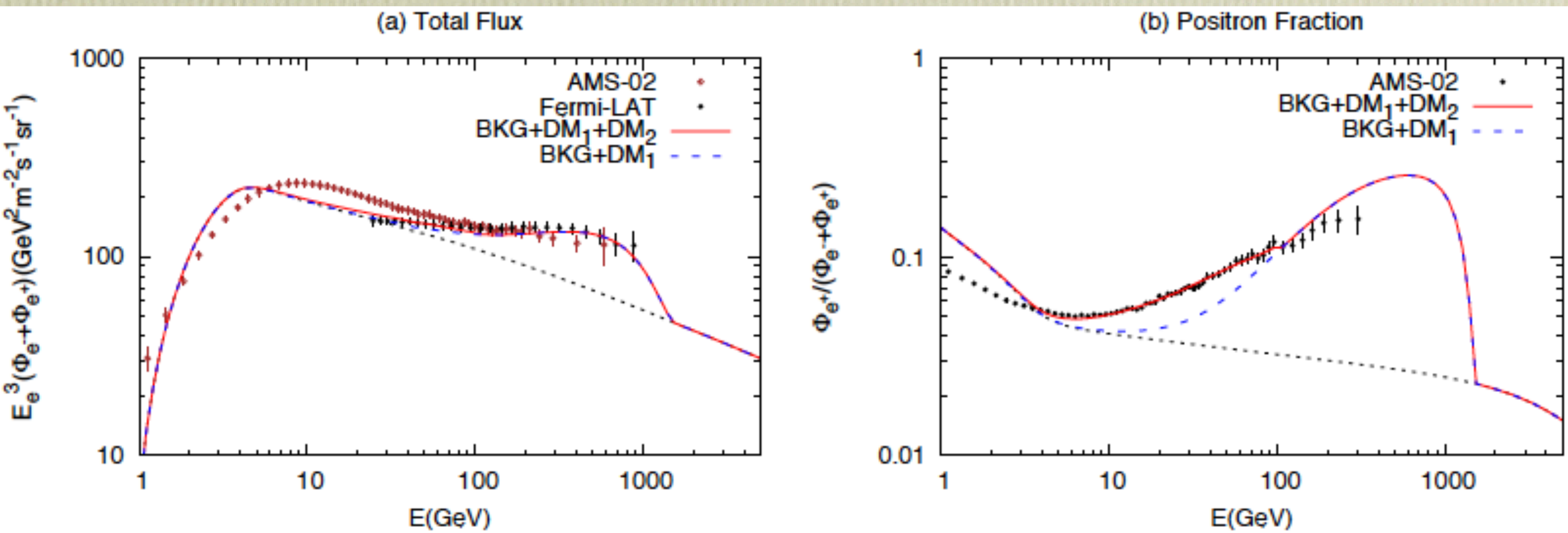
$$\Phi_p^{tot} = \Phi_p^{secondary} + \Phi_p^{DM}$$



In the two-component DM scenario, we only open the muon two-body decay for DM$_1$ and mainly the tau one for DM$_2$

Take $M_1 = 2500\,\text{GeV}$, $M_2 = 420\,\text{GeV}$, $E_{c1} = 1500\,\text{GeV}$, $E_{c2} = 100\,\text{GeV}$

κ	ϵ_H^e	ϵ_H^μ	ϵ_H^τ	$\tau_H(10^{26}\text{s})$	ϵ_L^e	ϵ_L^μ	ϵ_L^τ	$\tau_L(10^{26}\text{s})$	$\chi^2_{\min}$	$\chi^2_{\min}/d.o.f.$
0.844	0	1	0	0.76	0.018	0	0.982	0.82	62.3	1.06



Realization of two-component DM

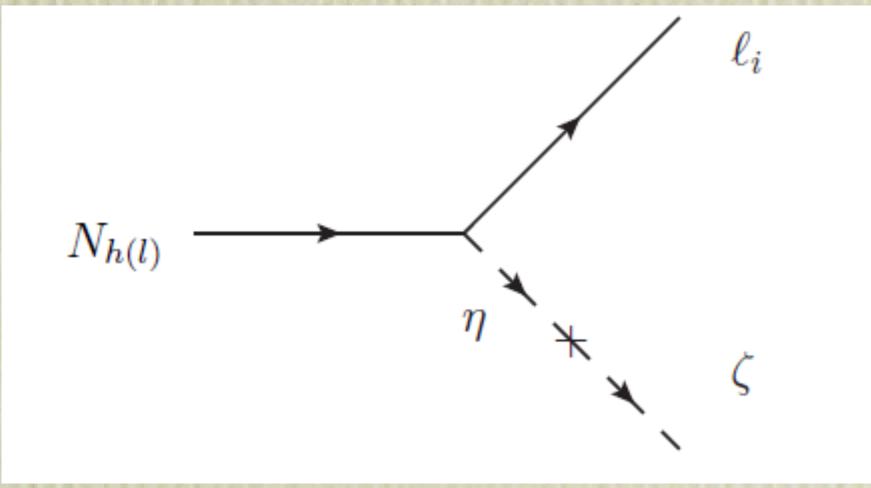
	N_{R1}	N_{R2}	η	ζ
Z_2	$-$	$-$	$-$	$+$
Z_2'	$+$	$+$	$+$	$-$

- Relevant Lagrangian

$$L = -\bar{L}_{Li}(Y_{1i}N_{R1} + Y_{2i}N_{R2})\eta - \frac{M_1}{2}\overline{(N_{R1})^c}N_{R1} - \frac{M_2}{2}\overline{(N_{R2})^c}N_{R2} - \mu^2\zeta^\dagger\eta - V\ ,$$

- Mass hierarchy: $M_\eta >> M_{1,2} > M_\zeta$

- Relevant Feynman Diagram



If $N_{h(l)}$'s lifetime is $O(10^{26})$s, then it only requires

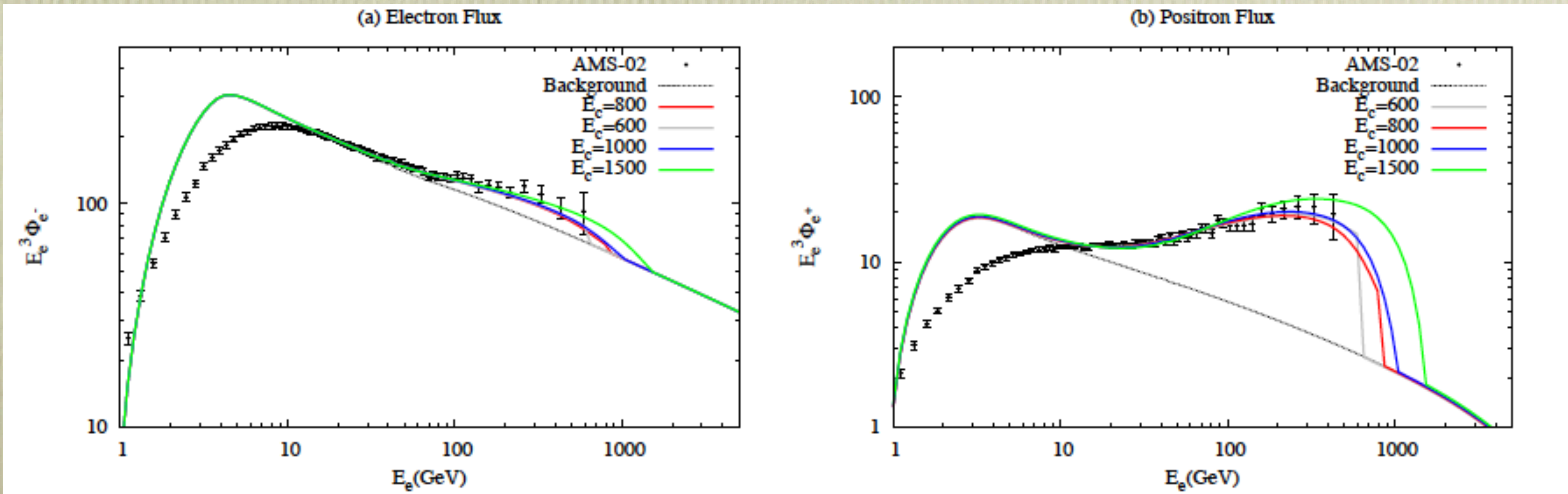
$Y_{1(2)i} \sim \mathcal{O}(10^{-6})$, $\mu \sim \mathcal{O}(1\ \mathrm{GeV})$ $\quad M_\eta \sim \mathcal{O}(10^{10}\ \mathrm{GeV})$

C.Q.Geng, D.Huang, C.Lai, 1411.3813 [astro-ph], Revisiting Multicomponent Dark Matter with New AMS-02 Data

$$\Phi_e^{(\mathrm{tot})} = \kappa_1 \Phi_e^{(\mathrm{primary})} + \kappa_2 \Phi_e^{(\mathrm{secondary})} + \Phi_e^{\mathrm{DM}},$$
$$\Phi_p^{(\mathrm{tot})} = \kappa_2 \Phi_p^{(\mathrm{secondary})} + \Phi_p^{\mathrm{DM}}.$$

$$\left(\frac{dN_{e,p}}{dE}\right)_i = \frac{1}{2}\left[\epsilon_i^e \left(\frac{dN^e}{dE}\right)_i + \epsilon_i^\mu \left(\frac{dN^\mu}{dE}\right)_i + \epsilon_i^\tau \left(\frac{dN^\tau}{dE}\right)_i\right],$$

E_{cH}(GeV)	κ_1	κ_2	$\epsilon^e_{H,L}$	$\epsilon^\mu_{H,L}$	$\epsilon^\tau_{H,L}$	$\tau_{H,L}(10^{26}\mathrm{s})$	χ^2_{min}	χ^2_{min}/d.o.f.
600	0.94	1.49	0.18, 0.02	0.74, 0.00	0.08, 0.98	1.52, 1.34	102	0.78
800	0.94	1.49	0.05, 0.02	0.65, 0.00	0.30, 0.98	1.08, 1.39	102	0.78
1200	0.94	1.50	0.00, 0.01	0.80, 0.00	0.20, 0.99	0.62, 1.61	102	0.78
1500	0.94	1.50	0.00, 0.04	1.00, 0.17	0.00, 0.79	0.60, 1.98	105	0.81



A Number of Unexplained or Ambiguous Observations Persist:

- Excess 511 keV emission from Galactic Bulge (INTEGRAL)
- Excess high-energy cosmic ray positrons (PAMELA, AMS)
- Excess isotropic radio emission (ARCADE, etc.)
- 130 GeV line from the Galactic Center (Fermi)
- 3.5 keV line from Galaxy Clusters (XMM-Newton, Chandra)
- Excess GeV emission from the Galactic Center (Fermi)

Any of these signals could plausibly be the result of annihilating/decaying dark matter particles (although most probably are not)

☺ Open questions in Dark Matter:

0. What is the real nature of Dark Matter?

1. Is Dark Matter a WIMP?

2. Can we observe it directly at the underground Labs or at the LHC?

3. Will AMS-2 or others show some conclusive new evidences for DM from the sky soon?

Preface

Lecture 1: The uniqueness of the standard model of particle physics and Beyond

Lecture 2: Dark Matter and Cosmic Ray Anomalies

Lecture 3: Understanding Dark Energy beyond the LCDM: Modified Theories of Gravity

Conclusions

Future prospects

Lecture 3
Understanding Dark Energy
beyond the LCDM
Modified Theories of Gravity

Outline

- *The Acceleration Universe: Dark Energy*
- *Modified Gravity Theories*
- *Teleparallel Dark Energy*
- *Open Questions*

• *The Acceleration Universe: Dark Energy*

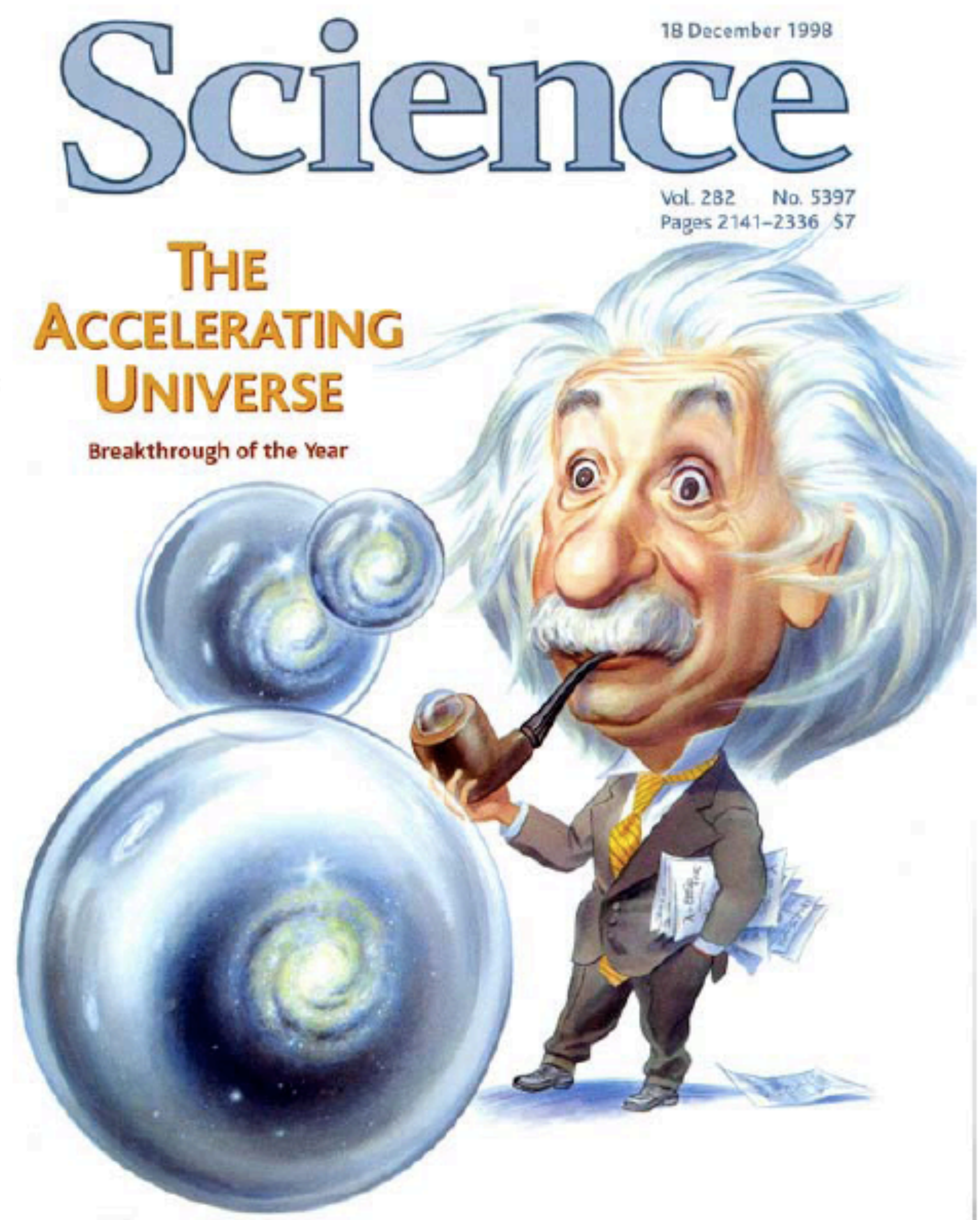
Big News in 1998!

High-Z Team

Riess et al. (1998)

Supernova Cosmology Project

Perlmutter et al. (1999)



The Nobel Prize in Physics 2011

"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"

Photo: Roy Kaltschmidt. Courtesy: Lawrence Berkeley National Laboratory

Saul Perlmutter

Photo: Belinda Pratten, Australian National University

Brian P. Schmidt

Photo: Homewood Photography

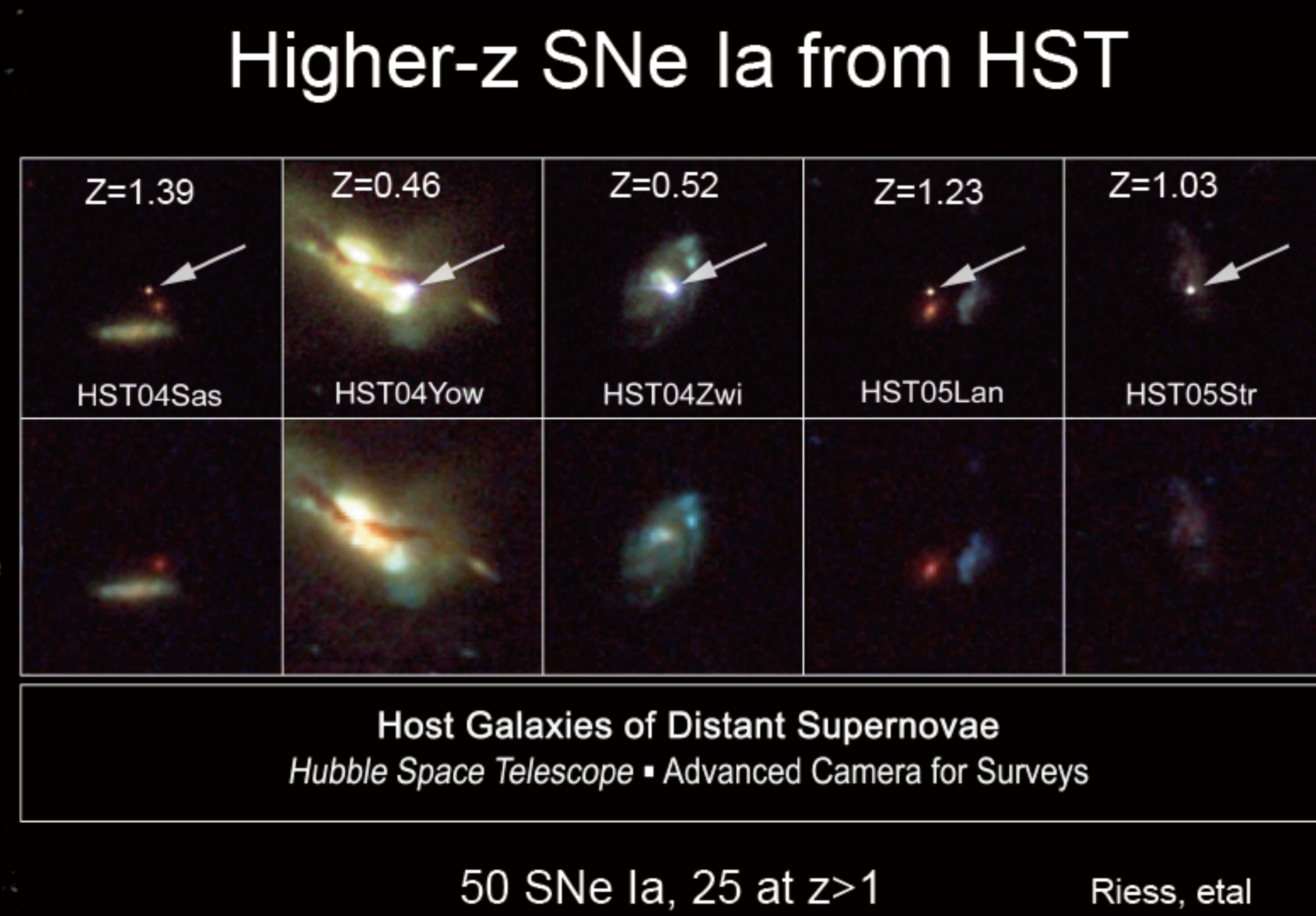
Adam G. Riess

2015 Breakthrough Prize in Fundamental Physics: 51 members splitting the $3 million

Distant supernovae

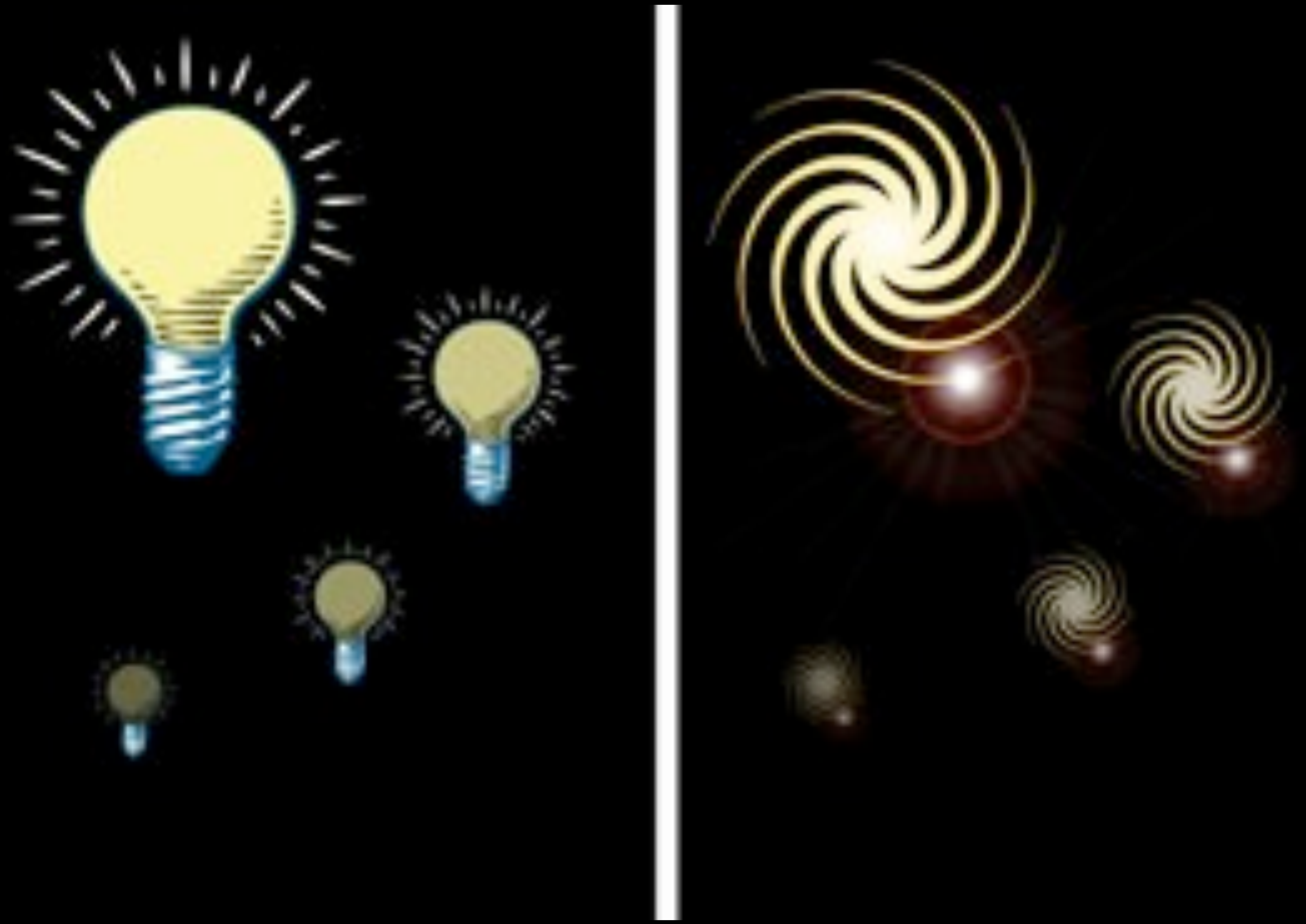
After

Before

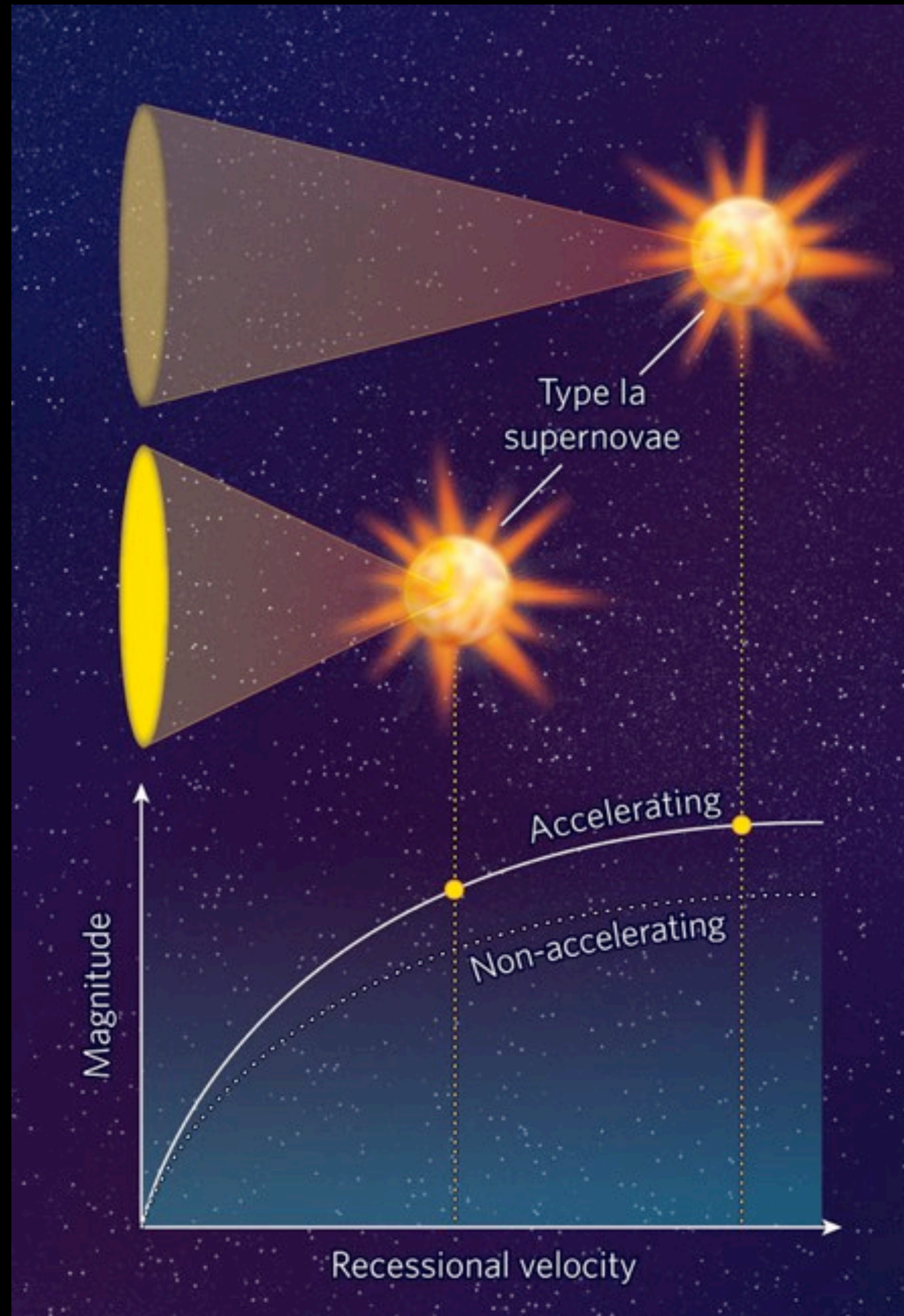


Distant supernovae

Standard candles:
Their intrinsic luminosity is known
Their apparent luminosity can be measured



Distant SN as standard candles



Luminosity distance:

$$d_L^2 = \frac{L_s}{4\pi \mathcal{F}}$$

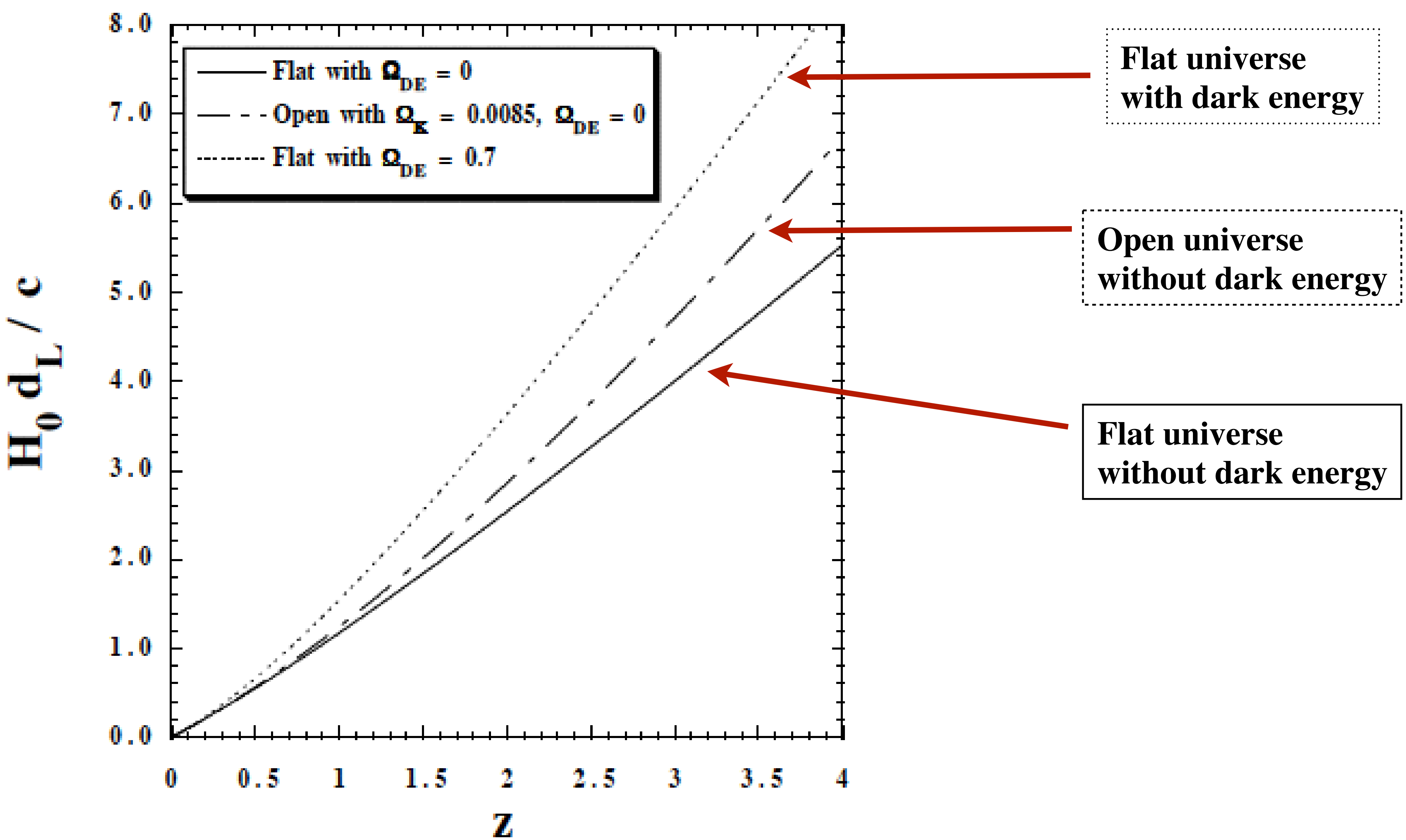
L_s the absolute luminosity of the source
F observed flux

$$d_L = \frac{c(1+z)}{H_0\sqrt{-K_0}} \sinh\left(\sqrt{-K_0}\int_0^z \frac{dz'}{E(z')}\right)$$

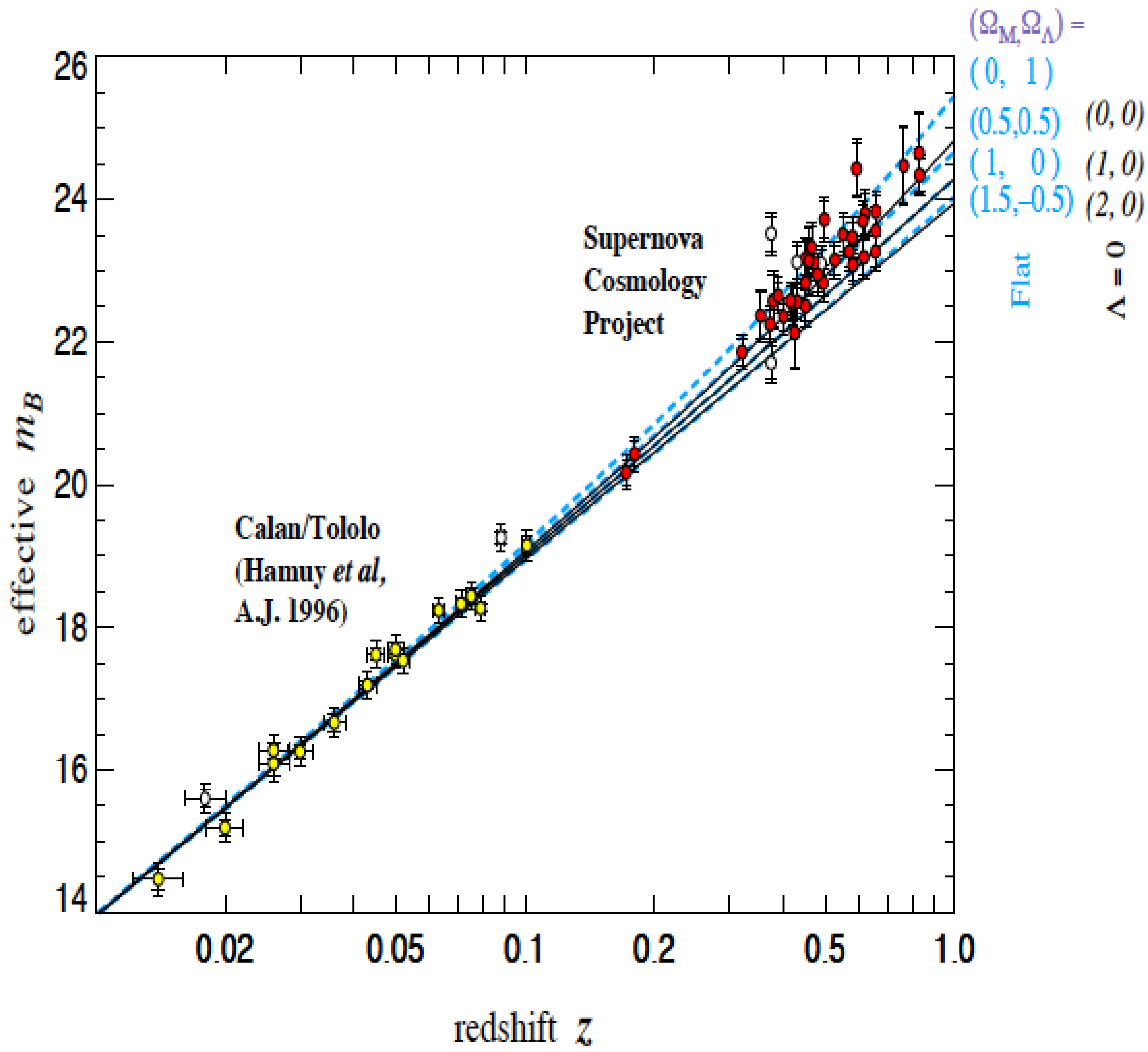
K>0: closed
K=0: flat
K<0: open

$$K_0 = Kc^2/a_0^2 H_0^2$$

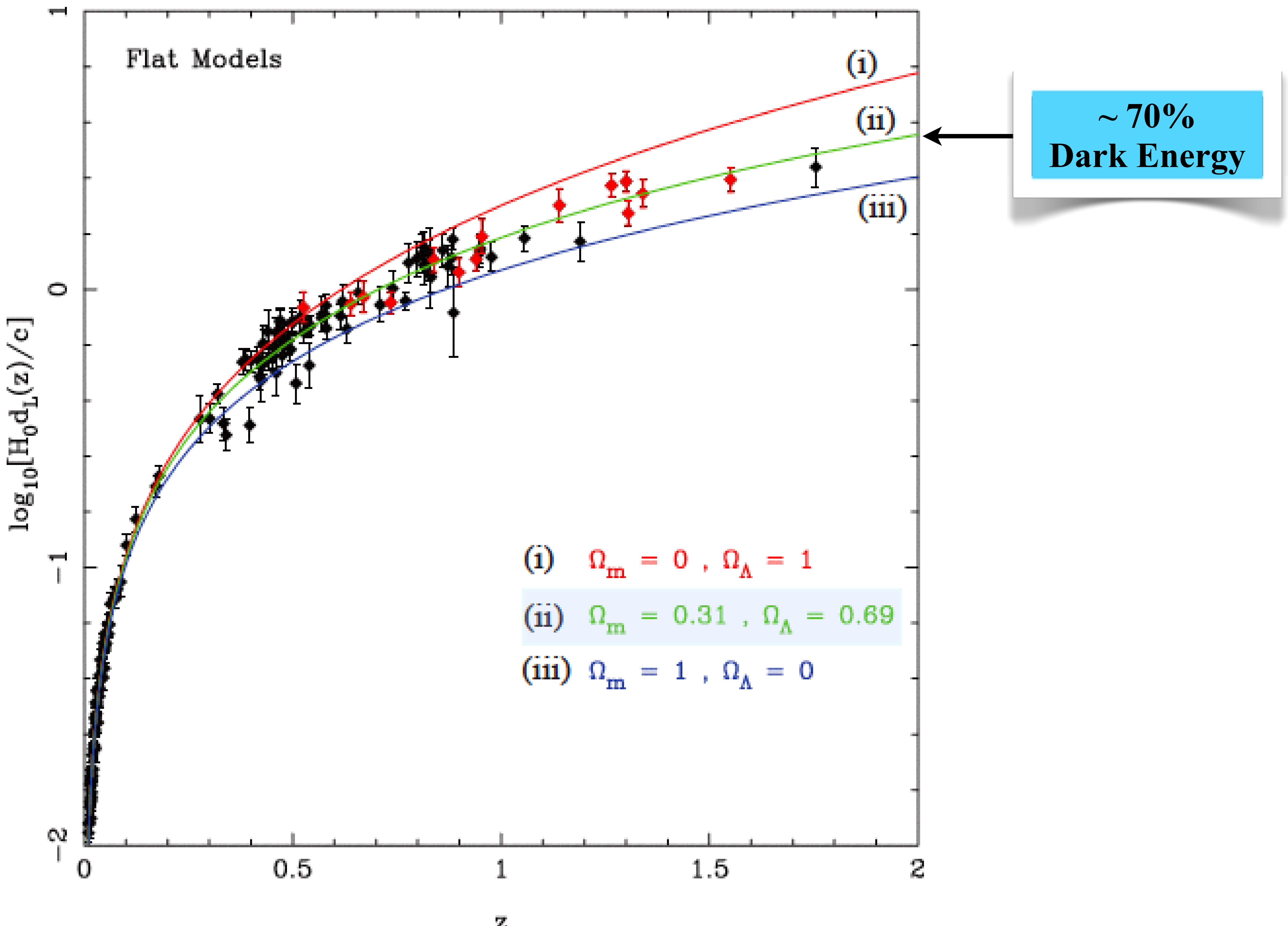
$$E(z) = \left[\Omega_m^{(0)}(1+z)^3 + \Omega_K^{(0)}(1+z)^2 + \Omega_{\rm DE}^{(0)} \exp\left\{\int_0^z \frac{3(1+w_{\rm DE})}{1+z'} dz'\right\}\right]^{1/2}$$



Perlmutter et al and Riess et al (1998)

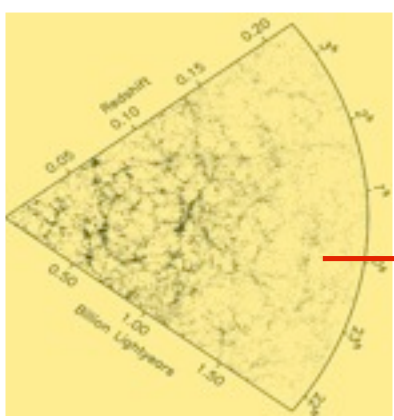


More data over the past 10 years

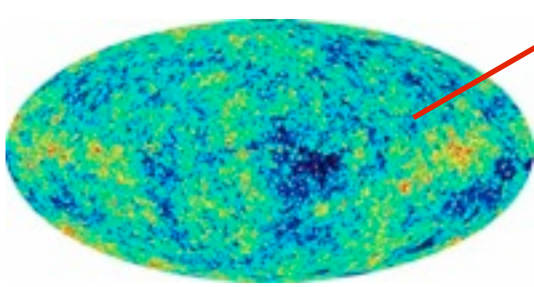


SNe Ia

LSS



CMB

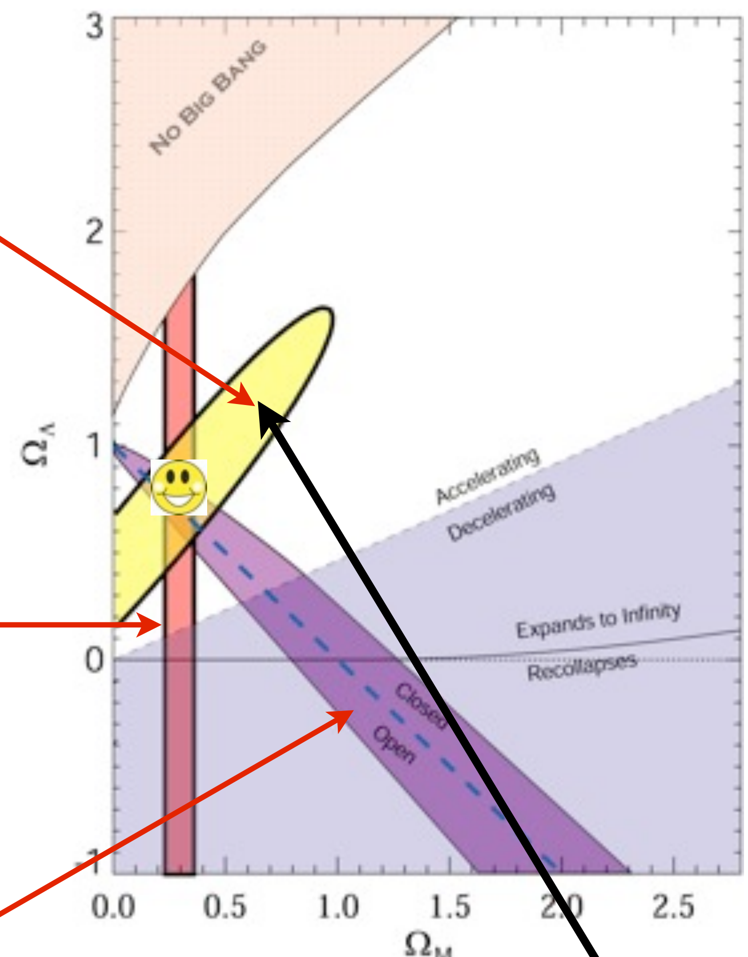


Concordance region:

68% dark energy

27% dark matter

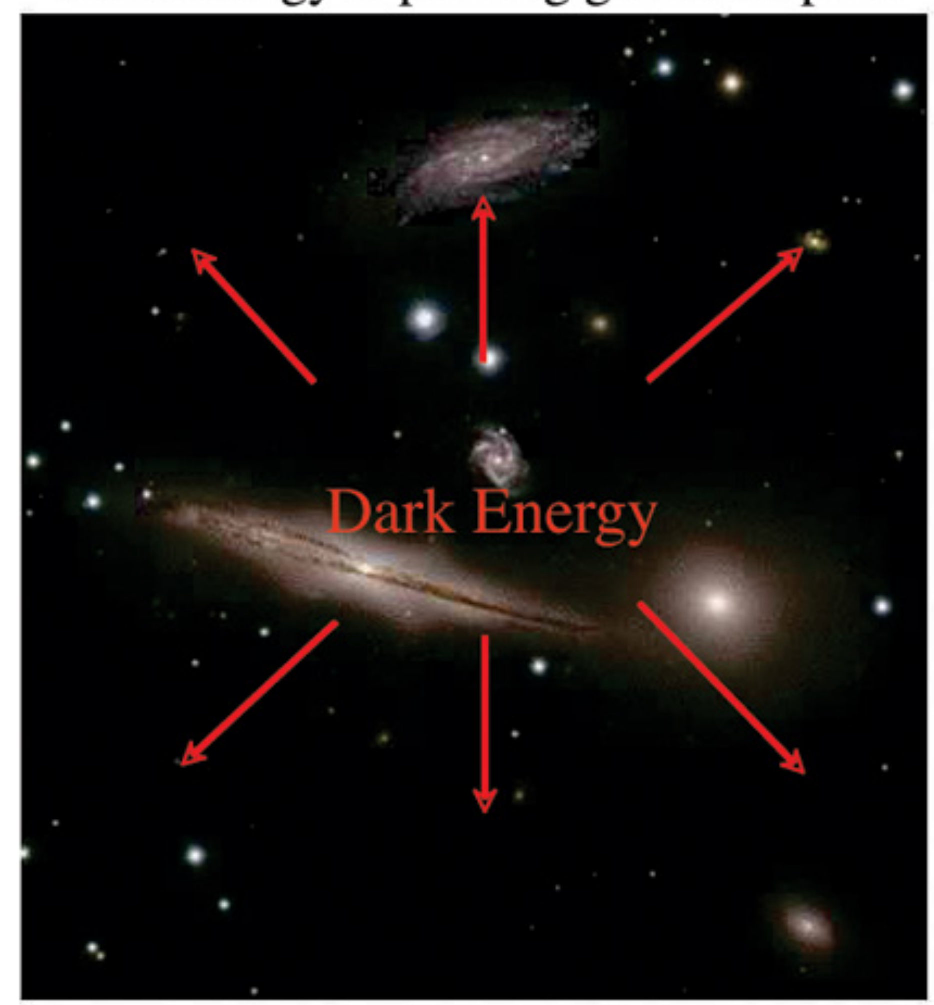
5% atoms



2011 Nobel Prize in Physics

The current universe is accelerating!

Dark energy is pushing galaxies apart.



Edward Witten

IAS, Princeton

‘Most embarrassing observation in physics’ – that’s the only quick thing I can say about dark energy that’s also true.”

Cosmological Dynamics

expansion rate | total energy | curvature

$$H^2 = 8\pi G\,(\rho_M+\rho_{DE})\,/\,3 - k\,/\,a^2$$

$$1 = \Omega_M + \Omega_{DE} - k\,/\,(a^2H^2)$$

G	Newton's constant
a	scale factor or radius
$H \equiv \dot{a}/a$	Hubble parameter
ρ	energy density
p	pressure
k=1, 0, -1	closed, flat, open

$$\Omega \equiv 8\pi G\rho/\,3H^2$$

Cosmic Scale factor *a(t)*

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\sum_i \rho_i(1+3w_i)$$

Friedmann Equation

Equation of state parameter $w_i = p_i/\rho_i$

For acceleration, $w_i < -1/3$ in dominant component

Cosmological constant Λ: $w = -1$

☞ **Negative pressure P of dark energy**

When w is constant

$$a \propto t^{2/3(1+w)} \qquad \rho \propto a^{-3(1+w)}$$

Radiation dominates at early times (small a), then matter and finally dark energy.

$$\dot{\rho} + 3\left(\frac{\dot{a}}{a}\right)(\rho + p) = 0$$

$$\frac{\dot{\rho}}{\rho} + \frac{3\dot{a}}{a}(1+w) = 0$$

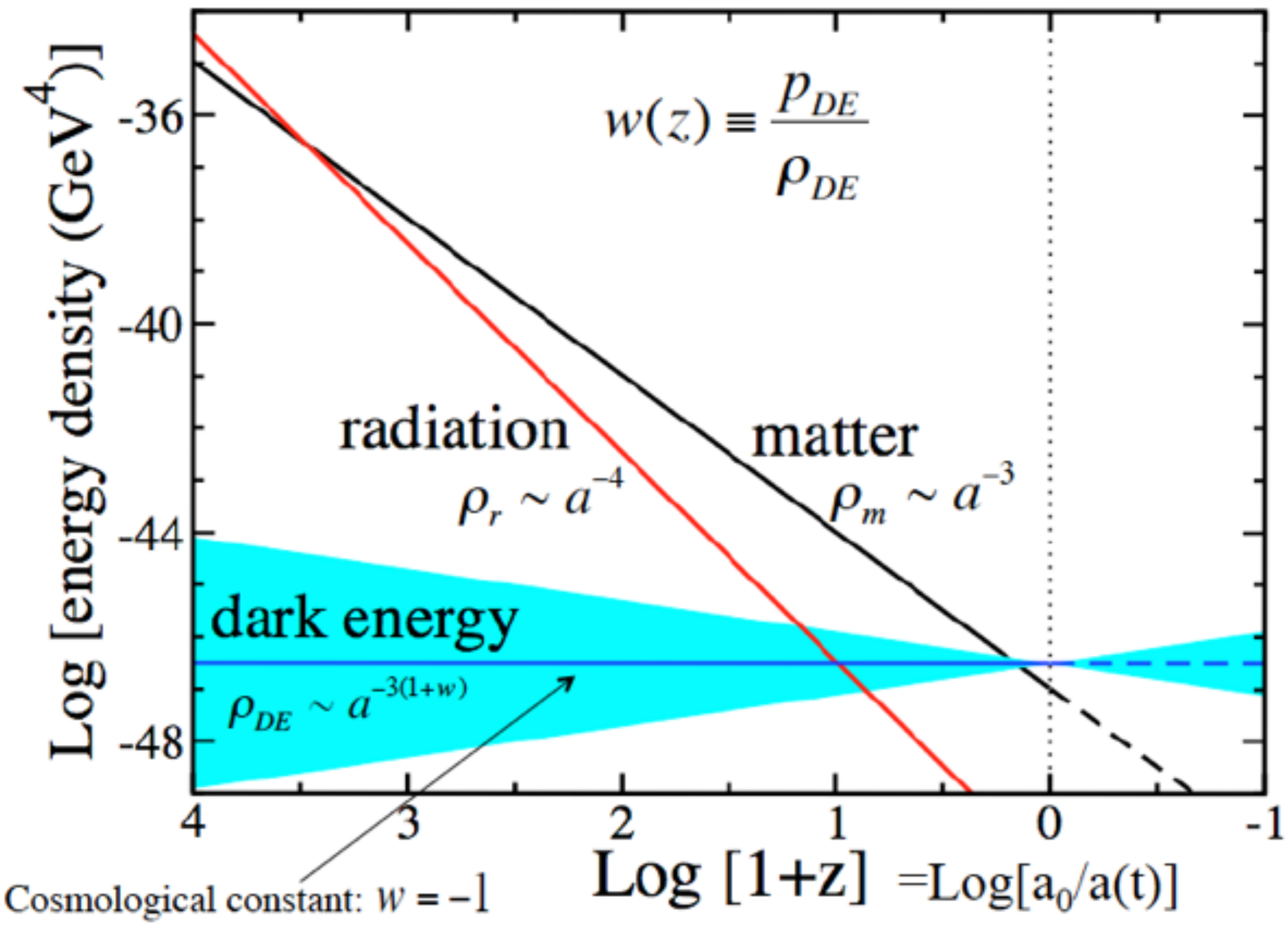
matter $w = 0 \rightarrow \rho \propto a^{-3}$

radiation $w = 1/3 \rightarrow \rho \propto a^{-4}$

constant vacuum energy $\dot{\rho} = 0 \rightarrow w = -1$

Cosmological Dynamics

Dark Energy Equation of State parameter w determines Cosmic Evolution



G	Newton's constant
	scale factor or radius
a	Hubble parameter
	energy density
	pressure
, -1	closed, flat, open

Gρ/ 3H²

nn

n

pressure P of dark energy

When w is constant

$$a \propto t^{2/3(1+w)} \quad \rho \propto a^{-3(1+w)}$$

Radiation dominates at early times (small a), then matter and finally dark energy.

$$\dot{\rho} + 3\left(\frac{\dot{a}}{a}\right)(\rho + p) = 0$$

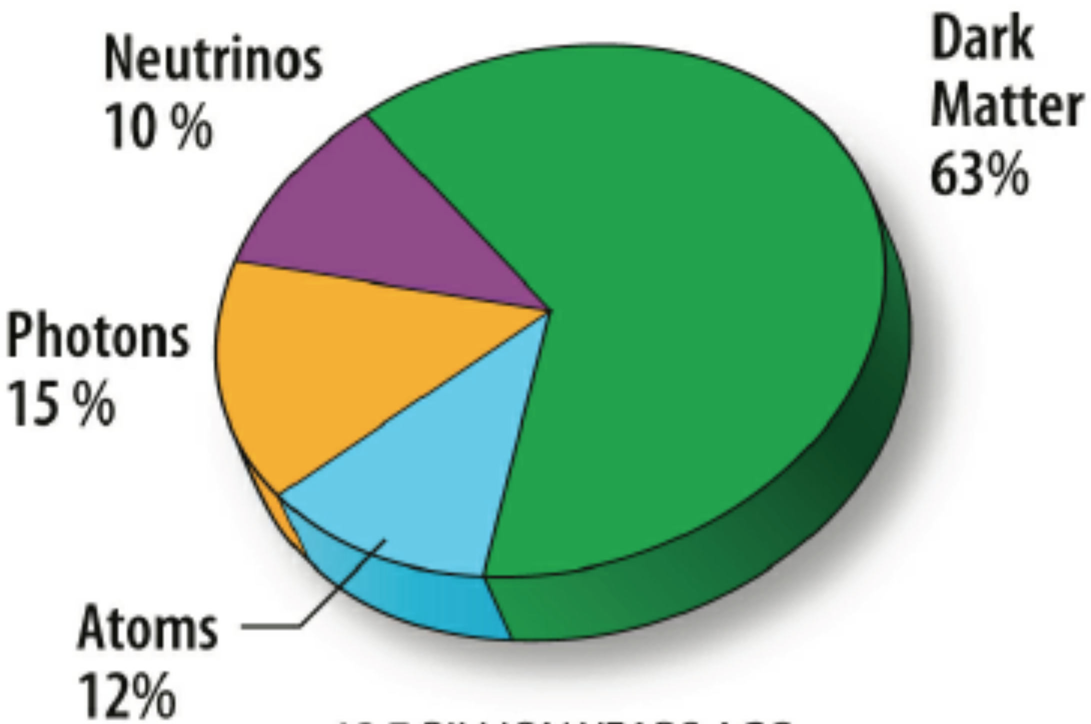
$$\frac{\dot{\rho}}{\rho} + \frac{3\dot{a}}{a}(1+w) = 0$$

$$\text{matter } w = 0 \to \rho \propto a^{-3}$$

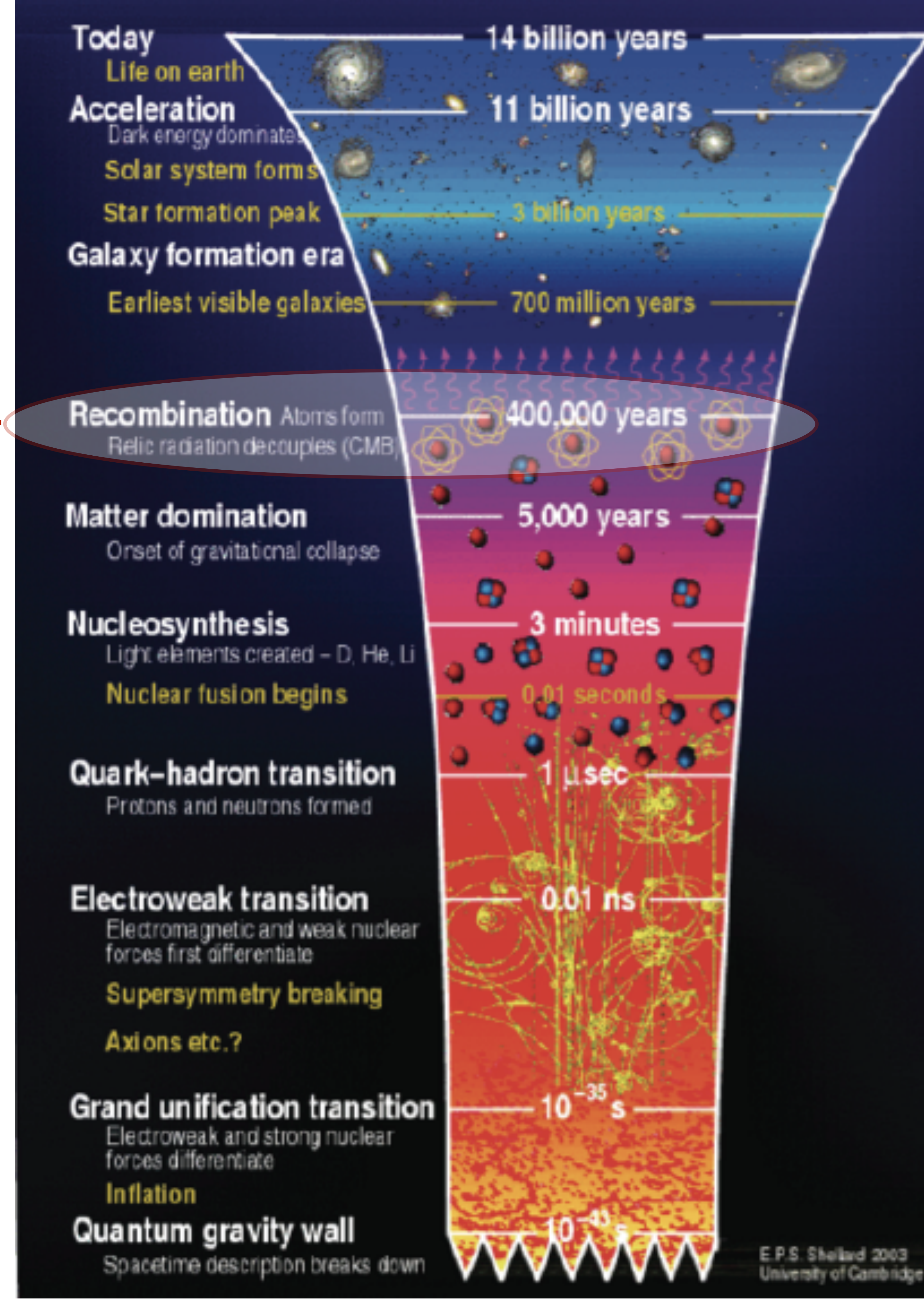
$$\text{radiation } w = 1/3 \to \rho \propto a^{-4}$$

$$\text{constant vacuum energy } \dot{\rho} = 0 \to w = -1$$

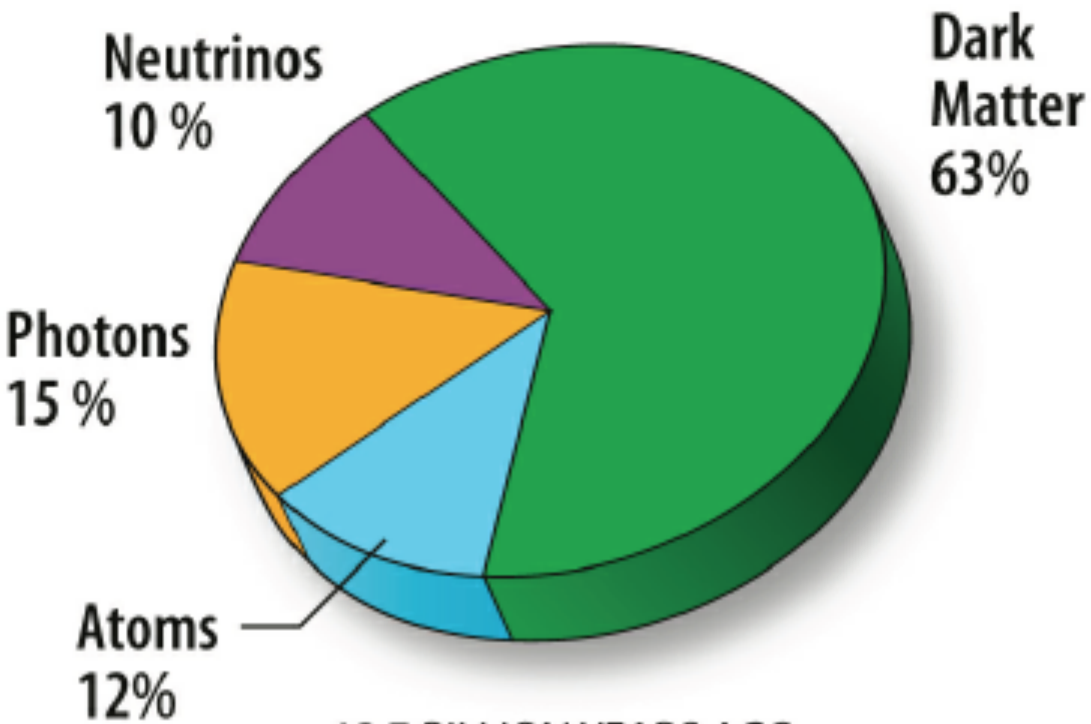
THE UNIVERSE, THEN



13.7 BILLION YEARS AGO
(Universe 380,000 years old)



The Universe, Then and Now



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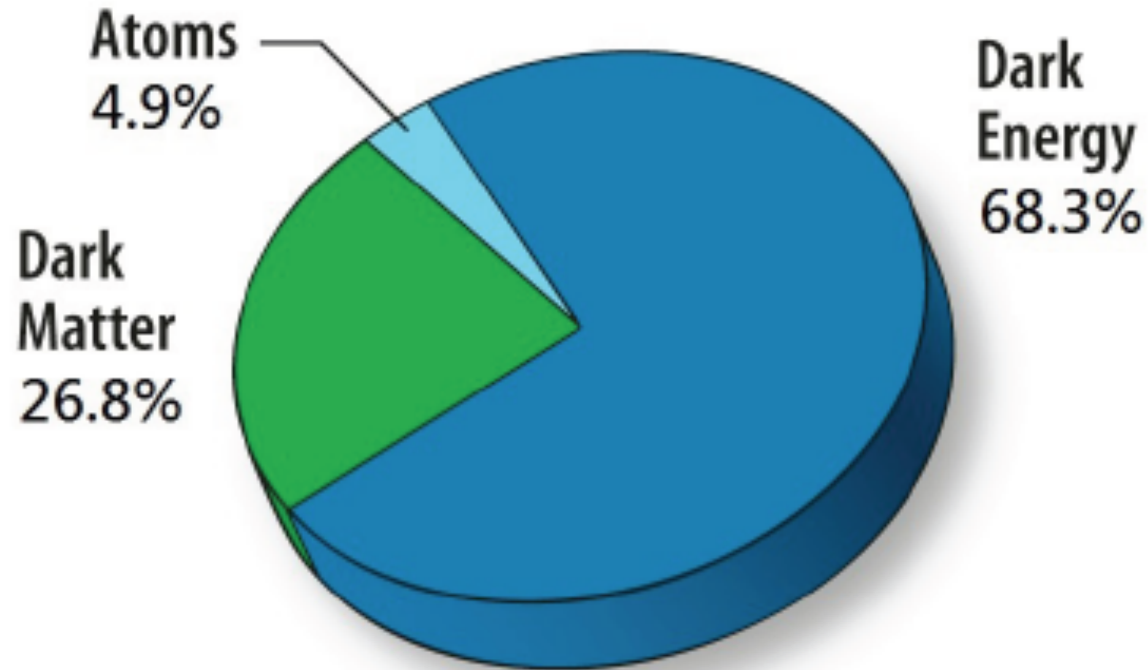


TODAY

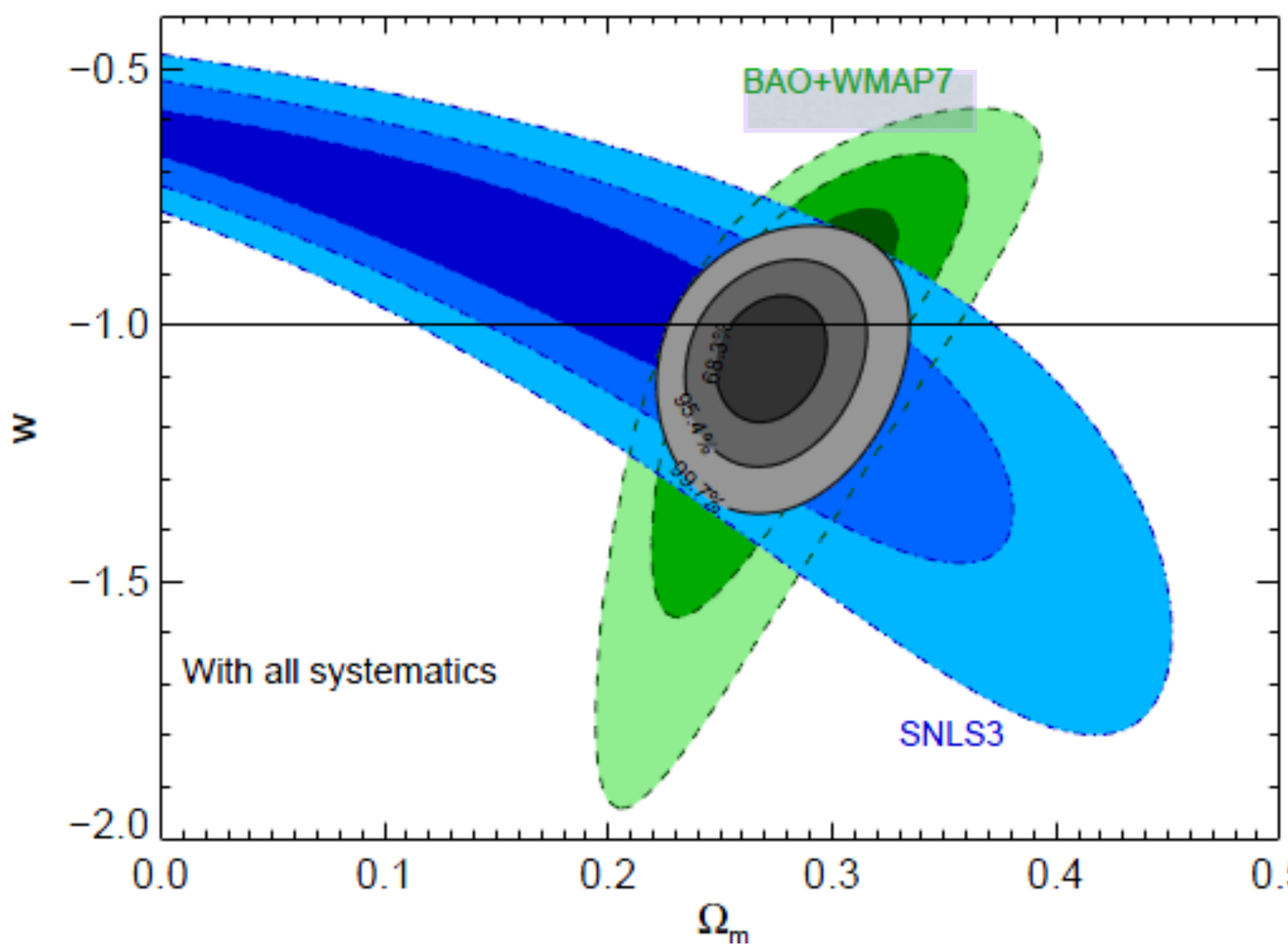
What is the value of the equation of state w?

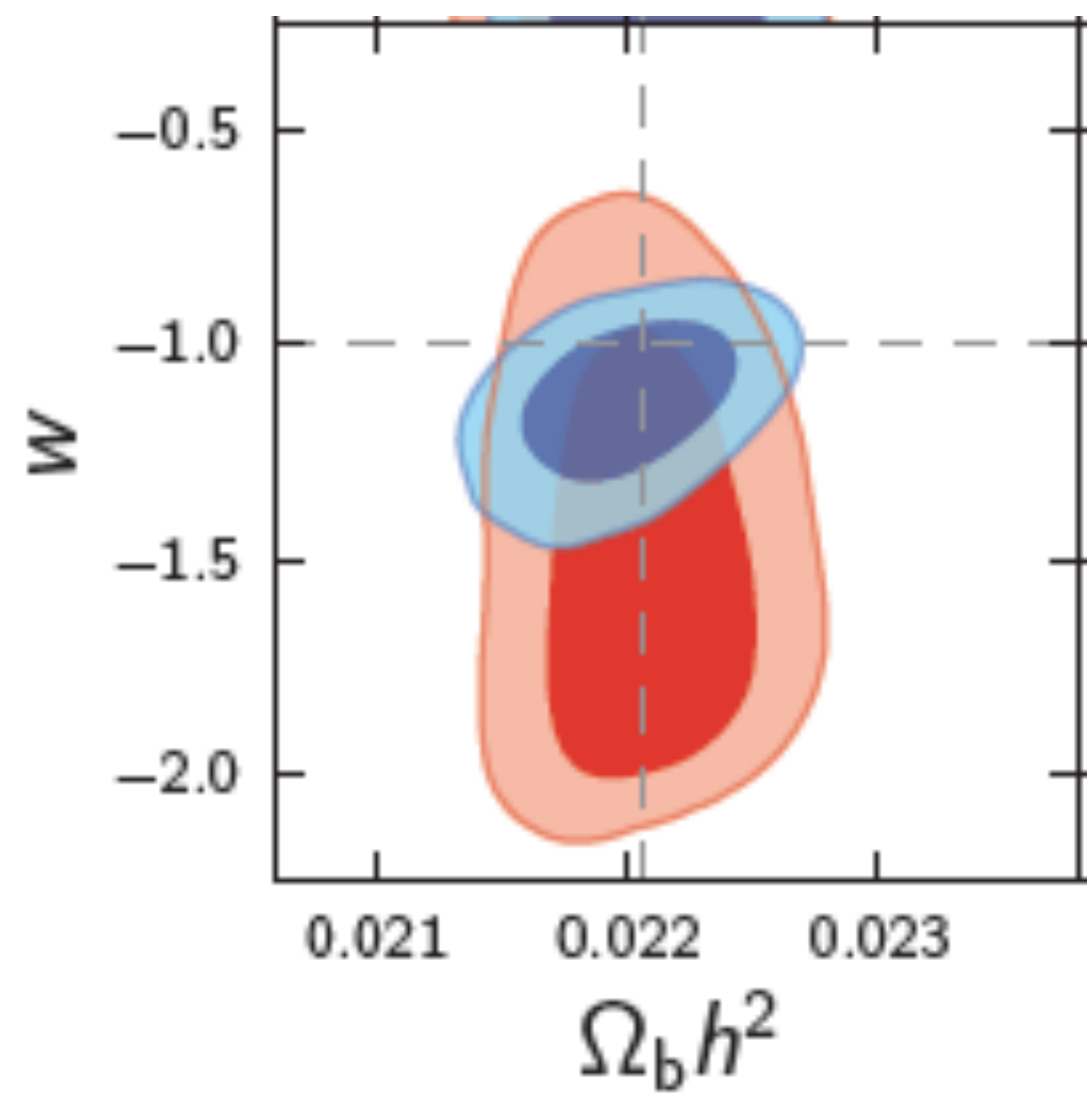
Does w vary with time? ☞ **``dynamical" dark energy**

Sullivan et al. (2011)
WMAP7

$$\Omega_{DE} = 0.731^{+0.015}_{-0.015}$$
$$w = -1.069^{+0.091}_{-0.092}$$

$$w = -1.13^{+0.24}_{-0.25} \quad (95\%; \textit{Planck}\text{+WP+BAO})$$



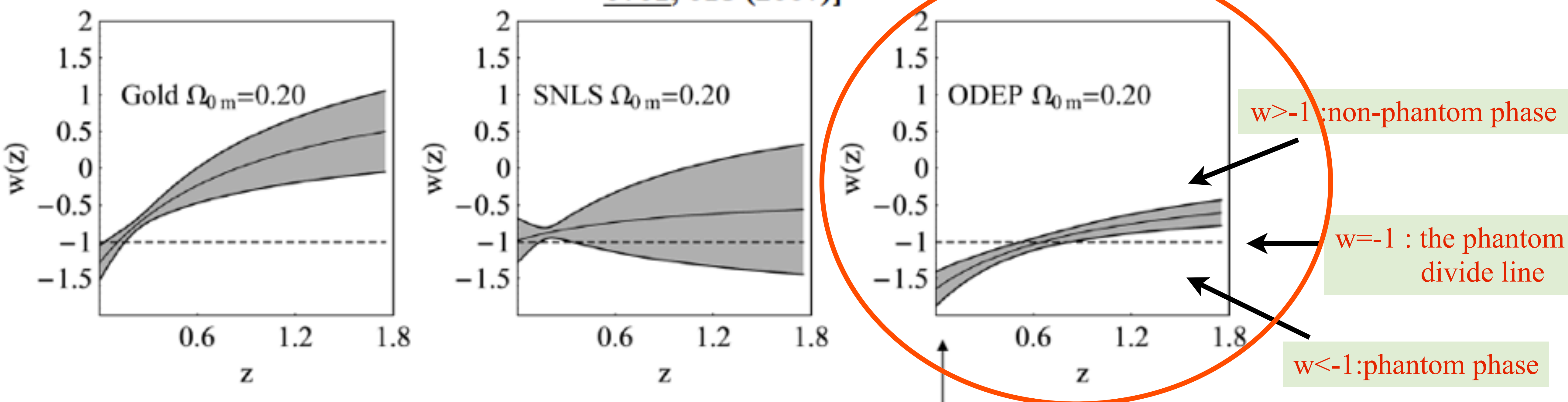


CPL

< Data fitting of $w(z)$ >

$$w(z) = w_0 + w_1 \frac{z}{1+z}$$

From [Nesseris and L. Perivolaropoulos, JCAP 0701, 018 (2007)]



SN gold data set

[Riess *et al.* [Supernova Search Team Collaboration], Astrophys. J. 607, 665 (2004)]

SNLS data set

[Astier *et al.* [The SNLS Collaboration], Astron. Astrophys. 447, 31 (2006)]

Shaded region shows 1σ error.

Cosmic microwave background radiation (CMB) data

[Spergel *et al.* [WMAP Collaboration], Astrophys. J. Suppl. 170, 377 (2007)]

+ SDSS baryon acoustic peak (BAO) data

[Eisenstein *et al.* [SDSS Collaboration], Astrophys. J. 633, 560 (2005)]

- For most observational probes (except the SNLS data), a low Ω_{0m} prior $(0.2 < \Omega_{0m} < 0.25)$ leads to an increased probability (mild trend) for the phantom crossing.

Ω_{0m} : Current density parameter of matter

☞ w(z) increases with z

w<-1 $\xrightarrow{w=-1}$ w>-1

phantom crossing

Physics Landscape Away From The High Energy Frontier

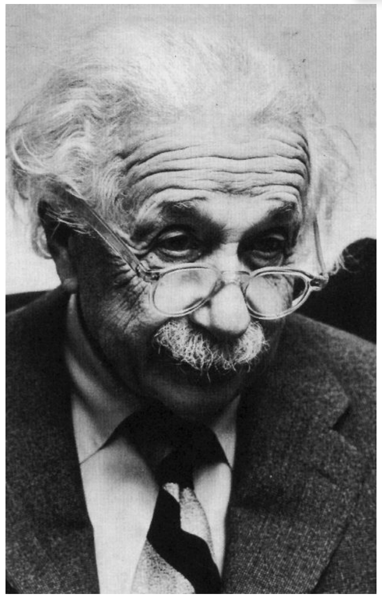
Edward Witten

CERN

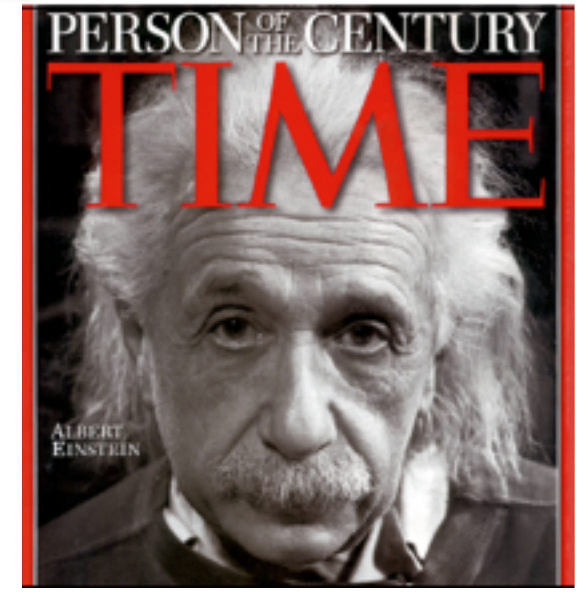
May 11, 2009

A discovery that the acceleration parameter w is not quite -1 would have almost as big an impact as the original discovery of dark energy.

Two main approaches to Dark Energy



$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$ **(Einstein equations)**



Modified Gravity

f(R) gravity
Scalar-tensor
DGP
f(T)
....

Modified Matter

Quintessence
K-essence
Quintom or
Nonsense
....

$$w \neq -1$$

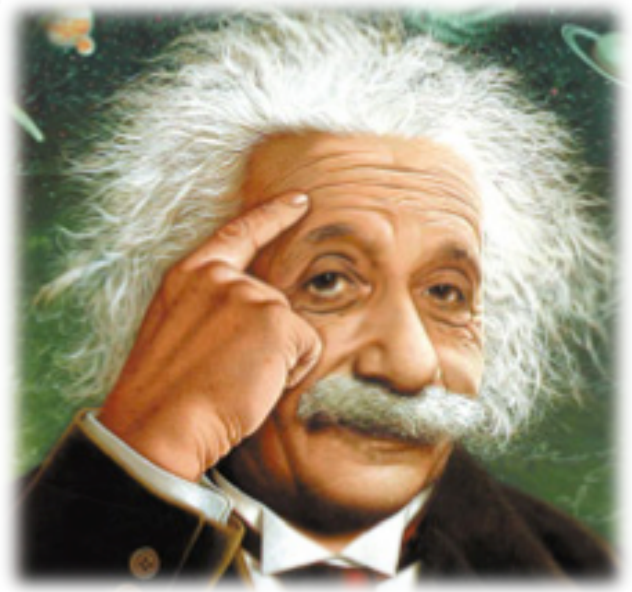
The simplest model: cosmological constant Λ

$$G_{\mu\nu} = 8\pi G T_{\mu\nu} - \Lambda g_{\mu\nu}$$

ΛCDM

$$w_{\mathrm{DE}} \equiv \frac{p_{\mathrm{DE}}}{\rho_{\mathrm{DE}}} = -1$$

Comments on the ΛCDM model:



Cosmological constant:
``biggest blunder''

See Sola's lectures

Cosmological constant Λ causes accelerating expansion.

- Action

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}(R - 2\Lambda) + S_m$$

- Einstein equation

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = 8\pi G T_{\mu\nu} - \Lambda g_{\mu\nu}$$

$$= 8\pi G\left(T_{\mu\nu} + T^{\rm DE}_{\mu\nu}\right)$$

- Dark energy $T^{\rm DE}_{\mu\nu} = -\frac{\Lambda g_{\mu\nu}}{8\pi G}$, $w_{\rm DE} \equiv \frac{P_{\rm DE}}{\rho_{\rm DE}} = -1$

This corresponds to the energy scale $\rho_\Lambda = \frac{3H_0^2}{8\pi G} = 10^{-47}\ GeV^4$

If this originates from vacuum energy in particle physics, $\rho_{vac} \sim m_{pl}^4 = 10^{76}\ GeV^4$

$\frac{\rho^{\rm obs}}{\rho^{\rm th}} = 10^{-120}$

A difference of 120 orders of magnitude

S. Weinberg

Cosmological constant problem

Q1: Why so small?

Fine-tuning problem
(known even before the discovery of dark energy)

Q2: Why now?

$\rho^0_\Lambda \sim \rho^0_{\rm M}$

Coincidence problem

Remarks on Modified Matter Theories:

Quintessence $\mathcal{L} = (1/2)(\partial\phi)^2 - V(\phi)$ $\quad -1 \leq w \leq 1$

Phantom $\mathcal{L} = -(1/2)(\partial\phi)^2 - V(\phi)$

the kinetic energy of the scalar field is negative .

$$-1 \geq w = \frac{p}{\rho} = \frac{-\dot{\phi}^2/2 - V(\phi)}{-\dot{\phi}^2/2 + V(\phi)}$$

However, it is clearly problematic due to the UV quantum instability.

``The phantom of the OPERA''

K-essence $\mathcal{L} = \mathcal{L}(\phi,\ X), \quad X = (1/2)\partial_\mu\phi\partial^\mu\phi$

$-1 \leq w \leq 1$ or $-1 \geq w$ but no crossing of w= -1

Quintom=Quintessence+Phantom=Hessence ``Nonsense!''

(with the phantom crossing of w= -1)

Is there a gravity theory with phantom crossing without the stability problem?

Modified Gravity Theory

- **Modified gravity theories**

Function $f(R)$ causes accelerating expansion.

- Action

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}f(R) + S_m$$

- Field equation $\qquad (F = df/dR)$

$$FR_{\mu\nu} - \frac{1}{2}f g_{\mu\nu} - (\nabla_\mu\nabla_\nu - g_{\mu\nu}\nabla^\lambda\nabla_\lambda)F = 8\pi G T_{\mu\nu}$$

i.e.

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi G\left(T_{\mu\nu} + \boxed{T^{\mathrm{DE}}_{\mu\nu}}\right)$$

$$\boxed{T^{\mathrm{DE}}_{\mu\nu} = \frac{1}{8\pi G}\left[(1-F)R_{\mu\nu} - \frac{1}{2}(R-f)g_{\mu\nu} + (\nabla_\mu\nabla_\nu - g_{\mu\nu}\nabla^\lambda\nabla_\lambda)F\right]}$$

$f(R) = R - 2\Lambda$ ☞ the ΛCDM model

f(R) gravity:

The conditions for the cosmological viability of f(R) models

1. $f_{,R} > 0$ $\Rightarrow$ **To avoid ghosts**

2. $f_{,RR} > 0$ $\Rightarrow$ $f(R) = R - \dfrac{\mu^{2(n+1)}}{R^n}$ **model does not satisfy this condition.**

- **The mass M of a scalar-field degree of freedom needs to be positive for the consistency with local gravity constraints (LGC).**

$$M^2 \approx 1/3f_{,RR} > 0$$ not a tachyon

- **This condition is also required for the stability of perturbations.**

3. $f(R) \to R - 2\Lambda \quad \text{for} \quad R \gg R_0$

For the presence of the matter era and for the consistency with LGC.

- **Realization of the Λ CDM-like behavior in the large curvature regime**

4. **The presence of a stable late-time de Sitter point**

$$0 < \frac{Rf_{,RR}}{f_{,R}}(r=-2) < 1\,, \quad \text{at} \quad r = -\frac{Rf_{,R}}{f} = -2$$

Others: **constraints from the equivalence principle and solar-system**

TABLE I. Explicit forms of $f(R)$ in (i) Hu-Sawicki, (ii) Starobinsky, (iii) Tsujikawa, and (iv) the exponential gravity models.




model	$f(R)$	Constant parameters
(i)	$R - \frac{c_1 R_{\rm HS}(R/R_{\rm HS})^p}{c_2(R/R_{\rm HS})^p+1}$	c_1, c_2, $p(>0)$, $R_{\rm HS}(>0)$
(ii)	$R + \lambda R_{\rm S}\left[\left(1+\frac{R^2}{R_{\rm S}^2}\right)^{-n} - 1\right]$	$\lambda(>0)$, $n(>0)$, $R_{\rm S}$
(iii)	$R - \mu R_{\rm T} \tanh\left(\frac{R}{R_{\rm T}}\right)$	$\mu(>0)$, $R_{\rm T}(>0)$
(iv)	$R - \beta R_{\rm E}\left(1 - e^{-R/R_{\rm E}}\right)$	β, $R_{\rm E}$

For example:

(iv) the exponential gravity

$$f(R) = R - \beta R_s \left(1 - e^{-R/R_s}\right)$$

E. V. Linder, Phys. Rev. D **80**, 123528 (2009)

P. Zhang, Phys. Rev. D **73**, 123504 (2006)

S. Tsujikawa, Phys. Rev. D **77**, 023507 (2008).

``**Cosmological evolution in exponential gravity**,''
K. Bamba, **CQG** and C.C. Lee, **JCAP** 1008, 021 (2010);
``**Observational constraints on exponential gravity**,''
L. Yang, C.C. Lee, L.W. Luo, **CQG, PRD82**, 103515 (2010).

1. When $\beta < e^{R/R_s}$, $F(R) = 1 - \beta e^{-R/R_s} > 0$.

2. When $\beta > 0$ and $R_s > 0$, $f''(R) = F'(R) = (\beta/R_s)\, e^{-R/R_s} > 0$

3. $f(R) - R \to -\beta R_s =$ constant for $R/R_s \gg 1$

4. When $\beta > 1$, $0 < m(R = R_d) < 1$ where $m \equiv Rf''(R)/f'(R) = RF'(R)/F(R)$

The action of f(R) gravity with matter:

$$S = \int d^4x \sqrt{-g}\, f(R) + S_m$$

$$FG_{\mu\nu} = \kappa^2 T^{(\mathrm{matter})}_{\mu\nu} - \frac{1}{2} g_{\mu\nu} \left(FR - f \right) + \nabla_\mu \nabla_\nu F - g_{\mu\nu} \Box F$$

where $G_{\mu\nu} = R_{\mu\nu} - (1/2)\, g_{\mu\nu} R$ is the Einstein tensor, $F(R) \equiv df(R)/dR$, ∇_μ is the covariant derivative operator associated with $g_{\mu\nu}$, $\Box \equiv g^{\mu\nu}\nabla_\mu\nabla_\nu$ is the covariant d'Alembertian for a scalar field, and $T^{(\mathrm{matter})}_{\mu\nu}$ is the contribution to the energy-momentum tensor from all perfect fluids of matter.

The Friedmann equations:

$$3FH^2 = \kappa^2 \rho_{\mathrm{M}} + \frac{1}{2}\left(FR - f \right) - 3H\dot{F},$$
$$-2F\dot{H} = \kappa^2 \left(\rho_{\mathrm{M}} + P_{\mathrm{M}} \right) + \ddot{F} - H\dot{F},$$

$$\dot{\rho}_m + 3H\rho_m = 0$$

The dark energy equation of state:

$$w_{\mathrm{DE}} \equiv P_{\mathrm{DE}}/\rho_{\mathrm{DE}},$$
$$\rho_{\mathrm{DE}} = \frac{1}{\kappa^2}\left[\frac{1}{2}\left(FR - f \right) - 3H\dot{F} + 3\left(1 - F \right) H^2 \right],$$
$$P_{\mathrm{DE}} = \frac{1}{\kappa^2}\left[-\frac{1}{2}\left(FR - f \right) + \ddot{F} + 2H\dot{F} - \left(1 - F \right)\left(2\dot{H} + 3H^2 \right) \right],$$

$$\dot{\rho}_{\mathrm{DE}} + 3H\left(\rho_{\mathrm{DE}} + P_{\mathrm{DE}} \right) = 0$$

(i) Hu-Sawicki

W. Hu and I. Sawicki, Phys. Rev. D **76**, 064004 (2007)

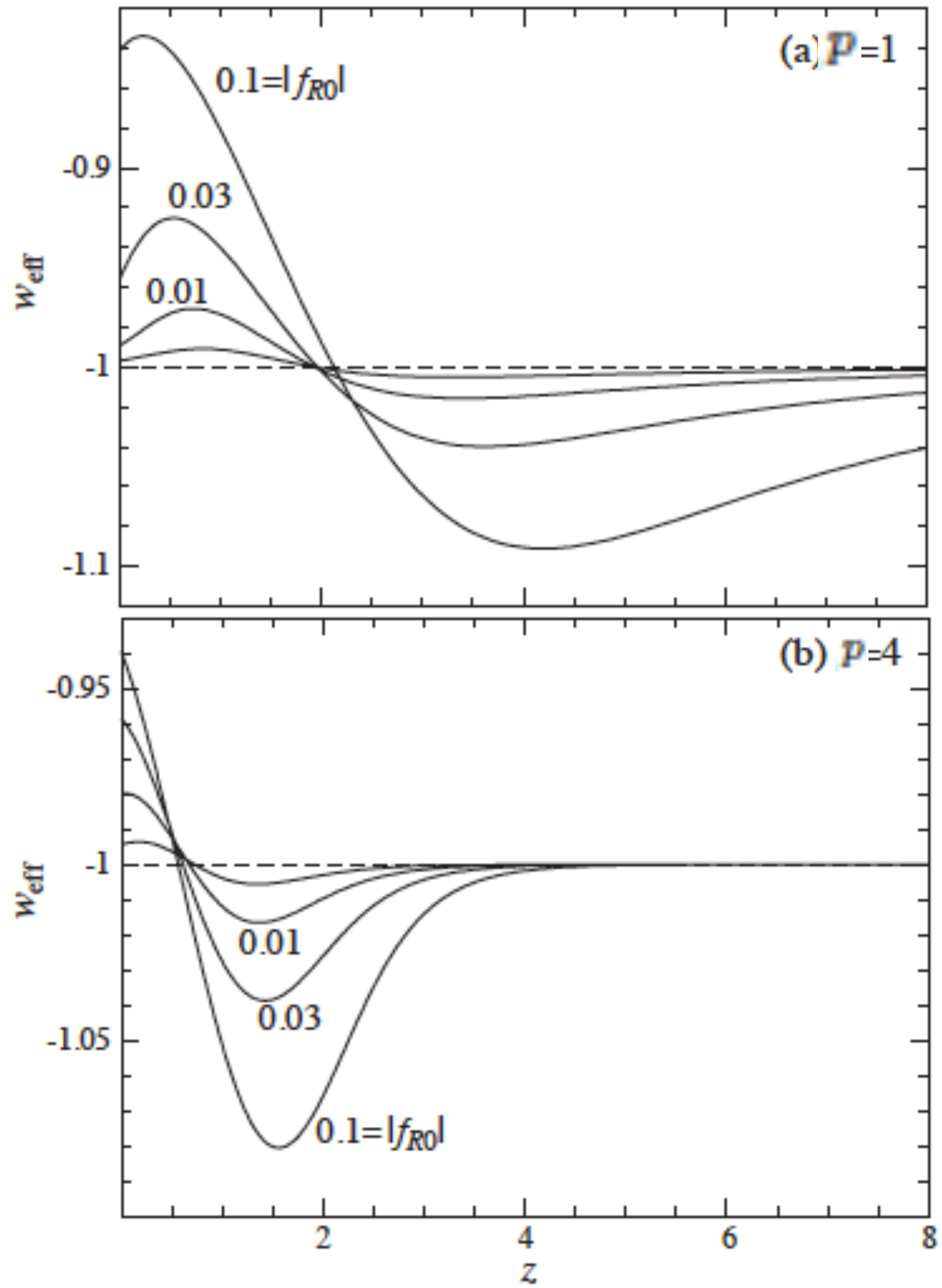
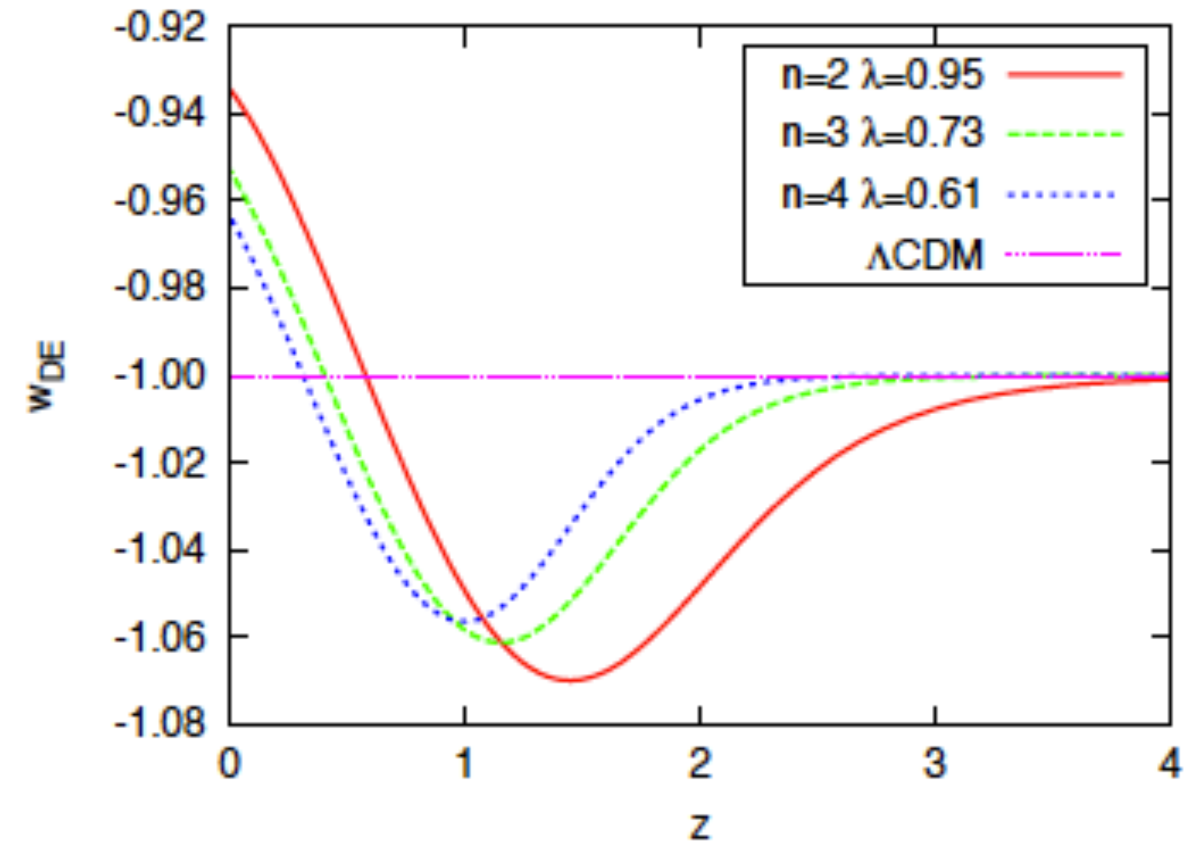


FIG. 3: Evolution of the effective equation of state for $p = 1, 4$ for several values of the cosmological field amplitude today, f_{R0}. The effective equation of state crosses the phantom divide $w_{\rm eff} = -1$ at a redshift that decreases with increasing p leading potentially to a relatively unique observational signature of these models.

(ii) Starobinsky

A. A. Starobinsky, JETP Lett. **86**, 157 (2007)

H. Motohashi, A. A. Starobinsky and J. Yokoyama, arXiv:1002.1141 [astro-ph.CO].



Evolution of $w_{\rm DE}$ for $\lambda_{\rm min}$ for $n = 2, 3$, and 4.

(iv) the exponential gravity

E. V. Linder, Phys. Rev. D **80**, 123528 (2009)

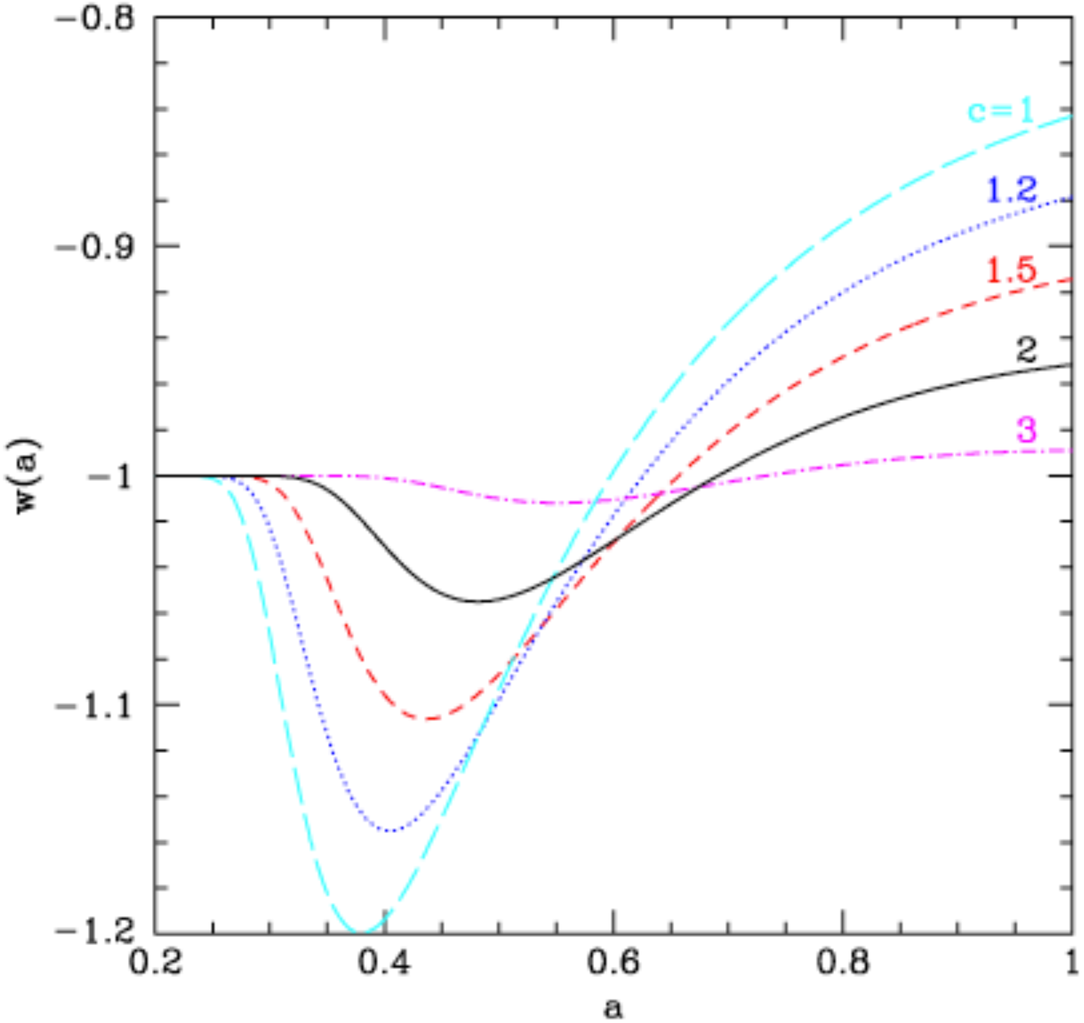
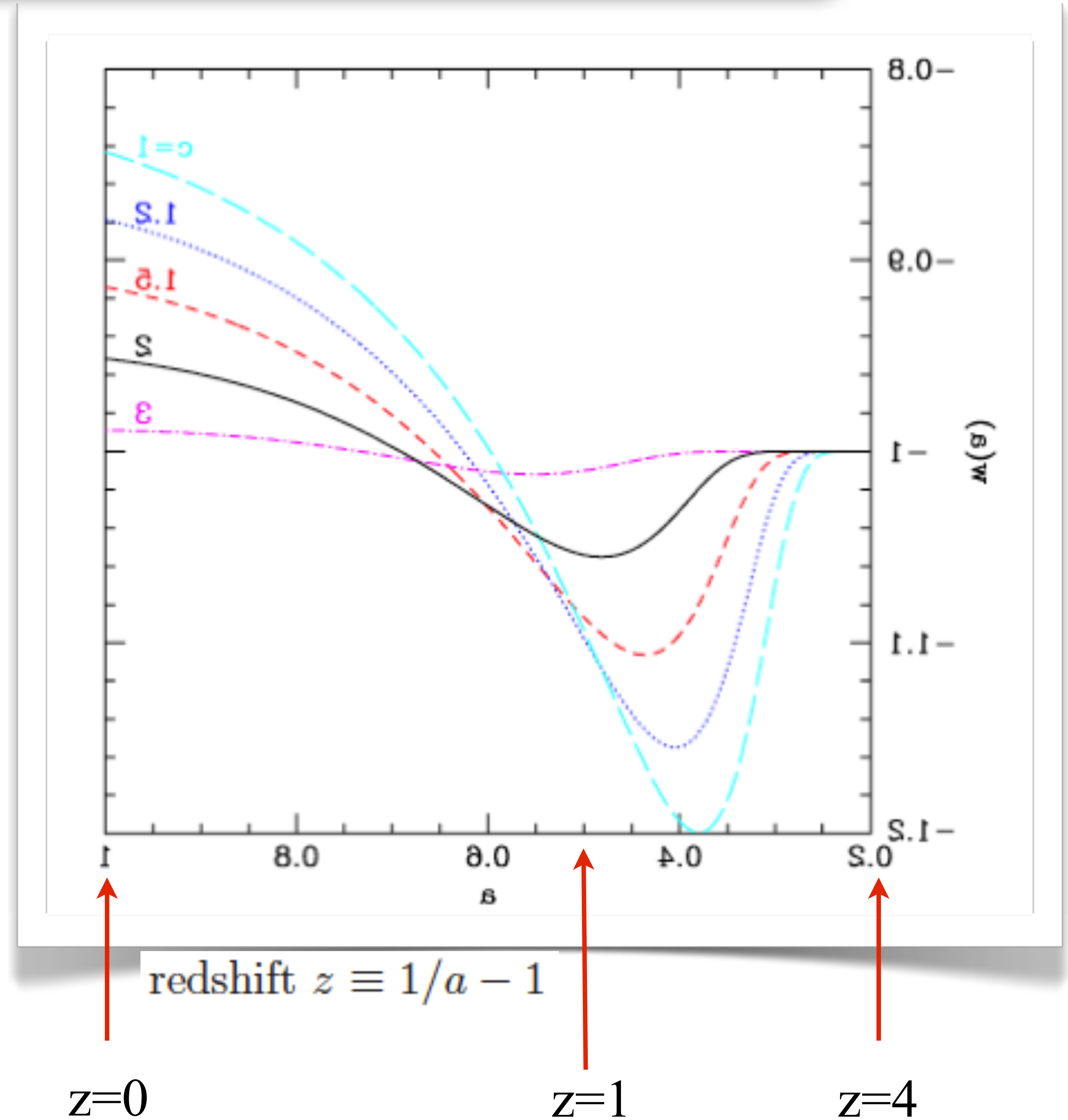


FIG. 3 (color online). The effective dark energy equation of state evolution is shown for various values of c. As c gets large, the expansion history becomes indistinguishable from ΛCDM.



Several Remarks on f(R):

a. In f(R) gravity, the phantom phase of w<-1 is allowed without the stability problem unlike the phantom model.

b. In the past (z>0), the phantom crossing is a generic feature in the popular viable f(R) gravity theories.

c. However, the tendency seems to be opposite to the data, i.e., the crossing is from non-phantom (w>-1) to phantom phase (w<-1) in f(R), whereas the data indicates that it is from phantom to non-phantom phase, as z increases.

d. In the Future: z<0

``Generic feature of future crossing of phantom divide in viable f(R) gravity models,'' K. Bamba, **CQG** and C.C. Lee, JCAP1011, 001 (2010).

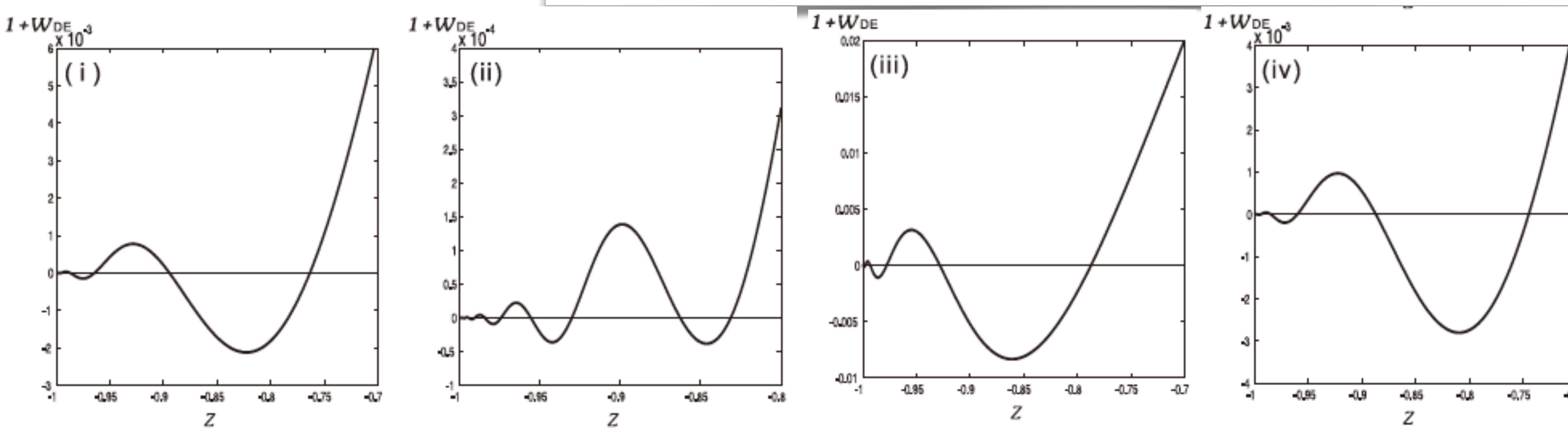


FIG. 1. Future evolutions of $1 + w_{\rm DE}$ as functions of the redshift z in (i) Hu-Sawicki model for $p = 1$, $c_1 = 2$ and $c_2 = 1$, (ii) Starobinsky model for $n = 2$ and $\lambda = 1.5$, (iii) Tsujikawa model for $\mu = 1$ and (iv) the exponential gravity model for $\beta = 1.8$, respectively. The thin solid lines show $1 + w_{\rm DE} = 0$ (cosmological constant).

• Teleparallel Dark Energy

Teleparallel gravity:

<u>Alternative Gravitational Theory</u>

Einstein's unified field theory:
``Riemannian Geometry with Maintaining the Notion of Distant Parallelism”
(Teleparallelism, Einstein 1928)

Torsion scalar (Einstein 1929)

Teleparallel Lagrangian is equivalent to the Riemann scalar (Lanczos 1929)

Generalization: New General Relativity (NGR)
(Hayashi & Shirafuji 1979)

EINSTEIN: RIEMANN-Geometrie mit Aufrechterhaltung d. Begriffes d. Fernparallelismus 217

RIEMANN-Geometrie mit Aufrechterhaltung des Begriffes des Fernparallelismus.

Von A. EINSTEIN.

Die RIEMANNsche Geometrie hat in der allgemeinen Relativitätstheorie zu einer physikalischen Beschreibung des Gravitationsfeldes geführt, sie liefert aber keine Begriffe, die dem elektromagnetischen Felde zugeordnet werden können. Deshalb ist das Bestreben der Theoretiker darauf gerichtet, natürliche Verallgemeinerungen oder Ergänzungen der RIEMANNschen Geometrie aufzufinden, welche begriffsreicher sind als diese, in der Hoffnung, zu einem logischen Gebäude zu gelangen, das alle physikalischen Feldbegriffe unter einem einzigen Gesichtspunkte vereinigt. Solche Bestrebungen haben mich zu einer Theorie geführt, welche ohne jeden Versuch einer physikalischen Deutung mitgeteilt werden möge, weil sie schon wegen der Natürlichkeit der eingeführten Begriffe ein gewisses Interesse beanspruchen kann.

Die RIEMANNsche Geometrie ist dadurch charakterisiert, daß die infinitesimale Umgebung jedes Punktes P eine euklidische Metrik aufweist, sowie dadurch, daß die Beträge zweier Linienelemente, welche den infinitesimalen Umgebungen zweier endlich voneinander entfernter Punkte P und Q angehören, miteinander vergleichbar sind. Dagegen fehlt der Begriff der Parallelität solcher zwei Linienelemente; der Richtungsbegriff existiert nicht für das Endliche. Die im folgenden dargelegte Theorie ist dadurch charakterisiert, daß sie neben der RIEMANNschen Metrik den der »Richtung« bzw. Richtungsgleichheit oder des »Parallelismus« für das Endliche einführt. Dem entspricht es, daß neben den Invarianten und Tensoren der RIEMANNschen Geometrie neue Invarianten und Tensoren auftreten.

Curvature vs Torsion

A general spacetime can, in principle, present two different properties – **curvature** and **torsion**

TORSION AND CURVATURE

CURVATURE

Consider the parallel transport of a vector around a closed curve

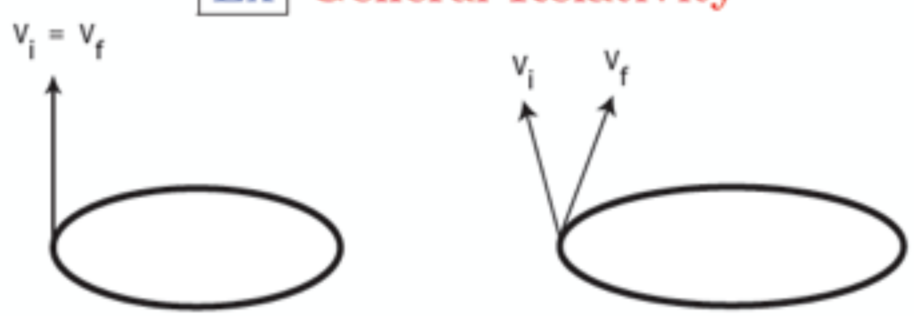
$\Downarrow$

If, when returning to the initial point, there is an angular deficit, the surface is said to be curved

$\Downarrow$

The curvature of the surface is proportional to this angular deficit

Ex **General Relativity**



TORSION

Consider now the parallel transport of two vectors

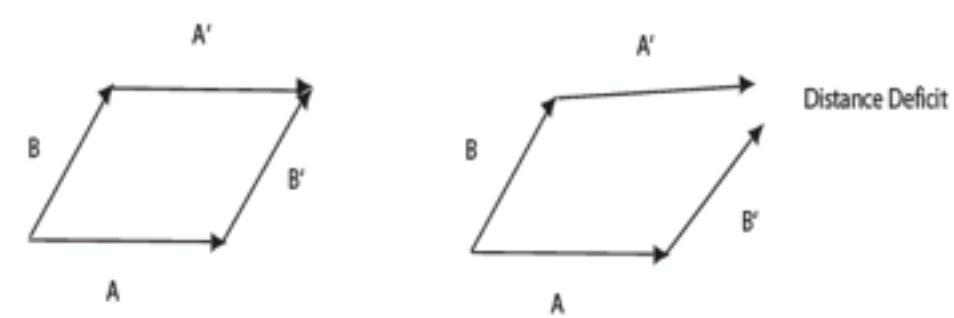
$\Downarrow$

If, when parallel transported one along the other, they do not close a parallelogram the surface is said to present torsion

$\Downarrow$

The torsion of the surface is proportional to the gap — or distance deficit

Ex **Teleparallel Gravity**



TELE-PARALLEL GEOMETRY

Metric-affine

$$\begin{tikzcd}[column sep=small]
 & (L_4\,,\,g) \arrow[d, "Q=0"] & \\
 & U_4 \arrow[dl, "T=0"'] \arrow[dr, "R=0"] & \\
V_4 \arrow[dr, "R=0"'] & & T_4 \arrow[dl, "T=0"] \\
 & M_4 &
\end{tikzcd}$$

vanishing non-metricity $Q=0$ i.e. $D_\mu(\Gamma)g_{\alpha\beta}=0$

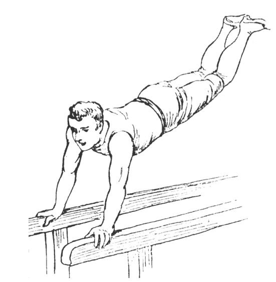
Riemann-Cartan PGT

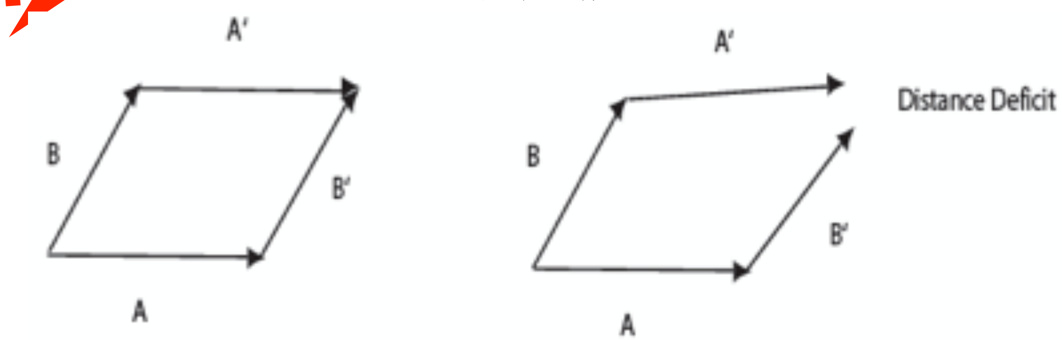
Riemann
GR

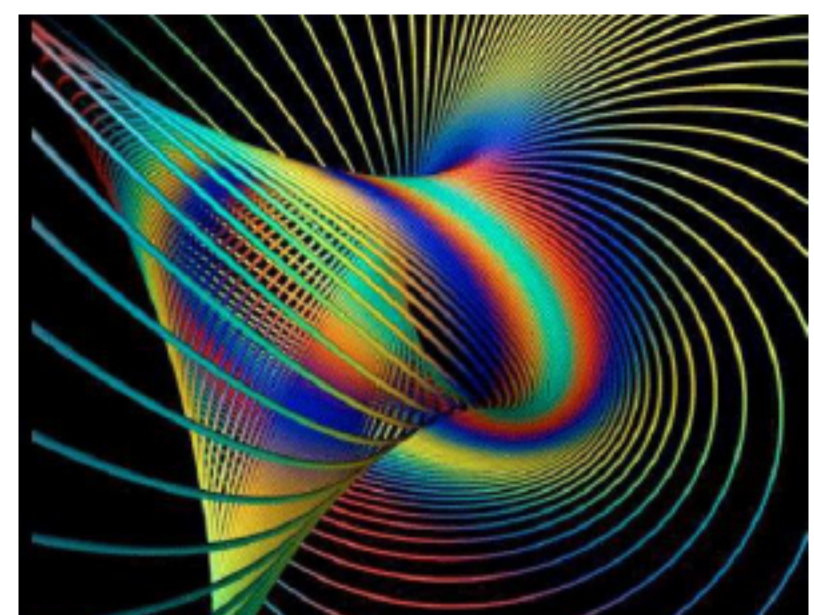
TG
$GR_{\|}$

Minkowski
SR

~~curvature~~







Torsion Field: Einstein's Metric Torsion Tensor allows a spin-field to twist spacetime.

Teleparallel gravity:

Teleparallelism

The torsion $T^{\rho}{}_{\mu\nu}$ and contorsion $K^{\mu\nu}{}_{\rho}$ tensors are defined by

$$T^{\rho}{}_{\mu\nu} \equiv e^{\rho}_{A}\left(\partial_{\mu}e^{A}_{\nu} - \partial_{\nu}e^{A}_{\mu}\right) ,$$
$$K^{\mu\nu}{}_{\rho} \equiv -\frac{1}{2}\left(T^{\mu\nu}{}_{\rho} - T^{\nu\mu}{}_{\rho} - T_{\rho}{}^{\mu\nu}\right) .$$

Weitzenböck connection $\overset{w}{\Gamma}{}^{\lambda}_{\nu\mu} \equiv e^{\lambda}_{A}\,\partial_{\mu}e^{A}_{\nu}$

~~Levi Civita~~

e^{A}_{μ} is the orthonormal tetrad component

vierbeins : *parallel* vector fields

$g_{\mu\nu} = \eta_{AB}e^{A}_{\mu}e^{B}_{\nu}$ $\quad \mathbf{e}_A \cdot \mathbf{e}_B = \eta_{AB}$

$\eta_{AB} = diag(1,-1,-1,-1)$

parallel : $0 = \overset{w}{\nabla}_{\nu}e^{\lambda}_{A} = \partial_{\nu}e^{\lambda}_{A} + \overset{w}{\Gamma}{}^{\lambda}_{\mu\nu}e^{\mu}_{A}$

coordinate basis: $\mathbf{e}_A = e^{\mu}_{A}\partial_{\mu}$

$$T \equiv S_{\rho}{}^{\mu\nu}T^{\rho}{}_{\mu\nu}$$
$$S_{\rho}{}^{\mu\nu} \equiv \frac{1}{2}\left(K^{\mu\nu}{}_{\rho} + \delta^{\mu}_{\rho}\,T^{\alpha\nu}{}_{\alpha} - \delta^{\nu}_{\rho}\,T^{\alpha\mu}{}_{\alpha}\right)$$

Torsion scalar: $T = \frac{1}{4}T^{\rho\mu\nu}T_{\rho\mu\nu} + \frac{1}{2}T^{\rho\mu\nu}T_{\nu\mu\rho} - T_{\rho\mu}{}^{\rho}T^{\nu\mu}{}_{\nu}$

$e^{A}_{\mu} = \mathrm{diag}(1,a,a,a),$ $\quad |e| = \det\left(e^{A}_{\mu}\right) = \sqrt{-g}.$

quadratic form in terms of torsion tensor

Teleparallel gravity: $\quad S = \int \mathrm{d}^4x e\left[\frac{T}{2\kappa^2} + \mathcal{L}_m\right]$

Teleparallel Equivalent of General Relativity (TEGR)

$$S = \int d^4x\, e \left[\frac{T}{2\kappa^2} + \mathcal{L}_m \right]$$

$$e = \det\left(e^A_\mu\right) = \sqrt{-g}$$

" = "

$$T = R + 2\nabla^\mu T^\rho{}_{\rho\mu}$$

$$GR: \quad S = \int d^4x \sqrt{-g} \left[\frac{R}{2\kappa^2} + \mathcal{L}_m \right]$$

Scalar field minimally coupled to Teleparallel Gravity

" = "

Scalar field minimally coupled to GR

Scalar field *non-minimally* coupled to Teleparallel Gravity

not eq.

" $\neq$ "

Scalar field ***non-minimally*** coupled to GR

~ "*scalar-teleparallel theory*"

a simple extension of TEGR

$$S = \int d^4x e \left[\frac{T}{2\kappa^2} + \frac{1}{2} \left(\partial_\mu \phi \partial^\mu \phi + \xi T \phi^2 \right) - V(\phi) + \mathcal{L}_m \right]$$

~ *scalar-tensor theory*

a simple extension of GR

$$S = \int d^4x \sqrt{-g} \left[\frac{R}{2\kappa^2} + \frac{1}{2} \left(\partial_\mu \phi \partial^\mu \phi + \xi R \phi^2 \right) - V(\phi) + \mathcal{L}_m \right]$$

Teleparallel Dark Energy

Teleparallel dark energy:

CQG, C.C. Lee, E. N. Saridakis,Y.P. Wu, ``**Teleparallel dark energy,**''
Phys. Lett. B704, 384 (2011) [arXiv:1109.1092 [hep-th]];
CQG, C.C. Lee, E.Saridakis, ``**Observational constraints on teleparallel dark energy**,''
JCAP 1201, 002 (2012) [arXiv:1110.0913 [astro-ph.CO].

$$S=\int d^4x e\left[\frac{T}{2\kappa^2}+\frac{1}{2}\Big(\underbrace{\partial_\mu\phi\partial^\mu\phi}_{\text{canonical}}+\underline{\xi T\phi^2}\Big)-\underbrace{V(\phi)}_{\text{potential}}+\mathcal{L}_m\right]$$

non-minimal coupling to T

Friedmann equations:

$$H^2=\frac{\kappa^2}{3}\Big(\rho_\phi+\rho_m\Big),$$

$$\dot{H}=-\frac{\kappa^2}{2}\Big(\rho_\phi+p_\phi+\rho_m+p_m\Big)$$

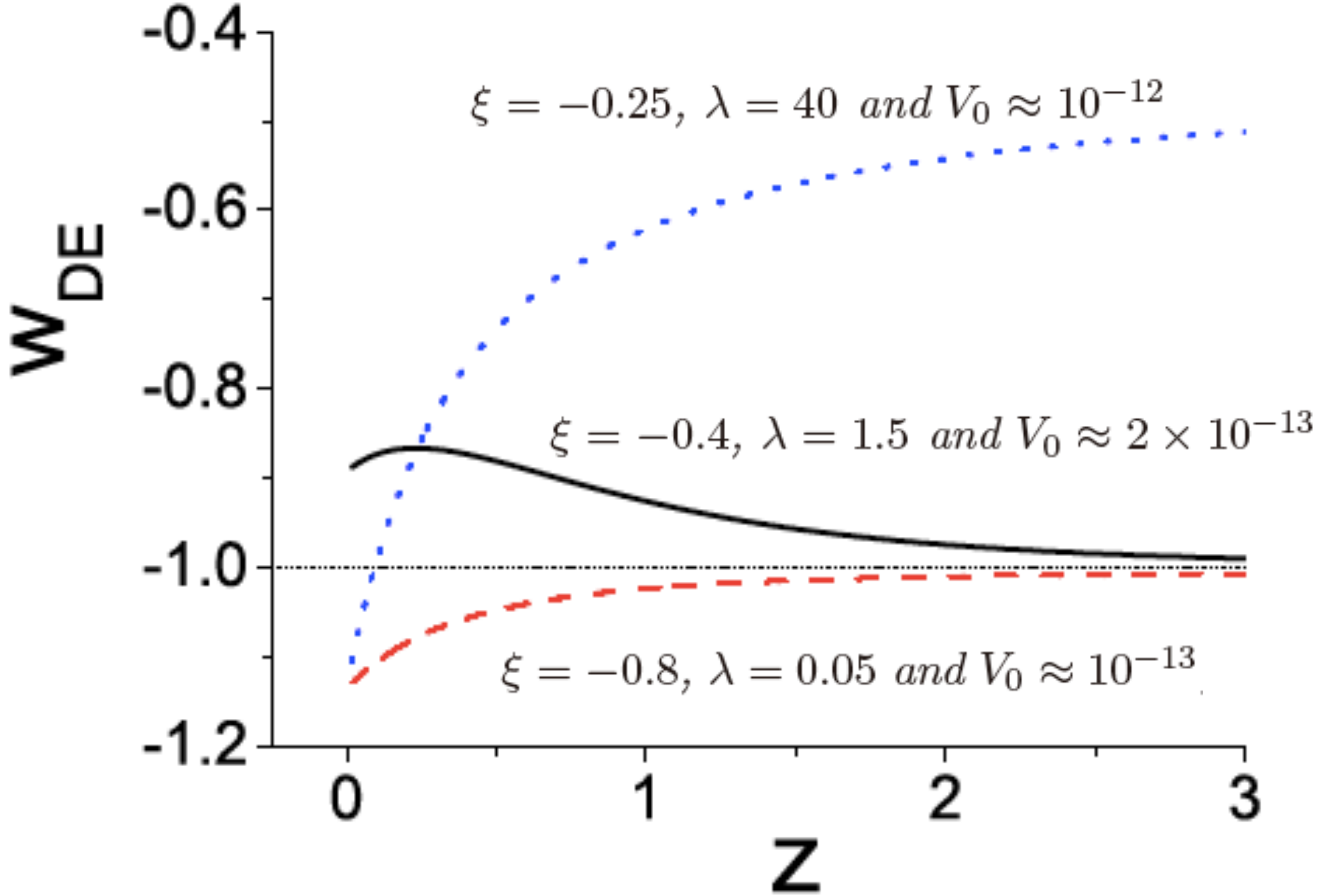
The torsion energy density and pressure:

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi) - 3\xi H^2\phi^2,$$
$$p_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi) + 4\xi H\phi\dot{\phi} + \xi\left(3H^2 + 2\dot{H}\right)\phi^2$$

Equation of state:

$$w_{DE} \equiv w_\phi = \frac{p_\phi}{\rho_\phi}$$

$$V = V_0 e^{\lambda\phi}$$



Teleparallel Dark Energy with V=0

J.A. Gu, C.C. Lee, **CQG**, **``Teleparallel dark energy with purely non-minimal coupling to gravity,'' PLB718, 722 (2013)** [arXiv:1204.4048 [astro-ph.CO]].

$$S = \int d^4x\, e \left[\frac{T}{2\kappa^2} + \frac{1}{2}\left(\partial_\mu\phi\partial^\mu\phi + \xi T\phi^2\right) + \mathcal{L}_m \right]$$

No potential

- Non-minimal term alone can drive cosmic acceleration; need no potential, no non-canonical kinetic term (in contrast to conventional ϕDE models: *quintessence*, *k-essence*, …).

Field equations:

$$\ddot{\phi} + 3H\dot{\phi} + 6\xi H^2\phi = 0$$

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{\kappa^2}{3}\left(\rho_\phi + \rho_{\rm m} + \rho_{\rm r}\right)$$

$$\dot{H} = -\frac{\kappa^2}{2}\left(\rho_\phi + p_\phi + \rho_{\rm m} + 4\rho_{\rm r}/3\right)$$

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 - 3\xi H^2\phi^2\,,$$

$$p_\phi = \frac{1}{2}\dot{\phi}^2 + 3\xi H^2\phi^2 + 2\xi\frac{d}{dt}\left(H\phi^2\right)$$

We consider $\xi < 0$ to guarantee *positive* ρ_ϕ and for having *negative* p_ϕ

$\rho_{\rm m} \propto a^{-3}$ $\qquad$ $\rho_{\rm r} \propto a^{-4}$

Eff. EoS:	**+1**	**-1**	**NA**	**0**	**1/3**

Analytic Solution of $\phi(t)$

$$\ddot{\phi} + 3H\dot{\phi} + 6\xi H^2 \phi = 0$$

- $H = \alpha/t,\ a(t) \propto t^{\alpha}$ **RD**: $\alpha = 1/2$ **MD**: $\alpha = 2/3$

$$\phi(t) = C_1 t^{l_1} + C_2 t^{l_2}$$

$$l_{1,2} = \frac{1}{2}\left[\pm\sqrt{(3\alpha-1)^2 - 24\xi\alpha^2} - (3\alpha - 1)\right]$$

$$\rho_\phi = \left[l_1^2/2 - 3\xi\alpha^2\right] C_1^2 t^{2(l_1-1)},$$

$$p_\phi = \left[l_1^2/2 + 3\xi\alpha^2 + 2\xi\alpha(2l_1 - 1)\right] C_1^2 t^{2(l_1-1)}$$

$$w_\phi \equiv \frac{p_\phi}{\rho_\phi} = 1 + \frac{4\xi\alpha}{l_1} = -1 + \frac{2(1-l_1)}{3\alpha},$$

RD: $\alpha = 1/2$ **MD**: $\alpha = 2/3$

$$w_\phi = \frac{1}{3}\left(2 - \sqrt{1-24\xi}\right),\ \frac{1}{2}\left(1 - \sqrt{1-32\xi/3}\right)$$

Depend only on ξ; indep. of *initial condition*.

$\Rightarrow$ ***Tracker behavior*** of w_ϕ in ***RD*** and ***MD*** eras.

- ***ϕ-dominated era:***

$$\phi(a) = \pm\frac{\sin\theta}{\sqrt{-\kappa^2\xi}},\quad \theta(a) \equiv \sqrt{-6\xi\ln a + C_4}$$

$$w_\phi = -1 - \sqrt{-32\xi/3}\tan\theta$$

- ***Phantom divide***: $w_\phi \searrow$, crossing -1, along with expansion.

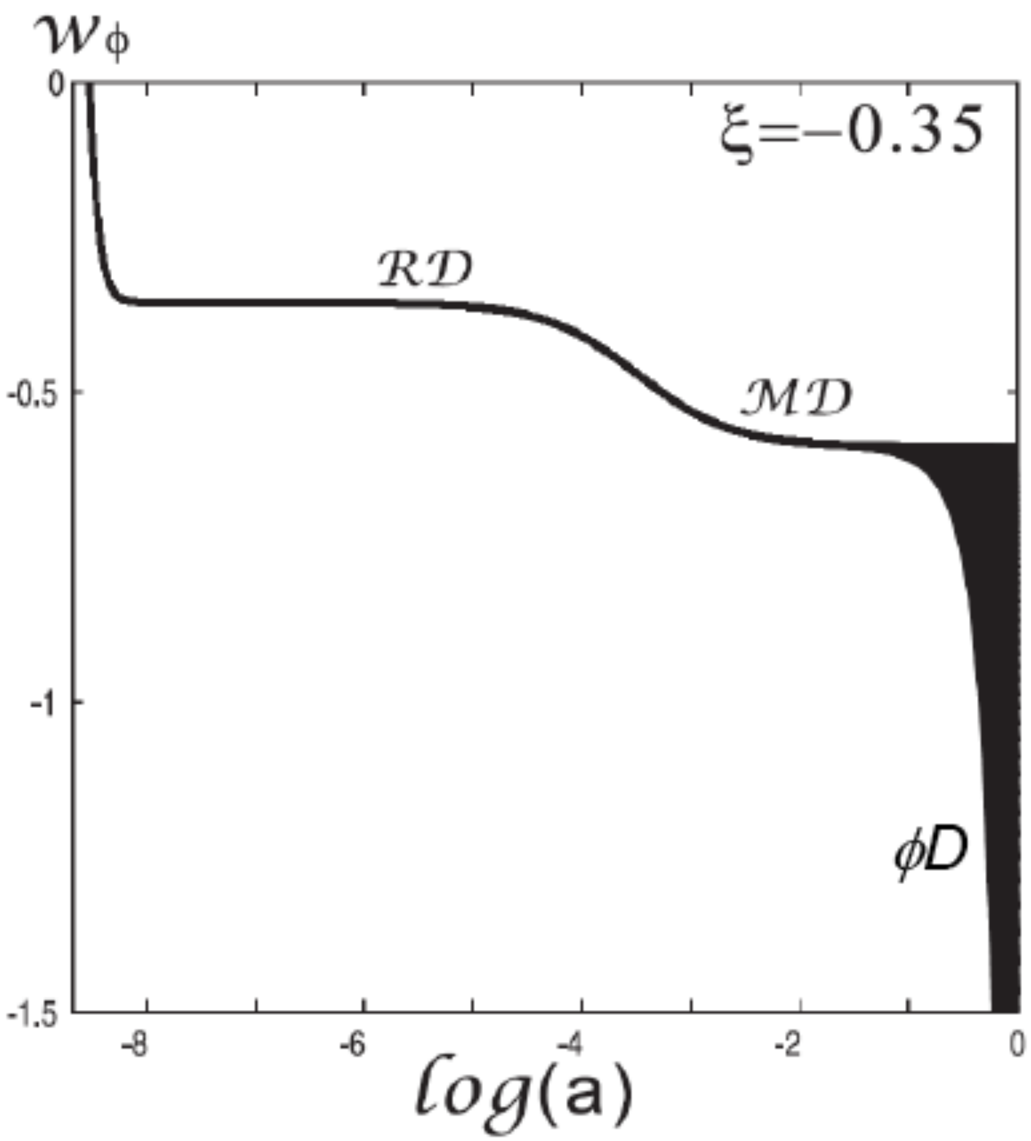
  $w_\phi = -1$ at $\theta = 0$

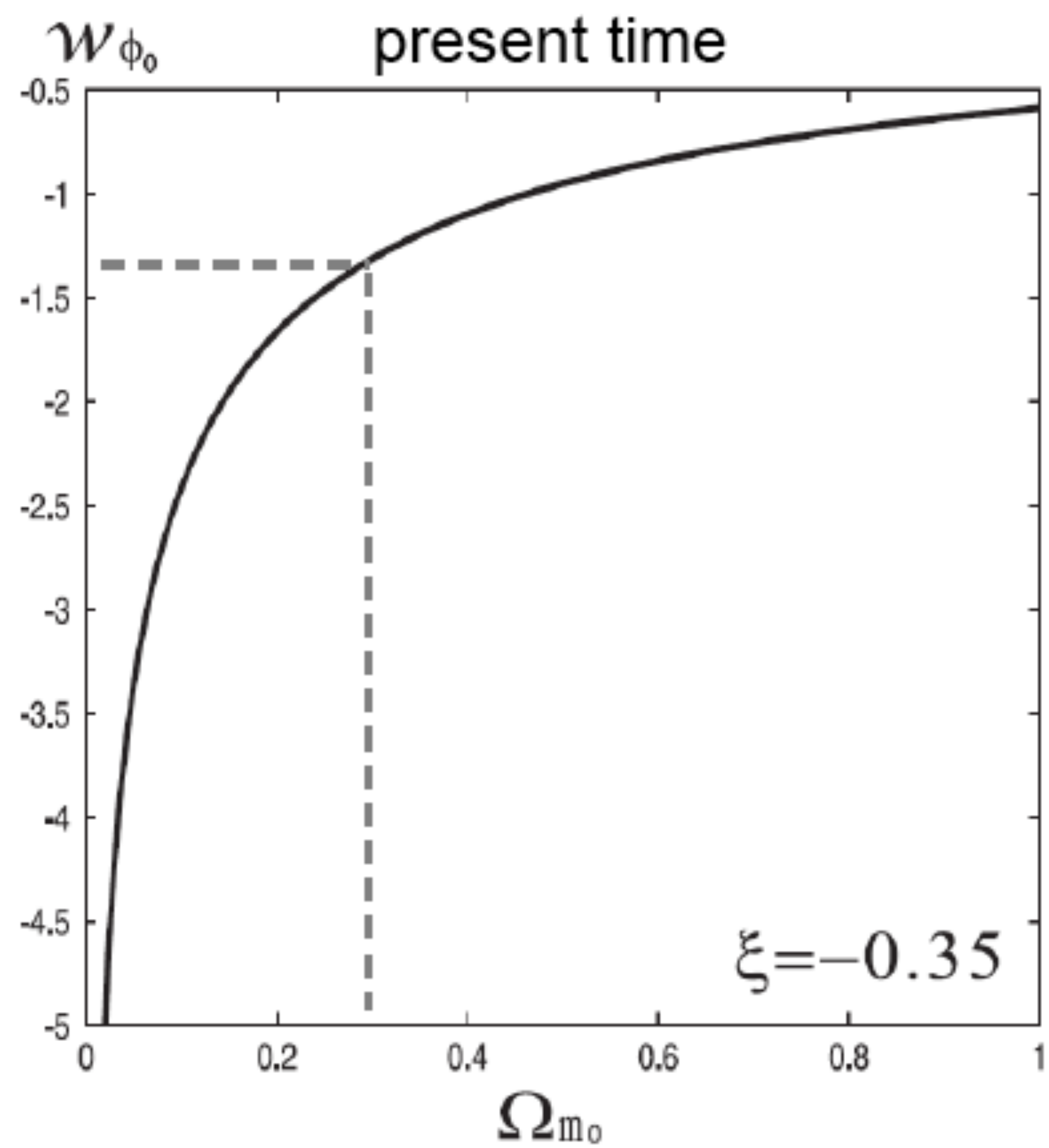
- ***Future Singularity***: $H \nearrow \infty$ at finite time when $\theta = (n + 1/2)\pi$

  $w_\phi \searrow -\infty$

  i.e. $\phi = \pm 1/\sqrt{-\kappa^2\xi}$

Behavior of w_ϕ with various initial conditions (IC)

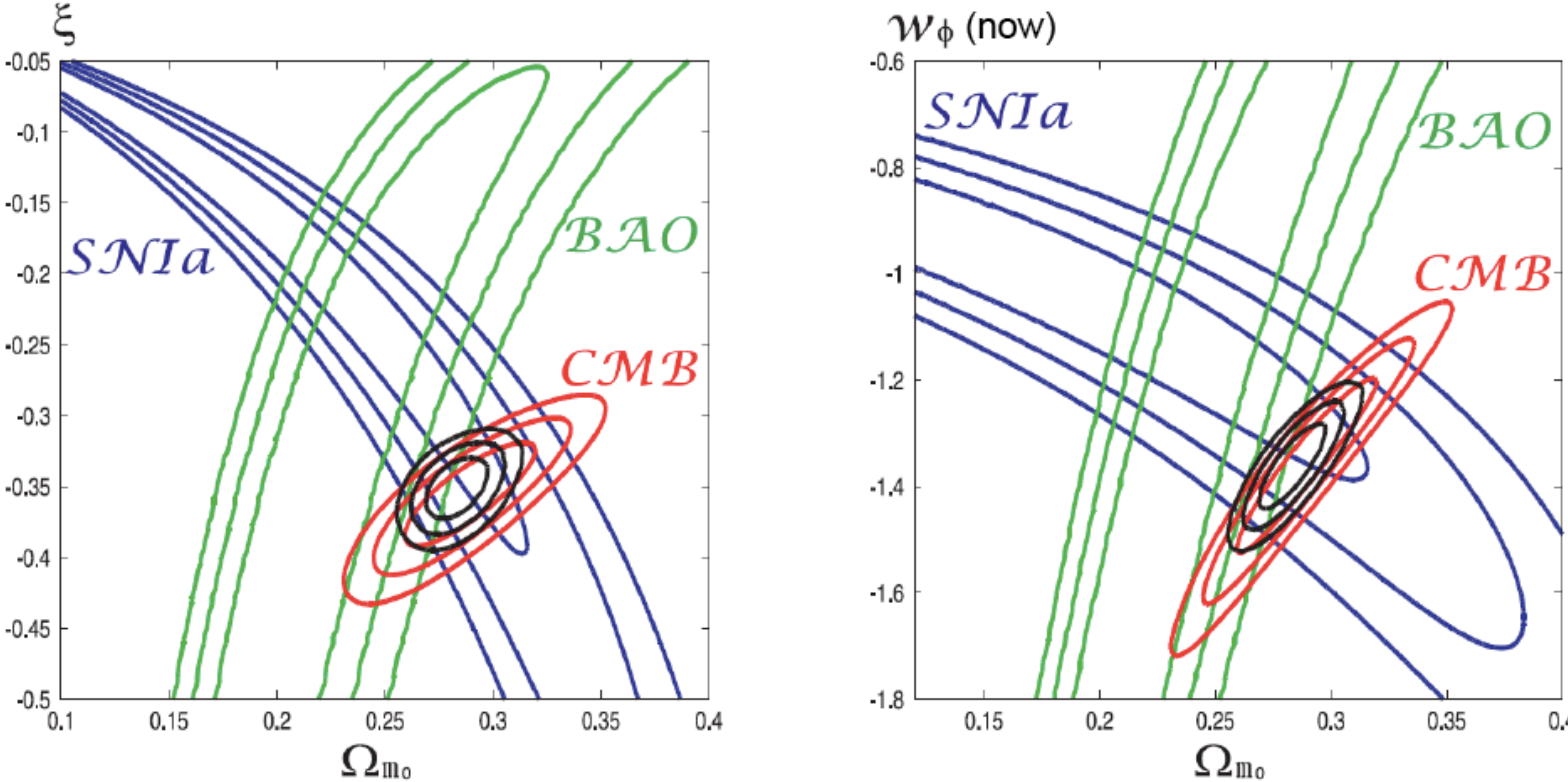




RD & *MD* — *ϕD*

w_ϕ : insensitive to *IC* — sensitive to *IC*

Data Fitting with SNIa, BAO, CMB



Best fit: $\xi \cong -0.35\,,\ \Omega_{m0} \cong 0.28$

☺ Open questions in Dark Energy:

0. What is the real nature of Dark Energy?

1. Is the accelerating universe due to cosmological constant or modified matter or modified gravity?

2. How to distinguish among them?

3. Can we observe dark energy directly?

• Conclusions

- Currently, we know much, but we understand very little about our universe. Only 5% of our universe, ordinary matter, is well described by the SM in particle physics, whereas the rest is DARK with dark matter (27%) and dark energy (68%).

- The SM of particle physics has been well established, in which the quark and lepton representations and charges under $SU(3)_c \times SU(2)_L \times U(1)_Y$ can be determined uniquely by the anomaly cancellations with minimality condition. However, the *family problem* is still unsolved. Moreover, the origins of the *neutrino masses* and *matter-antimatter asymmetry* in the universe are still unknown. These three problems are clearly the windows to *new physics* beyond the SM.

- So far, Dark Matter has only been seen from the large scale structure with gravitational effect. Future direct and indirect as well as collider searches are crucial for us to understand the nature of Dark Matter.

- To understand the cosmic accelerating expansion of the universe, Dark Energy is needed. The simplest candidate is the cosmological constant with EoS=-1. For the other two main approaches: modified gravity and matter theories, EoS changes dynamically.

Future prospects

Modern Particle Physics: 7 Periods

1. **< 1945 -- *Pre-Modern Particle Physics Period***
2. ***Startup Period (1945 -- 1960)：Early contributions to the basic concepts of modern particle physics.***
3. ***Heroic Period (1960 -- 1975):Formulation of the standard model of strong and electroweak interactions.***
4. ***Period of Consolidation and Speculation (1975 -- 1990): Precision tests of the standard model and theories beyond the standard model.***
5. ***"Frustration" and "Waiting" Period (1990 -- 2005)***

Neutrino oscillations
Cosmic microwave fluctuations
Dark energy

6. ***Preparation Period (2005--2020)***
7. ***Super-Herioic Period (2020--2035)***

LISA *2030*
100 TeV Collider *2030*

+ something unexpected?

Future prospects

Heroic Period (1960 -- 1975):

Nobel Prizes in Particle Physics: [work done]
20xx: ?
2013: Englert, Higgs – Higgs particle [1964]
2008: Nambu,Kobayashi,Maskawa–broken symmetry [1961,1973]
2004: Gross, Politzer, Wilczek–asymptotic freedom [1973]
1999: ‘t Hooft, Veltman–electroweak force [1972]
1995: Perl,Reines–tau lepton [1975], electron neutrino [1953]
1990: Friedman, Kendall, Taylor–quark model [1972]
1988: Lederman,Schwartz,Steinberger -muon neutrino [1962]
1980: Cronin, Fitch–symmetry breaking (CP violation) [1964]
1979: Glashow, Salam, Weinberg–electroweak theory [1961,67]
1976: Richter,Ting–charm quark (J/Psi) [1974]
1969: Gell-Mann–classification of elementary particles [1964]

more?

=11

Neutrino oscillations
Cosmic microwave fluctuations
Dark energy

7. *Super-Herioic Period (2020--2035)*

LISA *2030*
100 TeV Collider *2030*

+ something unexpected?

How many Nobel Prizes in Particle Physics for the Super-Heroic Period?

>10

Just the beginning of the story

Thank you!