I. Overview and motivations for light DM

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Summer Institute 2019, Korea

Plan for lectures

I. Overview of DM landscape and motivations/questions for light dark matter

II. Models and mediators for light dark matter, focusing on benchmarks for direct detection

III. Introduction to techniques for computing DM scattering in low-threshold direct detection materials

Most references cited throughout;
overall structure mostly based on TL1904.07915

Outline

Dark matter theory space

heavy, WIMPy, ultralight

Light dark matter

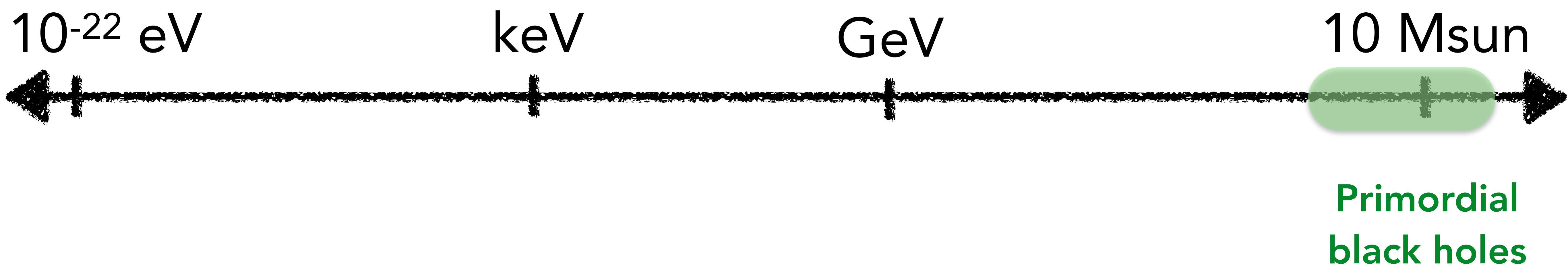
motivations

introduction to models

Mass scale of dark matter

Many well-defined targets (lampposts) &
general classes of dark matter models,
over an enormous mass range.

Mass scale of dark matter



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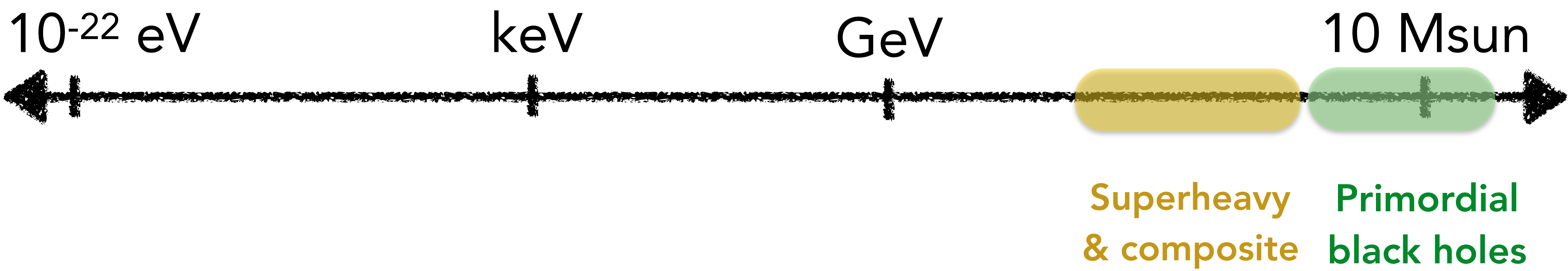

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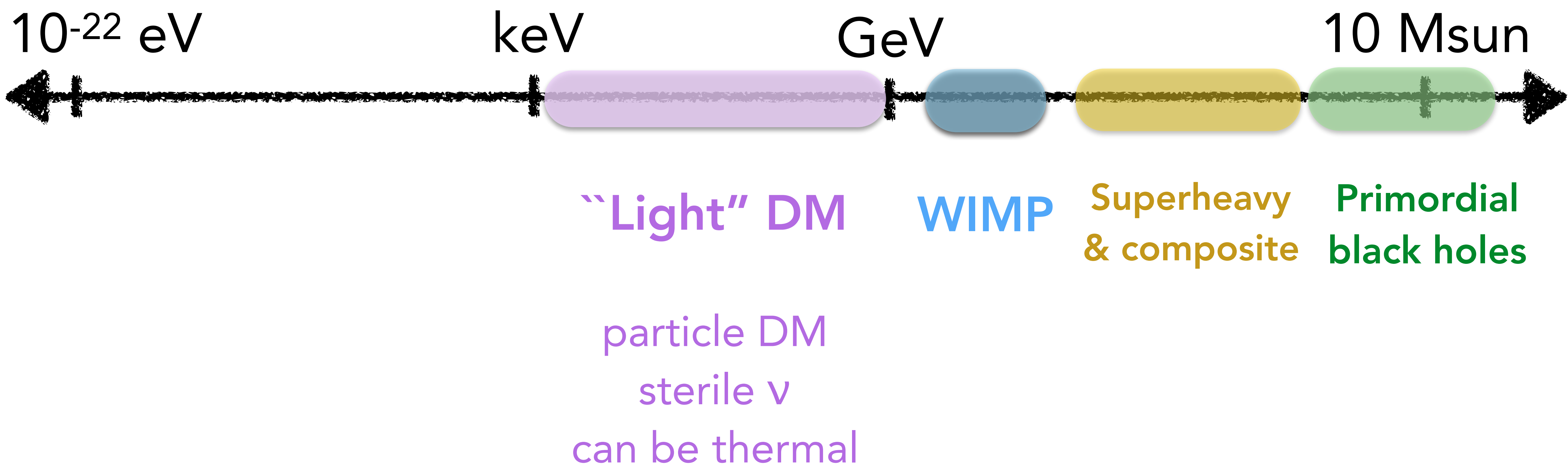

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Mass scale of dark matter

``Ultralight" DM

bosonic field
axions
non-thermal

``Light" DM

particle DM
sterile ν
can be thermal

WIMP

Superheavy & composite

Primordial black holes

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How do we tackle this model space?

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Large and small-scale structure of DM
CMB, 21cm
Multimessenger

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CMB, 21cm
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LHC++
Low-energy/high-intensity accelerator
``Tabletop” experiments

How do we tackle this model space?

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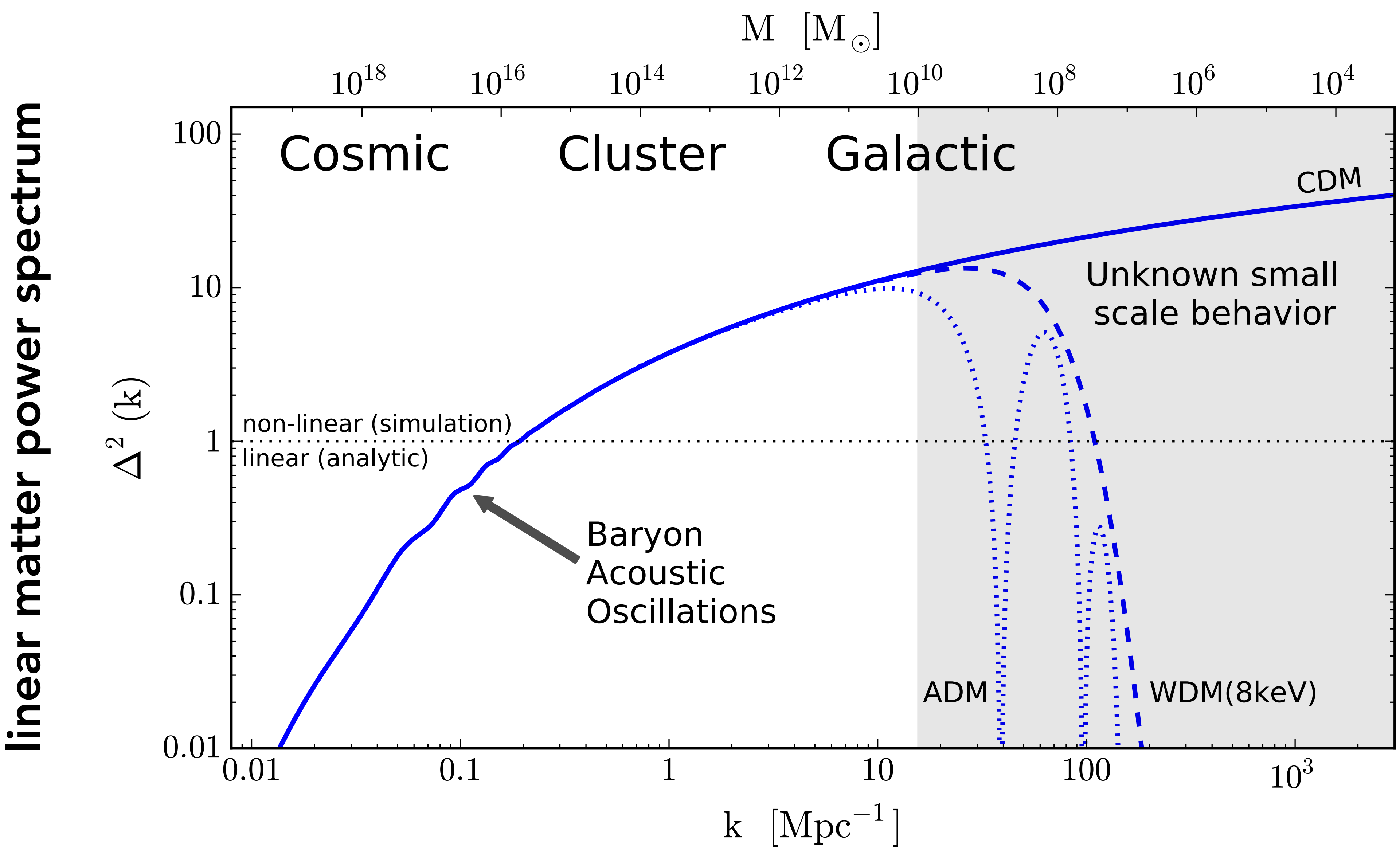

Figure from Kuhlen, Vogelsberger, Angulo

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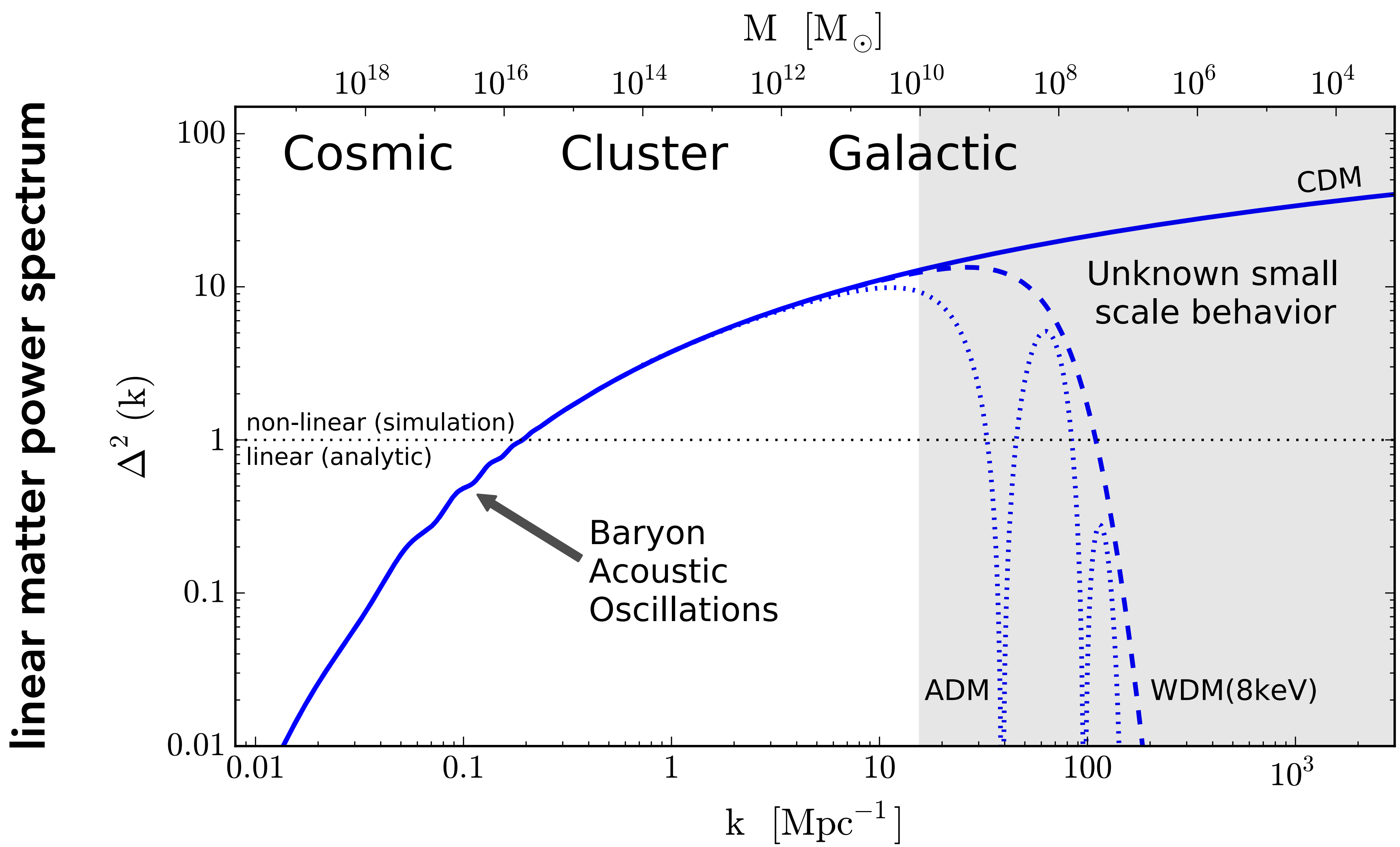

Comparison with data requires forward-modeling from theory

Figure from Kuhlen, Vogelsberger, Angulo

How do we tackle this parameter space?

Theory and data-driven questions

Is dark matter structure on small scales described by CDM?

What particle properties of DM are detectable with next generation of astro/cosmo observations? Lab-based experiments?

Goal: simple, viable *models* and *model frameworks* where we can determine:

1. relic abundance
2. predicted signal strength in experiments

We also need to understand background systems!

Primordial black holes

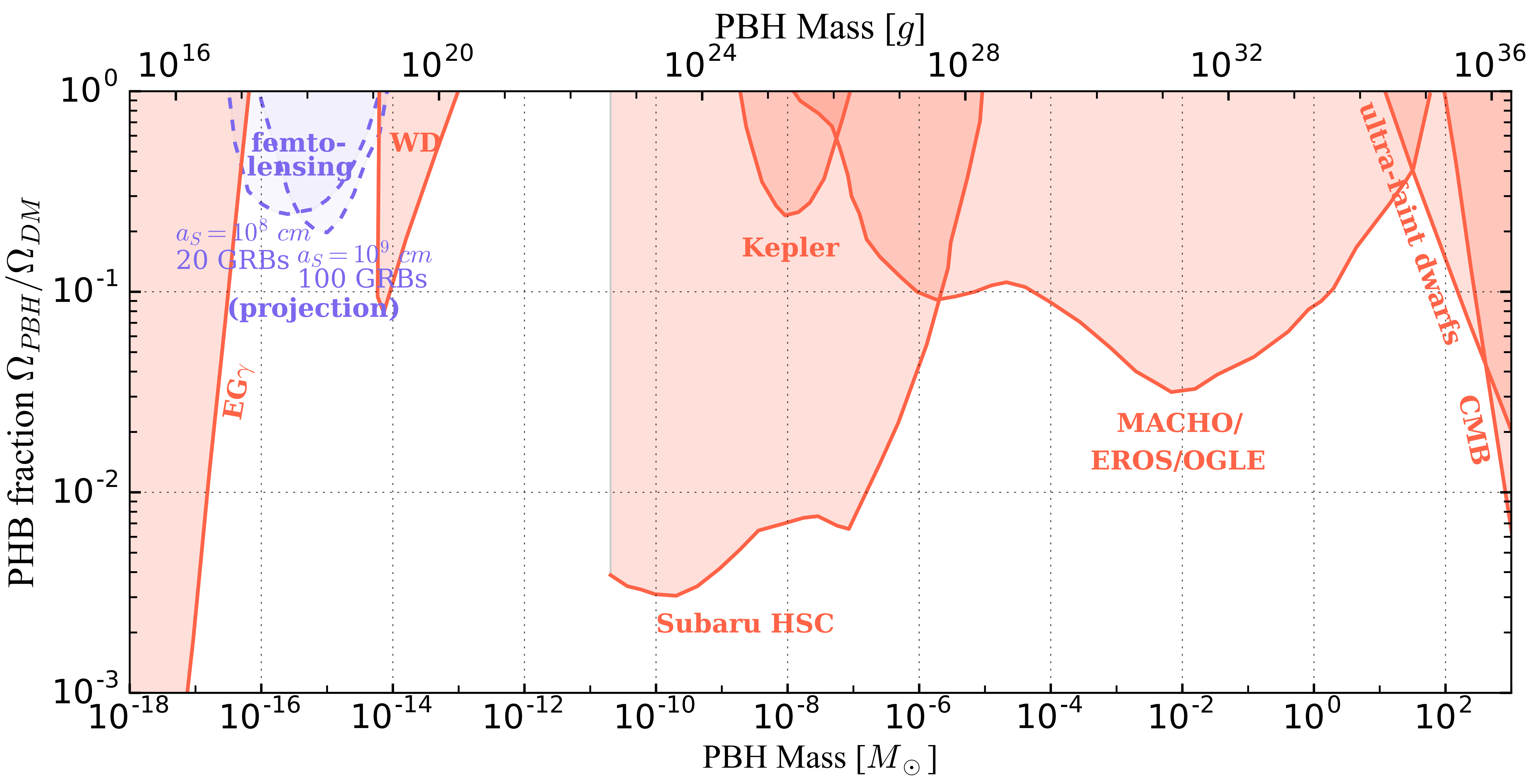

Figure from 1807.11495

Review by Sasaki et al. 1801.05235

Primordial black holes

Relic density

Collapse of O(1) over densities from inflation, phase transitions, matter-dominated era, etc…
what is the mass spectrum and spin spectrum?

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Predicted signatures

How can we test PBH in the mass range 1e-16 to 1e-11 Msun?

[Bai & Orlofsky 2018, Jung & Kim 2019]

Can we search for less compact DM overdensities? What is the predicted signal in gravitational waves or EM waves?

[e.g. 1903.04424]

Composite & superheavy dark matter

Unitarity bound on thermal production $m_\chi \lesssim 100\ \mathrm{TeV}$

Nonthermal production (WIMPzillas, GUTzillas)

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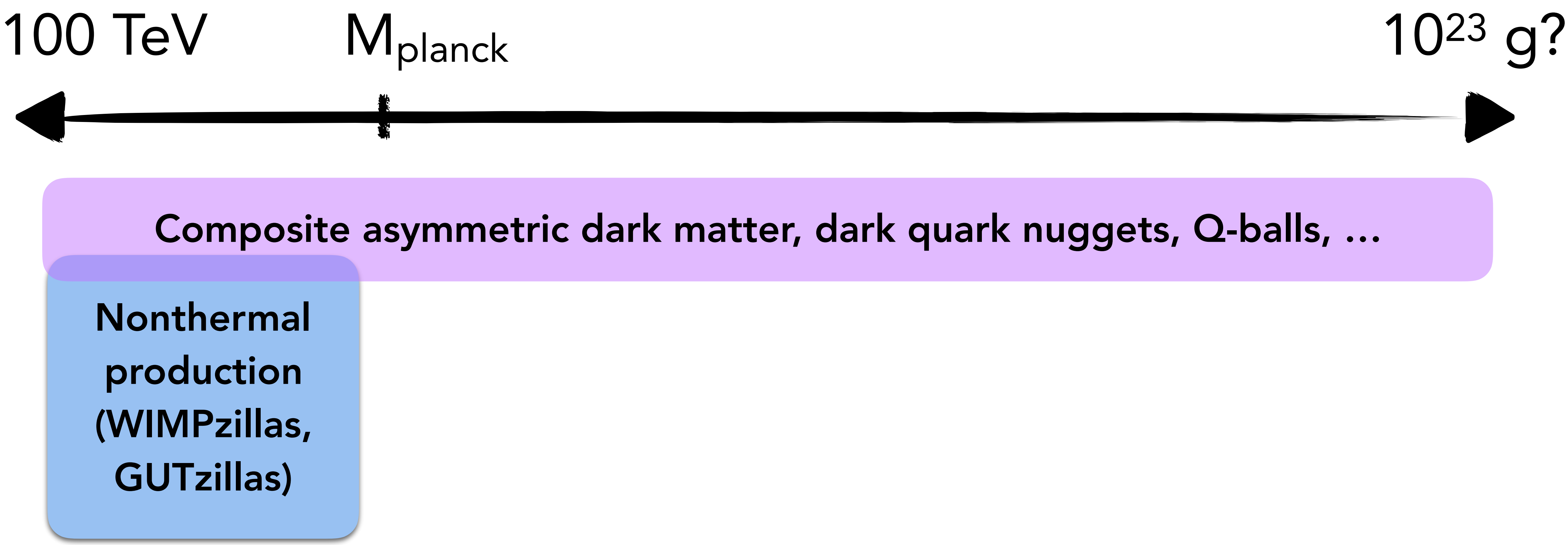

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100 TeV — M_{planck} — 10^{23} g?

Composite asymmetric dark matter, dark quark nuggets, Q-balls, …

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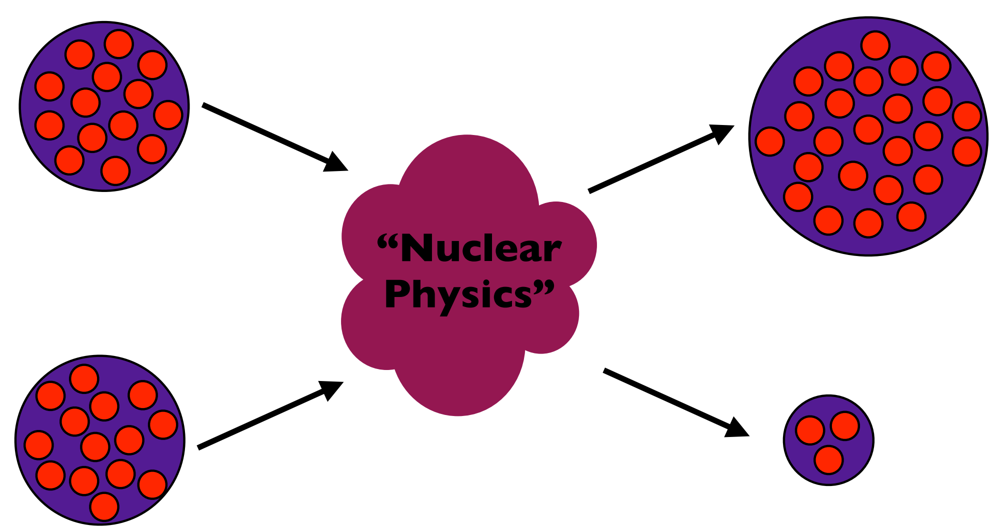

[Krnjaic+'14, Coskuner, Grabowska+'18]

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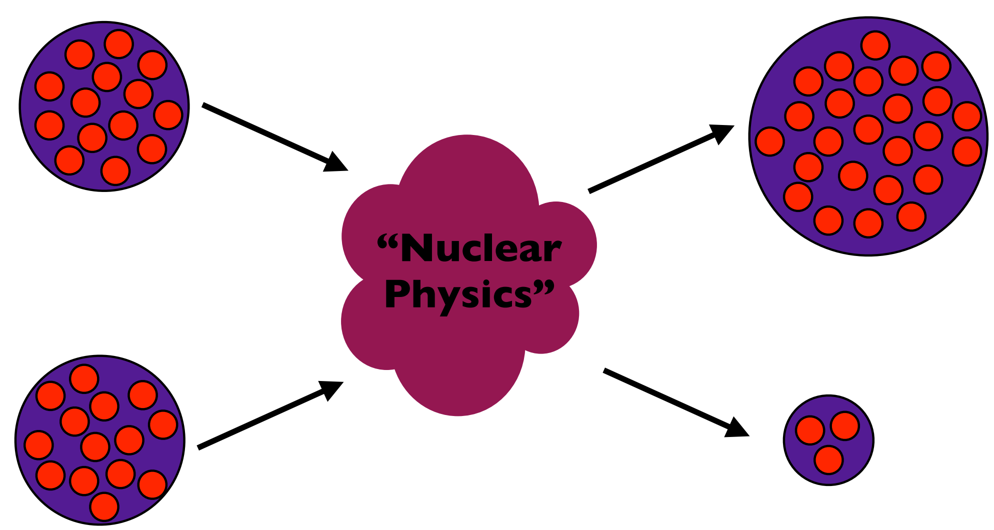

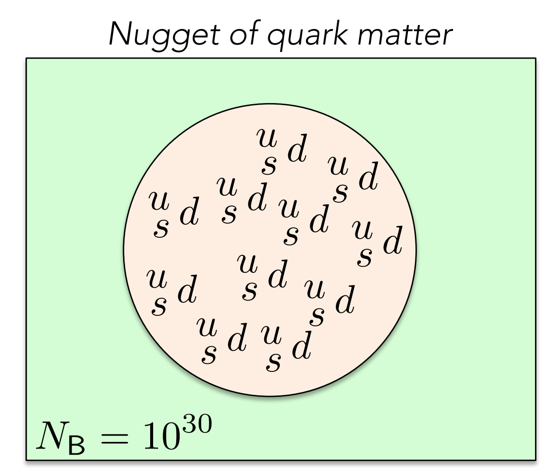

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Predicted signatures

Are there long-lived metastable states that would affect BBN through extra energy injection?

What are direct detection signatures of extended objects with excitation of internal composite DM modes?

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- Candidates:
  - Hidden photon
  - Pseudoscalar (axion)
  - Scalar

} appear in UV completions of Standard Model

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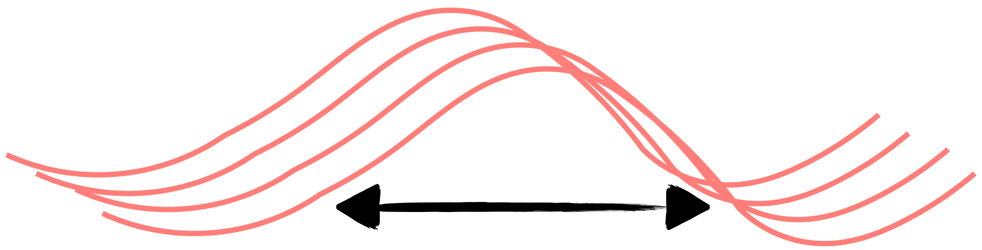
- Coherent field below *m* ~ eV

Occupation number is high:

$$\frac{\rho_{\rm DM}}{m_{\rm DM}} \gg \lambda_{\rm dB}^{-3}$$



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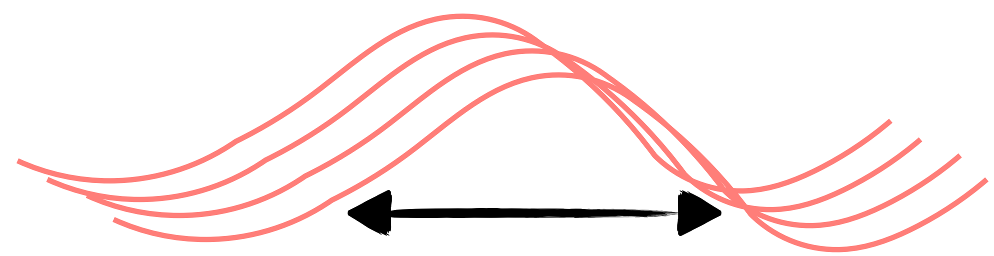

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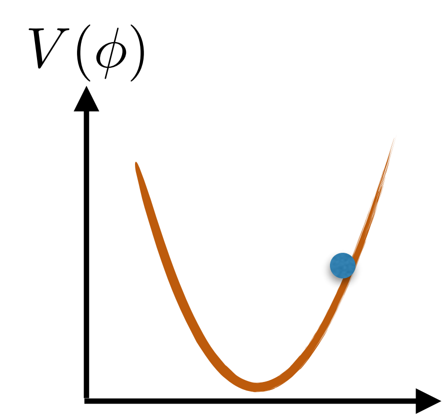
- Non-thermal relic abundance

$$\rho_{\rm DM} = \frac{1}{2} m_{\rm DM}^2 \phi_0^2$$

ϕ_0 — field amplitude today



Relic abundance for axions & scalars

Misalignment for axions

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Close relation between relic abundance, mass, and direct detection signal

$$g_{a\gamma\gamma} \propto \frac{\alpha m_a}{m_\pi f_\pi}, \quad g_{ann} \propto \frac{m_a}{m_\pi f_\pi}$$ for QCD axion

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Many recent works for non-standard QCD axions, ALPs.

Much less studied for scalars.

Relic abundance for axions & scalars

Predictions for QCD axion DM are increasingly refined:

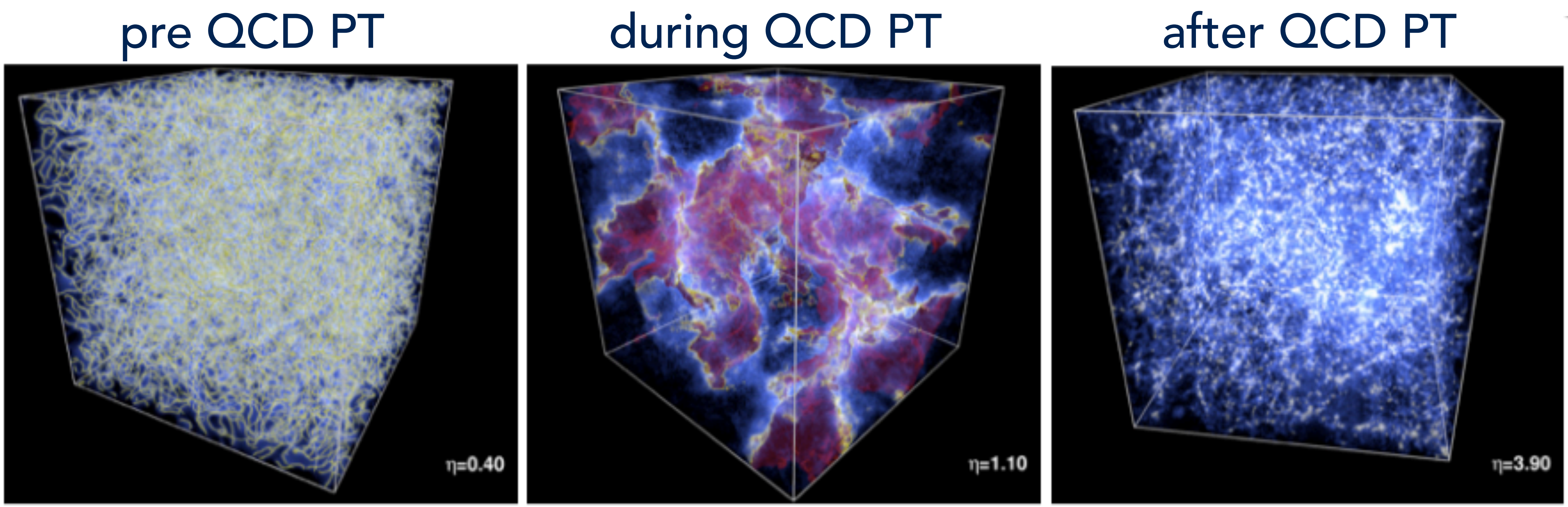


Figure 1. Each panel illustrates the string network (yellow strings), domain walls (red mesh), and energy density of the axion field (blue-white intensity) before (left), during (middle), and after (right) the QCD phase transition (see animation).

Fig. from Bushmann, Foster, Safdi 2019

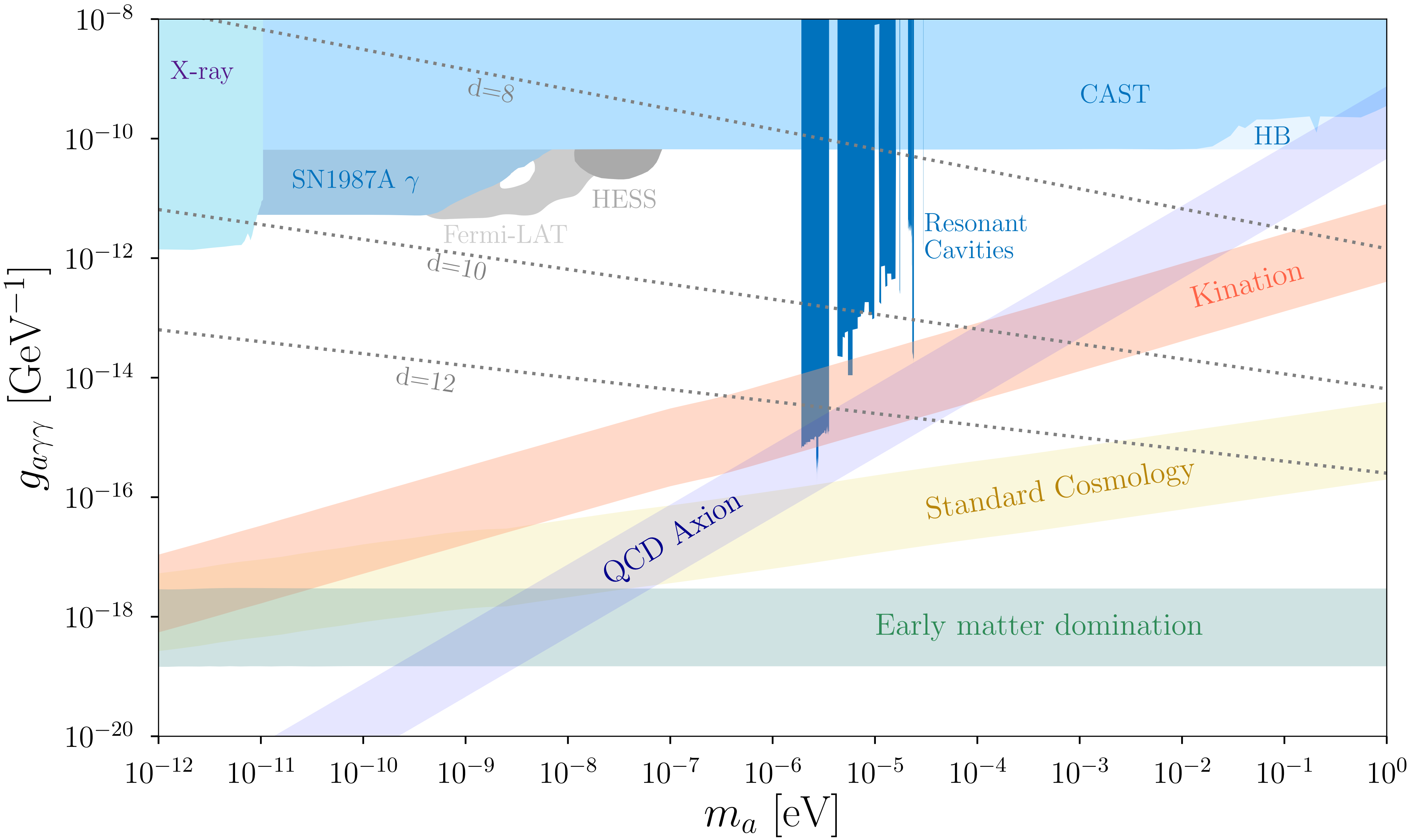
$m_a = 25.2 \pm 11.0\ \mu\text{eV}$ for post-inflation PQ breaking

Formation of ultra-compact mini-halos

Relic abundance for axions & scalars

(Some) cosmological targets for axion-like particles as DM

Assume $g_{a\gamma\gamma} \propto \frac{1}{f_a}$



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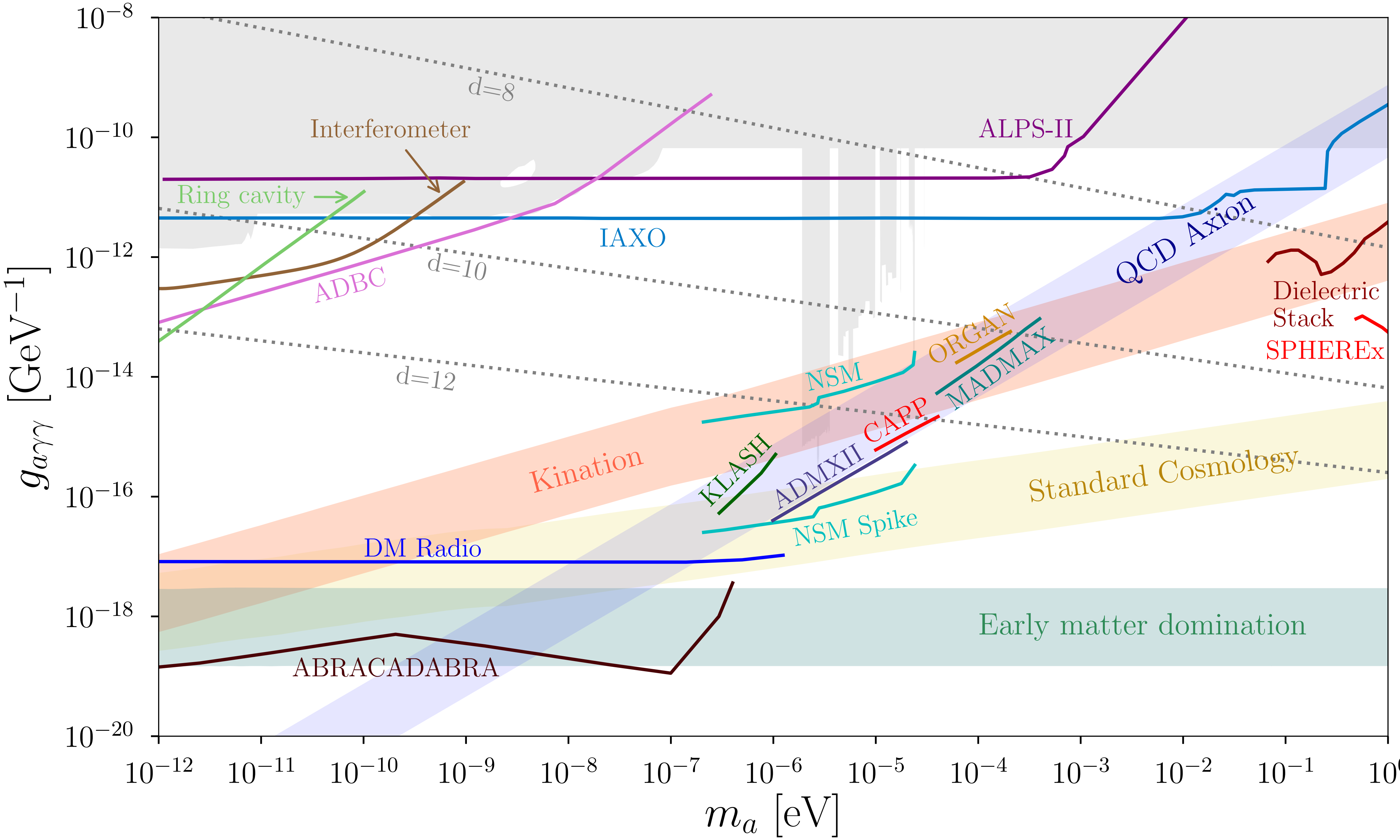

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Relic abundance for vector DM

Usual misalignment doesn't work for vectors
minimally coupled to gravity. [Arias et al. 1201.5902]

10^{-22} eV — 10^{-5} eV — keV

String production [1901.03312], tachyonic instabilities [1810.07188+]

Production independent
of coupling to SM!

Inflationary production of longitudinal mode [1504.02102]

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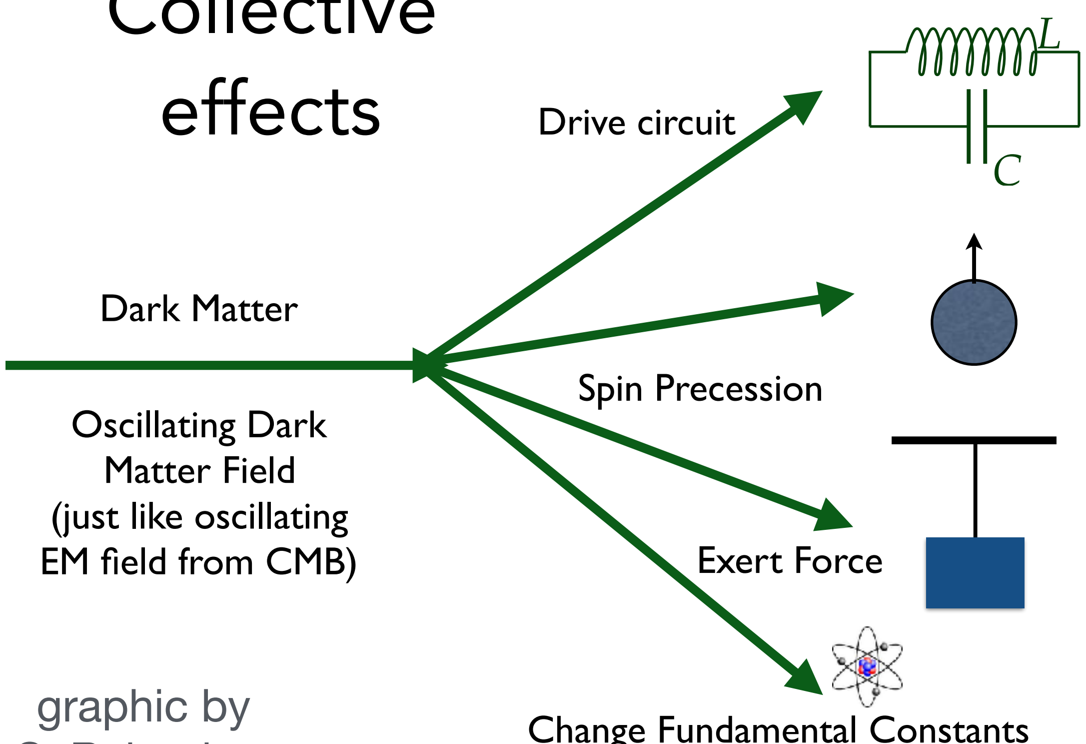
Much less work has been devoted to production of vector DM.
How do relic abundance mechanisms influence lab/astro signals?

Predicted signatures

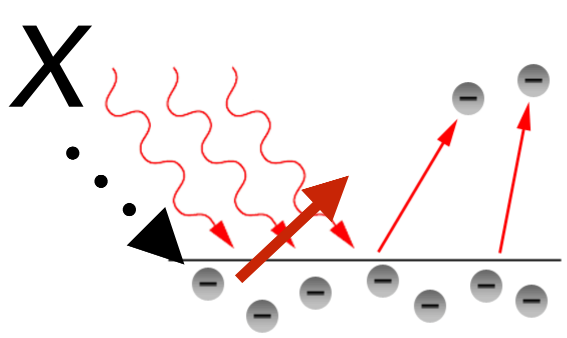
Direct detection

Collective effects



graphic by
S. Rajendran

Absorption signals



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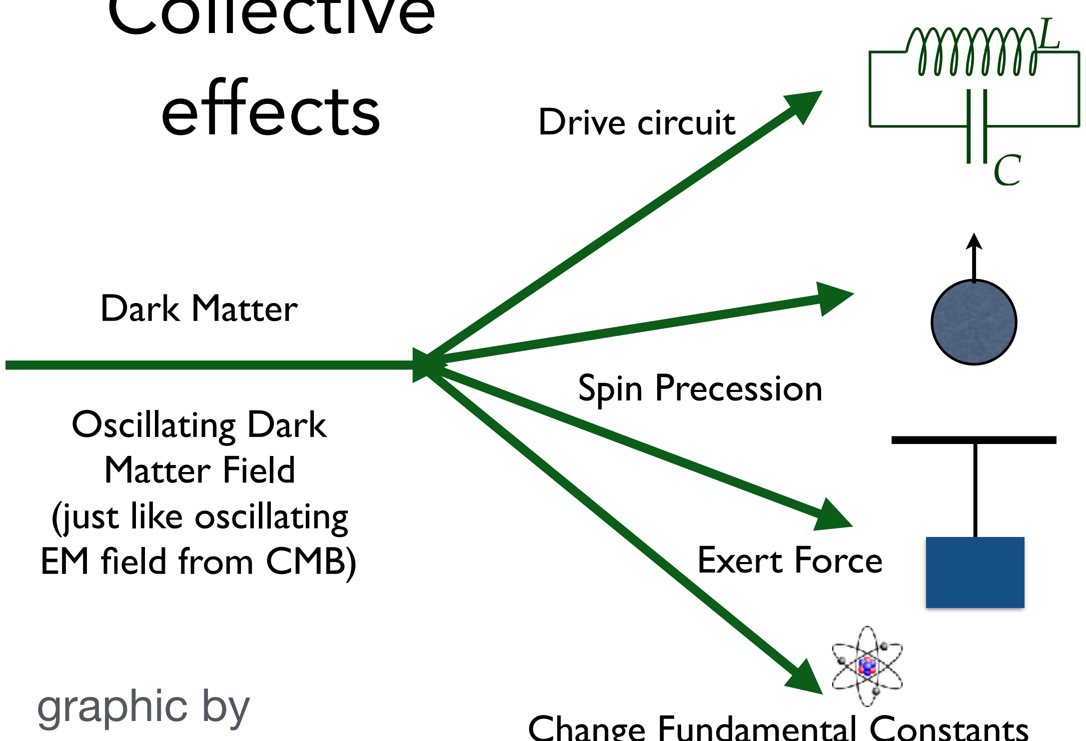

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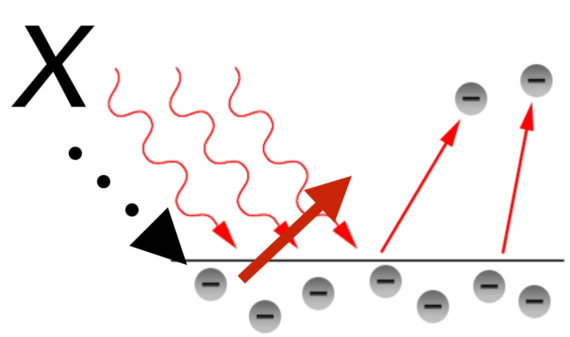


Most existing proposals look for mean DM field in solar system.

How does symmetry-breaking scale, presence/absence of BEC, or (very) small scale structure affect predicted signals?

Predicted signatures

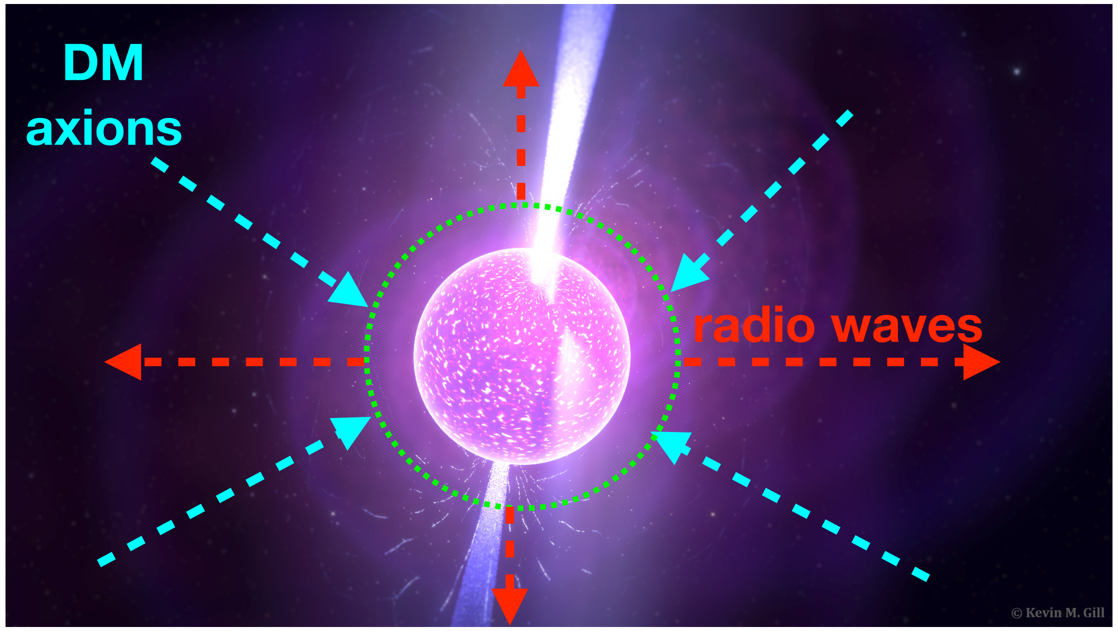
Dense environments as sources:
black holes, neutron stars, …
(multimessenger astronomy)

How well do we understand
the (nuclear) astrophysics
of these sources for DM
or other BSM states?

How well do we understand
the small-scale structure?

Astrophysical sources

NS with strong B-field and surrounding plasma



DM axions resonantly convert to radio waves when $m_a = m_\gamma$

[fig by B. Safdi]

Conversion to visible light
Extra energy loss mechanisms

Thermal(ish) production of dark matter

Relic abundance of SM particles are determined by early universe thermodynamics, baryon-to-photon ratio

Thermal(ish) mechanisms are independent of reheating model

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abundance $Y_{\rm fo} \equiv \left.\frac{n_\chi}{s_\gamma}\right|_{\rm fo}$ $\rho_\chi^{\rm today} = m_\chi Y_{\rm fo} s_{\gamma,{\rm today}}$

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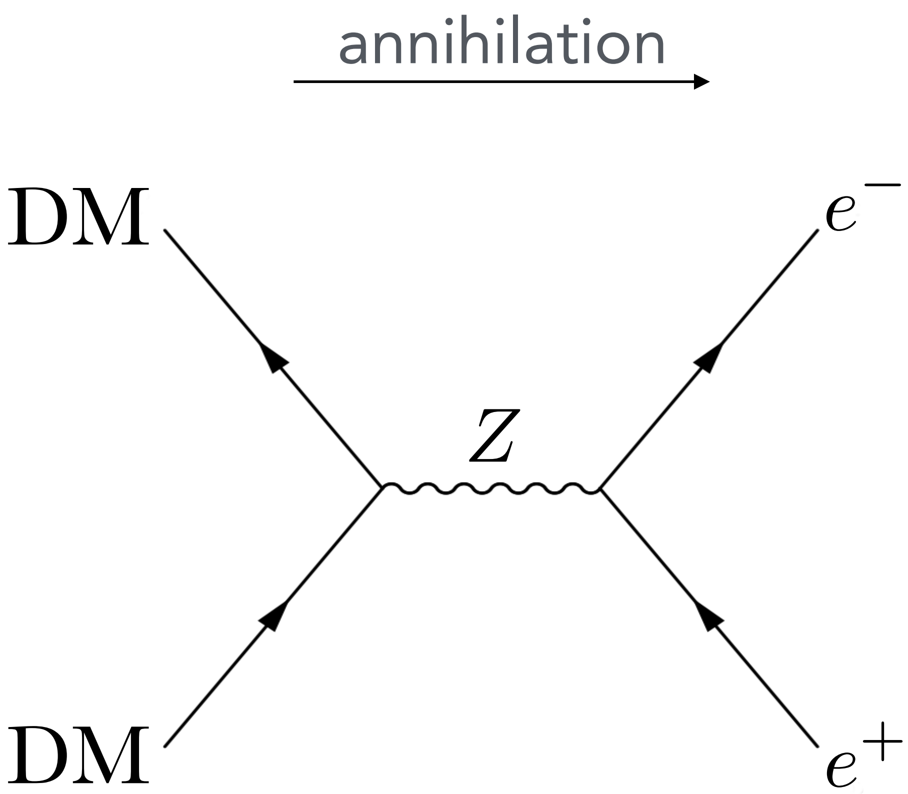
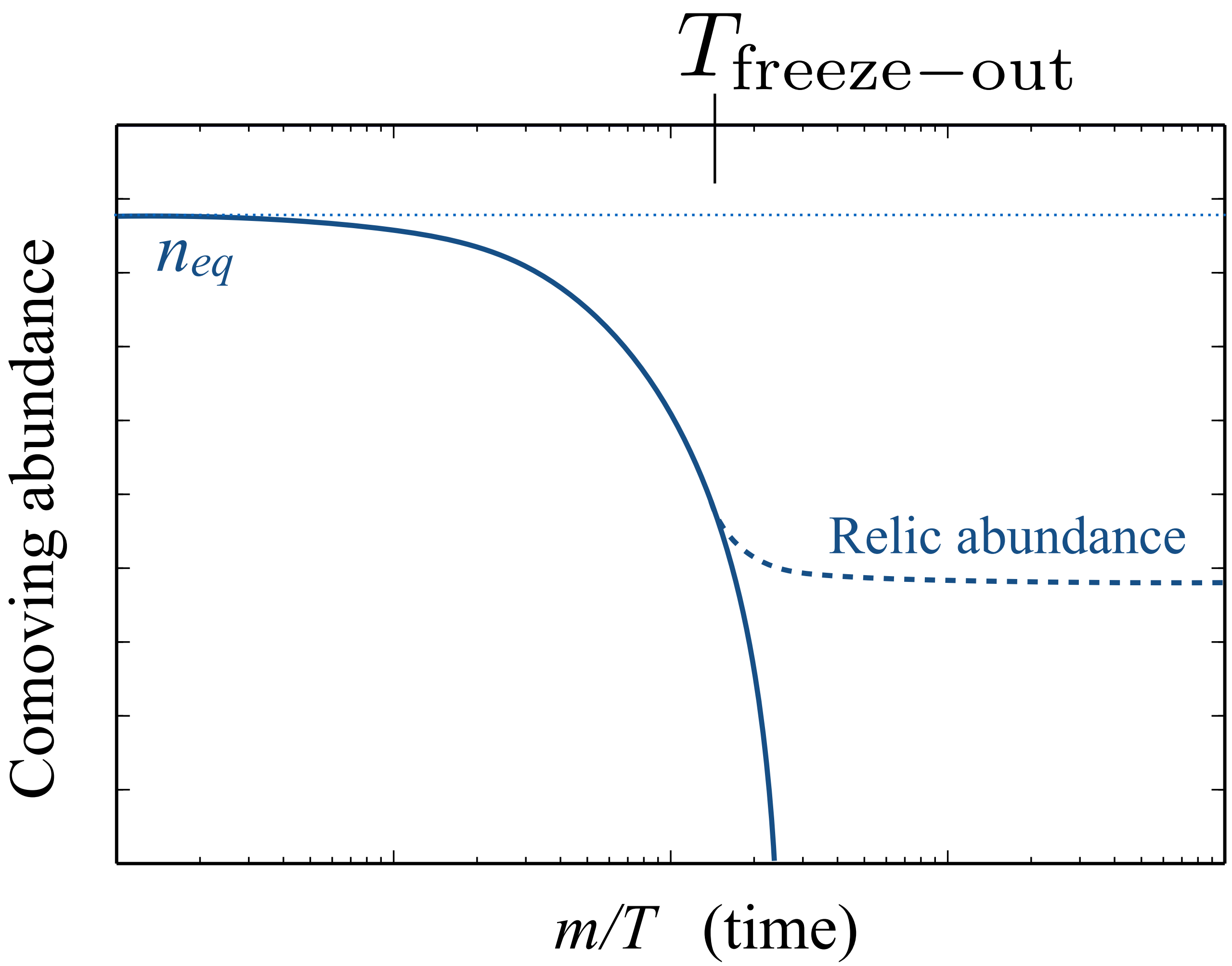
Warm dark matter bounds mX > few keV (approx)
Need a mechanism for producing abundance Y << 10^{-3}

WIMPs (M ~ GeV to few TeV)





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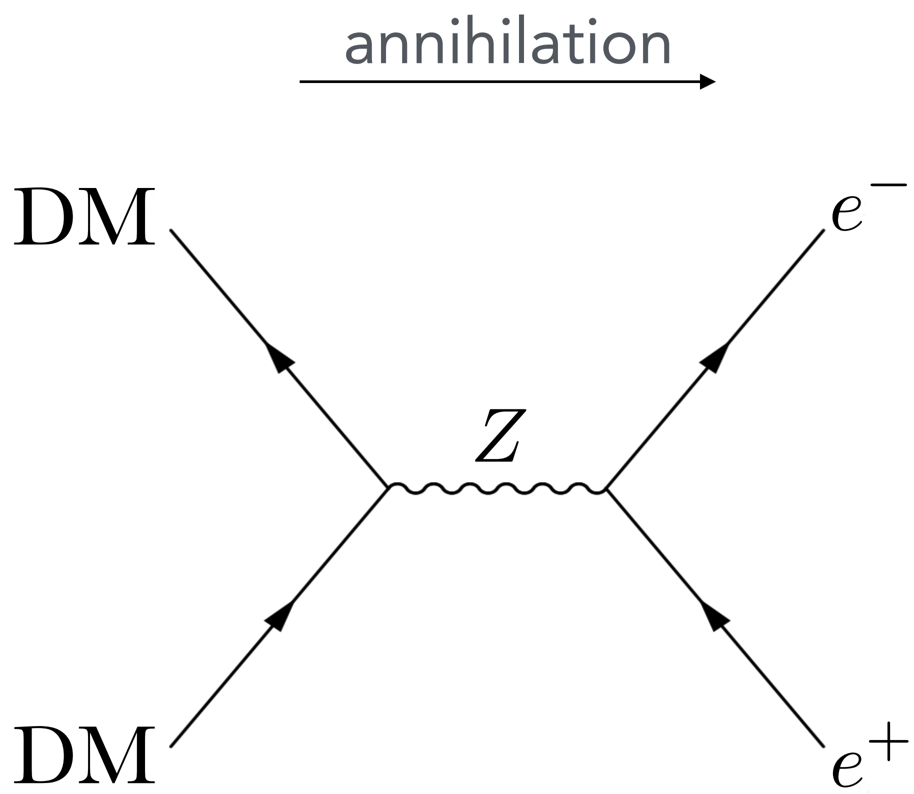
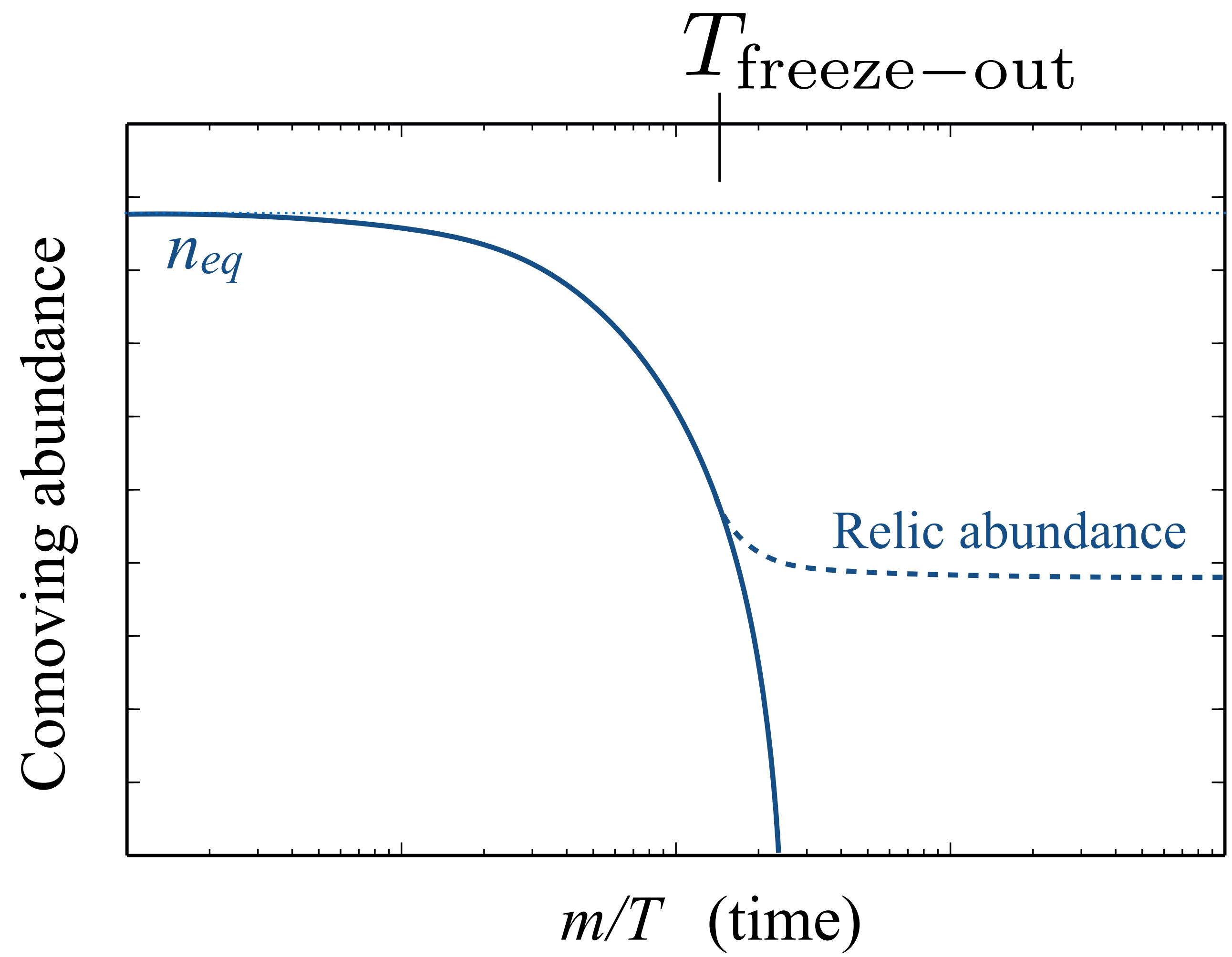




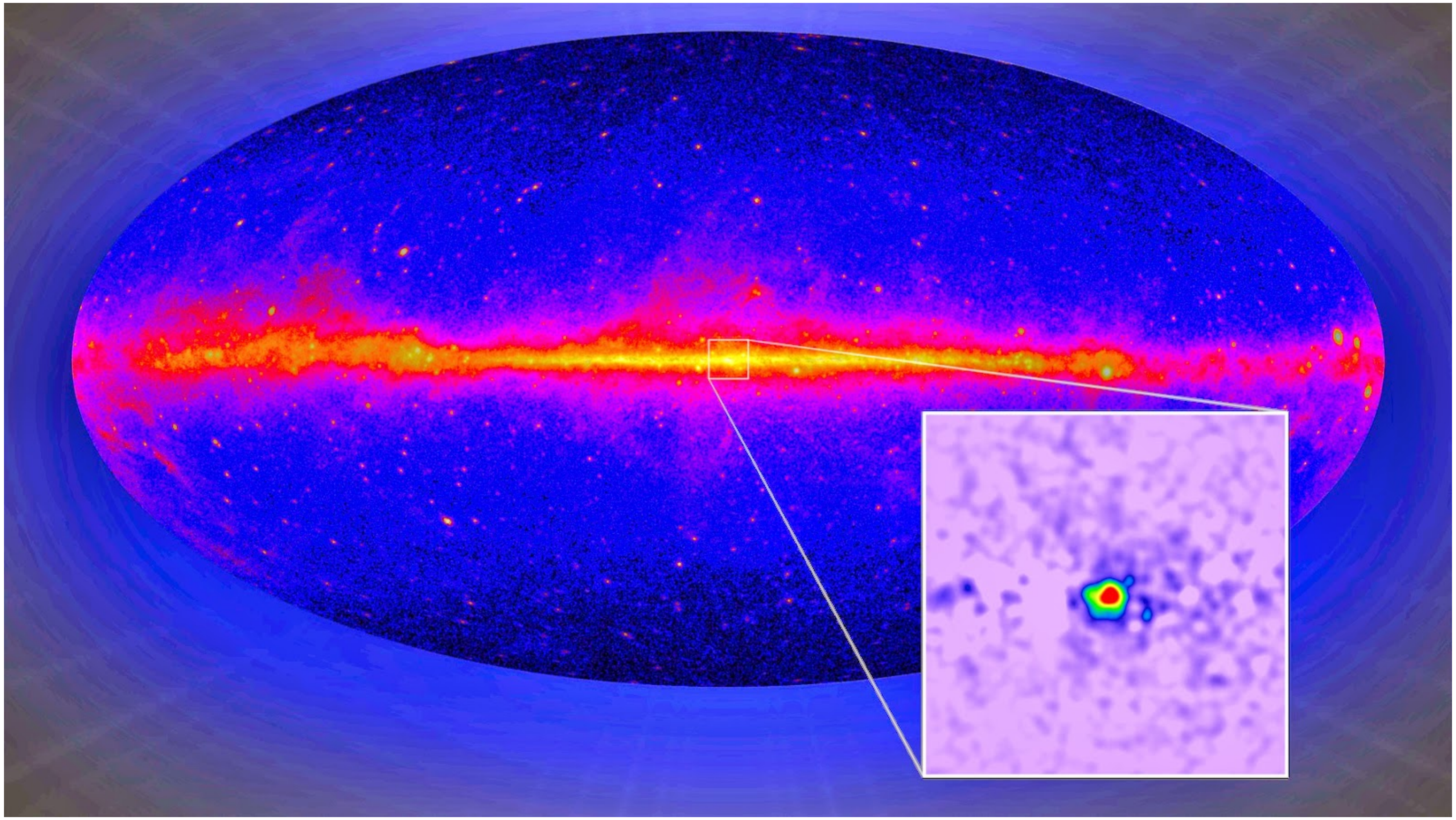
Freezeout when DM is nonrelativistic: → $\langle \sigma v \rangle \simeq \dfrac{\alpha_W^2 m_\chi^2}{M^4} \sim \dfrac{\alpha_W^2}{\text{TeV}^2}$

Favored DM mass range of 10 GeV - 10 TeV

May be tied to new physics at the weak scale

WIMPs (M ~ GeV to few TeV)

WIMP studies and searches are at a much more mature stage. Ex: point sources at the Galactic Center?



e.g. Hooper and Goodenough **2010**

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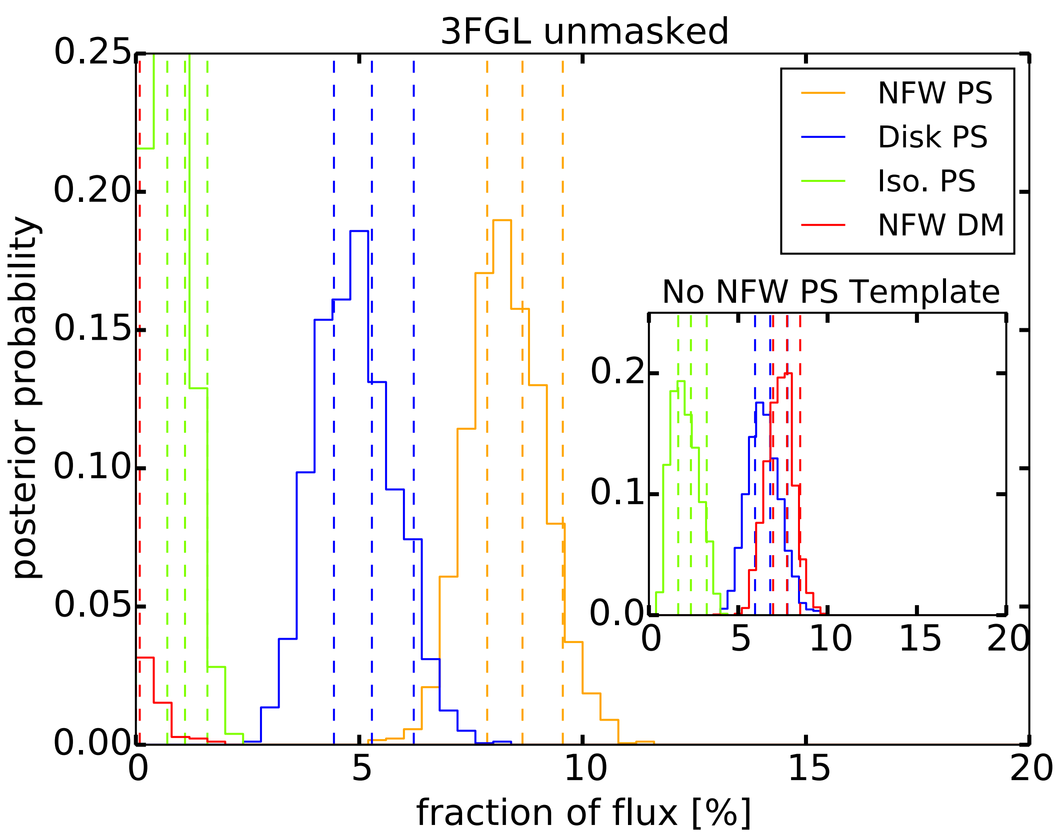
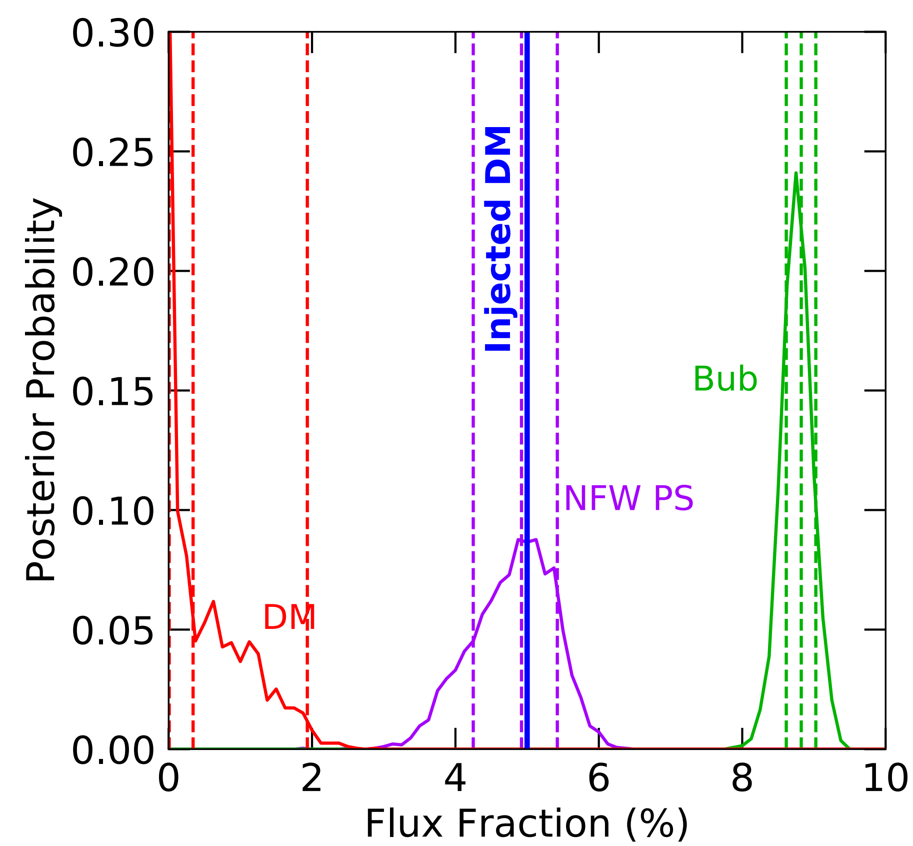


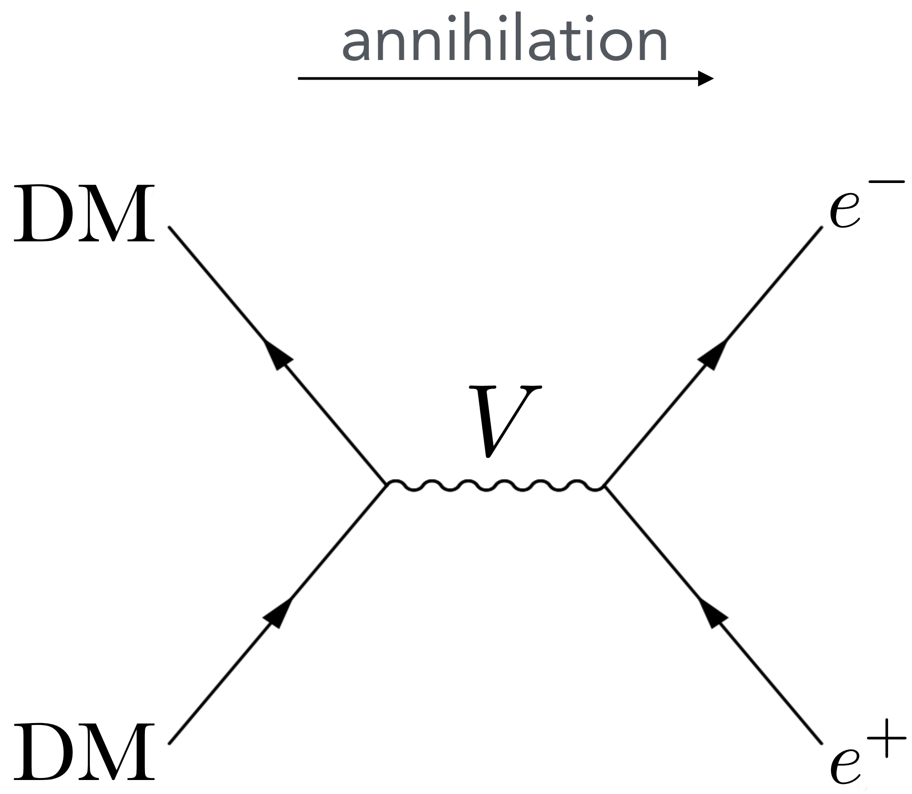
Lee et al. **2015**



Leane & Slatyer **2019**

We expect future debates for non-WIMP candidates…

``Light" DM (M = keV-GeV)



For heavy mediator V:

$$\langle \sigma v \rangle \simeq \frac{16\pi \alpha_\chi^2 m_\chi^2}{m_V^4}$$

For weak interactions

$$m_V = m_W, \alpha_\chi = \alpha_w$$

sub-GeV dark matter is overproduced
[Lee-Weinberg bound]

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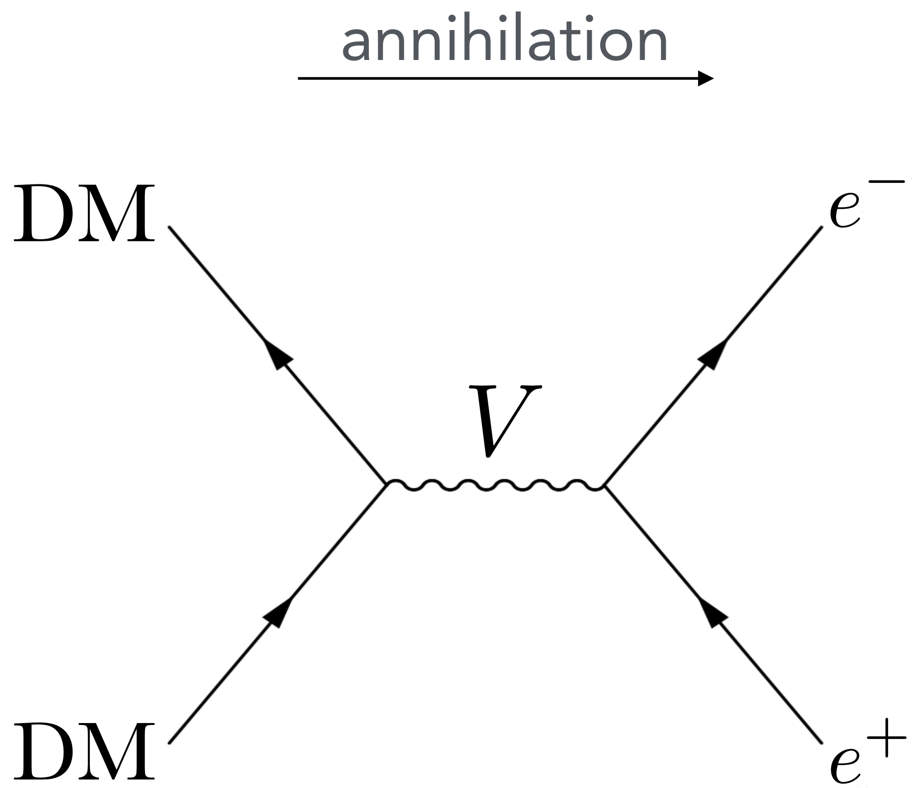

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Reproduces some successes of WIMP miracle.
New mediators below the weak scale are needed for thermal freeze-out (freeze-in is an exception!)

Light dark matter

Heuristic arguments pointing towards weak scale change with the presence of new mass scales and interactions

Processes depleting the dark matter number density:

Light dark matter

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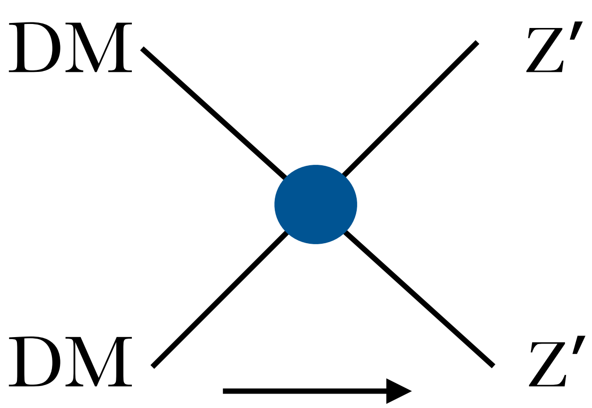
Processes depleting the dark matter number density:

annihilation to light mediators



e.g. Boehm and Fayet 2003, Pospelov et al. 2007, Feng and Kumar 2008

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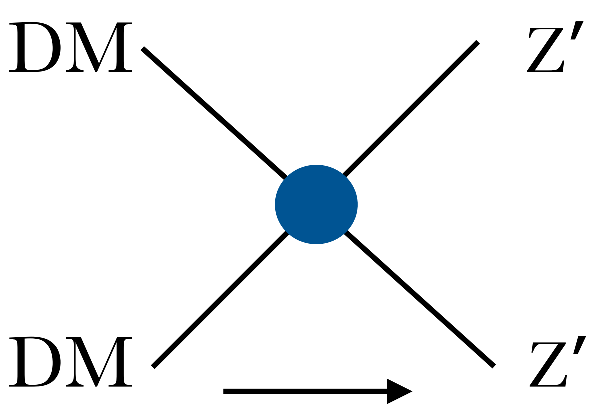

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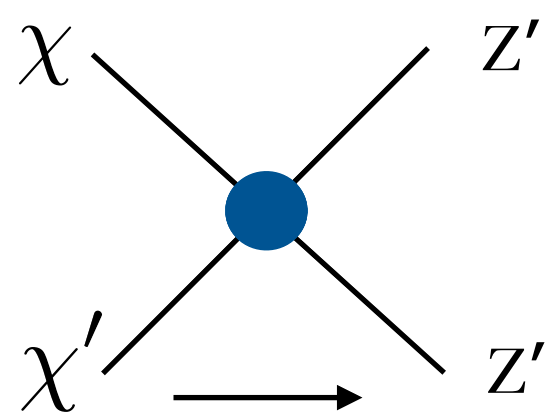
co-annihilation and co-scattering



e.g. Griest and Seckel 1991
D'Agnolo et al. 2017
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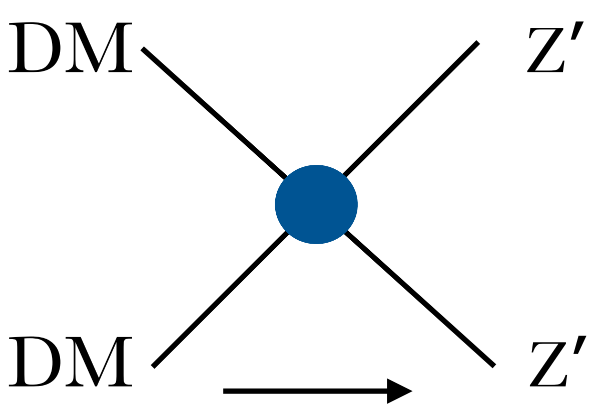

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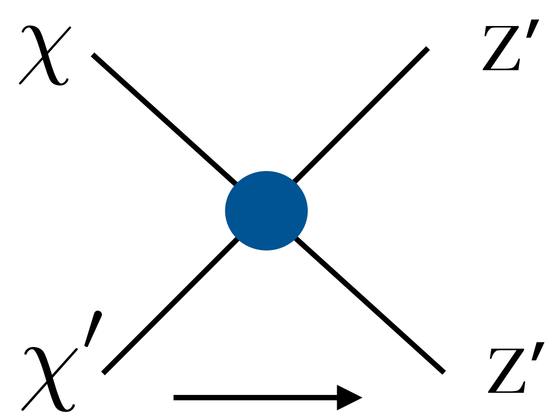

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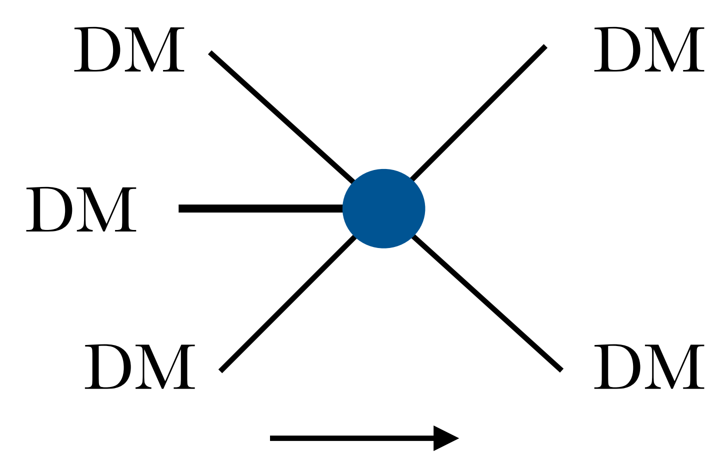
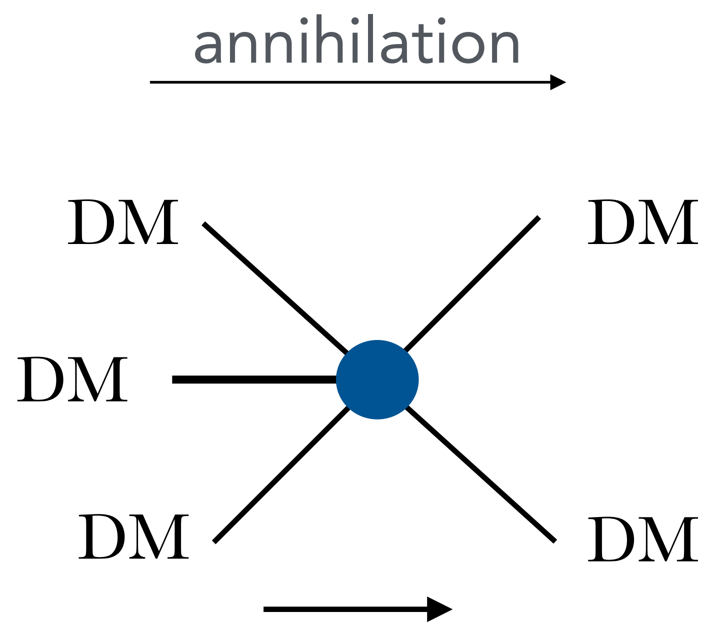
3 to 2 annihilation

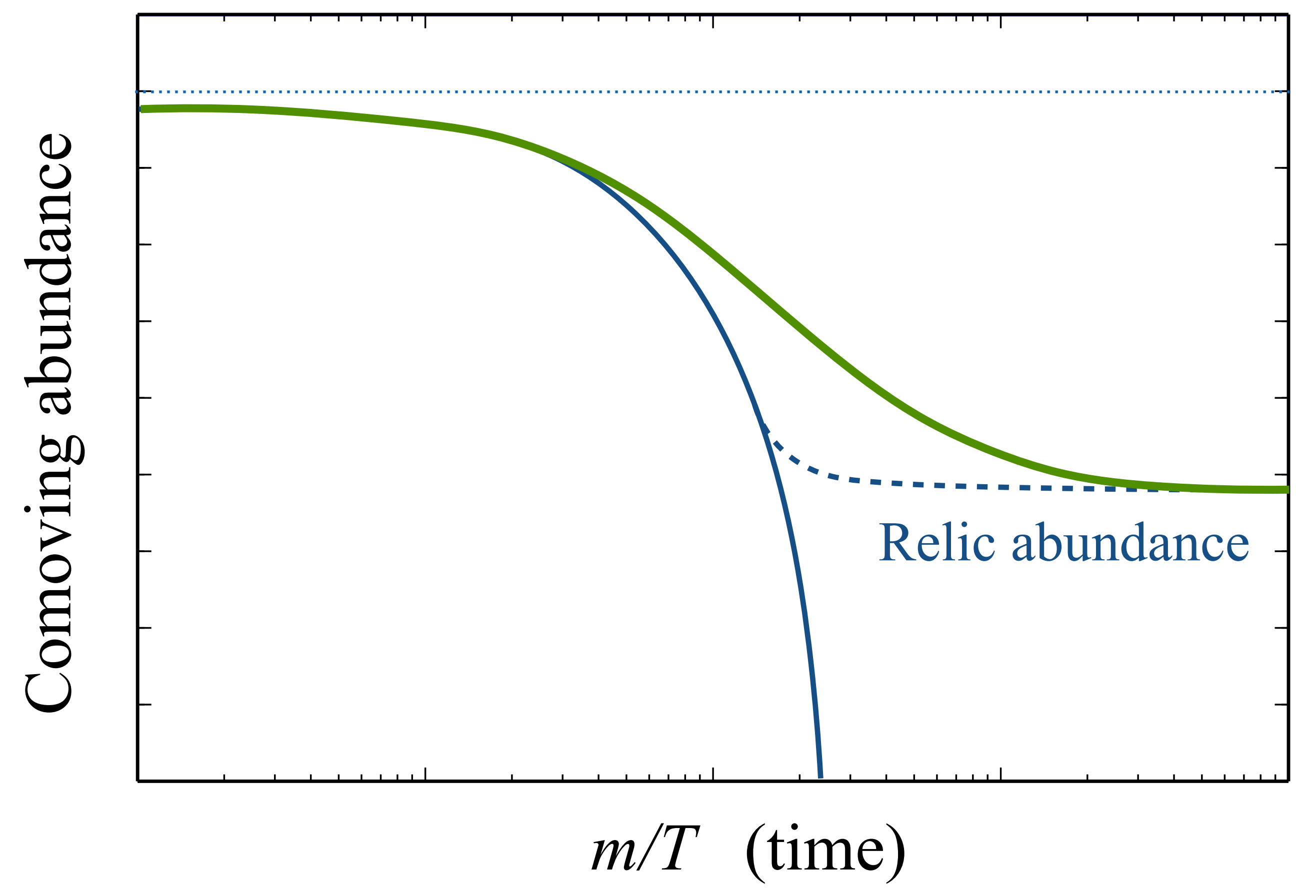


e.g. Carlson et al. 1992
Hochberg et al. 2014, 2015
Kuflik et al. 2015
Farina et al. 2016

SIMPs, Cannibal DM



$$m_{\rm DM} \sim \alpha_{\rm eff} \left(T_{\rm eq}^2 M_{\rm Pl}\right)^{1/3} \sim 100 \text{ MeV}$$



Number changing processes in dark sector can also heat up dark sector thermal bath

Carlson et al. 1992
Hochberg et al. 2014a, 2014b
Pappadopulo, Ruderman, Trevisan 2016
Farina et al. 2016

Light dark matter

1. Thermal relic benchmarks for masses down to ~**keV** (warm DM)

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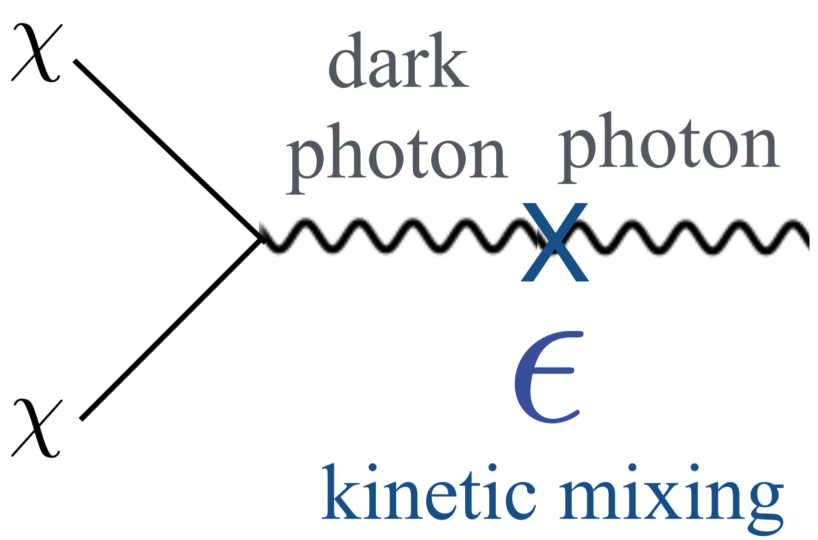
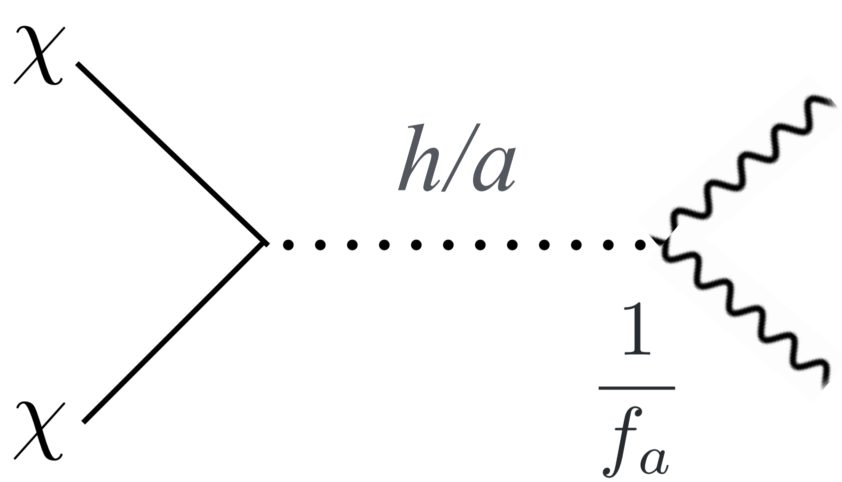
Portals to the Standard Model

vector portal

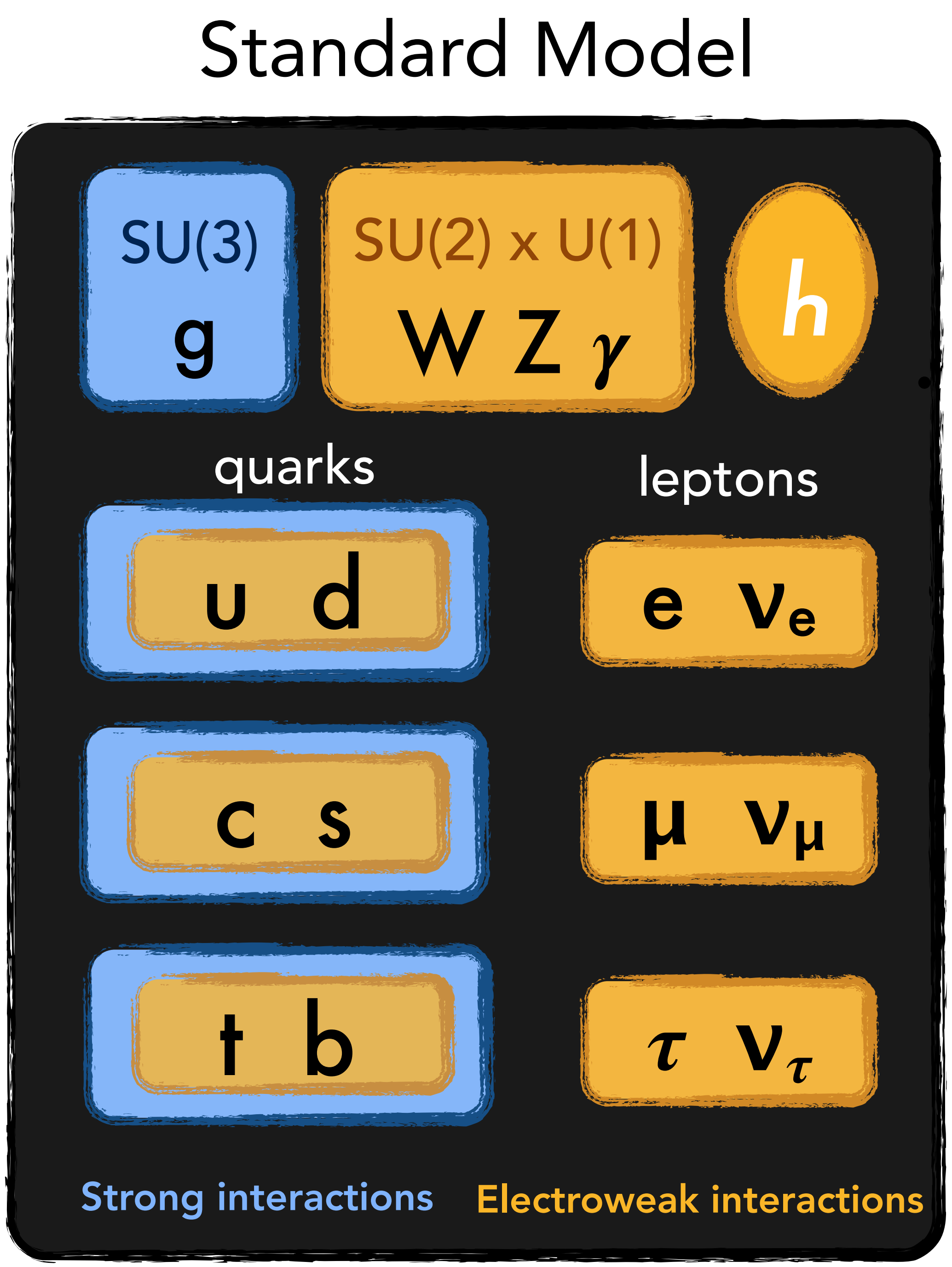


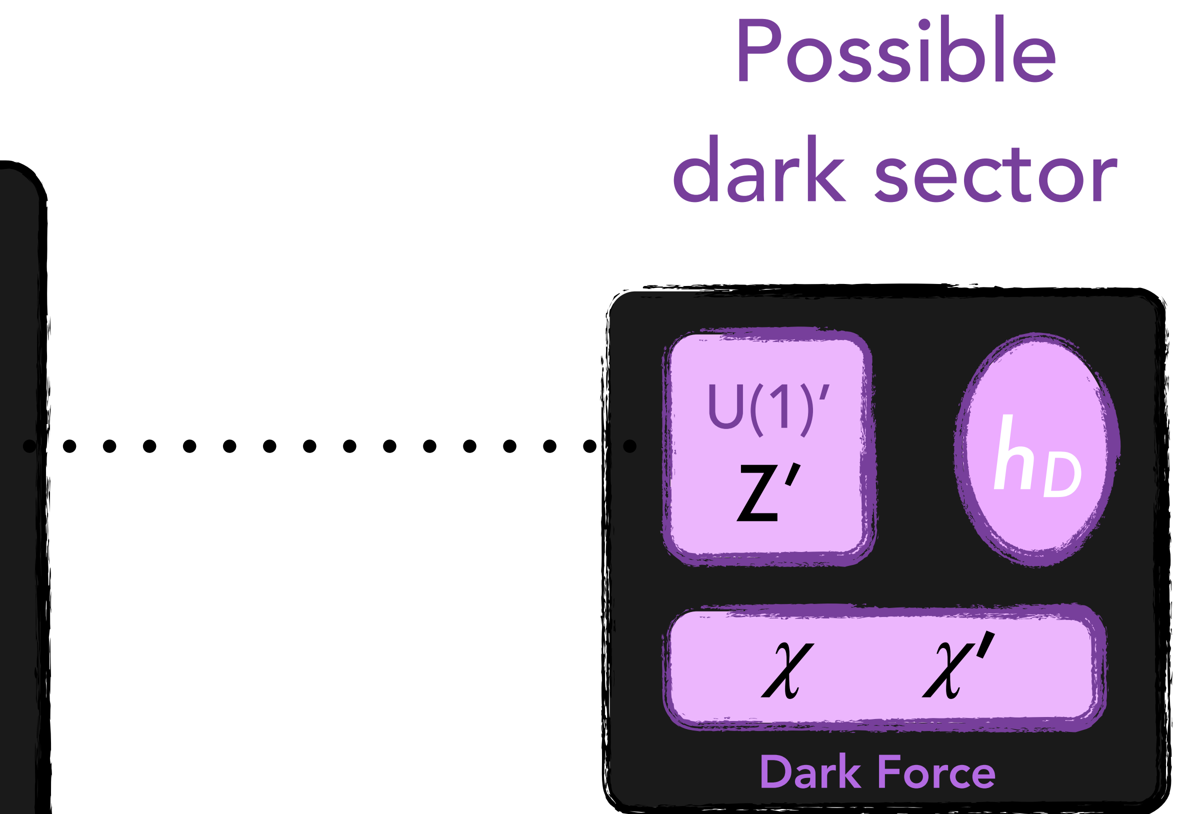
Higgs or axion portal



+ neutrino portal

Dark sectors





Theory landscape includes dark gauge forces, flavor, higgs, inelastic DM, etc.

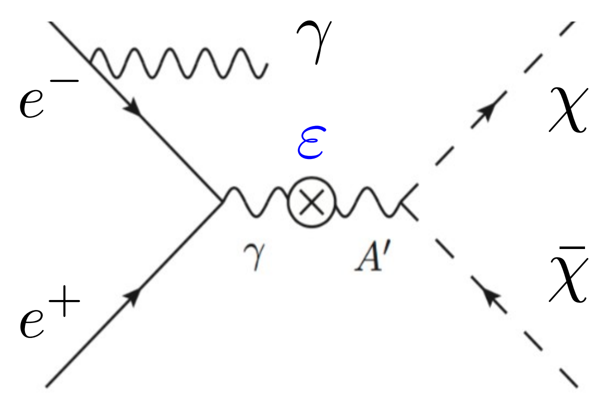
Predicted signatures

Varied new phenomenology in the presence of low-mass dark sectors; not a complete classification!

Predicted signatures

Accelerators

e+e- colliders
fixed target
searches for new
mediators / LLPs



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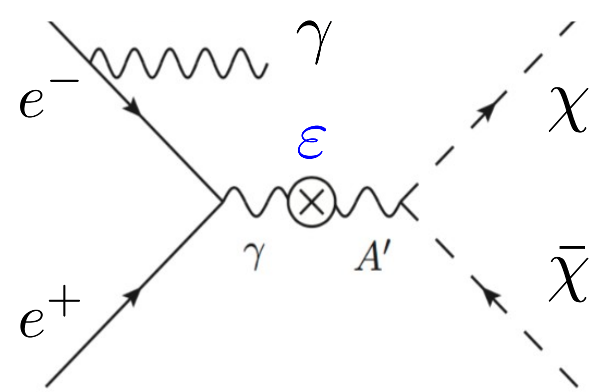

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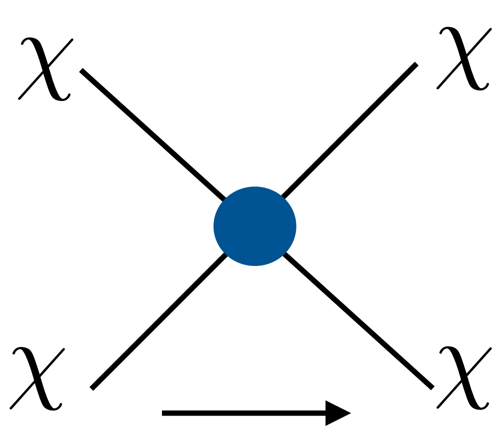
Astrophysics and Cosmology



self interactions
stellar production
DM annihilation
baryon drag/cooling

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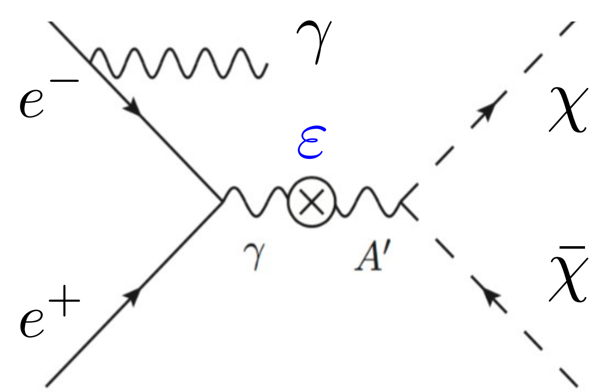

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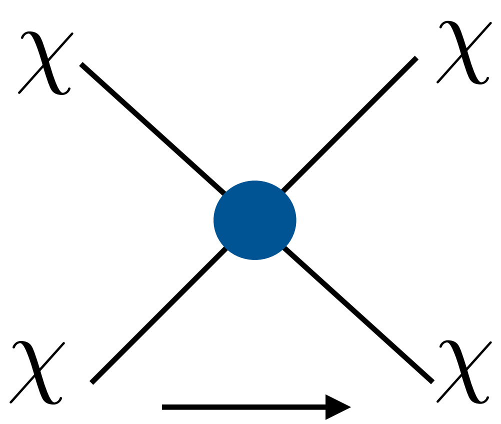

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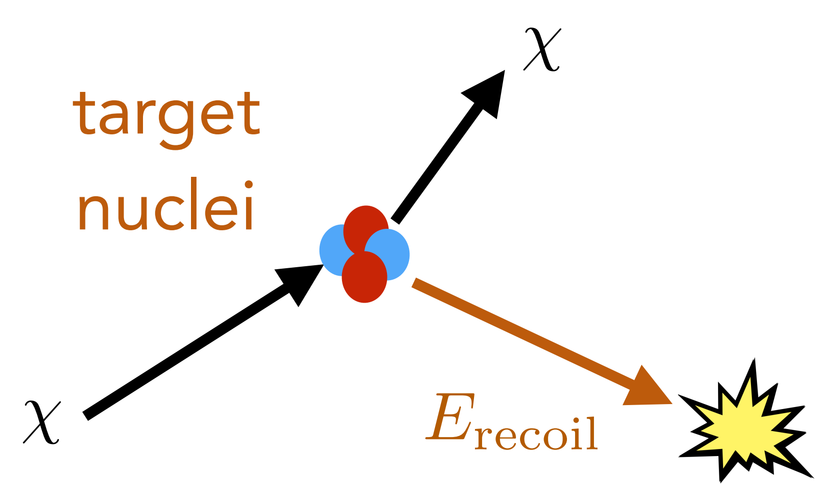
Direct detection



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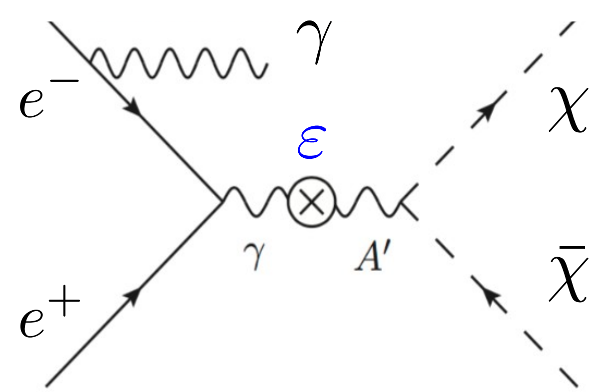

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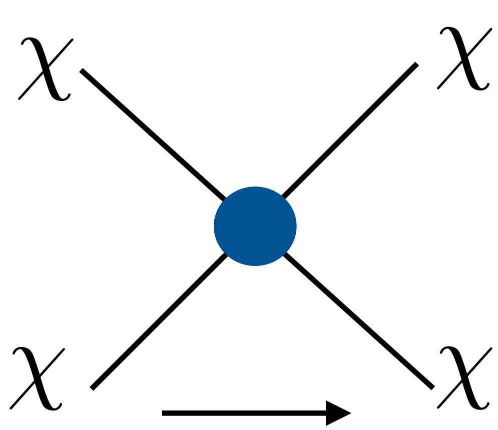

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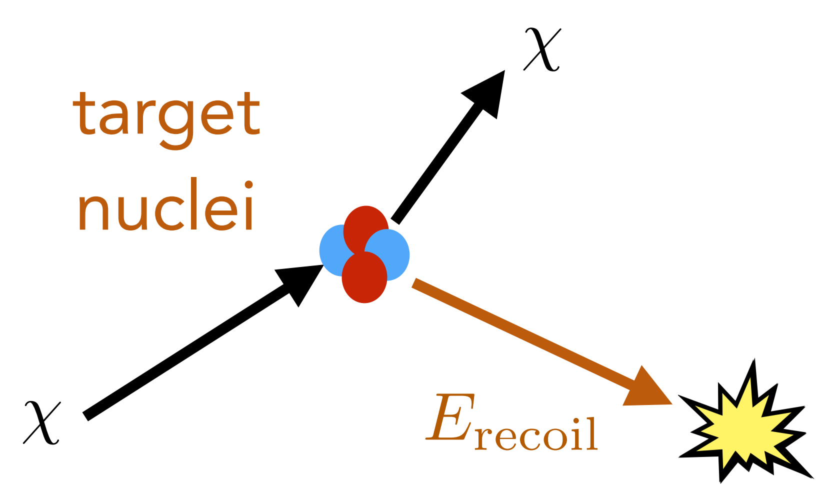
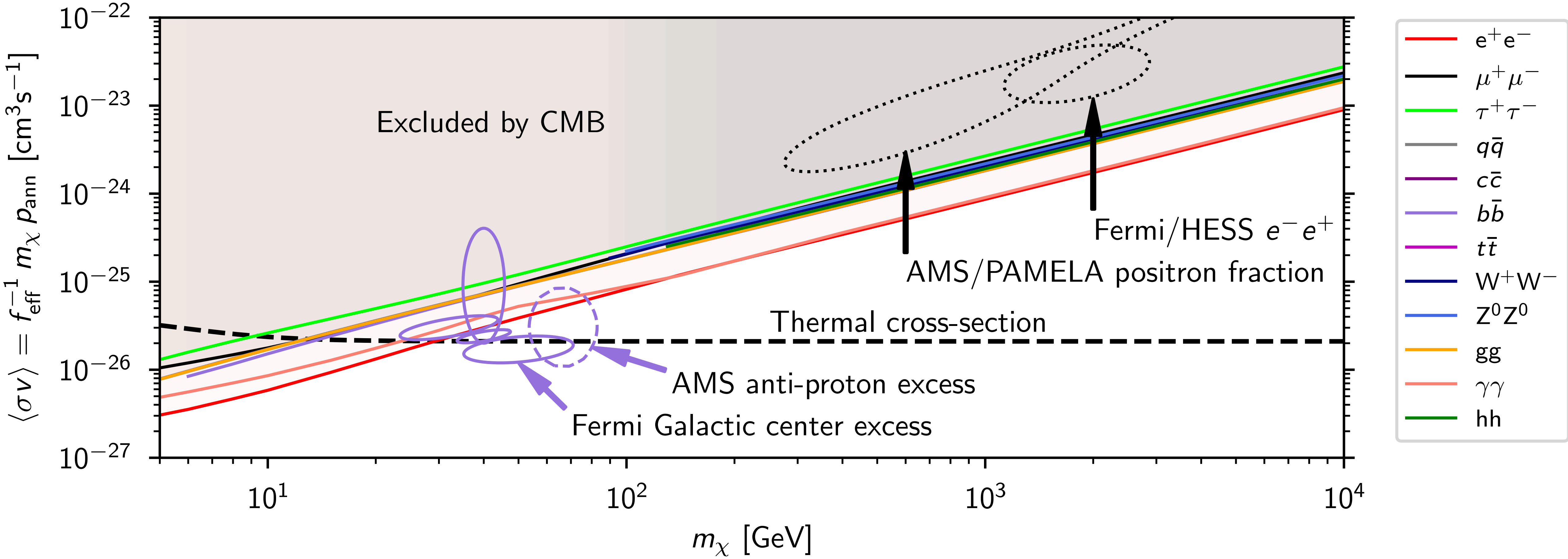


Thermal freeze-out

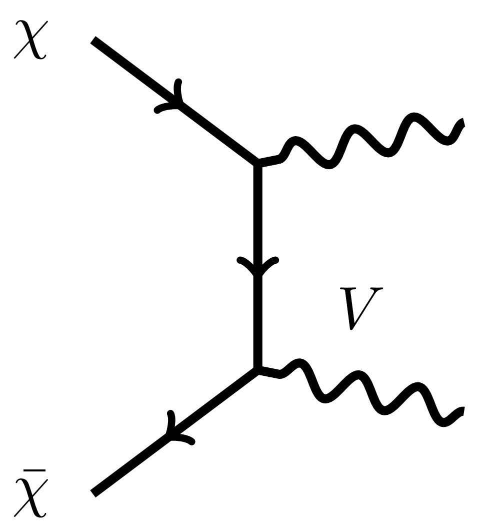
Target annihilation cross section



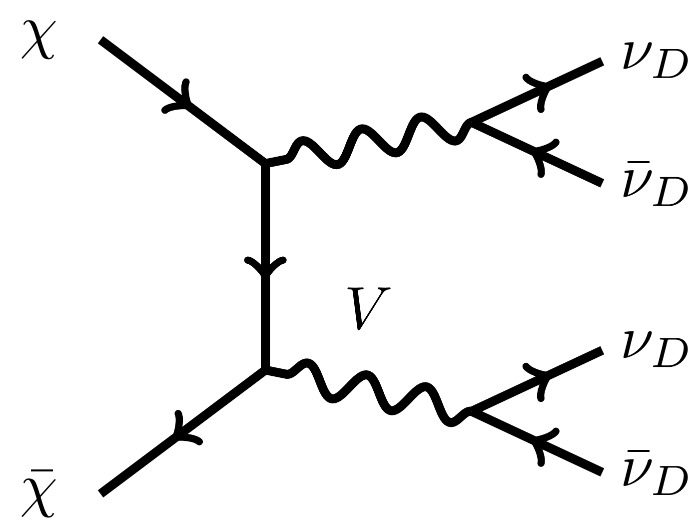
Thermal relic DM with s-wave annihilation to SM states (except νν) is strongly constrained by CMB bounds m < 10 GeV

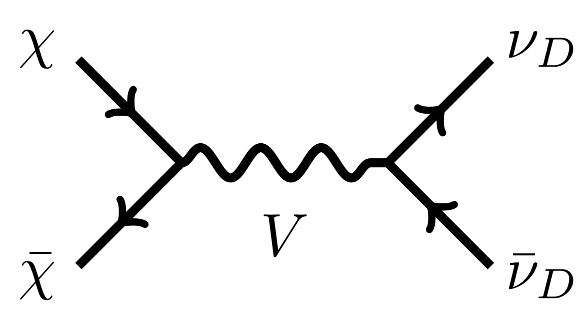
Thermal freeze-out

- Secluded sectors



$m_\chi > m_V,\ m_V \ll \mathrm{eV}$





$m_\chi > m_V > 2m_{\nu_D},\ m_{\nu_D} \ll \mathrm{eV}$

Annihilation to mediator *V* is not sufficient, if mediator decays to SM products. Need to dump energy into dark radiation.

Thermal freeze-out

- Asymmetric dark matter

- Complex scalar DM with vector mediator (p-wave)

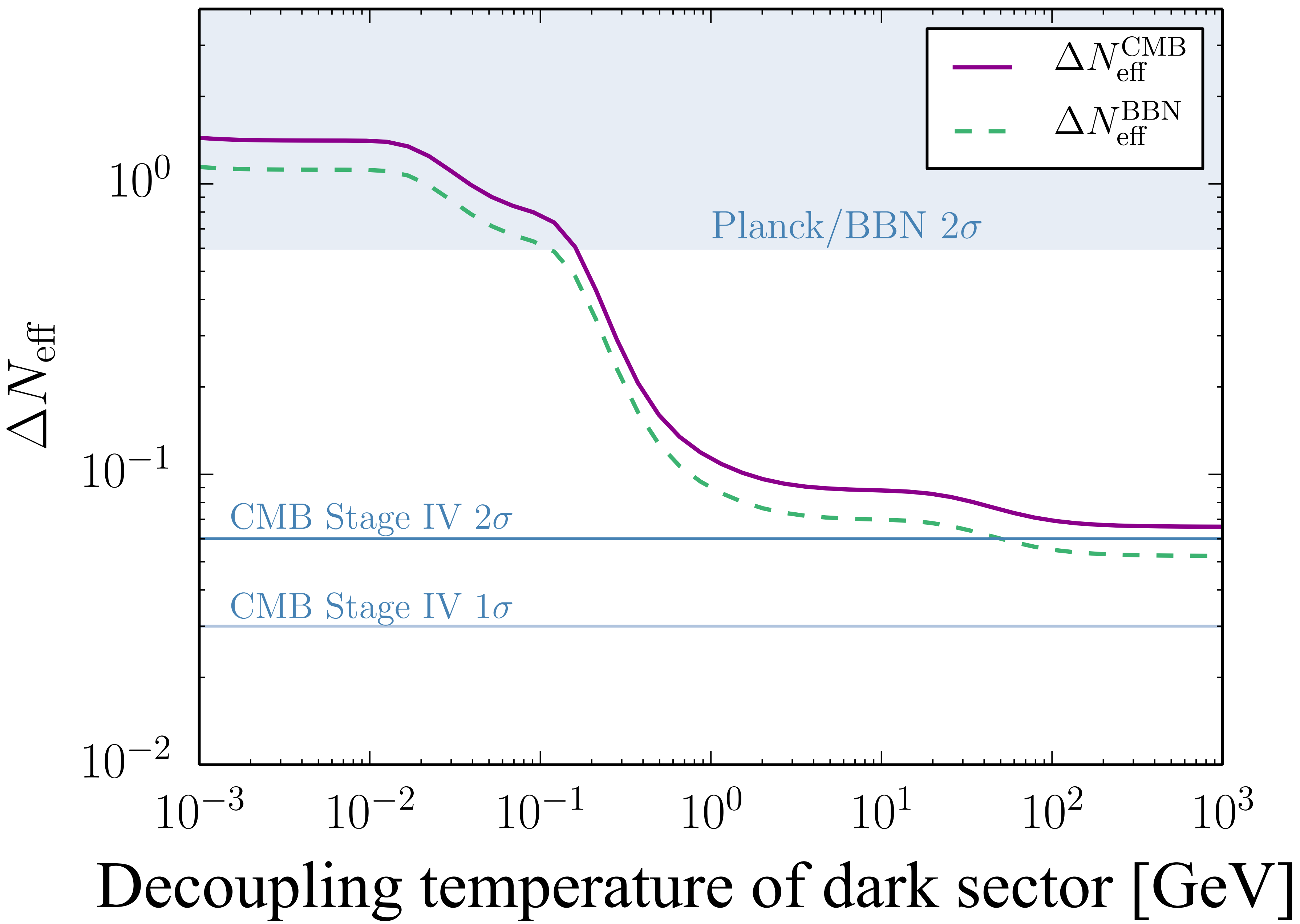
$$g_\phi V^\mu \left(i\phi^* \partial_\mu \phi + \text{h.c.}\right) + g_f V^\mu \bar{f}\gamma_\mu f \quad \longrightarrow \quad \langle \sigma v \rangle_{\phi\phi^* \to \bar{f}f} = \frac{1}{6\pi} \frac{g_\phi^2 g_f^2 m_\phi^2 v_{\text{rel}}^2}{(4m_\phi^2 - m_V^2)^2 + m_V^2 \Gamma_V^2}$$

- Kinematic suppression at CMB epoch (and today) from inelastic splittings, etc.

So we're good at hiding visible products of DM annihilation…

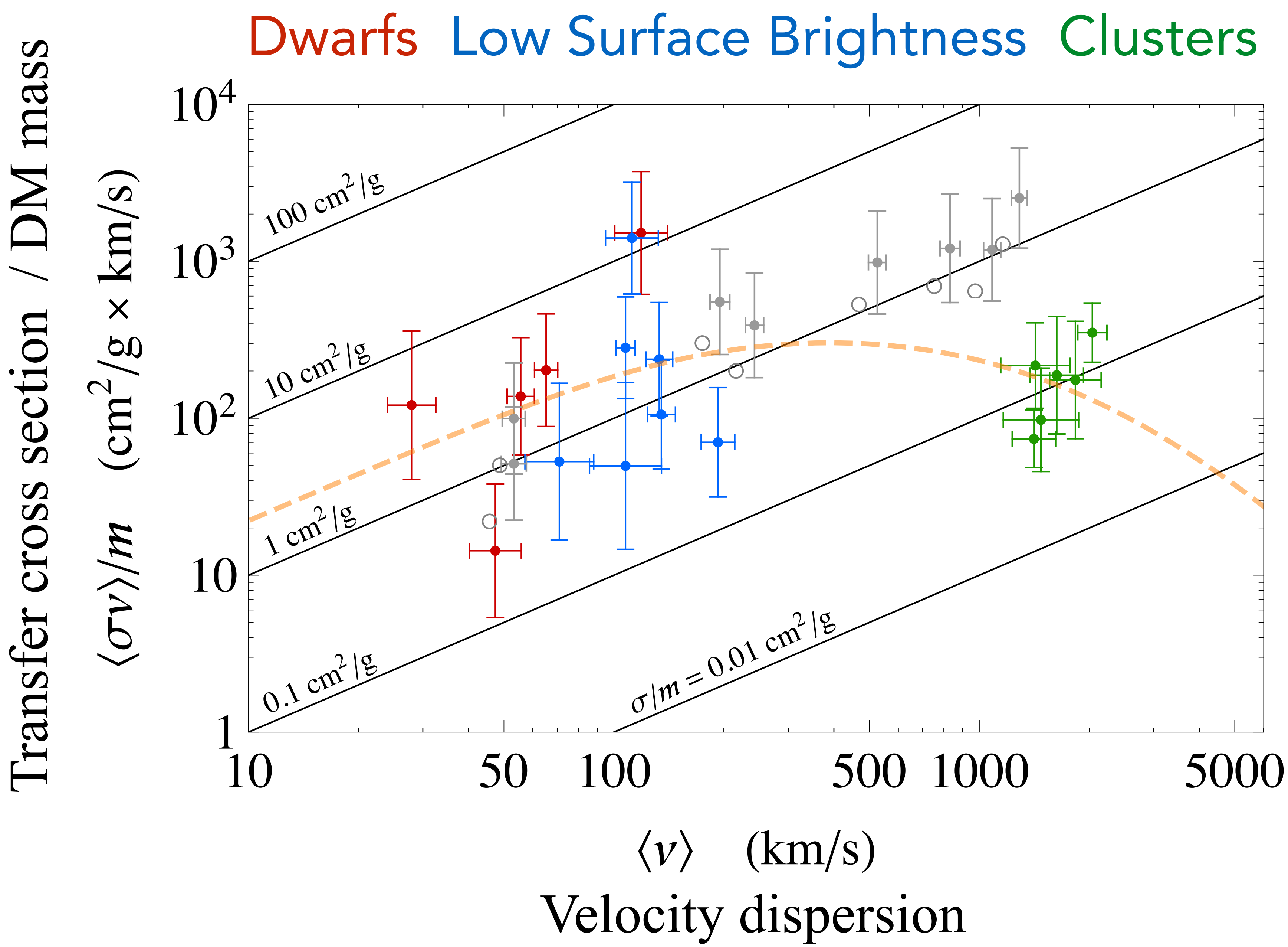
Cosmology of light DM

sub-GeV dark sectors contribute to relativistic degrees of freedom



See also Green and Rajendran 2017

Self-interactions



Low-mass dark sectors also affect late-time gravitational clustering on small scales.

$$\Gamma \approx \frac{\rho_{\rm DM}}{m_\chi}\sigma v \approx \frac{1}{10^9\ \rm year}$$

From Kaplinghat, Tulin, Yu 2015

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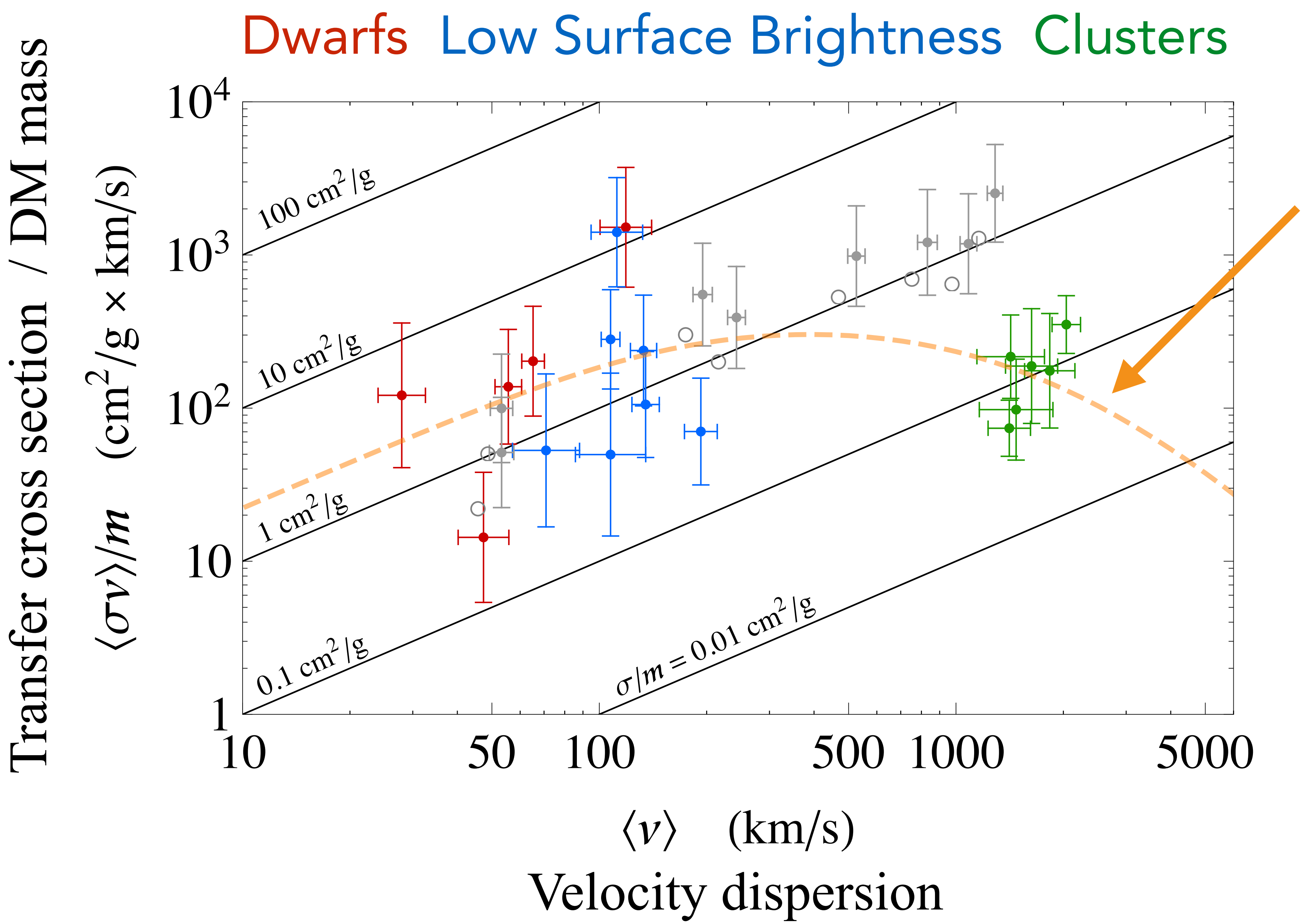

Fit to data with
$m_\chi = 15$ GeV
$m_V = 17$ MeV

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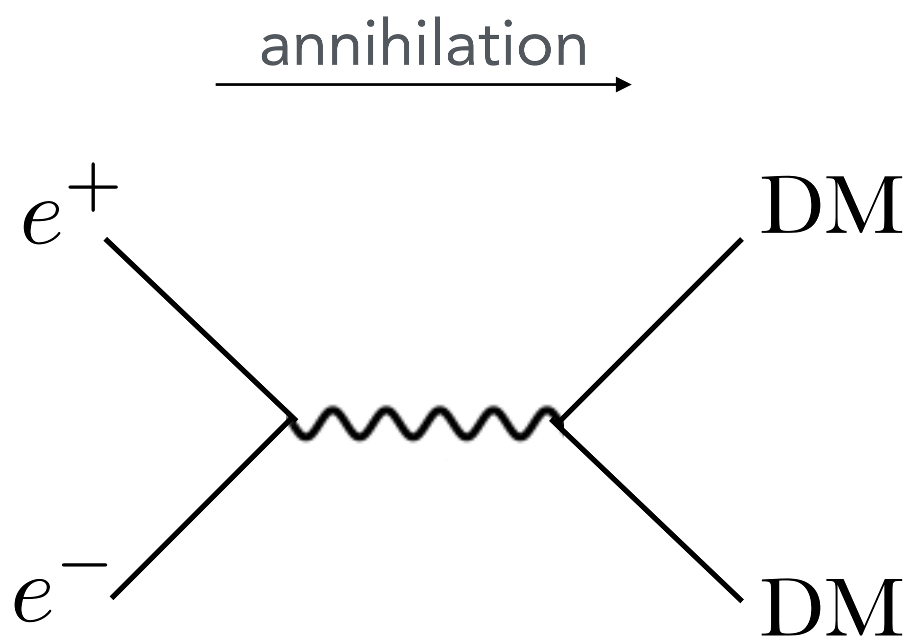
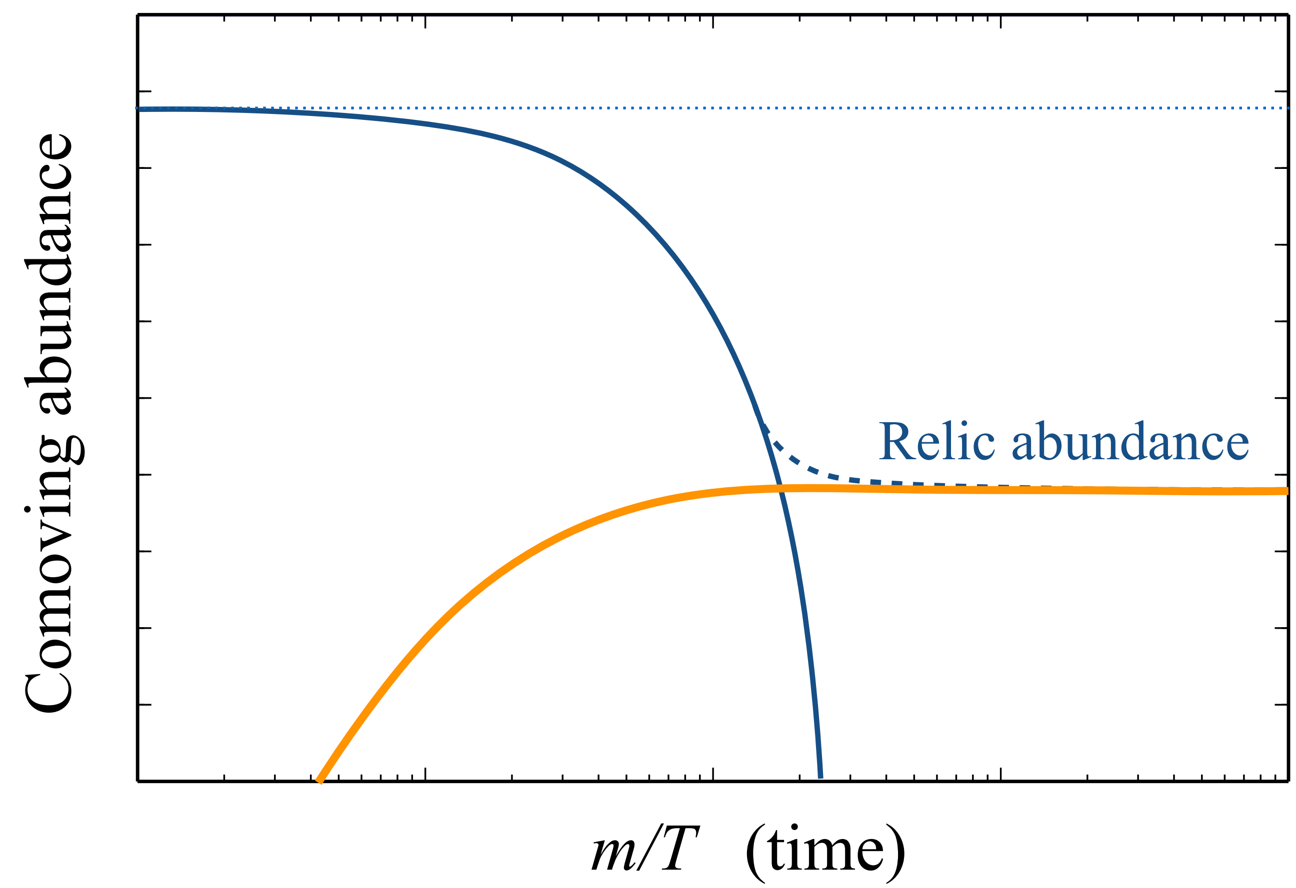
Freeze-in

Not just thermal freeze-out for light DM!



See also: sterile neutrino



Dark matter *only* populated by out-of-equilibrium annihilations of SM into dark sector

Dodelson and Widrow 1993
Hall et al. 2009
Chu, Hambye, Tytgat 2011
Essig, Mardon, Volansky 2011
Bernal et al. 2017 (review)

Freeze-in

UV freeze-in: $$Y_{\rm DM} \sim \frac{\Gamma}{H} \simeq \frac{\alpha_f \alpha_X T^3 M_{\rm pl}}{\Lambda^4}$$

Dominated by highest temperatures, reheating

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Dominated by lowest temperatures (m_f or m_{DM})

For correct relic abundance: $$g_X g_f \sim 10^{-12} \times \min(1, \sqrt{m_f/m_{\rm DM}})$$

Freeze-in through a light mediator reproduces some appealing features of thermal freeze-out. Is it testable? (Talk 2)

Predictions & signatures for light DM

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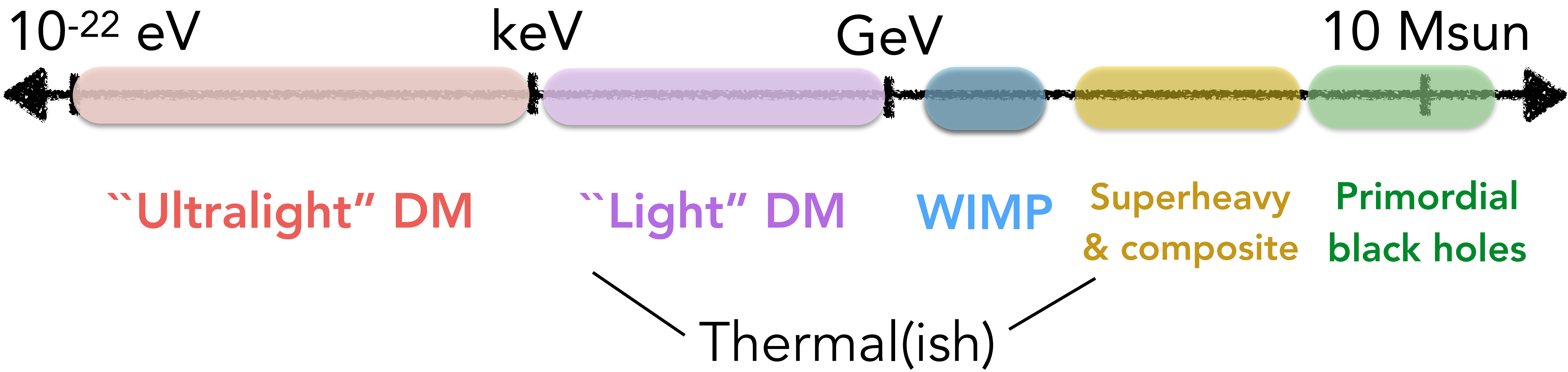
- Effects of asymmetric dark matter on dense environments & stellar astrophysics?

- Laboratory signatures of dark sectors (next talks)? How well do we understand backgrounds?

Conclusions



Is dark matter structure on small scales described by CDM?

What particle properties of DM are detectable with next generation of astro/cosmo observations? Lab-based experiments?

What other classes of candidates are we not considering?

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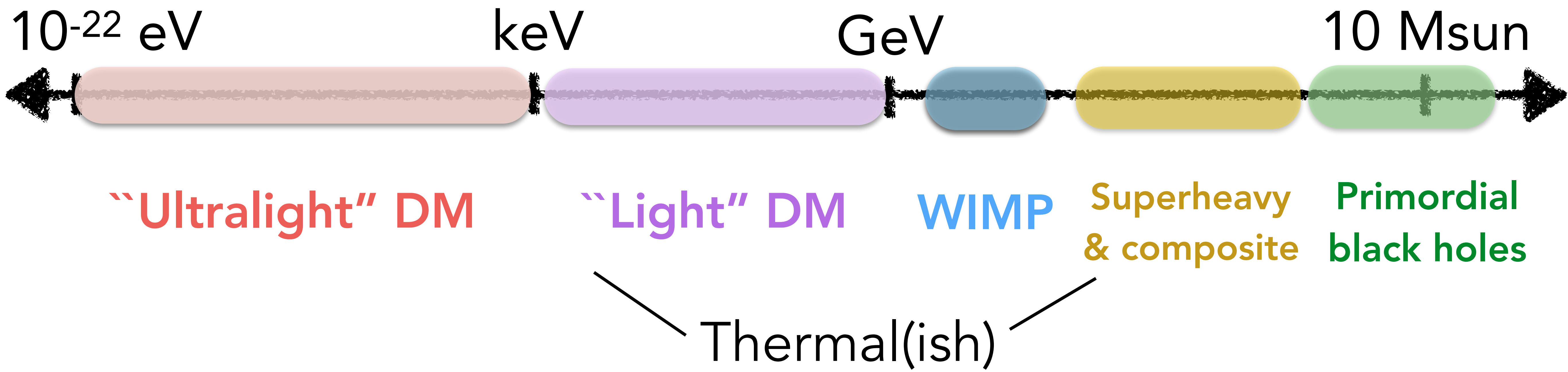

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Light dark matter offers opportunity to test broad class of thermal scenarios in the near future.