# Introduction to Hidden Sectors

## Model Building for Dark Sectors

**Flip Tanedo**

**November 6, 2023**
Interacting Dark Sectors in astrophysics, cosmology, & in the lab
YOUNGST@RS MITP

# Outline

## Mostly p/re/over-view to contextualize talks today

- **Introduction:** working definitions
- **WIMPS**: what is *not* a hidden sector
- **Dark photons:** a simple example
- **Models:** why build them?
- **Production mechanisms:** populating the dark sector

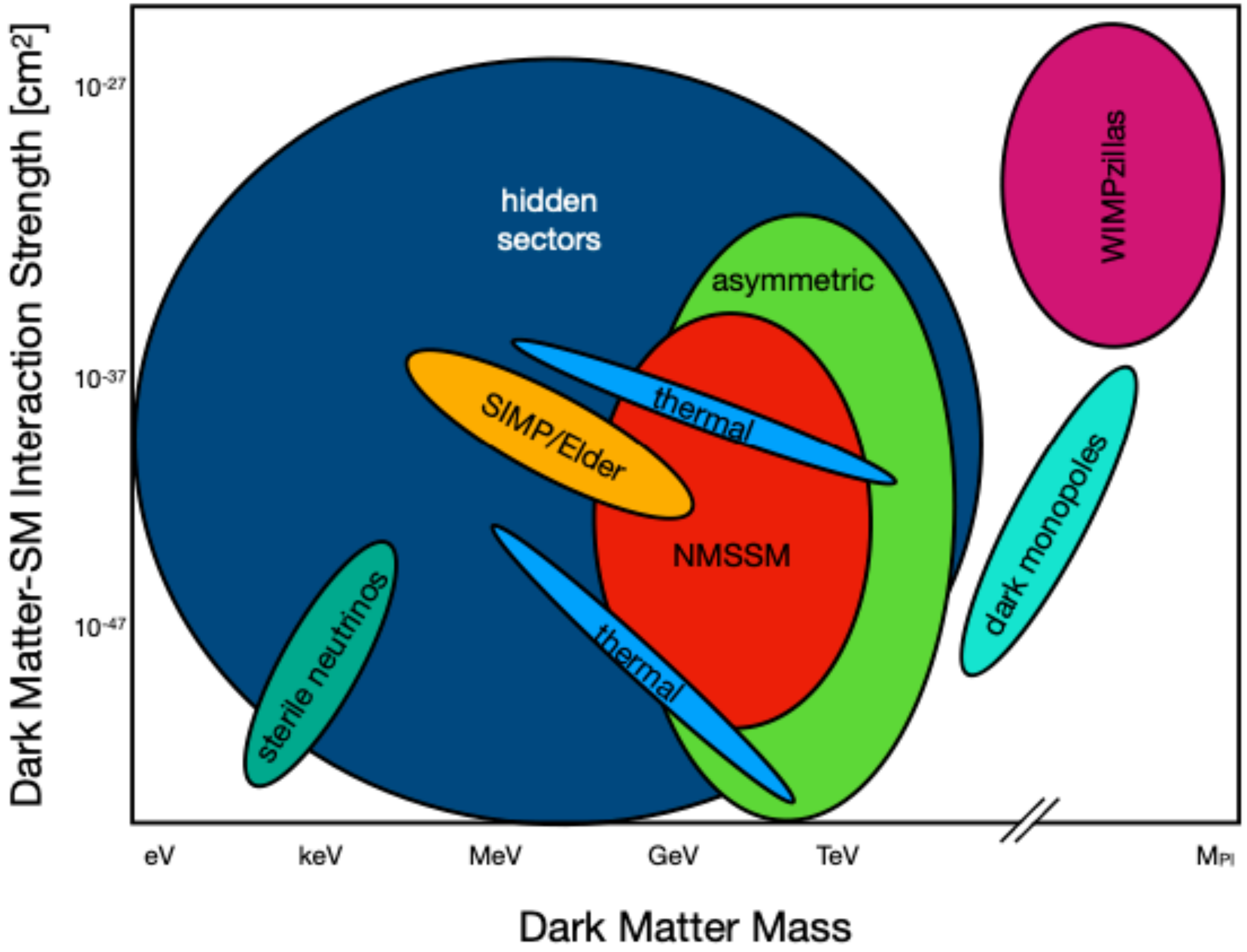
Apologies: we will be a bit idiosyncratic, but the lessons are general.

# Some useful definitions

# Hidden sector, n.

Set of particles whose interactions with the Standard Model vanish when a coupling goes to zero.

| | |
|---|---|
| Higgs singlet | $(H^\dagger H)(\lambda S^2 + AS)$ |
| Kinetic mixing | $F^{\mu\nu}F'_{\mu\nu}$ |
| Neutrino mixing | $LHN$ |
| Axion-like | $J^\mu \partial_\mu (a/f)$ |



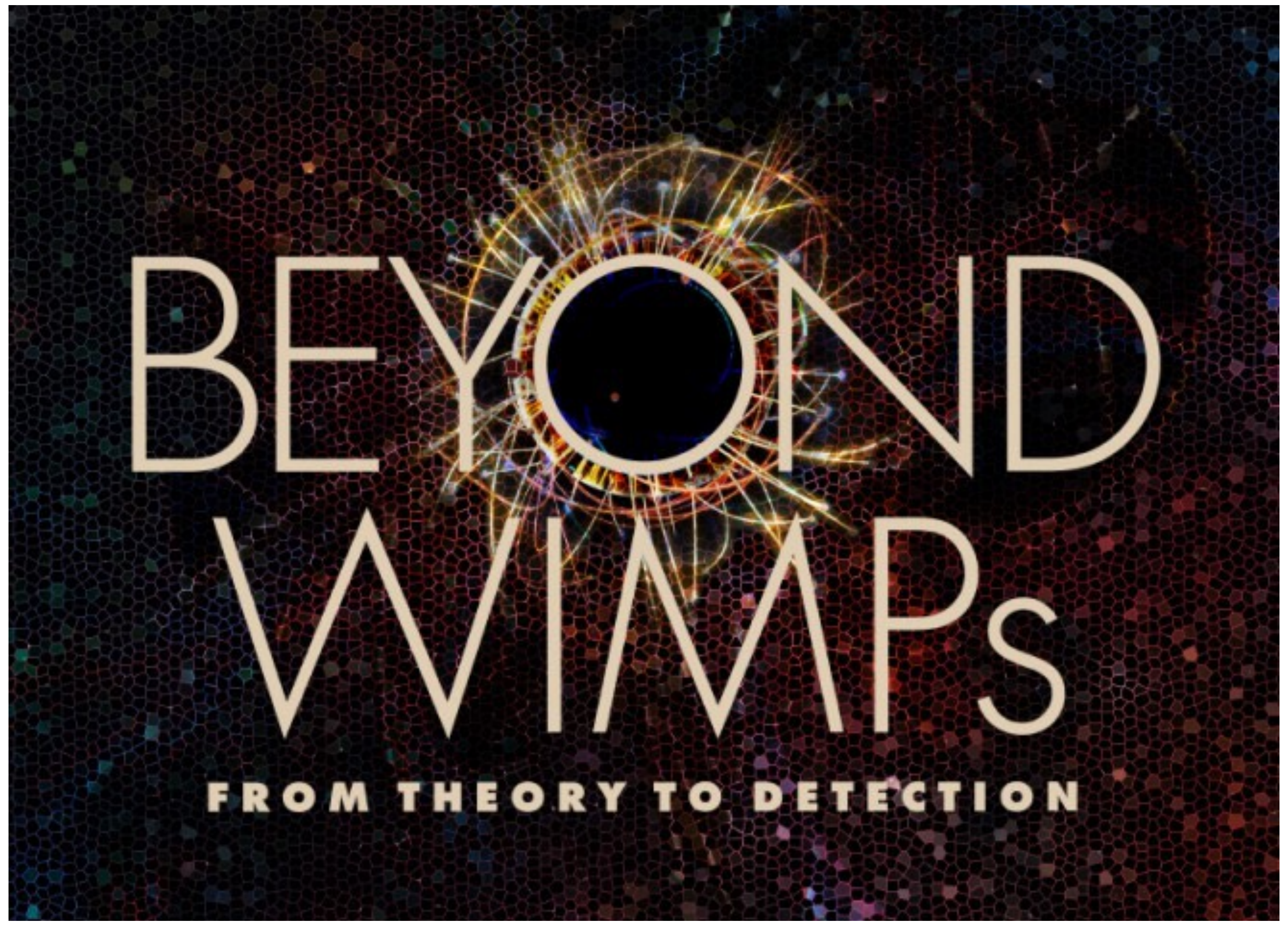

+ others (variations of mass mixing, rich dark sectors, …)

Snowmass: Particle dark matter 2209.07426

# Dark sector, n.

A hidden sector that is also a **model of dark matter**. Contains at least one dark matter particle that is sufficiently stable.

Dark matter candidates realize the observed dark matter abundance. In this way, dark sectors have a target for model building.


SLAC Workshop on Dark Sectors 2016, Simons Center “Beyond WIMPS” 2017

# Model of dark matter

## A checklist for model-builders

- **What is it?** Particle(s) and their interactions, written as a Lagrangian.
- **How did it get here?** Production mechanism.
- **Why is it still here?** Stability on cosmological scales.
- **Why isn't it ruled out?** Existing observations.
- **How do we discover it?** New observations, techniques, …

# Weakly Interacting Massive Particles

## A useful example of what is *not* a hidden sector... and how we got here

# Two Big Puzzles in Particle Physics in the 90s

$m_h$ ?

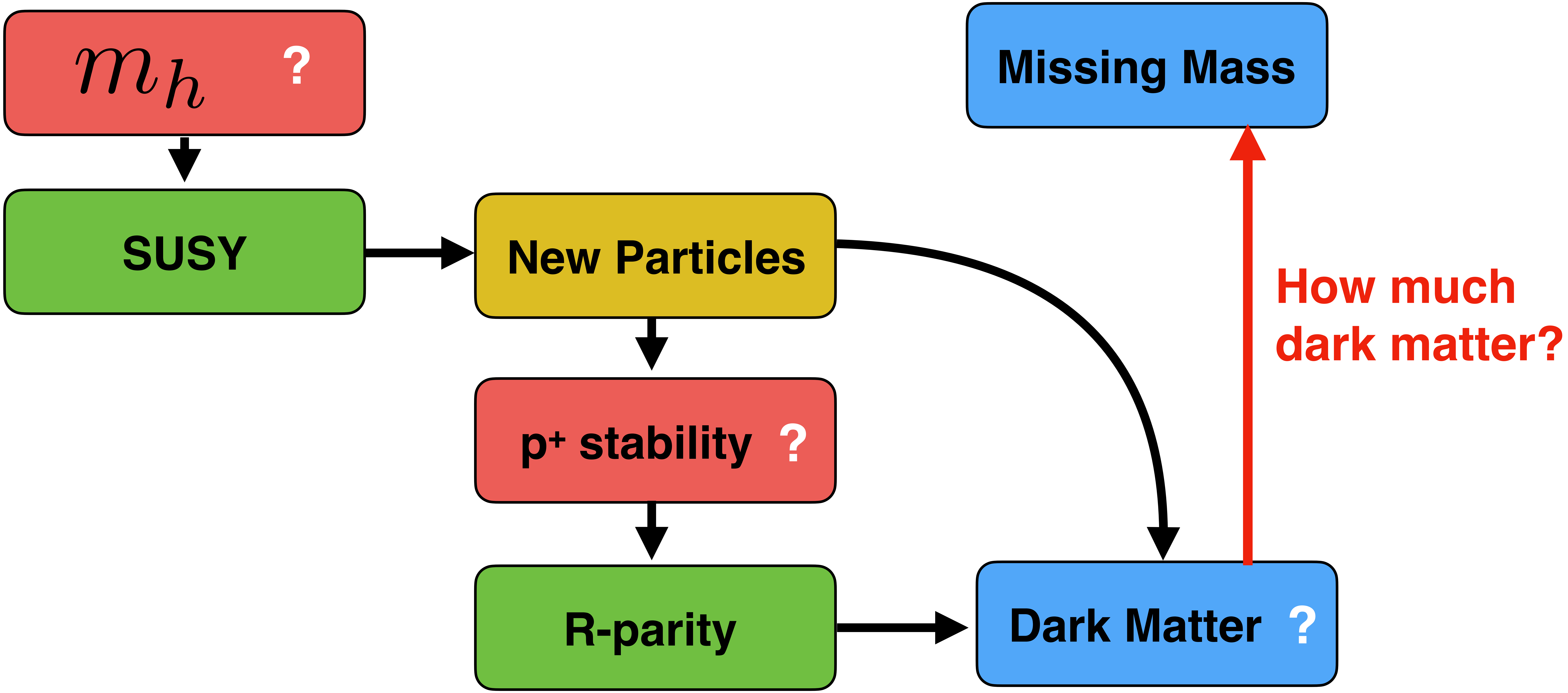
**Missing Mass**



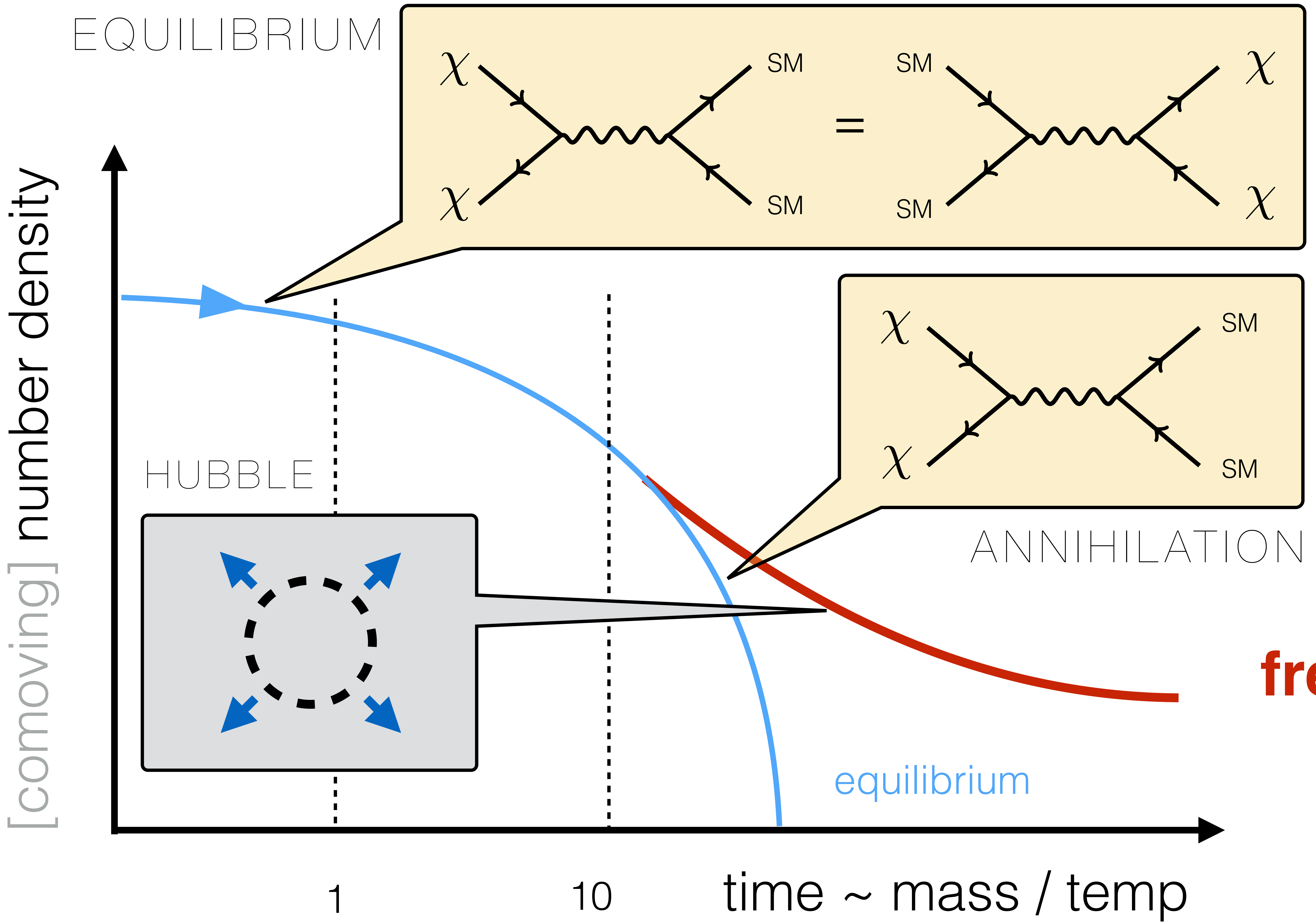
**... and now a *brief* summary of the best [& mostly unrealized] ideas in theoretical particle physics from the 1980s to 2010s: WIMP variants**

Images: Cham and Whiteson, *We Have No Idea*

# The story of supersymmetry



# How much dark matter is there? WIMP miracle



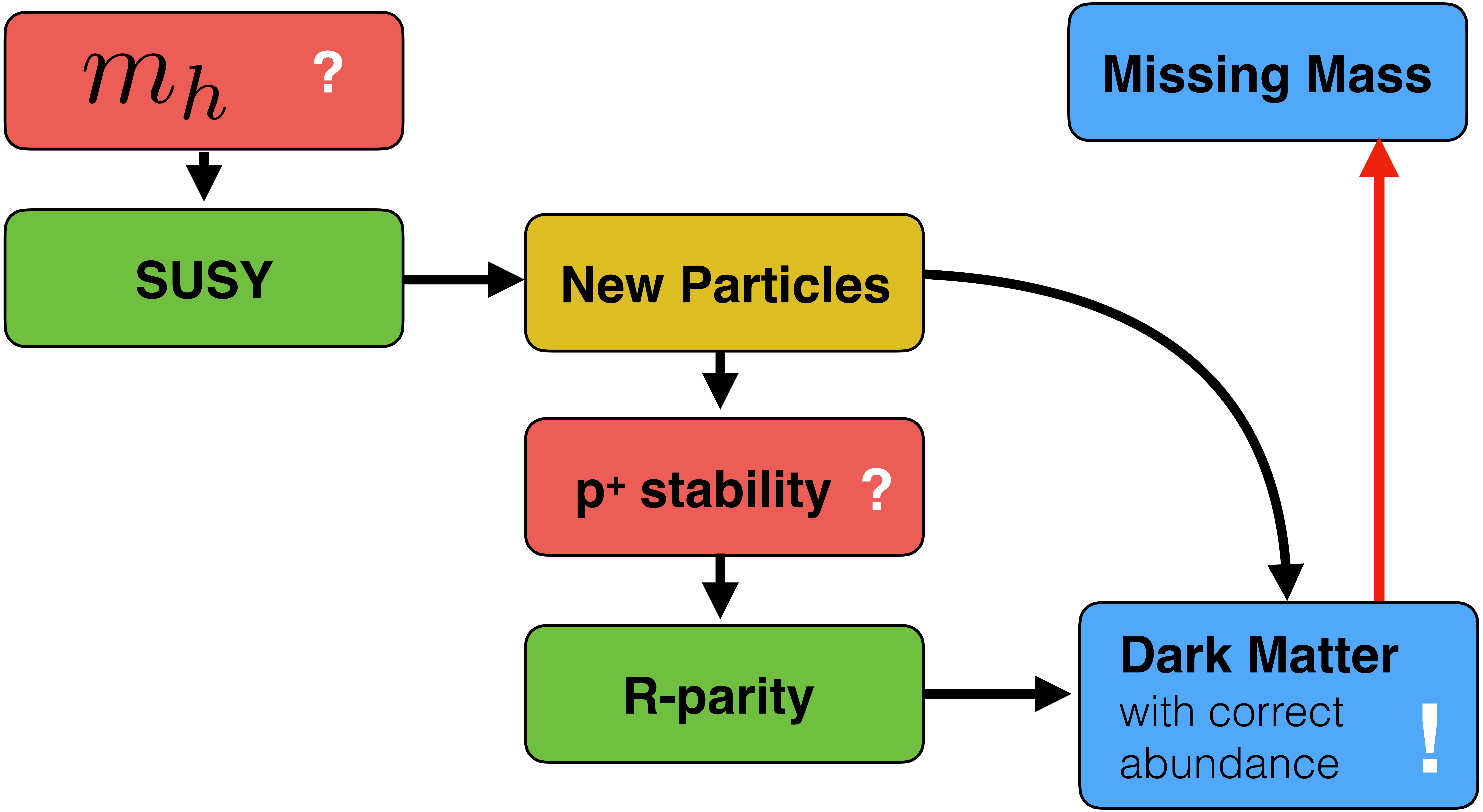

OBSERVED **AMOUNT OF DARK MATTER** TODAY

$$\Omega_\chi h^2 \sim \frac{0.1\ \text{pb}}{\langle \sigma_{\text{ann}} v \rangle}$$

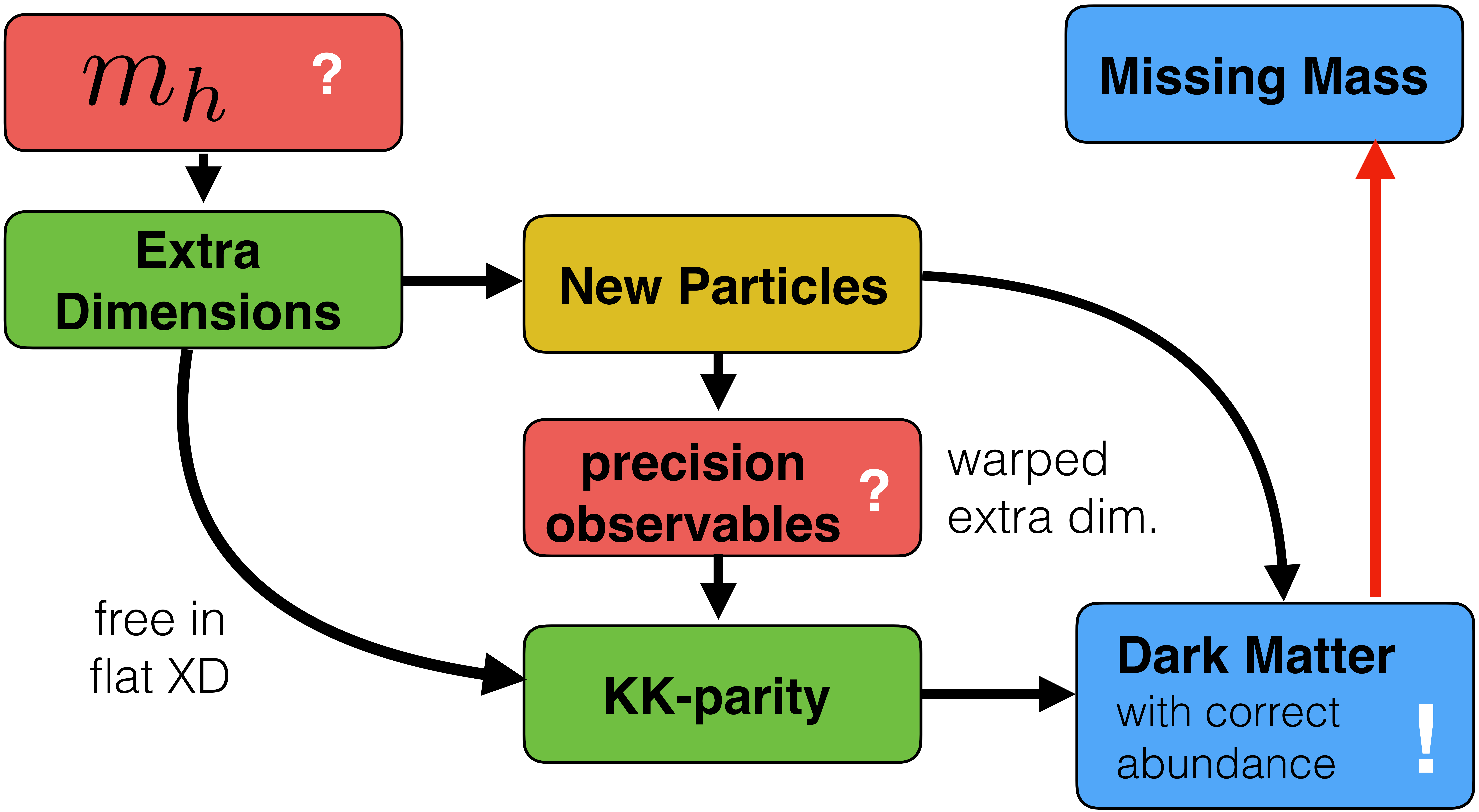
"WEAK SCALE" **ANNIHILATION** RATE

Assume m~100 GeV

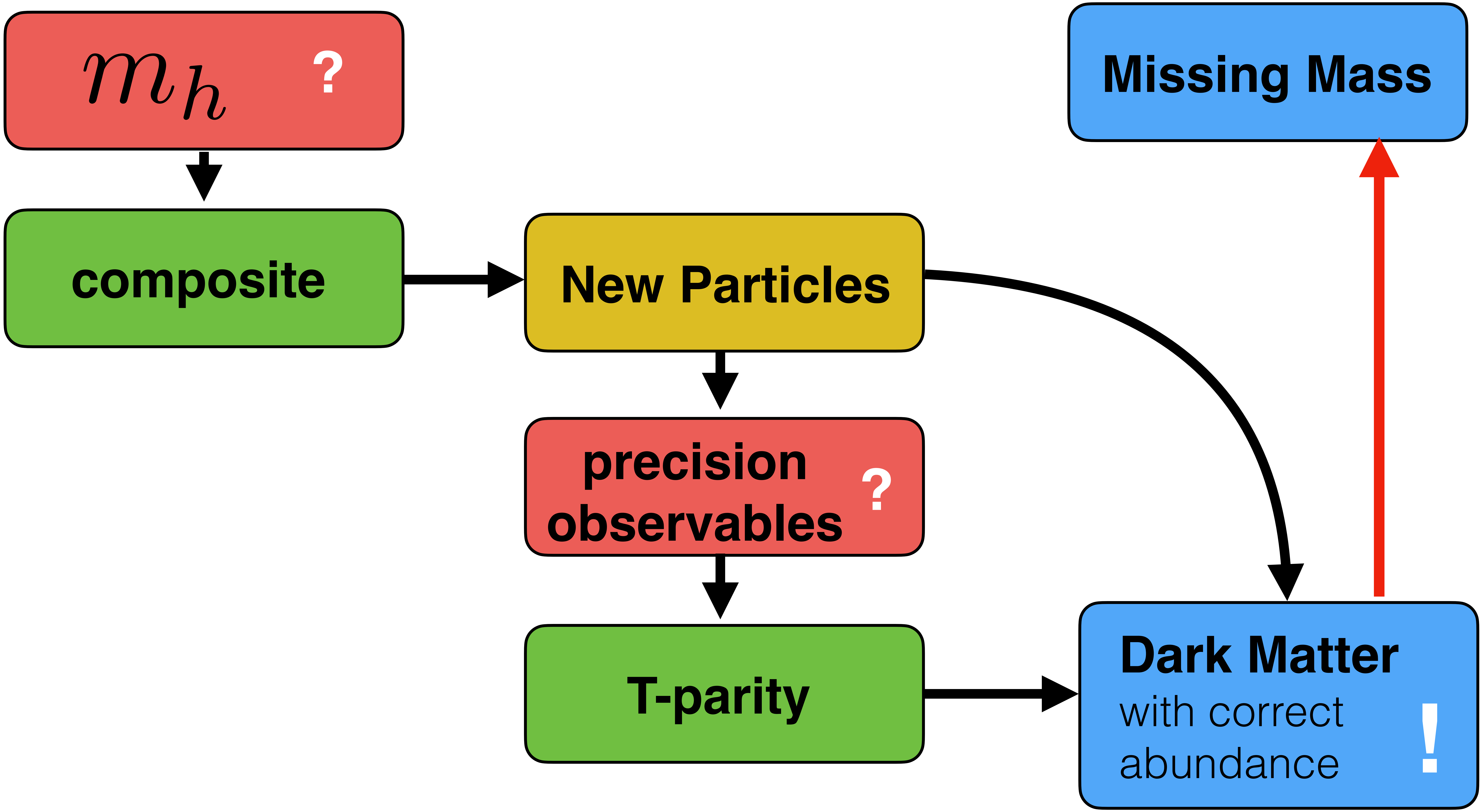
# The story of supersymmetry



# The story of extra dimensions



# The story of compositeness



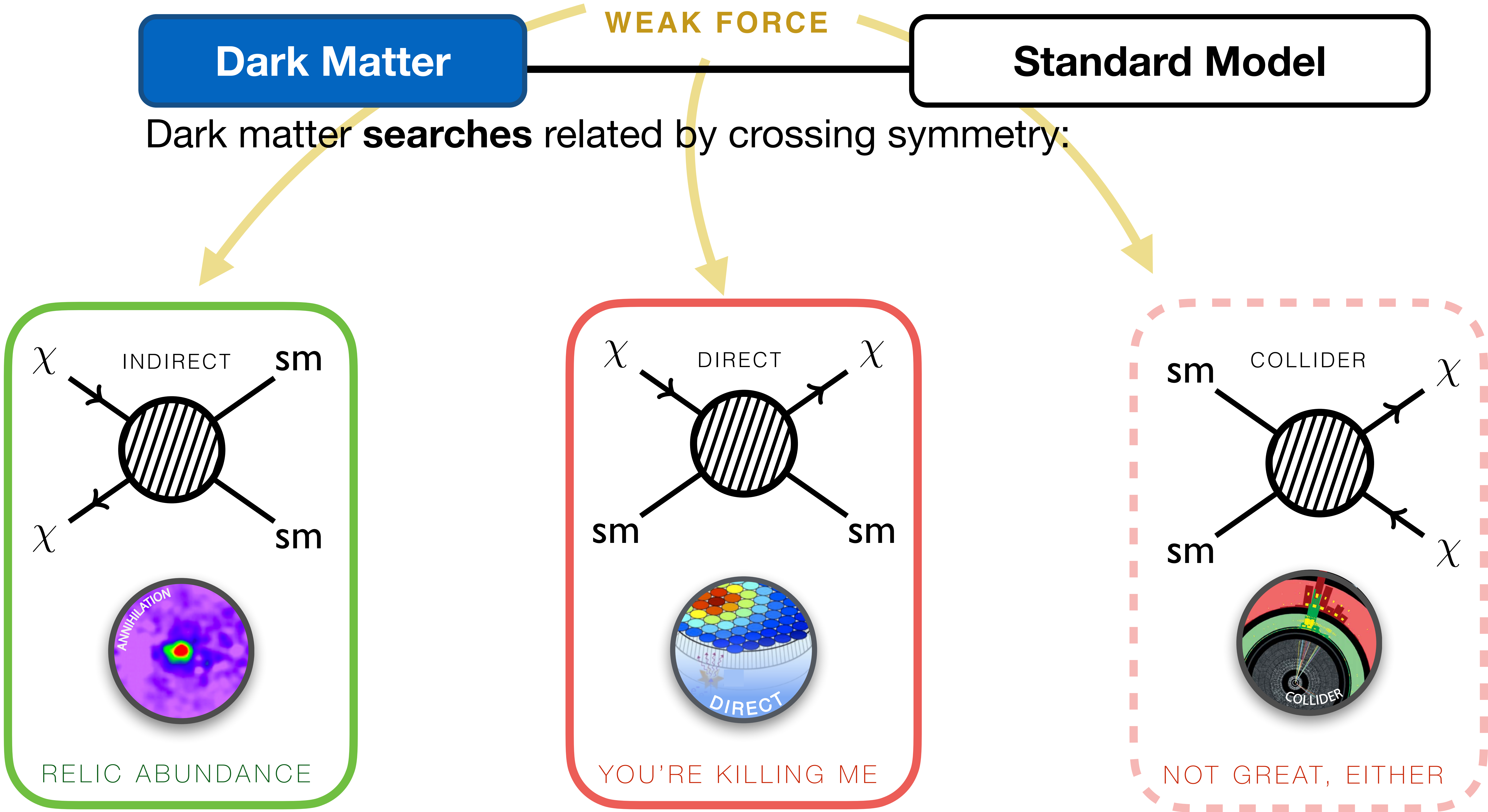
# Model of dark matter

## Typical WIMP

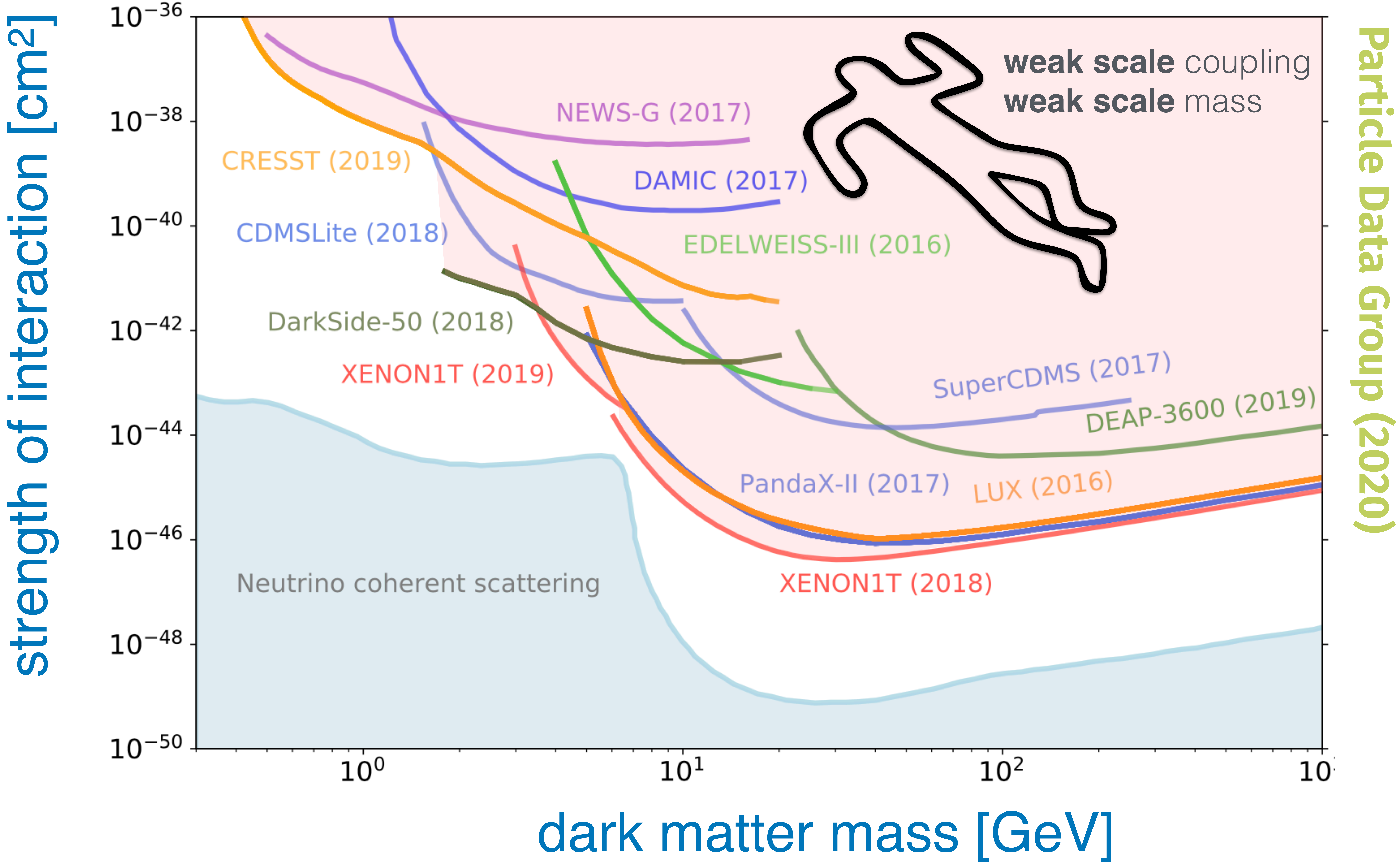
- **What is it?** Lightest parity-odd partner of an extended EW sector
- **How did it get here?** Thermal freeze out (miracle)
- **Why is it still here?** Parity (introduced for other reasons)
- **Why isn't it ruled out?** … tuning? (e.g. pure Higgsino)
- **How do we discover it?** … (in)direct detection, LHC

# WIMP Complementarity

**... a phrase from Snowmass 2013**



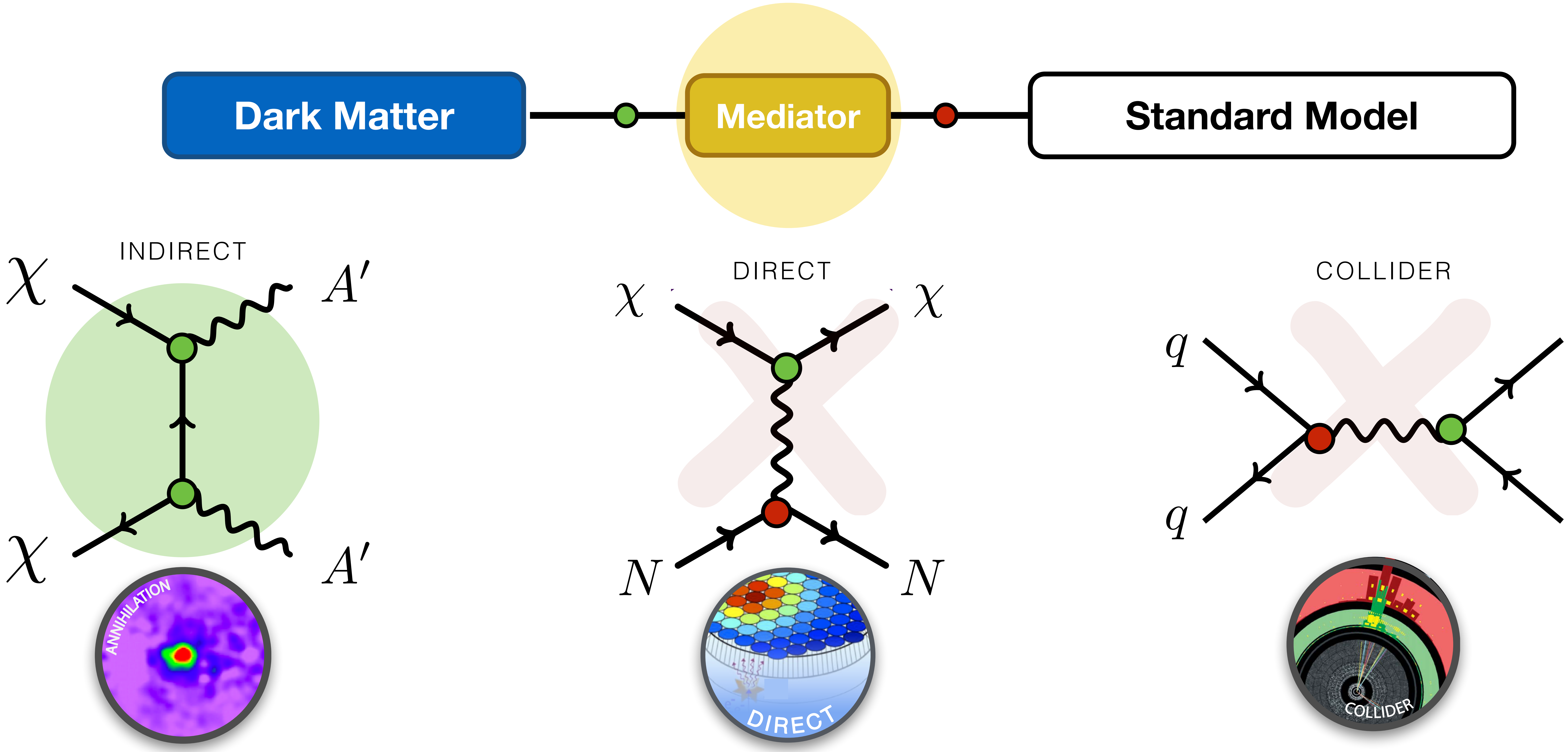

*"Shake it, make it, break it"* … but by around 2015 we got sick of hearing this phrase and seeing this slide.



strength of interaction [cm²]
10−36
10−38
10−40
10−42
10−44
10−46
10−48
10−50
10⁰
10¹
10²
dark matter mass [GeV]
weak scale coupling
weak scale mass
NEWS-G (2017)
CRESST (2019)
DAMIC (2017)
CDMSLite (2018)
EDELWEISS-III (2016)
DarkSide-50 (2018)
XENON1T (2019)
SuperCDMS (2017)
DEAP-3600 (2019)
PandaX-II (2017)
LUX (2016)
XENON1T (2018)
Neutrino coherent scattering
Particle Data Group (2020)

# Introducing mediators

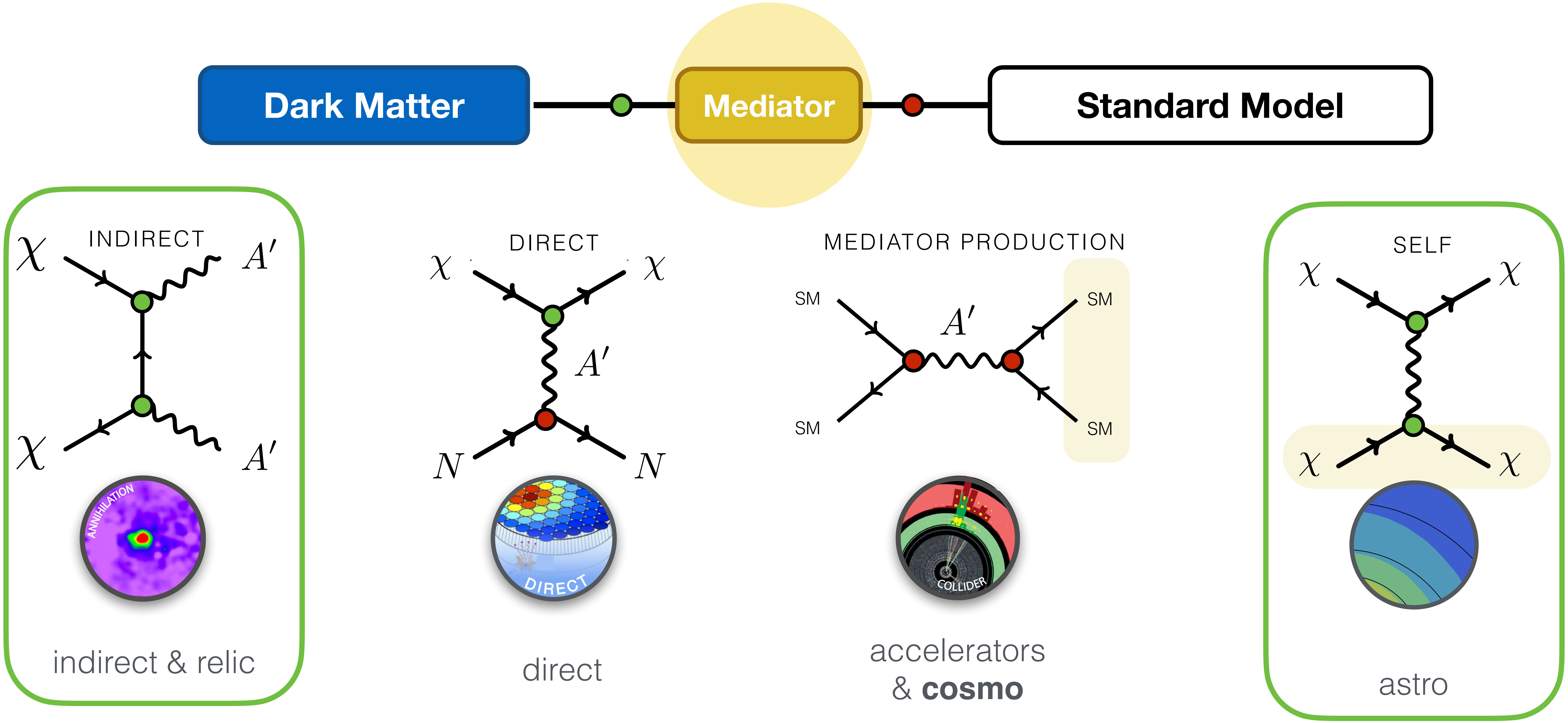
**... breaking WIMP complementarity**




Feature: keep thermal relic, parametrically hide from WIMP searches. Cost: more parameters.

# Introducing mediators

**… breaking WIMP complementarity**




Feature: keep thermal relic, parametrically hide from WIMP searches. Cost: more parameters.

# Model of a dark sector

## Example of a "vanilla" dark photon model

- **What is it?** Some state carrying the dark charge
  (not the interesting question!)
- **How did it get here?** Thermal freeze out (by construction)
  … may have a much richer answer!
- **Why is it still here?** Dark charge (introduced for other reasons)
- **Why isn't it ruled out?** Small Standard Model coupling
- **How do we discover it?** e.g. effects of dark photon
  … may have a much richer answer!

# Why is it still here?

## Total stability is not necessary

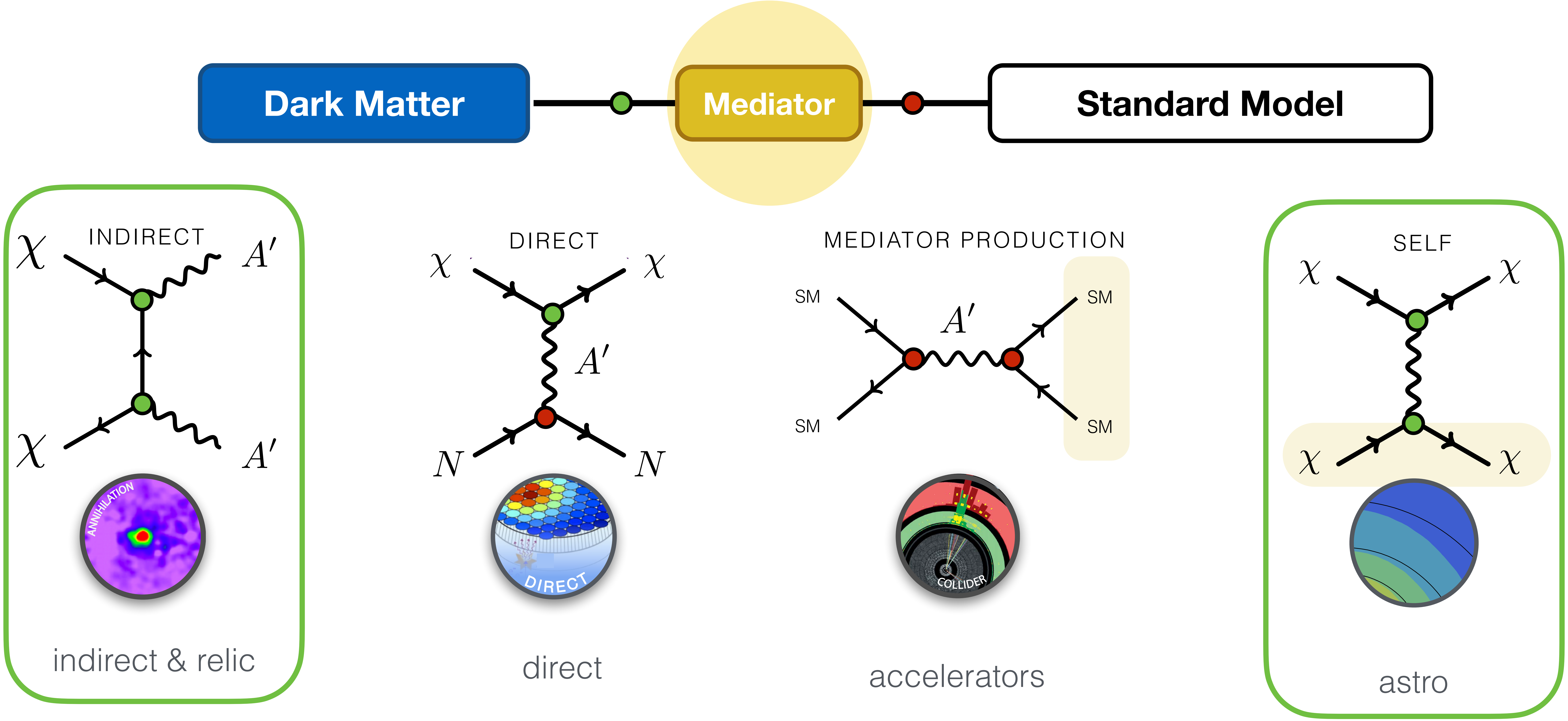

Snowmass: Particle Dark Matter Topical Group 2209.07426

# Dark photons

## A useful example of what *is* a hidden sector

# Introducing mediators

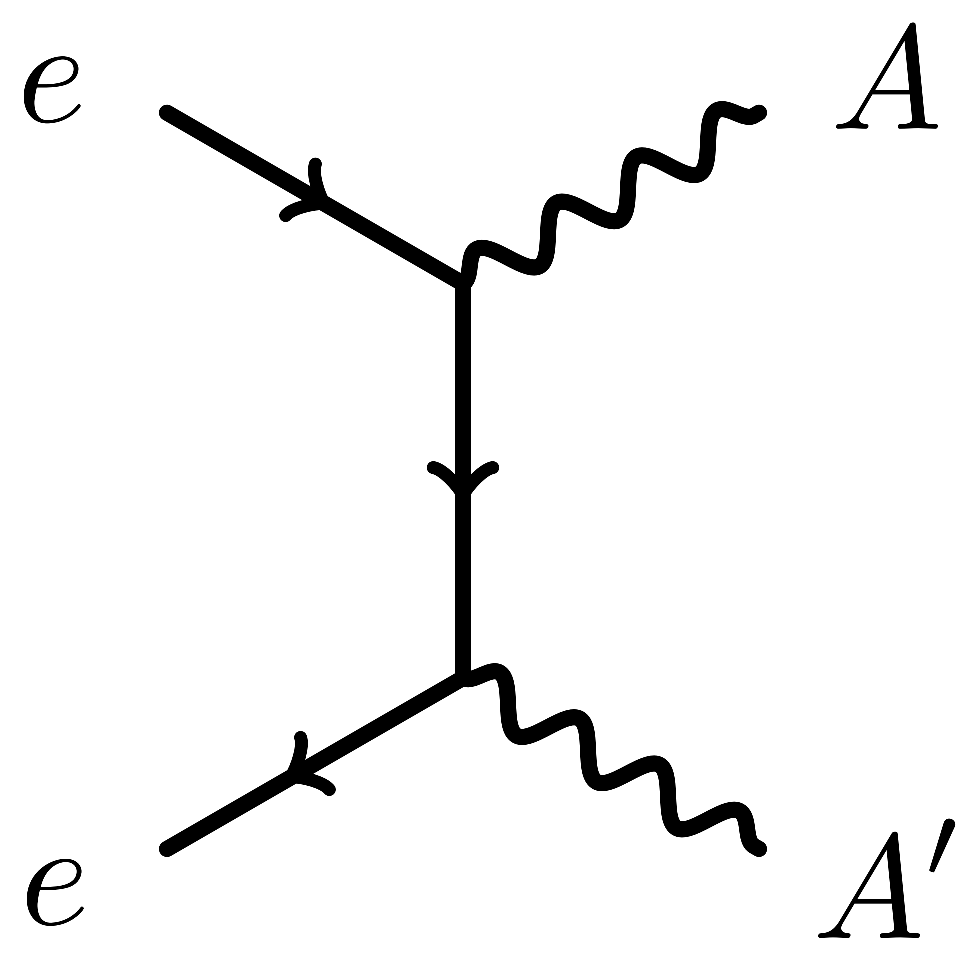
**... breaking WIMP complementarity**



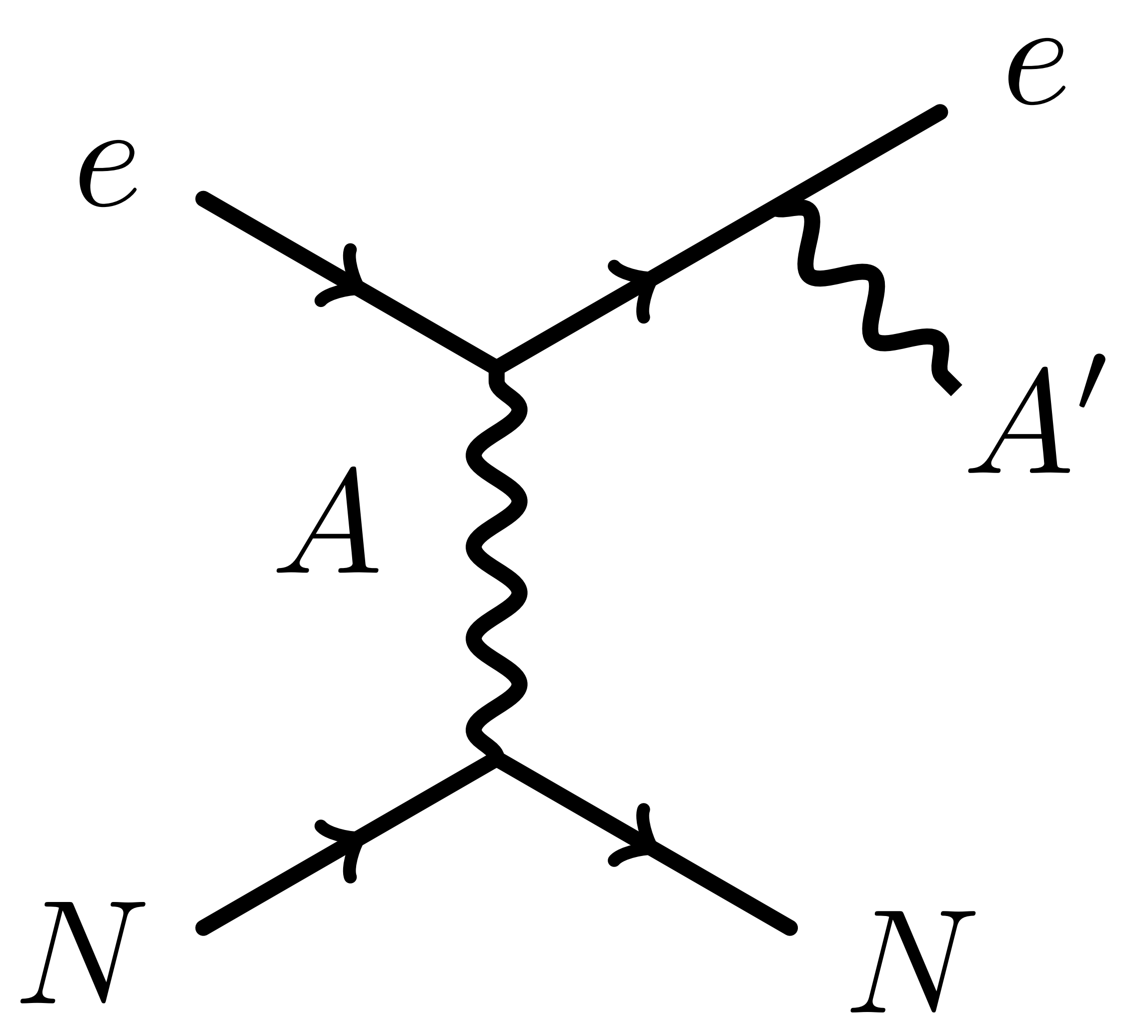

Feature: keep thermal relic, parametrically hide from WIMP searches. Cost: more parameters.

# Step 1: Mediator Production

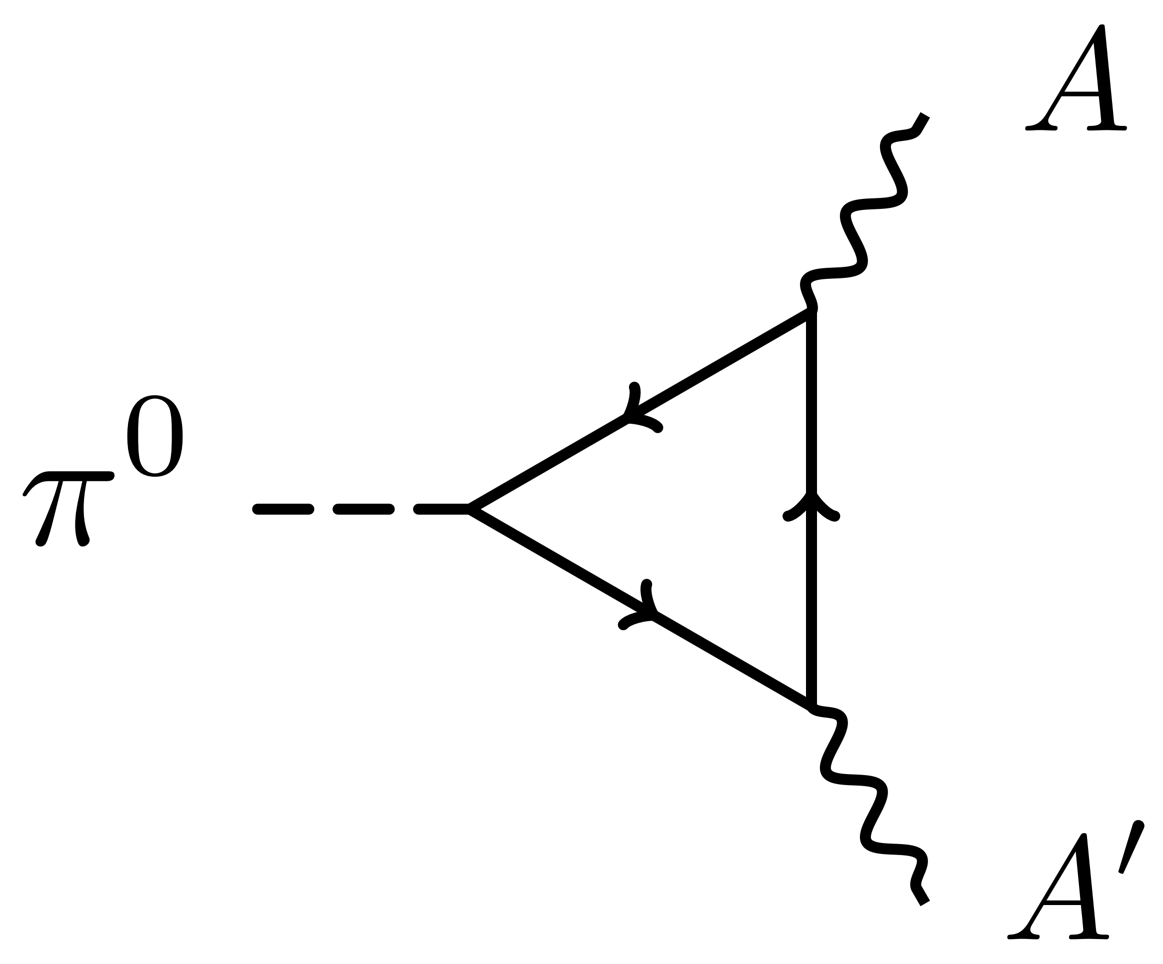
## Some examples of light mediator production




annihilation




bremsstrahlung

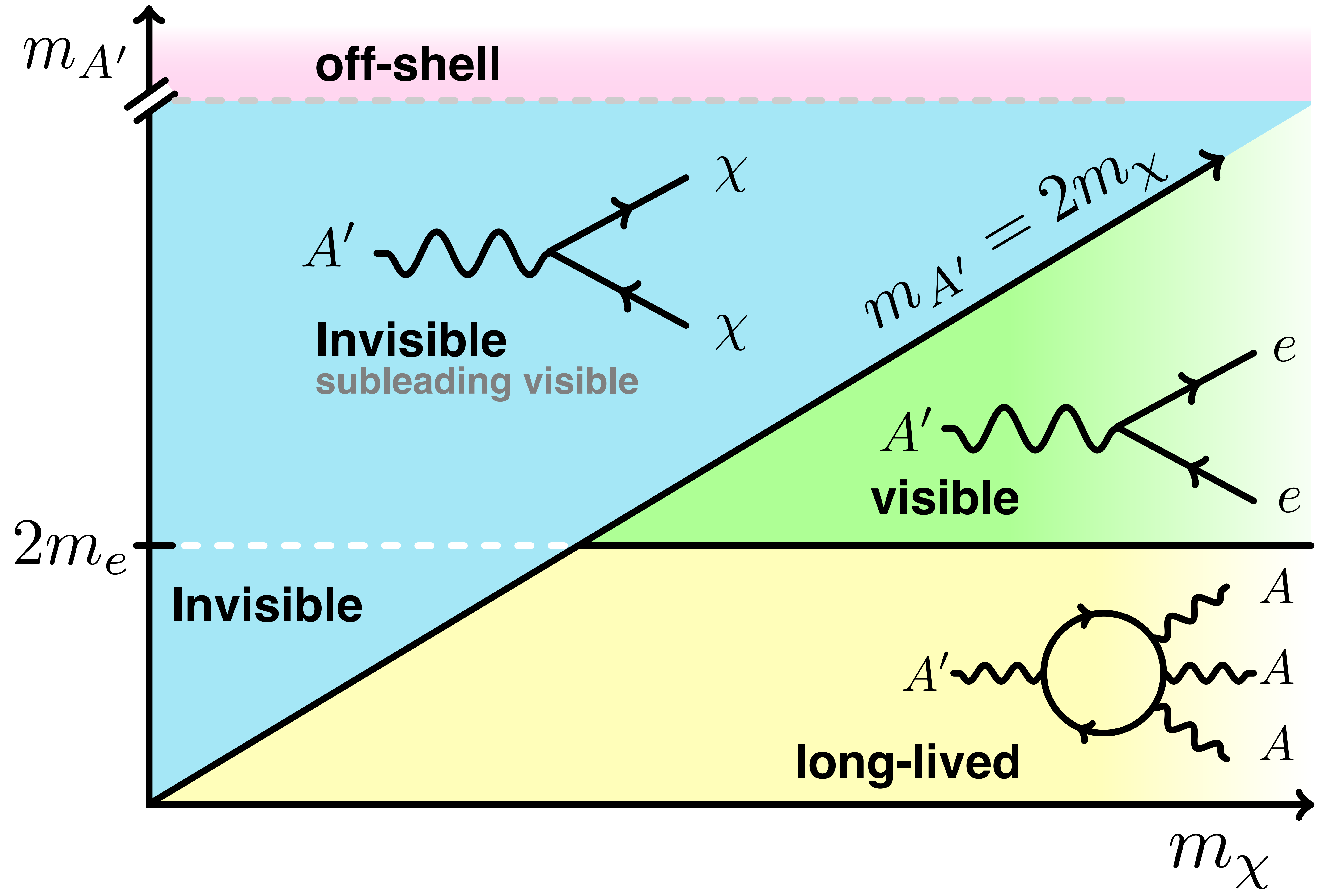


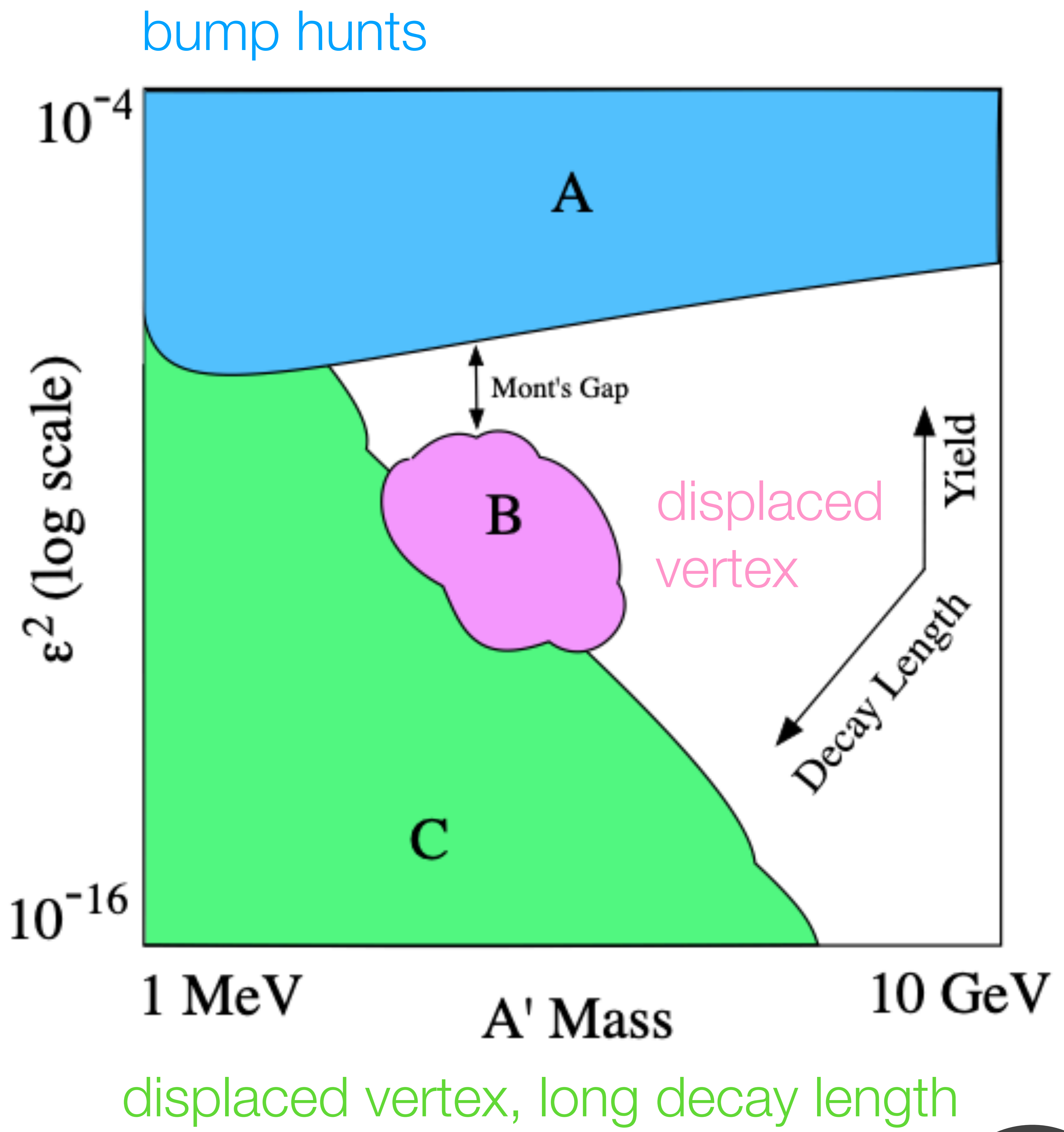

meson decay

… and not necessarily in a collider!

# Step 2: Mediator Decay

## Produces dark matter (invisible) or ordinary matter?

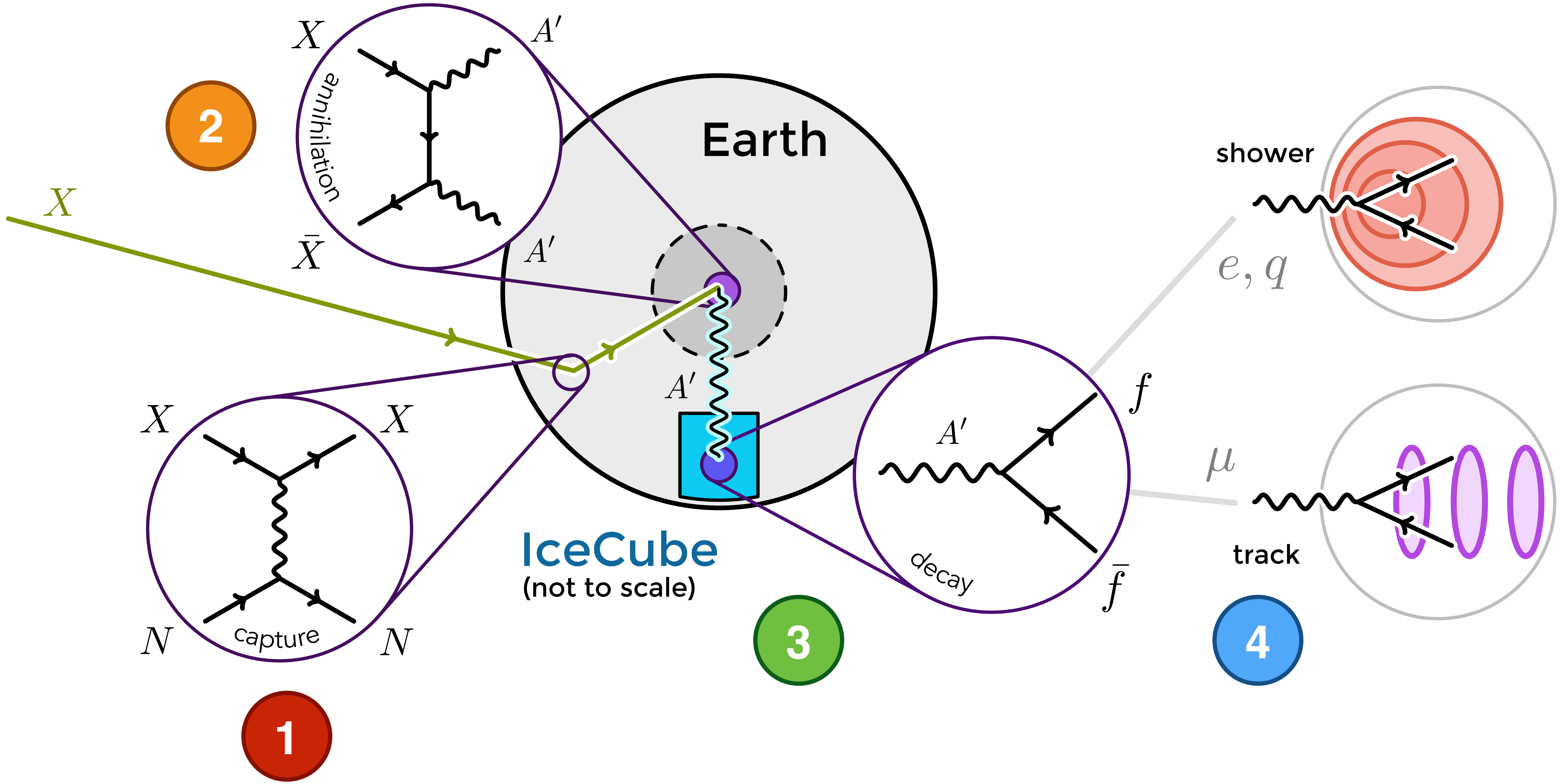



Dark Sectors 2016 Workshop: Community Report 1608.08632

# Remixing complementarity

## Something that you could not do with neutralinos




J. Feng, J. Smolinsky, FT 1509.07525; for see, e.g. Leane and Smirnov 2309.00669 for more recent updates

# Model building targets

## Why build models of hidden sectors?

# Reasons for building a model (examples)

## Theoretical puzzle

- ~~Electroweak naturalness~~
- Strong CP problem (axions)
- Neutrino mass (scotogenesis)
- Baryogenesis

## Experimental opportunity

- JWST, Rubin, …
- Hyper-K, next Milky Way SN
- Gravitational waves
- DUNE, future collider, …

## Experimental puzzle ("anomaly")

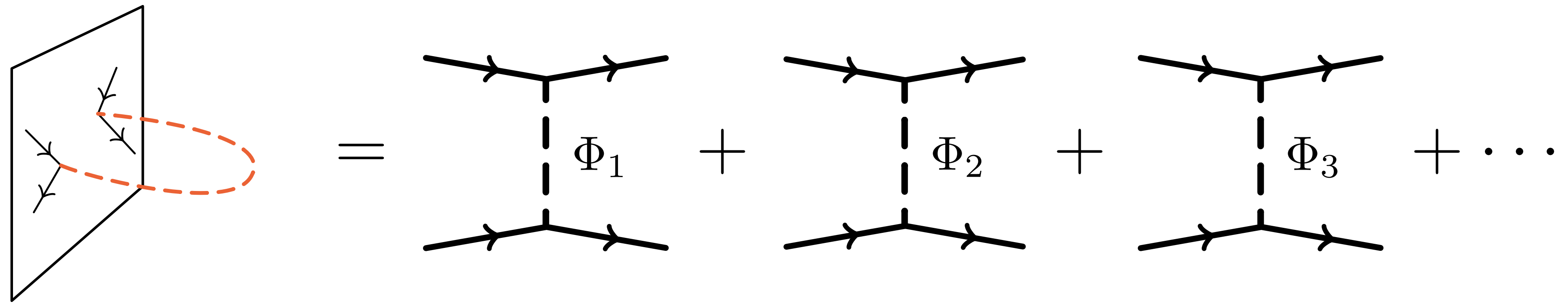
- Hubble tension
- Muon magnetic moment
- KOTO, ANITA, LSND/MiniBooNE
- Galactic Center Excess, 3.5 keV Line

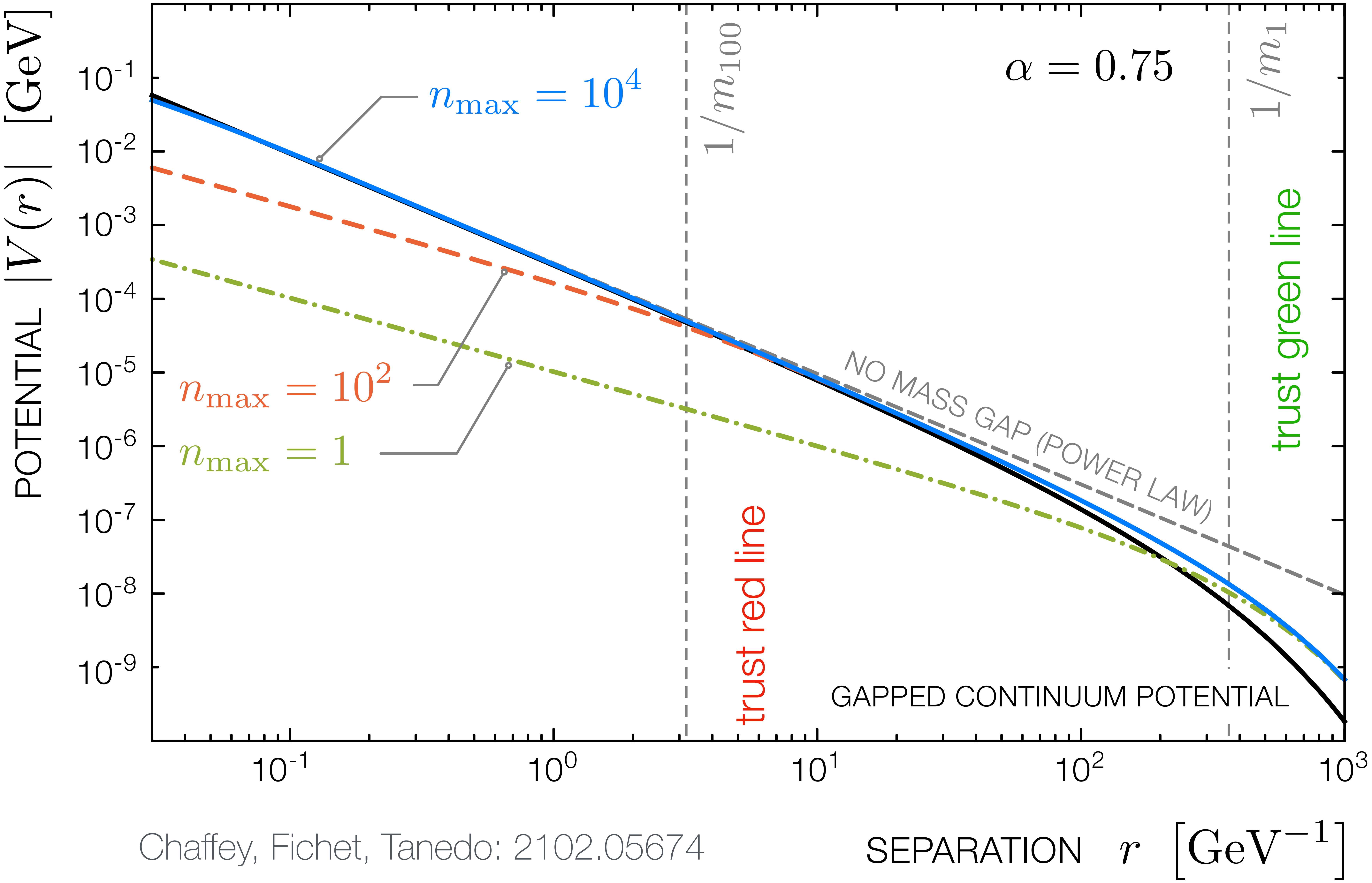
## Theoretical curiosity

- e.g. SIDM c. 2013: solution to non-perturbative Yukawa potential? (1302.3898)
- continuum fields: e.g. 2210.16326 (DM), 2102.05674 (mediator)

# Curiosities of the continuum

## Can behave like sum of many discrete modes...




Chaffey, Fichet, Tanedo: 2102.05674

Sum of many KK modes reproduces a fractional power potential.

n.b. KK picture is consistent as long as you're within the effective theory (do not probe beyond heaviest KK mode)

**Many KK modes**

**5D Green's function**
Large spacelike momentum asymptotic

# Curiosities of the continuum

## … or can surprise you with completely different behavior

We study the cosmology of a 3-brane in a specific five-dimensional scalar-gravity (i.e., soft-wall) background, known as the linear dilaton background. We discover that the Friedmann equation of the brane world automatically contains a term mimicking pressureless matter. We propose to identify this term as dark matter. This dark matter arises as a projection of the bulk black hole on the brane, which contributes to the brane Friedmann equation via both the Weyl tensor and the scalar stress tensor.

Cosmological dark matter from a bulk black hole

Sylvain Fichet, Eugenio Megías, and Mariano Quirós
Phys. Rev. D **107**, 115014 – Published 12 June 2023

Analogous to "dark radiation" in RS2,
See e.g. Hebecker and March-Russell
hep-ph/0103214

Does it form halos?

---

Unstable particles decay sooner or later, so they are not described by asymptotic one-particle states and they should not be included as independent states in unitarity relations such as the optical theorem. The same applies to any countable collection of unstable particles. We show that the behaviour of unparticle stuff, that is, a continuous collection of particles with different masses and common decay channels, is pretty different: it has a non-vanishing probability of surviving for ever and the corresponding asymptotic states must be taken into account to comply with unitarity. We also discuss compressed spectra and the transition from the discrete to the continuous case.

UNDECAY

Megias, Perez-Victoria, Quiros
2310.16593

(quasi-)stable continuum states
despite apparent decay channels due
to breakdown of narrow width approx.

# Dark matter production mechanisms

## How did it get here?

# Dark matter production

## ... often tied to dark sector phenomenology

| | |
|---|---|
| **Asymmetries in Extended Dark Sectors: A Cogenesis Scenario** | *Giacomo Landini* |
| *Mainz Institute for Theoretical Physics, Johannes Gutenberg University* | 08:15 - 08:40 |
| **Freeze-in at stronger couplings** | *Catarina Cosme* |
| *Mainz Institute for Theoretical Physics, Johannes Gutenberg University* | 08:40 - 09:05 |

| | |
|---|---|
| **Shining Light on Hidden Sector Dark Matter** | *Himanish Ganjoo* |
| *Mainz Institute for Theoretical Physics, Johannes Gutenberg University* | 09:15 - 09:40 |
| **Neutrino Detectors & Dark Sectors** | *Kevin Kelly* |
| *Mainz Institute for Theoretical Physics, Johannes Gutenberg University* | 09:40 - 10:05 |
| **Dark matter production in exponential growth scenarios** | *Disha Bhatia* |
| *Mainz Institute for Theoretical Physics, Johannes Gutenberg University* | 10:05 - 10:30 |
| **Coleman-Weinberg dynamics of dark matter and right-handed neutrinos** | *Ryan Plestid* |
| *Mainz Institute for Theoretical Physics, Johannes Gutenberg University* | 10:30 - 10:55 |

indico.mitp.uni-mainz.de/event/361/timetable/

# Dark matter production

## An incomplete map

- **Thermal:** freeze out/ freeze in/ number-changing
- **Asymmetric:** relate to baryogenesis; also comes in WIMPy version
- **Axion:** Misalignment and oscillation; also topological defects
- **Neutrino:** e.g. Dodelson-Widrow
- **PBH:** also includes dark matter production from Hawking radiation
- … others? Remixes of the above?

See also "Three exceptions in the calculation of relic abundances," Greist and Seckel, Phys. Rev. D 43, 3191 (1991)

# Twists on thermal relics

modify Hubble

e.g. relentless DM (1703.04793)

change assumptions

e.g. number changing interactions

$$\dot{n} + 3Hn = -\langle \sigma v \rangle (n^2 - n_{\text{eq}}^2)$$

modify cross section

e.g. enhancements, thermal effects

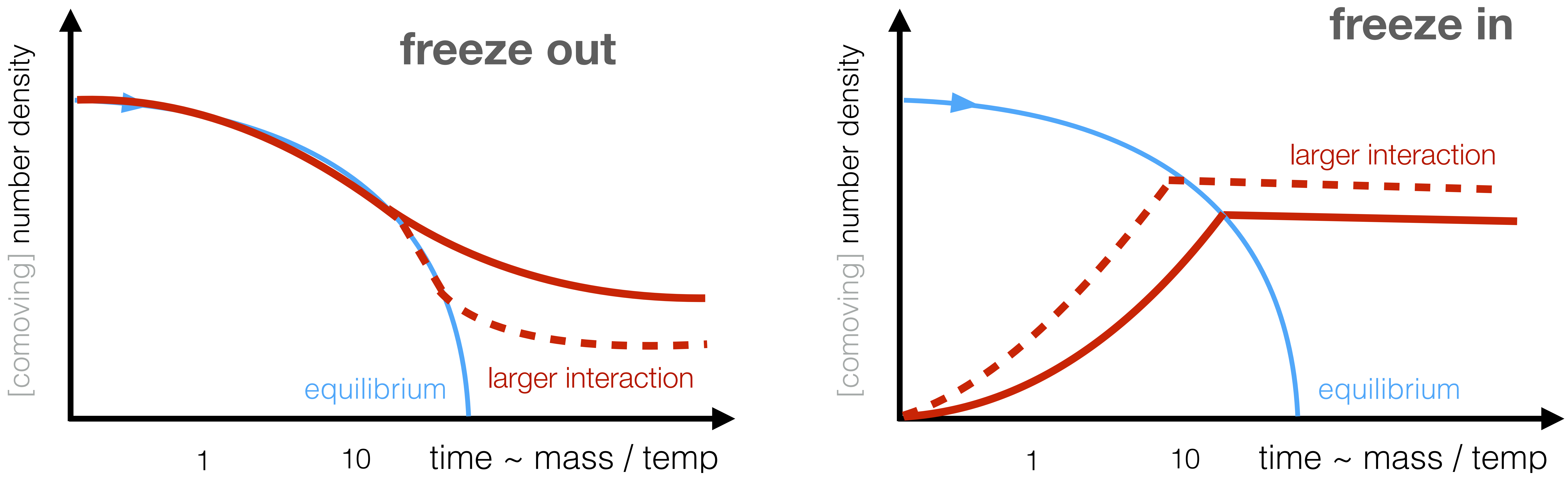
modify initial condition

e.g. freeze-in

Adapted from Julia Harz: "Dark Matter & Particle Cosmology" CRC TRR 257 meeting (Oct 2020)

# Freeze In

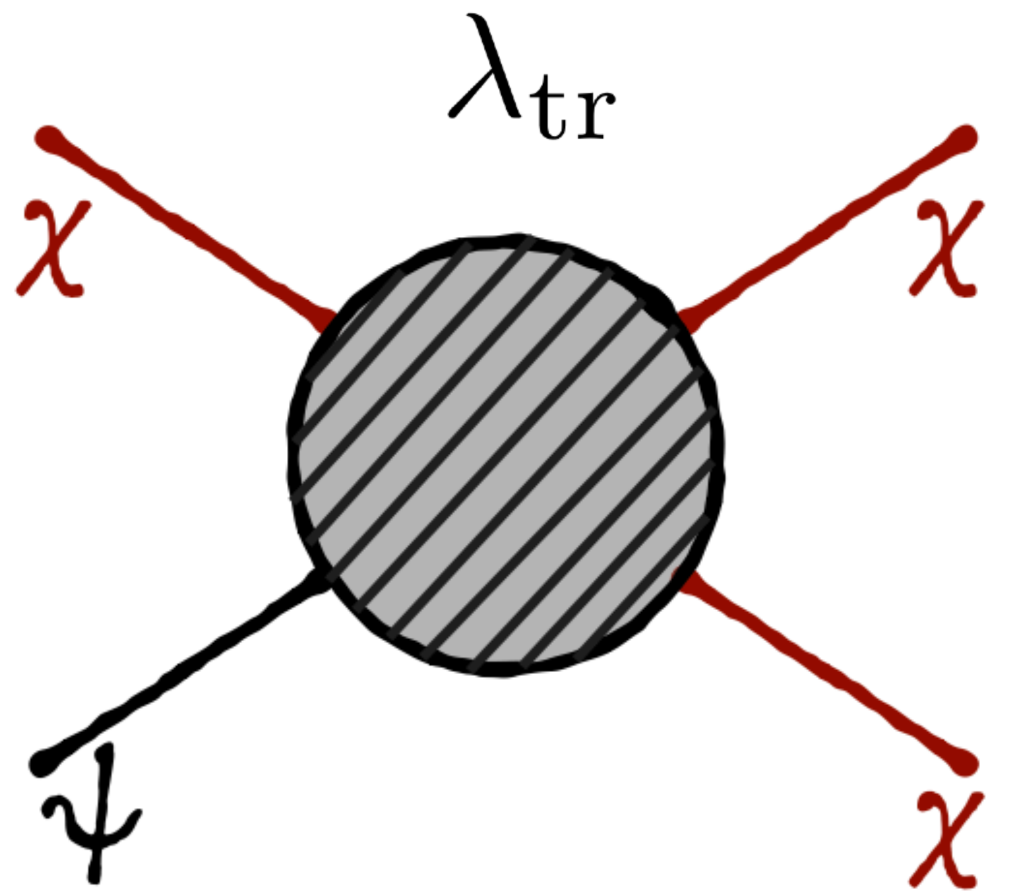
## A thermal relic, but not initially in equilibrium




More sophisticated: resonances, medium effects, phase transitions in DarkSUSY: 2111.14871

# Freeze In Variant: Pandemic

## A thermal relic, but not initially in equilibriun




Thermal Bath Particle

Exponential growth of dark matter from drawing energy out of the thermal bath.

example of number changing interaction
n.b. "pandemic" because similar to SIR model; but PRL title is "exponential growth"

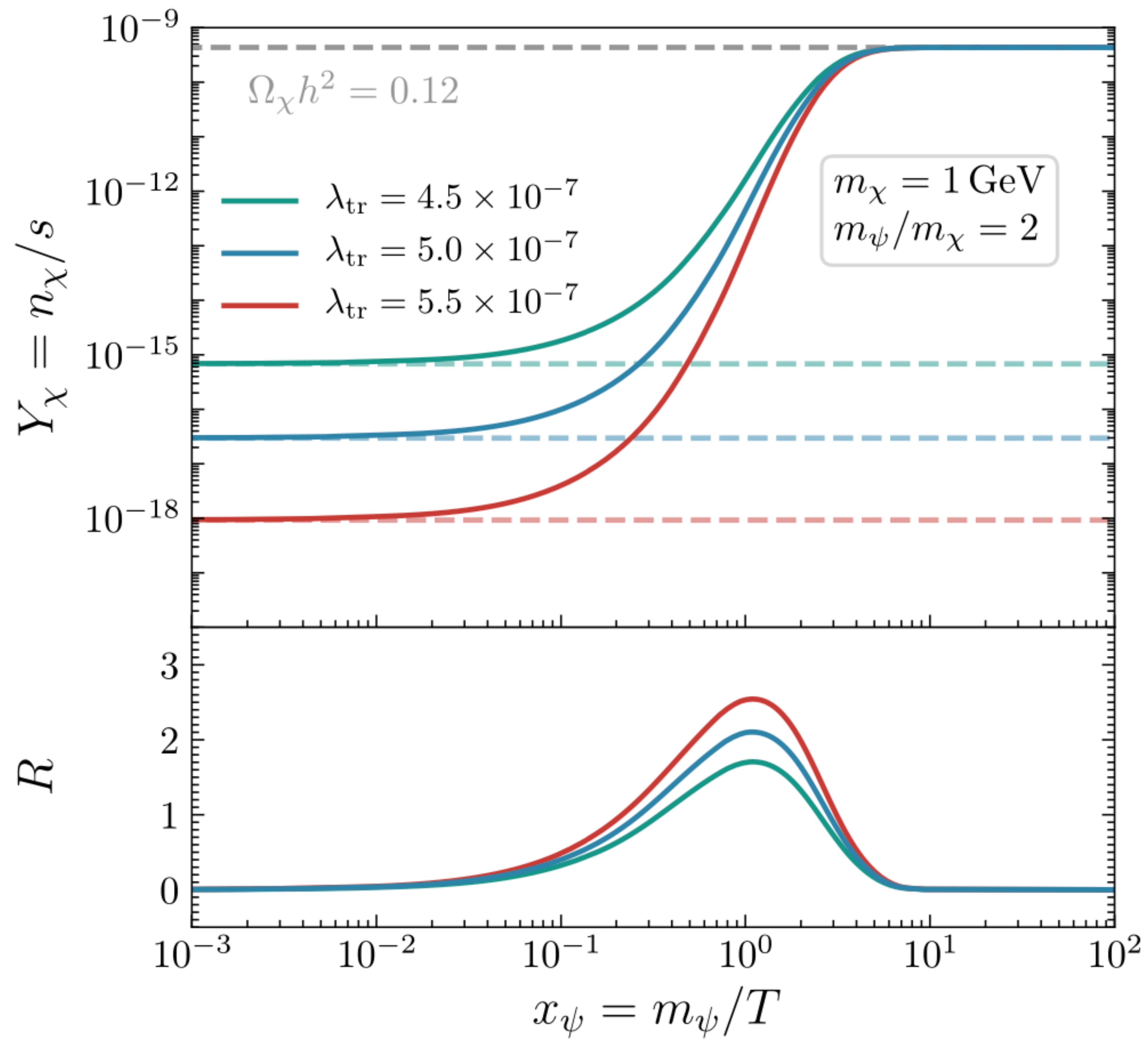
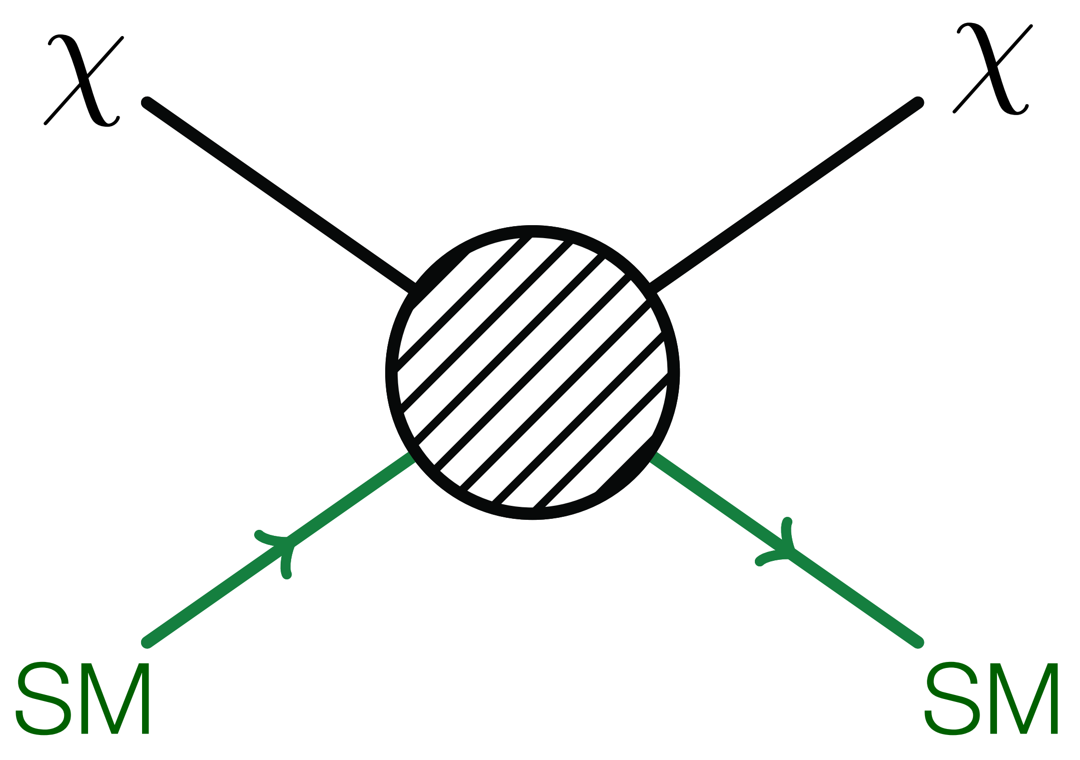



FIG. 2. Top: Number density of $\chi$ relative to the entropy density of the heat bath (solid lines) for $m_\chi = 1$ GeV, $m_\psi = 2$ GeV and different values of the transformation coupling $\lambda_{\text{tr}}$. For each value of $\lambda_{\text{tr}}$, we fix the initial abundance of $\chi$ (dashed lines) such that the final abundance corresponds to the observed DM density. Bottom: $R$ value corresponding to the abundance evolution in the top panel.

Bringmann, Depta, Hufnagel, Ruderman, Schmidt-Hoberg, *PRL* 127 (2021) "Dark Matter from Exponential Growth"

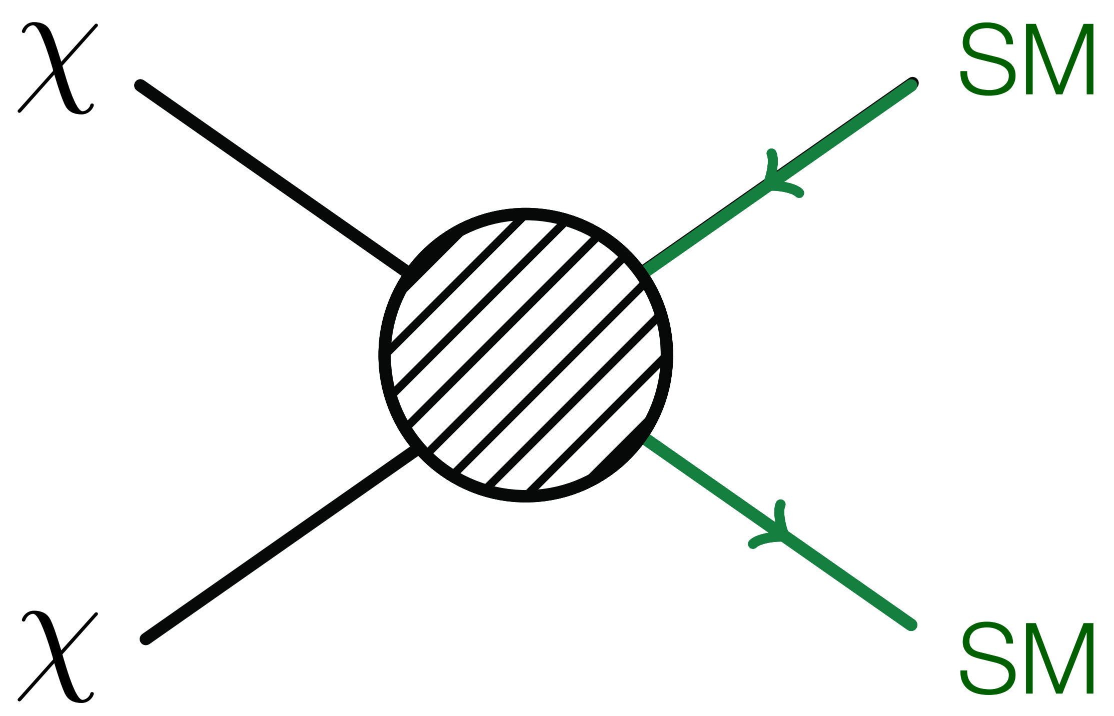
# SIMPs, ELDERs, Cannibals...

## Controlling the abundance through elastic scattering (temperature control)



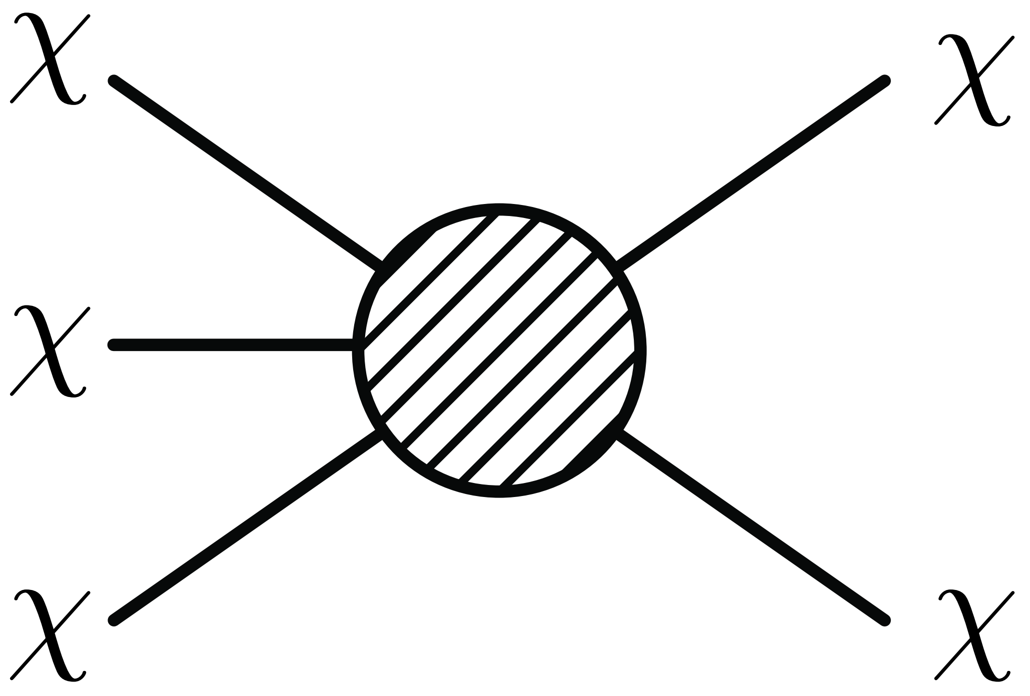

Elastic scattering with SM

Usually not related to abundance



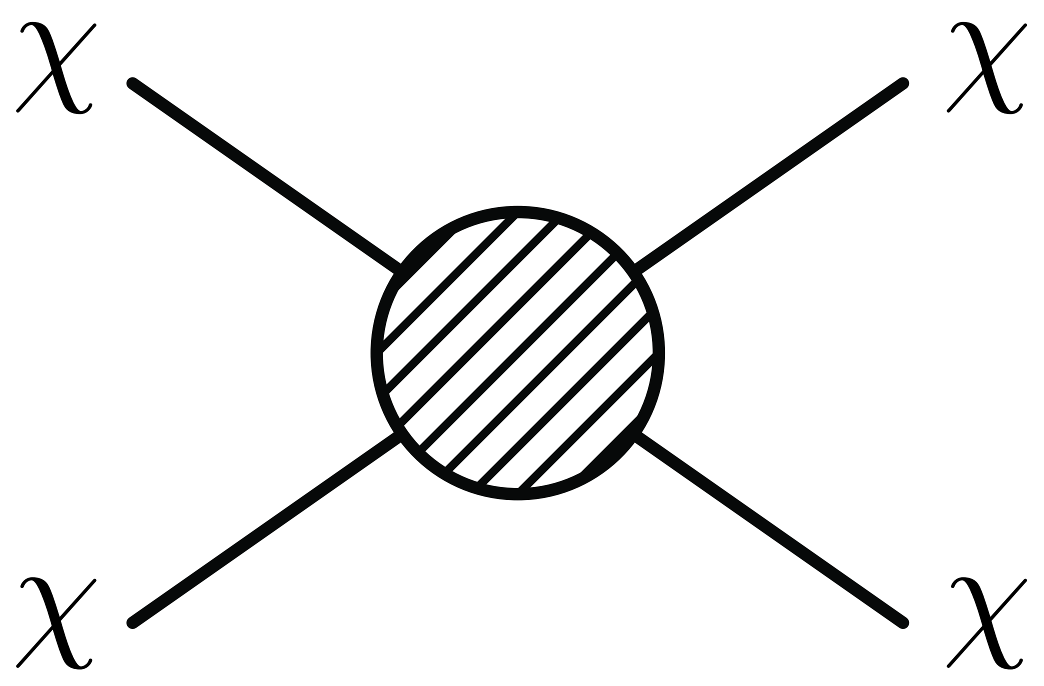

Annihilation into SM

This term is small




Number changing

Cannibalize X number to keep X warm (changes equilibrium temperature)




Elastic self-scattering

Thermal energy distribution within dark sector

**SIMP**: SM elastic scattering decouples *after* number-changing scattering

**ELDER**: SM elastic scattering decouples *before* number-changing scattering

Other variations with mediators, e.g. cannibal dark matter (1602.04219)

See e.g. Hochberg, "SIMP Dark Matter," *SciPost Phys. Lect. Notes* 59 (2022); Cornell group 1706.05381

# Asymmetric and Cogenesis

## Non-thermal and semi-thermal

$$\Omega_{DM} \simeq 5\,\Omega_{VM}\ ,$$

Suppose no anti-dark matter. Propose a common origin of the baryon–anti-baryon asymmetry and dark matter–anti-dark matter asymmetry. Cogenesis: asymmetric "WIMPy" dark matter.

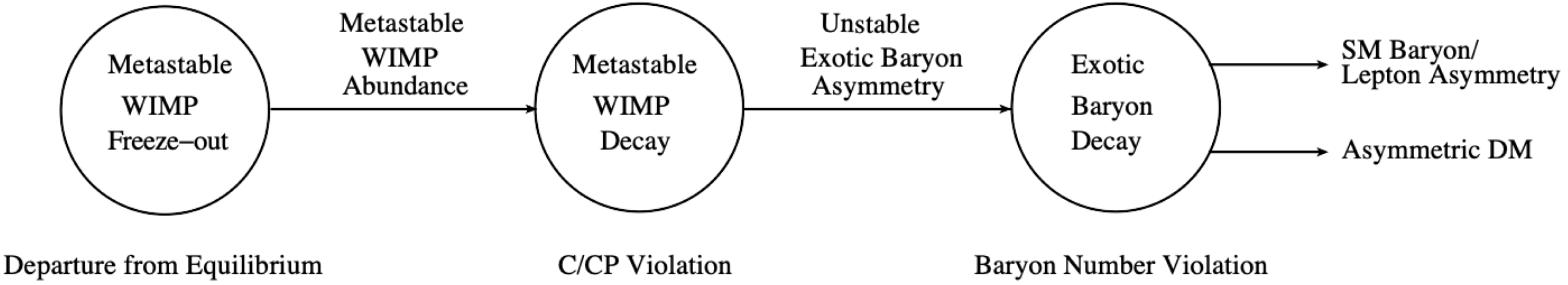
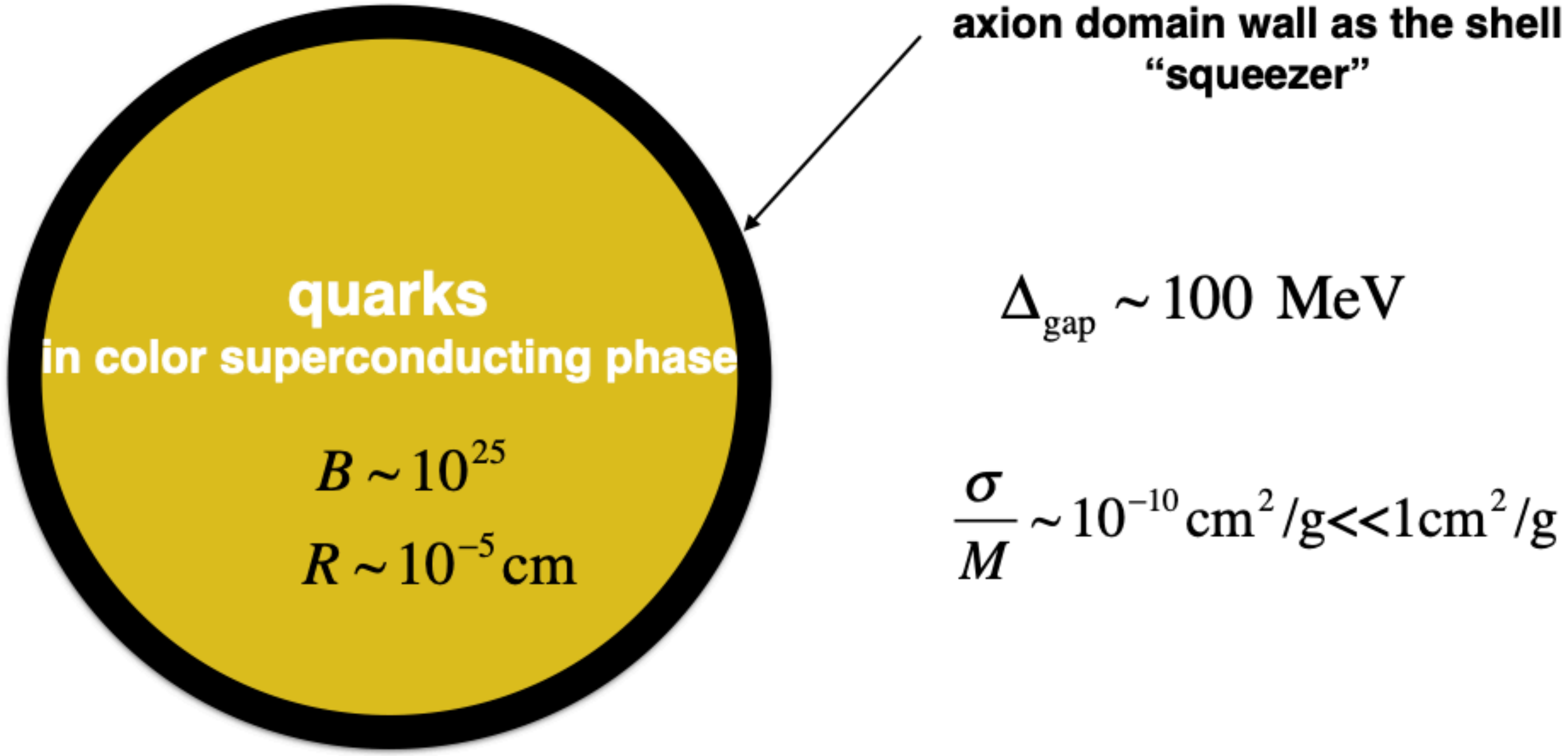



**Figure 1:** Schematic diagram outlining the key stages in WIMP cogenesis mechanism. Each dynamical stage of WIMP cogenesis, shown in the bubbles, satisfies one of the Sakharov conditions.

Asymmetric Review, 1305.4939; WIMP Cogenesis: 2002.05170

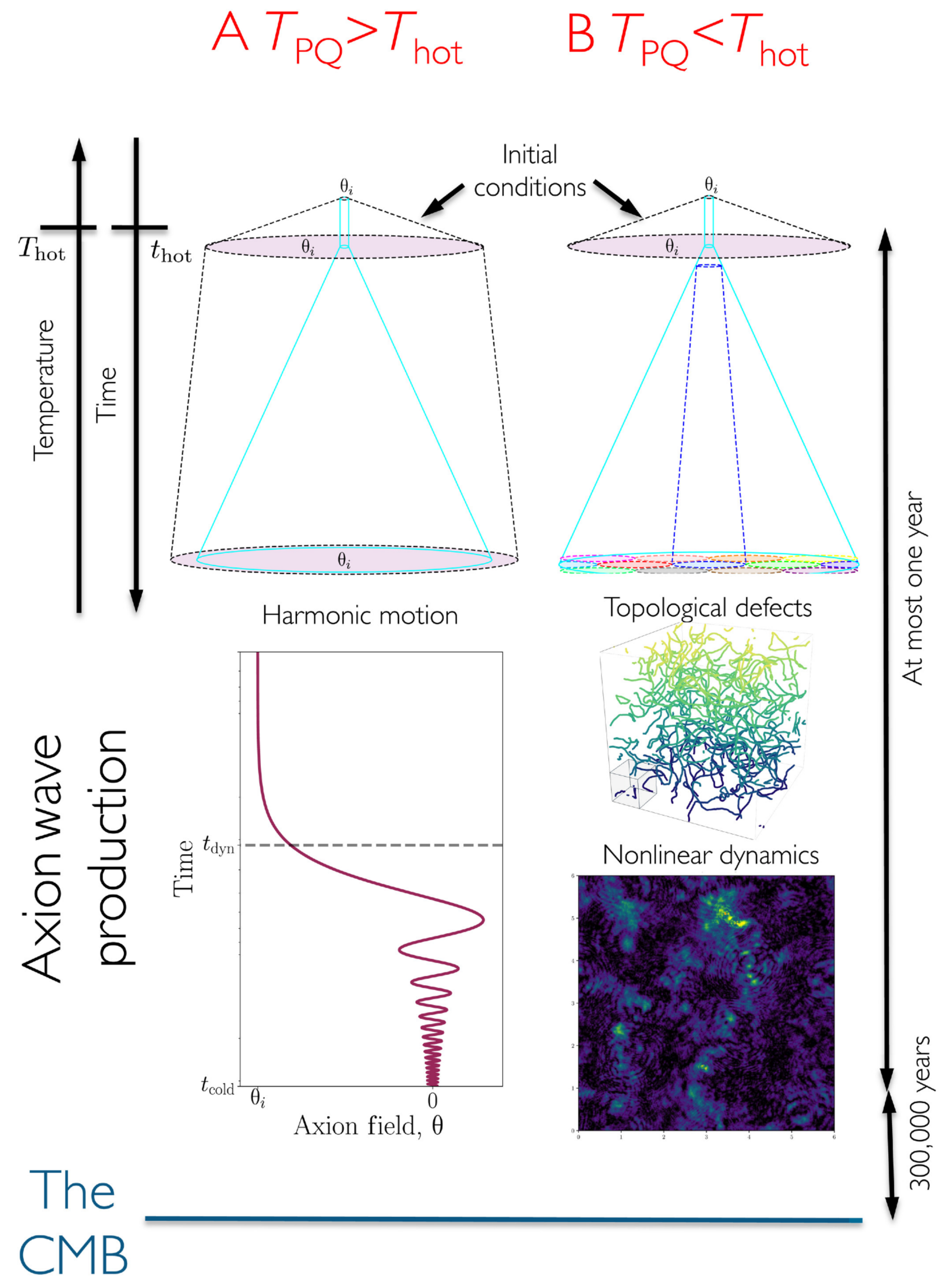
# Axions and related

axion quark nugget: axion + baryogenesis




$$\Delta_{\mathrm{gap}} \sim 100\ \mathrm{MeV}$$

$$\frac{\sigma}{M} \sim 10^{-10}\,\mathrm{cm}^2/\mathrm{g} << 1\,\mathrm{cm}^2/\mathrm{g}$$




Right: Chadha-Day et al. “Axion dark matter: What is it and why now?” *Science Advances* 10.1126/sciadv.abj361
Left: Ge, “AQN Dark Matter” at IPA 2018. Review: Zhitnitsky, 2105.08719

# Dodelson-Widrow Reloaded

## Non-thermal production of [self-interacting] sterile neutrino dark matter

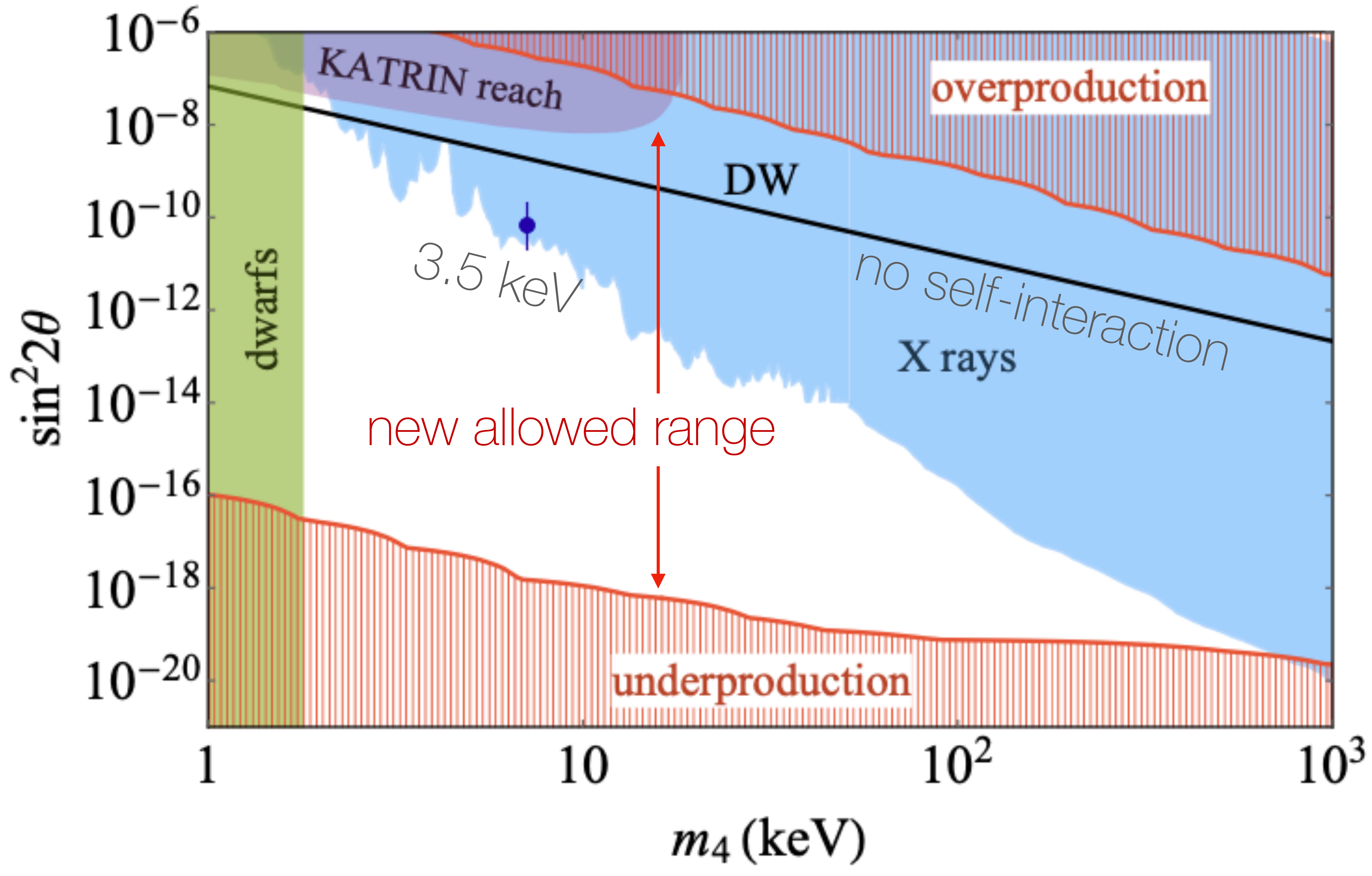
produce active neutrino (weak eigenstate)

$$\nu_4 = \cos\theta\, \nu_s + \sin\theta\, \nu_a$$

measurement may collapse to sterile component

Regular DW: excluded by X-ray lines

Sterile self-interactions: new production channels, changes interaction rate and thermal potential.

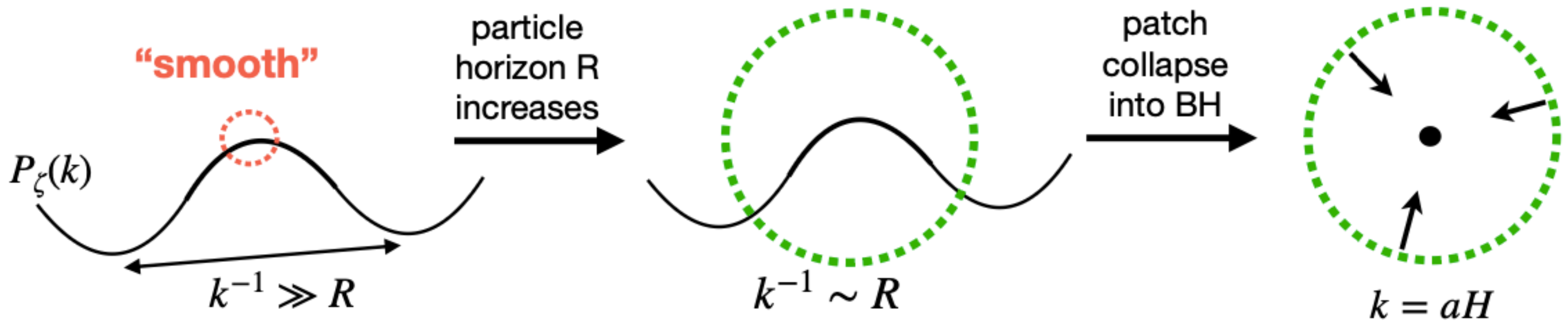



See, e.g. Abazajian, "Sterile Neutrinos in Cosmology" 1705.01837; de Gouvêa, Sen, Tangarife, Zhang 1910.04901

# Primordial Black Holes

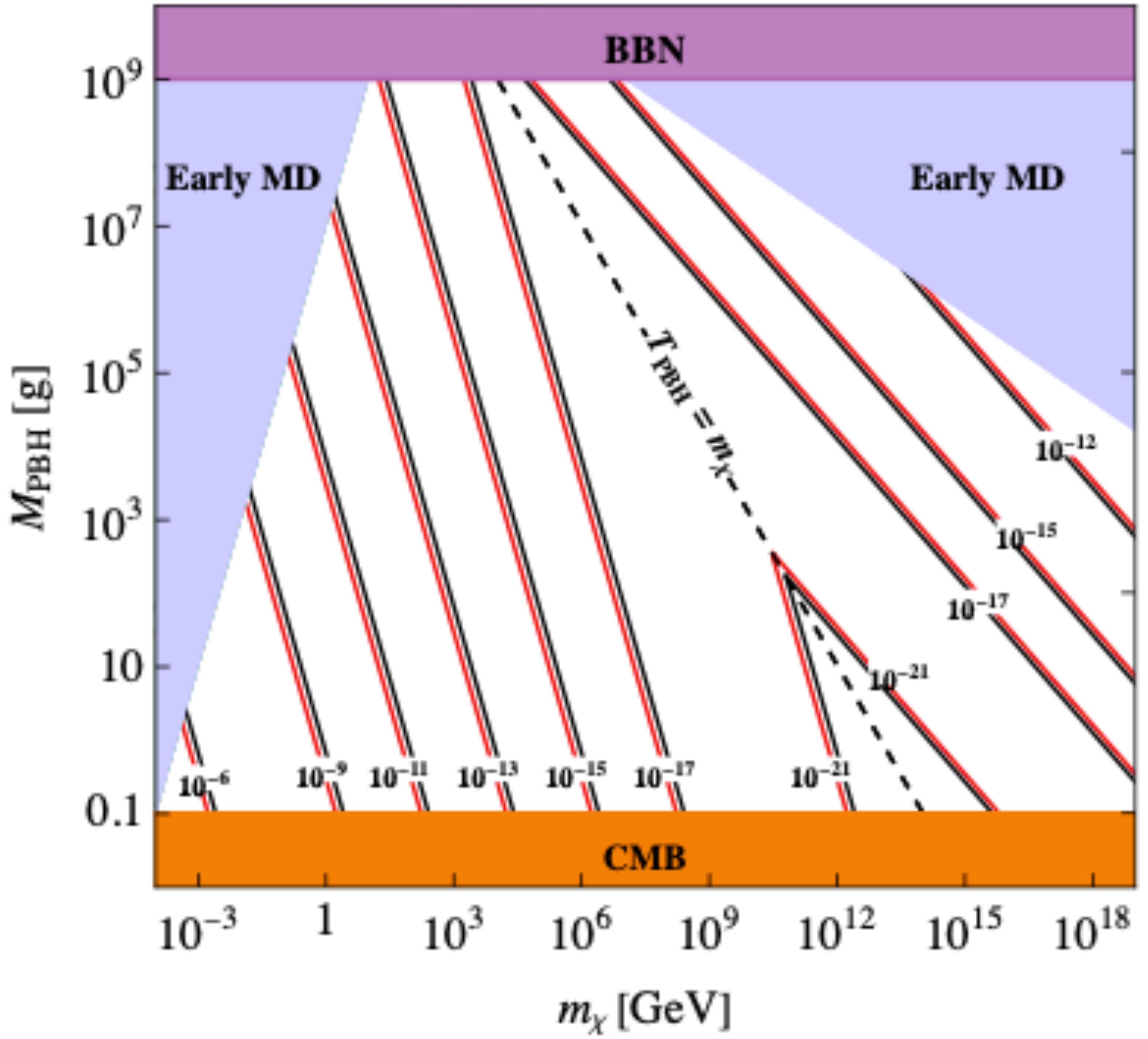
## Both as dark matter, and as dark matter factories

PBH form from the **collapse of large over-dense regions** in the early universe




PBH may be dark matter candidates…

or can non-thermally produce dark matter through Hawking radiation




Tao Xu, "Asteroid-mass Dark Matter" CETUP* 2023;
Gehrman, Haghi, Sinha, Xu, "The PBHs that Disappeared" 2304.09194

# Models of dark sectors

## Versus typical WIMP

- **What is it?** Some new particle… doesn't have to be "deep"
- **How did it get here?** Many options and room for more creativity
- **Why is it still here?** Sufficient stability from small interactions?
- **Why isn't it ruled out?** Small interaction with Standard Model
- **How do we discover it?** Room for creativity!
  Usually related to "how did it get here?"

# Thanks!

| | | |
|---|---|---|
| **Asymmetries in Extended Dark Sectors: A Cogenesis Scenario** *Mainz Institute for Theoretical Physics, Johannes Gutenberg University* | *Giacomo Landini* | 08:15 - 08:40 |
| **Freeze-in at stronger couplings** *Mainz Institute for Theoretical Physics, Johannes Gutenberg University* | *Catarina Cosme* | 08:40 - 09:05 |
| **Shining Light on Hidden Sector Dark Matter** *Mainz Institute for Theoretical Physics, Johannes Gutenberg University* | *Himanish Ganjoo* | 09:15 - 09:40 |
| **Neutrino Detectors & Dark Sectors** *Mainz Institute for Theoretical Physics, Johannes Gutenberg University* | *Kevin Kelly* | 09:40 - 10:05 |
| **Dark matter production in exponential growth scenarios** *Mainz Institute for Theoretical Physics, Johannes Gutenberg University* | *Disha Bhatia* | 10:05 - 10:30 |
| **Coleman-Weinberg dynamics of dark matter and right-handed neutrinos** *Mainz Institute for Theoretical Physics, Johannes Gutenberg University* | *Ryan Plestid* | 10:30 - 10:55 |