Dark Matter Theory Overview

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Topics in Astroparticle and Underground Physics
Laurentian University, Sudbury
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Outline

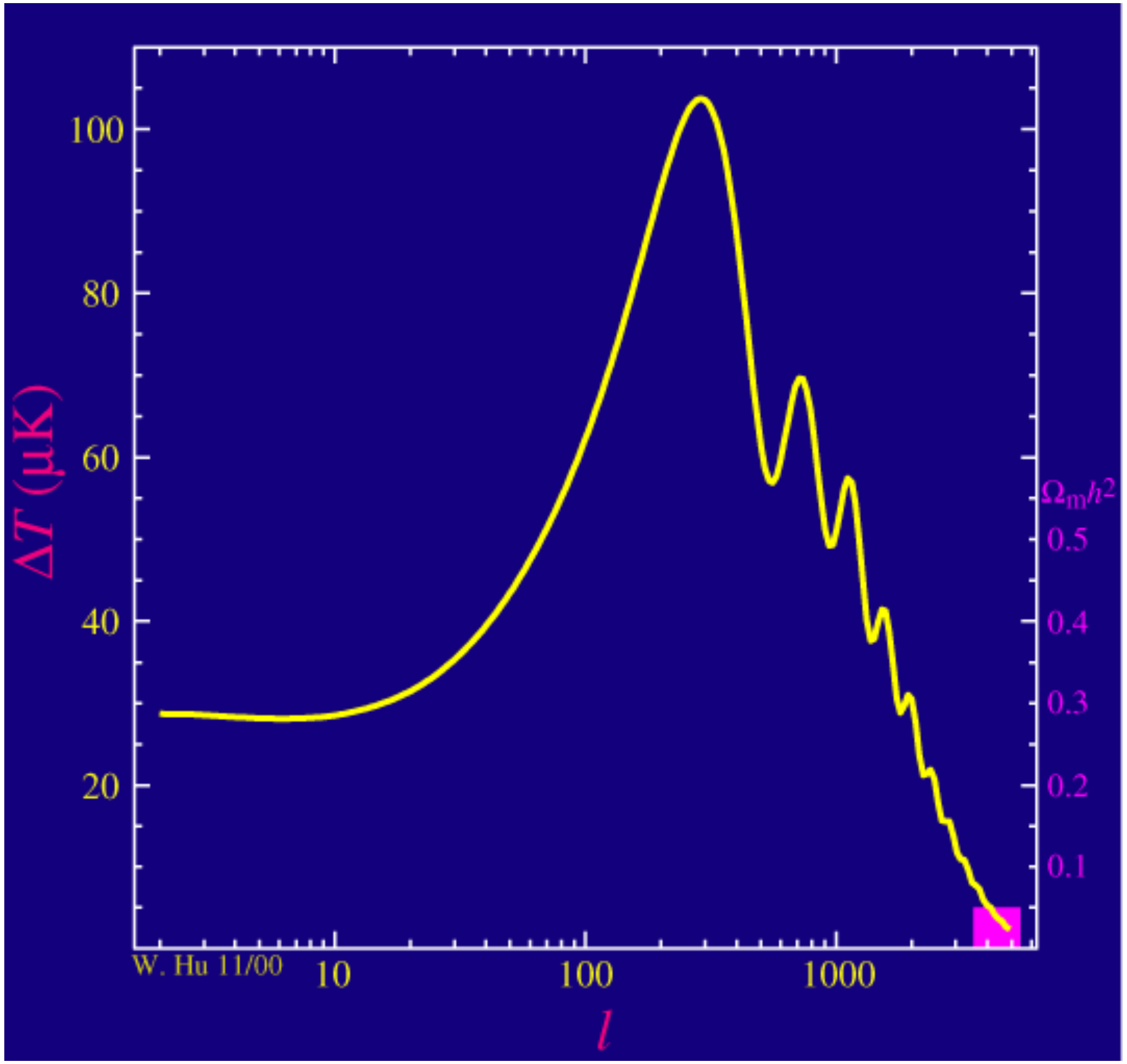
Disclaimer: this is a broad overview + survey of selected topics, not a comprehensive review!

- The parameter space of possible dark matter models
- Thermal freezeout as a benchmark
  - Where do WIMPs stand?
  - Thermal relics beyond the weak scale
  - General constraints on thermal scenarios
- Beyond the thermal regime: light bosonic dark matter
- Primordial black holes as dark matter

What is dark matter?

We know it:

- Is roughly 80% of the matter in the universe.
- Isn't made up of any known particle (e.g. protons, electrons).
- Has mass (and hence gravity).
- Doesn't scatter/emit/absorb light (really "transparent matter"!)
- Interacts with other particles weakly or not at all (except by gravity).



Wayne Hu, http://background.uchicago.edu/~whu

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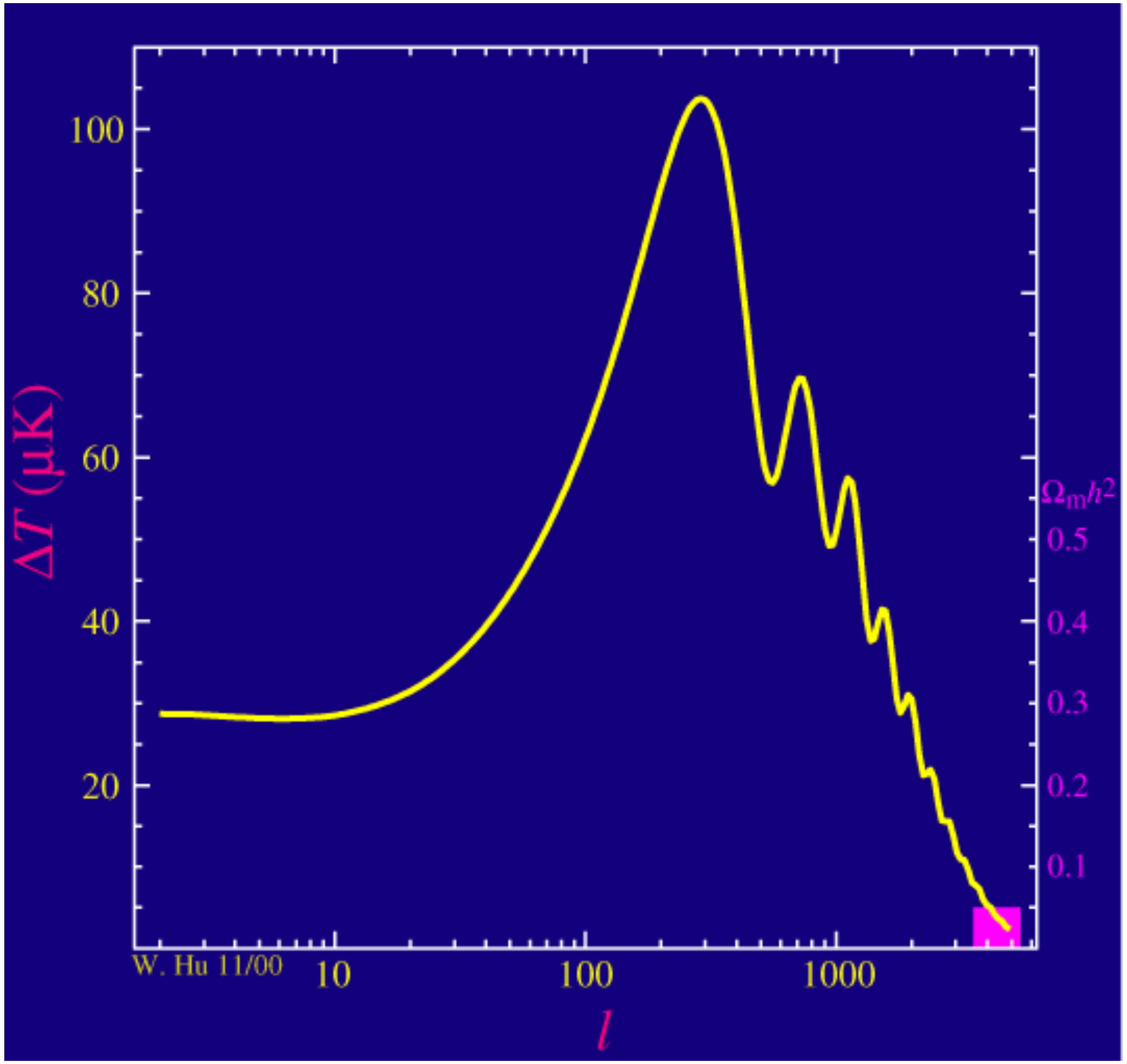

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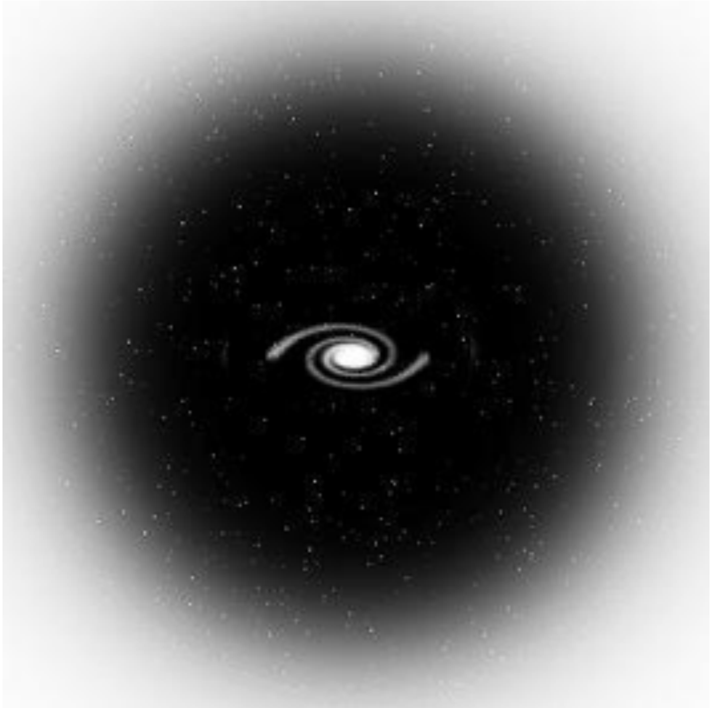

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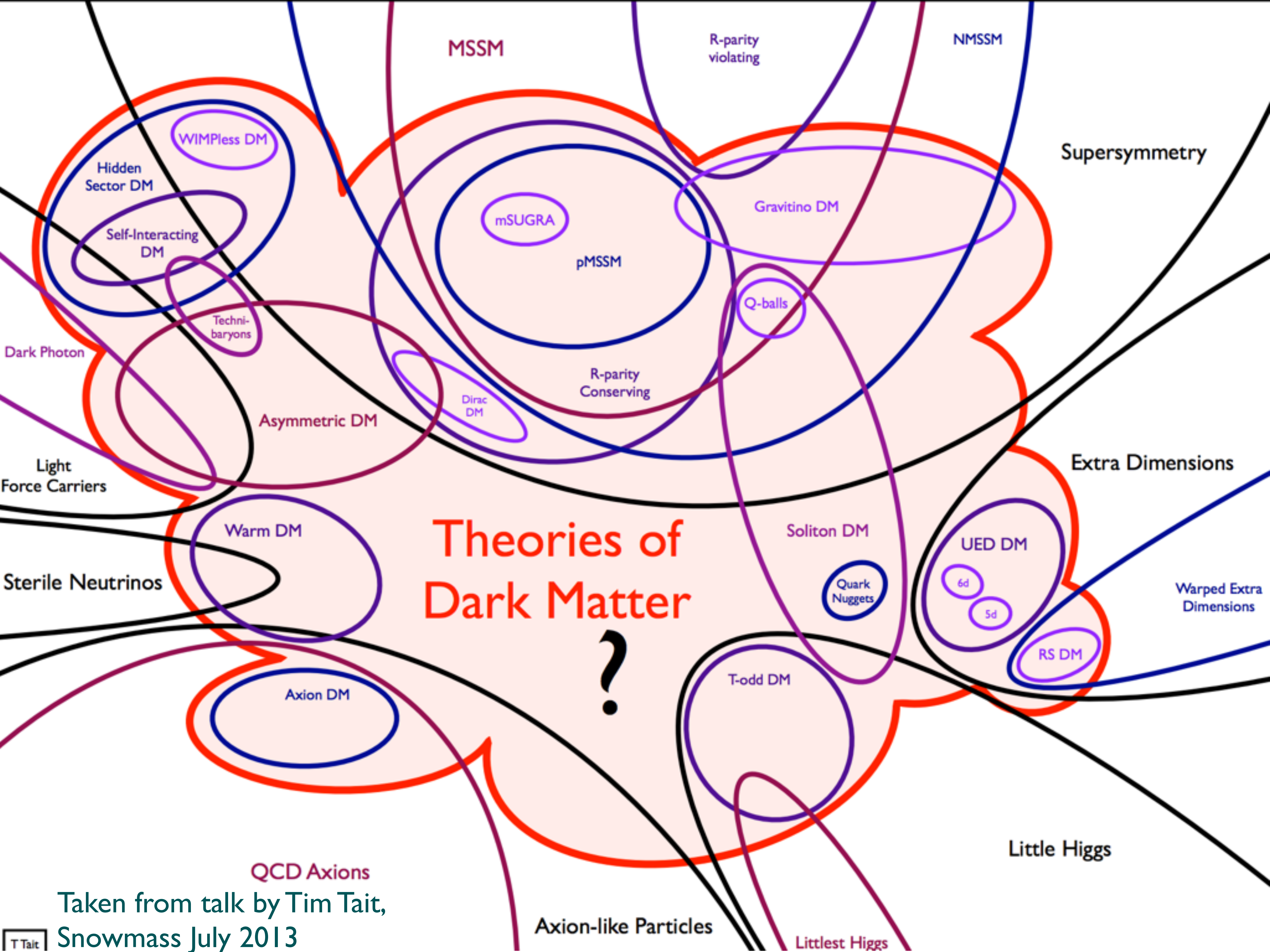
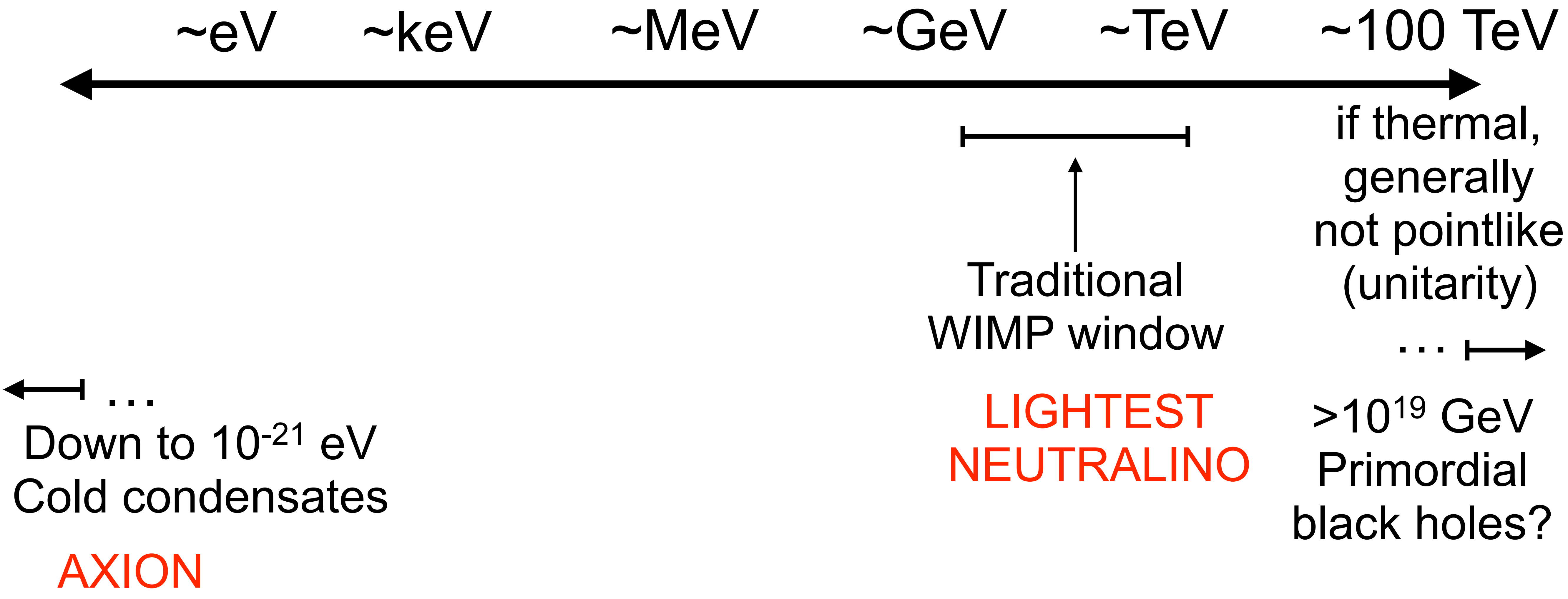


Taken from talk by Tim Tait, Snowmass July 2013

Dark matter mass scales



~eV ~keV ~MeV ~GeV ~TeV ~100 TeV

if thermal,
generally
not pointlike
(unitarity)

Traditional
WIMP window

LIGHTEST
NEUTRALINO

…

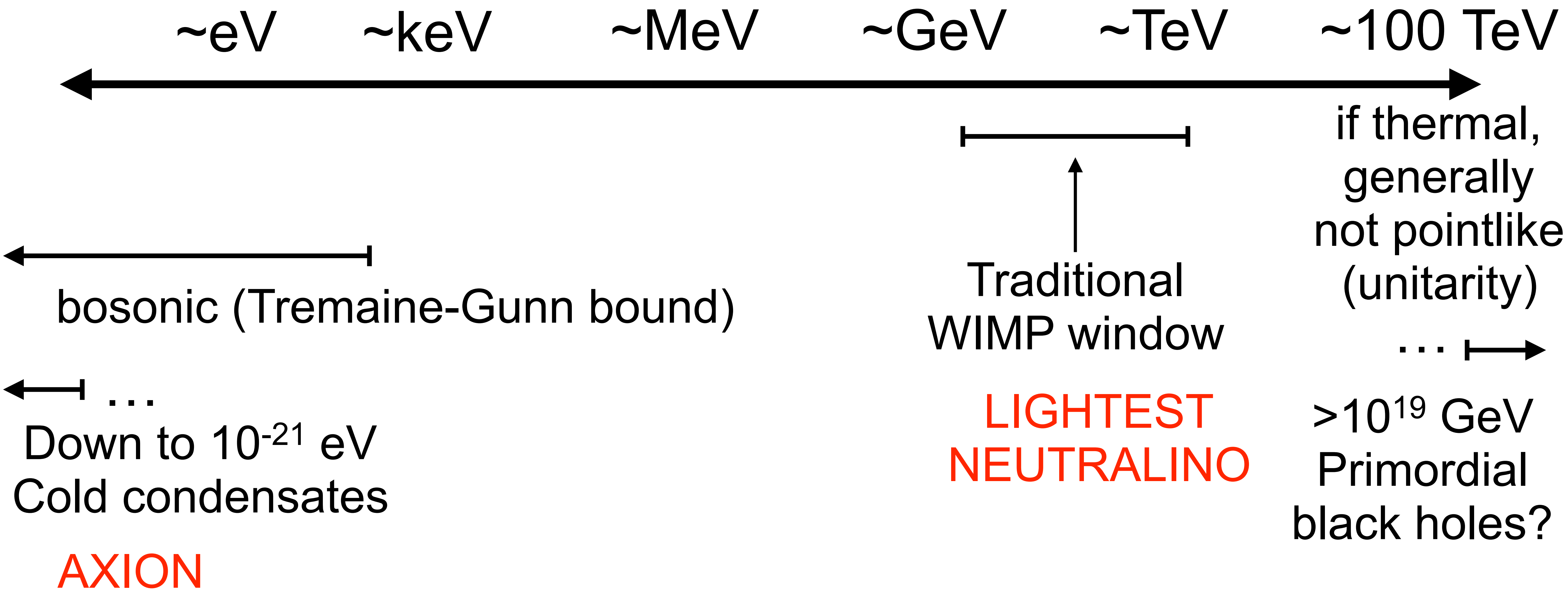
$>10^{19}$ GeV
Primordial
black holes?

…

Down to 10^{-21} eV
Cold condensates

AXION

Dark matter mass scales



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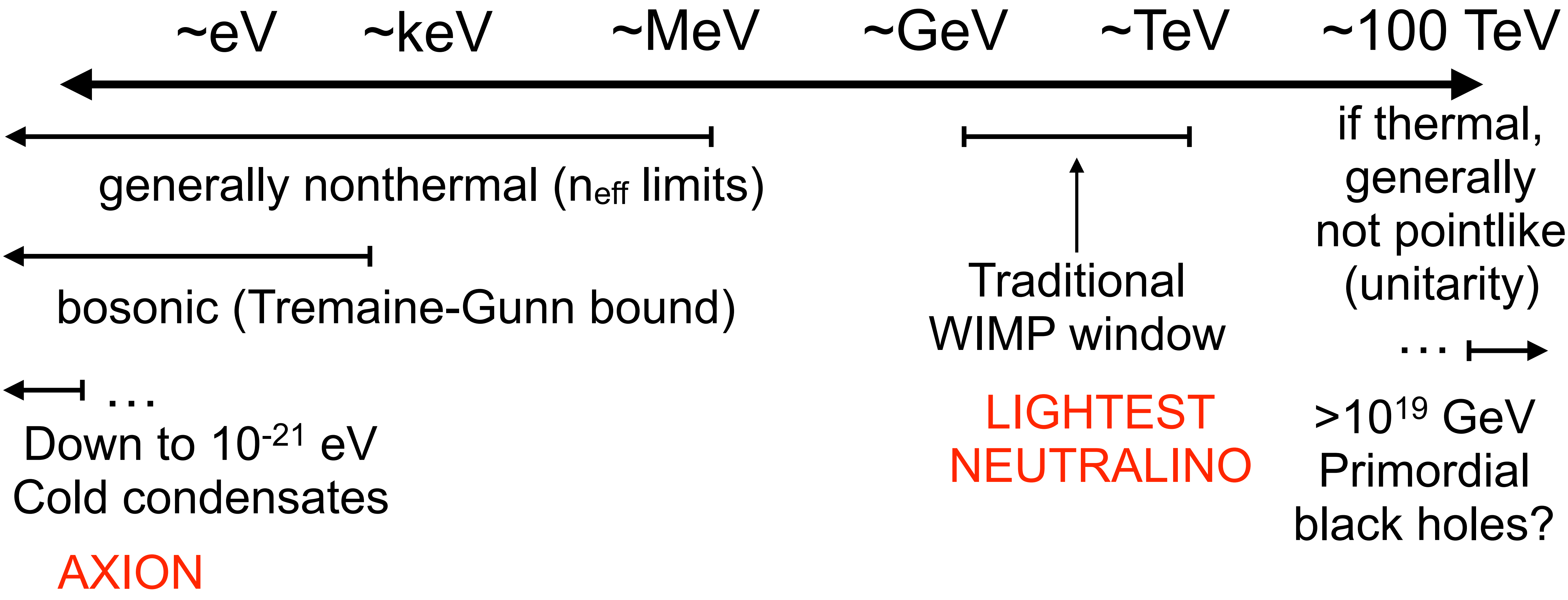

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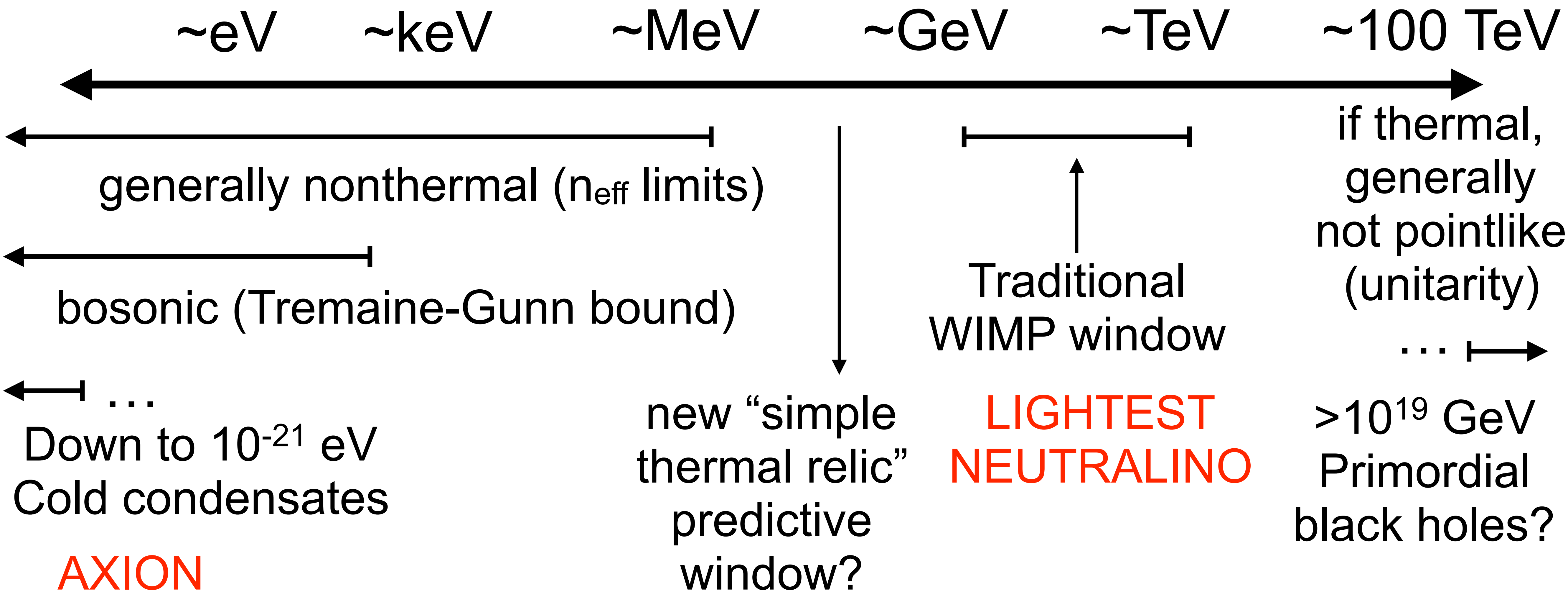

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new “simple
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Thermal freezeout

- In the early universe, suppose DM & Standard Model (SM) particles are in thermal equilbrium.
- DM can annihilate to SM particles, or SM particles can collide and produce DM.

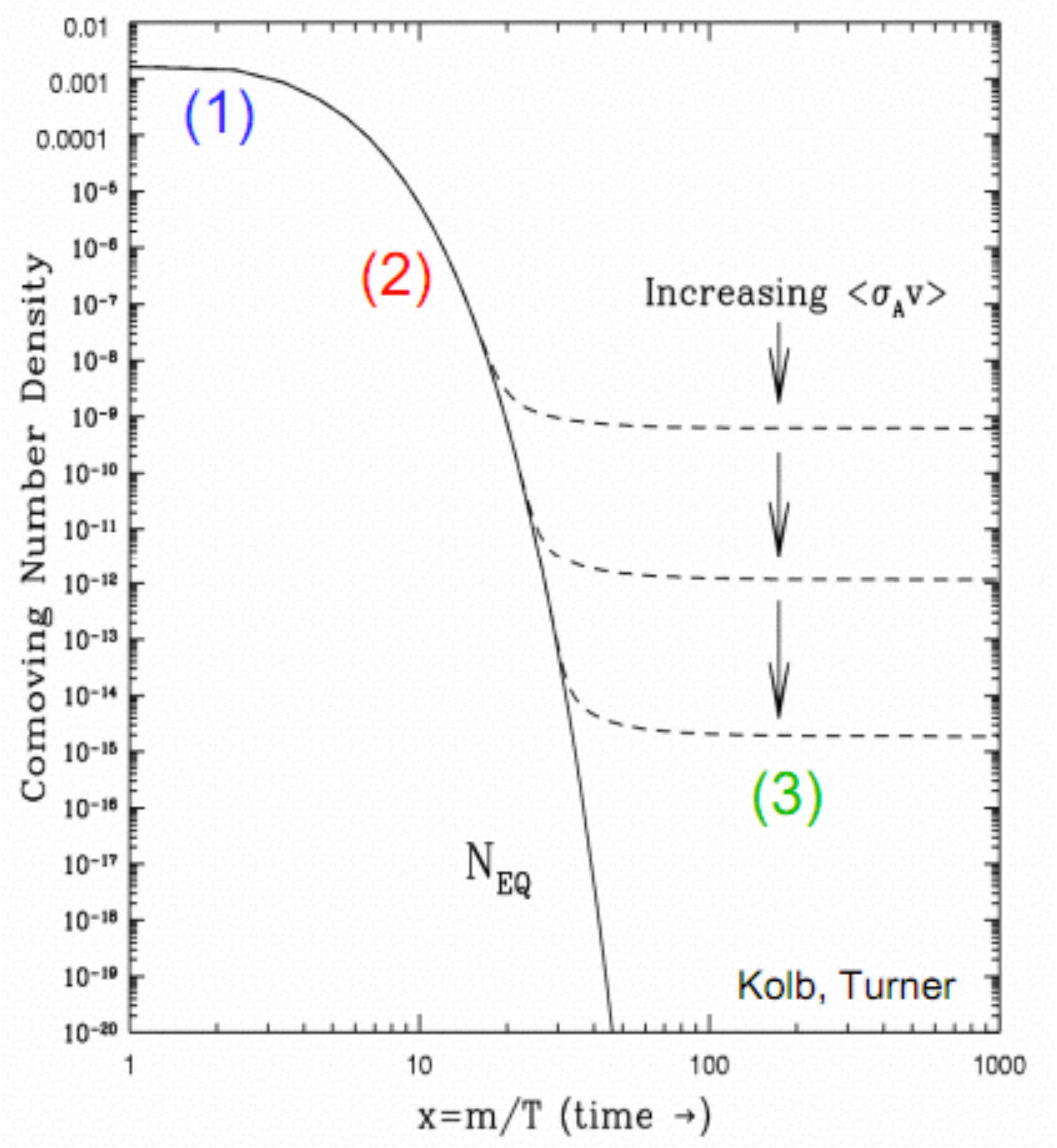
$$\chi\chi \leftrightarrow \mathrm{SM}\,\mathrm{SM} \quad (1)$$

- Temperature(universe) < particle mass => DM can still annihilate, but can't be produced.

$$\chi\chi \rightarrow \mathrm{SM}\,\mathrm{SM}$$
$$\chi\chi \not\leftarrow \mathrm{SM}\,\mathrm{SM} \quad (2)$$

- Abundance falls exponentially, cut off when timescale for annihilation ~ Hubble time. The comoving dark matter density then <u>freezes out</u>.

$$(3)$$



The WIMP miracle

$$n_f \langle \sigma v \rangle \sim H \sim T_f^2 / m_{\rm Planck} \sim m_\chi^2 / m_{\rm Planck}$$

$$n_f = \rho_f / m_\chi \sim (m_\chi / T_{\rm eq})^3 \rho_{\rm eq} / m_\chi \sim m_\chi^2 T_{\rm eq}$$

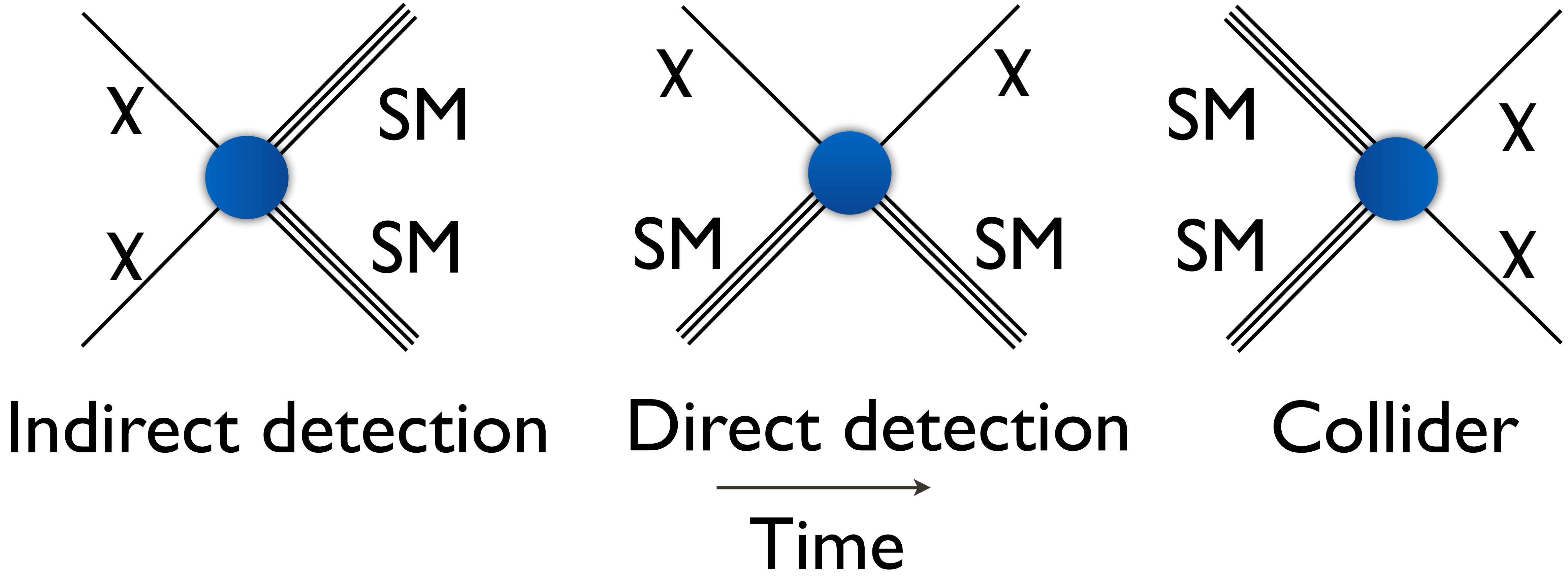
$$\langle \sigma v \rangle \sim \frac{1}{m_{\rm Planck} T_{\rm eq}} \sim \frac{1}{(10^{19}{\rm GeV} \times 1{\rm eV})} \sim \frac{1}{(10^{14}{\rm eV})^2}$$

$$\sim \frac{1}{(100{\rm TeV})^2} \sim \left(\frac{10^{-2}}{1{\rm TeV}}\right)^2 \sim \frac{\alpha^2}{m_\chi^2}$$

- Perturbativity requires DM mass below ~100 TeV (unitarity bound ~200 TeV [von Harling & Petraki '14]). Some caveats exist: e.g. late-time entropy injection can relax bound by many orders of magnitude [Bramante & Unwin '17].

- The thermal cross section is naturally obtained for electroweak-scale couplings and masses - suggests a possible connection to electroweak physics + hierarchy problem.

WIMP searches



- Indirect detection: look for SM particles - electrons/positrons, photons, neutrinos, protons/antiprotons - produced by DM interactions.

- Direct detection: look for Standard Model particles recoiling from collisions with invisible dark matter.

- Colliders: produce DM particles in high-energy collisions and look for missing energy (e.g. at the LHC), or search for new light dark-sector particles.

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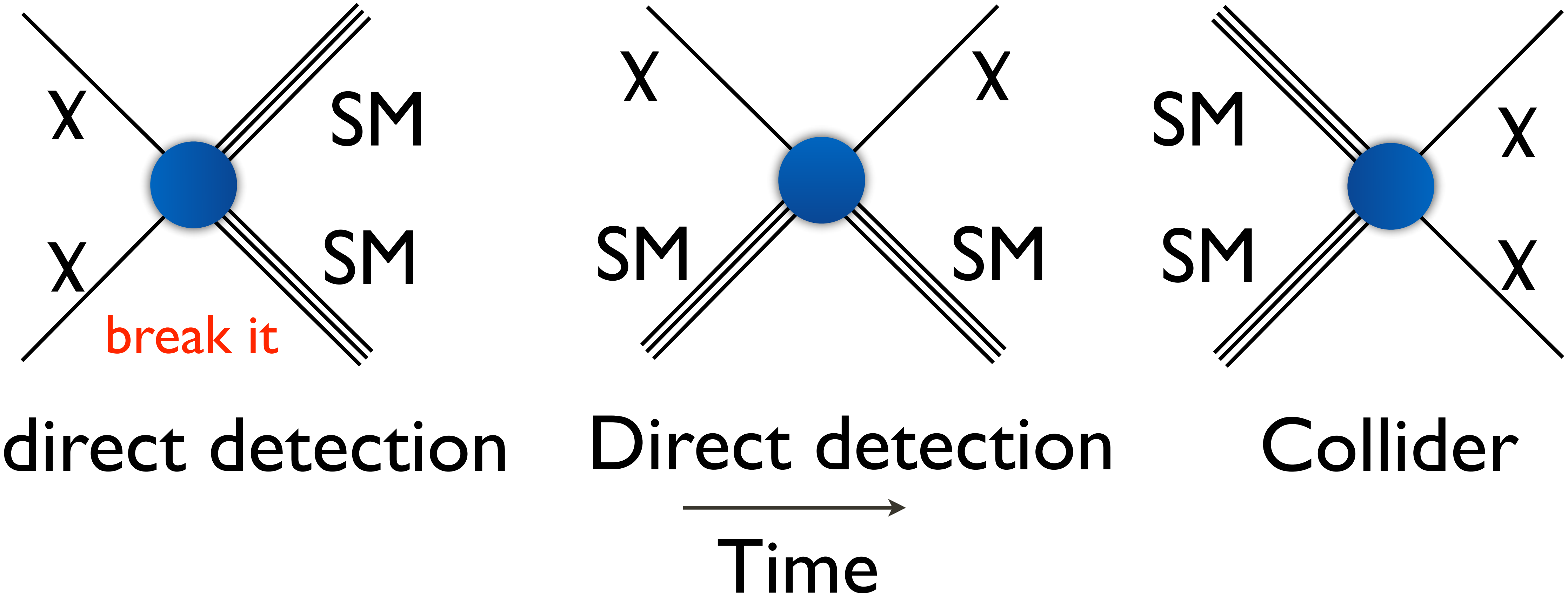

Indirect detection

Direct detection

Collider

Time

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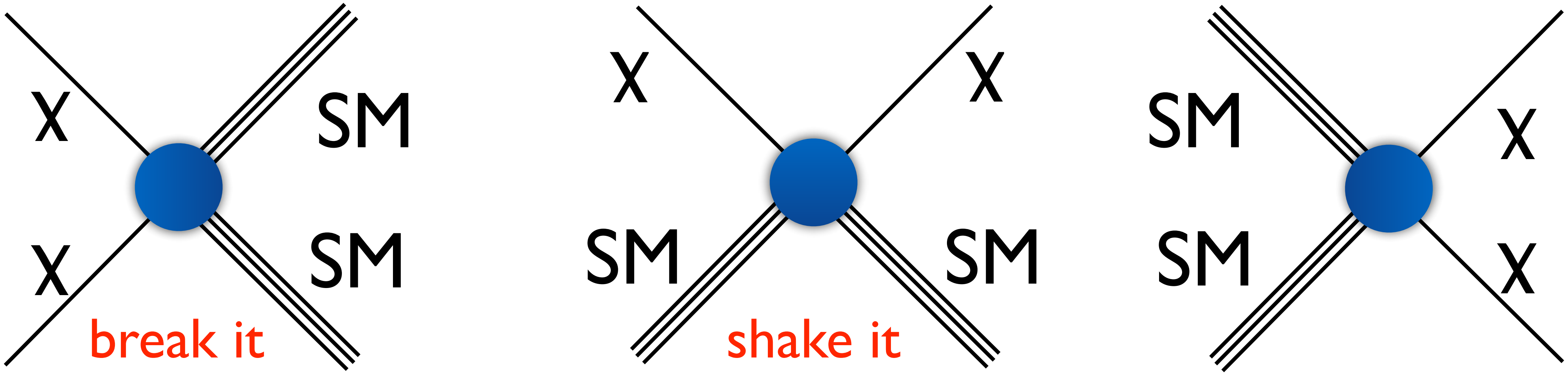

Indirect detection   Direct detection   Collider

→

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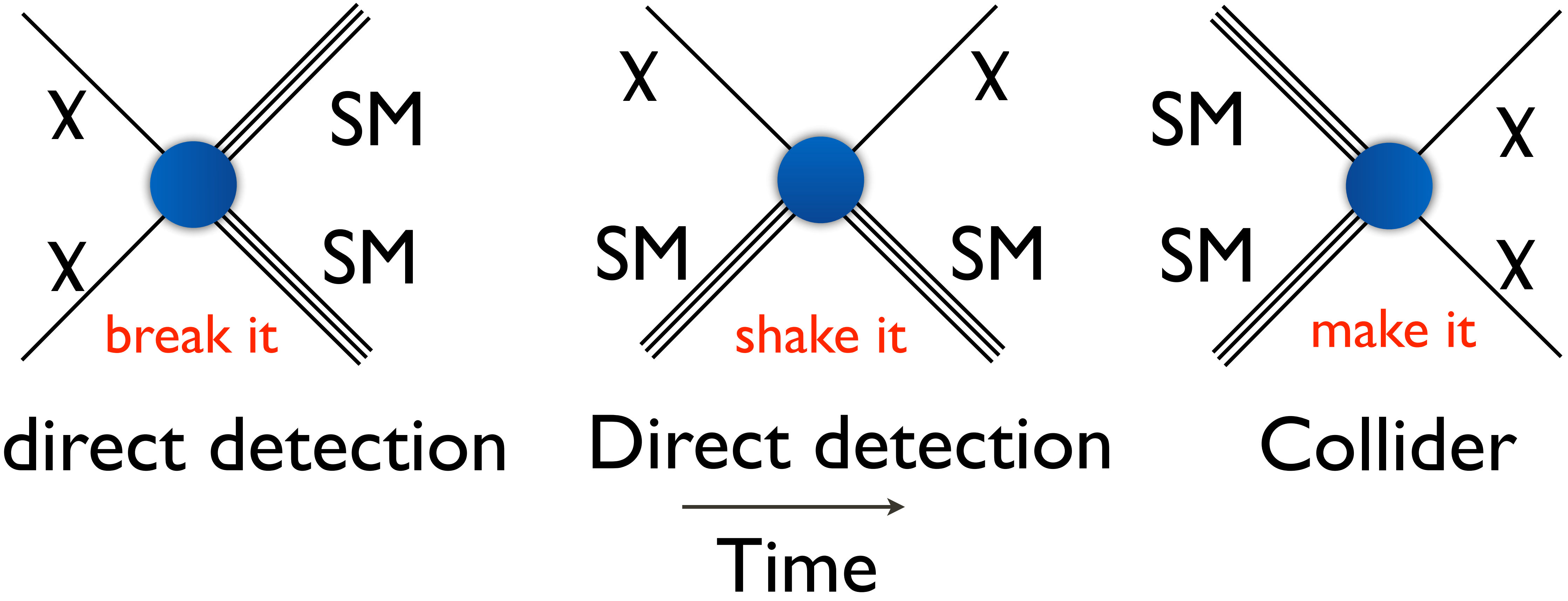

Indirect detection Direct detection Collider

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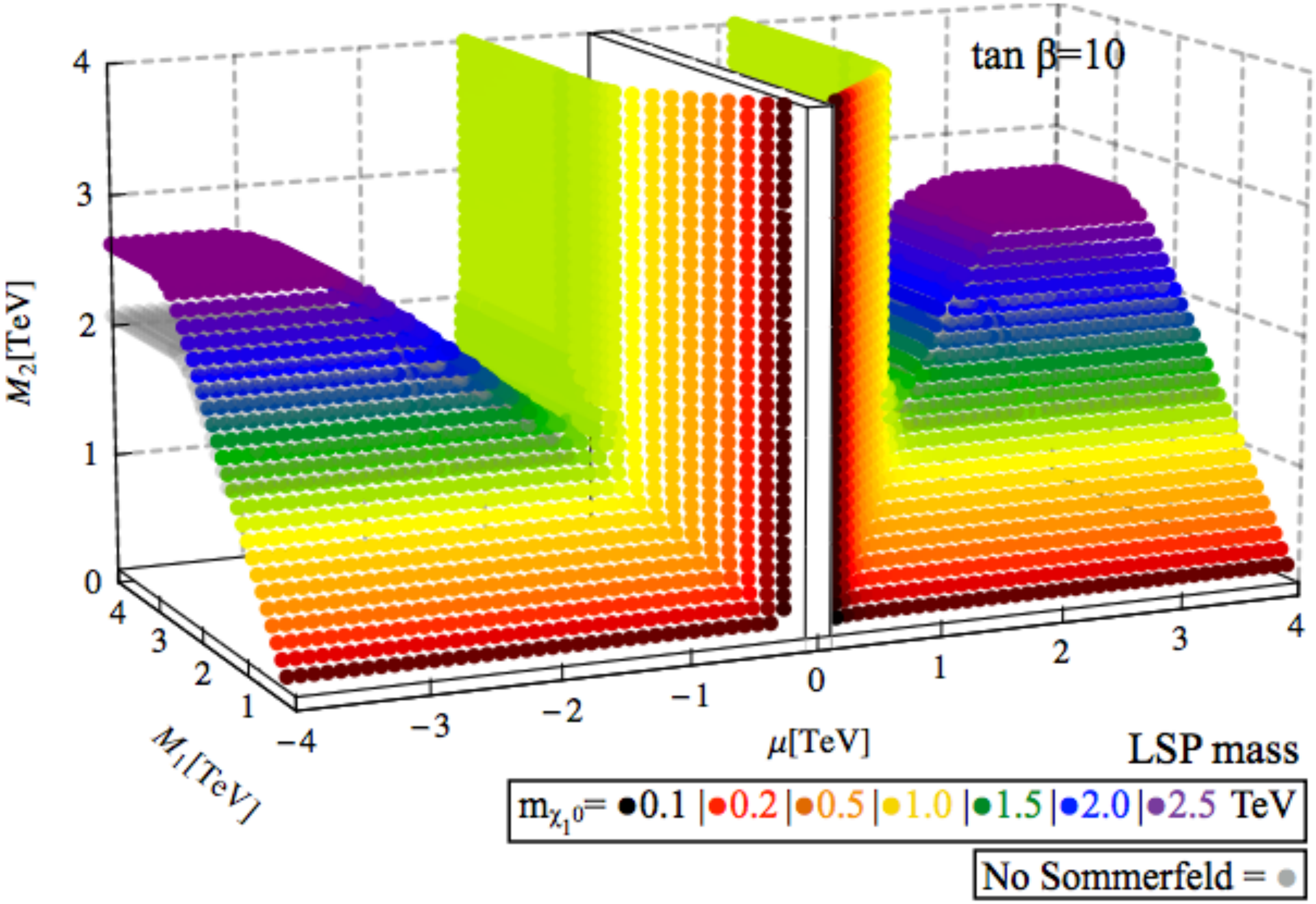
WIMPs under threat?

- No detection (yet) of new weak-scale physics at the LHC.
- No detection (yet) of WIMPs in direct or indirect dark matter searches - direct searches probing cross sections as small as 10^{-46} cm^2 (LUX Collaboration ’17).
- Can we exclude thermal relic dark matter where:
  - The DM transforms under the gauge groups of the Standard Model, or
  - The DM simply has roughly weak-scale masses and couplings?

Example: the lightest SUSY neutralino

- In supersymmetric models, lightest superpartner (LSP) is stabilized by R-parity.
- Typically the LSP is the lightest neutralino - admixture of wino, bino, and higgsino.
- Plot shows “relic density surface” where correct relic density is obtained, in terms of neutralino mass parameters M_1, M_2, μ.
- Here all superpartners except neutralinos and charginos are assumed to be heavy and decouple.



Bramante et al ‘16

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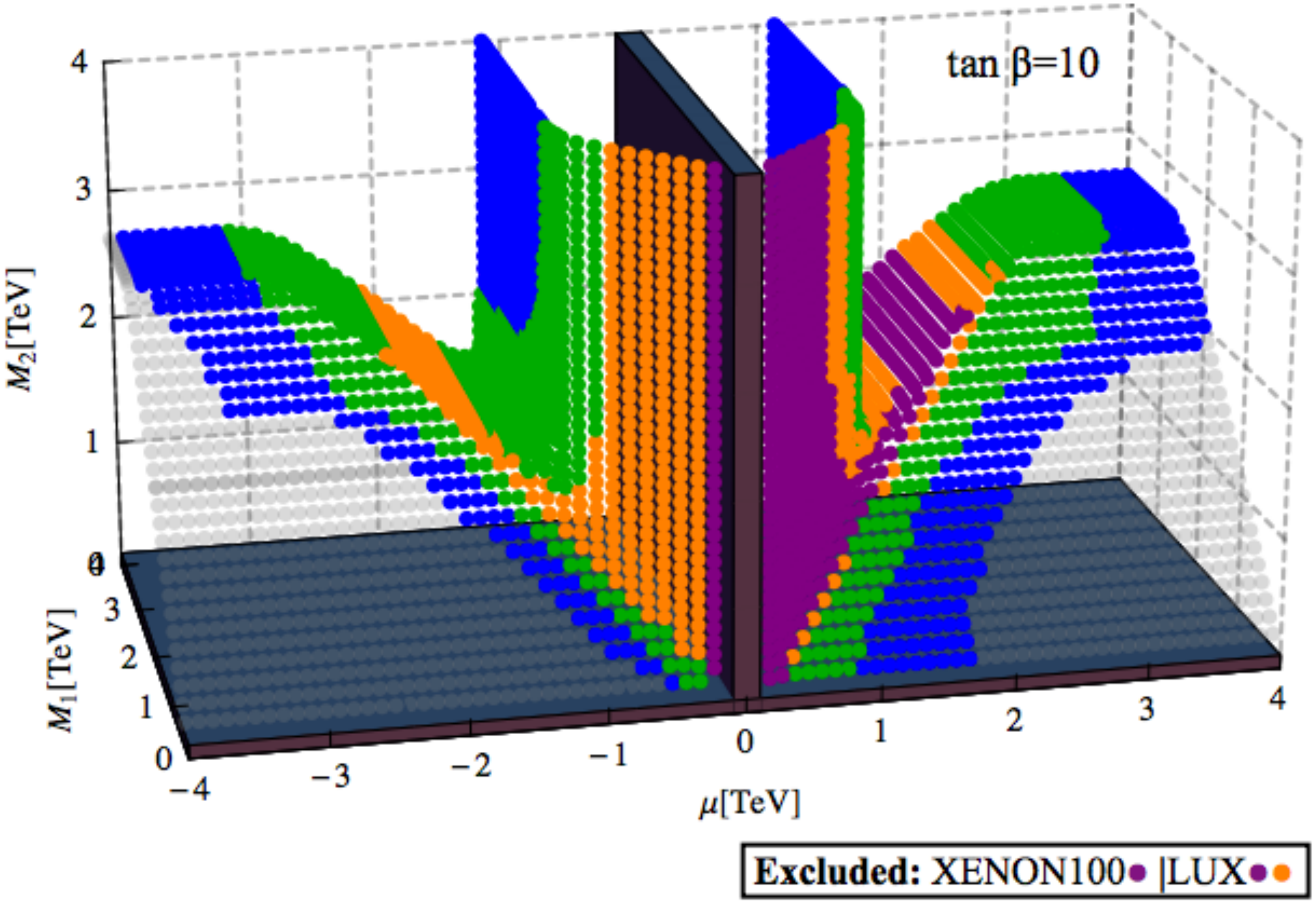
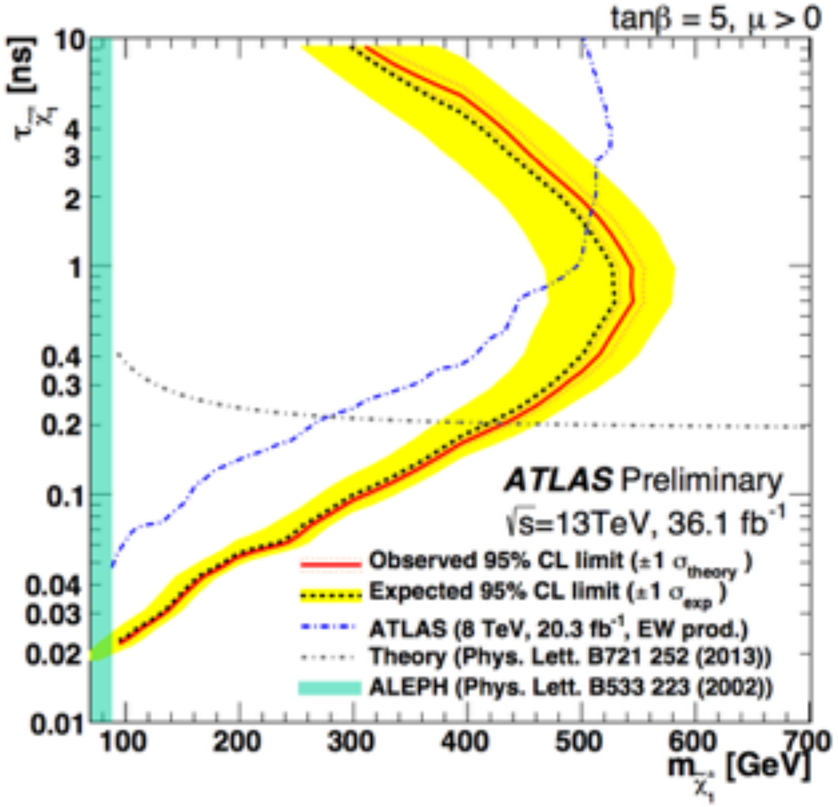


Bramante et al ‘16

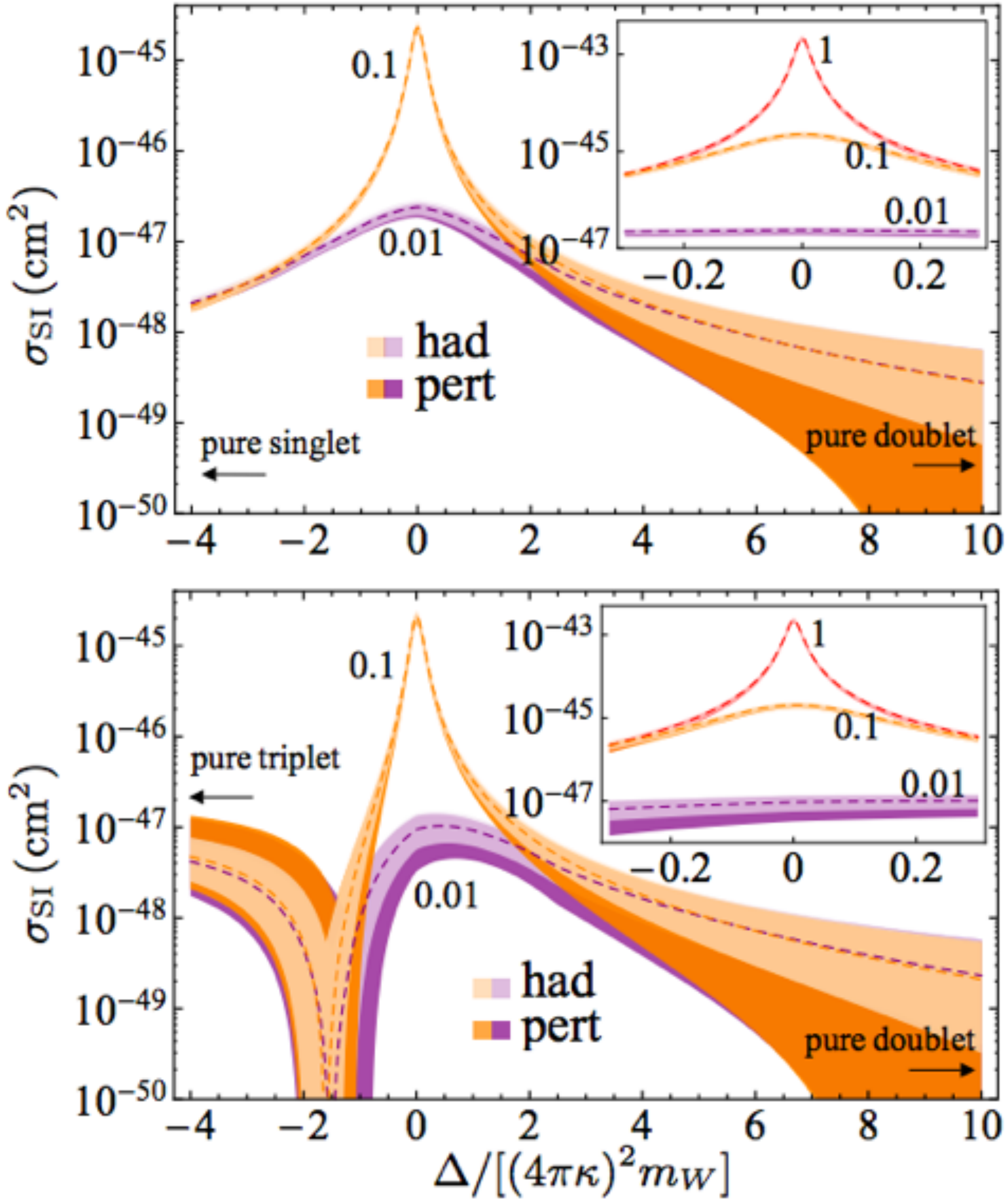
Example: the lightest SUSY neutralino

- Current set of constraints leaves open swathes of parameter space:
  - Pure higgsinos and winos, and much of bino-wino parameter space, still yield predicted DD signals below current limits.
  - Current collider limits on pure winos (higgsinos) only rule out masses below ~400 (~100) GeV [ATLAS-CONF-2017-017, Fukuda et al '17].
  - Heavy winos can be probed by indirect detection, but limits depend on the DM density profile of the Milky Way [e.g. Ovanesyan et al '17].



Limits on wino DM, ATLAS-CONF-2017-017

Hill & Solon '14



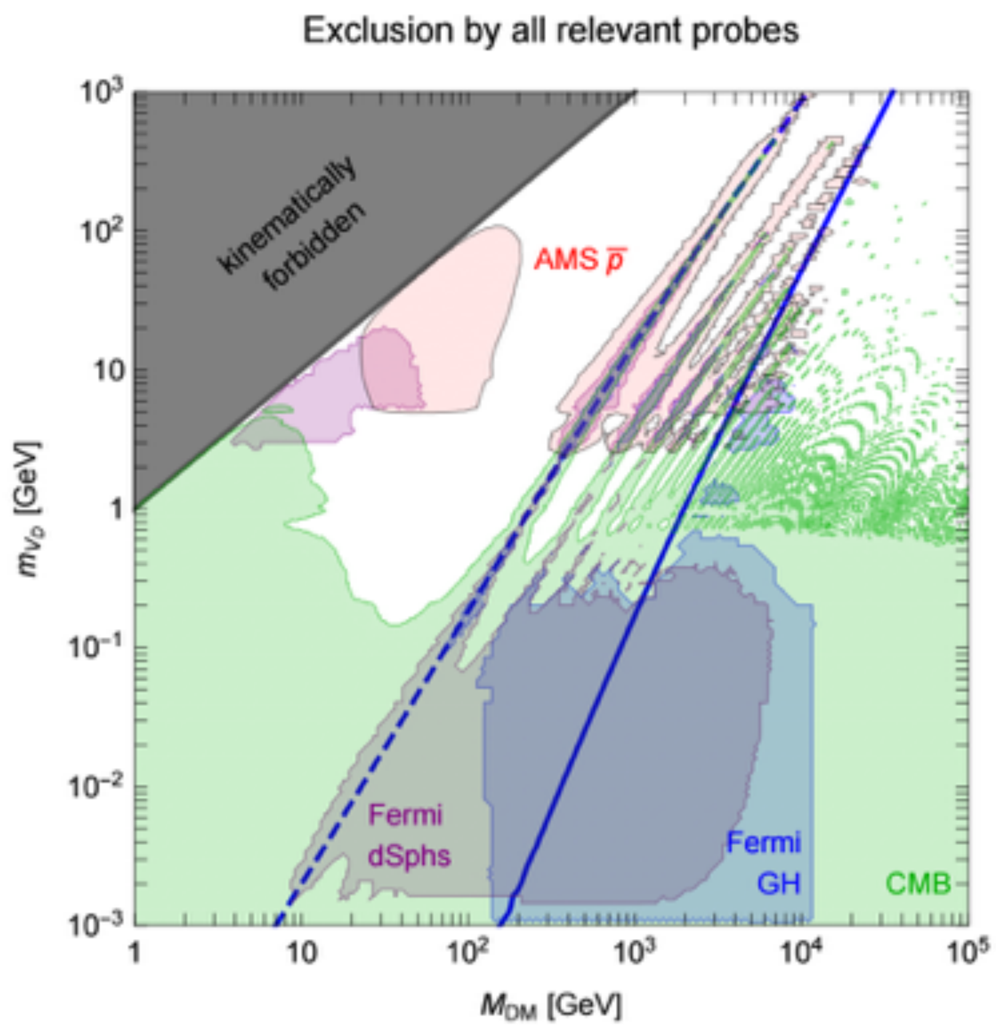
Predictions for direct detection of pure and mixed $SU(2)_L$ DM

Example: dark vector portal

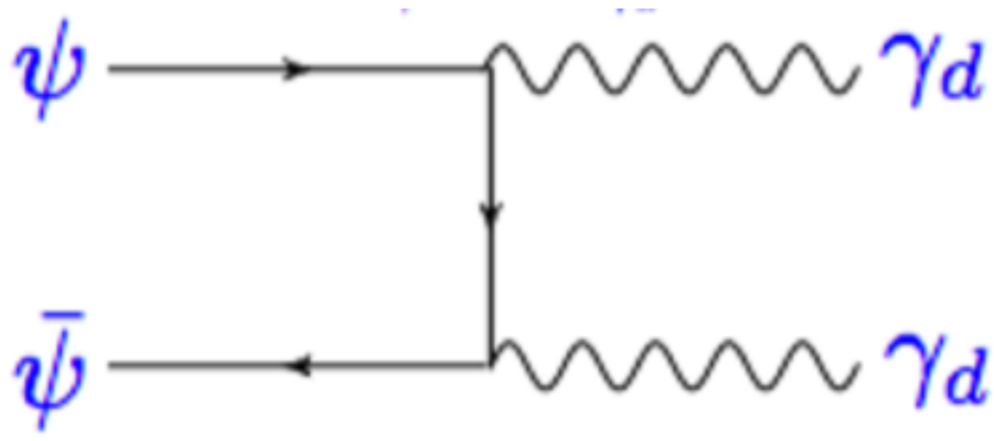
- Dark matter couples to dark photon which mixes slightly with Standard Model photon:

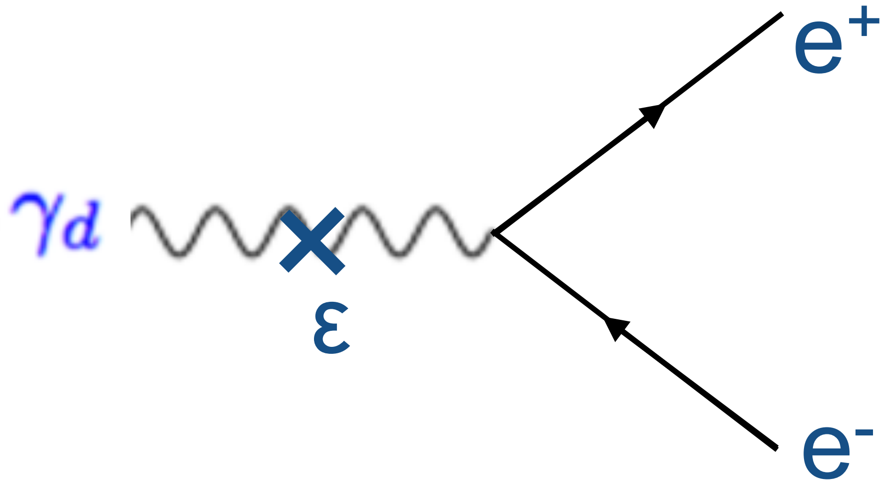
$$\mathcal{L}_{\rm mix} = \frac{\epsilon}{2} F^{\mu\nu} F^D_{\mu\nu}$$

- Direct and collider signatures are suppressed by small mixing.
- Relic density almost unaffected by small mixing if DM is heavier than dark photon.
- Can search with indirect detection, or by direct probes of the dark mediator - stringent limits for light dark photons and up to 100 TeV DM [Cirelli et al ‘17].



dominant annihilation channel





decay of dark photon

Broader benchmarks

- General symmetry arguments allow various “portals” between dark sector (containing DM) and Standard Model. Reasonable to expect modest DM-SM couplings.

- <u>Hypothesis</u>: DM-SM couplings play a role in determining the present-day DM abundance. Example mechanisms:

    - Thermal freezeout: as in WIMP case.

    - Asymmetric dark matter [Kaplan et al ’09]: relic abundance is set by initial asymmetry, but a large annihilation cross section is required to deplete the symmetric component. Implies a <u>lower</u> bound on couplings.

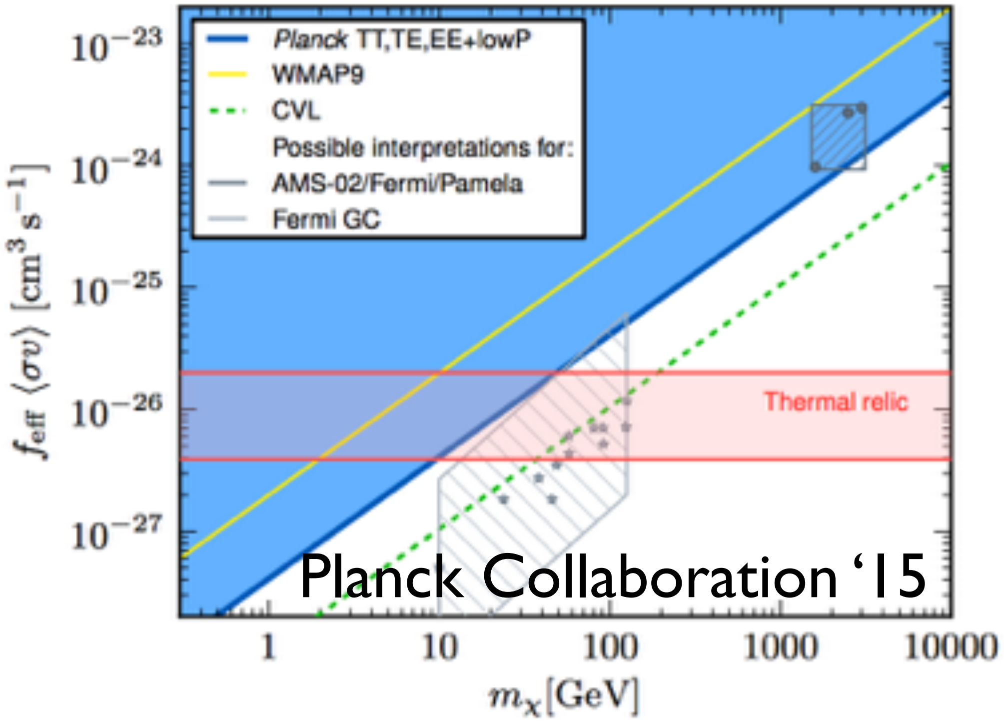
    - Freeze-in [Hall et al ’10]: DM is produced by collisions of thermal SM particles (but never achieves full thermal equilibrium). Implies larger abundances for <u>stronger</u> couplings, in contrast to freeze-out. Generally requires very small couplings.

    - SIMP/ELDER/secluded scenarios [Hochberg et al ’14, Kuflik et al ’16]: DM depletion occurs within a separate hidden sector, but couplings to SM determine when/whether the hidden sector can transfer entropy into the SM photon bath.

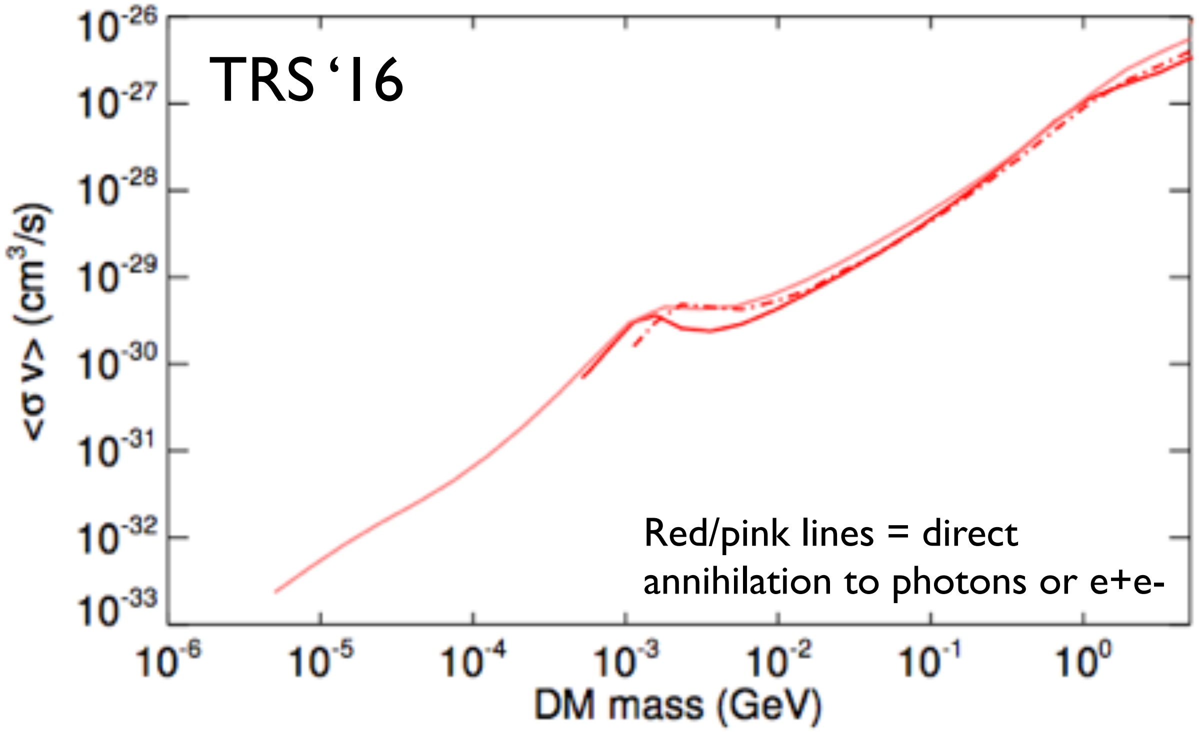
- Each of these mechanisms is predictive - re-examine complementarity between direct/indirect/accelerator searches for different relic density mechanisms, masses below the WIMP window. (See Battaglieri et al ’17, Cosmic Visions report, for much greater detail!)

Challenges for light thermal dark matter

- Many new ideas for experimental dark matter searches in the keV-GeV mass range - direct detection, beam dumps, fixed-target experiments, MeV-GeV gamma-ray telescopes, etc.
- But also many existing constraints!
- Most model-independent bounds on thermal relic annihilation rate come from indirect detection.
- Example: too large an annihilation rate producing photons/electrons during the cosmic dark ages leads to extra ionization - perturbs the CMB.
- Thermal annihilation cross section during this epoch is ruled out for DM masses below 1 GeV, unless DM annihilates mostly/entirely to neutrinos.



Planck Collaboration '15



TRS '16

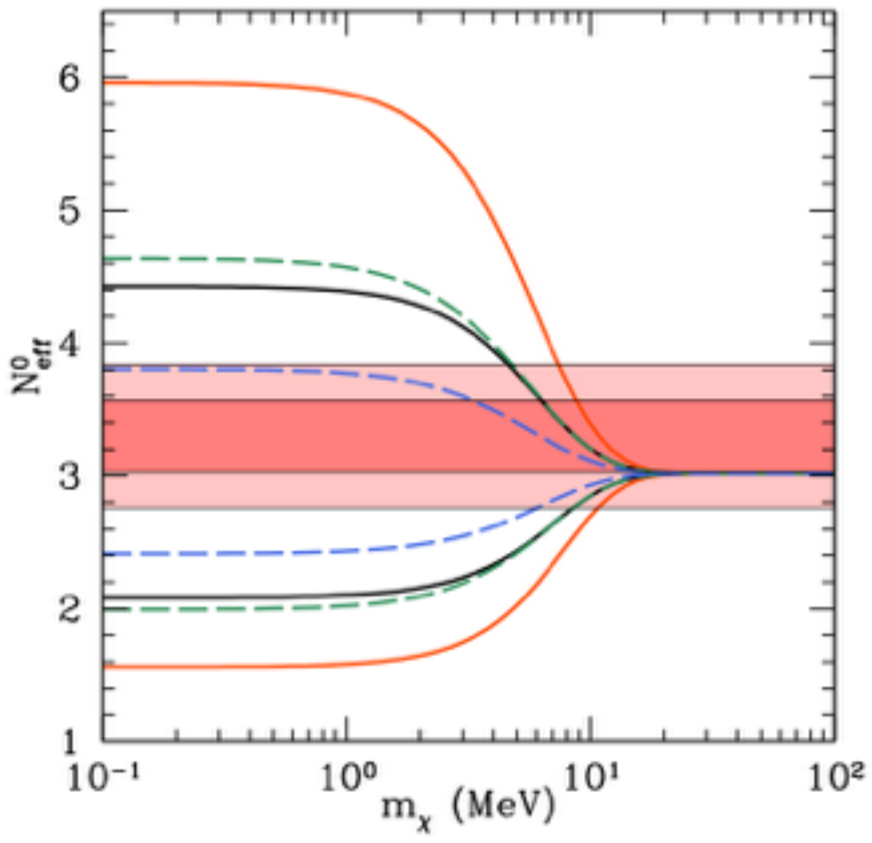
Red/pink lines = direct annihilation to photons or e+e-

Examples: light thermal DM

- Some examples of theoretical models with thermal freezeout, which yield the correct relic density with extremely suppressed annihilation at late times (to evade CMB and other indirect detection limits):
  - Dominantly p-wave annihilation: main annihilation channel is suppressed by $(v/c)^2$.
  - Annihilation against a partner particle which is not present at late times (e.g. because it decays).
  - Forbidden dark matter [d’Agnolo & Ruderman ‘15]: DM annihilates to heavier states, suppressing natural annihilation rate; annihilation is exponentially suppressed at DM temperatures much less than the mass splitting.
  - Impeded dark matter [Kopp, Liu, TRS, Wang & Xue]: DM annihilates to near-degenerate states; due to phase space suppression, annihilation rate is suppressed by (v/c) down to a cutoff velocity.
  - Strongly interacting massive particles [Hochberg et al ’14], not-forbidden dark matter [Cline, Liu, TRS & Xue], assisted annihilation [Dey et al ‘17]: 3→2 or 4→2 number-changing processes within a dark sector dominate freezeout.
    - rate is naturally smaller due to stronger density dependence
    - natural mass for freezeout is $m_\chi \sim \alpha \sqrt[n]{m_{\text{Planck}} T_{\text{eq}}^{n-1}}$
    - Suggests few-MeV scale (or below) for 3→2 processes, few-keV scale (or below) for 4→2 processes.

How low can (thermal) DM go?

- n_{eff} bound: Big Bang nucleosynthesis (BBN) and CMB data constrain number of effective relativistic degrees of freedom.
- After electrons/positrons become non-relativistic, neutrinos have temperature $(4/11)^{1/3}$ T_{CMB}; $\Delta n_{eff} = 1$ corresponds to the addition of one extra neutrino species (or other relativistic species at neutrino temperature).
- Planck 2015 data: $n_{eff} = 3.15 \pm 0.23$ (Planck Collaboration '15).
- If DM is in thermal equilibrium with the Standard Model down to O(MeV) temperatures, n_{eff} limit is generally violated [Nollett & Steigman '14, '15]:
  - If DM is still relativistic during BBN (T~1 MeV), can increase n_{eff} directly (independent of coupling to SM).
  - If DM annihilates away after neutrinos decouple from photon bath (T~1 MeV), either to photons or neutrinos, it can substantially modify the neutrino temperature relative to the photon temperature - alter n_{eff} indirectly.



How low can (thermal) DM go? (round II)

- n_{eff} bound can be evaded if:
  - DM undergoes thermal freezeout to its own dark sector, which is not thermally coupled to the SM, and is colder (e.g. because this sector decoupled from SM before QCD phase transition [Green & Rajendran ‘17]).
  - DM first reaches thermal equilibrium with SM at temperatures below 1 MeV (after BBN), then decouples again before the CMB epoch [Berlin & Blinov ’17].
- Additional limitation: DM itself cannot be too warm/hot during structure formation.
  - Bounds from Lyman-alpha forest exclude thermal DM below ~2-5 keV [e.g. Garzilli et al ’15, Irsic et al ‘17].
  - Limits relaxed for DM substantially colder than CMB photon bath - requires early thermal decoupling (or no thermal coupling at all).

How low can DM (ultimately) go?

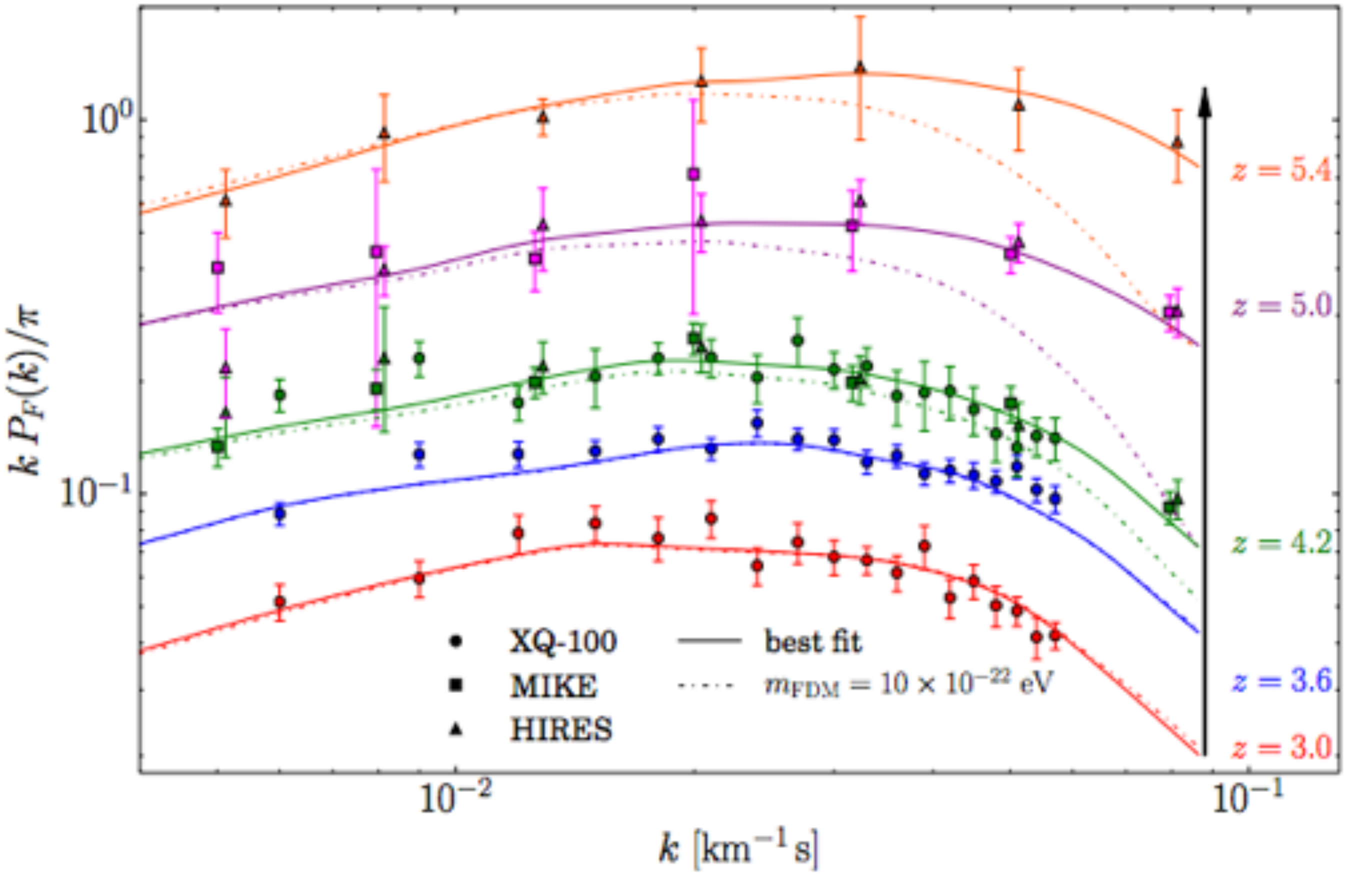
- Minimum DM mass scale: de Broglie wavelength of DM must be smaller than size of smallest observed DM structures.

- Dwarf galaxies: size O(kpc), typical velocity dispersion O(10) km/s.

- DM mass of 10^{-22} eV => de Broglie wavelength ~ kpc.

- Lower-mass DM would not allow for observed dwarf galaxies.

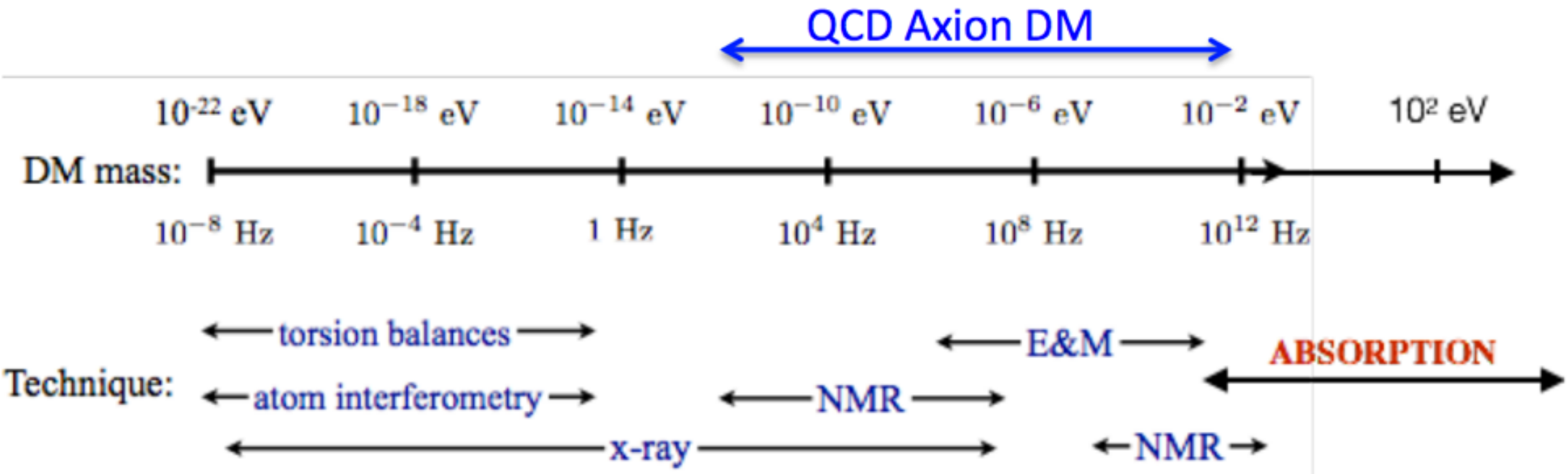
Irsic et al ‘17



- We can do better: Lyman-alpha forest data constrain cutoff in the matter power spectrum, require that $m_{DM} > 2\text{-}3\text{x}10^{-21}$ eV [Irsic et al ’17, Armengaud et al ‘17].

- There are many proposed experiments to search for axions, axion-like particles, or very light dark photons (see e.g. Cosmic Visions ’17 report).

Light bosonic dark matter



Cosmic Visions '17

- Two main parameter regions for sub-keV bosonic dark matter
  - meV-keV: DM can be absorbed onto target electrons in semiconductors or superconductors via phonon emission [Hochberg, Lin & Zurek '16-'17, Bloch et al '16]
  - 10^{-21} eV - meV: DM can be regarded as coherently oscillating classical field, opens up a range of new detection methods targeting continuous wave signals (rather than individual particles).

The high mass scale: status of MACHOs

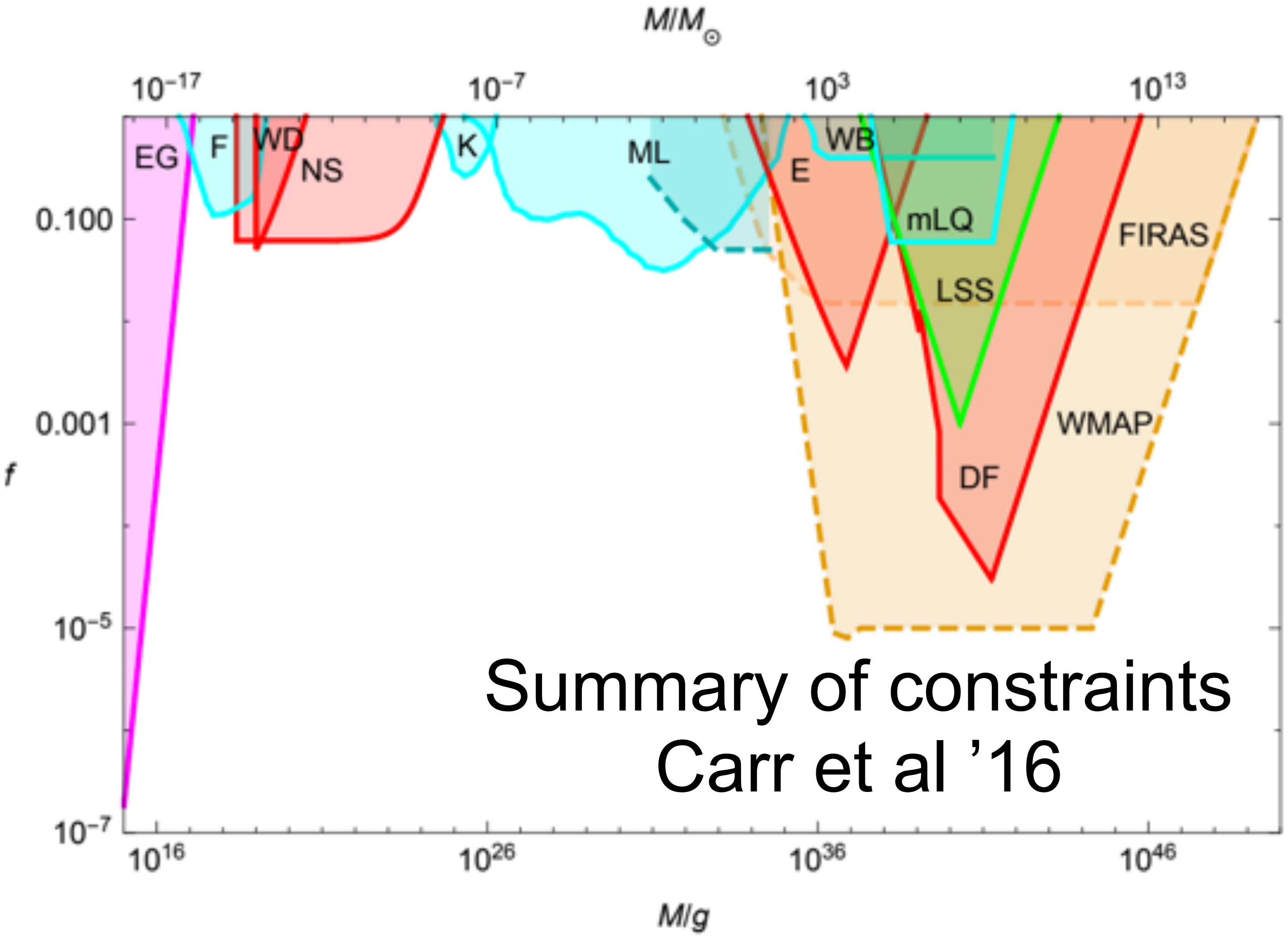
- Primordial black holes (BHs) with masses above ~10^{14} g could constitute a possible DM candidate.

- Below ~10^{-15} solar masses, gamma-rays from BH evaporation are excluded for BHs constituting 100% of DM.

- Limits on femtolensing of gamma-ray bursts and interaction of black holes with neutron stars/white dwarfs constrains the 10^{-16}-10^{-10} solar mass window.

- Microlensing surveys rule out 100% of DM being 10^{-7}-10 solar mass BHs.

- (Lack of) dynamical heating of star clusters and ultrafaint dwarf galaxies constrains heavier BHs - together they exclude 10^{-7}-10^{5} solar mass BHs as 100% of DM [Green '16].



Summary of constraints
Carr et al '16

- It appears there is still an open window for primordial black holes to constitute 100% of the DM, around 10^{-10}-10^{-7} solar masses (~lunar mass scale).

Summary

- We know dark matter is present in our universe, but it could inhabit any of an enormous range of mass scales, from ~10^{-21} eV bosons up to moon-mass primordial black holes.

- Searches have long focused on WIMP and axion scenarios, connected to hierarchy problem and strong CP problem respectively - now timely to consider theoretical frameworks for broader classes of DM scenarios.

  - In many classes of models (beyond simple thermal freezeout), DM-SM couplings are important in setting the relic density of DM - allows predictivity.

  - MeV-GeV mass window admits new thermal-relic target region - recent flourishing of models that naturally generate the required relic density while respecting current limits. Cosmological constraints put stringent requirements on thermal dark matter below the MeV scale.

- Now is a time of many exciting new DM-related ideas - including many I didn't mention, e.g. searching for neutron-star heating by DM-SM scattering [Baryakhtar et al '17] - I look forward to hearing about more of them over the next few days!

BONUS SLIDES

Forbidden dark matter

d'Agnolo & Ruderman, Phys. Rev. Lett. 115, 061301 (2015)

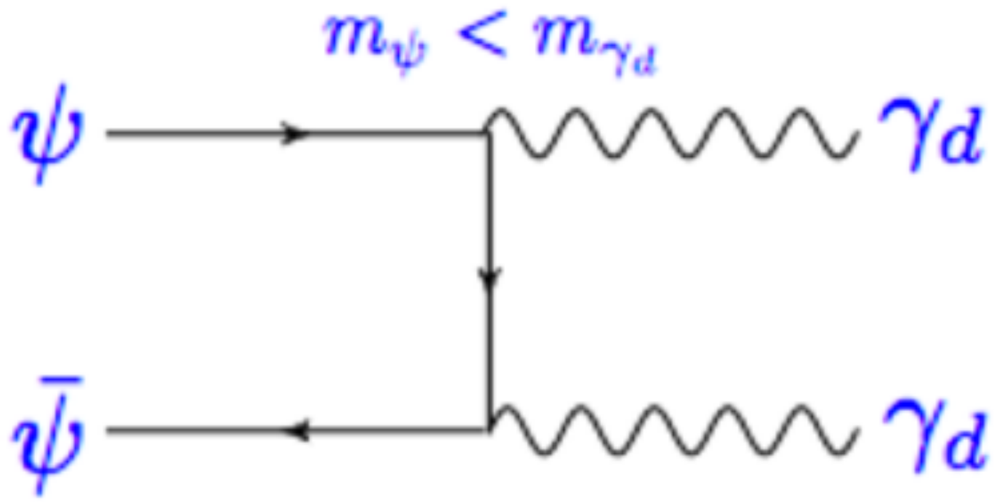
- Dominant annihilation channel during freezeout is DM DM → $\gamma_D\gamma_D$, where:

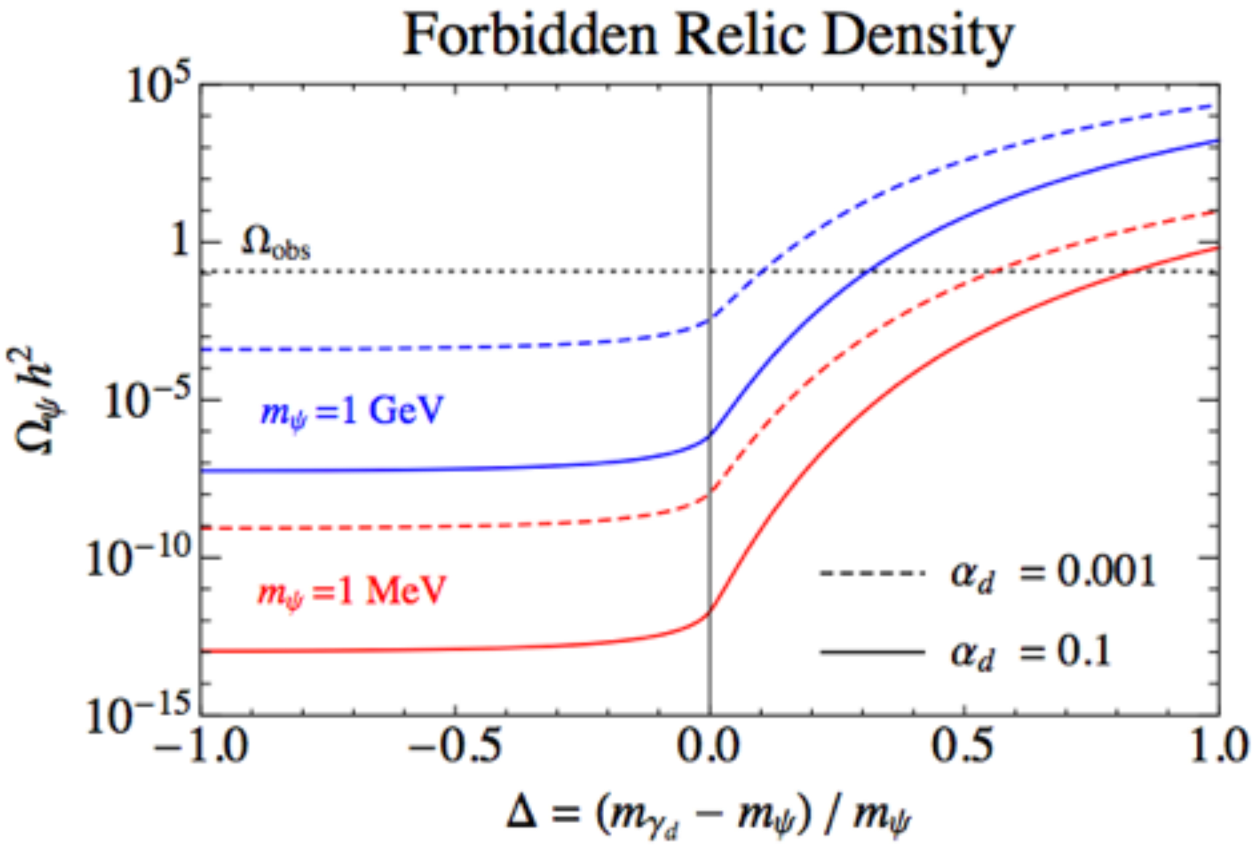
$$m_{\rm DM} < m_{\gamma_D} < m_{\rm DM} + {\rm KE}$$

- Requires DM on tail of the Boltzmann distribution: exponential suppression allows light DM with moderate-to-large couplings.

- At late times: forbidden channel is negligible, indirect signals dominated by direct annihilation to SM particles, controlled by small mixings.

- Requires a dark-sector particle with mass comparable to the DM, but slightly heavier.



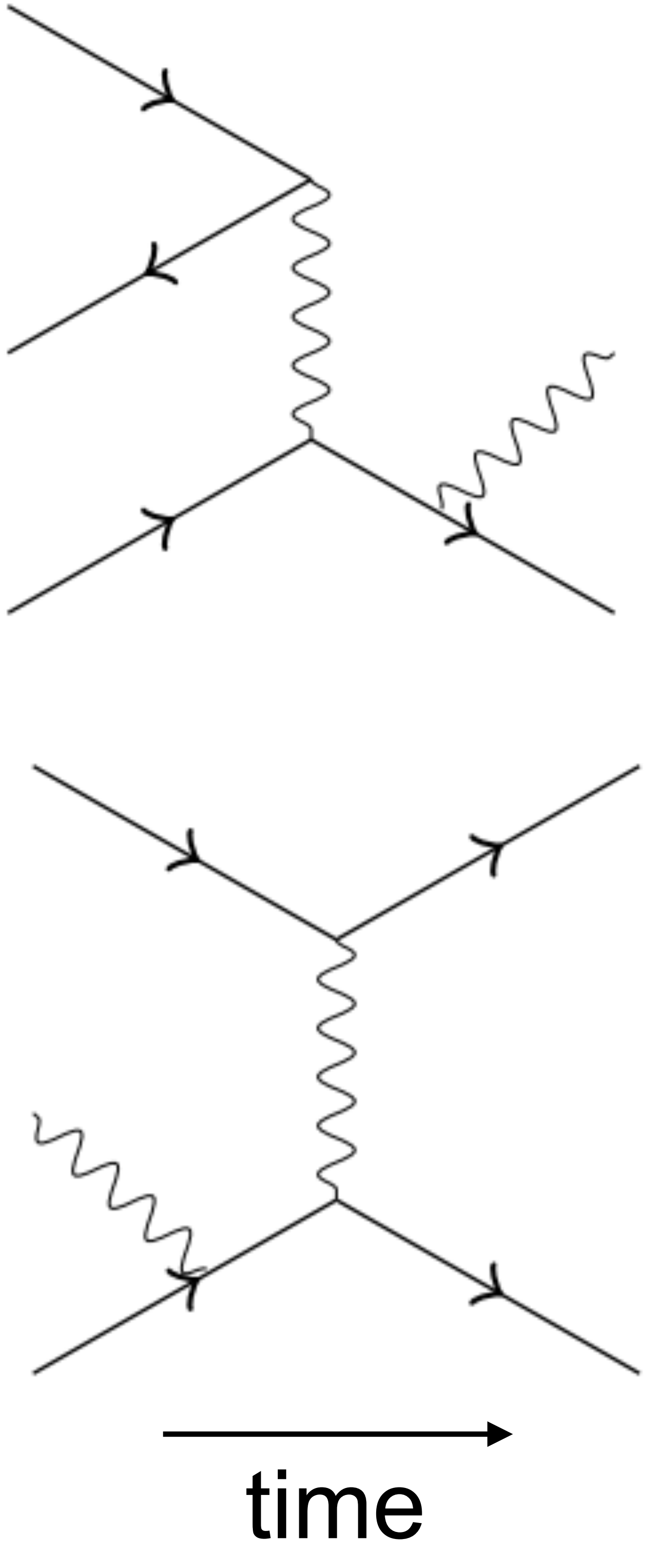


Beyond forbidden channels

- However, as 2→2 annihilations become increasingly suppressed, other channels can play key roles.
- Simple example: consider model where DM is a Dirac fermion charged under a dark U(1).
- If the dark U(1) is broken such that the dark photon has mass satisfying:

$$2m_{\rm DM} > m_{\gamma_D} > m_{\rm DM}$$

- Then 3-body annihilations can dominate freezeout (also seen e.g. in SIMP models).



~~Forbidden~~ DM cosmology

- Need to solve coupled Boltzmann equations for DM and dark photon populations, including 2- and 3-body annihilation processes, and dark photon decays.

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\frac{1}{4}\langle\sigma v^2\rangle_{\substack{\chi\chi\bar\chi\\ \to\chi A'}}\left(n_\chi^3 - n_{\chi,0}^2 n_\chi \frac{n_{A'}}{n_{A',0}}\right) + \langle\sigma v\rangle_{\substack{A'A'\\ \to\bar\chi\chi}}\left(n_{A'}^2 - n_{A',0}^2\frac{n_\chi^2}{n_{\chi,0}^2}\right)$$

$$\begin{aligned}\frac{dn_{A'}}{dt} + 3Hn_{A'} = {} & \frac{1}{8}\langle\sigma v^2\rangle_{\substack{\chi\chi\bar\chi\\ \to\chi A'}}\left(n_\chi^3 - n_{\chi,0}^2 n_\chi \frac{n_{A'}}{n_{A',0}}\right) - \frac{1}{4}\left(\langle\sigma v^2\rangle_{\substack{\chi\bar\chi A'\\ \to\chi\bar\chi}} + \langle\sigma v^2\rangle_{\substack{\chi\chi A'\\ \to\chi\chi}}\right)\left(n_\chi^2 n_{A'} - n_\chi^2 n_{A',0}\right) \\ & - \langle\sigma v\rangle_{\substack{A'A'\\ \to\bar\chi\chi}}\left(n_{A'}^2 - n_{A',0}^2\frac{n_\chi^2}{n_{\chi,0}^2}\right) - \Gamma_{A'\to f\bar f}\left(n_{A'} - n_{A',0}\right)\end{aligned}$$

- In general: two functions to solve for, n_χ and $n_{A'}$. Two fastest processes dominate evolution equations: fastest process gives one constraint on n_χ and $n_{A'}$, second-fastest maintains both n_χ and $n_{A'}$ at equilibrium values if it is faster than Hubble.
- Thus freezeout begins when second-fastest process rate becomes comparable to H; interplay between fastest and second-fastest processes controls freezeout.

~~Forbidden~~ DM cosmology

- Classic freezeout: decay of A’ is fastest process, fast enough to keep $n_{A'}$ in equilibrium. Freezeout of n_χ set by second-fastest process, annihilation $\chi\chi \longleftrightarrow$ A’A’.
- Not-forbidden DM: either decay + 3→2 annihilation, or 2→2 + 3→2 annihilation, can also control freezeout - wide range of possible scenarios.
- When should 3→2 annihilation dominate?

$n_{i,0} \sim \exp(-m_i/T)$, in equilibrium

$$\Gamma_{\substack{\chi\chi\bar{\chi} \\ \to\chi A'}} \sim \langle \sigma v^2 \rangle_{\substack{\chi\chi\bar{\chi} \\ \to\chi A'}} n_{\chi,0}^2$$
$$\sim \exp(-2m_\chi/T)$$

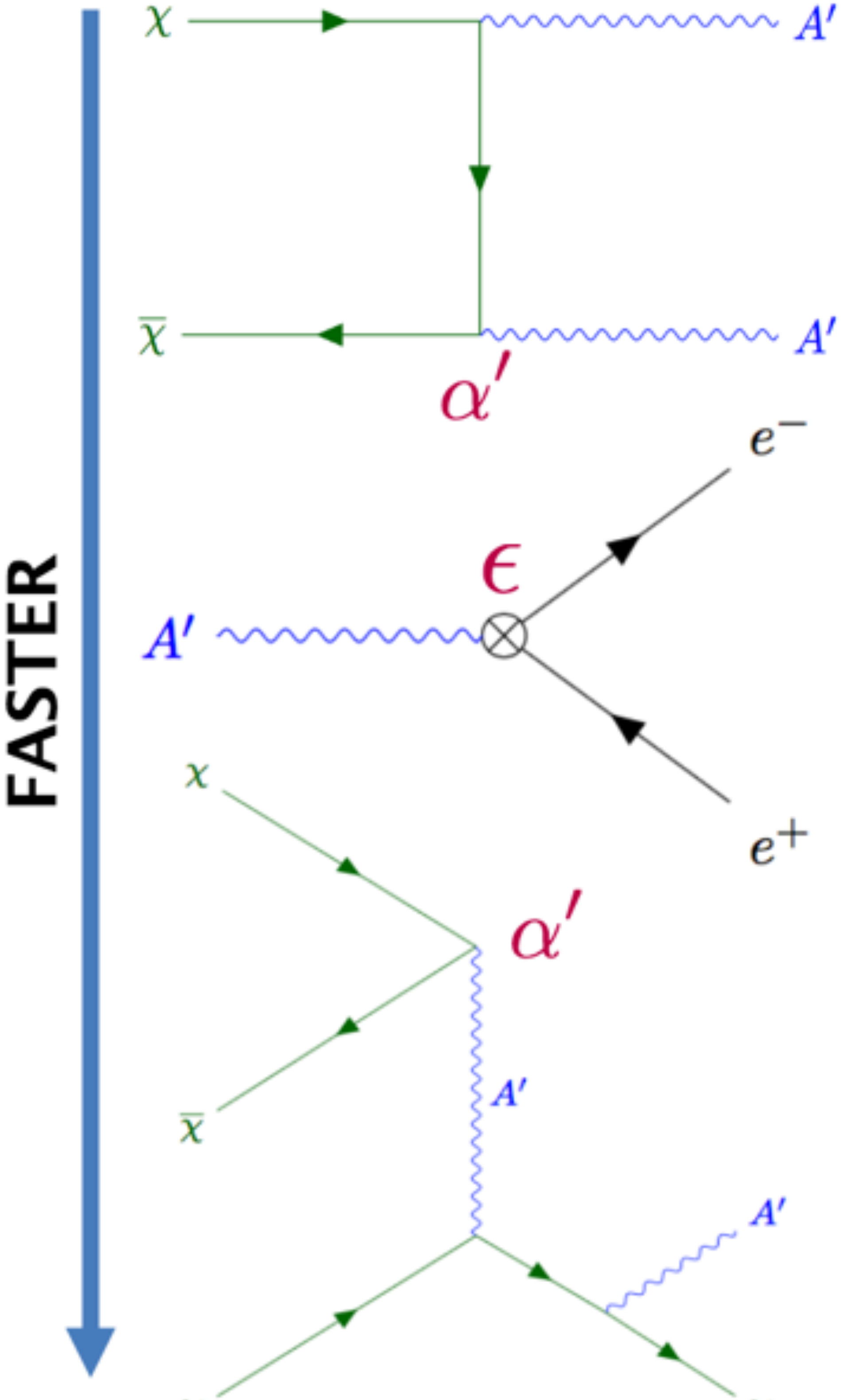
$$\begin{aligned}\Gamma_{\bar{\chi}\chi\to A'A'} &\sim \langle \sigma v \rangle_{\bar{\chi}\chi\to A'A'} n_{\chi,0} \\ &\sim \langle \sigma v \rangle_{A'A'\to\bar{\chi}\chi} n_{A',0}^2 / n_{\chi,0} \\ &\sim \exp(-(2m_{A'} - m_\chi)/T)\end{aligned}$$

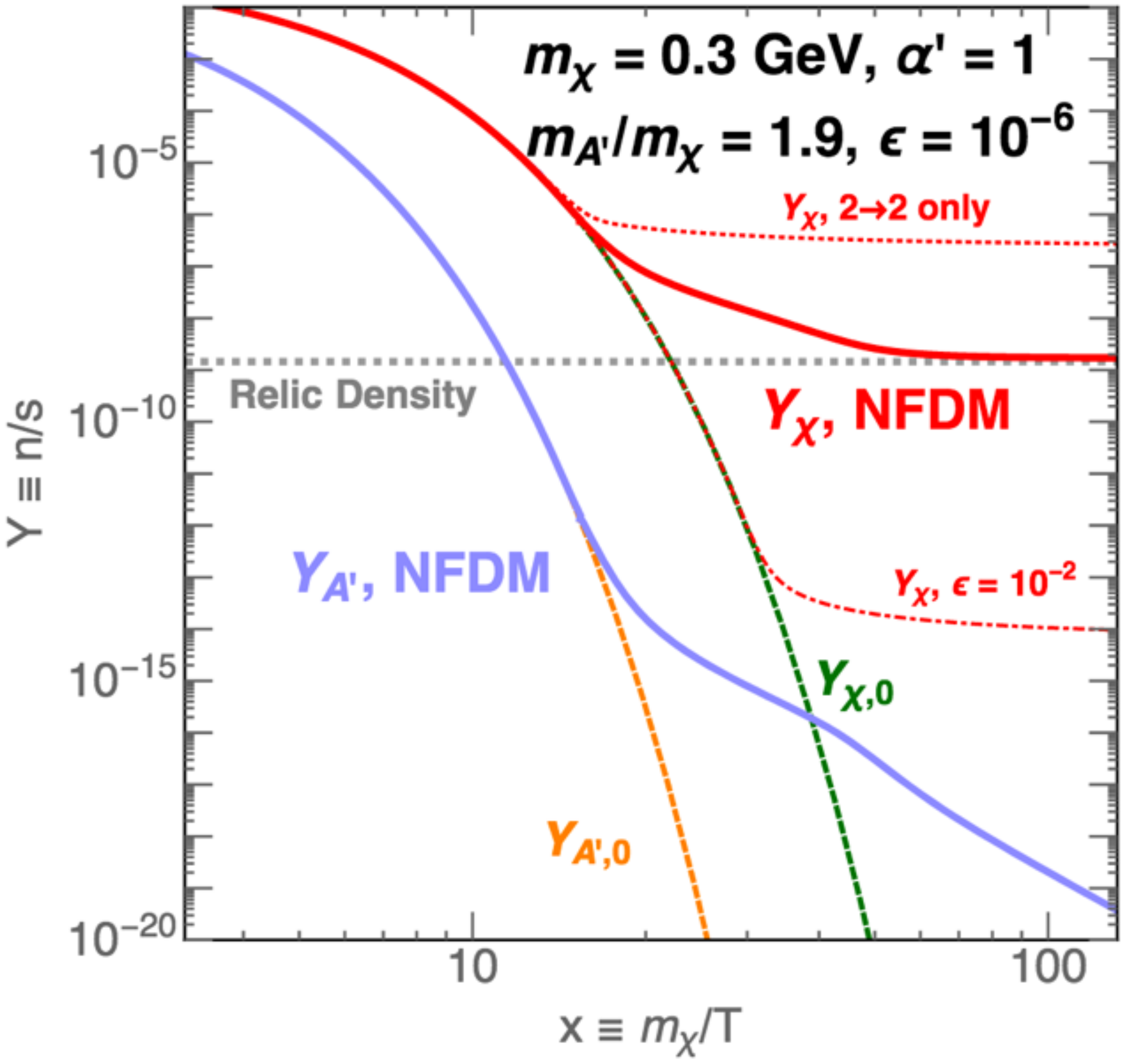
3→2 annihilation exponentially enhanced (suppressed) relative to 2→2 for:

$$m_{A'} \gtrsim (\lesssim) \frac{3}{2} m_\chi$$

Not-forbidden DM region

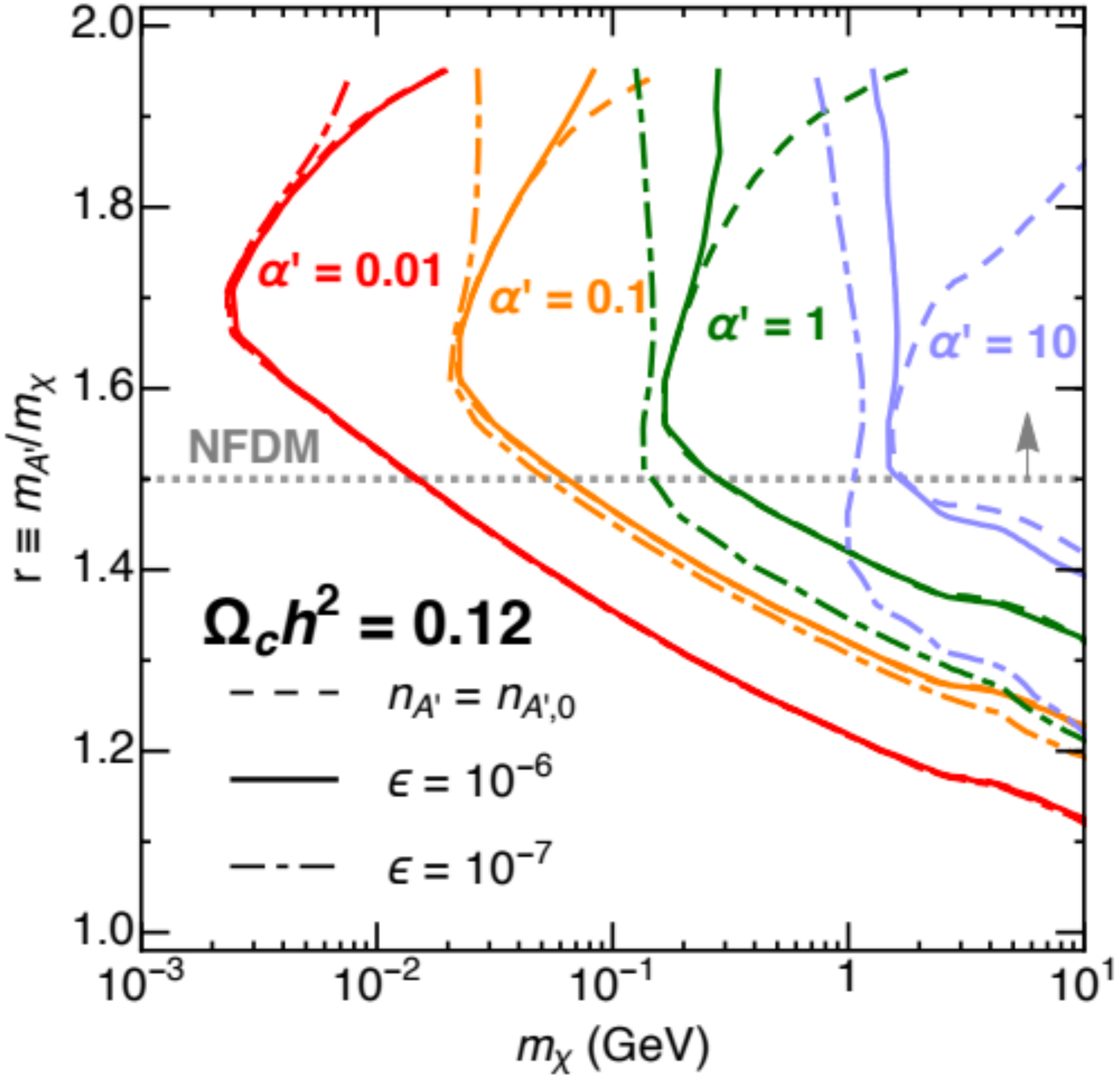
Freezeout


FASTER
χ
A′
χ̄
A′
α′
e−
ϵ
A′
e+
χ
α′
χ̄
A′
A′
χ
χ


mχ = 0.3 GeV, α' = 1
mA'/mχ = 1.9, ϵ = 10−6
Yχ, 2→2 only
Relic Density
Yχ, NFDM
YA', NFDM
Yχ, ϵ = 10−2
Yχ,0
YA',0
Y ≡ n/s
10−5
10−10
10−15
10−20
10
100
x ≡ mχ/T

Relic density

- Lower half of plot: “forbidden DM” region, forbidden 2→2 process dominates, strong dependence on mass ratio r.
- Upper half of plot: NFDM region, kinematically allowed 3→2 process dominates.
- Coupling needed to yield correct relic density no longer highly sensitive to $m_{A'}$
- Similar to standard WIMP, but without requiring very small/large couplings for MeV-GeV DM.



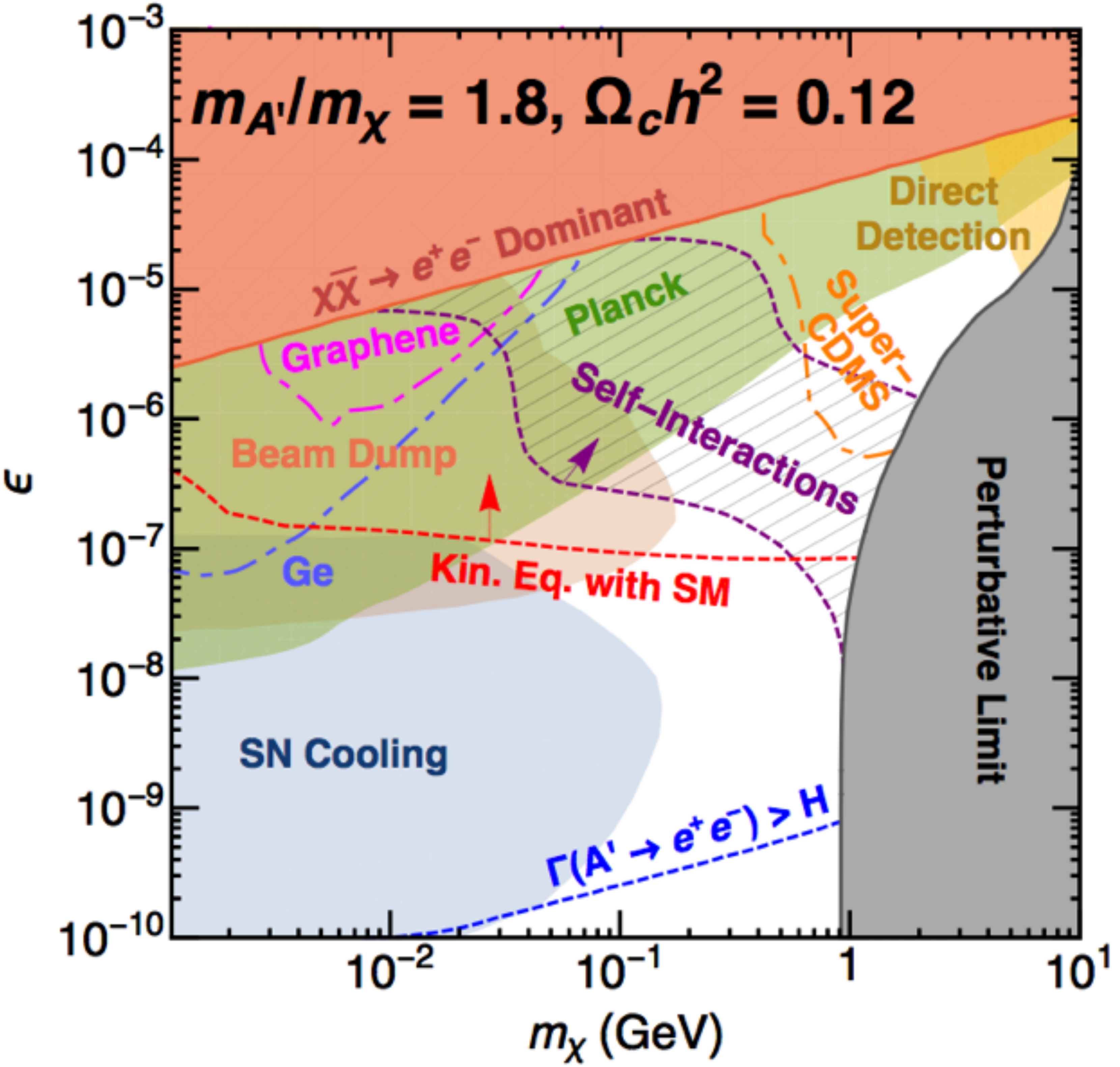
Constraints on NFDM

- Coupling chosen to produce correct relic density.

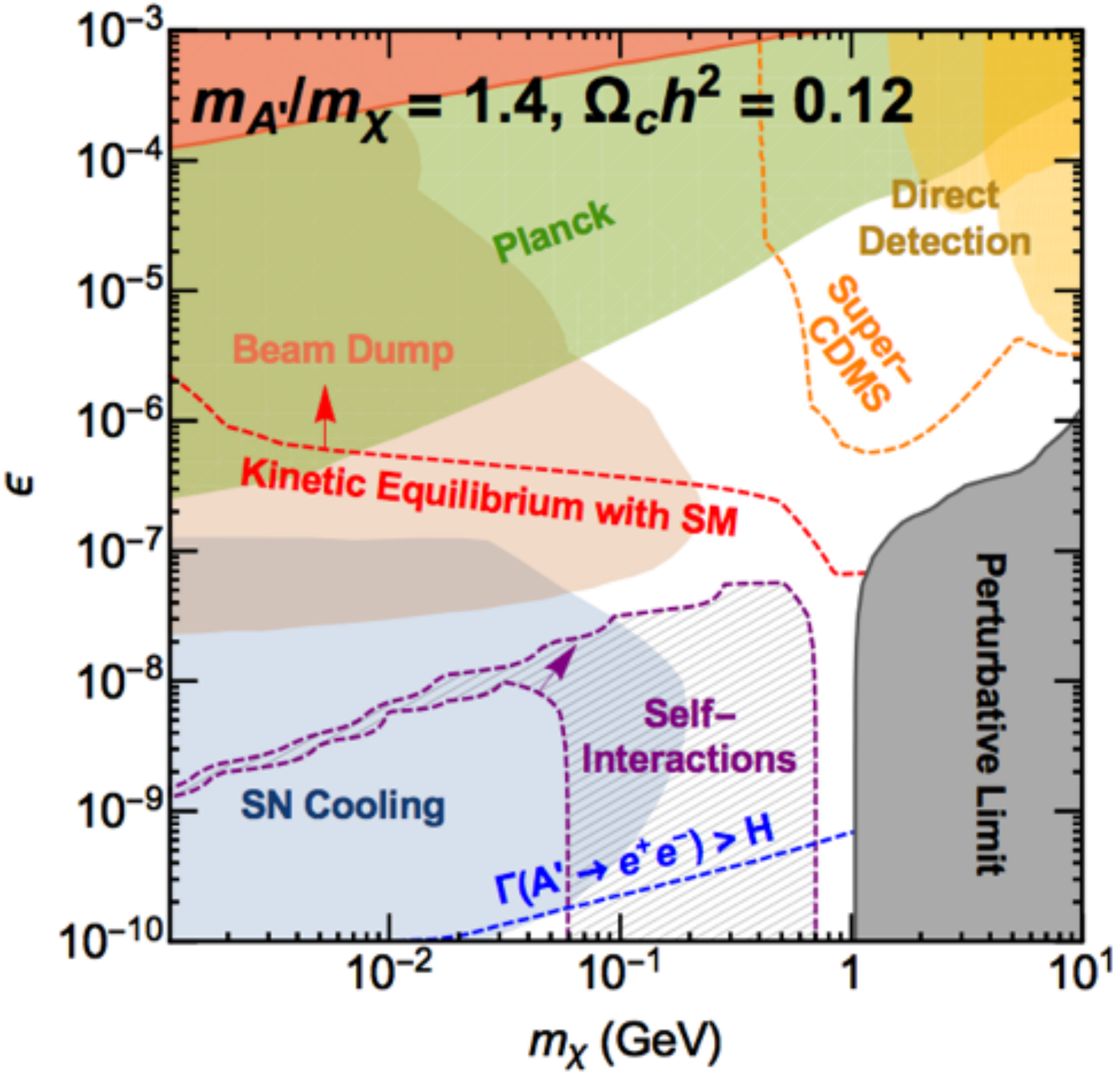
- CMB limits on annihilation through s-channel A’ to e^+e^- (3-body annihilation negligible due to low DM density).

- Beam dump, SN cooling limits bound dark photon directly.

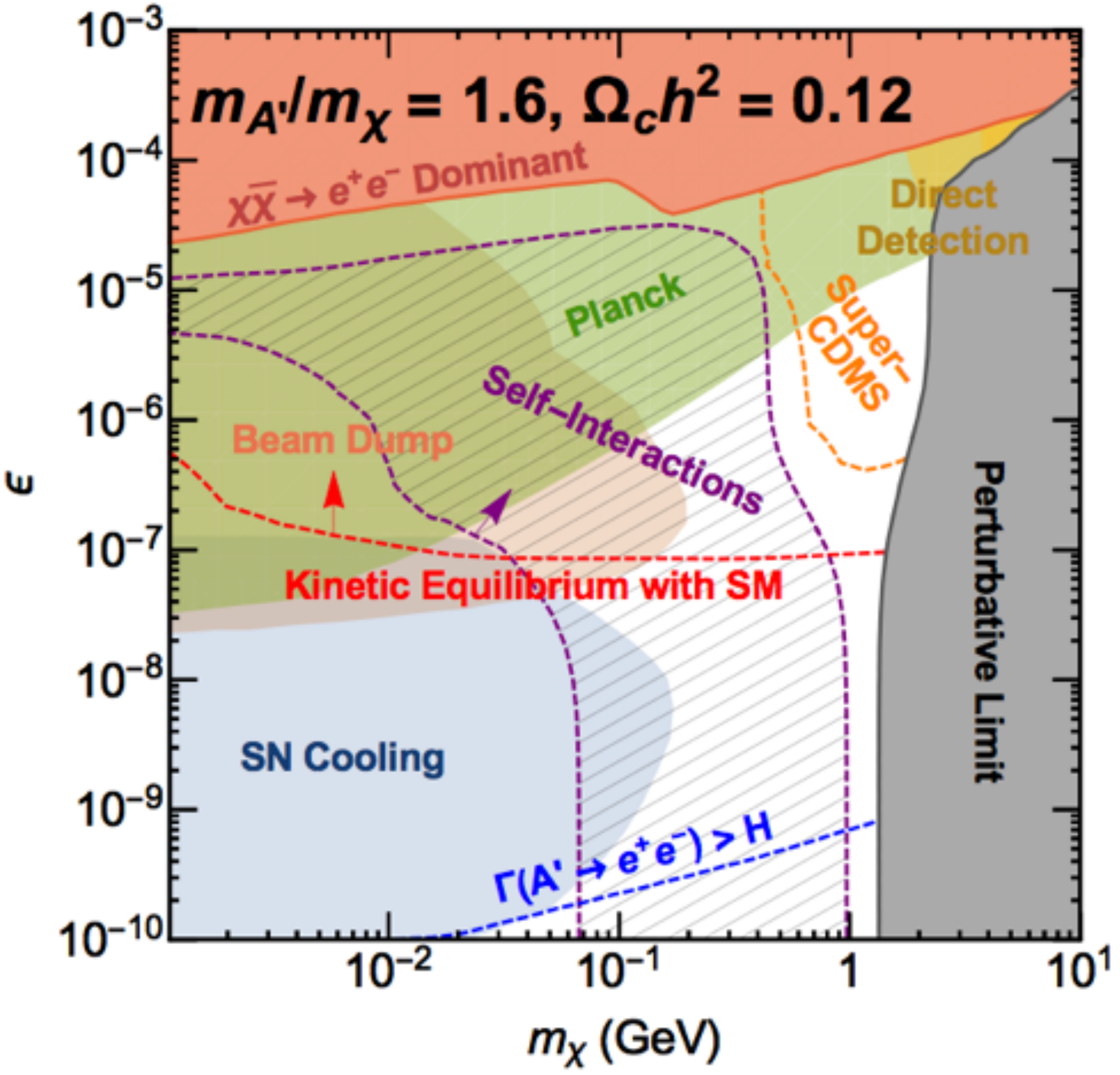
- Allowed region naturally predicts self-interaction of correct size to explain small-scale structure issues.



Enabled DM for other values of r

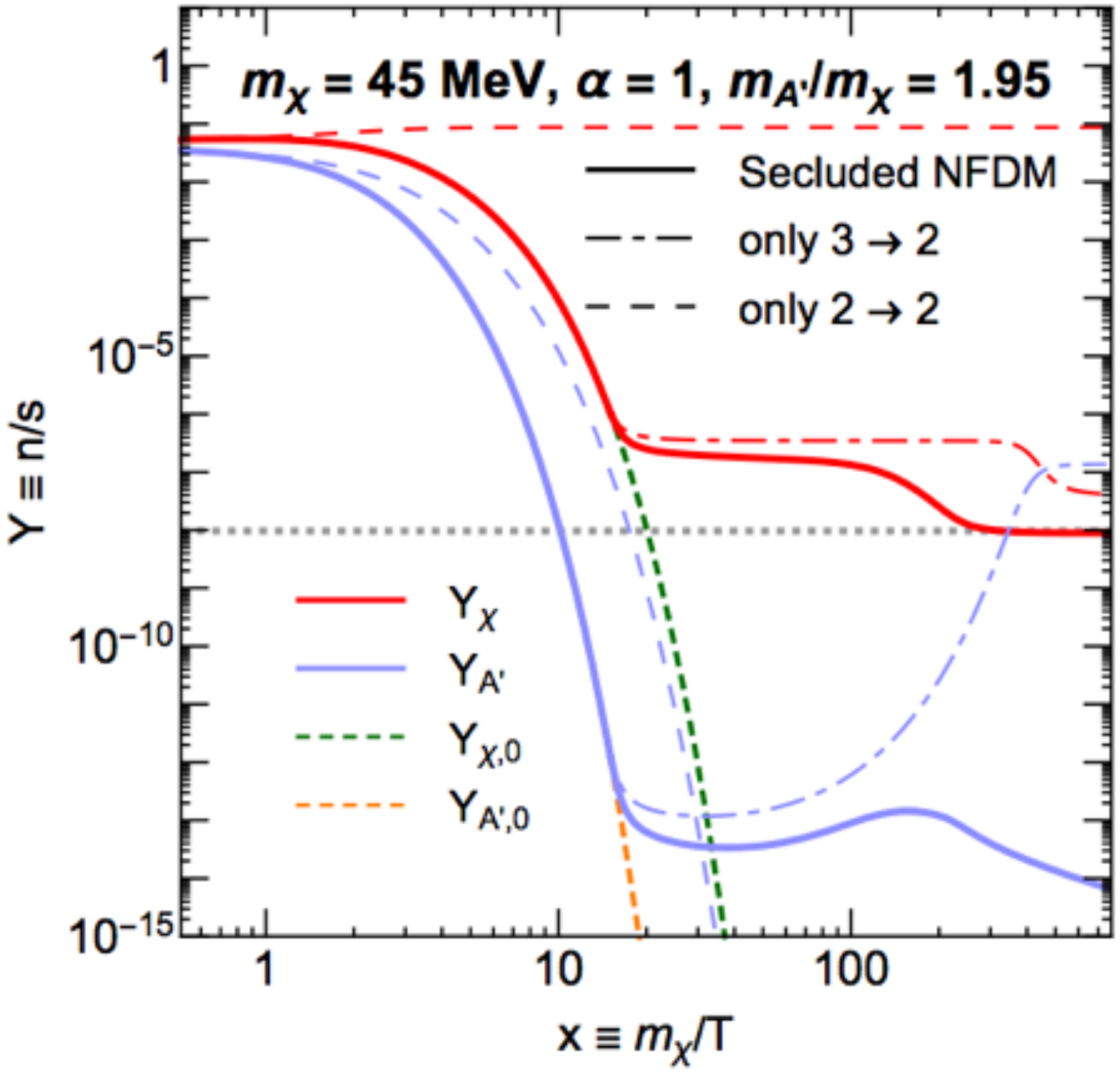


(a)

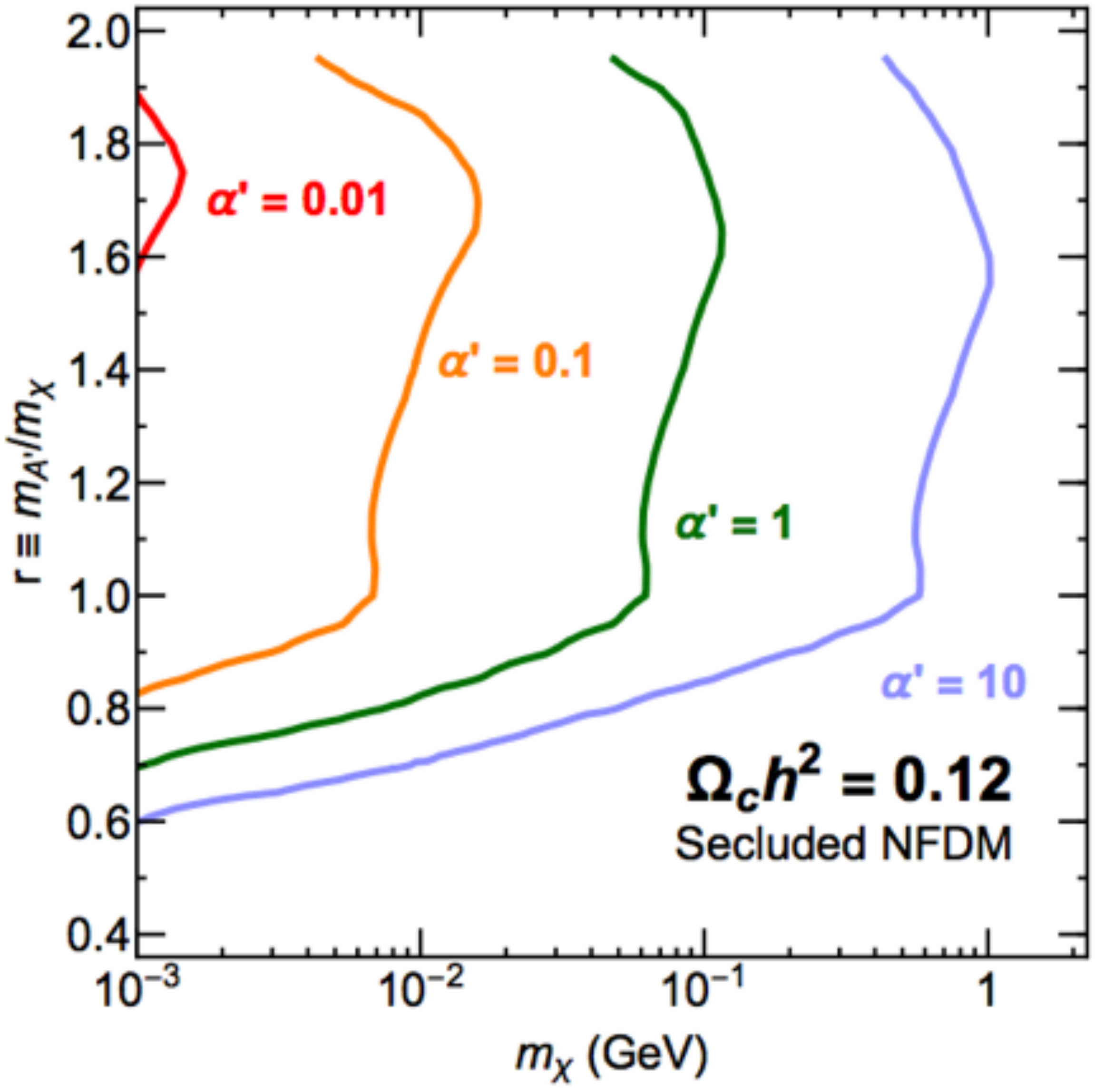


(b)

Secluded enabled DM



(a)



(b)

- Switch off decays of A'; freezeout determined by interplay of 3→2 and 2→2 processes.
- Note: need to add more ingredients to dark sector in this case, to avoid an overly high DM temperature (as dark sector cannot dissipate entropy into the Standard Model).

Impeded dark matter

- Similar to (not) forbidden DM, but mass splittings between DM and annihilation products (denoted X) are much smaller - do not cause exponential suppression during freezeout.

- Define $\Delta = m_{DM} - m_X$. Δ can be either positive or negative.

  - Δ negative: similar to forbidden case. Annihilation exponentially suppressed below a characteristic velocity scale. For small Δ, this scale is usually far below freezeout, but can be relevant for indirect detection.

  - Δ positive: annihilation never forbidden, but phase space suppresses rate.

Phase space suppression

- For s-wave processes, matrix element for scattering/annihilation is momentum-independent.
- Consequently, cross section for any 2→2 process scales as (COM frame): $\sigma \propto \frac{1}{s}\frac{|\vec{p}_{\rm out}|}{|\vec{p}_{\rm in}|}$
- For non-relativistic DM, approximate s = $(2\ m_{DM})^2$, initial momentum $m_{DM}\ v_{rel}/2$, so we have: $\sigma v_{\rm rel} \propto |\vec{p}_{\rm out}|$
- For typical DM annihilation to much lighter species, p_{out} ~ m_{DM}, so σv_{rel} is momentum-independent.
- For DM-DM scattering, p_{out} ~ $m_{DM}\ v_{rel}$, so σ is momentum-independent.
- For DM-DM annihilation to XX, with mass m_X:

$$p_{\rm out} = \sqrt{E_{\rm DM}^2 - m_X^2}$$

assuming non-relativistic DM

$$\approx \sqrt{\left(m_{\rm DM} + \frac{1}{2} m_{\rm DM} v_{\rm rel}^2/4 + m_X\right)\left(m_{\rm DM} + \frac{1}{2} m_{\rm DM} v_{\rm rel}^2/4 - m_X\right)}$$

$$\approx 2 m_{\rm DM} \sqrt{\frac{2\Delta}{m_{\rm DM}} + \frac{1}{4} v_{\rm rel}^2}$$

approximating $\Delta = m_{DM} - m_X << m_{DM}$

Impeded dark matter

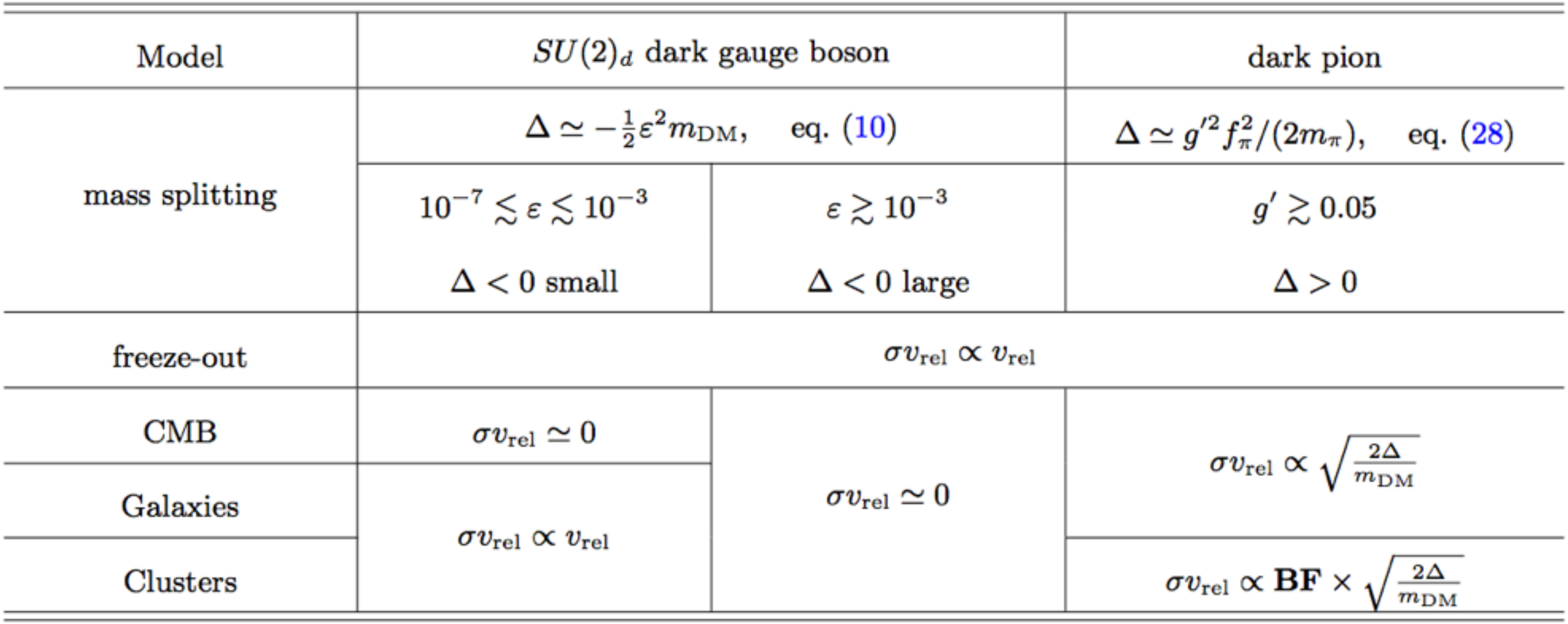
- For $1 >> v_{rel}^2 >> 8\,|\Delta| / m_{DM}$, behavior is the same independent of sign of Δ; σv_{rel} scales as v_{rel}, similar to scattering rather than s-wave annihilation.

- More mild velocity suppression than p-wave annihilation ($\sigma v_{rel} \propto v_{rel}^2$), but similar qualitative impact: suppresses indirect signals in objects/regions/epochs with small velocity dispersions, e.g. the epoch of recombination (no bound DM structures ⇒ very small velocity dispersion) or dwarf galaxies.

- For $v_{rel}^2 < 8\,|\Delta| / m_{DM}$, behavior depends on sign of Δ; for Δ negative, the annihilation becomes kinematically forbidden, for Δ positive, σv_{rel} becomes constant but with a phase-space suppression factor of order $(\Delta/m_{DM})^{1/2}$.

Example models

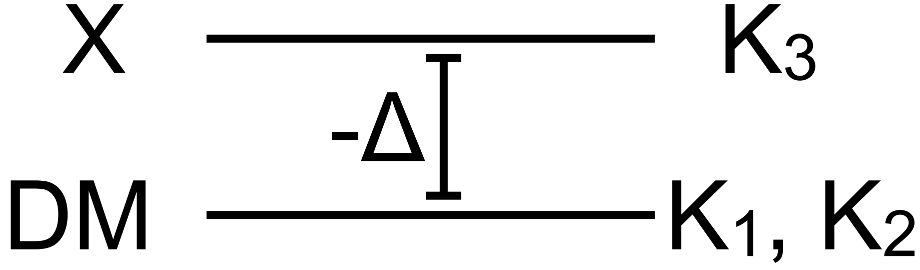
- Adapt examples of states with similar mass from Standard Model
  - Gauge bosons with masses connected by residual symmetry after breaking
  - Charged and neutral pions



Model	$SU(2)_d$ dark gauge boson		dark pion
mass splitting	$\Delta \simeq -\frac{1}{2}\varepsilon^2 m_{\rm DM}$, eq. (10)		$\Delta \simeq g'^2 f_\pi^2/(2m_\pi)$, eq. (28)
	$10^{-7} \lesssim \varepsilon \lesssim 10^{-3}$ $\Delta < 0$ small	$\varepsilon \gtrsim 10^{-3}$ $\Delta < 0$ large	$g' \gtrsim 0.05$ $\Delta > 0$
freeze-out	$\sigma v_{\rm rel} \propto v_{\rm rel}$		
CMB	$\sigma v_{\rm rel} \simeq 0$	$\sigma v_{\rm rel} \simeq 0$	$\sigma v_{\rm rel} \propto \sqrt{\frac{2\Delta}{m_{\rm DM}}}$
Galaxies	$\sigma v_{\rm rel} \propto v_{\rm rel}$		
Clusters			$\sigma v_{\rm rel} \propto \mathbf{BF} \times \sqrt{\frac{2\Delta}{m_{\rm DM}}}$

Example model: Δ < 0

- Dark sector consists of a dark SU(2) + dark scalar doublet Φ to break symmetry.



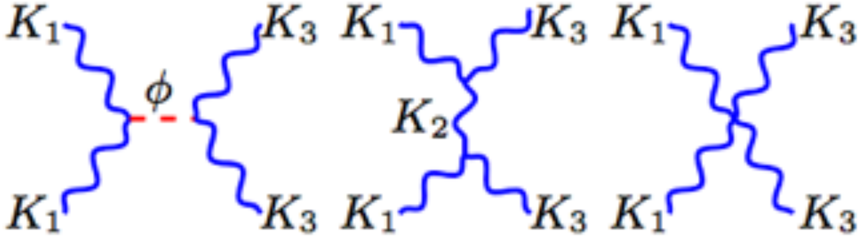
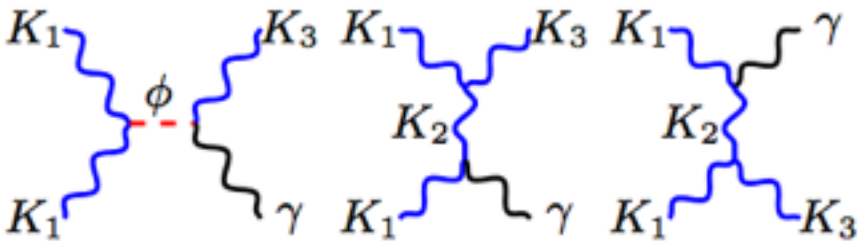
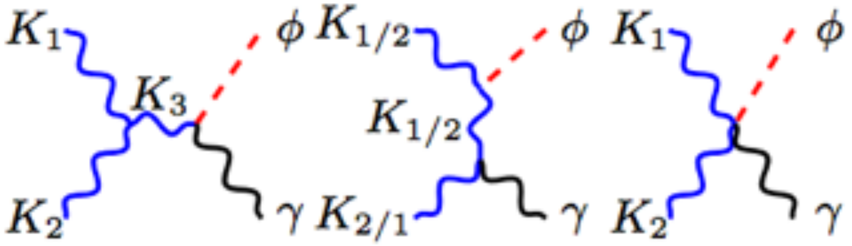
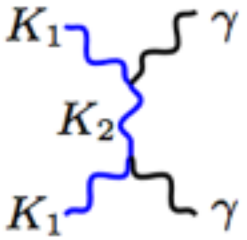
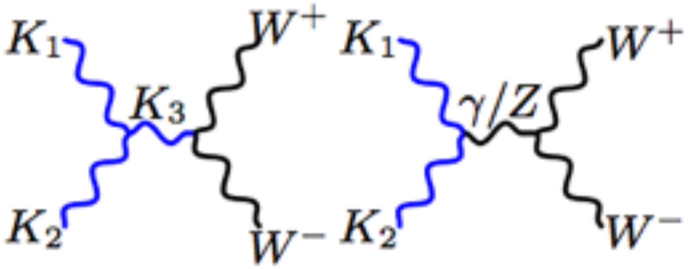
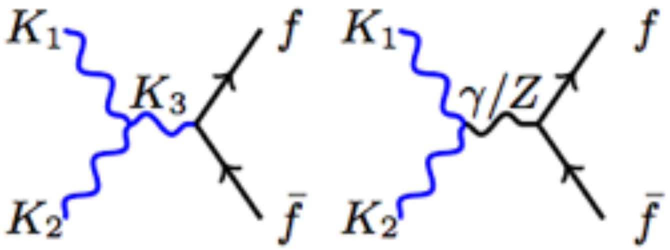
- DM is lightest SU(2) gauge boson(s); undergoes impeded annihilation to heavier SU(2) gauge bosons.

- Dark SU(2) coupled to SM through dimension-6 non-Abelian kinetic mixing term:

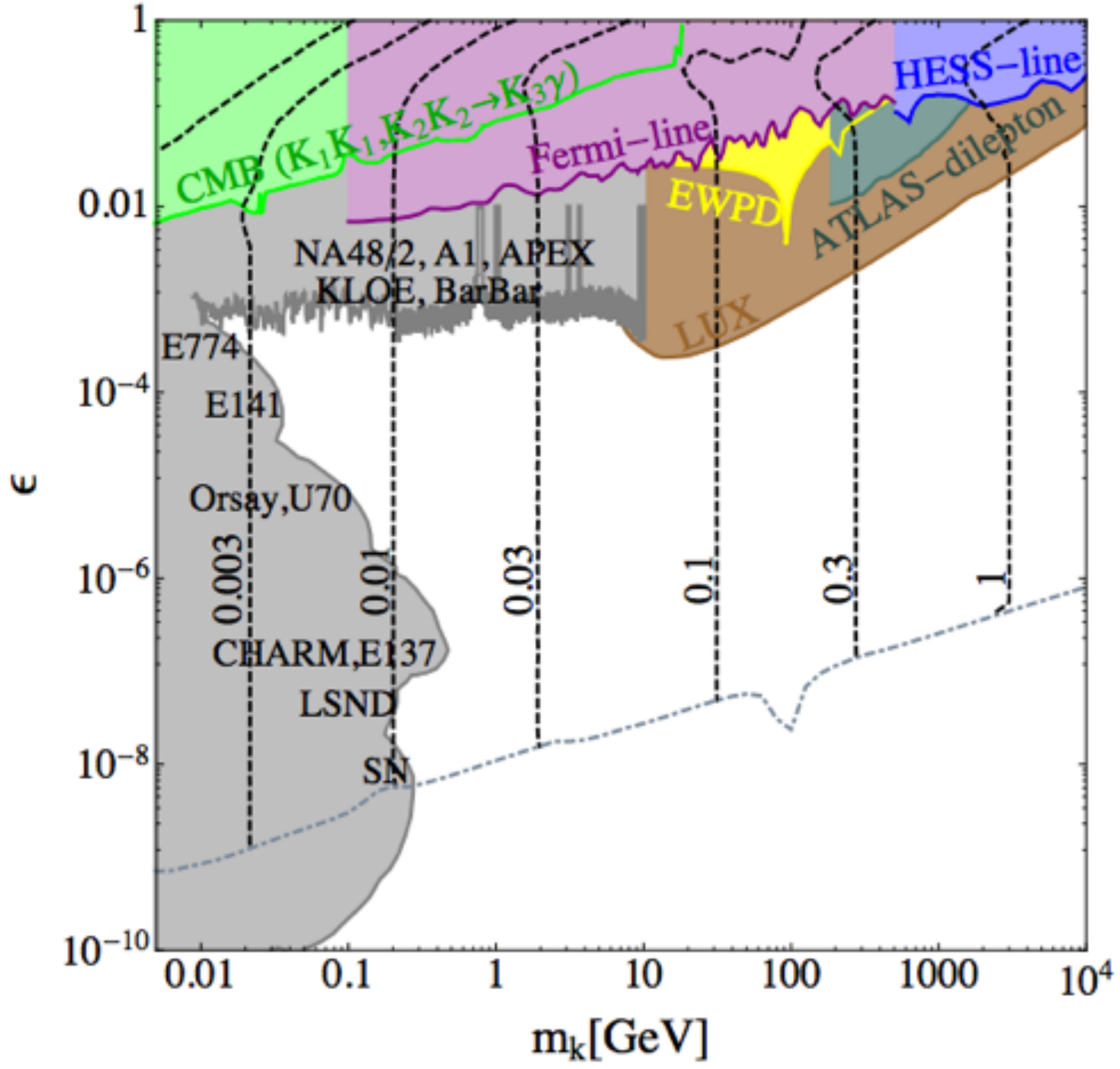
$$\mathcal{L}_{\rm mix} = \frac{1}{\Lambda^2}(\Phi^\dagger T^a \Phi) K^a_{\mu\nu} B_{\mu\nu}$$

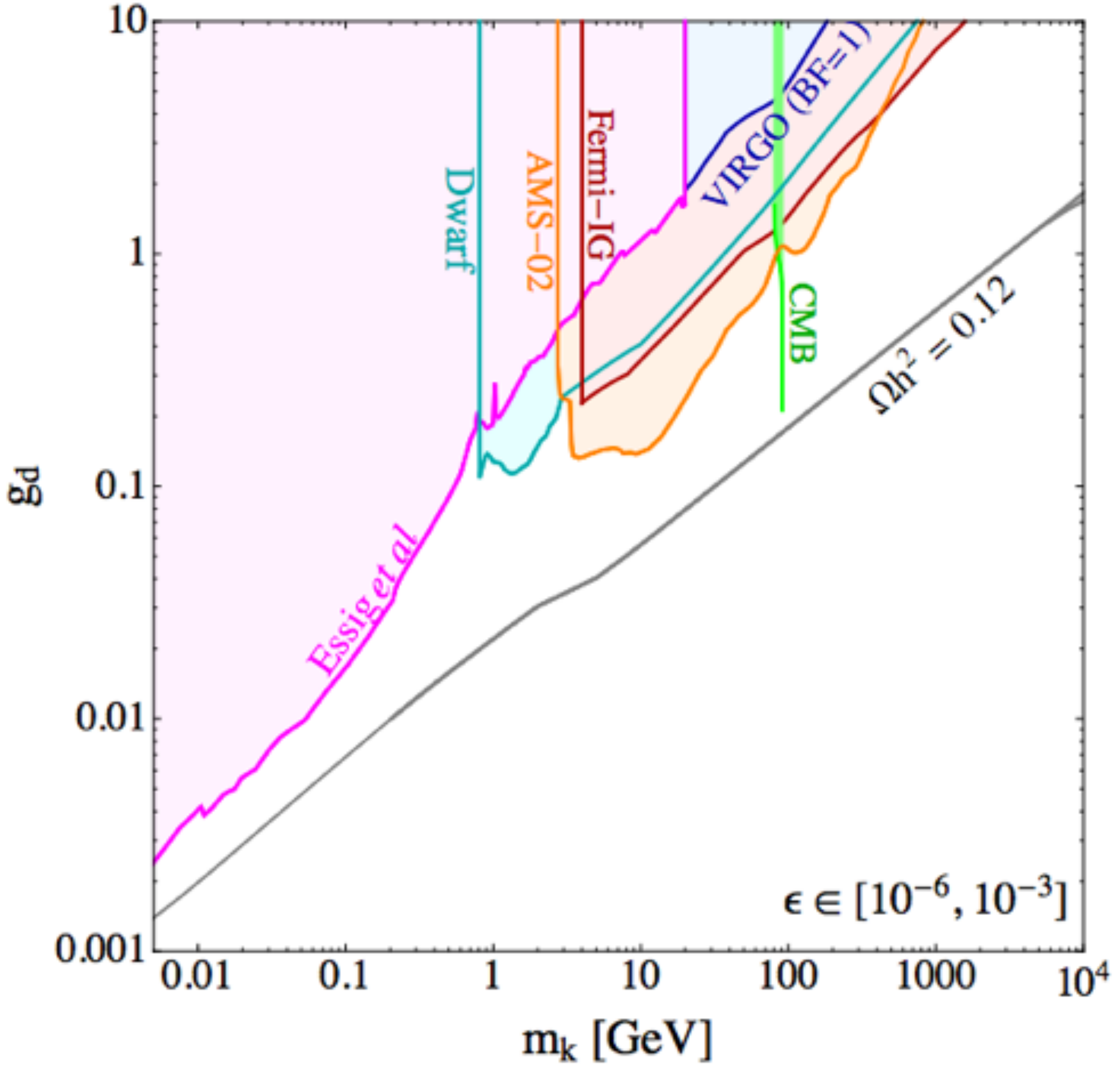
- After SU(2) breaking, only K_3^μ (denoting gauge bosons by K_a^μ) mixes with SM Z and photon fields - induces a mass splitting between K_3^μ (functions as unstable X) and K_1^μ , K_2^μ (constitute the DM).

$$\Delta \equiv m_k - m_{K_3} \simeq -\frac{m_k}{2}\frac{\varepsilon^2}{\cos^2\theta_w}\frac{(m_k^2 - \cos^2\theta_w m_{Z,\rm SM}^2)}{m_k^2 - m_{Z,\rm SM}^2} \qquad \varepsilon \equiv -v_d^2 \cos\theta_w/(2\Lambda^2)$$

process	$v_{\rm rel}$-dependence	ε-dependence	freeze-out	CMB	Indirect Detection
	$\sqrt{\frac{v_{\rm rel}^2}{4}+\frac{2\Delta}{m_{\rm DM}}}$	1	dominant	negligible	✓
	1	ε^2	subdominant	dominant	✓ (γ line)
	1	ε^2	subdominant (requires $m_\phi < 2m_k$)	dominant (requires $m_\phi < 2m_k$)	✓ (γ line if $m_\phi < 2m_k$)
	1	ε^4	negligible	negligible	negligible
	$v_{\rm rel}^2$	ε^2	subdominant	negligible	negligible
	$v_{\rm rel}^2$	ε^2	subdominant	negligible	negligible

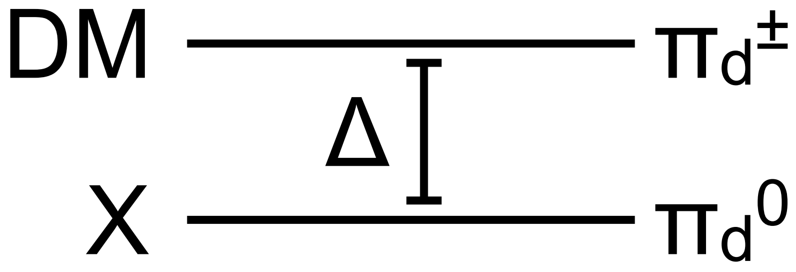
Constraints on dark SU(2)
Δ < 0 model





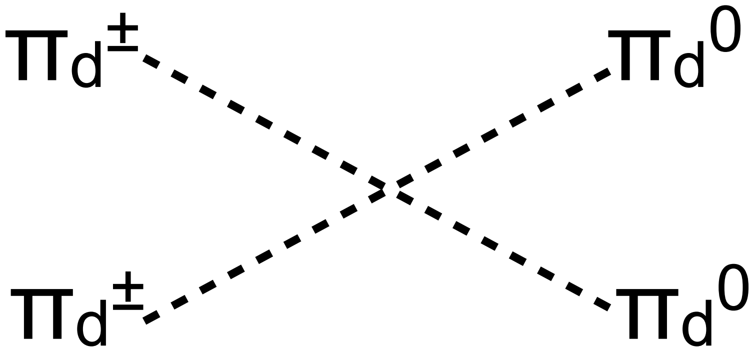
Example model: Δ > 0

- Dark sector has a SU(N) x U(1) gauge symmetry, based on SM strong+electromagnetic interactions. Contains two light "dark quarks", and a dark scalar field with U(1)-charge 2, which breaks the dark U(1) symmetry.



- Dark matter = dark "charged pions", stabilized by residual Z_2 symmetry after U(1) breaking.

- Freezeout dominated by impeded annihilation of DM to neutral pions.



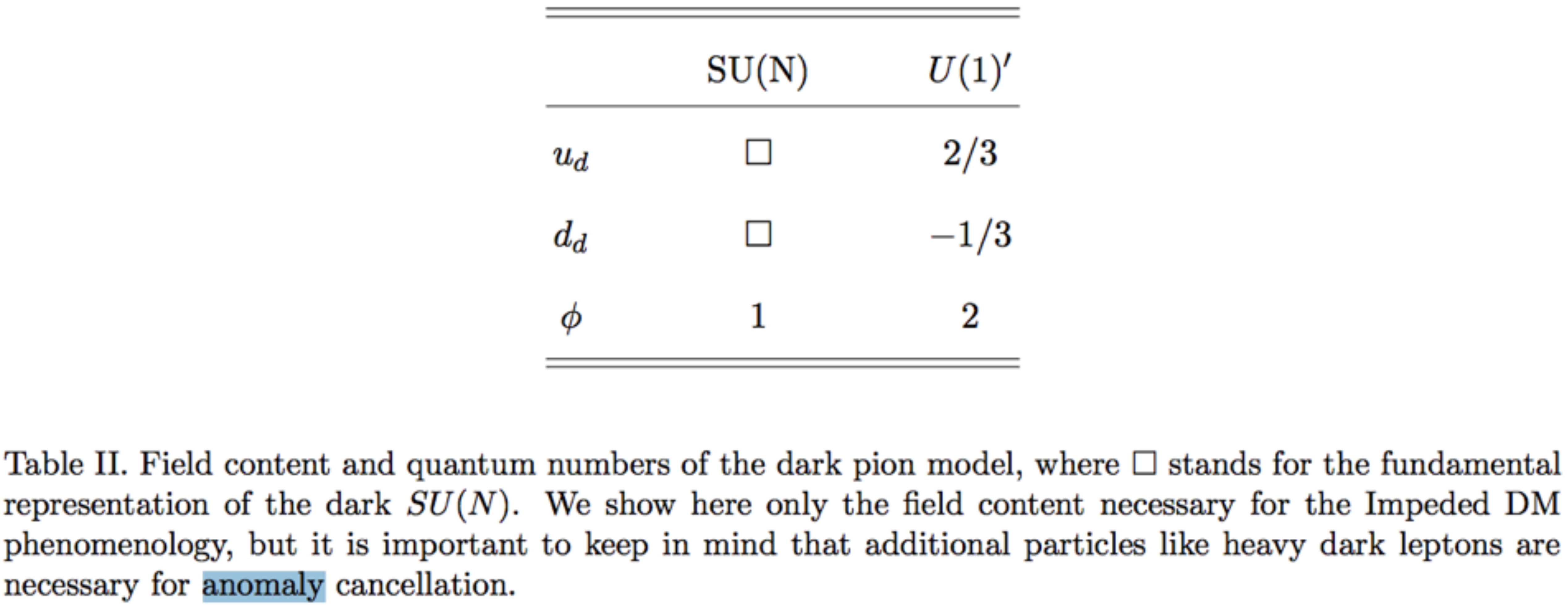
- Dark "neutral pion" decays to dark photons (through chiral anomaly), in analogy to SM.

- Dark photons kinetically mix with SM photon.

- Radiative mass splitting: $\Delta \equiv m_{\pi_d^\pm} - m_{\pi_d^0} \approx \frac{g'^2}{16\pi^2}\frac{\Lambda_N^2}{2m_\pi}$ $\quad \Lambda_N = 4\pi \underset{\uparrow}{f_\pi}$

set by relic density

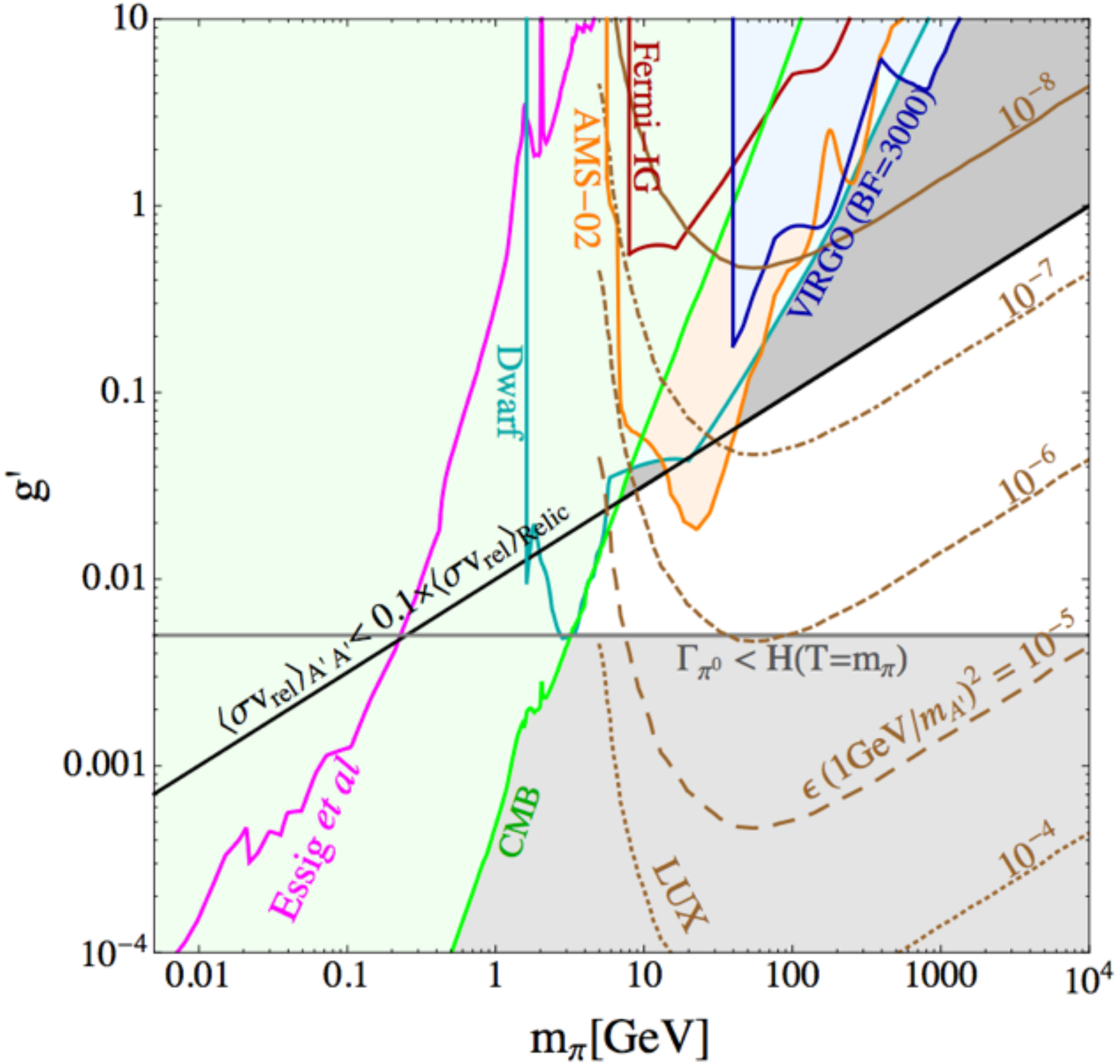
Field content for dark pion model



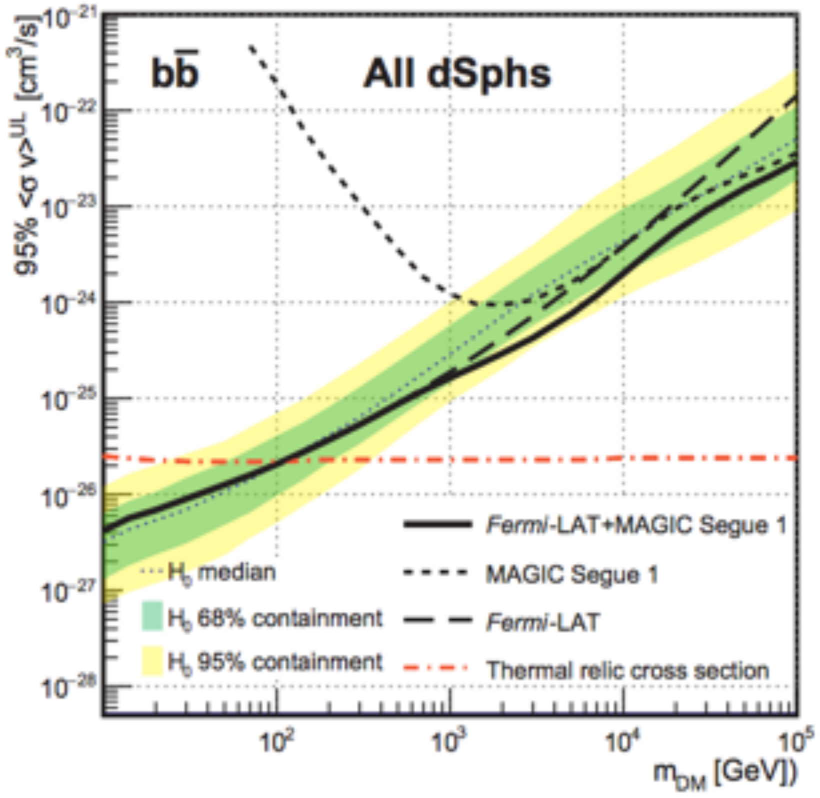
	SU(N)	$U(1)'$
u_d	$\Box$	$2/3$
d_d	$\Box$	$-1/3$
ϕ	1	2

Table II. Field content and quantum numbers of the dark pion model, where $\Box$ stands for the fundamental representation of the dark $SU(N)$. We show here only the field content necessary for the Impeded DM phenomenology, but it is important to keep in mind that additional particles like heavy dark leptons are necessary for anomaly cancellation.

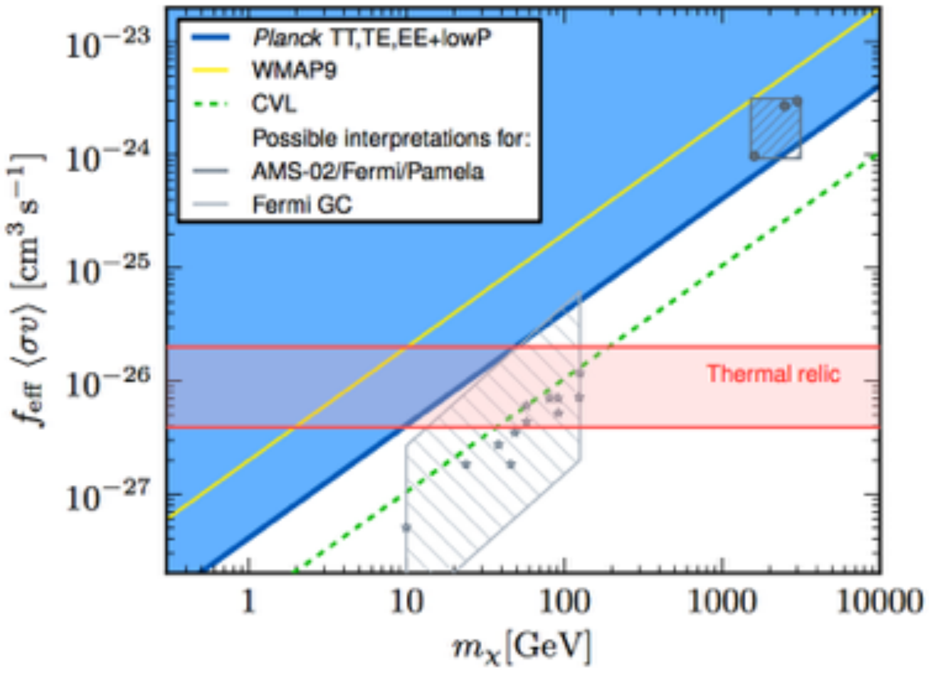
Constraints on the dark pion model



Ahnen et al '16

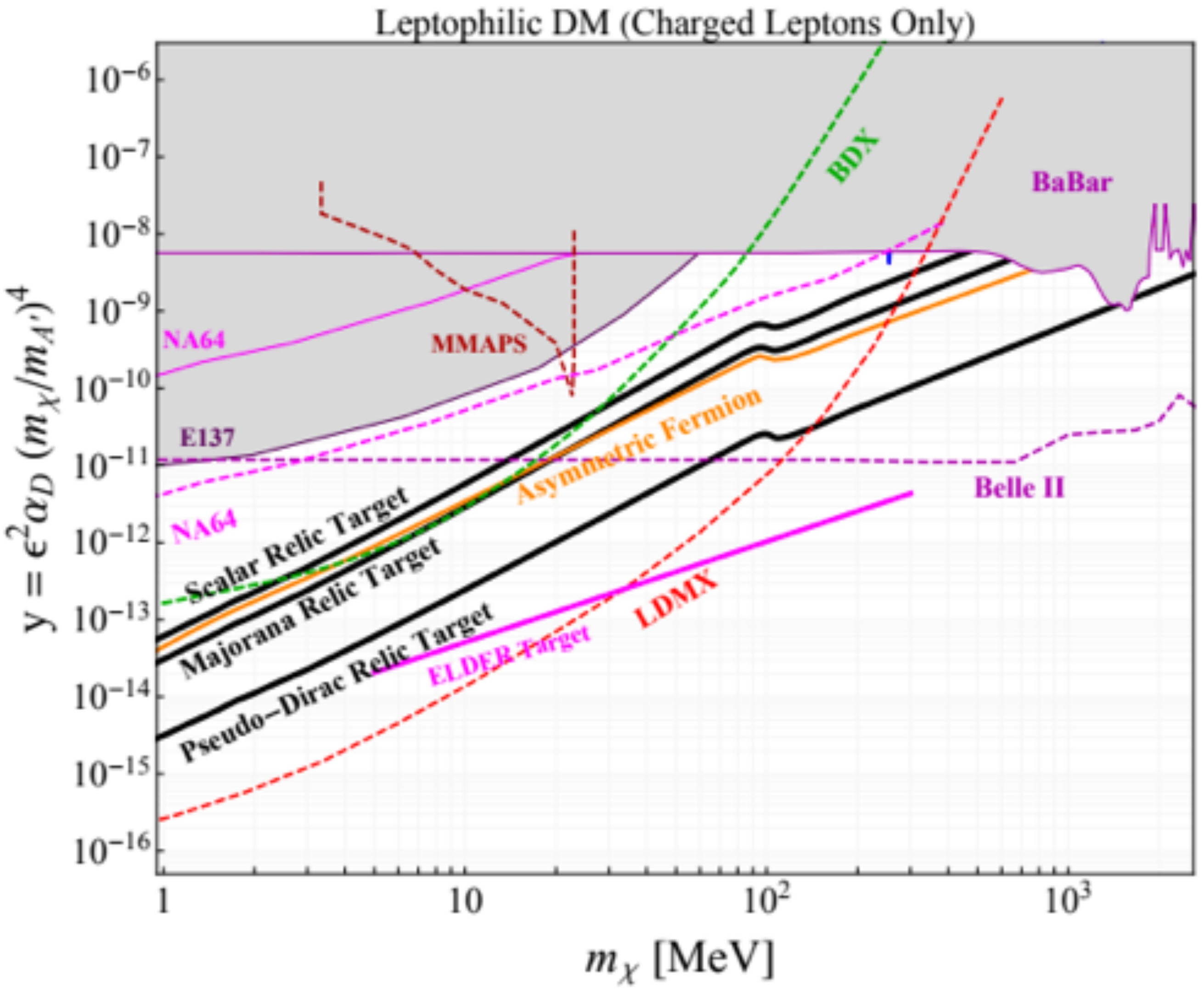


Planck Collaboration 2015



The low-mass thermal region

- Suppose we continue to focus on thermal freezeout, but consider the sub-GeV mass range.
- Approach:
  - consider simplified models of scalar/ Majorana fermion/pseudo-Dirac fermion DM,
  - fix coupling to annihilation products via thermal relic calculation,
    - if DM directly coupled to Standard Model, explore implications of thermal coupling,
    - if DM annihilates within dark sector, search for mediators between dark and visible sectors, invisible decays, etc.
  - re-examine complementarity between direct/indirect/accelerator searches.



Example for thermal relic DM annihilating through a leptophilic mediator
Battaglieri et al ’17, Cosmic Visions report