BSM
Lecture 1

Taller de Altas Energias (2021)

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Why BSM?

Empirical evidence of BSM

(What we cannot deny)

Neutrinos

Dark Universe

Matter-antimatter asymmetry

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

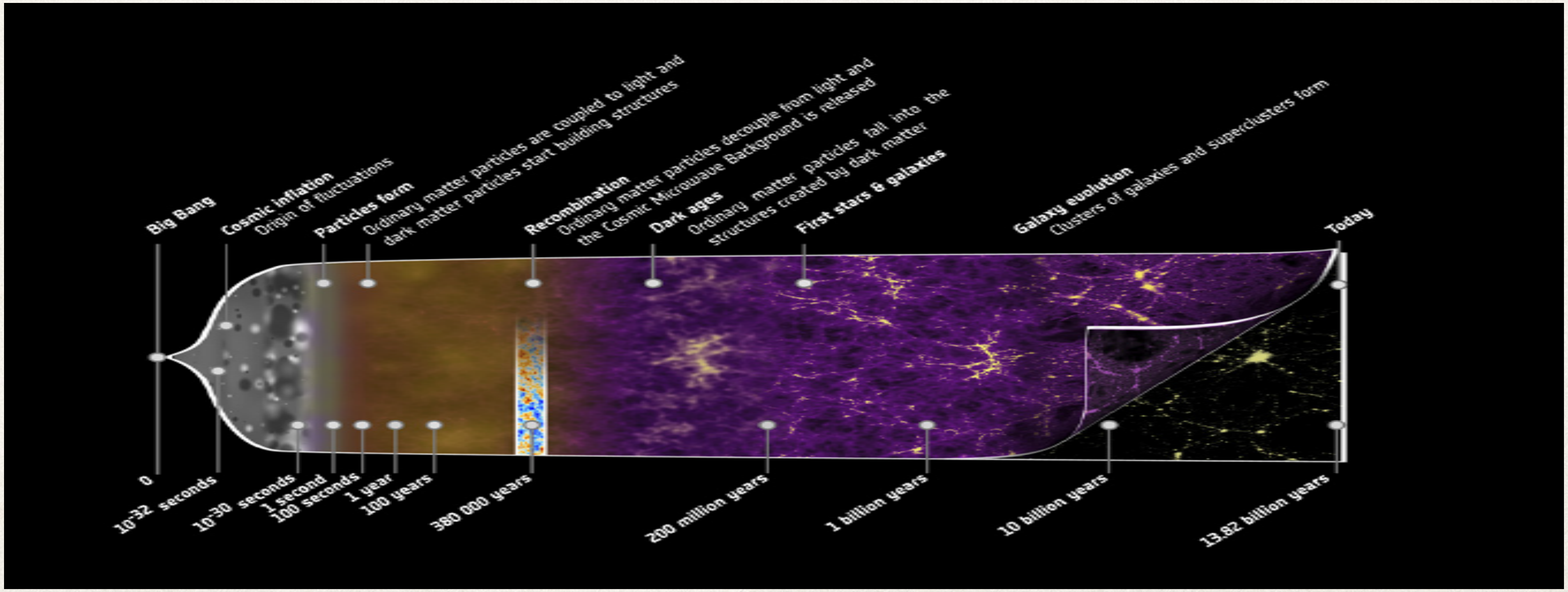
e.g. naturalness or gauge coupling unification

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

Hard-core BSM evidence:

Let's start with Dark Matter

Dark Matter in a nutshell

- ~ 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

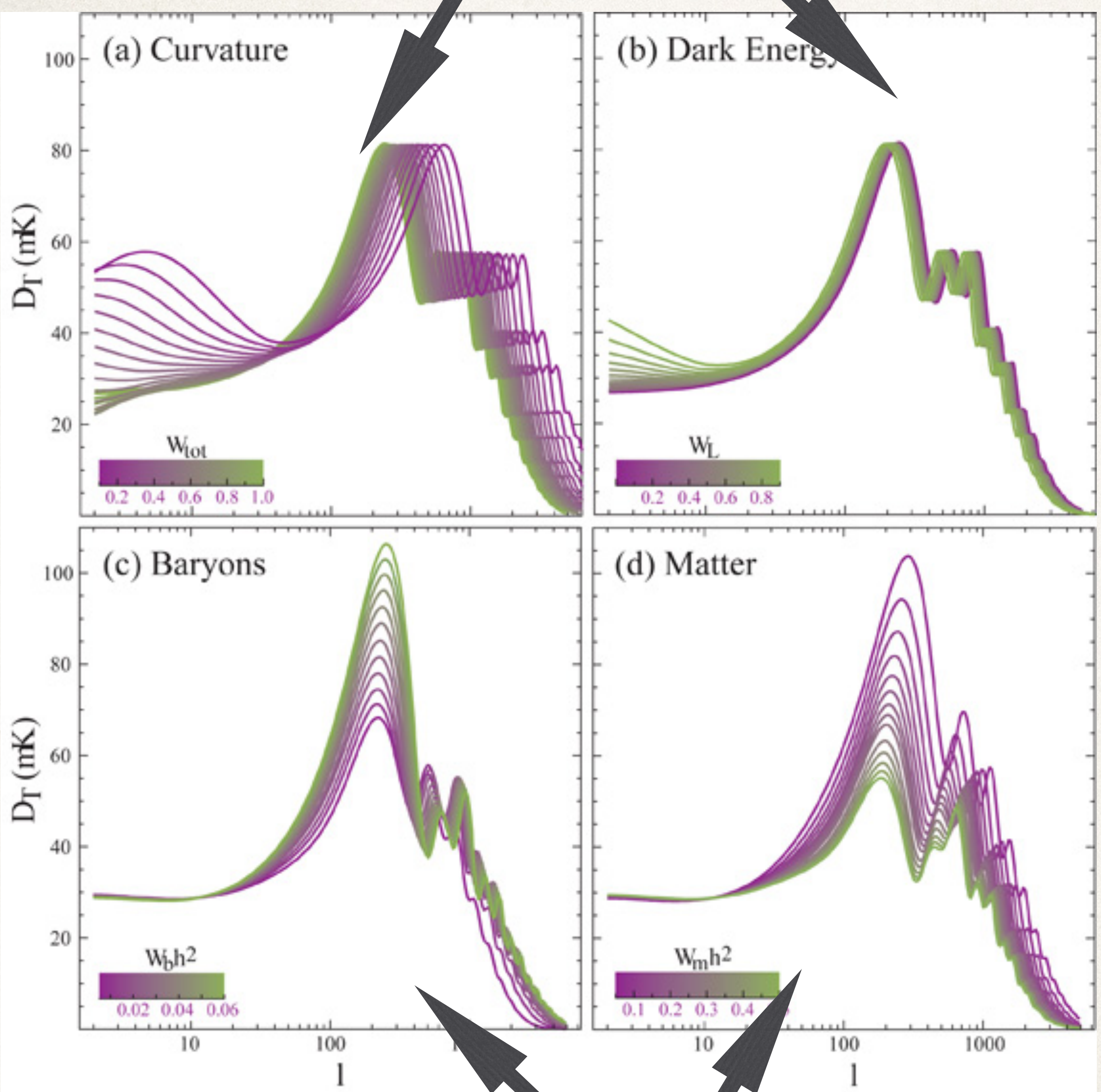
Astrophysical/cosmological
rotation curves
structure formation (e.g. simulations)
dynamical events, e.g. galaxy mergers
CMB (Planck) …

No evidence so far of other interactions

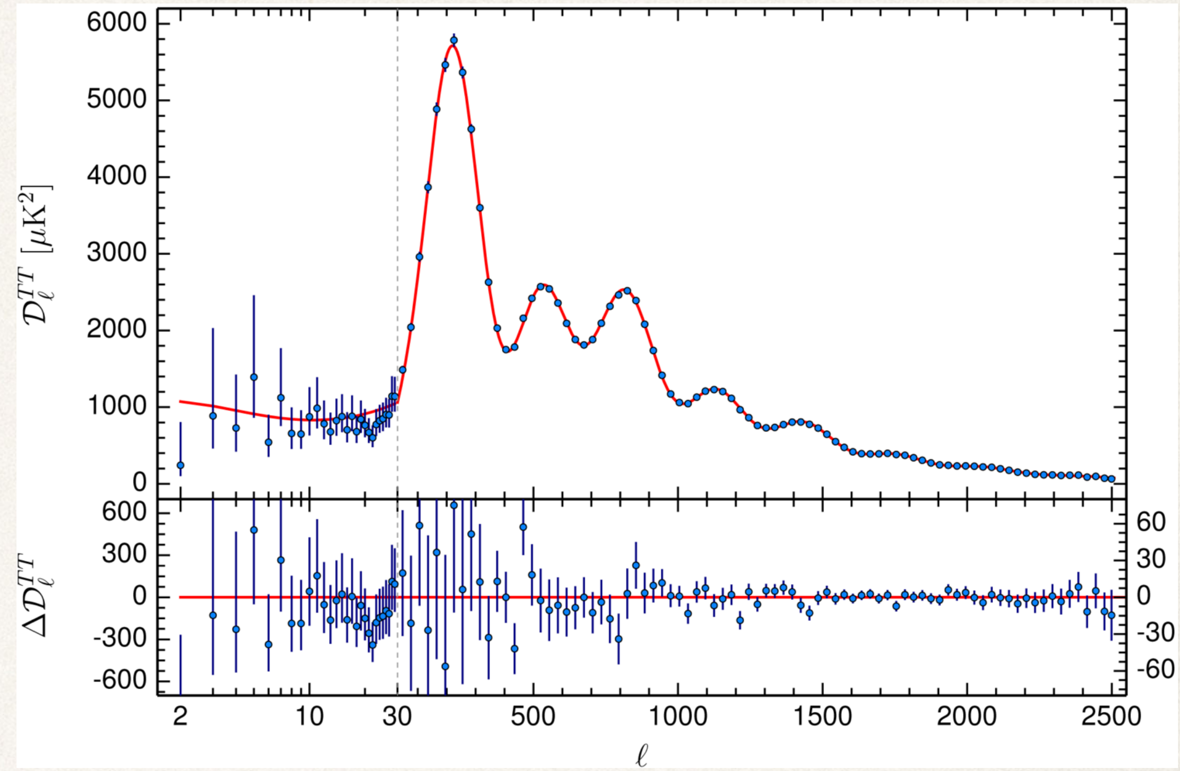
Direct detection experiments
Indirect detection via production of SM particles

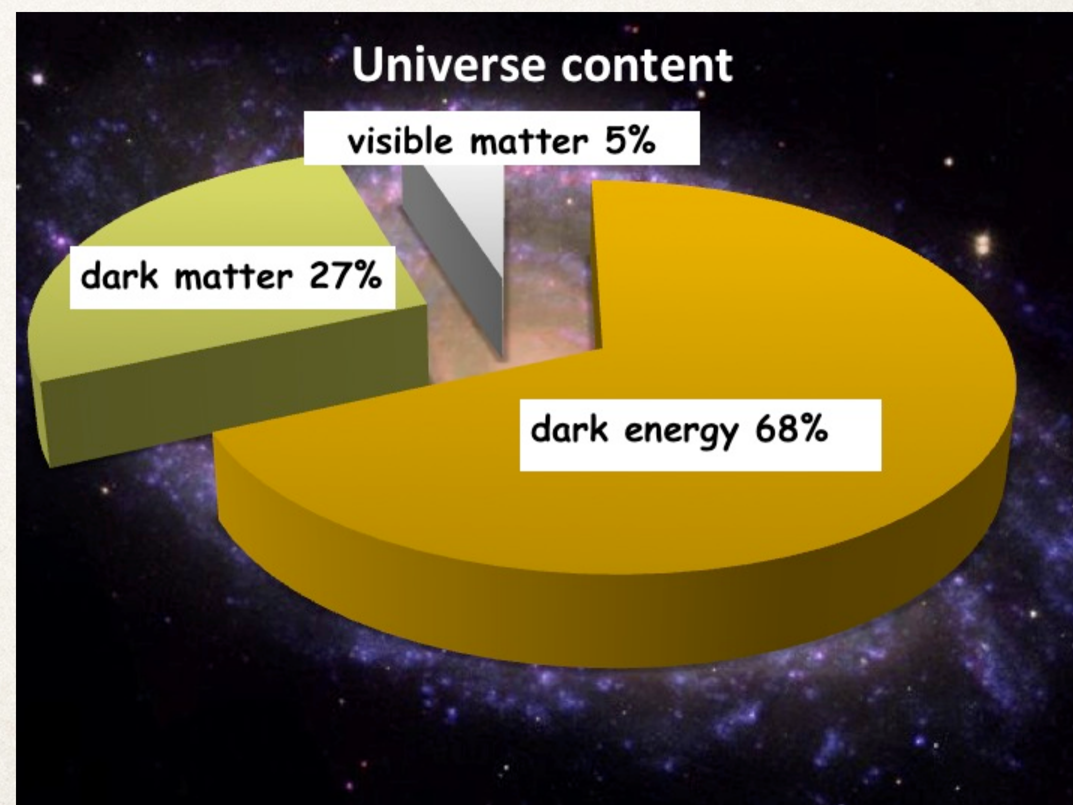
Dark Matter: CMB evidence

position

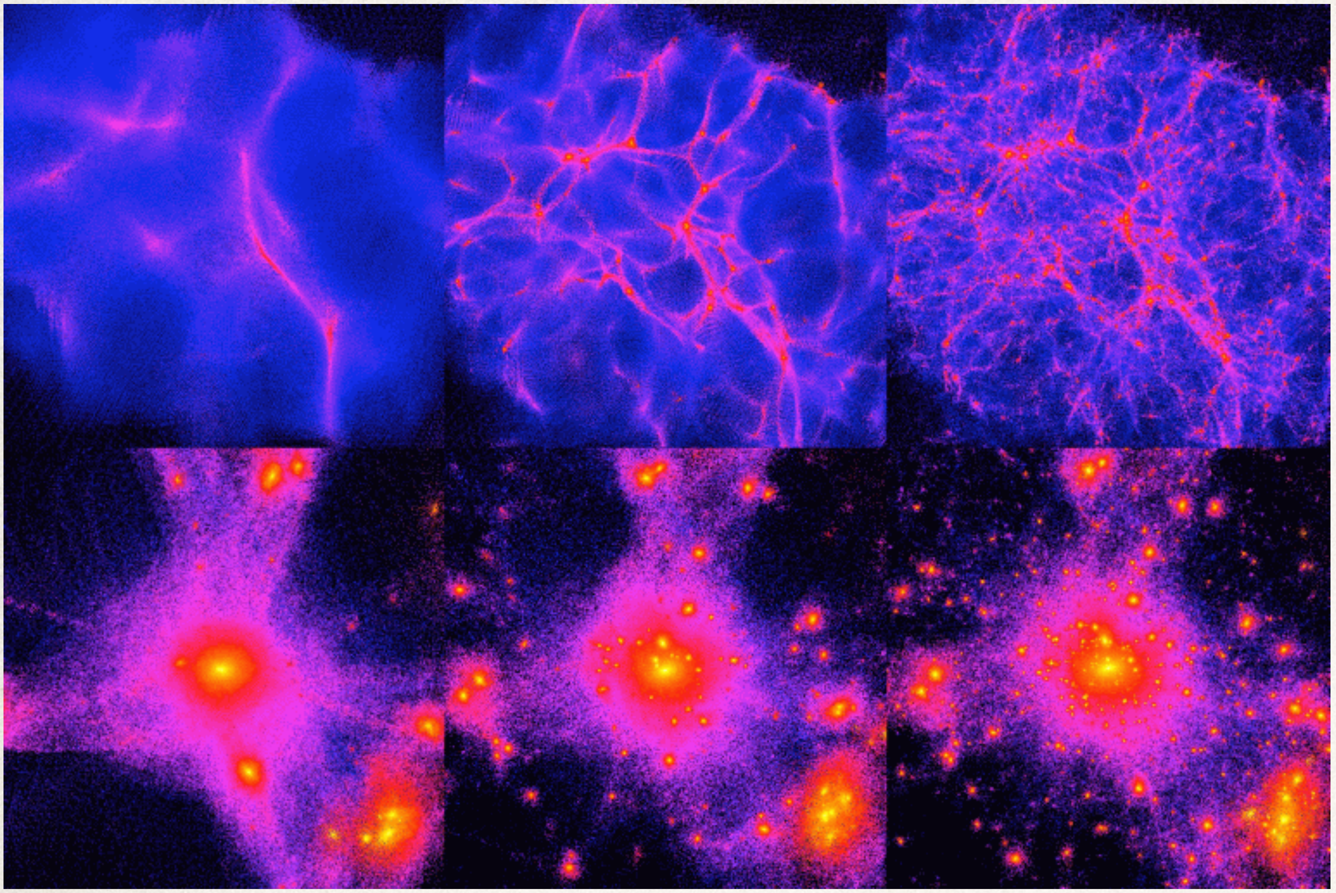


shapes





Dark Matter: simulations, mergers

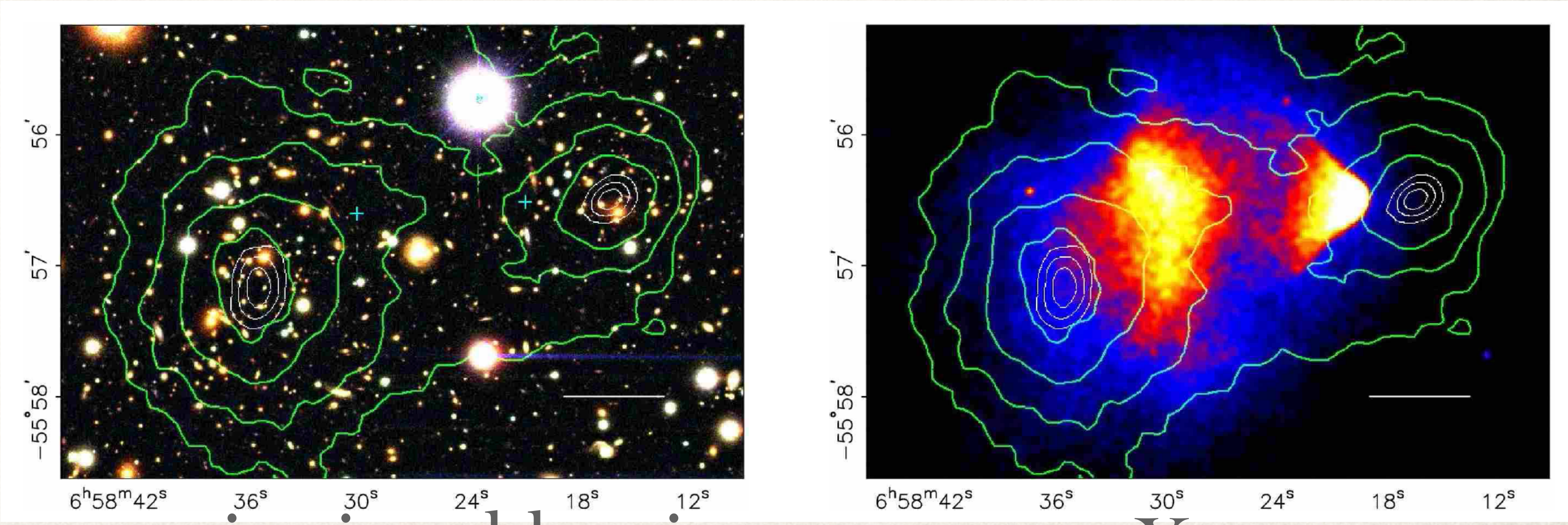


(hot, warm, cold)

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

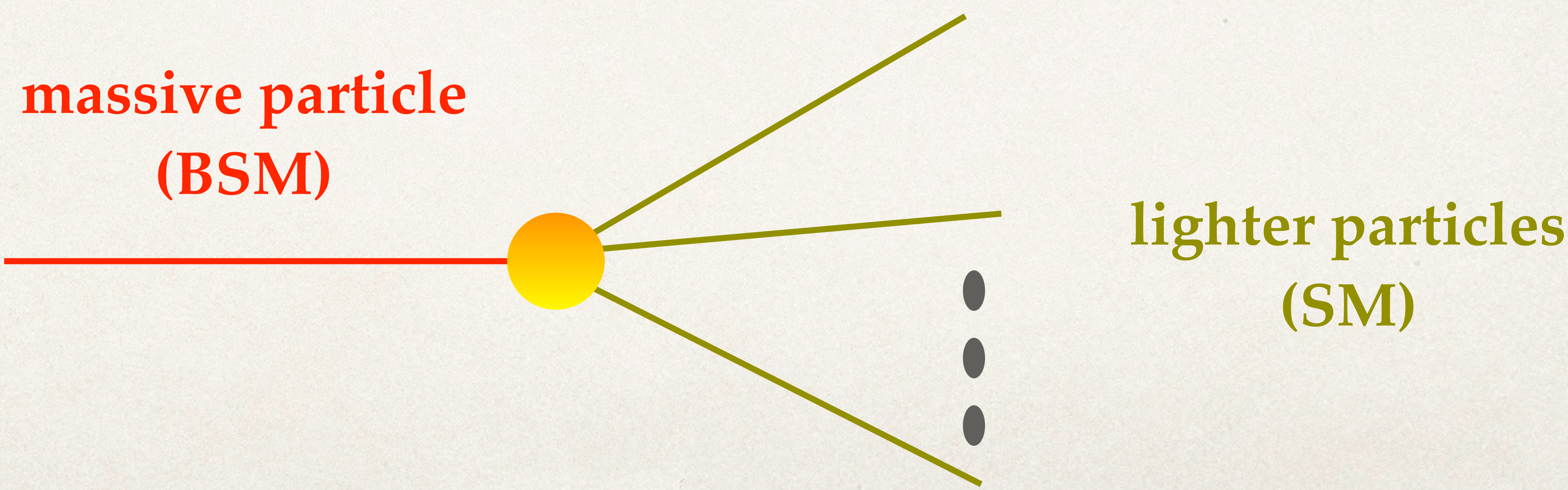
Archetypical Dark Matter

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))

STABILITY



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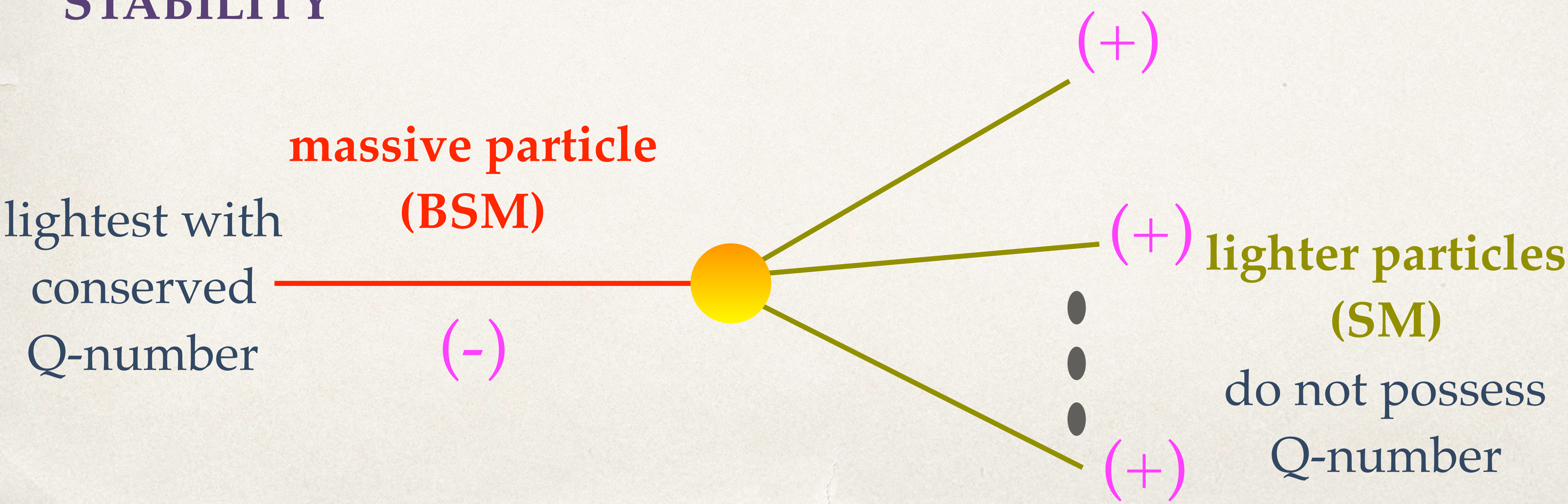

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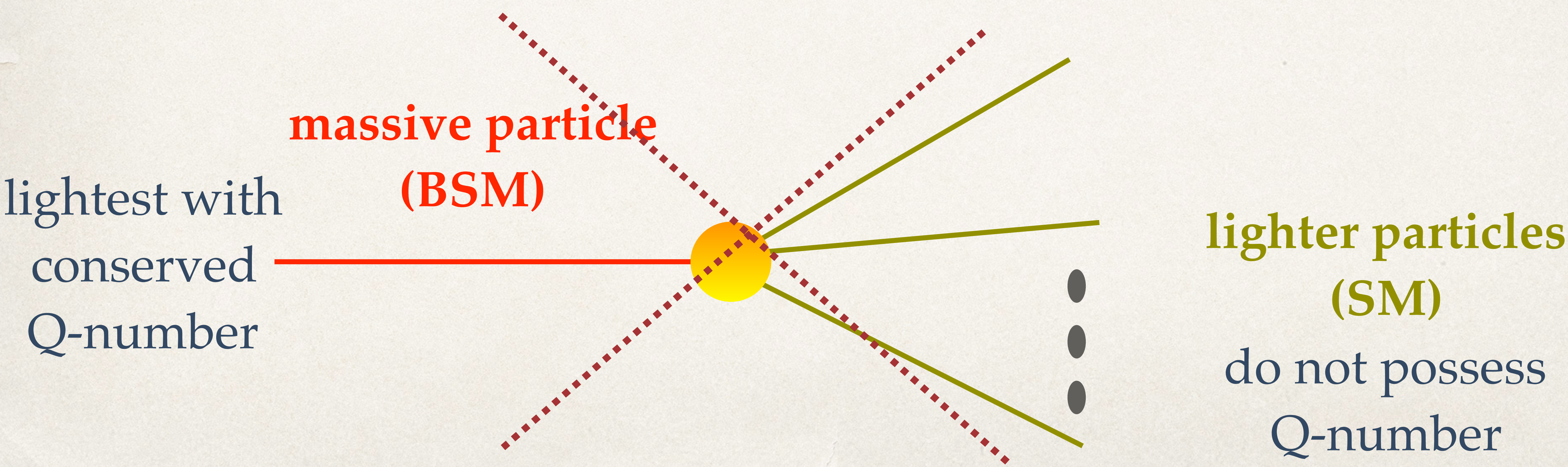

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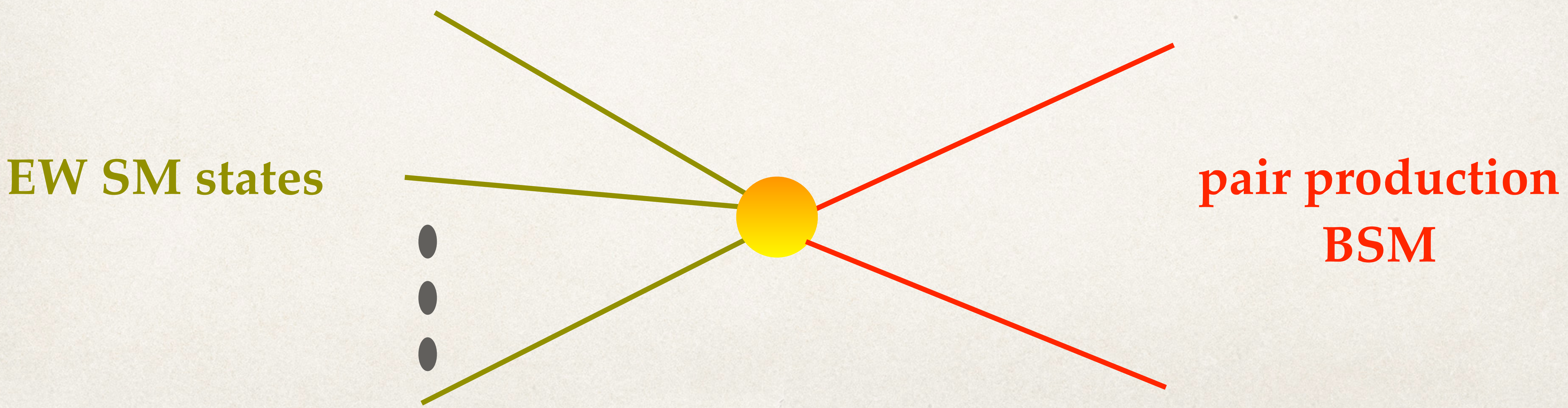
DIRECT DETECTION



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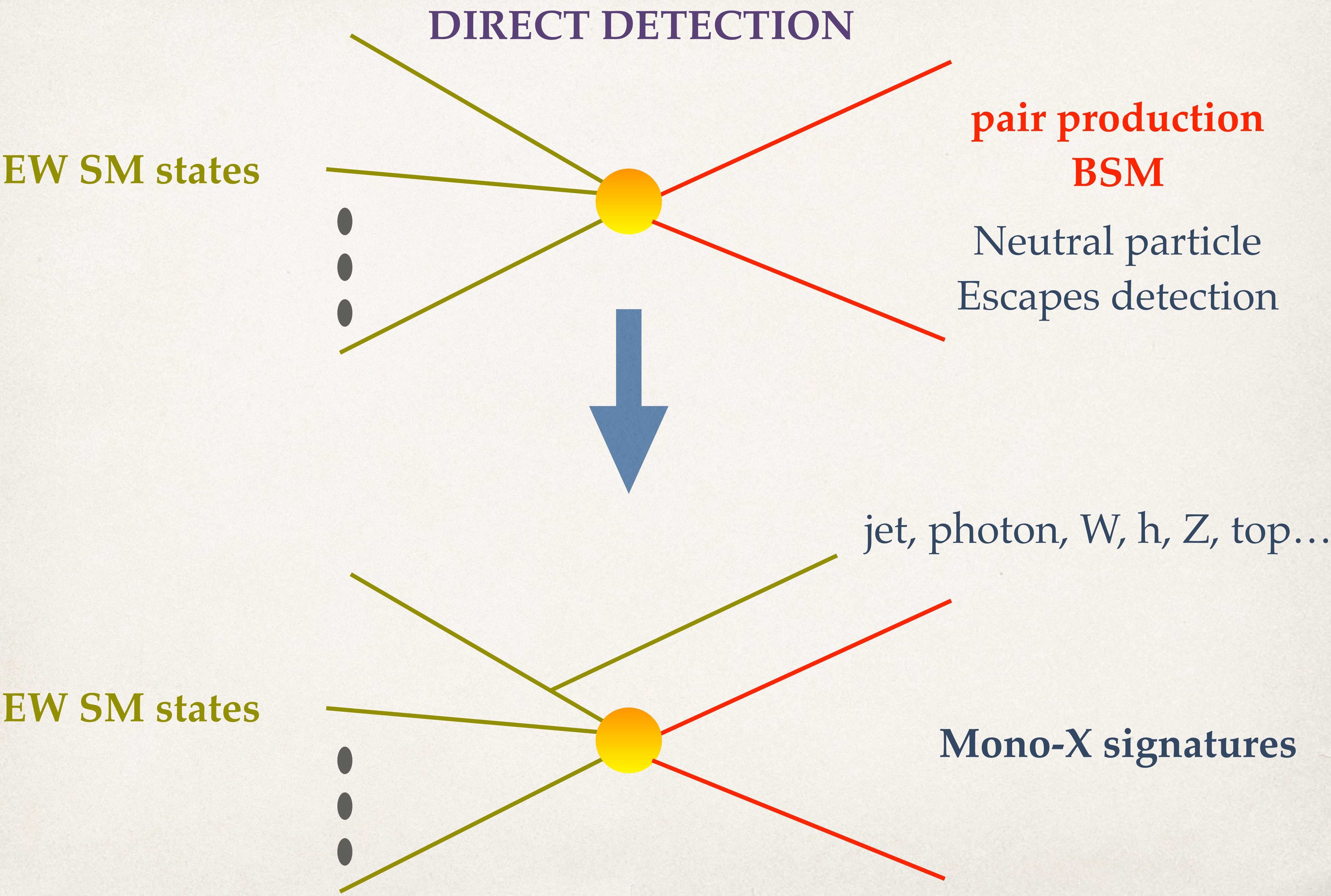

Archetypical Dark Matter

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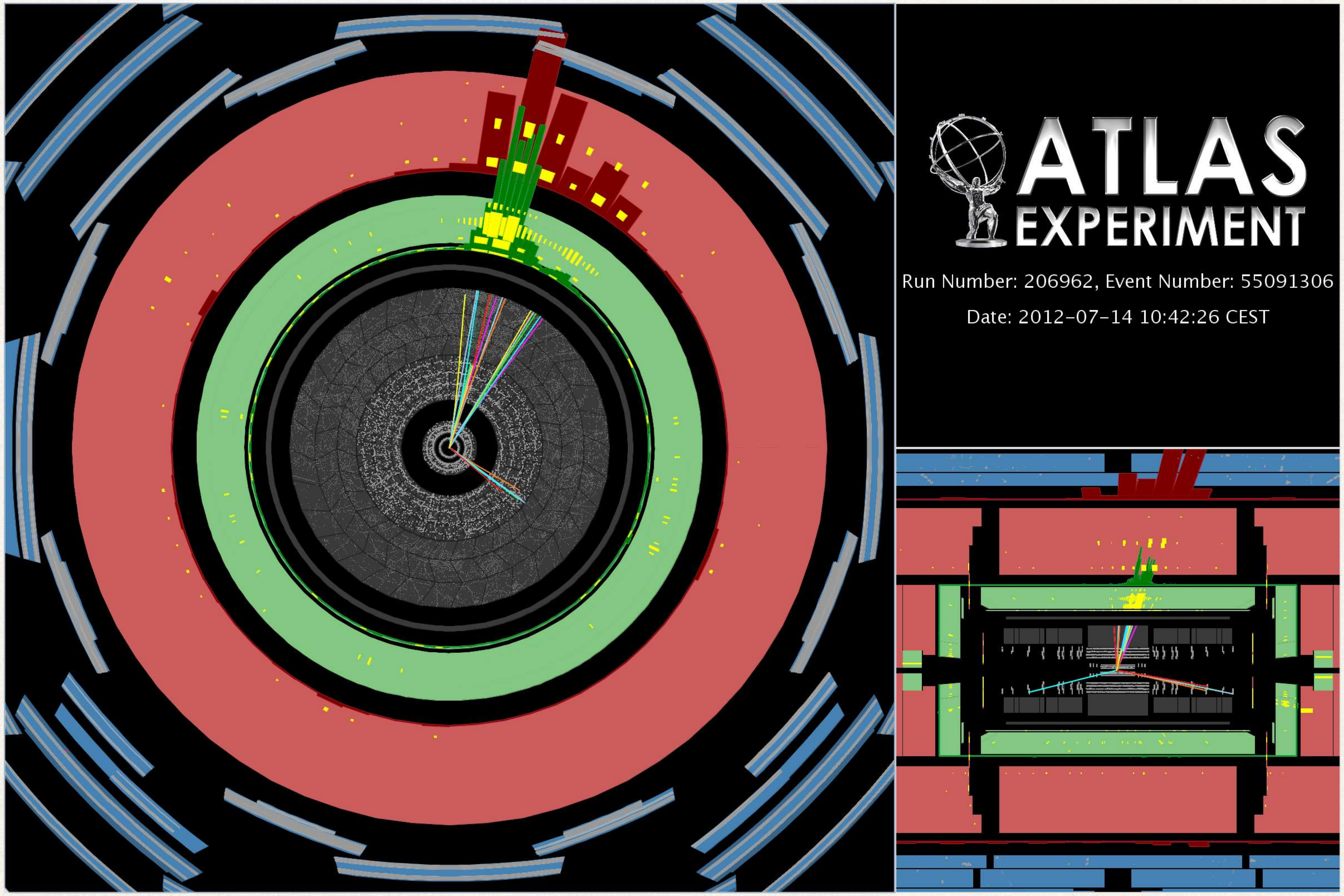
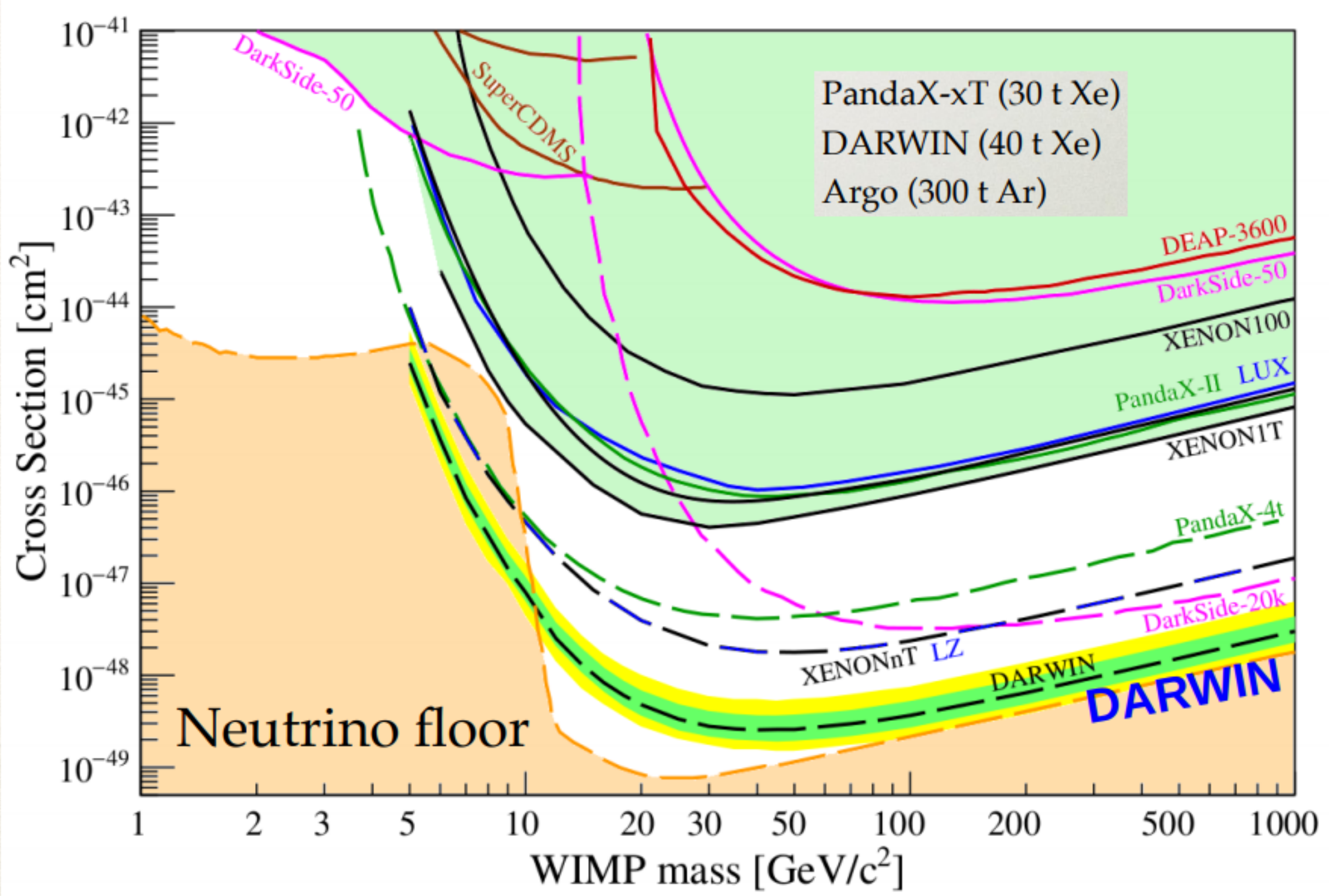


Archetypical Dark Matter

DIRECT DETECTION

Recoil instead of production

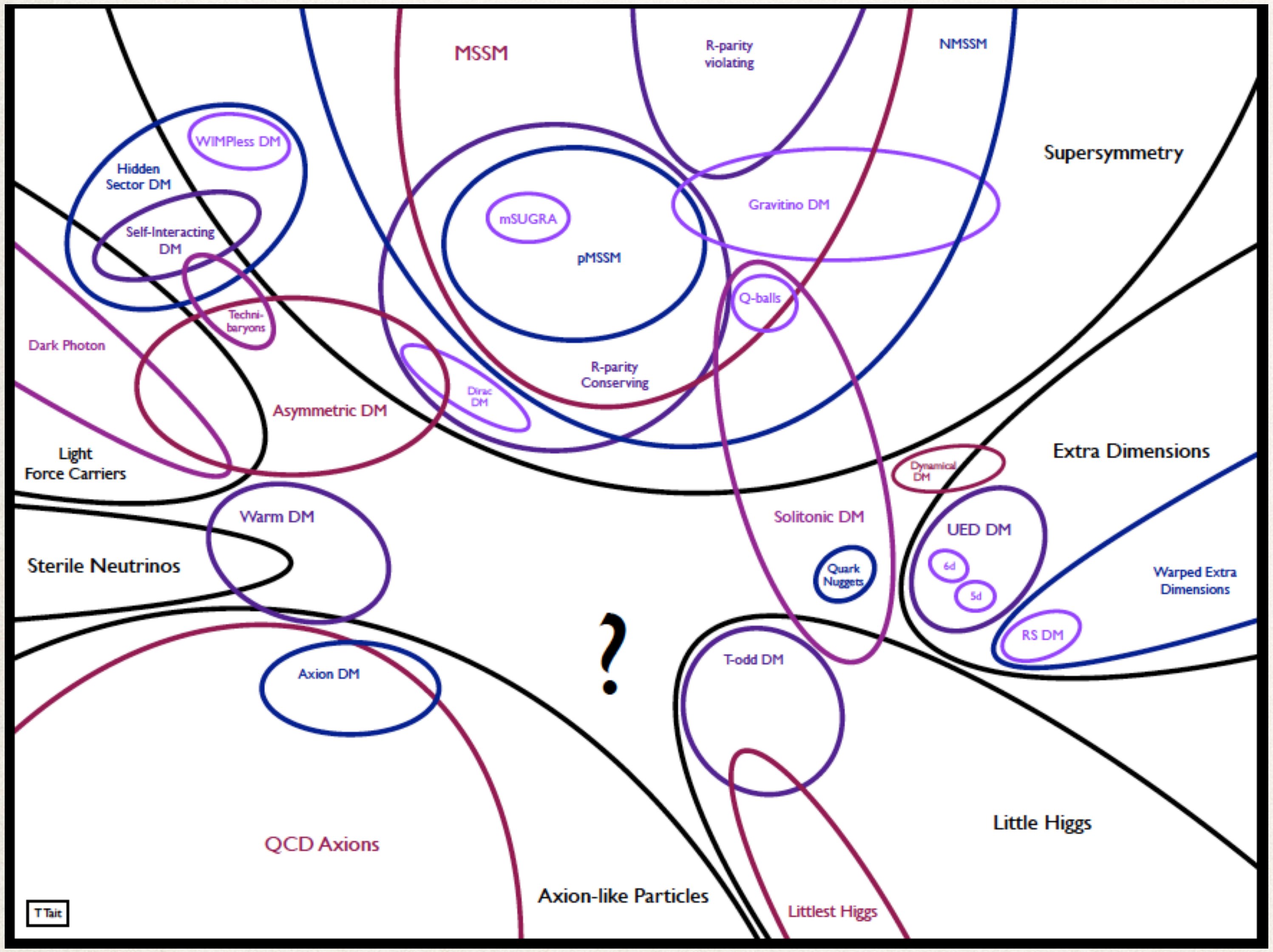
interactions
with nucleons



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)



Thanks to Tim Tait

A snapshot of models for Dark Matter

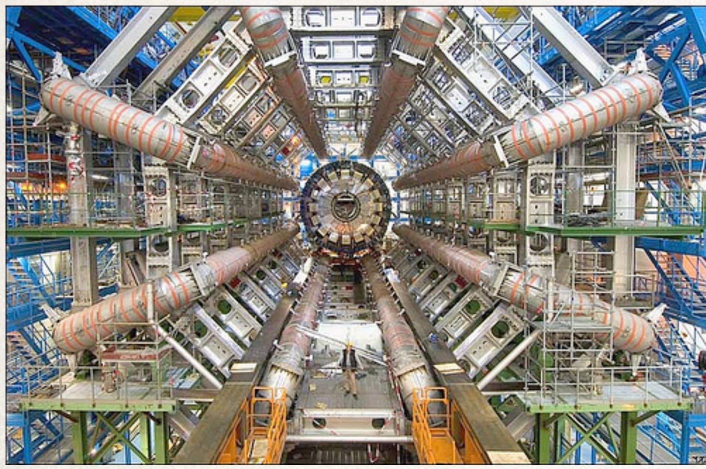
Popular models = linked to solutions to other problems in the SM

Discovery to characterization of Dark Matter leading to new discoveries

DM: a poster-child for complementarity

THEORY
Discrete symmetries
Dynamical stability
self-interactions
Link to Higgs…

COLLIDERS



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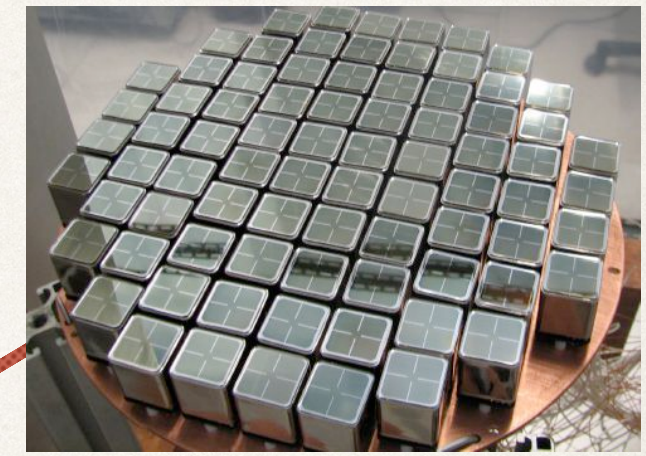
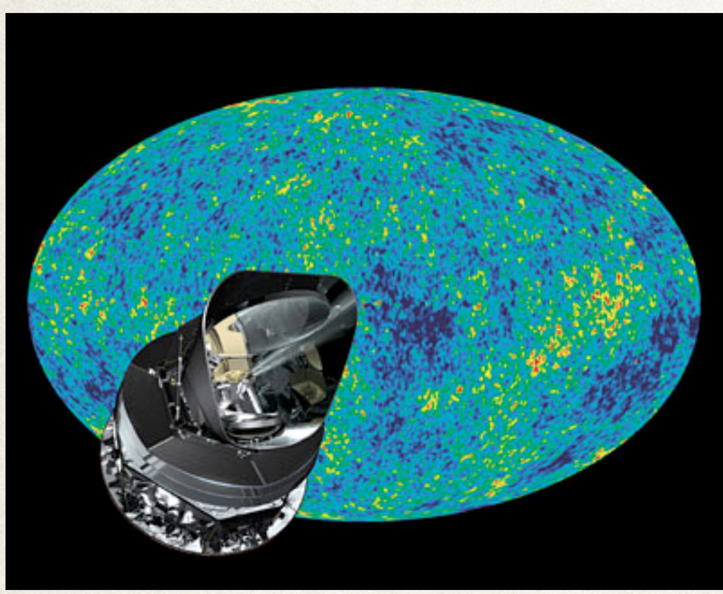
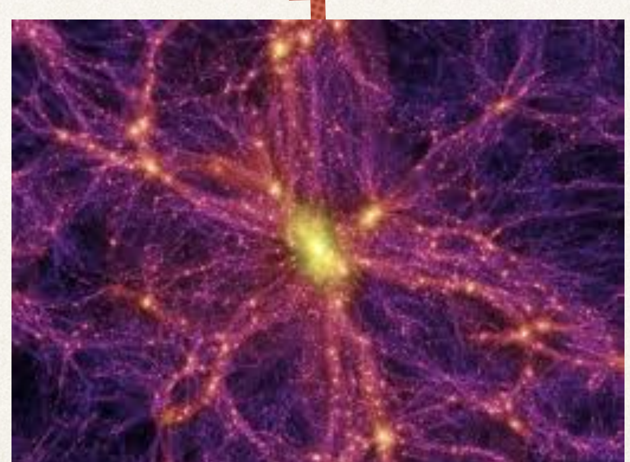


DARK MATTER

CMB: relic, tilt



INDIRECT DETECTION



SIMULATIONS

Dark Matter overview

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

Dark Matter overview

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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 (<TeV) sterile neutrinos
type I see-saw mechanism

Yukawa interaction

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

active sterile

EWSB mass mixing

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

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

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

Neutrino overview

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

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

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

$$r = 16\epsilon$$

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

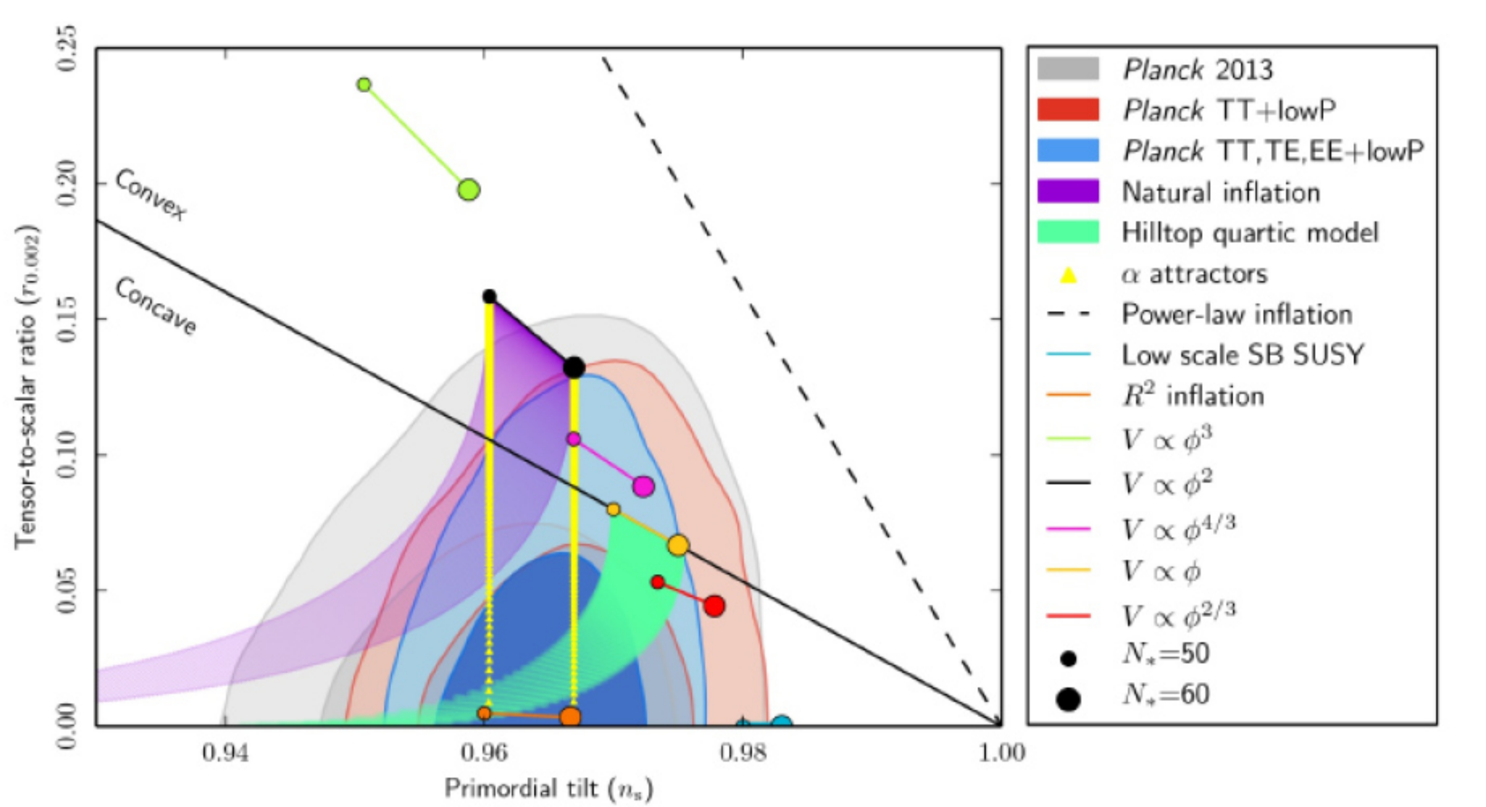

Fig. 12. Marginalized joint 68 % and 95 % CL regions for n_s and $r_{0.002}$ from *Planck* in combination with other data sets, compared to the theoretical predictions of selected inflationary models.

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 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

Additional material (Exercises)

Dirac, Weyl and Majorana Fermions

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

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

Further recall (from Standard Model tutorial 1) that the action of charge congugation can be represented as a matrix acting on Ψ:

$$\Psi^c = C\,\overline{\Psi}^T \qquad\qquad C = -i\,\gamma^2\gamma^0 \tag{2}$$

If we define

$$\Psi \equiv \begin{pmatrix} \xi \\ \overline{\eta} \end{pmatrix} \equiv \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix} \ , \tag{3}$$

then ξ and η are left- and right-handed[1] two-component (Weyl) spinors respectively, and the equation of motion (1) becomes two coupled differential equations:

$$(\overline{\sigma}_\mu p^\mu)\,\xi = m\,\overline{\eta} \tag{5a}$$
$$(\sigma_\mu p^\mu)\,\overline{\eta} = m\,\xi \tag{5b}$$

Remember that in the chiral basis,

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

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

---

[1] We can project onto the left- and right-handed components with

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

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 congugate. 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:

$$\overline{\Psi}_1 \Psi_2 \, , \qquad \overline{\Psi}_1 P_L \Psi_2 \, , \qquad \overline{\Psi}_1 P_R \Psi_2 \, , \qquad \overline{\Psi}_1 \gamma_\mu \Psi_2 \, . \tag{8}$$

d) Re-write the two-component expressions you got for (8) assuming that Ψ_1 and Ψ_2 are Majorana fields.

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

$$\text{Dirac} \qquad M_0 \, \overline{\Psi} \Psi \tag{9a}$$

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

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.

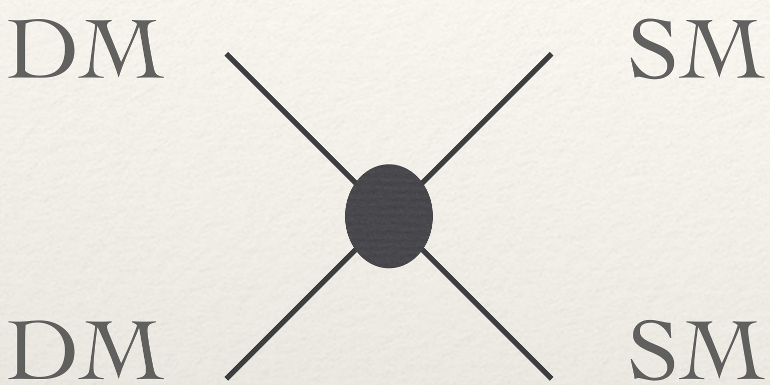
f) Show how M_D, m_L and m_R transform under the action of charge conjugation.

g) Show that a fermion with a Dirac mass term is equivalent to two degenerate Majorana fermions.

Example of DM calculation

thermal production

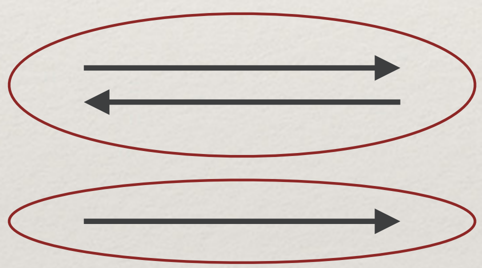
cold (massive) DM



@ T >> mass

@ T ~ mass

@ T << mass *freeze-out*



compute relic abundance after freeze-out (xF=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..*

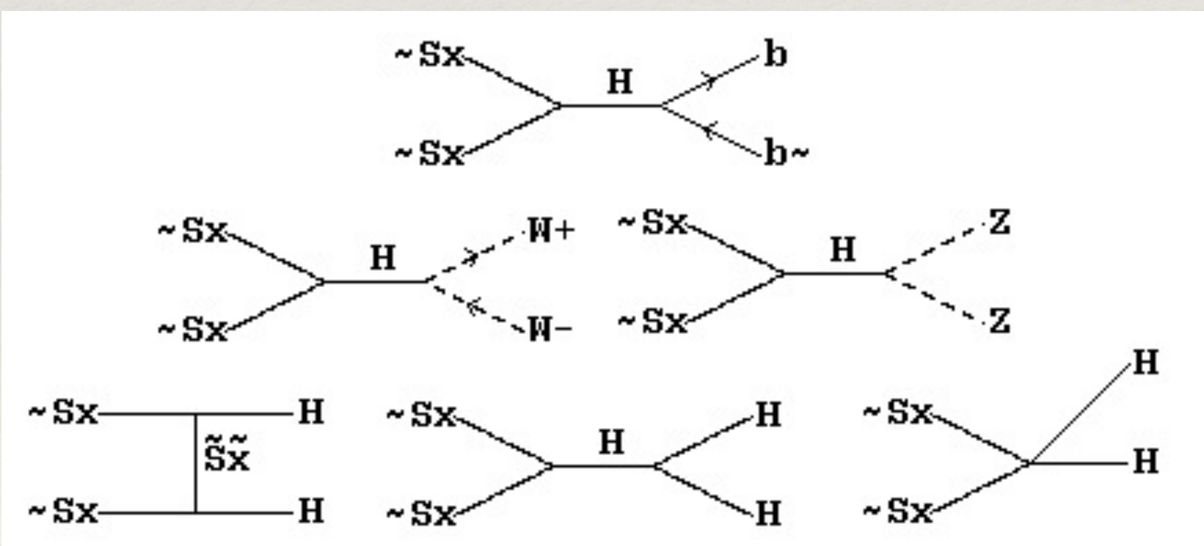
here, analytical expressions

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

$$\lim_{v \ll c} \sigma_{ann} v = a + b v^2 + \ldots$$

s-wave p-wave

thermal average is simply

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

4. Compute the relic abundance

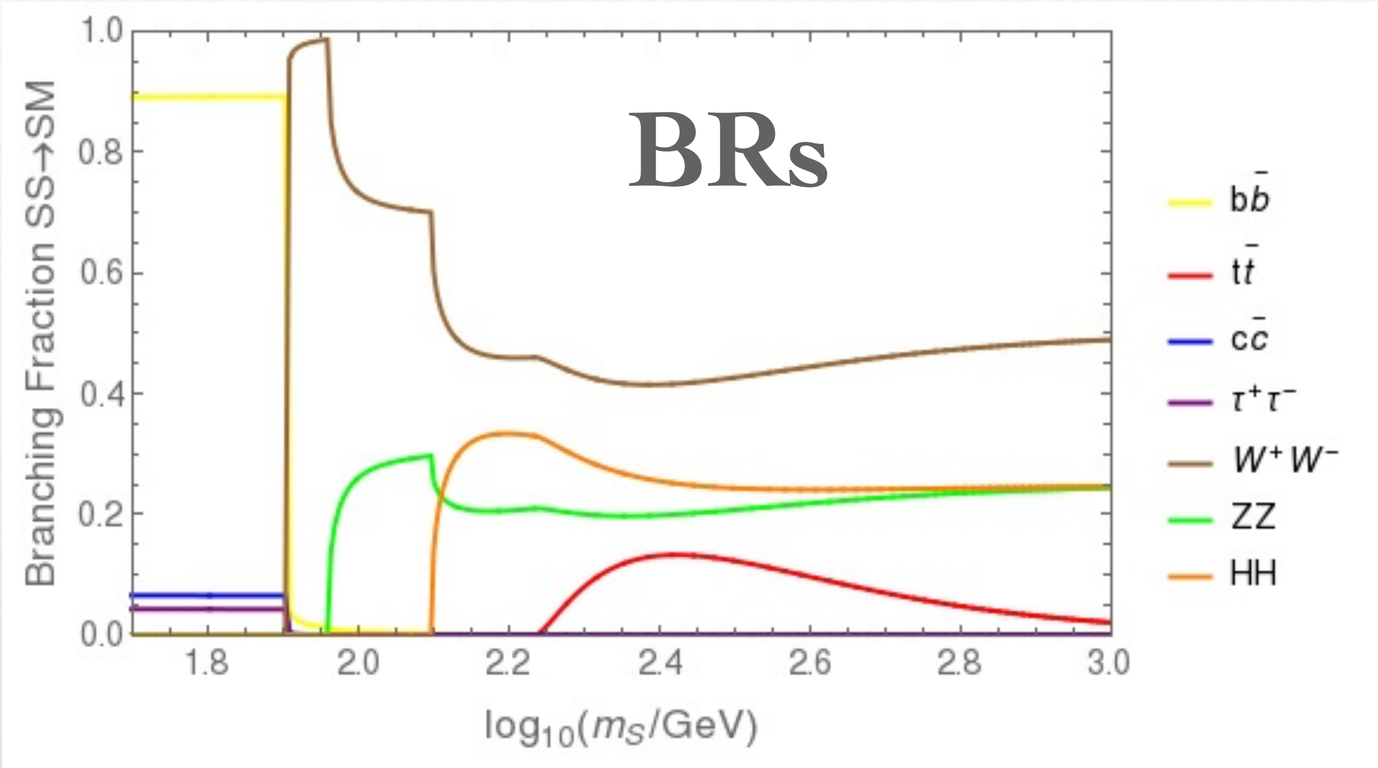
e.g. for s-wave (unsuppressed)

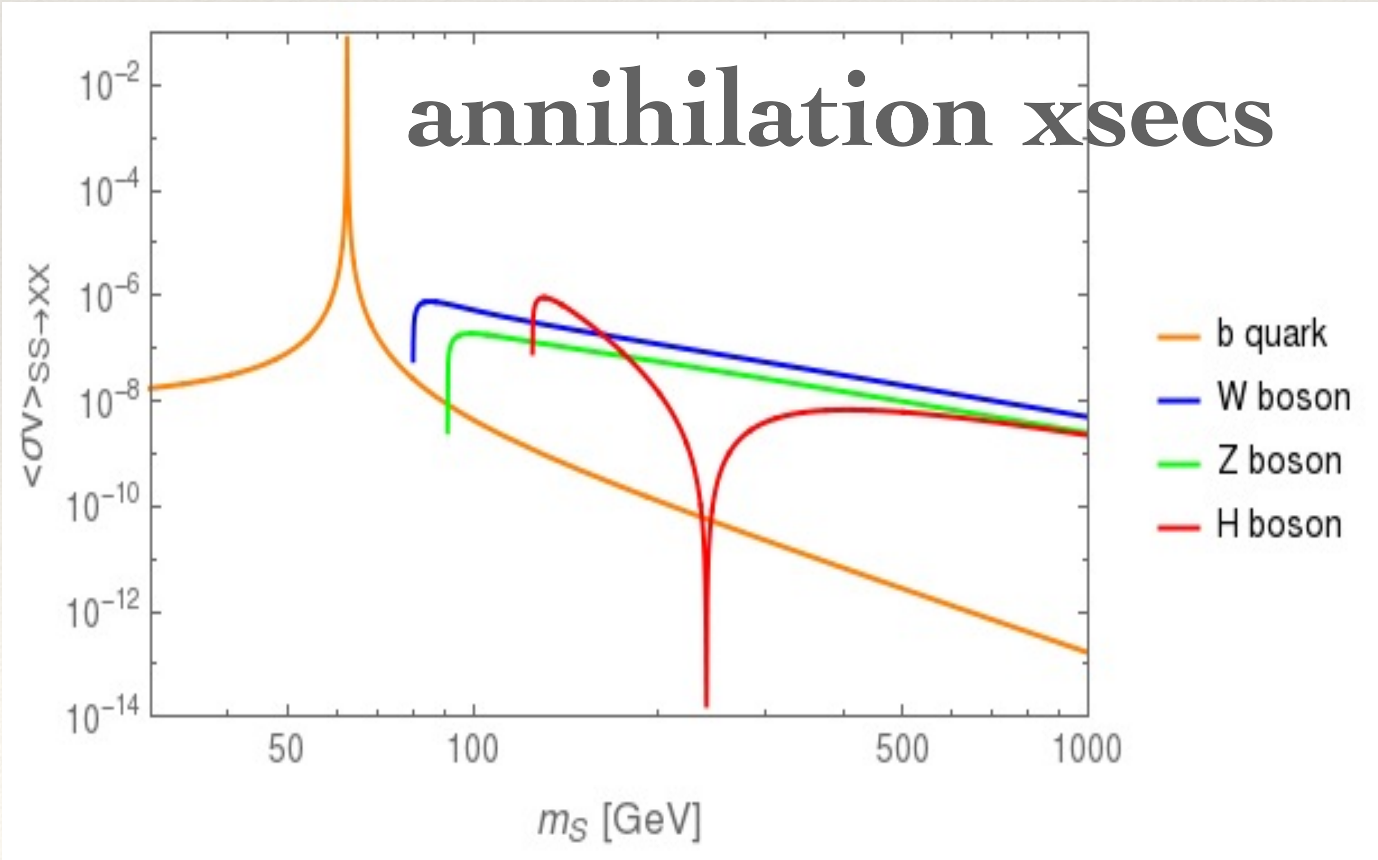
$$\Omega_{DM} h^2 = 1.69 \times \frac{x_f}{20} \sqrt{\frac{100}{g_*}} \left(\frac{10^{-10}\,\mathrm{GeV}^{-2}}{\langle \sigma v \rangle_0} \right)$$

compare with Planck

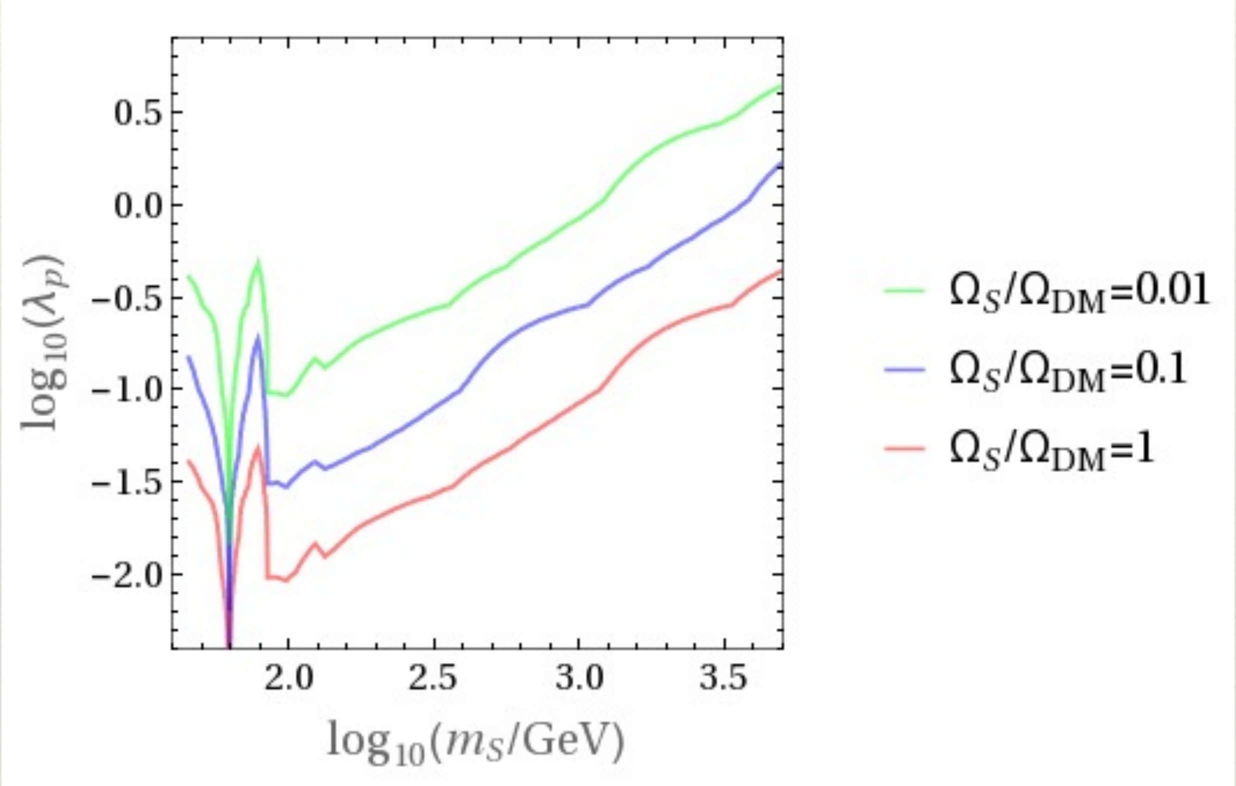
$$\Omega_{DM} h^2 = 0.1188 \pm 0.0010$$

Example of DM calculation





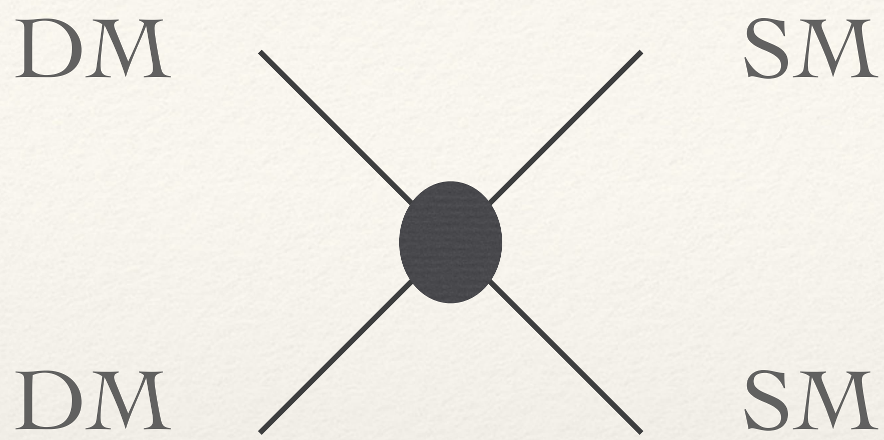
Planck constraints



Example of DM calculation

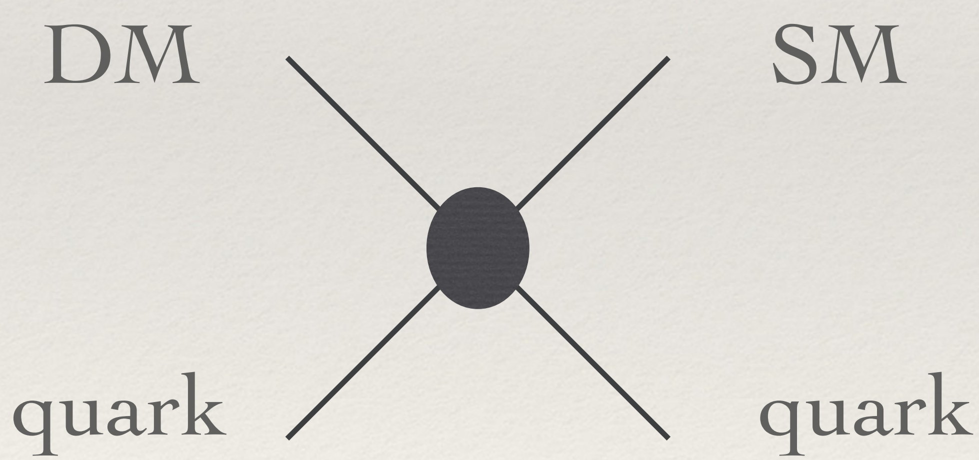
similar calculation for **direct and indirect detection**

relic abundance



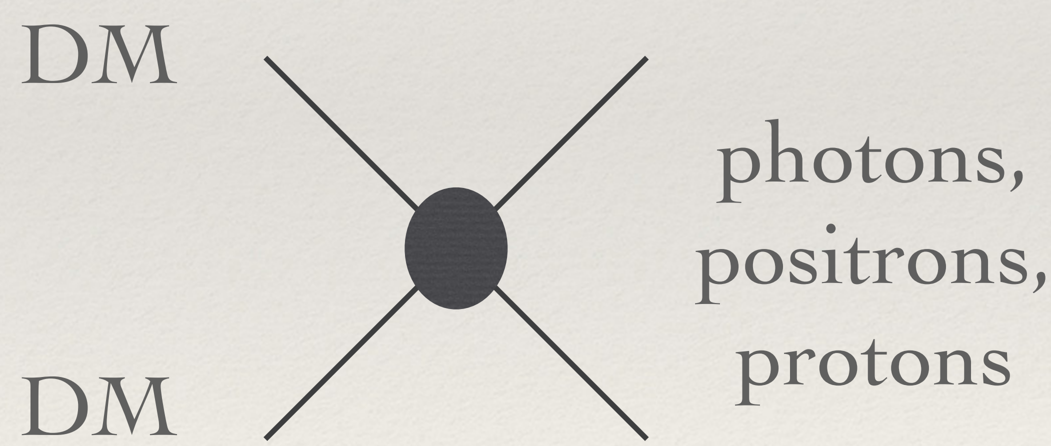
@freeze-out

direct detection



today, local DM density

indirect detection



today, DM density at source
CMB tilt

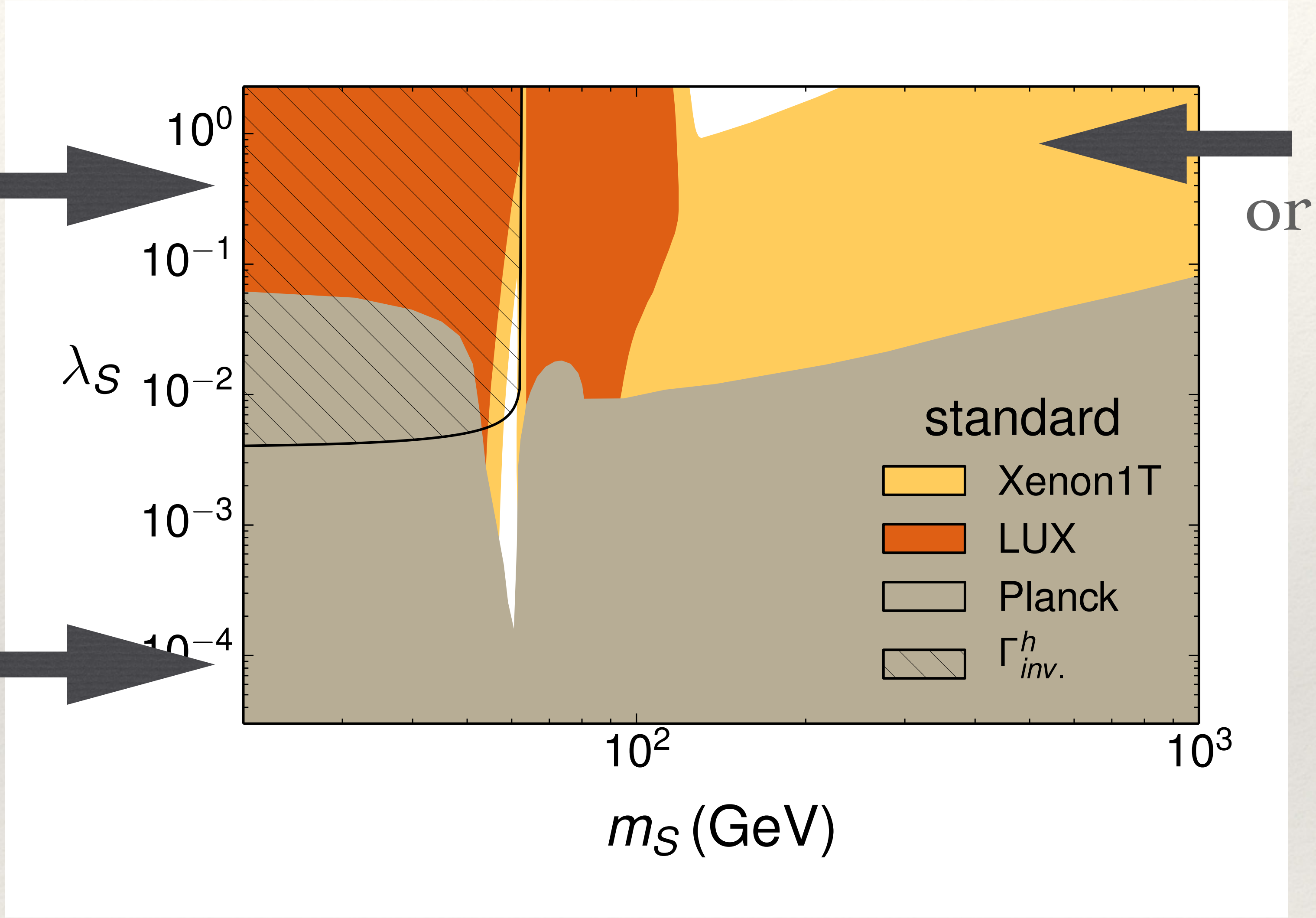
Example of DM calculation

Summary for Higgs portal

constrained by DD, relic abundance and Higgs invisible width

EXCLUDED by DD

EXCLUDED by Planck



will be EXCLUDED or discovered soon

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