What can Galactic gamma rays tell us about dark matter?

Tracy Slatyer

Yale “Physics Club” Colloquium
17 October 2022

JCAP02(2017)005 (corrected v3 appeared on arXiv last month)
with Pouya Asadi, Matthew Baumgart, Patrick Fitzpatrick & Emmett Krupczak
JHEP 1901 (2019) 036, PRD98 123014 (2018), and JHEP 1803 (2018) 117,
with Matt Baumgart, Tim Cohen, Emmanuel Moulin, Ian Moult, Lucia Rinchiuso, Nicholas Rodd, Mikhail Solon, Iain Stewart and Varun Vaidya
work in progress
with Matthew Baumgart, Nicholas Rodd & Varun Vaidya

Outline

- The puzzle of dark matter (DM) and WIMPs as a DM candidate

- Gamma-ray observations set limits on DM annihilation and decay that constrain broad classes of models

- Can we exclude the simplest/minimal heavy WIMPs?

    - Collider/direct constraints (and lack thereof) + the need for indirect detection

    - Theoretical challenges to calculating signals from these models

    - Indirect detection estimates & implications

What is dark matter?

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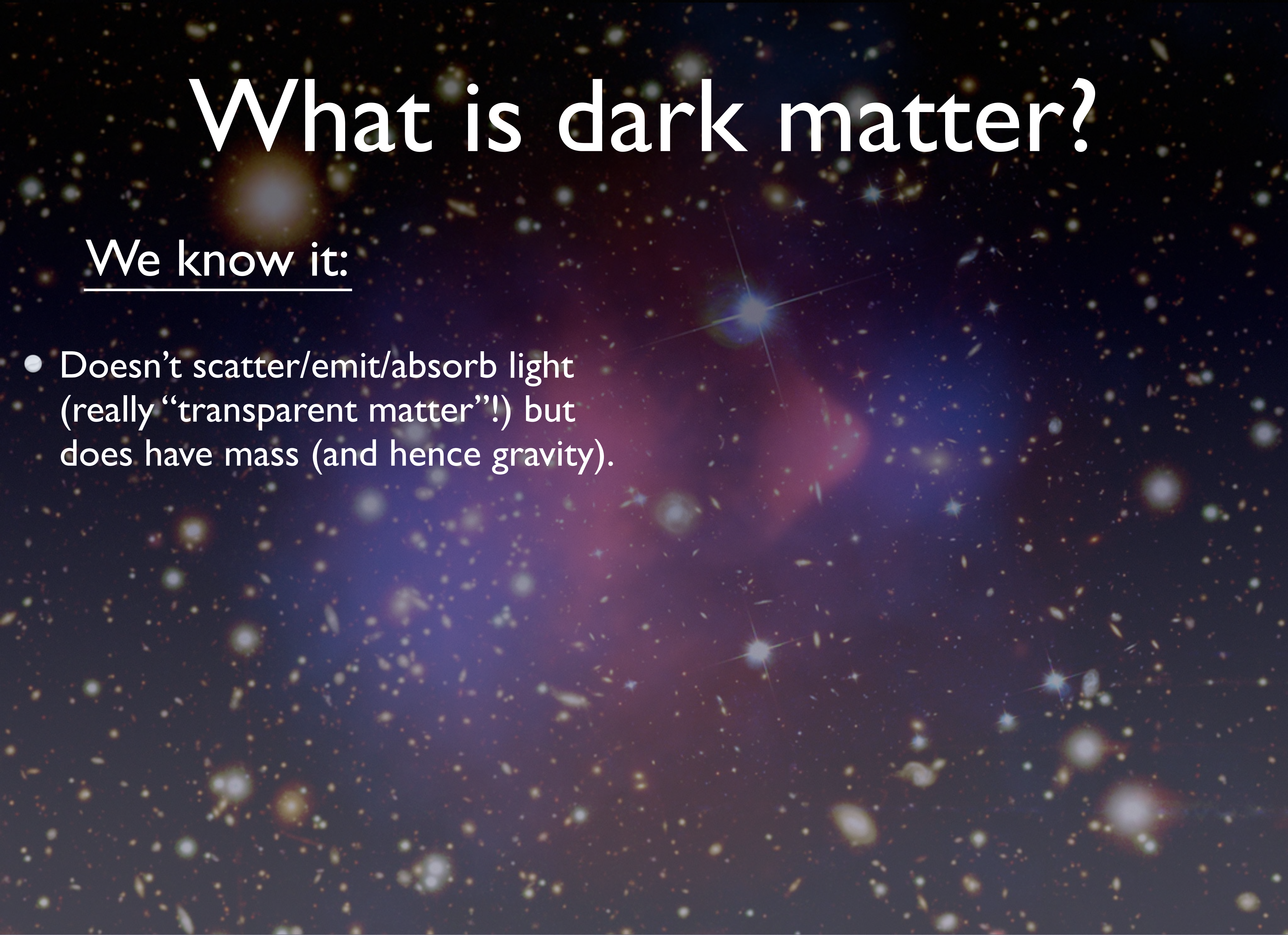

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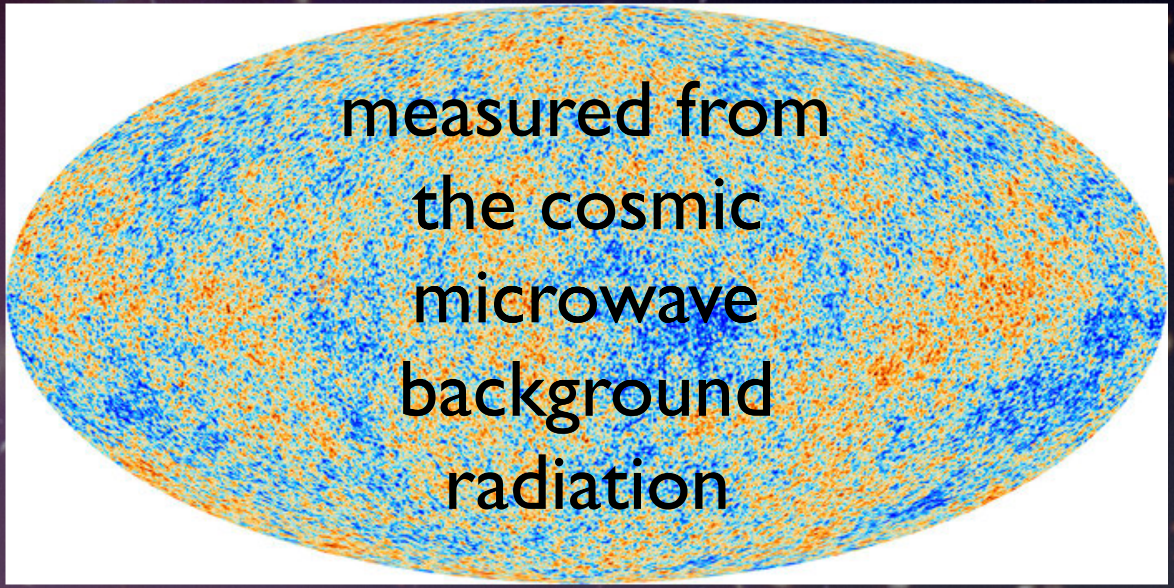

measured from the cosmic microwave background radiation

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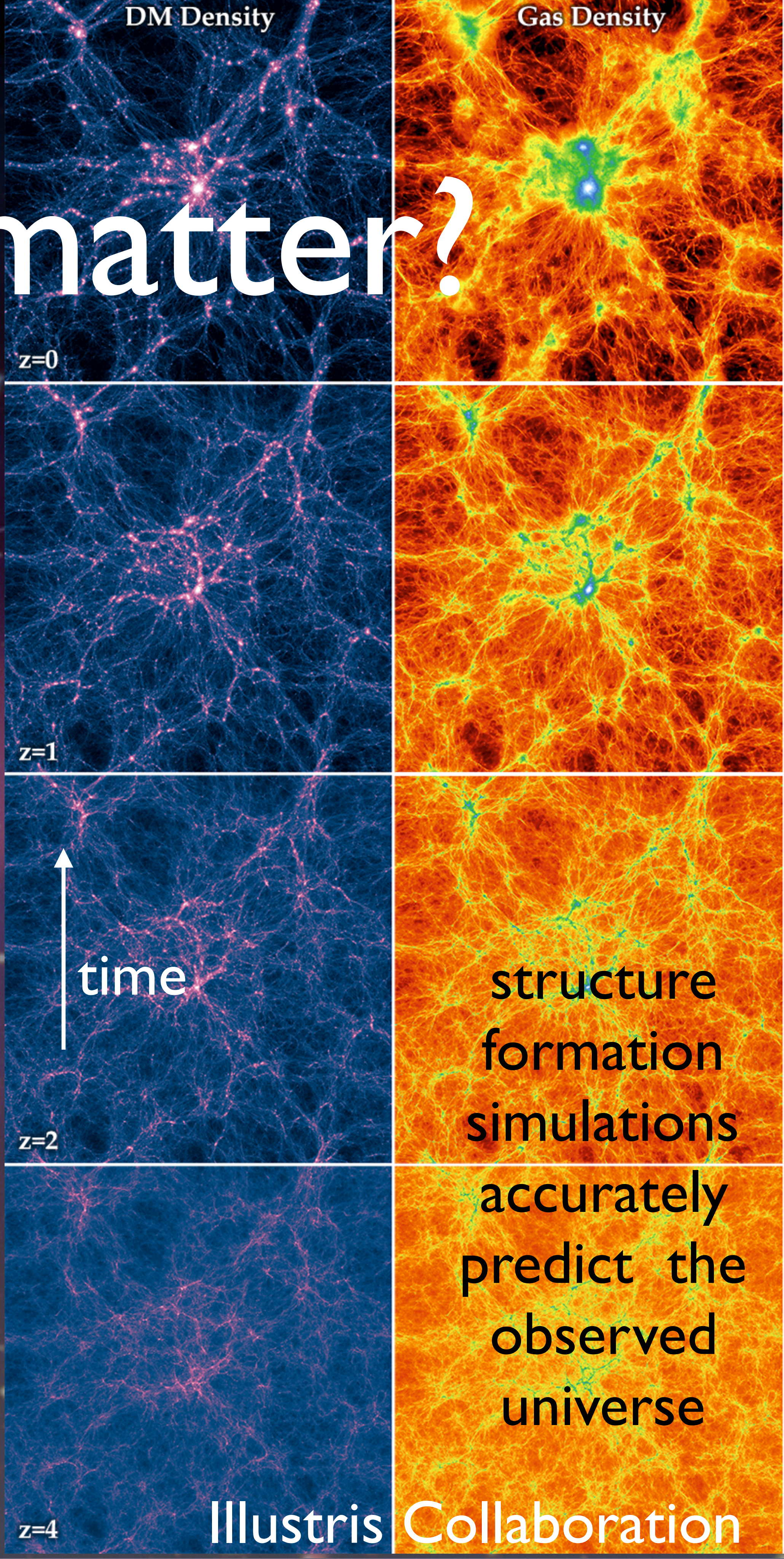

structure formation simulations accurately predict the observed universe

Illustris Collaboration

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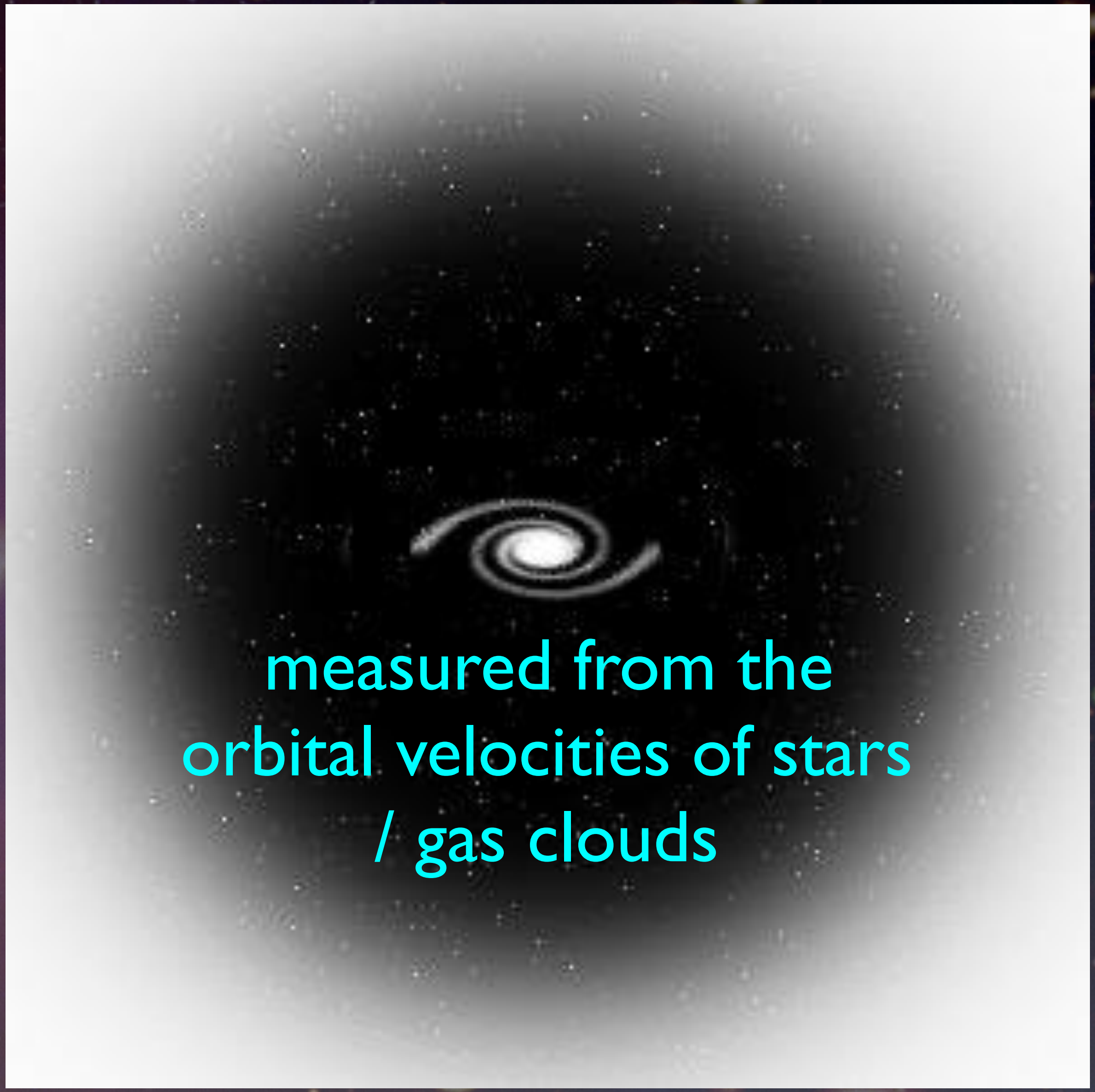

measured from the orbital velocities of stars / gas clouds

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- Interacts with other particles weakly or not at all (except by gravity).

null results of
existing searches

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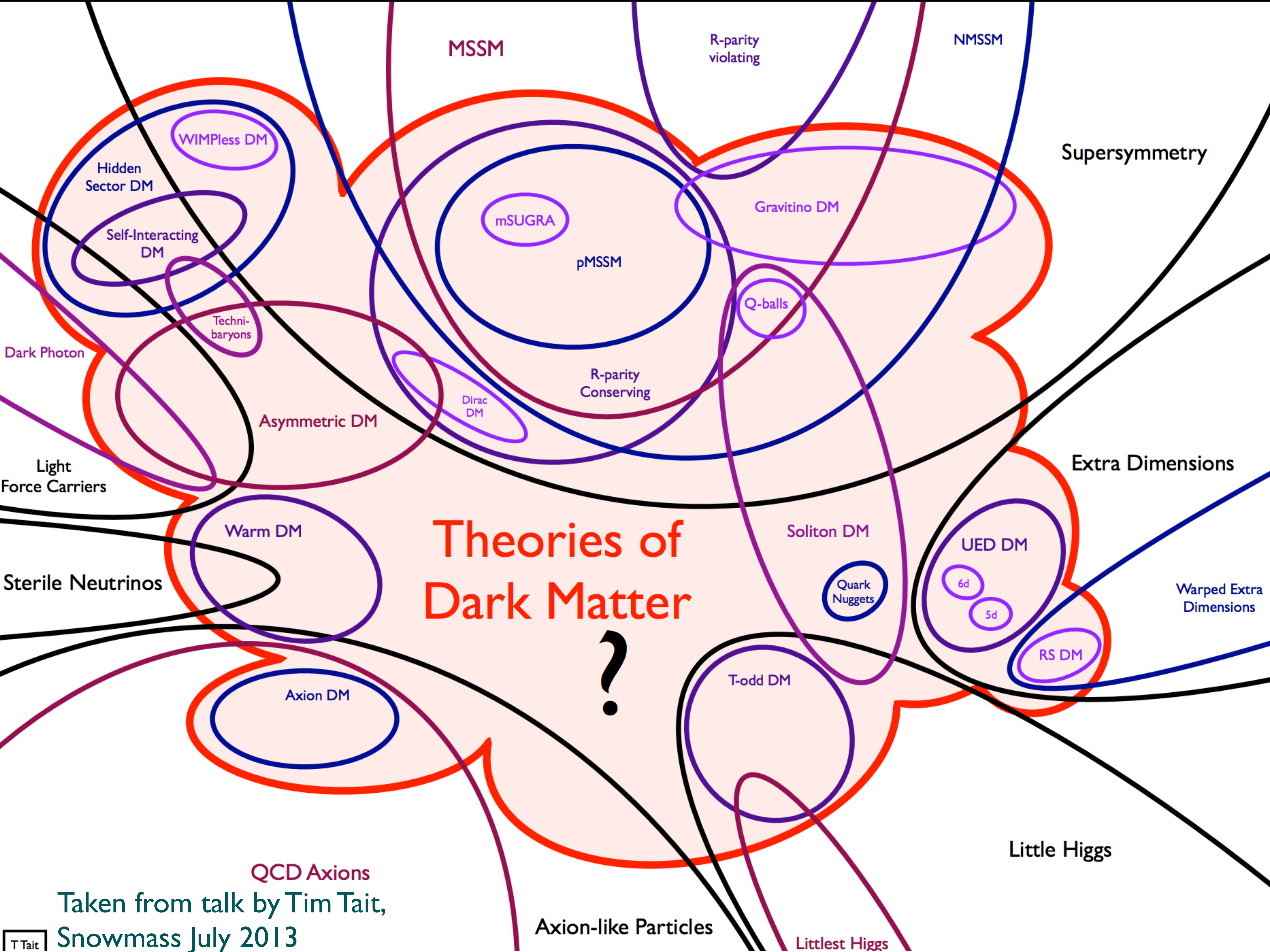
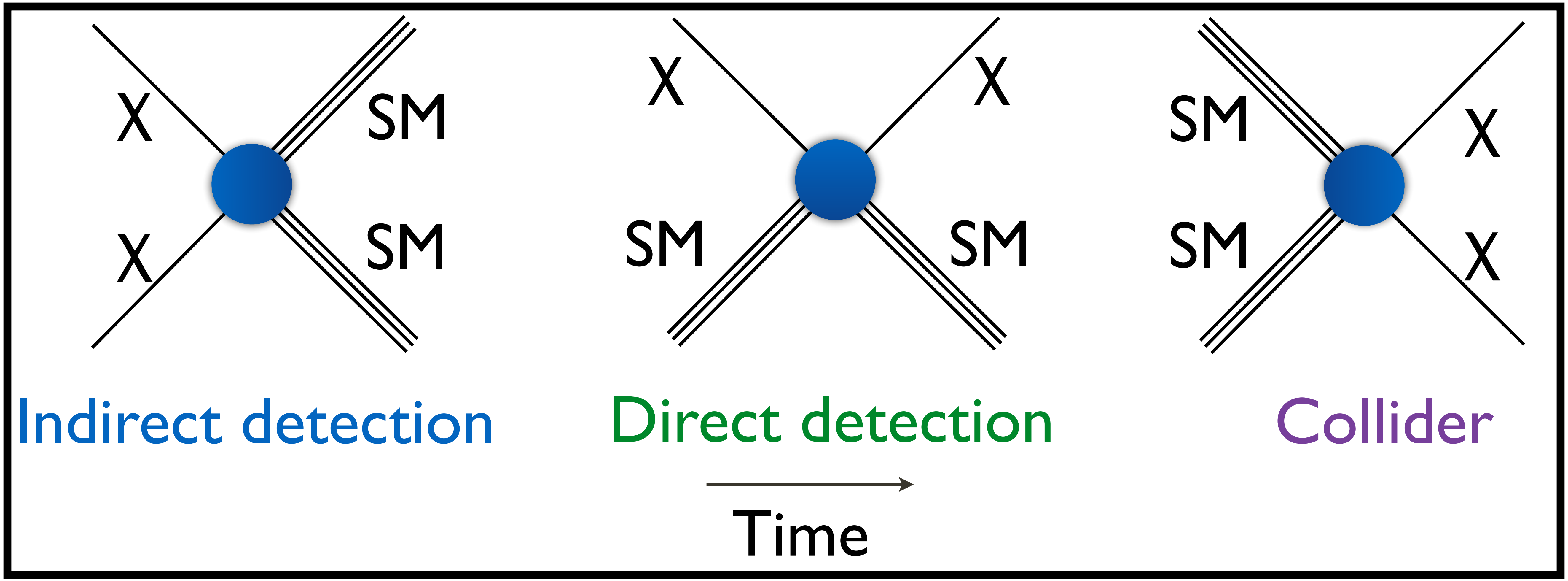
- Why its abundance is what it is.
- If/how it’s connected to other deep problems in particle physics.



Taken from talk by Tim Tait, Snowmass July 2013

Searches for dark matter



Indirect detection

Direct detection

Collider

Time

- Indirect detection: look for Standard Model particles - electrons/positrons, photons, neutrinos, protons/antiprotons - produced when dark matter particles collide or decay.

- Direct detection: look for atomic nuclei “jumping” when struck by dark matter particles, using sensitive underground detectors.

- Colliders: produce dark matter particles in high-energy collisions, look at visible particles produced in the same collisions, check for apparent violation of energy/momentum conservation.

- Not an exhaustive list - in recent years also a great deal of attention to oscillation (e.g. photon-axion conversion), absorption (in direct detection experiments for light particles), etc

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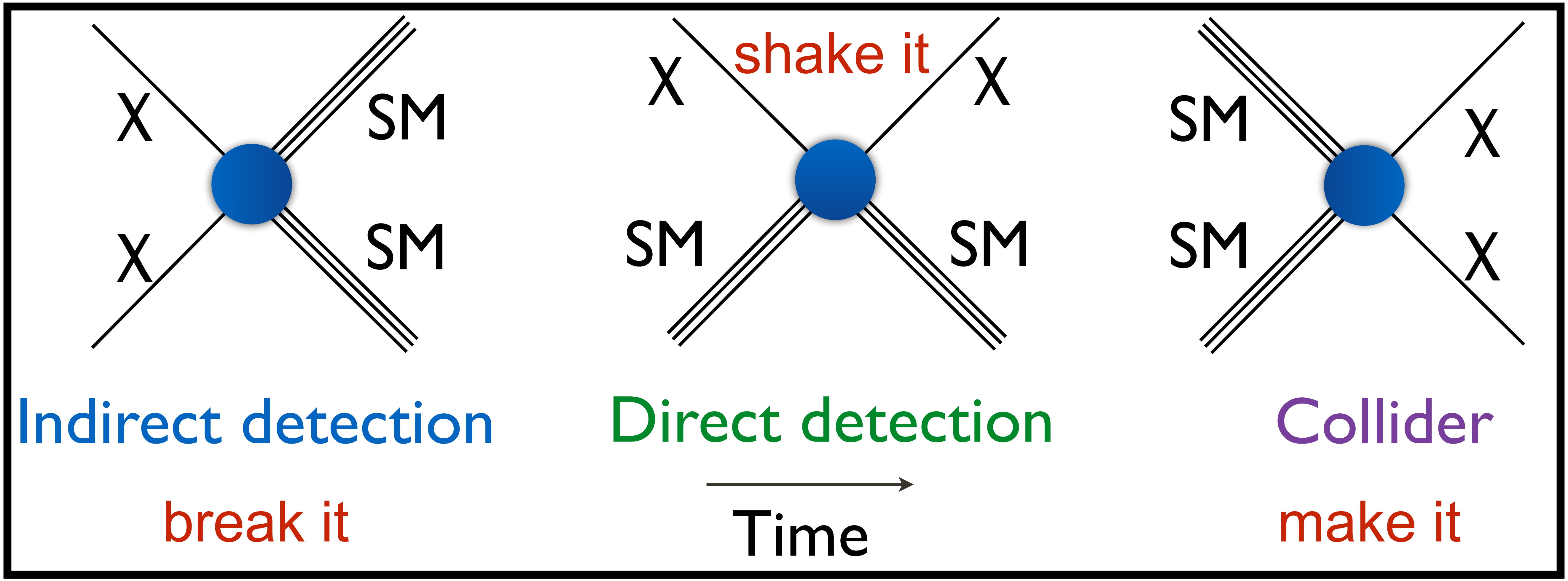

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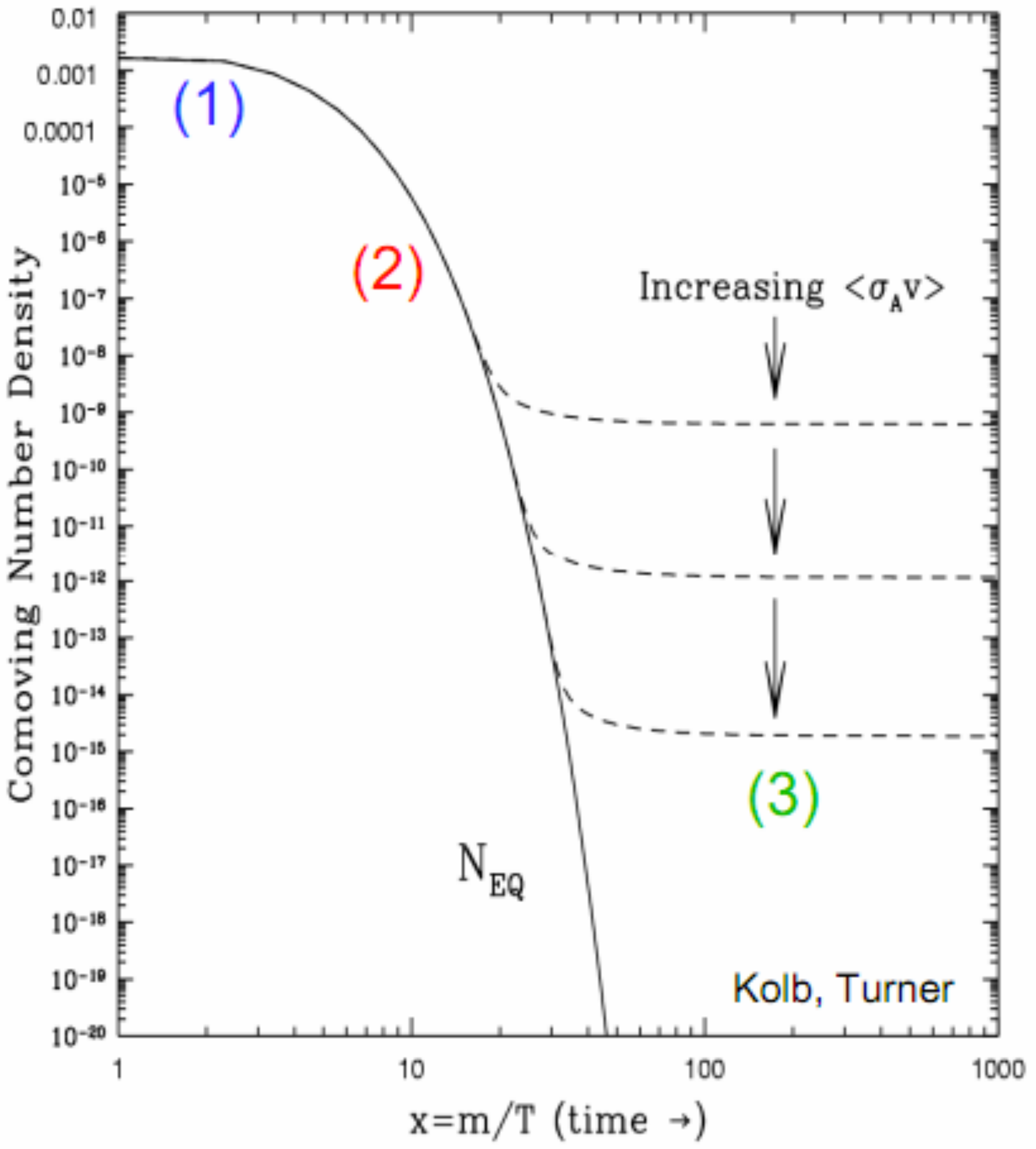
Thermal freezeout

- If DM particles can annihilate to visible particles, when the universe was sufficiently hot the reverse process would also occur - producing DM in thermal equilibrium with Standard Model (1)
- When the temperature fell below the DM mass, DM production would become inefficient while annihilation continued - leading to depletion (2)
- Eventually annihilation would also become inefficient relative to cosmic expansion (3), leading to a plateau set by the strength of annihilation



The case for WIMPs

- Required annihilation cross section to match the abundance is
  $\langle\sigma v\rangle \sim 2 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s} \sim 1/(100\ \mathrm{TeV})^2 \sim \alpha^2/\mathrm{TeV}^2$
  consistent with the expected perturbative cross section ($\sim\alpha^2/M^2$) for weak-scale mass and interaction strength, or masses up to the O(100 TeV) scale with stronger interactions.

- Motivates DM as a Weakly Interacting Massive Particle (WIMP).

- More generally, in this “thermal freezeout” scenario, DM must have a mass between ~1 MeV and 100 TeV (in standard cosmology).

Are WIMPs ruled out?

- The GeV-TeV mass range most strongly motivated by this argument has been studied extensively (& lots of recent+ongoing work on the sub-GeV range).

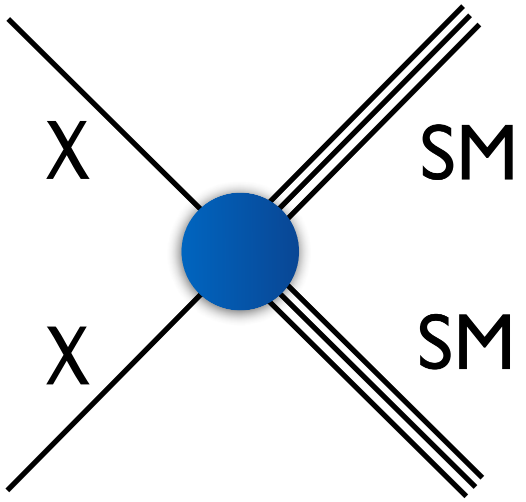
- No detection (yet) of new weak-scale physics at the LHC.

- No detection (yet) of WIMPs in direct or indirect dark matter searches - direct searches probing cross sections as small as $6\text{x}10^{-48}$ cm^2 [LZ collaboration '22].

- Can we exclude thermal freezeout as an origin for DM across the MeV — 100 TeV mass range?

- Can we even exclude the more specific case where the DM interacts through the W and Z gauge bosons?

Indirect limits on annihilation



- Using telescopes, we can search for signatures of DM annihilation in the present-day universe - same process that sets original thermal relic abundance (although conditions are different today)

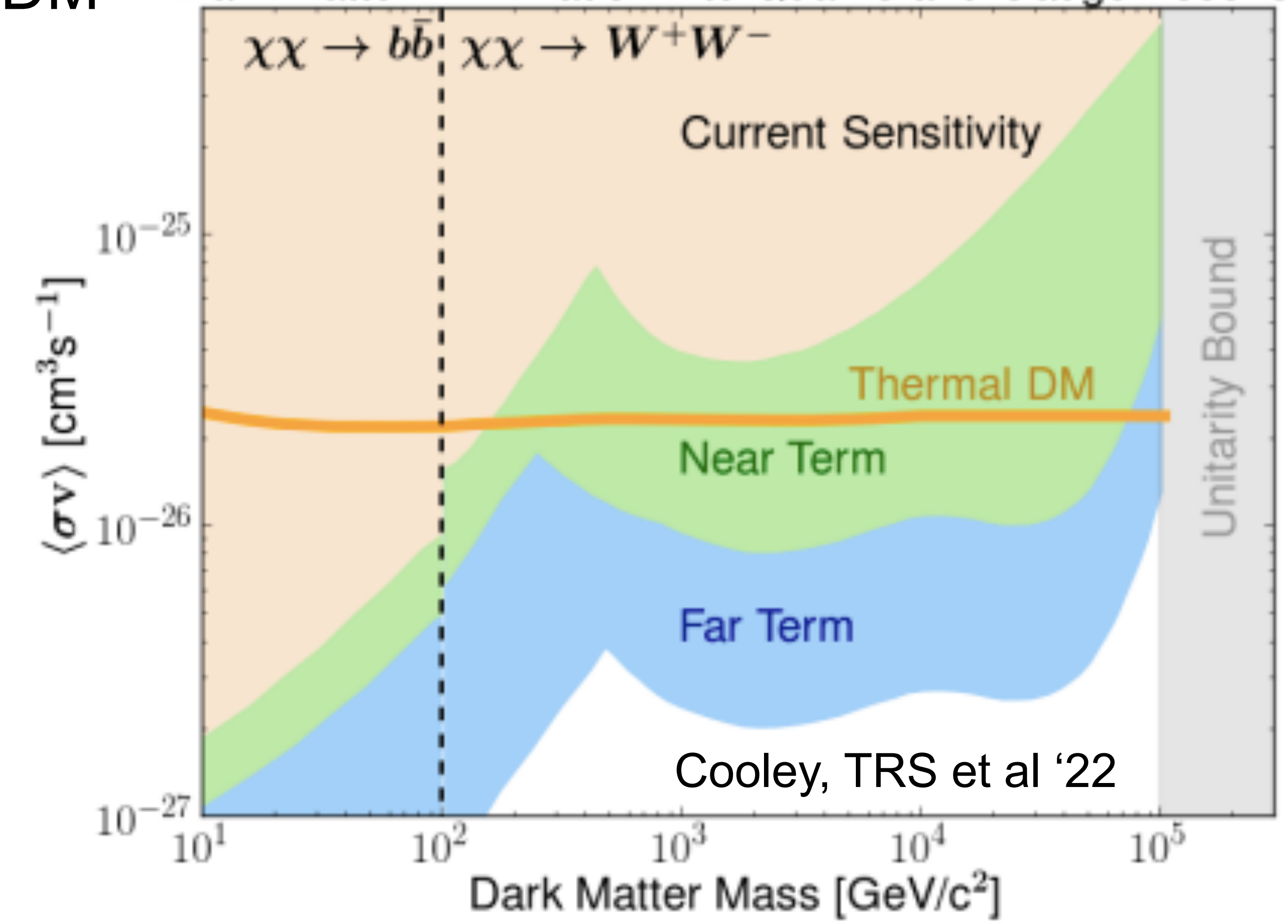
- Cosmological bounds can also set limits on DM annihilation at earlier times, especially for light DM

- Combined constraints currently test thermal relic cross-sections up to hundreds of GeV, depending on final states

- Next-generation telescopes could push this limit to 10s of TeV masses

- Also some puzzling excesses - better understanding of astrophysical backgrounds is critical [see Leane et al 2203.06859]

Dark Matter Annihilation into Quarks and Gauge Bosons



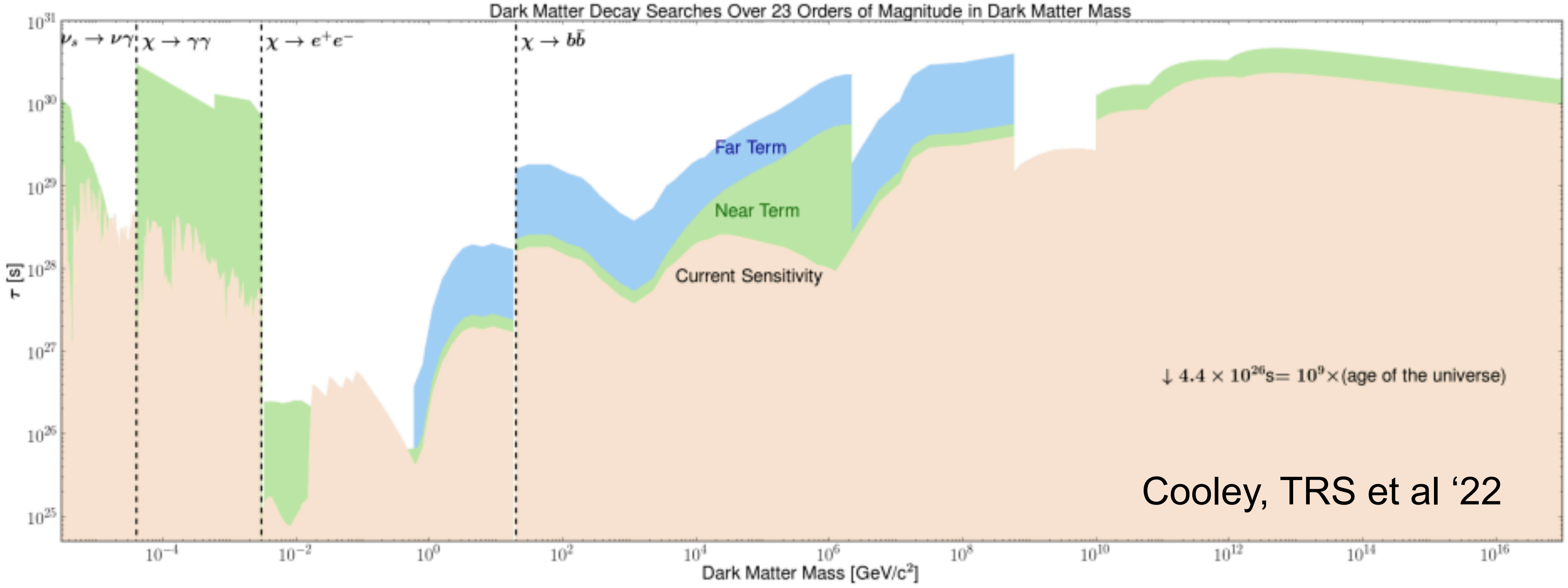
Cooley, TRS et al ‘22

What about non-thermal DM?

- Not all DM candidates are relics of thermal freezeout, and those that are can have present-day cross sections that are enhanced or suppressed relative to the freezeout cross section.

- At low masses, DM annihilation rates far below the thermal cross-section can be constrained, especially if proposed future balloon- and space-based gamma-ray telescopes are realized.

- With similar searches, we can also set limits on DM decay over a huge range of masses.



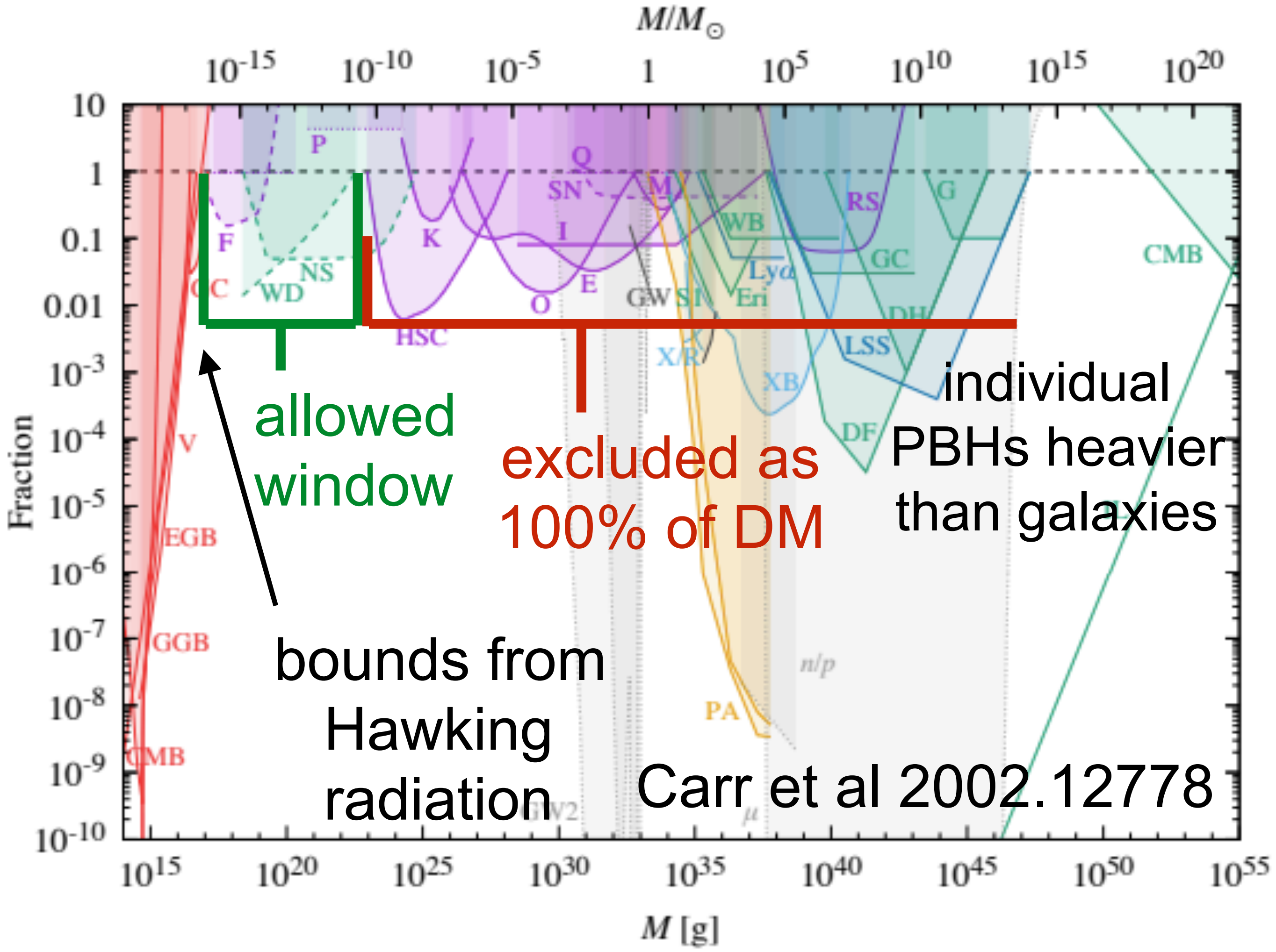
Cooley, TRS et al ‘22

Primordial black holes

- Primordial black holes (PBHs) can also serve as a DM candidate if they lie in the right mass range - $10^{17\text{-}23}$ g PBHs appear viable to constitute 100% of the DM.

- PBHs are decaying DM - they slowly decay through Hawking radiation (with temperatures far less than the BH mass), PBHs around 10^{17} g would produce X-ray and soft gamma-ray radiation.

- The non-observation of this radiation sets the strongest current bounds on such PBHs - possible to improve the limit with future MeV-band observations, where a number of new telescopes have been proposed.



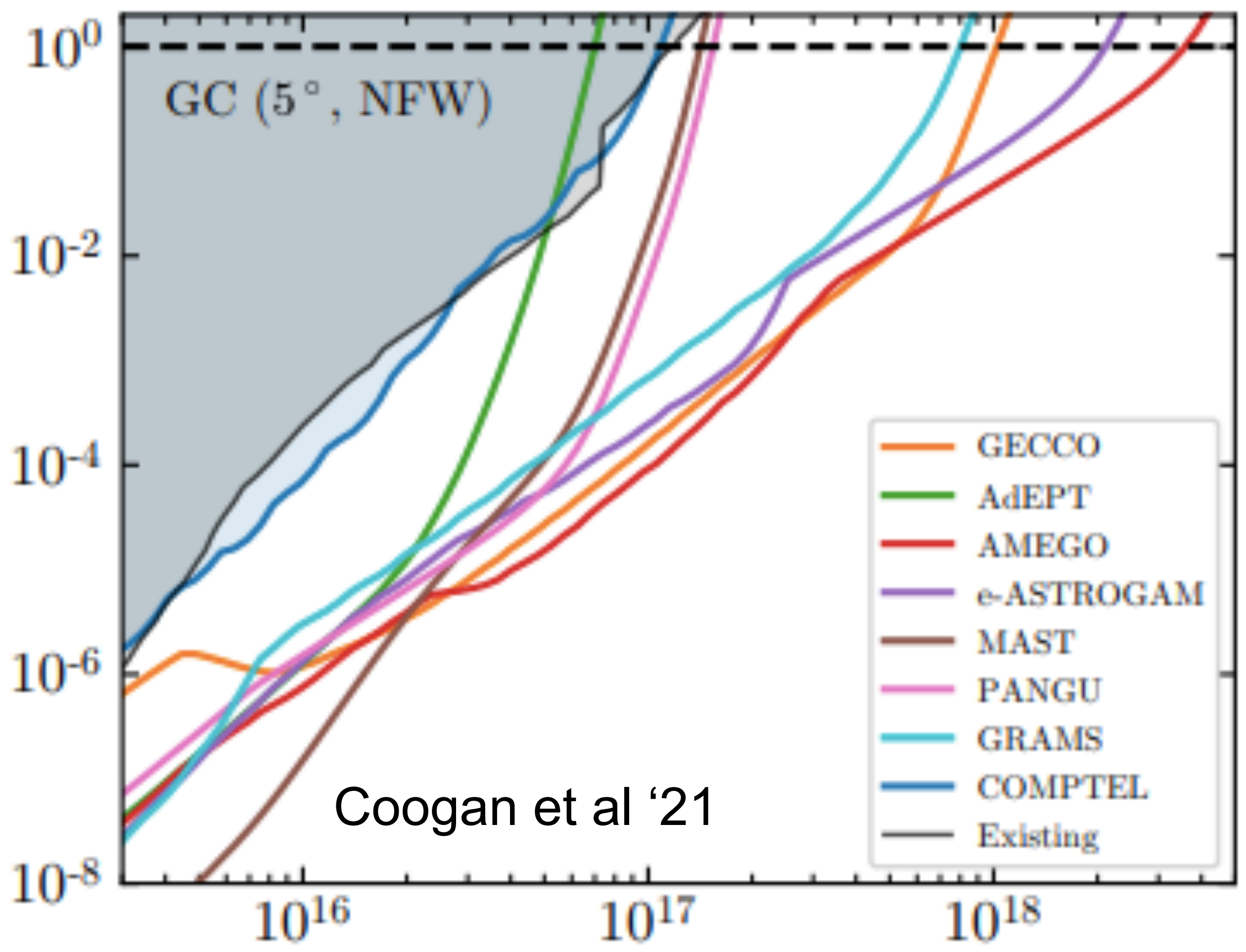
allowed window

excluded as 100% of DM

individual PBHs heavier than galaxies

bounds from Hawking radiation

Carr et al 2002.12778



Coogan et al ‘21

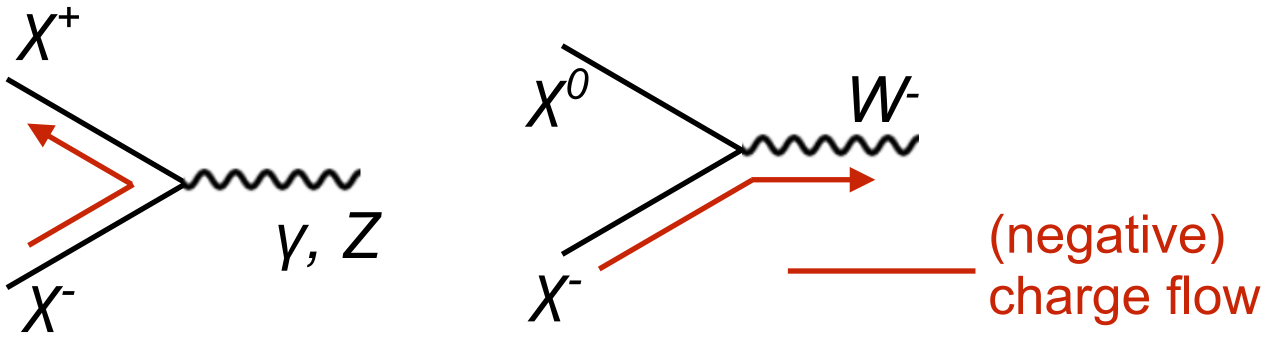
Can we exclude the classic WIMP: DM that interacts with the Standard Model via the W and Z bosons?

Minimal dark matter (MDM)

- Let us focus on the highly predictive scenario where DM is charged under the Standard Model weak interactions & transforms as part of a new $SU(2)_L$ multiplet [Cirelli et al ’05] - in the same way electrons & neutrinos interact via the W/Z bosons

- Other particles in the multiplet can carry electric charge

- DM interactions with W and Z bosons + number of partner particles are completely fixed by representation of $SU(2)_L$

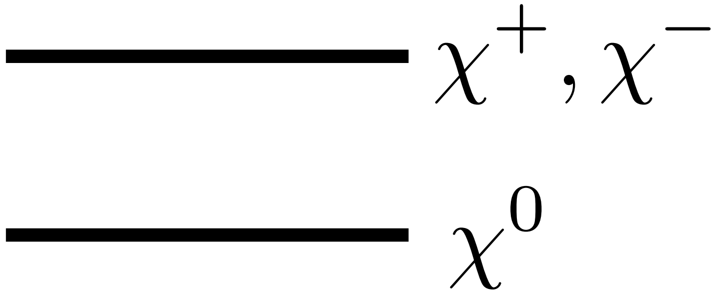


Example in “triplet” case - DM + two partners

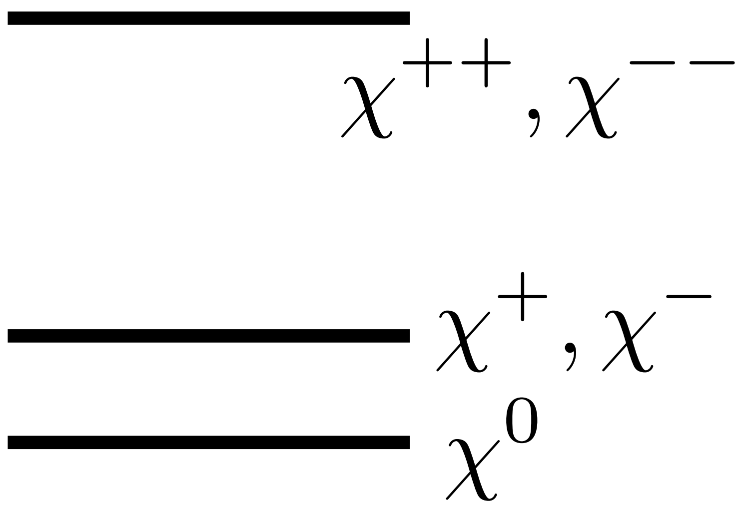
- DM obtains abundance via thermal freezeout - late-time relic density fixed by DM mass once representation + cosmological history are known

Examples for small representations

- wino / triplet representation:
  3 total particles (DM + two partners with charge ±1),
  appears as the counterpart of the W boson in models of supersymmetry,
  explains full DM abundance at DM mass of <u>3 TeV</u>



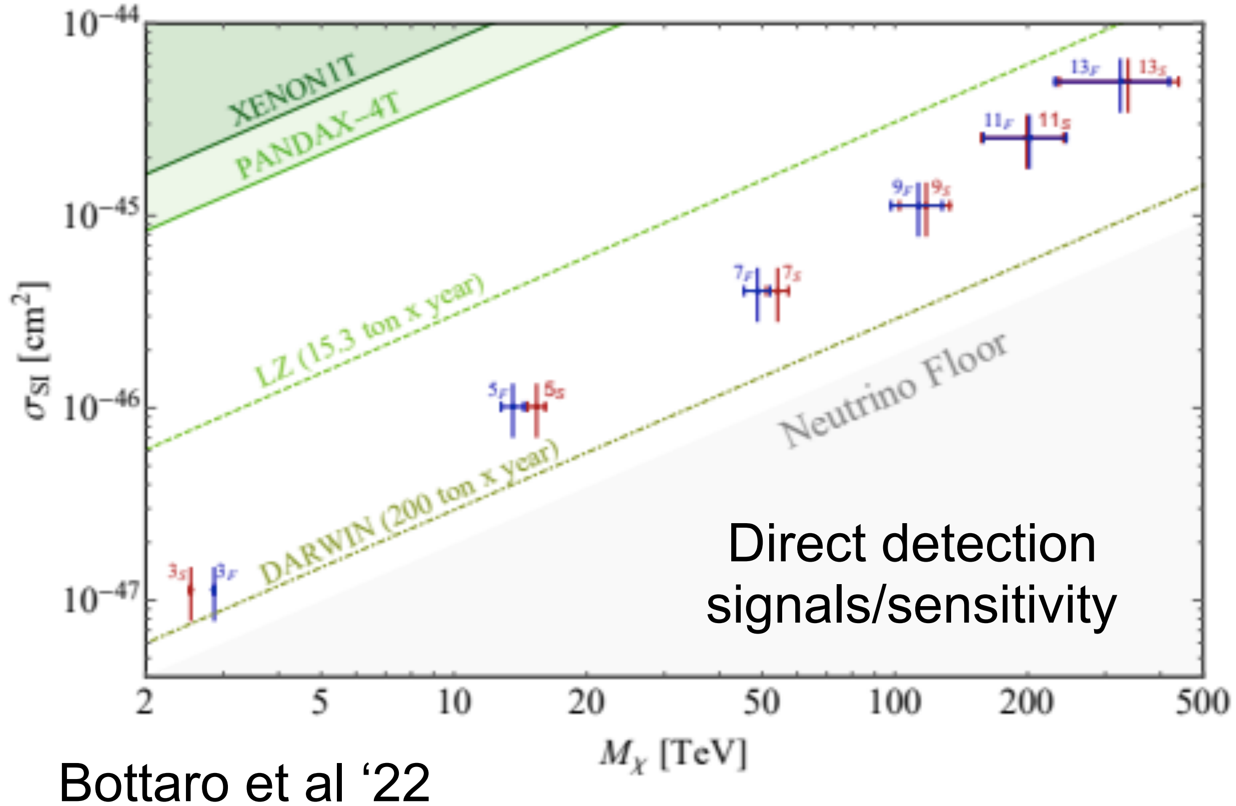
- quintuplet representation:
  5 total particles (DM + partners with charge ±1, ±2),
  explains full DM abundance at DM mass of <u>14 TeV</u>



- etc…

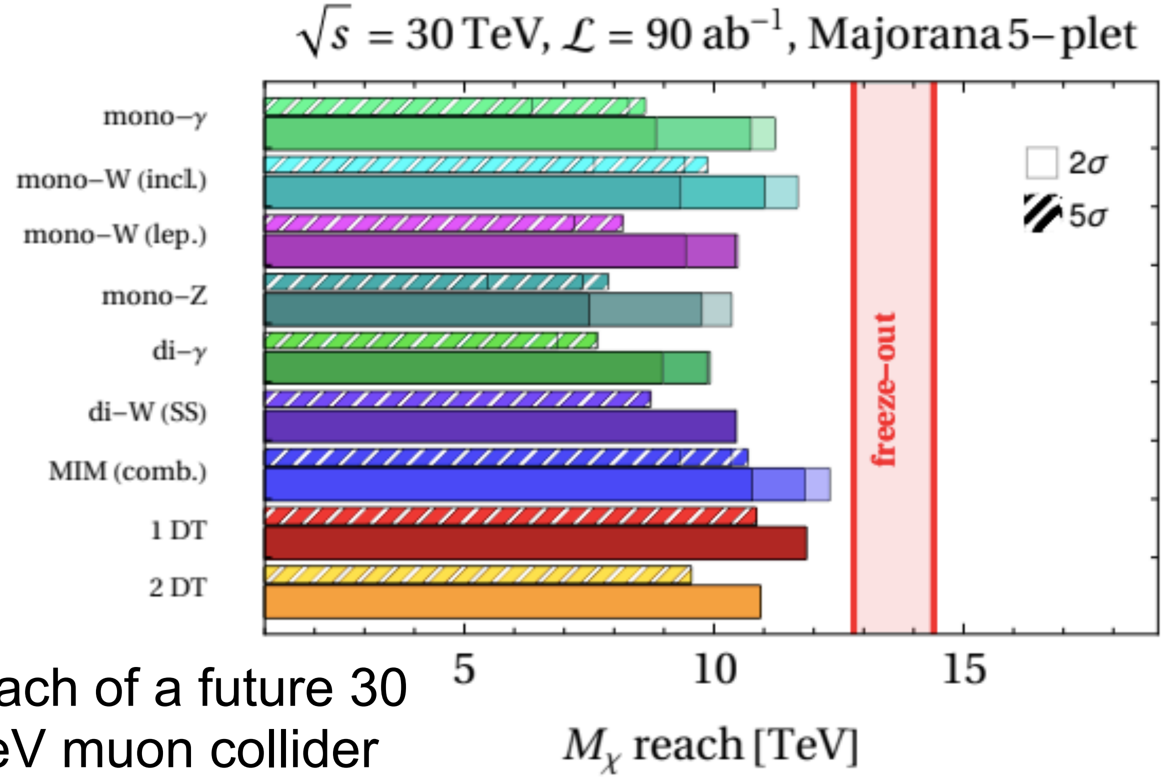
Testing minimal dark matter

- Despite being predictive and simple, these models are very hard to exclude!
- Direct detection cross sections are below the reach of current searches (albeit in reach of next-gen experiments - above the irreducible neutrino background)
- High masses needed to explain full DM relic density make collider detection very challenging, although possible for smaller representations or subdominant DM components
- What about indirect detection?



Direct detection signals/sensitivity

Bottaro et al ‘22

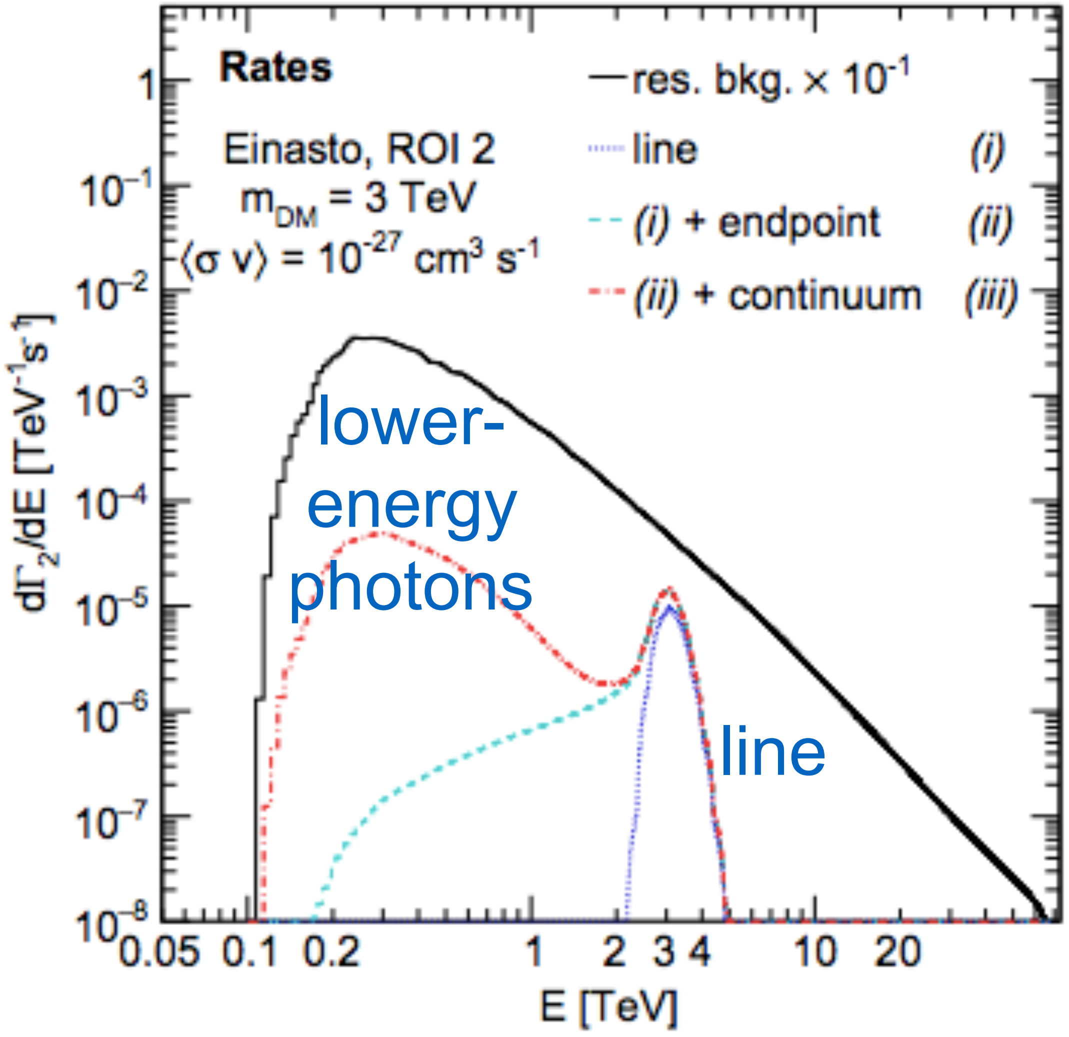


Reach of a future 30 TeV muon collider

What signals do we expect?

- Dream signal: two DM particles collide & produce two gamma rays, each carrying energy = DM mass.
- Gamma-ray “spectral line” - many photons with identical energy.
- Essentially zero background at gamma-ray energies.
- But expected to be small - DM is dark, does not interact directly with light.
- Other signals: lower-energy gamma rays, charged particles from DM particles colliding to make quarks, gauge bosons, etc → subsequently decay producing many secondary particles

Example signal & background



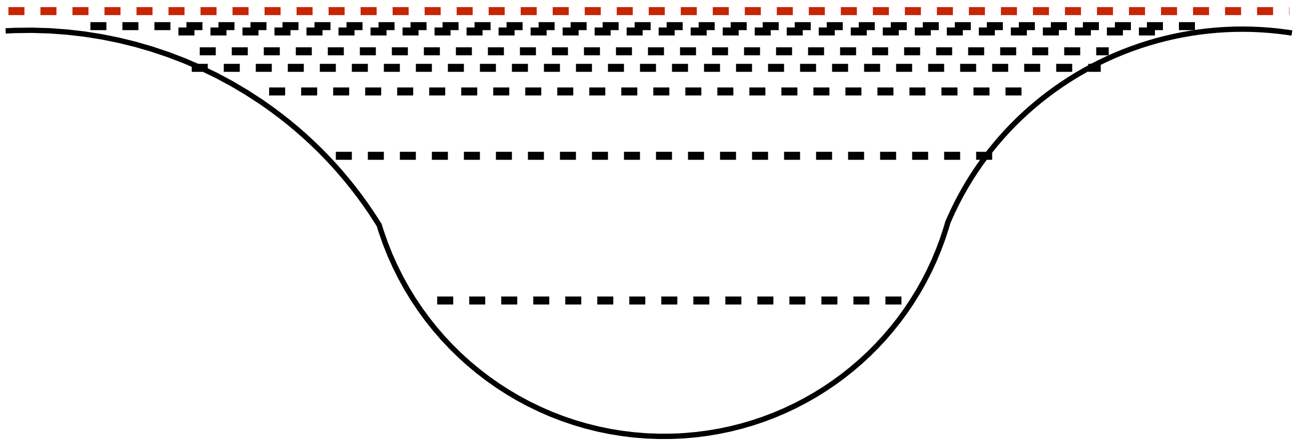
Predicting MDM signals

- We need to be able to predict the rate with which DM particles collide and annihilate in our target region
- Depends on DM density in our target region (major uncertainty) but let’s assume for the moment we can infer the density - how can we predict the overall signal?
- Standard method: use perturbative methods in quantum field theory
- Issue #1: in MDM scenarios, there are long-range forces between particles - effects are not always perturbative!
- This also means the annihilation cross-section today need not match its early-universe value.

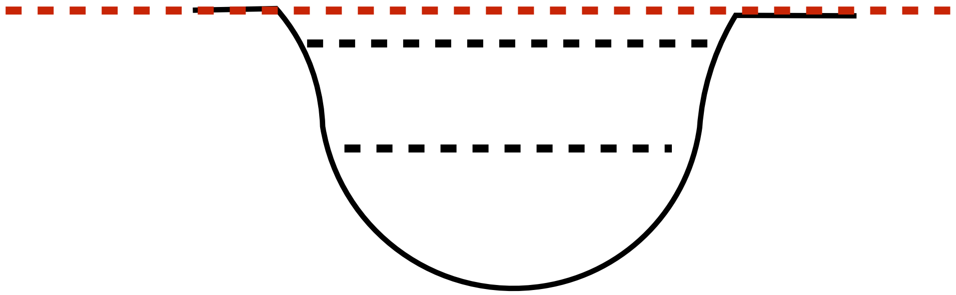
Non-perturbative effects: bound states

- Bound states are supported by long-range potentials
- Massless particles (like the photon) give rise to infinite-range forces (electromagnetism) - infinite tower of bound states
- More massive force carriers → shorter-range potentials → bound states become shallower, and the shallowest ones become unbound
- Criterion for bound states: Bohr radius < range of force, i.e. $m_{\text{force carrier}} < \alpha M$

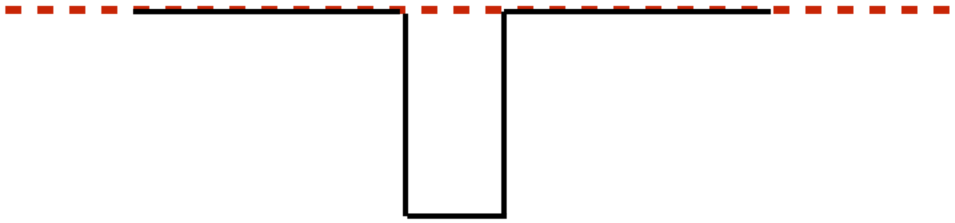
∞ range, ∞ bound states



shorter range, fewer bound states

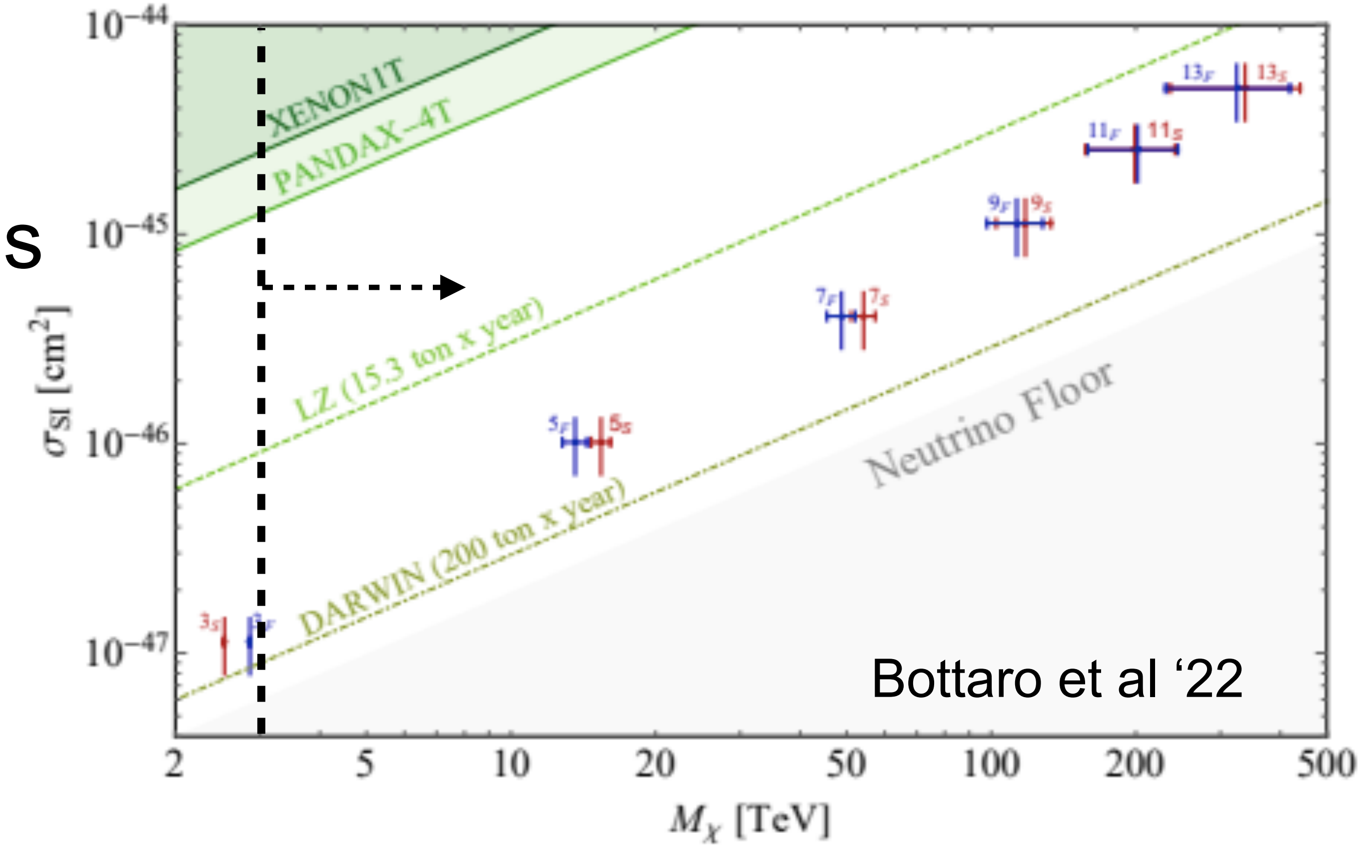


short range, zero bound states



Bound states in MDM?

- Force carriers are W and Z bosons
  - ~80-90 GeV in mass
  - coupling strength $\alpha_{weak} \sim 1/30$



Bottaro et al '22

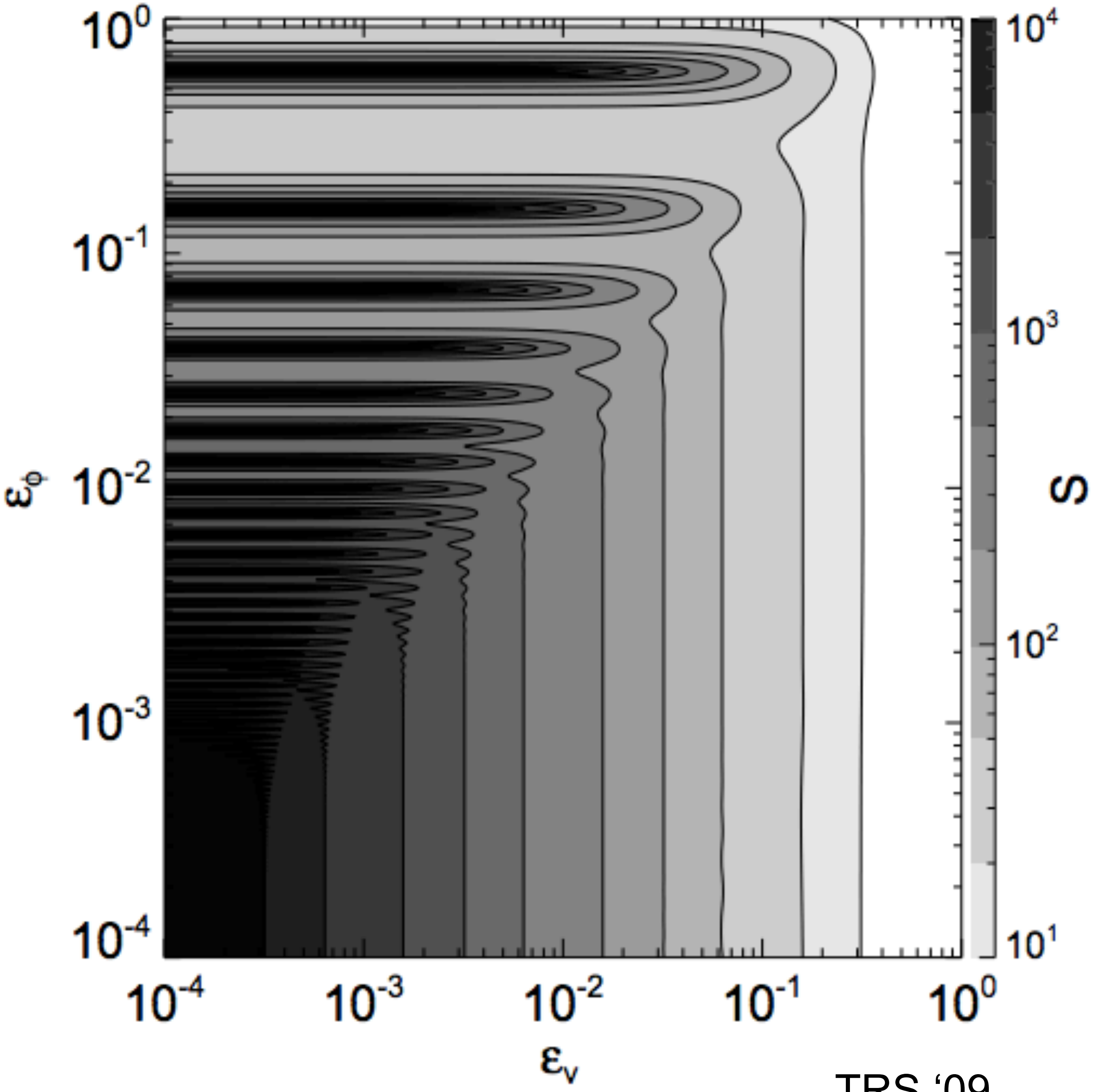
- Suggests bound states will form if the bound state constituents have mass around 100 GeV/$\alpha_{weak} \sim 3$ TeV or heavier
- We need to worry about formation of MDM bound states for all masses ~3 TeV and up
- These states will generally not be stable - they can decay through annihilation (like positronium) - contributing to indirect signal

Sommerfeld enhancement

- The presence of bound states also signals the effects of the potential can be large and non-perturbative
- When kinetic energy of incoming particles << potential energy, we can have large distortions to the wavefunction. Requires:

$$\mu v^2 \lesssim \alpha^2 \mu \Rightarrow v \lesssim \alpha$$

- Attractive interaction can greatly enhance annihilation ("Sommerfeld enhancement")

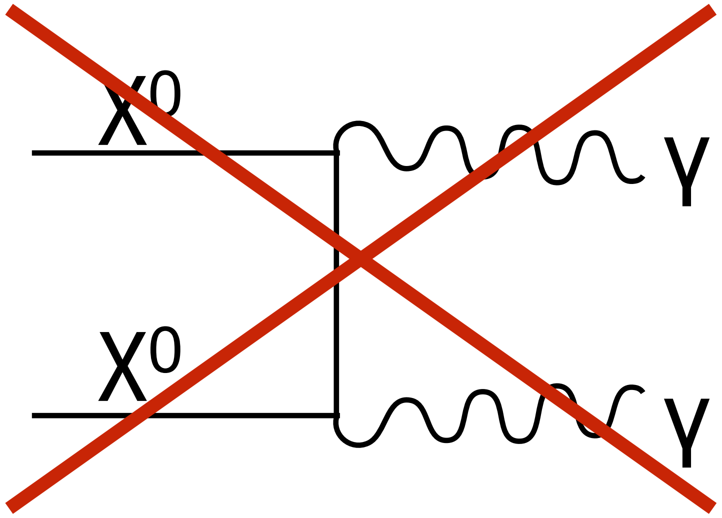


TRS '09

Enhanced line signals

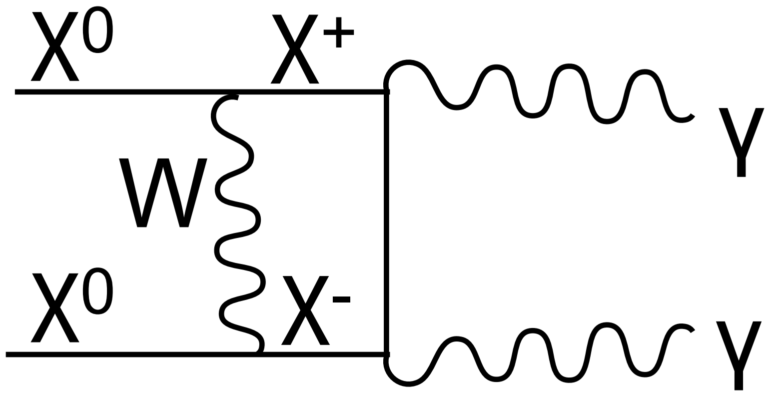
- The potential doesn't just enhance the overall annihilation rate - it can enhance particular final states
- In particular, the potential means that when DM particles get close to each other, they can effectively excite into the chargino partner states
- Charginos annihilate efficiently to gamma rays (just like electrons/positrons), unlike (electrically neutral) DM
- MDM is great at making gamma-ray lines!

Forbidden at tree-level

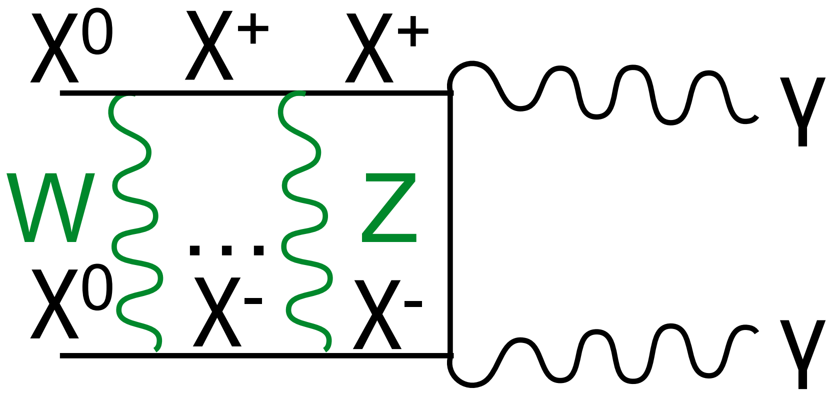


One-loop

$$\sim \sqrt{2}\frac{\alpha_W m_\chi}{m_W}$$



Long-range potential

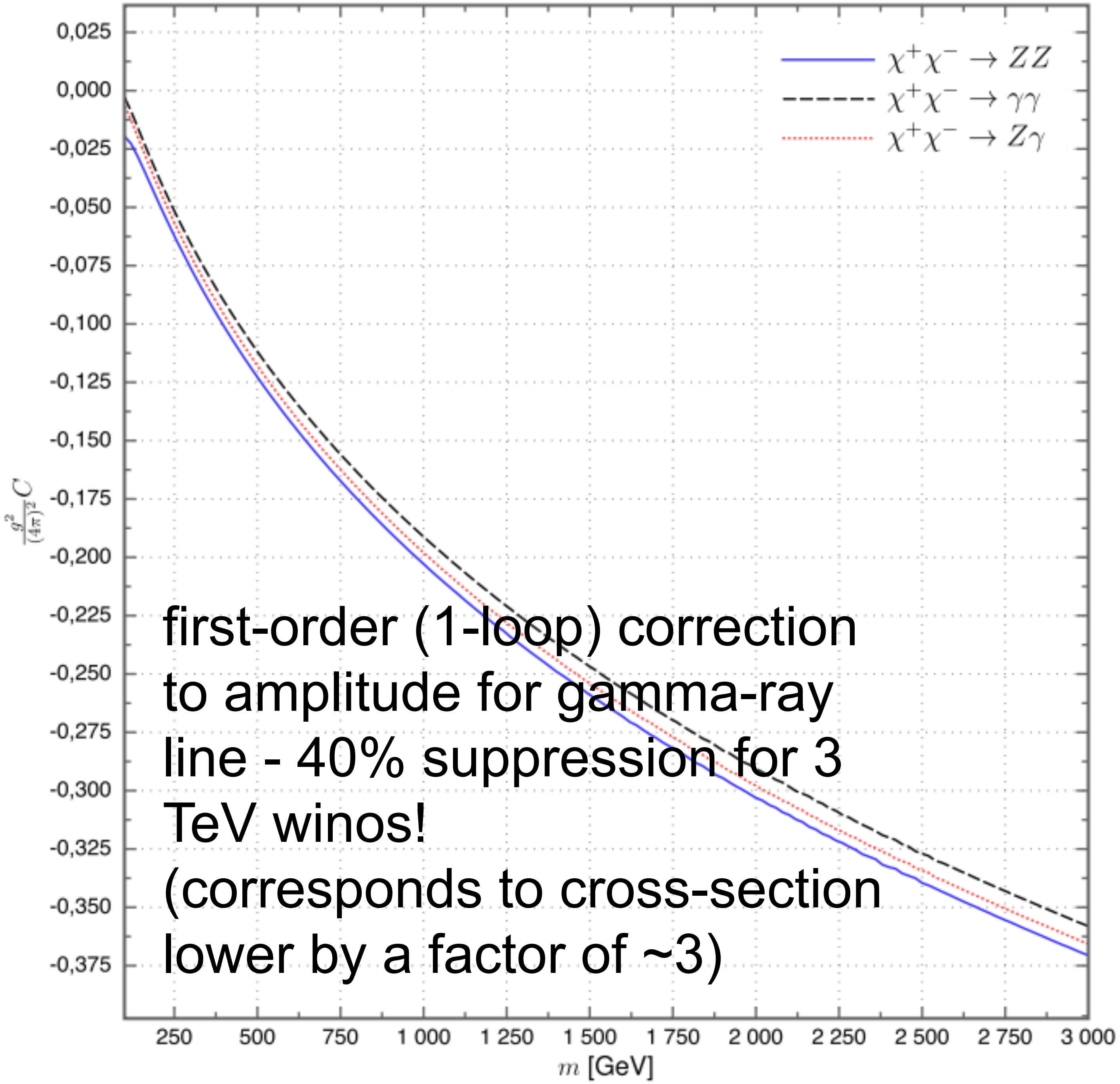


Non-perturbative IR effects

- The non-perturbative effects we have discussed so far are already known in quantum mechanics - can be studied using the Schrodinger equation for the initial-state non-relativistic particles.

- But (issue #2) there are additional large corrections arising from infrared effects in the perturbative quantum field theory calculation.

- Associated with radiation of low-energy or highly collimated particles.



first-order (1-loop) correction to amplitude for gamma-ray line - 40% suppression for 3 TeV winos!
(corresponds to cross-section lower by a factor of ~3)

Hryczuk & Iengo ‘12

Infrared divergences

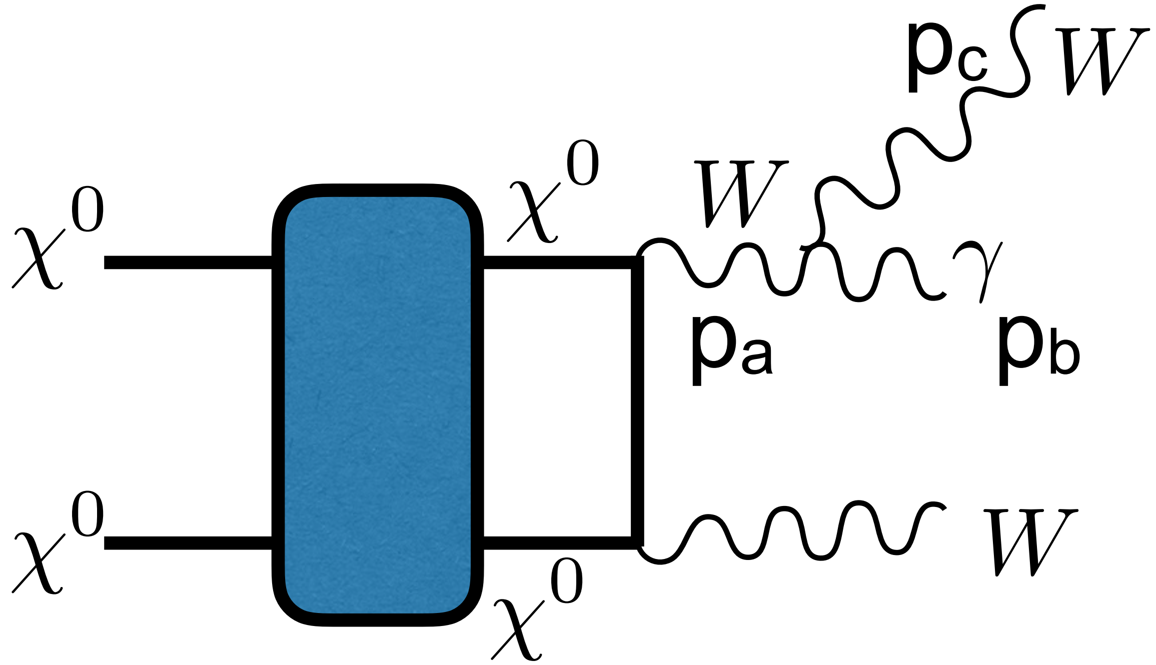
- Consider final states including at least one photon, visible to telescopes. In particular, consider photon-W+-W- final state, produced at tree level.

- Soft radiation: radiate low-energy particles from final state, E << m_χ.

- Collinear radiation: narrow splitting of one particle into two, small angle θ between particles.

- In the limit where W is massless, these parts of phase space produce infrared divergences - conceptually, these divergences signal that we cannot separate out final states with very soft or very collimated massless particles.

- Canceled order-by-order in perturbation theory, by corresponding IR divergence in one-loop diagrams with two-particle final state.



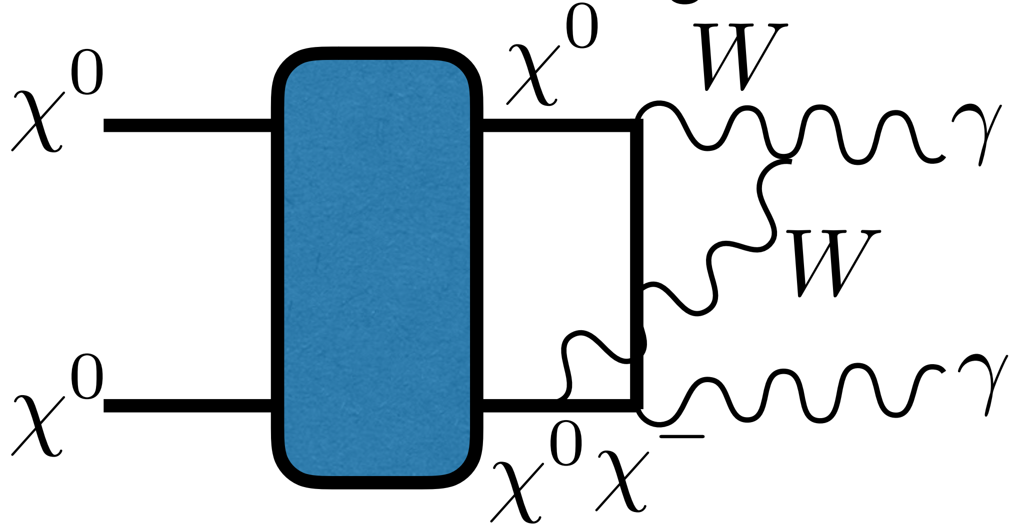
$$\propto \frac{1}{p_a^2} \approx \frac{1}{2E_b E_c(1-\cos\theta)}$$

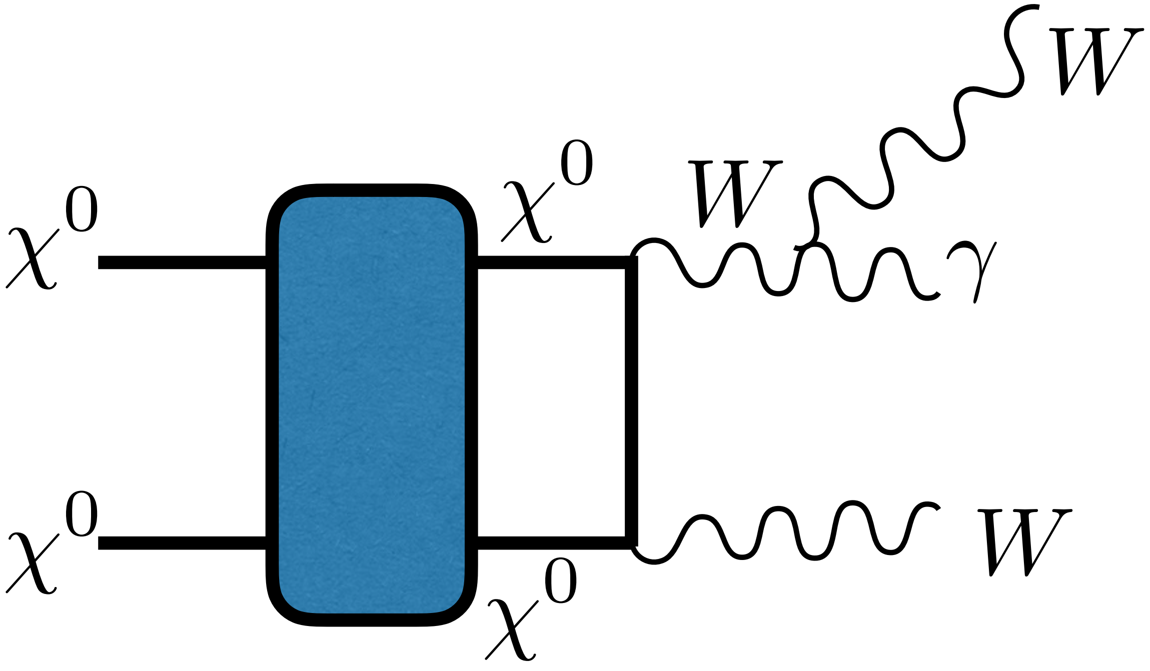
neglecting W mass

The origin of large logs

- Once a mass for the W is turned on, it regulates these IR divergences, but both kinds of diagrams (2-body and 3-body final states) still have large log-enhanced contributions, $\alpha_W \ln^2(m_\chi/m_W)$.
- Need to resum logs for reliable results.
- Need to account for enhanced 3-body final state - calculate full photon spectrum, not just line.
- In this case, logs of another small scale appear - the separation between the photon energy and the endpoint of the spectrum at $E_\gamma = m_\chi$.

line signal





continuum spectrum

The solution: soft collinear effective theory (SCET)

FIXED ORDER

SCET

$$\mathfrak{M} = \begin{pmatrix} 1 & & & & \\ \alpha L^2 & \alpha L & \alpha & & \\ \alpha^2 L^4 & \alpha^2 L^3 & \alpha^2 L^2 & \alpha^2 L & \alpha^2 \\ \alpha^3 L^6 & & \dots & & \\ \vdots & & & & \end{pmatrix}$$

tree

1-loop

⋮

$$\log \mathfrak{M} = \begin{pmatrix} \alpha L^2 & \alpha L & \alpha & & \\ \alpha^2 L^3 & \alpha^2 L^2 & \alpha^2 L & \alpha^2 & \\ \alpha^3 L^4 & \alpha^3 L^3 & \alpha^3 L^2 & \alpha^3 L & \alpha^3 \\ \alpha^4 L^5 & & & \dots & \\ \vdots & & & & \end{pmatrix}$$

LL NLL …

$$\mathfrak{M} = \begin{pmatrix} 1 & & & & \\ \frac{1}{\alpha} & 1 & \alpha & & \\ \frac{1}{\alpha^2} & \frac{1}{\alpha} & 1 & \alpha & \alpha^2 \\ \frac{1}{\alpha^3} & & \dots & & \\ \vdots & & & & \end{pmatrix}$$

Leading log regime

αL ~ 1

$$\log \mathfrak{M} = \begin{pmatrix} \frac{1}{\alpha} & 1 & \alpha & & \\ \frac{1}{\alpha} & 1 & \alpha & \alpha^2 & \\ \frac{1}{\alpha} & 1 & \alpha & \alpha^2 & \alpha^3 \\ \frac{1}{\alpha} & & & \dots & \\ \vdots & & & & \end{pmatrix}$$

Focus on the physical infrared degrees of freedom, which separate into “soft” and “collinear” fields.

SCET naturally yields an expansion for the amplitude that is convergent in the regime of interest where α is small but αL ~ 1 (L = log(high scale / low scale)).

Recipe for MDM indirect signals

- Solve the Schrodinger equation to determine:
  — the distortion of the wavefunction of the colliding particles (Sommerfeld enhancement)
  — the spectrum of bound states in the theory

- Use QM perturbation theory to compute the capture rate into bound states and transition rate between bound states, and the resulting spectral lines from these transitions

- Use SCET techniques to compute the annihilation rate of both unbound DM and all the (meta)stable bound states, and the spectrum of gamma rays produced

- The techniques developed here are also applicable to more general DM scenarios, whenever there is a large mass hierarchy between the DM and particles it interacts with

- In 2018-2019 we applied this approach to wino DM and found that current data from the H.E.S.S. gamma-ray telescope should be able to exclude wino DM, under conservative assumptions for the DM central density

Example: the wino bound state spectrum (high-mass)

Asadi, Baumgart, Fitzpatrick, Krupczak & TRS, ’16

	Spin-Singlet Spectrum	Spin-Triplet Spectrum
$\left\|\frac{E_n}{M_\chi \alpha_W^2}\right\| = \frac{1}{144}$		
$\left\|\frac{E_n}{M_\chi \alpha_W^2}\right\| = \frac{1}{100}$		
$\left\|\frac{E_n}{M_\chi \alpha_W^2}\right\| = \frac{1}{64}$	4S 4P 4D	4S 4P 4D
$\left\|\frac{E_n}{M_\chi \alpha_W^2}\right\| = \frac{1}{36}$	3S 3P 3D	3S 3P 3D
$\left\|\frac{E_n}{M_\chi \alpha_W^2}\right\| = \frac{1}{25}$		
$\left\|\frac{E_n}{M_\chi \alpha_W^2}\right\| = \frac{1}{16}$	2S 2P	2S 2P
$\left\|\frac{E_n}{M_\chi \alpha_W^2}\right\| = \frac{1}{9}$		
$\left\|\frac{E_n}{M_\chi \alpha_W^2}\right\| = \frac{1}{4}$	1S	1S
$\left\|\frac{E_n}{M_\chi \alpha_W^2}\right\| = 1$		

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$\left\lvert\frac{E_n}{M_\chi \alpha_W^2}\right\rvert = \frac{1}{36}$	3P	3S 3P 3D
$\left\lvert\frac{E_n}{M_\chi \alpha_W^2}\right\rvert = \frac{1}{25}$		
$\left\lvert\frac{E_n}{M_\chi \alpha_W^2}\right\rvert = \frac{1}{16}$	4S 4D 2P	2S 2P
$\left\lvert\frac{E_n}{M_\chi \alpha_W^2}\right\rvert = \frac{1}{9}$	3S 3D	
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$\lvert\frac{E_n}{M_\chi \alpha_W^2}\rvert = \frac{1}{4}$	2S	2P 1S
$\lvert\frac{E_n}{M_\chi \alpha_W^2}\rvert = 1$	1S	

Example: the wino bound state spectrum (high-mass)

Asadi, Baumgart, Fitzpatrick, Krupczak & TRS, ’16

	Spin-Singlet Spectrum	Spin-Triplet Spectrum
$\left\lvert\frac{E_n}{M_\chi \alpha_W^2}\right\rvert = \frac{1}{144}$		6D
$\left\lvert\frac{E_n}{M_\chi \alpha_W^2}\right\rvert = \frac{1}{100}$	5P	5D
$\left\lvert\frac{E_n}{M_\chi \alpha_W^2}\right\rvert = \frac{1}{64}$	4P	4S 4D
$\left\lvert\frac{E_n}{M_\chi \alpha_W^2}\right\rvert = \frac{1}{36}$	3P 6D	3S 3D
$\left\lvert\frac{E_n}{M_\chi \alpha_W^2}\right\rvert = \frac{1}{25}$	5D	5P
$\left\lvert\frac{E_n}{M_\chi \alpha_W^2}\right\rvert = \frac{1}{16}$	4S 2P 4D	2S 4P
$\left\lvert\frac{E_n}{M_\chi \alpha_W^2}\right\rvert = \frac{1}{9}$	3S 3D	3P
$\left\lvert\frac{E_n}{M_\chi \alpha_W^2}\right\rvert = \frac{1}{4}$	2S	1S 2P
$\left\lvert\frac{E_n}{M_\chi \alpha_W^2}\right\rvert = 1$	1S	

- Spectrum + decays of bound states are quite different to hydrogen/positronium
- Modifies which states are metastable, & energy gaps between states
- Note: at the thermal mass of 3 TeV, only the ground state is bound

Example: wino annihilation rate

Baumgart, Cohen, Moult, Rodd, Solon, TRS, Stewart & Vaidya ‘18

$$\frac{\mathrm{d}\sigma^{\mathrm{LL}}}{\mathrm{d}z} = 4\,|s_{0\pm}|^2\,\sigma^{\mathrm{tree}}\,e^{-2\,\Gamma_0\,\tilde{\alpha}_W\,L_\chi^2}\,\delta(1-z)$$

$$+\,4\,\sigma^{\mathrm{tree}}\,e^{-2\,\Gamma_0\,\tilde{\alpha}_W\,L_\chi^2}\left\{C_A\,\tilde{\alpha}_W\,F_1\left(3\,\mathcal{L}_1^S(z)-2\,\mathcal{L}_1^J(z)\right)e^{2\,\Gamma_0\,\tilde{\alpha}_W\,\left(\Theta_J L_J^2(z)-\frac{3}{4}\Theta_S L_S^2(z)\right)}\right.$$

$$\left.-\,2\,C_A\,\tilde{\alpha}_W\,F_0\,\mathcal{L}_1^J(z)\,e^{2\,\Gamma_0\,\tilde{\alpha}_W\,L_J^2(z)}\right\}. \qquad (5.30)$$

$$\Gamma_0 = 4\,C_A \qquad \tilde{\alpha}_W = \frac{\alpha_W}{4\pi}$$

$$L_J(z) = \log\left(\frac{m_W}{2\,M_\chi\sqrt{1-z}}\right) \quad L_S(z) = \log\left(\frac{m_W}{2\,M_\chi(1-z)}\right) \quad L_\chi = \log\left(\frac{m_W}{2\,M_\chi}\right)$$

$$\Theta_J = \Theta\left(1-\frac{m_W^2}{4\,M_\chi^2}-z\right)$$

$$\Theta_S = \Theta\left(1-\frac{m_W}{2\,M_\chi}-z\right)$$

large logs

$$\sigma^{\mathrm{tree}} = \frac{\pi\,\alpha_W^2\,\sin^2\theta_W}{2\,M_\chi^2\,v}$$

tree-level cross section

$$\mathcal{L}_1^J(z) = \frac{L_J}{1-z}\,\Theta_J\,, \quad \mathcal{L}_1^S(z) = \frac{L_S}{1-z}\,\Theta_S$$

power divergences
in (1-z)

$$F_0 = \frac{4}{3}\,|s_{00}|^2 + 2\,|s_{0\pm}|^2 + \frac{2\sqrt{2}}{3}\left(s_{00}\,s_{0\pm}^* + s_{00}^*\,s_{0\pm}\right),$$

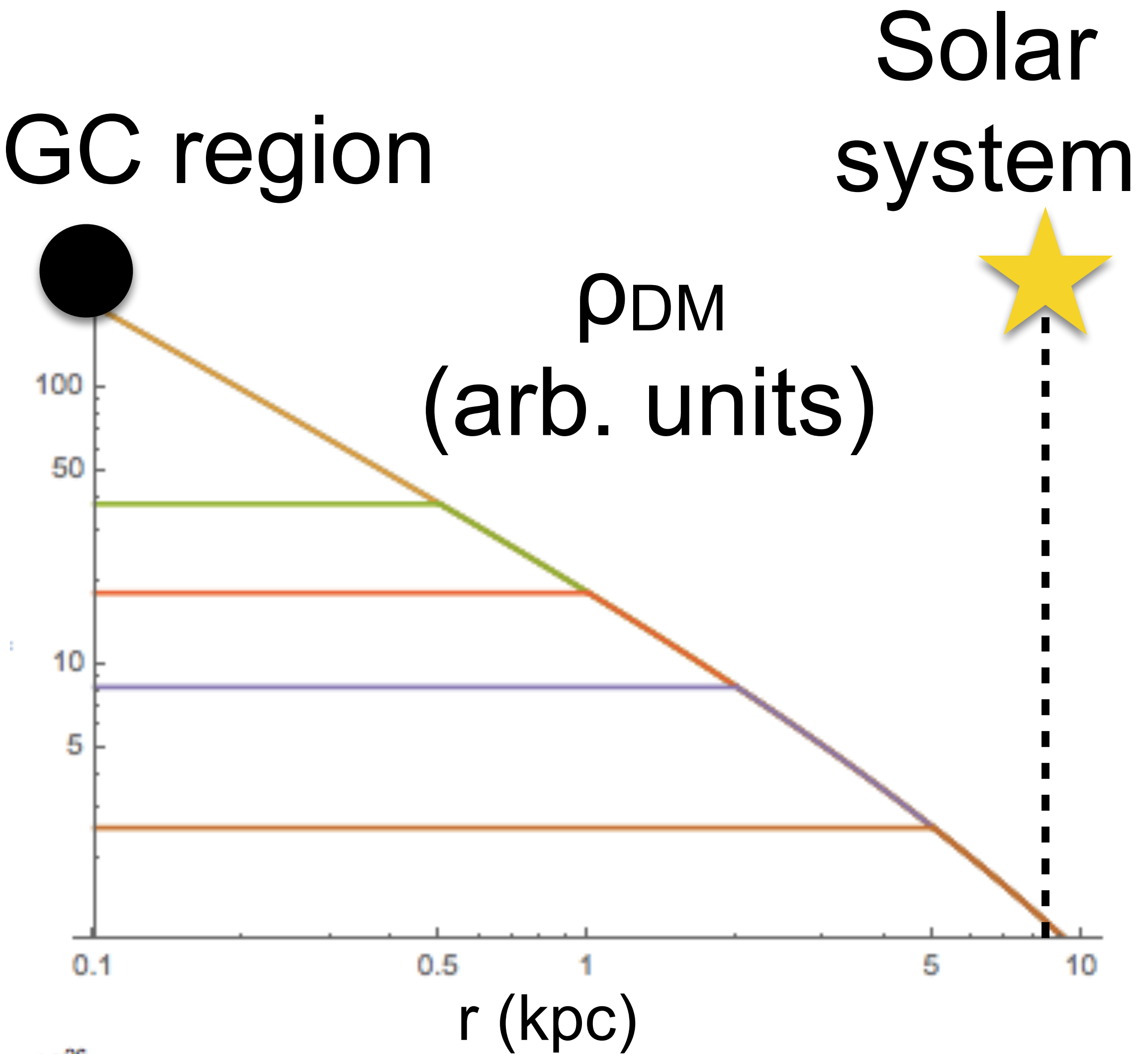
$$F_1 = -\frac{4}{3}\,|s_{00}|^2 + 2\,|s_{0\pm}|^2 - \frac{2\sqrt{2}}{3}\left(s_{00}\,s_{0\pm}^* + s_{00}^*\,s_{0\pm}\right),$$

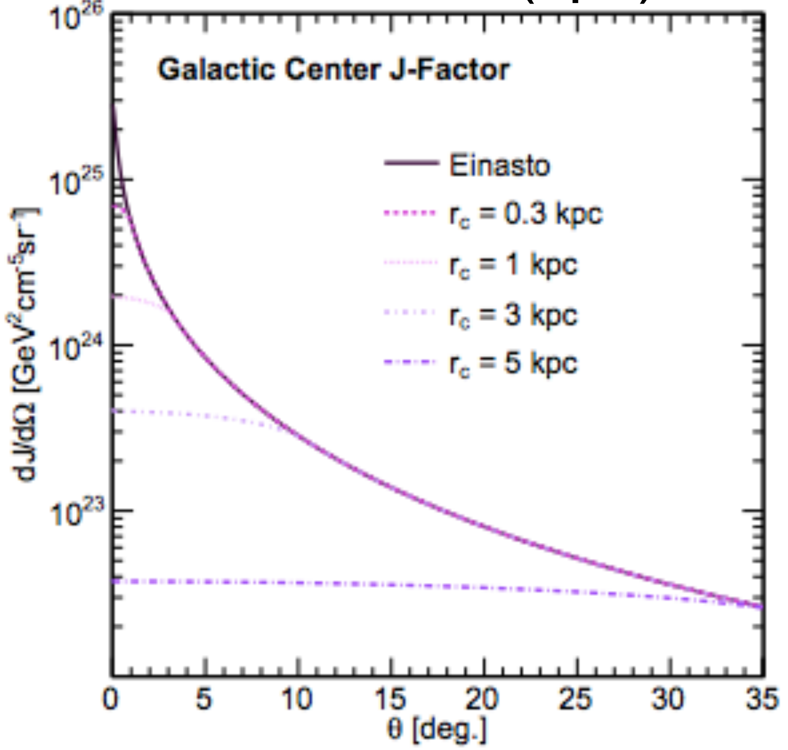
Sommerfeld
factors

At NLL, the
power-law terms
are dressed with
additional logs.

DM density profile

- Limits are really on photon flux - cross section is degenerate with amount of DM near GC, which has large uncertainties
  - N-body simulations suggest DM density should rise toward GC (roughly as 1/r), but flatten out at some “core” radius
  - Core size depends on details of baryonic physics - but from current simulations, expected to be ~1-2 kpc or smaller in the Milky Way
  - Distance from Earth to GC is ~8.5 kpc





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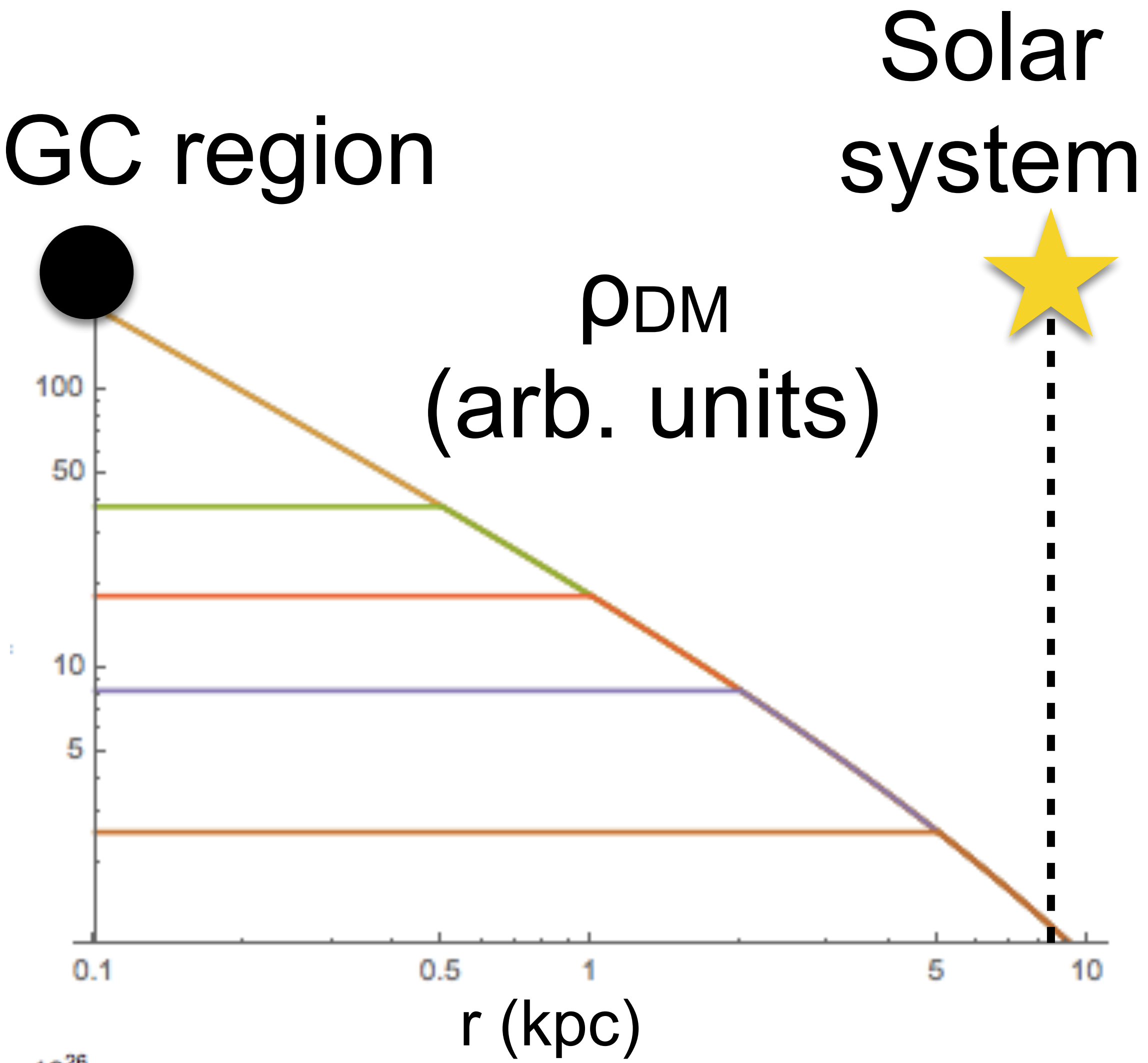
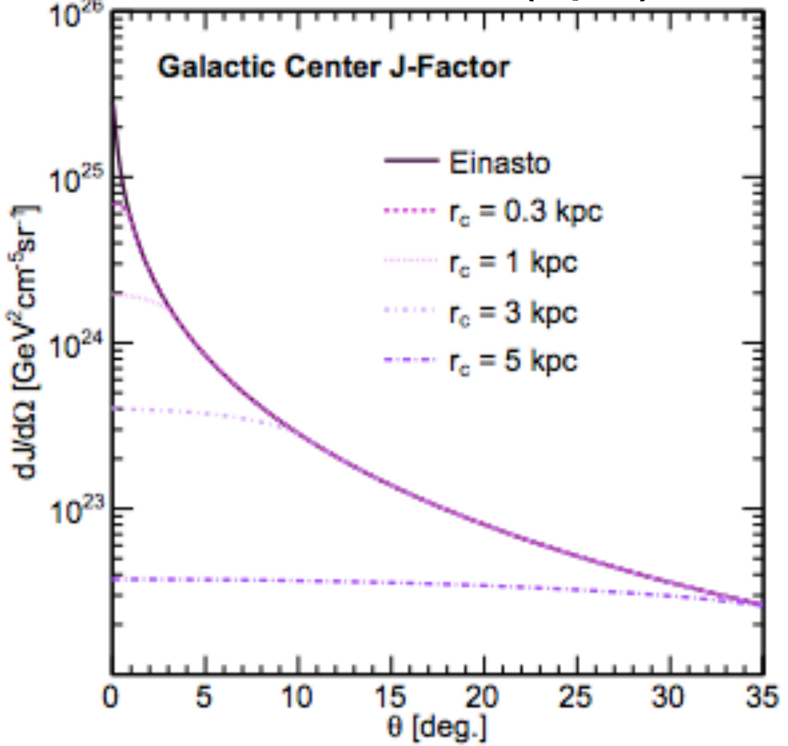


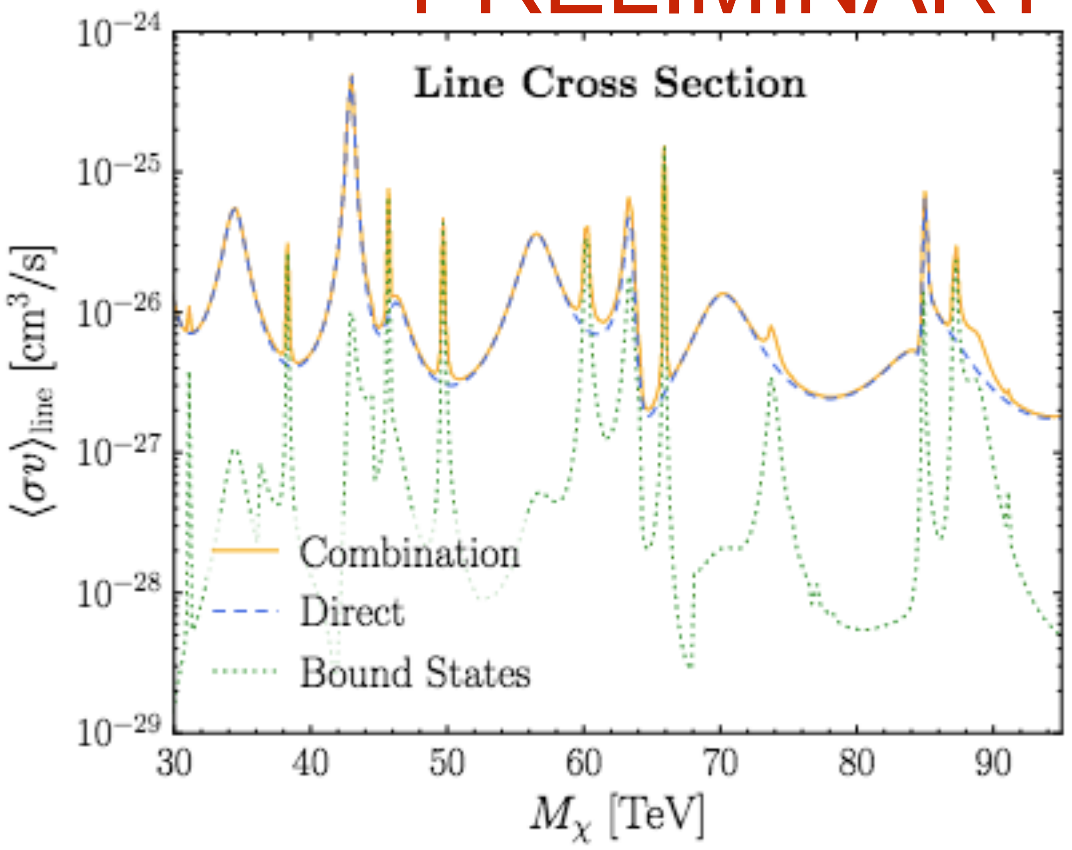


can we constrain the “thermal MDM + 1-2 kpc core” scenario?

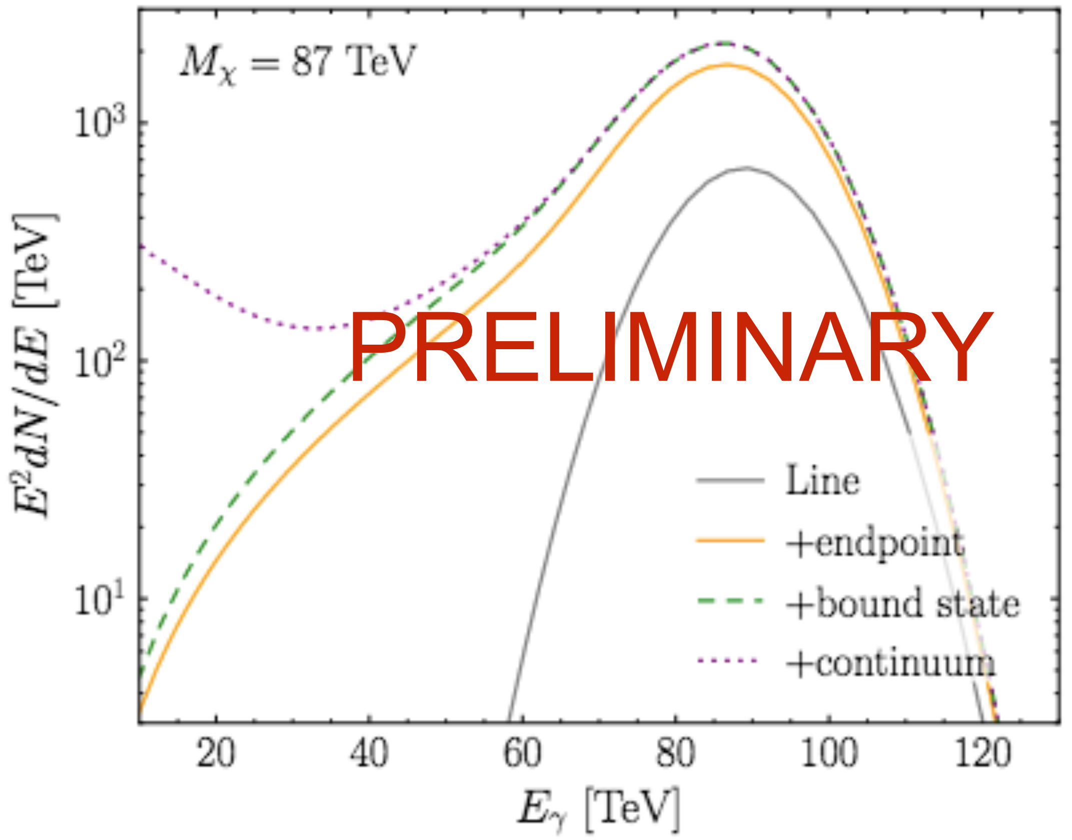
Quintuplet: preliminary results

- SCET analysis goes through straightforwardly - no obvious additional subtleties in quintuplet case
- Bound states turn out to be unimportant for wino DM at its thermal mass, but can matter for the quintuplet
- We compute formation and decay rates of each of the possible bound states - the resulting signal is substantial at some masses (although quite small at thermal mass)
- Need to account for branching ratio of each bound state to decay to SM vs deeper bound states
- Presence of interfering channels (due to multiple 2-particle states coupled by the potential) can lead to sharp features in the capture rate as a function of mass

PRELIMINARY



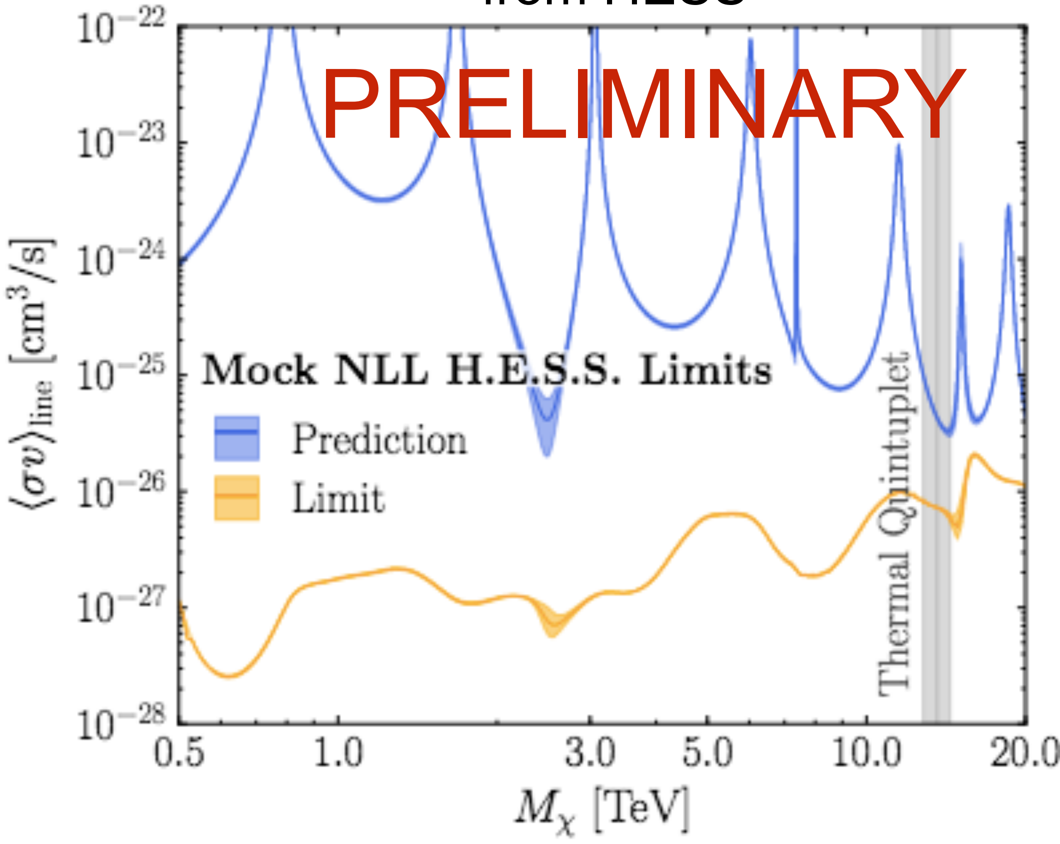
Quintuplet results



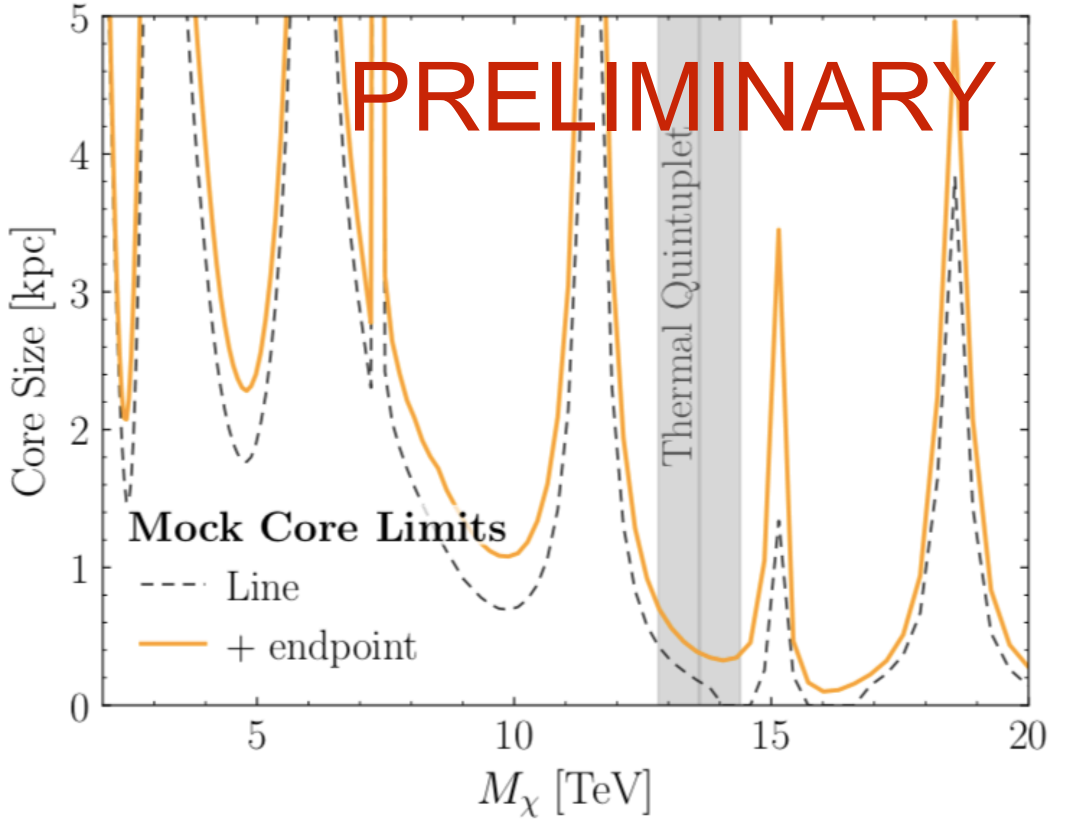
Estimated limits from indirect detection

- We can make a rough estimate of the sensitivity based on older H.E.S.S measurements of the inner Galaxy gamma-ray spectrum
- (PRELIMINARY) In this analysis, for the quintuplet, even a small flattened core (<0.5 kpc) would evade detection
- Montanari et al ’22 uses our signal prediction with a more sophisticated background model and confirms that in the non-cored case the quintuplet should be detectable by H.E.S.S

Estimated quintuplet sensitivity from HESS



Core size needed to evade estimated exclusion



Summary

- Gamma rays provide powerful probes of DM annihilation and decay across a broad mass range, from particle DM to primordial black holes.

- Can we exclude thermal WIMPs interacting through the W and Z bosons? We are getting close, but simple models still survive.

- In particular, predictive models where DM is in a $SU(2)_L$ multiplet are not yet excluded by colliders or direct detection; explaining the full DM relic density with the standard cosmological history requires high (>TeV) mass scales.

- At this mass range, weak interactions are effectively long-range: can support bound states and significantly enhance the annihilation cross section. The large hierarchy between DM mass and weak scale also leads to large enhancements to loop diagrams from IR effects - need to be resummed.

- We have calculated the hard photon spectrum from heavy $SU(2)_L$ triplet and quintuplet annihilation, including NLL resummation and inclusion of all bound states and their subsequent decays.

- The quintuplet appears to be at the edge of detectability with current telescopes - likely ruled out in the case of a NFW/Einasto profile, but tension can (currently) be removed by a modestly-sized flat-density core.