Dark Matter Theory at the TeV Scale

Tracy Slatyer

Very High Energy Phenomena in the Universe
14th Rencontres du Vietnam
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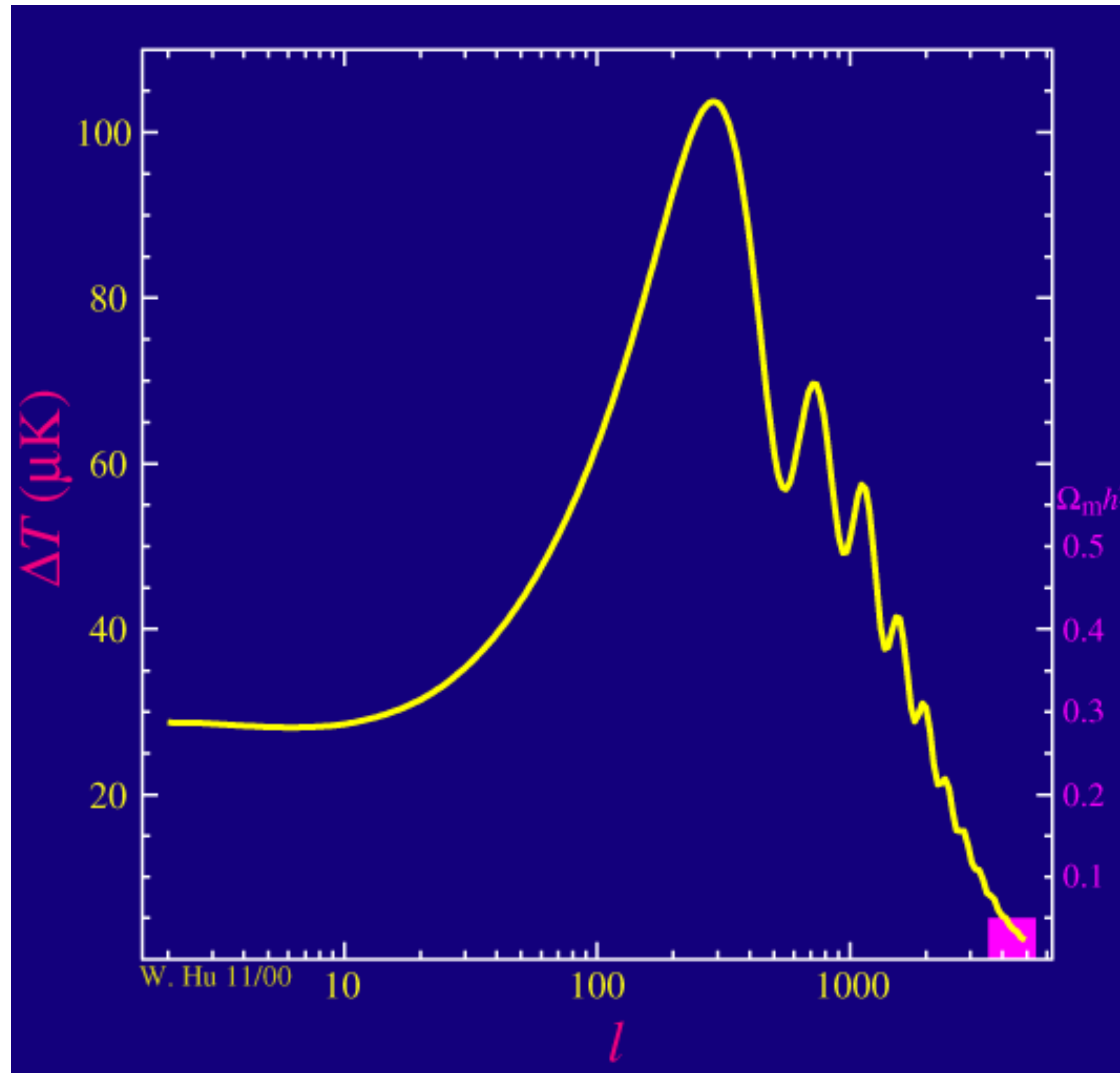
U.S. DEPARTMENT OF ENERGY | Office of Science

The puzzle of 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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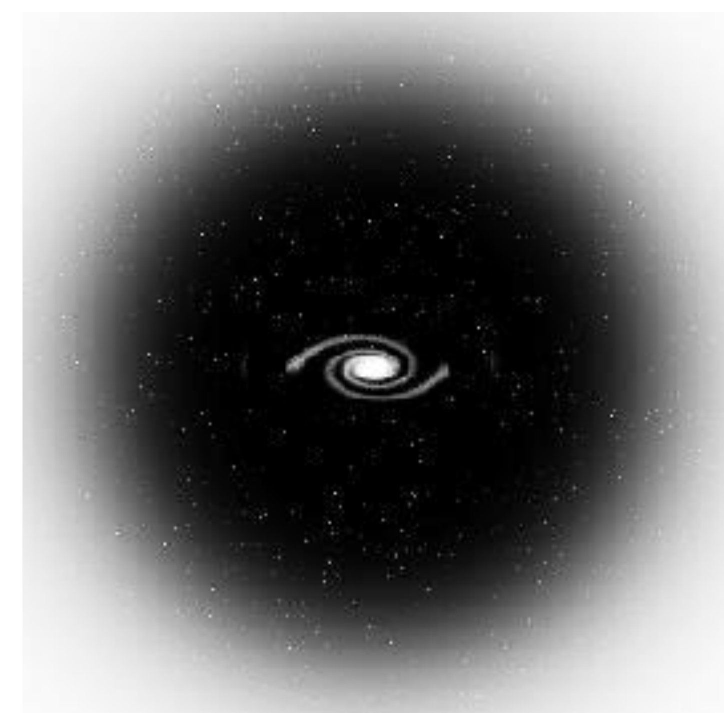

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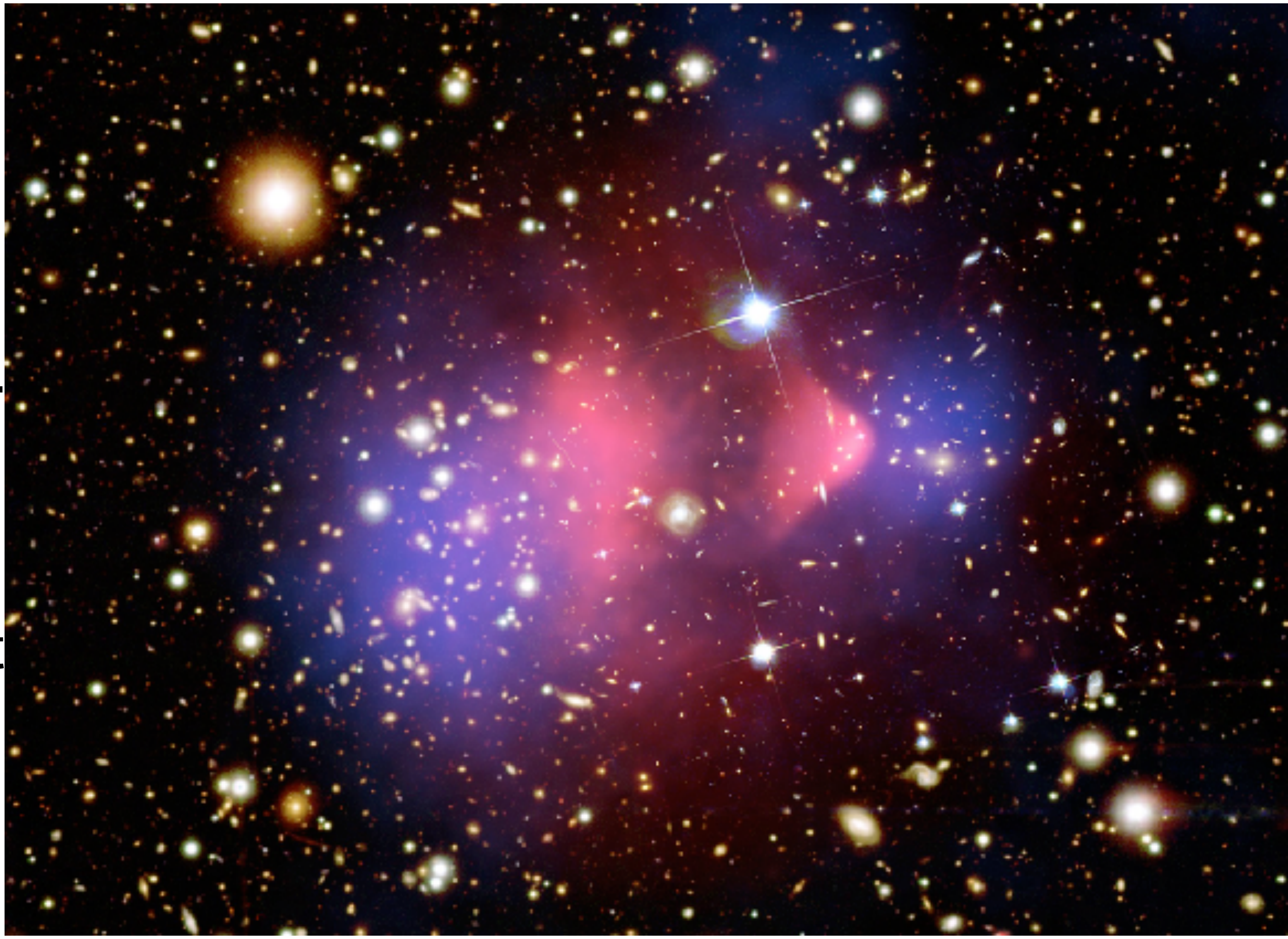

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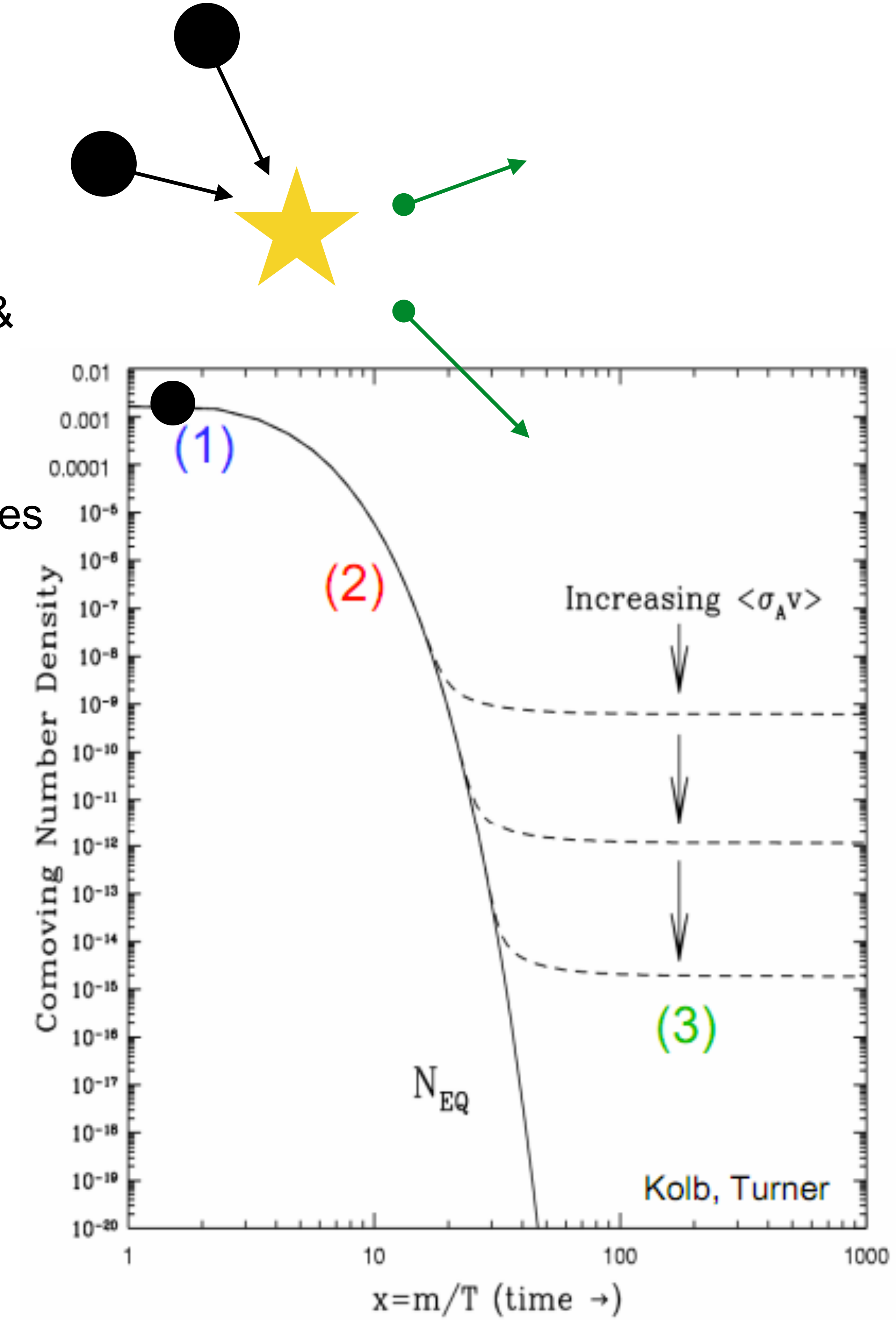
Dark matter and the TeV scale

- No good dark matter candidates within the SM (with the possible exception of primordial black holes - see talk by Simeon Bird on Wednesday)
- Enormous spectrum of possible candidates beyond the Standard Model, over a huge range of mass scales (10^{-21} eV → 100 $M_\odot$)
- There is a long-standing theory connection between dark matter and the TeV scale:
  - New physics at the O(TeV) scale could potentially help resolve the hierarchy problem
  - Interactions of TeV-scale DM through weak-scale mediators can naturally generate the observed abundance of dark matter

Thermal freezeout

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

$$\chi\chi \leftrightarrow \mathrm{SM}\,\mathrm{SM} \;\; (\mathrm{I})$$



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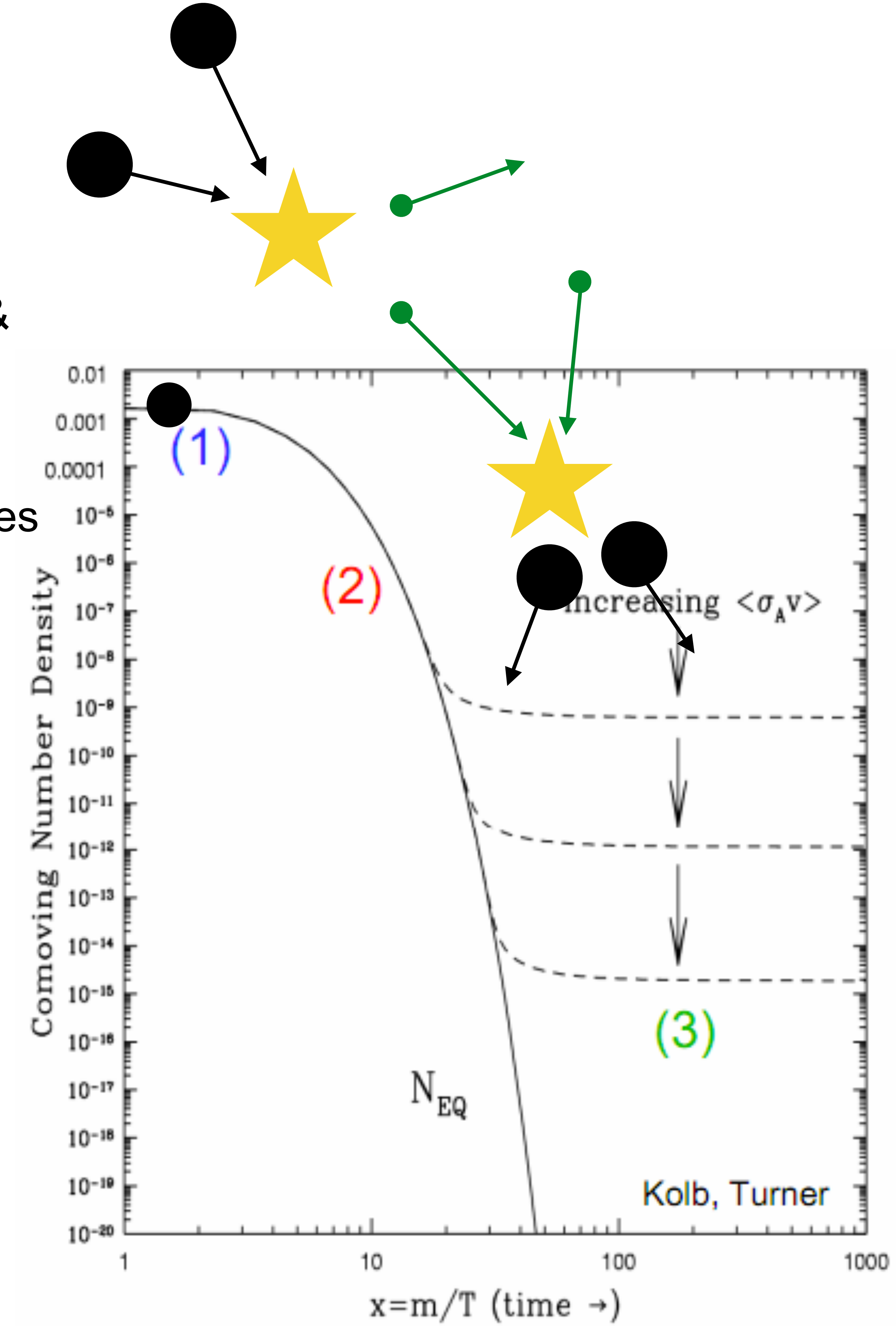

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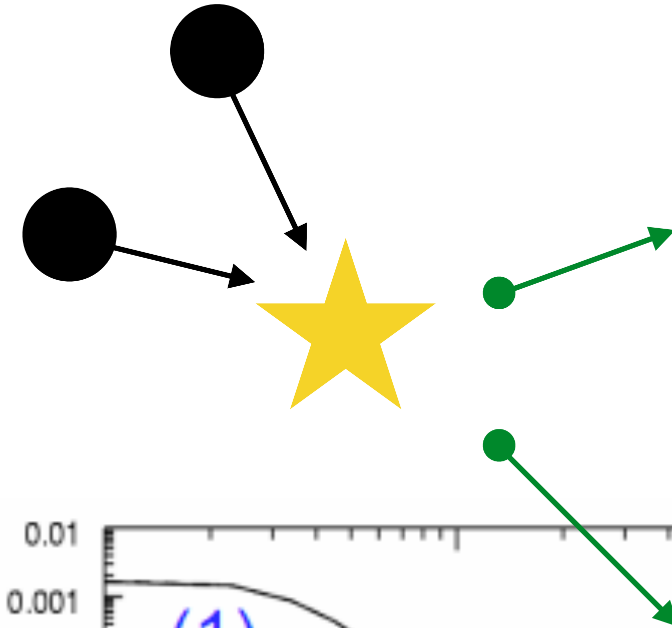

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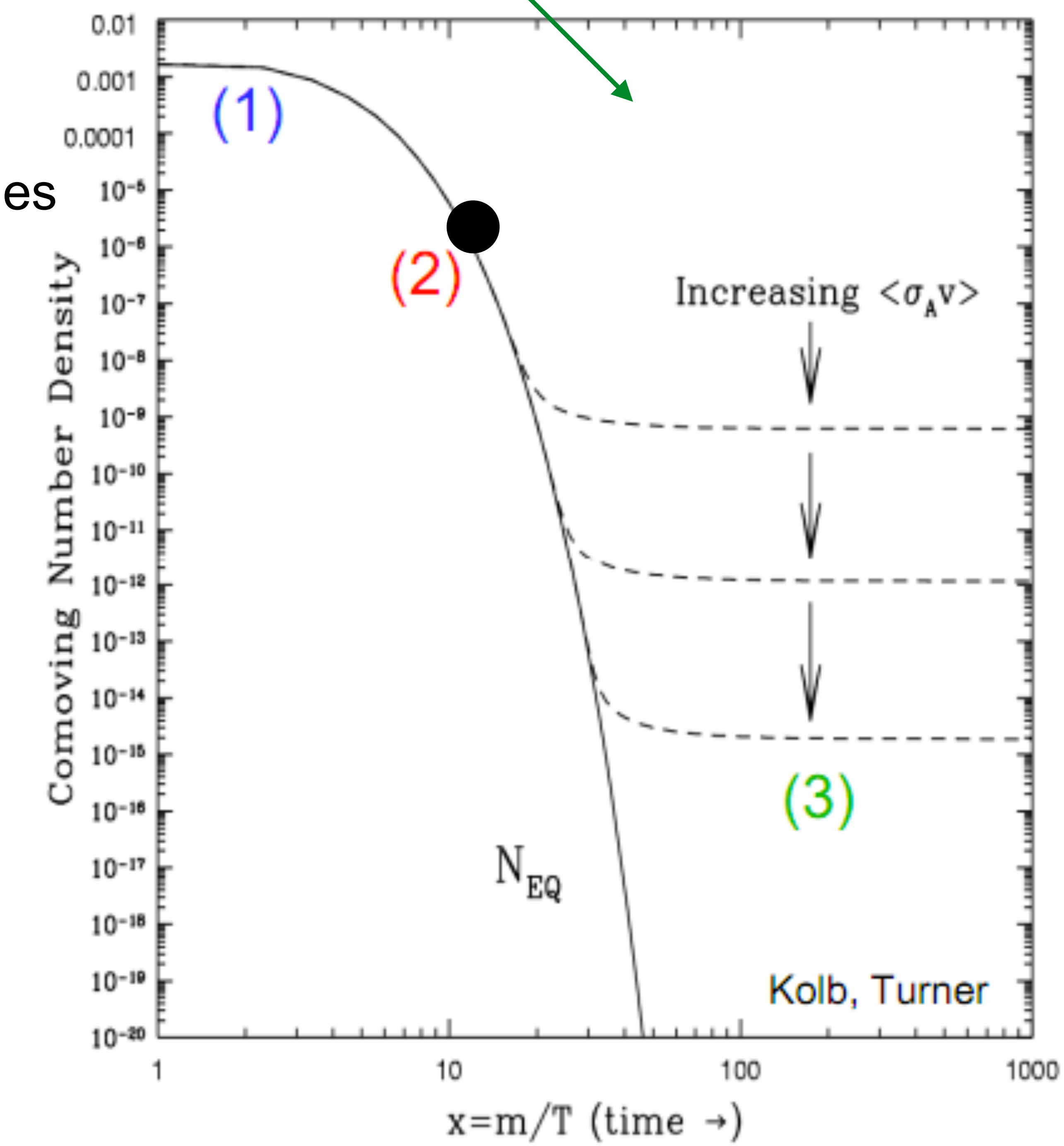

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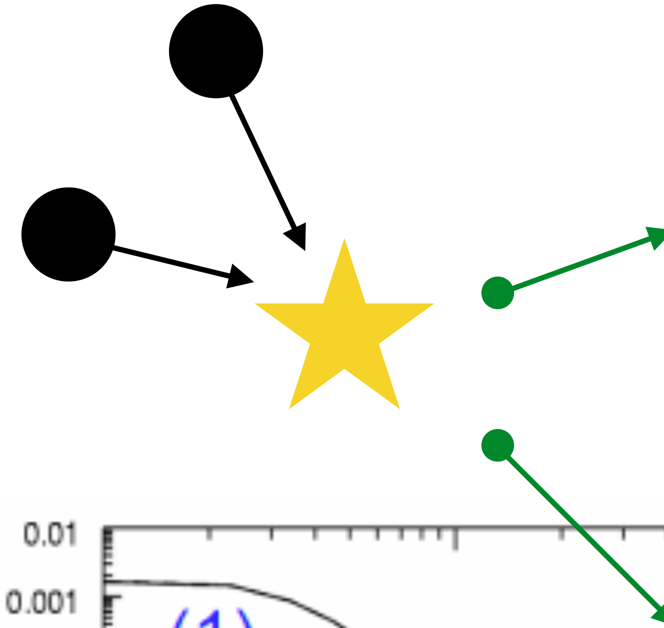

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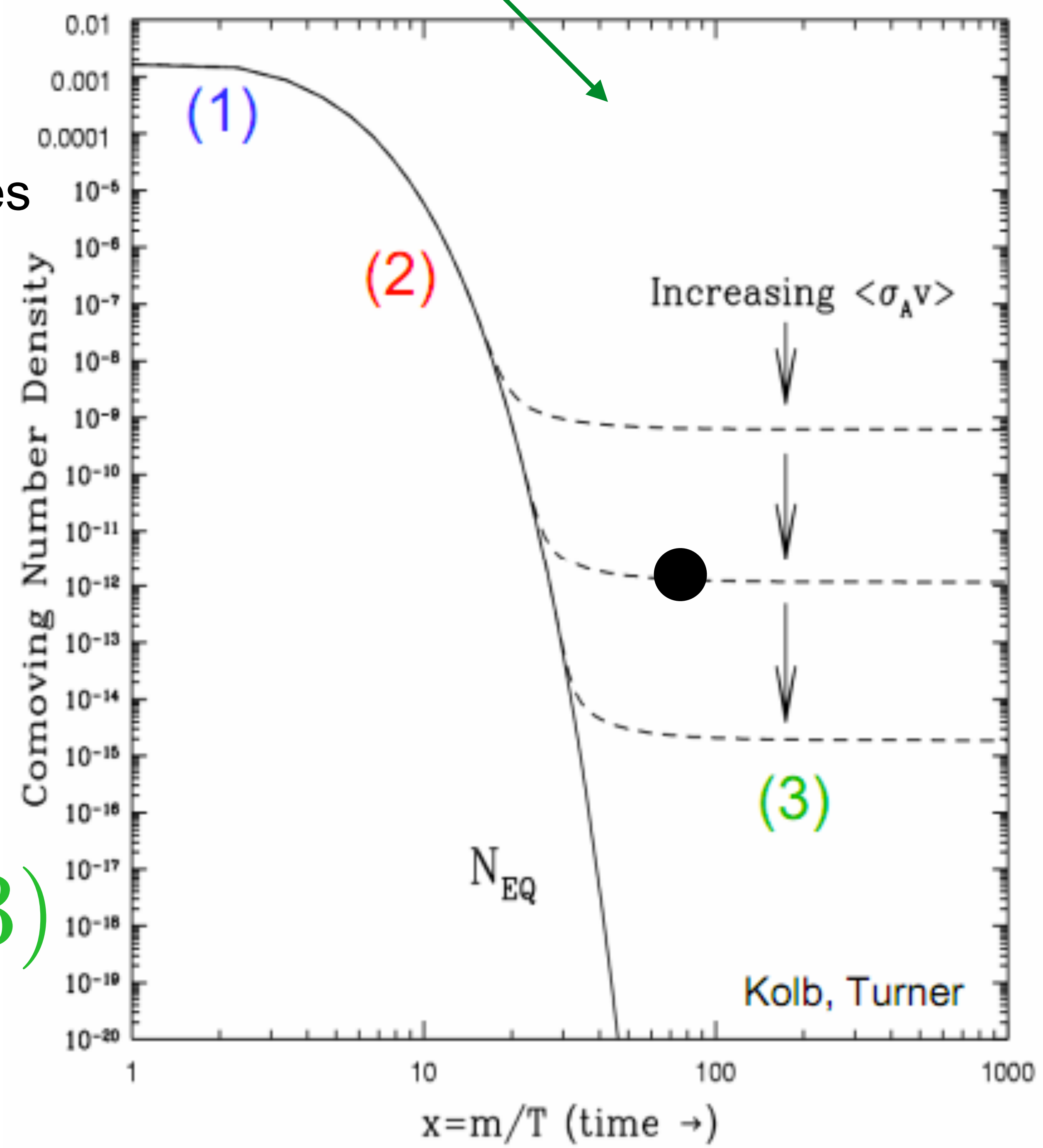

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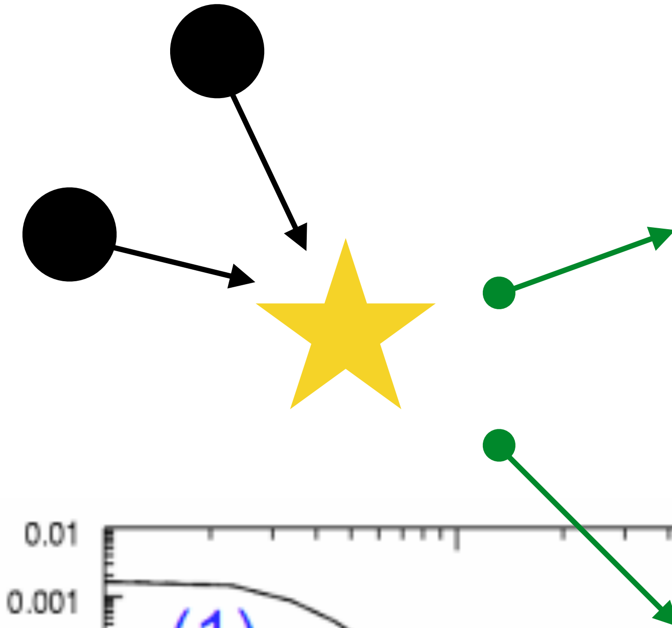

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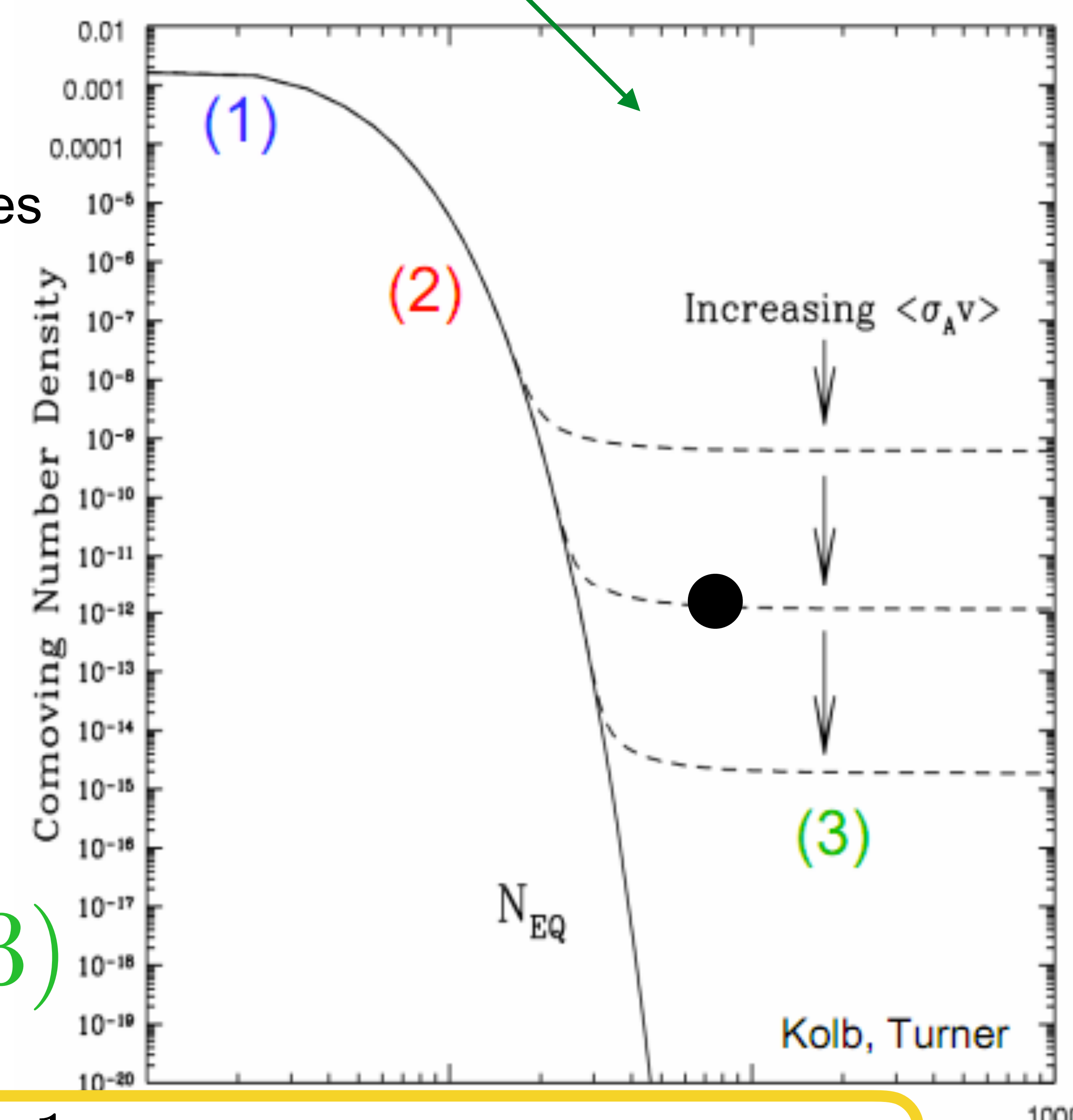


$$\langle\sigma v\rangle \sim \frac{1}{m_{\mathrm{Planck}}T_{\mathrm{eq}}} \sim \frac{1}{(100\mathrm{TeV})^2} \approx 2\times10^{-26}\mathrm{cm}^3/\mathrm{s}$$

The (100) TeV scale from cosmology

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

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

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

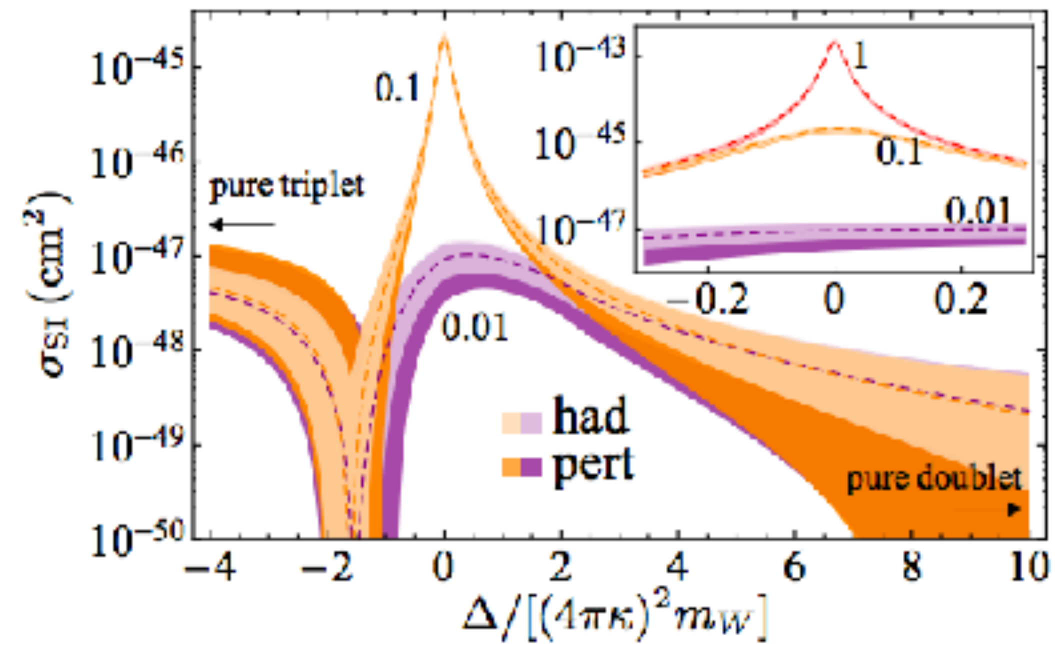
$$\sim \frac{1}{(100{\rm TeV})^2} \sim \left(\frac{10^{-2}}{1{\rm TeV}} \right)^2 \sim \frac{\alpha^2}{m_\chi^2}$$

- Perturbativity requires DM mass below ~100 TeV (unitarity bound ~200 TeV [von Harling & Petraki ’14]).
- The thermal cross section is naturally obtained for electroweak-scale couplings and masses. Suggestive of electroweak interactions - but works just as well for new dark TeV-scale physics more generally.

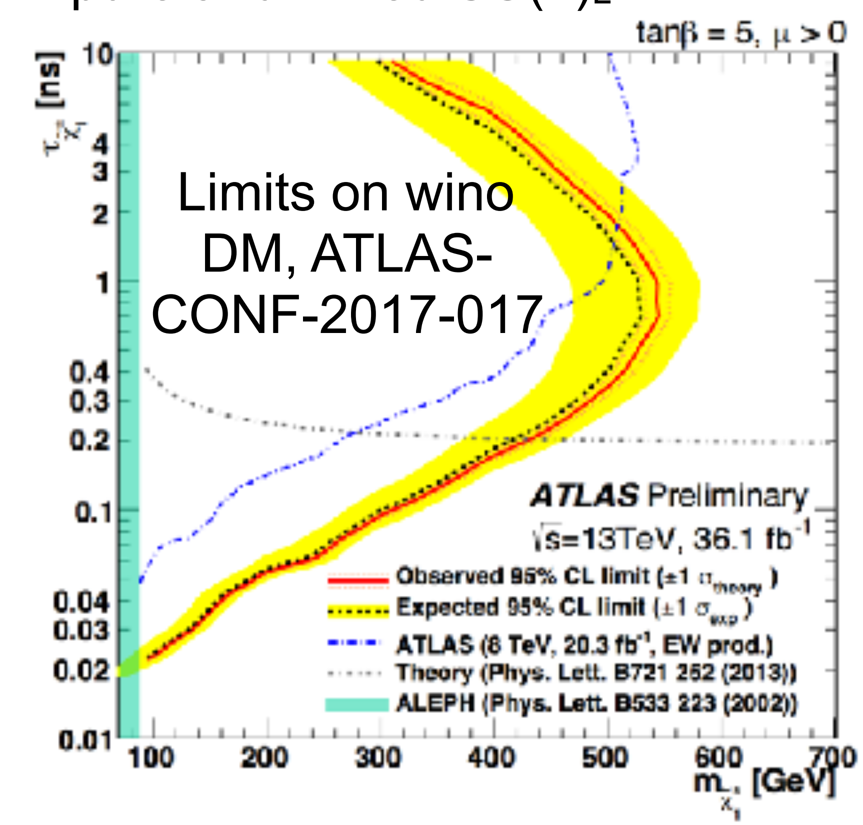
Are WIMPs dead?

- Weakly Interacting Massive Particle (WIMP) = new stable particle with weak-scale masses and interactions, or more specifically, a particle interacting through the SM weak gauge bosons.
- Classic example of the latter is the lightest neutralino in supersymmetric theories.
- 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].
- But this is expected for some of the simplest WIMP scenarios - e.g. pure higgsinos and winos produce the right dark matter abundance for masses of 1 TeV, 3 TeV respectively, and direct detection signals are well below current limits.

Hill & Solon '14



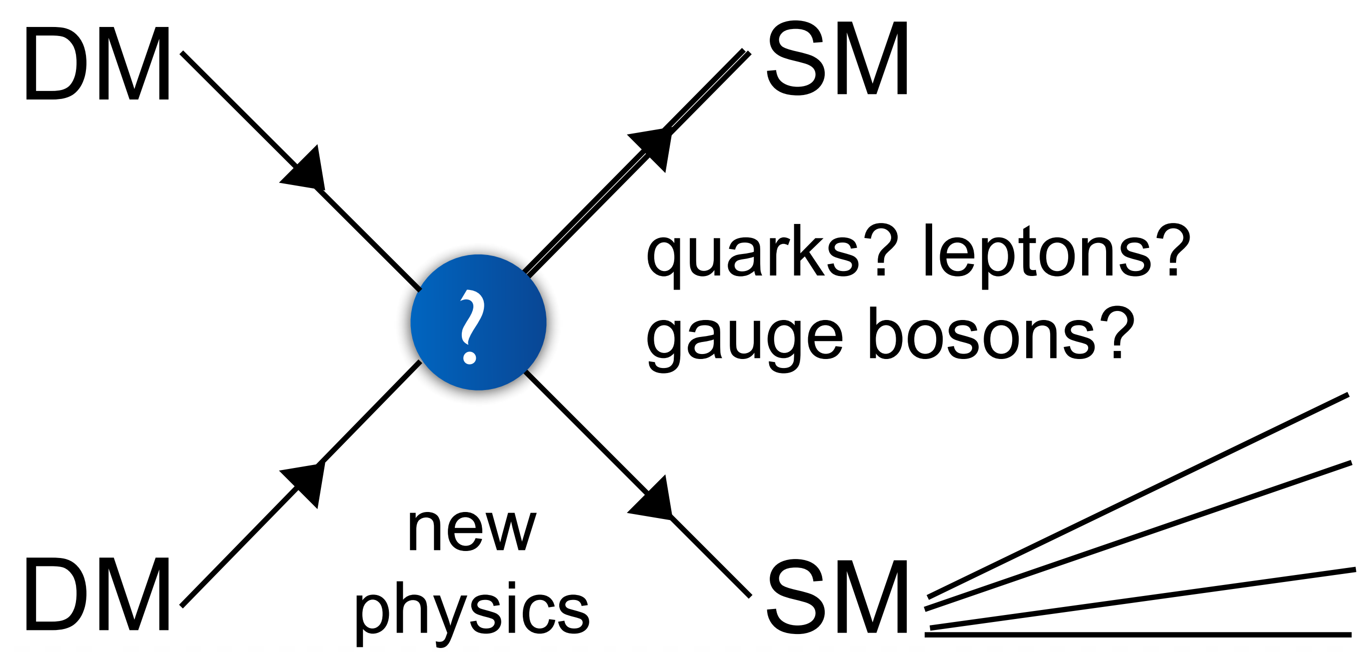
Predictions for direct detection of pure and mixed $SU(2)_L$ DM

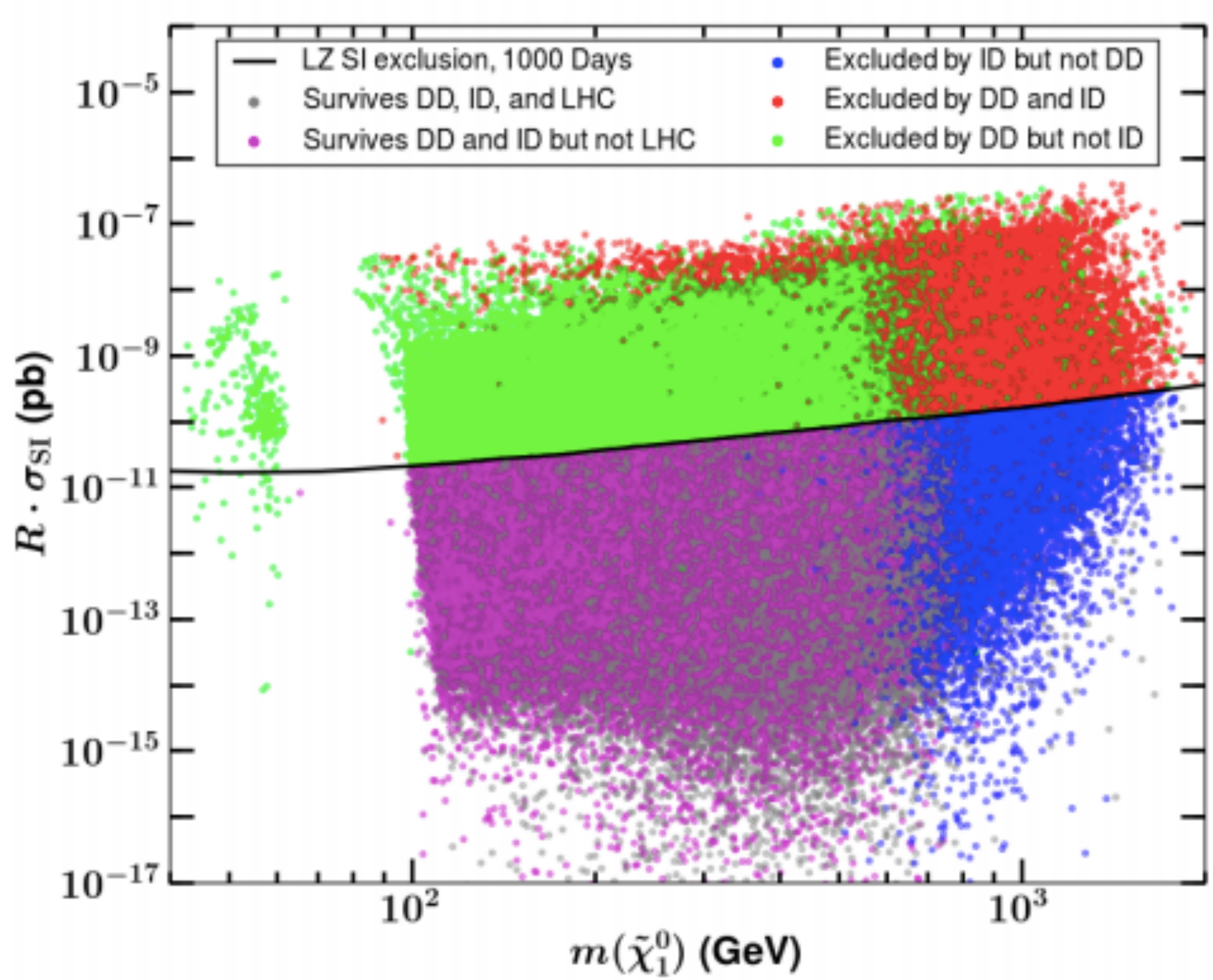


Limits on wino DM, ATLAS-CONF-2017-017

How to find heavy WIMPs

- Air/water Cherenkov telescopes (e.g. HESS, VERITAS, MAGIC, HAWC, CTA in the future) can measure gamma rays from ~100 GeV up to ~100 TeV.
- Sensitive to annihilation signals from heavy dark matter.
- Complements collider searches, which can probe sub-TeV masses.
- For dark matter searches at much <u>lighter</u> scales, MeV-GeV, see talk by Regina Caputo this afternoon.





Cahill-Rowley et al '14

Indirect searches for heavy dark matter

- Many possible sources - e.g. dwarf galaxies, Galactic center, Galactic halo, individual extragalactic sources (e.g. M31, clusters), anisotropies of extragalactic background radiation. See talk by Miguel Sanchez-Conde this afternoon on dark matter structure.

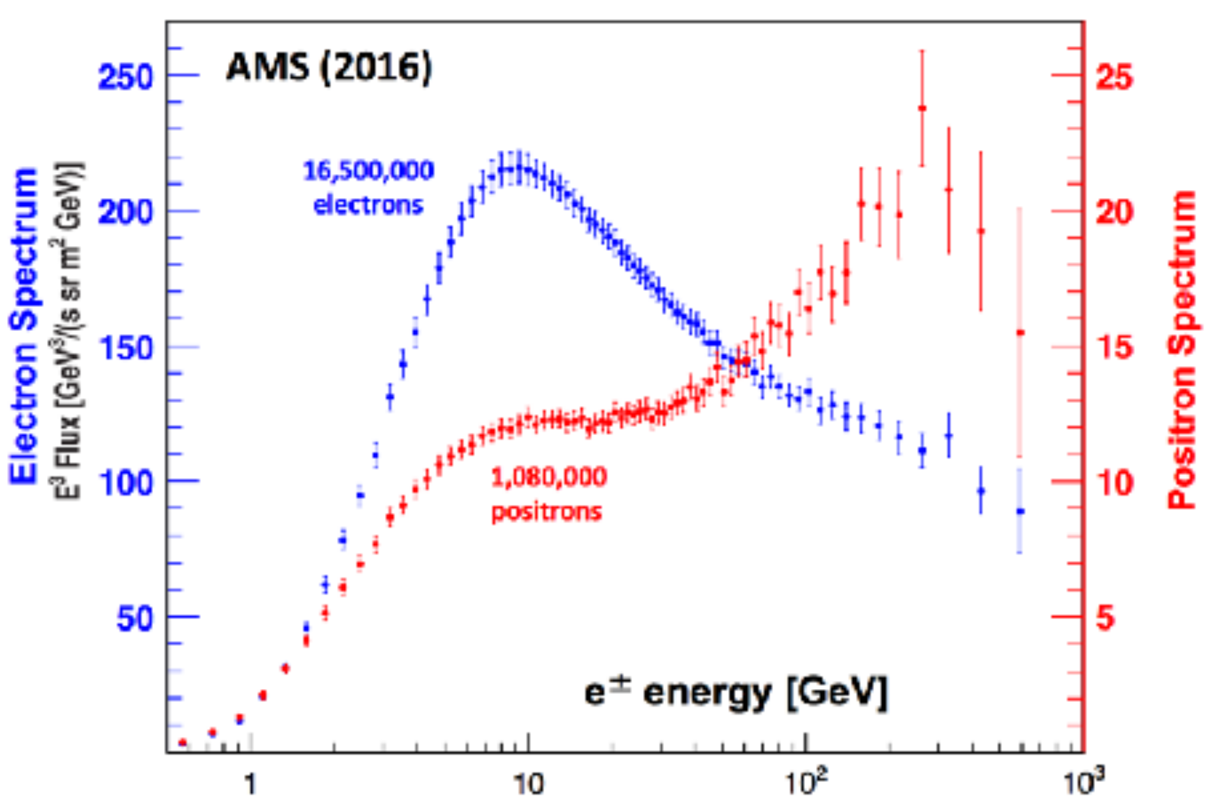
- Detection channels: gamma rays, neutrinos, charged cosmic rays. Can be directly produced by annihilation/decay, or secondaries from cascades (often especially important for very heavy DM).

- Example possible signal for TeV-scale DM: AMS-02 sees a large excess of positrons above ~10 GeV, compared to expectations.

- However, HAWC has detected extended gamma-ray emission around two nearby pulsars, Geminga and B0656+14 (Abeysekara et al '17, 2HWC catalog).

- Hooper et al '17, Profumo et al '18 argue these measurements imply pulsars provide a dominant contribution to the AMS-02 positrons.

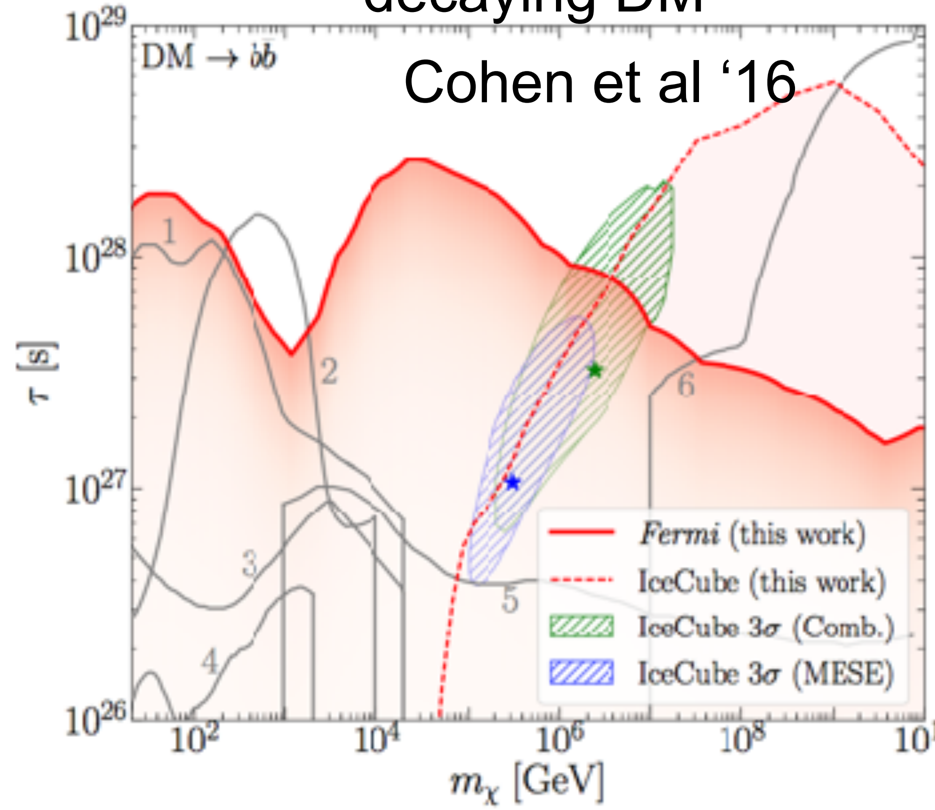
Sam Ting, CERN colloquium, December 2016

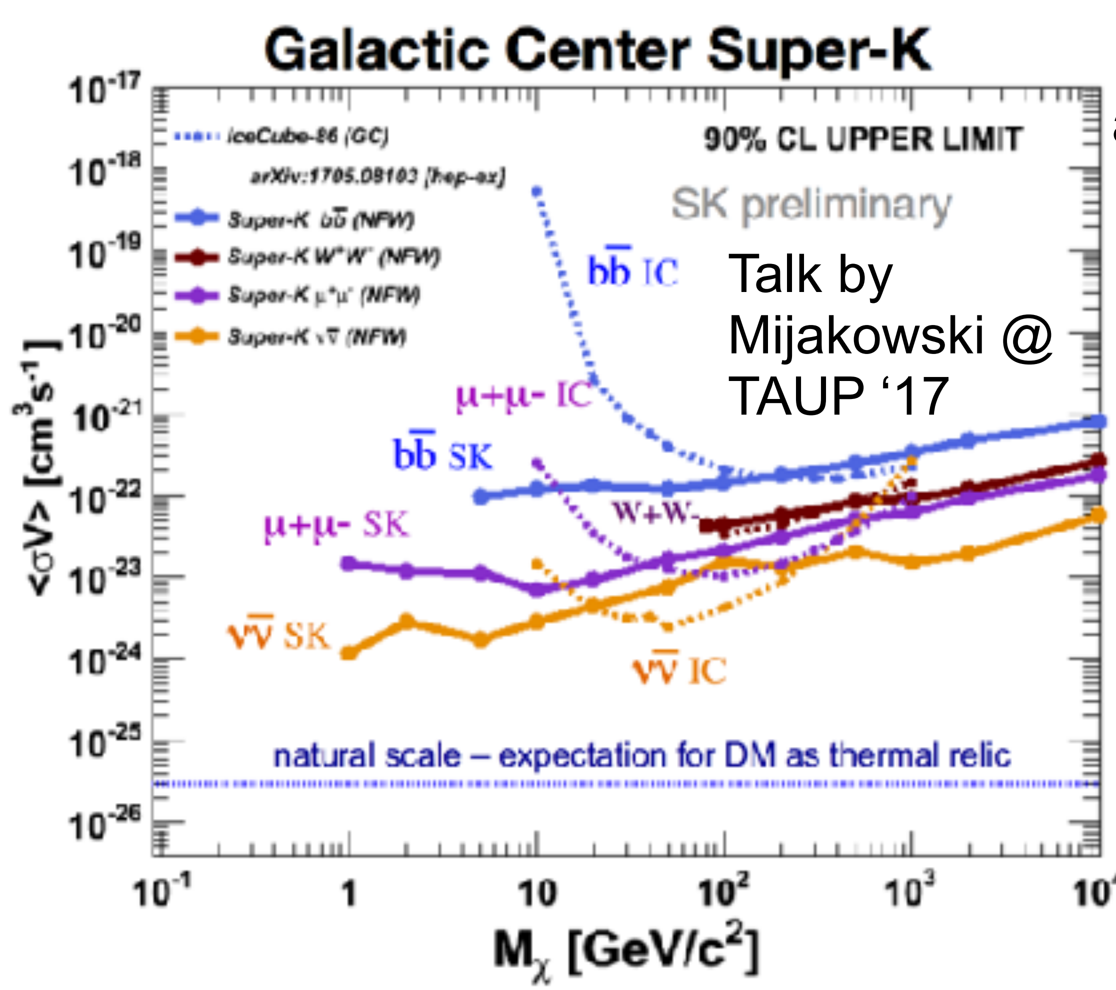


Indirect constraints on heavy dark matter

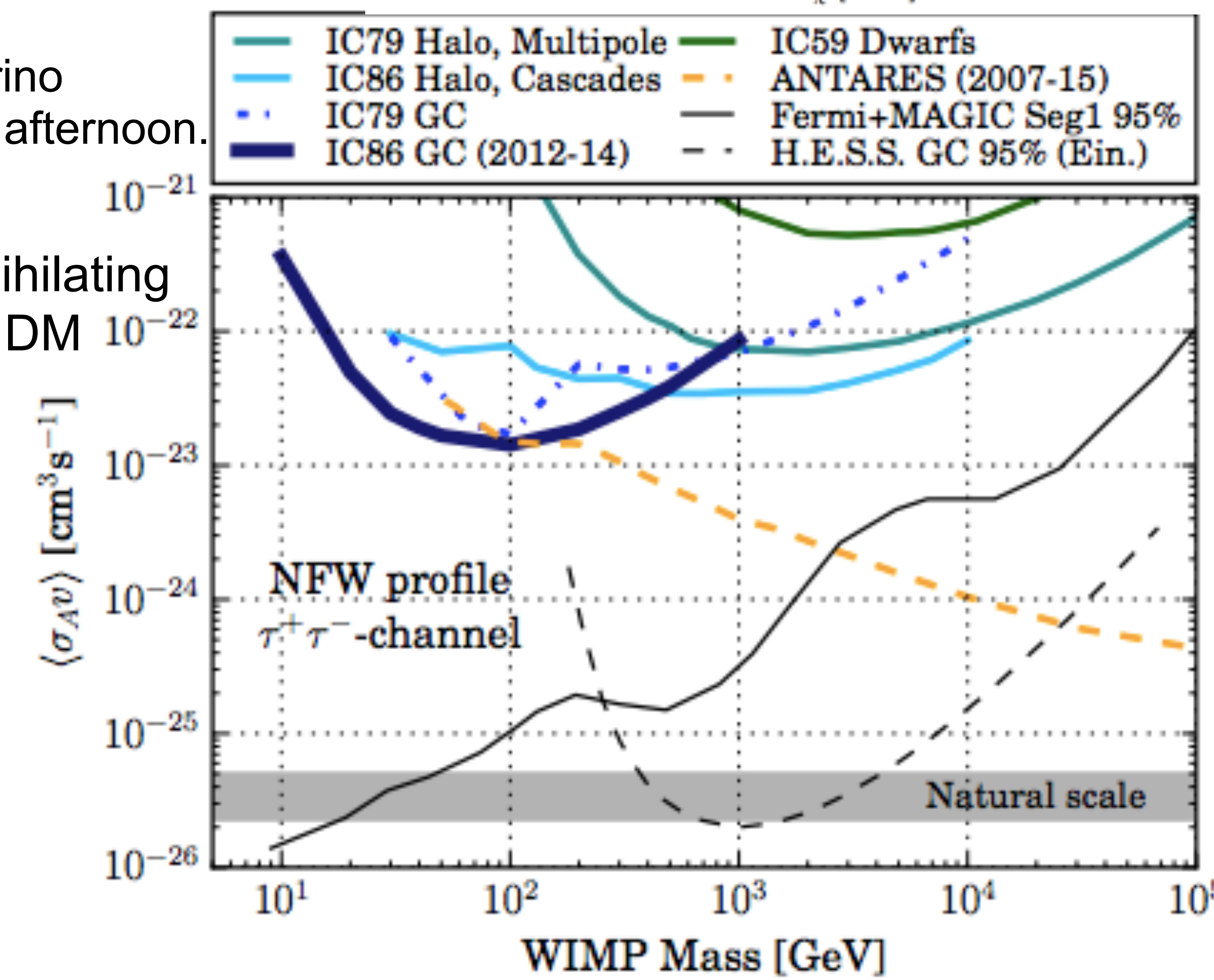
- Gamma-ray telescopes set stringent constraints on annihilation/decay - see talks by Andrea Albert and Emmanuel Moulin this afternoon.
- Antiproton measurements also set strong limits on TeV-scale dark matter [e.g. Cuoco et al '18].
- Even heavier mass scales can be probed by neutrino experiments. See talk by Christopher Toennis this afternoon.

decaying DM





annihilating DM

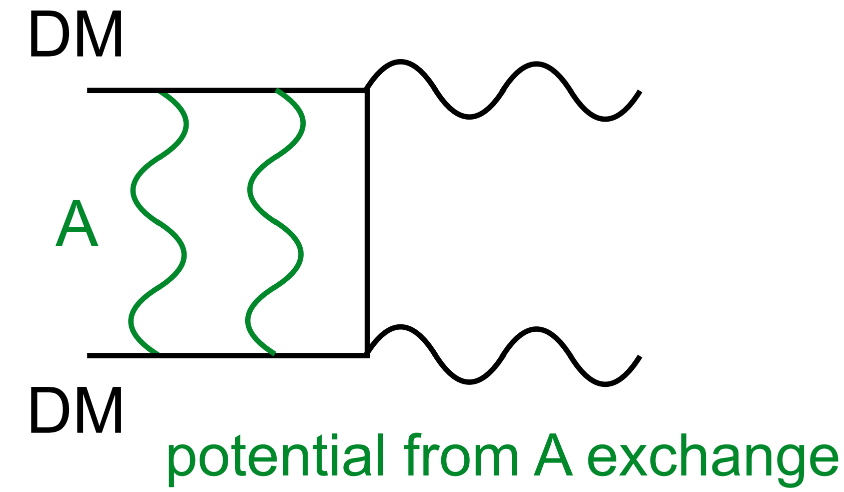


IceCube Collaboration '17 (1705.08103)

Forecasting annihilation signals

- Most of these limits are well above thermal benchmark (exception: H.E.S.S inner Galactic halo / Galactic center search - depends strongly on DM density profile)
- This does <u>not</u> mean they do not constrain DM parameter space - production could of course be non-thermal, but even in simplest thermal scenario, annihilation today can differ from annihilation at freezeout
- Especially natural if the heavy DM interacts through exchange of a lighter mediator (could be the W/Z/Higgs bosons, or a new force carrier)
  - long-range attractive force enhances annihilation at low velocities ("Sommerfeld enhancement")
  - attractive potential can support bound states, which form and then decay via annihilation

The Sommerfeld enhancement



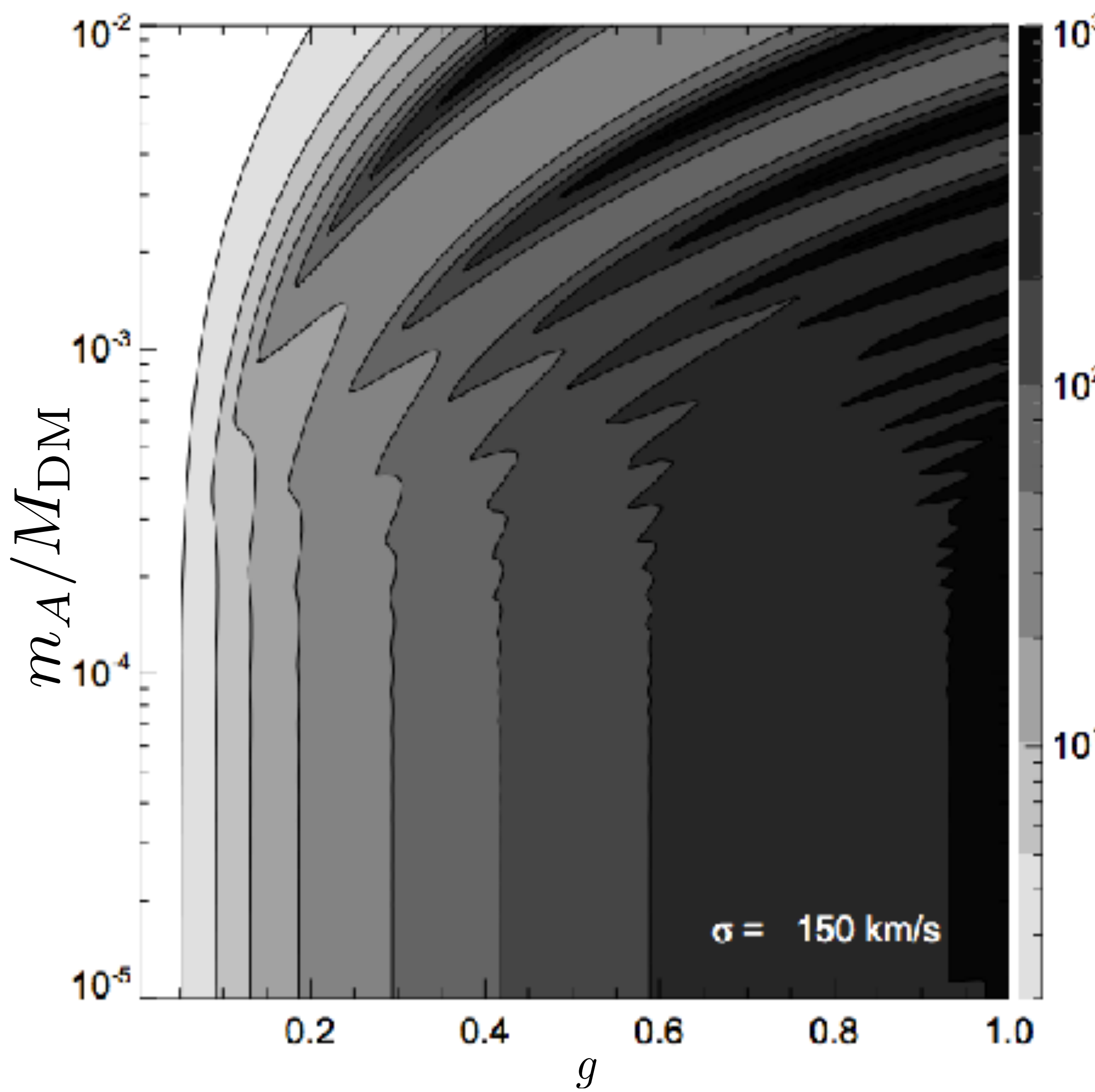
- General parametrics: becomes important when kinetic energy < potential energy,

$$m_{\rm DM} v^2 \lesssim \alpha^2 m_{\rm DM} \Rightarrow v \lesssim \alpha$$

+ long-range potential exists, i.e. Yukawa cutoff due to force carrier mass m_A occurs outside Bohr radius,

$$m_A \lesssim \alpha m_{\rm DM}$$

easier to satisfy this criterion for heavier DM

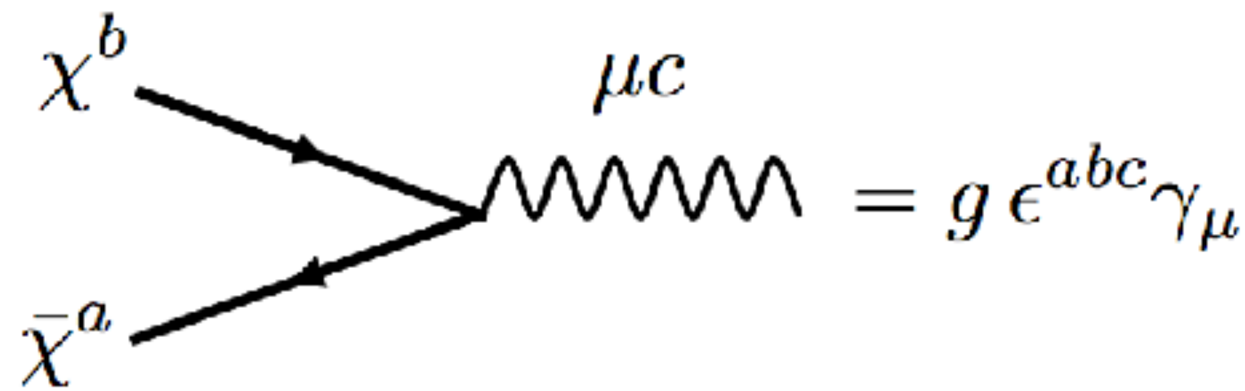


Arkani-Hamed, Finkbeiner, TRS & Weiner '08

- Scales roughly as α/v for $m_A/m_{DM} < v < \alpha$
- Saturates at $(\alpha\, m_{DM})/m_A$ for $v < m_A/m_{DM}$
- Large "resonance" peaks corresponding to presence of near-zero-energy bound states, enhancement scales as $1/v^2$ up to saturation [limited by unitarity; see Blum, TRS & Sato '16]

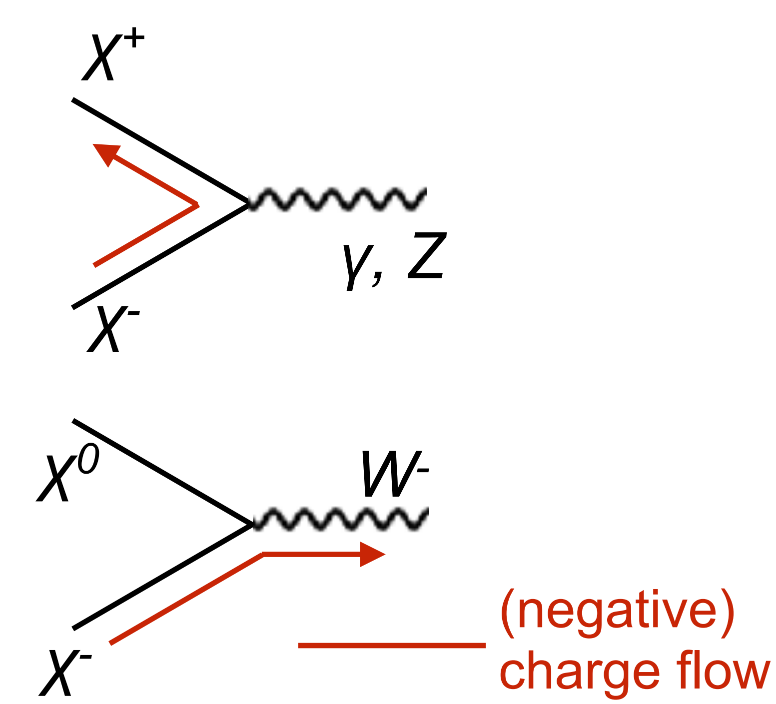
Case study: thermal wino dark matter

- Fermionic dark matter in adjoint representation of $SU(2)_L$. Acts as an illustrative model for heavy WIMP DM.



- In SUSY scenarios, nearly-pure winos are commonly the lightest neutralino and DM candidate.
- In pure-wino limit, after electroweak symmetry breaking, consists of Majorana neutralino χ^0 and slightly heavier Dirac chargino $\chi^+\chi^-$.
- Yields the correct thermal relic abundance with mass ~3 TeV.
- At the thermal mass, W and Z exchanges support a long-range potential that mixes neutralino and chargino states.

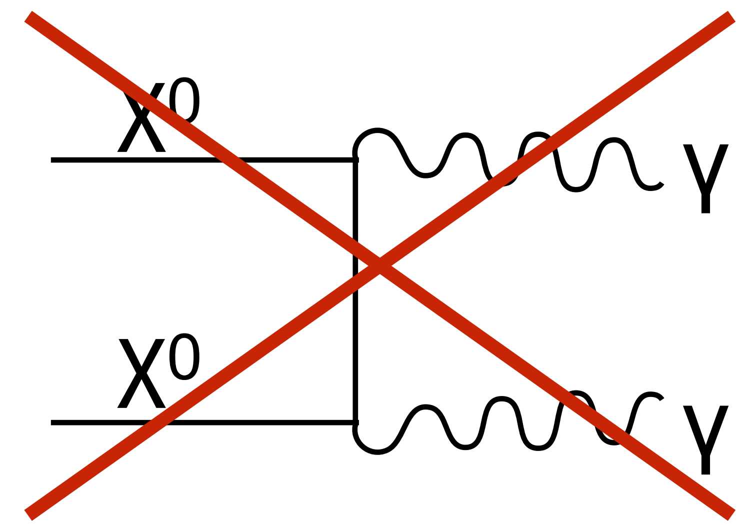
Spectrum/interactions after symmetry breaking:



Winos are great at making gamma-ray lines!

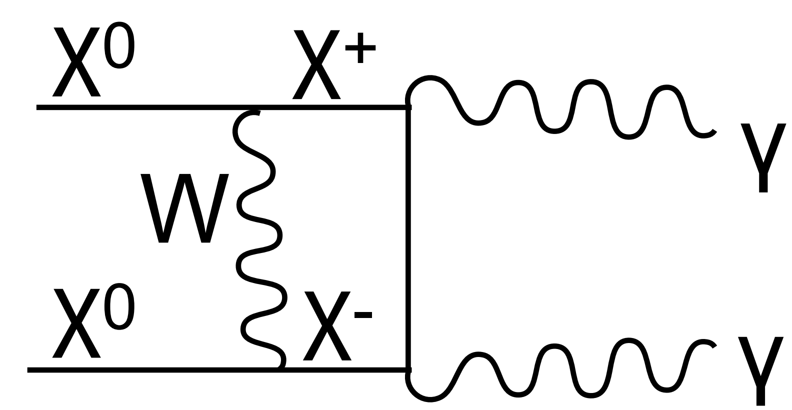
- Naive expectation: DM doesn't couple directly to photons, so line signal will be loop suppressed and small.
- This expectation breaks down for winos when DM mass $m_\chi > m_W/\alpha_W$, due to Sommerfeld enhancement.
- Long-range potential from W exchange allows virtual excitation from $\chi^0\chi^0$ to (nearly degenerate) $\chi^+\chi^-$ state. Can annihilate at tree-level to $\gamma\gamma$, γZ, ZZ.
- General lesson: Sommerfeld enhancement can affect <u>relative</u> detectability of different channels, enhancing line signals if Sommerfeld ladder involves charged particles.

Forbidden at tree-level

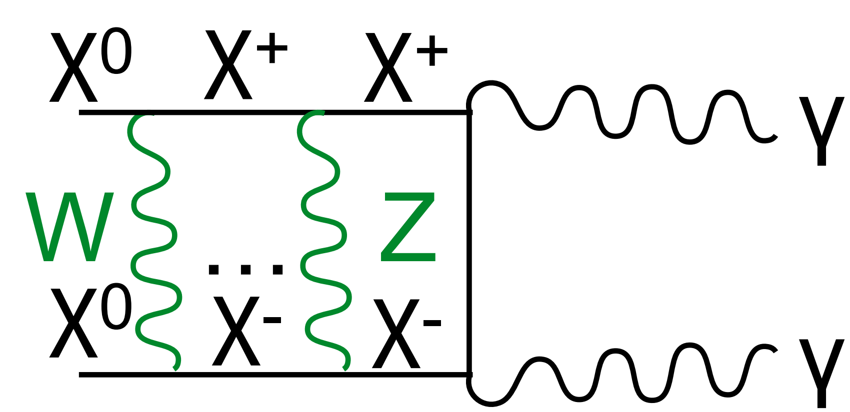


One-loop

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

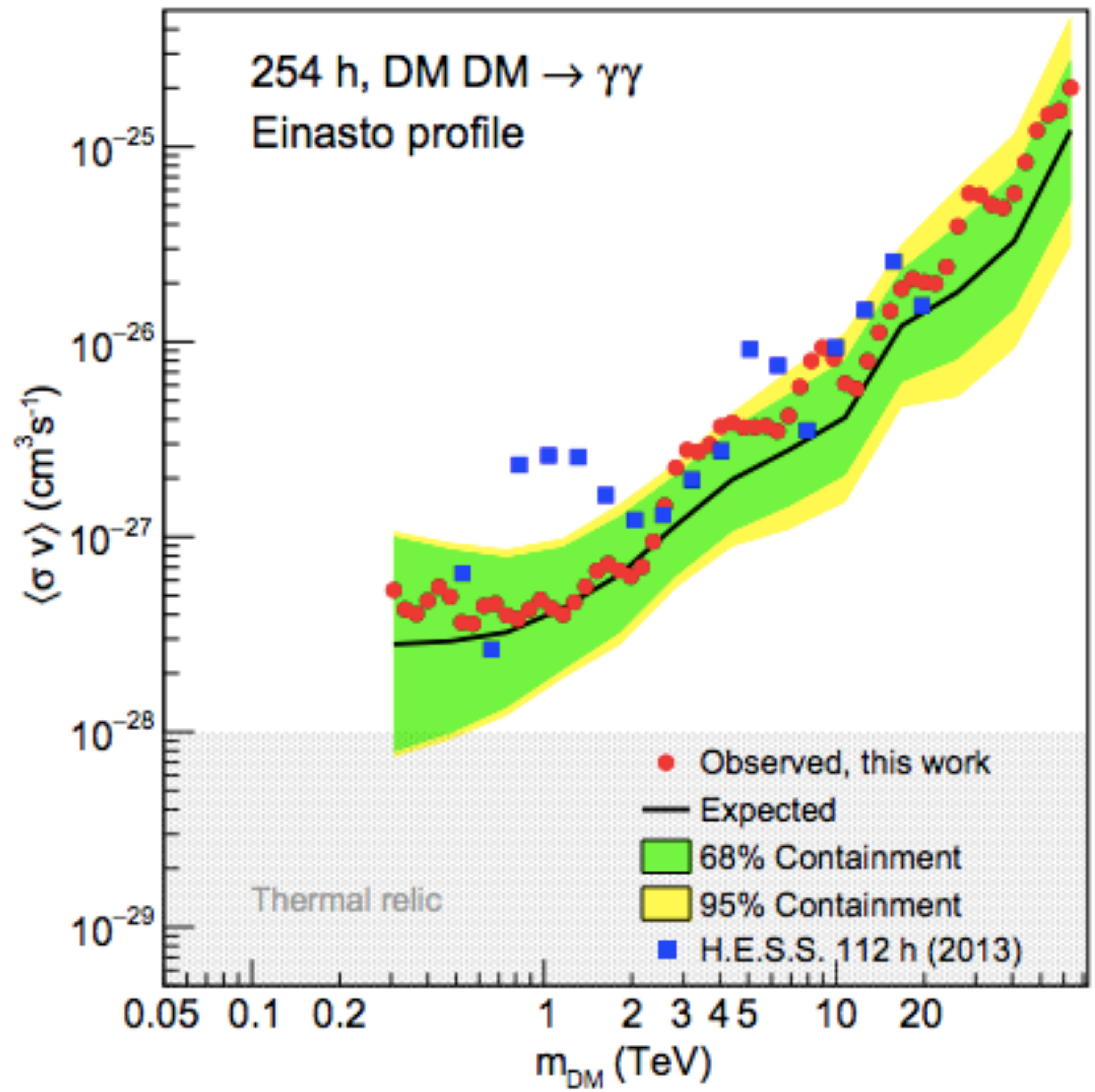


Long-range potential



Gamma-ray line searches

- Gamma-ray line signal from χχ→γγ or χχ→γZ is a very “clean” possible annihilation channel - no astrophysical lines expected.
- Best prospect for a “smoking gun” indirect signal for DM.
- Stringent constraints from Fermi-LAT at sub-TeV energies, H.E.S.S telescope at TeV+ energies.

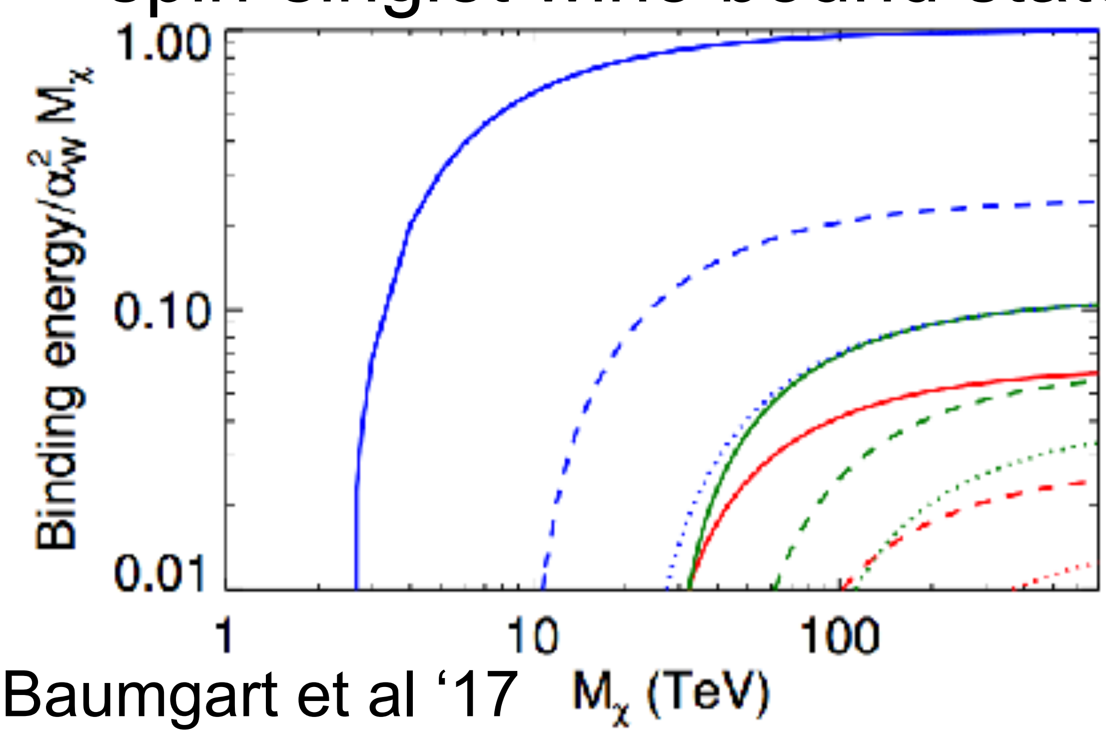


H.E.S.S. Collaboration ’18 (1805.05741)

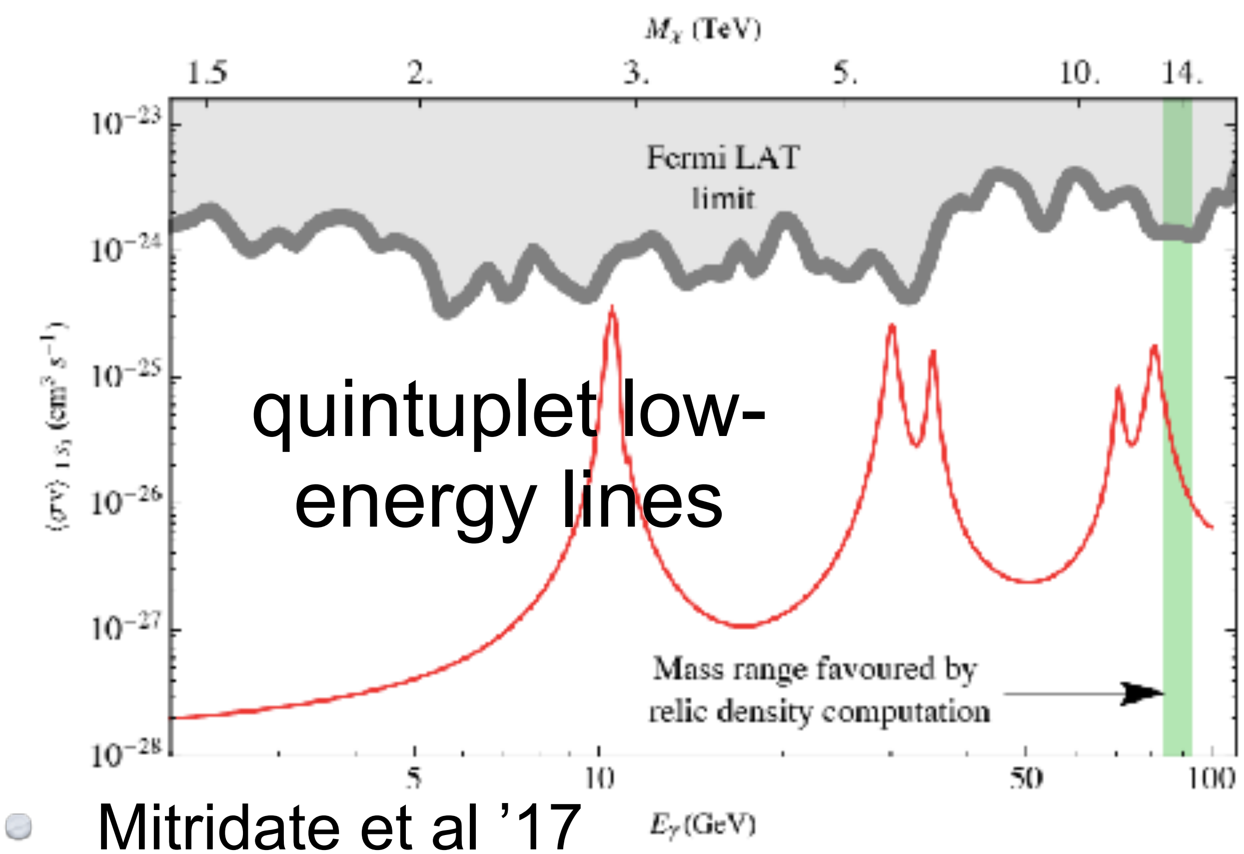
What about bound states?

- Wino DM would possess bound states - only one at 3 TeV thermal mass, rich structure at higher masses [Baumgart, TRS et al ’17]. Singlet and triplet states have different energies.
- However, radiative-capture rate into bound states is negligible compared to direct annihilation, and photons from capture/transition are well below the sensitivity of current experiments.
- Quintuplet DM (higher representation of $SU(2)_L$) is more promising for bound state searches - signal is exponentially sensitive to the representation.
- Note: a recent study [Harz & Petraki ’18] found a possible sign error in Baumgart et al ’17, we are working to cross-check. Changing the sign would make wino bound states slightly less visible.

spin-singlet wino bound states



Baumgart et al ‘17



- Mitridate et al ’17

Resummation: from the LHC to the sky

- Naive calculations of the line annihilation cross section for thermal winos [see e.g. Cohen, TRS et al ’14] run into a problem - standard Feynman diagram expansion breaks down!

- Large logs of the form $\alpha_w \ln^2(m_\chi/m_W)$ enhance terms that would usually be suppressed by α_w (and so safe to ignore).

- The same effect applies to the spectrum of photons from e.g. annihilation to $W^+W^-\gamma$, which overlaps with the line when the energy resolution of the instrument is taken into account.

- For precise constraints, we need to resum these large logs, for the full photon spectrum. Fortunately, the same logs appear in calculations for LHC signals - we can adapt those techniques.

- This behavior will be ubiquitous in cases where the DM annihilates to much lighter particles - important to understand for heavy DM in general. The wino is just a first case study.

A solution: soft collinear effective theory (SCET)

FIXED ORDER | SCET

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

tree
1-loop
⋮

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

LL NLL …

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

Leading log regime
$\alpha L \sim 1$

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

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)).

General strategy of SCET

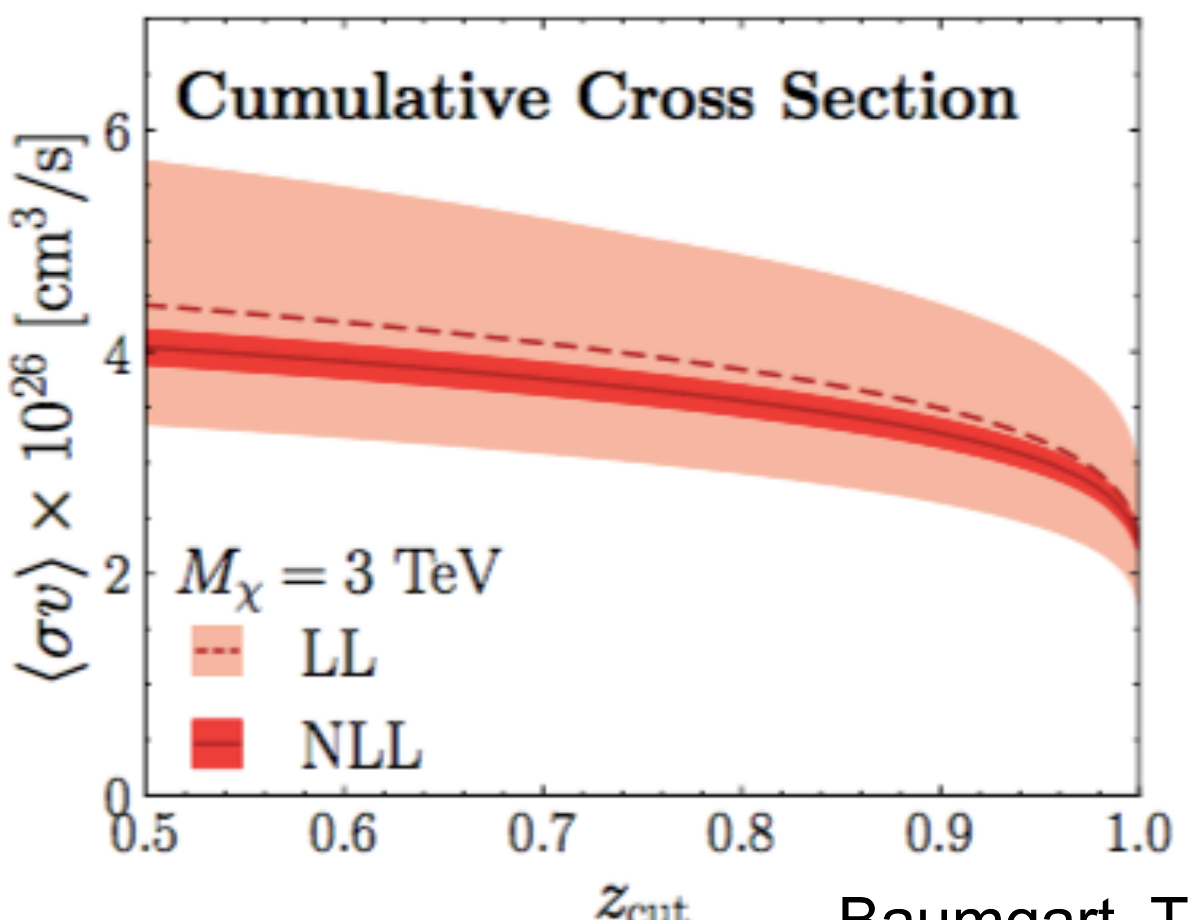
- Match onto full theory (or EFT valid to higher energies) at high scale.
- Run operators/fields of interest down to low scale using renormalization group of EFT (this captures large logs).
- Match onto desired observables at low scale.
- Subtlety for full spectrum near endpoint (vs line): there are two low scales, one for m_W and one for energy resolution - need to run down to higher of these two scales, then match onto a second EFT to complete the evolution. Need two separate RG evolution steps (+ matching at intermediate scale).

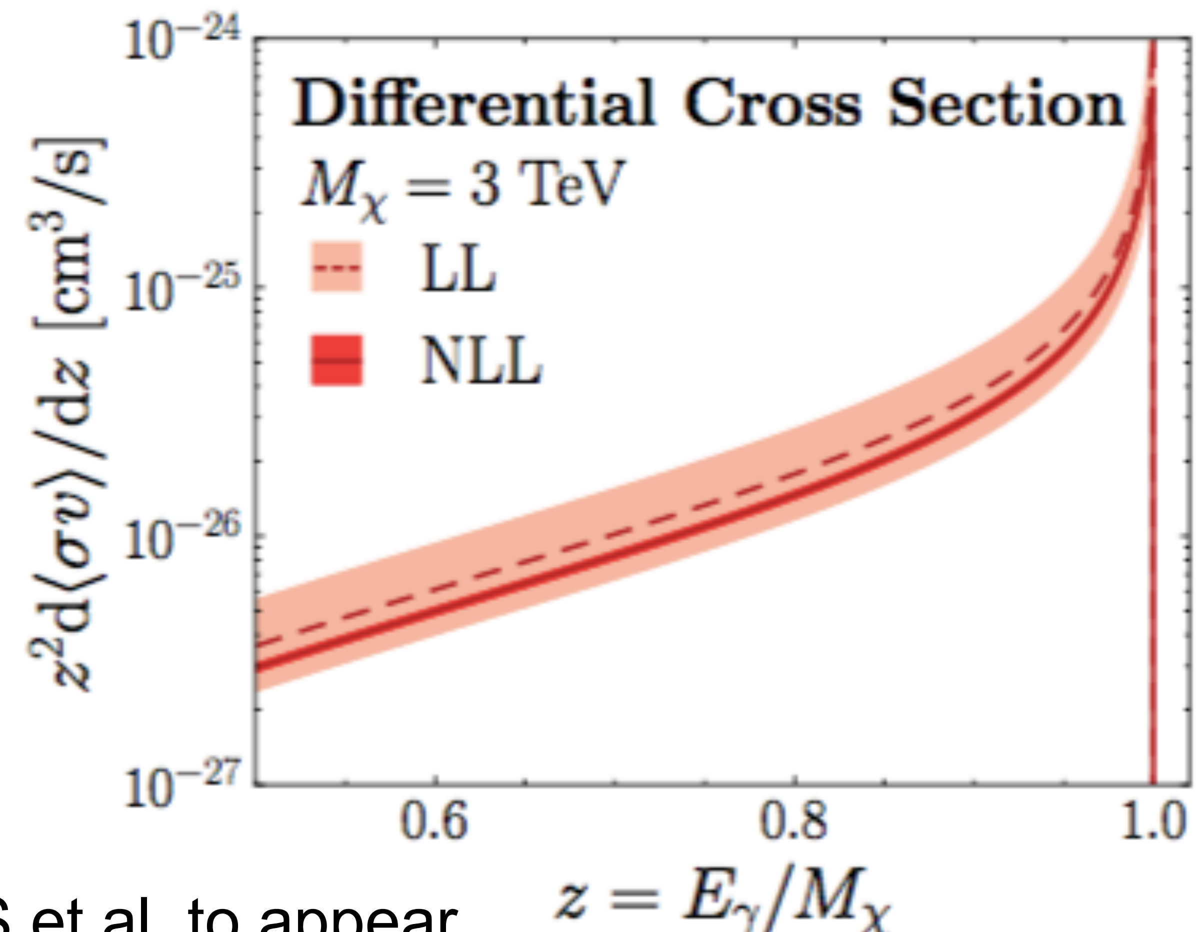
Results for the resummed spectrum

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

- We have computed the full resummed spectrum analytically to next-to-leading-log (NLL) [Baumgart, TRS et al, 1808.XXXXX], including the Sommerfeld enhancement; we previously computed the spectrum to LL in published work [Baumgart, TRS et al ’18].

- Our theory uncertainties are now at the level of 5%.



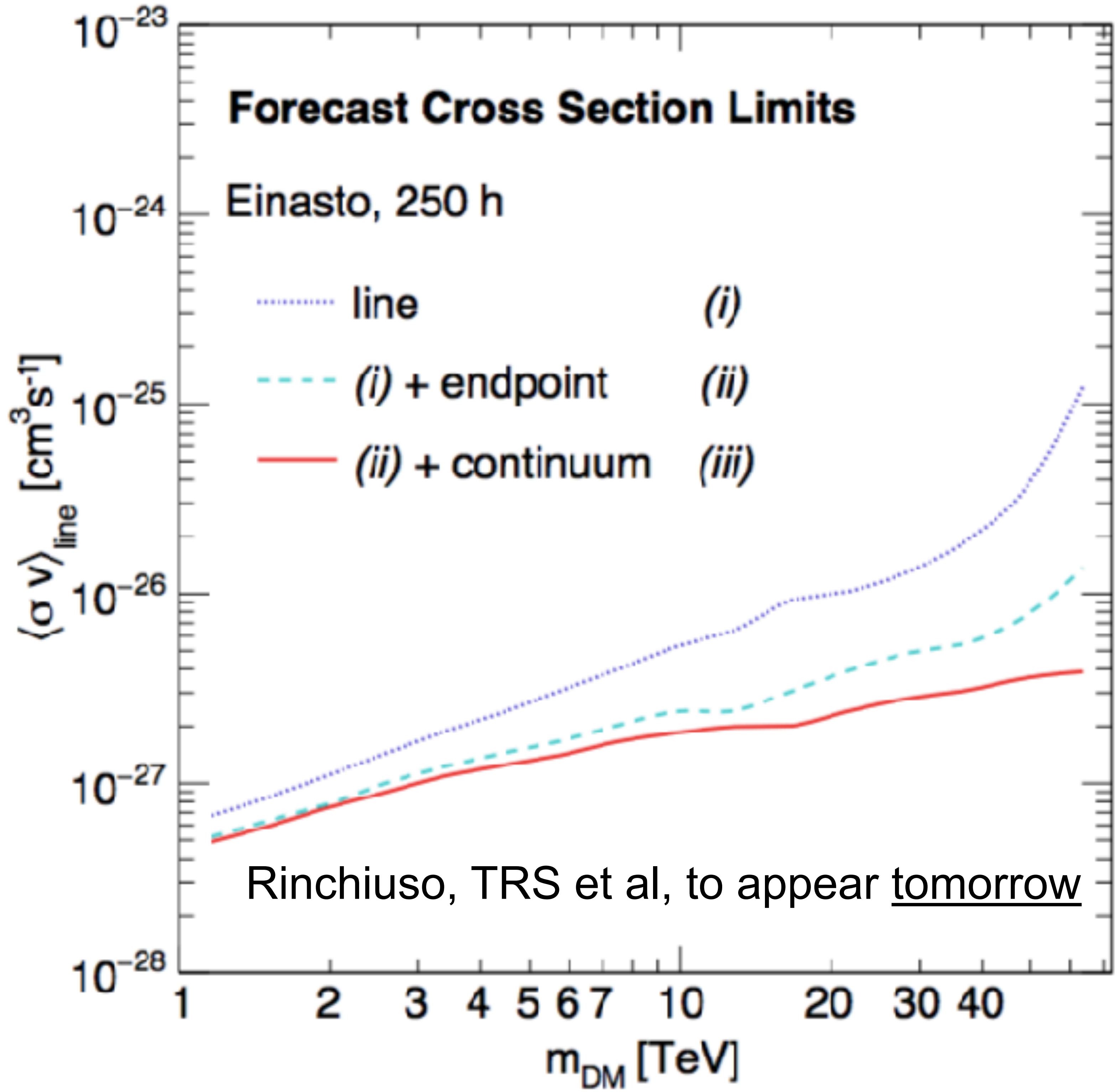


Baumgart, TRS et al, to appear

Implications for H.E.S.S searches

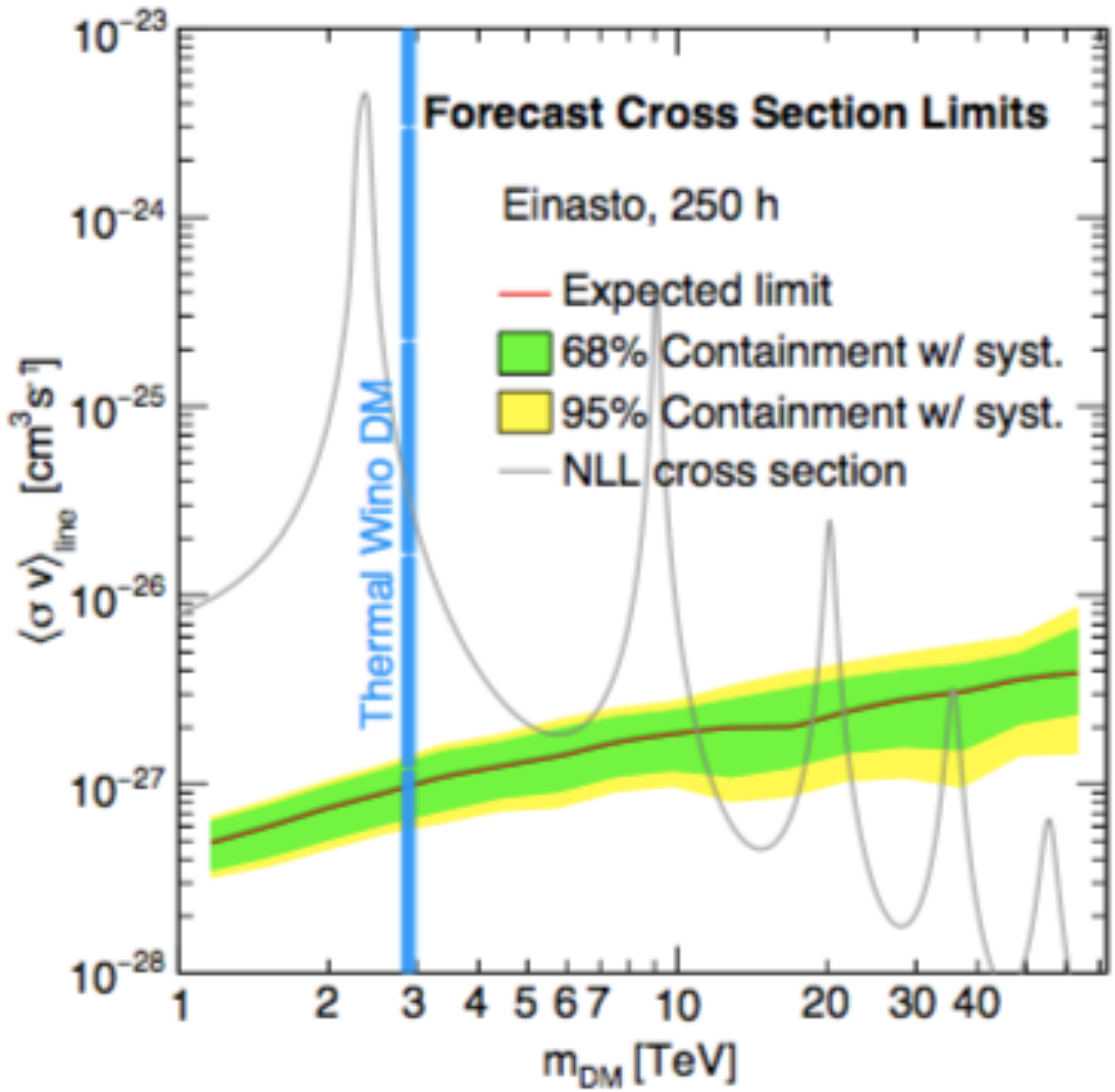
Rinchiuso, Rodd, Moult, Moulin, Baumgart, Cohen, TRS, Stewart & Vaidya ‘18

- In work led by Lucia Rinchiuso, we have forecast the constraints the current H.E.S.S Galactic Center data could set on thermal winos, accounting for the full spectrum.
- Improves over line search limits by a factor ~1.5 at thermal wino mass.
- Theory uncertainties now (at NLL) subdominant to experimental systematics.



The DM density profile

- Constraints already strong enough to strongly exclude thermal wino DM, under the assumption of a cuspy (Einasto) DM density profile.
- Simulations suggest that baryonic physics may flatten density profiles, producing O(kpc) “cores” of flat density.
- Analysis of current data should be able to exclude thermal wino DM with core radius below 2 kpc.
- New “Inner Galaxy Survey” strategy by H.E.S.S could allow improvement of limit on core size to nearly 5 kpc.



Rinchiuso, TRS et al, to appear tomorrow

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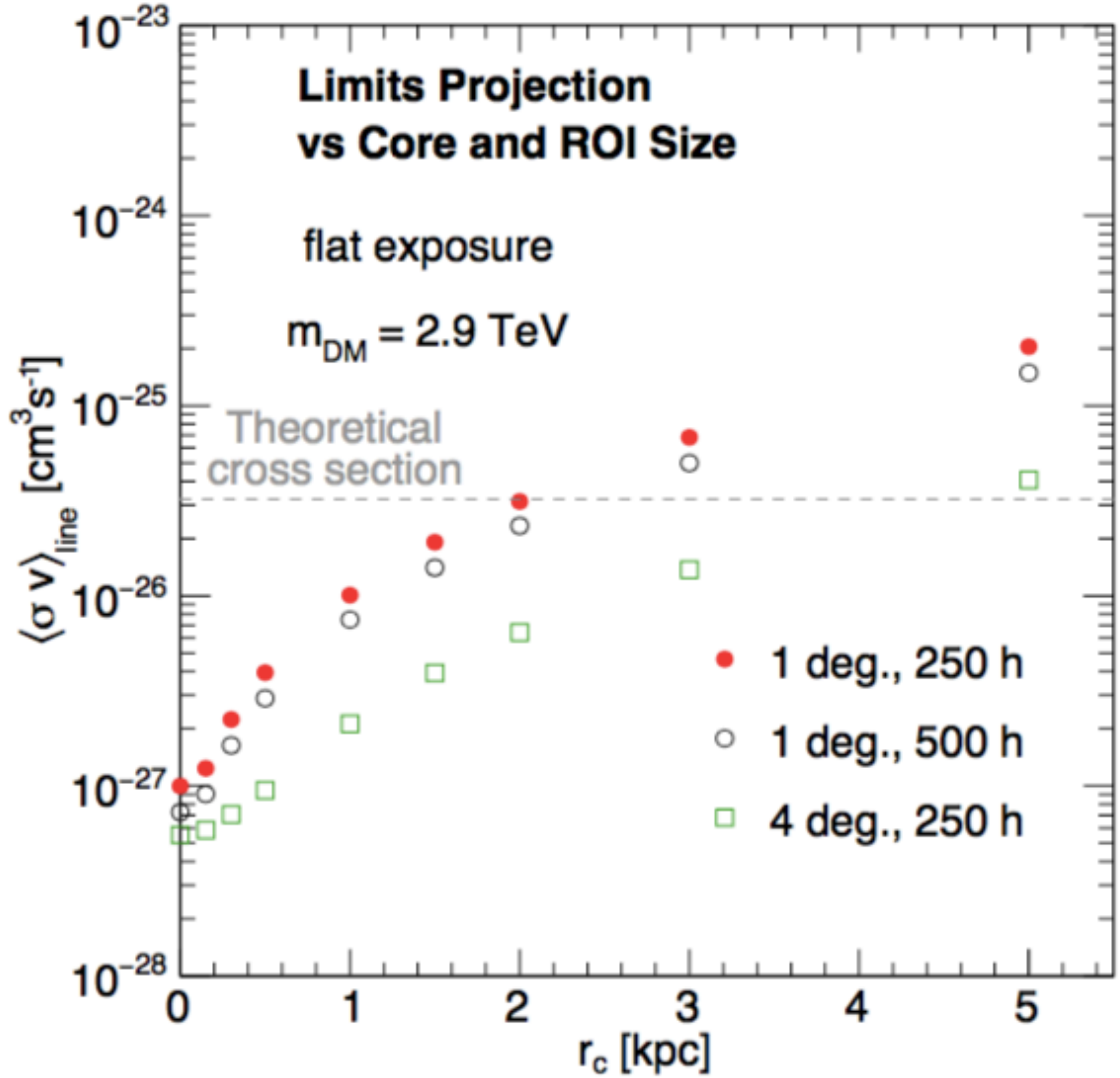
- Analysis of current data should be able to exclude thermal wino DM with core radius below 2 kpc.
- New “Inner Galaxy Survey” strategy by H.E.S.S could allow improvement of limit on core size to nearly 5 kpc.



Rinchiuso, TRS et al, to appear tomorrow

Summary

- TeV-scale dark matter allows a simple mechanism (thermal freezeout) to yield the observed abundance of dark matter.
- Indirect searches for annihilation/decay are particularly powerful for TeV+ DM:
  - Collider experiments cannot effectively probe this parameter space - some of the simplest WIMP models are unconstrained by LHC/direct detection.
  - Simple thermal relic scenario predicts benchmark cross-section that is not far below current detectability.
  - Interactions between DM and any lighter force carriers (including W/Z bosons, for DM heavier than ~2 TeV) naturally lead to large cross-section enhancements.
- Standard theoretical methods frequently break down at these masses. Active and ongoing program to adapt effective field theory techniques to make precise predictions for heavy WIMPs. For the thermal wino, we have achieved percent-level precision, substantial sensitivity improvements.