The landscape of Dark Matter's models

Enrico Bertuzzo

(University of São Paulo)

Multimessenger School - Principia Institute - May-June 2023

OR…

The hard life (?) of a Dark Matter theorist

Map

WHAT WE KNOW

- Properties of a DM candidate

- Which candidate?
- Constructing a Lagrangian
- Production mechanism?
- Detection?

What we know

Properties of a good DM candidate

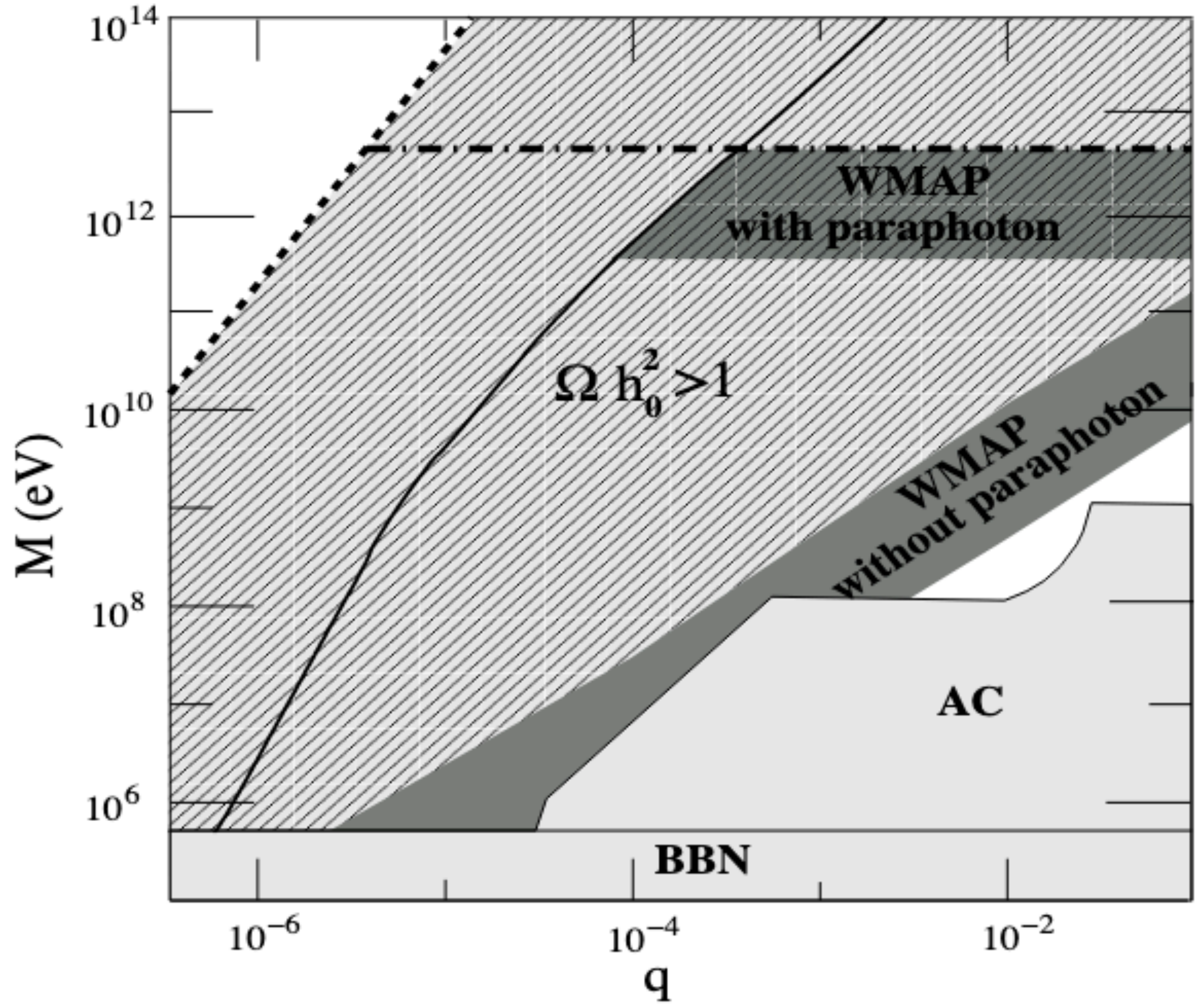
- **Massive** (not radiation)
- **Nearly pressureless** ($w \simeq 0$) when structure formation starts (around $T \sim$ keV)

DM is an essential ingredient to form structures (galaxies, clusters etc).

Models of modified gravity can maybe explain the astrophysical observations pointing towards DM, but not how structure formation can begin before matter-radiation equality

Properties of a good DM candidate

- **Electrically neutral** (we need to ensure that the EM interactions between DM and the SM plasma do not delay structure formation until recombination)



hep-ph/0311189

But it can still have a

Dipole with EM

Properties of a good DM candidate

- **Can be colored only if very heavy**

If $\chi \sim 8$ of $SU(3)_c$ then $m_\chi \gtrsim 12\,\text{TeV}$ (1801.01135)

Properties of a good DM candidate

- **Interactions**
  - gravity
  - maybe with the SM (necessary for thermal production & terrestrial experiments)
  - maybe with itself

$$\sigma_{\chi\chi}/m_\chi \lesssim 1\,\mathrm{cm}^2/\mathrm{g}$$

(self interaction bound from the Bullet Cluster)

Interactions apart from gravity are NOT GUARANTEED

Properties of a good DM candidate

- **Stable**

How much? At least the age of the universe

More precisely:

$$\tau_{dDM} \gtrsim 10 f_{dDM}\, \tau_{universe}$$

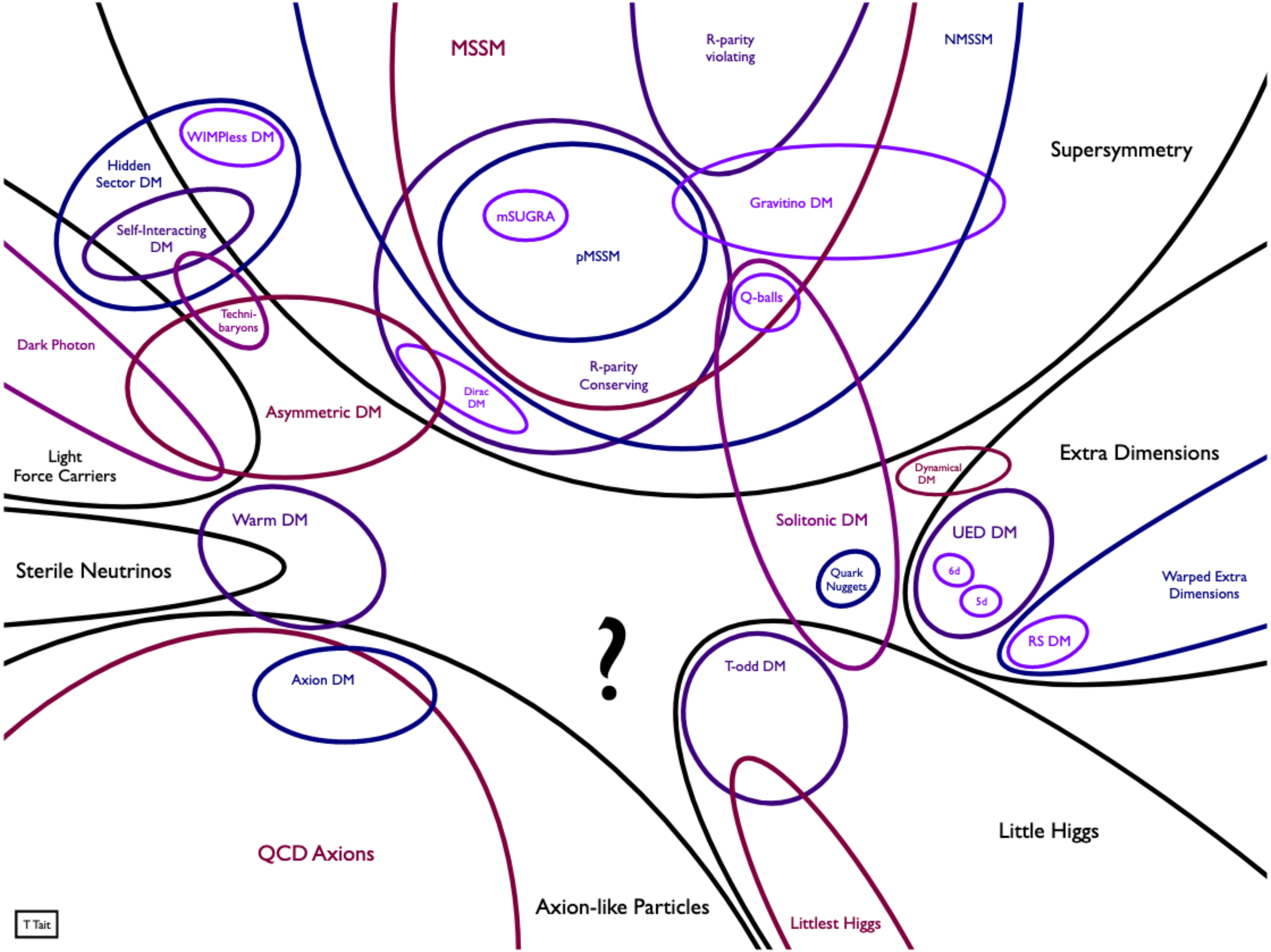
(dDM = decaying DM)

(f_{dDM} = fraction of dDM)

(1606.02073)

This is basically what we know about DM

What types of models did we come up with?



?

Mass is unknown

Spin is unknown

Quantum numbers are unknown

<u>Choices must be made to construct the theory</u>

Our discussion

- How to have a stable DM candidate
- How to produce a DM candidate in the early universe
- How can we hope to detect a DM candidate?

Stability

Easiest aspect to accommodate

Essentially two options to make a candidate stable:

Decays kinematically impossible

Interactions involve PAIRS of DM particles

"Kinematic stabilization"

"Symmetry stabilization"

$\Downarrow$

Possible Pandora box: how do we obtain the symmetry?
By hand, accidentally, gauged...

Production in the early universe

THERMAL CANDIDATES

Freeze-out

WIMPS $1\,\mathrm{GeV} \lesssim m \lesssim 1\,\mathrm{TeV}$

Dark sectors $1\,\mathrm{MeV} \lesssim m \lesssim 1\,\mathrm{GeV}$

NON-THERMAL CANDIDATES

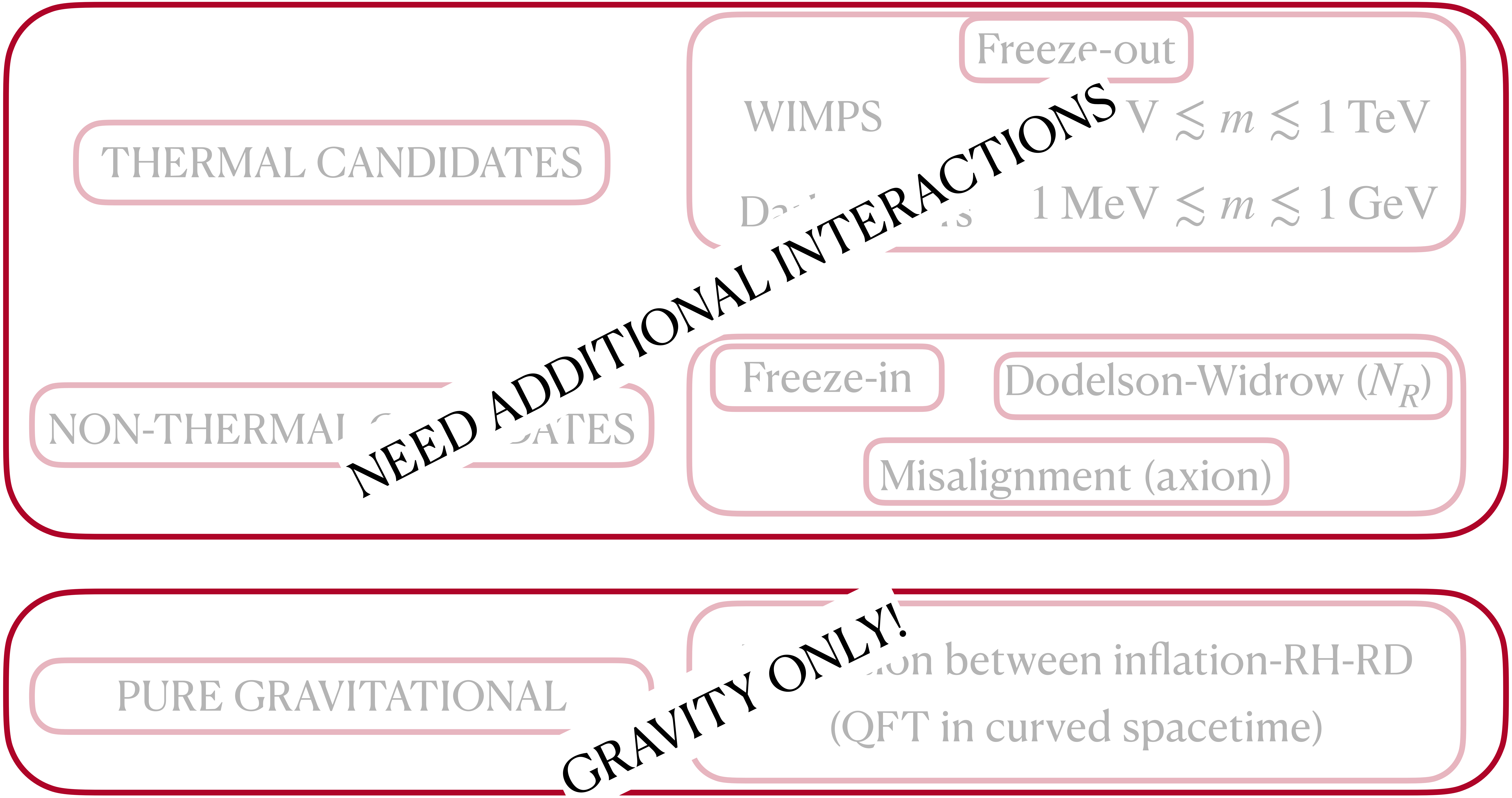
Freeze-in

Dodelson-Widrow (N_R)

Misalignment (axion)

PURE GRAVITATIONAL

Transition between inflation-RH-RD
(QFT in curved spacetime)



THERMAL CANDIDATES
Freeze-out
WIMPS
$\lesssim m \lesssim$ 1 TeV
$1\,\mathrm{MeV} \lesssim m \lesssim 1\,\mathrm{GeV}$
NEED ADDITIONAL INTERACTIONS
Freeze-in
Dodelson-Widrow (N_R)
Misalignment (axion)
PURE GRAVITATIONAL
GRAVITY ONLY!
between inflation-RH-RD
(QFT in curved spacetime)

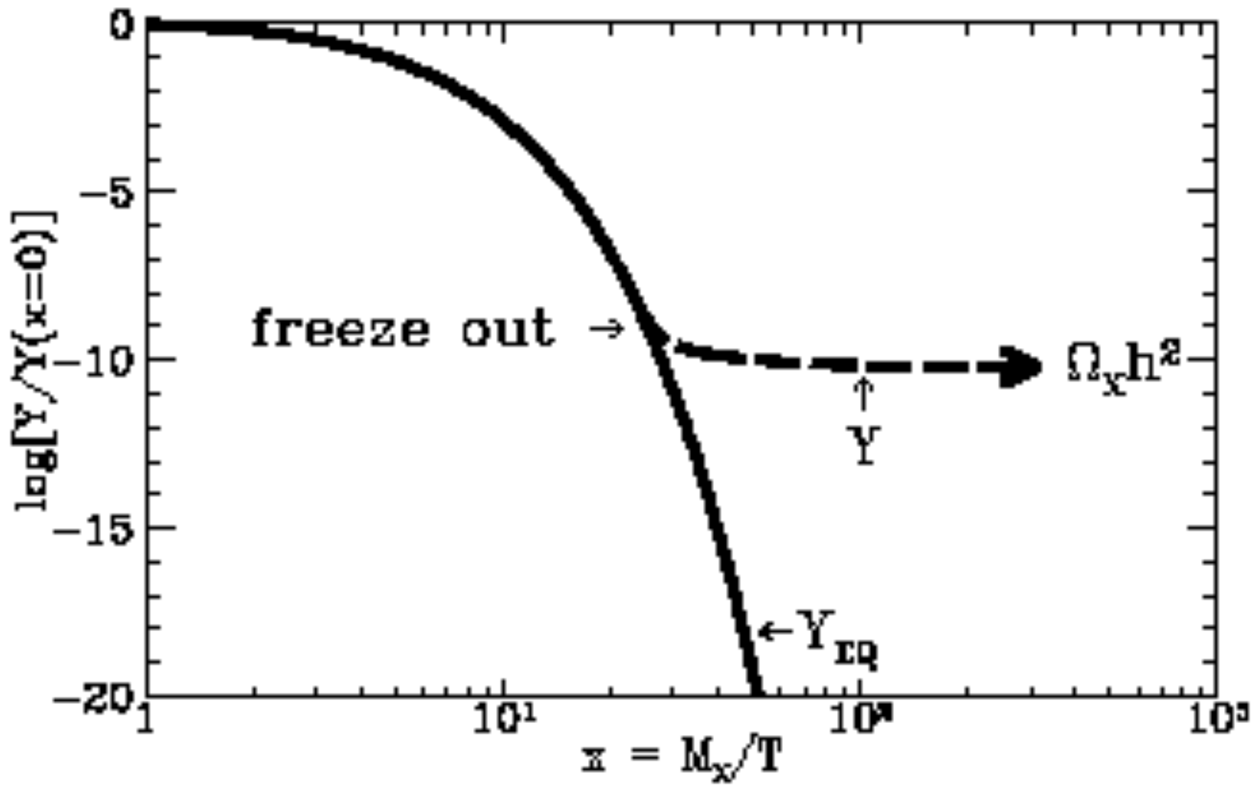
How to do calculations in the different cases

- **Freeze-out** (see Kolb & Turner, ch. 5)

  1. Once the theory is known, compute interaction rates (σ or Γ)
  2. Compute their thermal average (see Gondolo & Gelmini *Nucl.Phys.B* 360 (1991) 145-179)
  3. Solve the appropriate Boltzmann equation assuming thermal initial conditions

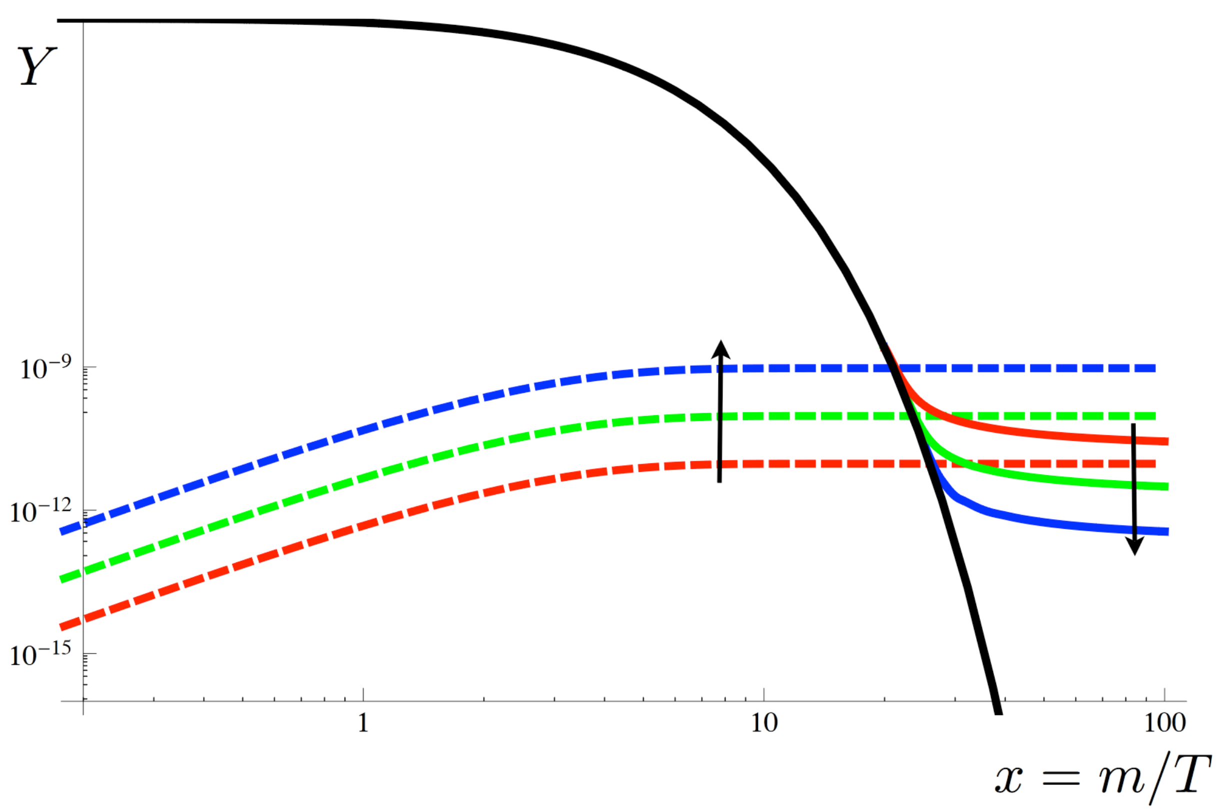
     For instance: for pure annihilations $\chi\bar{\chi} \to$ SM SM, solve

$$\dot{n}_\chi + 3Hn_\chi = -\langle\sigma v\rangle\left(n_\chi^2 - (n_\chi^{eq})^2\right)$$



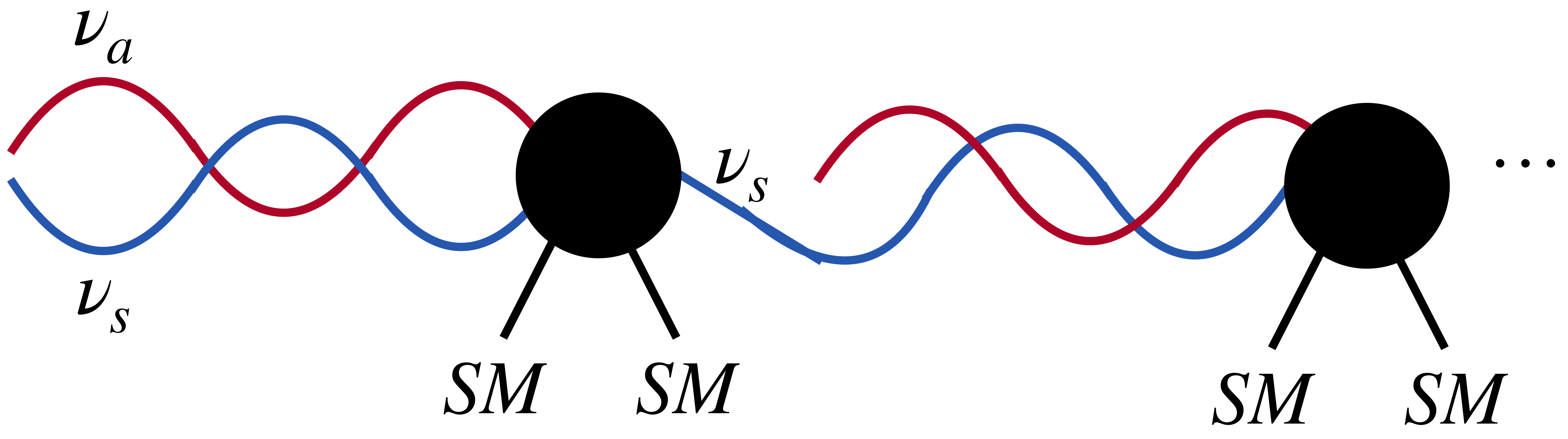
How to do calculations in the different cases

- **Freeze-in** (see Hall et al, *JHEP* 03 (2010) 080)
  1. As in the case of freeze-in, but now
     1. DM supposed to be a **F**eebly **I**nteracting **M**assive **P**article (FIMP), i.e. interaction rate with the SM is suppressed by tiny coupling
        $\Rightarrow$ DM never reaches thermal equilibrium with the SM
     2. DM typically assumed to have vanishing initial conditions
     3. Solve appropriate Boltzmann equation



How to do calculations in the different cases

- **Sterile neutrinos and Dodelson-Widrow mechanism**
  (see Dodelson & Widrow, Phys.Rev.Lett. 72 (1994) 17-20)

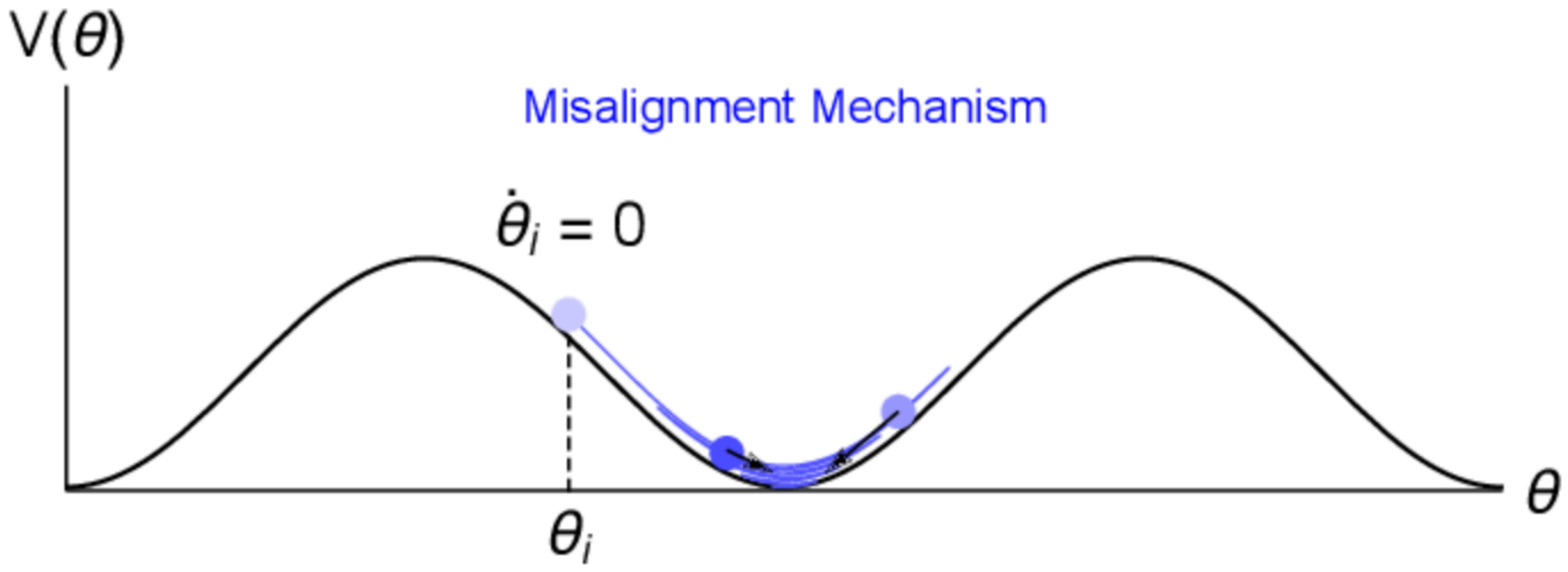


Non-thermal mechanism because based on active-sterile oscillations

$$\left(\frac{\partial}{\partial t} - HE\frac{\partial}{\partial E}\right) f_s = \left[\frac{1}{2}\sin^2(2\theta_M)\Gamma(E,t)\right] f_a$$

How to do calculations in the different cases

- **Axions and misalignment mechanism**
  (see Kolb & Turner, ch. 10)



During the oscillation the axion is cold to a very good approximation

$$\ddot{\phi} + 3H\dot{\phi} + V' = 0$$

How to do calculations in the different cases

- **Gravitational particle production**
  (see Kolb, GGI lectures 2023 and Mukhanov-Winitzki)

In a varying gravitational field, the notion of vacuum is **intrinsically ambiguous**

The vacuum at the beginning of inflation is not the vacuum later on

$\Rightarrow$ we create particles!

IMPORTANT: always present; not a matter of IF but of HOW MUCH

How can we hope to detect dark matter?

The nightmare scenario: only gravitational interactions

Only signal is gravitational, i.e. at astrophysics level

We will never produce DM in the lab

No (known) way of gathering informations on the DM nature

Maybe explains all the negative searches we have

If more interactions are present

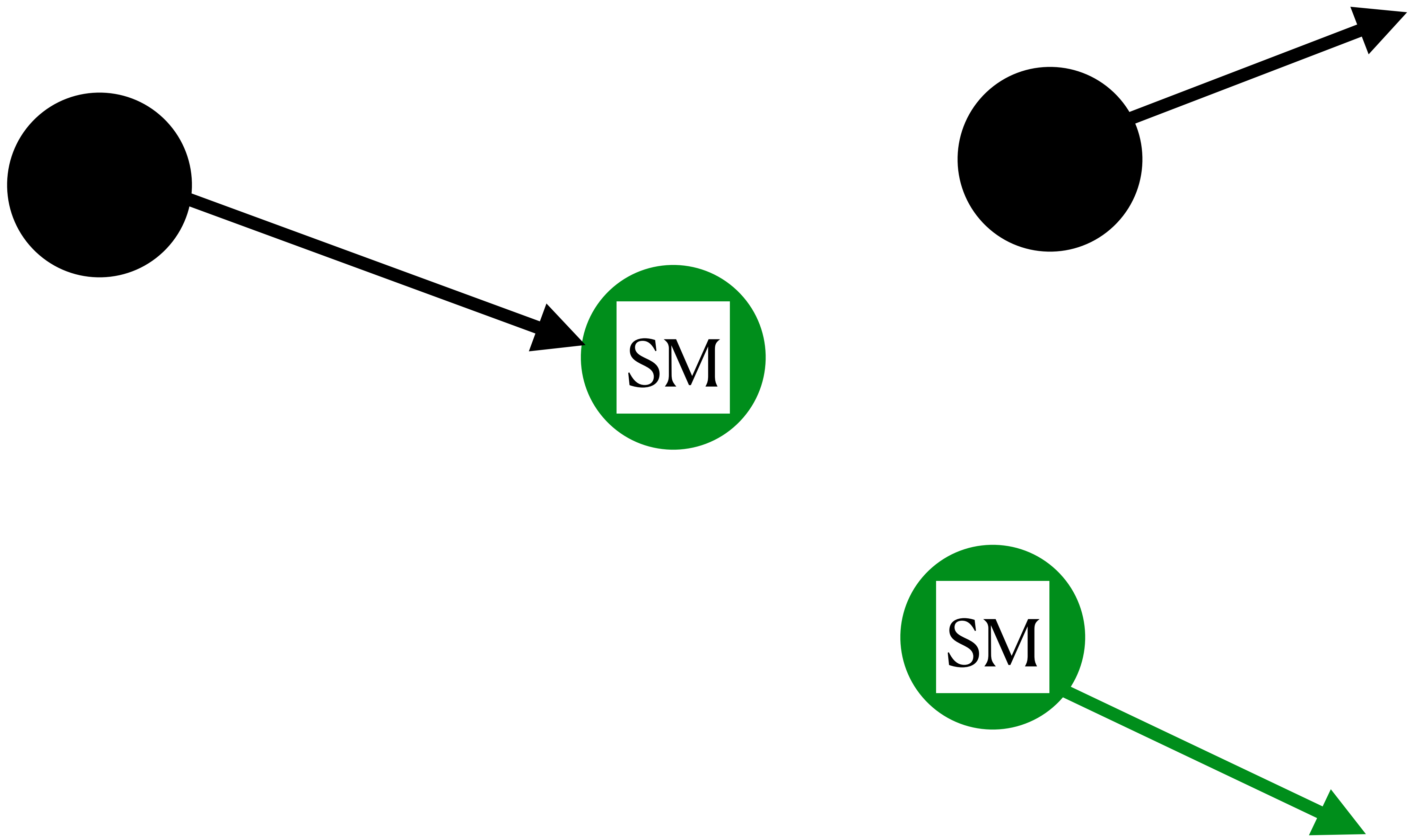
Nature of the interactions is unknown (weak-like for WIMPs, maybe new mediators...)

Interactions with the SM particles have consequences:

PROs: testable (in principle)

CONs: strong bounds

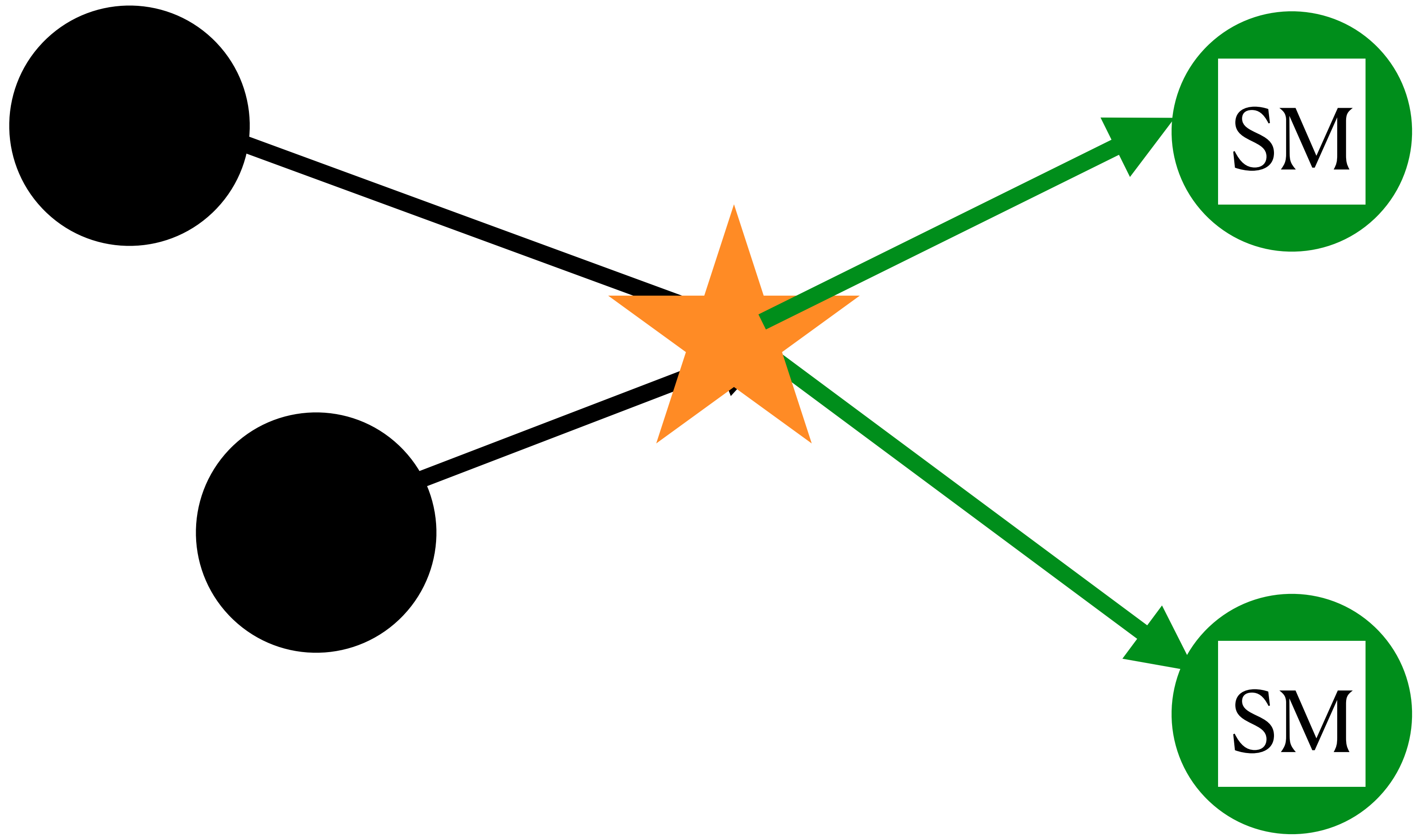
Example 1: direct detection



Scattering off SM particles in the LAB

(see Ivone Albuquerque's lecture)

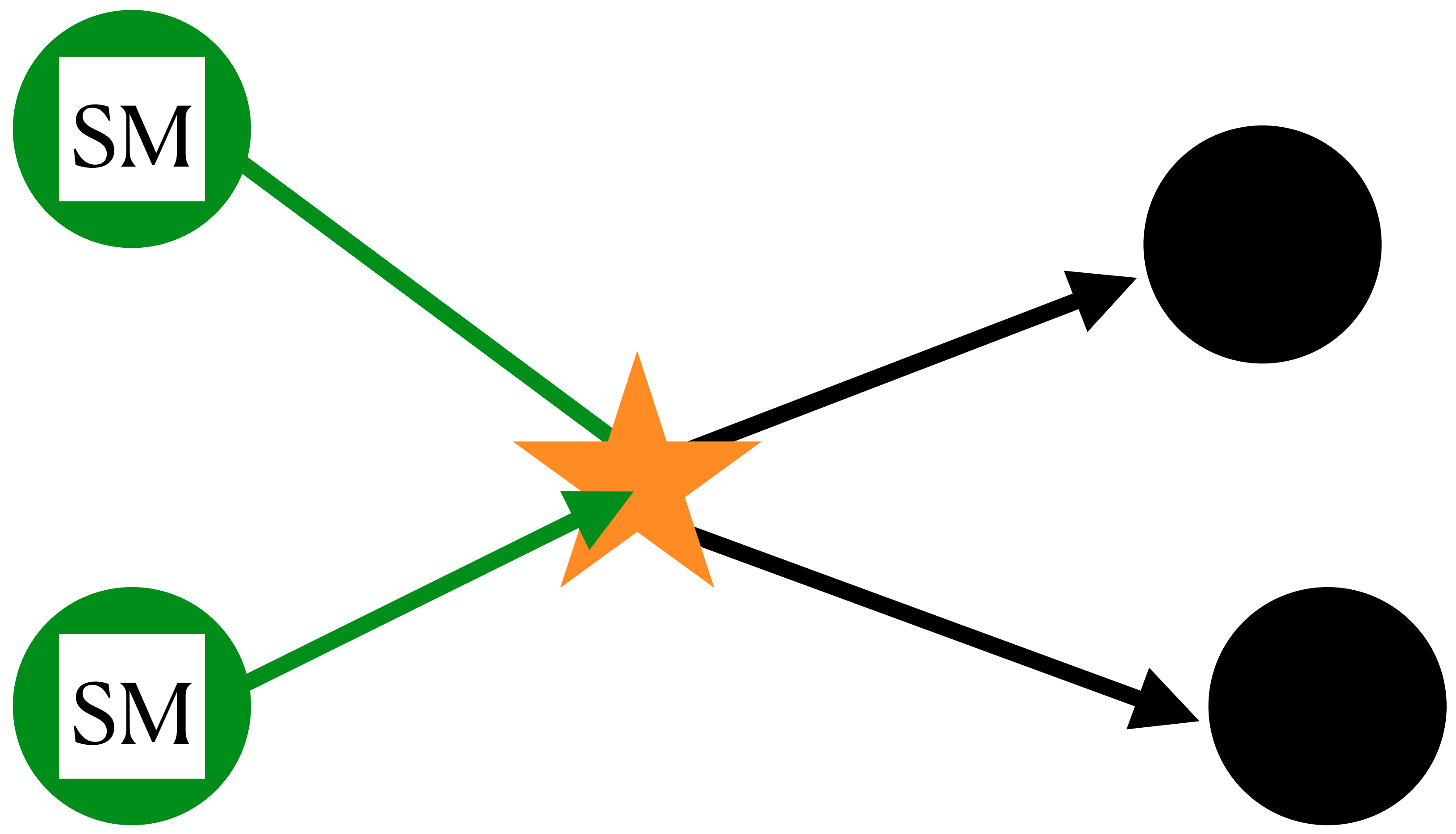
Example 2: indirect detection



Production of SM particles
in astrophysical environments

(see Aion Viana's lecture)

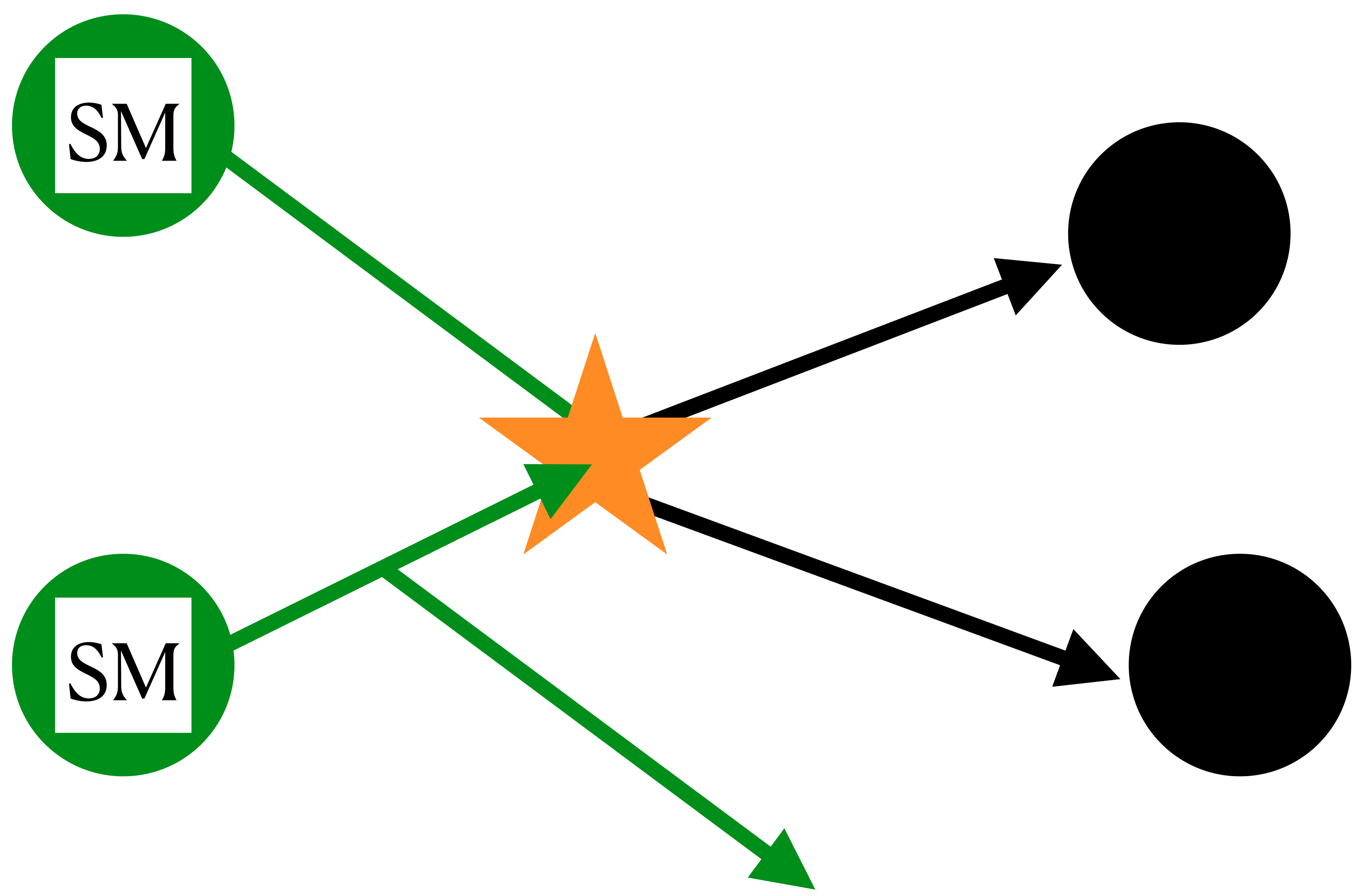
Example 3: colliders



Production of DM in (controlled)
SM particle scattering

Big problem: the signature is missing energy (because DM is neutral), so our detector measures...nothing

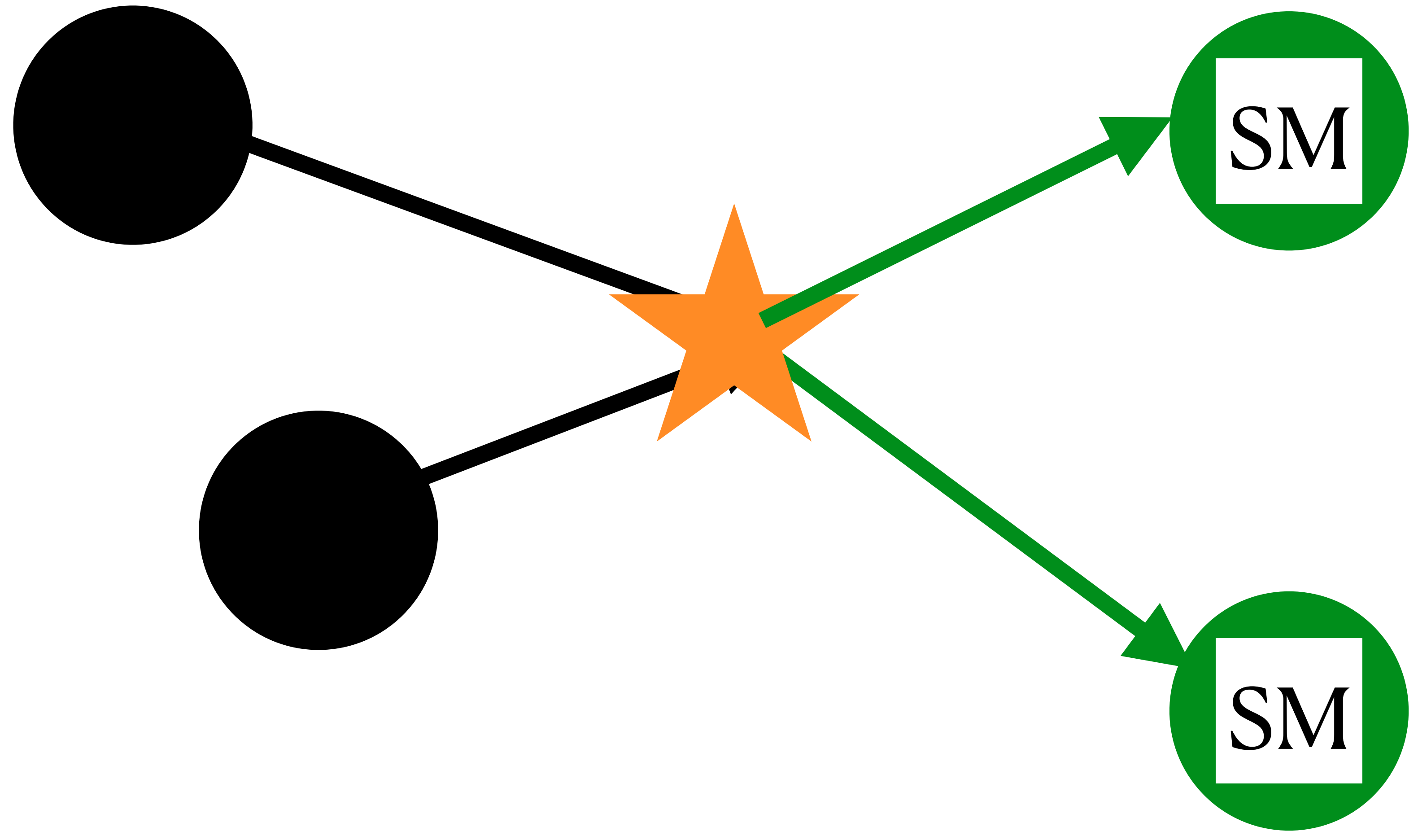
Example 3: colliders



Trick: we tag the event using some visible emission!

MONO-X searches (mono-γ, mono-Z, mono-h)

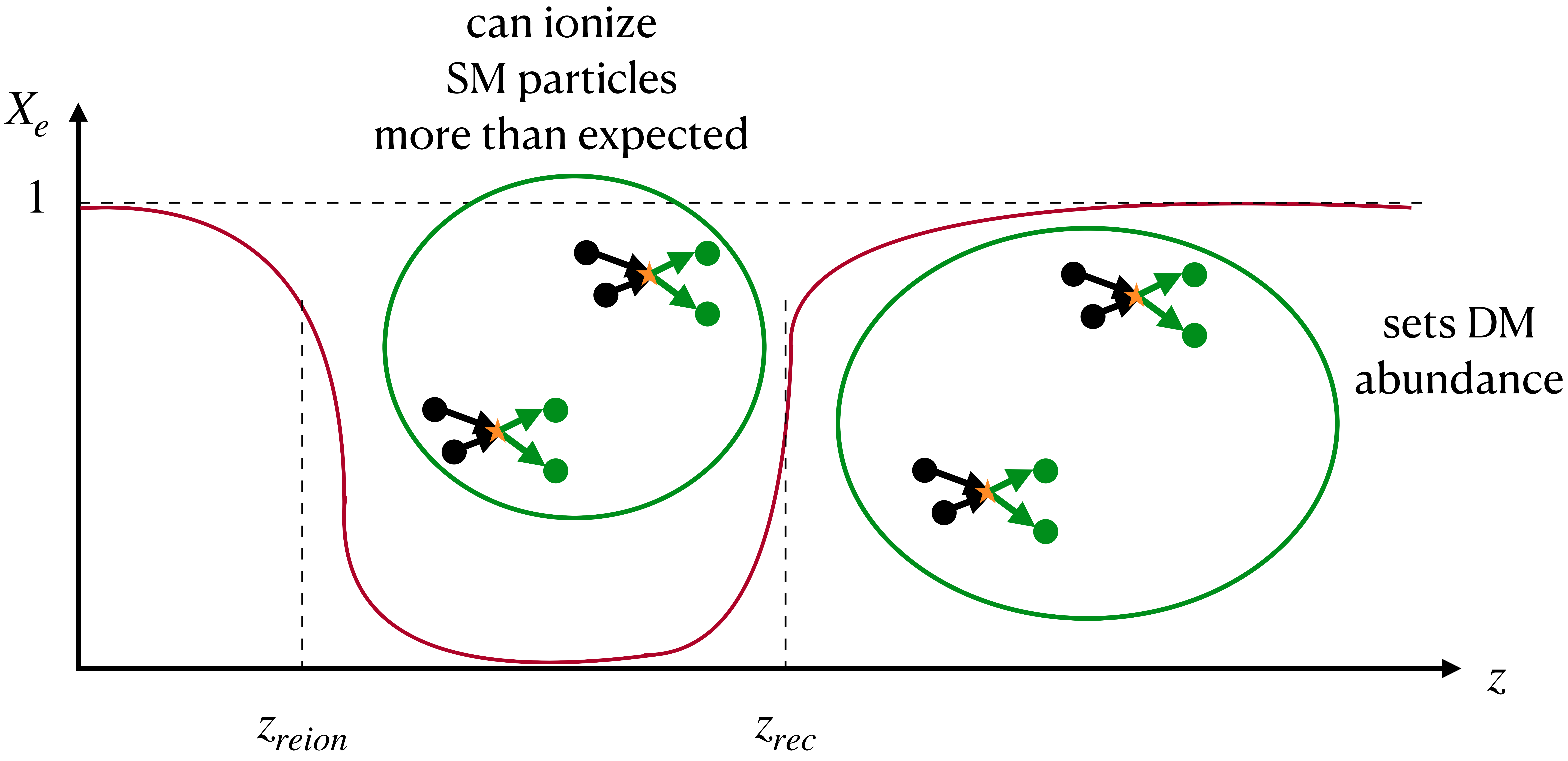
Example 4: CMB bound



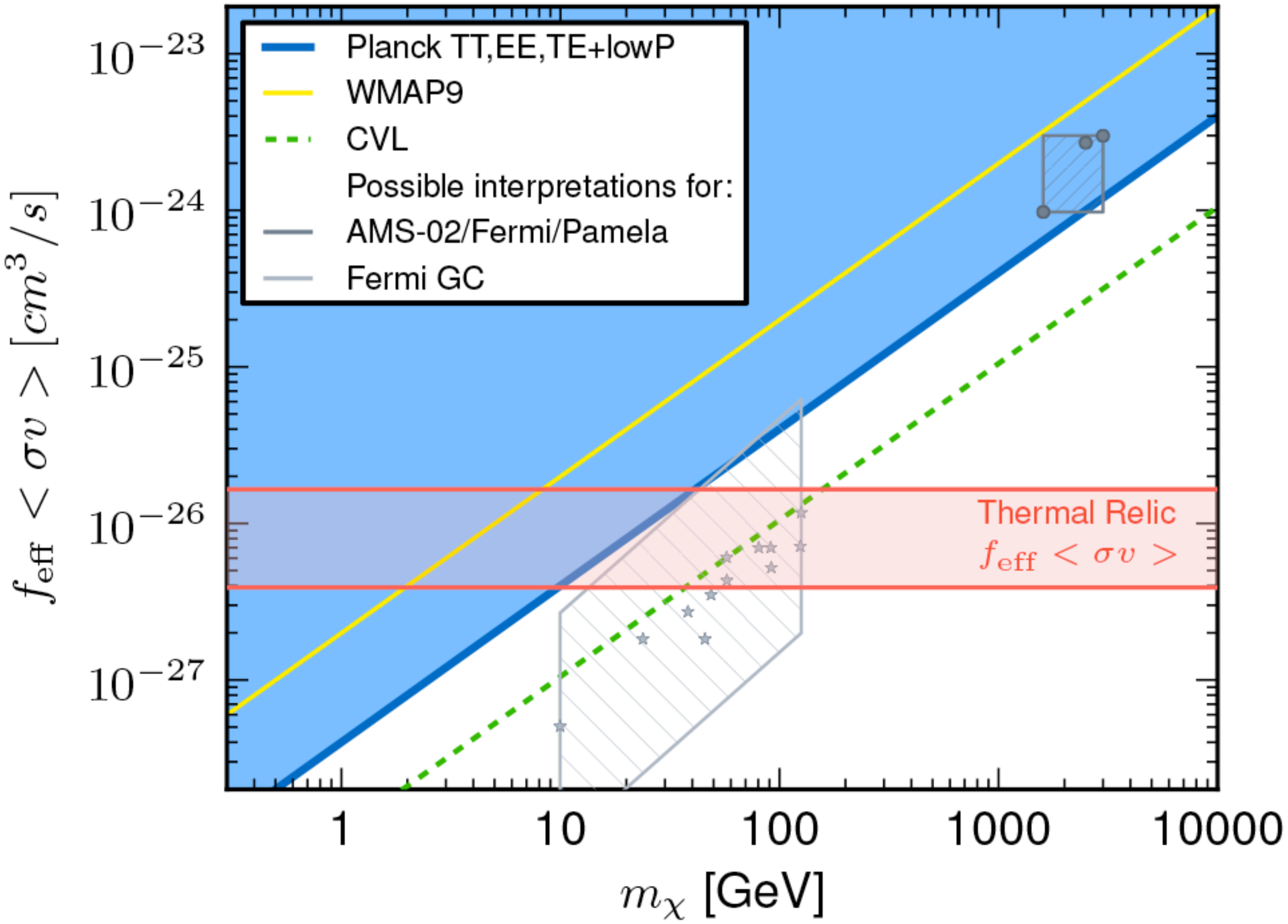
Production of SM particles
in the early universe

(essentially the same process that sets the DM abundance, at least for thermal candidates)

Example 4: CMB bound



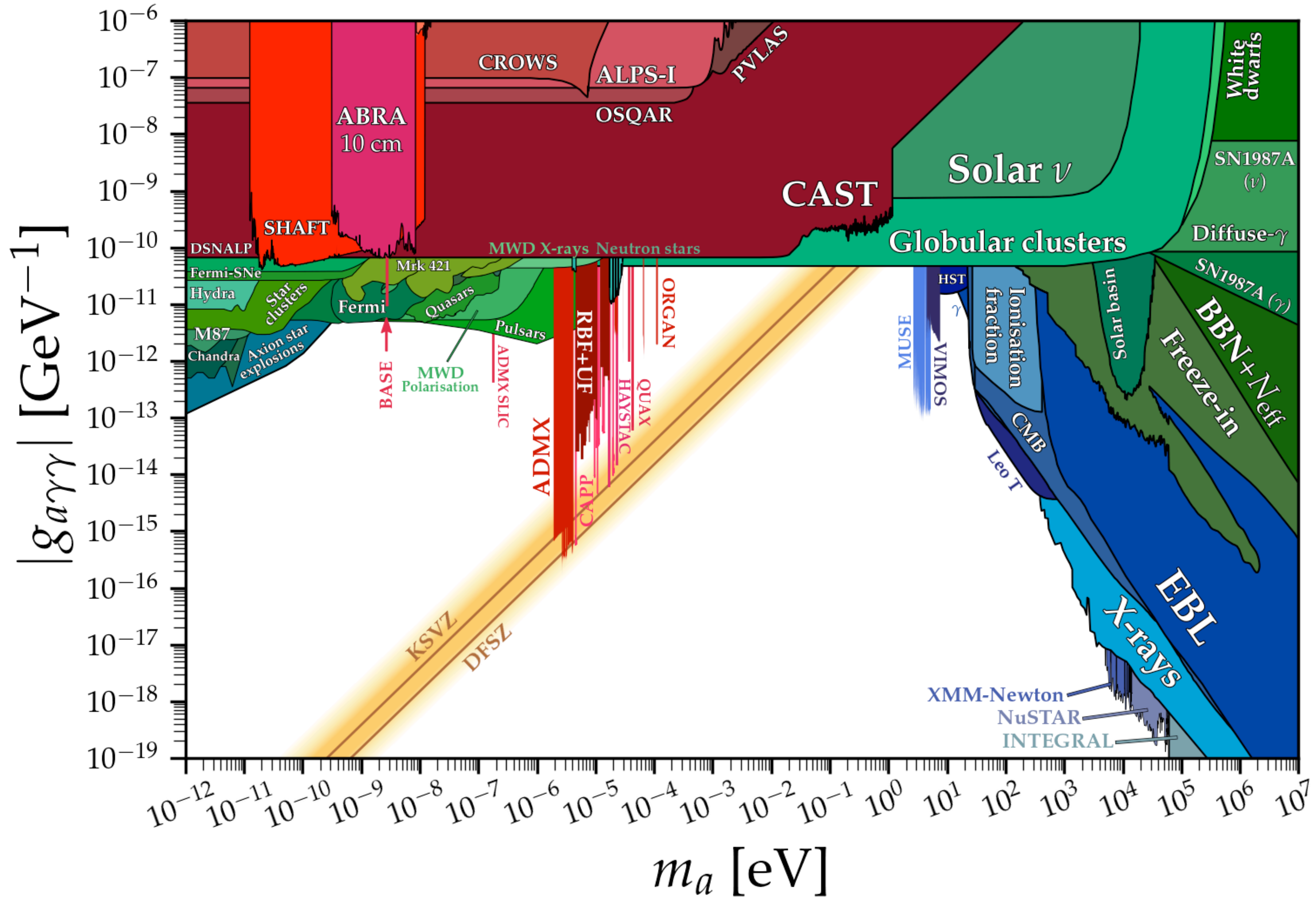
Example 4: CMB bound



Axions

The previous searches do not really apply to axions

New strategies are needed: helioscopes, light-shining-through-walls, astrophysics...



Main message:

We are in the dark

But...

Continuing the search

- We know DM is out there ⇒ we need to search for it
- Is it guaranteed that we will find it? NO
- But we will never know what DM is (and is not) if we don't search for it

Interesting parallelism: we knew of the existence of the top quark well before its discovery because of (i) consistency of the theory (absence of gauge anomalies) and (ii) its effect on EWPO. We were "lucky" that the top was guaranteed to have strong and EW interactions!