Searching for patterns in the Universe

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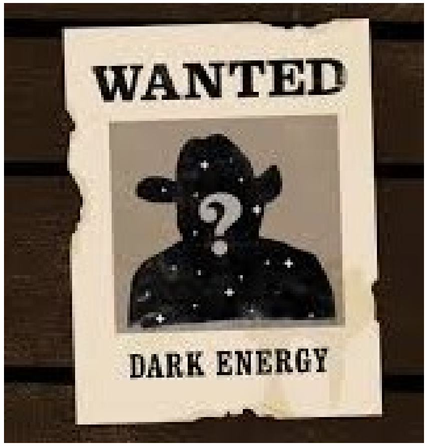
Content

Our Universe

What we know...

What we don't know...



Perturbation theory in the “cosmic collider”

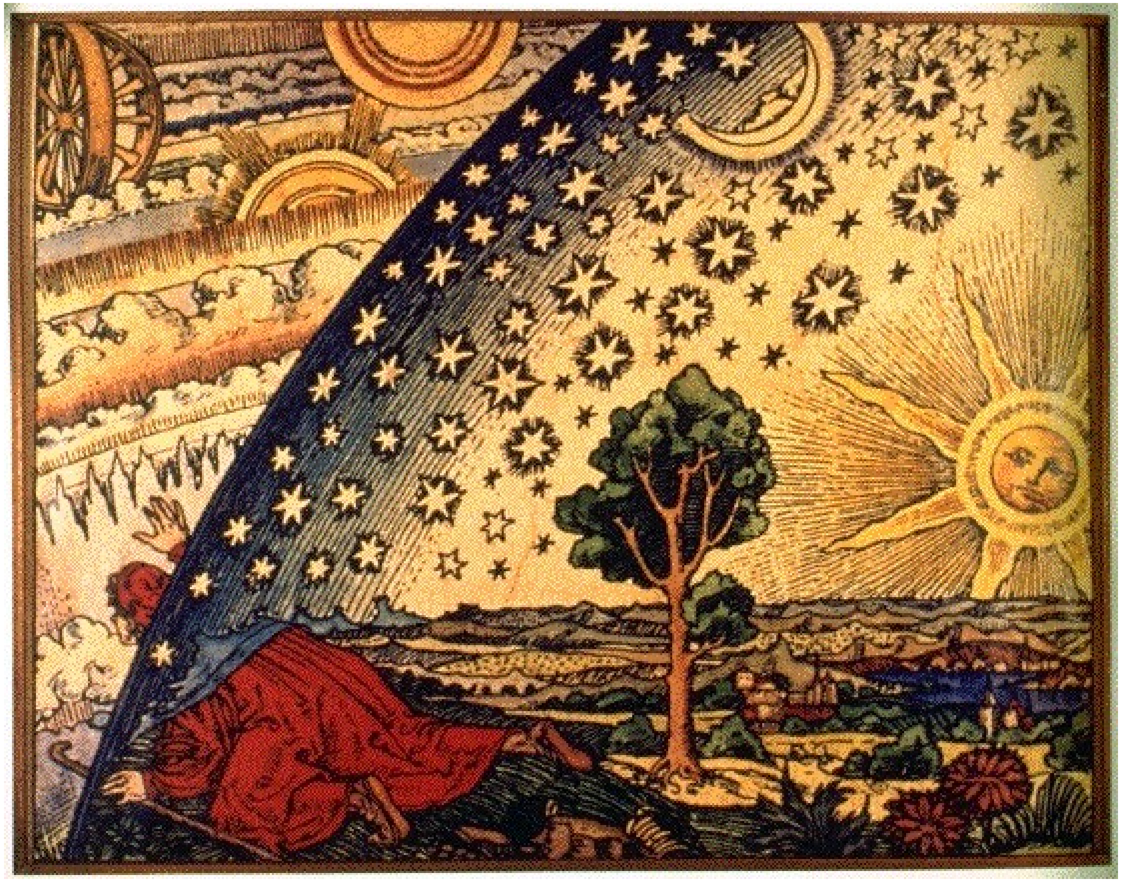
Early Universe

Cosmic Microwave Background (CMB)

Large Scale Structure (LSS)

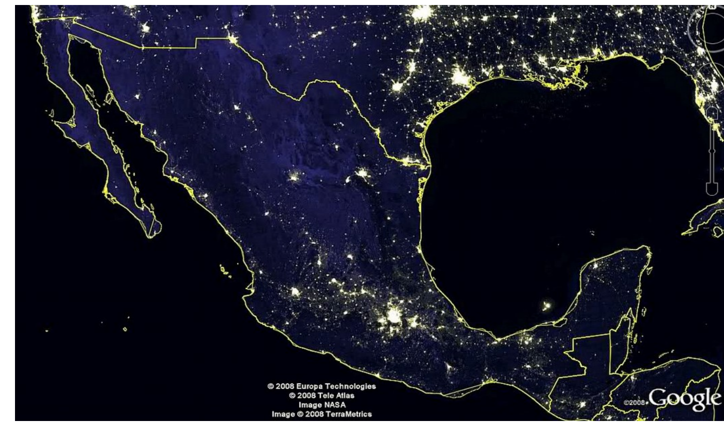
Dark Energy Spectroscopic Instrument

What do we know about the Universe?



Flammarion, 1888

What do we know about the Universe?



We observe the Universe by

1) Mostly  (photons)

2) but also by: neutrinos, alpha particles, gravitational waves, ...

Note: We observe the past and
only on the “light-cone”

What we know...

Sloan Digital Sky Survey

What we know...

Our visible Universe is BIG

93 billion light years = 10^{26} m

Universe

Sun 10^{8} m

Leon 10^{3} m

Proton 10^{-15} m

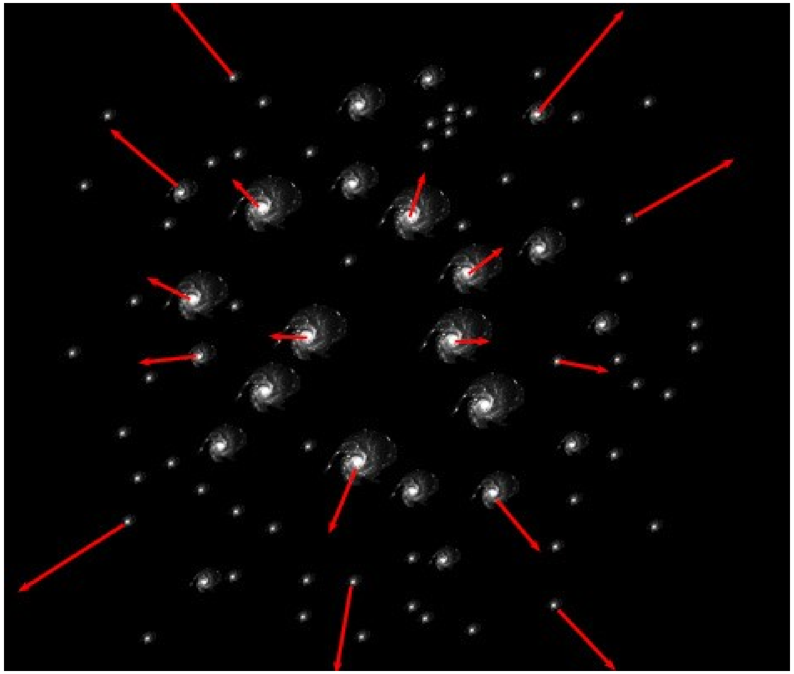
What we know...

13.7 billion years

Oldest stars ~ 13.6 billion years

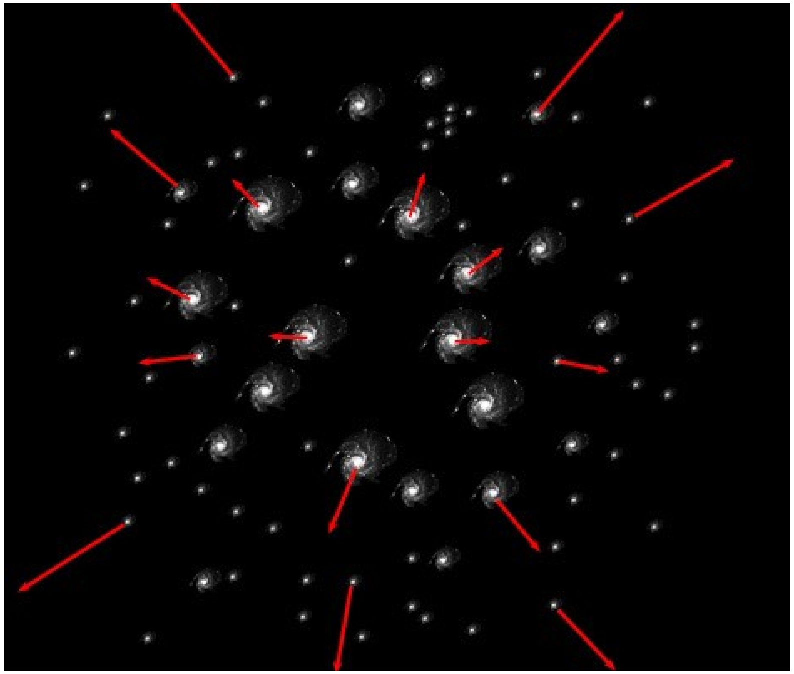
What we know...

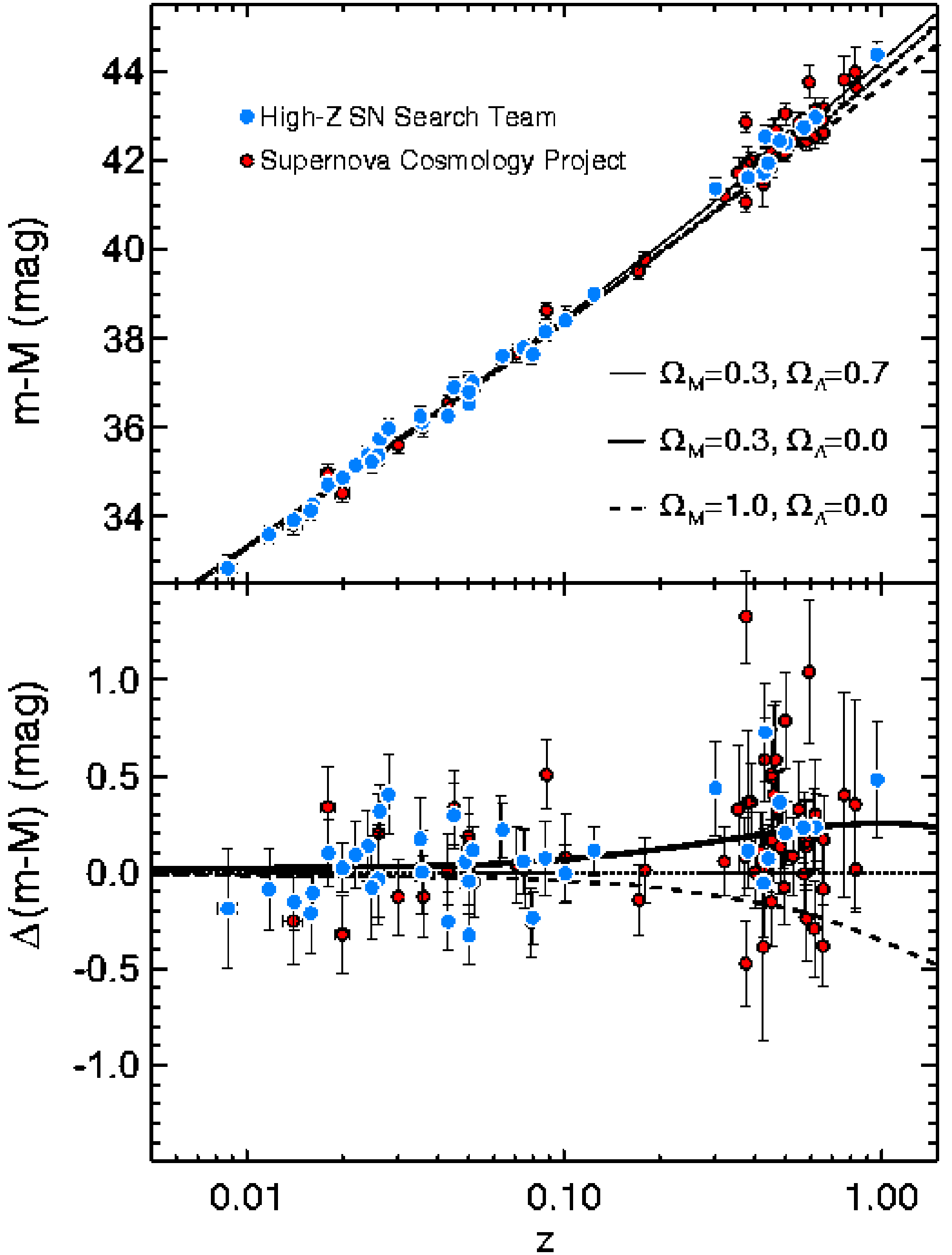
The Universe expands



What we know...

The Universe expands





What we know...

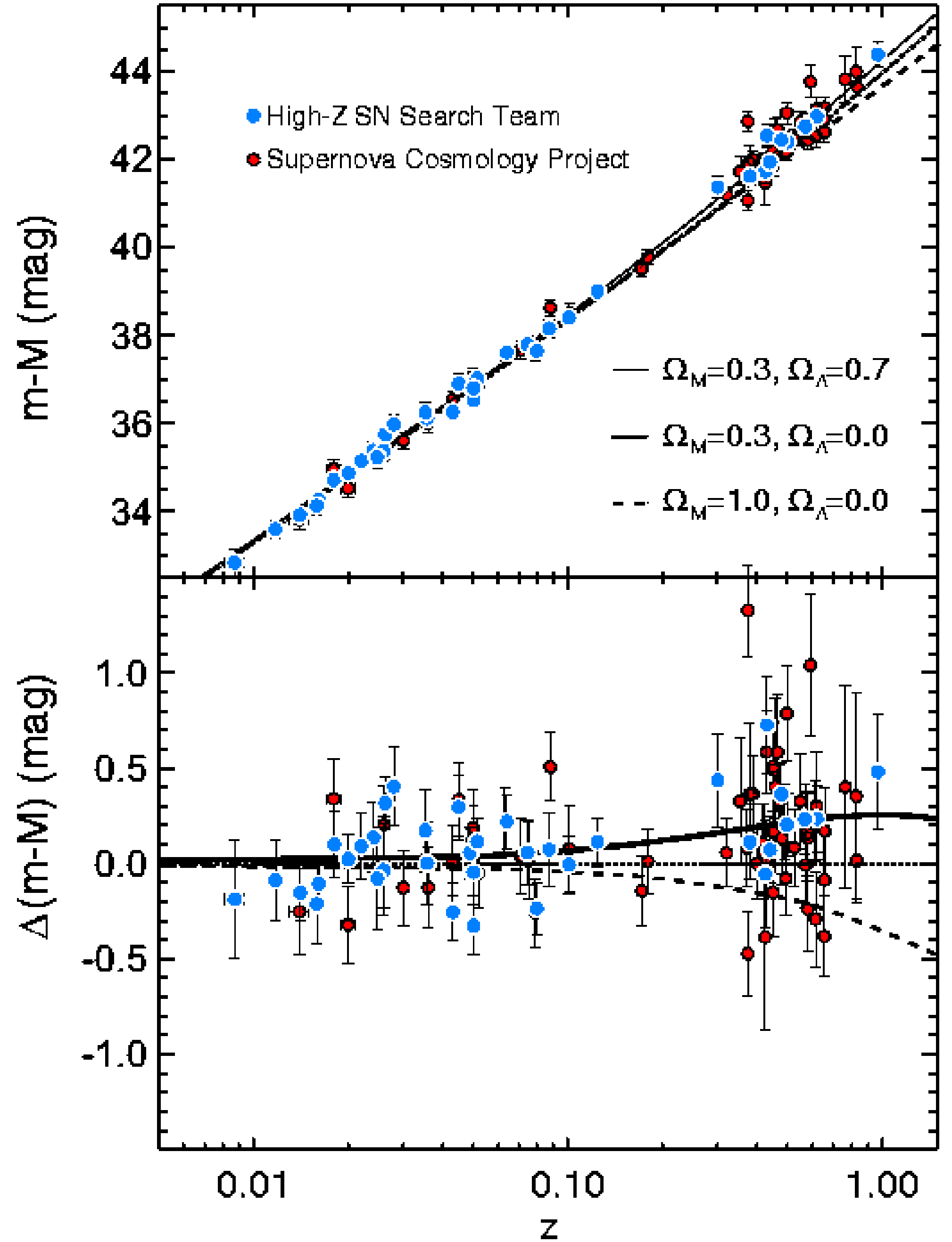
The Universe expands

Actually, it accelerates!

(Nobel 2011 to Perlmutter, Riess & Schmidt).

Cause:

DARK ENERGY!



What we know...

Expansion

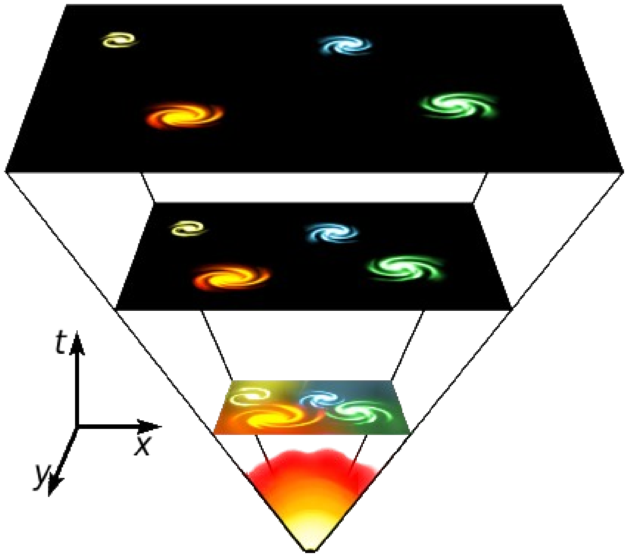
gave rise to the BIG BANG THEORY

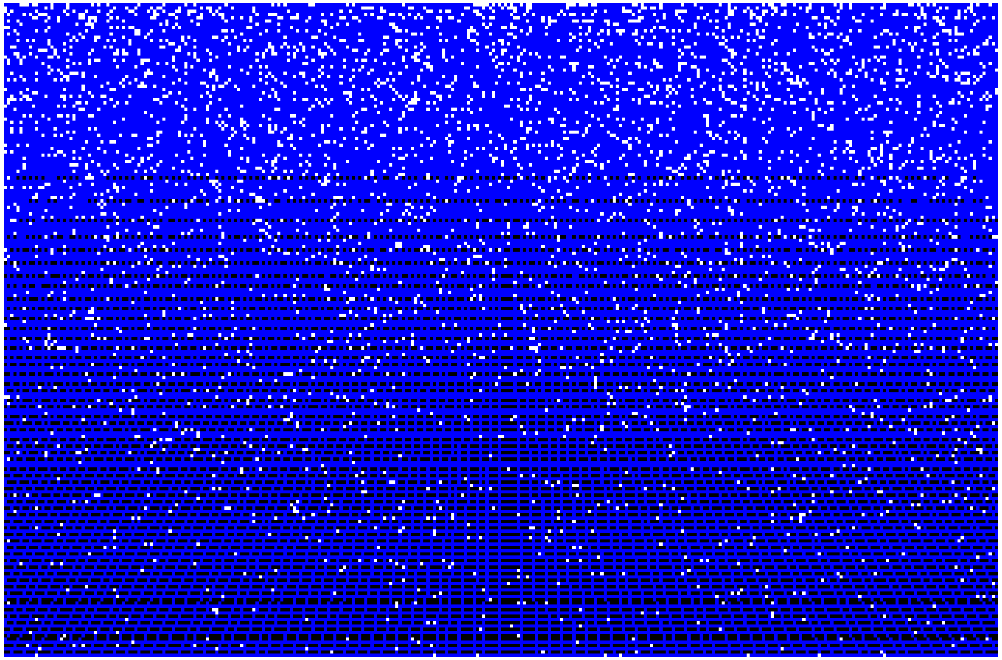
What we know...

Expansion

gave rise to

What we know...



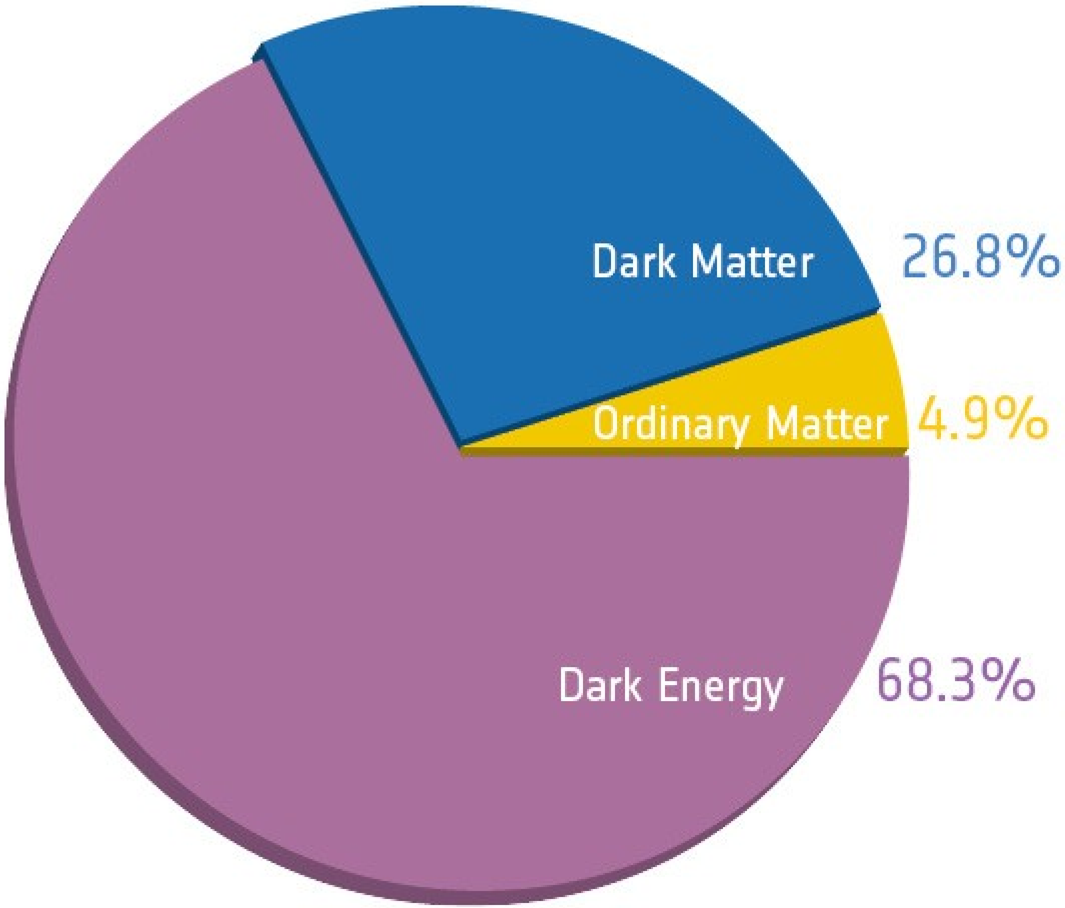


Observations

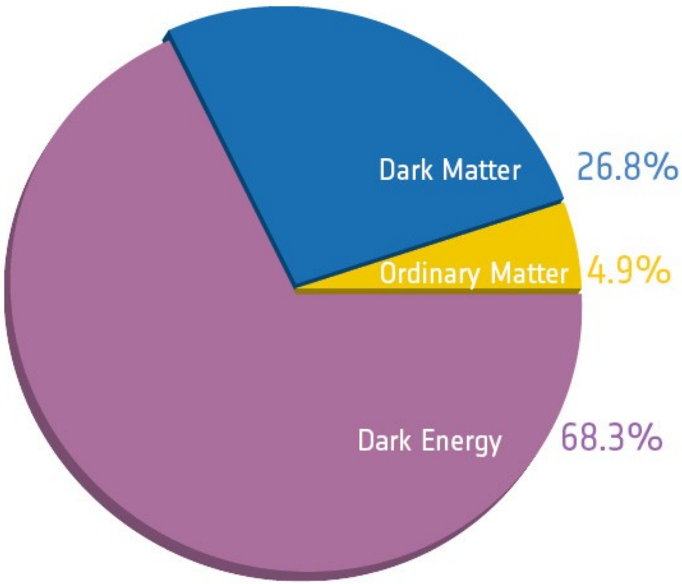
- There was no explosion
- No expansion into something else
- Expansion may be faster than speed of light

What we know...

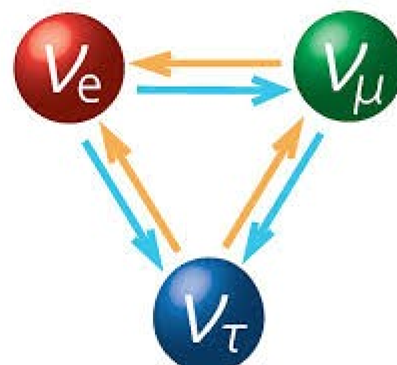
Composed today by



What we know...

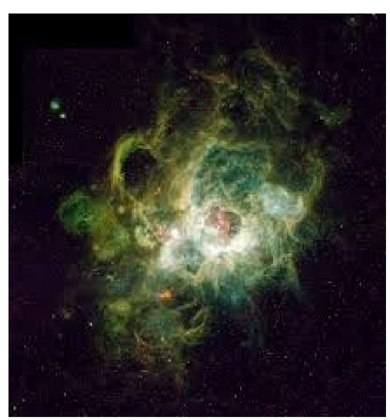


Heavy elements ~ 0.03%



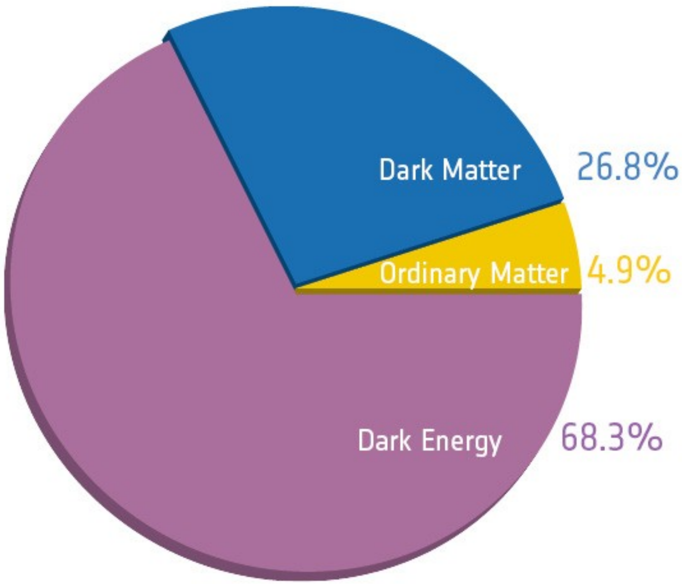
Neutrinos ~ 0.3%

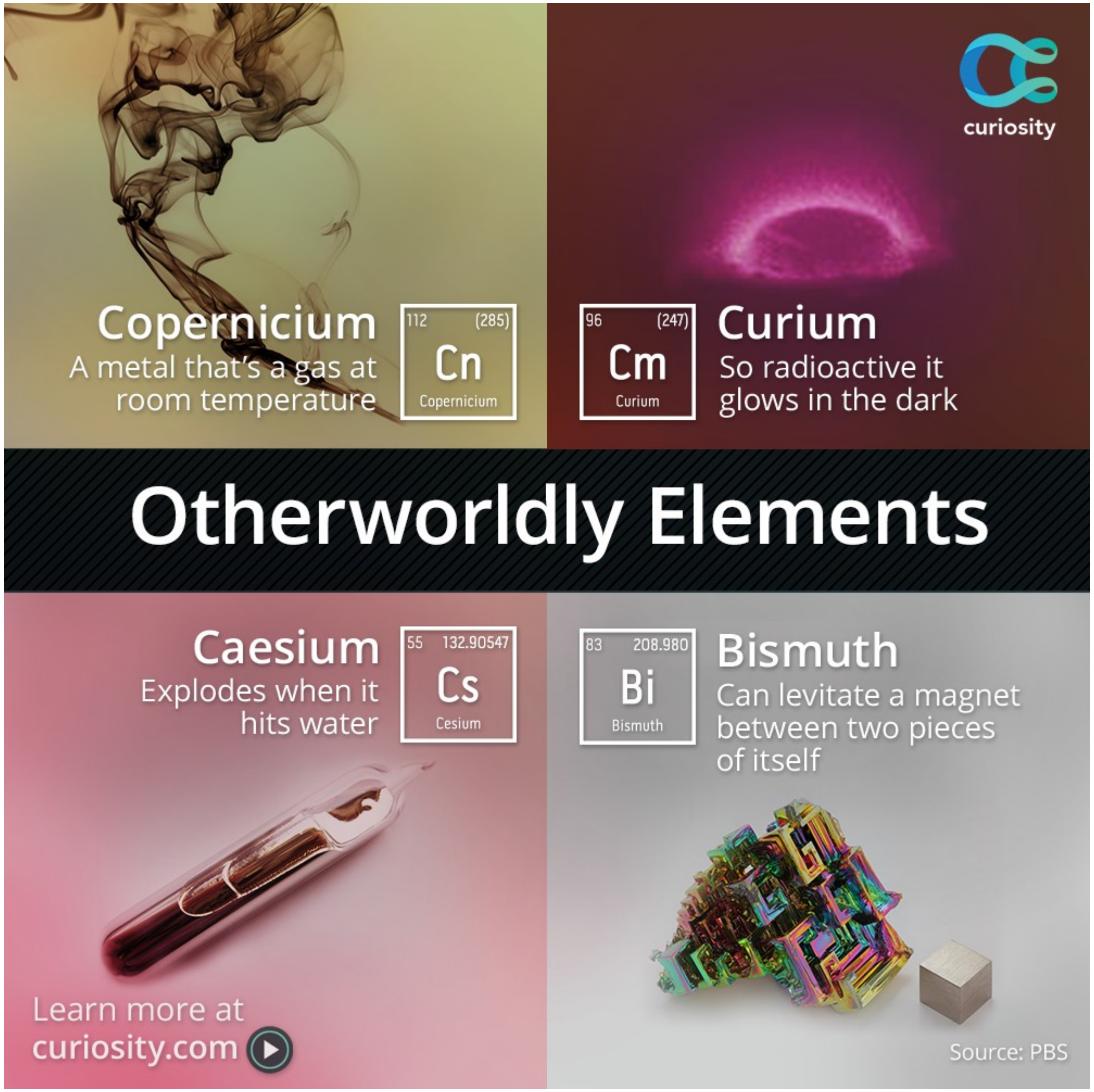
Stars ~ 0.5%



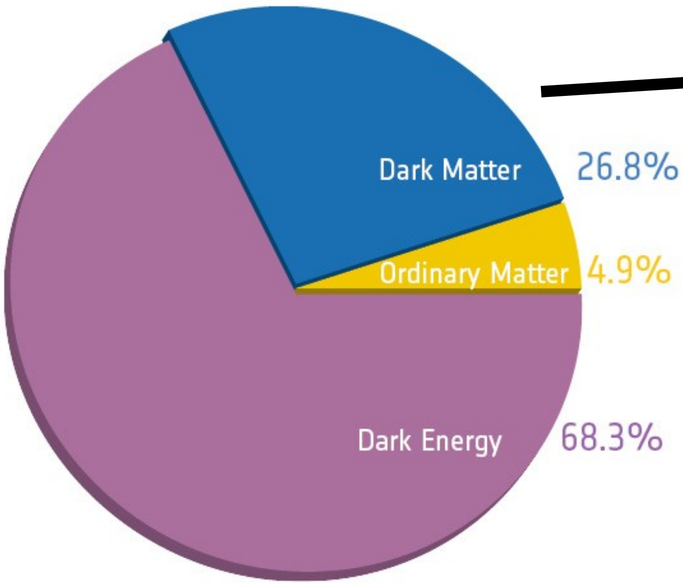
Free hydrogen & Helium ~ 4%

What we know...

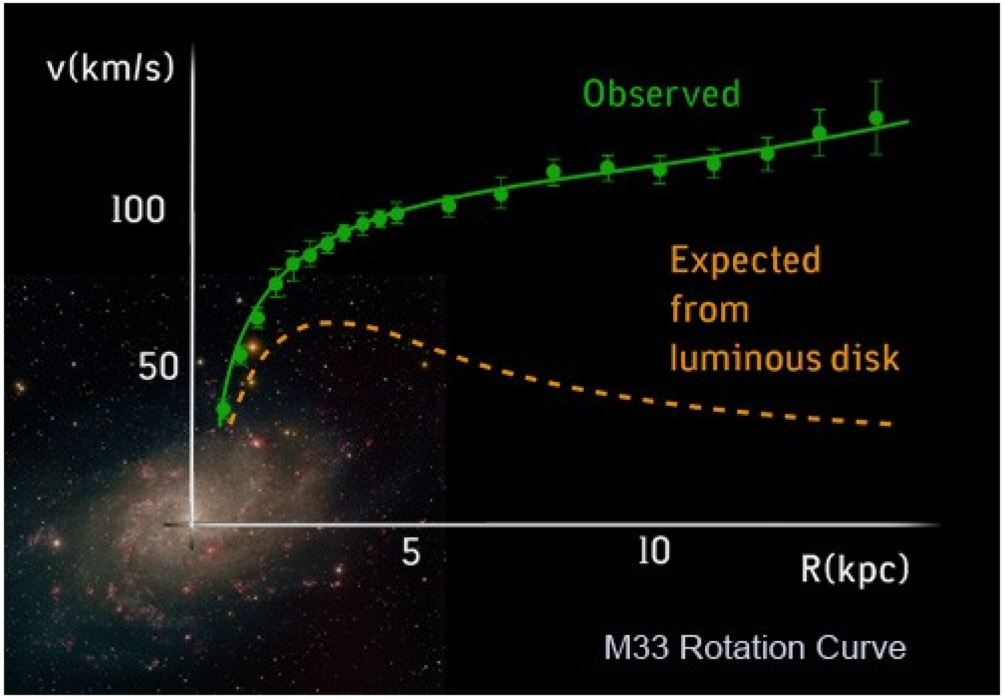

Dark Matter
26.8%
Ordinary Matter
4.9%
Dark Energy
68.3%


curiosity
Copernicium
A metal that's a gas at room temperature
112 (285) Cn Copernicium
96 (247) Cm Curium
Curium
So radioactive it glows in the dark
Otherworldly Elements
Caesium
Explodes when it hits water
55 132.90547 Cs Cesium
83 208.980 Bi Bismuth
Bismuth
Can levitate a magnet between two pieces of itself
Learn more at curiosity.com
Source: PBS

What we do not know...



Dark Matter

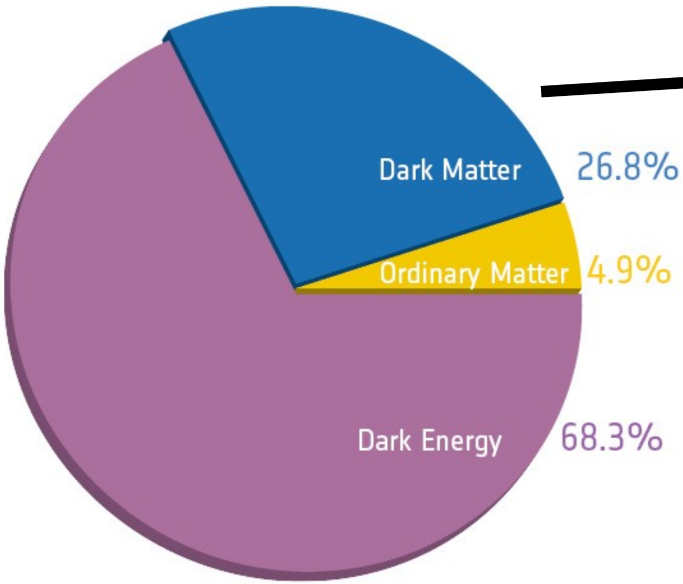


Best candidate:

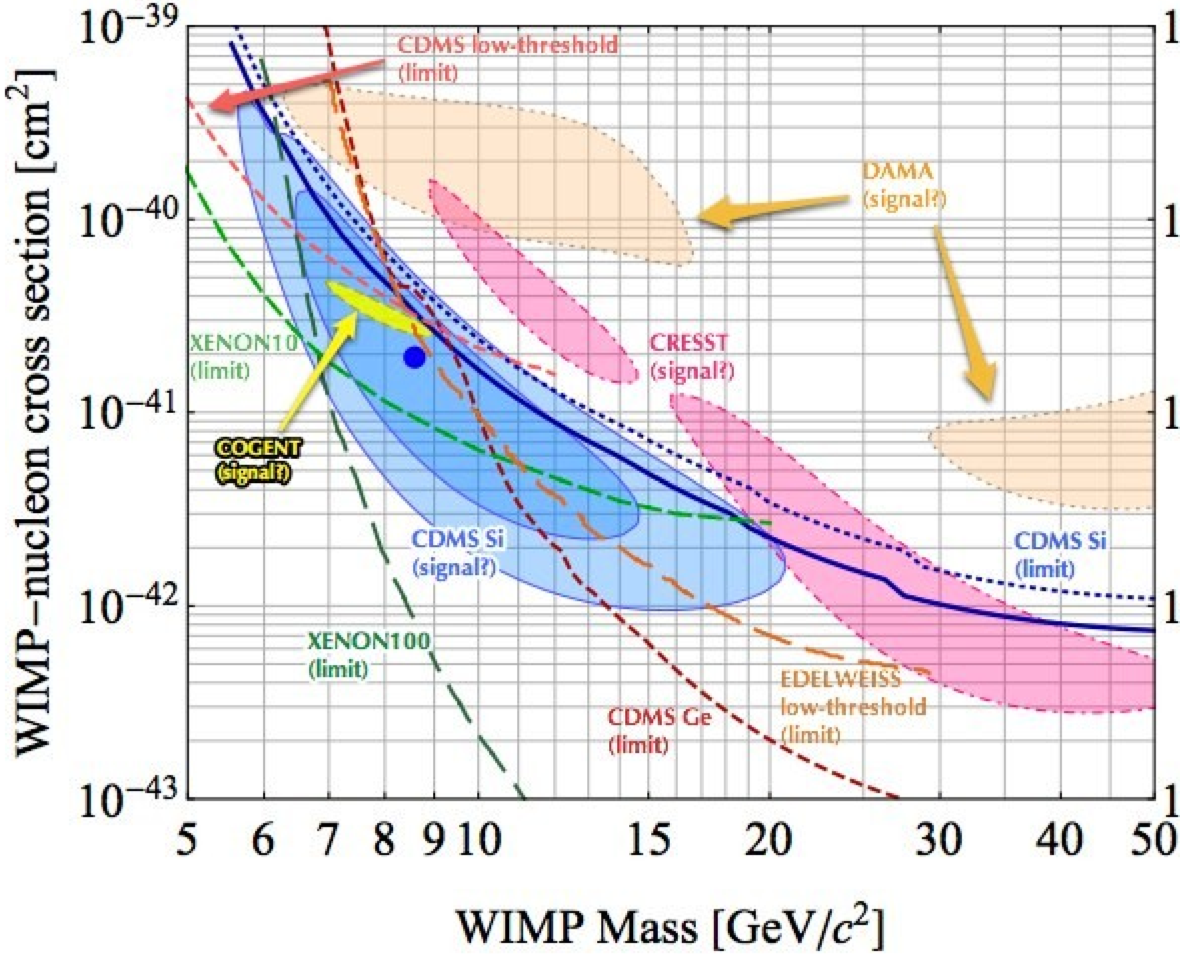
Massive particle with:

Null or weak interactions with the visible matter

What we do not know...



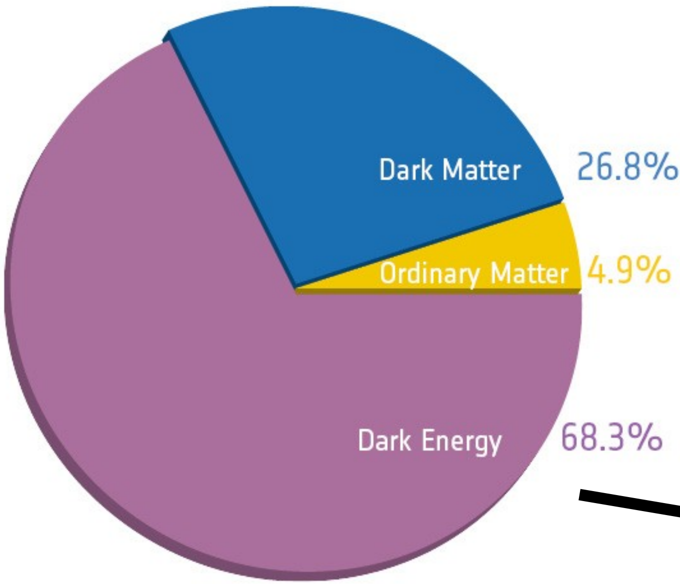
Dark Matter



Tens of experiments

...searching...

What we do not know...

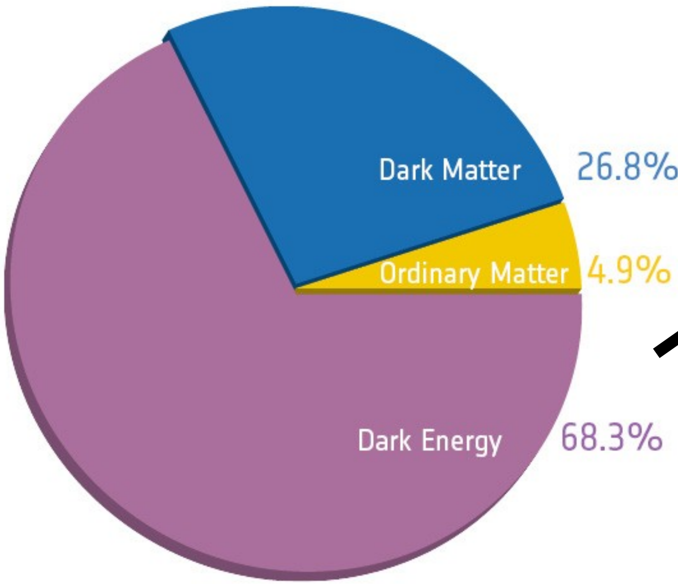


Dark Energy

Best candidate:

Cosmological Constant Λ

What we do not know...



Dark Energy

Theoretical problem

Cosmological Constant value

$$\Lambda_{vac} = 10^{120}\Lambda_{obs}$$

100000000000000000000000000000000
000000000000000000000000000000000
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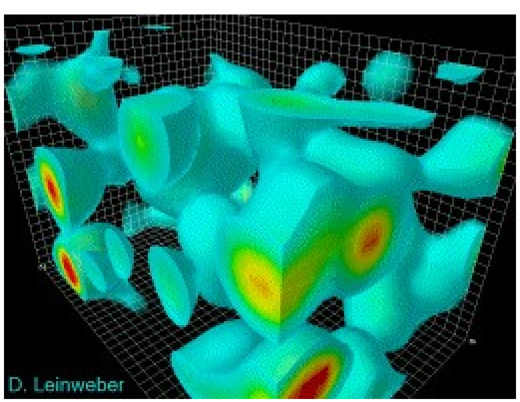
00000000000000000000000000000000



Empty space perturbations

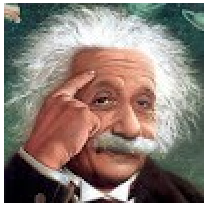
THE COSMIC COLLIDER

A Perturbed Universe

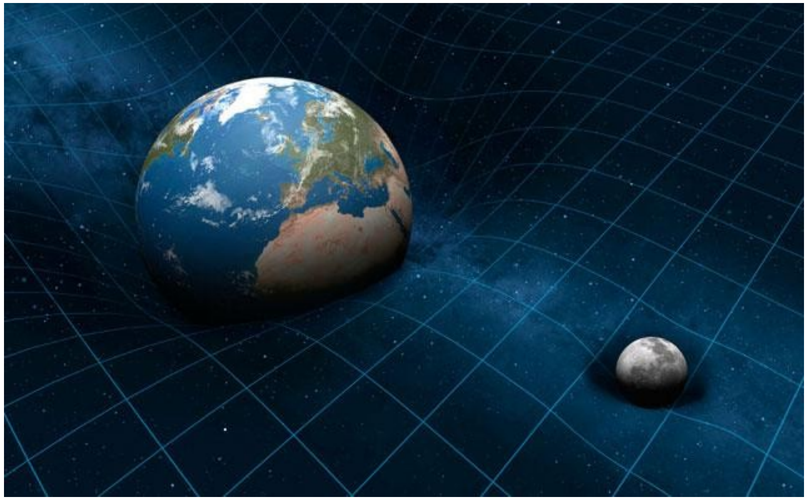
From Quantum Fluctuations to Human Beings...

Simple model

Einstein (1915)



$$G_{\mu\nu} = 8\pi G_N T_{\mu\nu}$$



Space-time

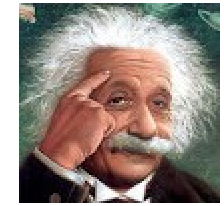
Geometry

Matter/energy

Non-linear theory - describes interactions!

Simple model

$$G_{\mu\nu} = 8\pi G_N T_{\mu\nu}$$



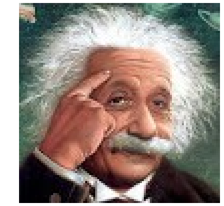
$$\mu = \nu = 3$$

$$
\begin{aligned}
&\frac{1}{4}\,\mathrm{g00}^{-1}\,\mathrm{g11}^{-1}\,\mathrm{g22}^{-1}\,\frac{\partial\,\mathrm{g00}}{\partial y}\,\frac{\partial\,\mathrm{g11}}{\partial y} + \frac{1}{4}\,\mathrm{g00}^{-1}\,\mathrm{g11}^{-1}\,\mathrm{g33}^{-1}\,\frac{\partial\,\mathrm{g11}}{\partial t}\,\frac{\partial\,\mathrm{g33}}{\partial t} + \frac{1}{4}\,\mathrm{g00}^{-1}\,\mathrm{g11}^{-1}\,\mathrm{g33}^{-1}\,\frac{\partial\,\mathrm{g00}}{\partial x}\,\frac{\partial\,\mathrm{g33}}{\partial x} + \\
&\frac{1}{4}\,\mathrm{g00}^{-1}\,\mathrm{g11}^{-1}\,\mathrm{g33}^{-1}\,\frac{\partial\,\mathrm{g00}}{\partial z}\,\frac{\partial\,\mathrm{g11}}{\partial z} + \frac{1}{2}\,\mathrm{g00}^{-1}\,\mathrm{g11}^{-1}\,\frac{\partial^2\,\mathrm{g11}}{\partial t^2} - \frac{1}{4}\,(\mathrm{g00}^{-1})^2\,\mathrm{g11}^{-1}\,\frac{\partial\,\mathrm{g00}}{\partial t}\,\frac{\partial\,\mathrm{g11}}{\partial t} - \\
&\frac{1}{4}\,\mathrm{g00}^{-1}\,(\mathrm{g11}^{-1})^2\left(\frac{\partial\,\mathrm{g11}}{\partial t}\right)^2 + \frac{1}{2}\,\mathrm{g00}^{-1}\,\mathrm{g11}^{-1}\,\frac{\partial^2\,\mathrm{g00}}{\partial x^2} - \frac{1}{4}\,(\mathrm{g00}^{-1})^2\,\mathrm{g11}^{-1}\left(\frac{\partial\,\mathrm{g00}}{\partial x}\right)^2 - \\
&\frac{1}{4}\,\mathrm{g00}^{-1}\,(\mathrm{g11}^{-1})^2\,\frac{\partial\,\mathrm{g00}}{\partial x}\,\frac{\partial\,\mathrm{g11}}{\partial x} + \frac{1}{4}\,\mathrm{g00}^{-1}\,\mathrm{g22}^{-1}\,\mathrm{g33}^{-1}\,\frac{\partial\,\mathrm{g00}}{\partial y}\,\frac{\partial\,\mathrm{g33}}{\partial y} + \frac{1}{2}\,\mathrm{g00}^{-1}\,\mathrm{g33}^{-1}\,\frac{\partial^2\,\mathrm{g33}}{\partial t^2} - \\
&\frac{1}{4}\,(\mathrm{g00}^{-1})^2\,\mathrm{g33}^{-1}\,\frac{\partial\,\mathrm{g00}}{\partial t}\,\frac{\partial\,\mathrm{g33}}{\partial t} - \frac{1}{4}\,\mathrm{g00}^{-1}\,(\mathrm{g33}^{-1})^2\left(\frac{\partial\,\mathrm{g33}}{\partial t}\right)^2 + \frac{1}{2}\,\mathrm{g00}^{-1}\,\mathrm{g33}^{-1}\,\frac{\partial^2\,\mathrm{g00}}{\partial z^2} - \\
&\frac{1}{4}\,(\mathrm{g00}^{-1})^2\,\mathrm{g33}^{-1}\left(\frac{\partial\,\mathrm{g00}}{\partial z}\right)^2 - \frac{1}{4}\,\mathrm{g00}^{-1}\,(\mathrm{g33}^{-1})^2\,\frac{\partial\,\mathrm{g00}}{\partial z}\,\frac{\partial\,\mathrm{g33}}{\partial z} + \frac{1}{4}\,\mathrm{g11}^{-1}\,\mathrm{g22}^{-1}\,\mathrm{g33}^{-1}\,\frac{\partial\,\mathrm{g11}}{\partial y}\,\frac{\partial\,\mathrm{g33}}{\partial y} + \\
&\frac{1}{2}\,\mathrm{g11}^{-1}\,\mathrm{g33}^{-1}\,\frac{\partial^2\,\mathrm{g33}}{\partial x^2} - \frac{1}{4}\,\mathrm{g11}^{-1}\,(\mathrm{g33}^{-1})^2\left(\frac{\partial\,\mathrm{g33}}{\partial x}\right)^2 - \frac{1}{4}\,(\mathrm{g11}^{-1})^2\,\mathrm{g33}^{-1}\,\frac{\partial\,\mathrm{g11}}{\partial x}\,\frac{\partial\,\mathrm{g33}}{\partial x} + \\
&\frac{1}{2}\,\mathrm{g11}^{-1}\,\mathrm{g33}^{-1}\,\frac{\partial^2\,\mathrm{g11}}{\partial z^2} - \frac{1}{4}\,\mathrm{g11}^{-1}\,(\mathrm{g33}^{-1})^2\,\frac{\partial\,\mathrm{g11}}{\partial z}\,\frac{\partial\,\mathrm{g33}}{\partial z} - \frac{1}{4}\,(\mathrm{g11}^{-1})^2\,\mathrm{g33}^{-1}\left(\frac{\partial\,\mathrm{g11}}{\partial z}\right)^2
\end{aligned}
$$

Non-linear theory

Simple model

$G_{\mu\nu} = 8\pi G_N T_{\mu\nu}$



$\mu = \nu = 3$

$$\frac{1}{4}\,g00^{-1}\,g11^{-1}\,g22^{-1}\,\frac{\partial g00}{\partial y}\,\frac{\partial g11}{\partial y} + \frac{1}{4}\,g00^{-1}\,g11^{-1}\,g33^{-1}\,\frac{\partial g11}{\partial t}\,\frac{\partial g33}{\partial t} + \frac{1}{4}\,g00^{-1}\,g11^{-1}\,g33^{-1}\,\frac{\partial g00}{\partial x}\,\frac{\partial g33}{\partial x} +$$

$$\frac{1}{4}\,g00^{-1}\,g11^{-1}\,g33^{-1}\,\frac{\partial g00}{\partial z}\,\frac{\partial g11}{} \cdots \frac{1}{4}\,(g00^{-1})^2\,g11^{-1}\,\frac{\partial g00}{\partial t}\,\frac{\partial g11}{\partial t} -$$

$$\frac{1}{4}\,g00^{-1}\,(g11^{-1})^2\left(\frac{\partial g11}{\partial t}\right)^2 + \cdots (g00^{-1})^2\,g11^{-1}\left(\frac{\partial g00}{\partial x}\right)^2 -$$

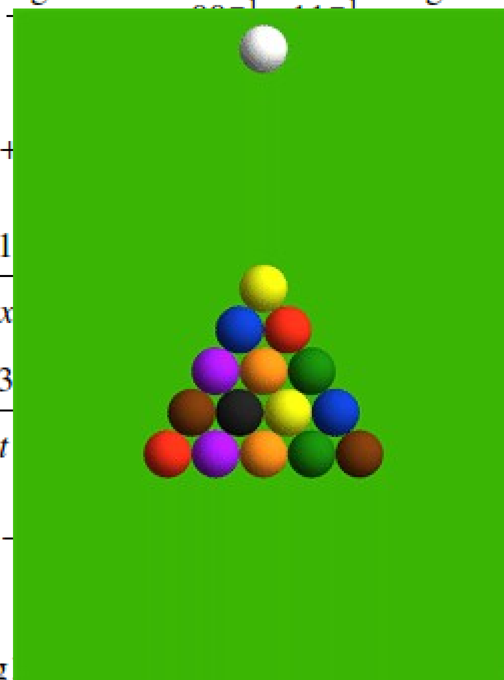
$$\frac{1}{4}\,g00^{-1}\,(g11^{-1})^2\,\frac{\partial g00}{\partial x}\,\frac{\partial g1}{\partial x} \cdots \frac{\partial g33}{\partial y} + \frac{1}{2}\,g00^{-1}\,g33^{-1}\,\frac{\partial^2 g33}{\partial t^2} -$$

$$\frac{1}{4}\,(g00^{-1})^2\,g33^{-1}\,\frac{\partial g00}{\partial t}\,\frac{\partial g3}{\partial t} \cdots + \frac{1}{2}\,g00^{-1}\,g33^{-1}\,\frac{\partial^2 g00}{\partial z^2} -$$

$$\frac{1}{4}\,(g00^{-1})^2\,g33^{-1}\left(\frac{\partial g00}{\partial z}\right)^2 \cdots + \frac{1}{4}\,g11^{-1}\,g22^{-1}\,g33^{-1}\,\frac{\partial g11}{\partial y}\,\frac{\partial g33}{\partial y} +$$

$$\frac{1}{2}\,g11^{-1}\,g33^{-1}\,\frac{\partial^2 g33}{\partial x^2} - \frac{1}{4}\,g \cdots 1^{-1})^2\,g33^{-1}\,\frac{\partial g11}{\partial x}\,\frac{\partial g33}{\partial x} +$$

$$\frac{1}{2}\,g11^{-1}\,g33^{-1}\,\frac{\partial^2 g11}{\partial z^2} - \frac{1}{4}\,g11^{-1}\,(g33^{-1})^2\,\frac{\partial g11}{\partial z}\,\frac{\partial g33}{\partial z} - \frac{1}{4}\,(g11^{-1})^2\,g33^{-1}\left(\frac{\partial g11}{\partial z}\right)^2$$



Describes interactions!

Simple model

$$G_{\mu\nu} = 8\pi G_N T_{\mu\nu}$$

Cosmological principle: Isotropy and homogeneity

$$ds^2 = -dt^2 + a^2(t)(dr^2 + f(r)^2 d\Omega_2^2)$$

FRWL

(Perfect) fluids $\quad \rho = \bar{\rho} \qquad p = \bar{p} = \omega \bar{\rho}$

Describes well the averaged Universe

Fractional components

$$H = H_0 \left(\frac{\Omega_b^0}{a^3} + \frac{\Omega_{dm}^0}{a^3} + \frac{\Omega_r^0}{a^4} + \frac{\Omega_k^0}{a^2} + \Omega_\Lambda^0 \right)$$

Beyond average

Universe is not fully homogeneous and isotropic

Trick: Use perturbation theory

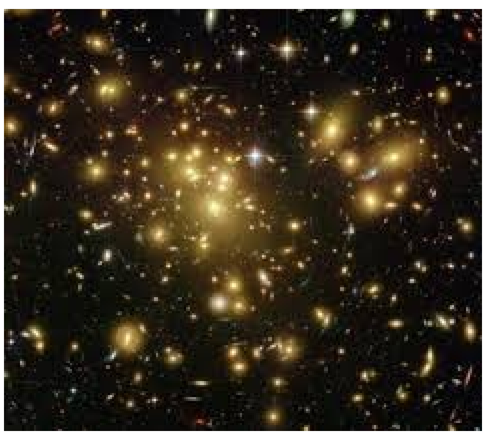
$$ds^2 = ds^2_{FRWL} + ds^2_{pert}$$

$$\rho = \bar{\rho}(1+\delta) \qquad \ldots$$

Beyond average

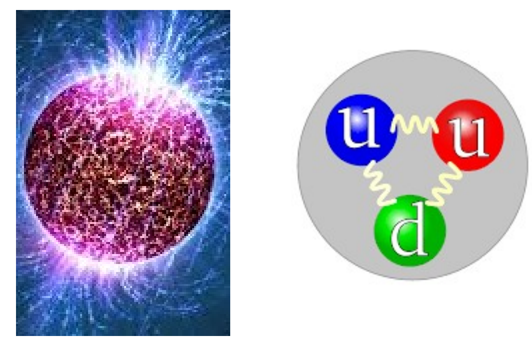
$$\rho = \bar{\rho}(1+\delta) \qquad\qquad \bar{\rho} \sim 10^{-26}\mathrm{Kg/m^3}$$

Note that



$\delta \sim 100$

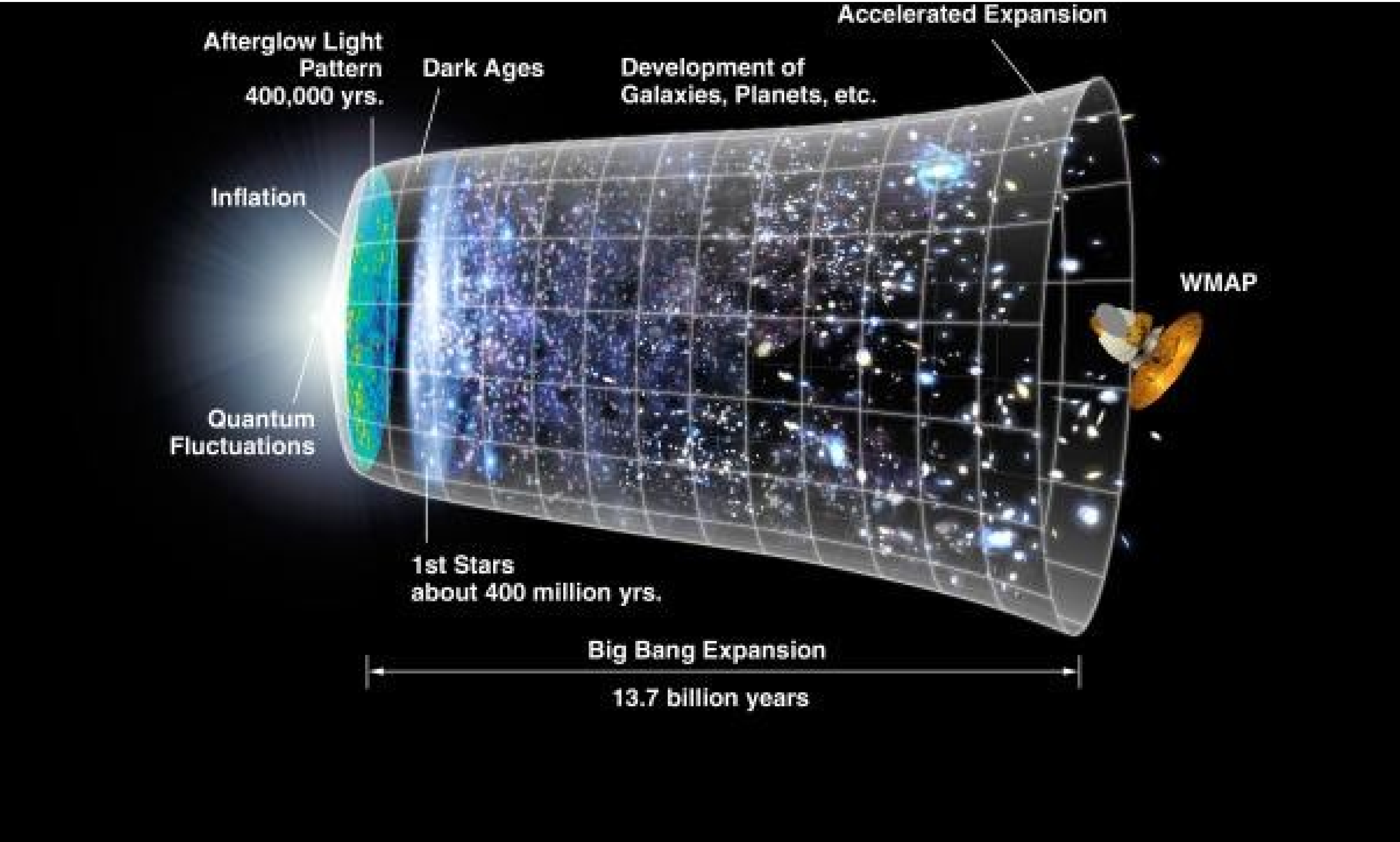
$\delta \sim 10^{29}$



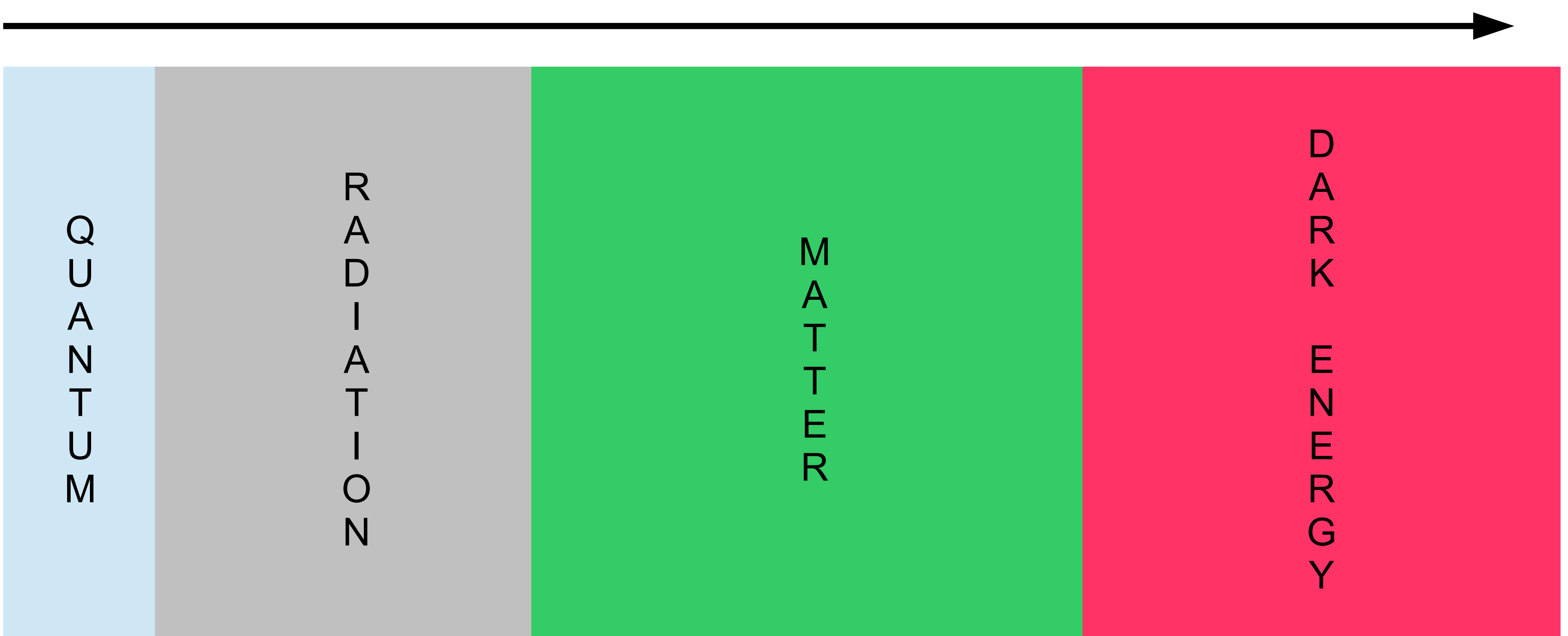
$\delta \sim 10^{43}$

Could it really describe our Universe?

Basic idea


Accelerated Expansion
Afterglow Light Pattern 400,000 yrs.
Dark Ages
Development of Galaxies, Planets, etc.
Inflation
WMAP
Quantum Fluctuations
1st Stars about 400 million yrs.
Big Bang Expansion
13.7 billion years

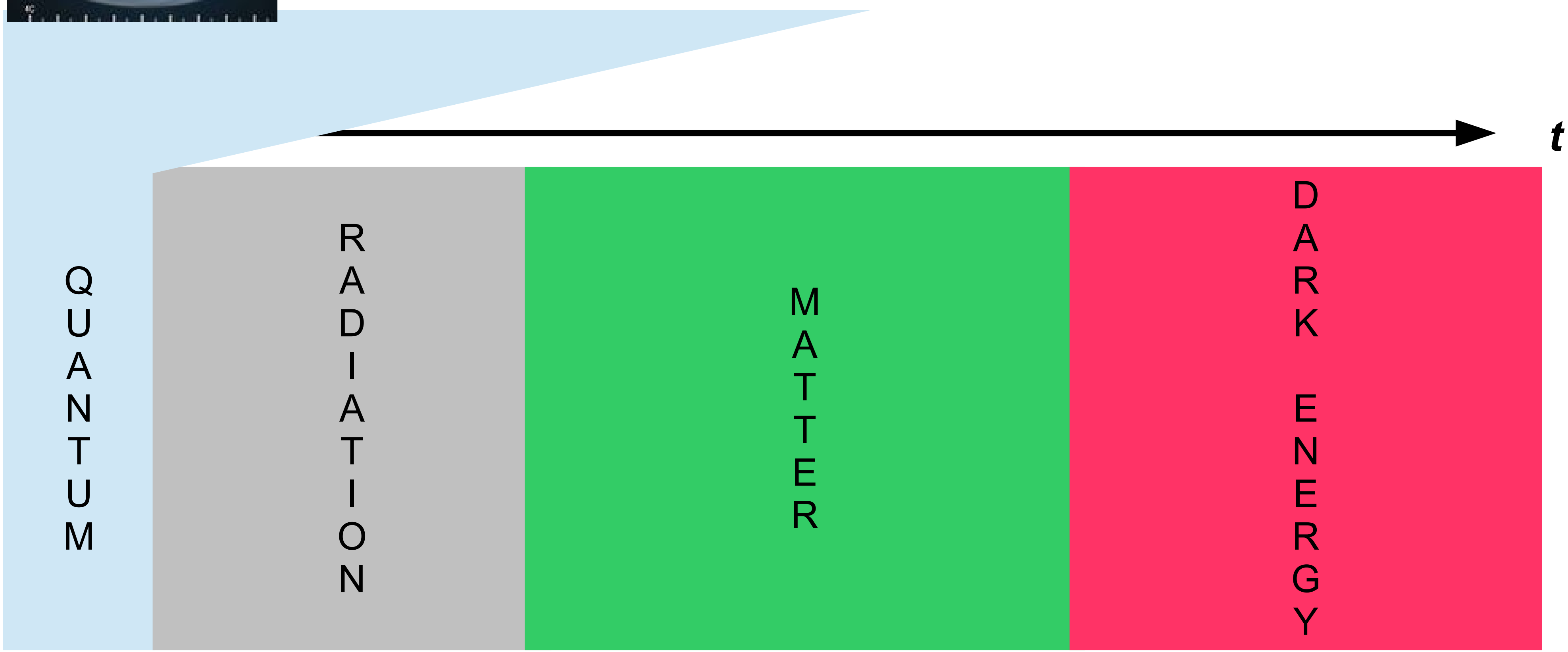
The story of "pertuby"



The story of "pertuby"

"Classical" pert.

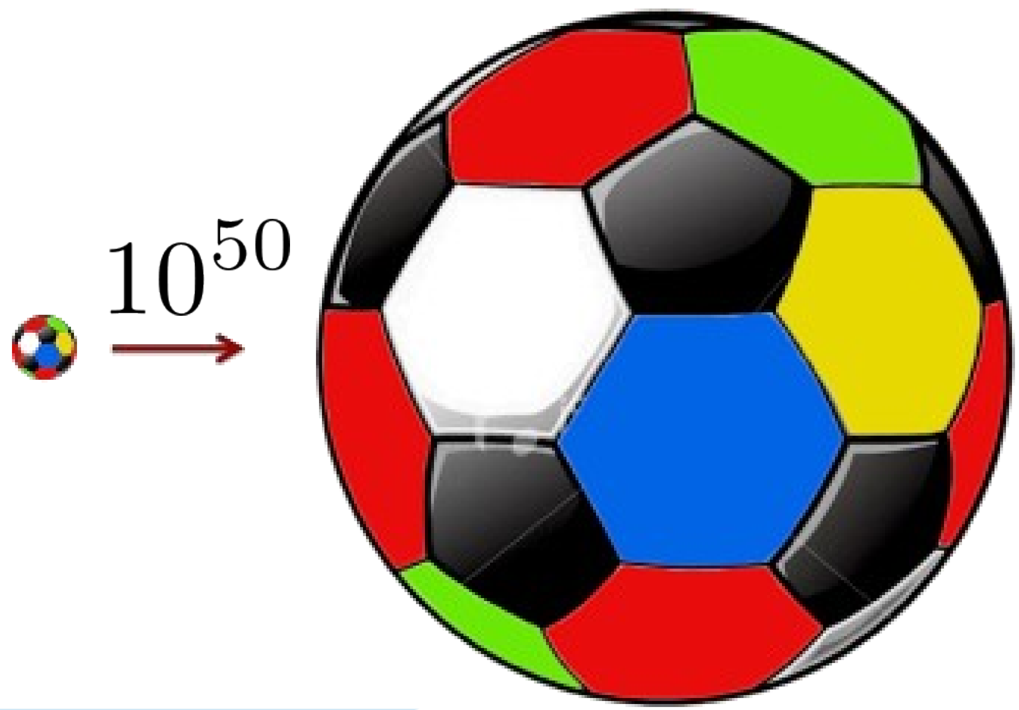
Interactions!

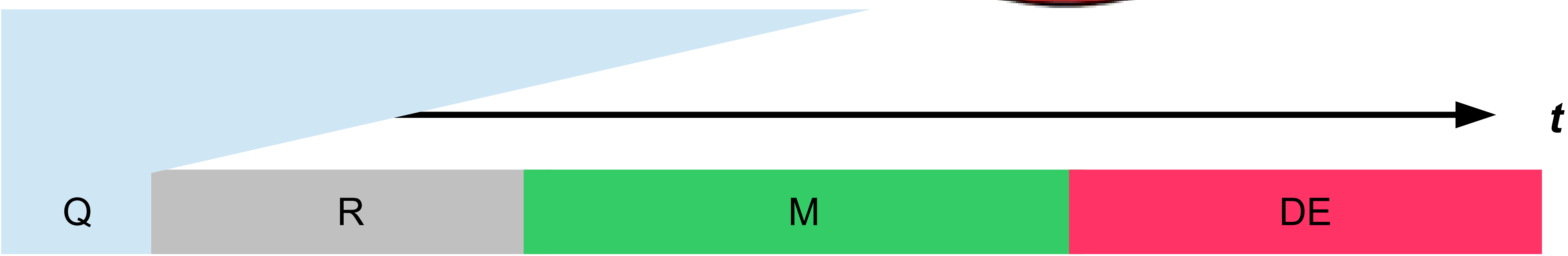


The story of "pertuby"

Formally (the inflationary mechanism)

$$t \sim 10^{-32}$$





The story of “pertuby”

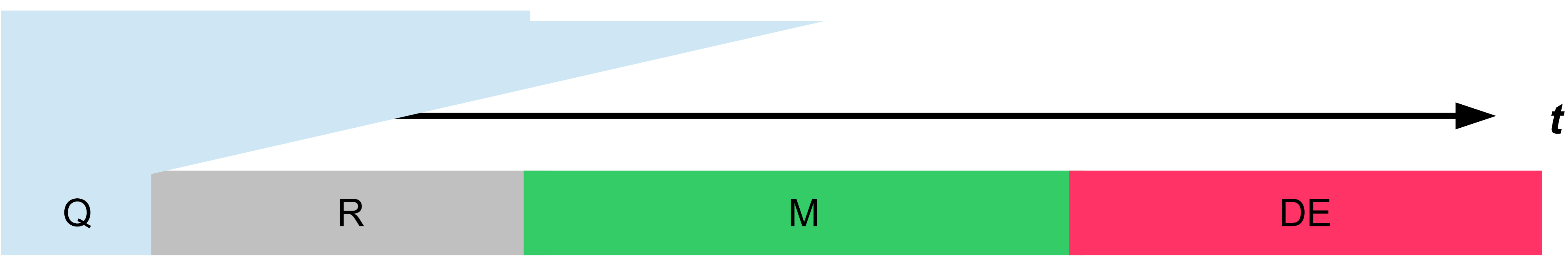
Formally (EFT perspective)

A single “clock” stopping de Sitter (accelerated) phase that spontaneously breaks time symmetry

$$\pi \sim \delta t \sim \frac{\delta\phi}{\dot{\phi}}$$

Goldstone mode related to metric perturbations

$$\zeta \sim \frac{\delta a}{a} \sim H\pi$$



The story of "pertuby"

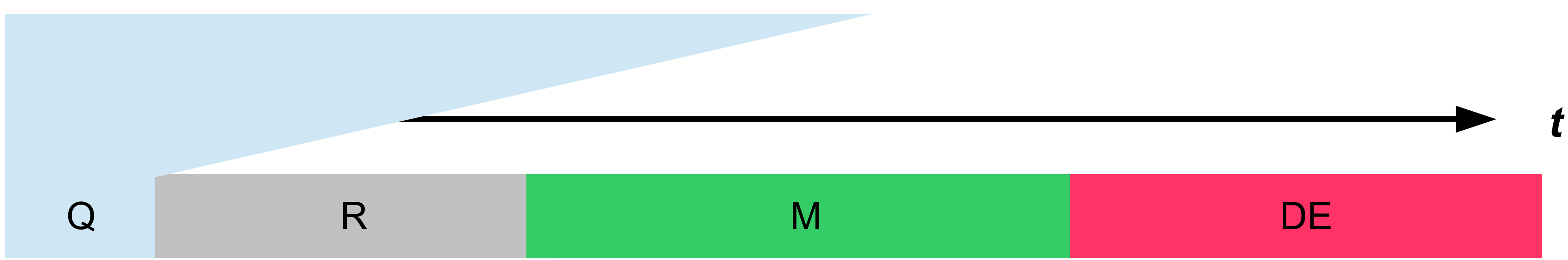
Most general Lagrangian which breaks time symmetry

$$S = \int d^4x \sqrt{-g} \quad \Big[\frac{1}{2} M_{\rm Pl}^2 R - M_{\rm Pl}^2 \left(3H^2(t+\pi) + \dot{H}(t+\pi)\right) +$$
$$+ M_{\rm Pl}^2 \dot{H}(t+\pi)\left((1+\dot{\pi})^2 g^{00} + 2(1+\dot{\pi})\partial_i \pi g^{0i} + g^{ij}\partial_i\pi\partial_j\pi\right) +$$
$$\frac{M_2(t+\pi)^4}{2!}\left((1+\dot{\pi})^2 g^{00} + 2(1+\dot{\pi})\partial_i \pi g^{0i} + g^{ij}\partial_i\pi\partial_j\pi + 1\right)^2 +$$
$$\frac{M_3(t+\pi)^4}{3!}\left((1+\dot{\pi})^2 g^{00} + 2(1+\dot{\pi})\partial_i \pi g^{0i} + g^{ij}\partial_i\pi\partial_j\pi + 1\right)^3 + \ldots\Big]$$

Cheung et al, ...

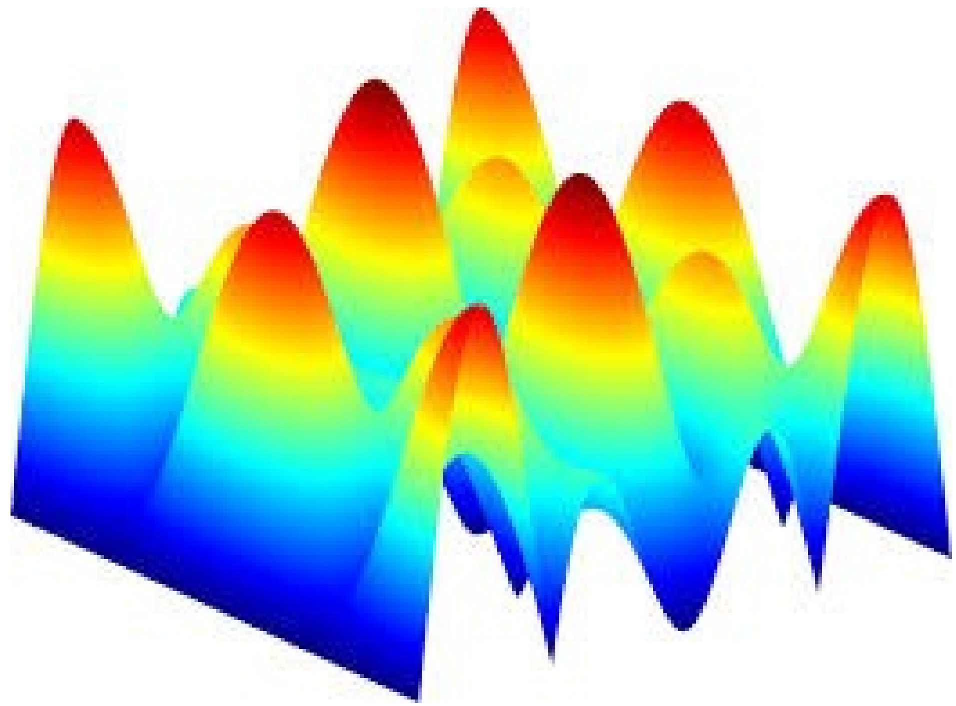
Tensors &
Higher der.

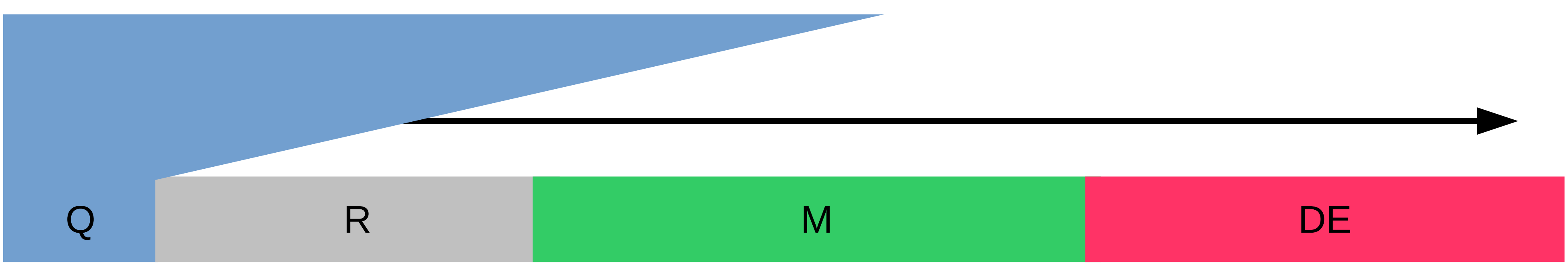
*Unifies most single field models
*Avoids questions about inflation



The story of “pertuby”

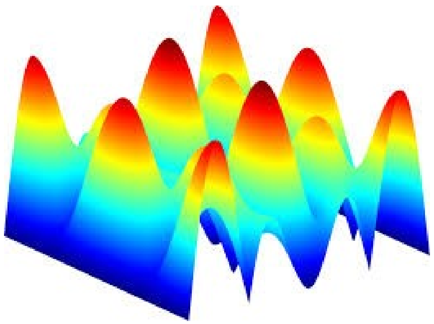
By the end of inflation we're left with a distribution of perturbations

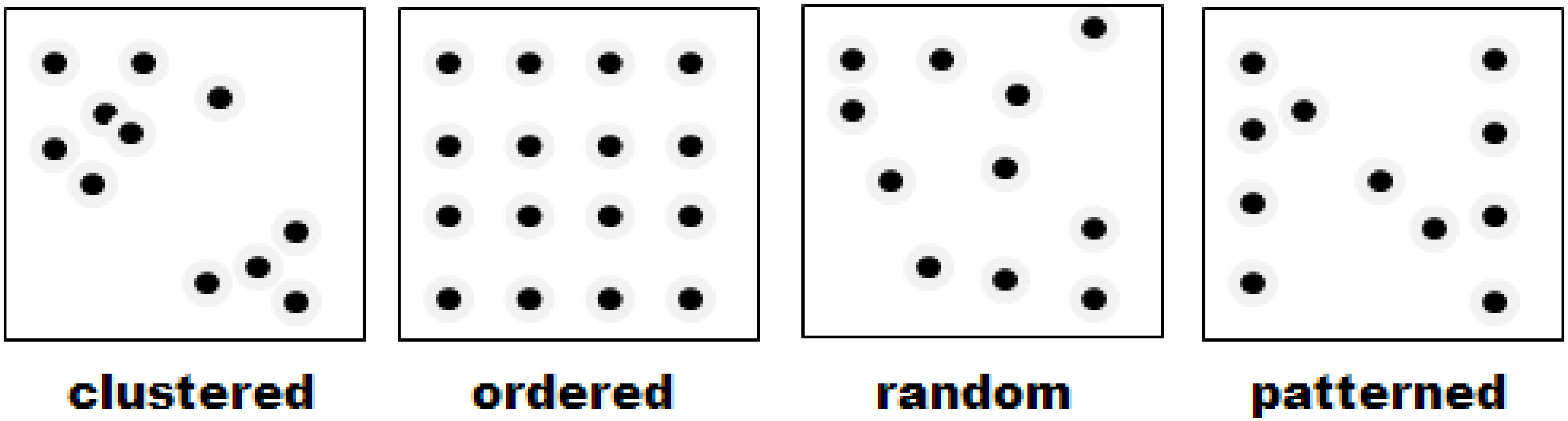


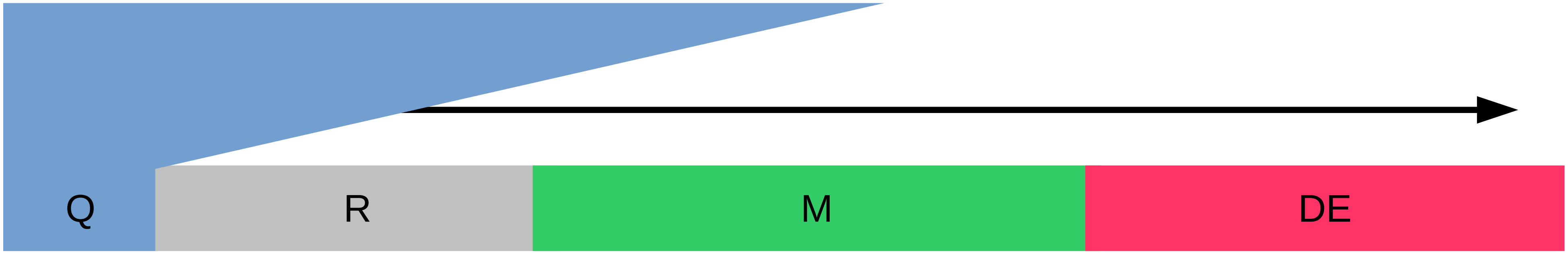


Detour

Charateresing distributions





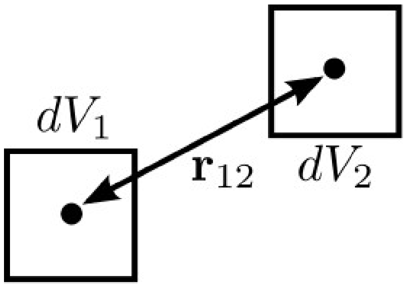


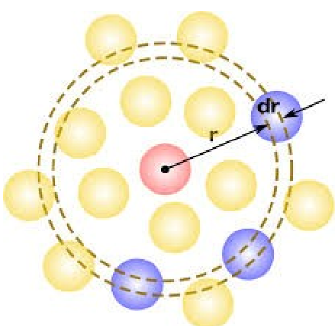
Detour

Usual to consider N-point correlation functions

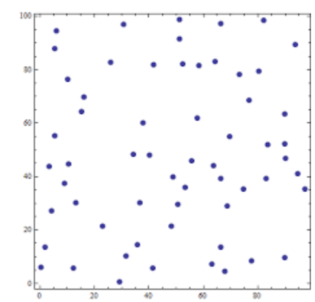
- N=2   (2pcf)

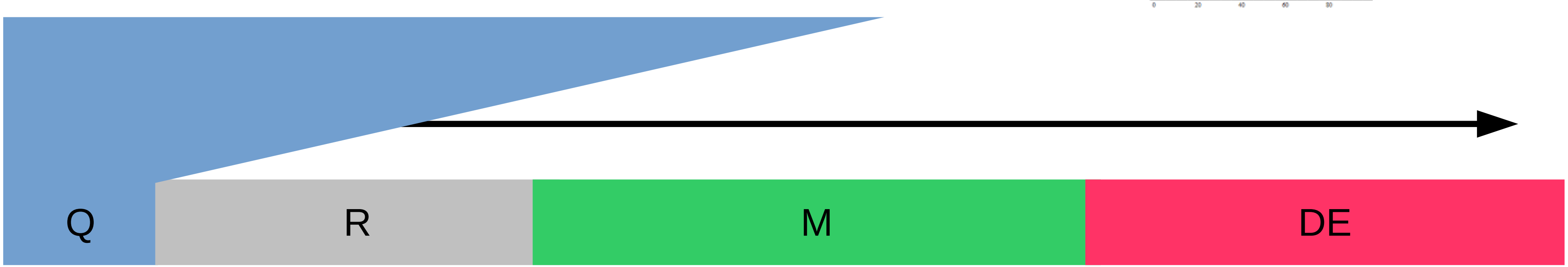
$$dP = \bar{n}^2 (1 + \xi^{(2)}(\mathbf{r_{12}})) dV_1 dV_2$$





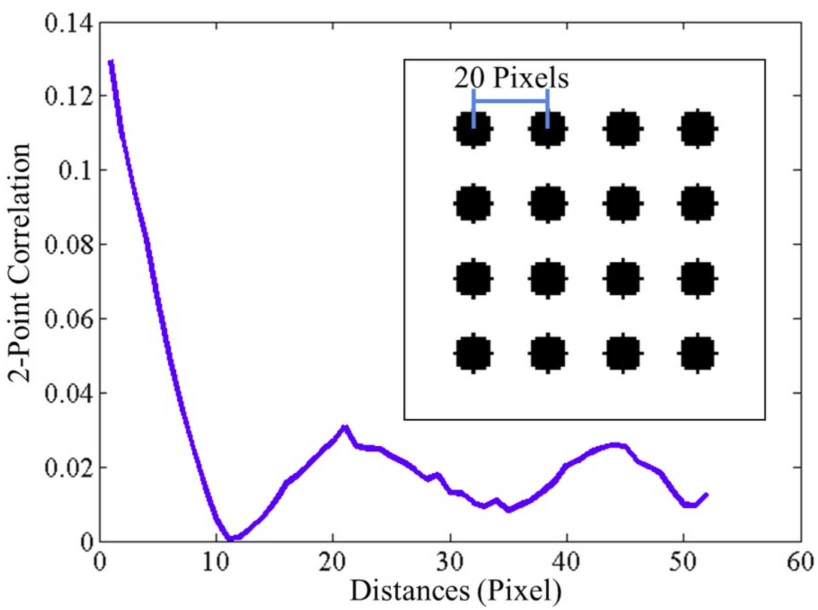
Excess correlation
over the random pairs

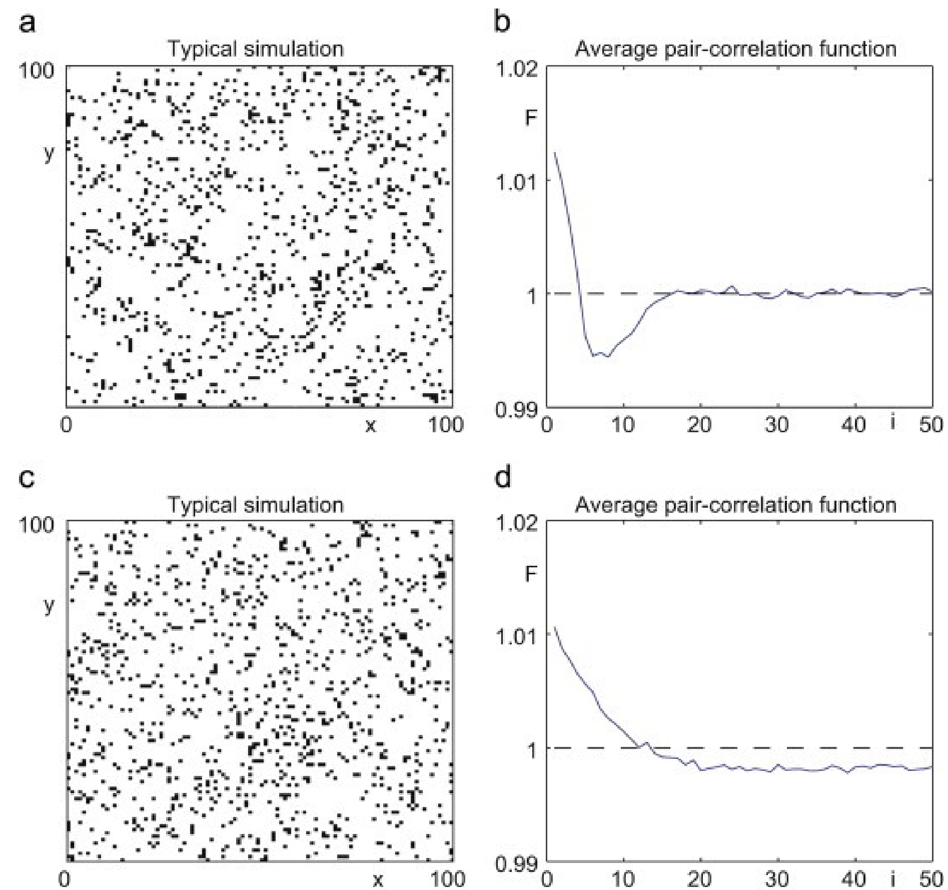


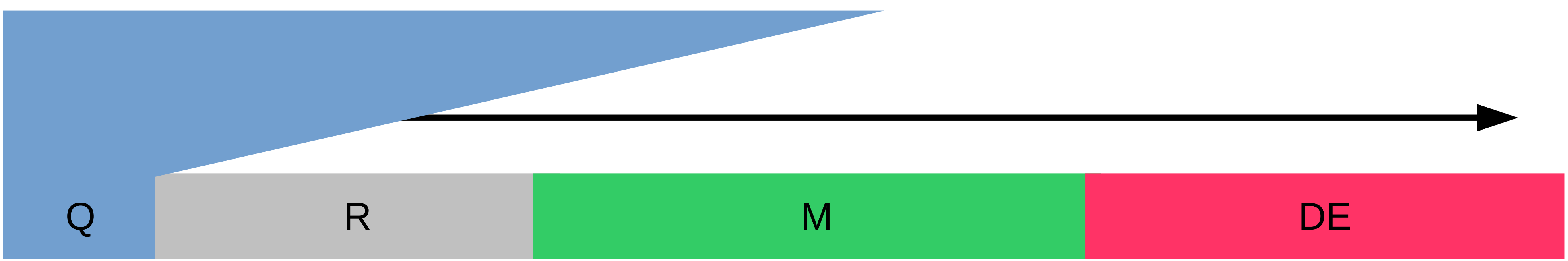


Detour

Examples







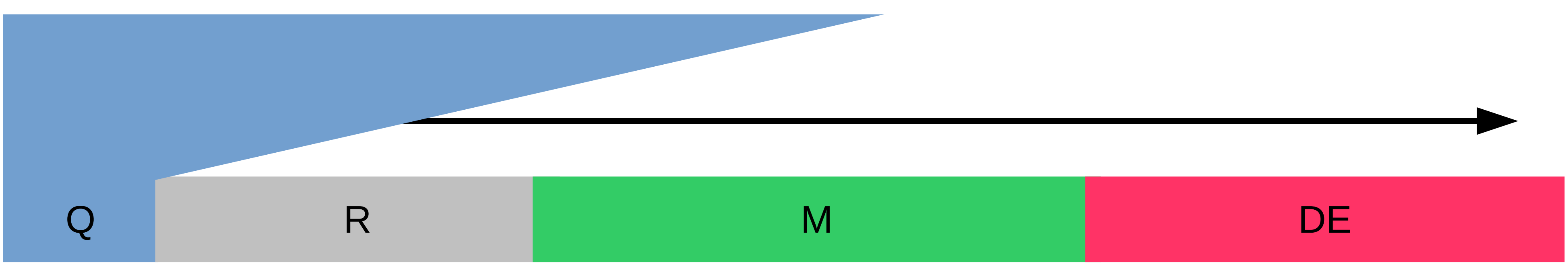
Detour

Real space $\xleftrightarrow{e^{ik\cdot x}}$ Fourier space

$$\xi^{(2)}(r) = \langle \delta(r)\delta(r') \rangle$$

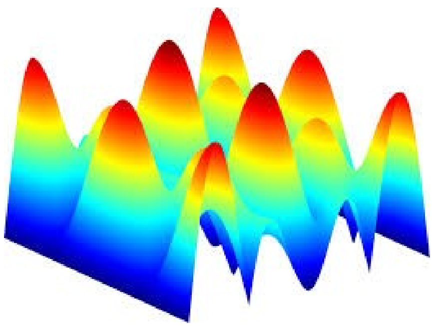
$$\langle \delta(k)\delta(k') \rangle = \delta(k-k')P(k)$$

Power Spectrum



The story of “pertuby”

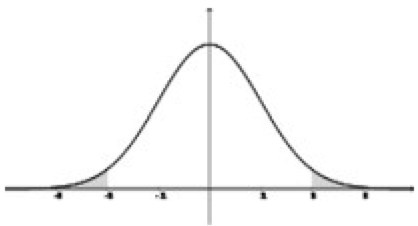
Rerturning to inflation, we're left with a distribution

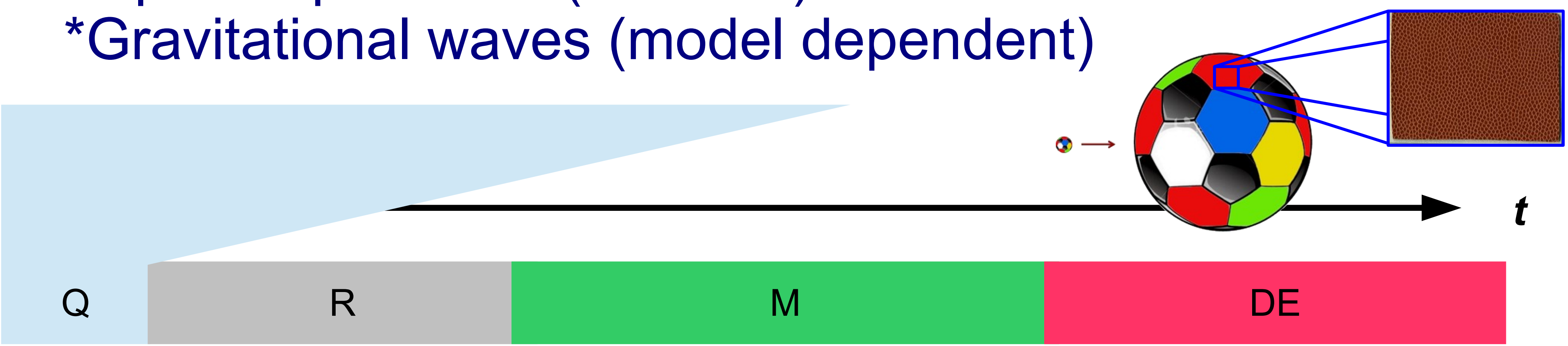


$\xi \sim \Big\langle$   $\Big\rangle$

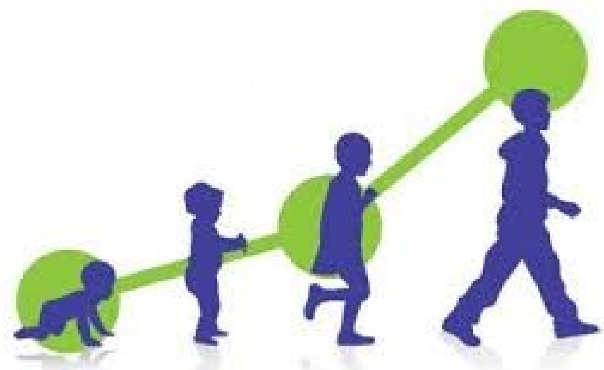
$$P(k)\delta(k-k') \sim <\hat{\delta}(k)\hat{\delta}(k')>$$

*Almost scale invariant
*Very Gaussian (2pt correlations are enough)
*Input amplitude of (0.00001).
*Gravitational waves (model dependent)

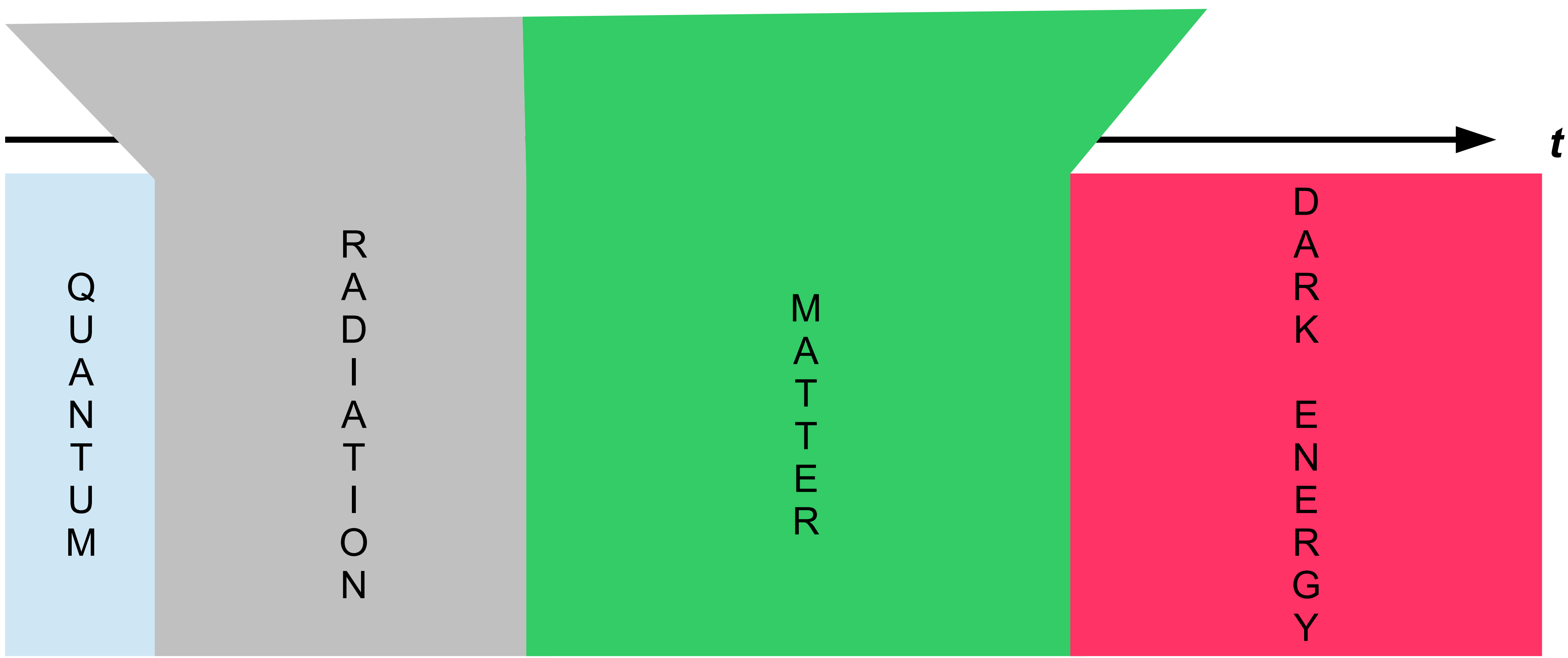




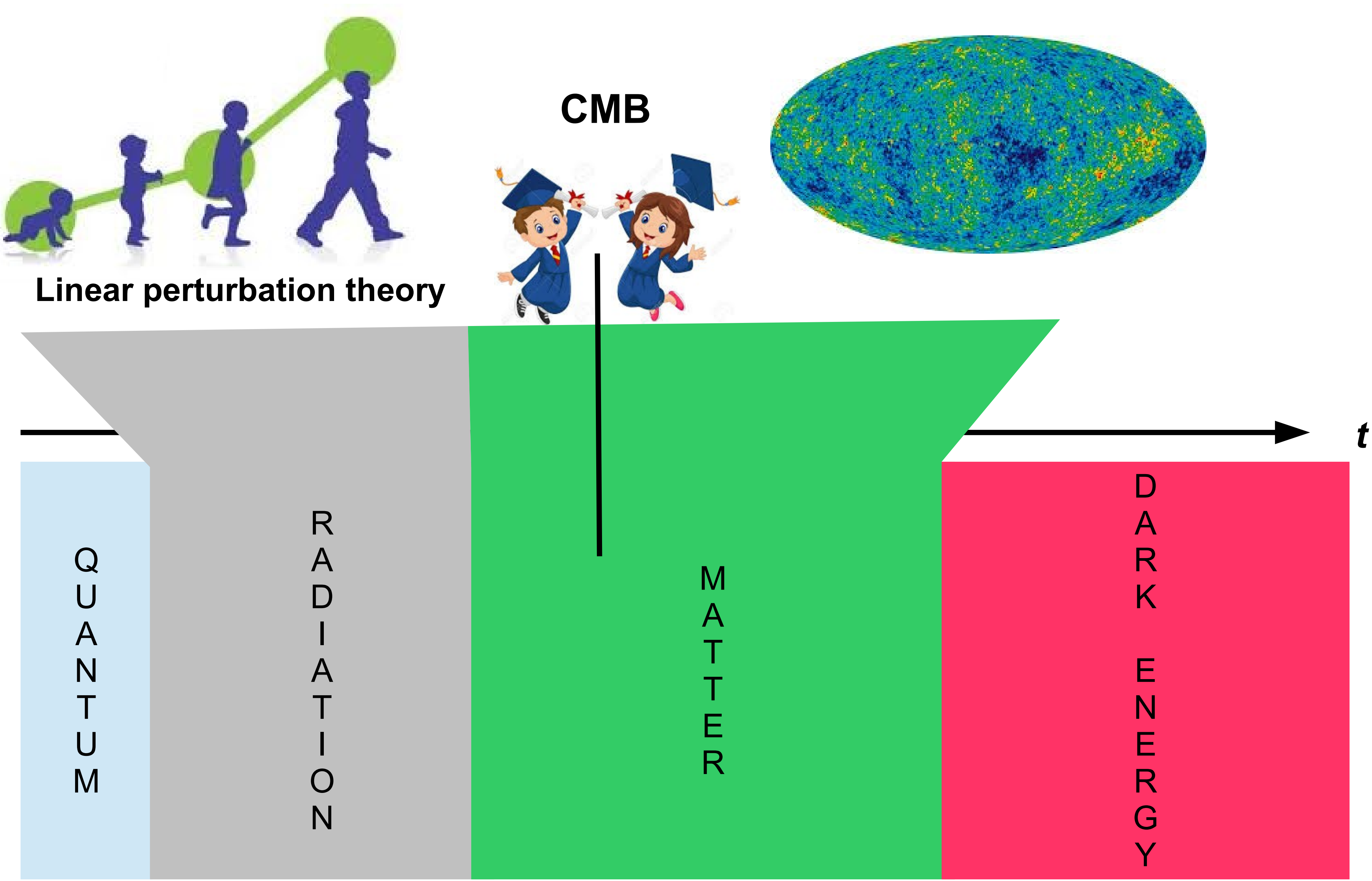
The story of “pertuby”



Linear perturbation theory

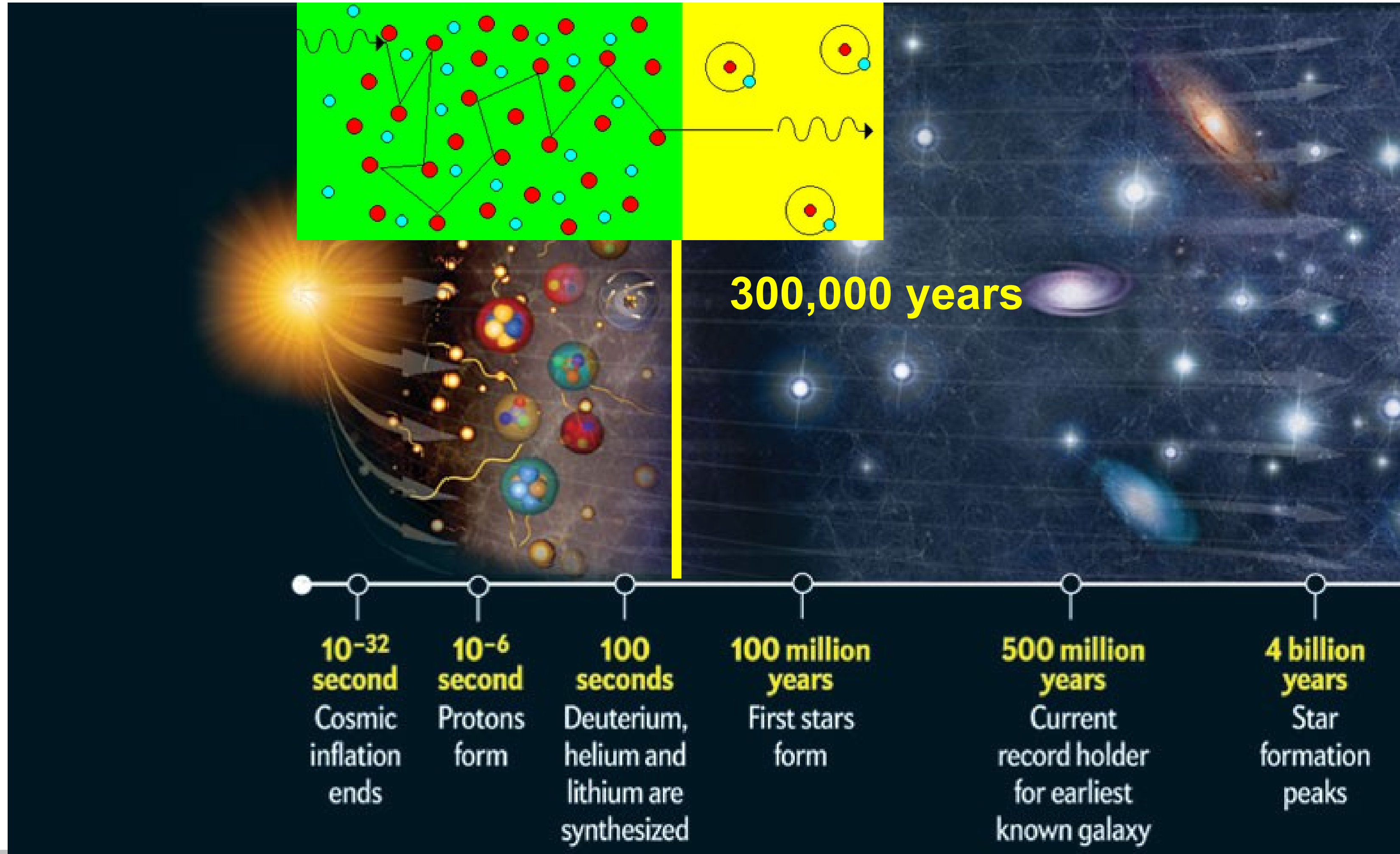


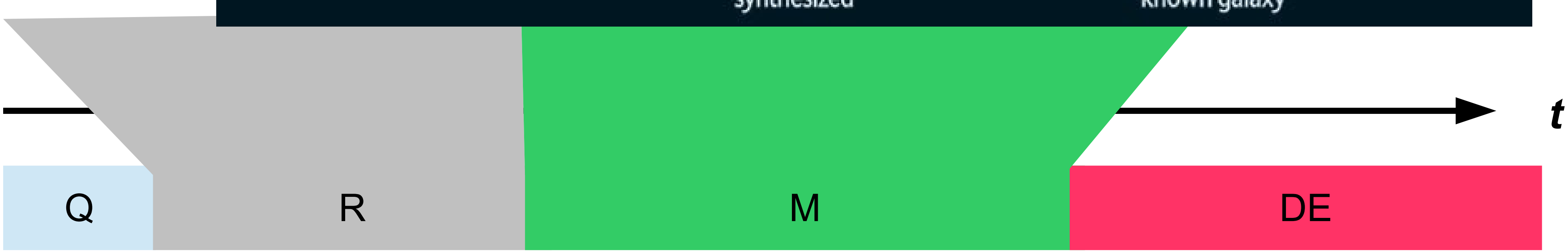
The story of “pertuby”



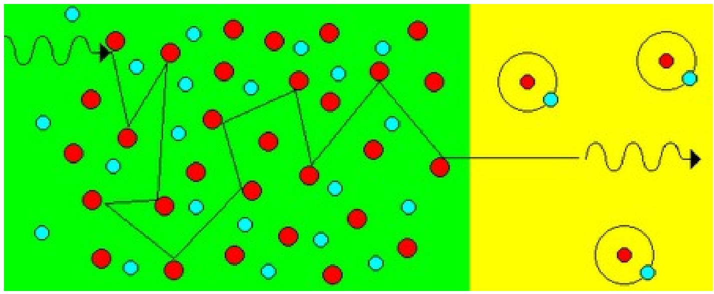
The story of "pertuby"

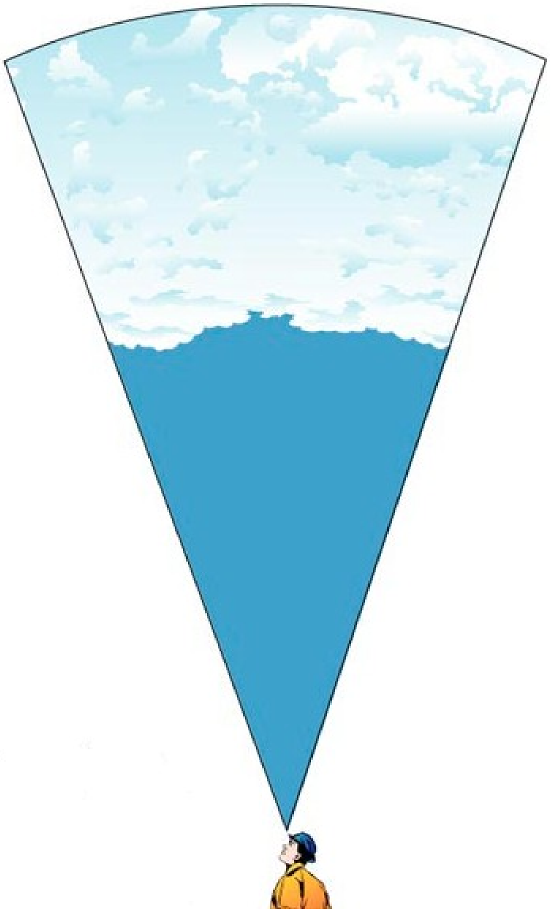
CMB



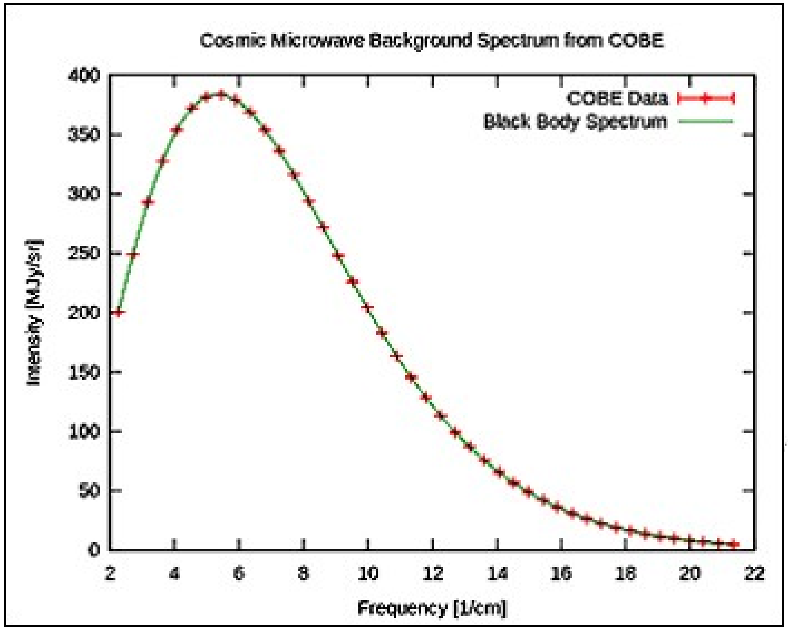


The story of “pertuby”





CMB
(First observable)

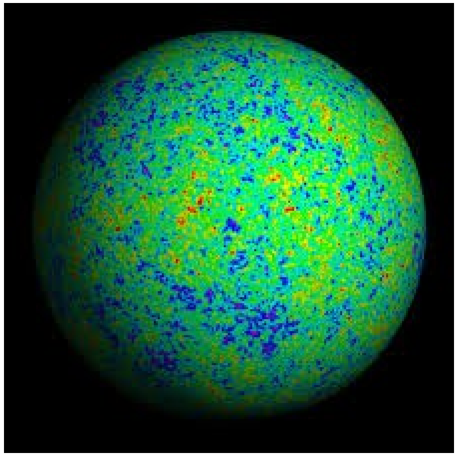


The story of "pertuby"

CMB Anisotropies

Natural to use spherical harmonics

$$\frac{\Delta T}{\bar{T}} = \sum_{lm} T_{lm} Y_{lm}$$

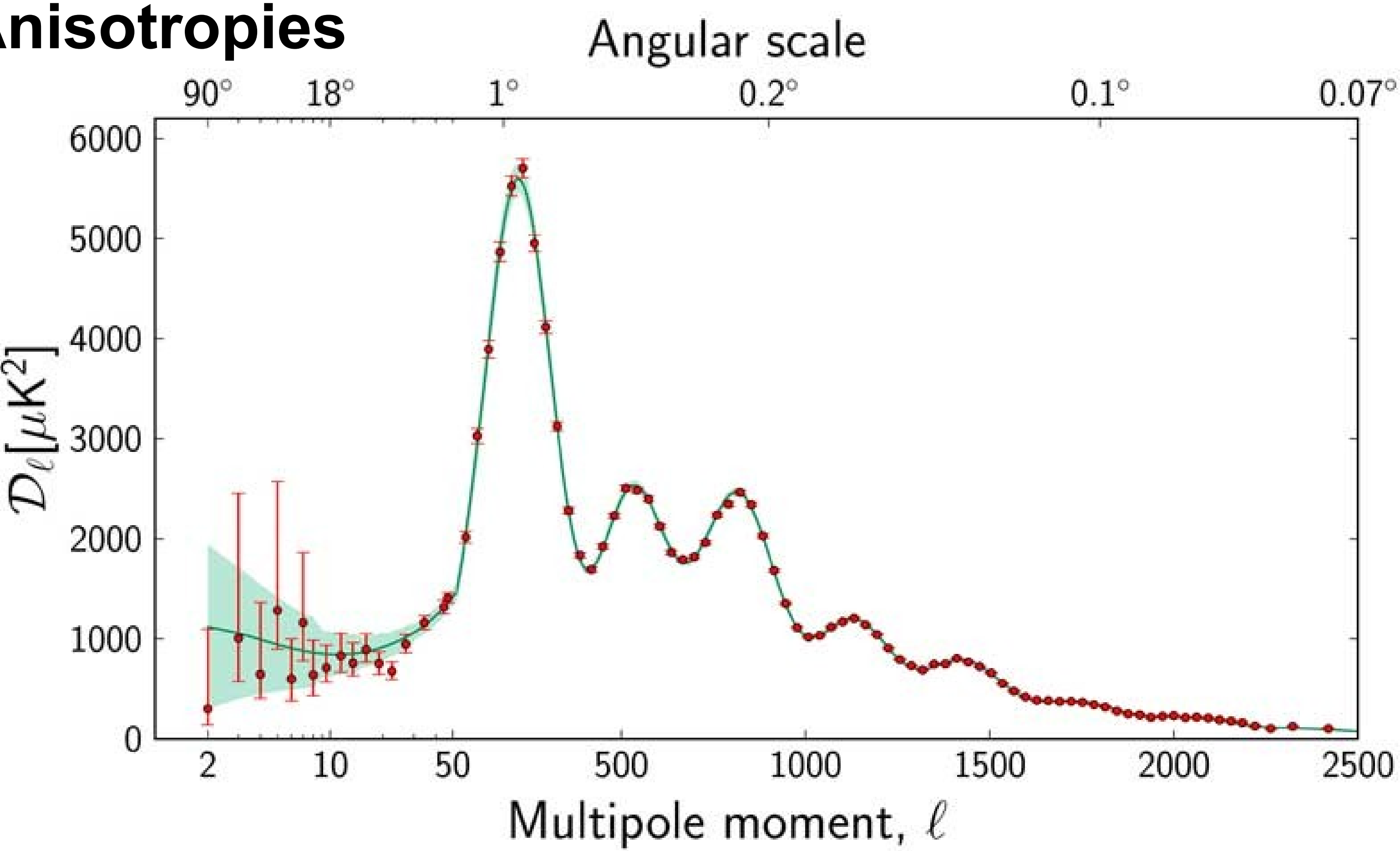


Power spectrum

$$< T_{lm} T_{l'm'} > = 2\pi \mathcal{D}_l \ \delta_{ll'} \delta_{mm'}$$

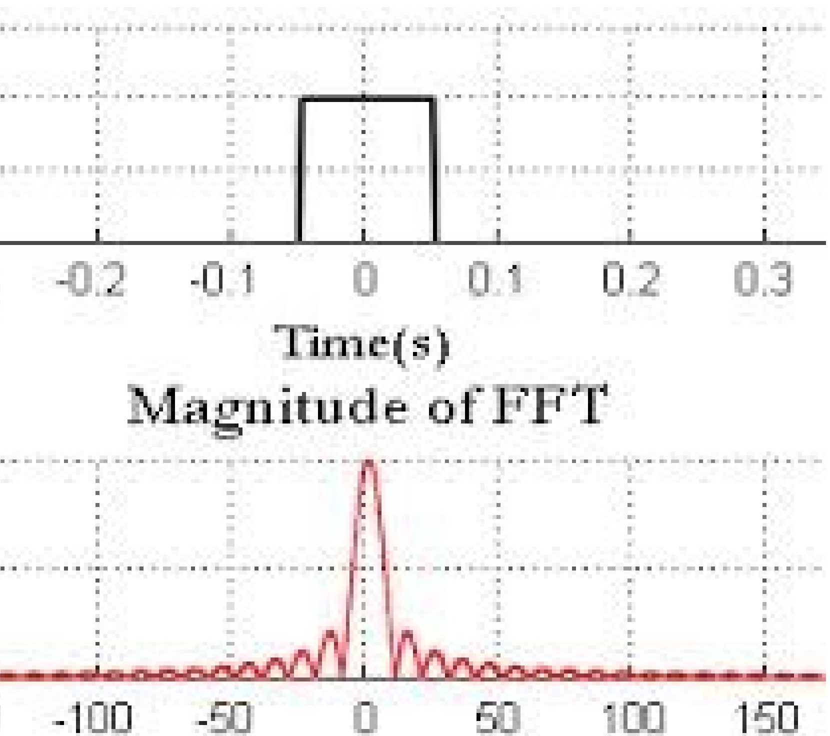
The story of “pertuby”

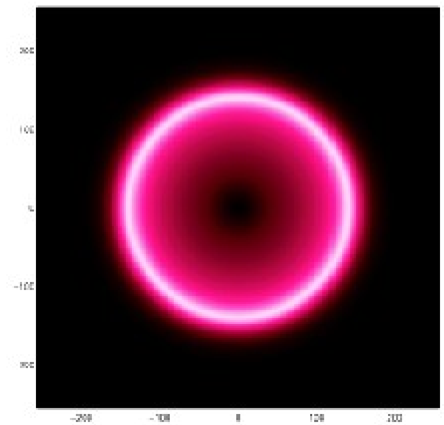
CMB Anisotropies



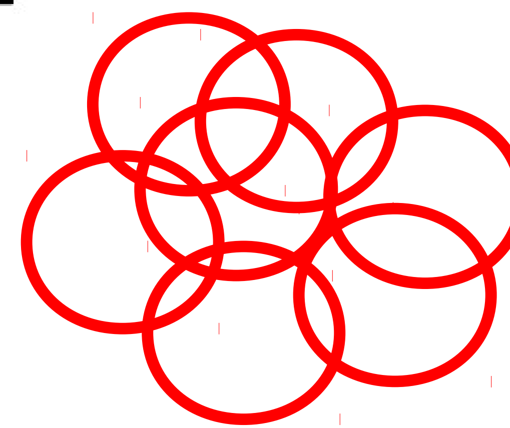
The story of “pertuby”

CMB Oscilations

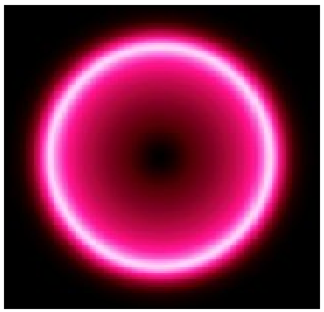


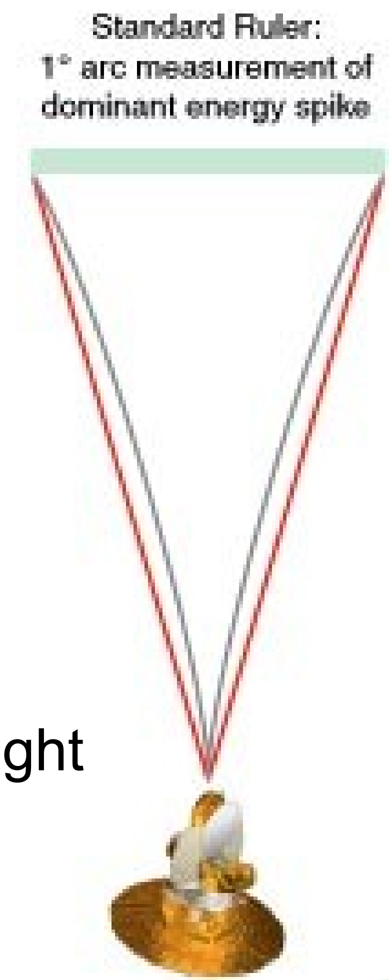


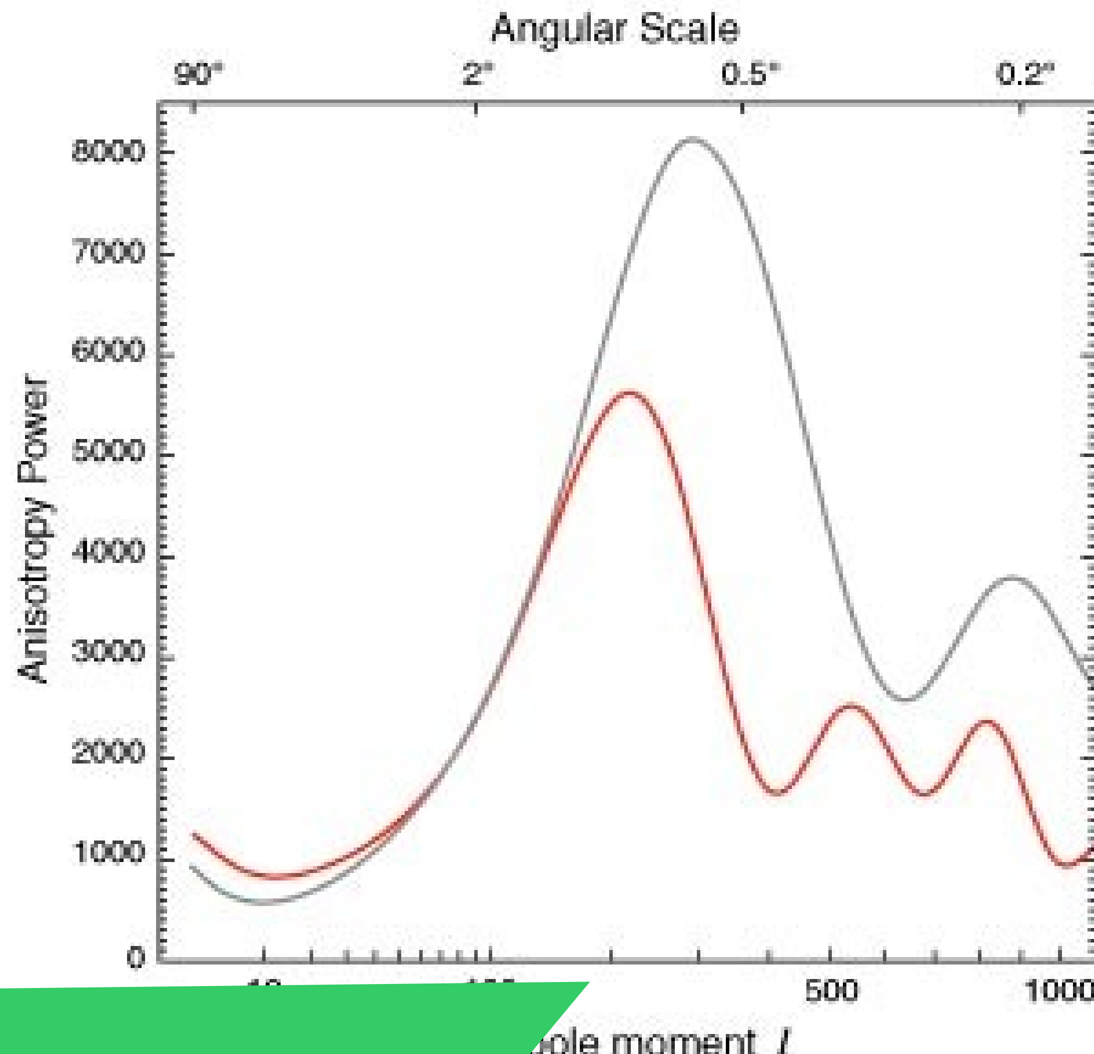
Remnant of photon's pressure



The story of “pertuby”

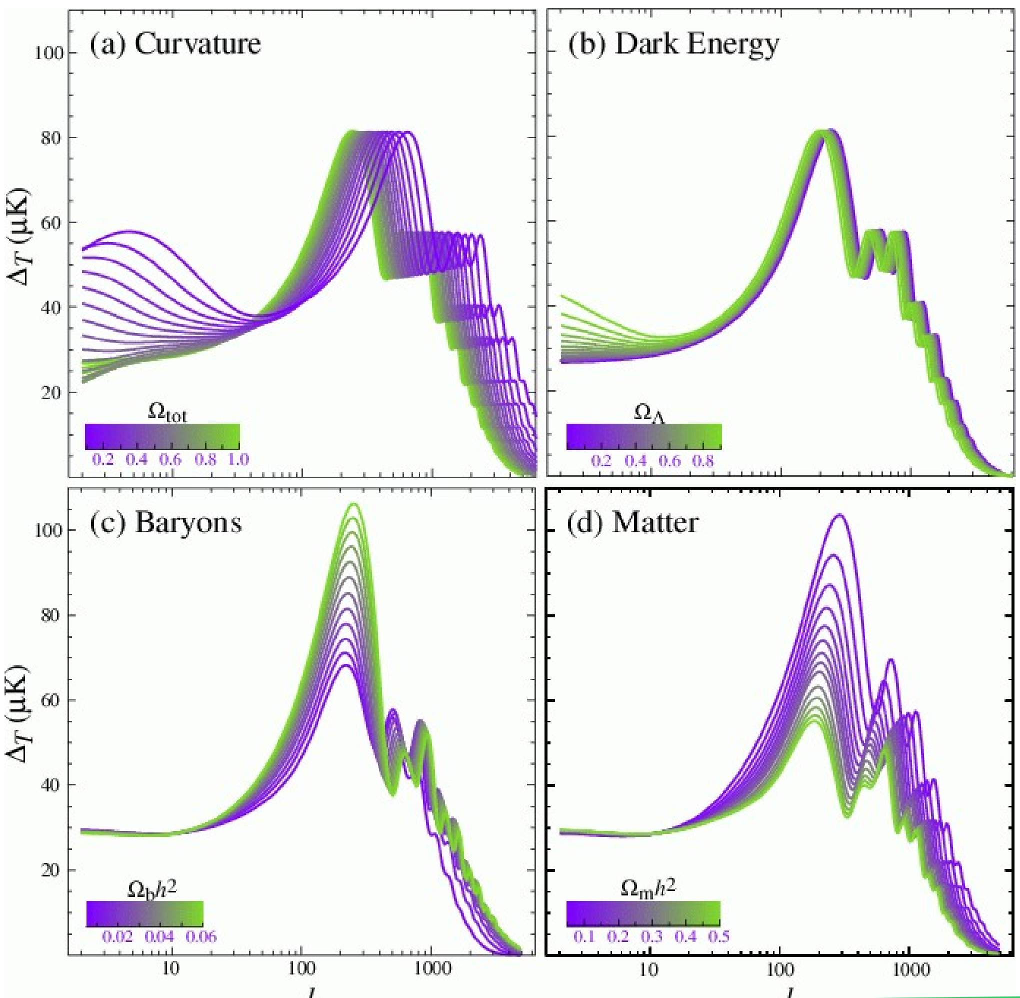






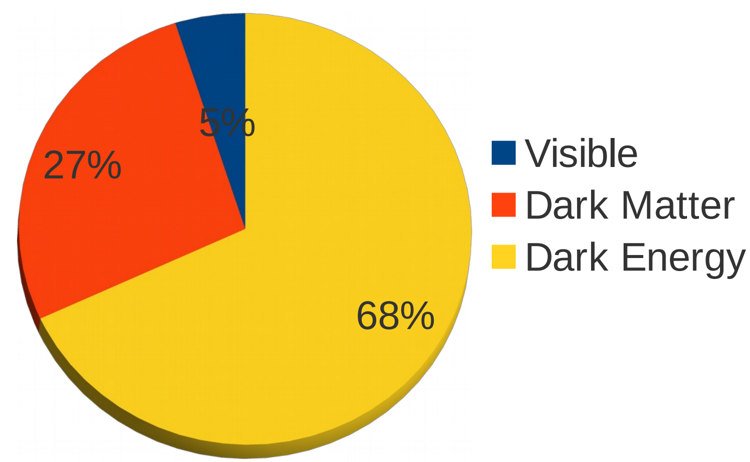
Planck
To 0.1% the flat
Universe model is right

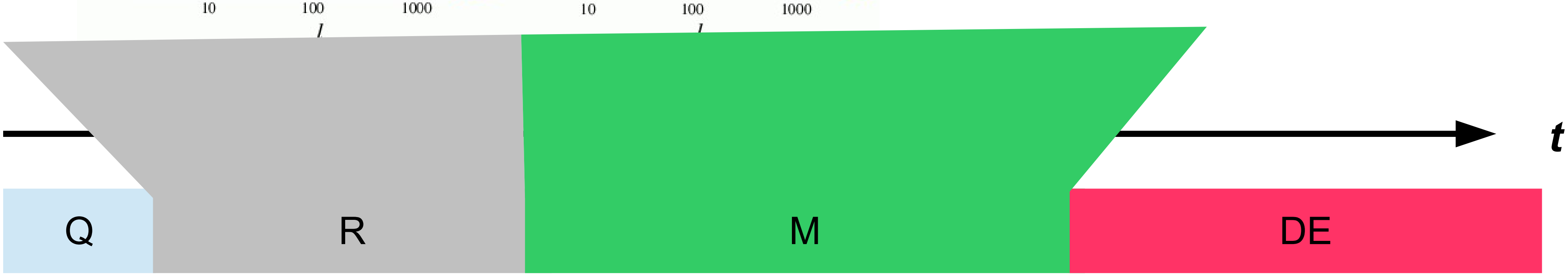
The story of "pertuby"



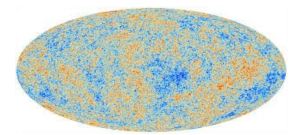
Planck satellite

Flat Universe to 0.1%





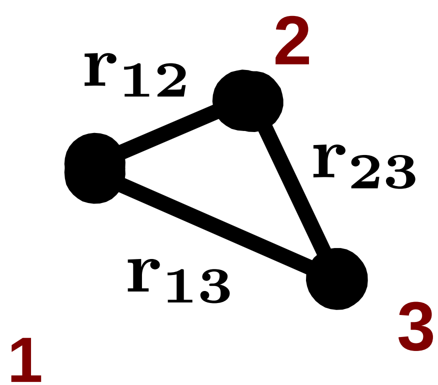
The story of “pertuby”

Is there more information in  ?

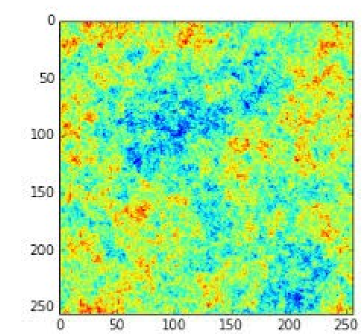
Higher N-point correlation functions

- N=3 (3pcf)

$$dP = \bar{n}^2(1+\xi^{(3)}(\mathbf{r_{12}},\mathbf{r_{13}},\mathbf{r_{23}}))dV_1dV_2dV_3$$



Excess correlation
over the random triples



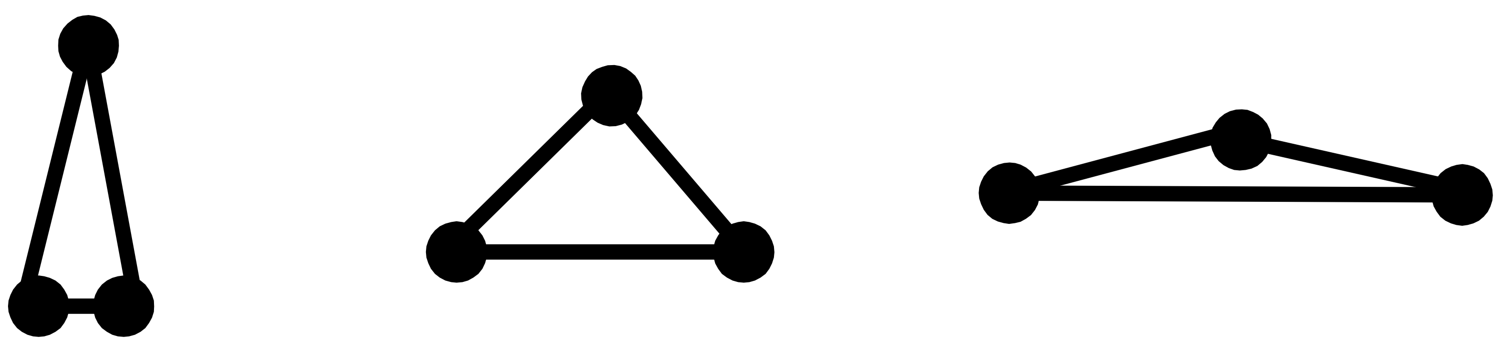
The story of "pertuby"

- Isotropy

$$\xi^{(3)}(\mathbf{r_1}, \mathbf{r_2}, \mathbf{r_3}) = \xi^{(3)}(r_1, r_2, r_3)$$

  - 3 parameter function → 4d plot!

Options A) Consider particular shapes

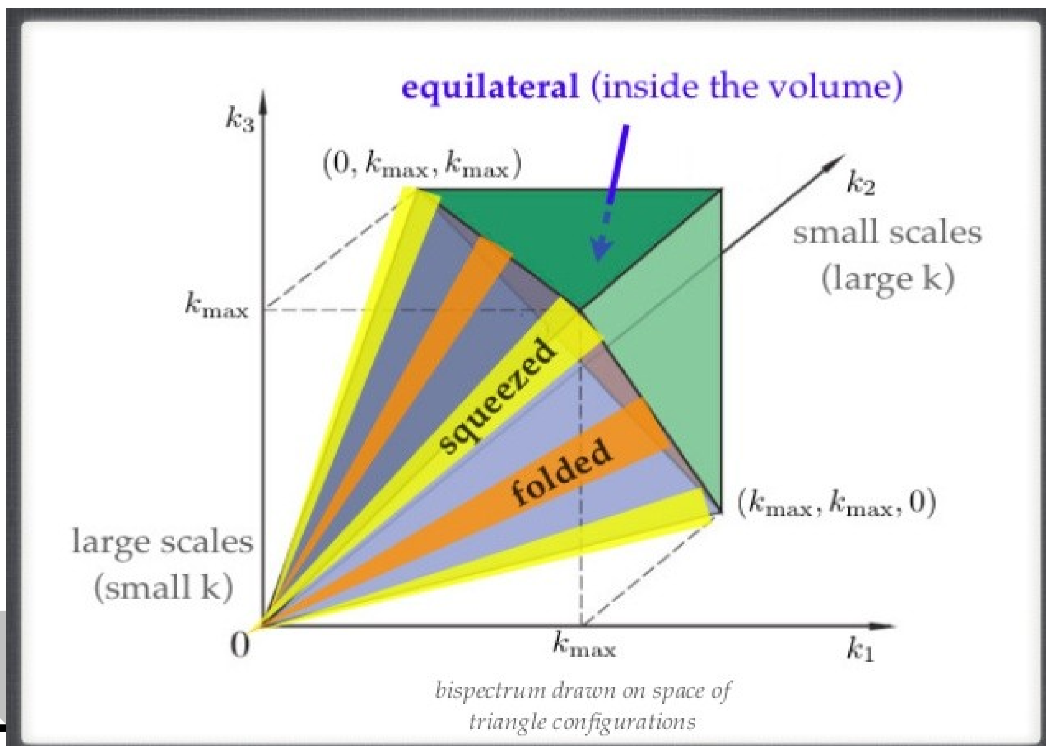


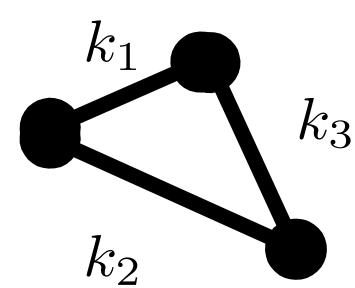
The story of “pertuby”

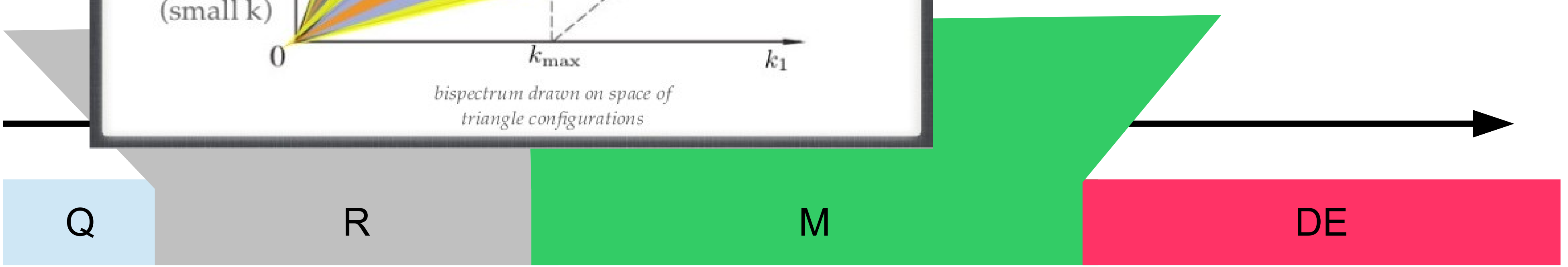
Real space $\xi^{(3)} = \langle \delta\delta\delta \rangle$

Fourier $\langle \delta(k_1)\delta(k_2)\delta(k_3) \rangle = \delta(\sum_i k_i) B(k_1, k_2, k_3)$

Bi-spectrum



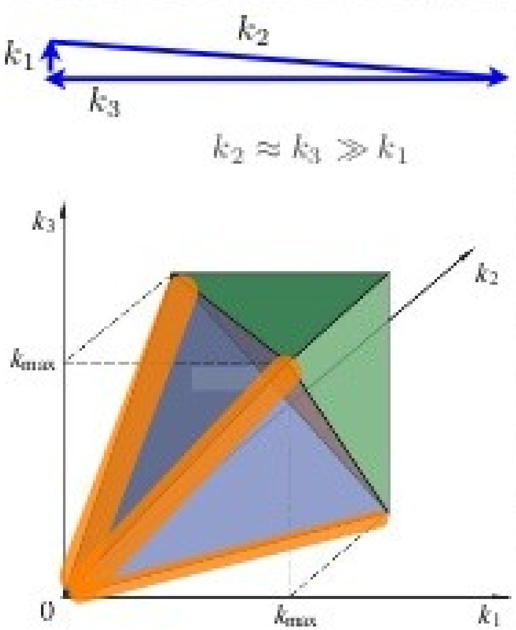




BISPECTRUM SHAPES

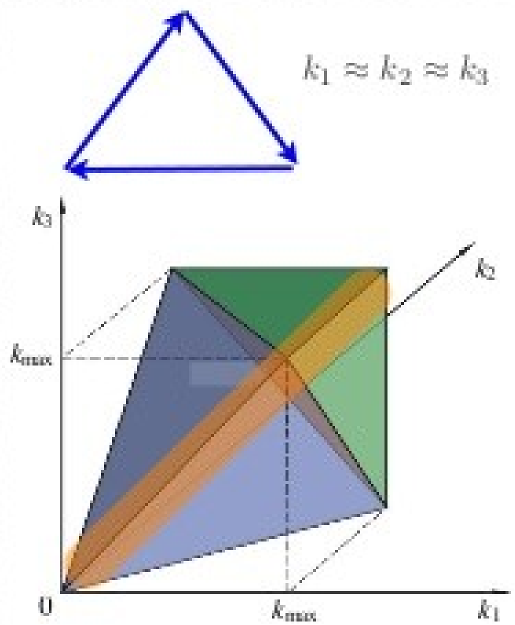
Different inflation models induce different momentum dependencies (shapes) of $B_\Phi(k_1, k_2, k_3)$

Squeezed triangles (local shape)



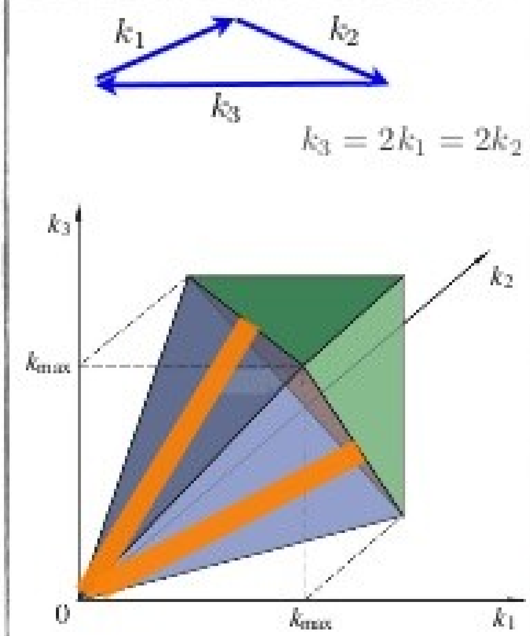
Arises in multifield inflation; detection would rule out all single field models!

Equilateral triangles



Typically higher derivative kinetic terms, e.g. DBI inflation

Folded triangles



E.g. non-Bunch-Davies vacuum

t

Q	R	M	DE

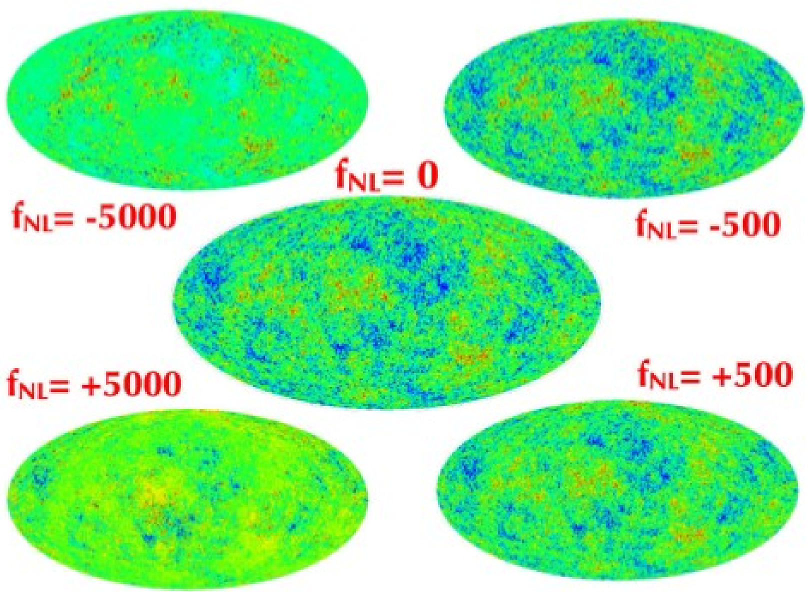
The story of “pertuby”

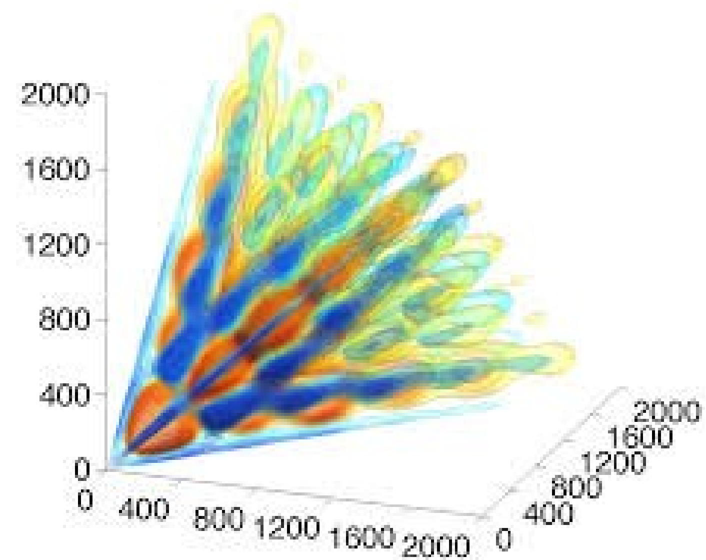
$$\phi = \phi_G + \phi_{NG}$$

Inflaton | Guassian Part | Non-Gaussian Part

Simplest case: non-local NG

$$\phi = \phi_G + f_{NL}(\phi_G^2 - \langle\phi_G\rangle^2)$$





The story of "pertuby"

CMB

- Consistent with EFT of inflation (Gaussian & almost scale invariant distribution)
- Not much about interactions

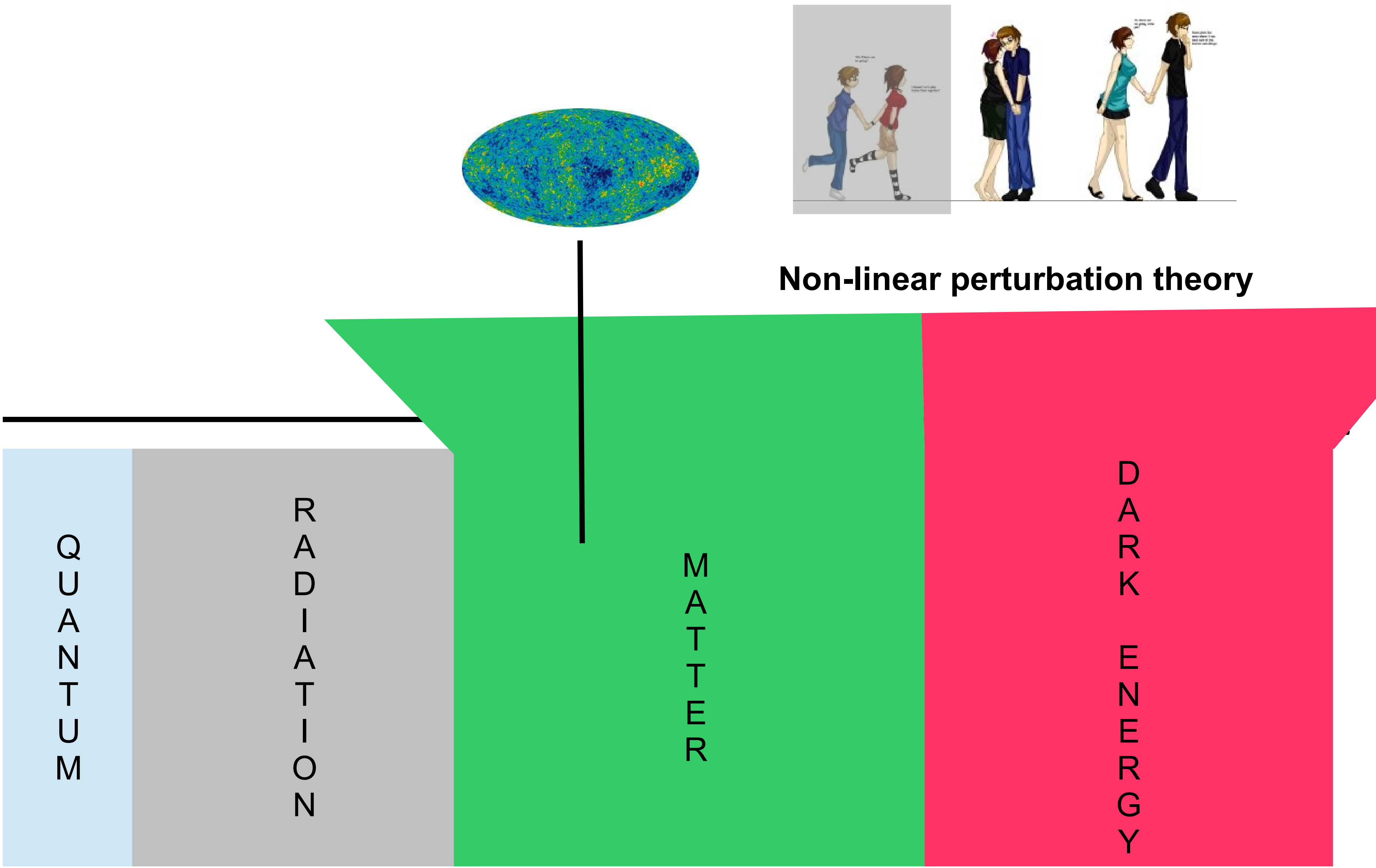
$$< \delta^n >$$

consistent with zero for *n*>2

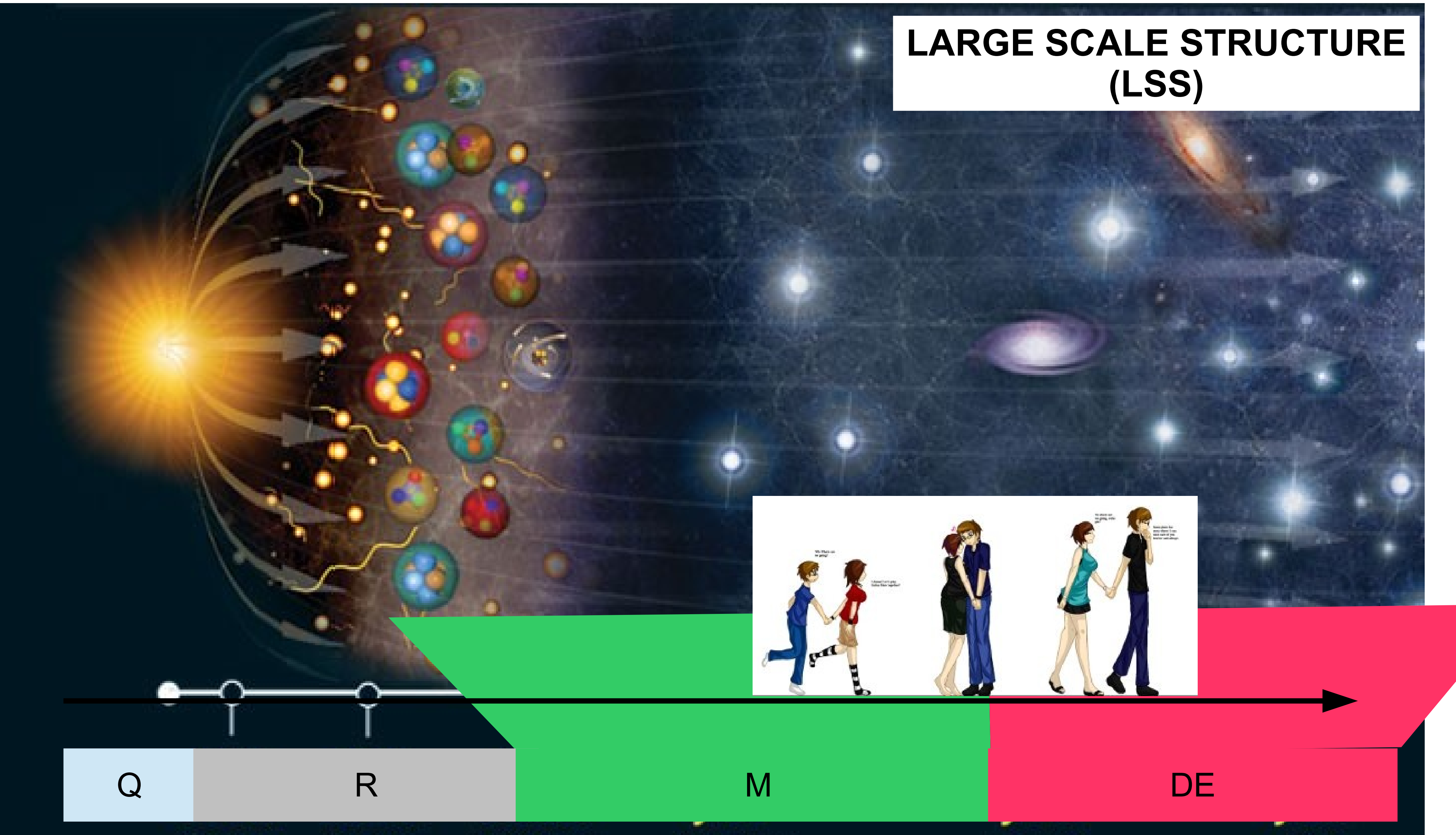
- Cannot gain more mode statistics to achieve better accuracy than with Planck

Future: explore the LSS

The story of “pertuby”

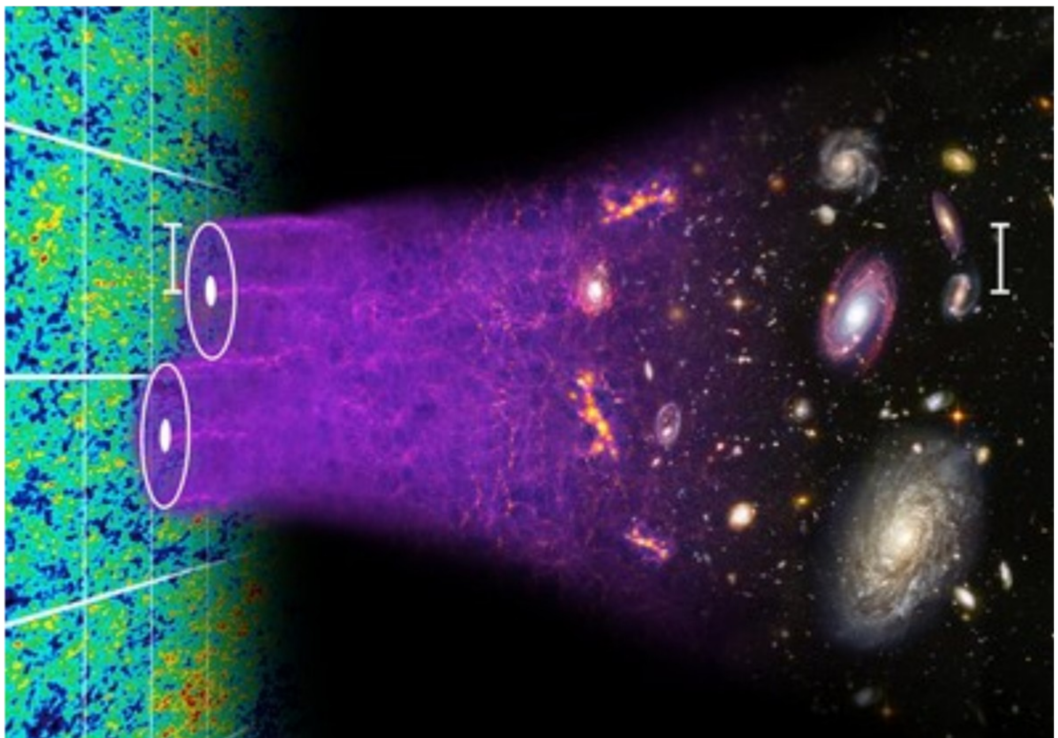


The story of "pertuby"

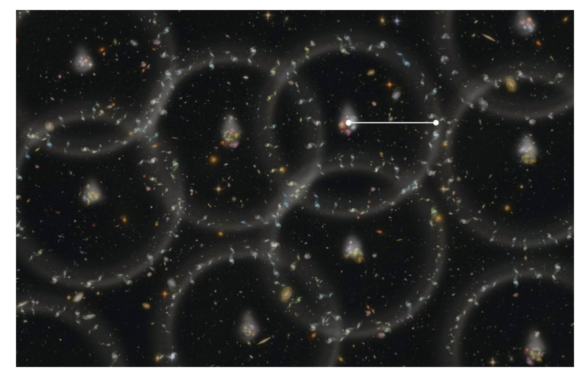


The story of “pertuby”

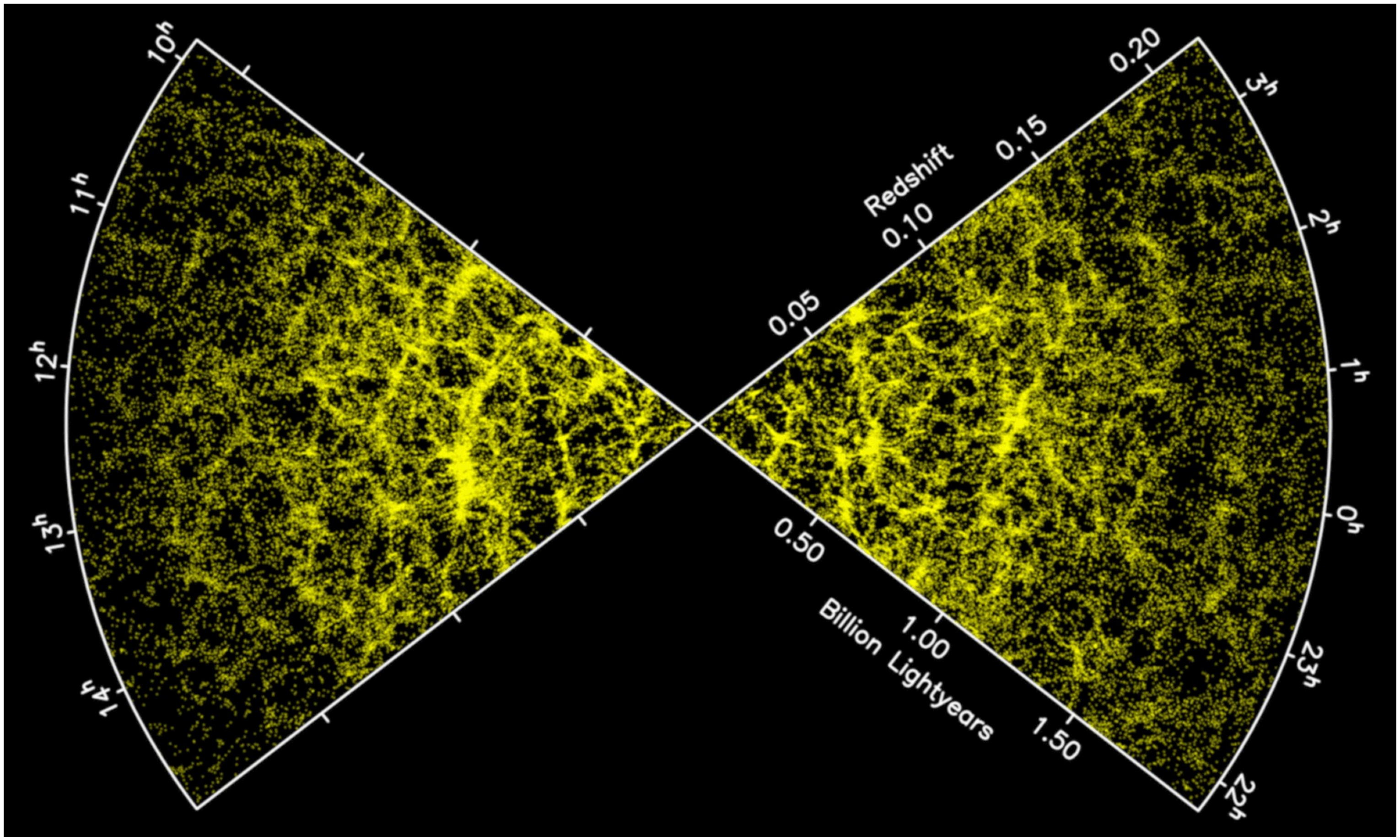
CMB seeds the structure at large scales

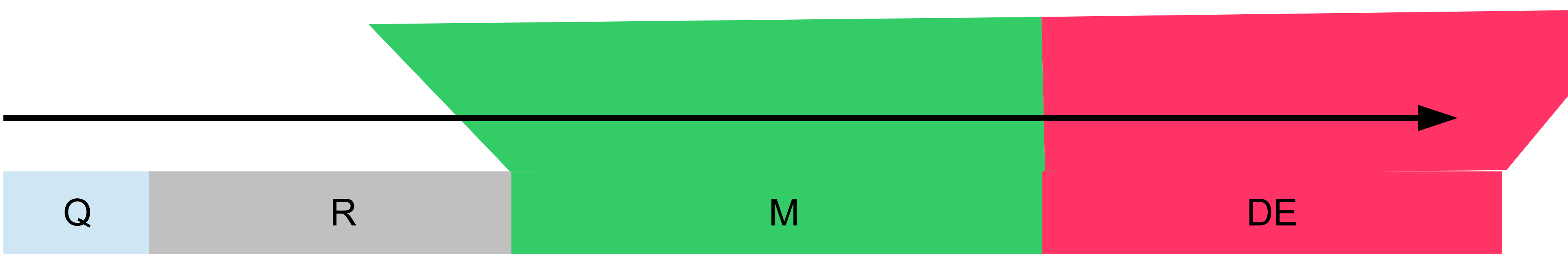


Baryonic
Acoustic
Oscillations



The story of "pertuby"



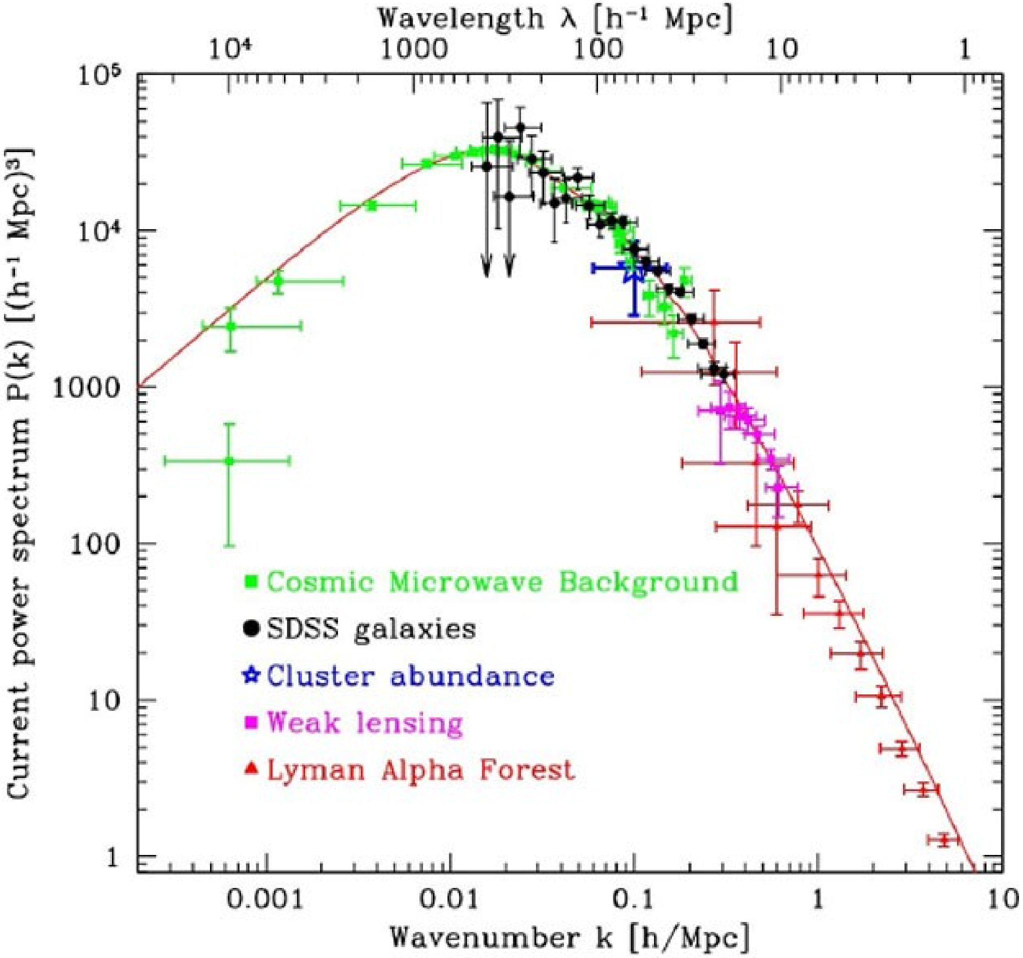


The story of “pertuby”

Benefits

1) Volume Vs area (CMB)
   *More Resolution!!!

2) Non-linear physics
   *More difficult
   *Richness



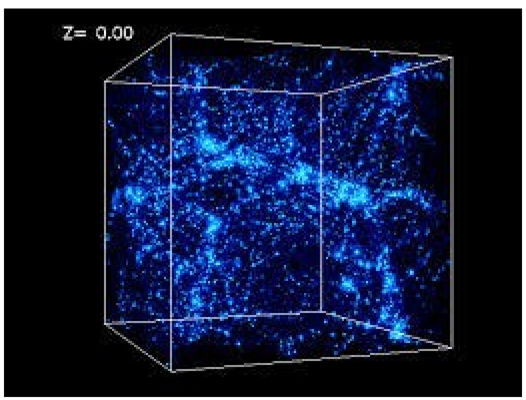
The story of “pertuby”

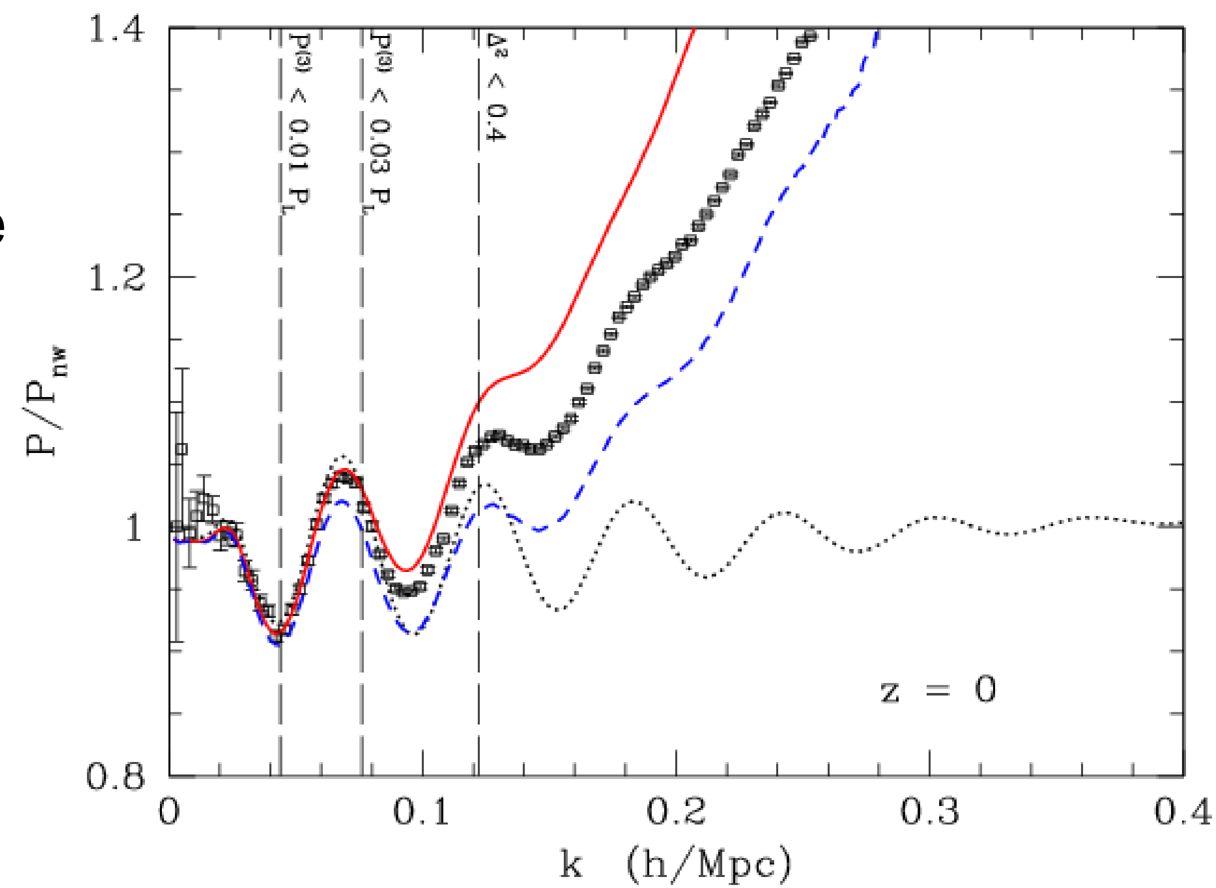
Perturbation theory

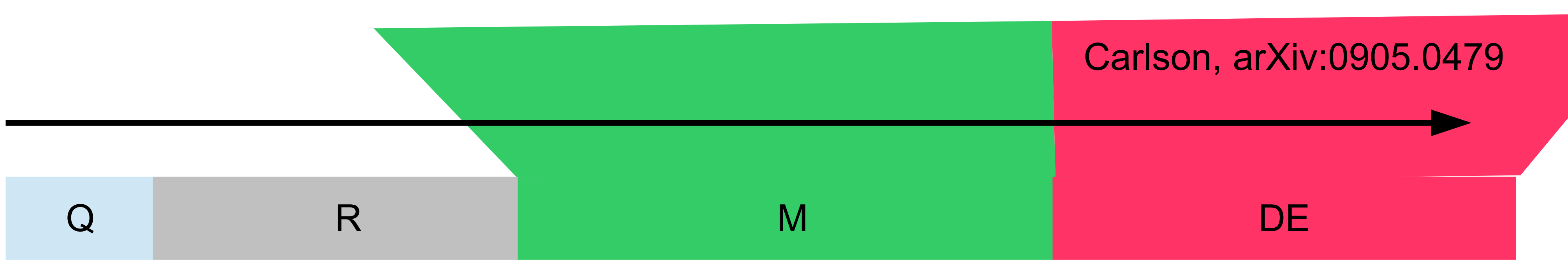
1) Series does not converge

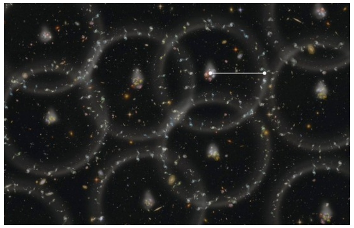
2) Active area of research

3) Tool



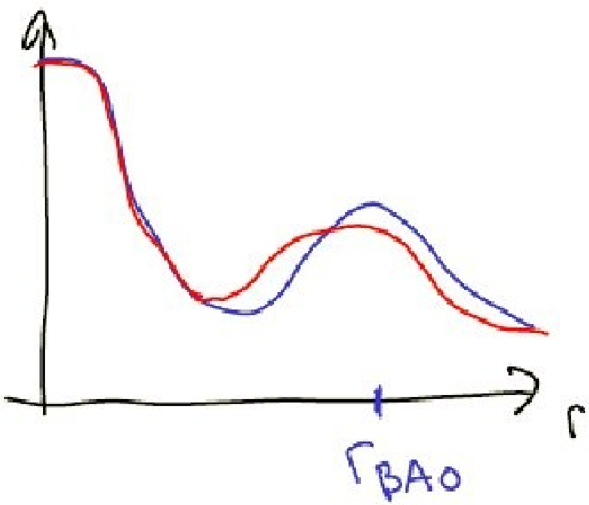


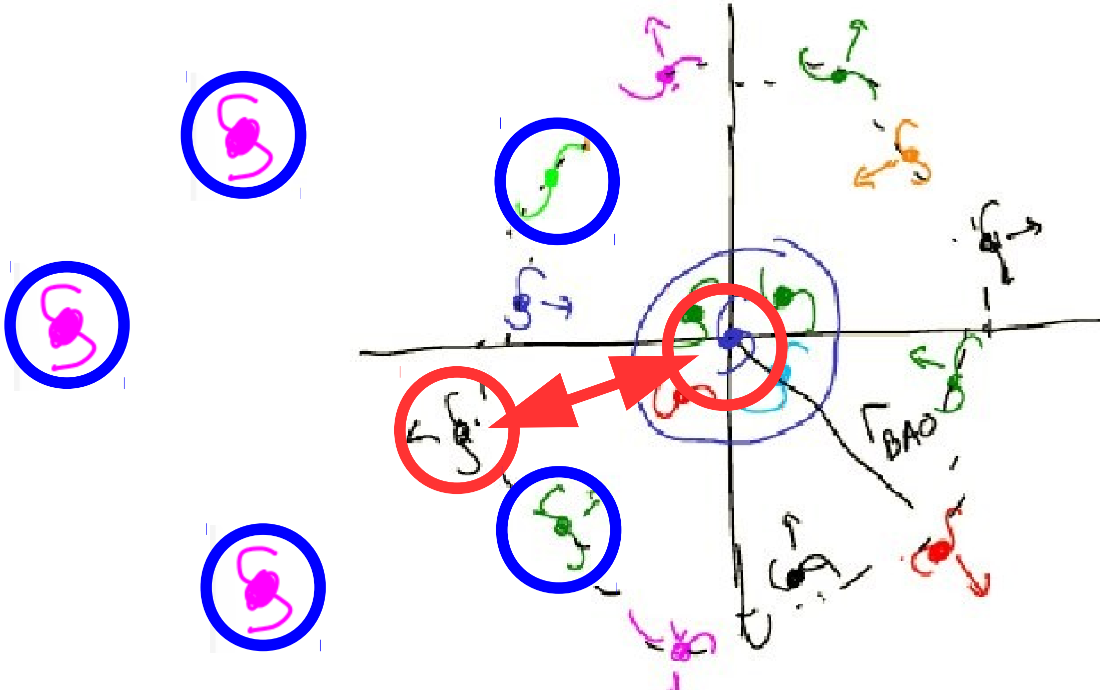


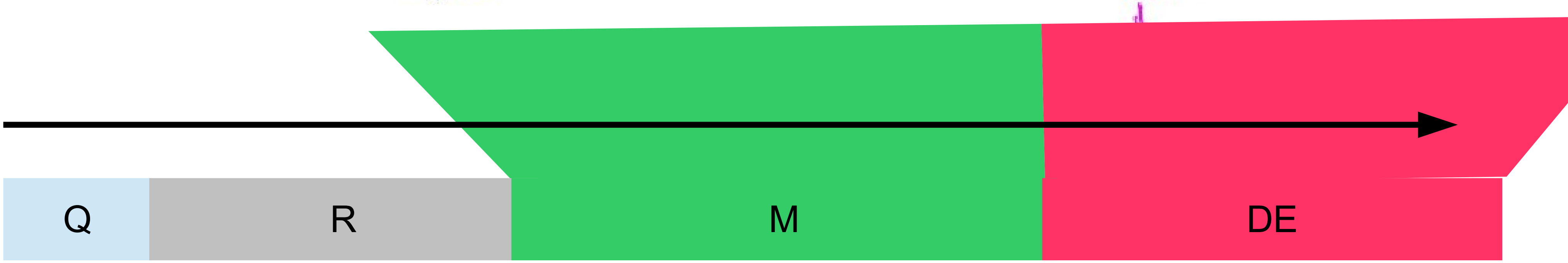


BAO signal in LSS

- 2PCF ➡ Non-linear mode evolution
  - It does contain the 3PCF, but *averaged*

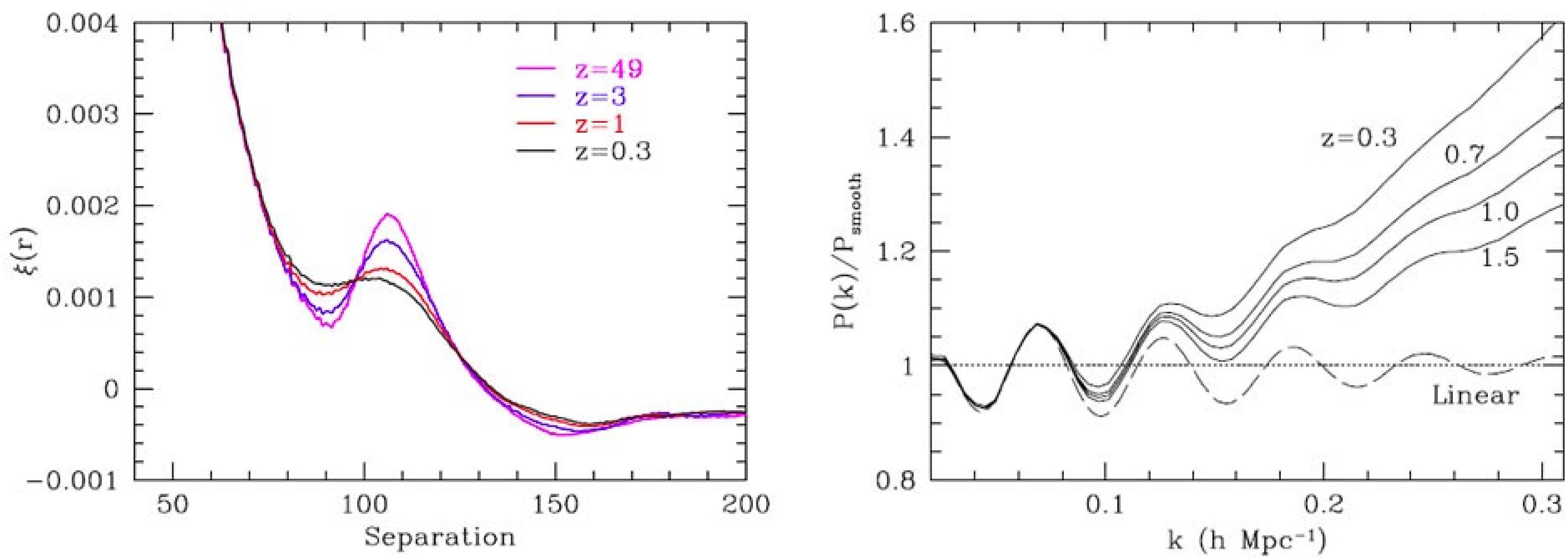


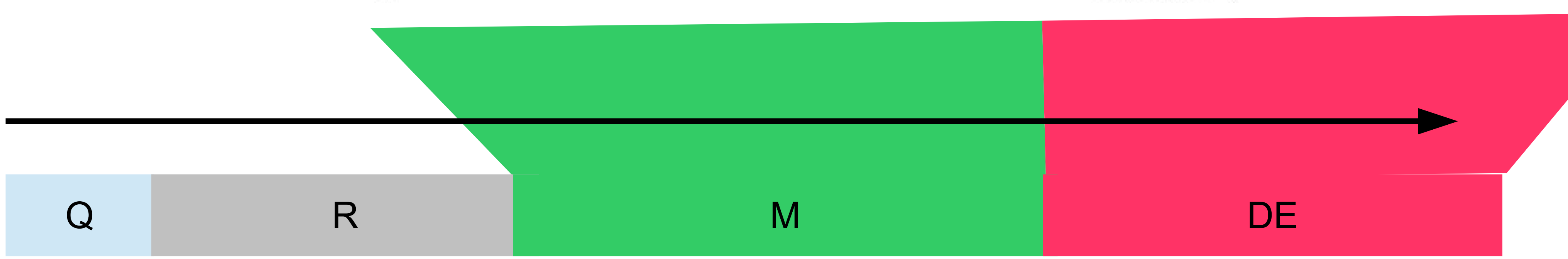




BAO signal in LSS

- 2PCF → Non-linear mode evolution





Equations (Eulerian)

Continuity

$$\dot{\delta} + \nabla \cdot [(1+\delta) v] = 0,$$

Euler

$$\dot{v} + (v \cdot \nabla) v = -\mathcal{H} v - \nabla \phi,$$

Poisson

$$\nabla^2 \phi = 4\pi G a^2 \bar{\rho} \delta,$$

(Conformal time and comoving coordinates)

Equations (Eulerian)

In Fourier space

$$\boxed{\frac{\partial \delta_{\boldsymbol{k}}}{\partial \tau}(\tau) + \theta_{\boldsymbol{k}}(\tau)} = -\int \frac{d^3 k_1}{(2\pi)^3} \int d^3 k_2 \delta^D(\boldsymbol{k}_1 + \boldsymbol{k}_2 - \boldsymbol{k}) \frac{\boldsymbol{k}\cdot\boldsymbol{k}_1}{k_1^2} \theta_{\boldsymbol{k}_1}(\tau), \delta_{\boldsymbol{k}_2}(\tau),$$

$$\boxed{\frac{\partial \theta_{\boldsymbol{k}}}{\partial \tau}(\tau) + \mathcal{H}(\tau)\theta_{\boldsymbol{k}}(\tau) + \frac{3}{2}\mathcal{H}^2(\tau)\Omega_{\mathrm{m}}(\tau)\delta_{\boldsymbol{k}}(\tau)}$$

$$= -\int \frac{d^3 k_1}{(2\pi)^3} \int d^3 k_2 \delta^D(\boldsymbol{k}_1 + \boldsymbol{k}_2 - \boldsymbol{k}) \frac{k^2(\boldsymbol{k}_1\cdot\boldsymbol{k}_2)}{2k_1^2 k_2^2} \theta_{\boldsymbol{k}_1}(\tau)\theta_{\boldsymbol{k}_2}(\tau),$$

Linear Piece

Non-linear Piece

Equations (Eulerian)

To first order in perts

$$\boxed{\frac{\partial \delta_{\boldsymbol{k}}}{\partial \tau}(\tau) + \theta_{\boldsymbol{k}}(\tau)} = 0$$

$$\boxed{\frac{\partial \theta_{\boldsymbol{k}}}{\partial \tau}(\tau) + \mathcal{H}(\tau)\theta_{\boldsymbol{k}}(\tau) + \frac{3}{2}\mathcal{H}^2(\tau)\Omega_{\mathrm{m}}(\tau)\delta_{\boldsymbol{k}}(\tau)} = 0$$

$\delta_k^{(1)} =$ Decaying mode + Growing mode

Standard Perturbation Theory (SPT)

At higher orders

$$\delta_n(\mathbf{k}) = \int \mathrm{d}^3\mathbf{q}_1 \ldots \int \mathrm{d}^3\mathbf{q}_n \, \delta_D(\mathbf{k} - \mathbf{q}_{1\ldots n}) F_n(\mathbf{q}_1, \ldots, \mathbf{q}_n) \delta_1(\mathbf{q}_1) \ldots \delta_1(\mathbf{q}_n)$$

Obey simple recursion relations for some backgrounds

(Bernardeau et al, Phys.Rept. 367 (2002) 1-248)

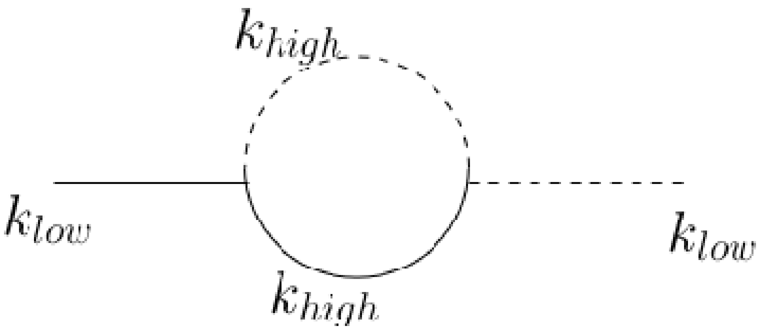
Standard Perturbation Theory (SPT)

FIRST ISSUE (UV)

$$\langle \delta_k^{(2)} \delta_k^{(2)} \rangle \sim \int d^3k' \, \langle \delta_{k-k'}^{(1)} \delta_{k-k'}^{(1)} \rangle \, \langle \delta_{k'}^{(1)} \delta_{k'}^{(1)} \rangle$$

Notice that

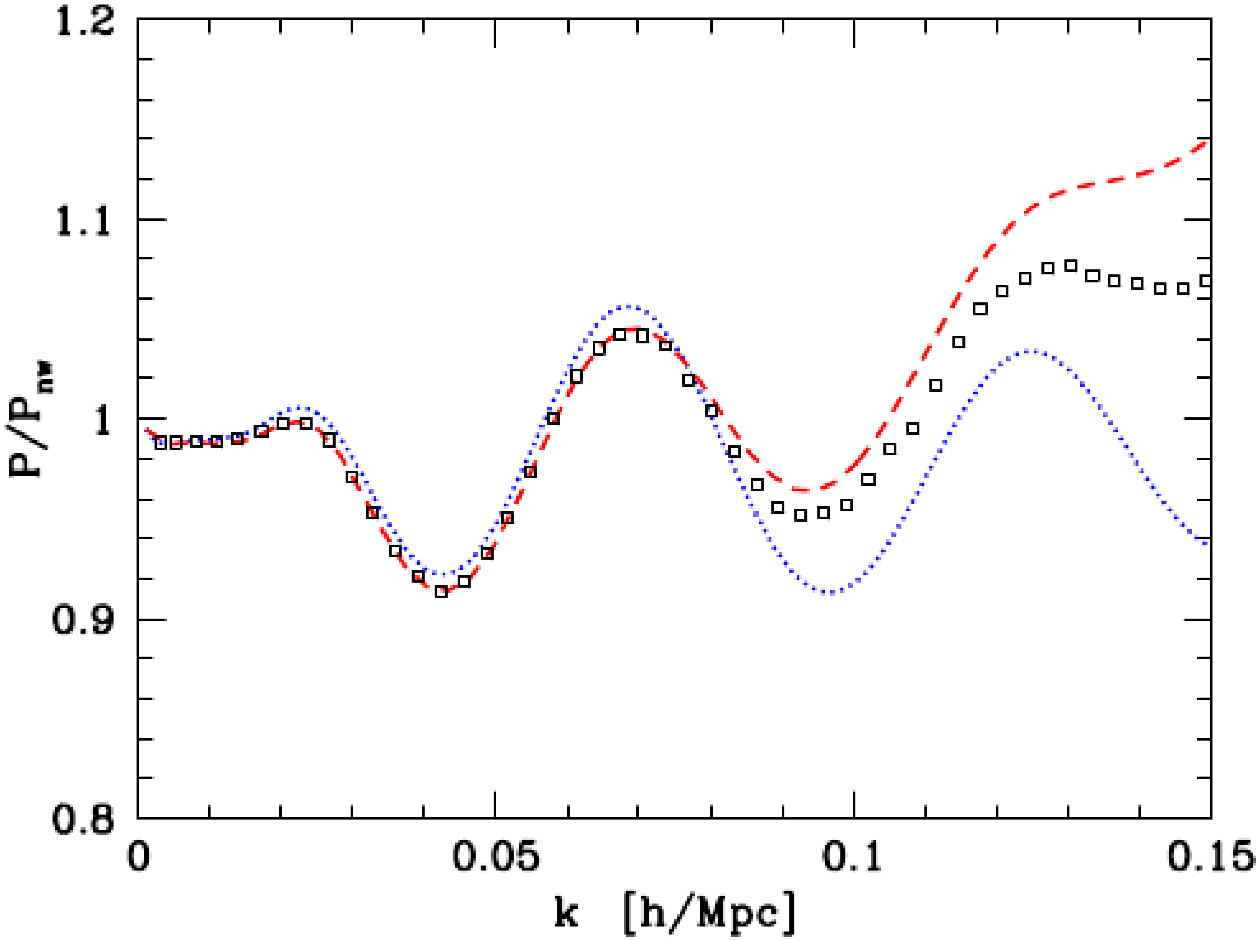
$$\delta \sim \frac{k}{k_{NL}} \gg 1 \quad \text{for} \quad k \gg k_{NL}$$



Perturbation theory breaks down!!!

Standard Perturbation Theory (SPT)

How does it fit our Universe (with BAO)?



M. White, COTB11 Talk

Bright Future

- DESI
- LSST
- DES
- HETDEX
- WFIRST
- EUCLID
- Others.....

Bright Future

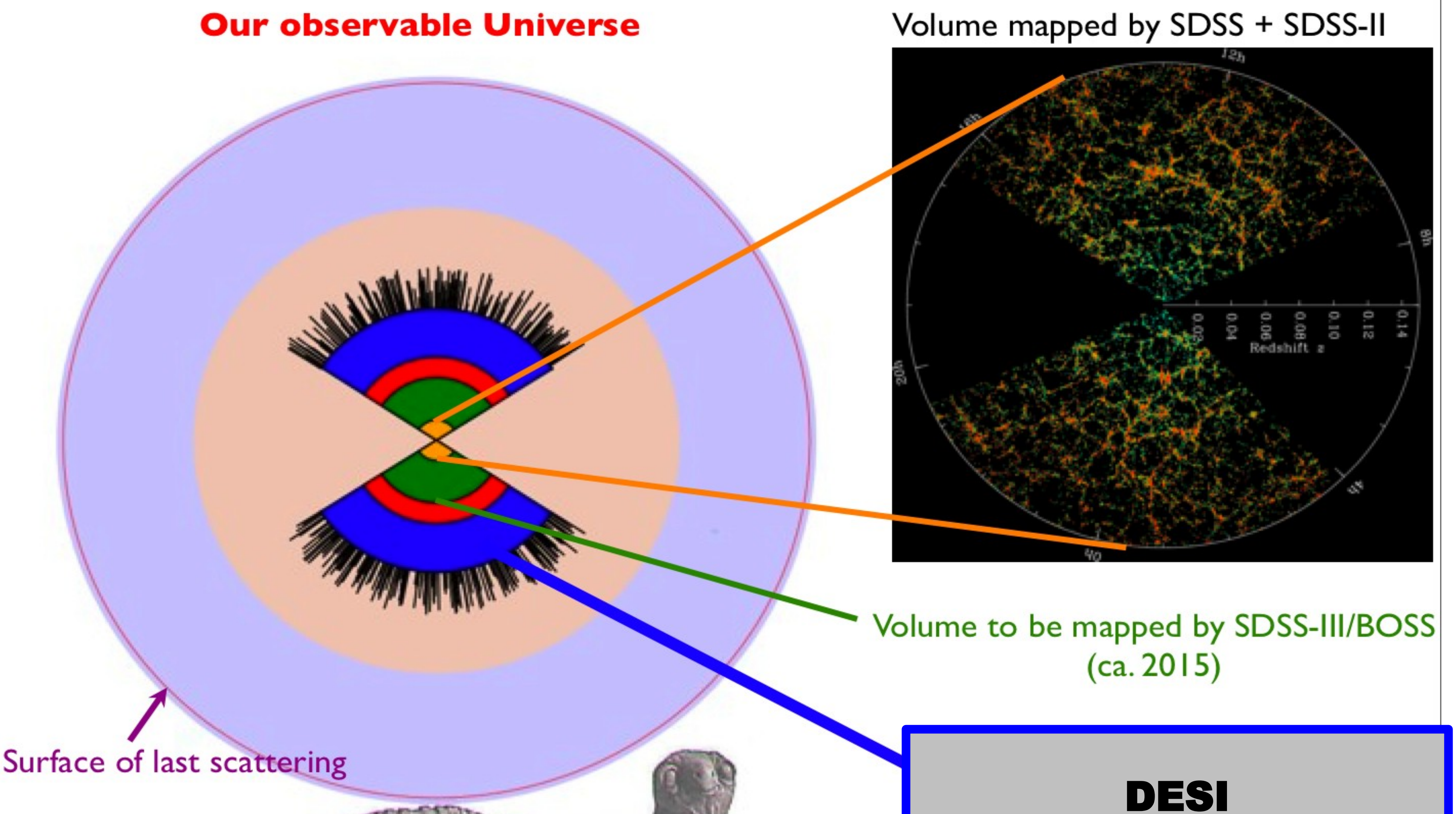
- DESI
- LSST
- DES
- HETDEX
- WFIRST
- EUCLID
- Others.....

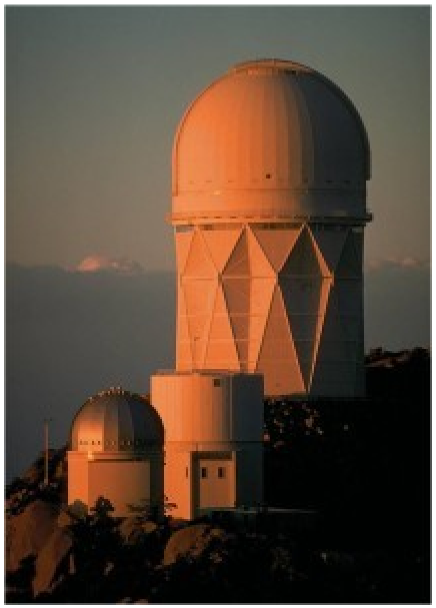
DESI MEXICO

- 10 researchers
  - 4 UNAM (A. de la Macorra & M. Vargas in IF, O. Valenzuela in IA, M. Alcubierre in CN)
  - 3 DCI-UG: Luis Ureña, Gustavo Niz, Alma González
  - 1 Cinvestav (T. Matos)
  - 1 ININ (J. Cervantes, A. Avilés)
- "Proyecto fronteras de la ciencia" CONACYT
- Cosmological simulations
- Data analysis
- LCDM-alternative models

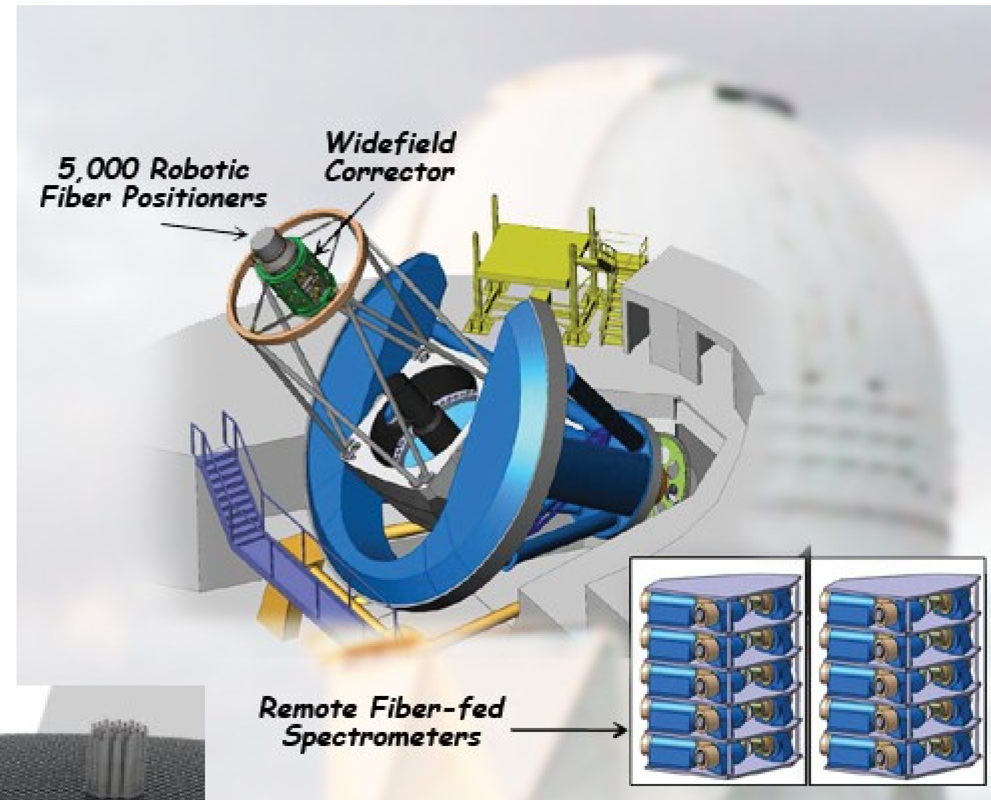
Dark Energy Spectroscopic Instrument

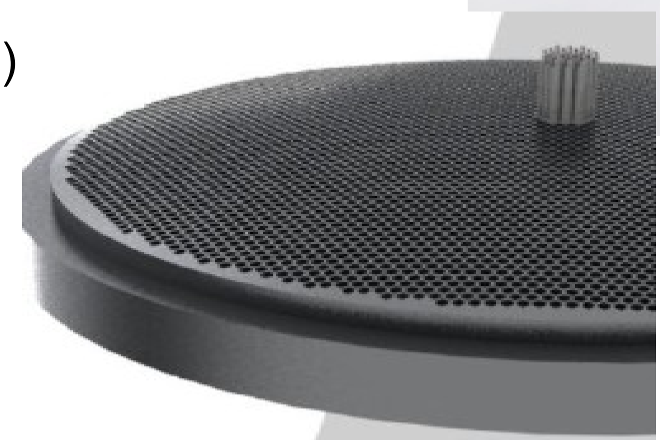
Sensitivity to new physics scales as volume surveys -- # of modes





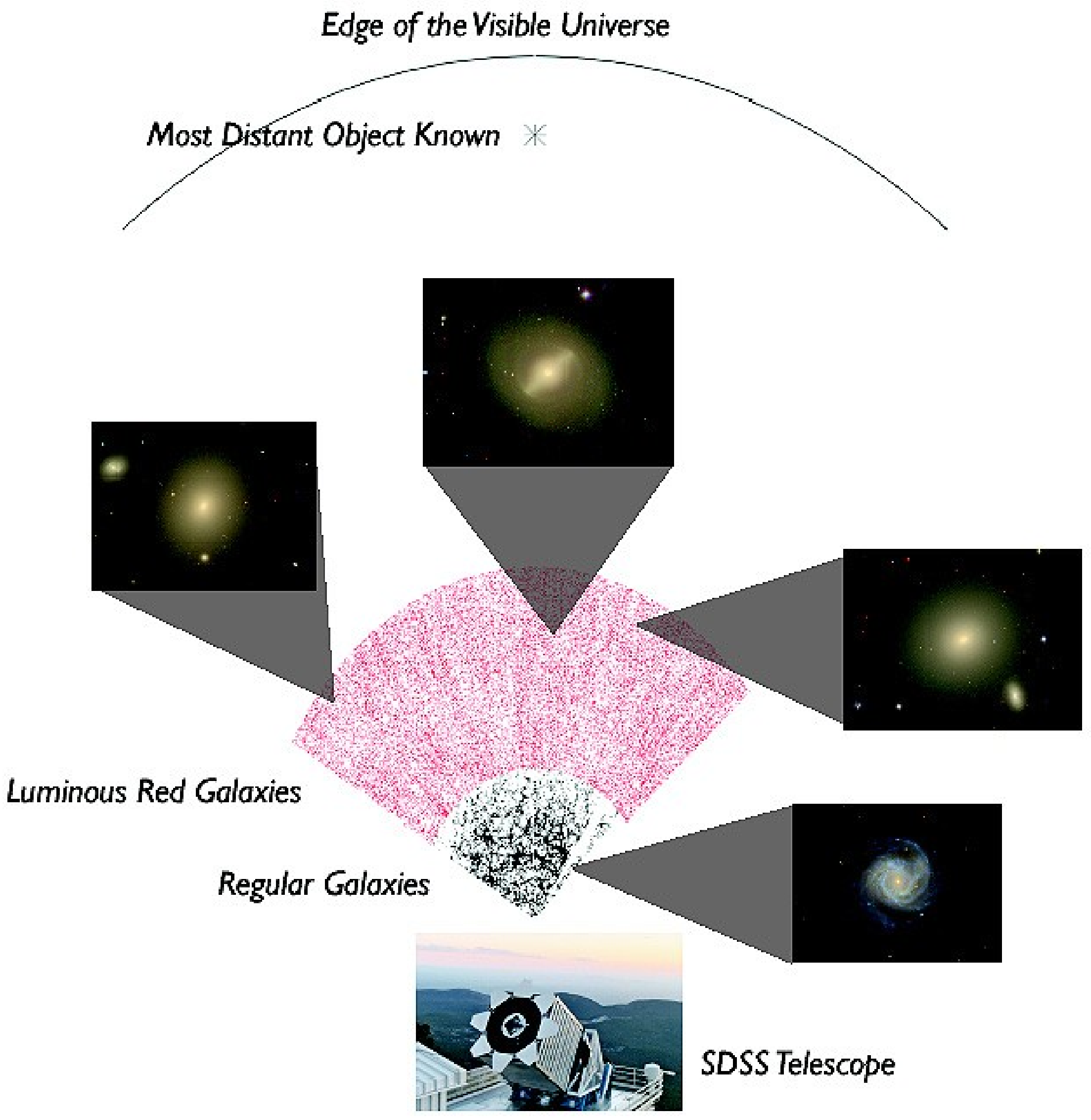
Kitt Peak (Mayall 4m)

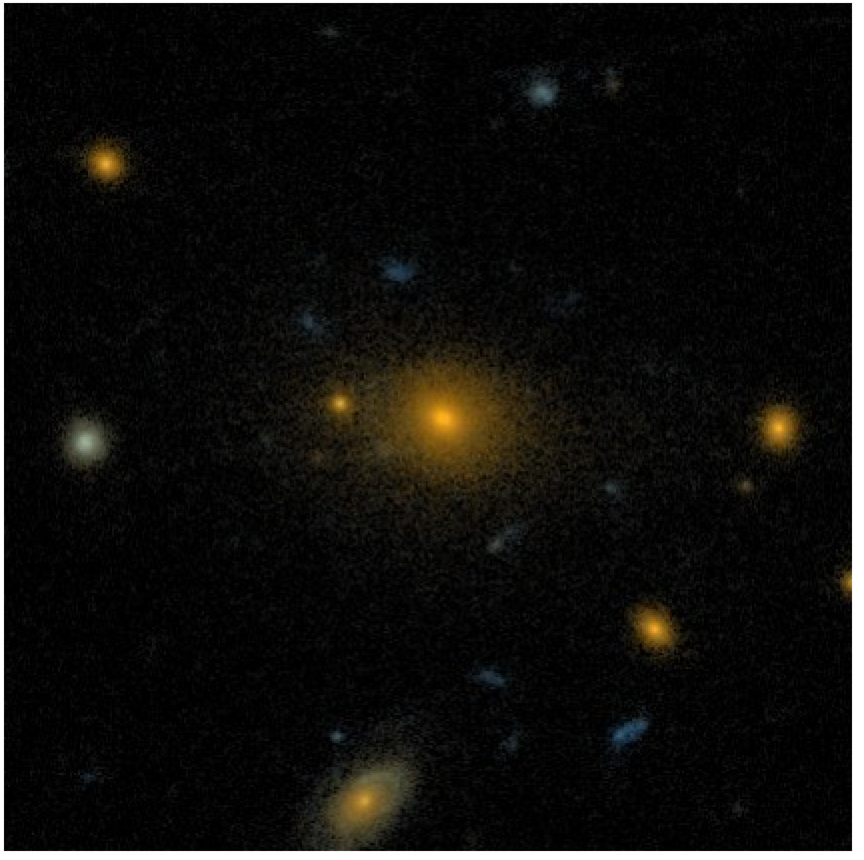




DESI

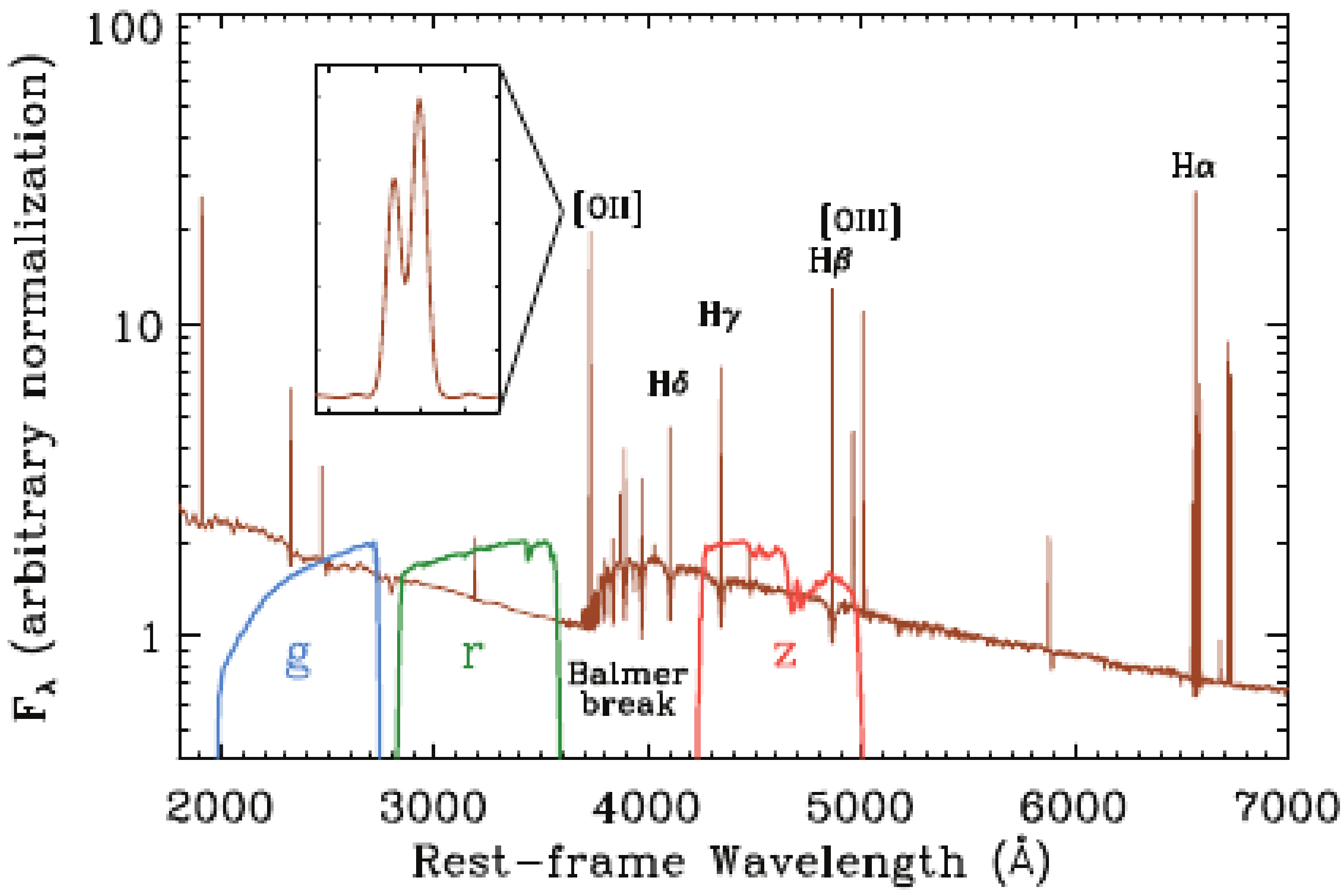
Luminous Red Galaxies (LRG)

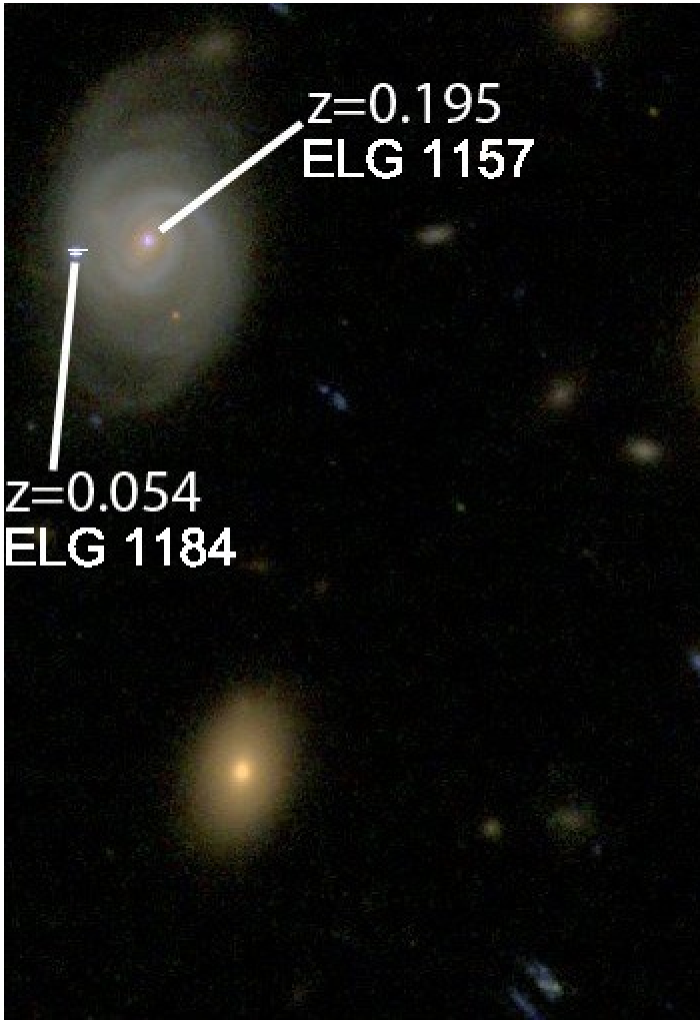




DESI

Emission Line Galaxies (ELG)

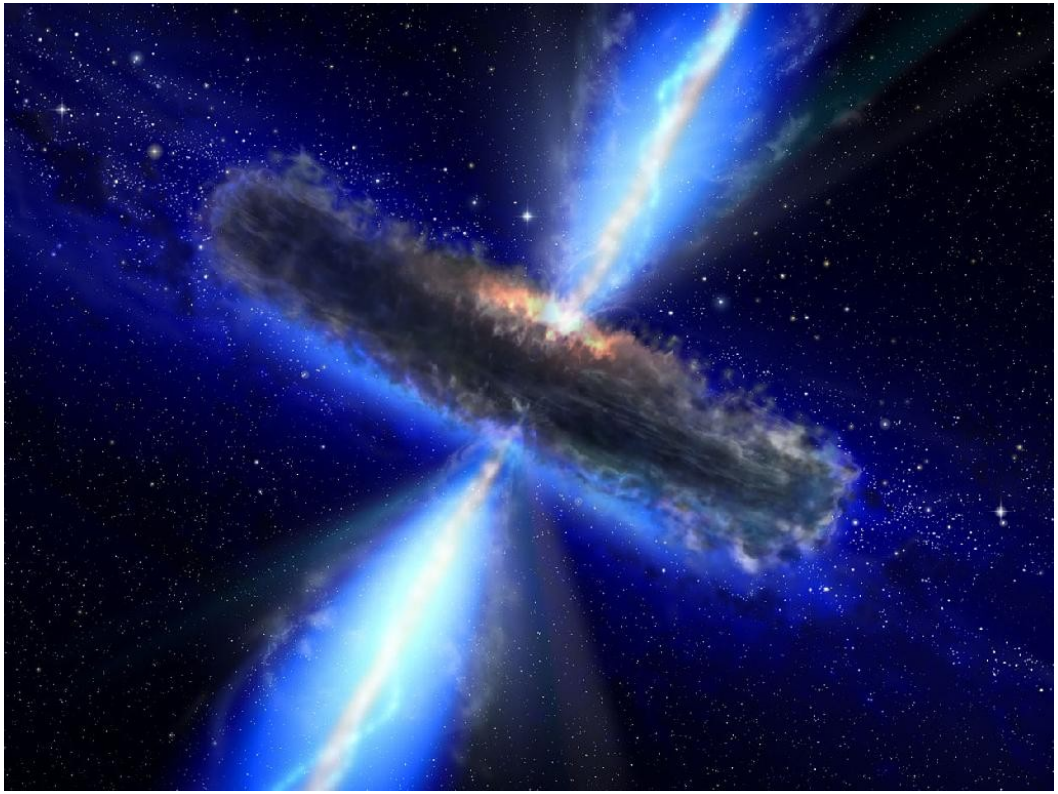




DESI

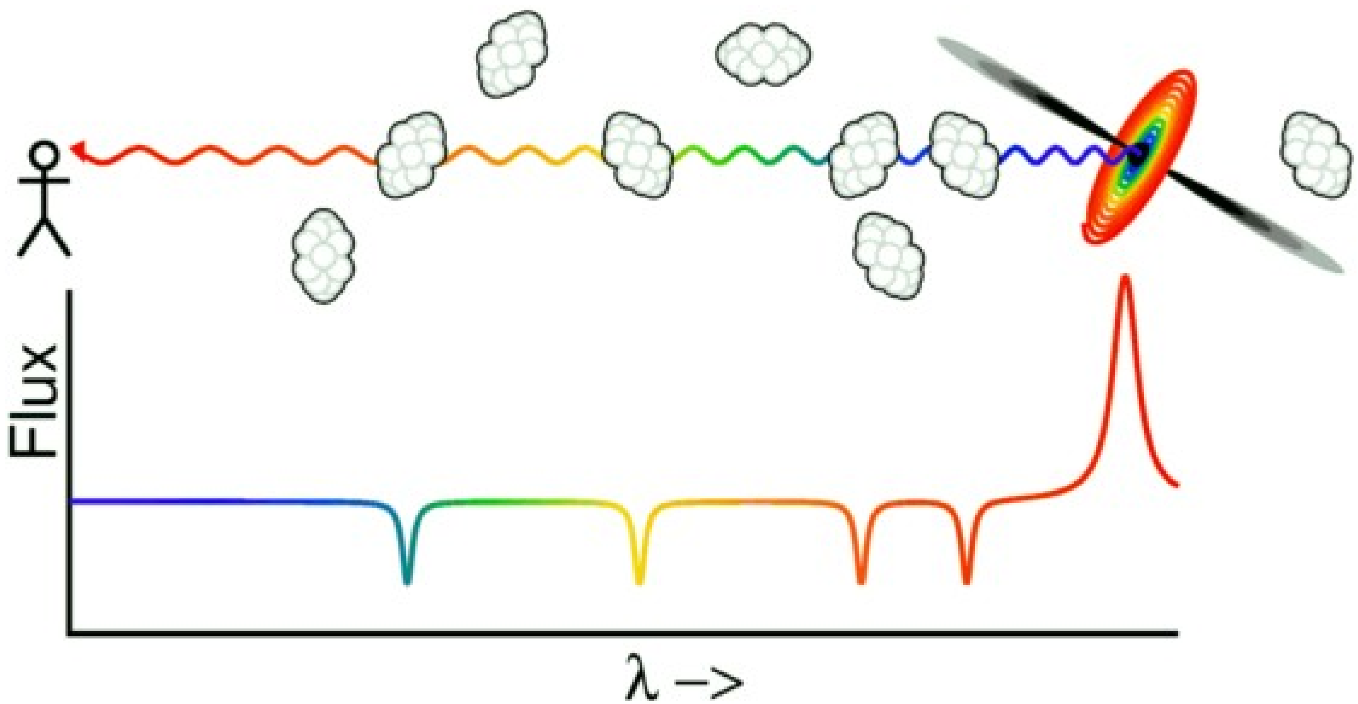
Quasars

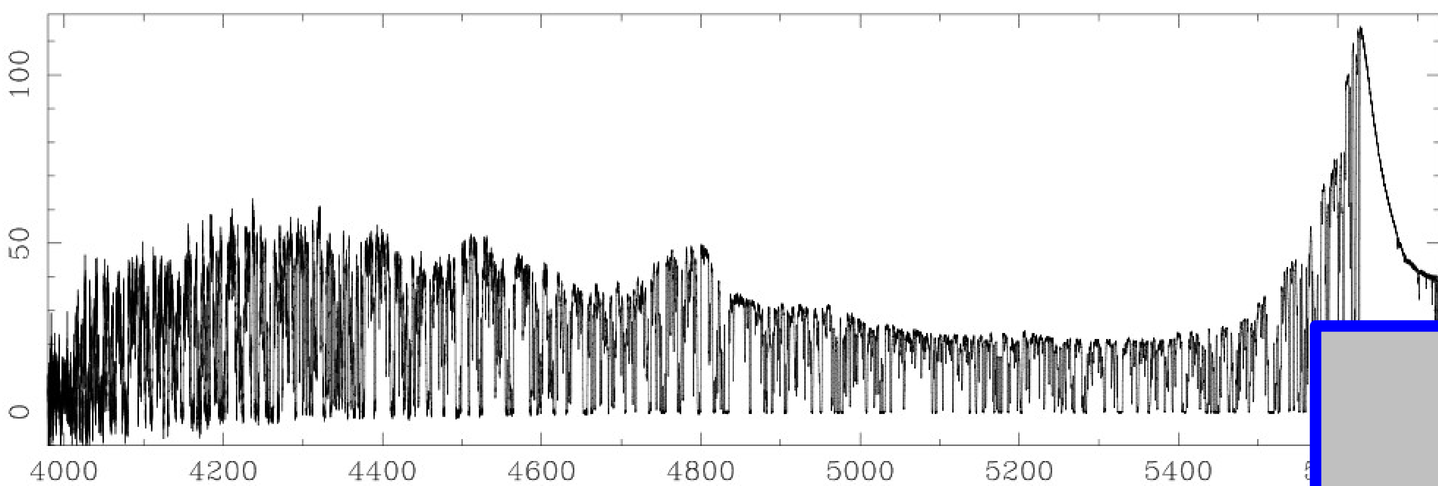
ULAS J1120+0641
(z~7)



DESI

Lyman-alfa forest





DESI

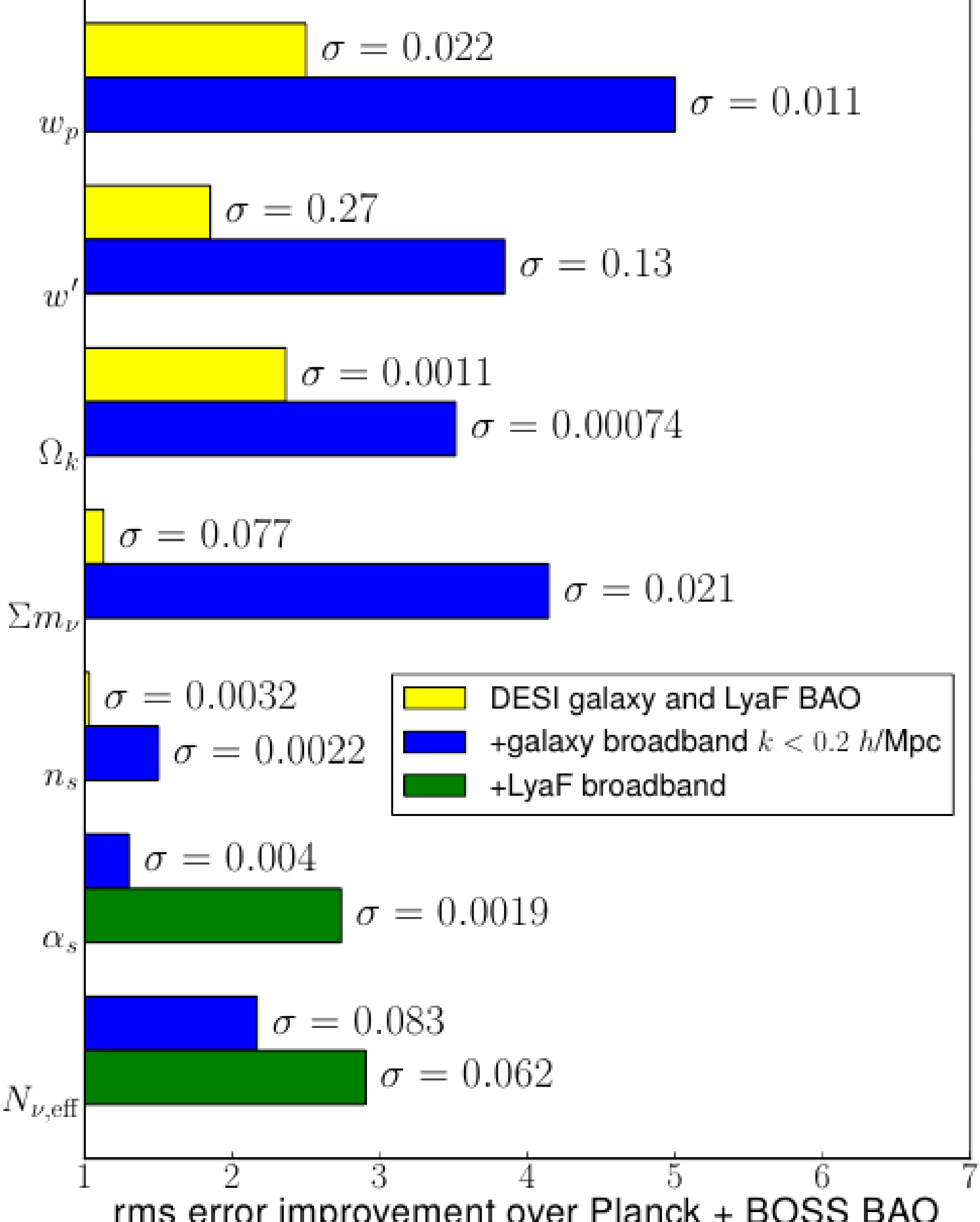
Dark Energy Spectroscopic Instrument

Goal: to map

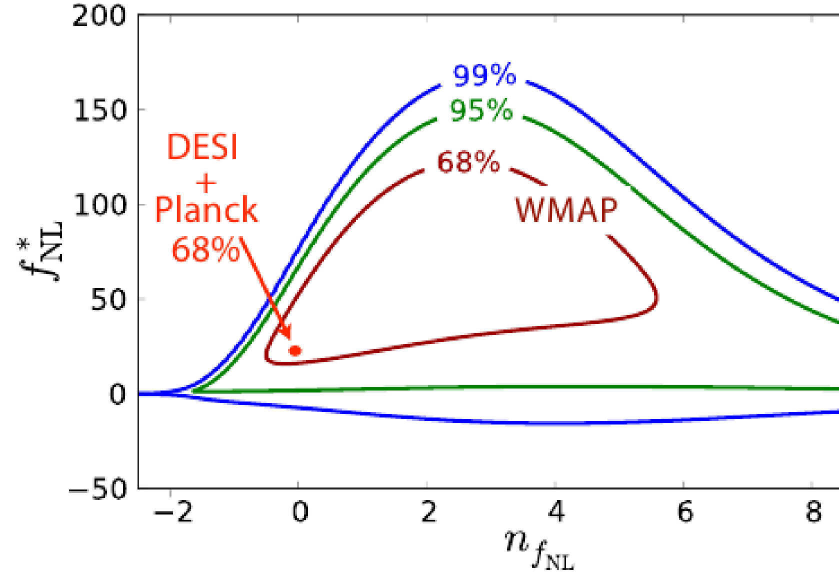
> 18 millions of ELG
> 4 millions of LRG
> 2.5 millions of quasars
> 0.5 millions of Ly-alfa forest

Precision < 1%

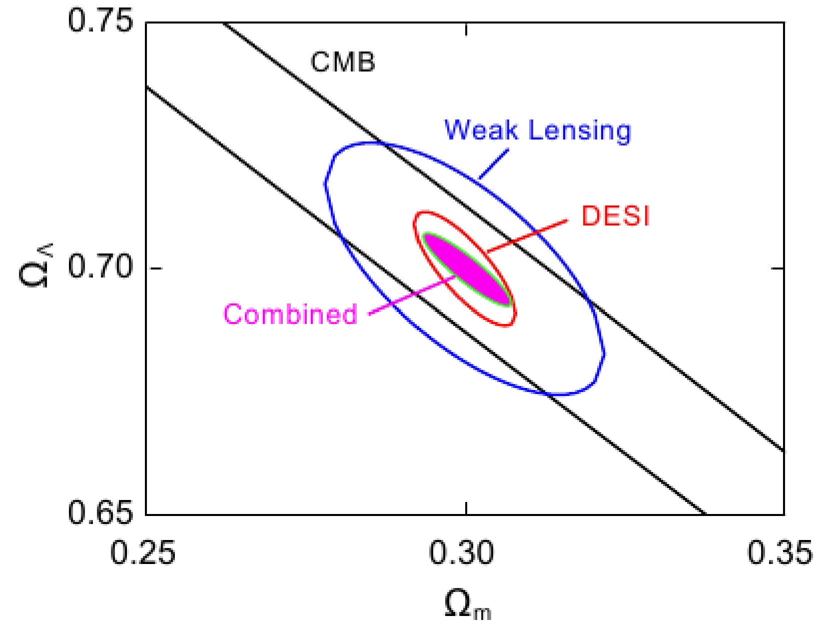
DESI



σ = 0.022
σ = 0.011
σ = 0.27
σ = 0.13
σ = 0.0011
σ = 0.00074
σ = 0.077
σ = 0.021
σ = 0.0032
σ = 0.0022
σ = 0.004
σ = 0.0019
σ = 0.083
σ = 0.062
w_p
w'
Ω_k
Σm_ν
n_s
α_s
$N_{\nu,\mathrm{eff}}$
DESI galaxy and LyaF BAO
+galaxy broadband $k < 0.2\ h$/Mpc
+LyaF broadband
1
2
3
4
5
6
7
rms error improvement over Planck + BOSS BAO



200
150
100
50
0
−50
−2
0
2
4
6
8
f^*_{NL}
$n_{f_{\mathrm{NL}}}$
99%
95%
68%
WMAP
DESI
+
Planck
68%



0.75
0.70
0.65
0.25
0.30
0.35
Ω_Λ
Ω_m
CMB
Weak Lensing
DESI
Combined

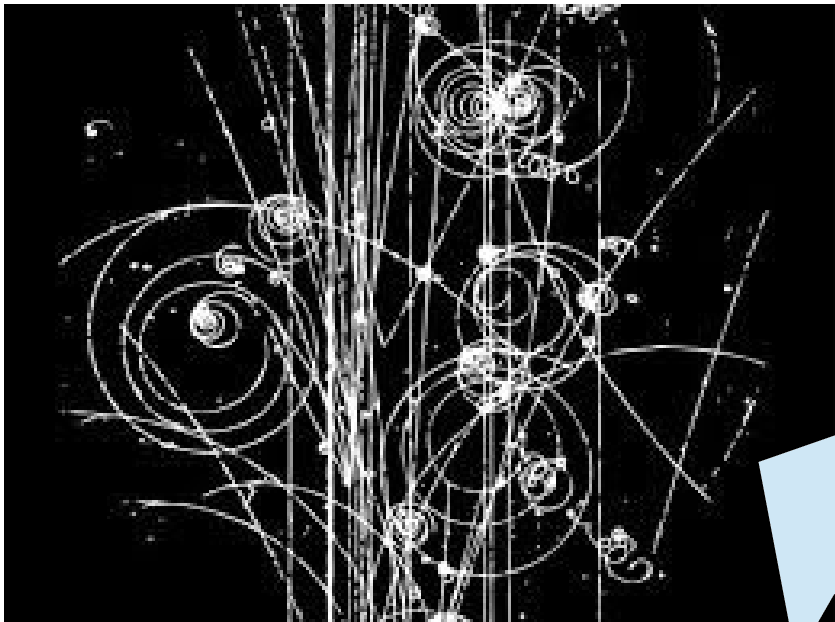
DESI

Conclusions

- Observables in the Universe (CMB & LSS) are a door to the Early Universe physics and the dark sector (dark matter & **dark energy**)

- High precision cosmology, such as **DESI**, will be the leading observationally experiment in the next decade

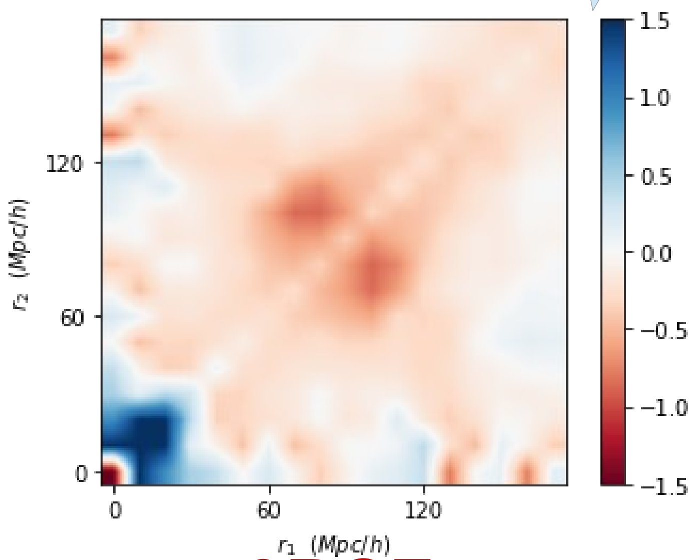
New perspective into the Universe



Cosmic collider

Universe evolution → Dark energy
Dark matter
(Modified) gravity

Distortion



3PCF