Gamma-Ray Tests of Elusive Dark Matter Candidates

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Based on arXiv:2004.00627 with Ranjan Laha and Julian Muñoz
and work to appear with Lucia Rinchiuso, Oscar Macias, Emmanuel Moulin & Nicholas Rodd

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Outline

- Primordial black holes
  - Existing limits and the low-mass window
  - New constraints on Hawking radiation from INTEGRAL data
- Heavy electroweakinos (higgsino, wino, quintuplet)
  - Theoretical challenges + soft collinear effective theory (SCET)
  - Sensitivity for H.E.S.S. and CTA

What is dark matter?

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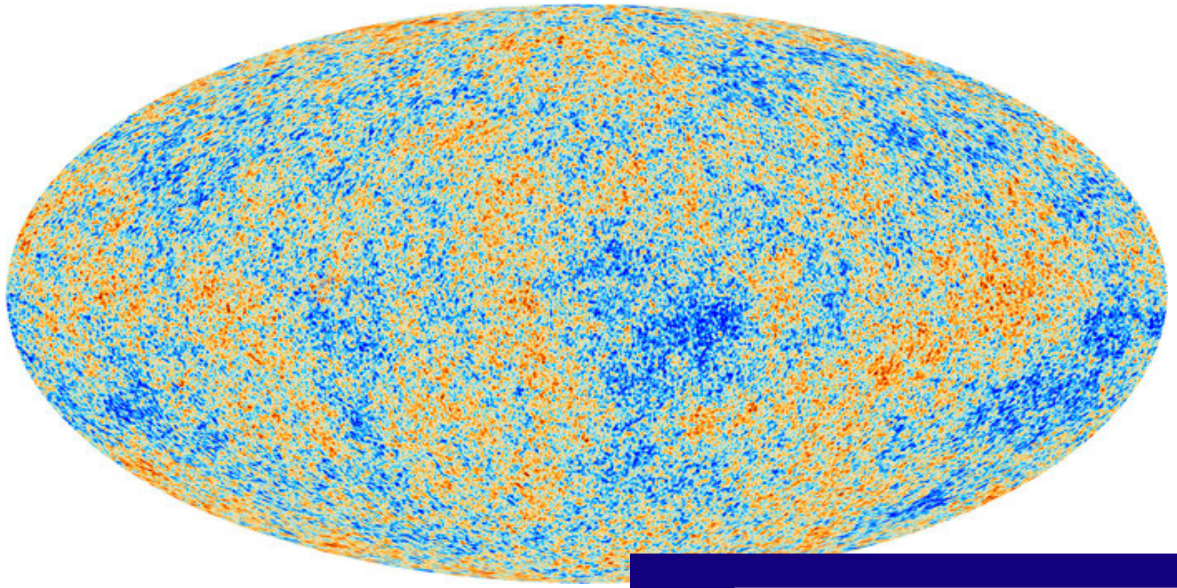

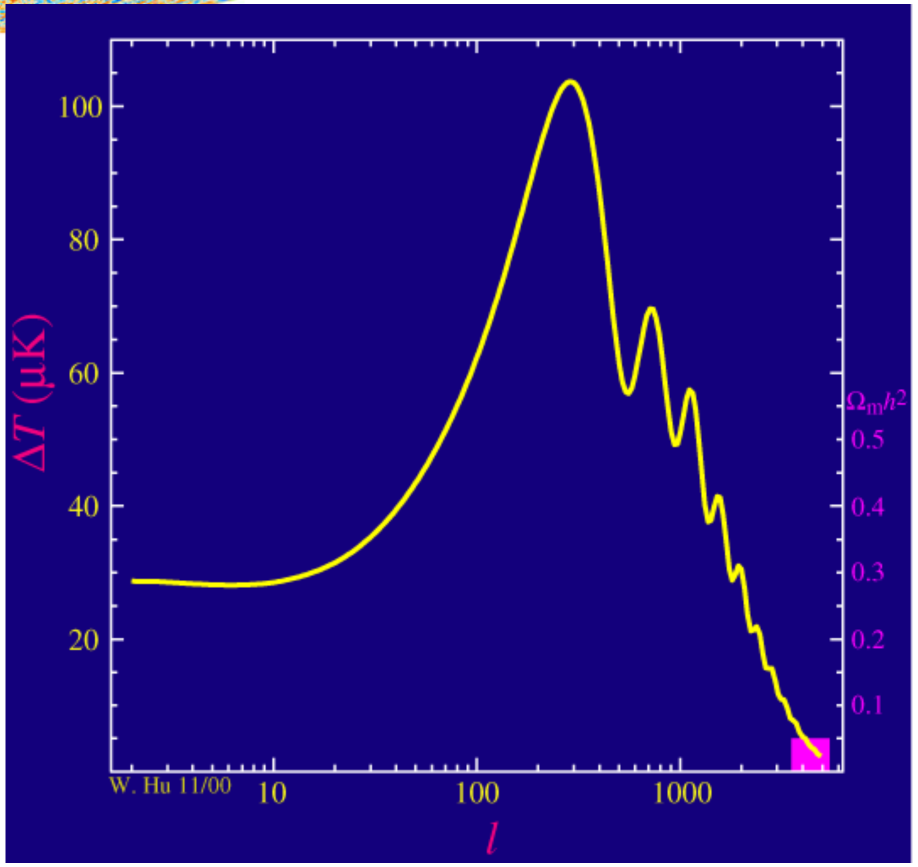

Wayne Hu, http://background.uchicago.edu/~whu/

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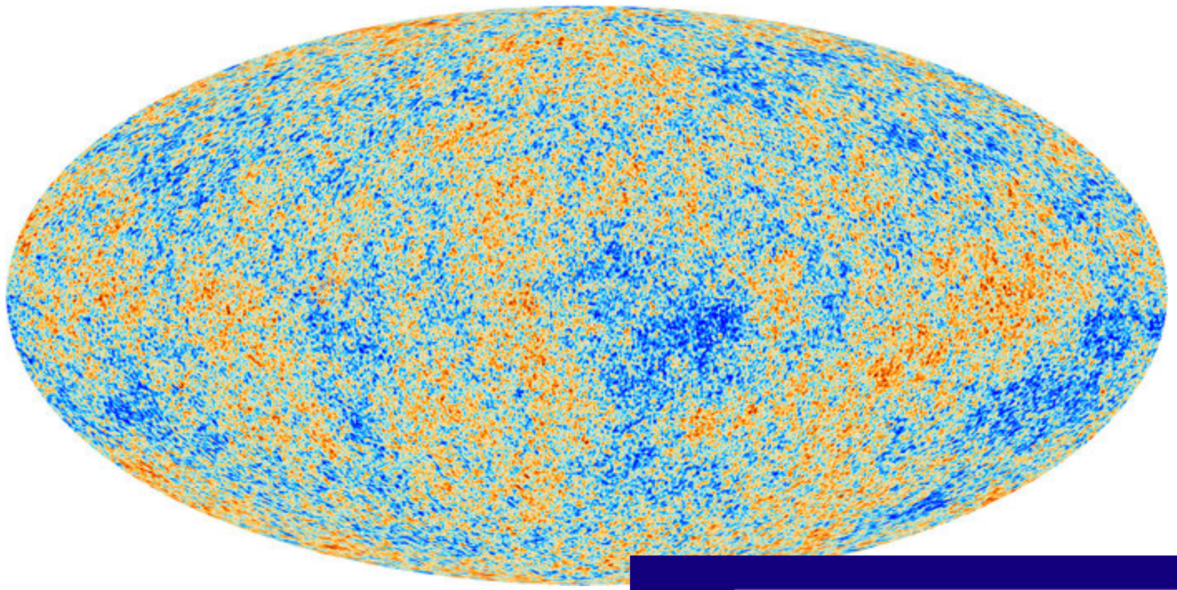

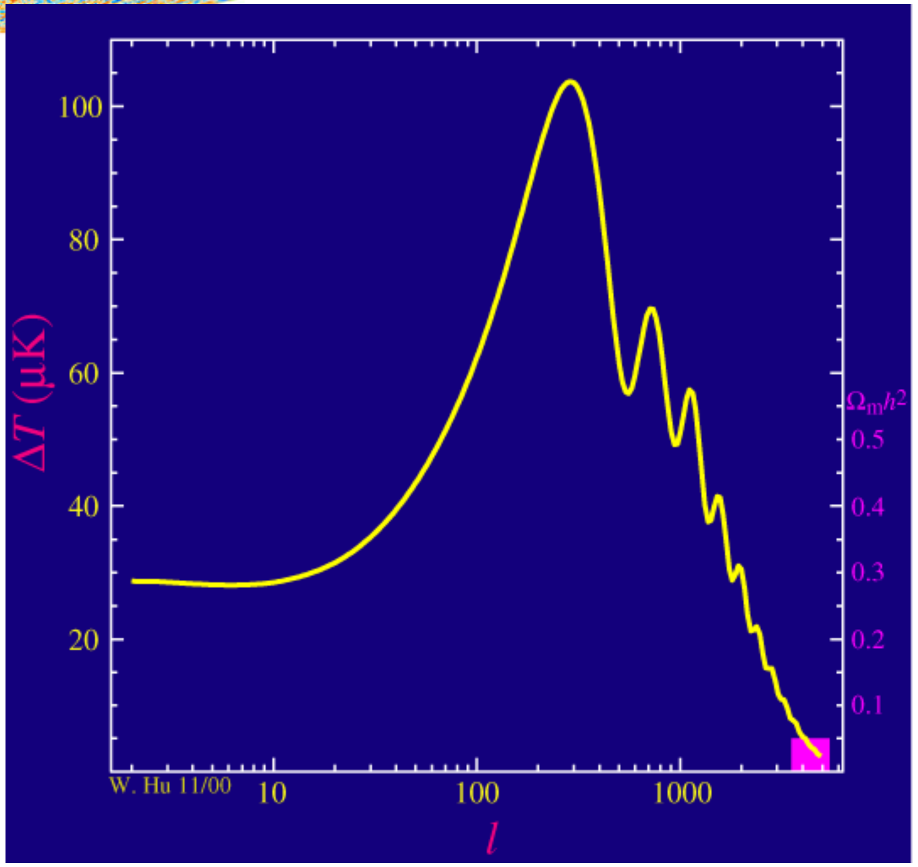

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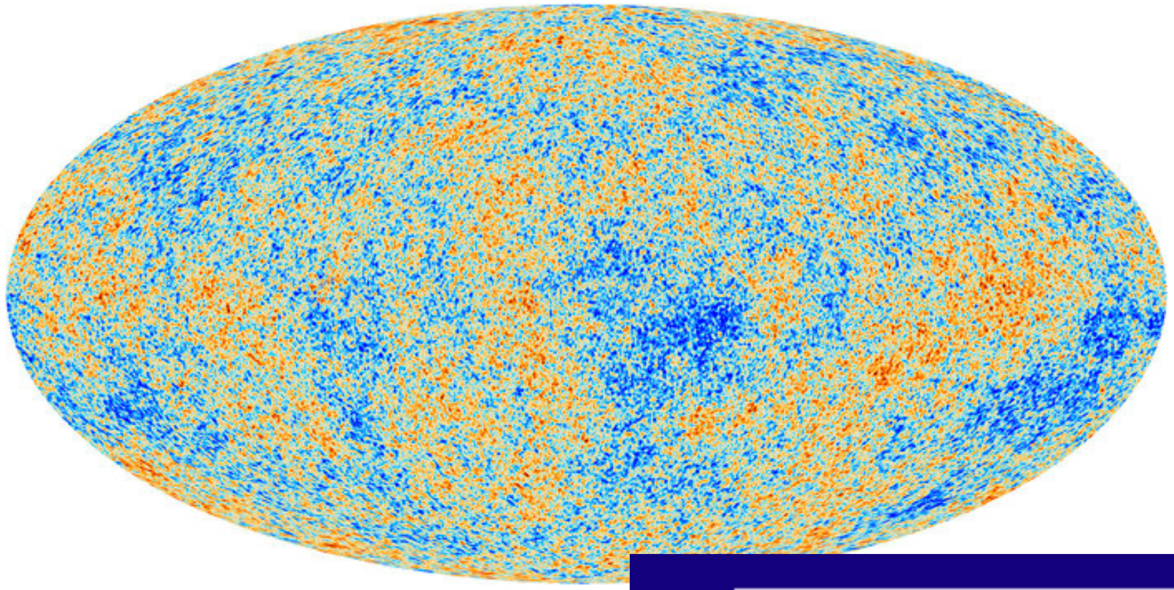

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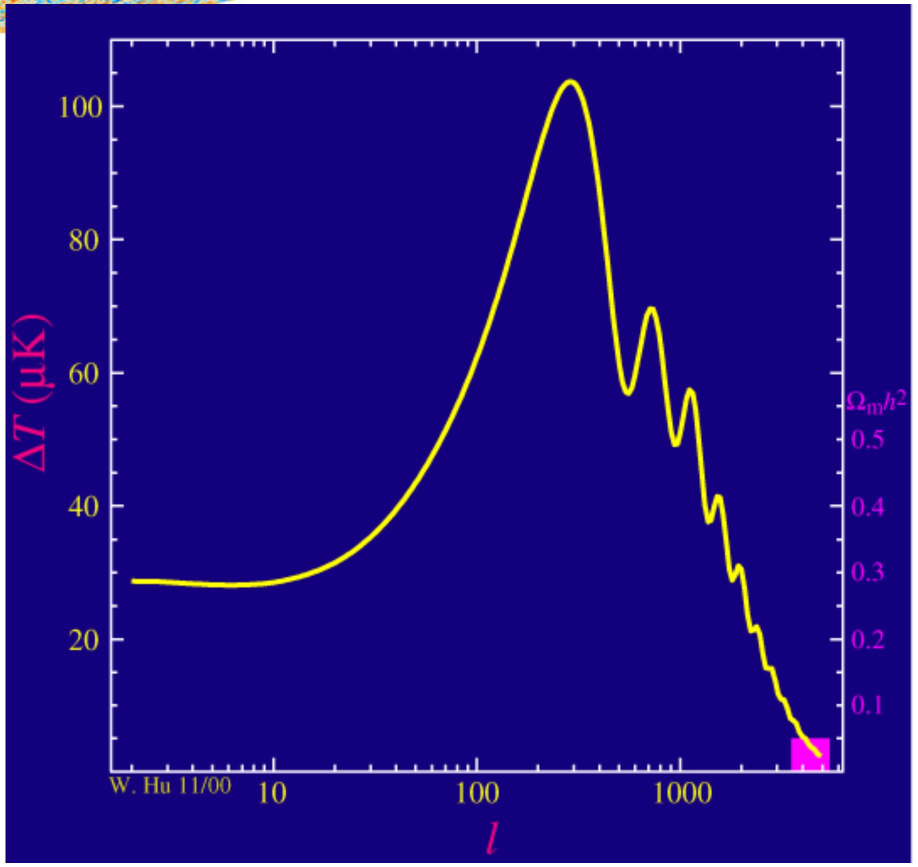

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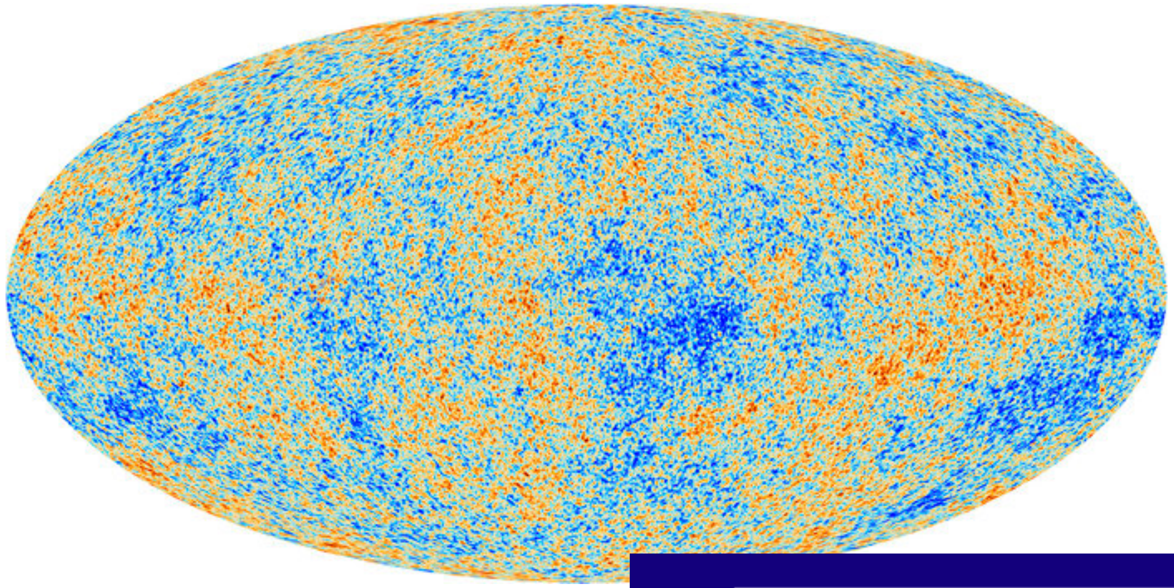

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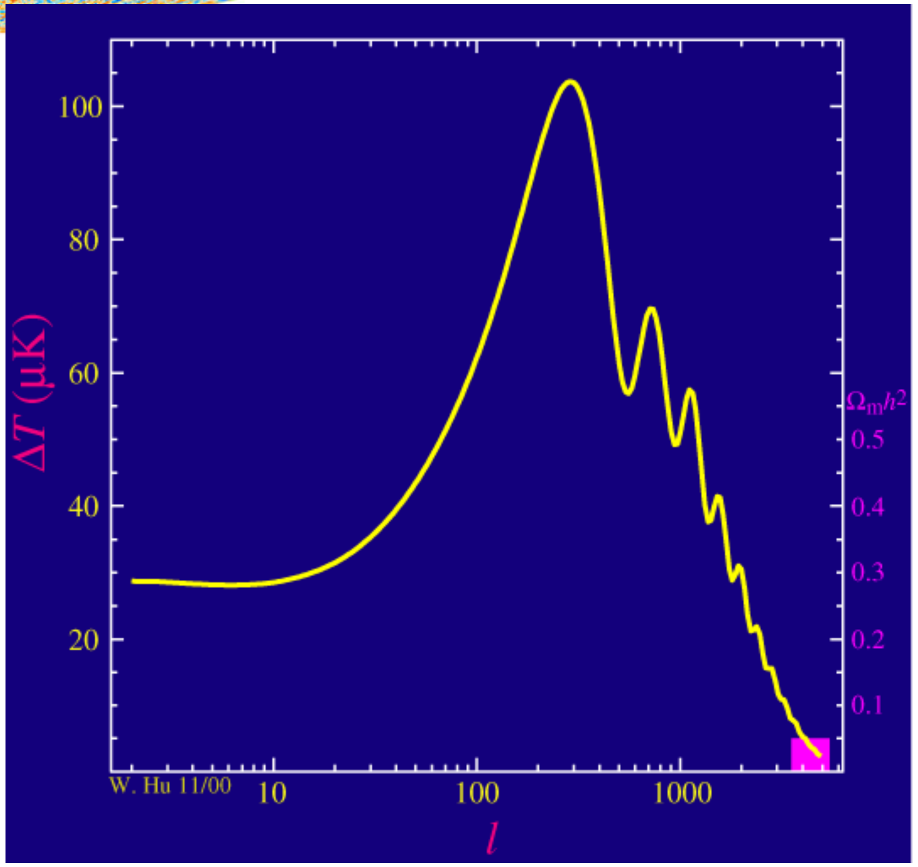

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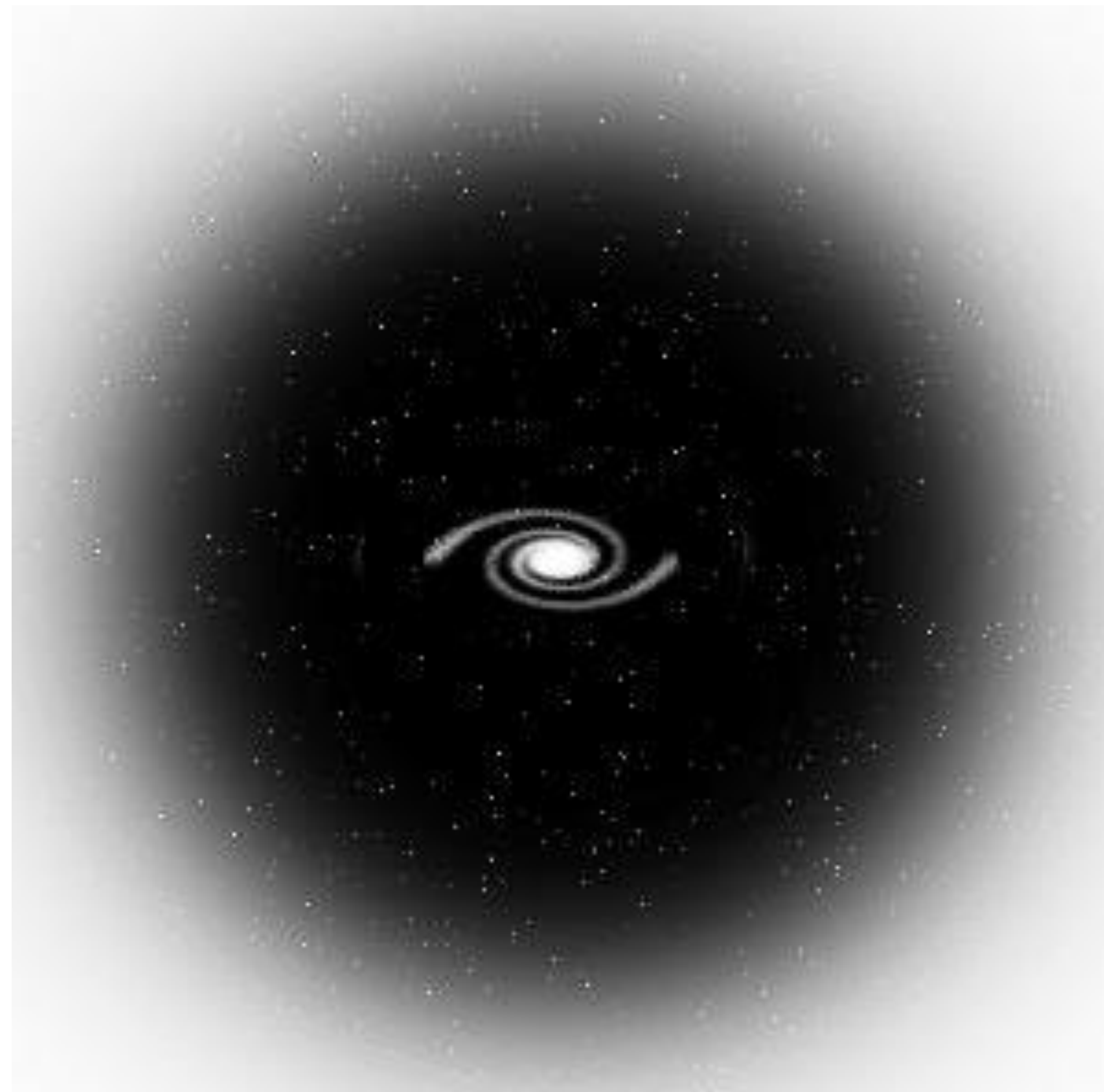

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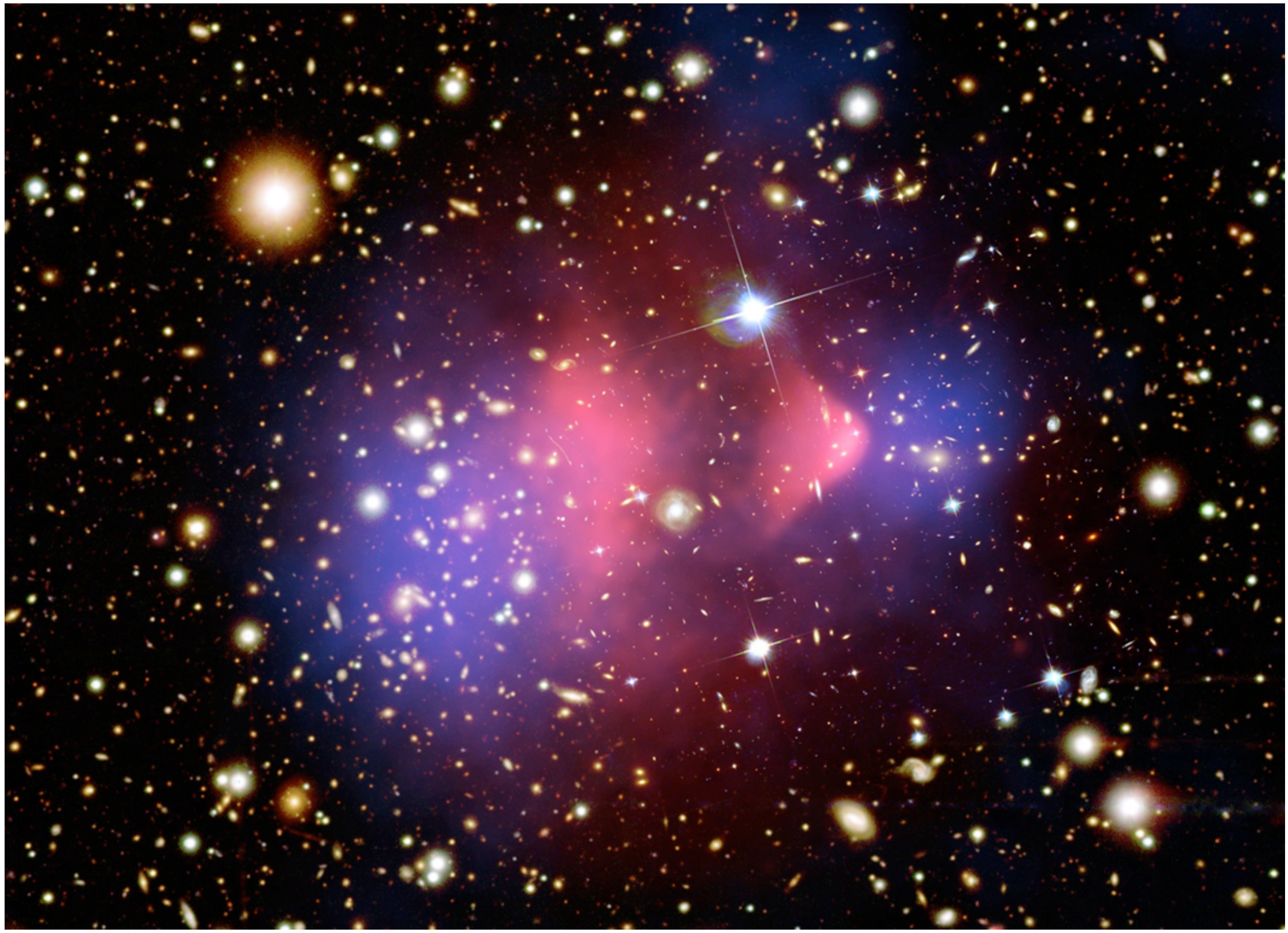

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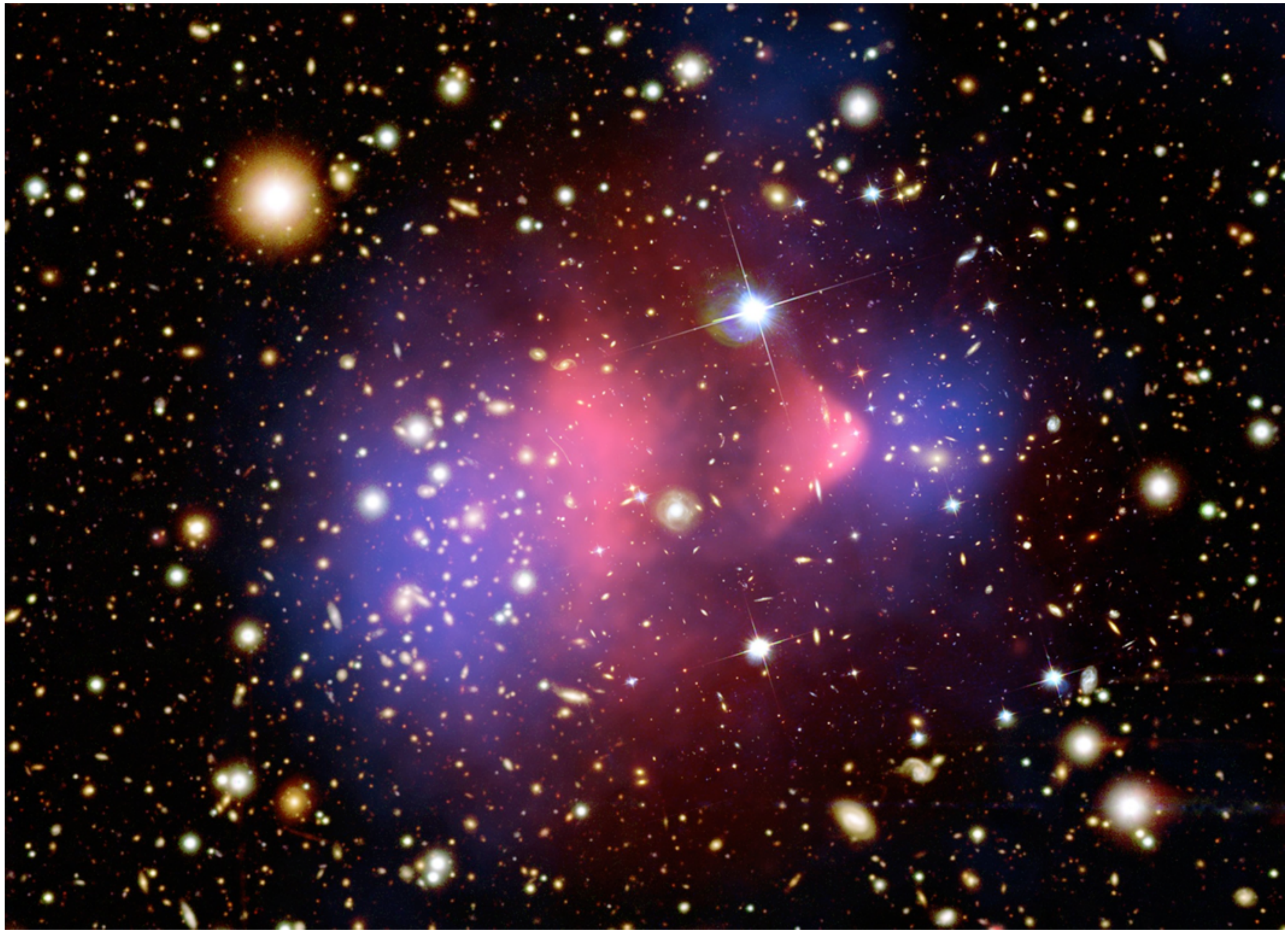
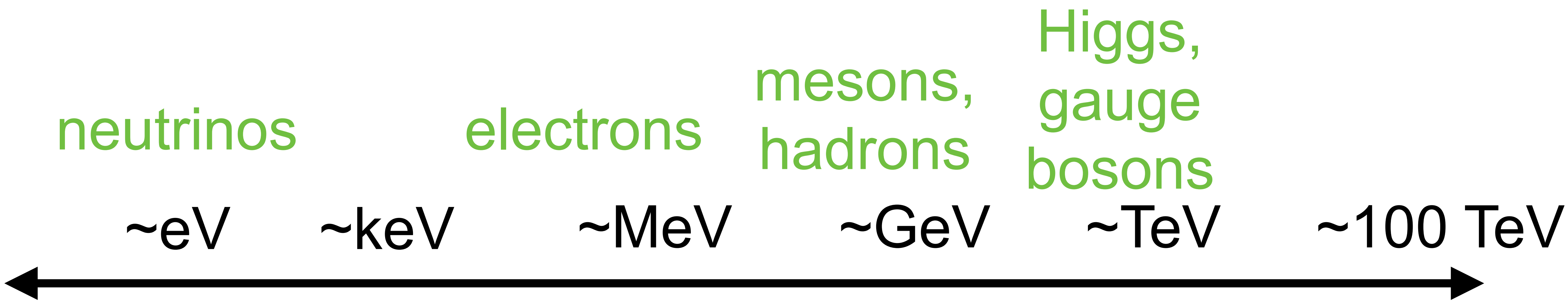
- Can't be explained in terms of a bath of known particles.



A spectrum of possible answers



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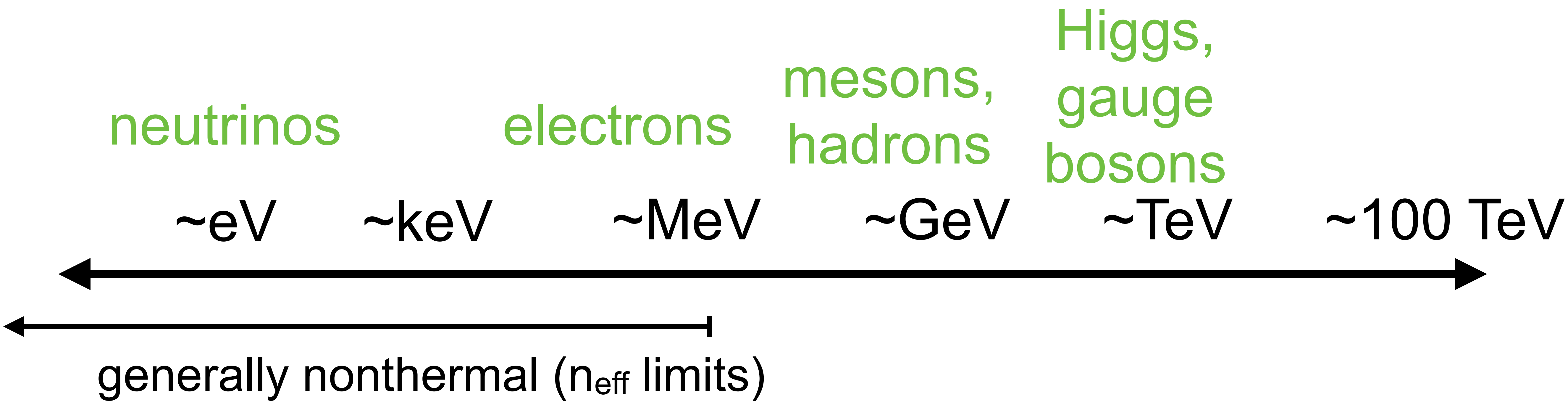

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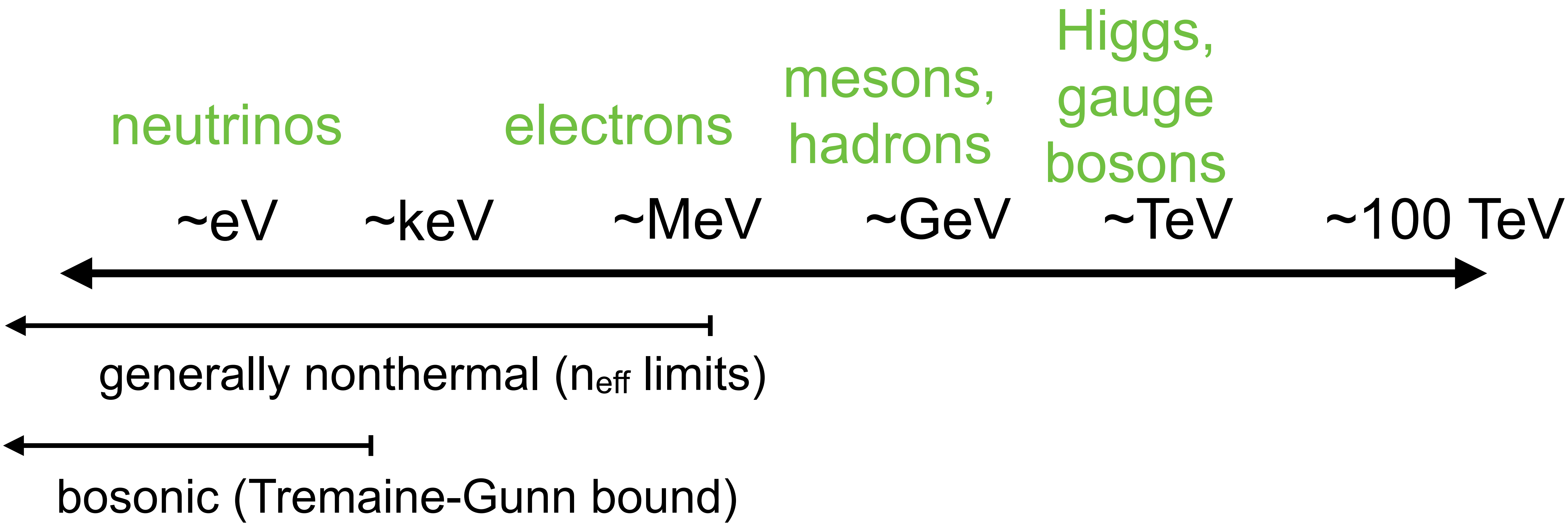

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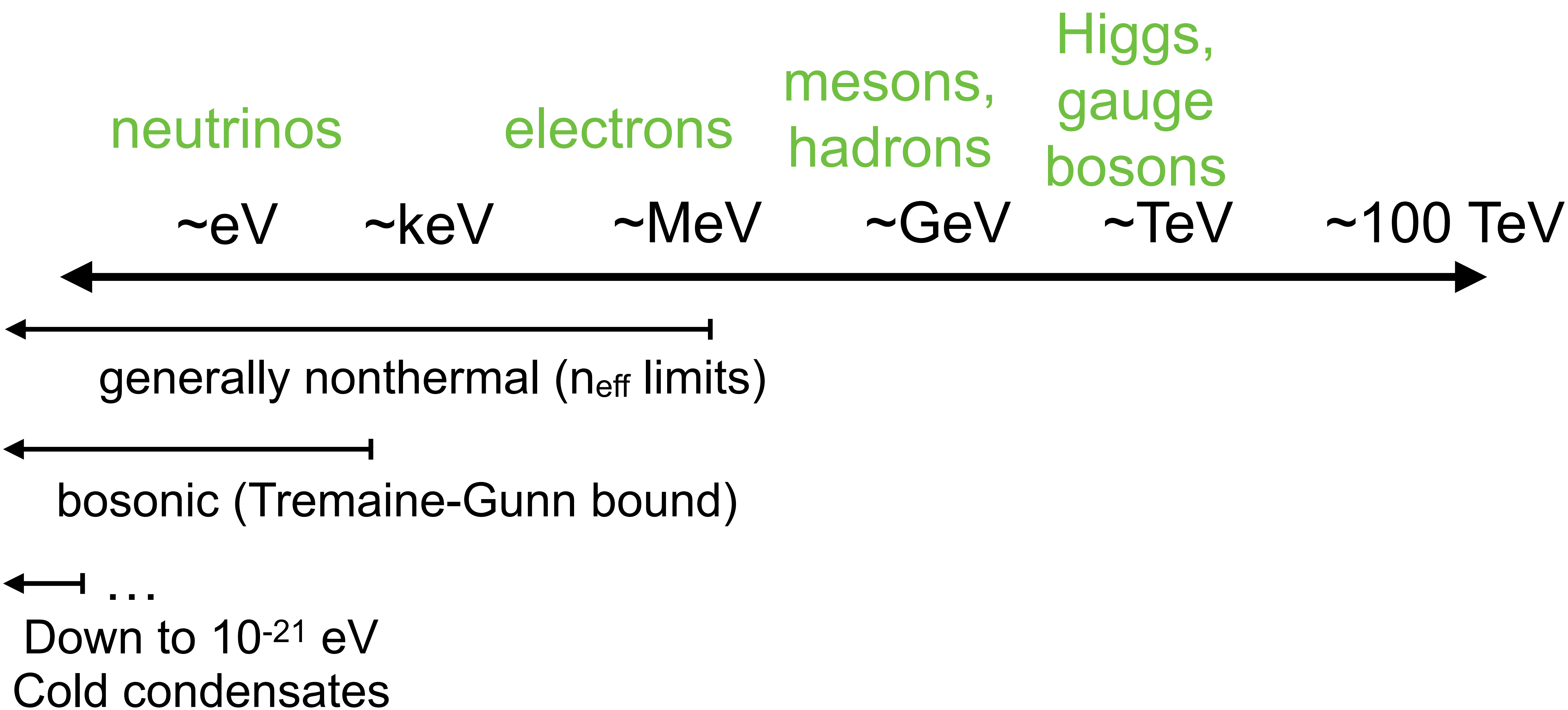

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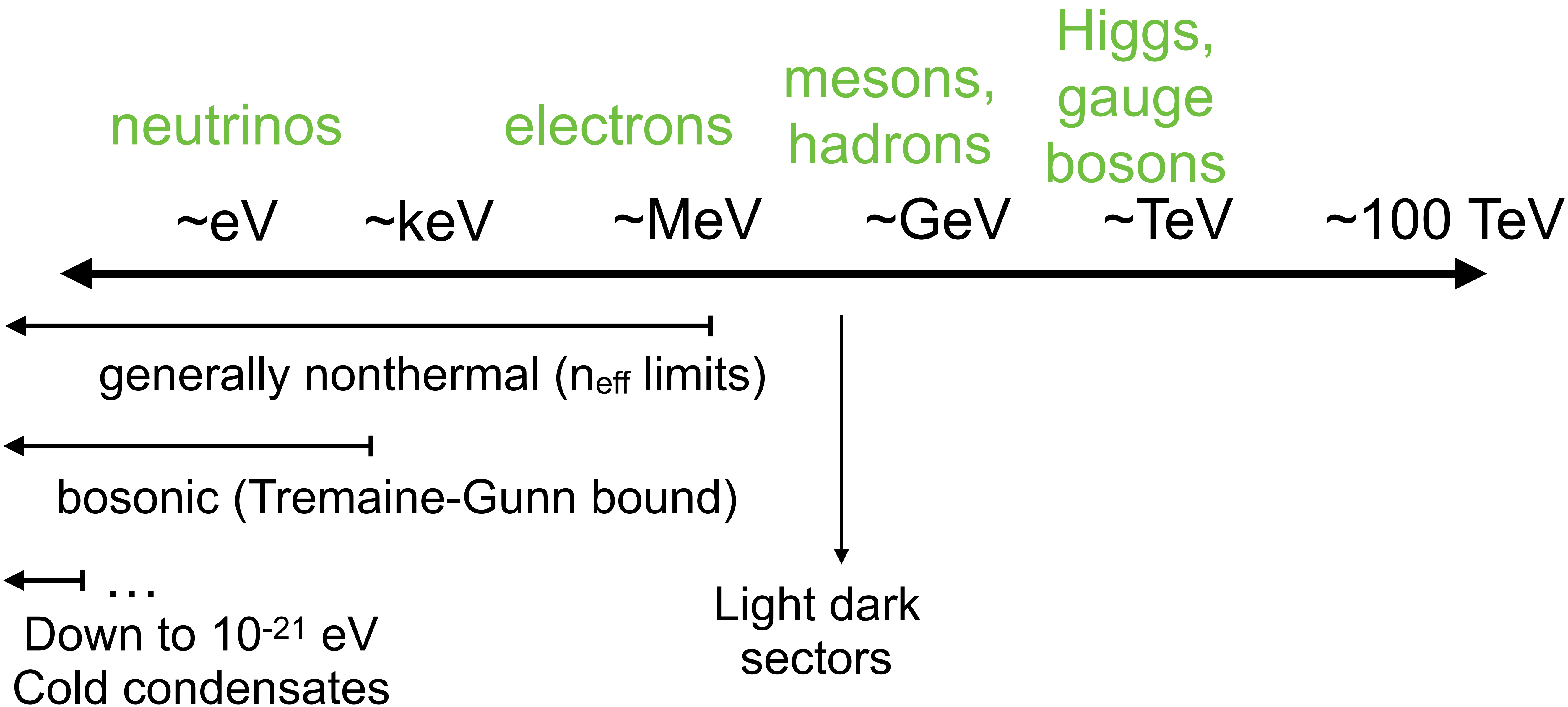

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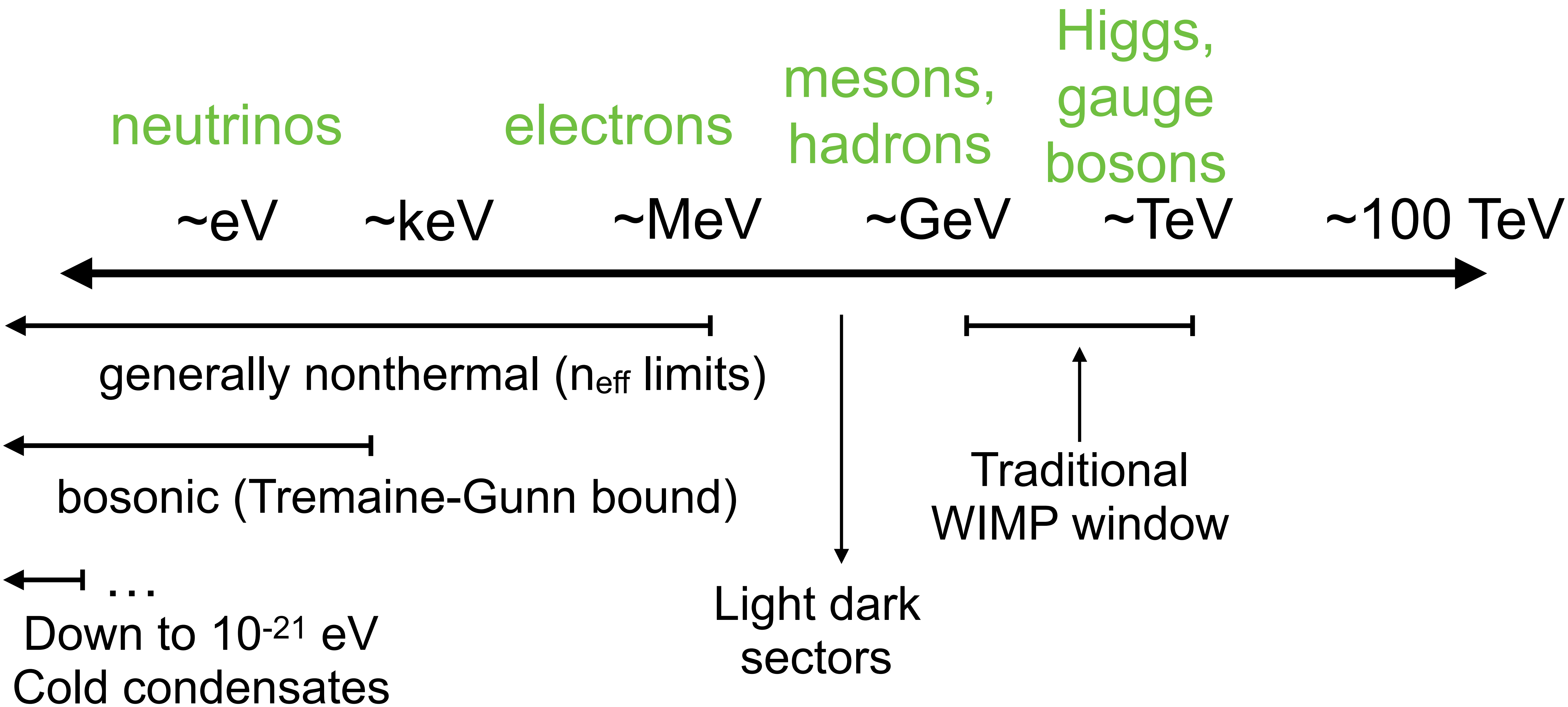

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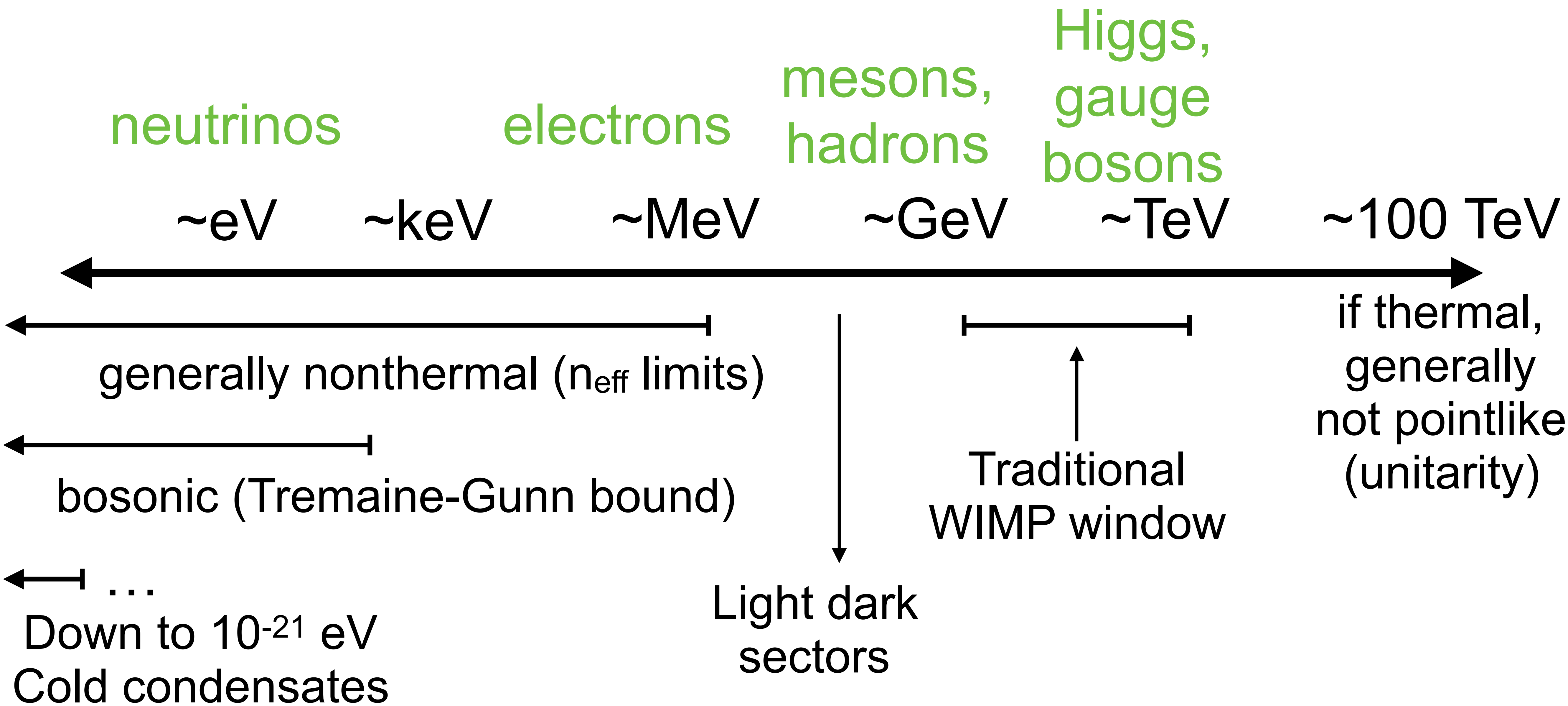

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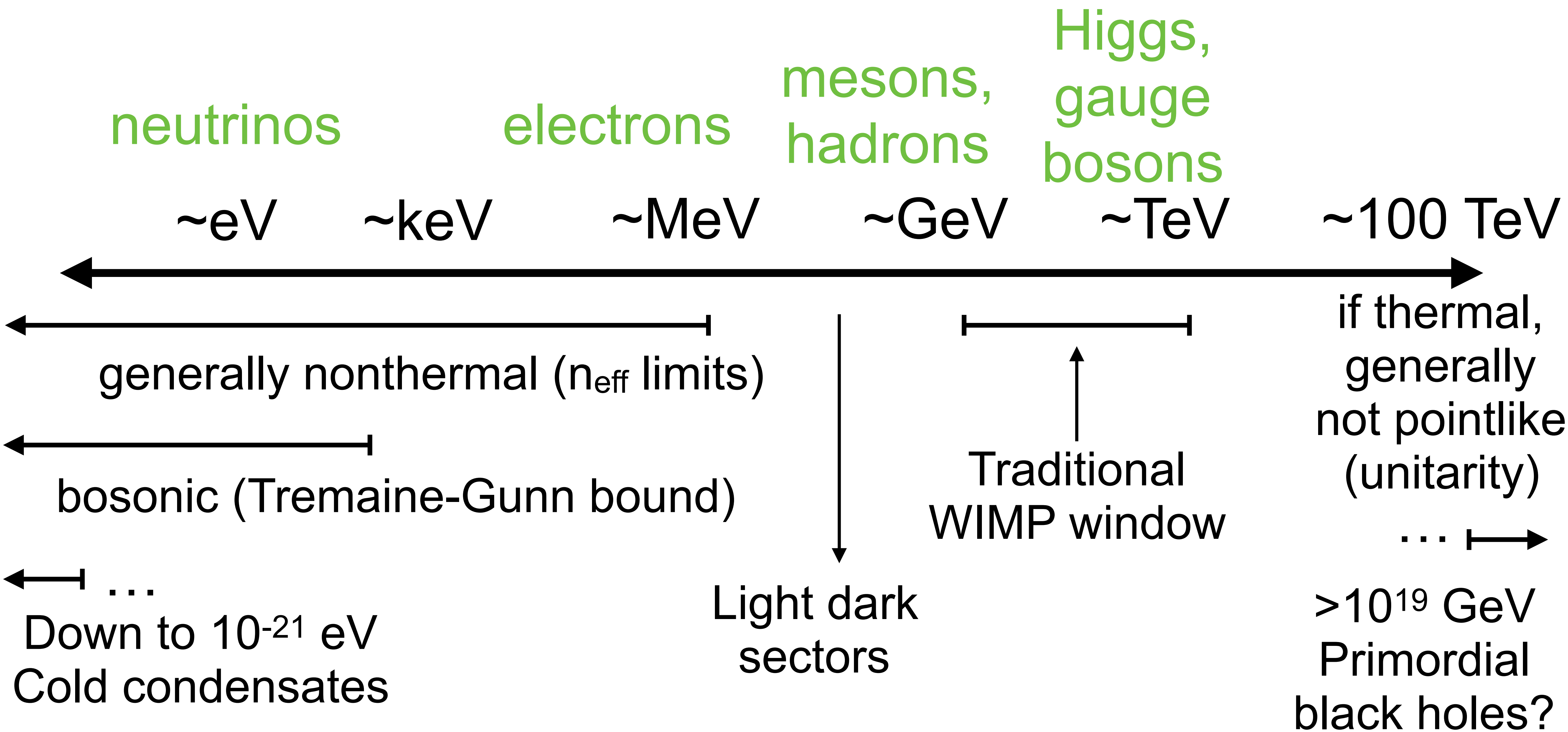

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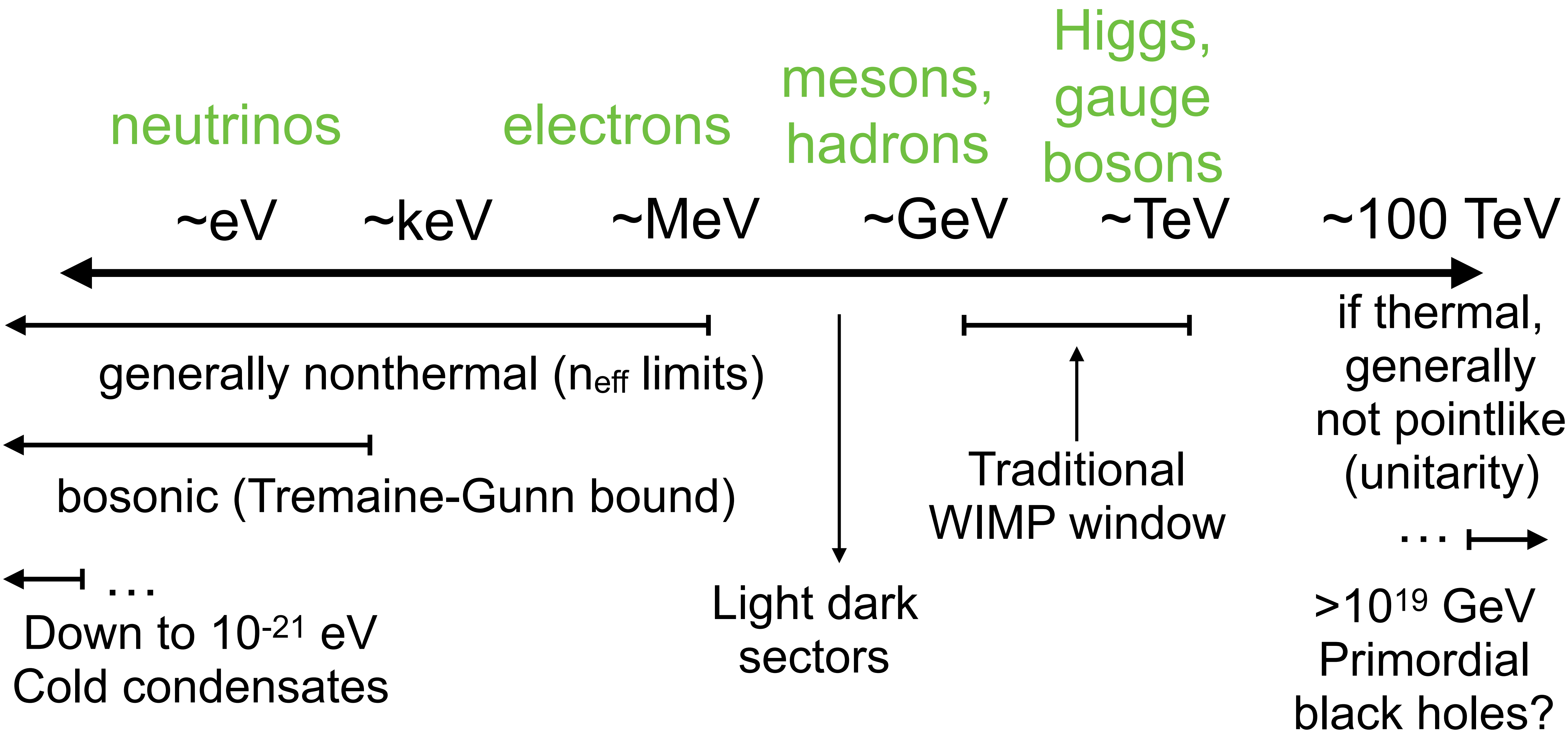

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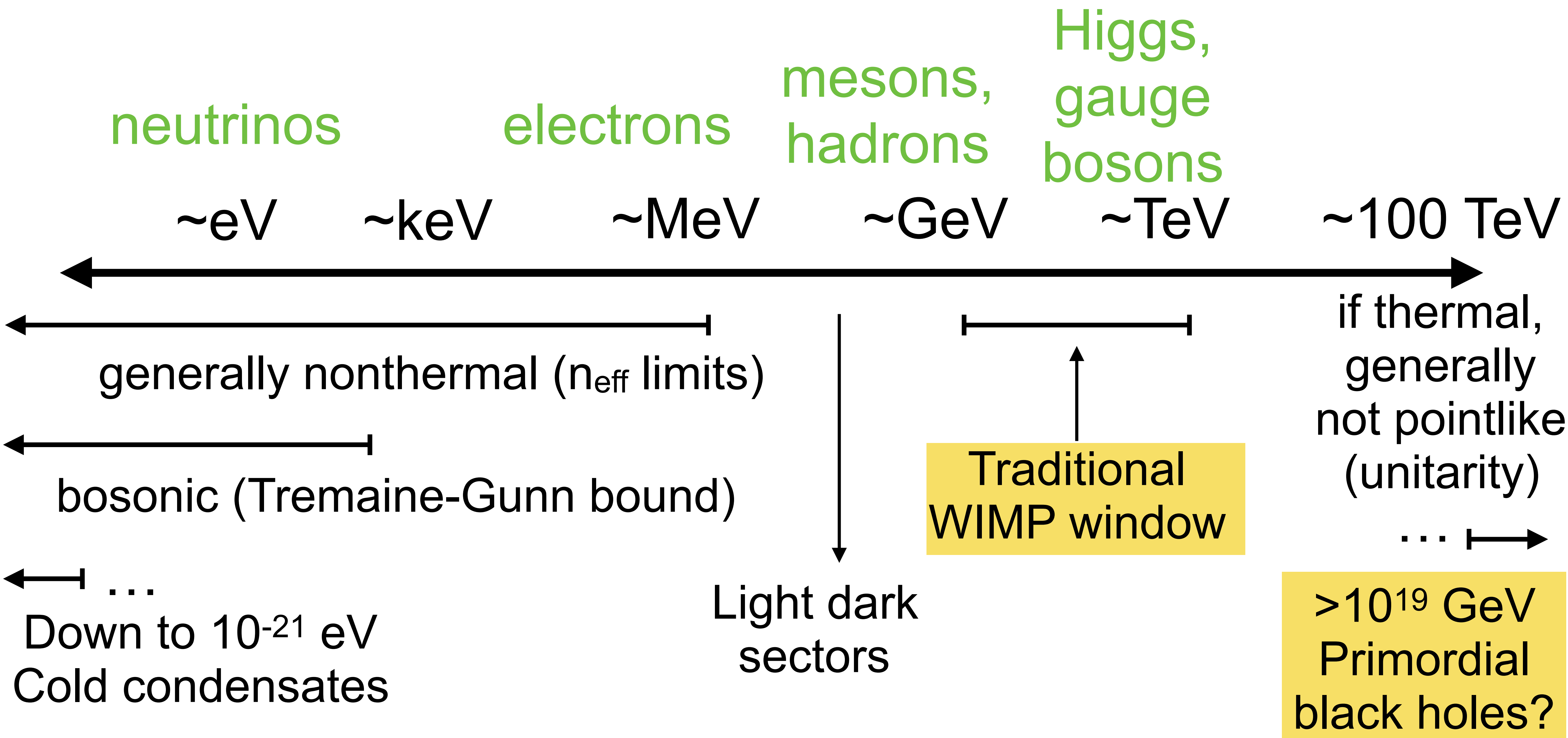

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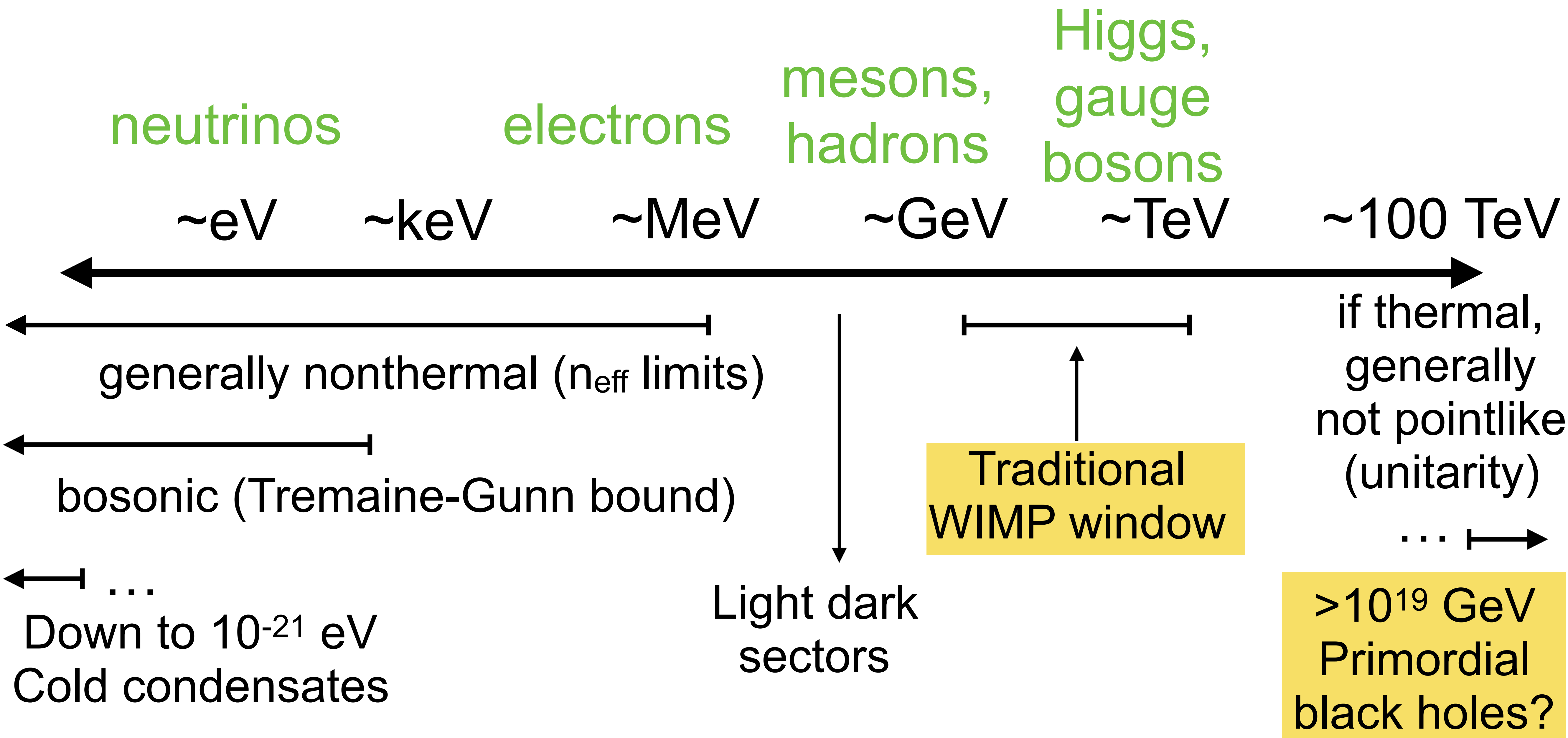


- Even in well-studied scenarios some regions of parameter space remain elusive
- What can we learn from current/future gamma-ray telescopes?

Primordial black holes (PBHs) as dark matter

- General idea: black holes can be formed from inhomogeneities in the high-density early universe [see Carr et al 2002.12778 for a recent review containing more comprehensive references].

- Black holes are electrically neutral (or quickly become so) and interact primarily via gravity.

- Sufficiently heavy black holes have a lifetime >> age of the universe.

- Black holes would be heavy, non-relativistic “particles”, and would play the cosmological role of DM provided they are formed well before matter-radiation equality - hence only primordial BHs are viable DM candidates, not those formed from stars.

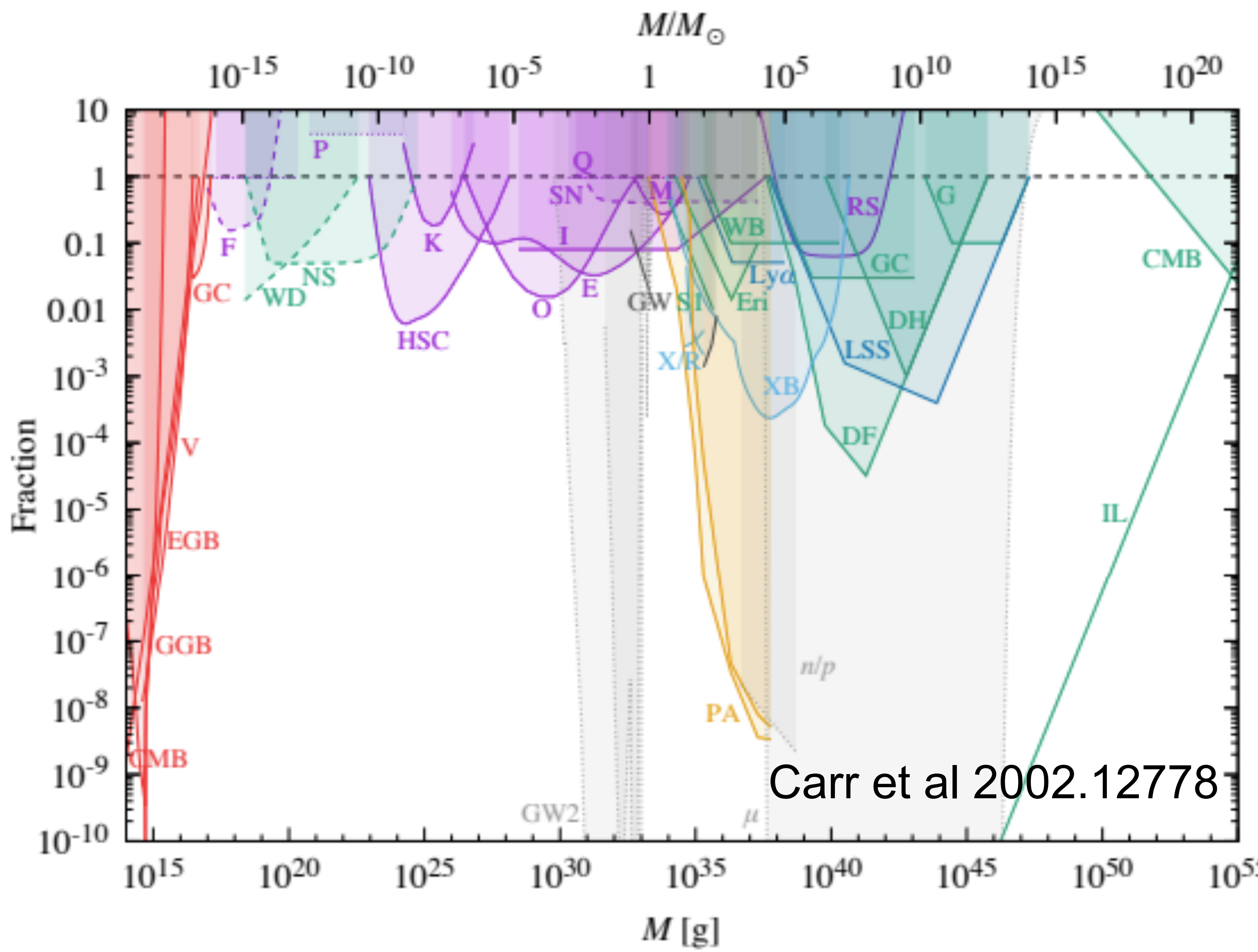
- Perhaps the most plausible DM scenario that does not require DM to be comprised of new particles beyond the Standard Model (although probably requires a non-minimal inflation model or other BSM physics)

Constraints on PBHs as DM

- Too-light PBHs evaporate via Hawking radiation - null searches for the radiation constrain lifetimes longer than the age of the universe

$$T_{\rm BH} = \frac{M_{\rm Pl}^2}{8\pi M} \qquad \tau \sim \frac{M^3}{M_{\rm Pl}^2}$$

- Over a wide mass range, PBHs can be probed with a combination of gravitational lensing + dynamical effects in astrophysical systems



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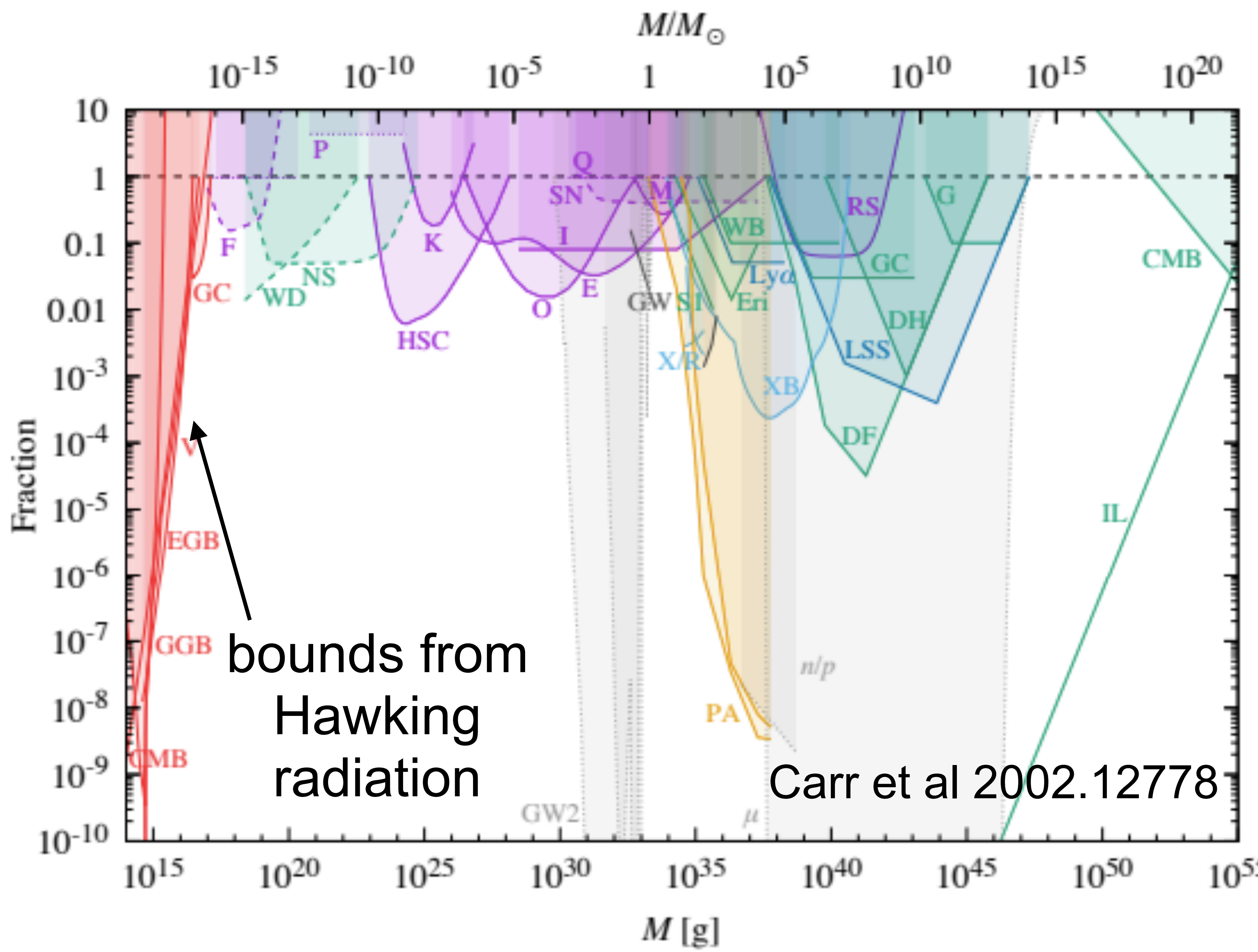

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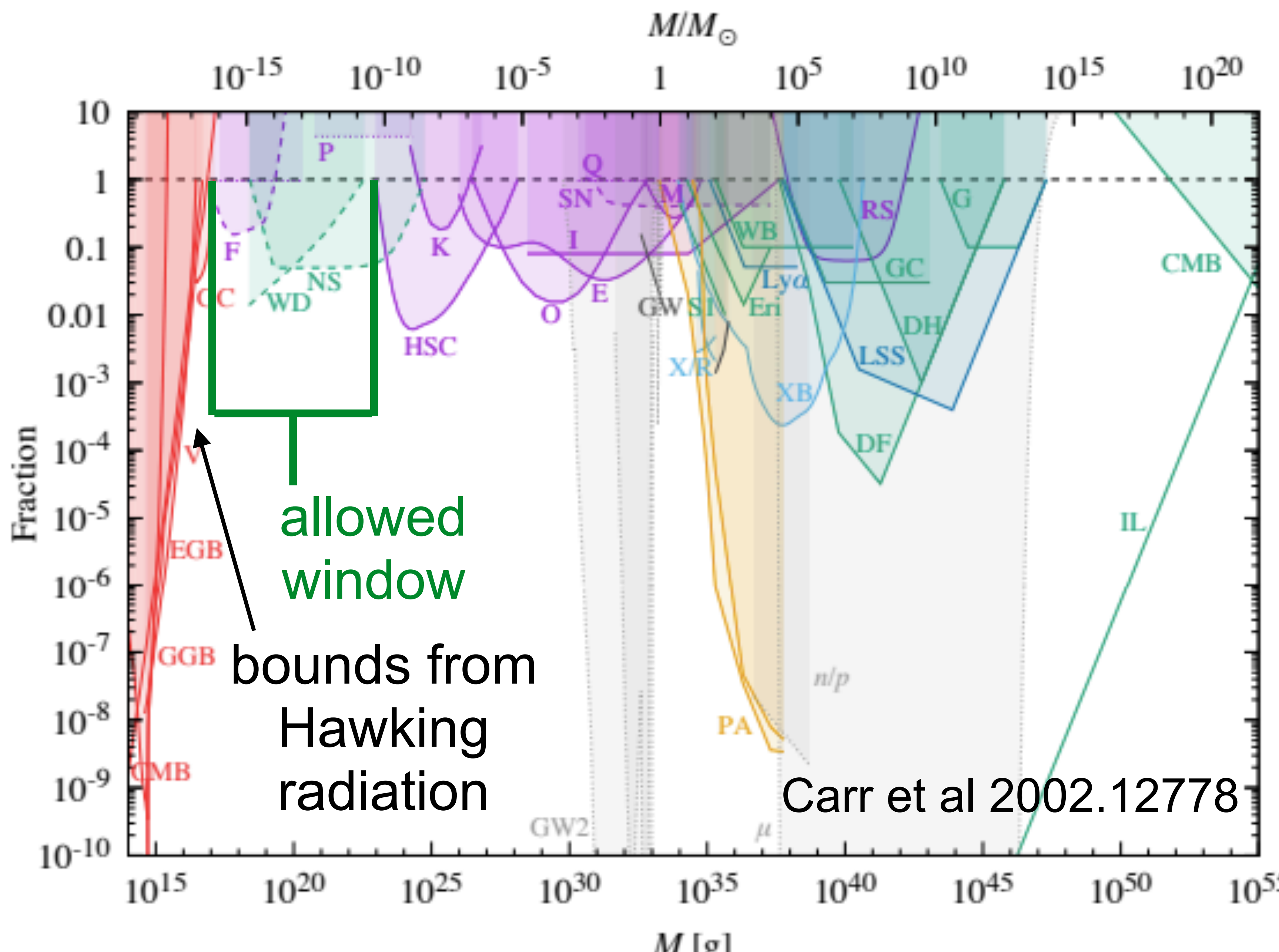

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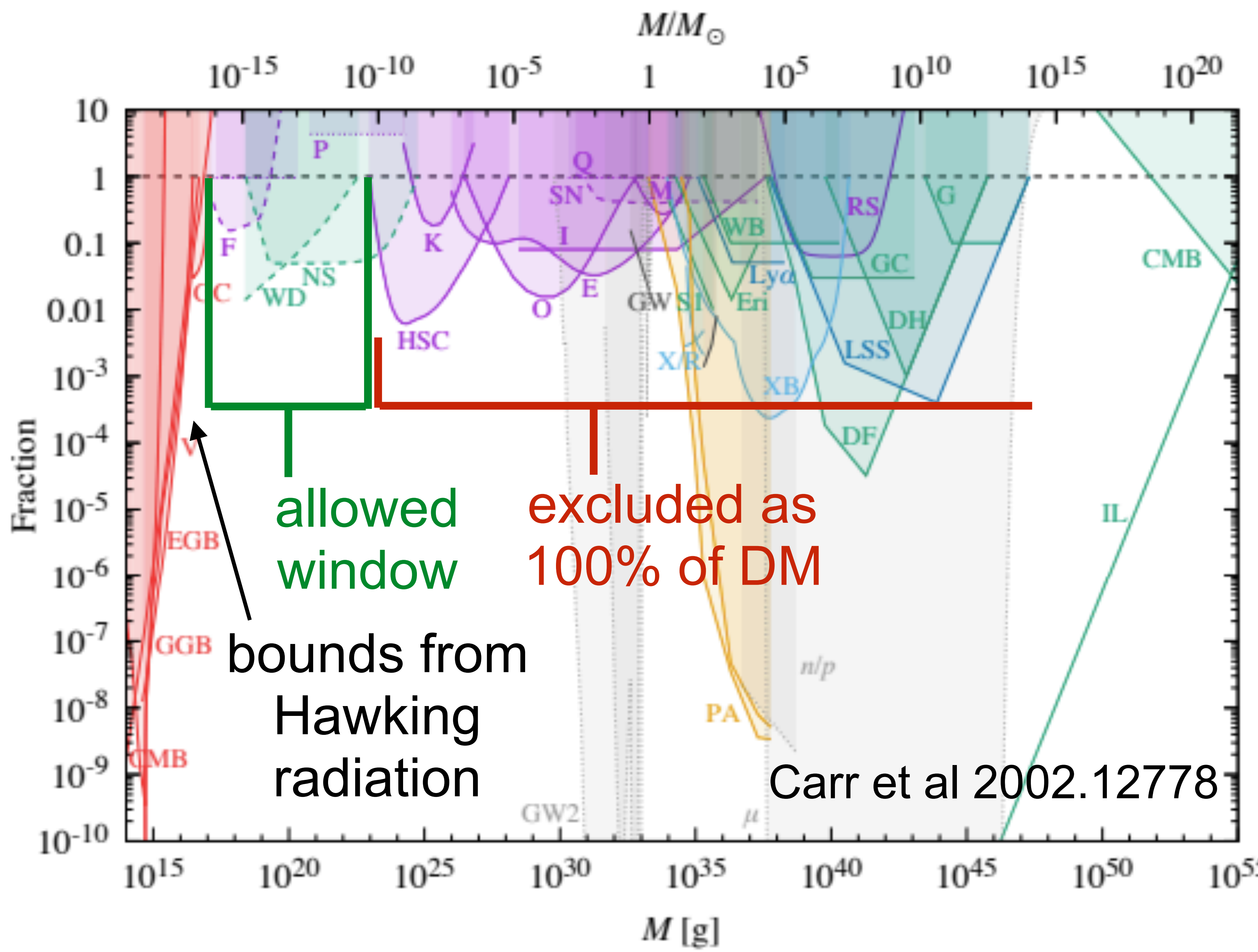

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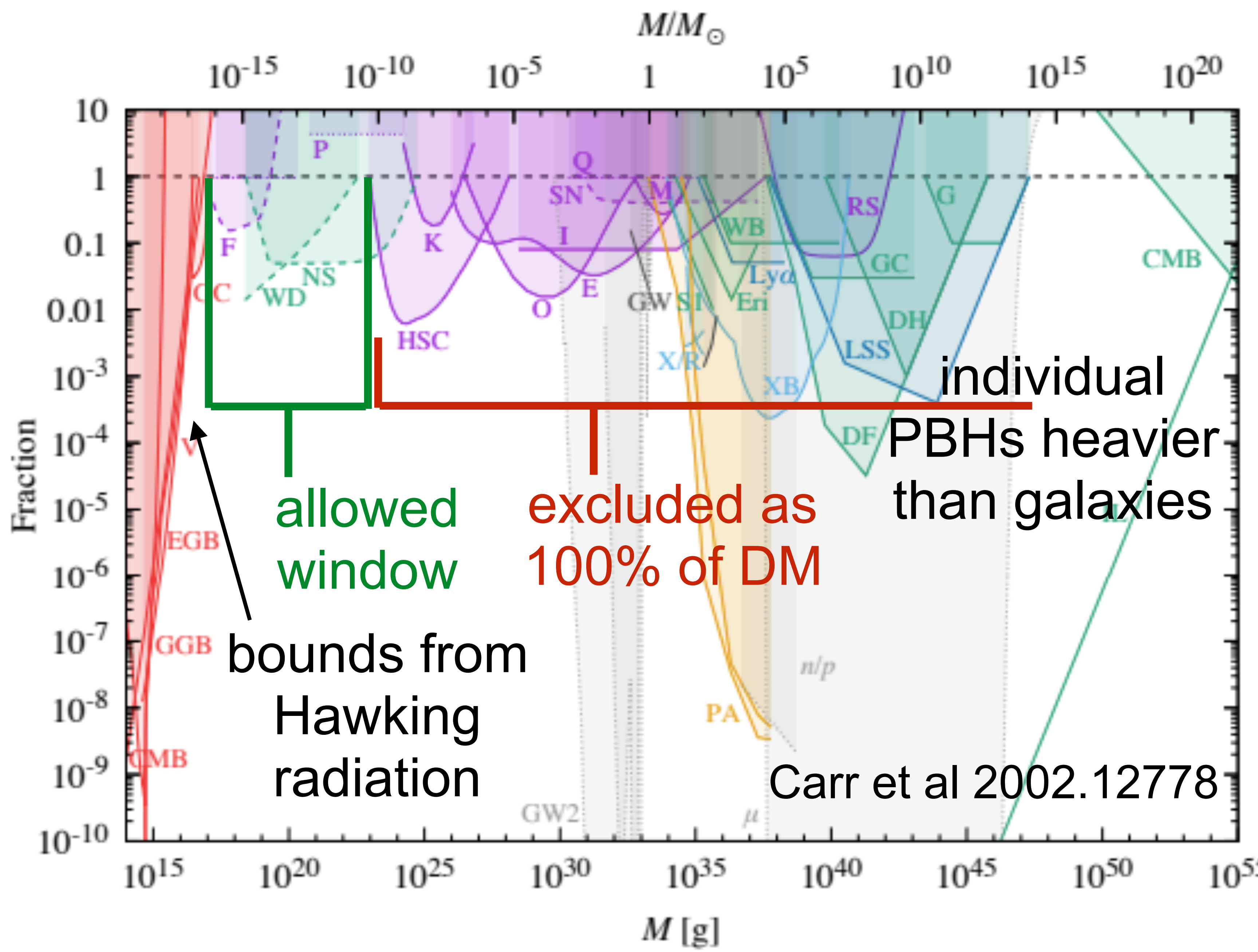

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Probing asteroid-mass PBHs

- Previous attempts to constrain this region have exploited [see e.g. 1906.05950 for a discussion]:
  - femtolensing of gamma-ray bursts (challenged due to not taking source extension into account),
  - the possibility of PBHs to trigger white dwarf explosions (found to be ineffective),
  - PBH capture onto neutron stars and white dwarfs (relies on assumptions about DM density in dense stellar systems, such as globular clusters).
- At present none of these limits seem to constrain the possibility of PBHs being 100% DM, although stellar disruption by captured PBHs might be constraining in the future
- How far can we push up the low-mass limit from Hawking evaporation?

The International Gamma-Ray Astrophysics Laboratory (INTEGRAL)

- Launched 2002 by the European Space Agency.
- SPI (spectrometer): covers 18 keV-8 MeV energy range, 2.5 degree angular resolution, 0.2% energy resolution.
- IBIS (imager): covers 15 keV-10 MeV energy range, 12 arcminute angular resolution, 8-10% energy resolution.
- <u>Note:</u> INTEGRAL does not measure isotropic gamma-ray background - isotropic signals are absorbed into the background model (also includes cosmic rays, instrumental backgrounds).

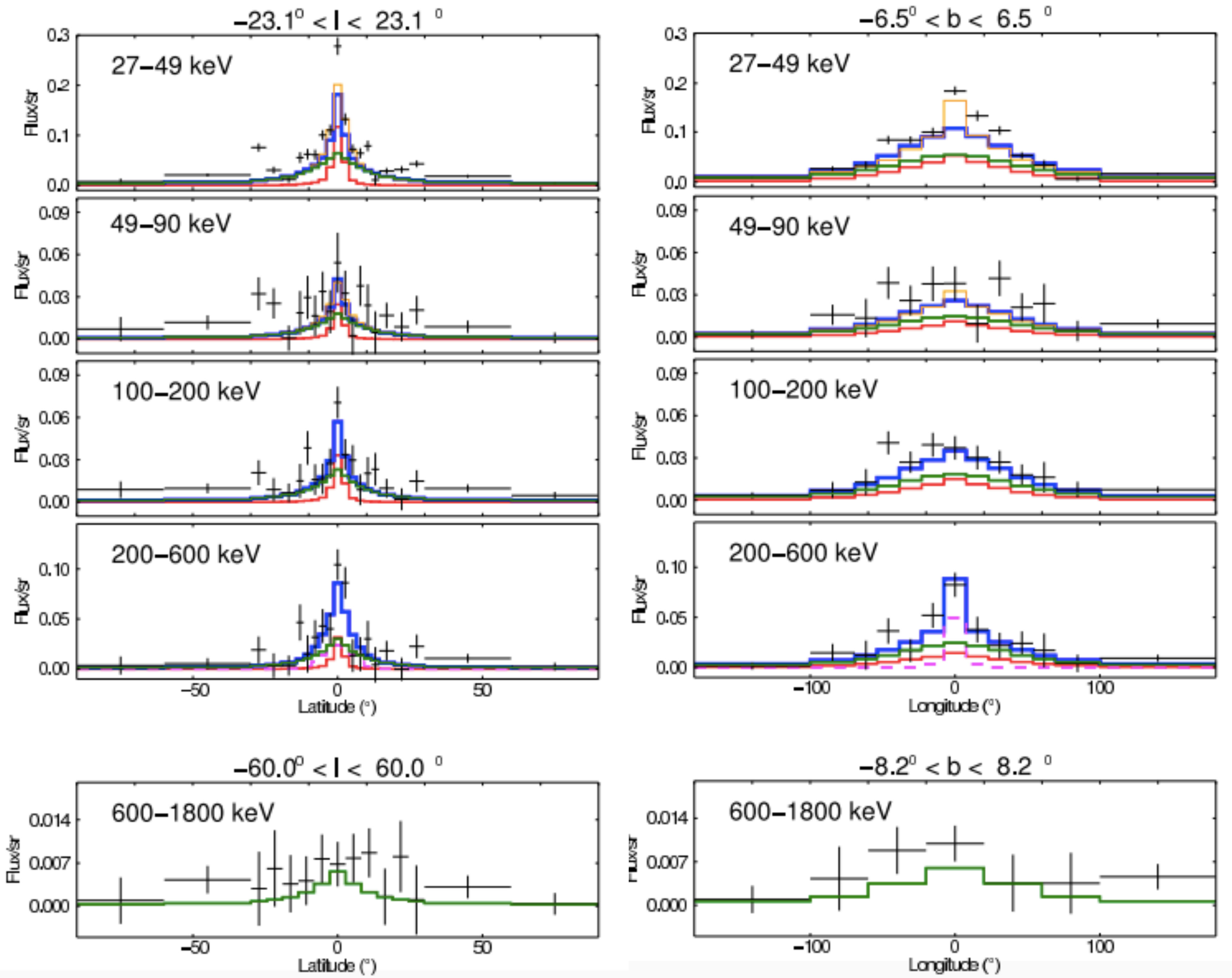
Analyzing INTEGRAL data

L. Bouchet, A. W. Strong, T. A. Porter, I. V. Moskalenko, E. Jourdain, & J.-P. Roques 2011 (1107.0200)

- Two approaches to modeling the diffuse gamma-ray emission:
  - Sky imaging - introduce point source locations as a priori information, simultaneously fit for intensities of diffuse pixels and point sources
  - Sky model fitting - introduce spatial templates for various expected contributions to the diffuse emission, fit for their intensity (together with point sources)
- Second approach provides more information to the fit, can lead to smaller uncertainties, but not clear how it will behave if there is a component (e.g. Hawking radiation from PBHs) not matching any of the assumed templates
- Ideally one would re-do the second approach including a template for the signal of interest
- As a simpler first-pass alternative, we can simply require that our signal not overproduce the model-independent diffuse emission from the sky-imaging approach

INTEGRAL data from the sky-imaging approach

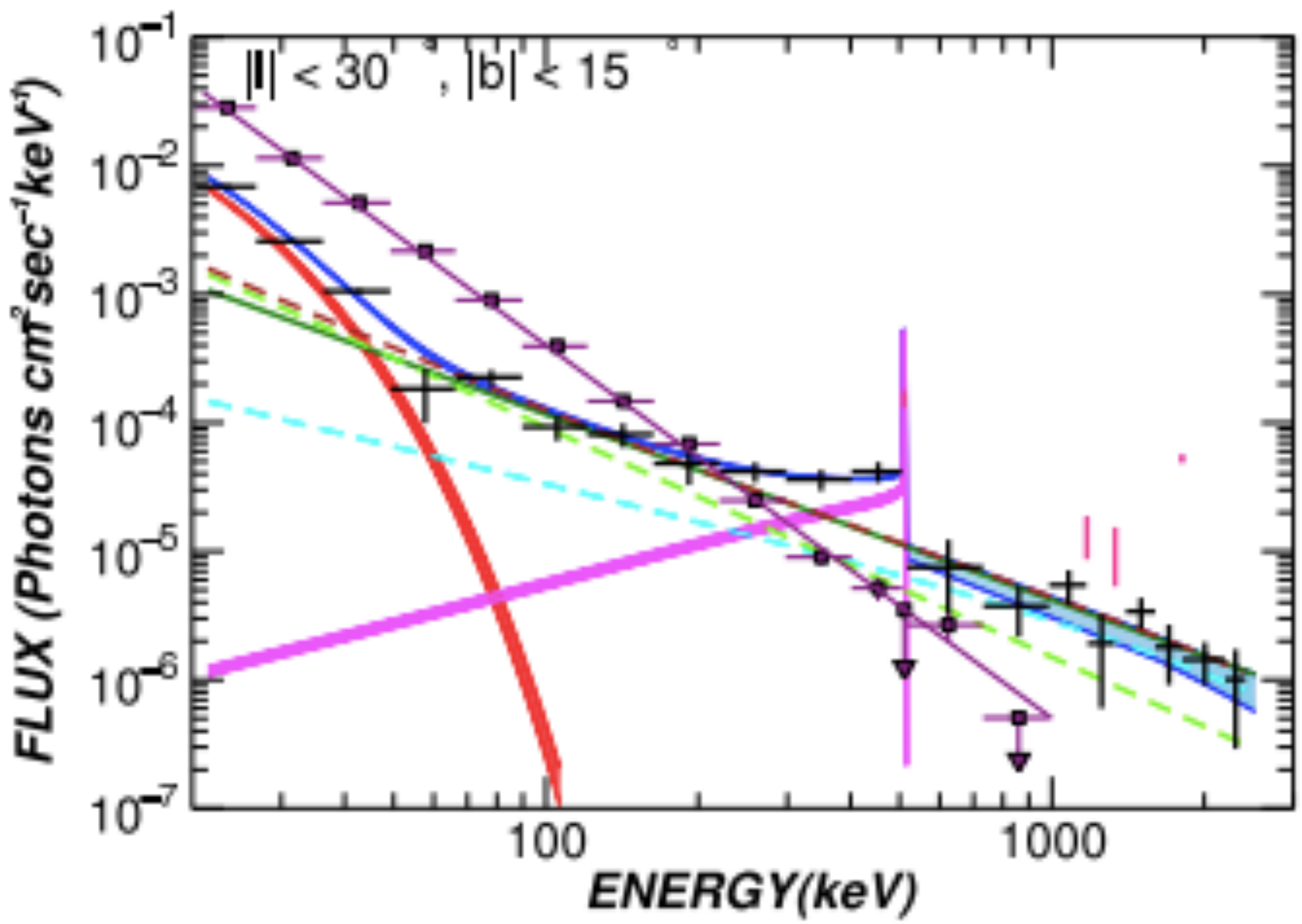
- The total diffuse gamma-ray emission is coarsely binned in latitude, longitude and energy
- We employ these results for our main constraints



INTEGRAL data from the sky-modeling approach

- The authors of 1107.0200 also present results for the spectrum of each diffuse-emission template, and the summed spectrum, in the region |l|<30°, |b|<15°

- These data give stronger constraints on a PBH signal, but there is a potentially large systematic uncertainty, since this spectrum does not account for all observed photons, only those following a specific (not DM-like) spatial morphology



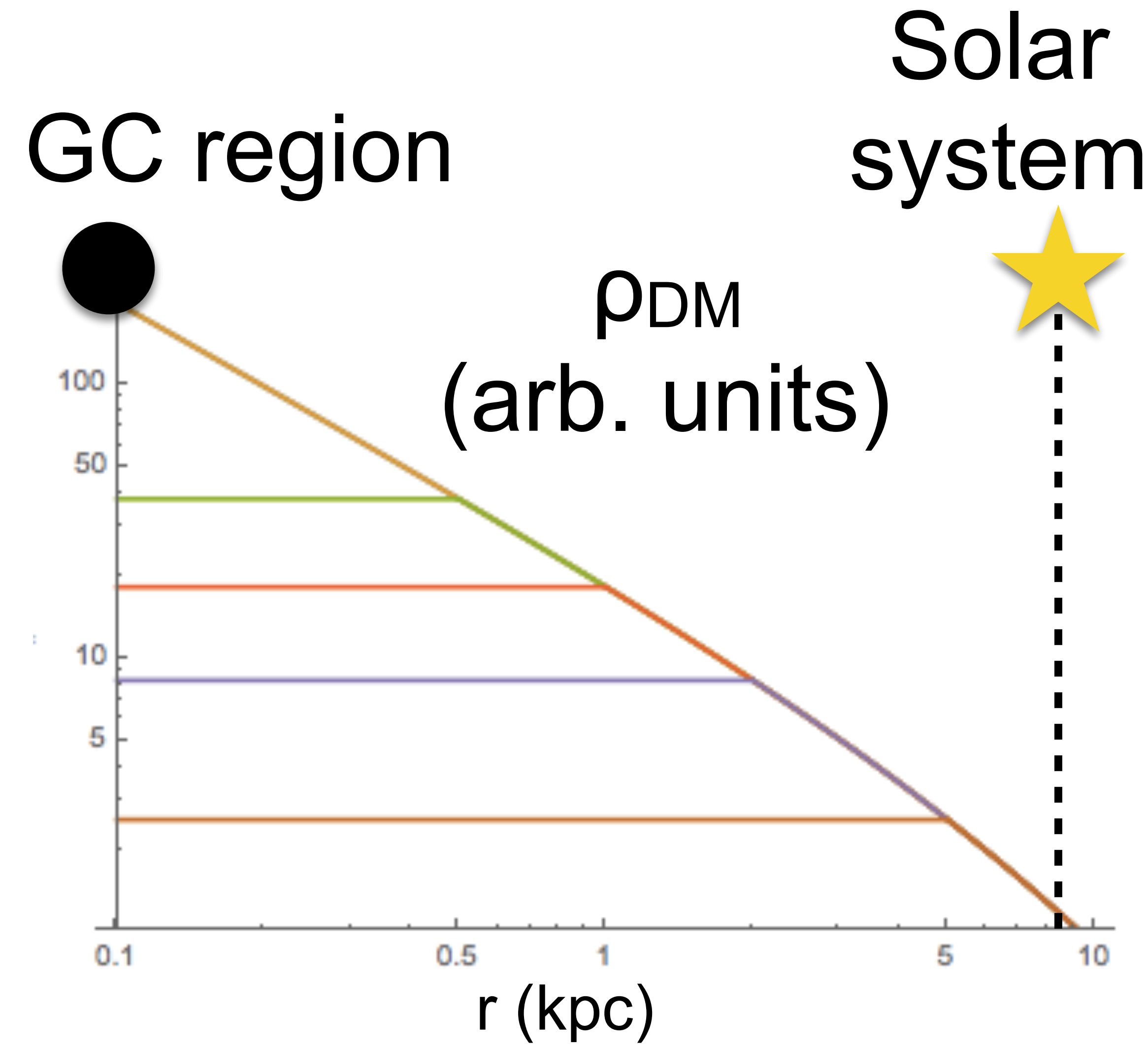
- These data were employed by Essig et al 1309.4091 to set bounds on light annihilating/decaying DM - we will revisit these limits

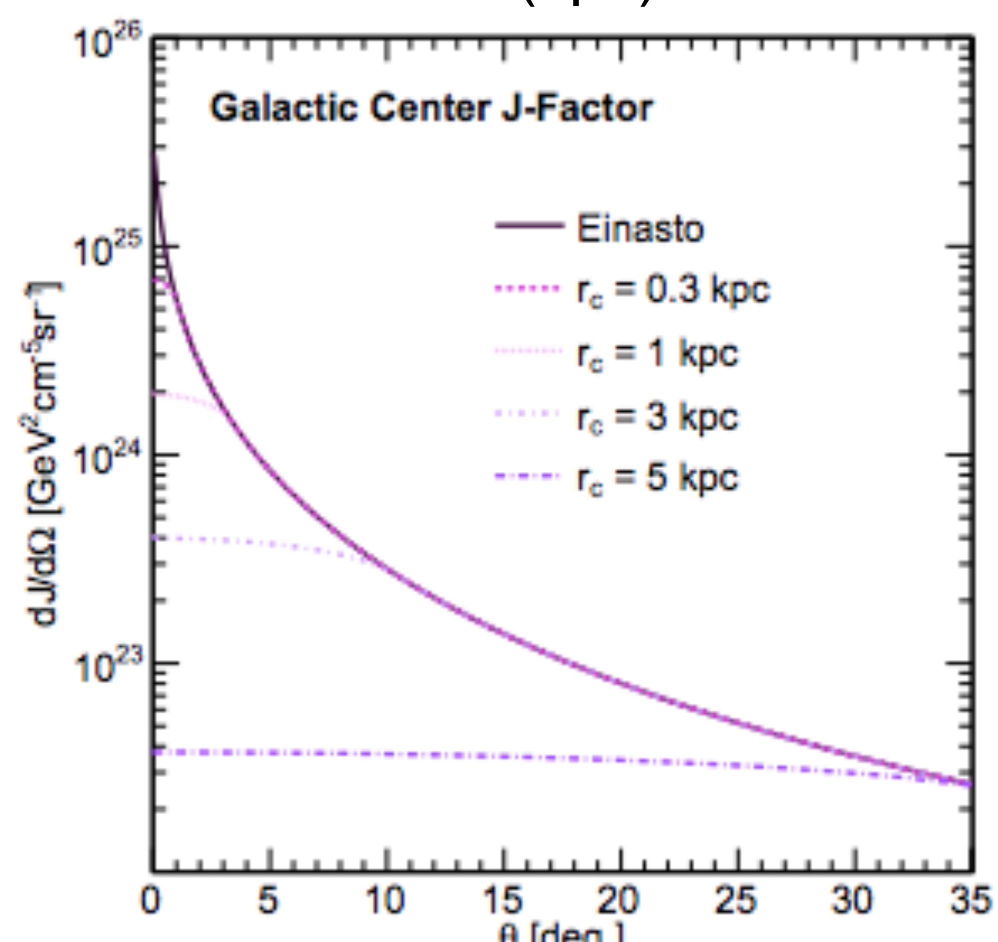
Predicting the PBH signal

- M_{PBH} controls both the signal spectrum and the overall signal strength
  - Peak energy $E \approx 5.77 T_{\rm BH} \approx \left(\frac{10^{17}\rm g}{M_{\rm PBH}}\right) 0.4 \rm MeV$
  - Decay rate scales as $1/M_{PBH}^3$, PBH density as f/M_{PBH}
- We also need to know the DM density in the region of interest; by default we assume a NFW profile with local DM density 0.4 GeV/cm^3
- Changing the DM density directly rescales the constraint on the PBH DM fraction f (the strong scaling with M_{PBH} means the constraint on M_{PBH} is usually much less affected)

The DM density profile

- The DM density profile in the Milky Way is not well known toward the Galactic Center, where baryonic matter comes to dominate the potential
- The DM local density can be measured by observing stellar motions, but still has large uncertainties / scatter between different methods
- N-body simulations suggest DM density should rise toward GC (following the NFW or Einasto forms), 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
- We take the Earth-GC distance to be 8.3 kpc

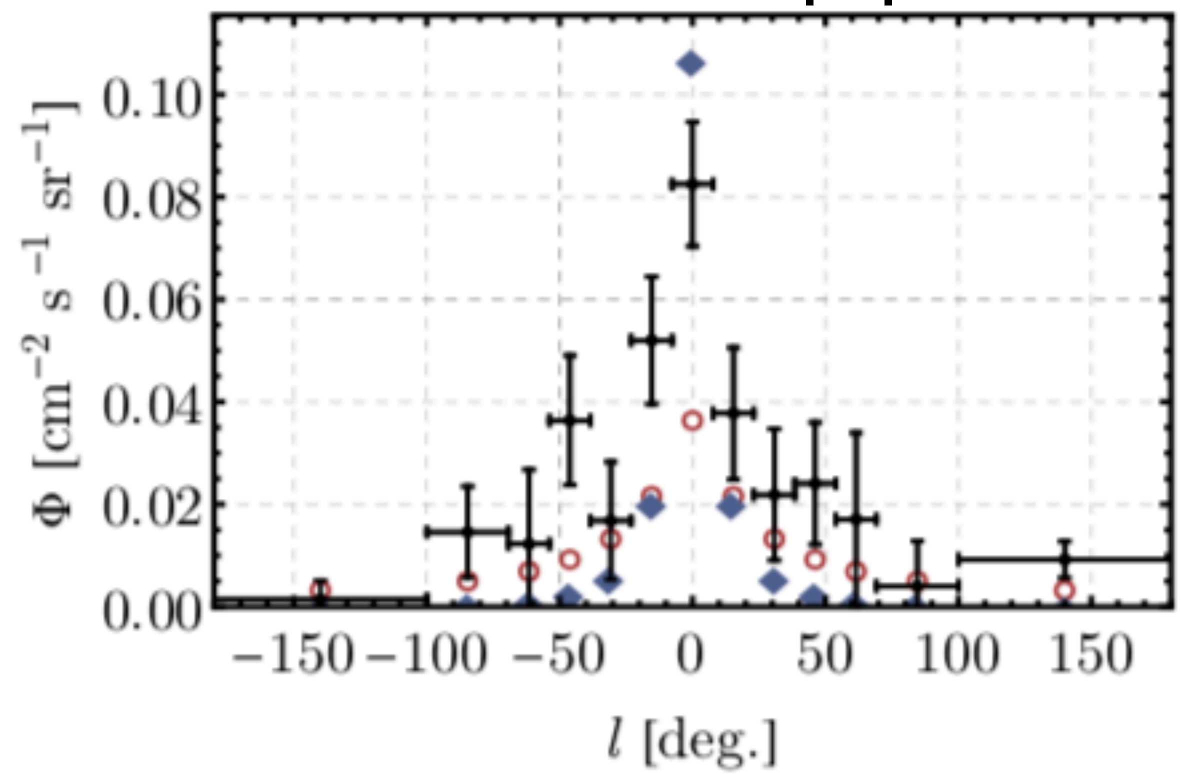




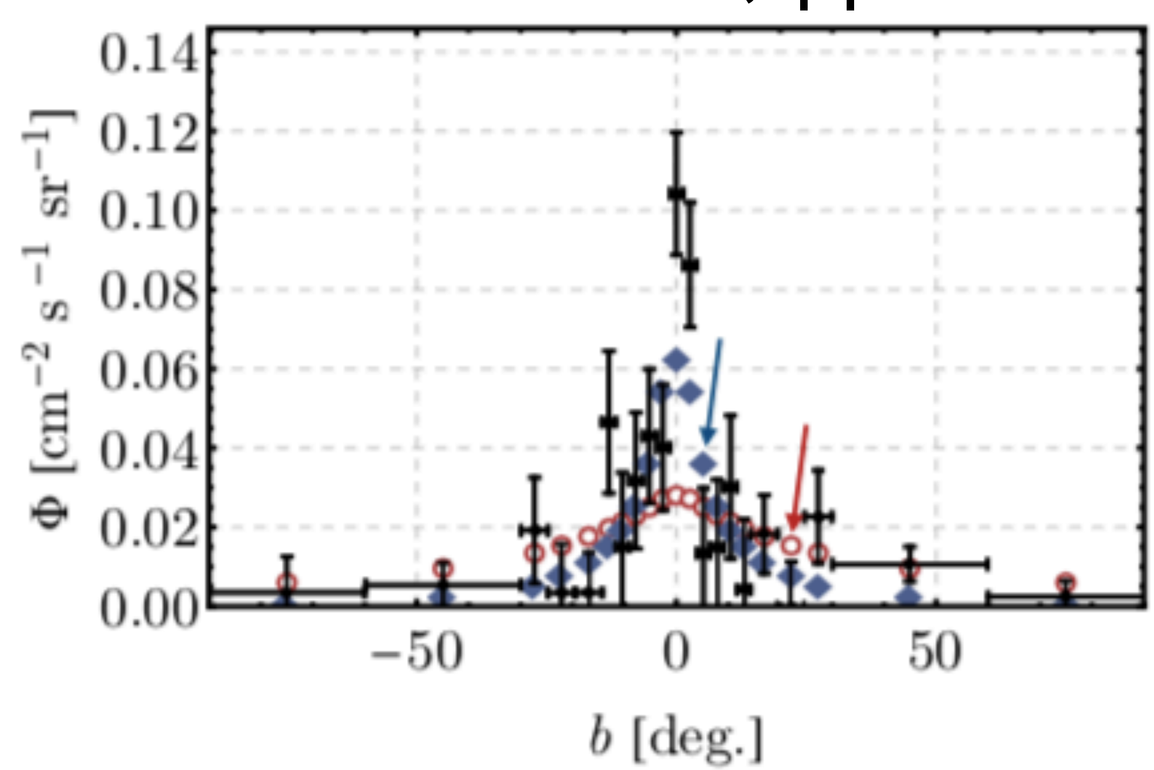
INTEGRAL data vs PBH decay signal

- We consider the INTEGRAL-SPI sky-imaging dataset for diffuse emission as a function of Galactic position
- Energy bin boundaries are E/MeV = [0.027, 0.049, 0.1, 0.2, 0.6, 1.8]
- We require that the PBH signal not overproduce any data point by more than 2x the error bar
- Stronger constraints could be obtained by simultaneously modeling the signal + astrophysical background

200-600 keV, |b|<6.5°

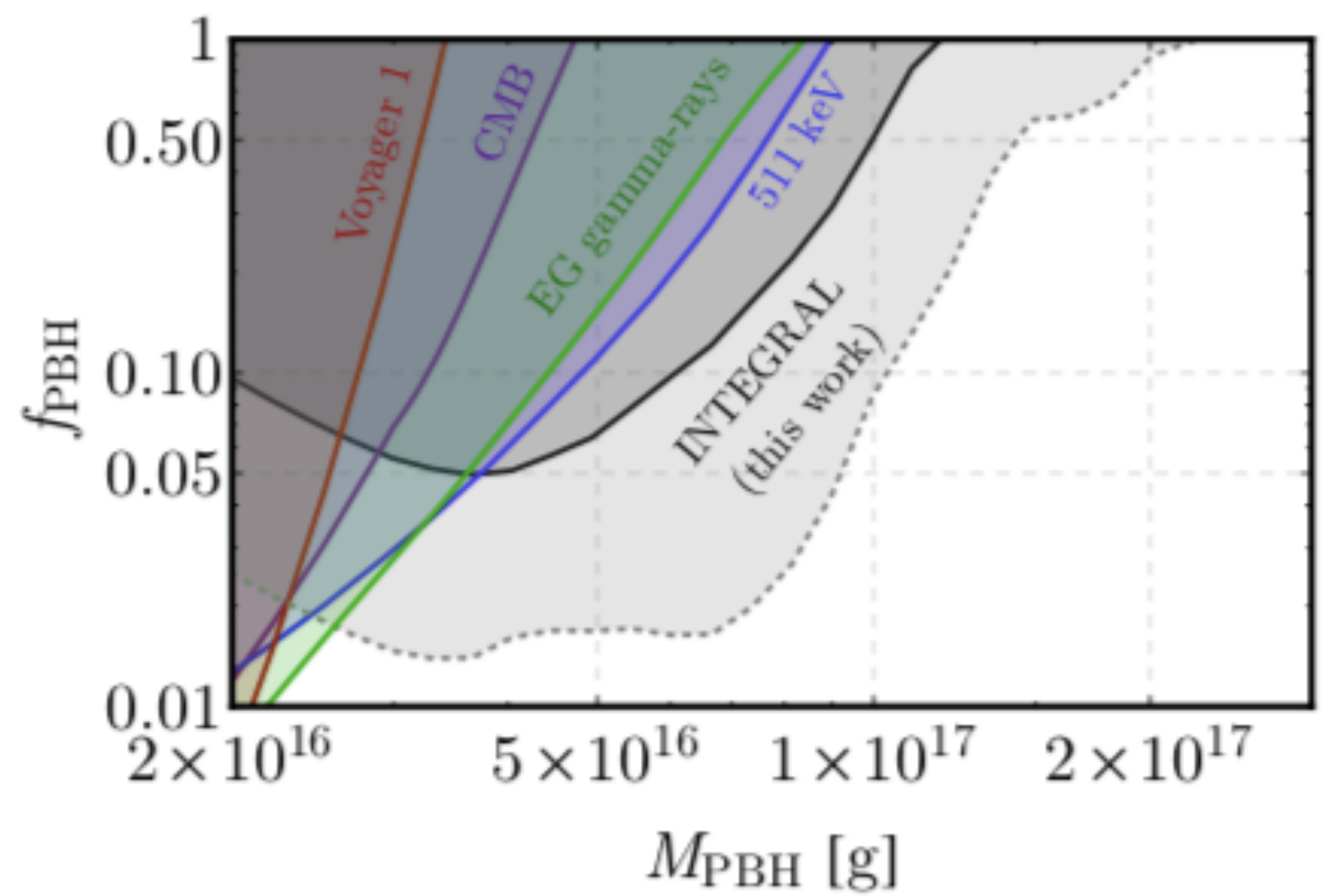


200-600 keV, |l|<23.1°



New constraints on PBHs

- We exclude f=1 for $M_{PBH} < 1.2 \times 10^{17}$ g, for our baseline assumptions.



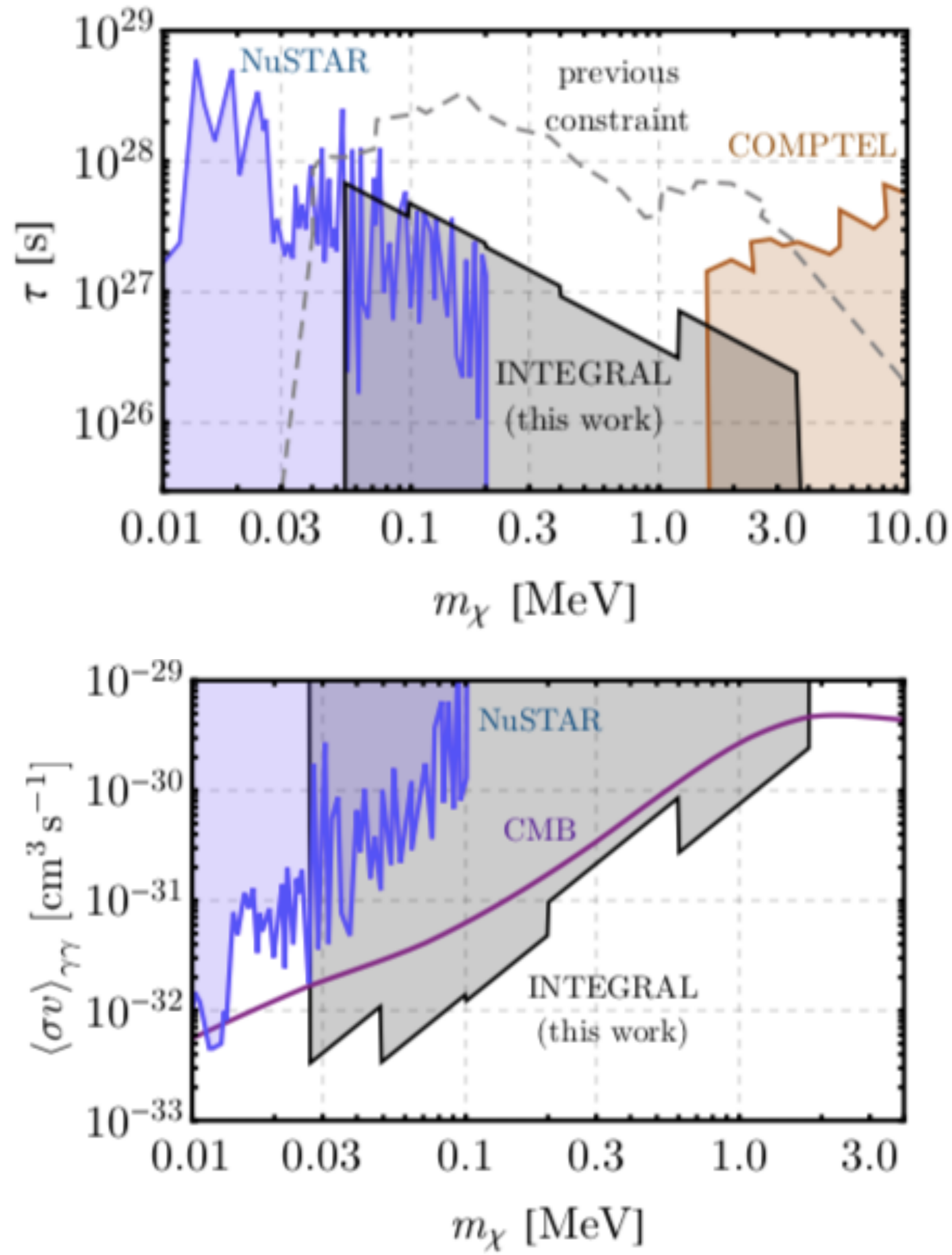
- Our limits do not change if the NFW profile has a flat-density central core of radius up to 5 kpc.

- We also tested the results of using the alternative SPI dataset (based on template fitting) assuming the sum of the templates provides an upper limit for the DM signal [as in Essig et al 1309.4091].

- In this case we find a stronger bound, excluding f=1 for $M_{PBH} < 2 \times 10^{17}$ g.

Updated constraints on decaying/annihilating DM

- We can perform the same analysis for photons from decay/annihilation of particle DM
- For DM with mass in the INTEGRAL energy range, INTEGRAL can provide the strongest bounds on annihilations/ decays to photons (in agreement with previous studies)
- However, our limits are weaker than those previously claimed [Essig et al ’13] as (a) that work included extragalactic (isotropic) signal contributions, (b) it used the data obtained from an astrophysical template fit, as discussed earlier



INTEGRAL/PBHs summary

- Very conservative analyses of coarsely-binned INTEGRAL data already provide the best limits on O(10^{17} g) PBHs, as well as decay/annihilation of DM to photons in the 30 keV-MeV DM mass range.

- A more detailed analysis of INTEGRAL data, including astrophysical background models and exploiting the full energy and angular resolution, could potentially significantly improve the sensitivity

- Future experiments covering the O(MeV) energy range (e.g. AMEGO) may be able to improve these limits even further

- Due to the steep M_{PBH} scaling of the evaporation signal, alternative probes will be needed to cover the current "gap" extending up to 10^{23} g

The case for WIMPs

- If DM is a particle, what determines its abundance?
- One possible scenario: annihilation reactions deplete DM in the early universe, control its present-day density.
- In this "thermal freezeout" scenario, DM must have a mass between ~1 MeV and 100 TeV (in standard cosmology).
- Required annihilation cross section is $\sim 1/(100\ \text{TeV})^2 \sim \alpha^2 / \text{TeV}^2$ - consistent with weak-scale mass and interaction strength.
- Motivates DM as a Weakly Interacting Massive Particle (WIMP).

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 4×10^{-47} cm^2 (XENON1T Collaboration ’18).
- 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?
- Classic example: dark matter as the Lightest Supersymmetric Particle (LSP), stabilized by R-parity. Typically the LSP is the lightest neutralino - admixture of bino, wino and higgsino (superpartners of gauge + Higgs bosons).

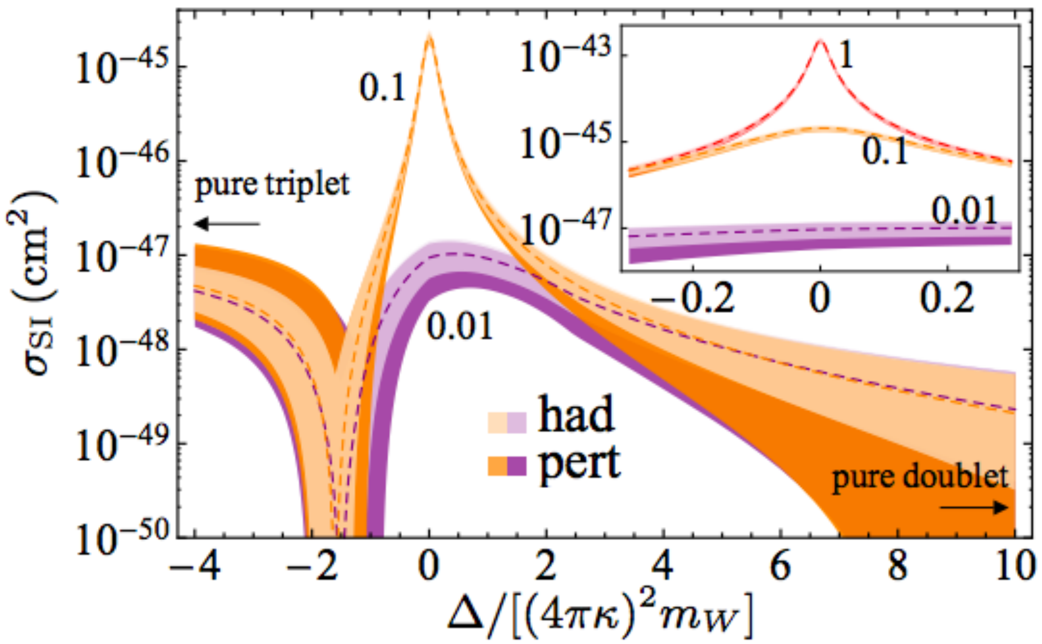
Minimal dark matter

- One simple benchmark: consider DM inhabiting near-pure representations of $SU(2)_W$
- Lightest state (must be neutral) is DM, it is accompanied by nearly-degenerate charged states.
- Only a small set of viable possibilities [Cirelli et al, hep-ph/0512090]: doublet, triplet, quintuplet representations (+scalar septuplet).
- Doublet and triplet fermions are realized in SUSY as the higgsino and wino respectively.
- Higgsinos, winos, and quintuplet fermions produce the right dark matter abundance for masses of 1 TeV, 3 TeV, 14 TeV respectively.

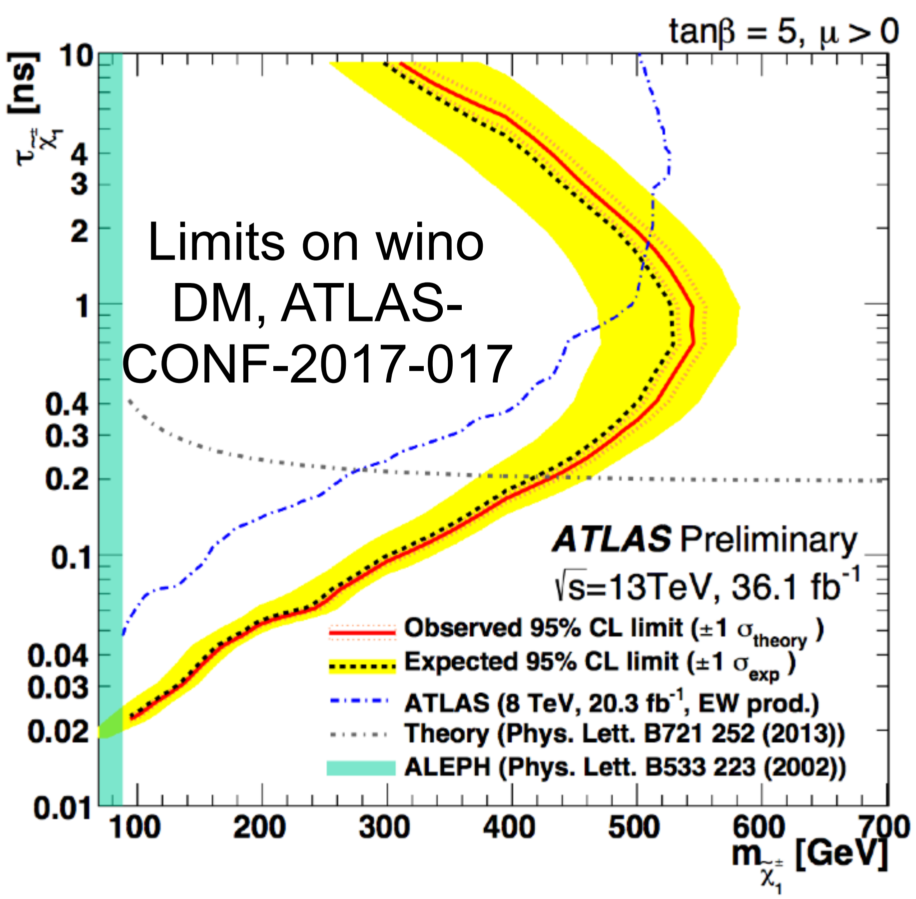
Searching for SU(2)$_W$ DM

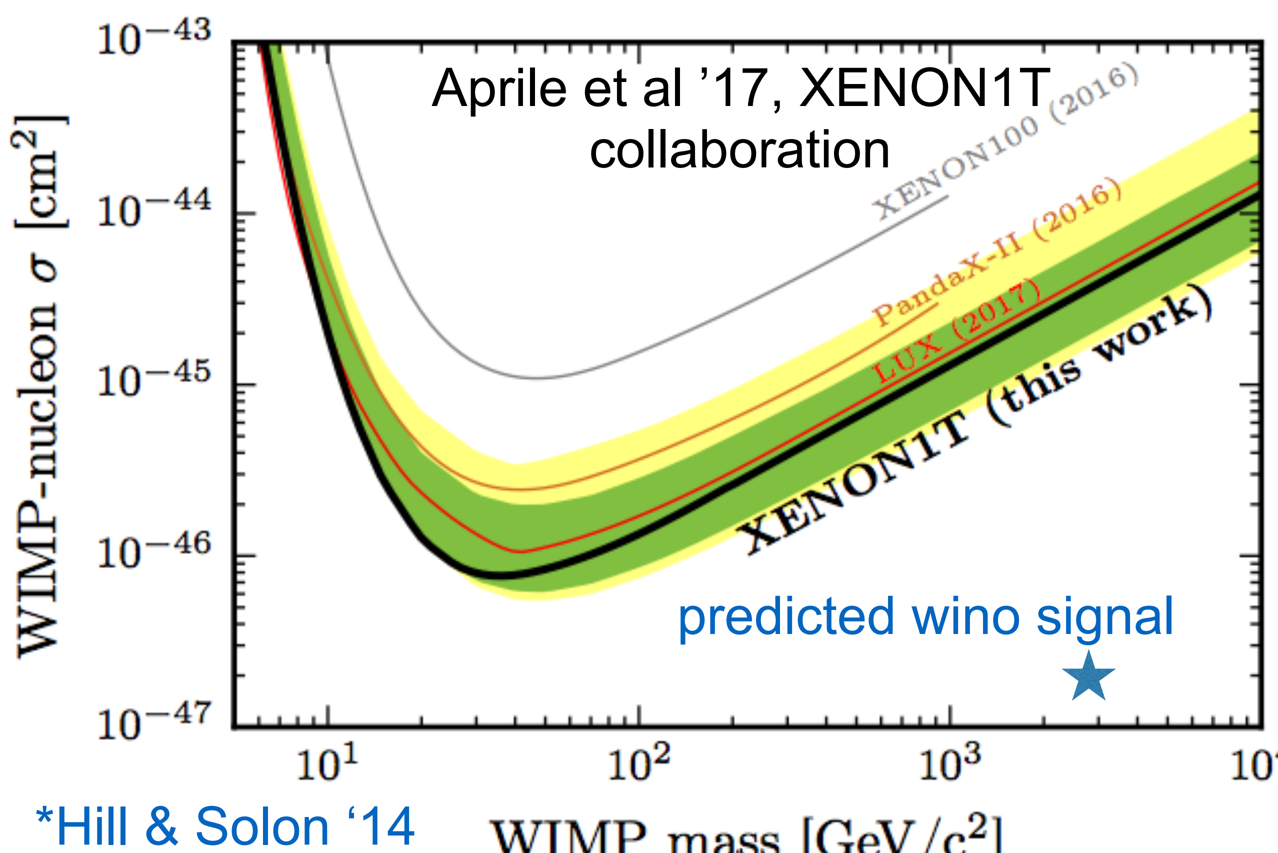
- Difficult to detect at colliders due to their high masses (CLIC may test the thermal higgsino).
- Direct detection occurs via loop processes and predictions are well below current limits.
- However, these scenarios can predict strong indirect-detection signals in high-energy gamma rays.

Hill & Solon '14



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

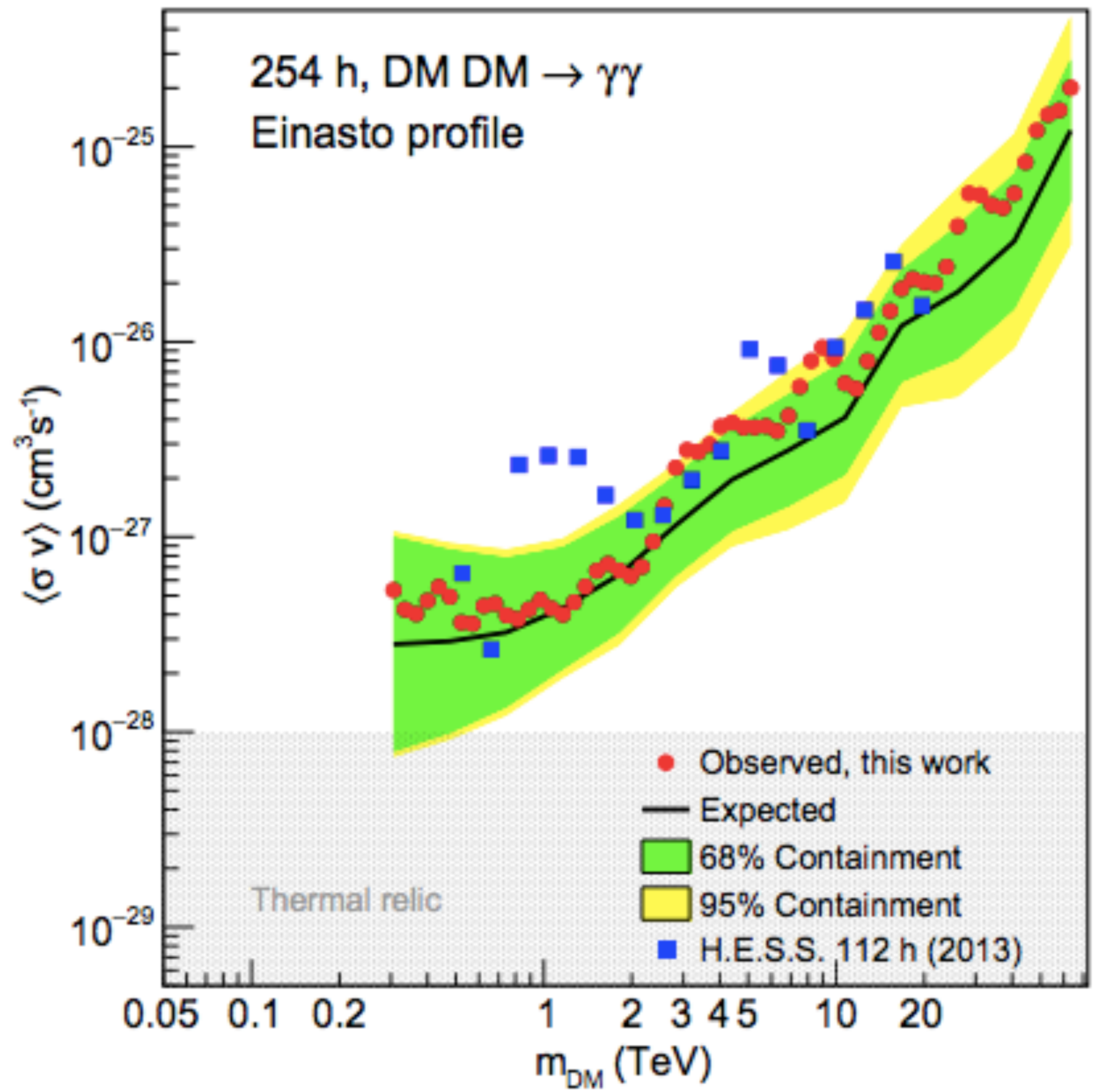




*Hill & Solon '14

Gamma-ray (line) searches

- Air/water Cherenkov telescopes can probe gamma rays in the 100 GeV - 100 TeV range.
- Gamma-ray line signal from $\chi\chi \rightarrow \gamma\gamma$ or $\chi\chi \rightarrow \gamma Z$ is a very “clean” possible annihilation channel - no astrophysical lines expected.
- Best prospect for a “smoking gun” indirect signal for DM. (Alternative channels include antiprotons, secondary photons from annihilation to unstable particles.)
- Branching ratio is typically expected to be small, as DM is dark - no direct coupling to photons - but can be significantly enhanced for heavy electroweakinos with charged partners.



H.E.S.S. Collaboration ’18 (1805.05741)

Consequences of a large mass hierarchy m_{DM}/m_W

1. Sommerfeld enhancement - long-range attractive potential enhances annihilation processes

2. Bound states - formation of bound states + subsequent decay acts as a new annihilation channel

3. Large logs from small force carrier masses - big radiative corrections to annihilation rate/spectrum, need to be resummed.

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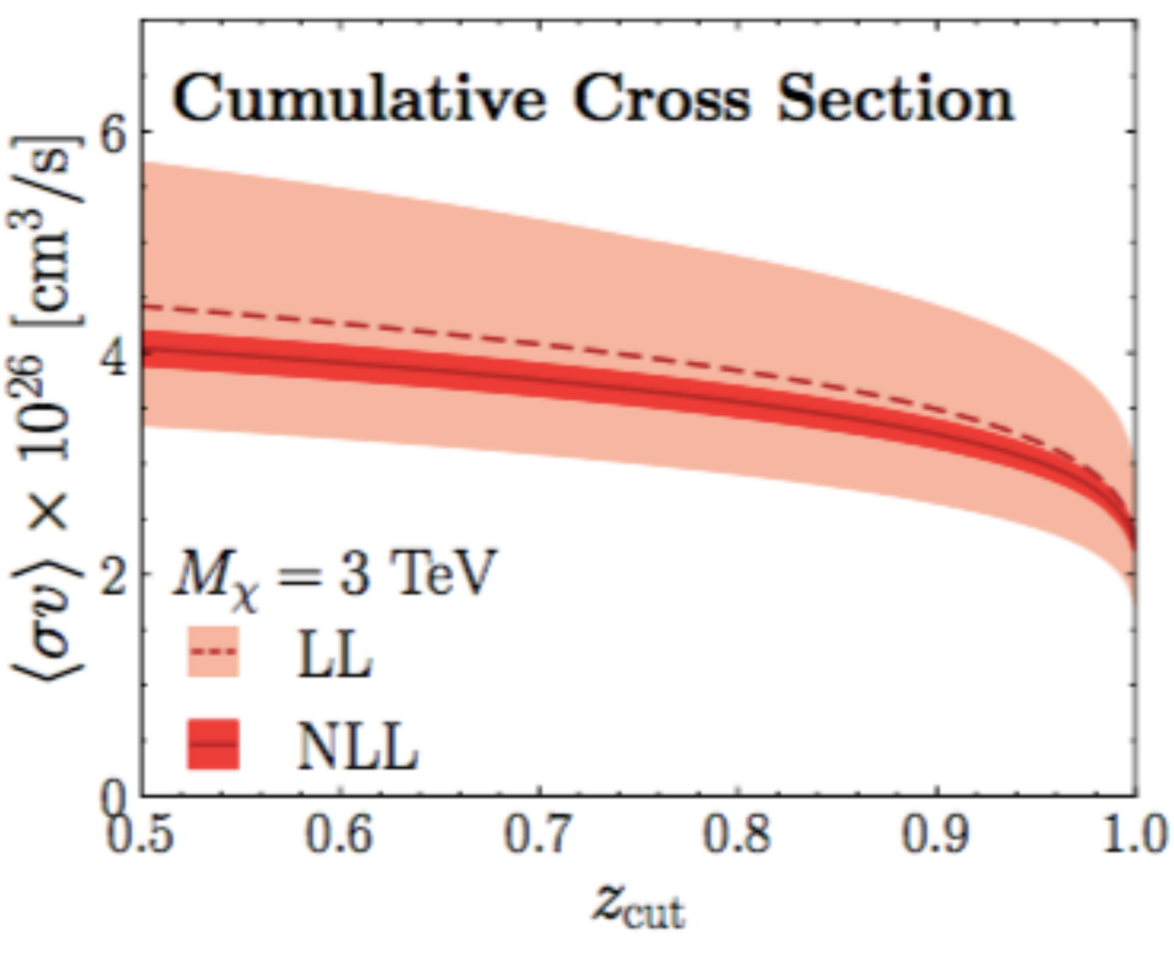
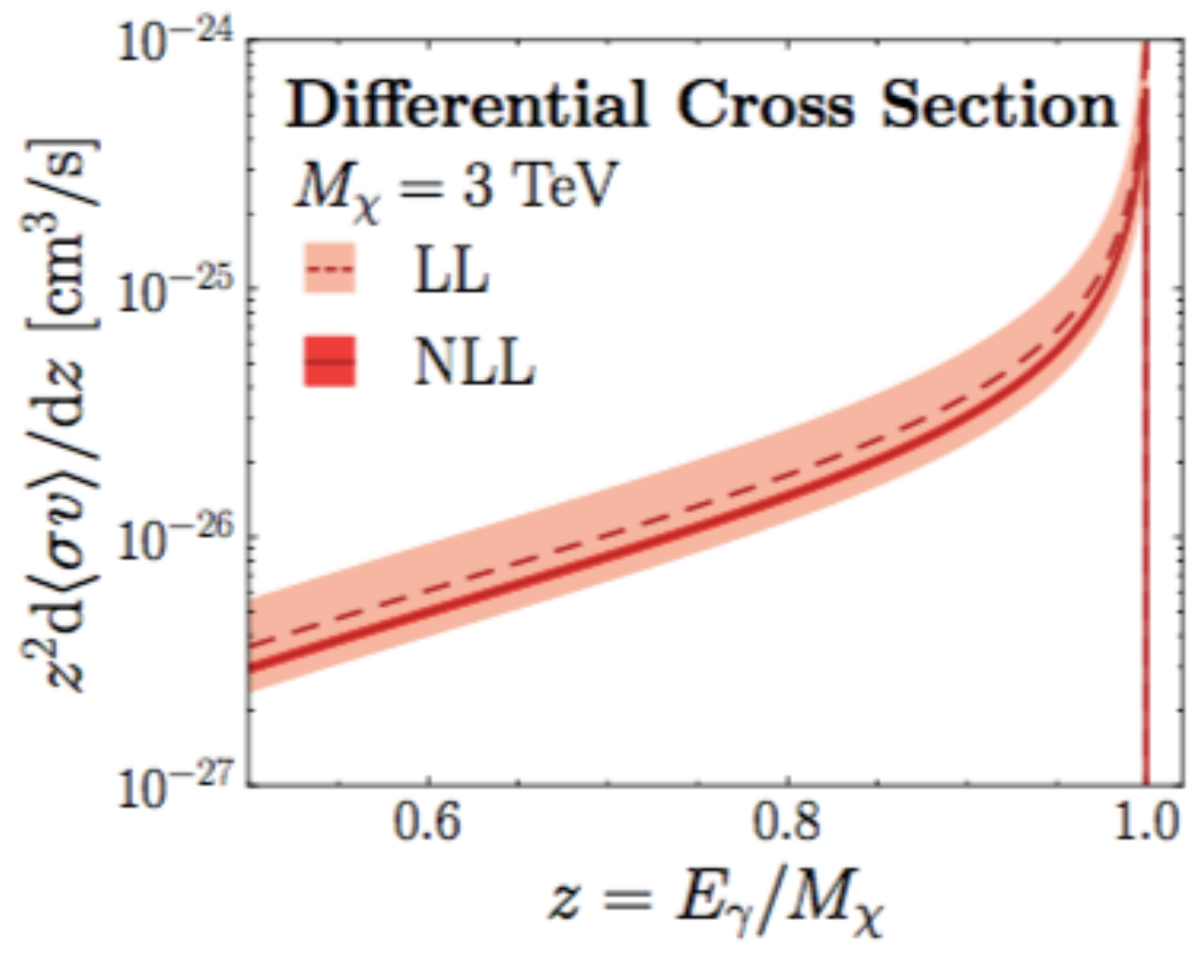
A high-precision gamma-ray spectrum for the wino

Baumgart, Cohen, Moulin, Moult, Rinchiuso, Rodd, TRS, Stewart & Vaidya '19

- For the wino, we have computed the full resummed hard photon spectrum analytically to next-to-leading-log (NLL), including the Sommerfeld enhancement. [See also Beneke et al '19 for region very close to endpoint.]
- Our theory uncertainties are now at the level of 5%.



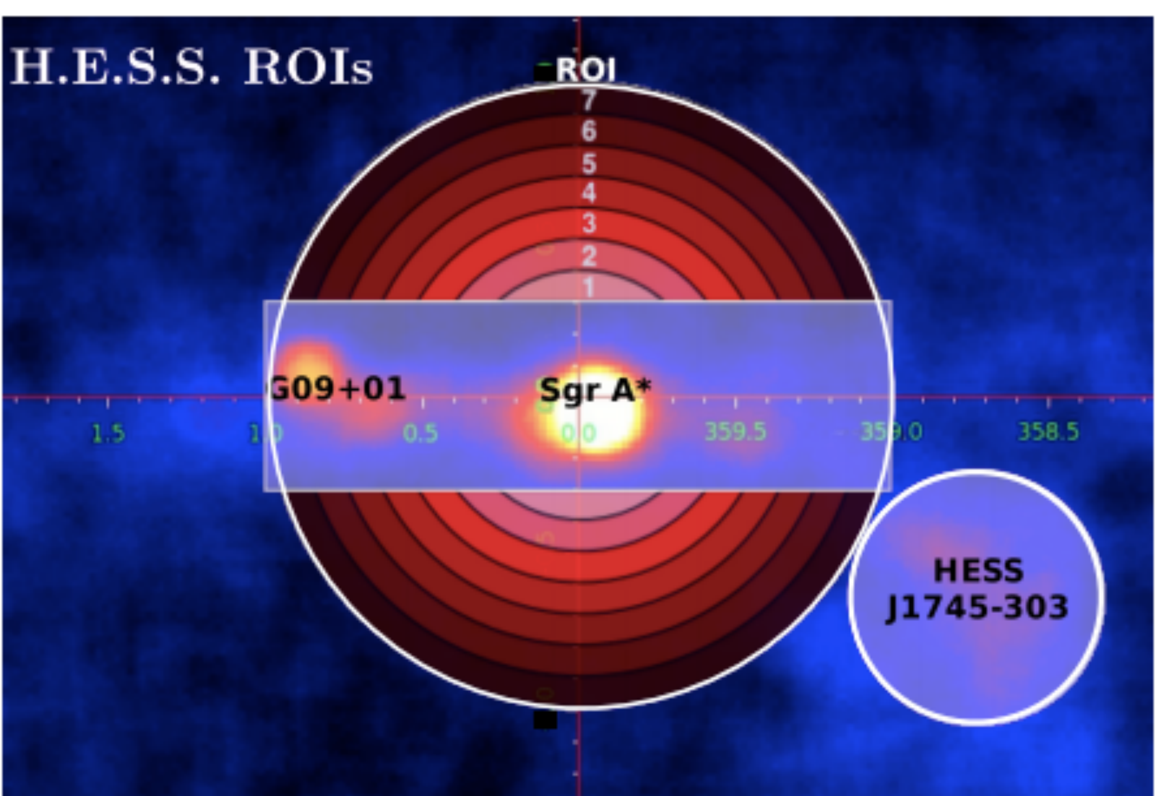


Hunting the wino with H.E.S.S

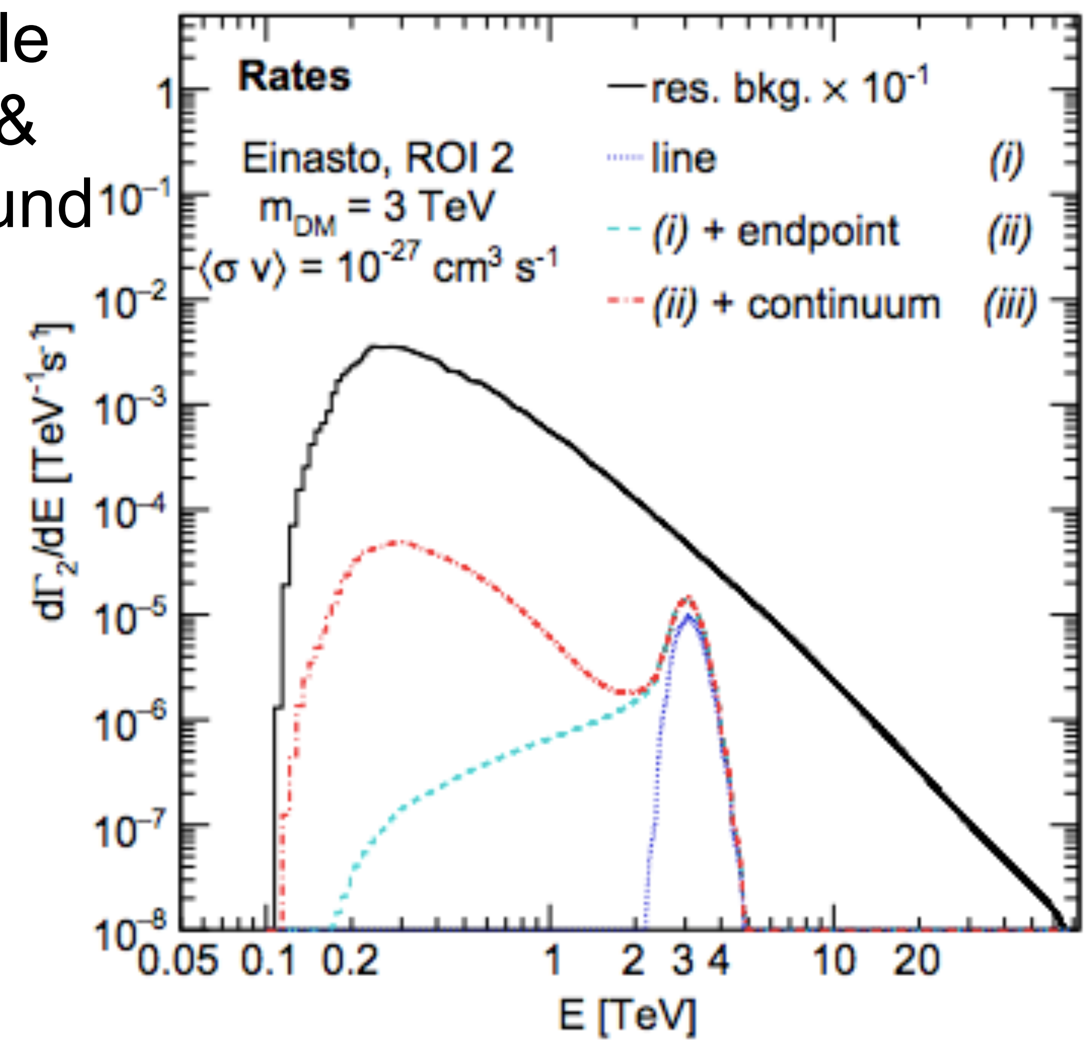
Rinchiuso, Rodd, Moult, Moulin, Baumgart, Cohen, TRS, Stewart & Vaidya '18

- In work led by Lucia Rinchiuso (H.E.S.S), we have forecast the constraints that current and future observations of the Galactic Center by the H.E.S.S. gamma-ray telescope could set on thermal winos.
- We consider a range of choices for the DM density profile, simulate backgrounds from cosmic rays and known gamma-ray sources, and account for the H.E.S.S. energy resolution.
- We perform a likelihood analysis on simulated data, binned in energy + distance from the Galactic Center.

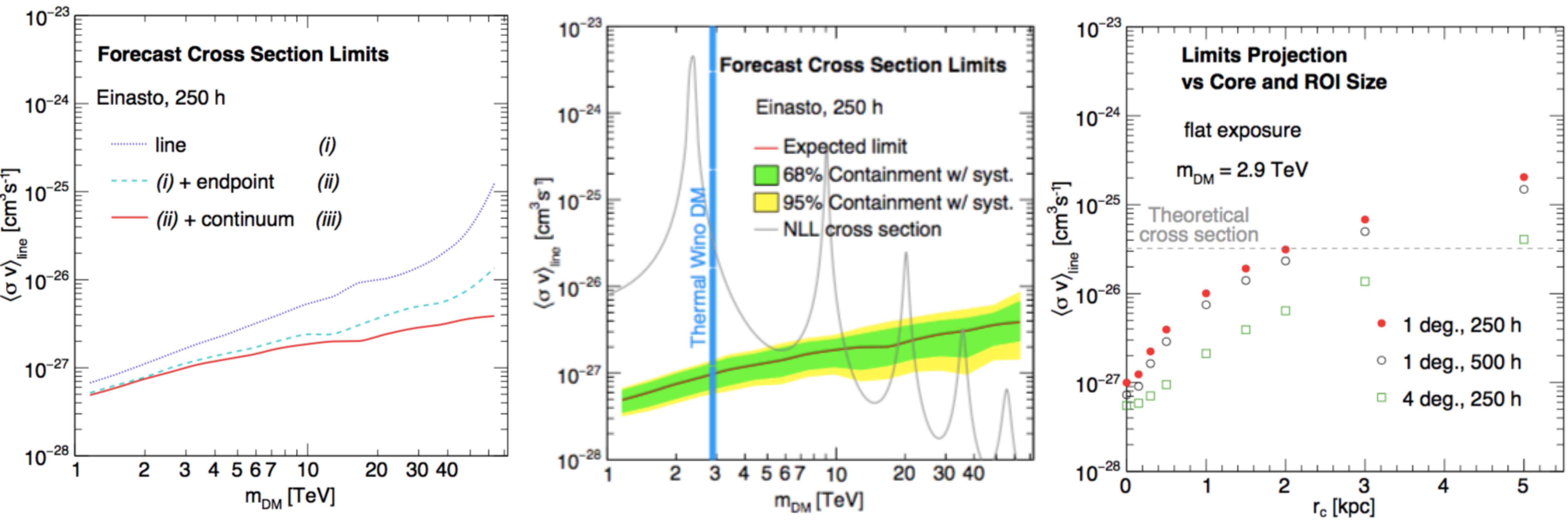
Spatial regions tested



Example signal & background



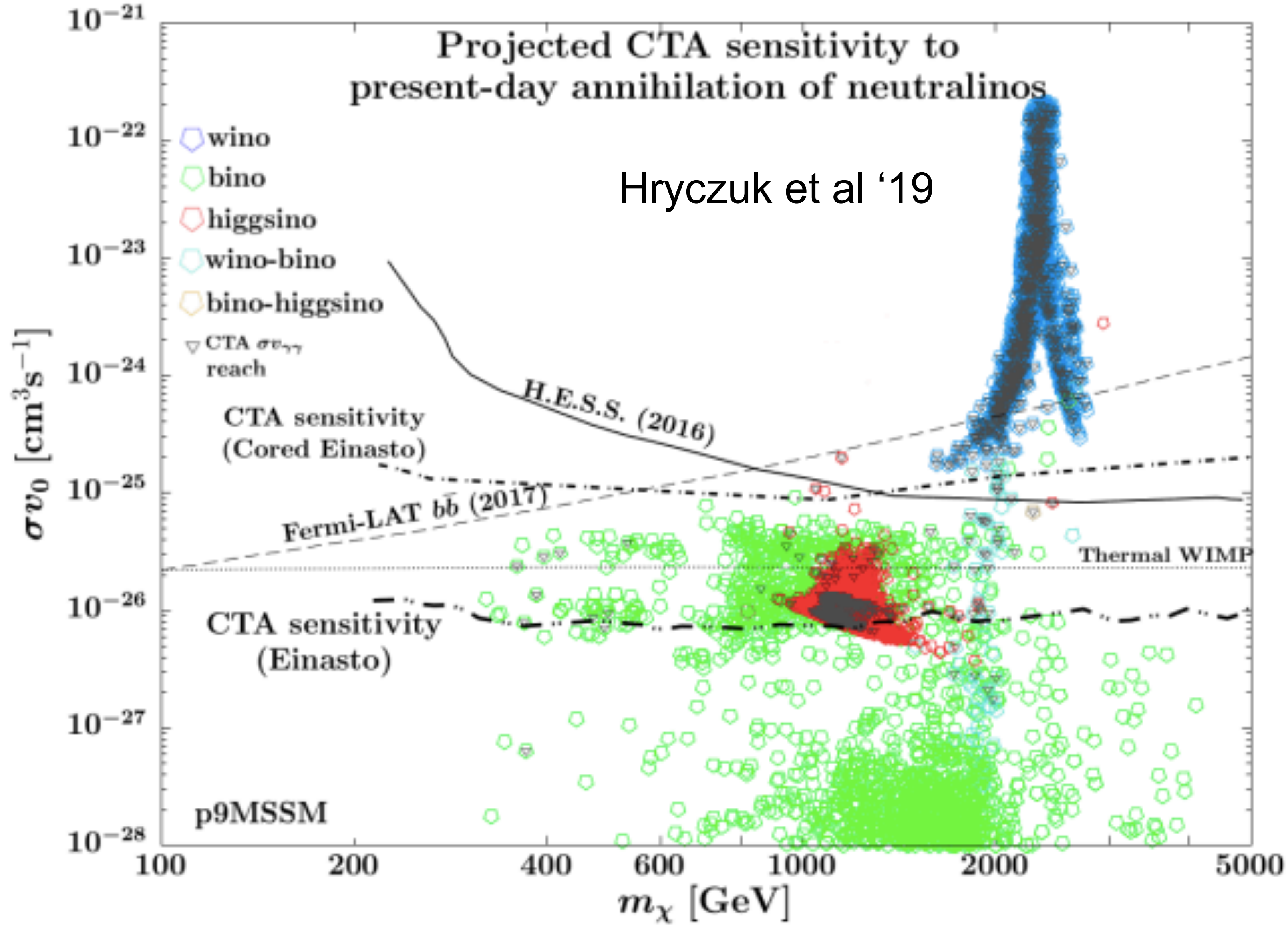
Forecast limits for H.E.S.S



- Using full spectrum improves limits by a factor ~1.5 for thermal wino compared to previous analyses including only the (resummed) gamma-ray line at the endpoint.
- Since this is a Galactic Center analysis, there is degeneracy between the limits and the DM density profile. However, an analysis of current data should have sensitivity to exclude thermal wino DM even if the Milky Way's DM density profile has a flat core, provided that the core radius is below 2 kpc.
- "Inner Galaxy Survey" strategy by H.E.S.S could test nearly 5kpc core sizes.

Future limits from CTA

- Recent analysis [Hryczuk et al '19] explores expected sensitivity of the next-generation Cherenkov Telescope Array (CTA) for phenomenological MSSM (not including SCET corrections)
- CTA expected to carve deep into higgsino-like region (green points = bino-like, red points = higgsino-like, blue points = wino-like) assuming an Einasto-like density profile



- How dependent is this result on the assumed density profile?
- Typically these analyses assume negligible diffuse astrophysical gamma-ray background (not detected by H.E.S.S.) - will this still be true with CTA's sensitivity?

Modeling uncertainties in wino/ higgsino searches with CTA

Rinchiuso, Macias, Moulin, Rodd & TRS, to appear

- Backgrounds we consider:
  - “Residual background” from misidentified cosmic rays (isotropic; spectrum taken from simulations).
  - Galactic diffuse emission from cosmic-rays interacting with the gas and starlight (extrapolate morphology + spectra from Fermi energy band).
  - Fermi Bubbles - hard spectrum extrapolated from Fermi energy band, test effect of a cutoff at 1 TeV or 20 TeV. We use an “inpainted" Bubbles spatial template [Macias et al 1901.03822].
- We mask known point sources from the Fermi high-energy source catalog - the angular resolution at these high energies is small enough that the loss of region-of-interest is small.
- As for the H.E.S.S. case we perform a binned likelihood analysis over the spatial pixels and energy bins.

Particle physics inputs

- For the wino we use the full SCET calculation for the hard-photon spectrum, + the Sommerfeld-enhanced tree-level cross section for annihilation to other final states (yields a continuum of lower-energy secondary photons)

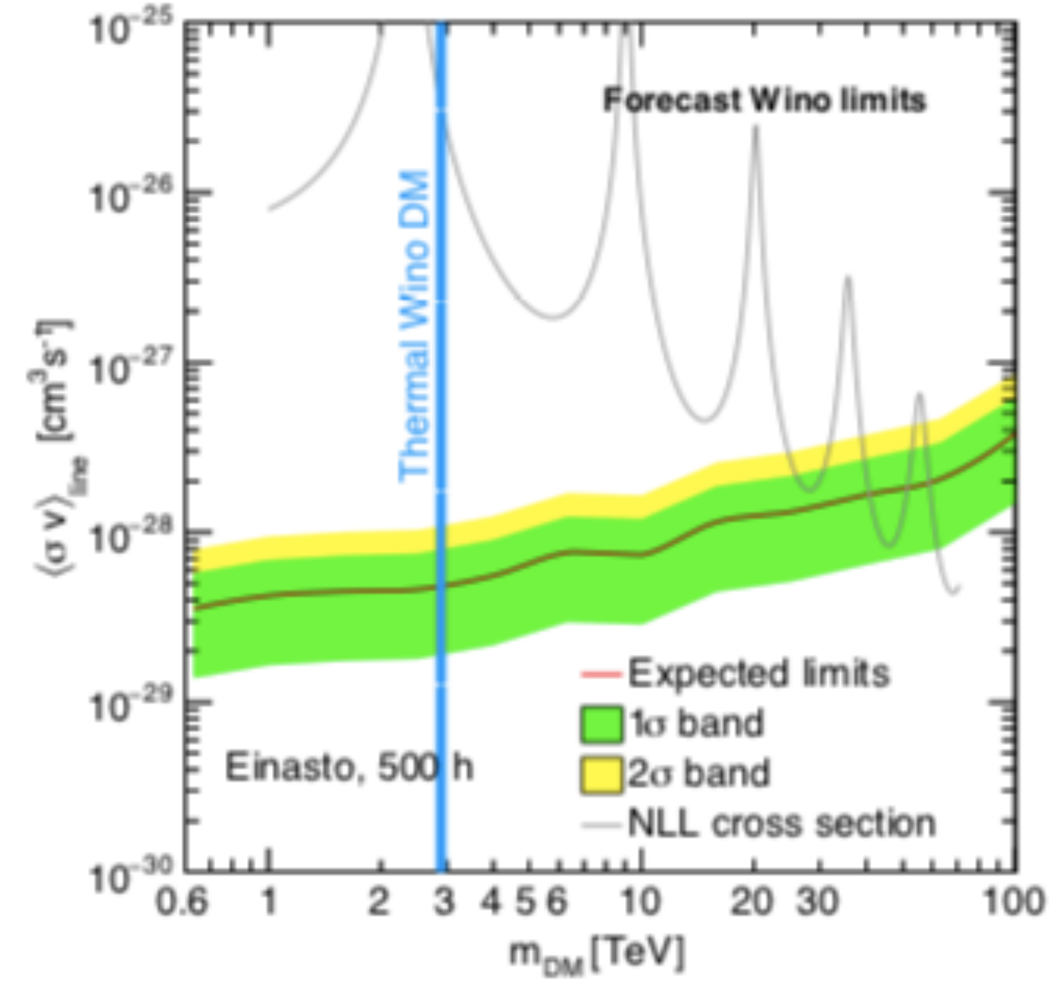
- For the higgsino we use the lowest-order fixed-order line cross section + the tree-level cross section for annihilation to other final states + FSR corrections + Sommerfeld enhancement - we leave a careful SCET treatment of the endpoint spectrum to future work [from Beneke et al 1912.02034, we expect O(1) effects at the endpoint, although for the thermal higgsino the constraints do not appear to be dominated by this region]

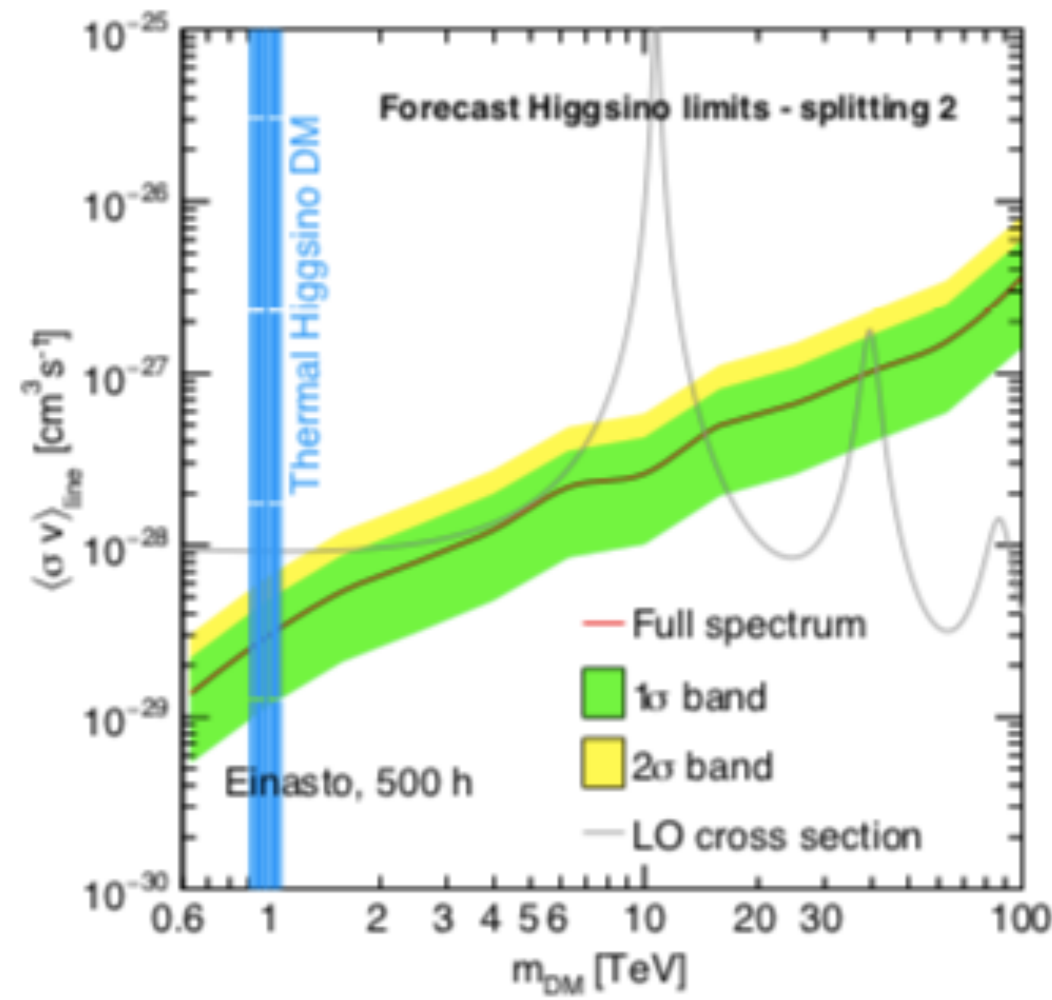
- In both cases we assume a near-pure wino/higgsino, only other near-degenerate DM-like states are part of the same multiplet

  - for the wino we assume the splitting between the neutral and charged states is purely radiatively generated, $\Delta m \sim 164$ MeV

  - for the higgsino there are two neutral states + one charged state - tiny mixings with heavier neutralinos can split the two neutral states (& they must be split to some degree to evade direct-detection bounds). We consider two example scenarios: (1) $\Delta m_{\pm} = 350$ MeV, $\Delta m_N = 200$ keV (2) $\Delta m_{\pm} = 480$ MeV, $\Delta m_N = 2$ GeV.

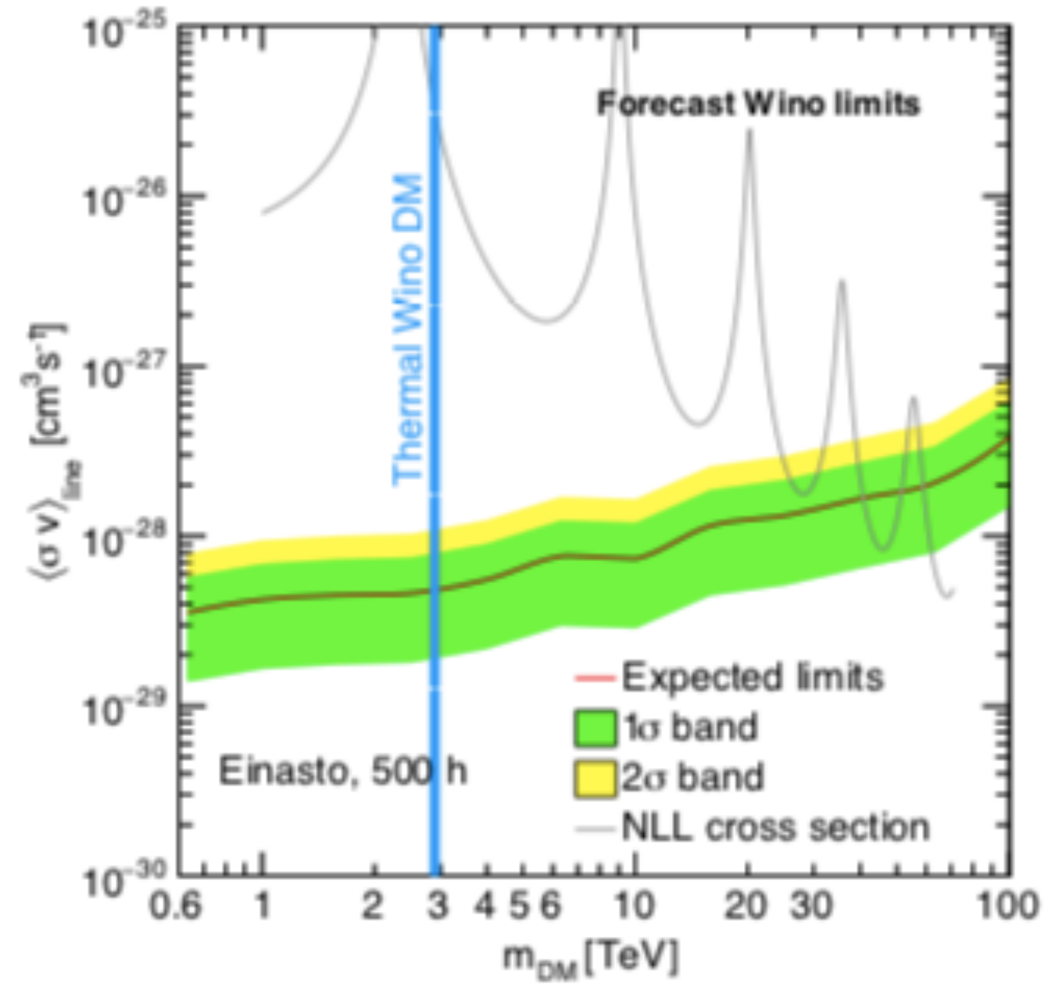
Results

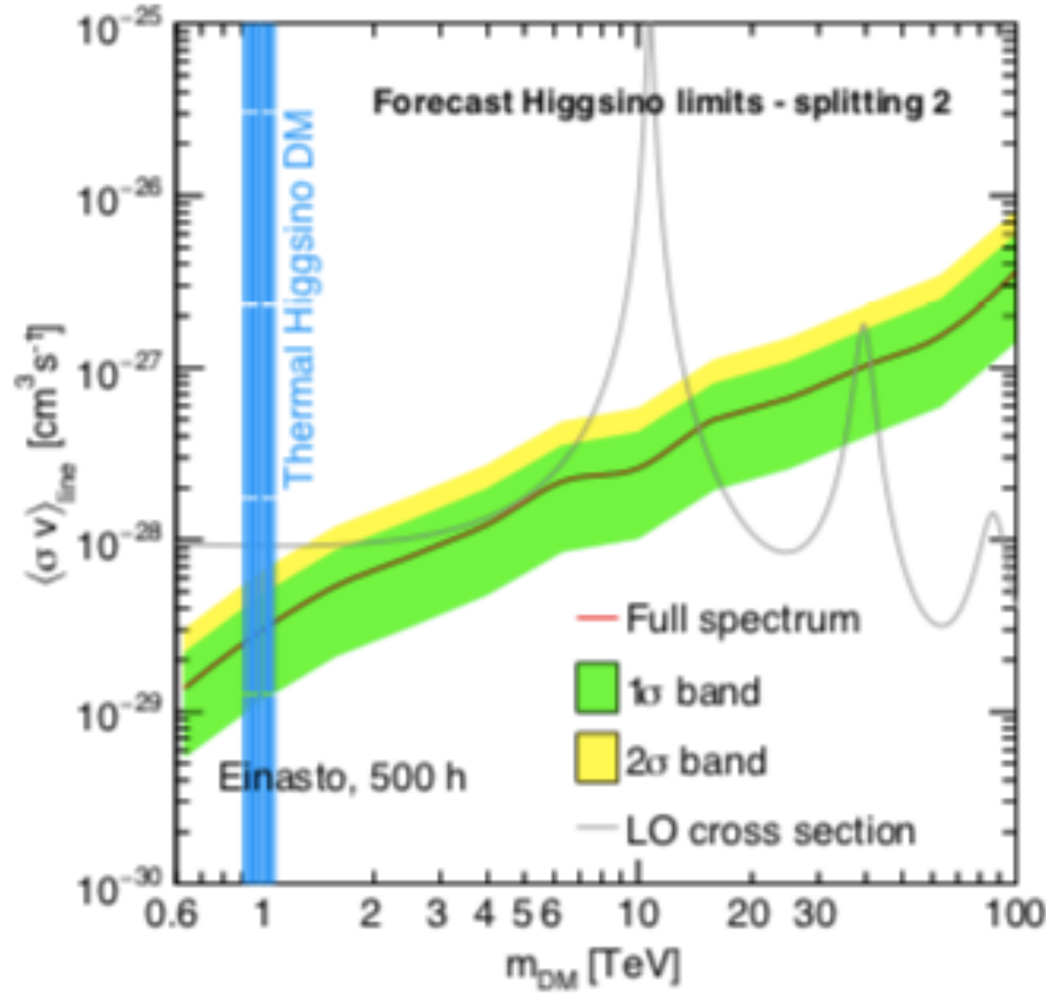

Forecast Wino limits
Thermal Wino DM
Expected limits
1σ band
2σ band
NLL cross section
Einasto, 500 h
⟨σ v⟩line [cm³s⁻¹]
mDM [TeV]


Forecast Higgsino limits - splitting 2
Thermal Higgsino DM
Full spectrum
1σ band
2σ band
LO cross section
Einasto, 500 h
⟨σ v⟩line [cm³s⁻¹]
mDM [TeV]

Results

- As expected, when we assume an Einasto profile and only the residual background is included, the CTA should be able to probe both the thermal wino and higgsino.





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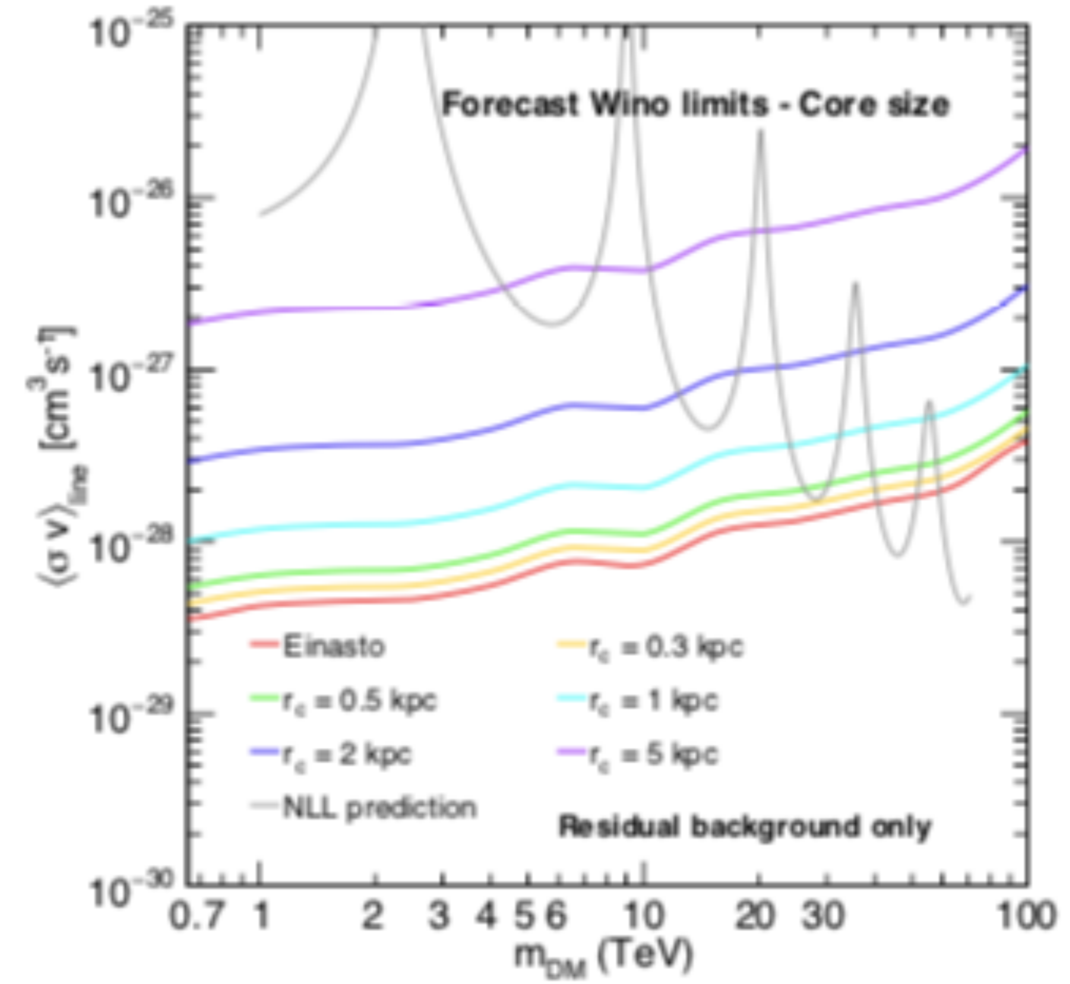

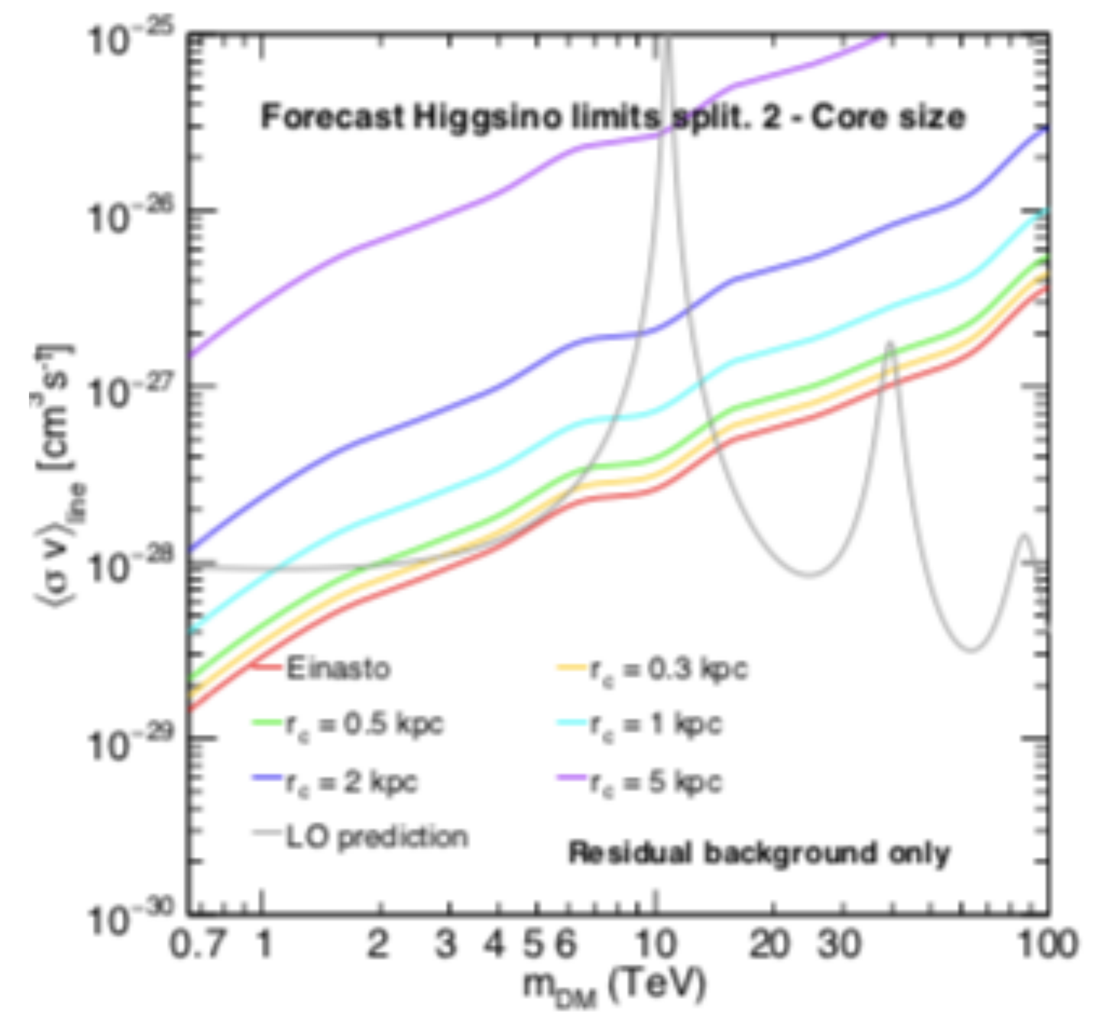

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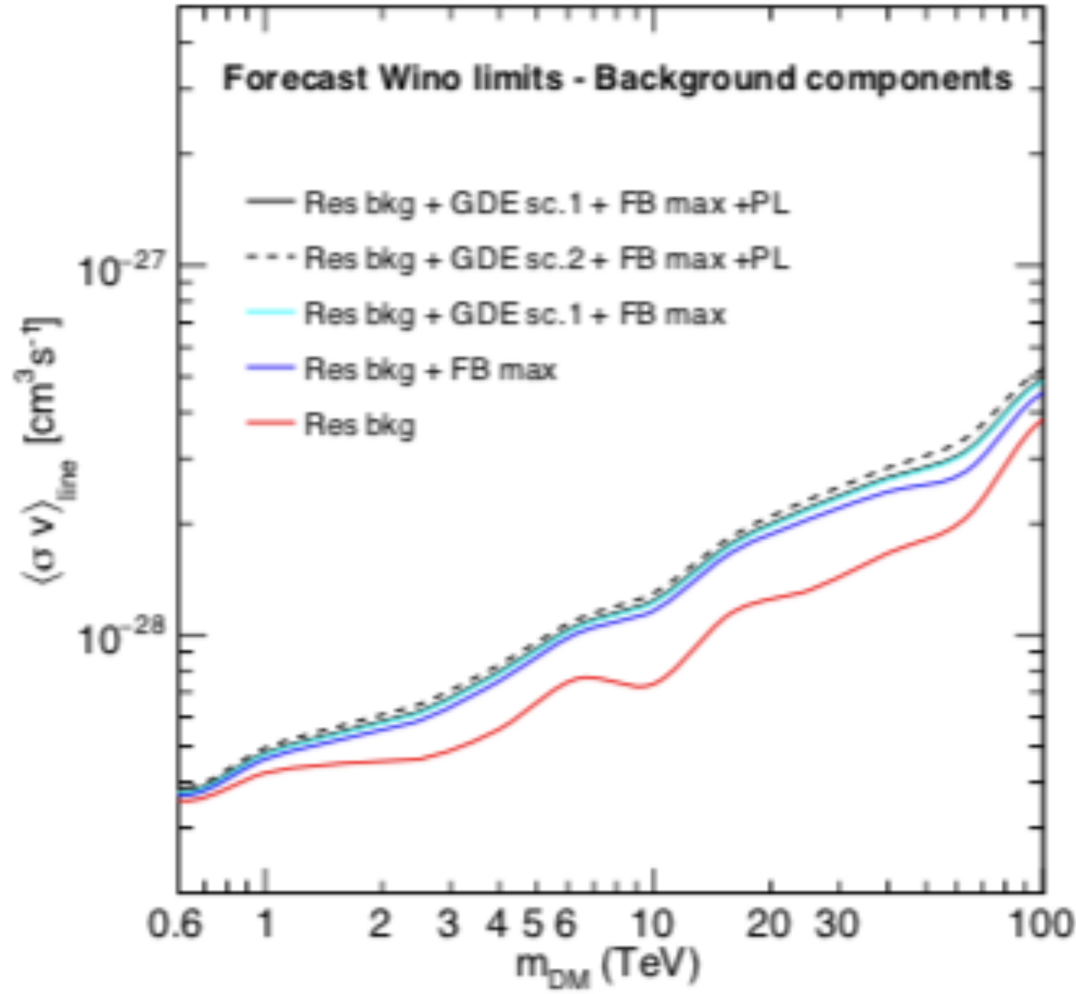

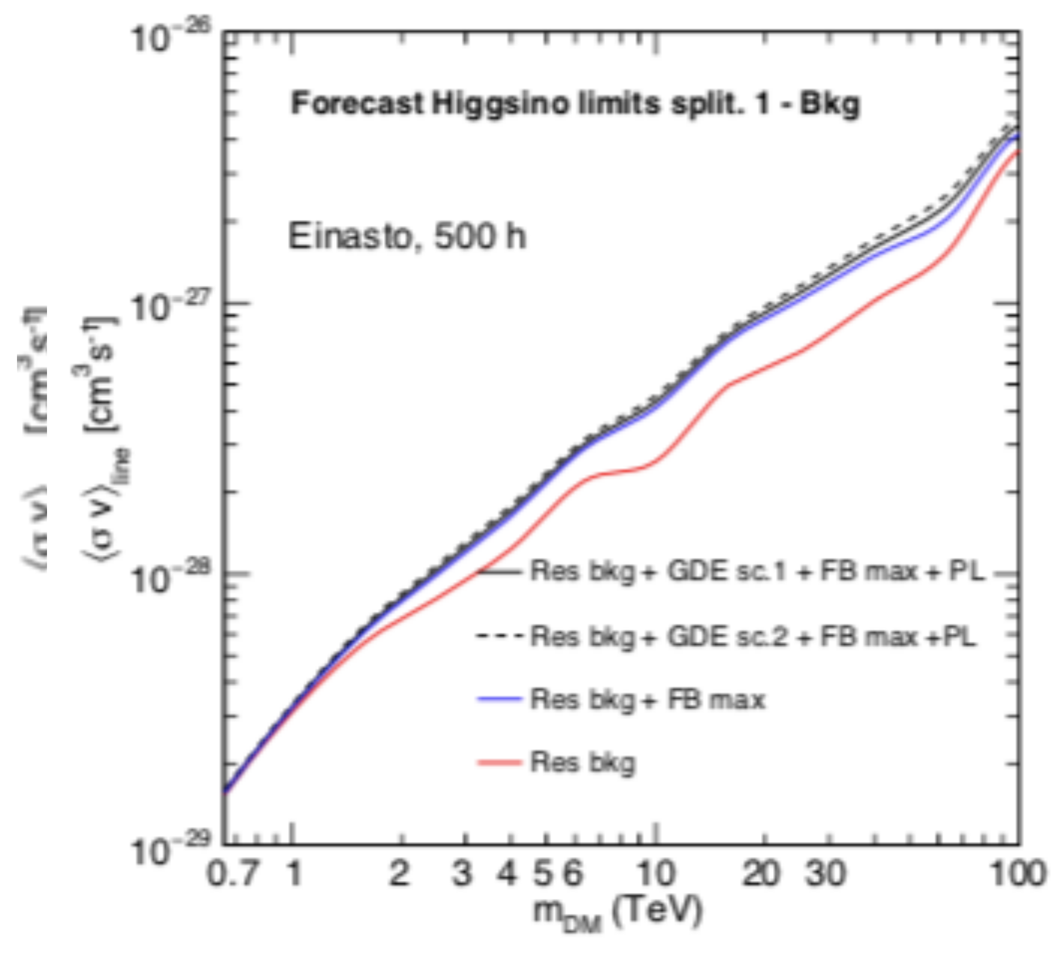

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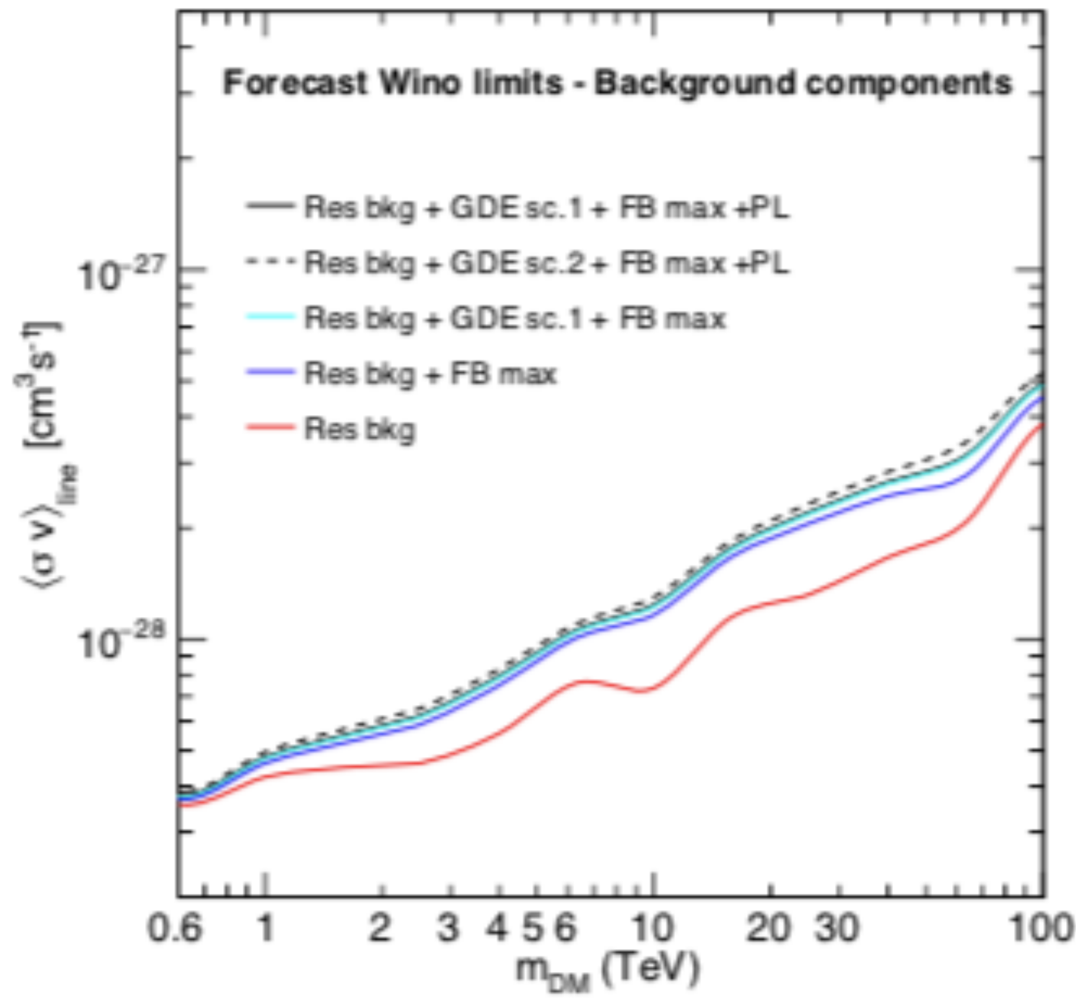
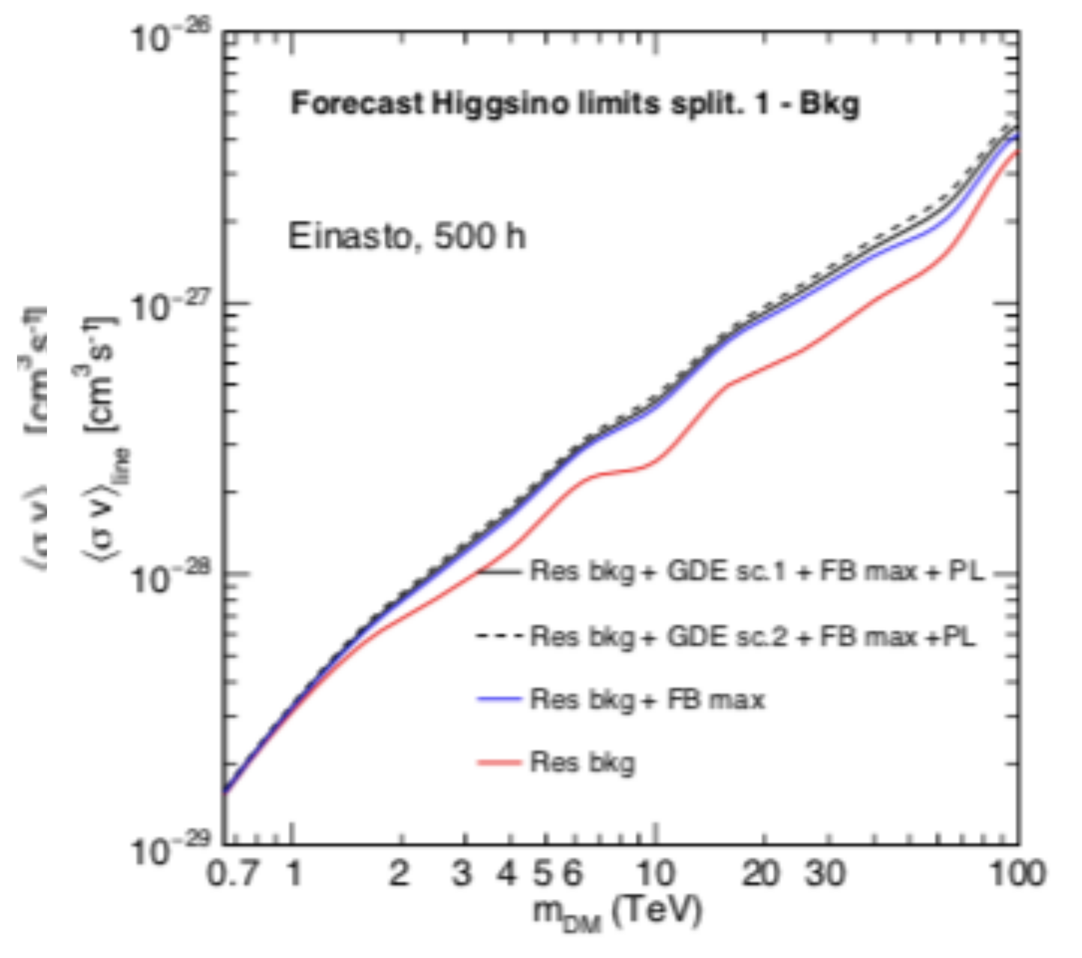
- However, for the thermal higgsino the effect of these backgrounds is minimal.





Takeaway points

- CTA is expected to have the sensitivity to constrain (or discover) the thermal higgsino even for O(kpc) cores and including astrophysical backgrounds
- Understanding/measuring the Fermi Bubbles at high energies and close to the GC may be important for attaining forecast sensitivity for CTA DM searches more generally
- Future work: extending the SCET calculation to the quintuplet, higgsino, general mixed neutralino
    - In the quintuplet case, the formation of unstable DM bound states that decay to SM particles can be important

Conclusions

- Primordial black holes are perhaps the cleanest “loophole" in the common statement that DM requires new BSM particles.
- We can exclude PBHs as 100% of DM over an enormous mass range, but there is a gap for 10^{17} g < M_{PBH} < 10^{23} g where they are very challenging to detect.
- At the low-mass end of this range, analyses of data from current and near-future gamma-ray telescopes may significantly improve the constraints on PBHs; a very simple+conservative analysis of INTEGRAL data already surpasses all other existing constraints.
- While electroweakly interacting GeV-TeV-scale DM has been the target of enormous experimental effort in recent years, some of the simplest models are still very challenging to constrain, in particular the pure wino and higgsino.
- H.E.S.S. already has the sensitivity to exclude thermal wino DM unless the Milky Way DM density profile has a multi-kpc flat-density core.
- We have shown that the future CTA telescope can have the sensitivity to discover or exclude the thermal higgsino for up to kpc-scale cores, even when plausible astrophysical backgrounds are included.