

# Beyond the Standard Model

## Lecture 1

*European School of HEP, St Petersburg*

Veronica Sanz (Sussex & Alan Turing Institute)

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**US**

University of Sussex

The  
Alan Turing  
Institute

# Let's recap

You already had an intense week!

*QFT and use of symmetries*

**(Bednyakov)**

*aspects of BSM physics*

DM, Axions **(Rubakov)**

CPV and Flavour **(Vysotsky)**

Higgs **(Ellis)**

Neutrinos **(Gonzalez-Garcia)**

*and what the LHC can do for us* **(Boyd)**

And now we are going to learn BSM in more breadth

# Why BSM?

## Empirical evidence of BSM

(What we cannot deny)

Neutrinos

Dark Universe

Matter-antimatter asymmetry

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## Rationale for BSM

(More subjective)

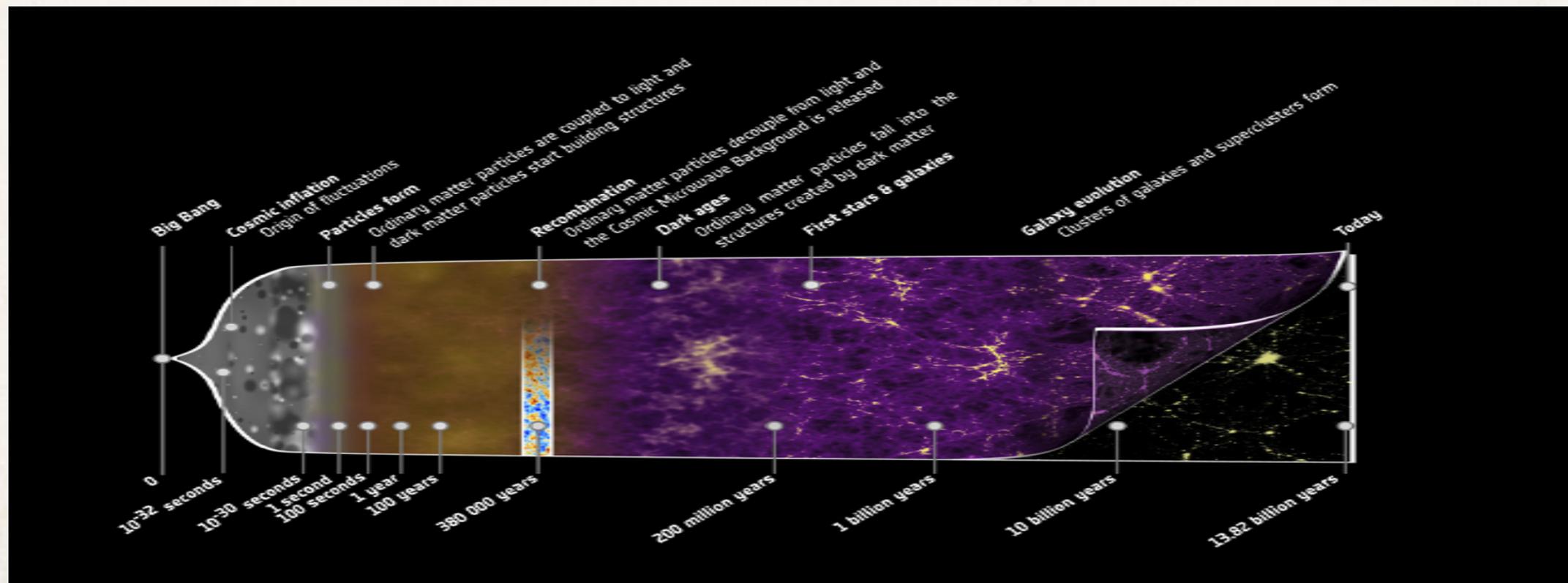
Motivations for new physics which are not based on experimental evidence, but instead on QFT knowledge and our **views** on how is implemented in Nature  
e.g. **naturalness** or **gauge coupling unification**  
or *end-of-the-road*: **perturbative unitarity**

# A body of knowledge

**Empirical evidence of BSM  
(Neutrino, Dark Universe, Asymmetry)**

*None* of these discoveries  
possible within Particle Physics  
need **Cosmology, Astrophysics and Nuclear Physics**  
to understand

**Expanding Universe, Solar model,  
Astrophysical production and propagation etc**



# A body of knowledge

Empirical evidence of BSM  
(Neutrino, Dark Universe, Asymmetry)

## ONE ATTITUDE

Particle Physics, Earth-based experiments

*Truly fundamental, true probes of Nature*

whereas others

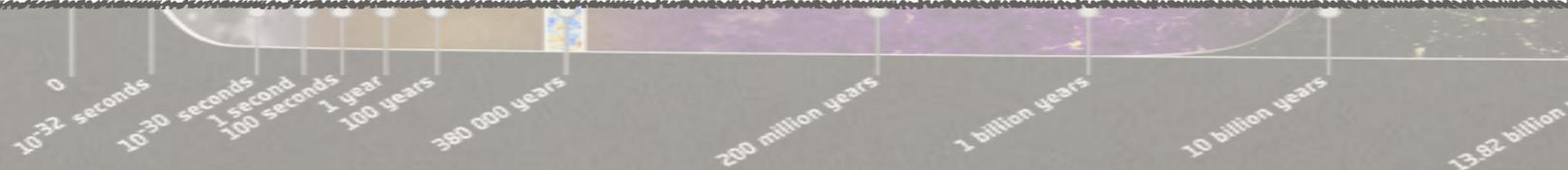
quantitative, modelling, uncontrollable sources

## ANOTHER ATTITUDE

Big gains at intersections among areas

Any source of information needs to be considered  
as progress may come from any direction

Don't pigeon-box yourself!



In these lectures

## BSM

1. Evidence

(DM, Neutrinos, Baryogenesis & Inflation )

2. Rationale

(Example of Naturalness)

3. Models for the Higgs and beyond

(Supersymmetry & Composite Higgs)

4. Looking ahead

# Evidence

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# Hard-core BSM evidence:

## Let's start with Dark Matter

### Dark Matter in a nutshell

- ❖  $\sim 1/4$  of the current Universe
- ❖ *likely* a particle
- ❖ dark: no coupling to EM
- ❖ massive (cold,  $> 10$  KeV)
- ❖ no color interactions
- ❖ stable

# Dark Matter

Strong evidence of some form of gravitational source  
consistent with the existence of a new sector BSM

## **Astrophysical/cosmological**

rotation curves

structure formation (e.g. simulations)

dynamical events, e.g. galaxy mergers

CMB (Planck) ...

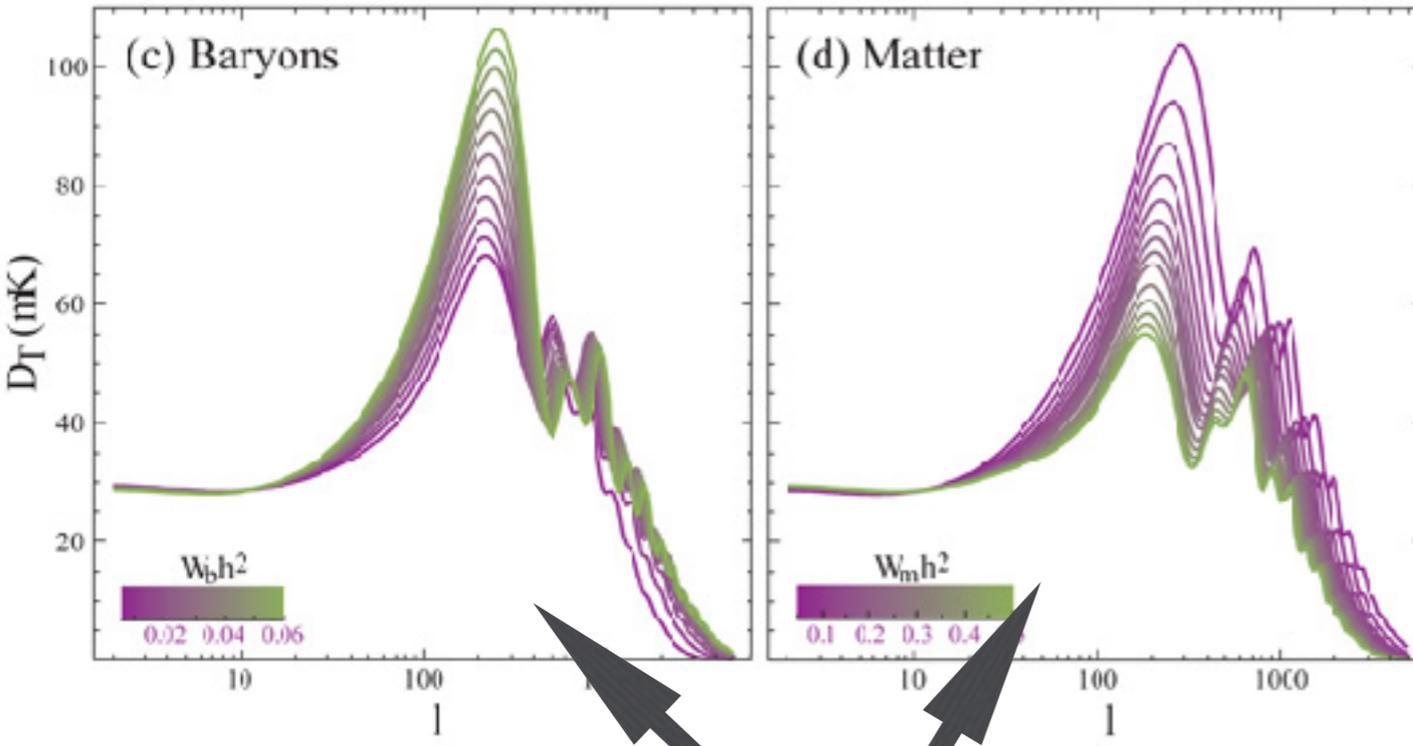
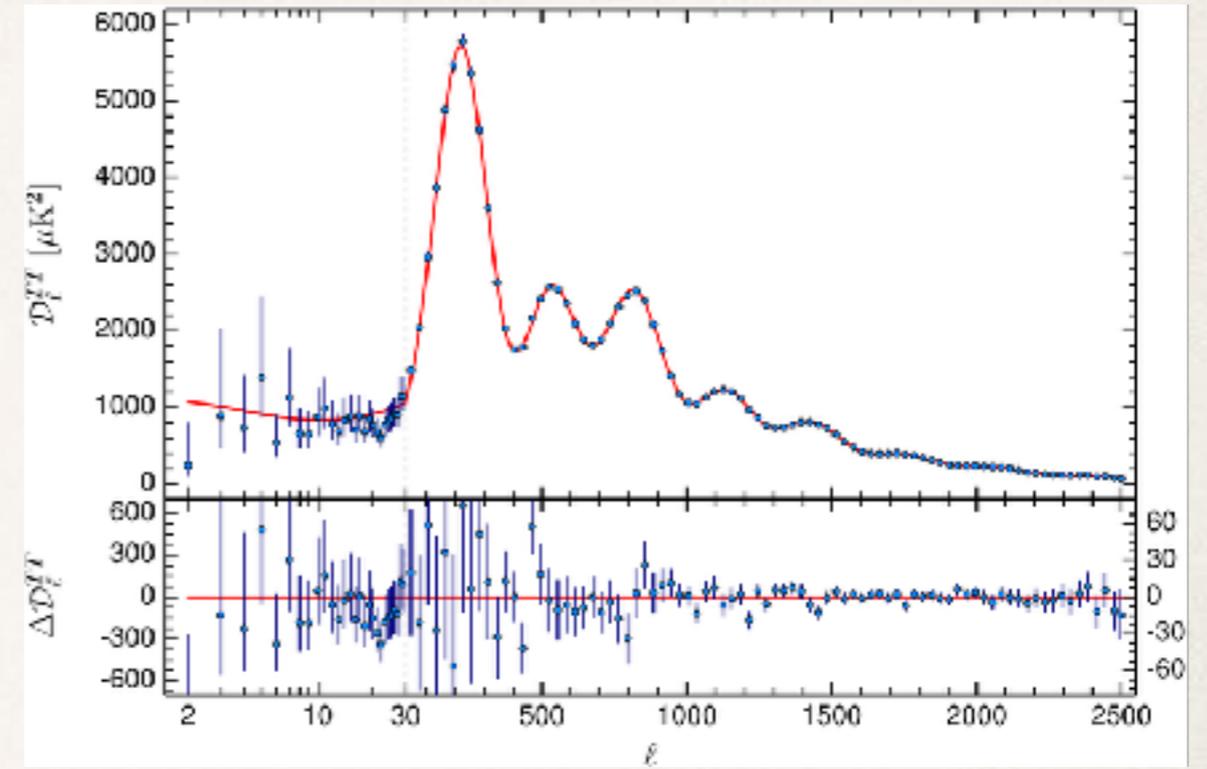
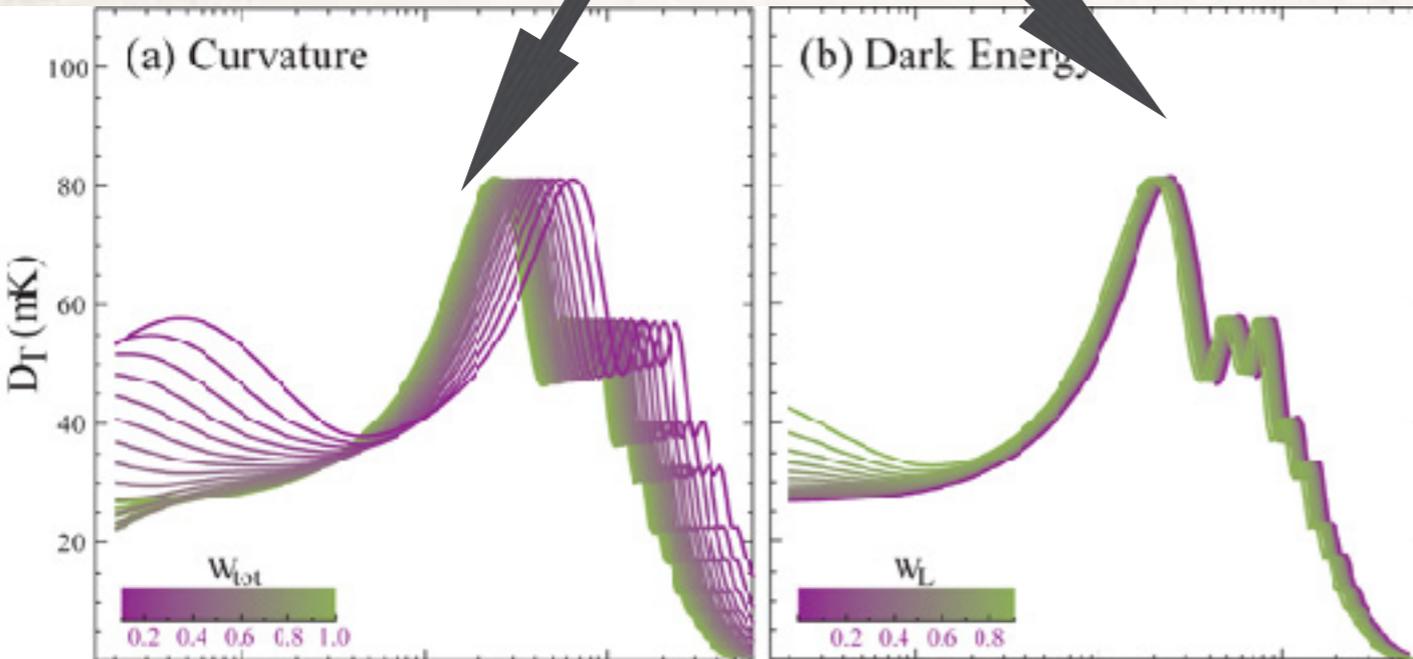
No evidence so far of other interactions

**Direct detection** experiments

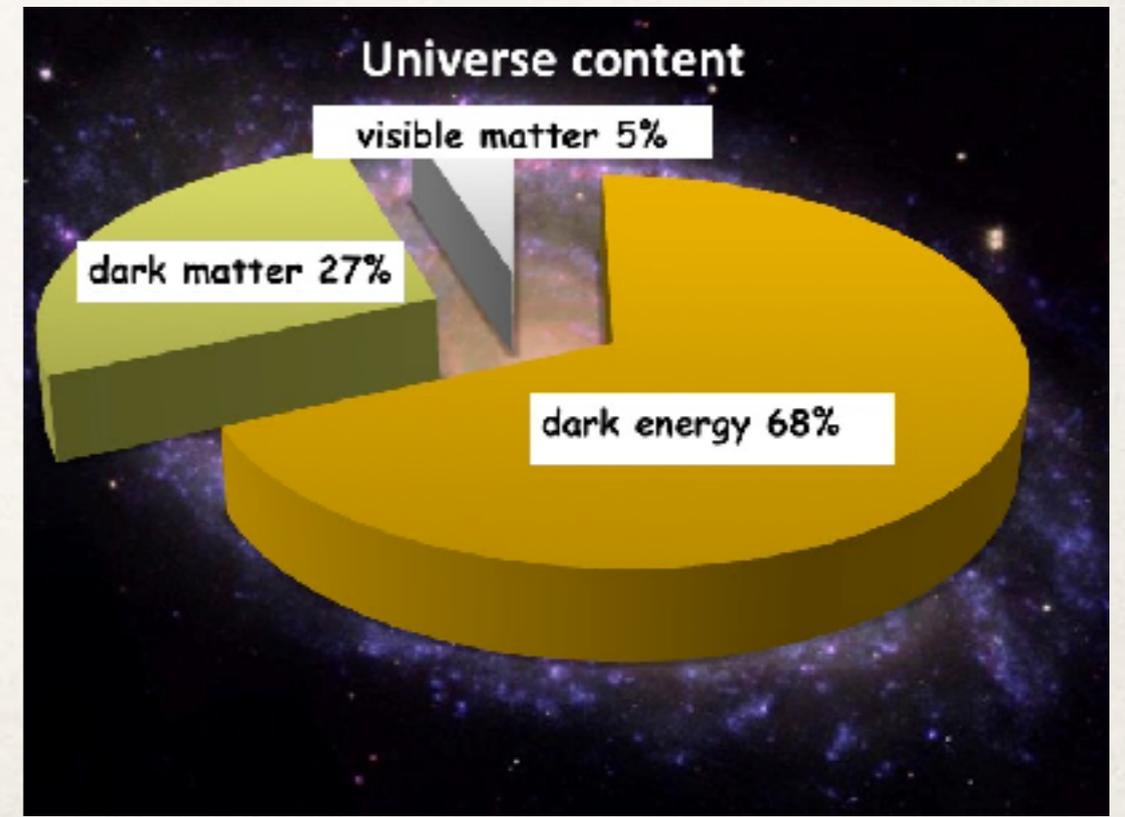
**Indirect detection** via production of SM particles

# Dark Matter: CMB evidence

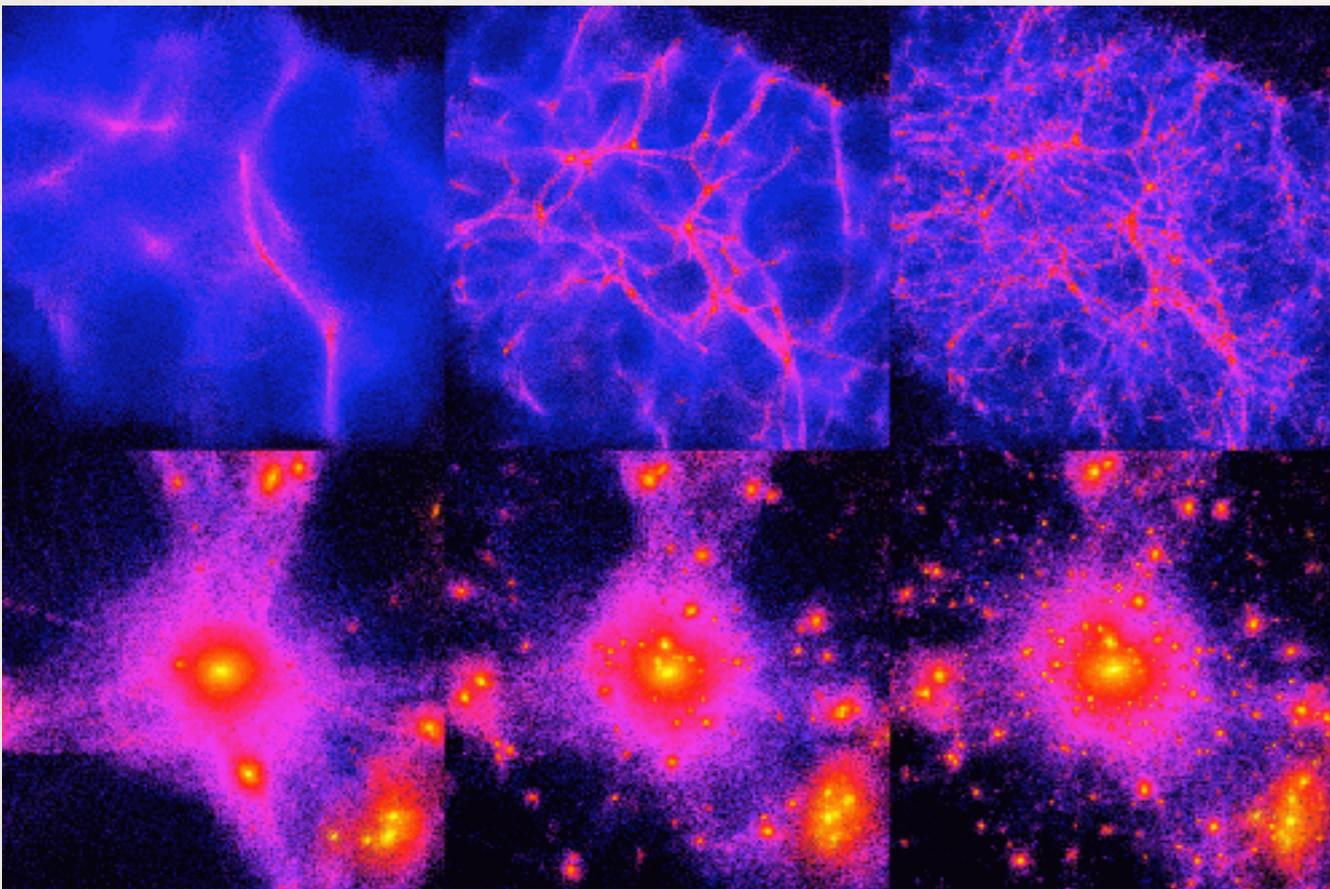
position



shapes



# Dark Matter: simulations, mergers

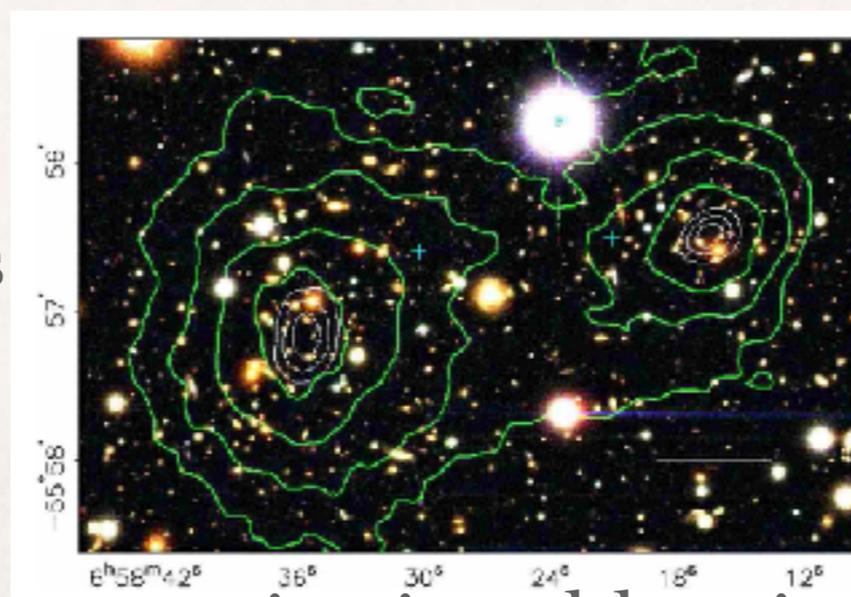


(hot, warm, cold)

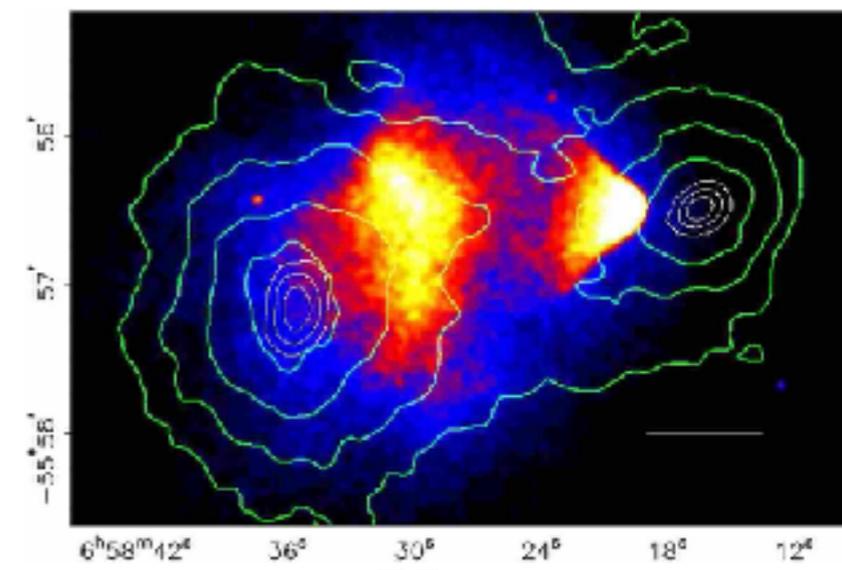
hotter DM dissolves *small* structures, only big survive and they collapse slowly  
not what we observe

warm (KeV) and/or cold (GeV)

dynamical processes  
maps of DM, strong tests  
of MOND vs CDM  
info on self-interactions



gravitational lensing



X-ray

# Archetypical Dark Matter

**E.g. SUSY Neutralino**

*(Tomorrow we will learn more on SUSY)*

**Massive:** mass comes from SUSY breaking

**Weak state:** SUSY partner of neutral Z or Higgs

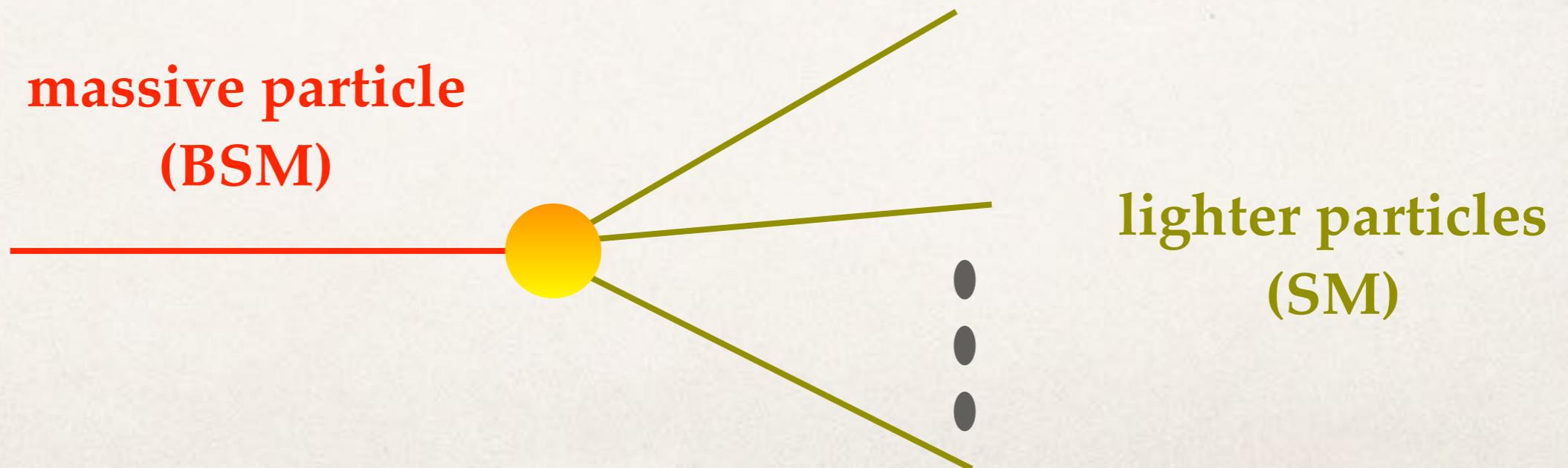
**Stable:** Consequence of a remnant symmetry

(Symmetries for DM: typically parities (R-parity))

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## STABILITY



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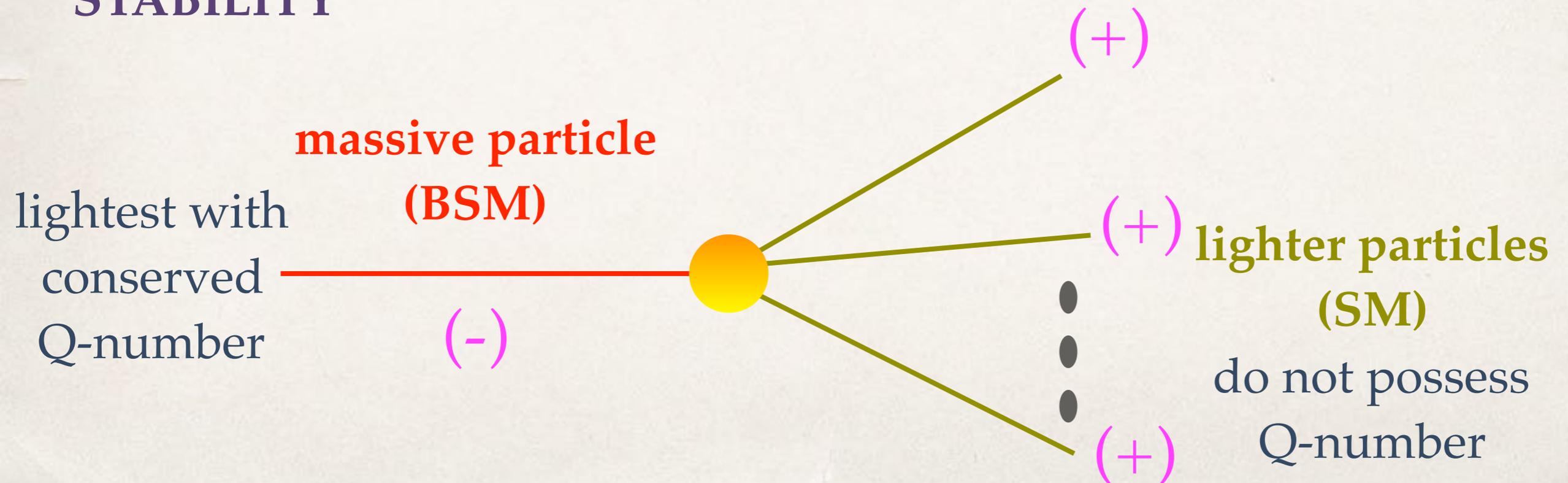
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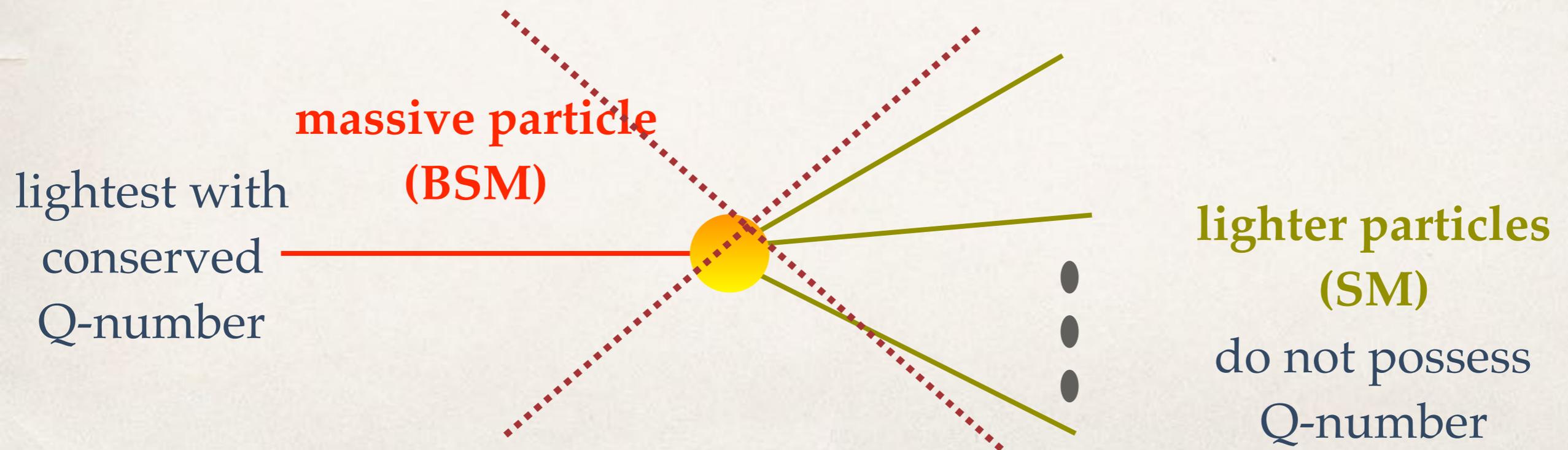
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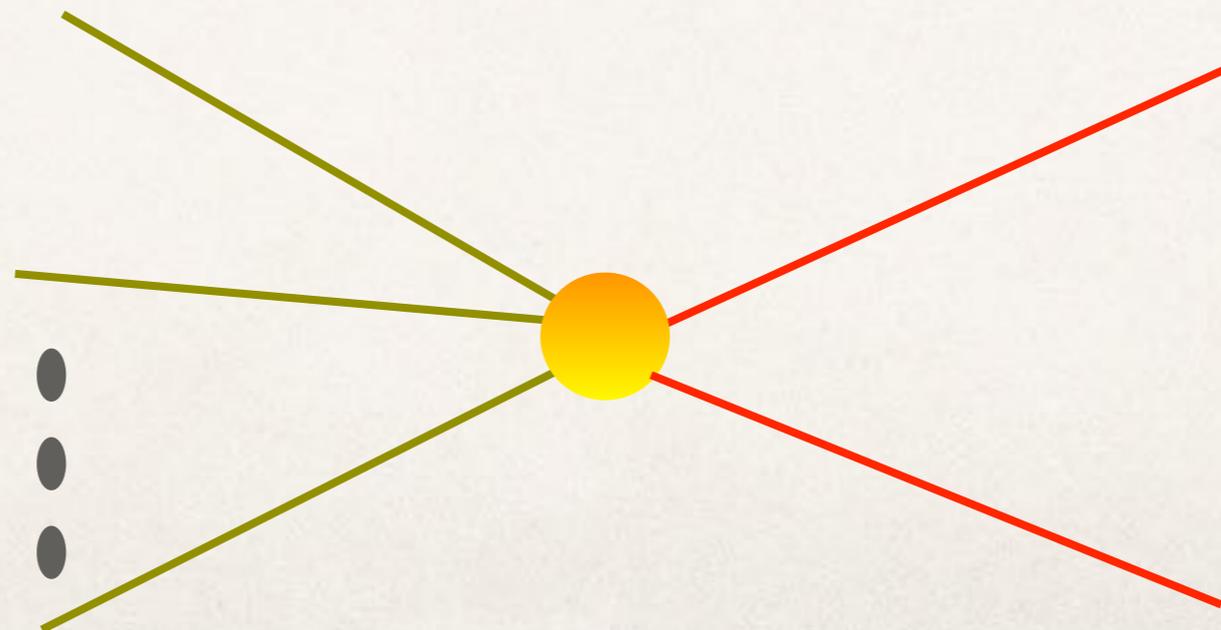
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## DIRECT DETECTION

EW SM states

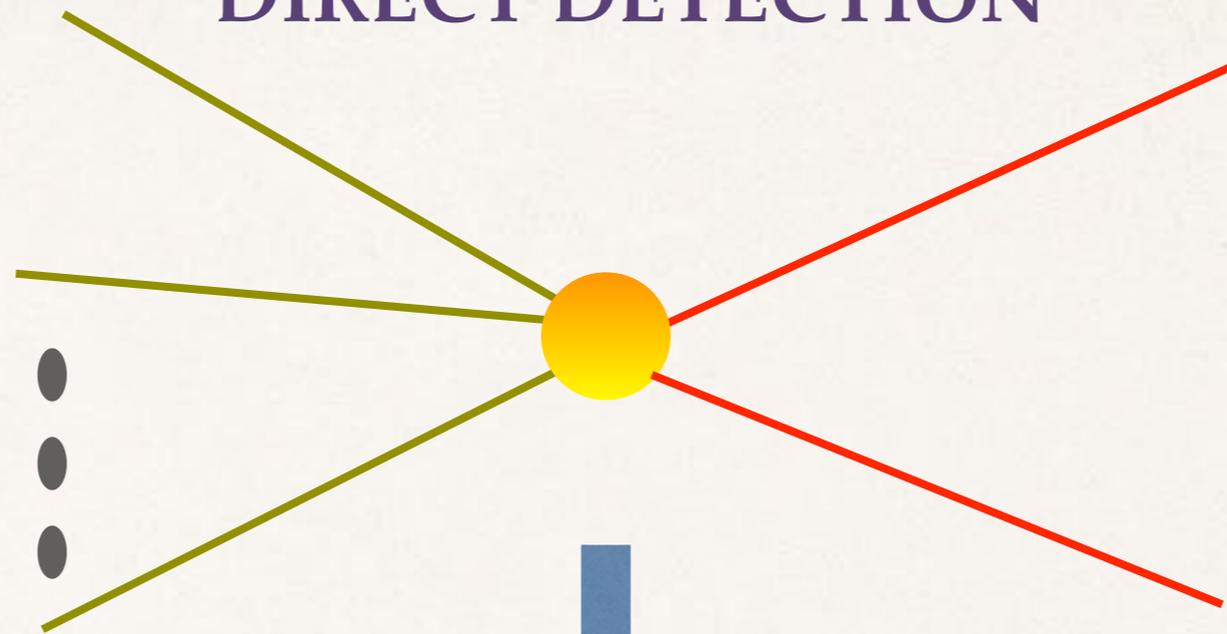


pair production  
BSM

# Archetypical Dark Matter

## DIRECT DETECTION

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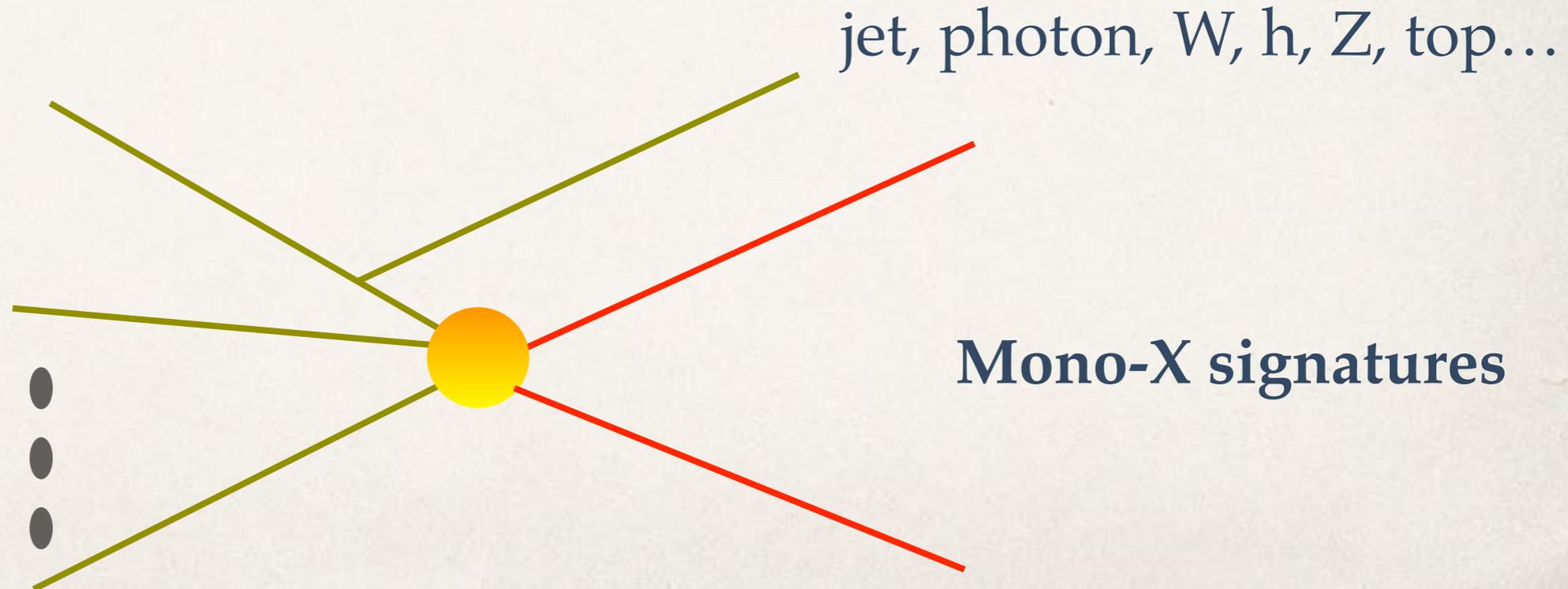


pair production

BSM

Neutral particle  
Escapes detection

EW SM states

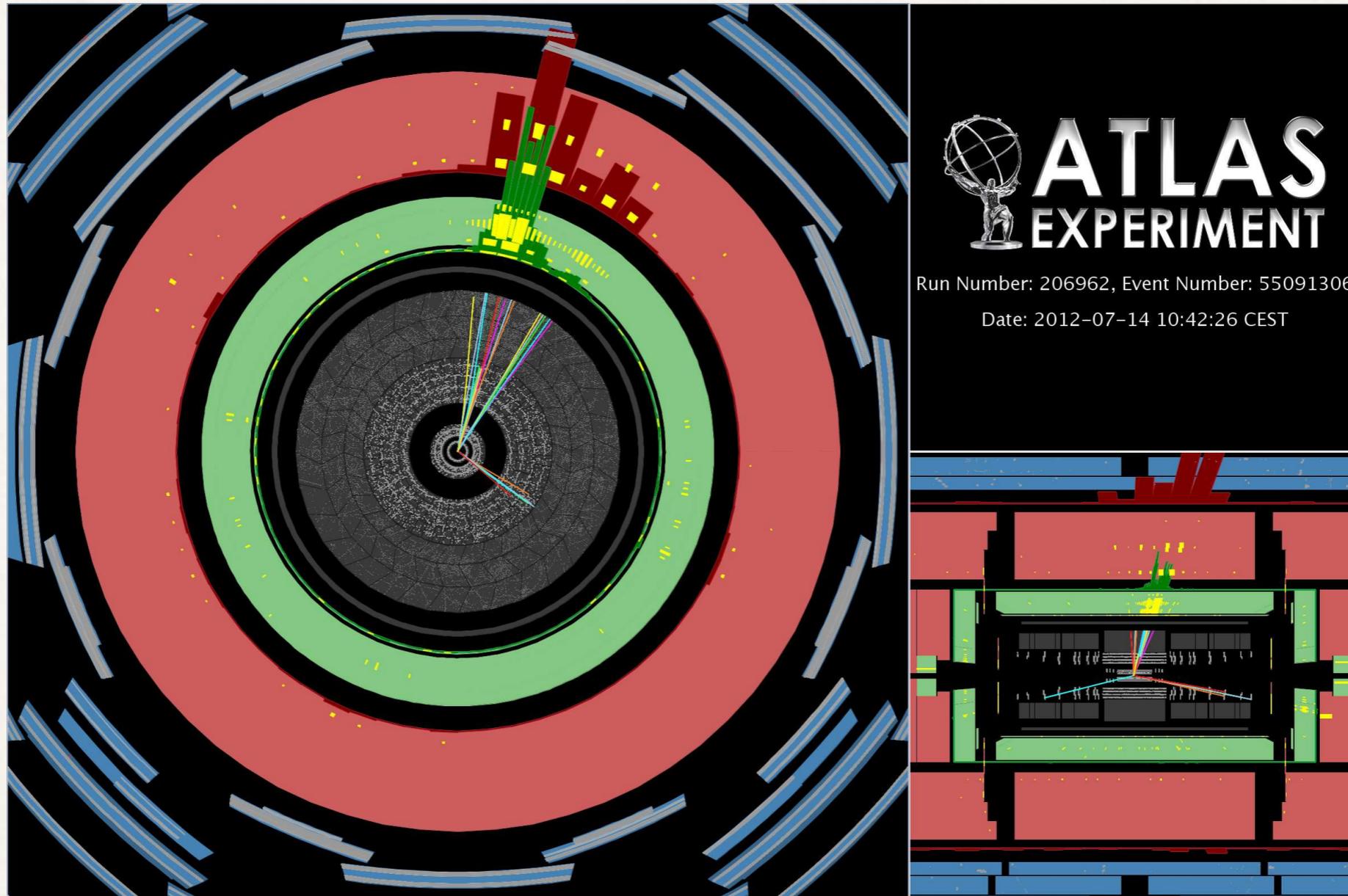


jet, photon, W, h, Z, top...

Mono-X signatures

# Archetypical Dark Matter

## DIRECT DETECTION

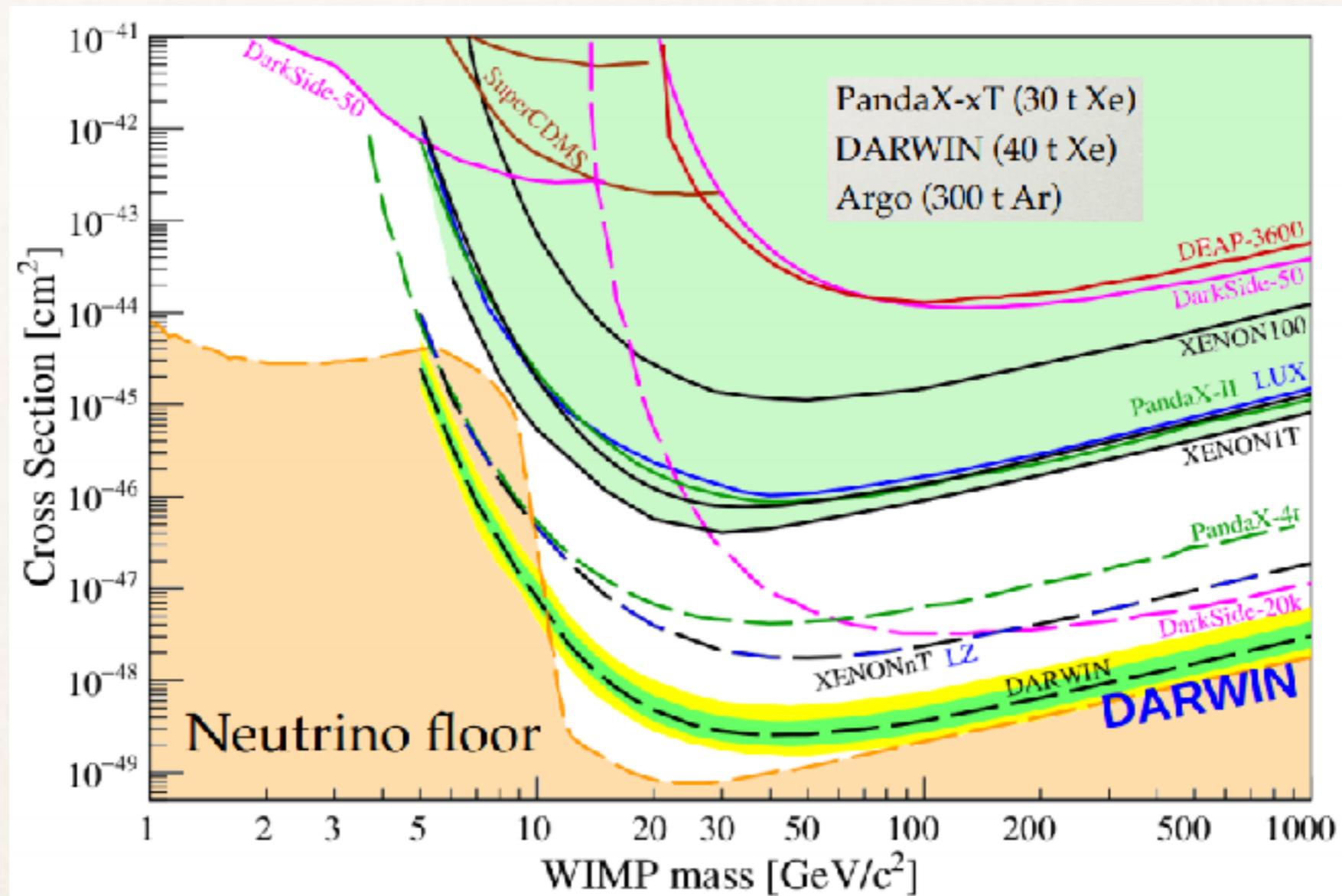


# Archetypical Dark Matter

## INDIRECT DETECTION

Recoil instead of production

interactions  
with nucleons



mass

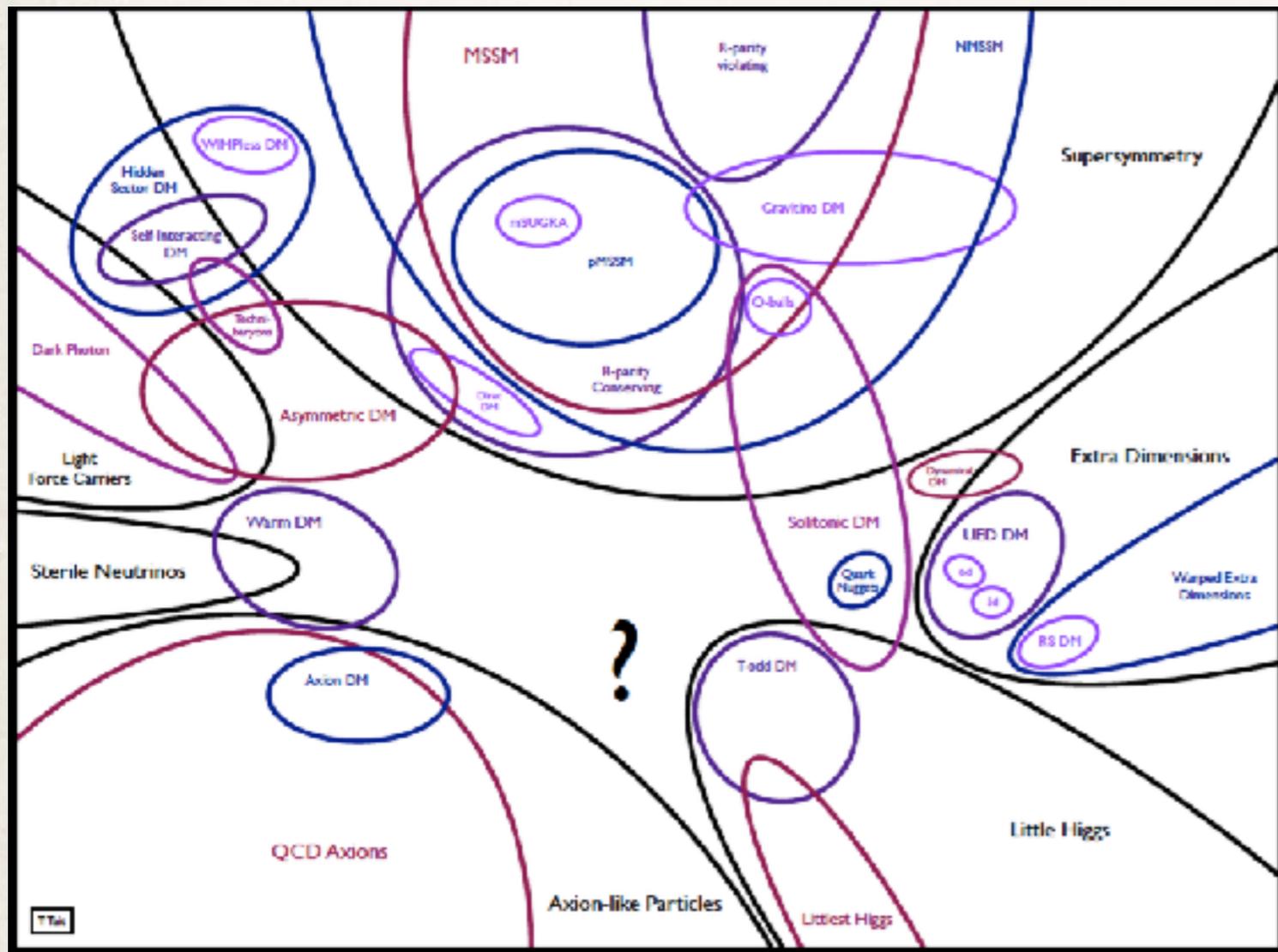
# Many theory possibilities for Dark Matter

For a long time, DM as a thermal WIMP was a *paradigm*

Model building: WIMPs in all kinds of scenarios

(SUSY, extra-dimensions, gauge extensions of SM...)

but we are becoming much more open (axion-like, very light/heavy)



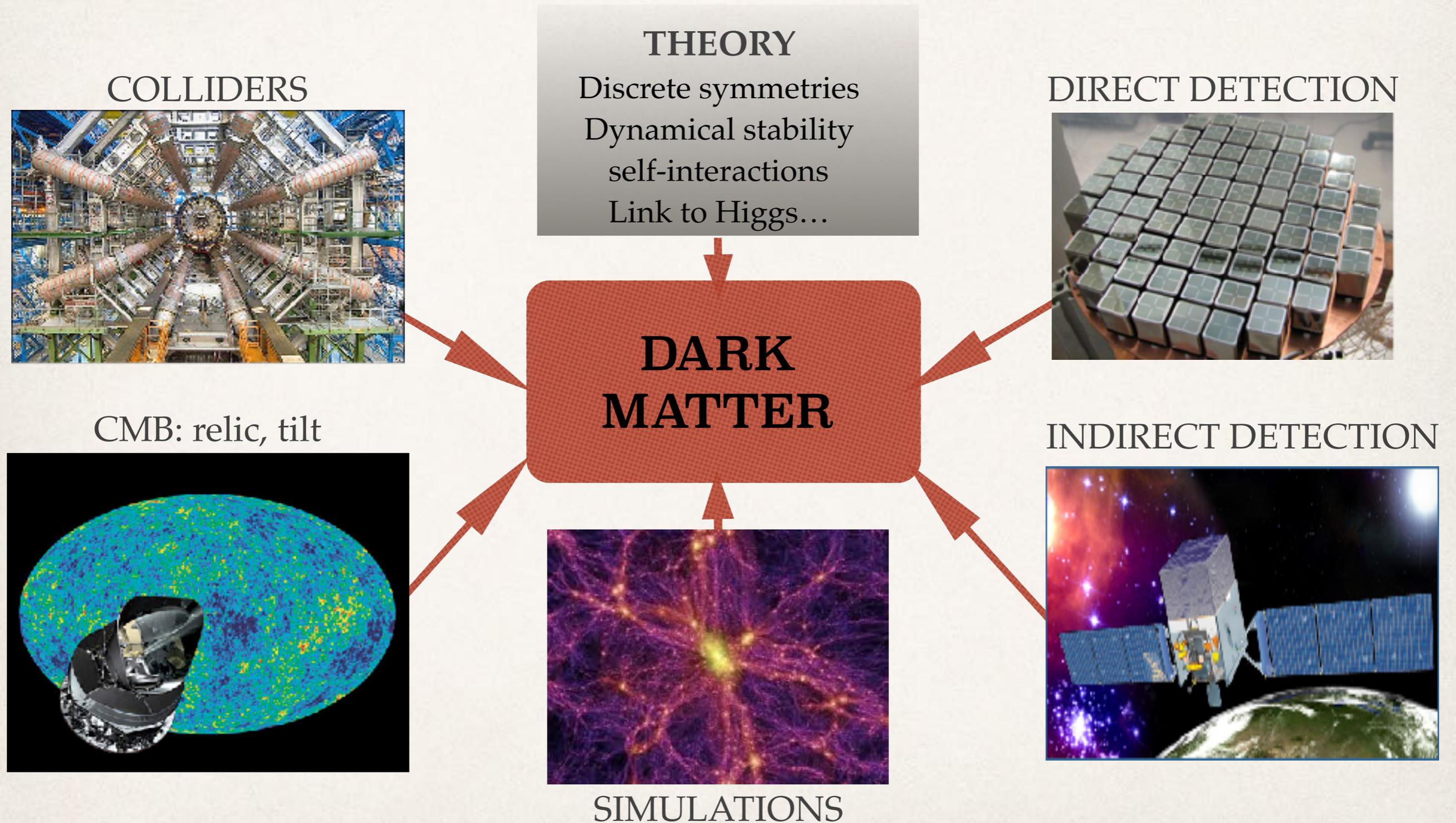
A snapshot of models for Dark Matter

**Popular models** =  
linked to solutions to other  
problems in the SM

Discovery to characterization  
of Dark Matter  
leading to new discoveries

THANKS TO TIM TAIT

# DM: a poster-child for complementarity



# Dark Matter overview

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DM is exciting because a discovery in one form of detection can be then be correlated to other handles for searches, hence characterization of the discovery is possible

Whereas there is plenty of evidence for DM, nothing ensures DM has non-gravitational interactions, incl self-interactions

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Whereas there is plenty of evidence for DM, nothing ensures DM has non-gravitational interactions, incl self-interactions

Often DM models are linked to solutions to other issues of the SM, and this implies some form of coupling to the SM

Writing down motivated models which explain the relic abundance is not hard, but hiding them from colliders/DD/ID can be quite problematic: Vanilla models like axions, SUSY WIMPS, etc are very much in trouble

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Null results from searches may be discouraging, but the BSM field had been dominated by a handful of proposals (SUSY and the likes)

There are lots of new ideas out there, waiting to be explored

# Neutrino masses (see exercise at the end)

Neutrino masses usually generated via **see-saw**  
new heavy state (**sterile** neutrino), mixes with **active** neutrinos

**Example:** light ( $< \text{TeV}$ ) sterile neutrinos  
type I see-saw mechanism

Yukawa  
interaction

$$Y_{\alpha a} \bar{L}_L^\alpha H \Psi_{Ra} + h.c.$$

active      sterile

EWSB  
mass mixing

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & m_N \end{pmatrix}$$

$$m_{\text{light}} \sim m_D^2 / m_N$$
$$m_{\text{heavy}} \sim m_N$$

if  $m_N$  is not too large: heavy neutrinos modify Higgs/massive gauge boson properties at LHC

# Neutrino overview

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Neutrino masses, via the see-saw, may open a window to heavy new physics

Neutrino experiment is an active area, and surprises could come from it e.g. measurement of CP violation, violation of fundamental symmetries

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Sterile neutrinos could be DM (KeV) and be the origin of the baryon asymmetry of the Universe via decays (leptogenesis)

Unfortunately at low energies we can measure only few reduced parameters, and cosmological/astrophysical constraints on the origin of this new sector are very model dependent, if any. The see-saw mechanism may not be falsifiable

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The window to heavy neutrino DM may be closed in the near future with experiments like SHIP

Focus should be on models which can be probed in other ways than oscillations

# Baryogenesis

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Matter/antimatter asymmetry of the Universe cannot be accommodated in the SM, evidence for BSM

Sakharov's conditions: we need models which provide new sources of CP violation and produce a **strong first order phase transition** or heavy particles which decay in a baryon/lepton-violating way

Most interesting scenarios are falsifiable (enough measurements can be done) and are related to other issues of the SM. An archetypical example is **EW baryogenesis**, which may be ruled out using various measurements (LHC, EDMs...)

Strong 1st order PT: Link to **detection of Gravitational Waves**

# Inflation

Large scale structure of the Universe homogeneous and flat

Period of rapid expansion of the Universe

**Example:** Inflation driven by a scalar particle (inflaton)  
**three parameters:**

1. height of the potential: usually means trans-planckian field excursions
2. spectral index: very close to 1, but not quite
3. scalar to tensor ratio: constrained to be small

In the usual paradigm

$$n_s = 1 + 2\eta - 6\epsilon$$

$$r = 16\epsilon$$

$$\epsilon = \frac{M_p^2}{2} \left( \frac{V'(\phi)}{V(\phi)} \right)^2 \quad \eta = M_p^2 \frac{V''(\phi)}{V(\phi)}$$

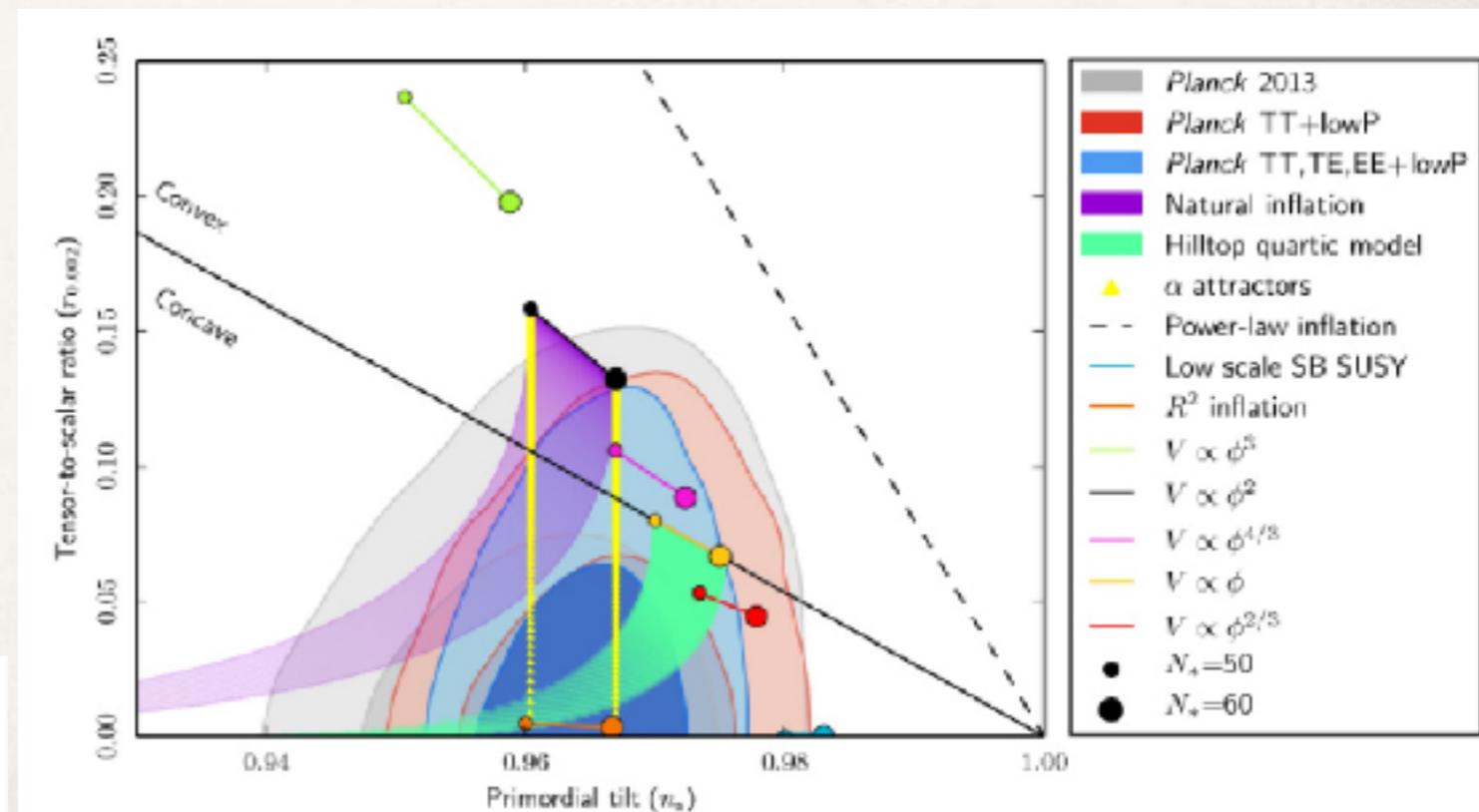


Fig. 12. Marginalized joint 68% and 95% CL regions for  $n_s$  and  $r_{0.002}$  from *Planck* in combination with other data sets, compared to the theoretical predictions of selected inflationary models.

# Inflation overview

---

Seems like a simple, elegant solution to the flatness problem but

Specific realizations require a set of tunings/unnatural features:

initial conditions, or when to start rolling

introduces a hierarchy problem (height to width of the potential)

trans-planckian field excursions may need quantum gravity

period of reheating/preheating is an obscure aspect (introduced by hand, not predictive)

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Other not so good features

no big deviations from almost-gaussian have been observed so after tuning of the height, spectrum is essentially **two parameters** and we may not be sensitive to models with small tensor-to-scalar ratio (i.e. would never see primordial gravitational waves)

In the field of Cosmology, the Inflationary paradigm seems like SUSY in Particle Physics back in the 90's

# Rationale

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# Rationale for New Physics

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Even if we had no evidence for BSM, there would be a rationale for new physics

**Rationale**

```
graph TD; Rationale([Rationale]) --> Hierarchies[Hierarchies  
gauge, mass, flavor]; Rationale --> EndOfTheRoad[End of the road  
unitarity, triviality, stability];
```

**Hierarchies**  
gauge, mass, flavor

**End of the road**  
unitarity, triviality, stability

**Symmetries and/or dynamics**  
New states

# Rationale for New Physics

## Example: Naturalness

Predictive theory: quantum mechanical. In QFT, physical quantities *run* mass term in a Lagrangian, quantum corrections

$$\mathcal{L}_m = -m_\Psi \bar{\Psi}\Psi - m_\phi^2 \phi^2$$

## Fermions

Massless fermion, additional symmetry

$$\Psi \rightarrow e^{-i\gamma_5\theta} \Psi$$

if this chiral symmetry is preserved QM



$\delta m_\Psi \propto m_\Psi \log(\mu_1/\mu_2)$

chiral symmetry **protects** fermions masses from large UV corrections  
Light fermions are **technically natural**

## Energy

Quantum Gravity

some other new physics

some new physics

energies we can probe

# Rationale for New Physics

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### Scalars

Massless scalar, scale invariance

This classical symmetry is not preserved  
QM (is anomalous)

scalars are **not protected** by a symmetry,  
are UV sensitive, natural value for the  
mass is the highest scale it couples to

**Light scalars are unnatural**

# Rationale for New Physics

## Example: Naturalness

Energy

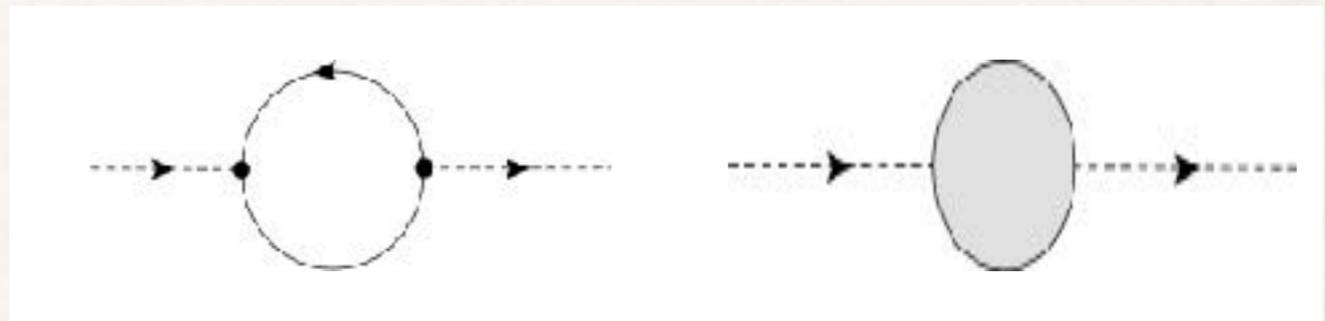
Quantum Gravity

some other new physics

some new physics

energies we can probe

Quantum corrections to scalars



threshold  
corrections

QGrav

$$\delta m_\phi^2 \propto c_1 \Lambda_{NP}^2 + c_2 M_{Pl}^2$$

$$(\text{Physical mass})^2 = (\text{bare mass})^2 + (\text{unsuppressed Qcorrections})^2$$

**light scalar = enormous fine-tuning**

The Higgs is a scalar, and there is no sight of new physics so far  
Should we just live with it?

# Is a tuning all there is?

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## Example: Naturalness

At the beginning of the EW theory, people were trying to figure out how to make sense of a gauge theory with massive W,Z

mass terms spoil renormalizability  
(predictivity) of the gauge theory

Feinberg (1958) proposed divergences were cancelled if a precise set of cancellations could happen (invoked fine-tuning)

At the end the story was more subtle  
The concept of Spontaneous Symmetry Breaking  
*secret renormalizability*

I view fine-tunings as calls for  
**new principles to be discovered**

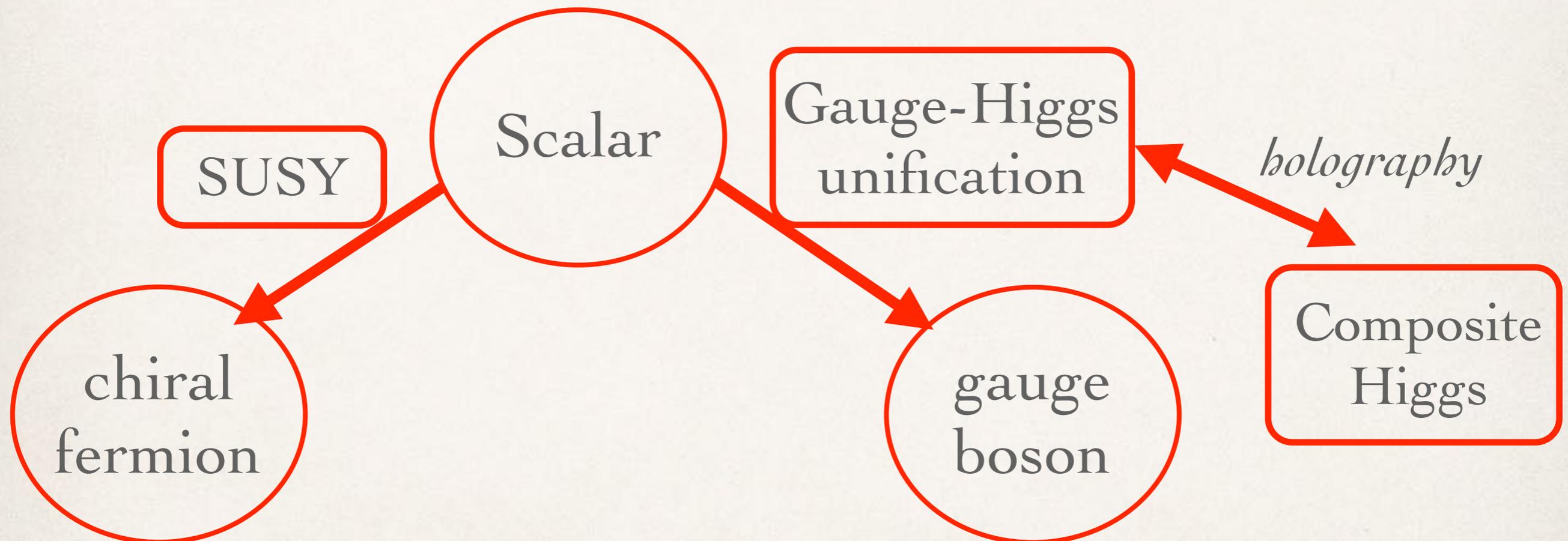
# Rationale for New Physics

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## Example: Naturalness

Now that the Higgs is a reality  
i.e. there is a light scalar in Nature!

symmetry/duality arguments to explain its nature



All these theories predict new states, to be discovered  
SUSY partners, techni-baryons and mesons, spin-two...  
and deviations in SM behaviour

# *Additional material (Exercises)*

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# Dirac, Weyl and Majorana Fermions

Recall the Dirac equation for a four-component (Dirac) fermion:

$$(\not{p} - m)\Psi = 0 \quad \text{where} \quad \not{p} = p_\mu \gamma^\mu . \quad (1)$$

Further recall (from Standard Model tutorial 1) that the action of charge conjugation can be represented as a matrix acting on  $\Psi$ :

$$\Psi^c = C \bar{\Psi}^T \quad C = -i \gamma^2 \gamma^0 \quad (2)$$

If we define

$$\Psi \equiv \begin{pmatrix} \xi \\ \eta \end{pmatrix} \equiv \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix} , \quad (3)$$

then  $\xi$  and  $\eta$  are left- and right-handed<sup>1</sup> two-component (Weyl) spinors respectively, and the equation of motion (1) becomes two coupled differential equations:

$$(\bar{\sigma}_\mu p^\mu) \xi = m \bar{\eta} \quad (5a)$$

$$(\sigma_\mu p^\mu) \bar{\eta} = m \xi \quad (5b)$$

Remember that in the chiral basis,

$$\gamma^\mu = \begin{pmatrix} 0 & \sigma^\mu \\ \bar{\sigma}^\mu & 0 \end{pmatrix} \quad \text{where} \quad \sigma^\mu = (\mathbb{1}_2, \vec{\sigma}) , \quad \bar{\sigma}^\mu = (\mathbb{1}_2, -\vec{\sigma}) . \quad (6)$$

Note that the two equations (5) decouple when  $m = 0$ .

<sup>1</sup>We can project onto the left- and right-handed components with

$$P_L = \frac{1}{2}(\mathbb{1} - \gamma^5) \quad P_R = \frac{1}{2}(\mathbb{1} + \gamma^5) . \quad (4)$$

Note:  $P_R + P_L = \mathbb{1}$  and  $P_R P_L = P_L P_R = 0$ .

# Dirac, Weyl and Majorana Fermions

- a) A *Majorana spinor* is one which is equal to its charge conjugate. In 4-component form, this condition reads

$$\psi^c = \psi \tag{7}$$

One can think of this as a reality condition for the spinor, just as real numbers satisfy  $z^* = z$ . Write the Majorana condition (7) in Weyl language.

- b) Is this condition preserved under charge conjugation?  
 c) Translate the following Dirac bilinears into Weyl notation:

$$\bar{\Psi}_1 \Psi_2, \quad \bar{\Psi}_1 P_L \Psi_2, \quad \bar{\Psi}_1 P_R \Psi_2, \quad \bar{\Psi}_1 \gamma_\mu \Psi_2. \tag{8}$$

- d) Re-write the two-component expressions you got for (8) assuming that  $\Psi_1$  and  $\Psi_2$  are Majorana fields.

There are two different types of mass terms that one can write for fermions:

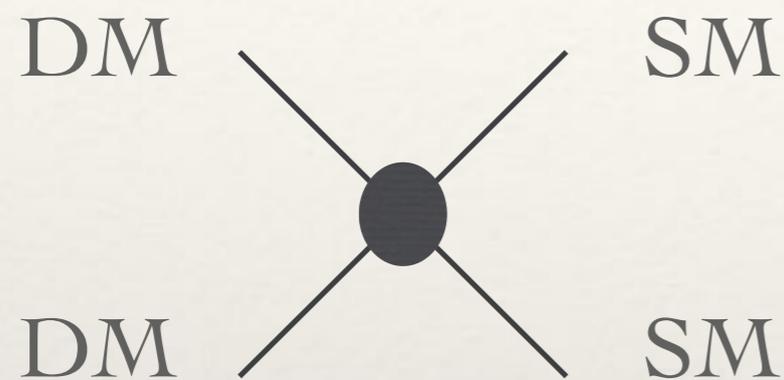
$$\text{Dirac} \quad M_D \bar{\Psi} \Psi \tag{9a}$$

$$\text{Majorana} \quad m_L \left( \overline{(\Psi^c)} P_L \Psi + \text{h.c.} \right) + m_R \left( \overline{(\Psi^c)} P_R \Psi + \text{h.c.} \right) \tag{9b}$$

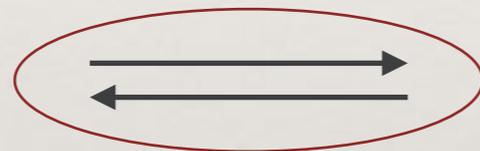
- e) Write the mass terms (9) in the language of Weyl spinors, combining all the terms and expressing the masses in the form of a matrix in  $(\xi, \eta)$ -space.  
 f) Show how  $M_D$ ,  $m_L$  and  $m_R$  transform under the action of charge conjugation.  
 g) Show that a fermion with a Dirac mass term is equivalent to two degenerate Majorana fermions.

# Example of DM calculation

thermal production  
cold (massive) DM



@  $T \gg \text{mass}$



@  $T \sim \text{mass}$



@  $T \ll \text{mass}$  *freeze-out*

compute relic abundance after  
freeze-out ( $x_F = m/TF$ ) and  
compare with Planck's value

example: Higgs portal



e.g. Scalar DM

$$\mathcal{L} \supset -\frac{\lambda_S}{2} S^2 \Phi^\dagger \Phi$$

**new parameters:**  
mass and coupling

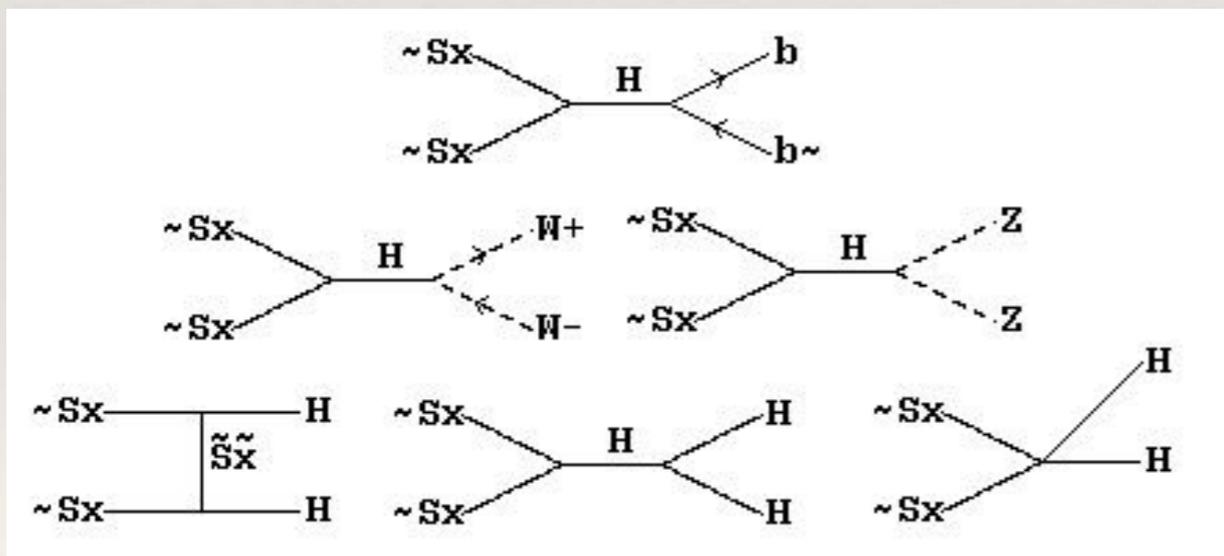
one could use numerical tools,  
*micromegas*, *madDM*, *SARAH*..  
here, analytical expressions

# Example of DM calculation

A step-by-step guide  
relic abundance calculation

1. Introduce the model in Feynrules  
and output in CompHep format

2. In CompHep, compute  
scattering amplitudes



and output to Mathematica

3. In Mathematica, **simplify  
expression and expand**

$$\lim_{v \ll c} \sigma_{ann} v = a + bv^2 + \dots$$

s-wave    p-wave

thermal average is simply

$$\langle \sigma_{ann} v \rangle = a + 3b/x_F$$

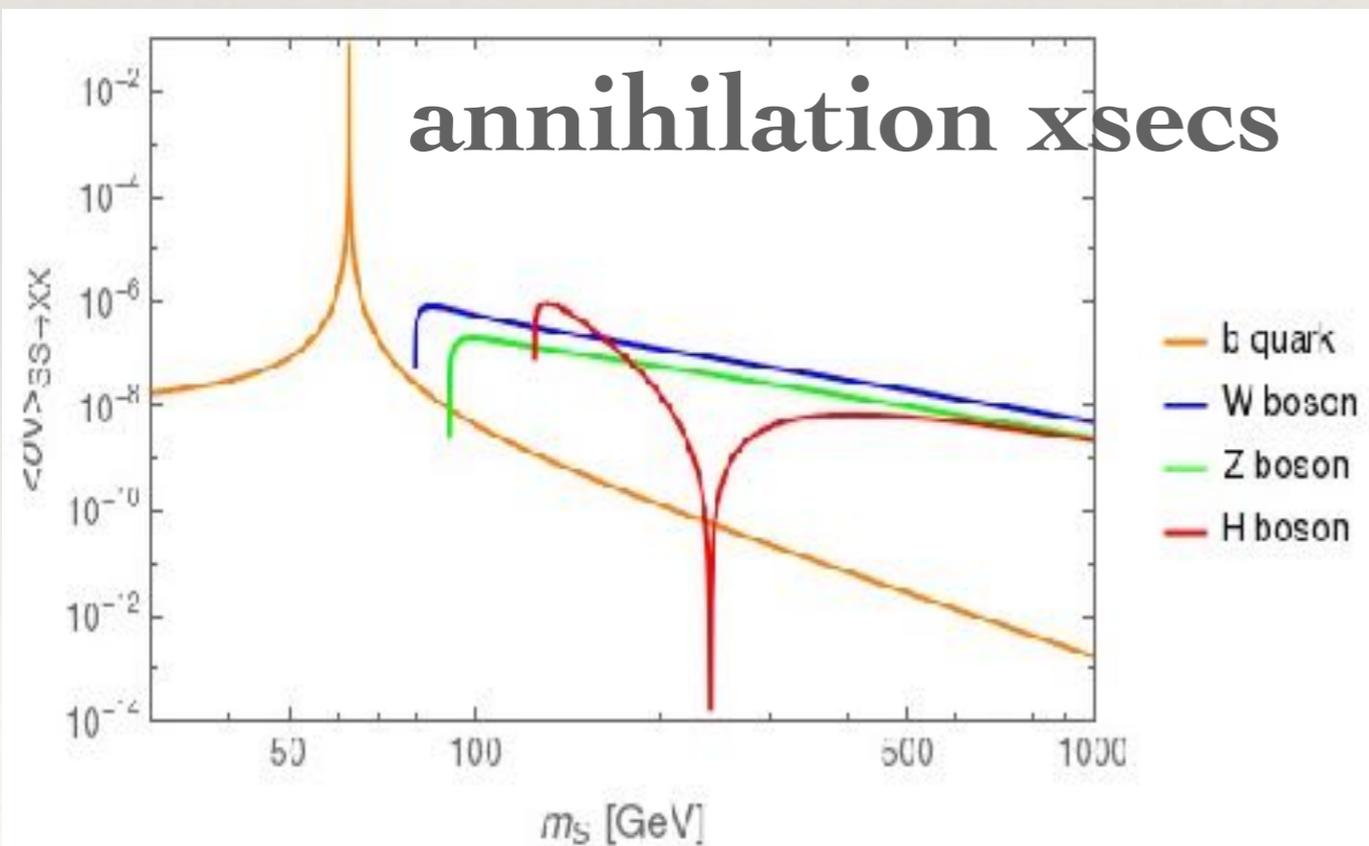
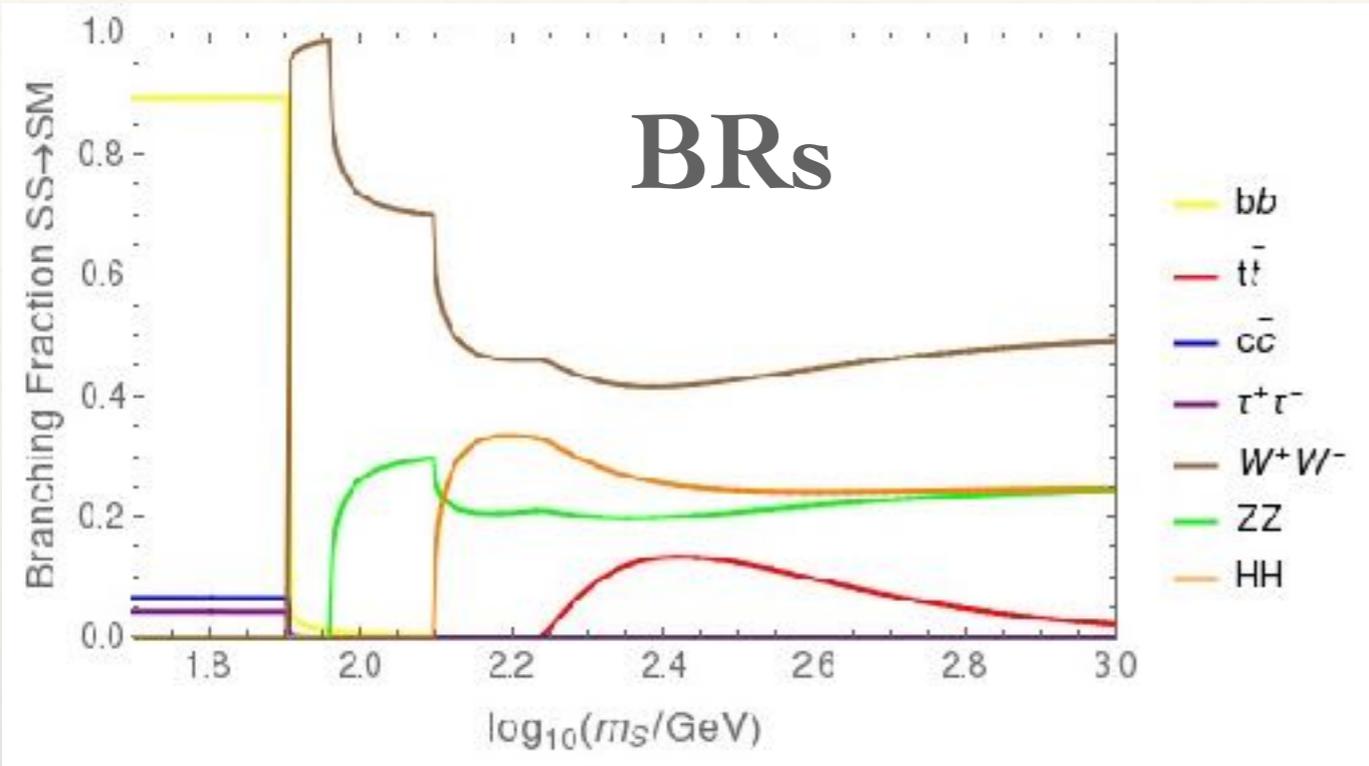
4. **Compute the relic abundance**  
e.g. for s-wave (unsuppressed)

$$\Omega_{DM} h^2 = 1.69 \times \frac{x_f}{20} \sqrt{\frac{100}{g_*}} \left( \frac{10^{-10} \text{ GeV}^{-2}}{\langle \sigma v \rangle_0} \right)$$

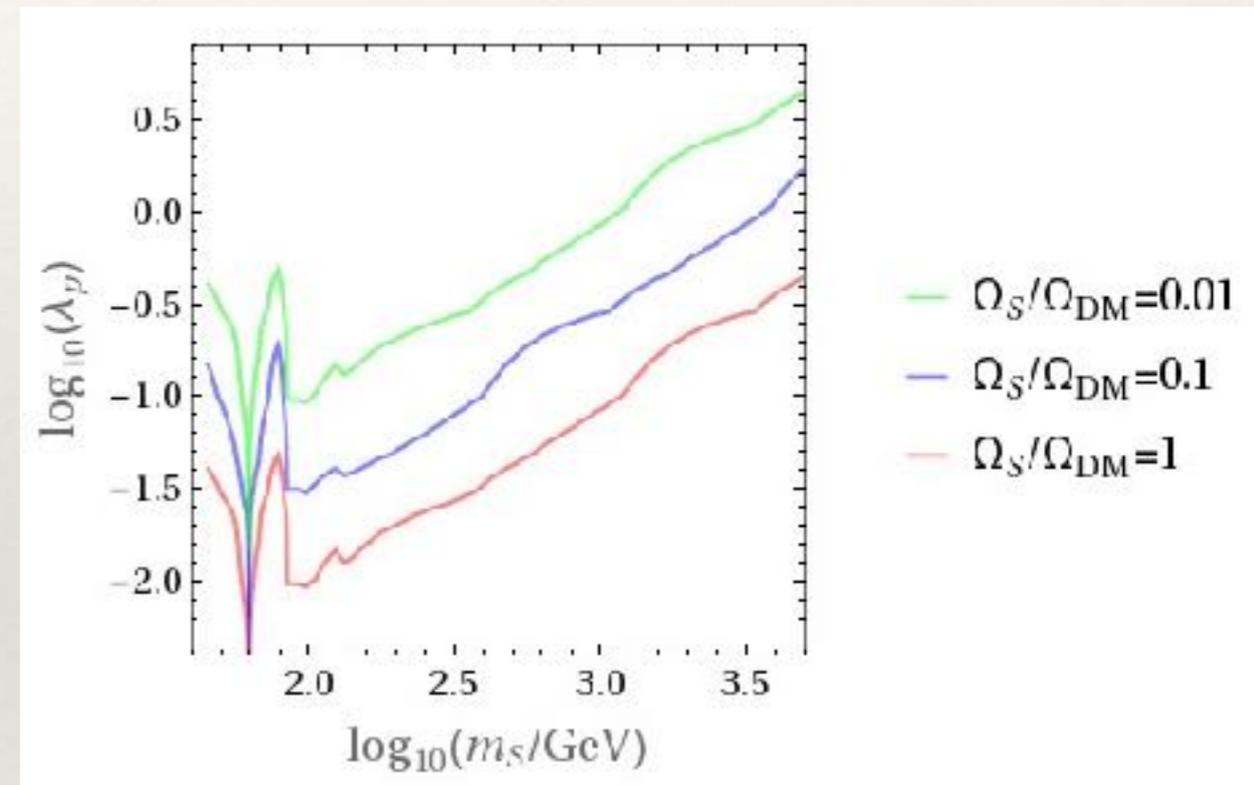
compare with Planck

$$\Omega_{DM} h^2 = 0.1188 \pm 0.0010$$

# Example of DM calculation



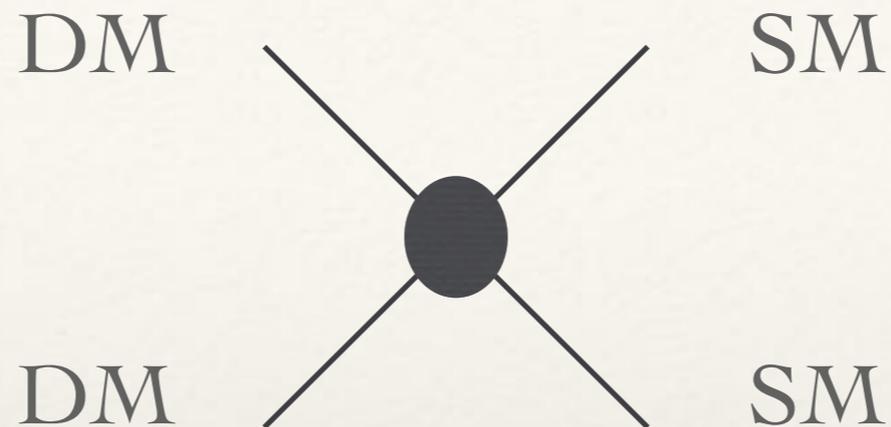
## Planck constraints



# Example of DM calculation

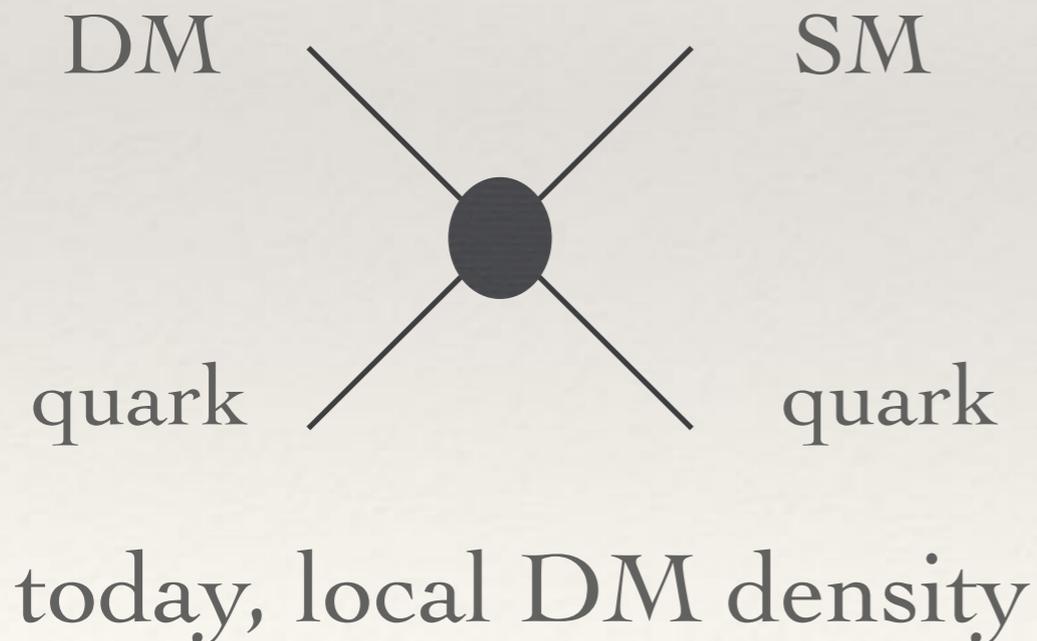
similar calculation for **direct** and **indirect** detection

**relic  
abundance**

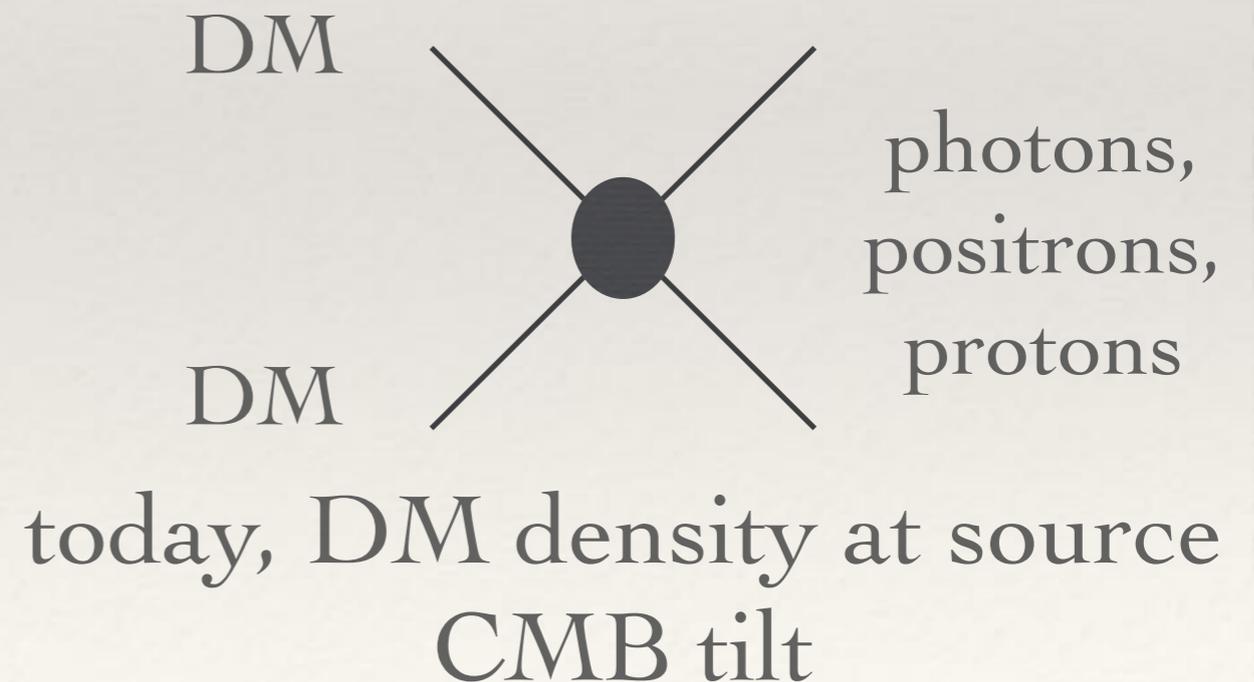


@freeze-out

**direct detection**



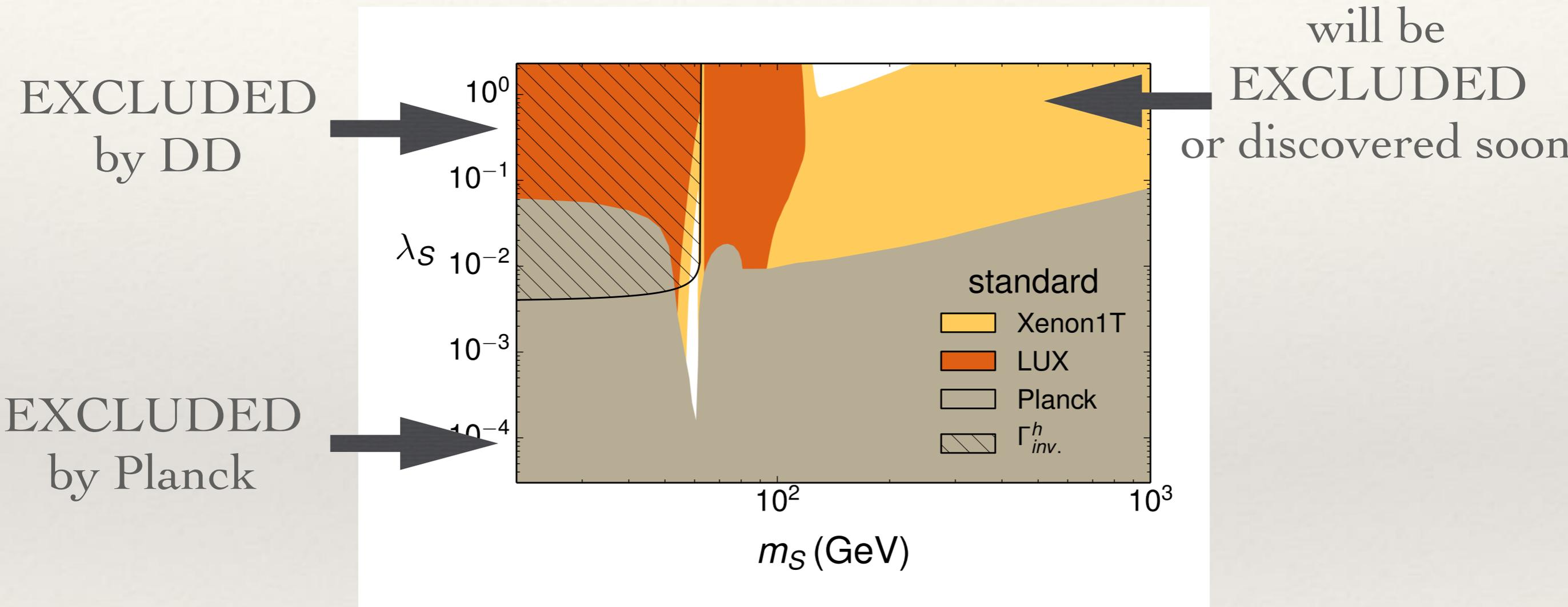
**indirect detection**



# Example of DM calculation

## Summary for Higgs portal

constrained by DD, relic abundance and Higgs invisible width



whereas indirect detection not relevant,  
only secondary photons from b's and W's