Dark Matter without SUSY

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OKC colloquium, Stockholm, 04/04/2017.

We don't see SUSY.

What theoretical frameworks motivate WIMP DM in her absence?

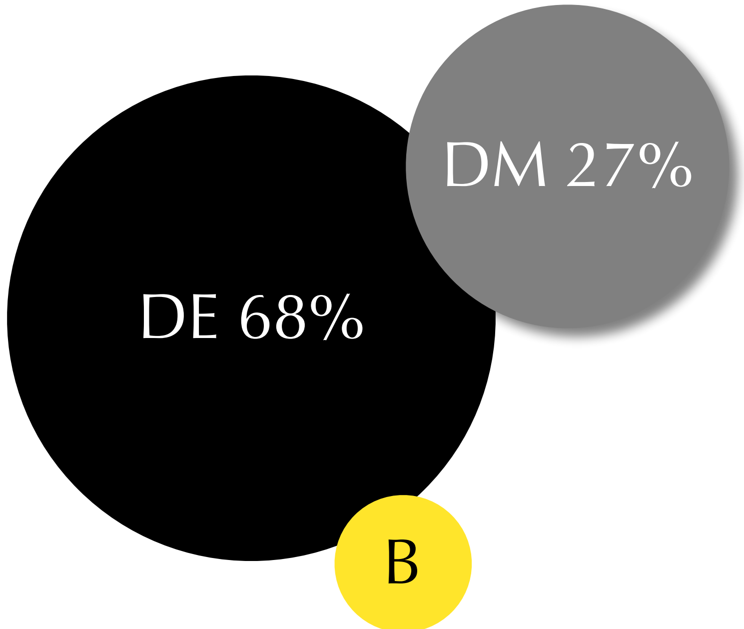
Plan of the talk

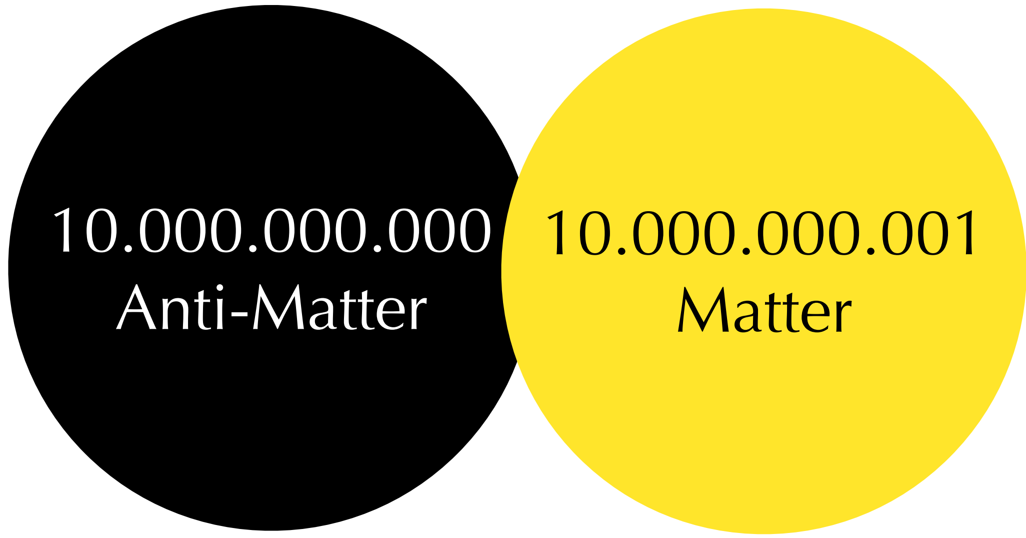
1. General introduction
2. Dark Matter models inspired by ...
   - Neutrinos
   - The Baryon Asymmetry
   - Grand Unified Theories
3. Summary

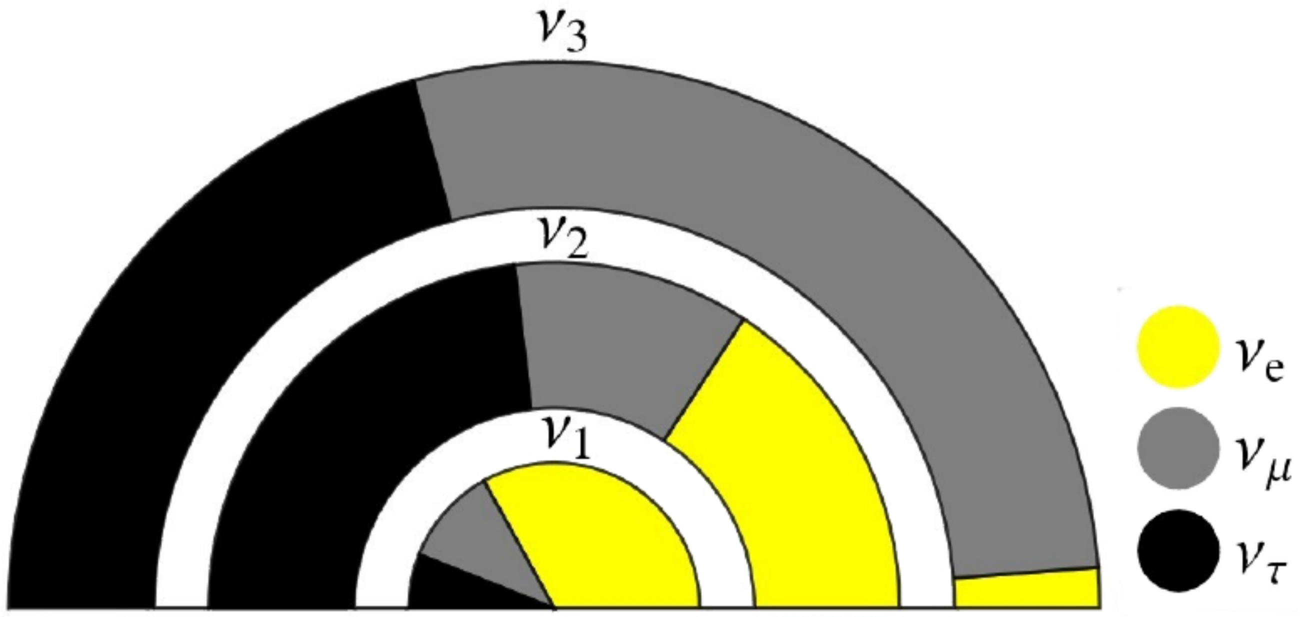
Part I/III
Introduction

The Standard Model is excessively successful … but New Physics is here!

- Neutrino masses
- **Dark Matter**
- Baryon asy**m**metry



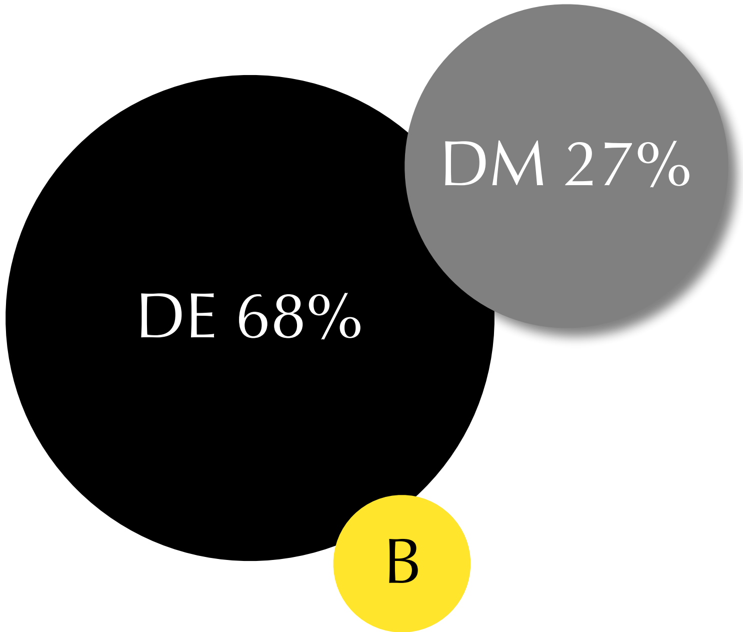


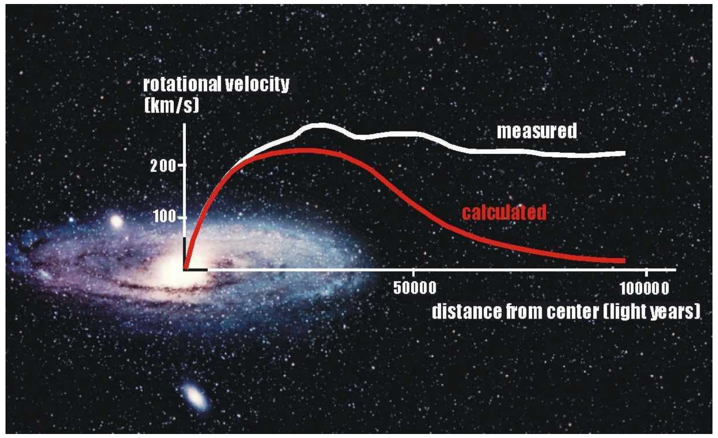


We live in a pretty dark place

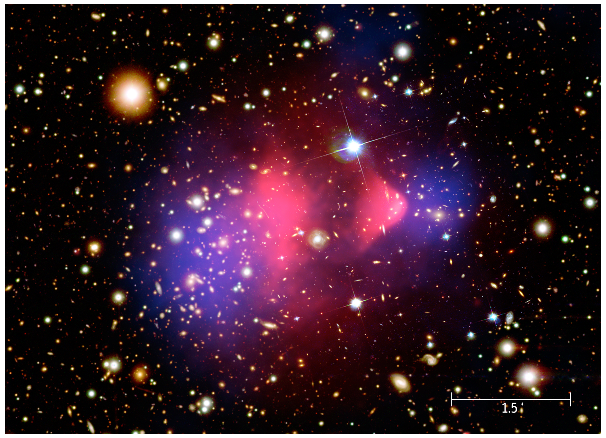
By now, we have a wide array of evidence for a nonbaryonic, clustering component.

DM accounts for ~ 85% of matter content of the Universe.

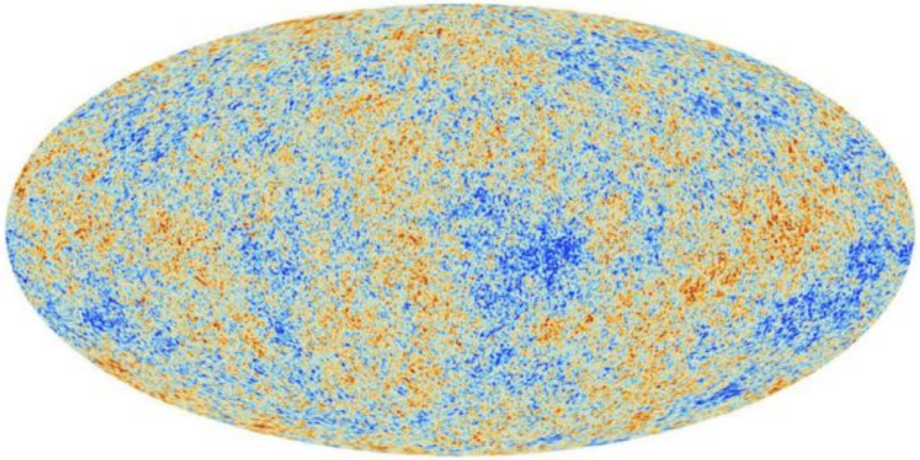




(10 kpc)



(Mpc)



(10 Gpc)

Known knowns about DM

An acceptable candidate should not only reproduce observed abundance but also be

- neutral-ish,
- cold-ish,
- quasi-stable,
- OK with BBN and astro,
- collisionless, and
- OK with search limits

Known knowns about DM

An acceptable candidate should not only reproduce observed abundance but also be

- neutral-ish,
- cold-ish,
- quasi-stable
- OK with BBN and astro
- collisionless
- OK with search limits

DM is very stable!

DM should be at least older than the Universe:

$$\tau_{\rm DM} \gtrsim H^{-1} \sim 10^{18}\rm s$$

However, it usually emits *gammas, e+, p,* etc, and to avoid bounds, the limit becomes:

$$\tau_{\rm DM} \gtrsim 10^{26}\rm s$$

Known unknowns about DM

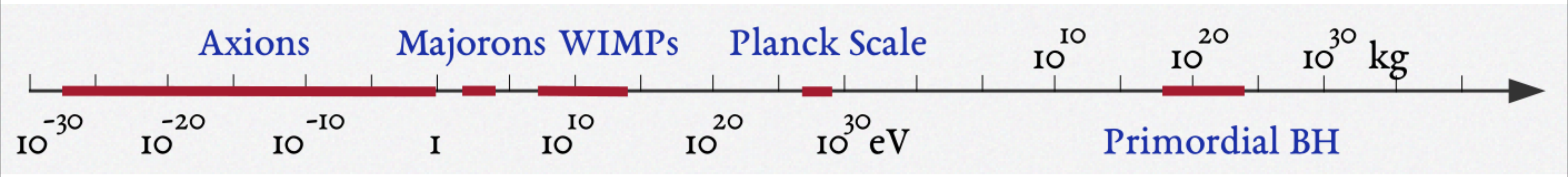
... which leads to many questions, e.g.,

- how is the DM produced?
- is the DM fermionic or bosonic?
- is the dark sector simple or complex?
- is it cold or warm?
- does it carry a new charge?
- is it decaying?
- can we detect it?

"I can't tell you what's in the dark matter sandwich. No one knows what's in the dark matter sandwich."

Dark Matter Candidates

- The SM does not contain any DM candidate
- Candidates of DM abound in literature!
- DM could be essentially at any mass scale...
- We can distinguish WIMPs from other candidates via production mechanism and detection prospects.



Known unknowns about DM

My assumptions for this talk:

... which leads to many questions, e.g.,

- how is the DM produced? Thermally
- is the DM fermionic or bosonic? Scalar or fermion
- is the dark sector simple or complex? Single particle
- is it cold or warm? Cold
- does it carry a new charge? Not necessarily
- is it decaying? Stable
- can we detect it? Yes.

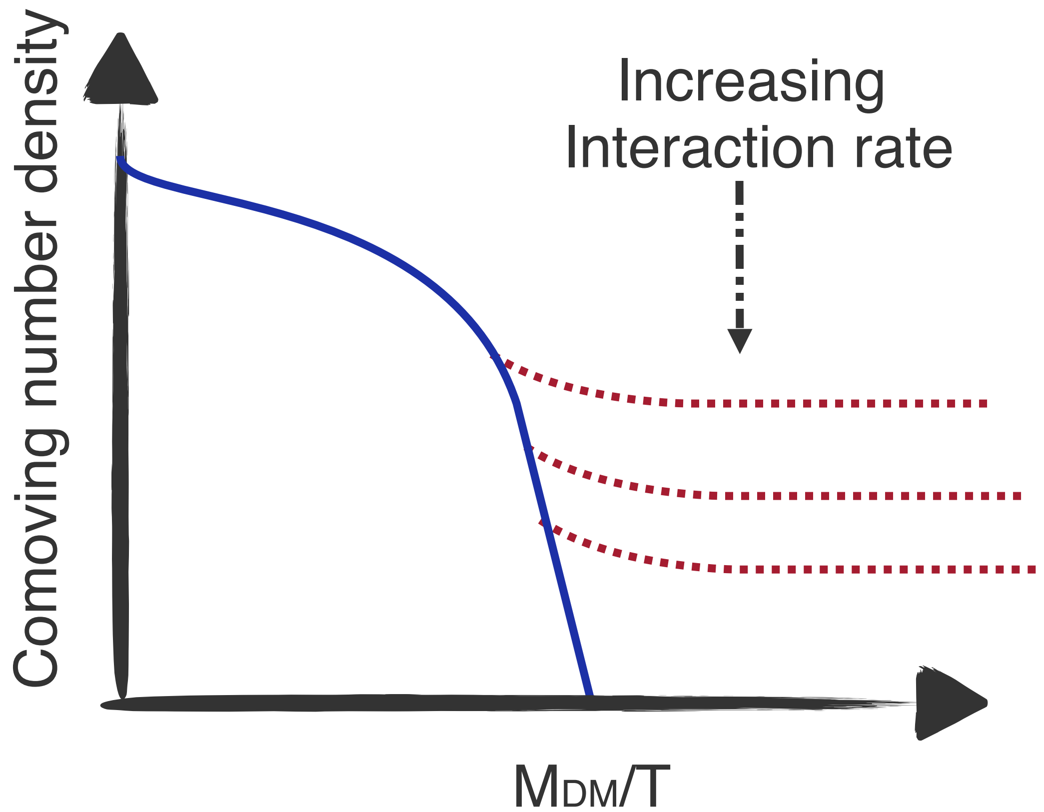
"I can't tell you what's in the dark matter sandwich. No one knows what's in the dark matter sandwich."

What are WIMPs?

For masses & interactions around the weak scale, the abundance is *naturally* close to observations:

$$\Omega_\chi h^2 \approx 0.1 \, \frac{3\times10^{-26}\ \mathrm{cm}^2/\mathrm{s}}{\langle \sigma_{\chi\bar{\chi}} |v| \rangle}$$

WIMPs have masses a few tens to thousands of times that of the proton. Interact through gravity and weak force.



The WIMP 'Miracle'!

What are WIMPs?

Assume

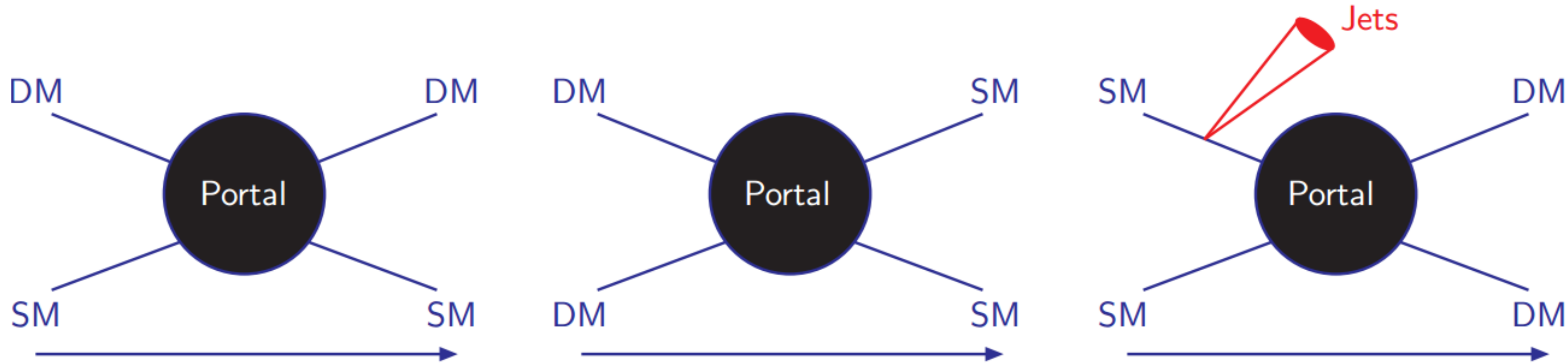
1. the Universe is divided into 2 parts: + and -. The SM lives in the + world, and DM in the -
2. the DM feels the weak force (can be generalized to a portal connects DM to SM).

Then

1. the lightest particle in the - world is stable.
2. interactions of the type DM.DM.SM are possible and lead to production and detection prospects of the DM.

Why WIMPs?

The same portal that produces WIMPs can be used to search for them.

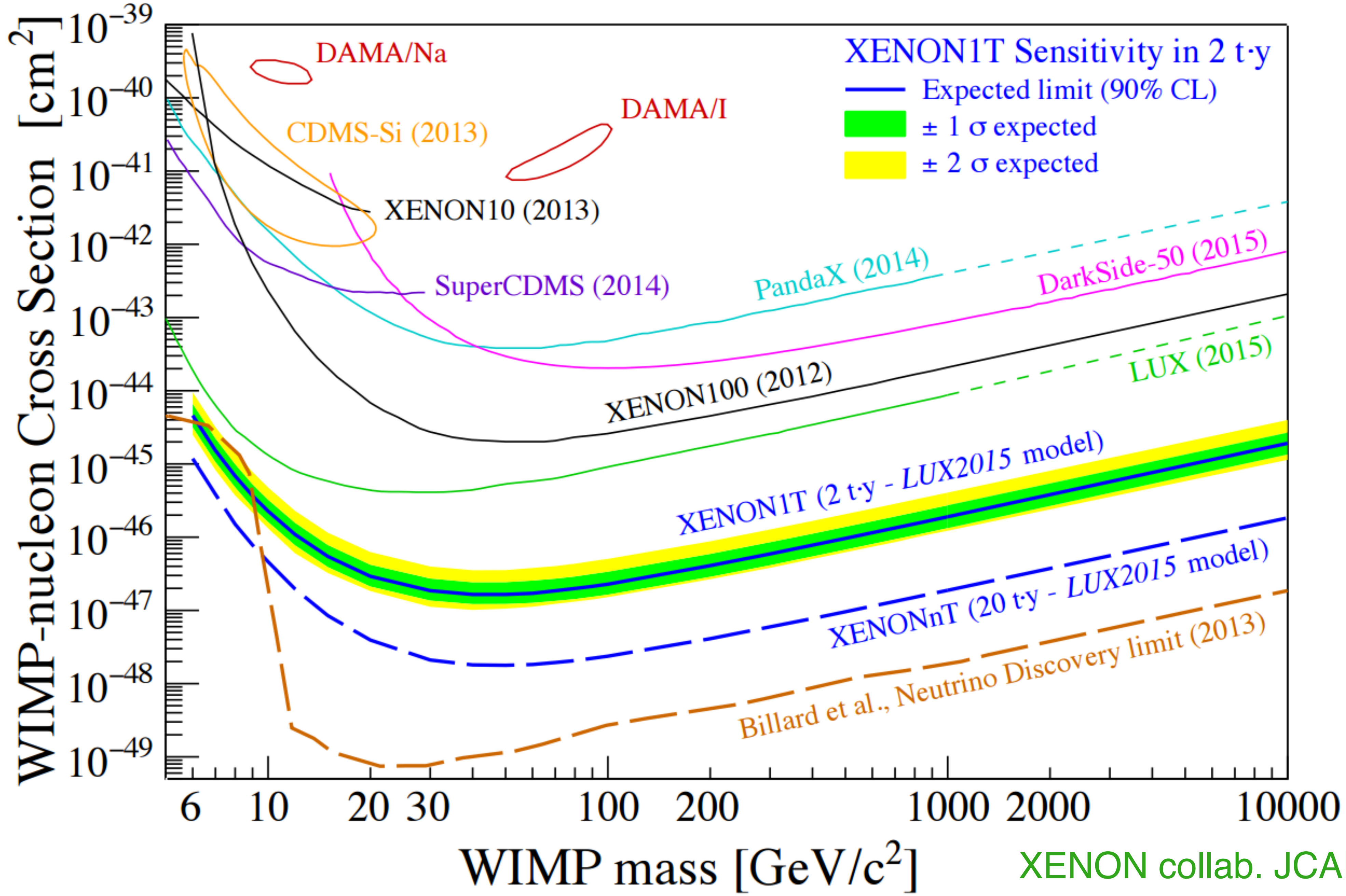


(a) Direct Detection (b) Indirect Detection (c) Collider Detection

Direct and indirect searches complement collider searches and cosmo probes.

The main advantage of WIMPs is ... Testability

Why WIMPs?



XENON collab. JCAP04(2016)027

The main advantage of WIMPs is …
Testability

So where do WIMPs come from?

The idealist: arise from theories addressing the stability of the electro-weak scale, e.g., supersymmetry.

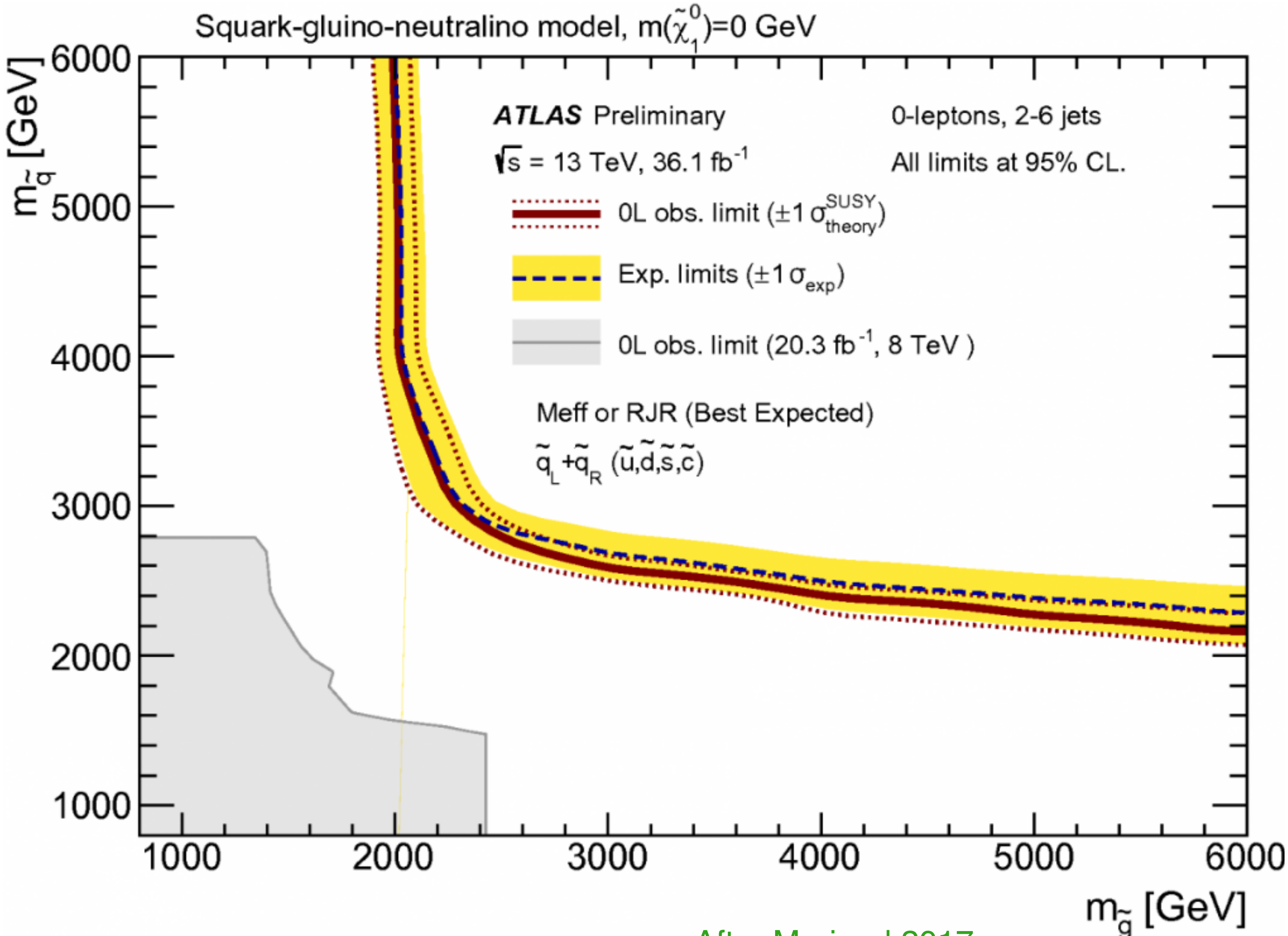
Why SUSY?

There are many idealistic motivations for supersymmetry: elegance, link matter-forces, link gravity-other forces, symmetry of nature, etc.

Other reasons suggest superparticles should be @ TeV scale:

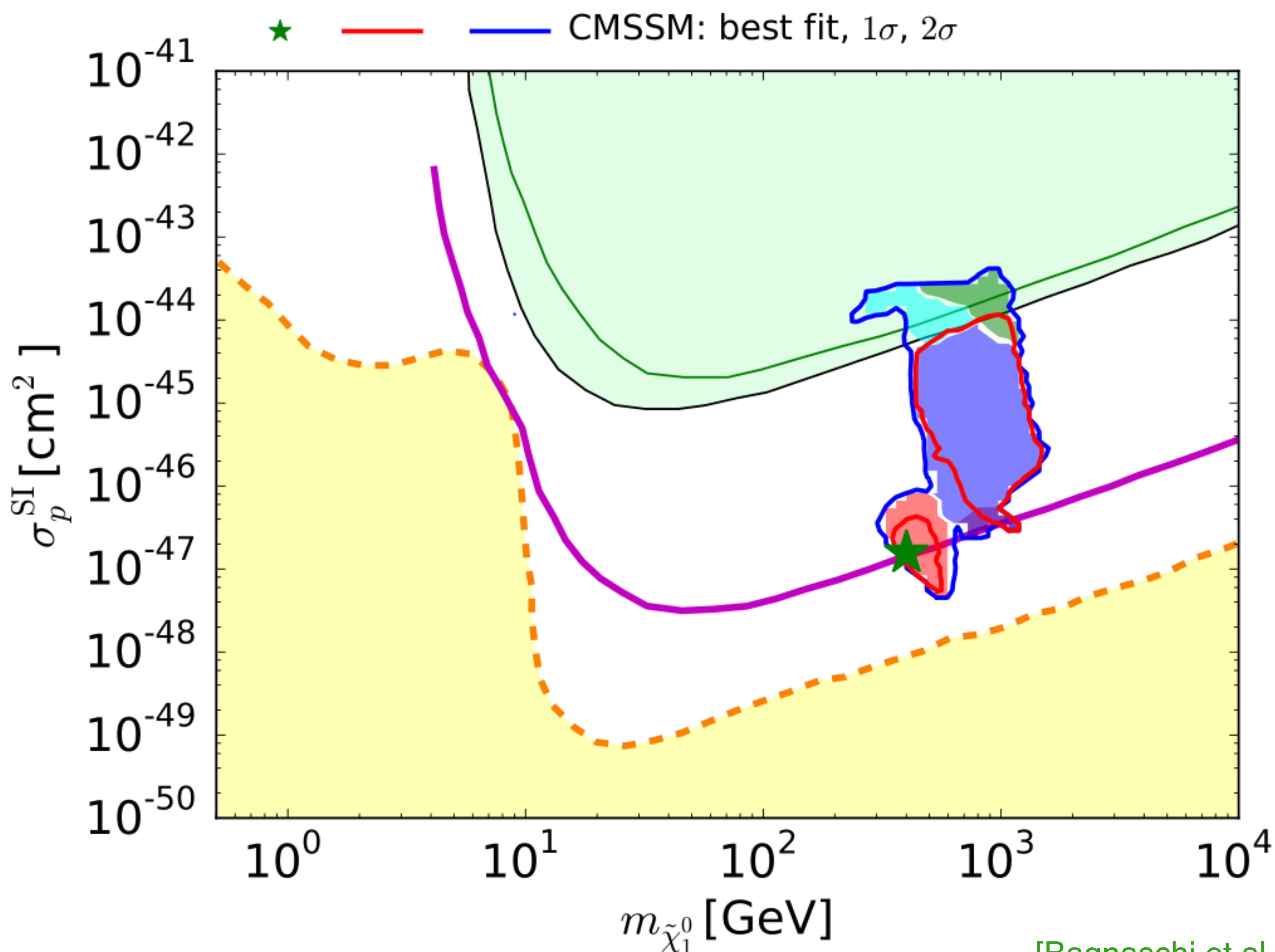
- Stabilization of the Higgs potential
- Gauge coupling unification
- MH=126GeV
- and ... with R-parity imposed (needed to avoid proton decay), SUSY offers excellent WIMP DM in the form of neutralinos: partners of the neutral gauge bosons and Higgses.

But … Where is SUSY?



After Moriond 2017.

And ... Where is SUSY DM?



[Bagnaschi et al., 1508.01173]

So where do WIMPs come from?

The idealist: arise from theories addressing the stability of the electro-weak scale, e.g., supersymmetry.

The minimalist: postulated-with stabilizing symmetry- to solve the DM issue.

Minimal DM

Or we could just add stable particles to the SM?!

Quantum numbers $SU(2)_L$	$U(1)_Y$	Spin	DM can decay into	DM mass in TeV	$m_{DM^\pm} - m_{DM}$ in MeV	Events at LHC $\int \mathcal{L}\, dt = 100/\text{fb}$	σ_{SI} in $10^{-45}\,\text{cm}^2$
2	1/2	0	EL	0.54 ± 0.01	350	$320 \div 510$	0.2
2	1/2	1/2	EH	1.1 ± 0.03	341	$160 \div 330$	0.2
3	0	0	HH^*	2.0 ± 0.05	166	$0.2 \div 1.0$	1.3
3	0	1/2	LH	2.4 ± 0.06	166	$0.8 \div 4.0$	1.3
3	1	0	HH, LL	1.6 ± 0.04	540	$3.0 \div 10$	1.7
3	1	1/2	LH	1.8 ± 0.05	525	$27 \div 90$	1.7
4	1/2	0	HHH^*	2.4 ± 0.06	353	$0.10 \div 0.6$	1.6
4	1/2	1/2	(LHH^*)	2.4 ± 0.06	347	$5.3 \div 25$	1.6
4	3/2	0	HHH	2.9 ± 0.07	729	$0.01 \div 0.10$	7.5
4	3/2	1/2	(LHH)	2.6 ± 0.07	712	$1.7 \div 9.5$	7.5
5	0	0	(HHH^*H^*)	5.0 ± 0.1	166	$\ll 1$	12
5	0	1/2	$-$	4.4 ± 0.1	166	$\ll 1$	12
7	0	0	$-$	8.5 ± 0.2	166	$\ll 1$	46

hep-ph/0512090

So where do WIMPs come from?

The idealist: arise from theories addressing the stability of the electro-weak scale, e.g., supersymmetry.

The minimalist: postulated-with stabilizing symmetry- to solve the DM issue.

The realist: arise from theories addressing neutrino masses and/or baryon asymmetry.

Disclaimer

100s of models have been proposed and studied. There's only a handful of concepts and ideas that are used. I'll discuss some of these ideas.

Part II/III
Inspired by lightness

Neutrinos are everywhere...

COSMO

ASTRO

BAU

GUT

DM

FLAVOR

Neutrino masses are a great window onto high scales/NP

nu Masses

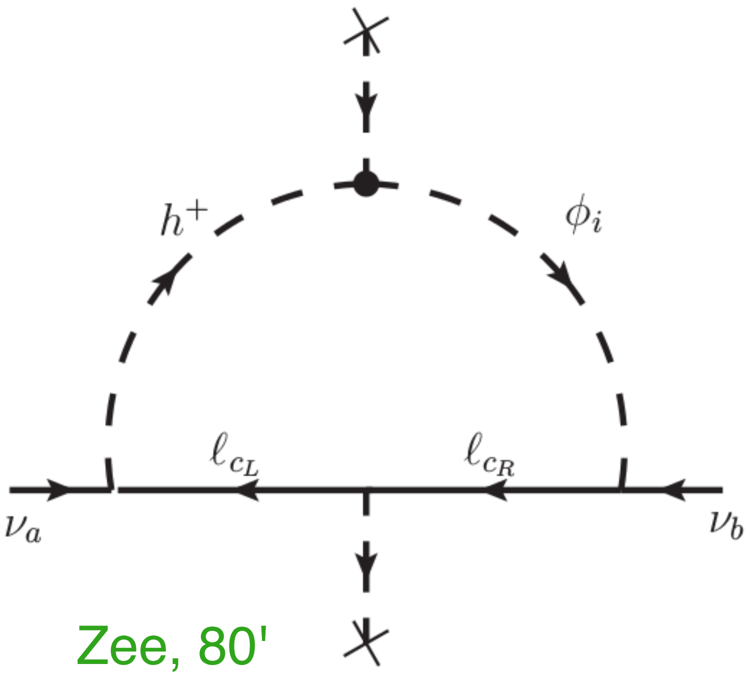
There are many, many ways to generate neutrino masses... but we can distinguish two main classes of models:

High scale models $$m_\nu \approx \frac{y^2 v^2}{M}$$

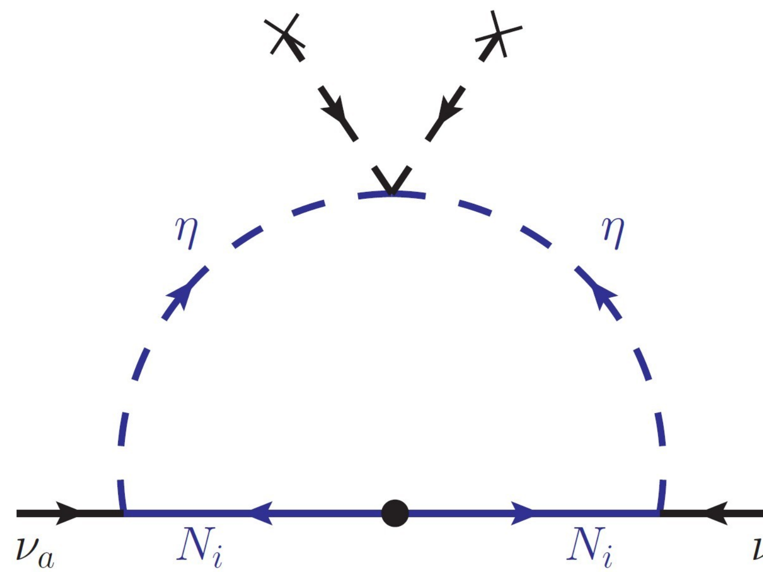
Low scale models $$m_\nu \approx \left(\frac{yv}{M}\right)^{(2)} \mu$$

$$m_\nu \approx \left(\frac{1}{16\pi^2}\right)^N f(yv, M)$$

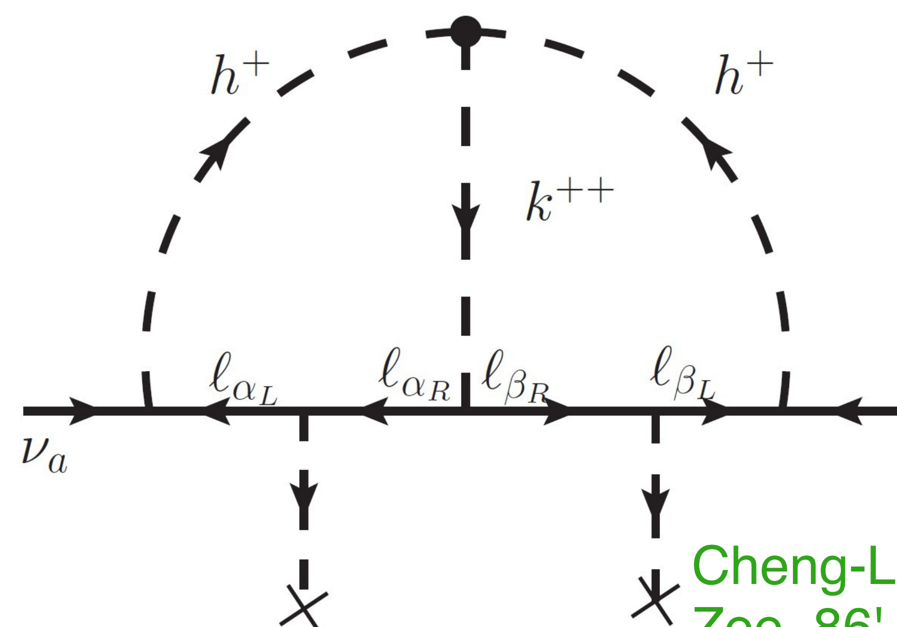
The low scale approach



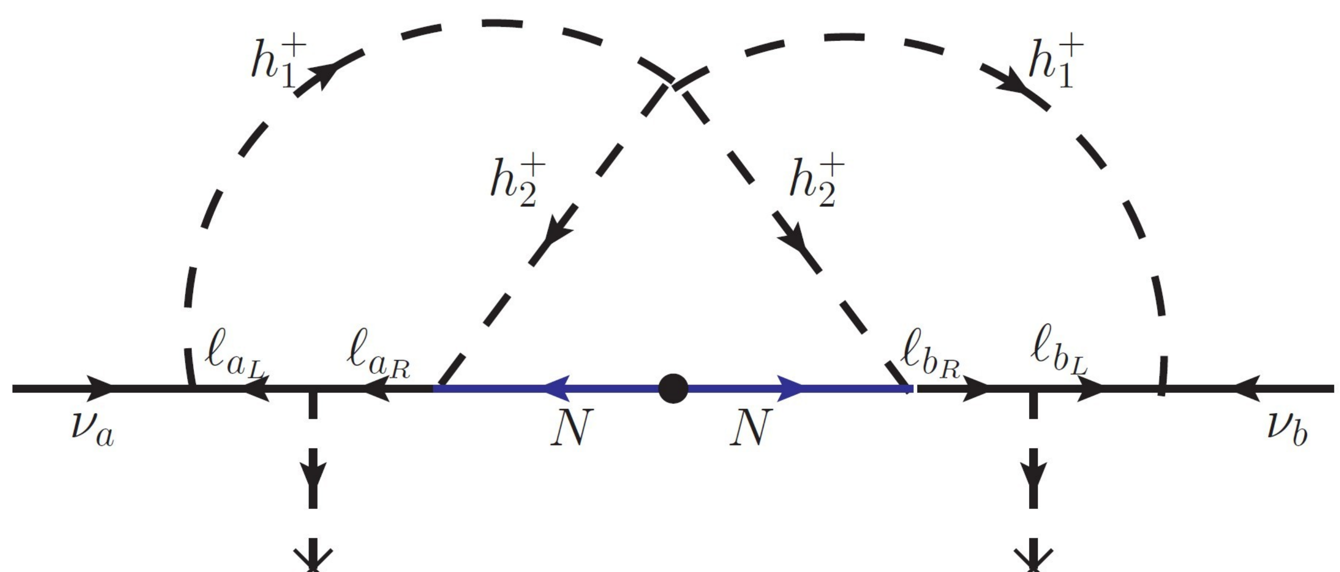
Zee, 80'



Ma, 98', 06'



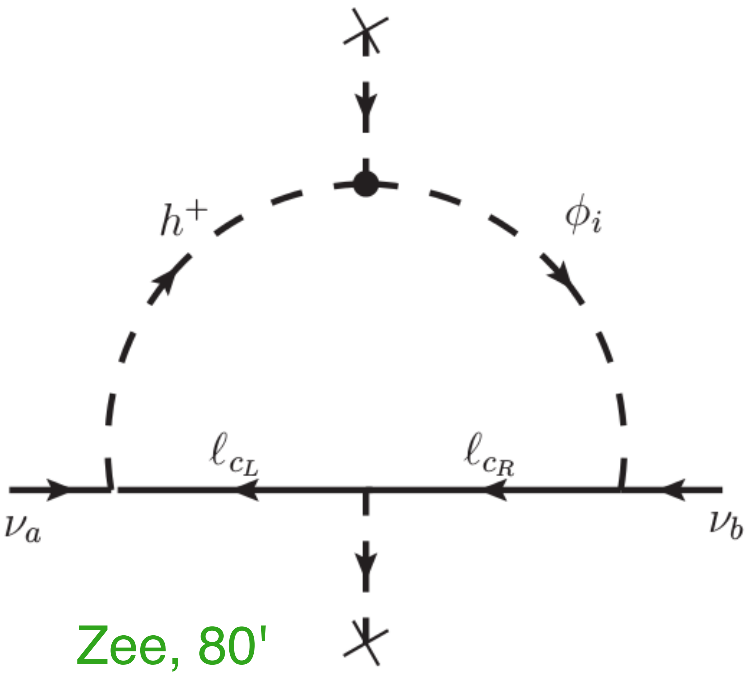
Cheng-Li, 80'
Zee, 86'
Babu, 88'



Krauss-Nasri-Trodden, 03'

Review: SB,Morisi,Valle, 14.

The low scale approach



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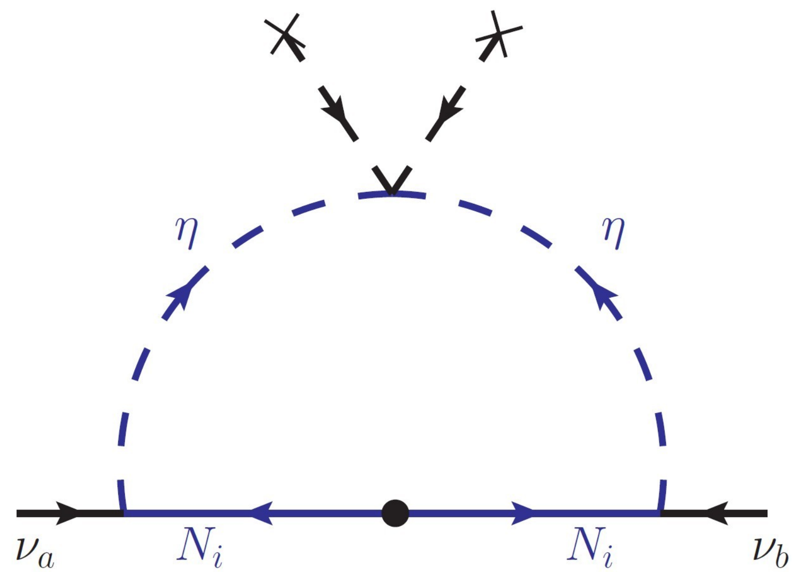

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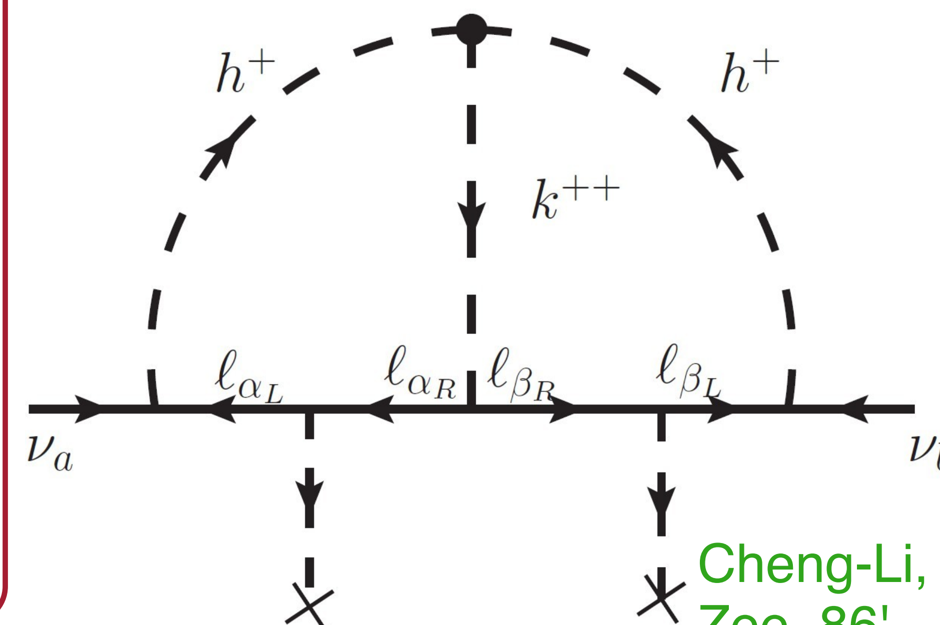

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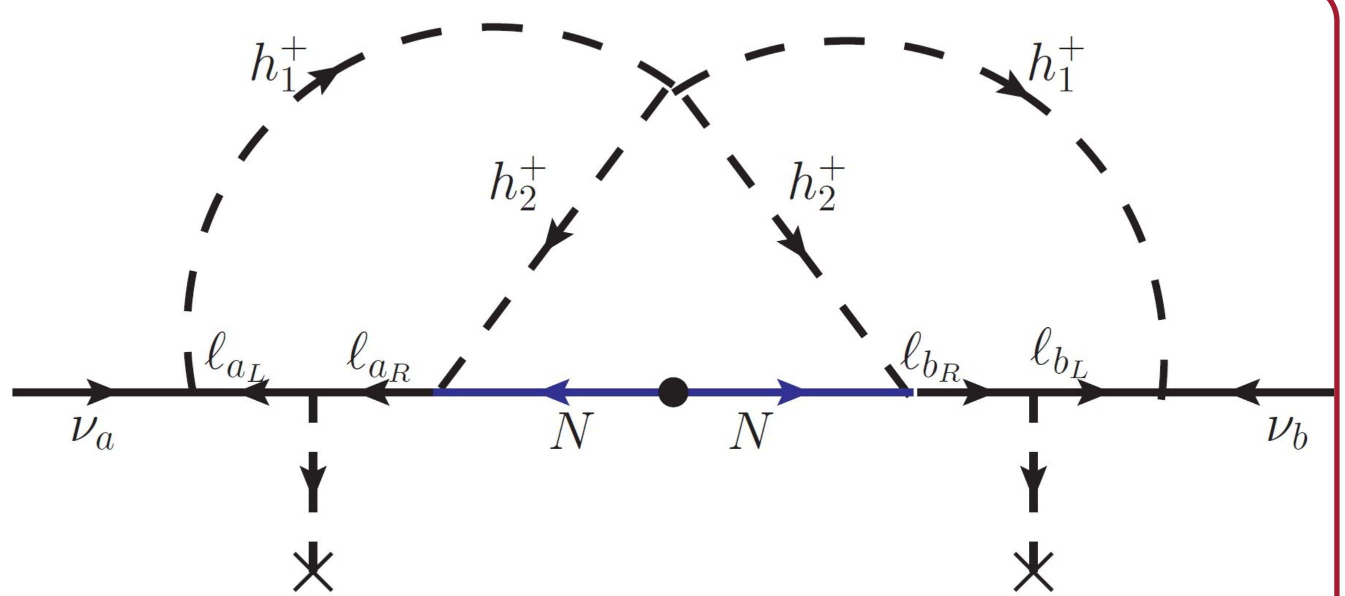

Krauss-Nasri-Trodden, 03'

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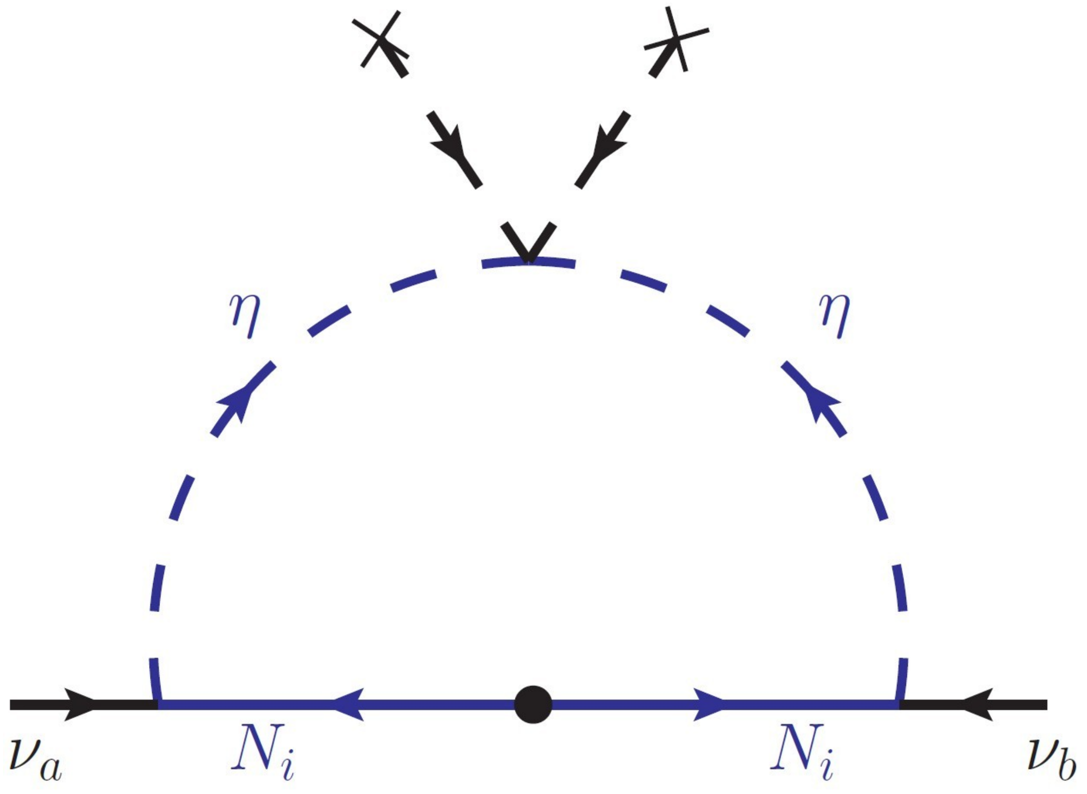
The Scotogenic model

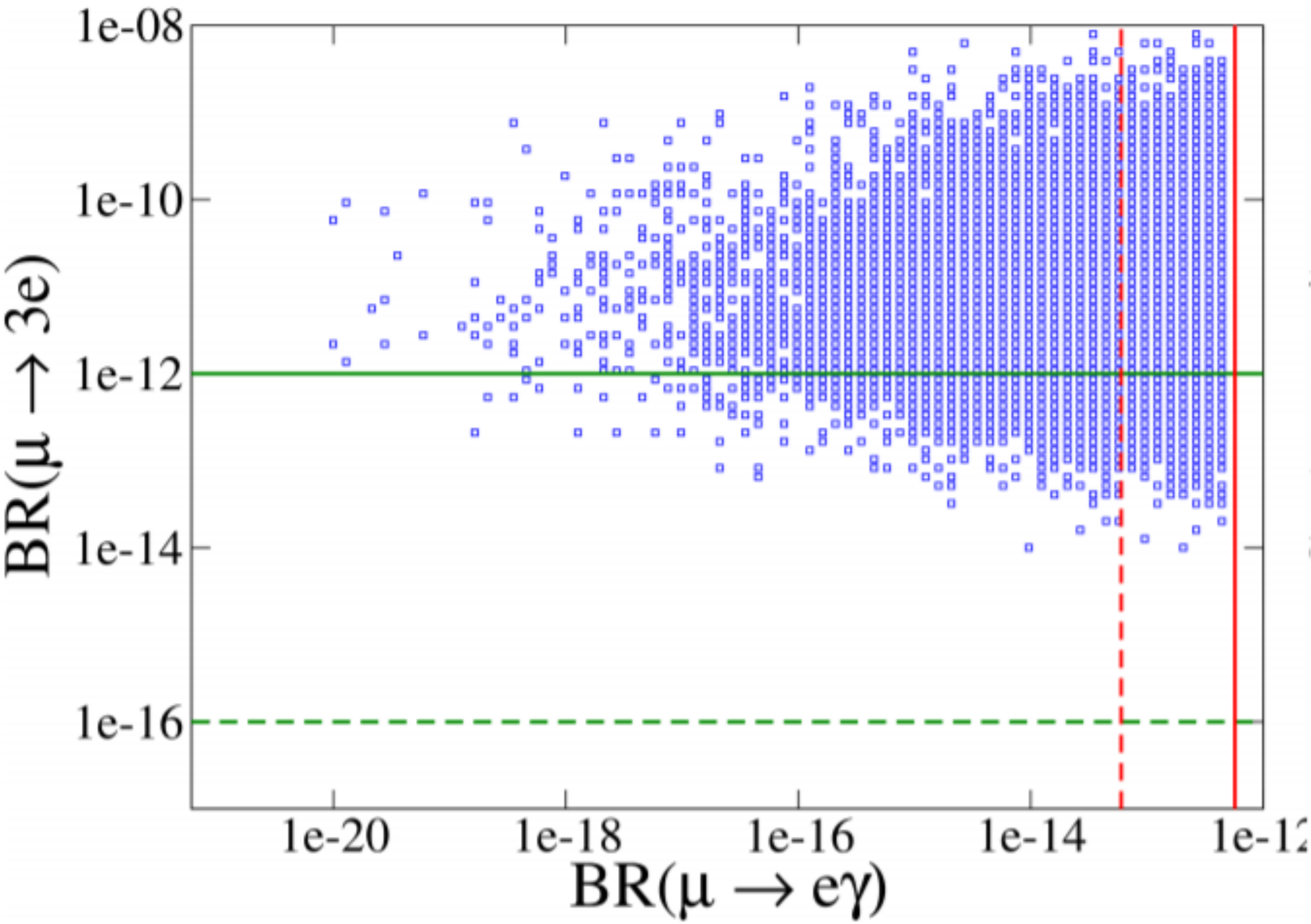
Field	$SU(2)_L \times U(1)_Y$	Z_2
L_i	$(2, -1/2)$	$+$
e_i	$(1, 1)$	$+$
ϕ	$(2, -1/2)$	$+$
N_i	$(1, 0)$	$-$
η	$(2, -1/2)$	$-$



Ma, 06'

The parity forbids tree-level nu masses and stabilized the DM at the same time. Neutrino masses are generated via 'dark' loops. DM is the lightest odd particle.

The Scotogenic model

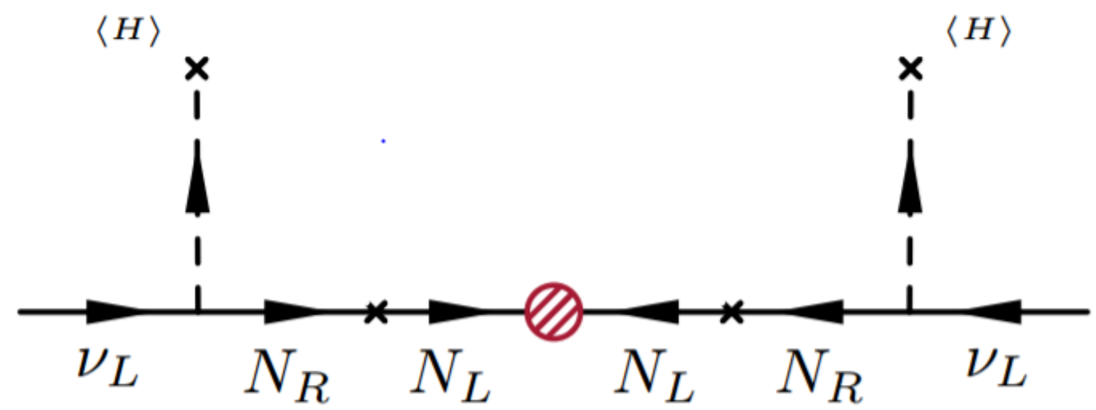


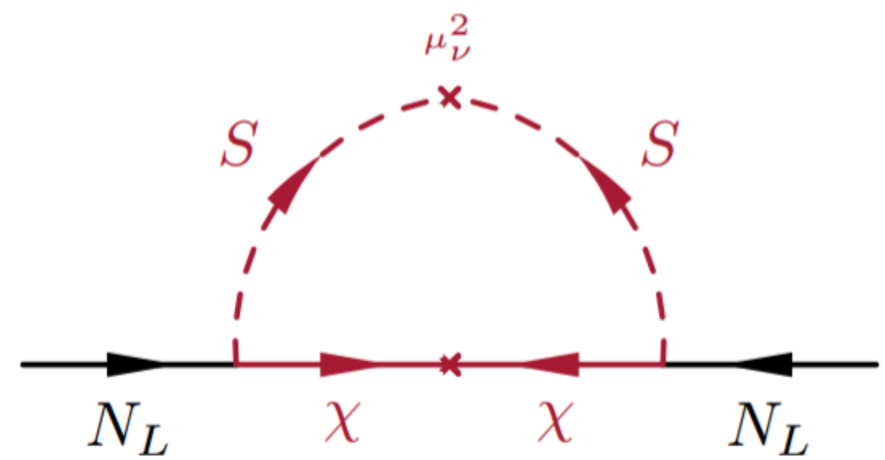
Vicente, Yaguna 14'

Neutrino loops, BAU, and DM

An interesting ingredient one could add to neutrino masses generated via dark loops is the possibility to account for the BAU.

Adding scalars at the EW-scale enhances the phase transition!



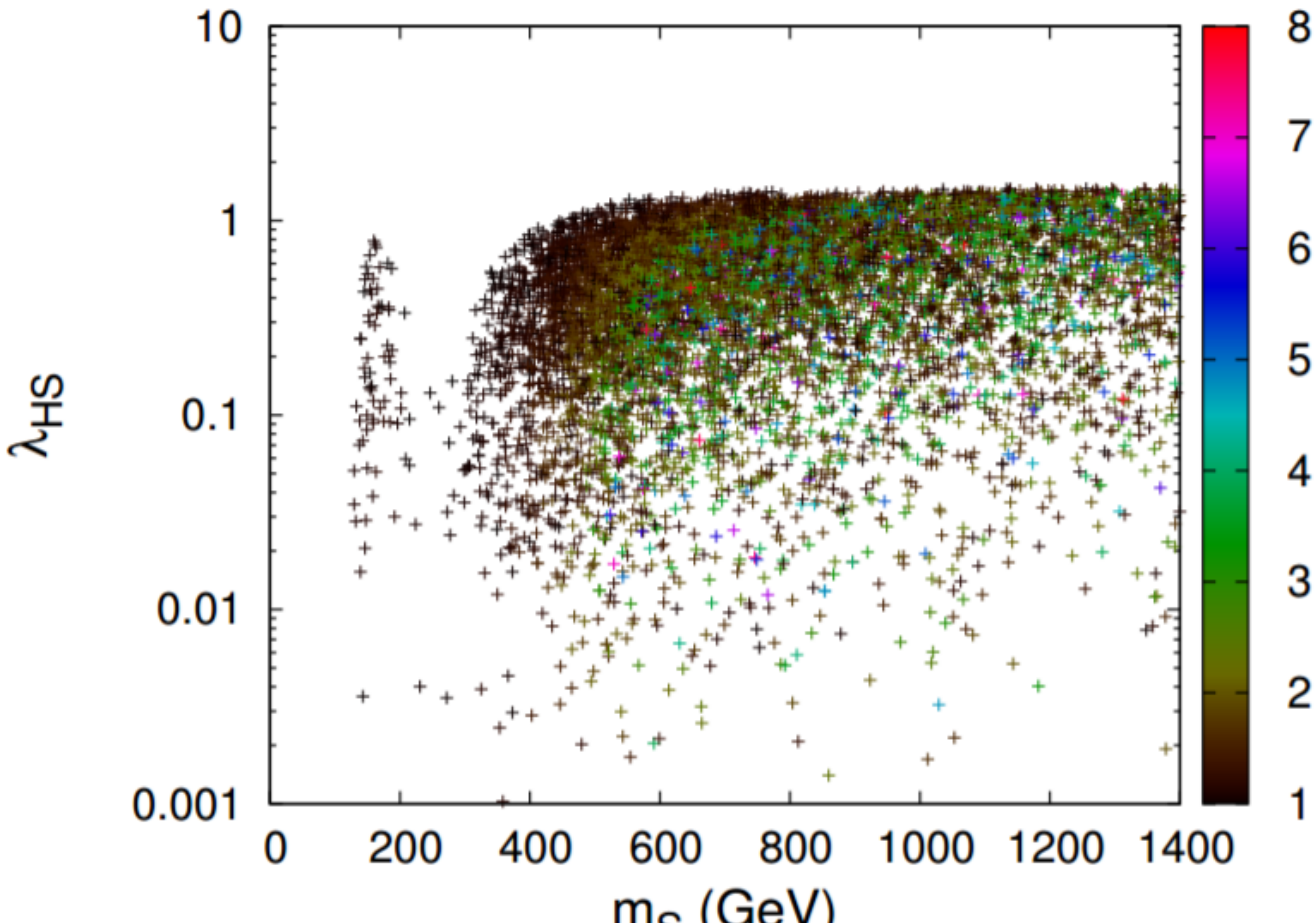


	L, ℓ_R, N_R, N_L	χ	H	S
$\mathbb{Z}_4$	i	-1	+1	i

Ahriche,SB,Nasri, 16'

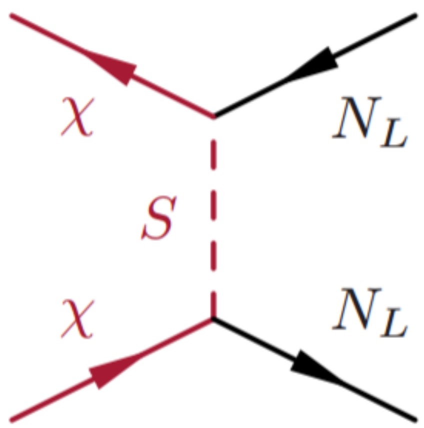
Neutrino loops, BAU, and DM

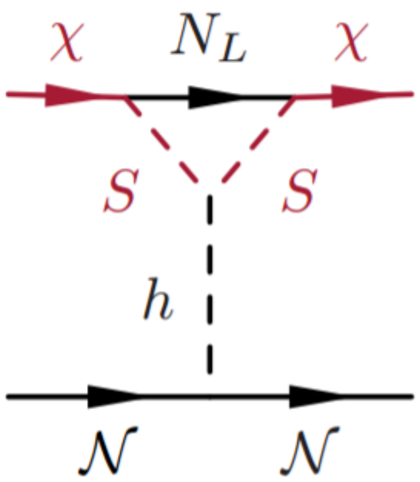
$$V = -\mu_H^2 H^\dagger H + \tfrac{1}{2}\lambda_H (H^\dagger H)^2$$
$$+\mu_S^2 S^\star S + \frac{\mu_\nu^2}{2}(S^2 + \mathrm{h.c.}) + \frac{\lambda_S}{2}(S^\star S)^2$$
$$+\lambda_{HS} H^\dagger H S^\star S.$$

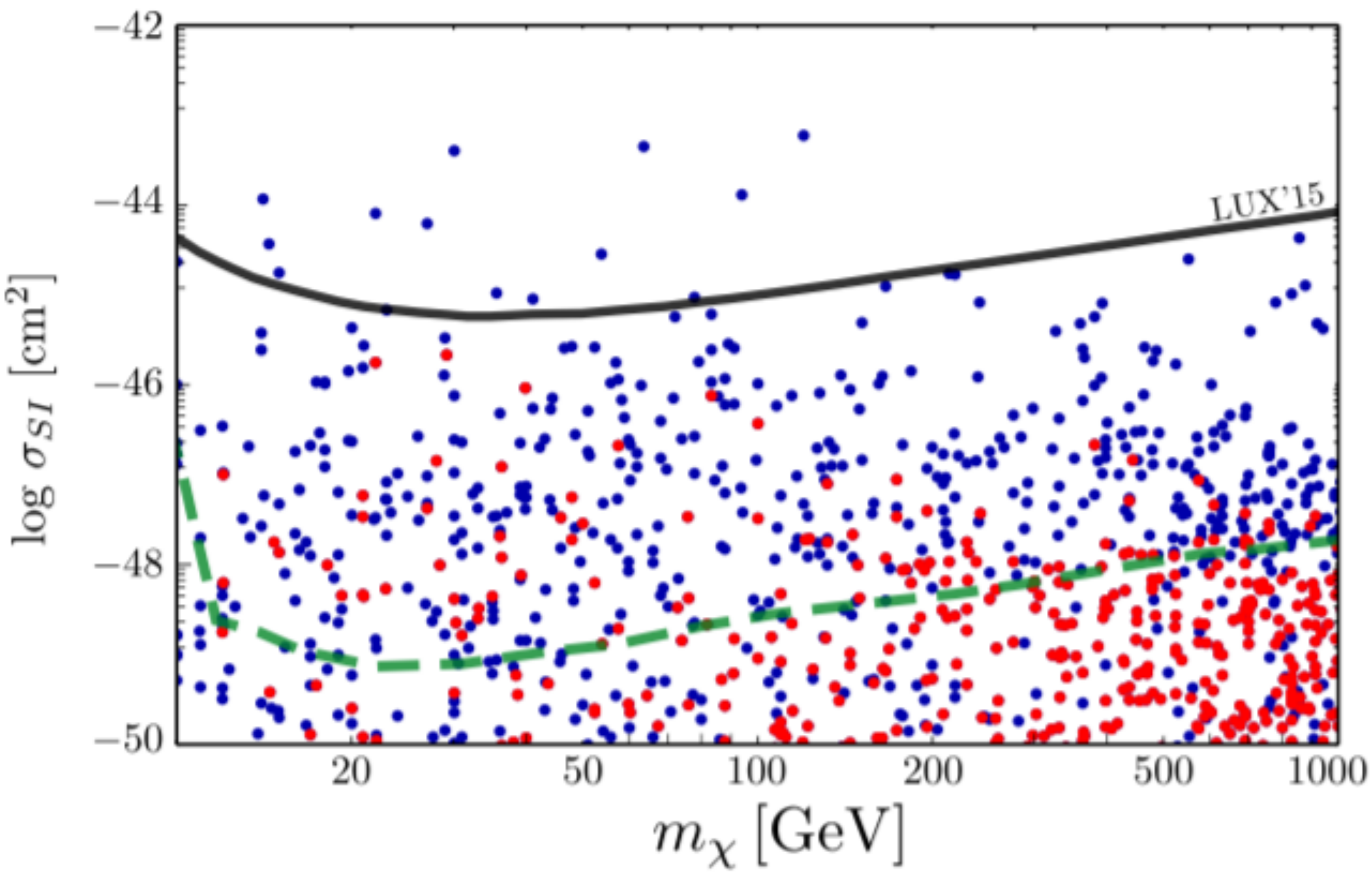


Ahriche,SB,Nasri, 16'

Neutrino loops, BAU, and DM







Ahriche,SB,Nasri, 16'

Part I Summary

- **Neutrino** masses offer a nice motivation for WIMP dark matter by justifying the parity and the particle content
- Couplings to leptons can constrain the parameter space of the DM (LFV, oscillation data,etc.)
- The required extended scalar sector can enhance the EW phase transition: BAU via electro-weak baryogenesis!

Part III/III
Inspired by asymmetry

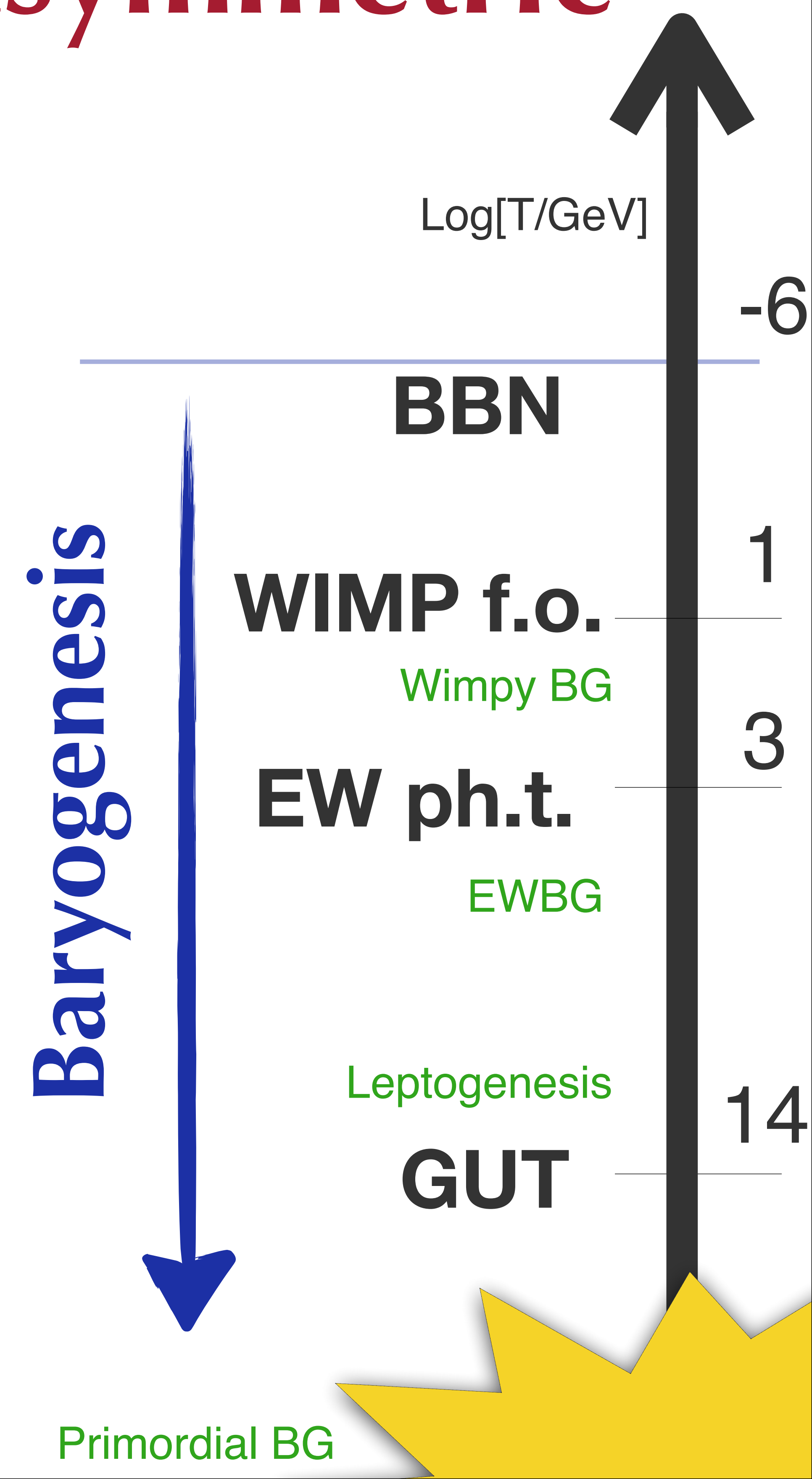
The Universe is very asymmetric

➢ No antimatter on earth, moon, solar system, Galaxy, and cosmic rays (~0.01%); No anti-planets/stars, No annihilation radiation (e.g. from Virgo); No matter-anti-matter patchwork Universe.

$$\eta_b^{CMB} = 6.2 \times 10^{-10}$$

$$\eta_b^{BBN} = 2.6 \div 6.2 \times 10^{-10}$$

$$\boxed{\eta_b^{obs} \gg \eta_b^{sym} \approx 10^{-18}}$$



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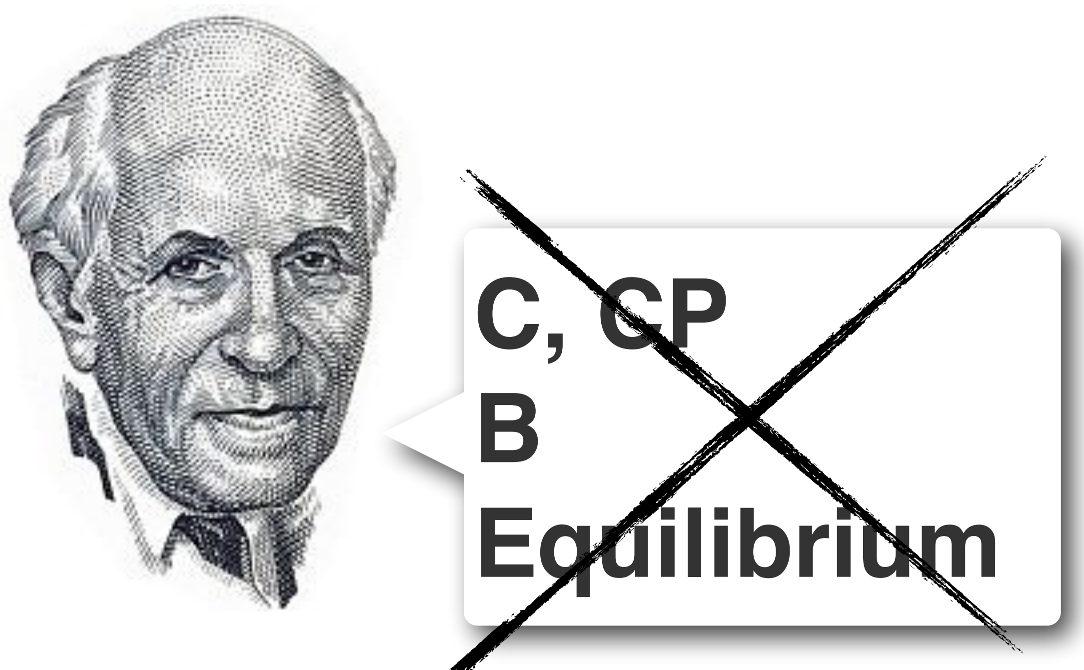
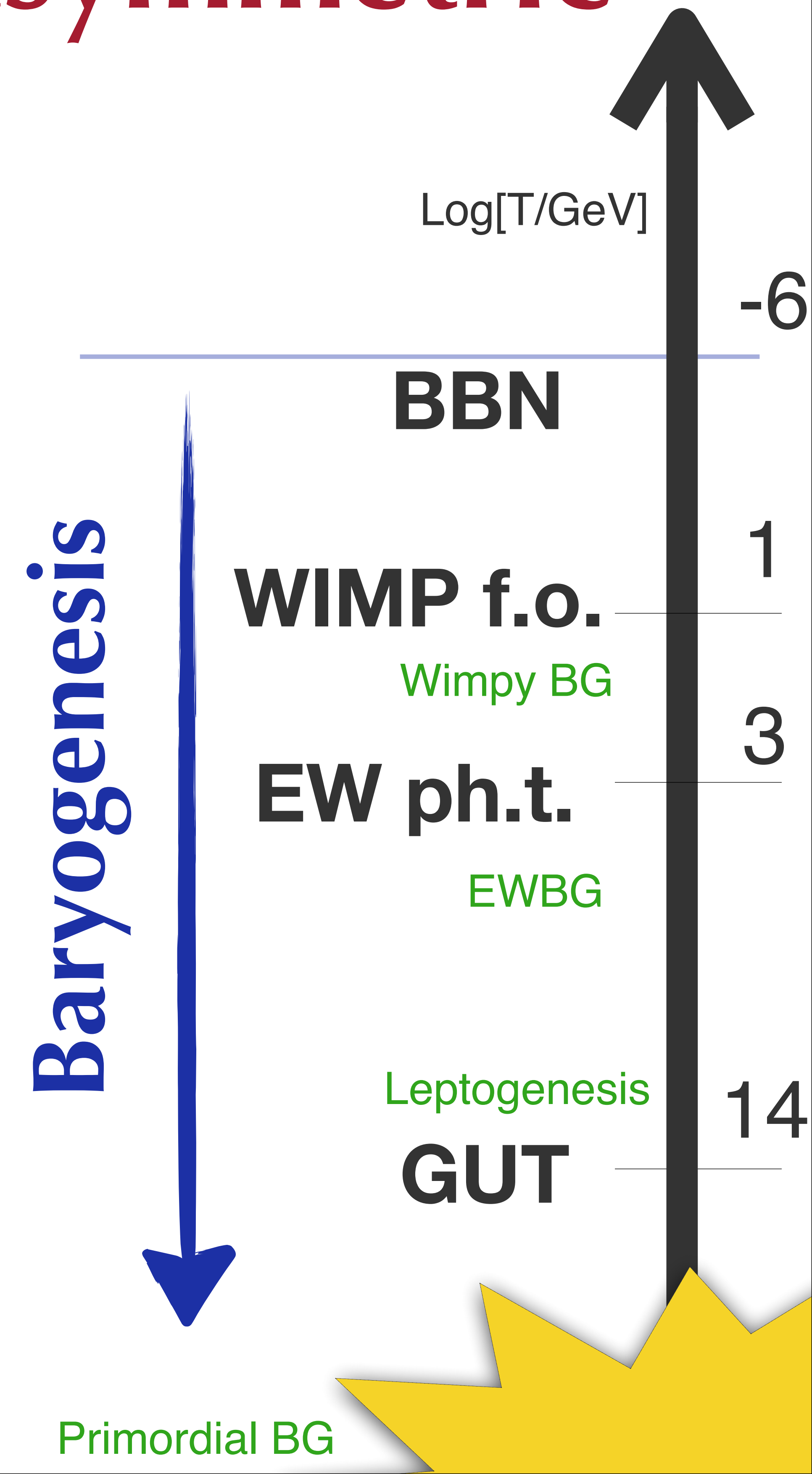
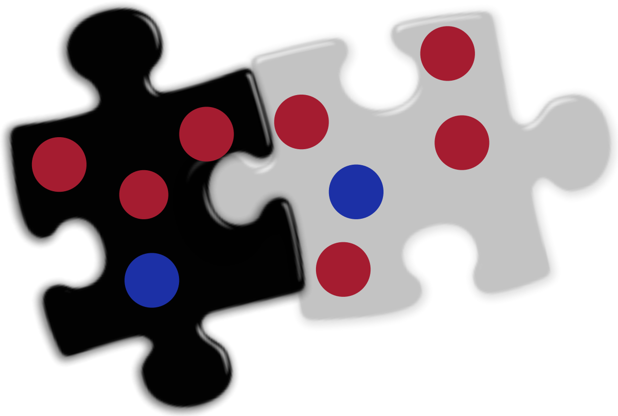


BAU offers gateway between HEP and Cosmo



Two empirical facts about matter:

1) Our Universe is quite **dark**
2) Its visible part is quite **asymmetric**



Are the dark and the asymmetric Universe related to each other?

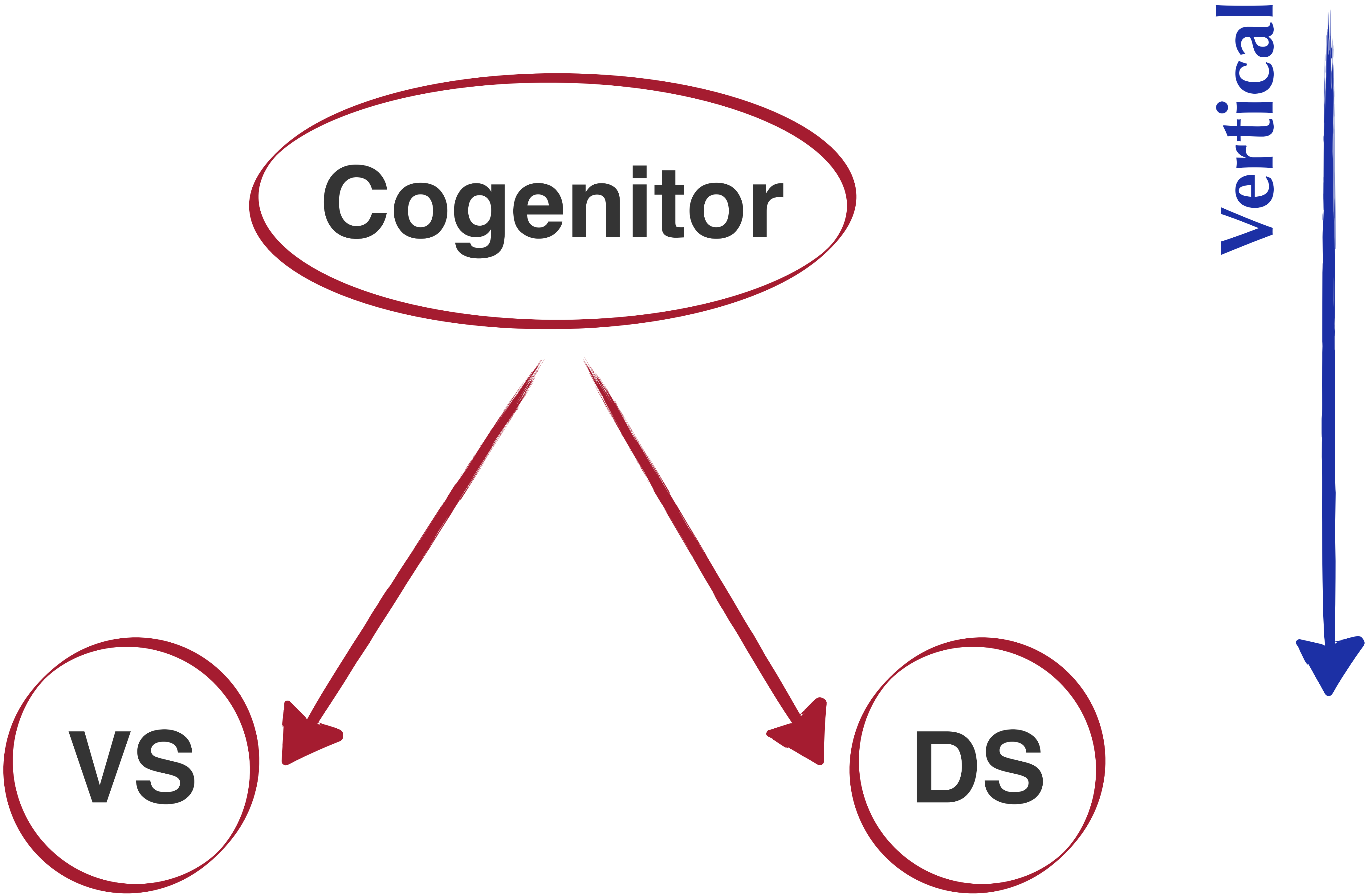
DM + BAU
A creative field of research

Darkogenesis; Aidnogenesis; Hylogenesis; Cladogenesis; Xogenesis; Pangenesis; Baryomorphosis; WIMPy [lepto]baryogenesis; Asymmetric Dark Matter; Electroweak Cogenesis; Spontaneous Cogenesis; Q-Genesis; [insert-your-favourite-Greek-prefix-here]genesis; etc., etc.

Types of connections

VS: visible sector
DS: dark sector

Review: SB, Morisi 13'



ADM models are usually of "vertical" type.

e.g., Hylogenesis [Davoudiasl, et al. PRL, 11'];
ADM leptogenesis [Falkowski, et al. JHEP, 11']

ADM

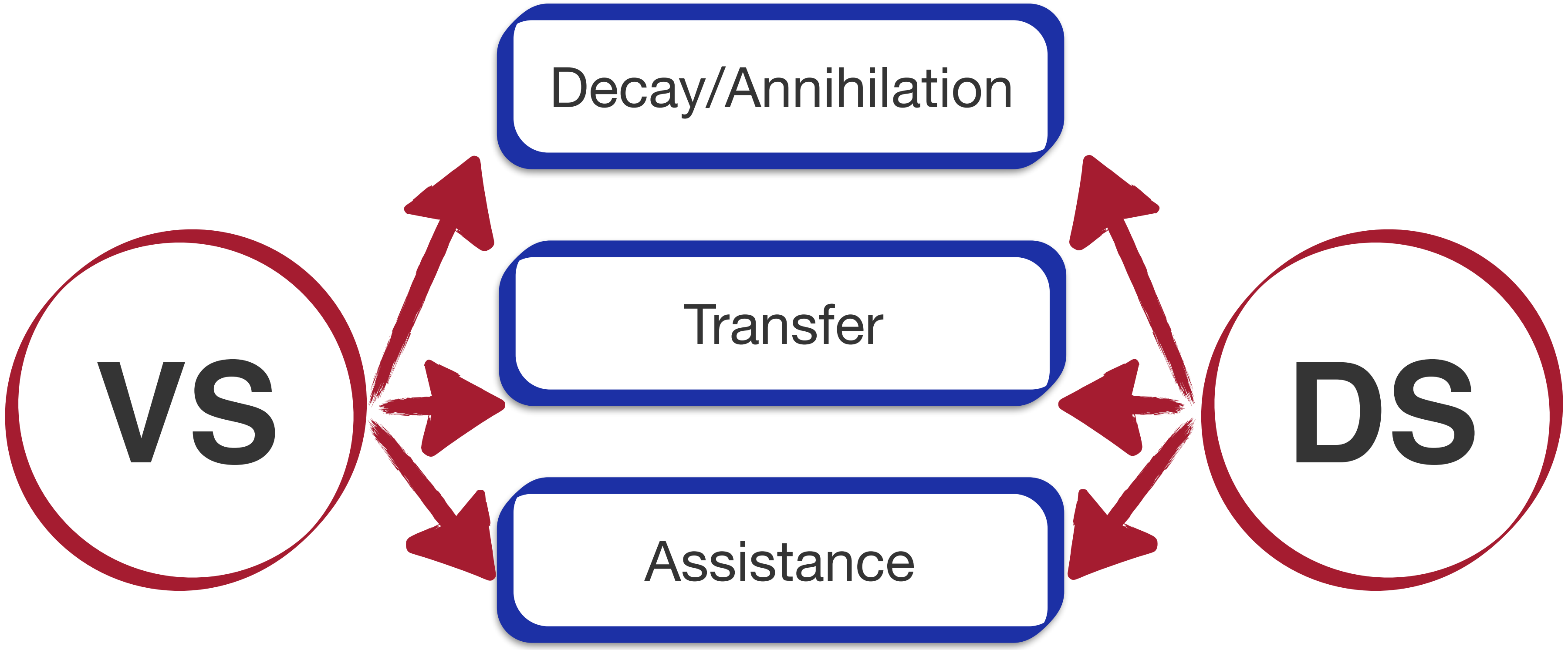
The WIMP paradigm is based on the coincidence between the observed DM density and that of weakly interacting (stable) particles.

ADM is about another coincidence,

$$\Omega_{DM} \sim 5\,\Omega_B$$

[Nussinov PLB, 85']
[Barr PRD, 91']
[Kuzmin PRN, 98']
[Foot, Volkas PRD, 04']
[Nardi, Sannino, Strumia JCAP, 05']
[Hooper,March-Russell, West PLB, 05']
[Kitano, Low PRD, 05']
[Kaplan, Luty, Zurek PRD, 09']
...

Horizontal



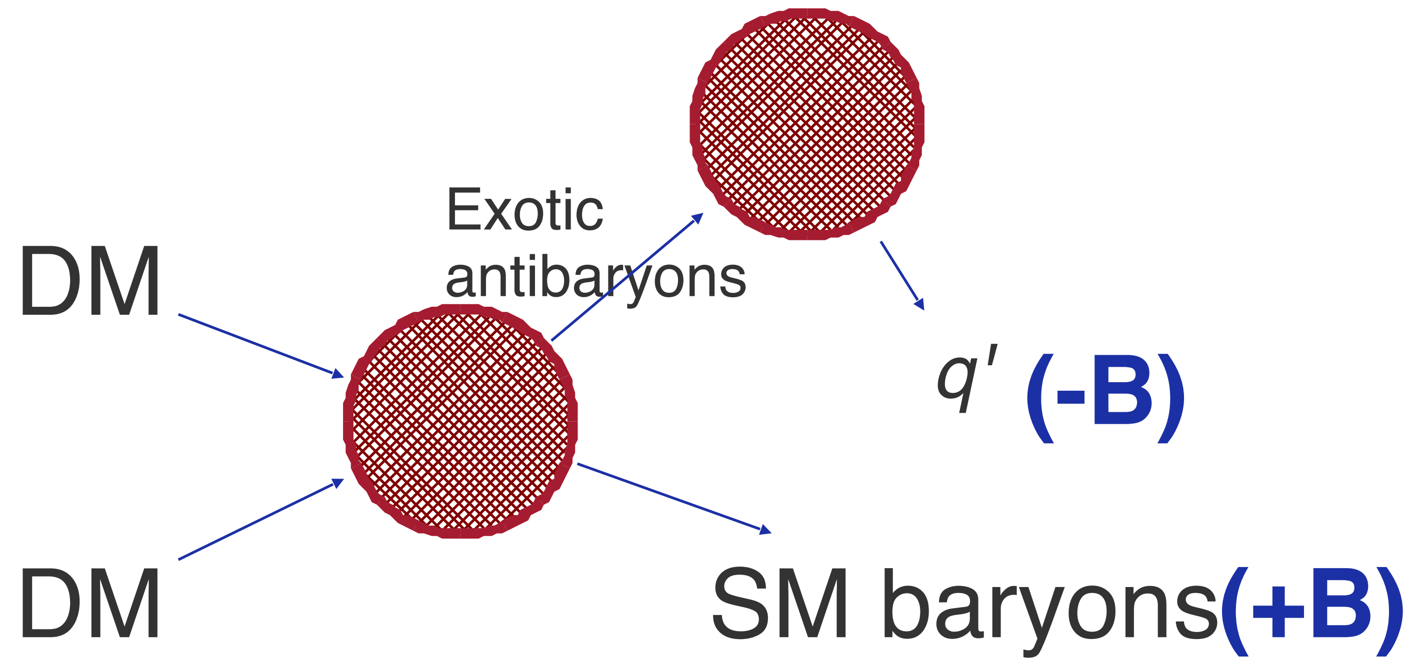
WIMP+BAU connections are usually of "horizontal" type.

Review: SB, Morisi 13'

BAU+WIMPs: WIMPy BG

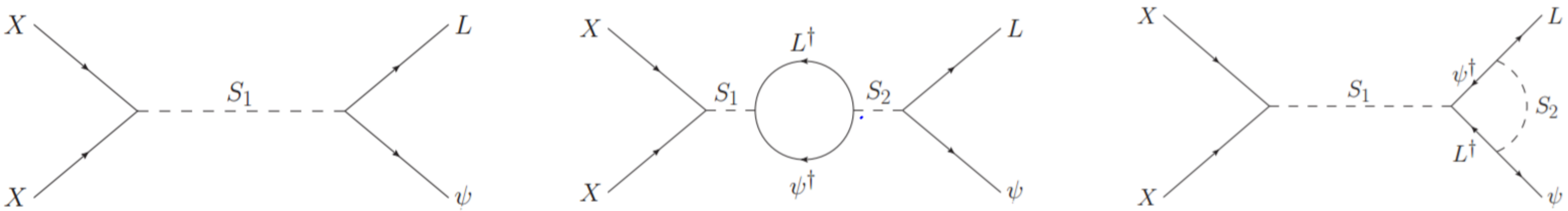
WIMPy Baryogenesis uses the conventional WIMP thermal relic scenario to generates the BAU through the WIMP annihilation.

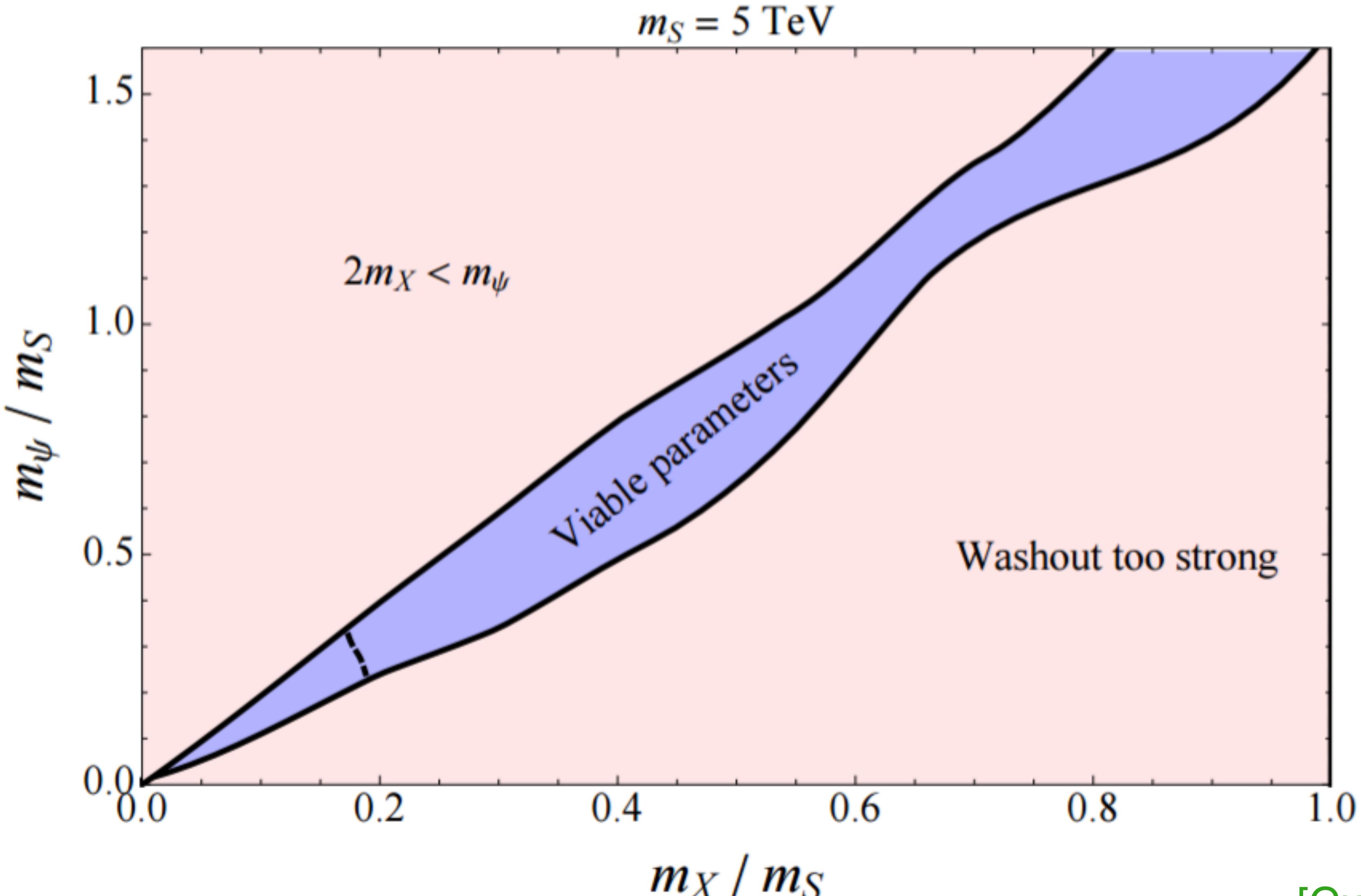
As a result, both DM and BAU are at the weak scale and the falsification/detection prospects are rich!



[Cui, Randall, Shuve, JHEP 12']

BAU+WIMPs: WIMPy BG



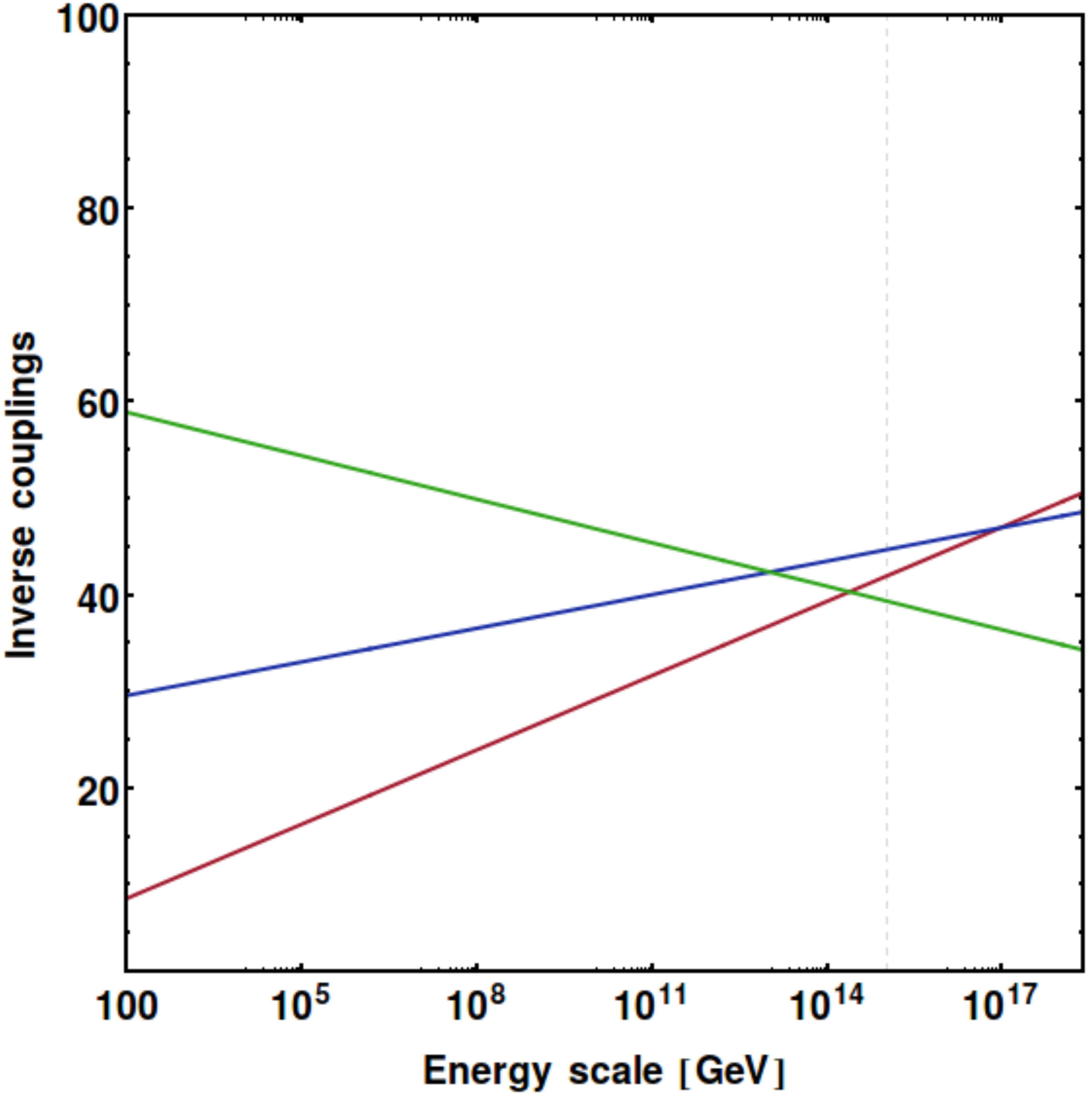


[Cui, Randall, Shuve, JHEP 12']

Part II Summary

- Taking the BAU measurement and the coincidence of dark and baryonic densities seriously leads to phenomenologically rich frameworks for WIMPs
- WIMPy baryogenesis implements Sakharov's conditions at the DM freeze-out
- Other frameworks exists, e.g., Metastable WIMPs, and Minimal Asymmetry Dark Matter.

Part III/III
Inspired by symmetry



+Other hints, e.g., Q quantization, tiny nu masses, axions.

Unification is a near-miss in the SM

GUT, in general, offer many nice features

- Unification of forces, and of quarks and leptons
- Charge quantization
- Top inspired

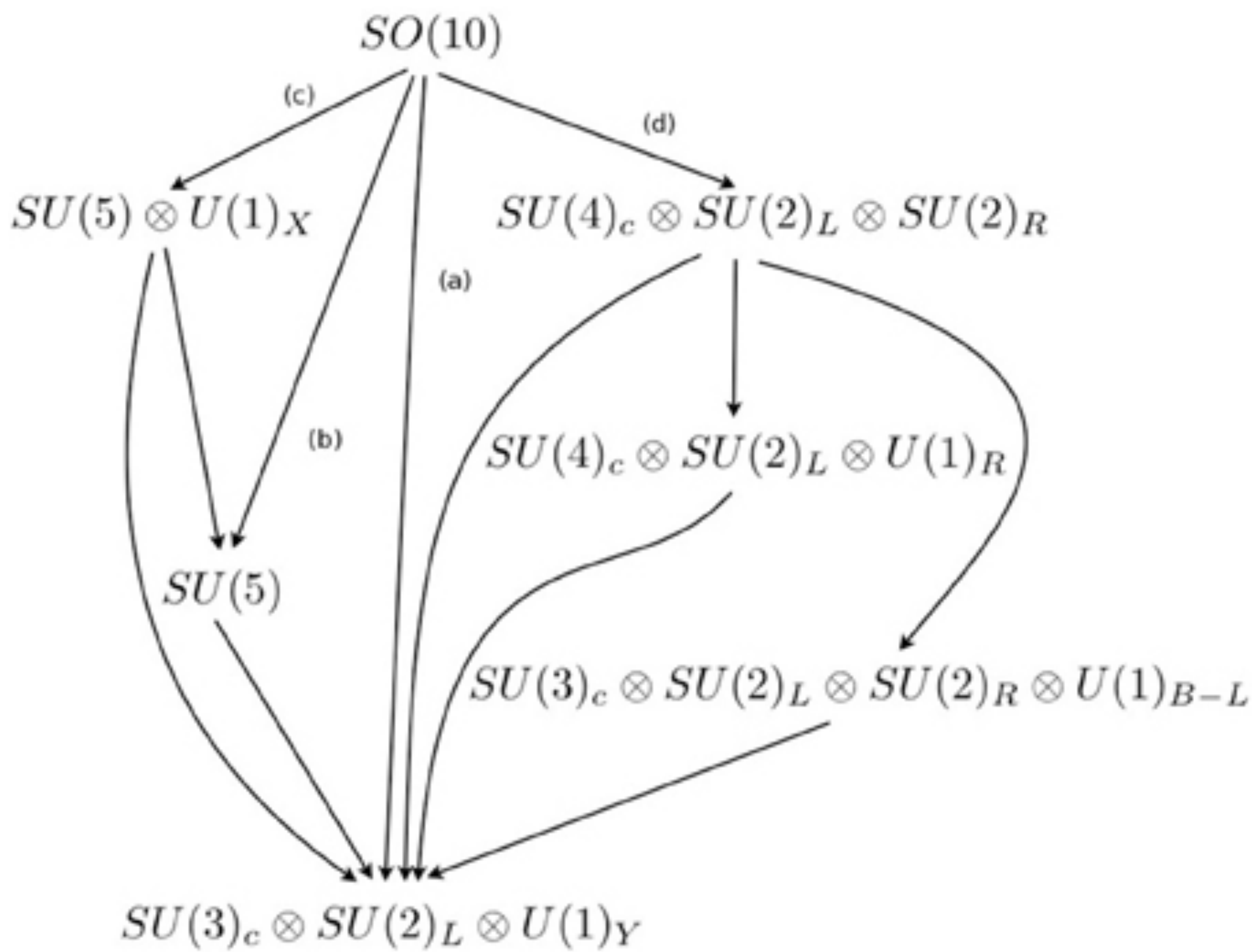
- Fermions masses and mixings
- Intermediate physical scales, e.g., LR
- Axions

- **GUT Inflation**
- **baryogenesis via leptogenesis**
- **Dark matter?**

What is SO(10)?

SO(10) is a group of rank 5, containing the SM. The adj is of dim **45**. Each generation of the spinorial rep contains the 15 SM fermions + 1 RHN per generation:

$$\boxed{\mathbf{16}^T = (Q,\ u^c,\ d^c,\ L,\ \nu^c,\ e^c)}$$



[Deppish et al., 14']

Georgi, 75'
Fritzsch-Minkowski, 75'

Why SO(10)?

Advantages

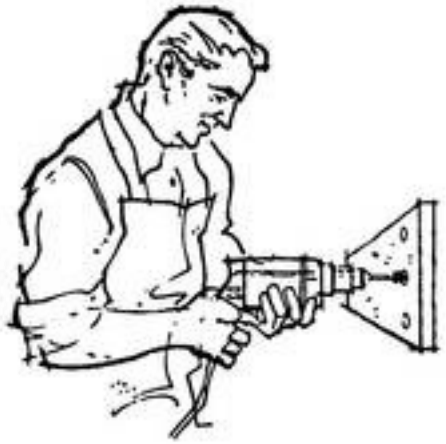
- Gauge and matter unification
- Automatic anomaly freedom
- Electric charge quantization
- **Neutrino masses** via seesaw
- Baryogenesis via **leptogenesis**
- Test: proton decay
- ...

Example of an SO(10) GUT

- The simplest non-SUSY SO(10) setup is to assume a one-step breaking: **SO(10) -> R -> SM**.
- Then, add some higgs representations, e.g.,

$$\mathcal{L}_{yuk} = 16_F(Y_{10}10_H + Y_{120}120_H + Y_{126}\overline{126}_H)16_F.$$

- Fit for SM parameters and impose gauge coupling unification constraint (+ eventually baryogenesis via leptogenesis).

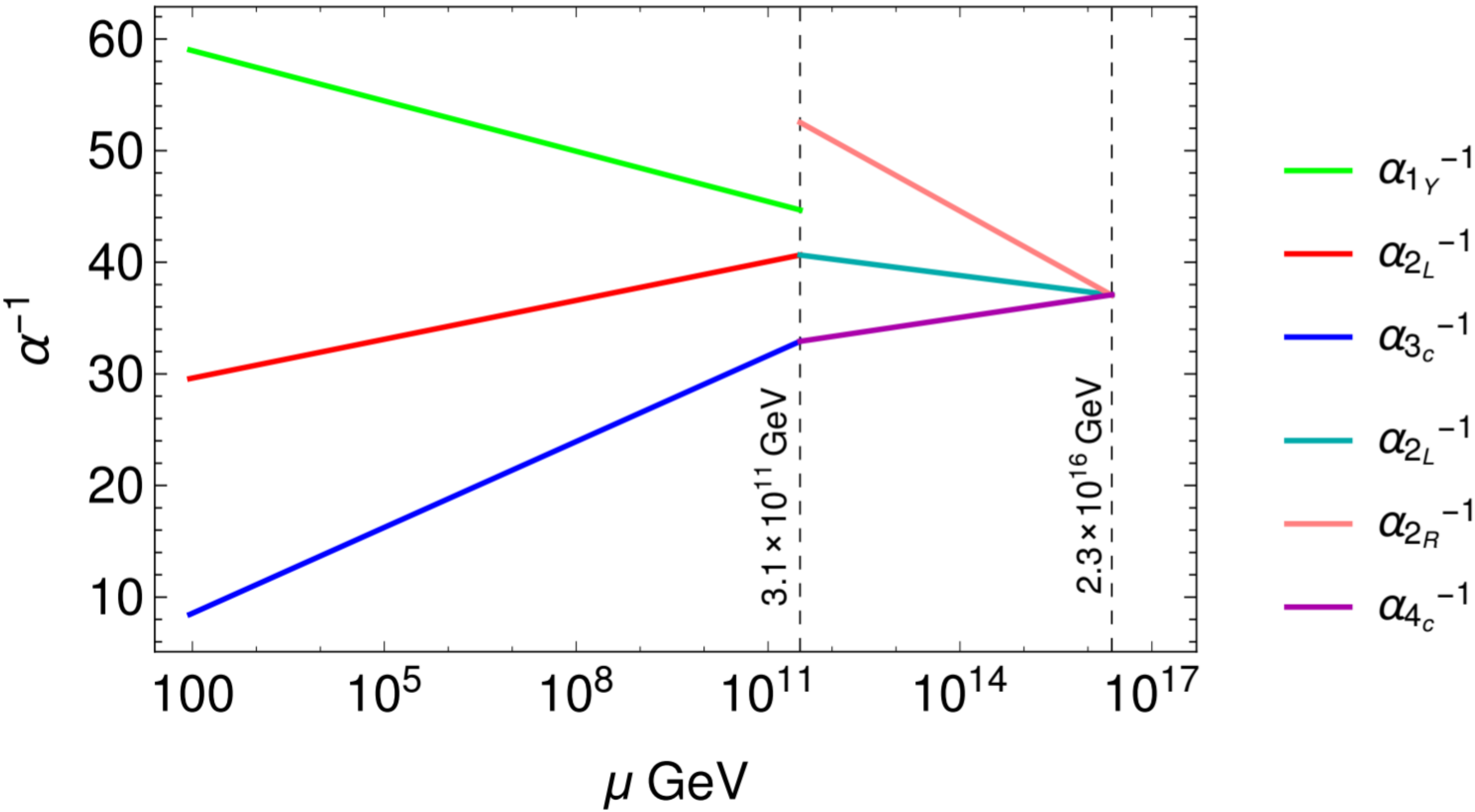


Example of an SO(10) GUT

Quark sector			Lepton sector		
Observable	μ_i	g_i	Observable	μ_i	g_i
m_d (GeV)	$1.72 \cdot 10^{-4}$	2.25	m_e (GeV)	$4.88 \cdot 10^{-4}$	-0.0597
m_s (GeV)	0.0178	2.40	m_μ (GeV)	0.103	-0.111
m_b (GeV)	2.89	0.0441	m_τ (GeV)	1.75	-0.0744
m_u (GeV)	$1.53 \cdot 10^{-3}$	-0.572	$r \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$	0.0298	-0.0695
m_c (GeV)	0.620	$-7.15 \cdot 10^{-3}$	$\sin^2 \theta^\ell_{12}$	0.309	0.0484
m_t (GeV)	172	-0.0197	$\sin^2 \theta^\ell_{13}$	0.0216	0.0183
$\sin \theta^q_{12}$	0.225	$3.11 \cdot 10^{-3}$	$\sin^2 \theta^\ell_{23}$	0.441	-0.0454
$\sin \theta^q_{13}$	$3.46 \cdot 10^{-3}$	0.126			
$\sin \theta^q_{23}$	0.0420	$-9.29 \cdot 10^{-3}$			
$\delta_{\mathrm{CKM}}\,(\pi)$	0.387	$1.27 \cdot 10^{-3}$			

Meloni, Ohlsson, Riad, 17'

Example of an SO(10) GUT



Babu, Bajc, Saad '17

Why SO(10)?

Spin(10) offers some interesting hidden symmetries. E.g., those appearing in the Yukawa sector could be related to the flavor problem.

One symmetry stands out: **Spin(10)** (as all **Spin(4n+2)** groups) has a ***Z*₄** center. We can therefore partition the collection of *irreps* according to the action of the central elements and obtain 4 congruence classes:

$$\begin{array}{cccccc} \mathcal{Z} & : & \psi & \to +i & \psi \\ & : & \overline{\psi} & \to -i & \overline{\psi} \\ & : & \phi_{2n+1} & \to - & \phi_{2n+1} \\ & : & \phi_{2n} & \to + & \phi_{2n} \end{array}$$

$$\begin{array}{ccccc} \mathcal{Z}^2 & : & \psi & \to & -\psi \\ & : & \phi & \to & +\phi \end{array}$$

Kibble, Lazarides, Shafi, 82'
C.f. also O'raifeartaigh, 86'

If no spinor (16,144,..) breaks Spin(10): Remnant parity - Stable particles!

The SO(10) parity

	SO(10) reps.	DM candidates (SM)	$\mathbb{Z}_2$
Fermions	**10,** **45, 54, 210** **126** **...**	**(1,2,**1/2**)** **(1,1,**0**)+(1,3,**0**)** **(1,1,**0**)**	**+**
Scalars	**16, 144** **...**	**(1,1,**0**)**	**-**

[From **16.10.16**, with **16** odd and **10** even:
new fermions (scalars) are stable if even (odd)]

Simplest possibility: 10.

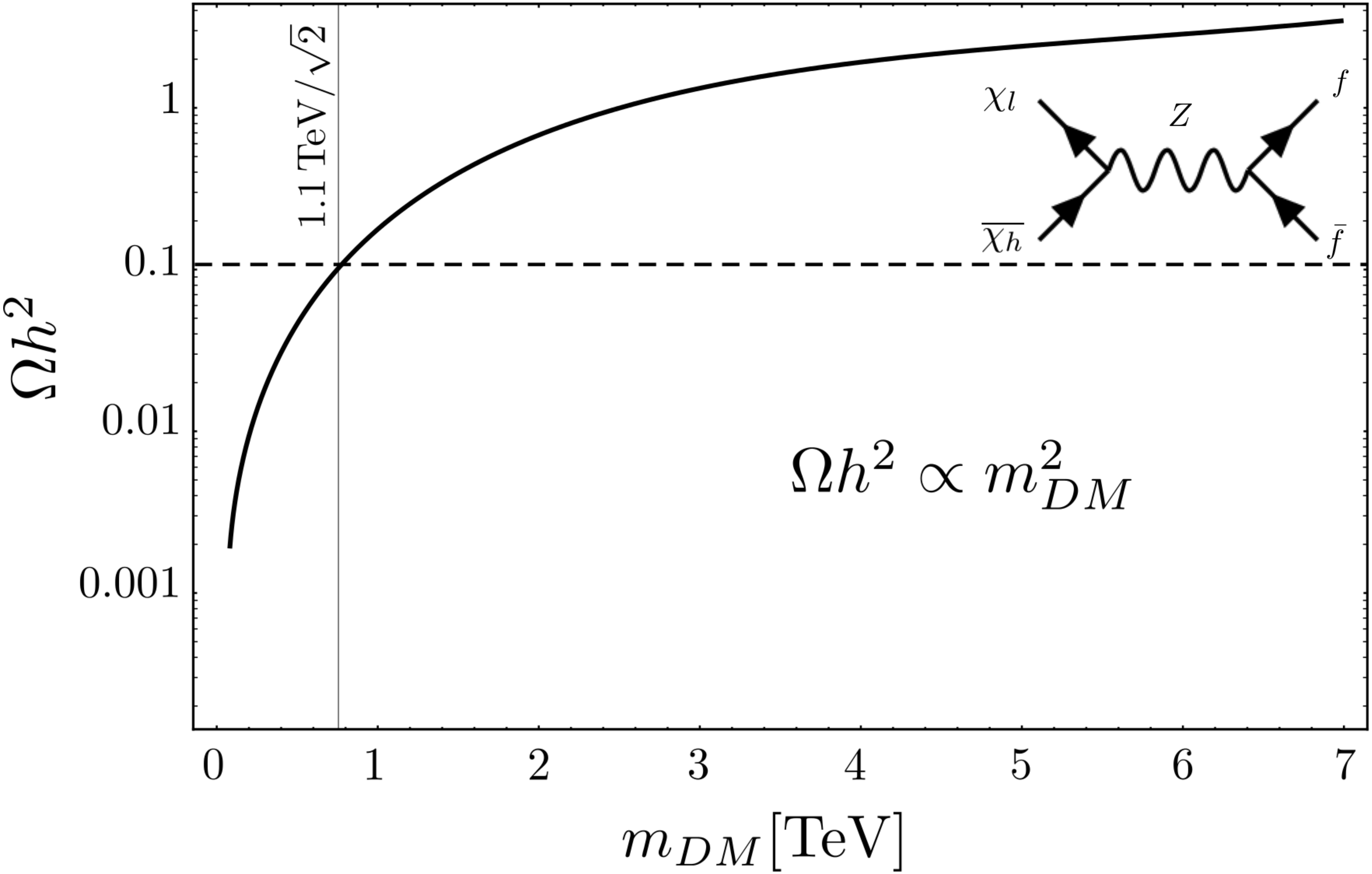
The **10** of SO(10) offers the simplest possibility to include DM in realistic models. The fermionic 10 representation contains an SU(2) doublet: higgsino-like DM.

However, due to the rich gauge structure of the GUT, this low energy doublet interacts via new gauge bosons as well.

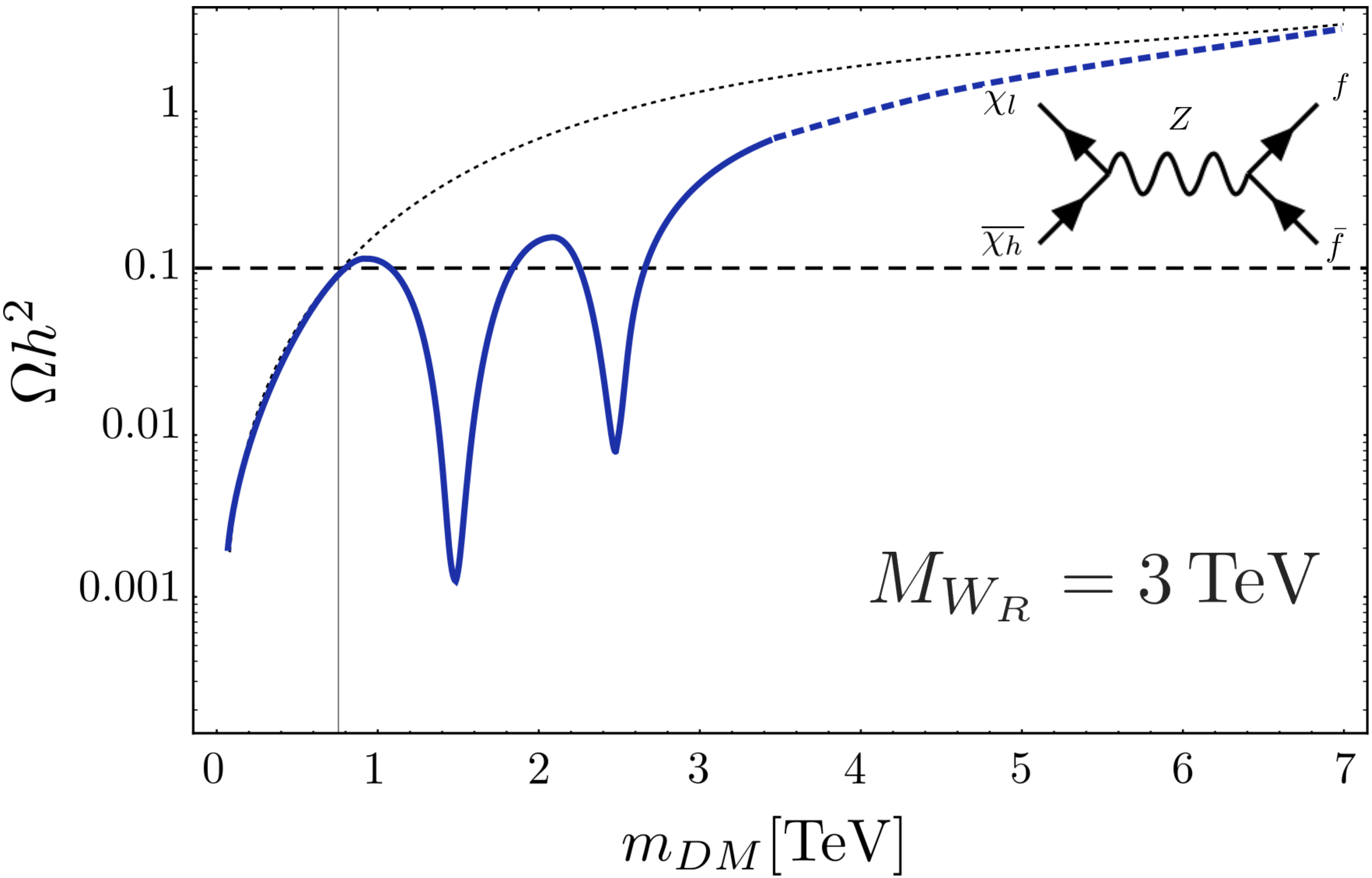
This leads to enhanced phenomenological predictions.

[SB, Nardi, Krauss, 16']

DM from 10 of SO(10) - Relic density



DM from 10 of SO(10) - Relic density



Part III Summary

- **SO(10)** provides a natural framework to motivate WIMP DM. The pheno is rich with possible interplays with neutrino masses, BAU, unification, inflation, and new mass scales.
- Simplest possibility consists of adding a **10**plet, leading to a bi-doublet DM. Direct detection bounds force the LR r scale to be low: testable scenario; interplay DD/ID/LHC.

Summary

Summary

- **LHC** has pushed weak-scale SUSY to constrained corners
- WIMPs can be motivated from neutrino and BAU physics: further constraints on their parameter space
- **SO(10)** models offer a rich and appealing framework to motivate WIMP DM and explain neutrino masses and baryon asymmetry

Tack!