Signals of DM Annihilation at Super-Kamiokande

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Neutrinos, Rencontres du Vietnam, 16-22 July 2017

DISCLAIMER

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I am a phenomenologist

This is why experimental scientists hate theoretical scientists.

Outline

- Motivation

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- Why neutrinos? Why SK?

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- Future prospects and conclusions

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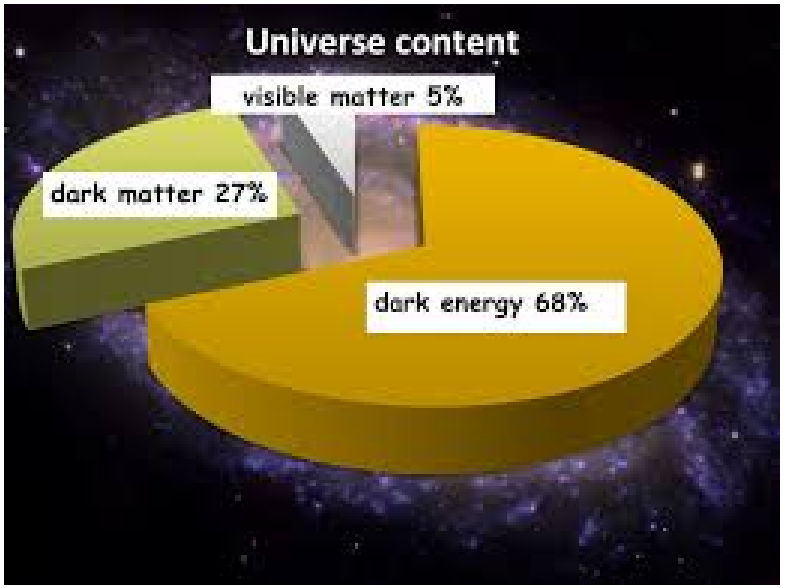
- There is **Dark Matter** in the universe

$$\Omega_\chi h^2 = 0.1188 \pm 0.0010$$

[Planck 2015 Results, arXiv:astro-ph/1502.01589]



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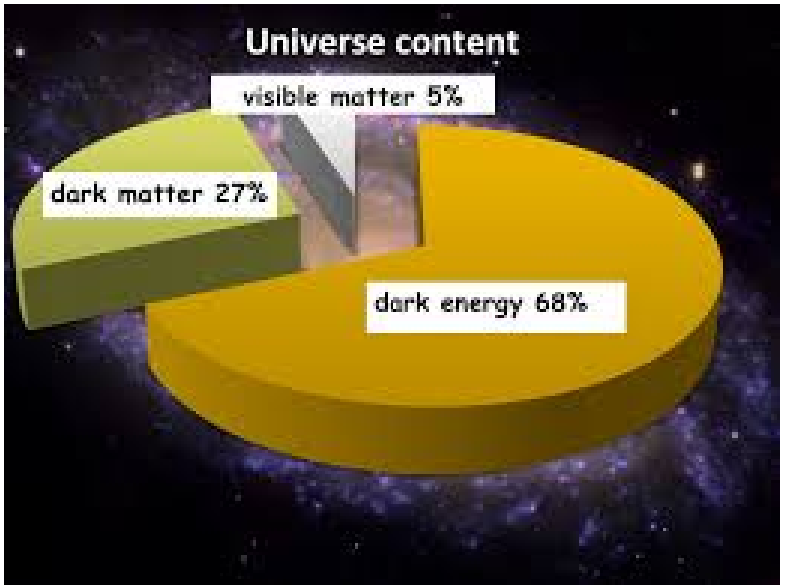
- A particle description of DM is still **missing**



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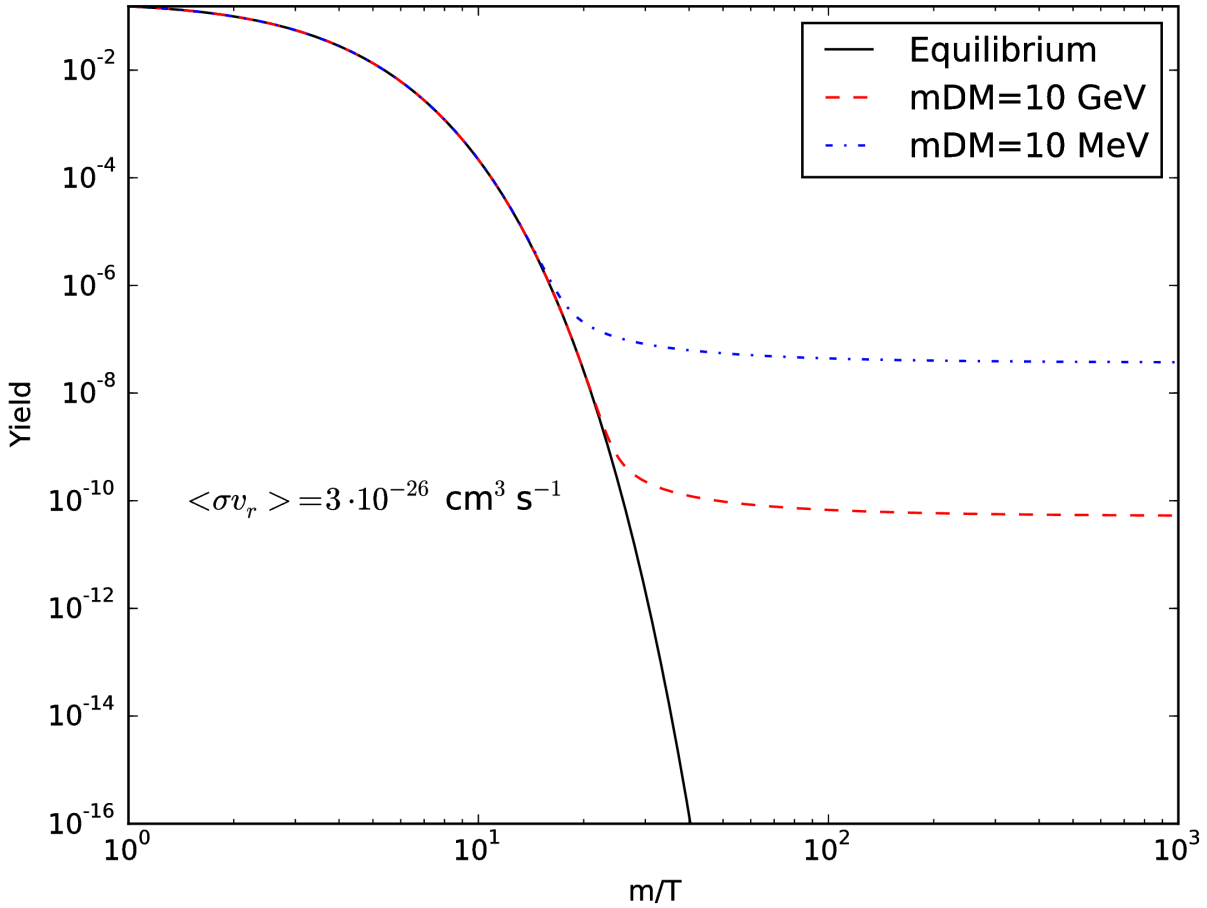
$$\langle \sigma v_{\mathrm{r}} \rangle = 3 \cdot 10^{-26}\,\mathrm{cm}^3\mathrm{s}^{-1}$$



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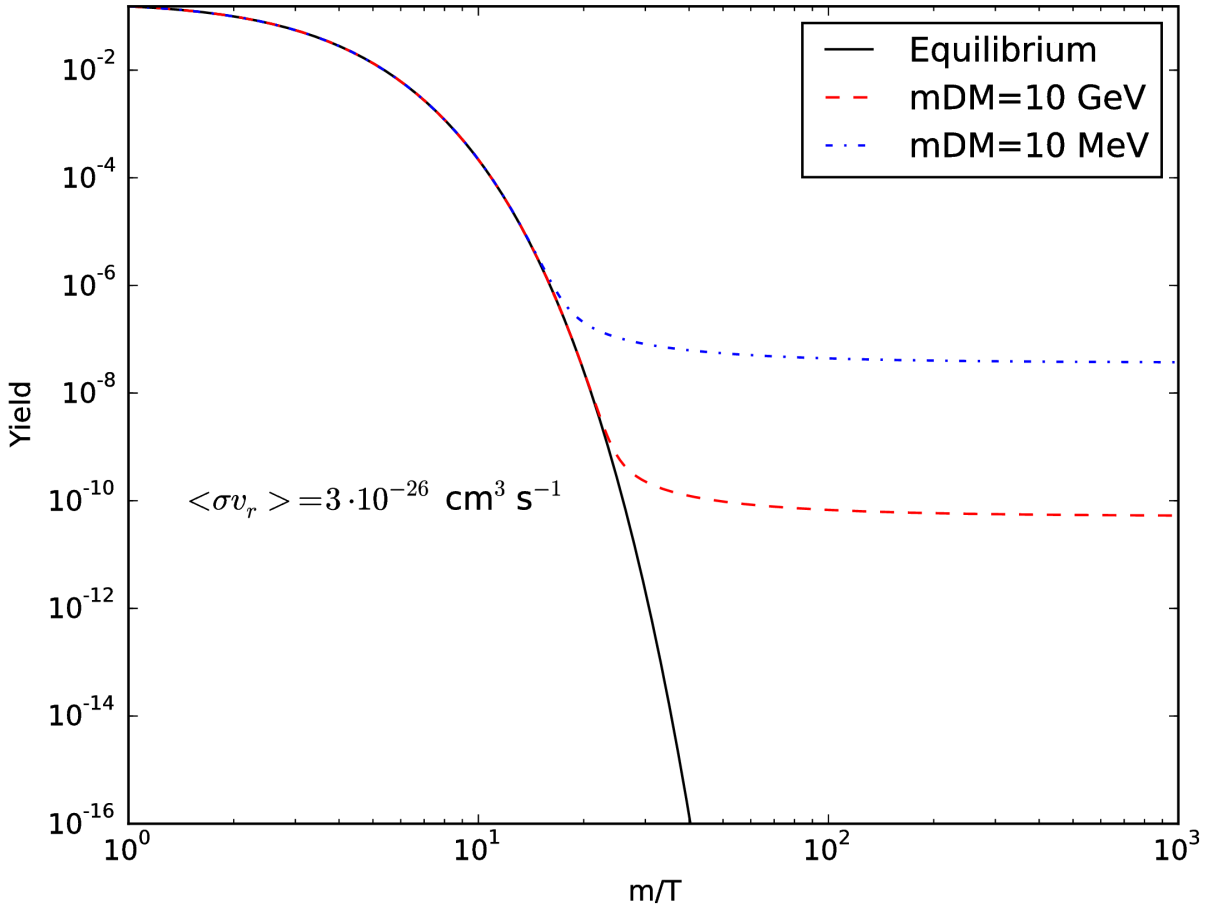

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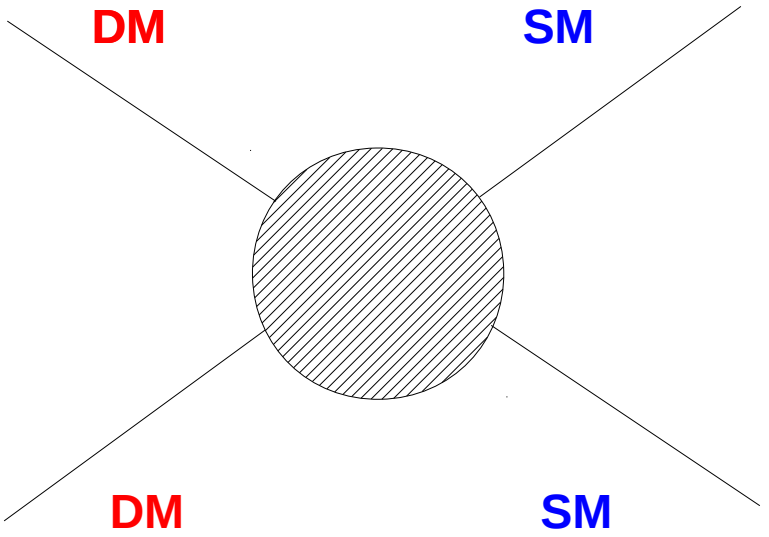
- Masses in the **MeV-TeV range** are allowed:

  O(100) TeV > M_{DM} > O(10) MeV

  [C.Boehm, et. al., arXiv:hep-ph/1303.6270, K. Griest et. al., PRL 1990]

DM Searches



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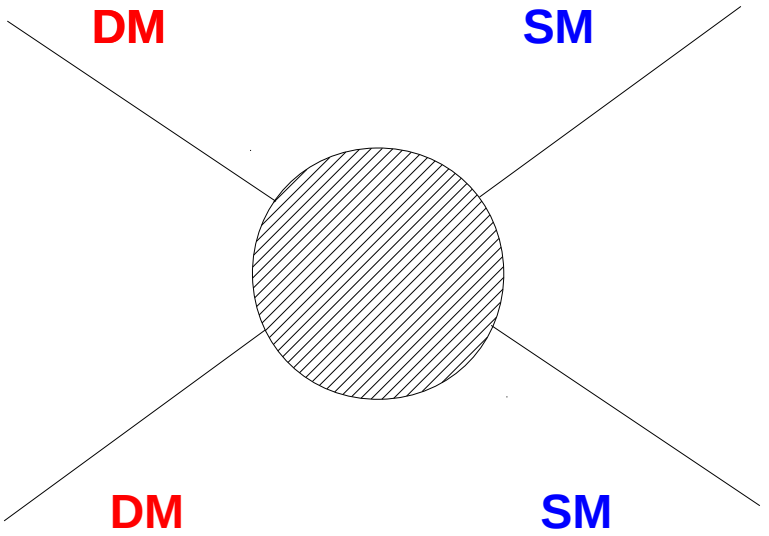
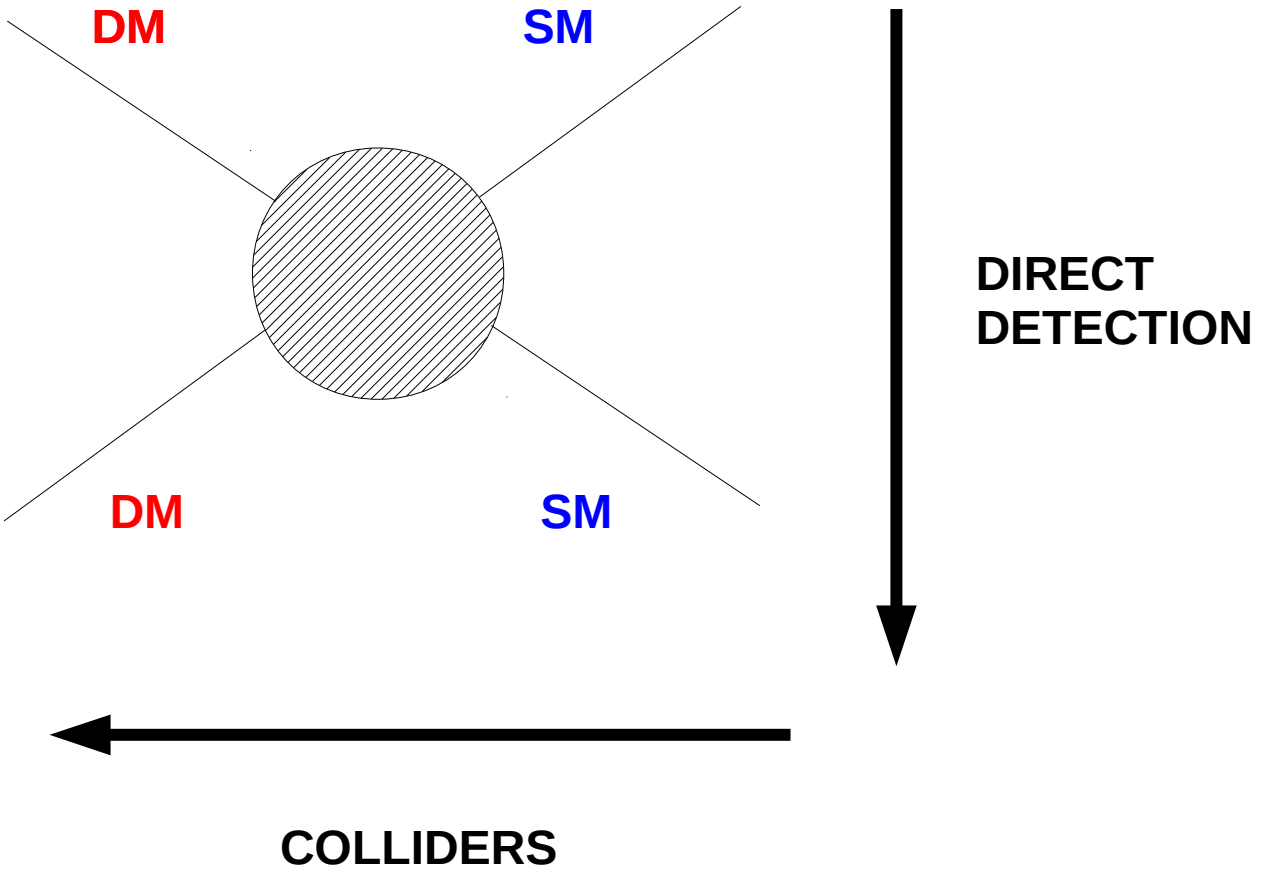


COLLIDERS

DM Searches



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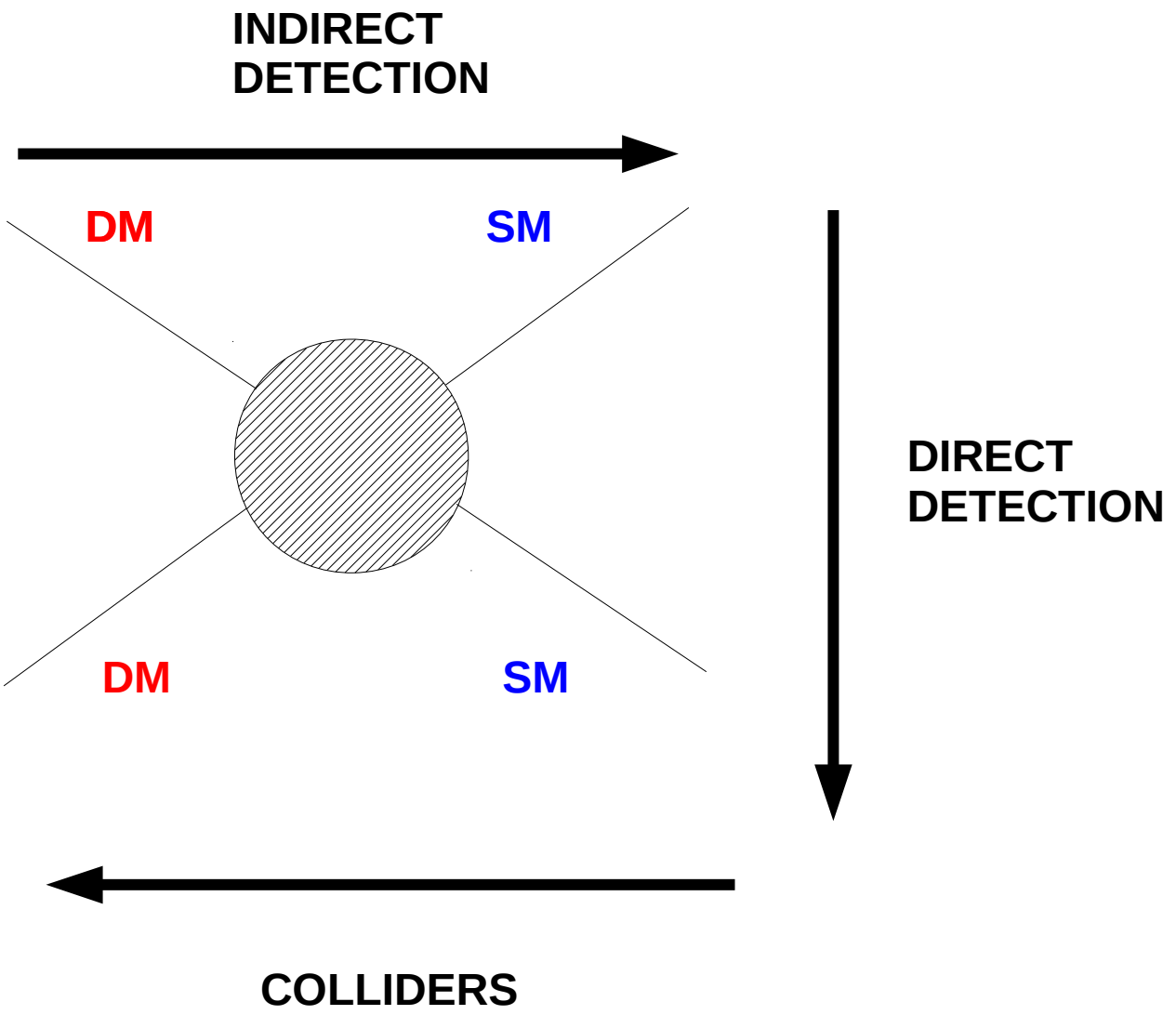
DM Searches



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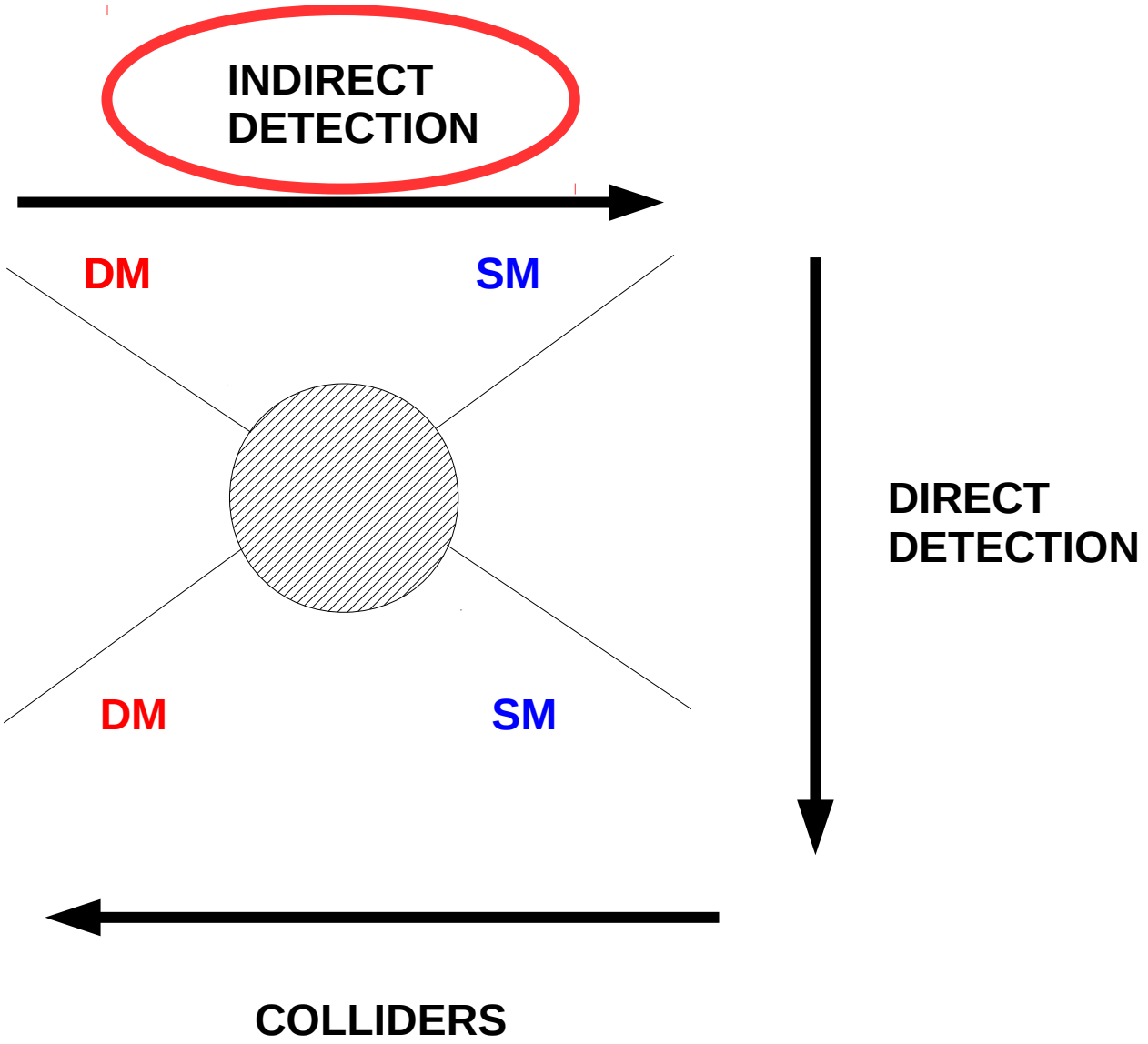
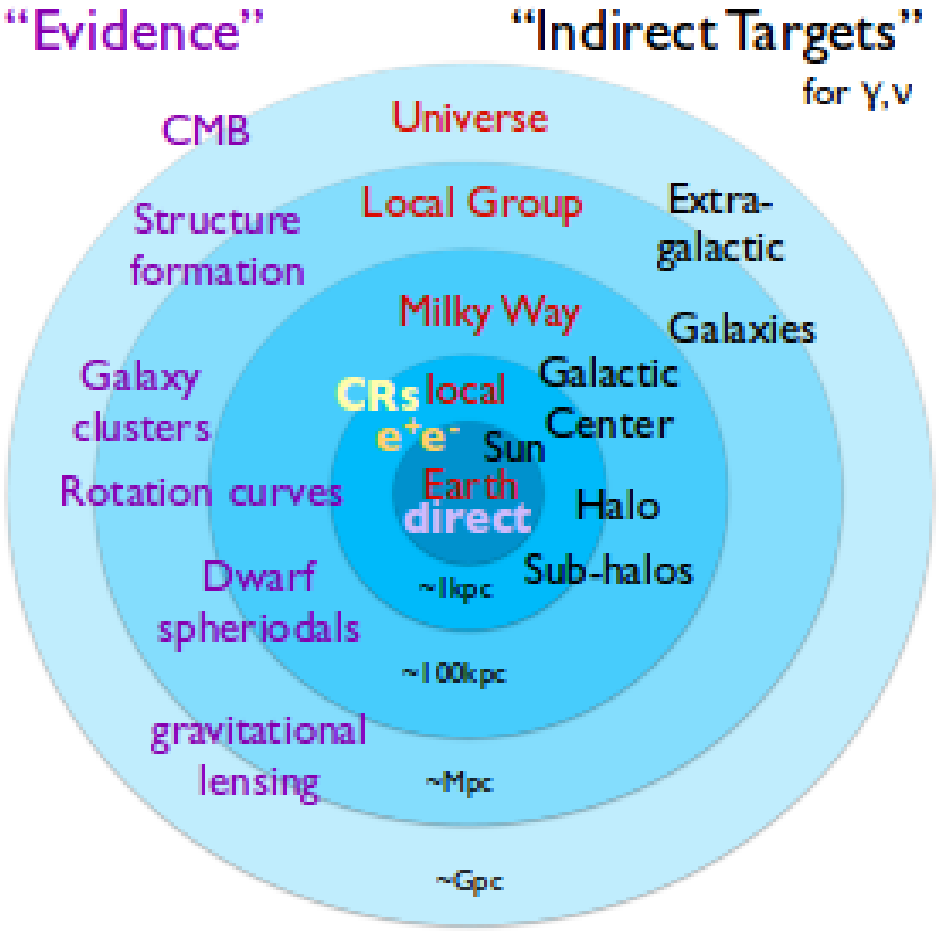


Why Neutrinos?

- Plethora of astrophysical sources of neutrinos produced from DM self-annihilation



[C. Rott, arXiv: atro-ph.HE/1210.4161]

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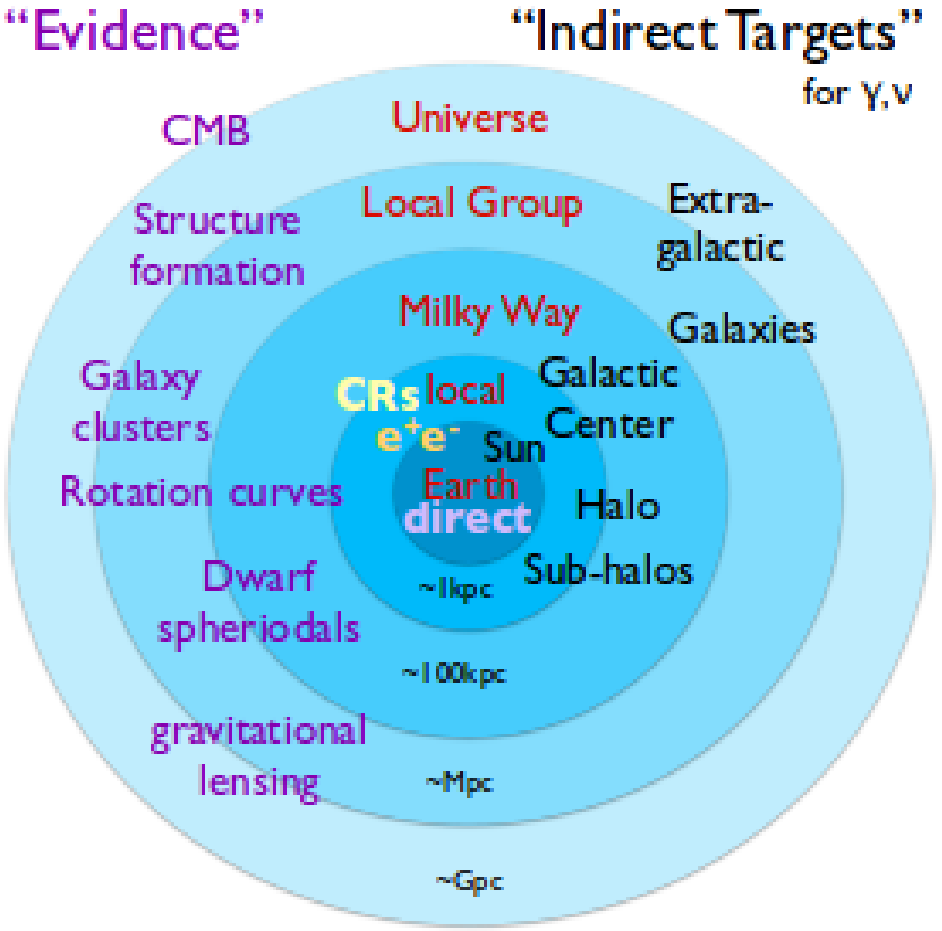

[C. Rott
arXiv: atro-ph.HE/1210.4161]

- Upper bound on total annihilation cross section

[J. F. Beacom, et al.,
arXiv: atro-ph/0707.0196]

Low Energetic Neutrinos

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- Can use low energy data from the search for diffuse supernova relic neutrinos

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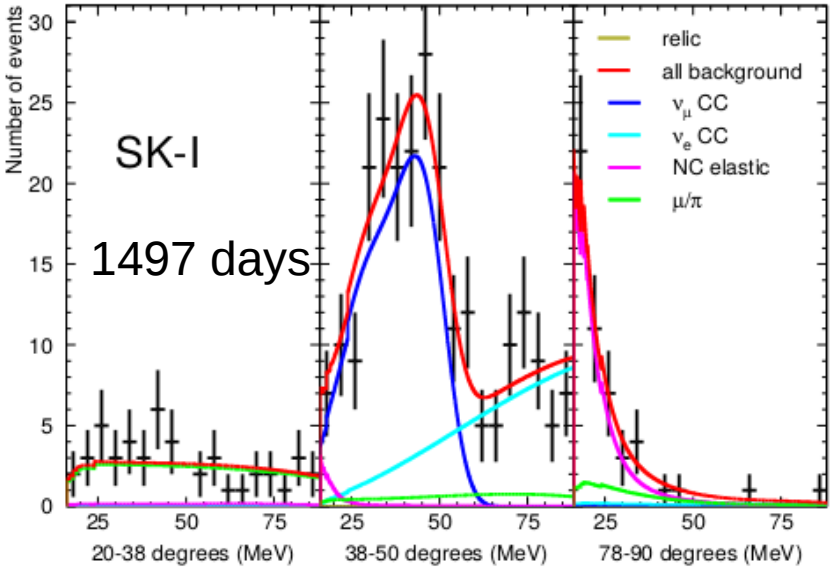

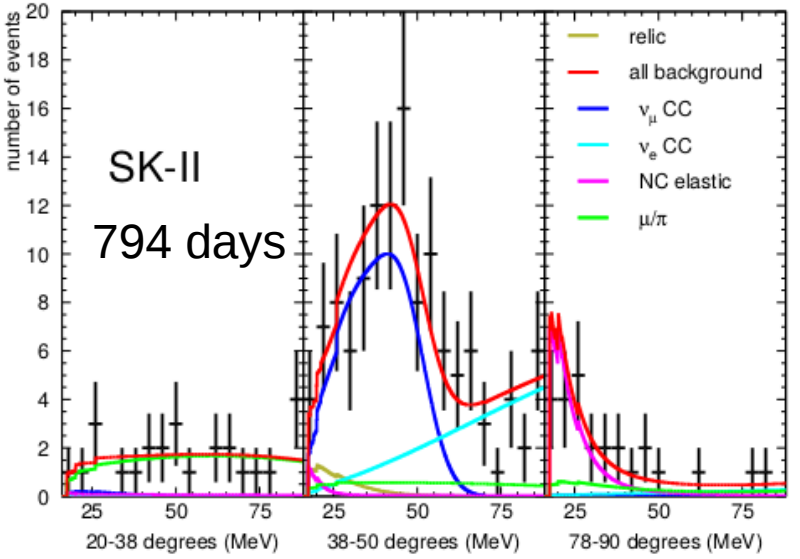

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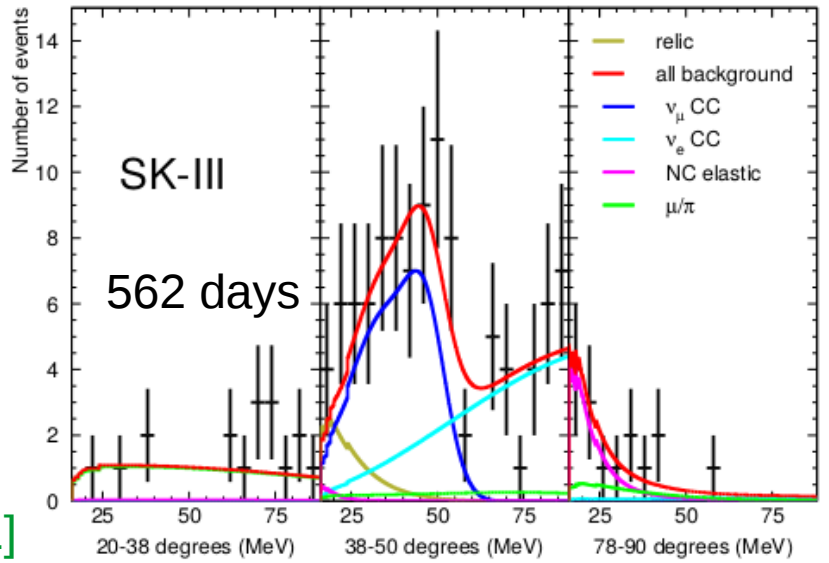
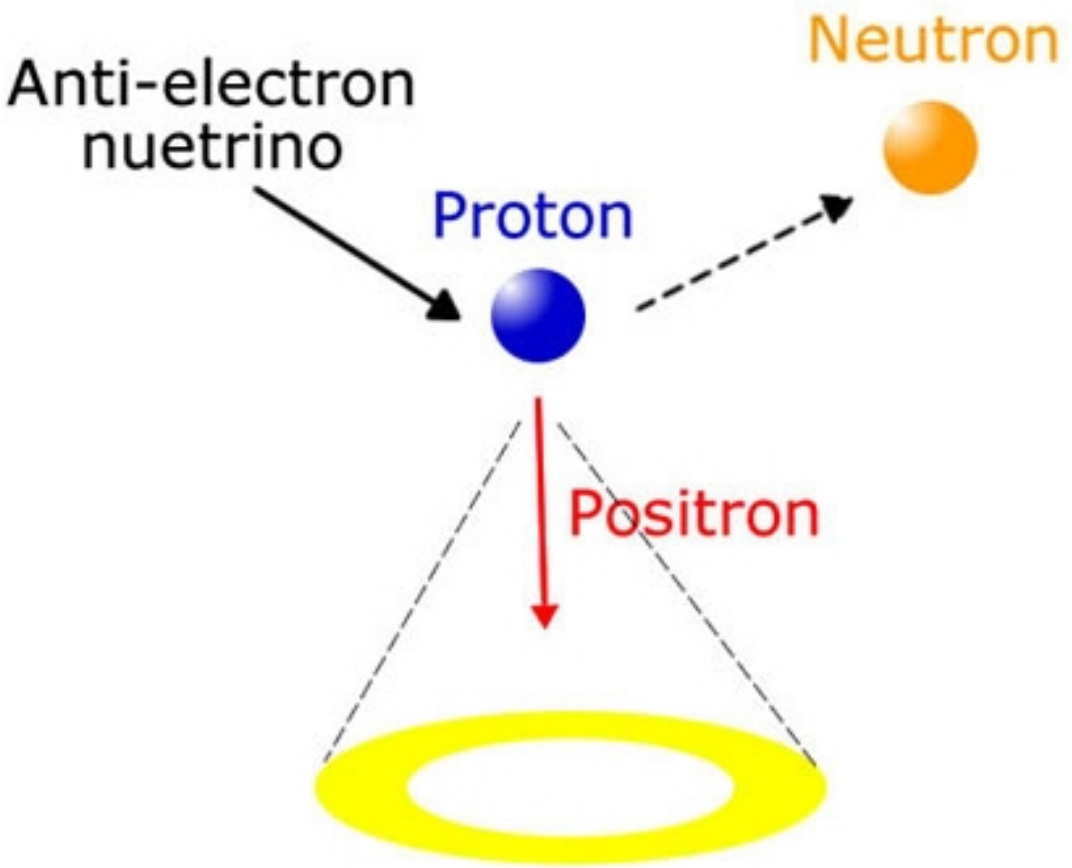
[K. Bays, et. al., arXiv: hep-exp/1111.0531]



Detection

- $\bar{\nu}_e + p \rightarrow e^+ + n$

  dominates at low energies



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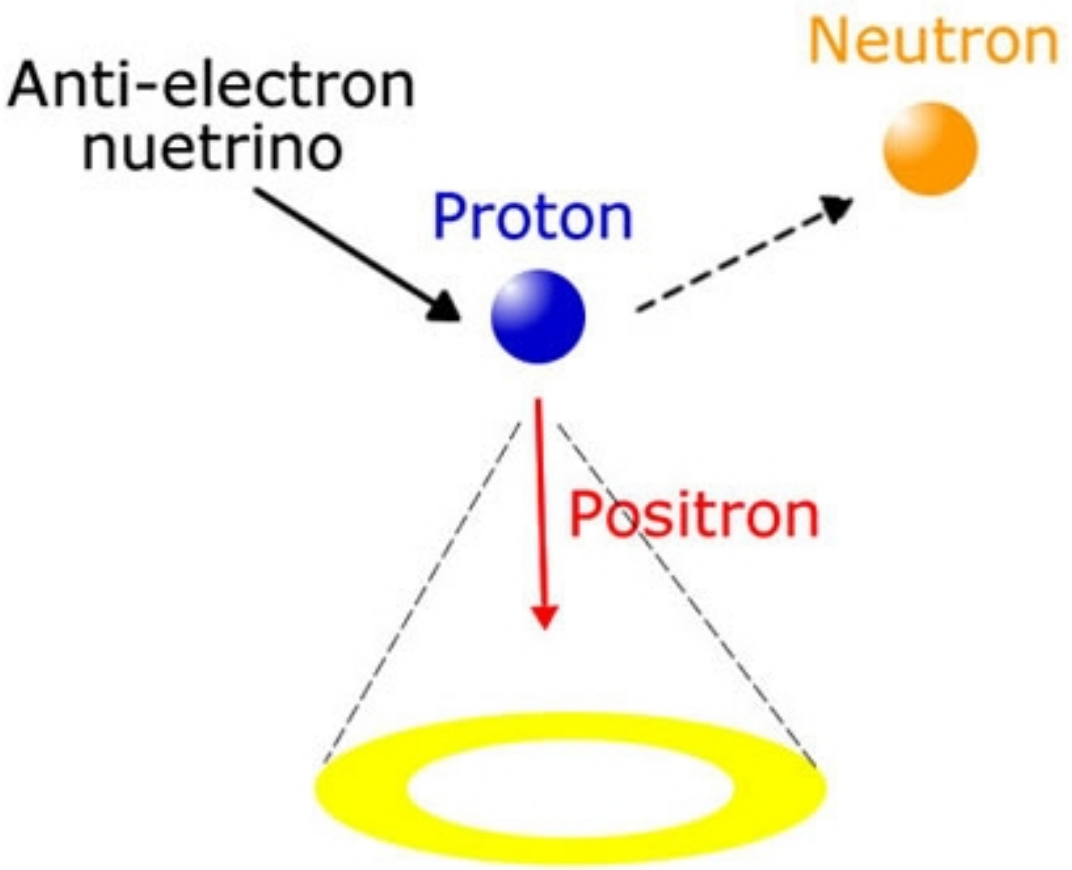

- Neutrino interactions with bound nucleons give also relevant contributions

Detection (II)

$$A_l = A_s \int \Big[\Big(\frac{d\sigma_f^{\bar{\nu}_e}}{dE_e}(E_{\bar{\nu}_e}, E_e) + \frac{1}{2}\frac{d\sigma_b^{\bar{\nu}_e}}{dE_e}(E_{\bar{\nu}_e}, E_e) \Big) \frac{d\Phi^{\bar{\nu}_e}}{dE_{\bar{\nu}_e}}(E_{\bar{\nu}_e}) + \frac{1}{2}\frac{d\sigma_b^{\nu_e}}{dE_e}(E_{\nu_e}, E_e)\frac{d\Phi^{\nu_e}}{dE_{\nu_e}}(E_{\nu_e}) \Big] dE_e dE_{\nu_e} E_{\bar{\nu}_e} \times \times \int_{E_l}^{E_{l+1}} \epsilon(E_{\rm vis}) R(E_e, E_{\rm vis}) dE_{\rm vis}$$

Detection (II)

Inverse beta decay

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Bound nucleons

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Detector efficiency and energy resolution

Dominant Backgrounds

- **Spallation** products from cosmic muons → Sets lower energy threshold of the analysis to **16 MeV (17.5 MeV)** for SKI-III (SKII)

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- **Michel** electrons and positrons from invisible muons

Analysis

- Simulate the expected backgrounds

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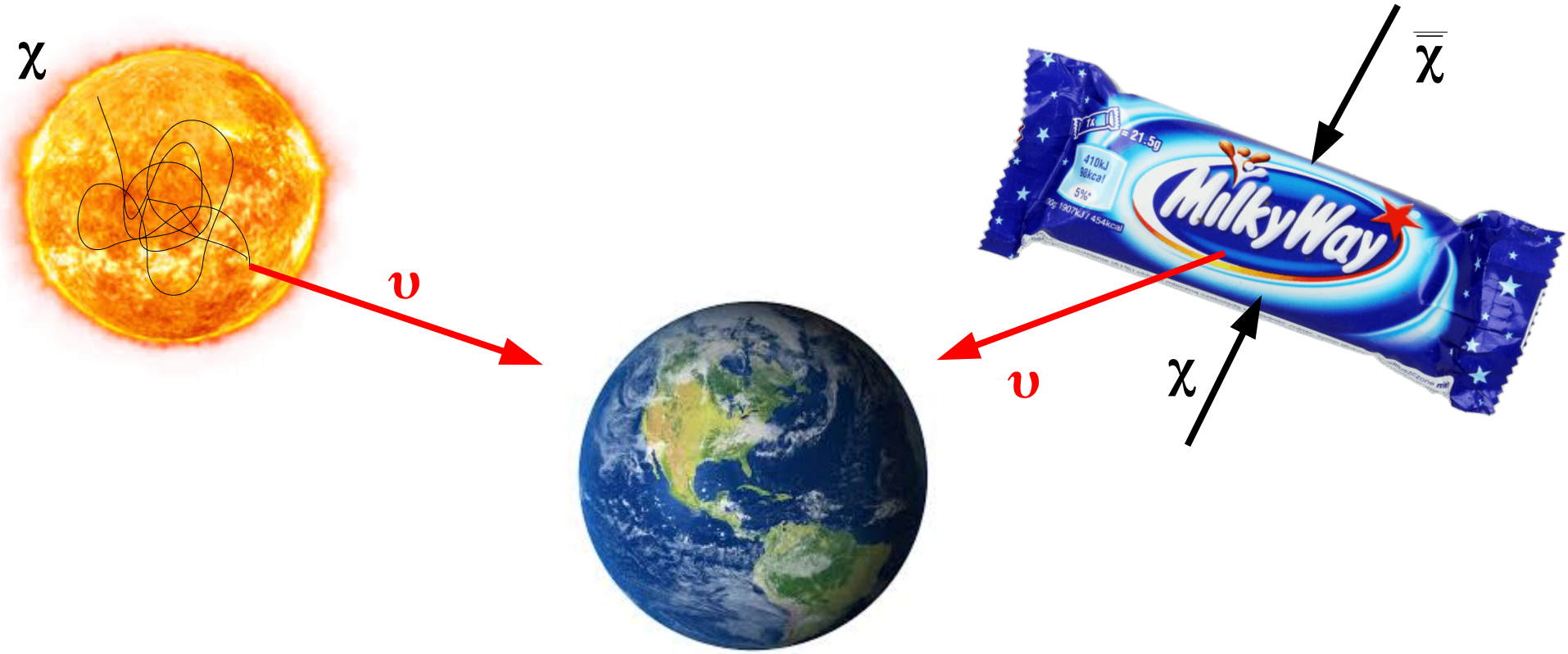
- Simulate the expected backgrounds

- Likelihood analysis

Focus on Two Sources



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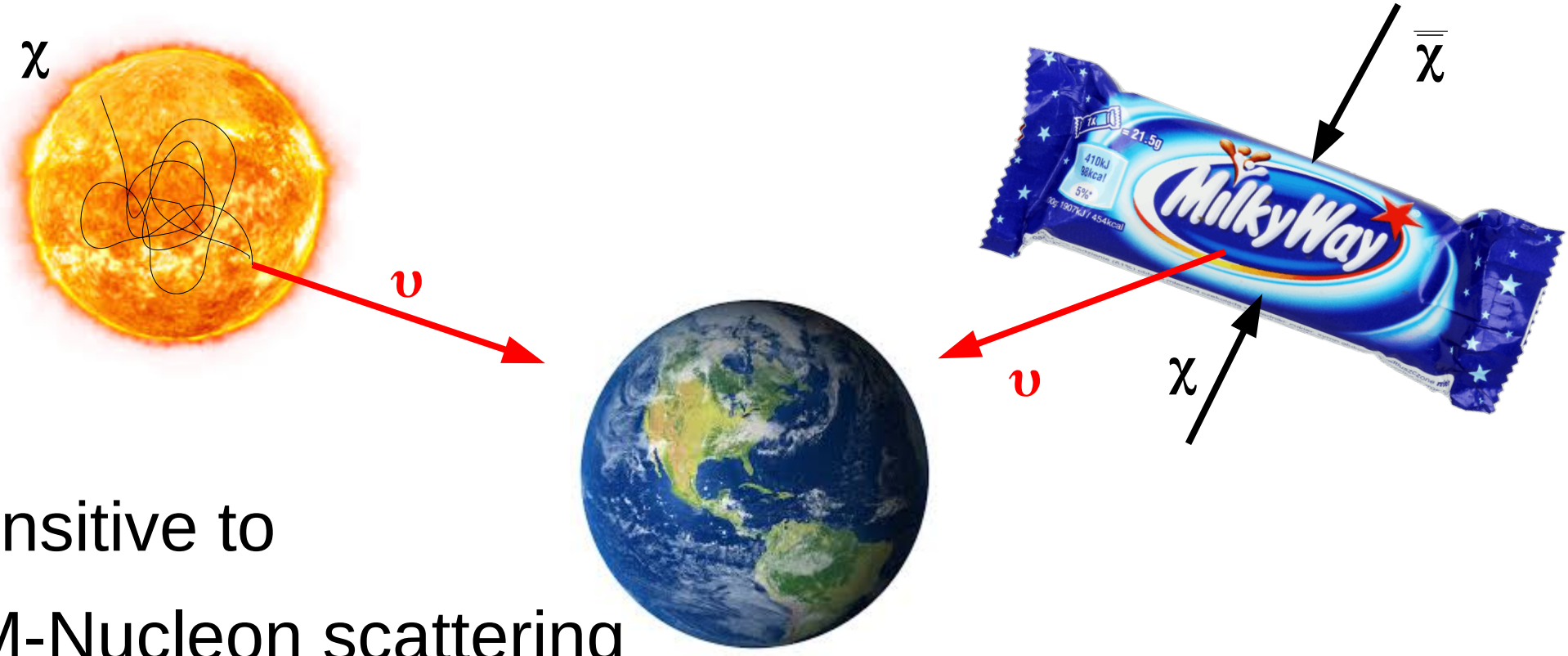

- Sensitive to DM-Nucleon scattering

[C. Rott, et. al., arXiv:hep-ph/1510.00170, N. Bernal, et al., arXiv: hep-ph/1208.0834, C. Rott, et. al., arXiv:astro-ph.HE/1208.0827]

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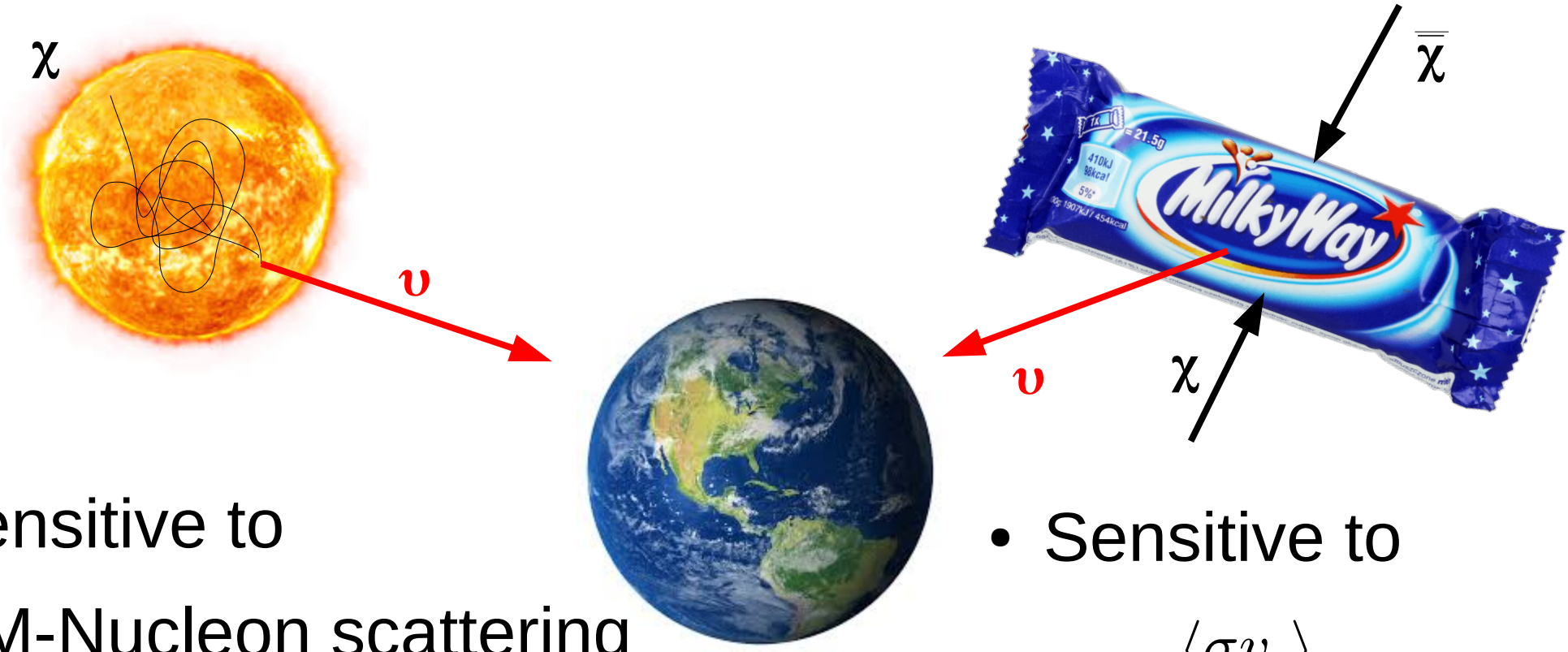

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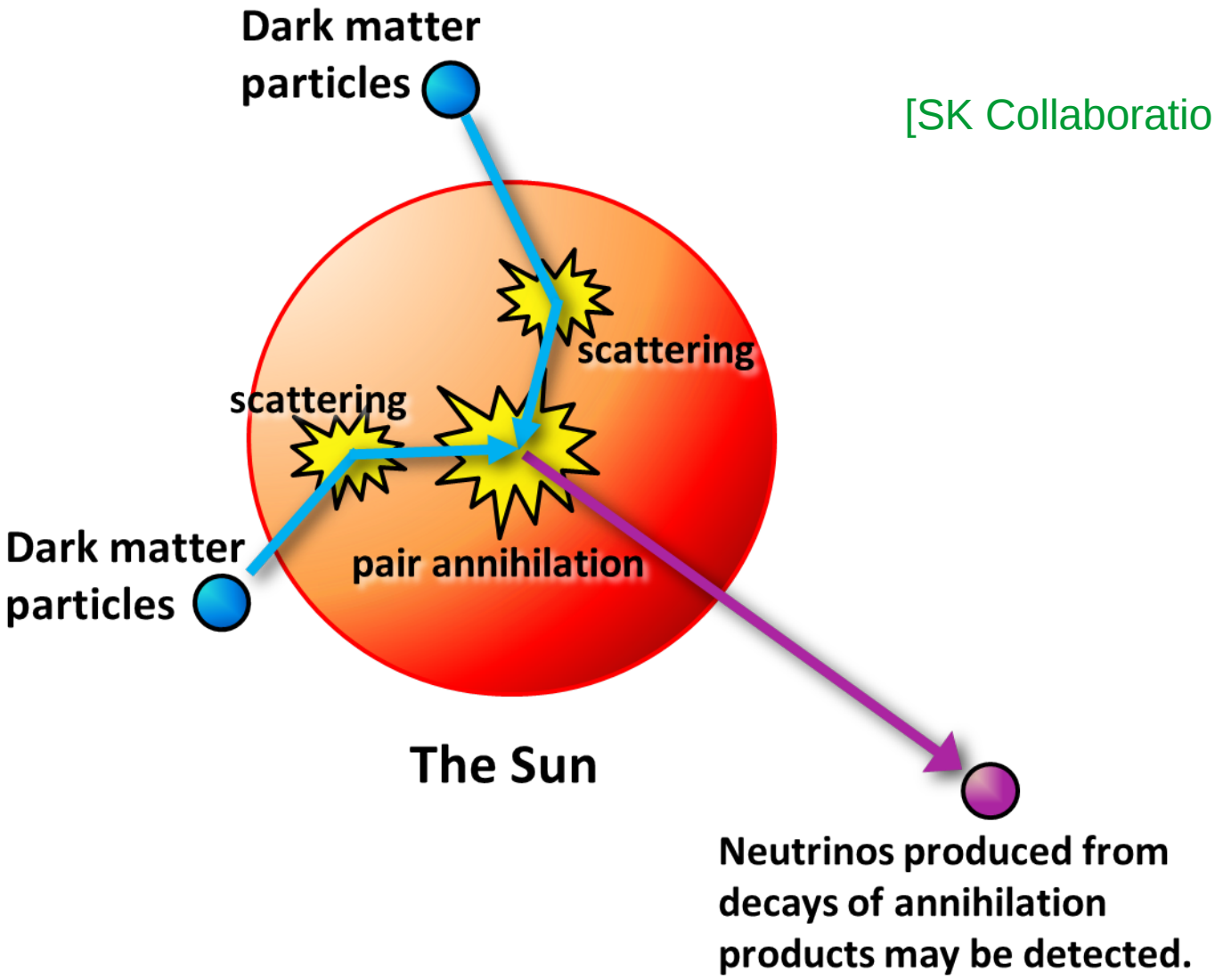
- Sensitive to $\langle \sigma v_{\mathrm{r}} \rangle$

[C. Boehm, AO, S. Palomares-Ruiz, S. Pascoli, work in progress, S. Palomares-Ruiz, et. al., arXiv: hep-ph/0710.5420]

Neutrinos from the Sun



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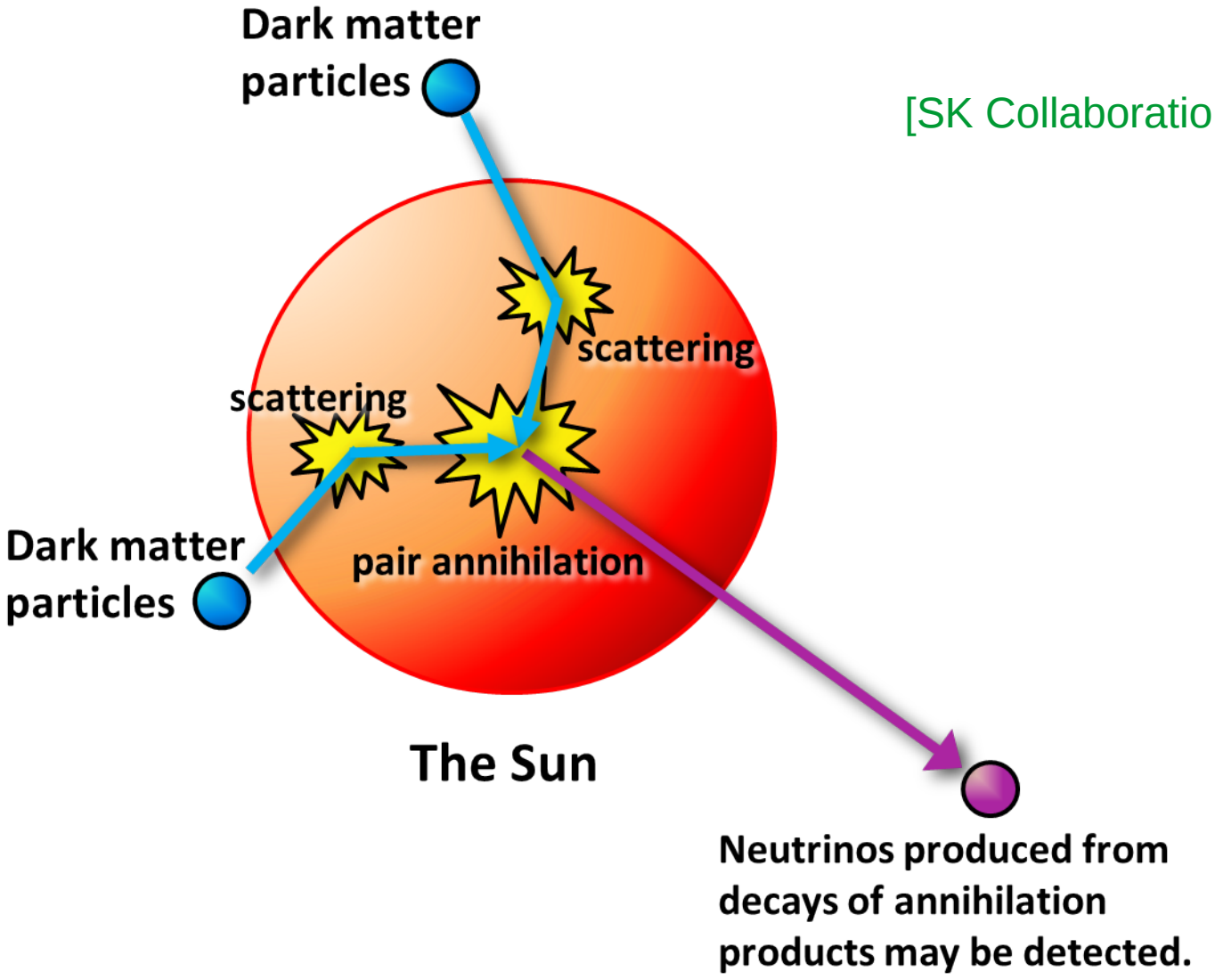


- Assume equilibrium → Capture = Annihilation

Low Energy Neutrinos from the Sun

- Looking at DM annihilation into light quarks and leptons

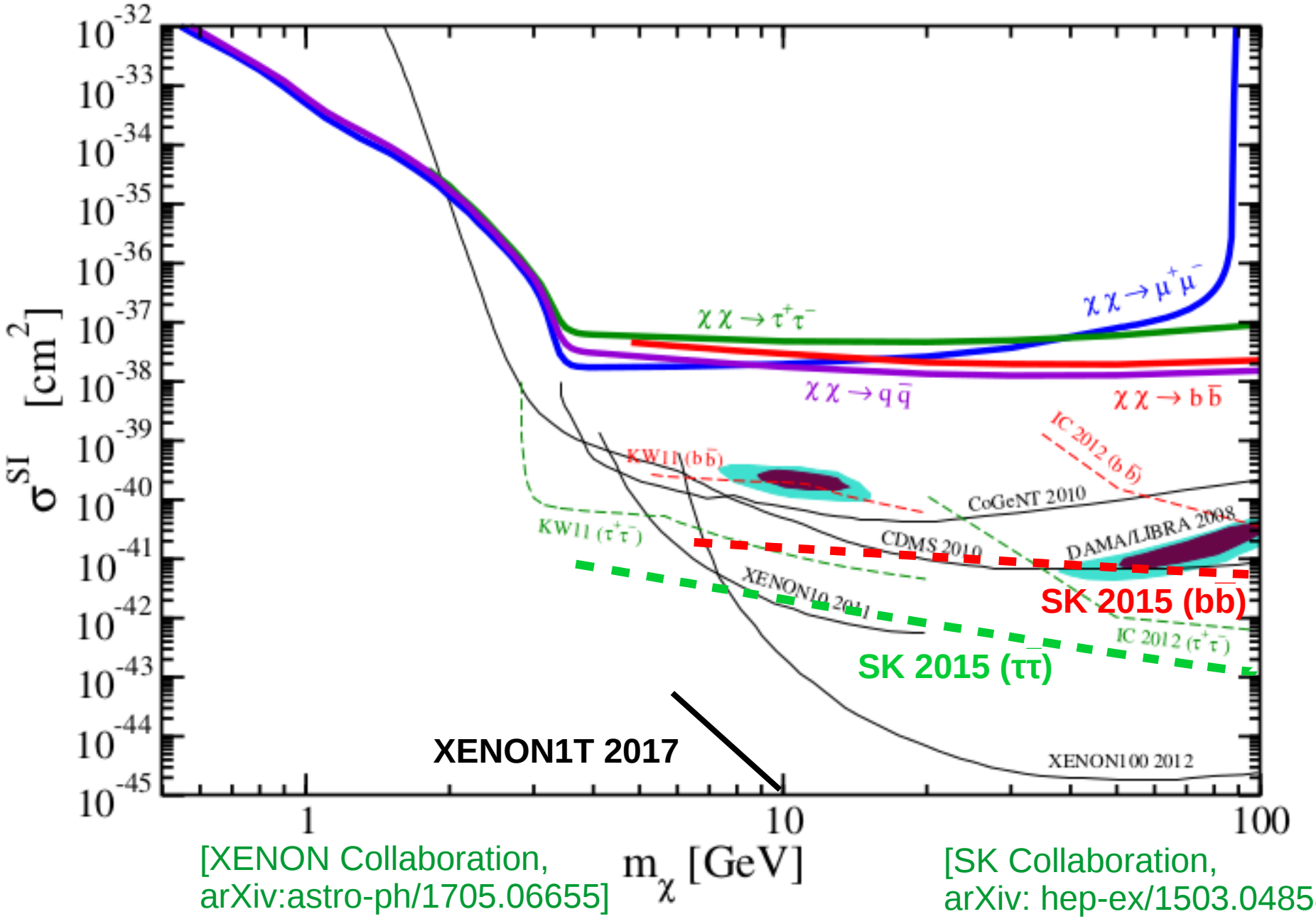
Low Energy Neutrinos from the Sun

- Looking at DM annihilation into light quarks and leptons

- Allows for complementary information on DM-nucleon cross section for annihilation to extra channels

Results (I)

[N. Bernal, et al., arXiv: hep-ph/1208.0834]



[XENON Collaboration, arXiv:astro-ph/1705.06655]

[SK Collaboration, arXiv: hep-ex/1503.04858]

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Link to particle physics

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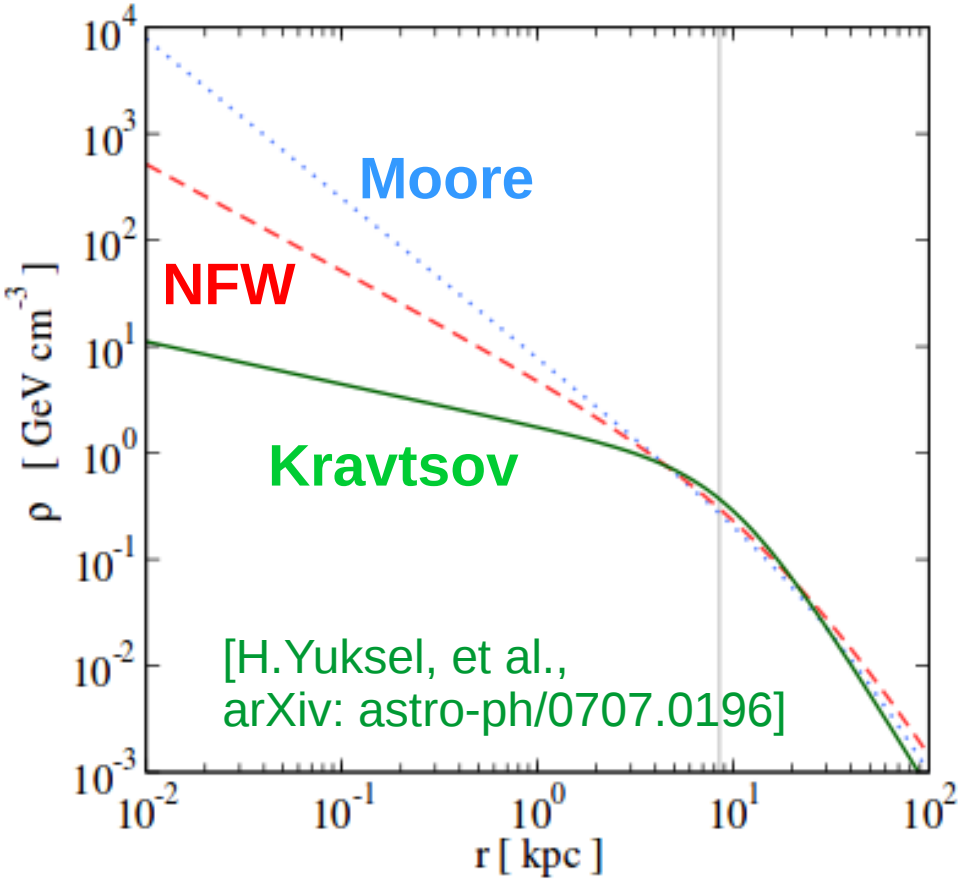

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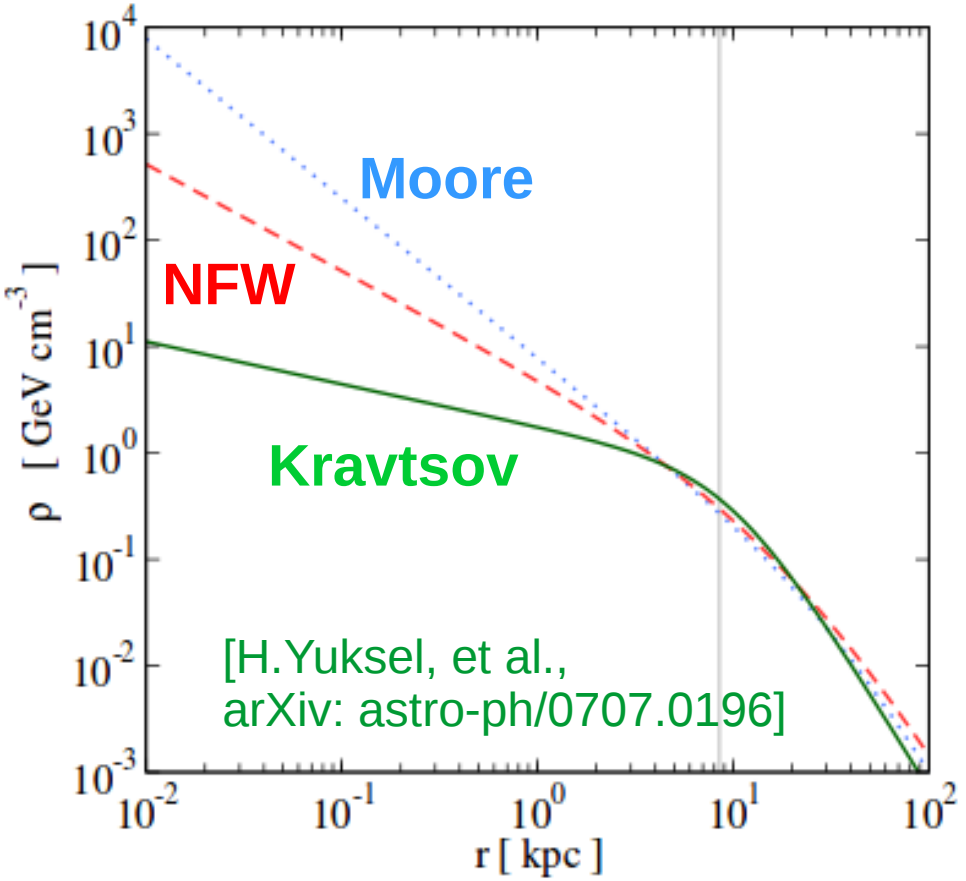
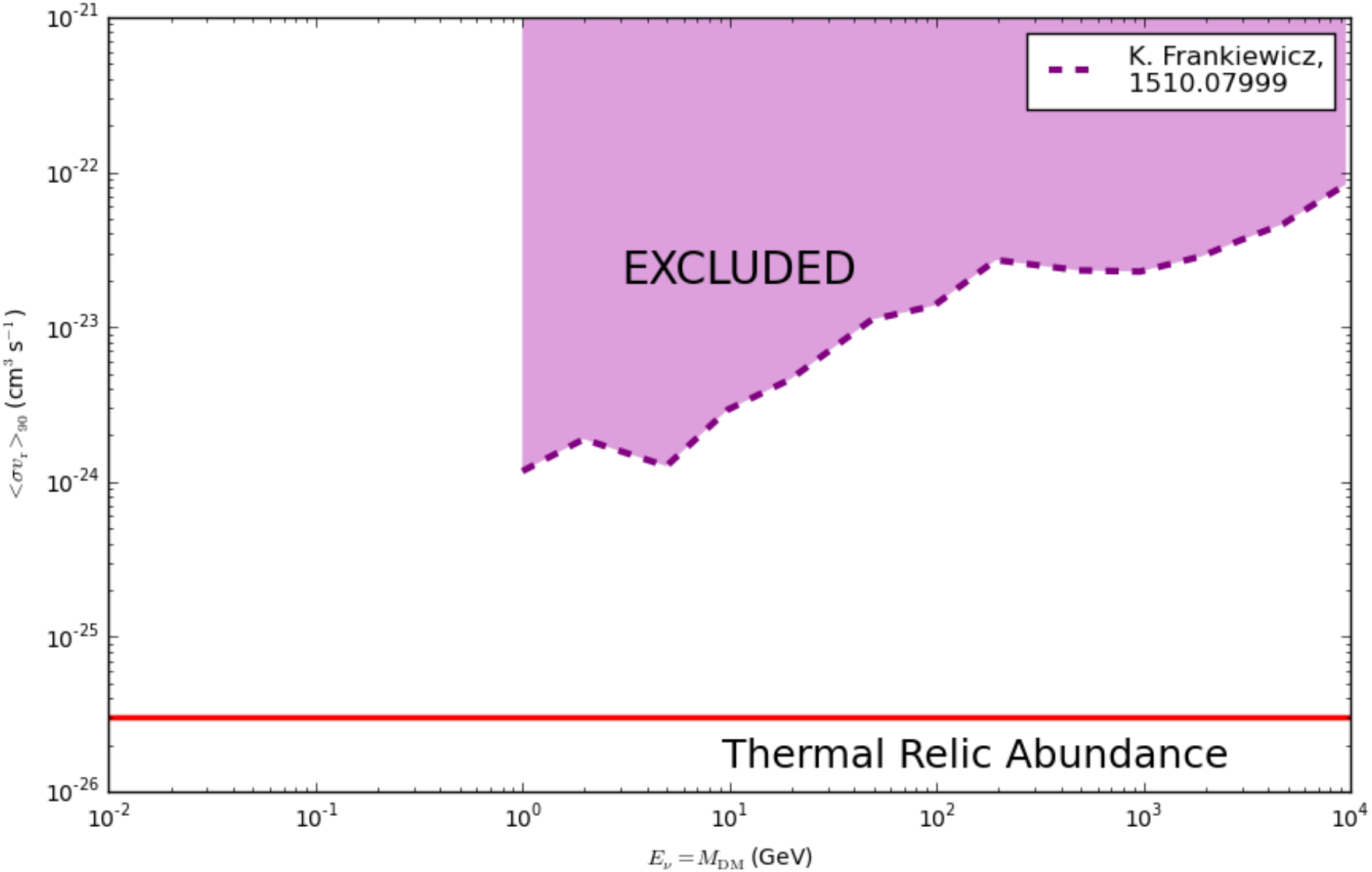
Halo dependence → Large uncertainties

- When averaging over the whole sky, small differences so we use reference value

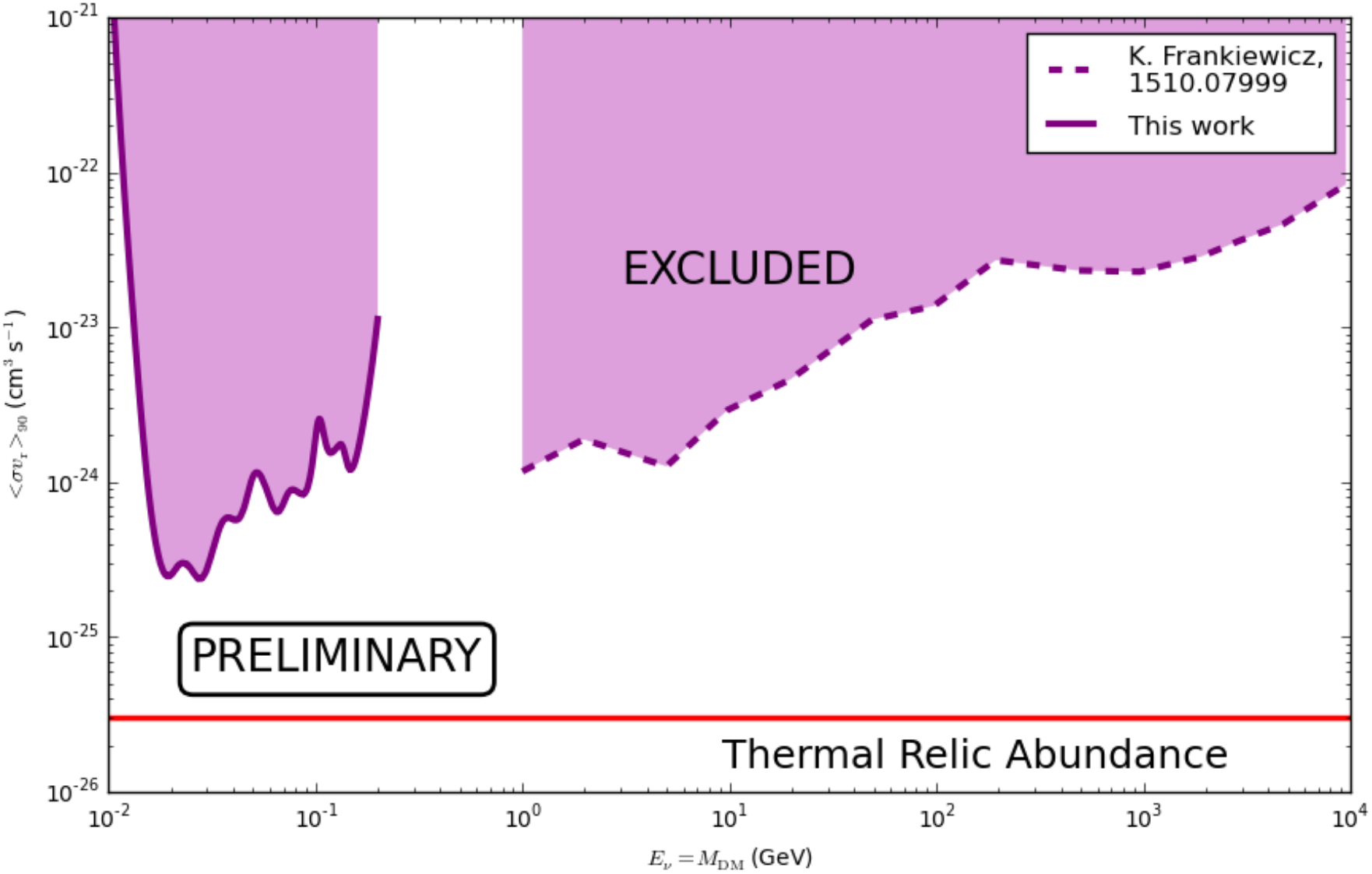
$$\mathcal{J}_{\rm avg} = 5$$



Results (II)


K. Frankiewicz,
1510.07999
EXCLUDED
Thermal Relic Abundance
$<\sigma v_r>_{90}$ (cm^3 s^{-1})
$E_\nu = M_{\rm DM}$ (GeV)
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

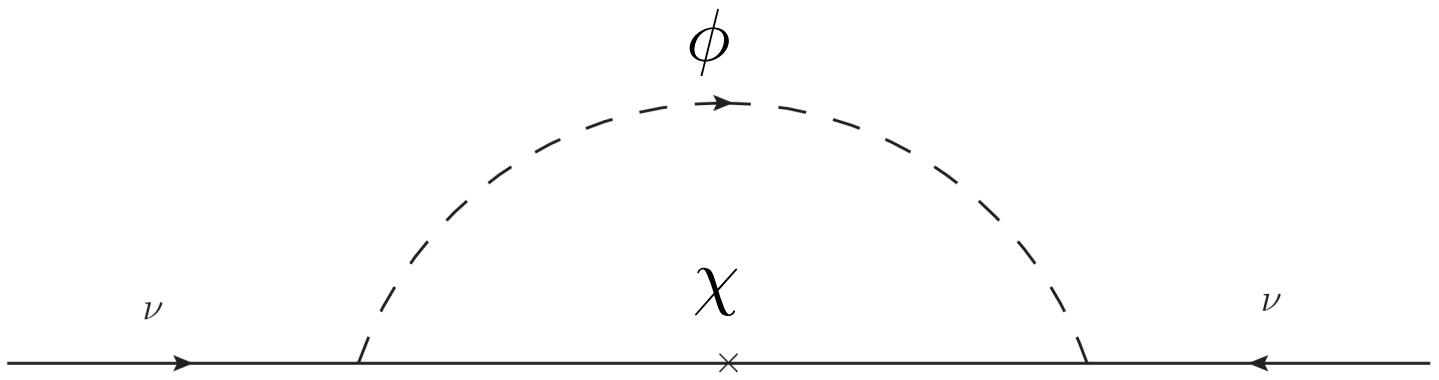
Results (II)



[Updated version of
arXiv: hep-ph/0710.5420]

Low DM Masses

- Several models in the literature [C. Boehm, et. al., arXiv: 0612228, E. Ma,et. al., arXiv:1512.08796 ...]



Complementarity

$$\mathcal{L}_{\rm int} \supset -\sum_{\alpha} g_\alpha \bar{\chi}_R \, \phi \cdot L_\alpha \; + \; {\rm h.c.}$$

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[C. Boehm, AO, S. Palomares-Ruiz, S. Pascoli, work in progress]

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$$\langle \sigma v_{\rm r} \rangle = \frac{g^4}{32\pi} \frac{m_{\rm DM}^2}{(m_{\rm DM}^2 \; + \; m_\phi^2)^2}$$

[C. Boehm, AO, S. Palomares-Ruiz, S. Pascoli, work in progress]

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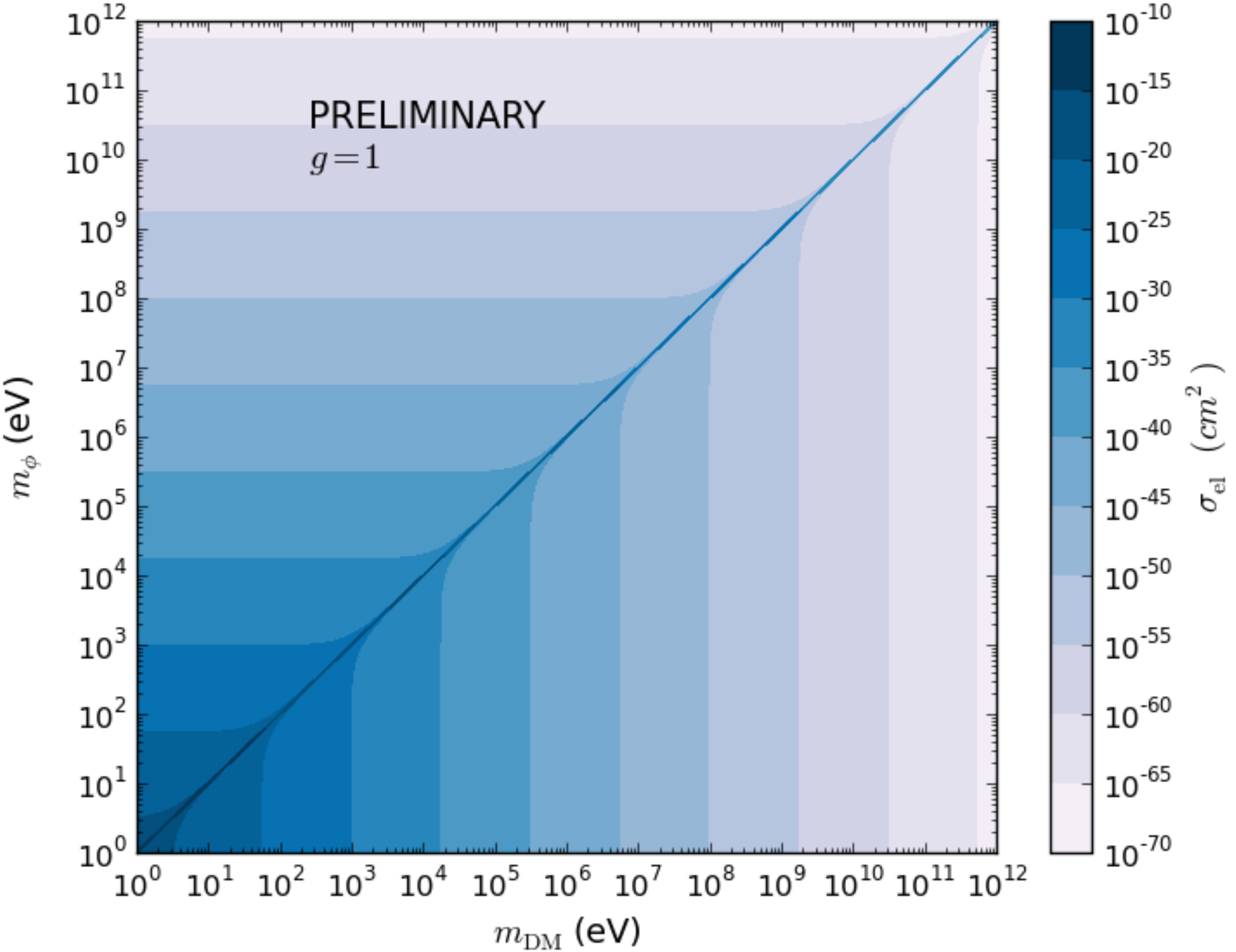
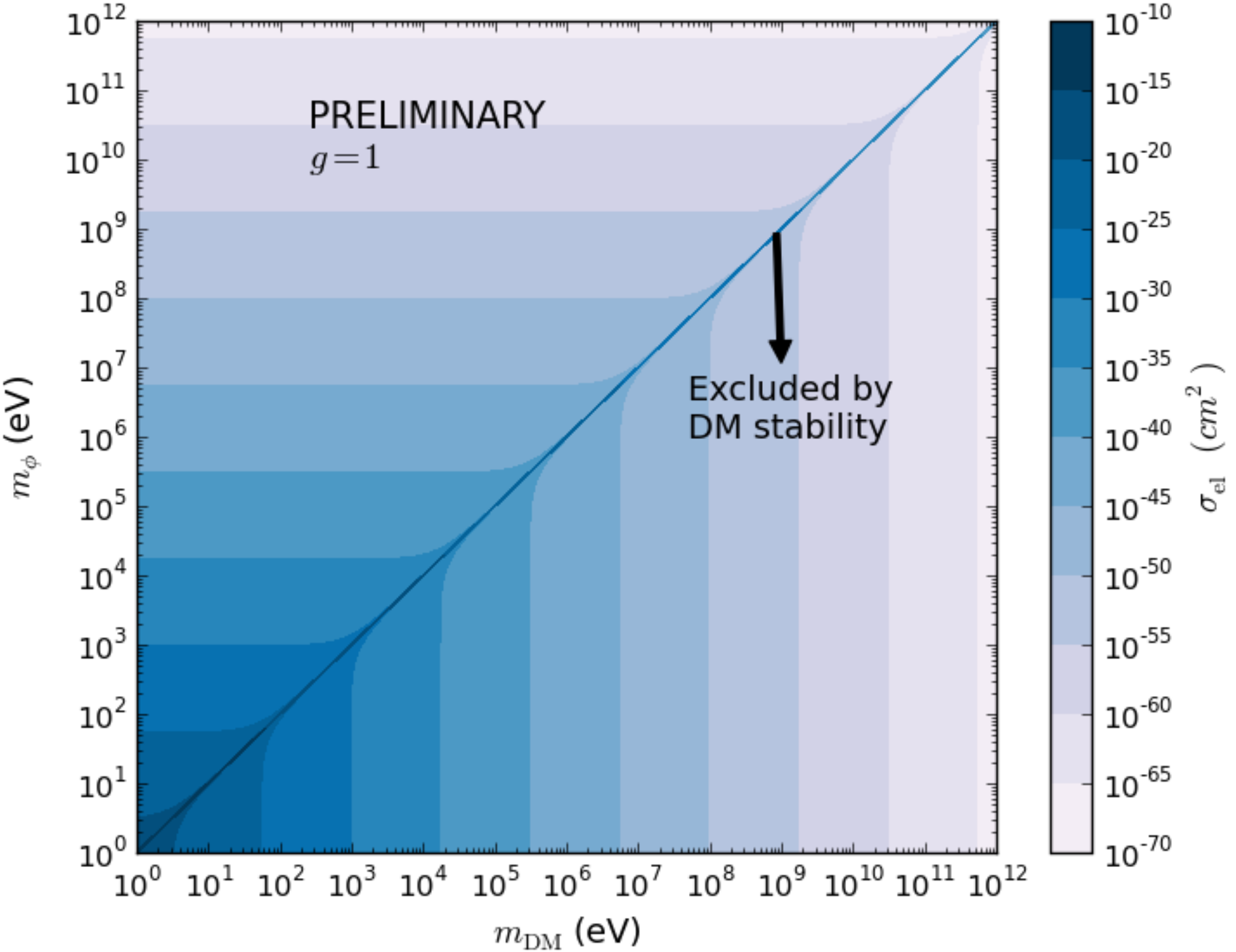
[C. Boehm, AO, S. Palomares-Ruiz, S. Pascoli, work in progress]

$$E_\nu \sim 2.35 \; \times \; 10^{-4} \; {\rm eV} \ll {\rm m_{DM}, m_\phi}$$

$$\sigma_{\rm el} = \frac{g^4}{8\pi} \frac{E_\nu^2}{(m_\phi^2 \; - \; m_{\rm DM}^2)^2}$$


PRELIMINARY
$g=1$
m_ϕ (eV)
$m_{\rm DM}$ (eV)
$\sigma_{\rm el}$ (cm^2)
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
10^{-35}
10^{-40}
10^{-45}
10^{-50}
10^{-55}
10^{-60}
10^{-65}
10^{-70}


PRELIMINARY
$g=1$
Excluded by
DM stability
m_ϕ (eV)
$m_{\rm DM}$ (eV)
$\sigma_{\rm el}$ (cm^2)
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
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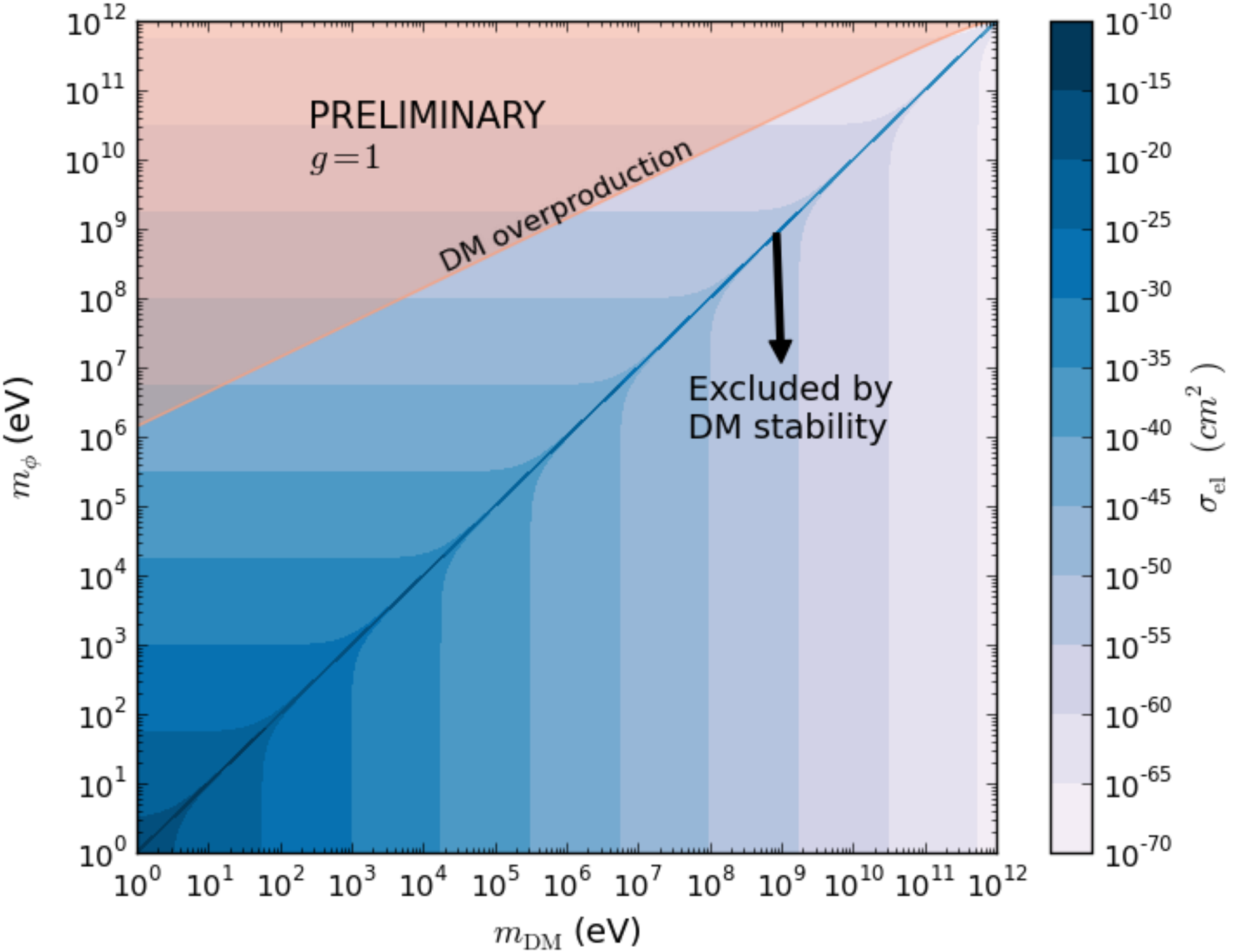
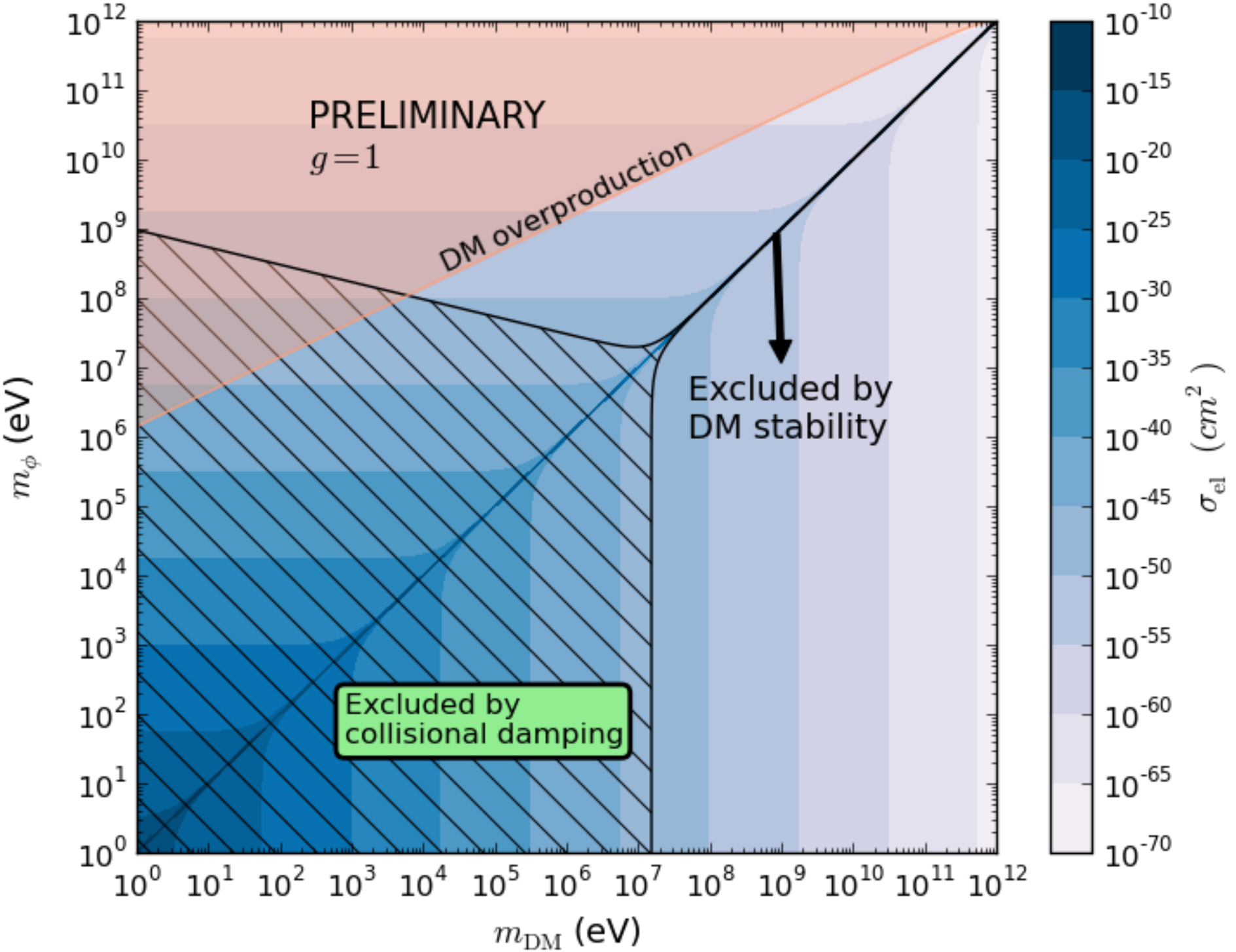

PRELIMINARY
$g=1$
DM overproduction
Excluded by
DM stability
m_ϕ (eV)
$m_{\rm DM}$ (eV)
$\sigma_{\rm el}$ (cm^2)
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
10^{-35}
10^{-40}
10^{-45}
10^{-50}
10^{-55}
10^{-60}
10^{-65}
10^{-70}


PRELIMINARY
$g=1$
DM overproduction
Excluded by
DM stability
Excluded by
collisional damping
m_ϕ (eV)
$m_{\rm DM}$ (eV)
$\sigma_{\rm el}$ (cm^2)
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7} 10^{8} 10^{9} 10^{10} 10^{11} 10^{12}
10^{-10}
10^{-15}
10^{-20}
10^{-25}
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10^{-55}
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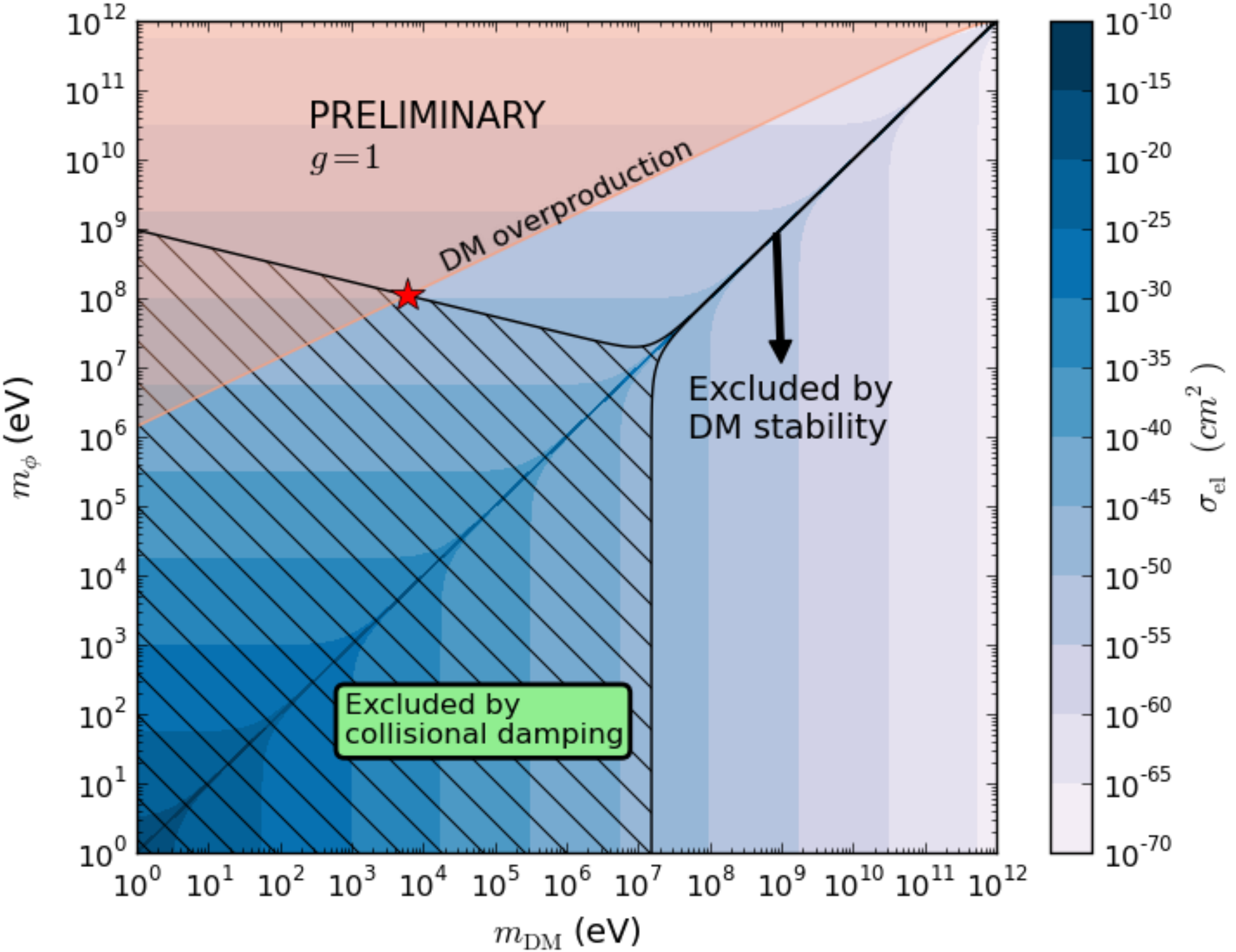
10^{-70}


PRELIMINARY
$g=1$
DM overproduction
Excluded by
DM stability
Excluded by
collisional damping
m_ϕ (eV)
$m_{\rm DM}$ (eV)
$\sigma_{\rm el}$ (cm^2)
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-10}
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10^{-20}
10^{-25}
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10^{-40}
10^{-45}
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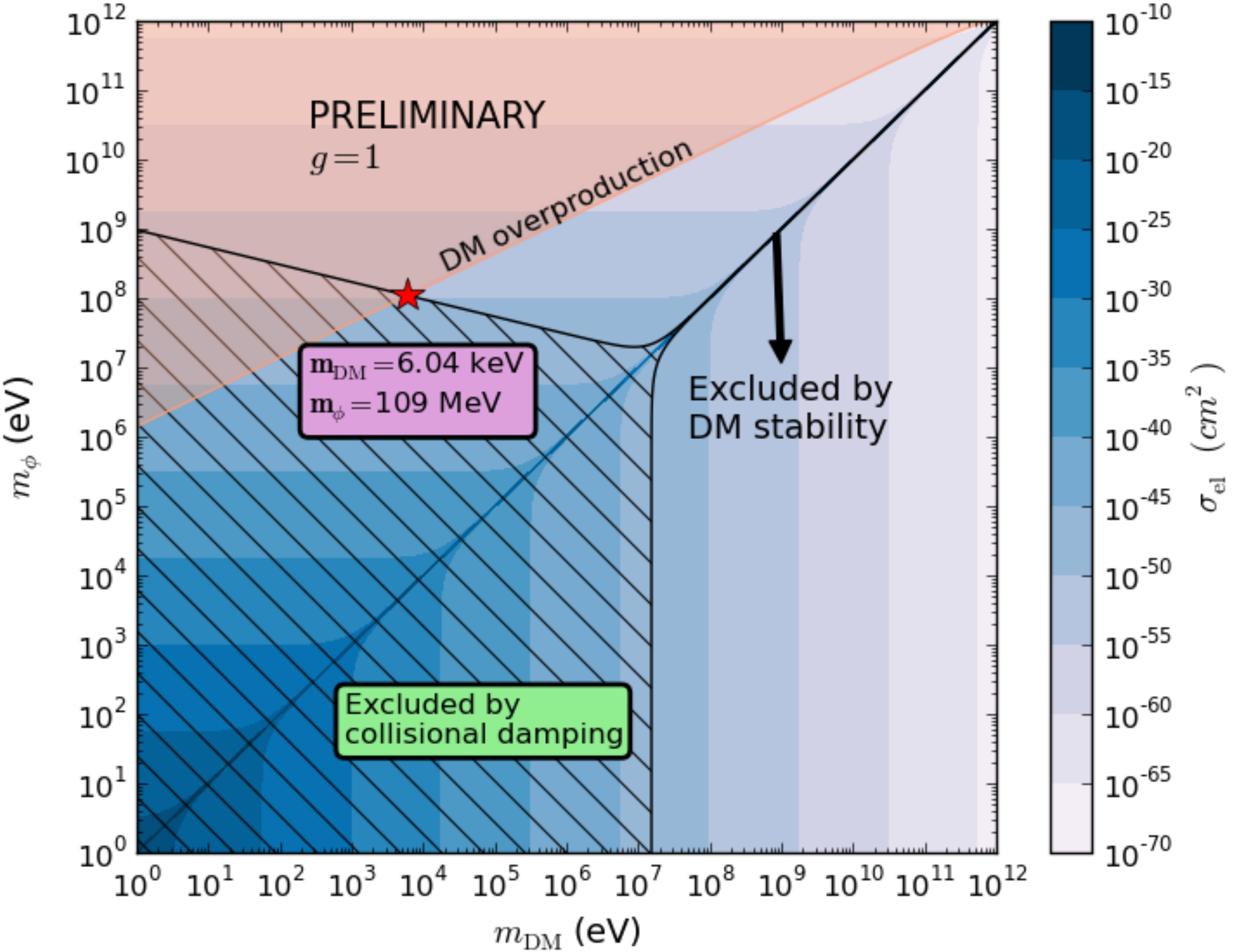
PRELIMINARY
$g=1$
DM overproduction
$\mathbf{m}_{\mathrm{DM}}=6.04$ keV
$\mathbf{m}_{\phi}=109$ MeV
Excluded by
DM stability
Excluded by
collisional damping
m_{ϕ} (eV)
m_{DM} (eV)
σ_{el} (cm^2)
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-10}
10^{-15}
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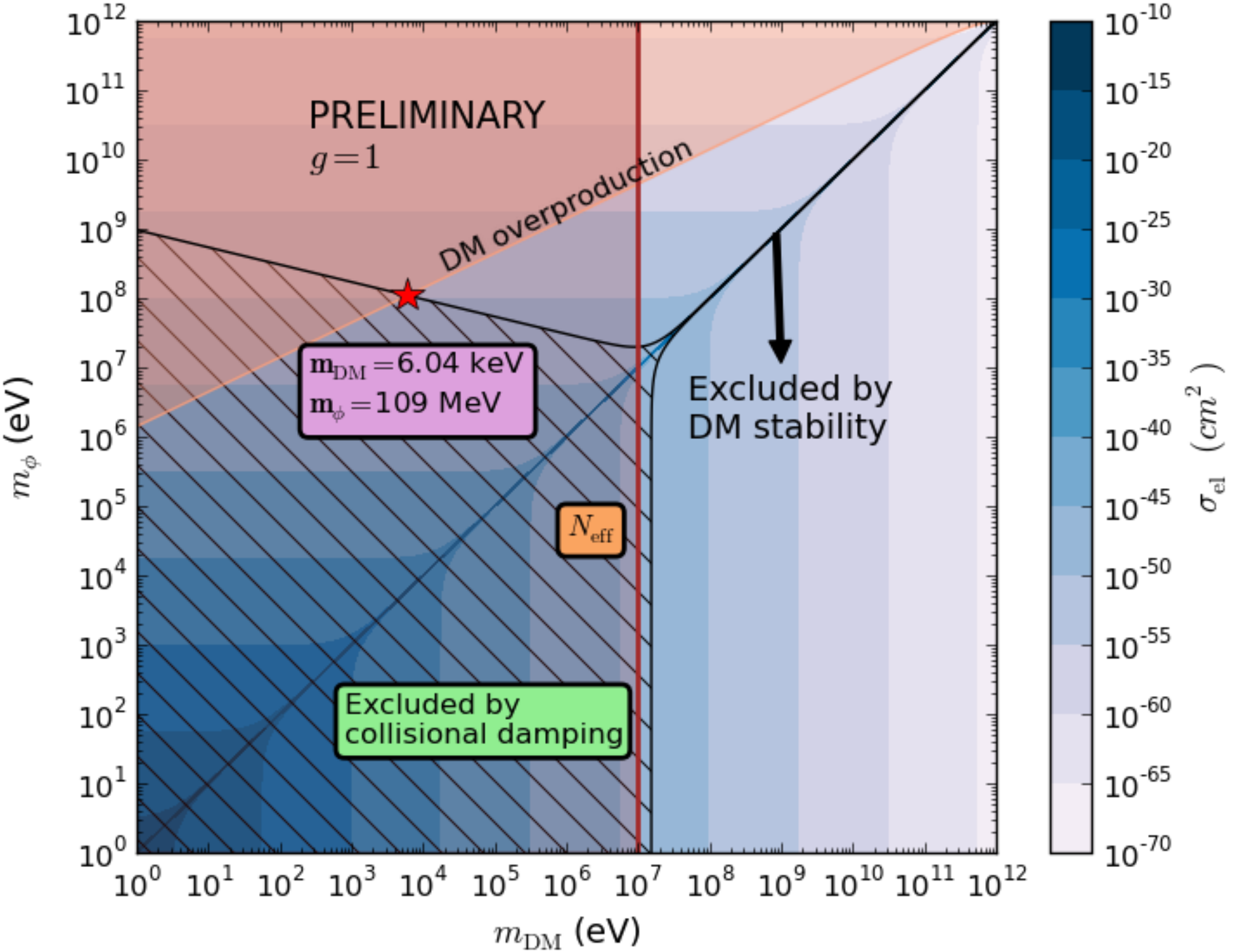
PRELIMINARY
$g=1$
DM overproduction
$\mathbf{m}_{\mathrm{DM}}=6.04$ keV
$\mathbf{m}_{\phi}=109$ MeV
Excluded by
DM stability
N_{eff}
Excluded by
collisional damping
m_{ϕ} (eV)
m_{DM} (eV)
σ_{el} (cm^2)
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
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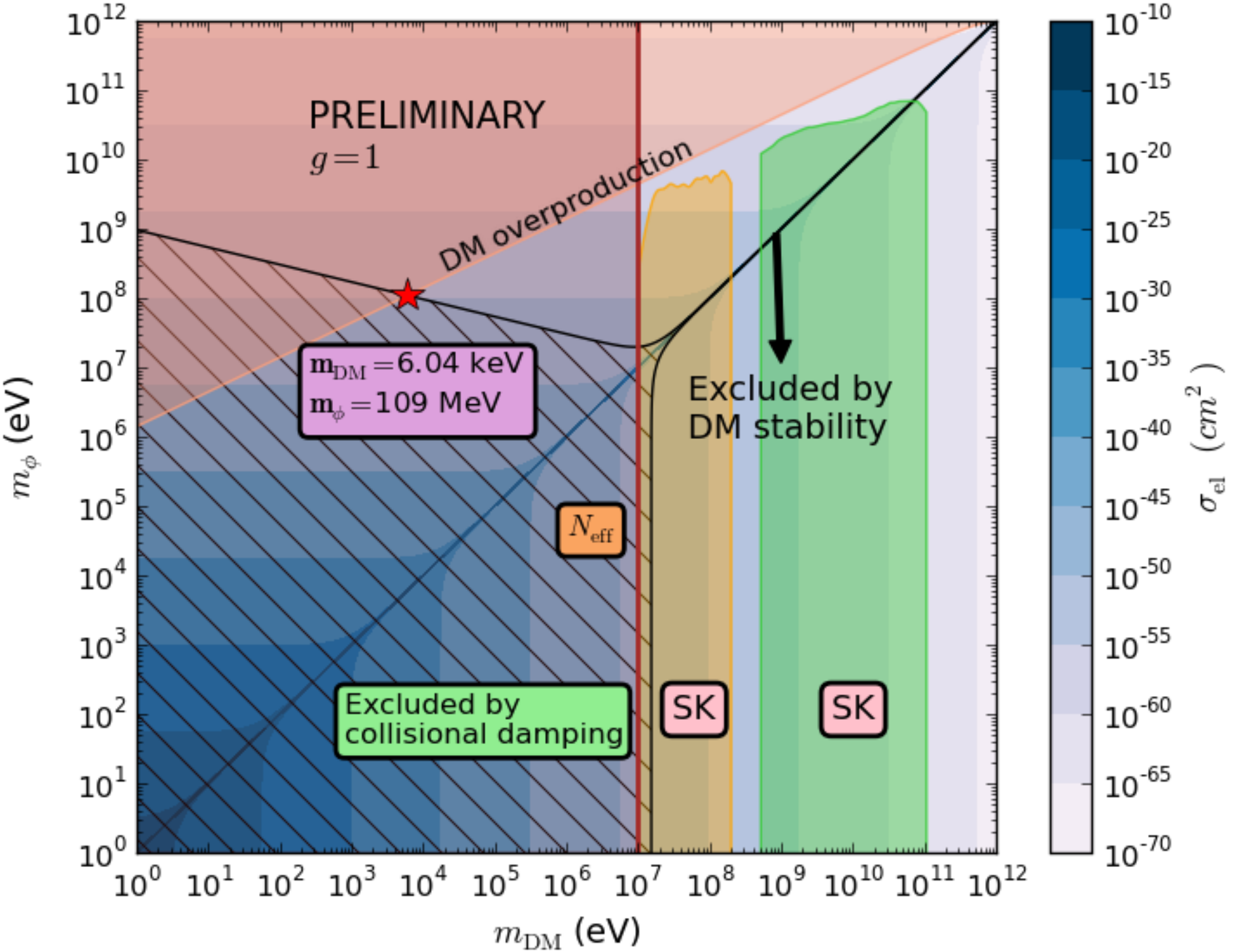
PRELIMINARY
$g=1$
DM overproduction
$\mathbf{m}_{\mathrm{DM}}=6.04$ keV
$\mathbf{m}_{\phi}=109$ MeV
Excluded by
DM stability
N_{eff}
Excluded by
collisional damping
SK
SK
m_{ϕ} (eV)
m_{DM} (eV)
σ_{el} (cm^2)
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
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10^{-65}
10^{-70}

Future

- New techniques? → Gd doping would reduce dominant background

Future

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- HyperK → More data

Future

- New techniques? → Gd doping would reduce dominant background
- HyperK → More data
- More sophisticated analysis

Conclusion

- Neutrinos can give us a lot of information about DM properties → Complementary is key!

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TAKE HOME MESSAGE

- The analysis of low energetic neutrinos at SK can:

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TAKE HOME MESSAGE

- The analysis of low energetic neutrinos at SK can:

  - Bound **DM-nucleon scattering** for **additional** annihilation channels

Conclusion

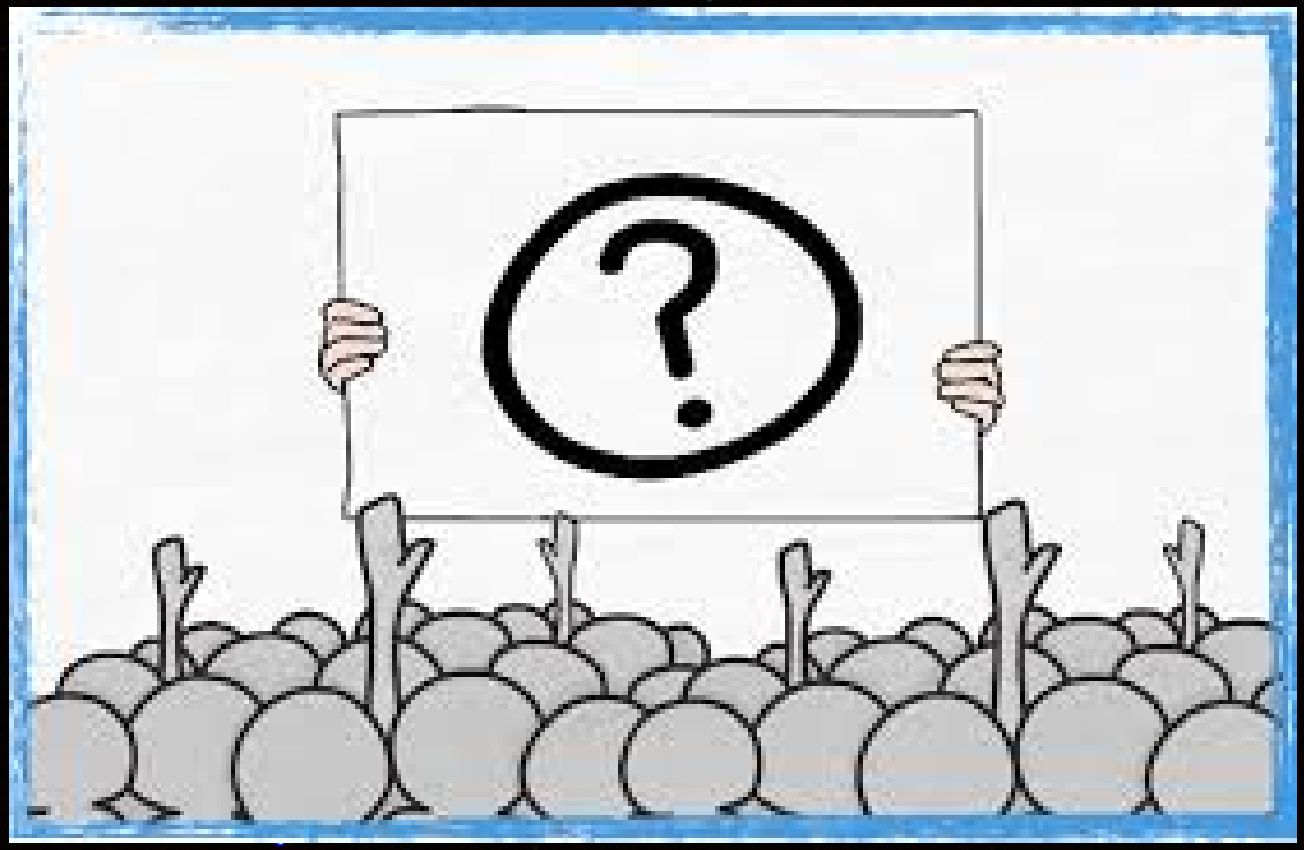
- Neutrinos can give us a lot of information about DM properties → Complementary is key!

TAKE HOME MESSAGE

- The analysis of low energetic neutrinos at SK can:

  - Bound **DM-nucleon scattering** for **additional** annihilation channels
  - Bound the **DM annihilation cross** section for **low** DM masses

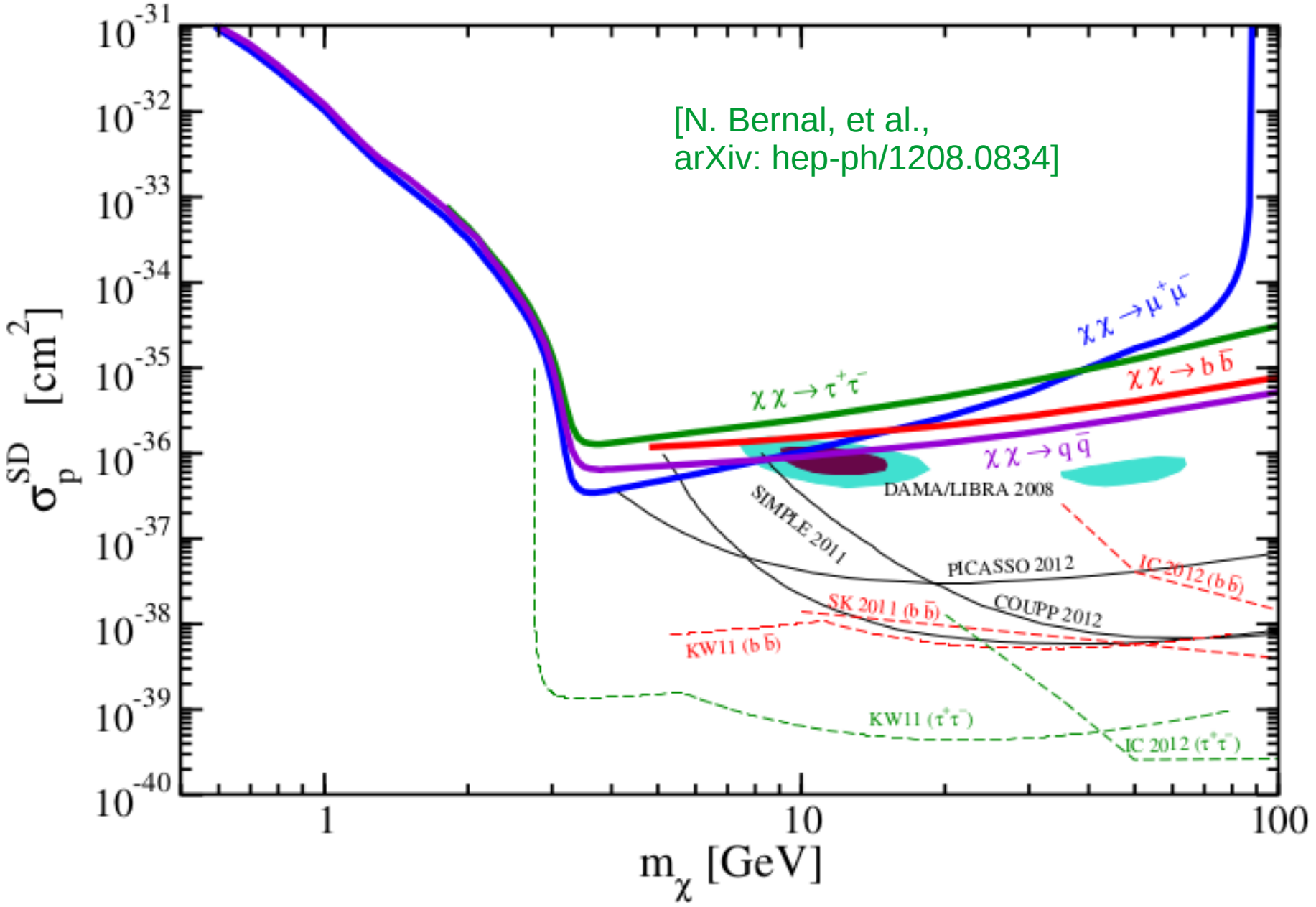
Thanks for listening



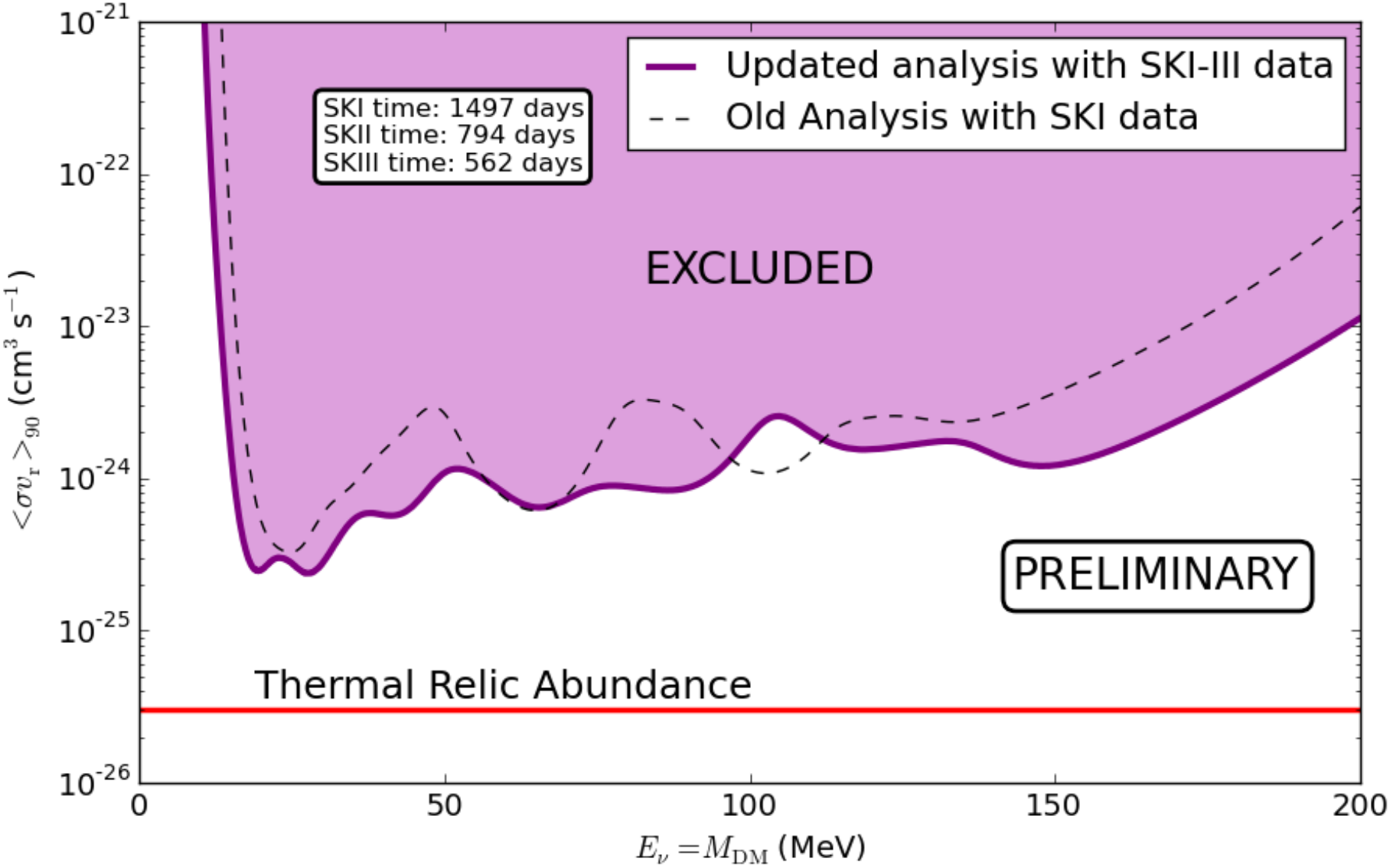
Questions?

Back Up Slides

Spin-Dependent Cross Section

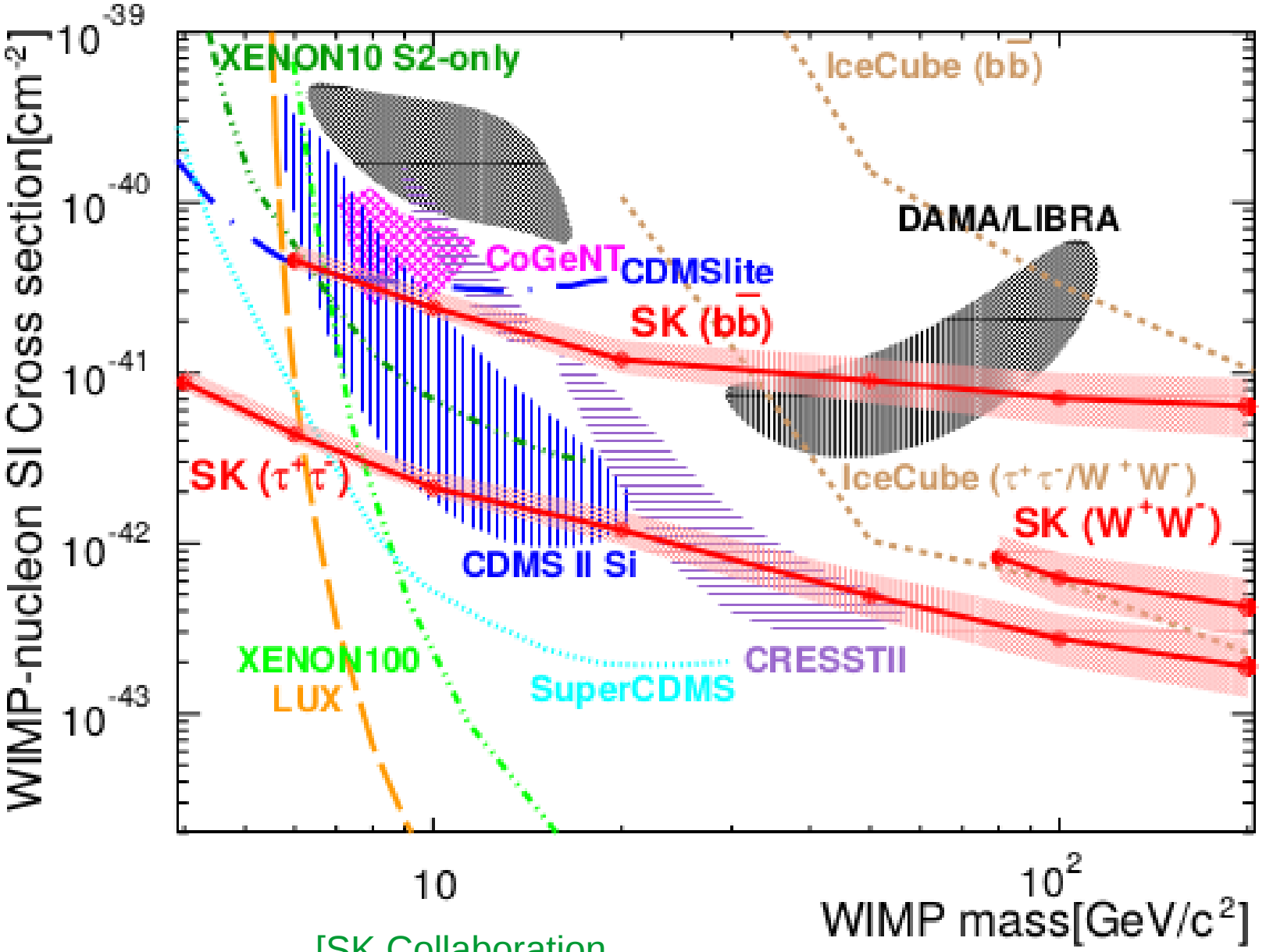


Milky Way Results Zoom



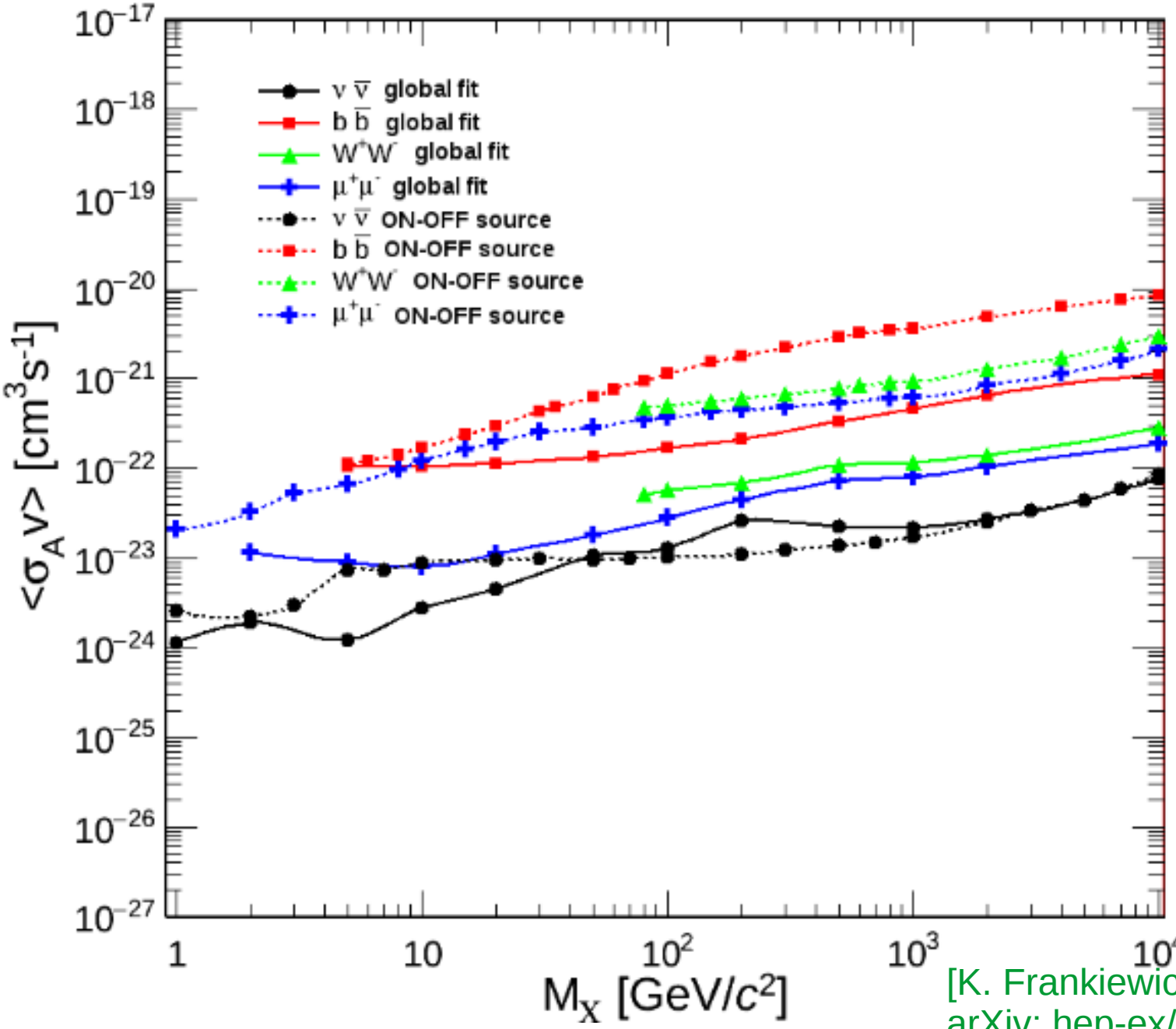
1497 days 794 days 562 days

Sun GeV Analysis



[SK Collaboration,
arXiv: hep-ex/1503.04858]

Galactic Centre GeV Analysis



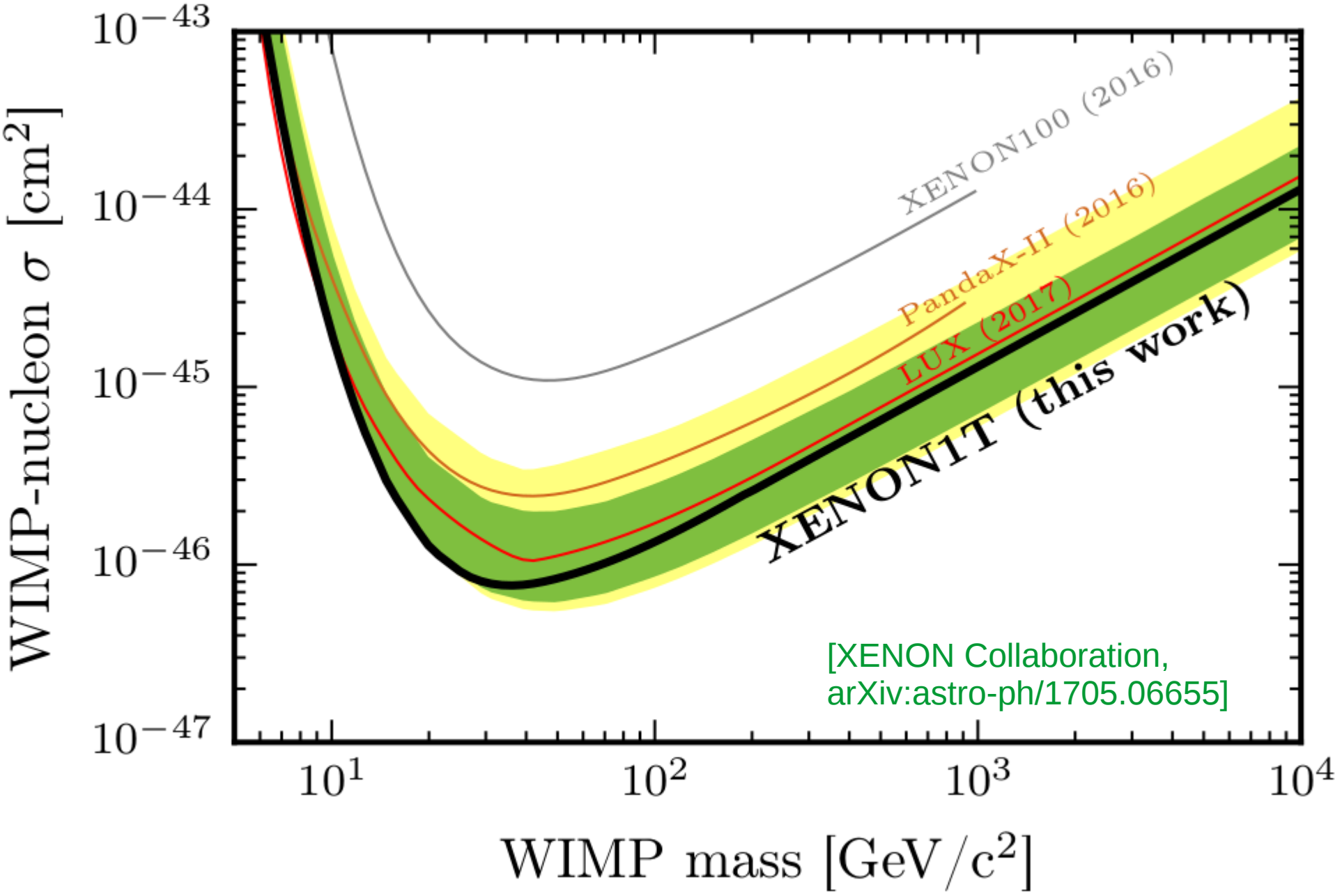
[K. Frankiewicz, arXiv: hep-ex/1510.07999]

Halo properties

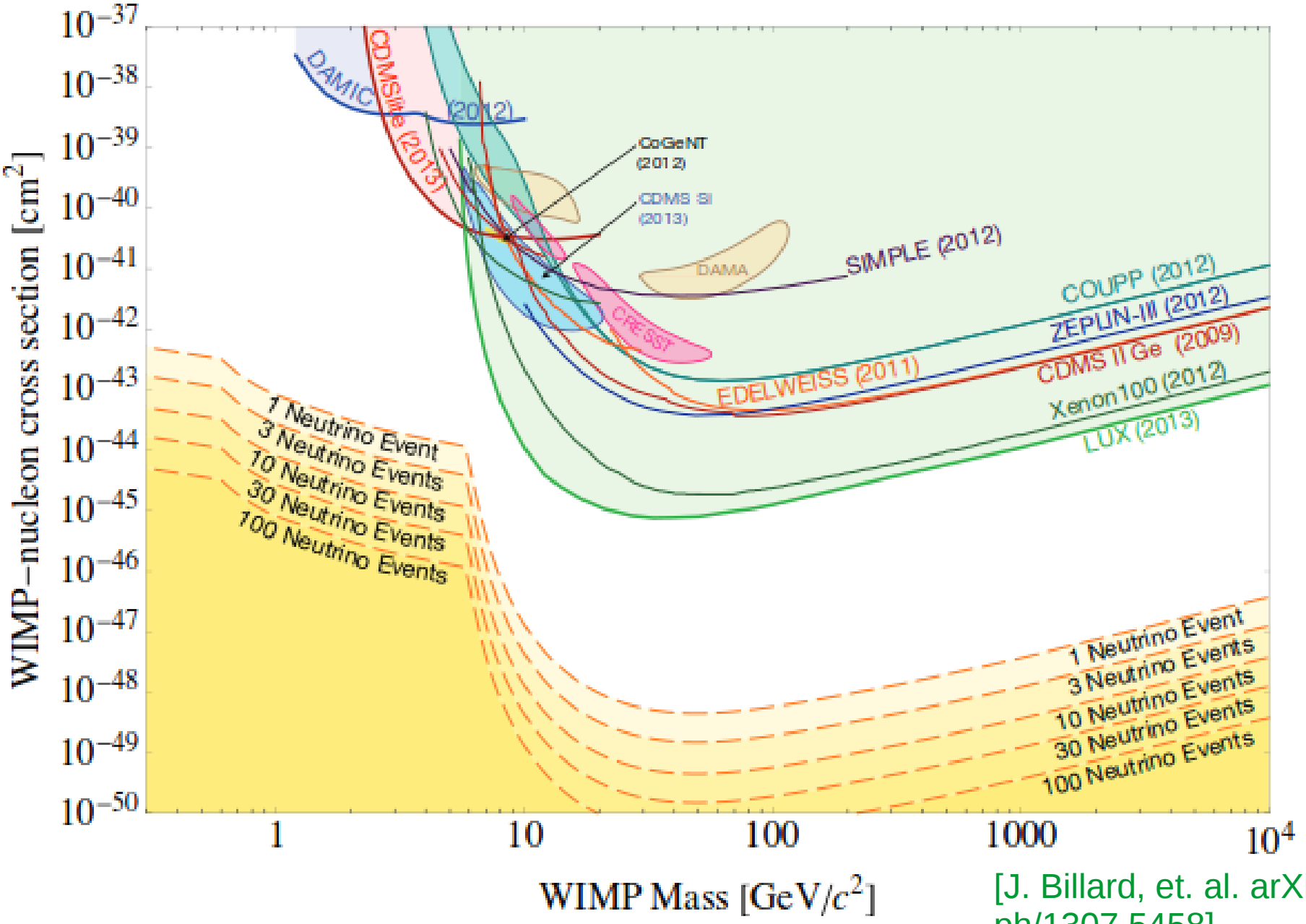
$$\mathcal{J}_{avg} = \frac{1}{2R_{sc}\,\rho_0^2} \int_{-1}^{1} \int_{0}^{l_{max}} \rho^2(r)\, dl\, d(\cos\psi),$$

where $r = \sqrt{R_{sc}^2 - 2lR_{sc}\cos\psi + l^2}$, $\rho_0 = 0.3\ \mathrm{GeV\ cm^{-3}}$ is a normalizing DM density, which is equal to the commonly quoted DM density at R_{sc}, and the upper limit of integration is $l_{max} = \sqrt{(R_{halo}^2 - \sin^2\psi R_{sc}^2)} + R_{sc}\cos\psi$

Direct Detection

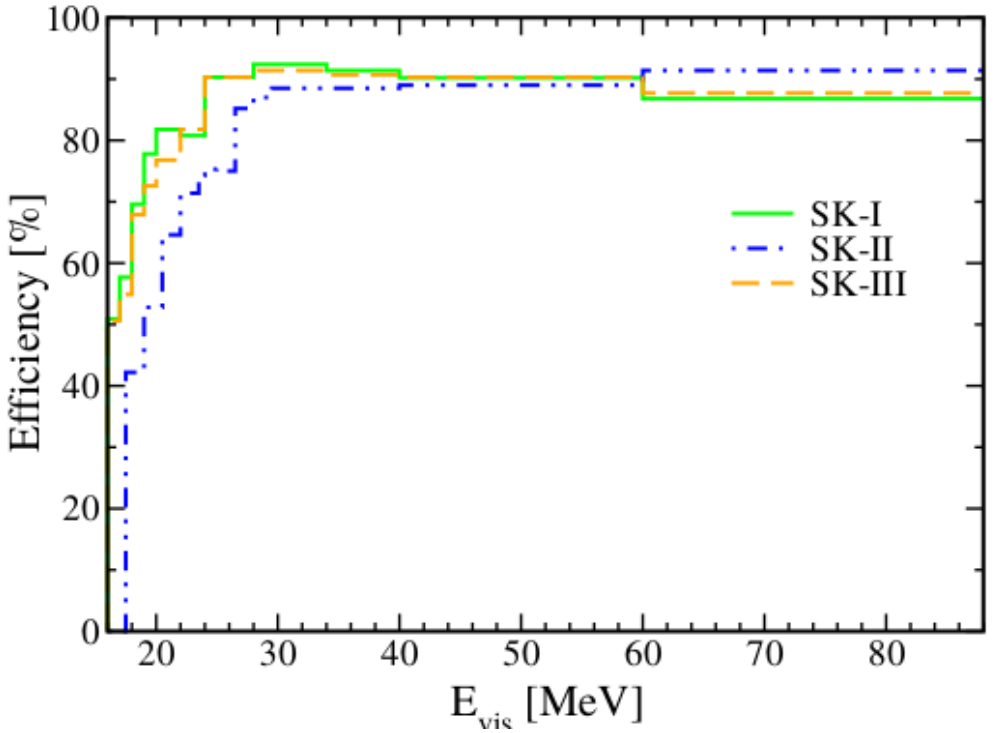


Direct Detection (II)



[J. Billard, et. al. arXiv:hep-ph/1307.5458]

Detector Properties



[N. Bernal, et al.,
arXiv: hep-ph/1208.0834]