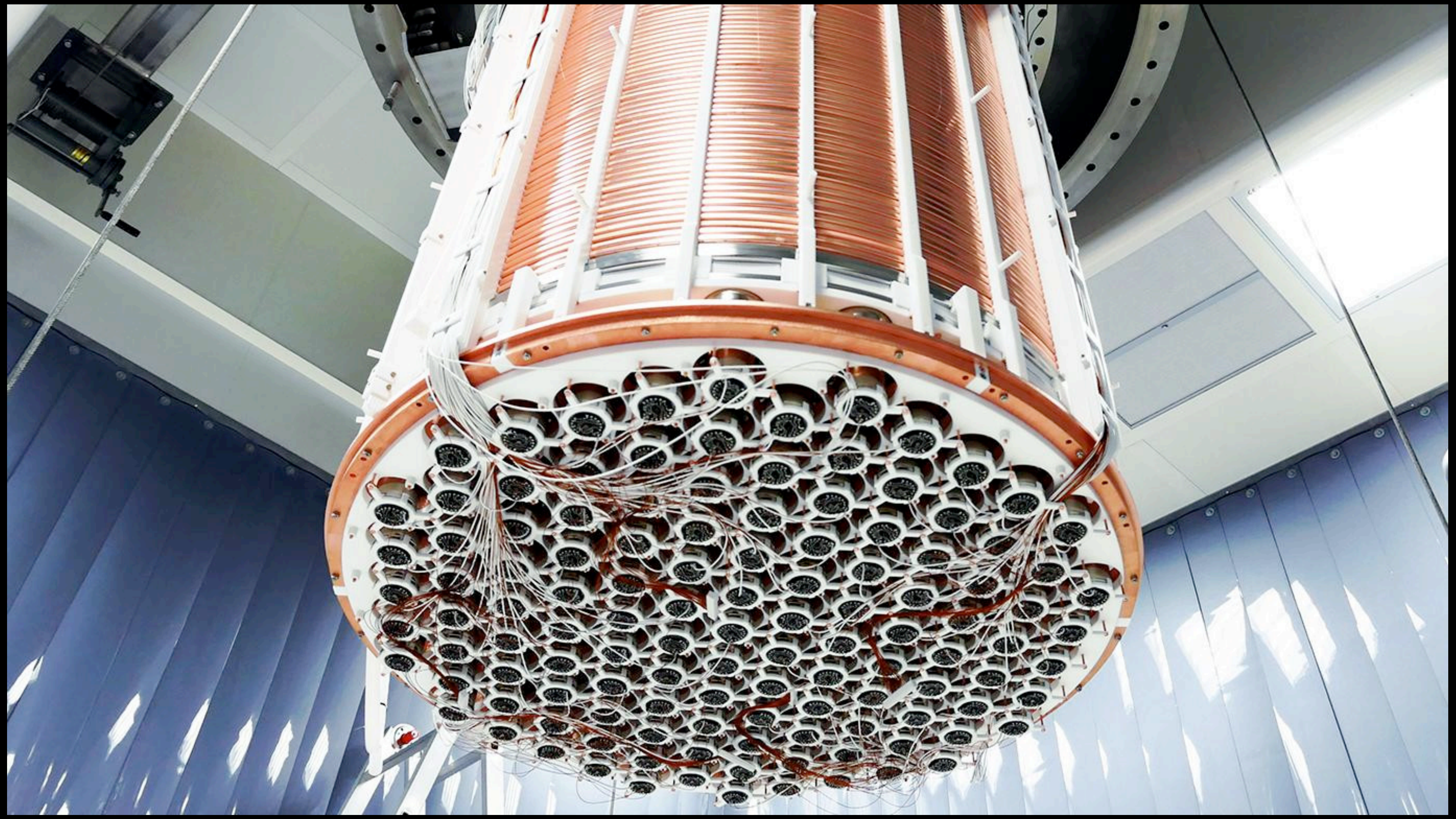
Celestial Bodies as Dark Matter Detectors

Tim Linden

Stockholms universitet

Celestial Bodies vs. Direct Detection

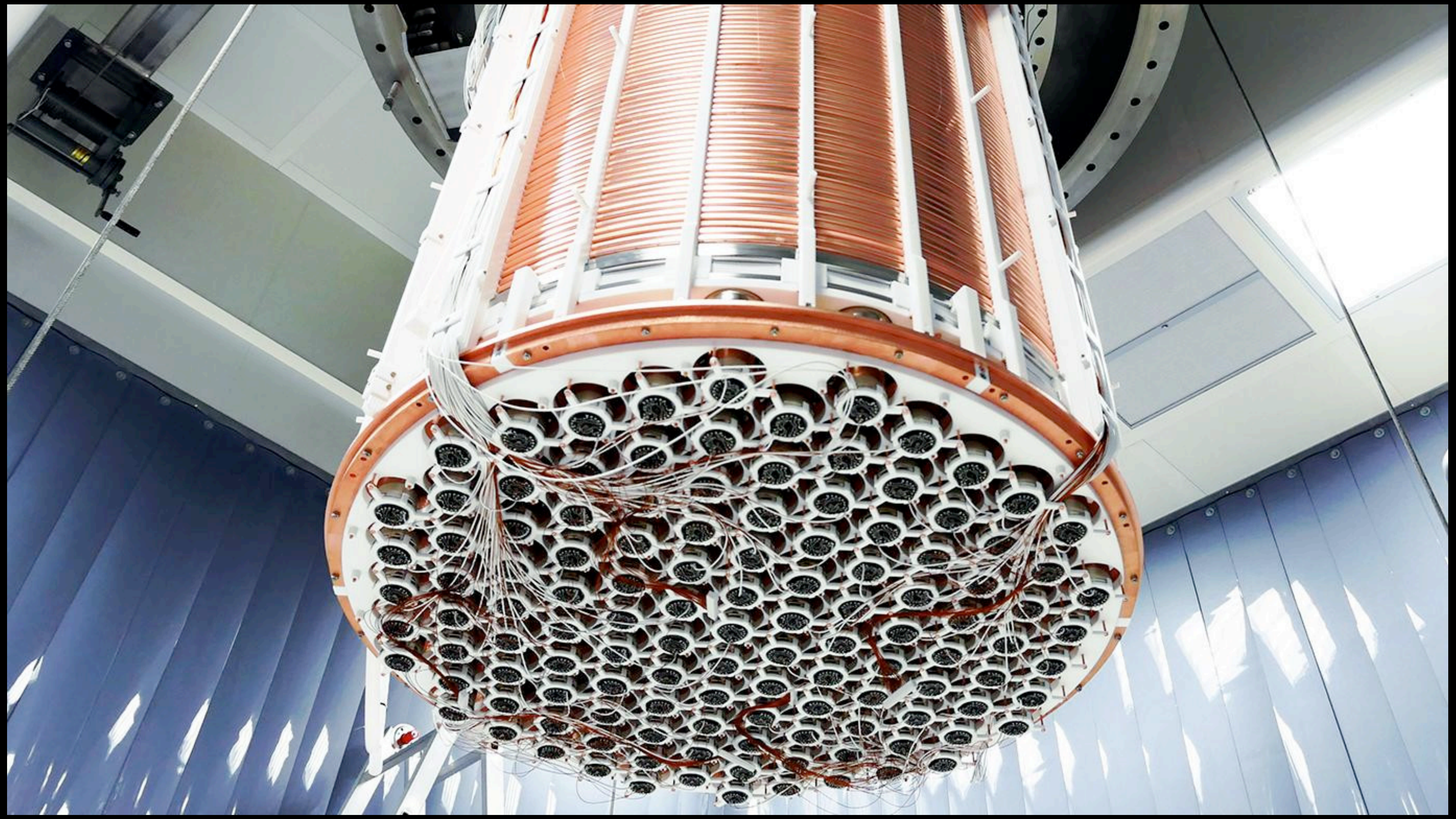


XENONnT

- **8600 kg**
- **1000 days**

8×10^6 kg day

Celestial Bodies vs. Direct Detection



XENONnT

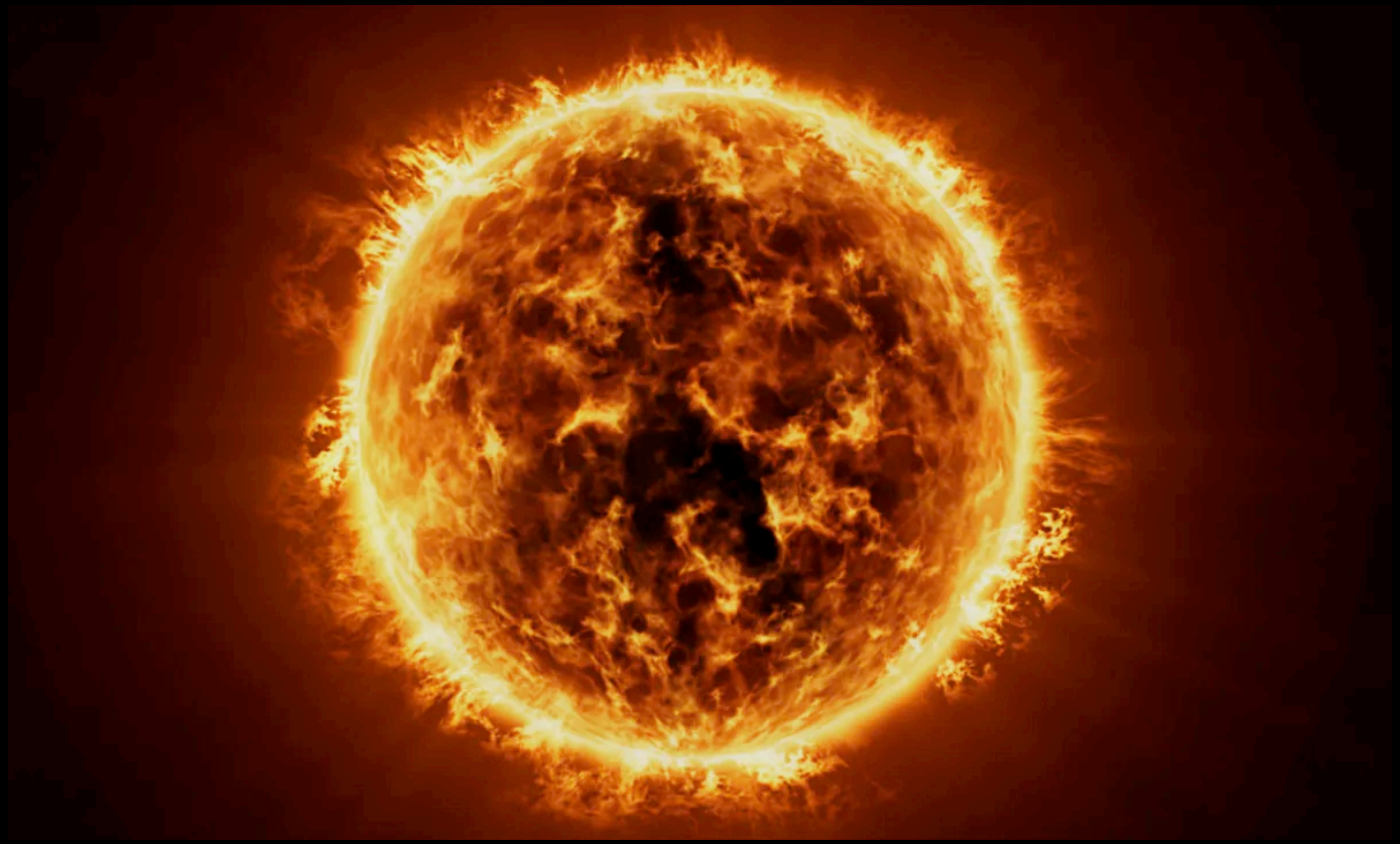
- 8600 kg
- 1000 days

8×10^{6} kg day

Sun

- 3×10^{30} kg
- 2×10^{10} days

6×10^{40} kg day



Celestial Bodies vs. Direct Detection

6×10^{40} kg day > 8×10^{6} kg day

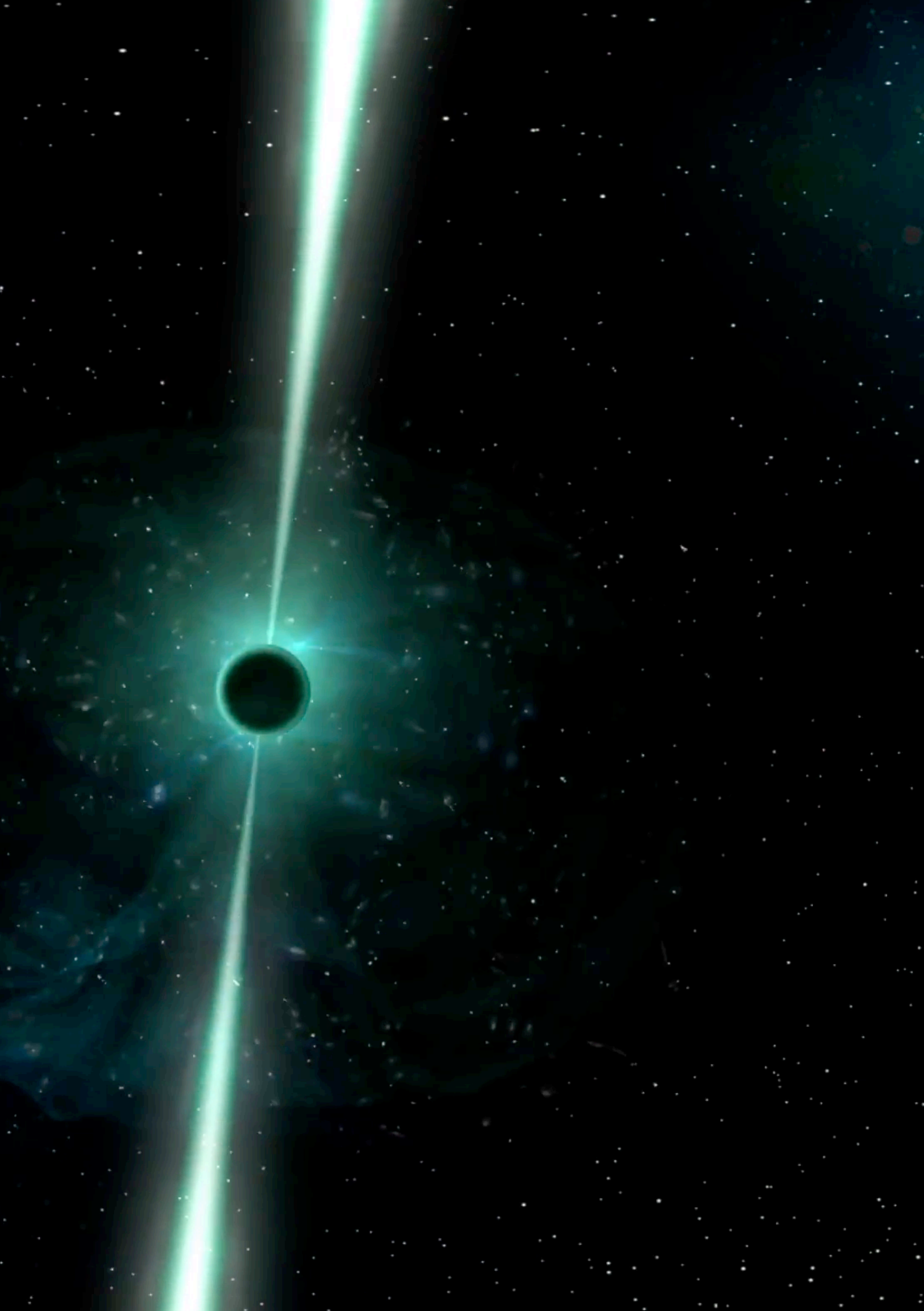
Precision Physics is Possible

- Neutron star spin among the best measured quantities in physics.

PSR J1713+0747

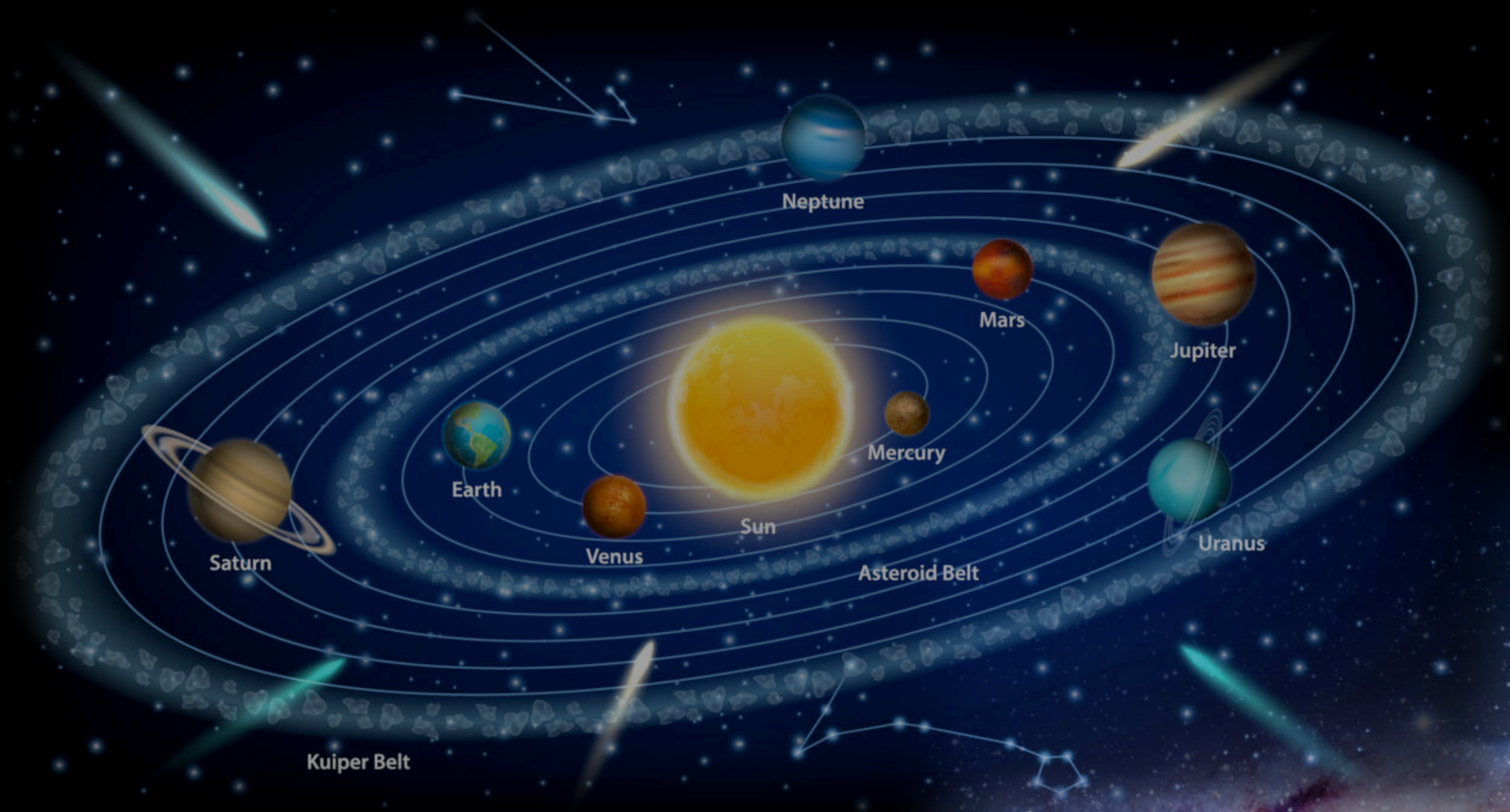
$F = 218.8118437960826270 \pm 0.0000000000000988\ s^{-1}$

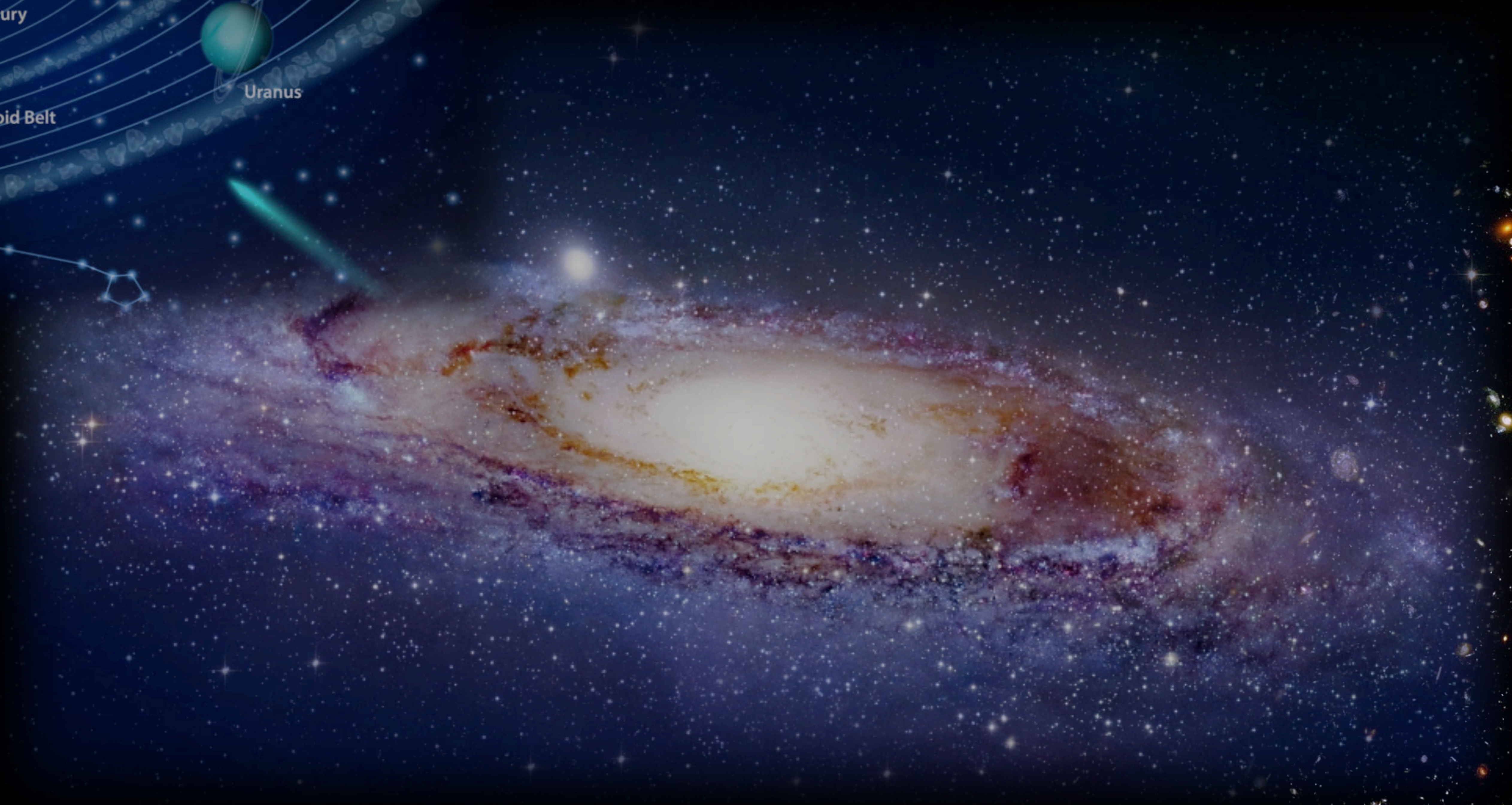
$F' = -4.083888637248 \pm 0.0000143324982645 \times 10^{-16}\ s$



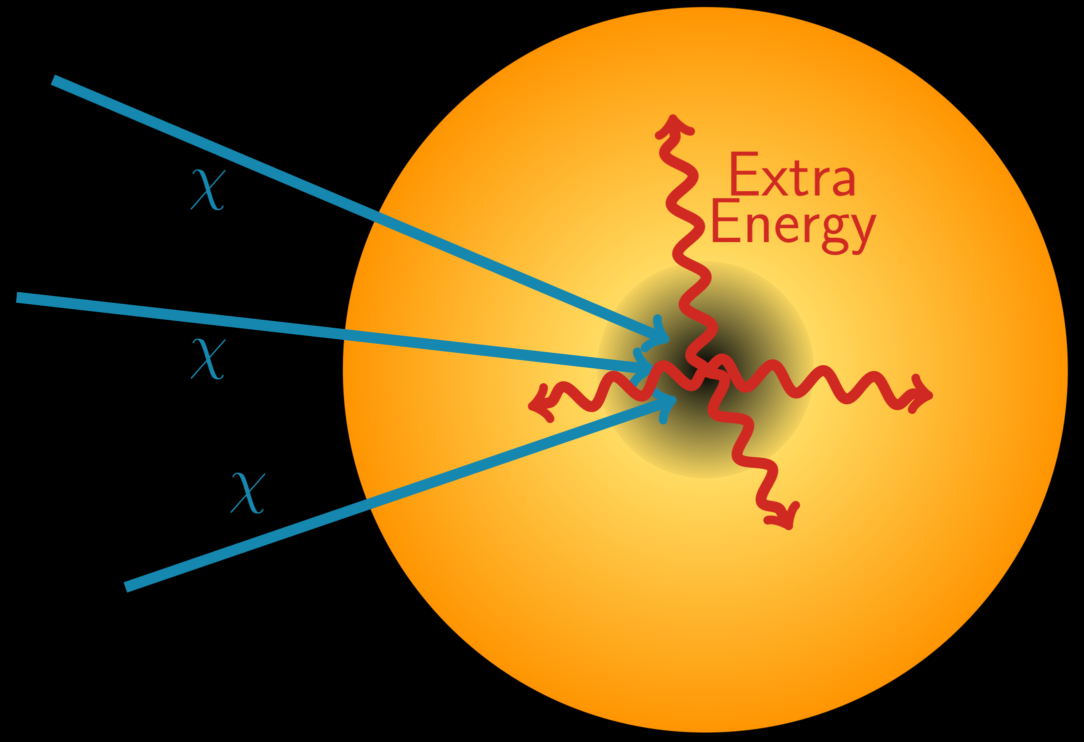
NANOGrav Collaboration (1801.02617)

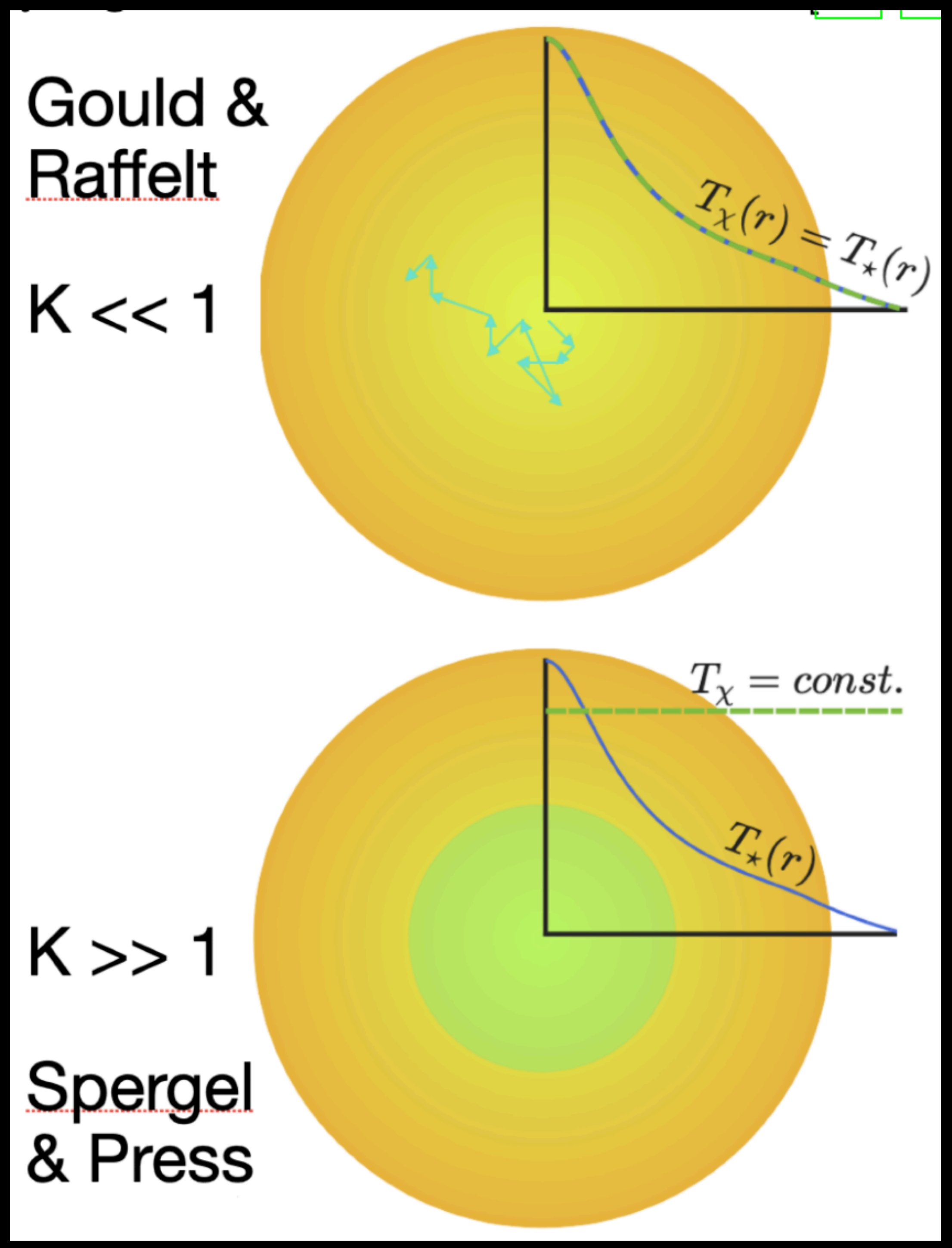
A Multitude of Targets

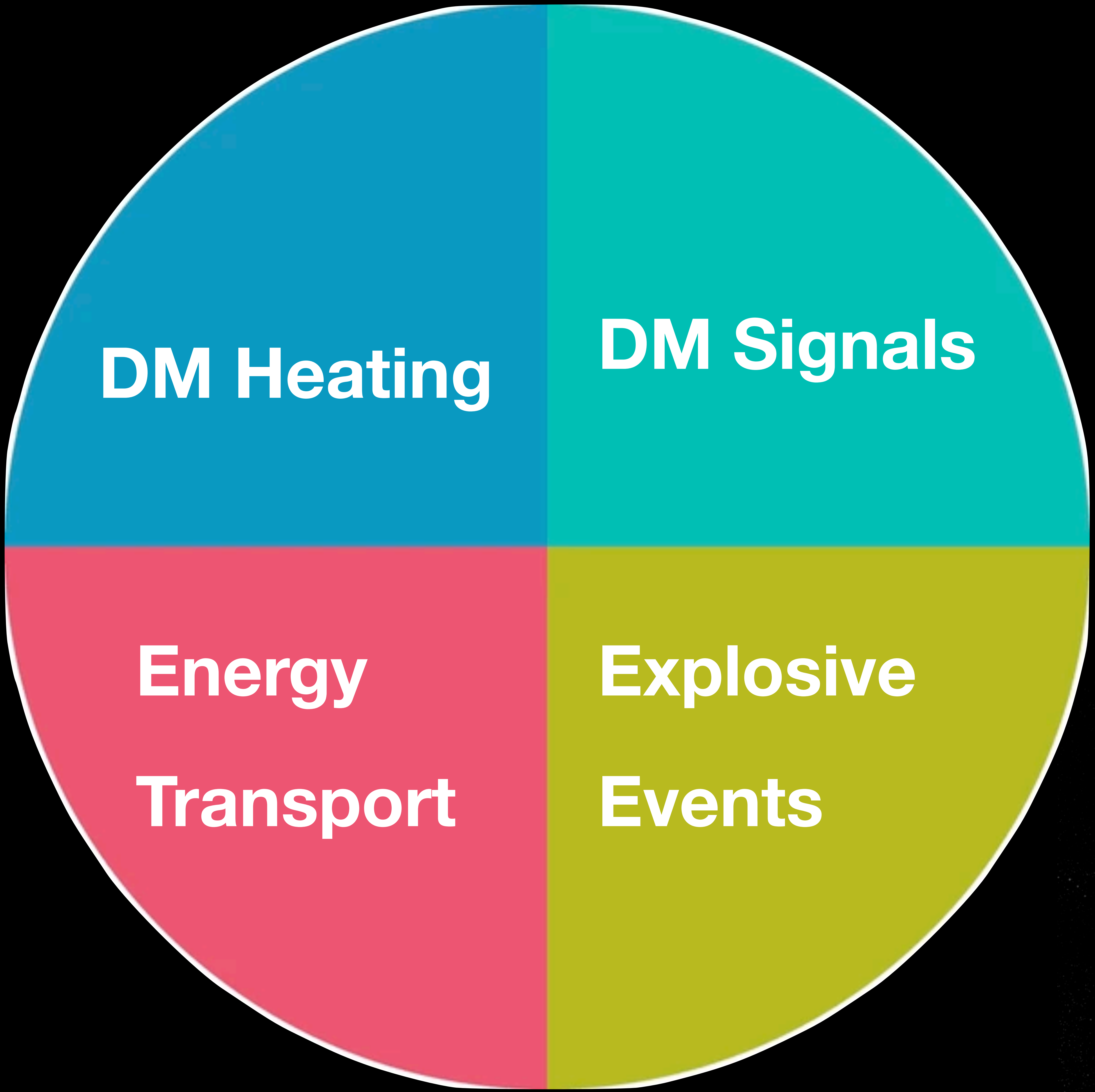


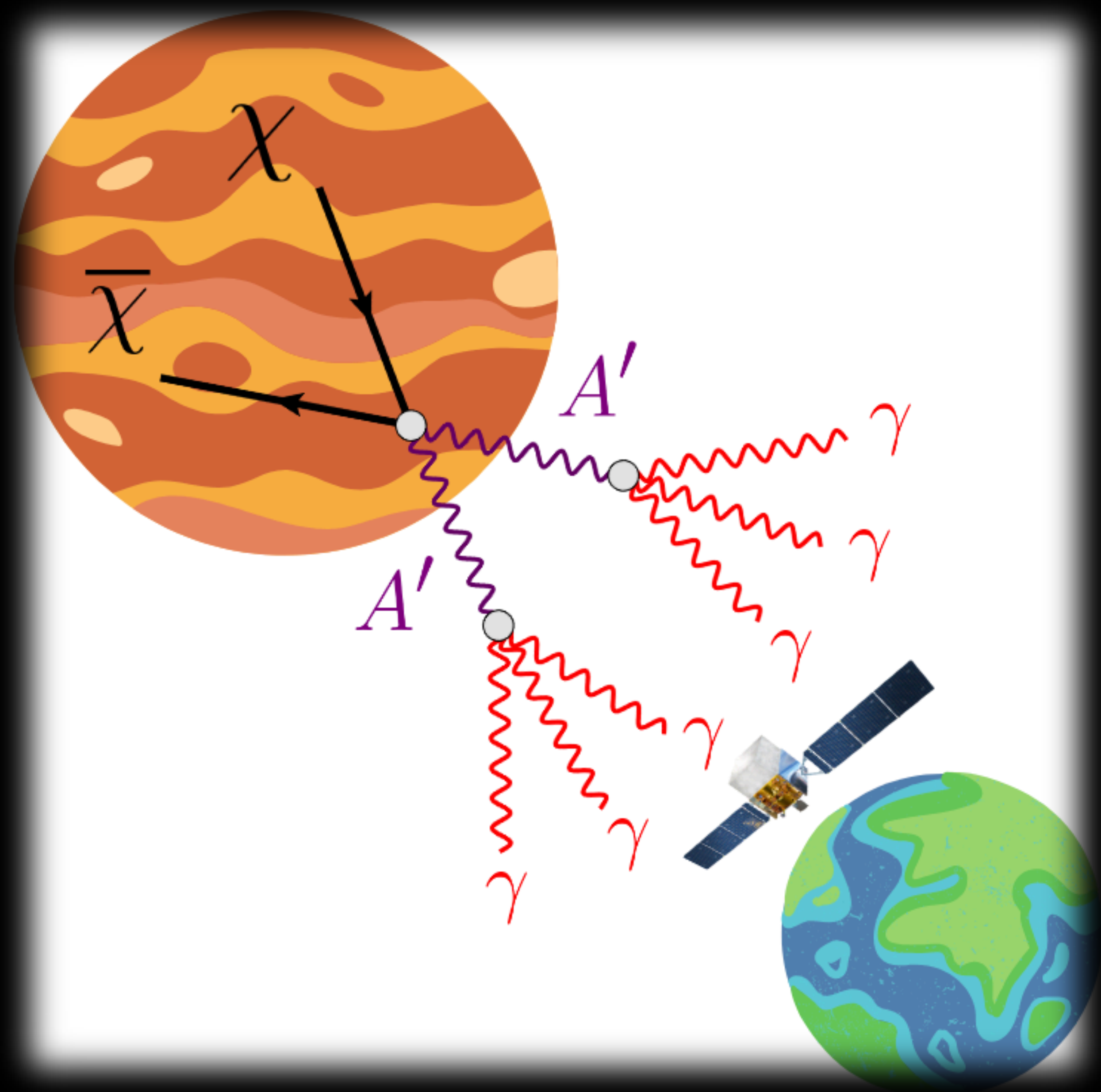


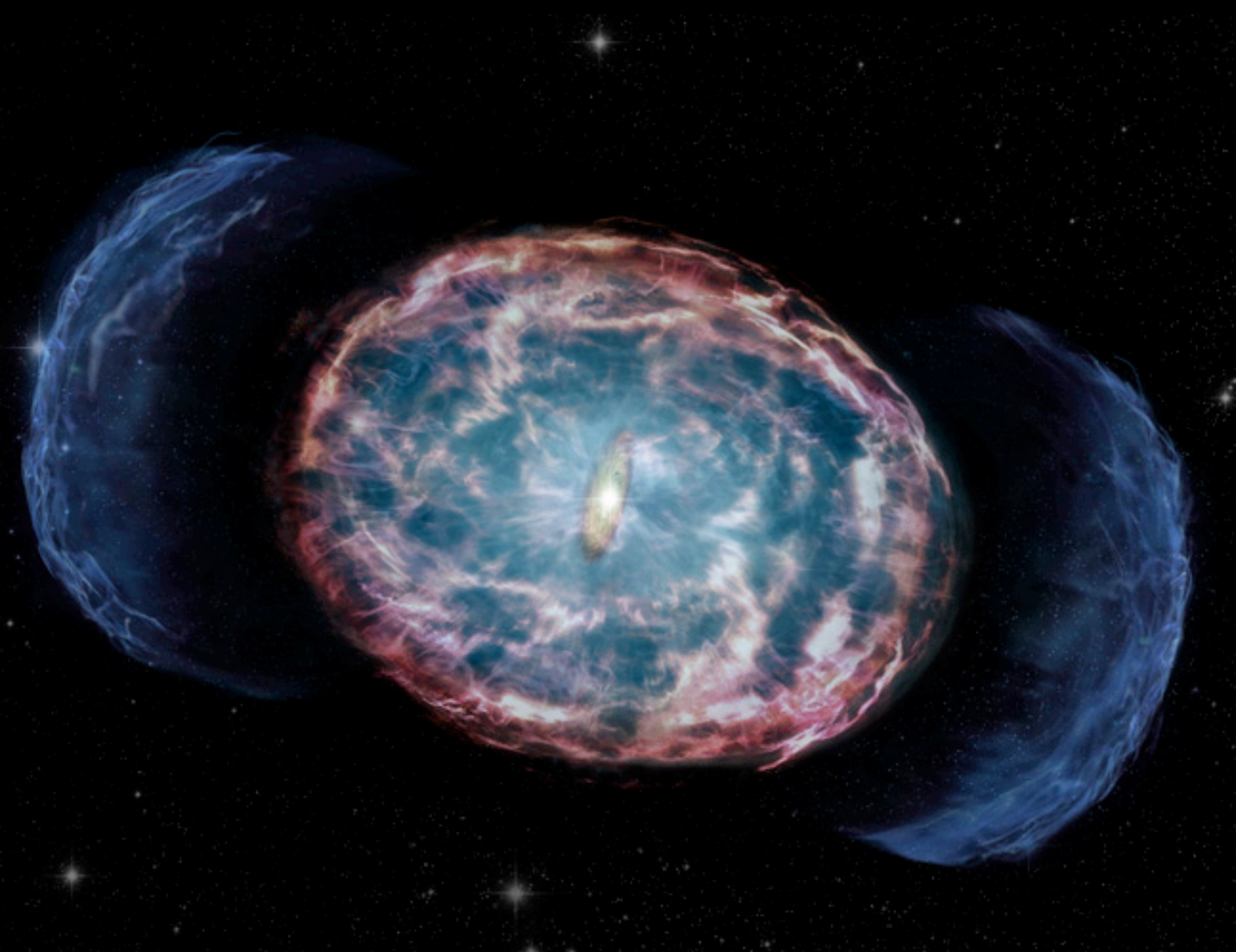
A Multitude of Signatures



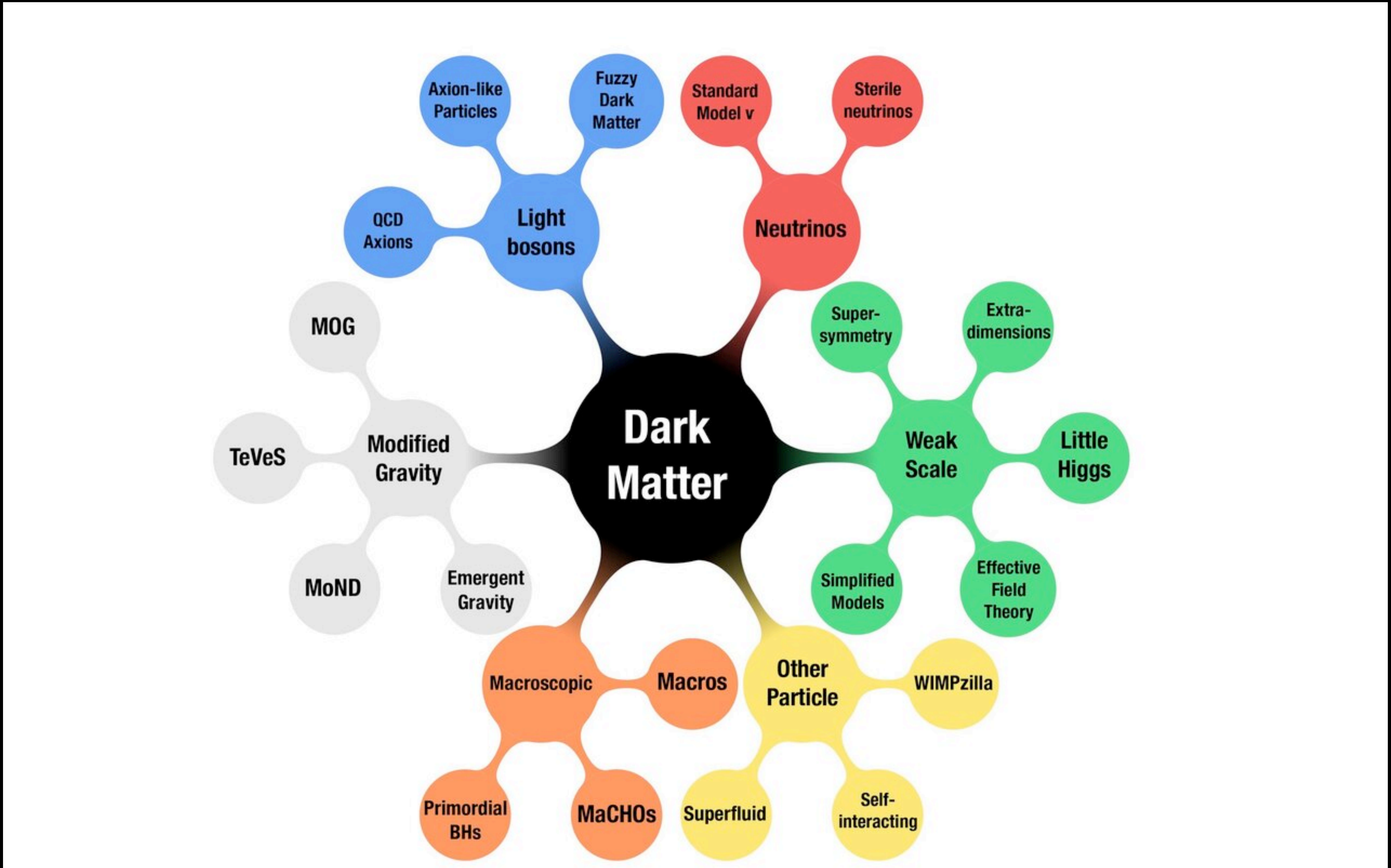




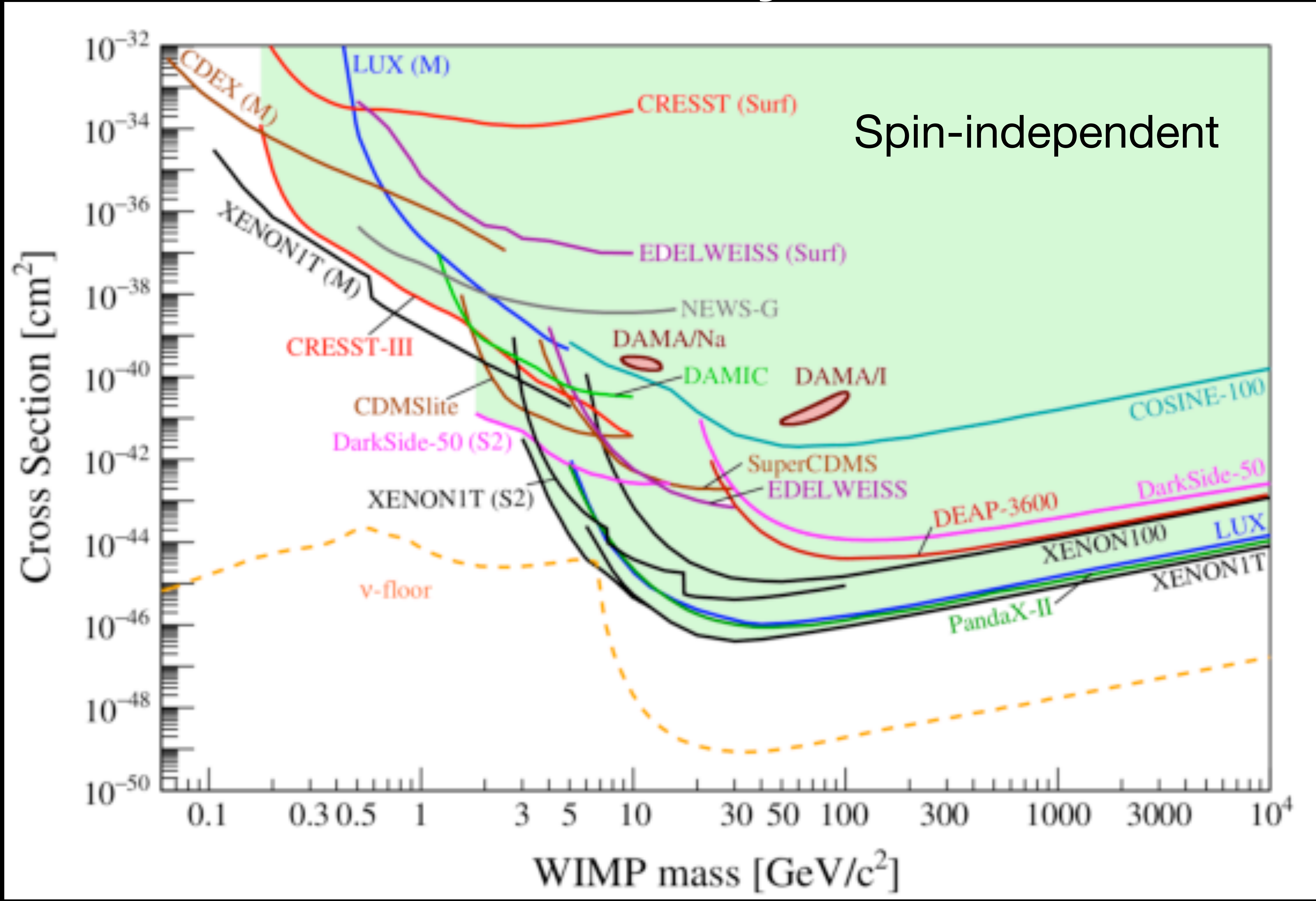




A Multitude of Dark Matter Models



Standard Searches Fail in Many of These Scenarios



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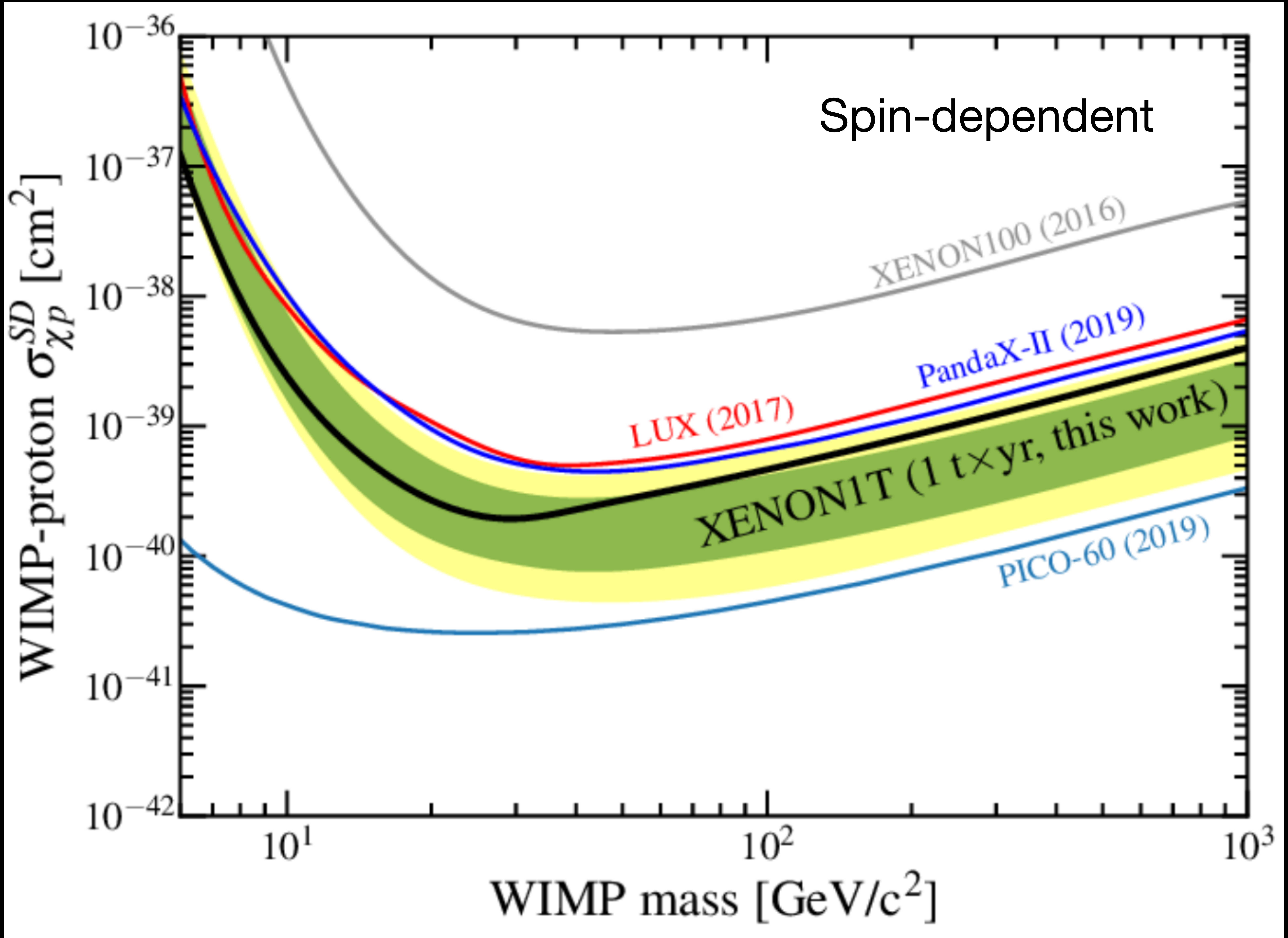

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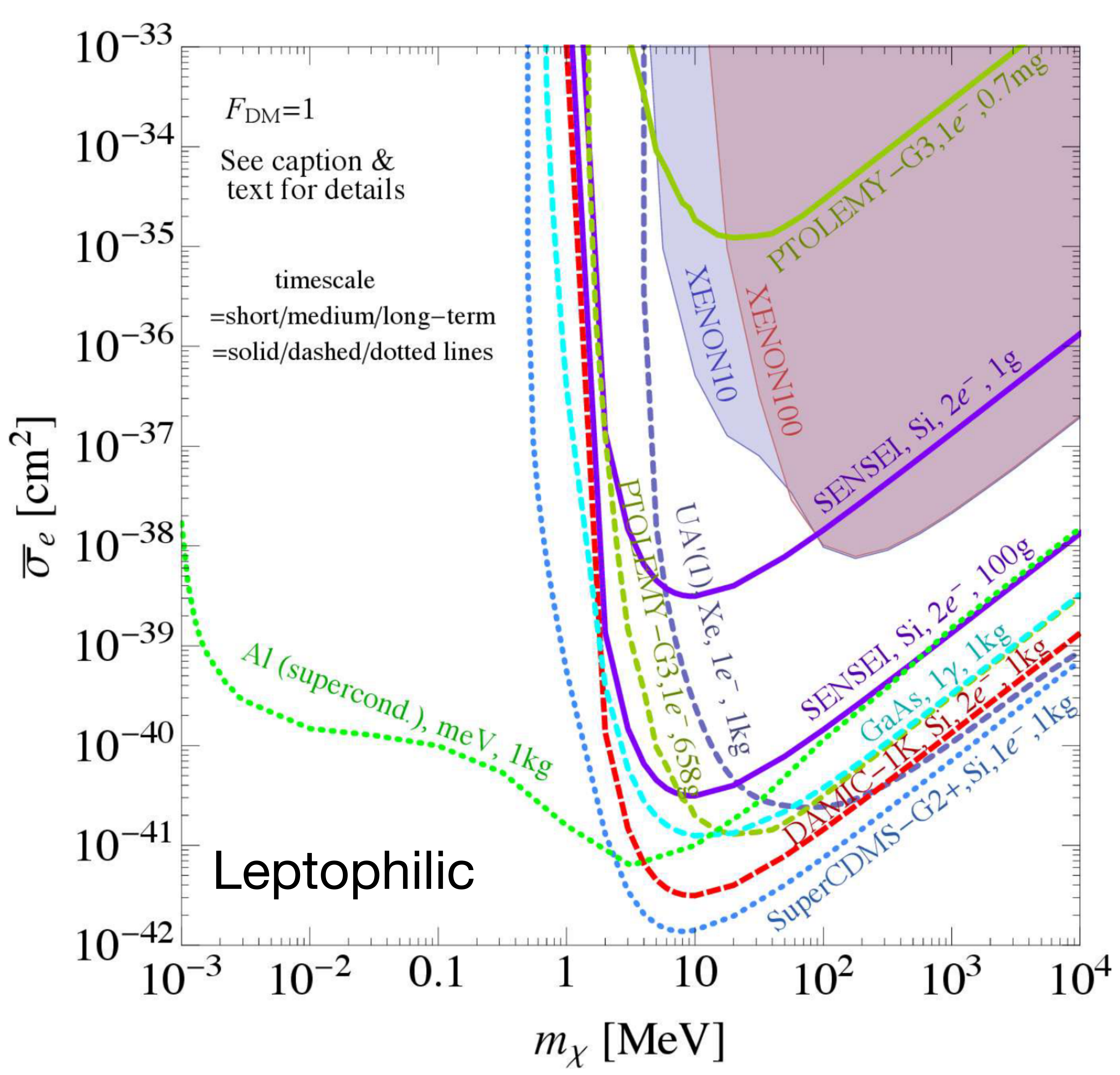
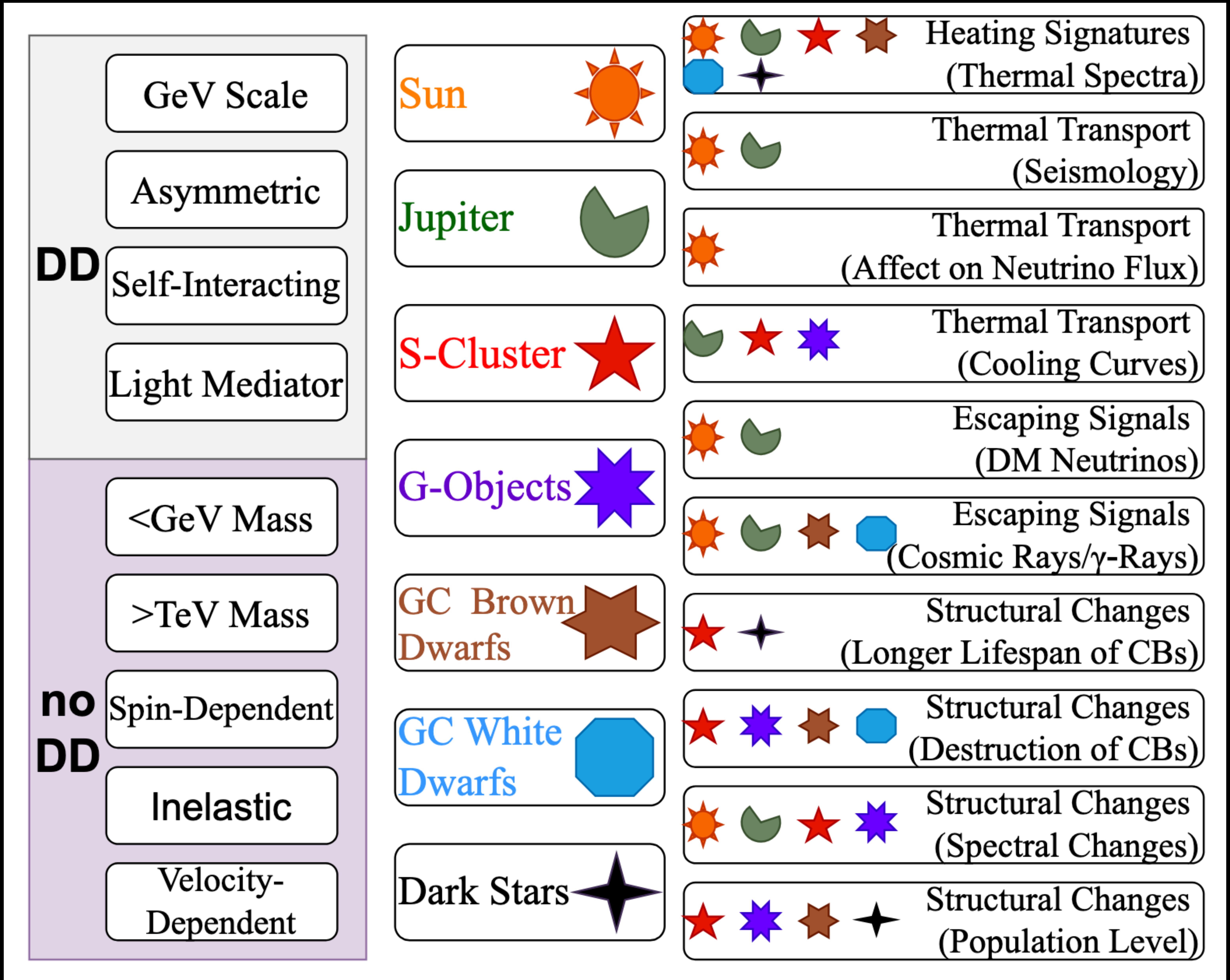


A Cacophony Of Studies




PEPE

How to Do Science in the High-Risk High-Reward Regime

1.) Avoid Two-Miracle Studies

- Standard model miracles cost half.
- Miracles can be correlated

2.) Focus on observables

- When the risk is high, observers will not spend effort on studies.

3.) Attack the biggest uncertainty, and then move on.

- Every individual study is individually unlikely.

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$$A - M \geq 0$$

Possible detections

How to Do Science in the High-Risk High-Reward Regime

“Wear your ~~character~~ theory as lightly as a cap.”

A Few Recent Studies

1.) SuperK Neutrino Searches in the Sun (2501.14864)

2.) Stellar Heating at the Galactic Center (2311.16228; 2405.12267)

3.) Missing Pulsars at the Galactic Center (1405.1031, 1706.00001)

Super-Kamiokande Searches for the Sun

1.) **Astrophysical Target:** The Sun

2.) **Dark Matter Target:** Annihilating Leptophilic Dark Matter

3.) **Detection Technique:** Escaping Signals (Neutrinos)

Super-Kamiokande Strongly Constrains Leptophilic Dark Matter Capture in the Sun

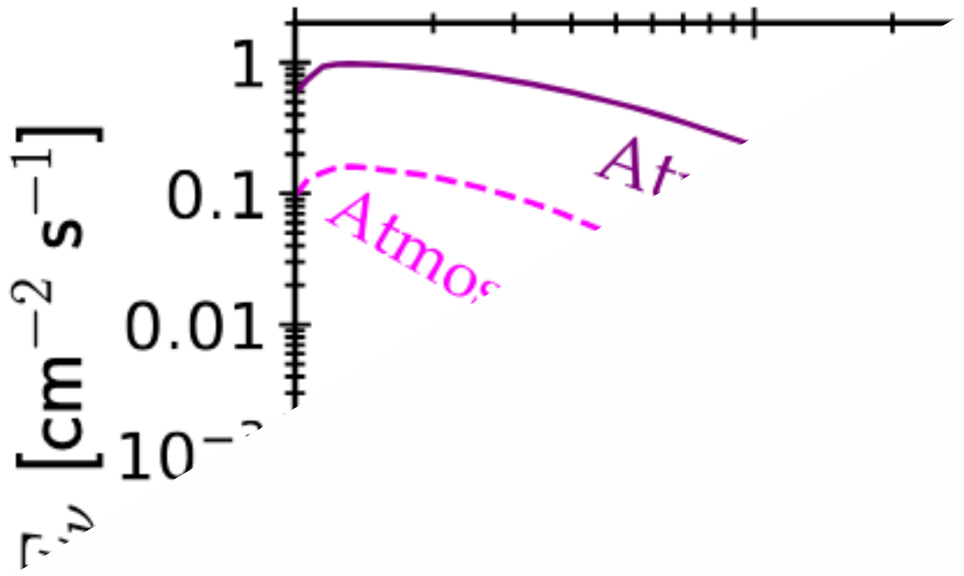
Thong T.Q. Nguyen,[1,*] Tim Linden,[1,†] Pierluca Carenza,[1,‡] and Axel Widmark[1,2,§]

[1] *Stockholm University and The Oskar Klein Centre for Cosmoparticle Physics, Alba Nova, 10691 Stockholm, Sweden*
[2] *Columbia University, 116th and Broadway, New York, NY 10027 USA*

The Sun can efficiently capture leptophilic dark matter that scatters with free electrons. If this dark matter subsequently annihilates into leptonic states, it can produce a detectable neutrino flux. Using 10 years of Super-Kamiokande observations, we set constraints on the dark-matter/electron scattering cross-section that exceed terrestrial direct detection searches by more than an order of magnitude for dark matter masses below 100 GeV, and reach cross-sections as low as $\sim 4 \times 10^{-41}$ cm^{-2}.

...duction. — Detecting the particle interactions of ...ter is a cornerstone in our efforts to study be... ...dard model physics [1–3]. Many of the most ...nts depend on searching for rare scat... ...tween the dark matter particle and ... [4–11].

...motivate current searches. ...rial detectors, uses un... ...sical backgrounds ...r interact...



Neutrinos from the Sun can discover dark matter-electron scattering

...Nath Maity,[1,2,3,*] Akash Kumar Saha,[3,†] Sagnik Mondal,[3,‡] and Ranjan Laha
[1] Harish-Chandra Research Institute, A CI of Homi Bhabha National Institute, Chhatnag Road, Jhunsi, Prayagraj (Allahabad) 211019, India
[2] Regional Centre for Accelerator-based Particle Physics, Harish-Chandra Research Institute, Prayagraj (Allahabad) 211019, ...
...Energy Physics, Indian Institute of Science, C. V. Raman Avenu...

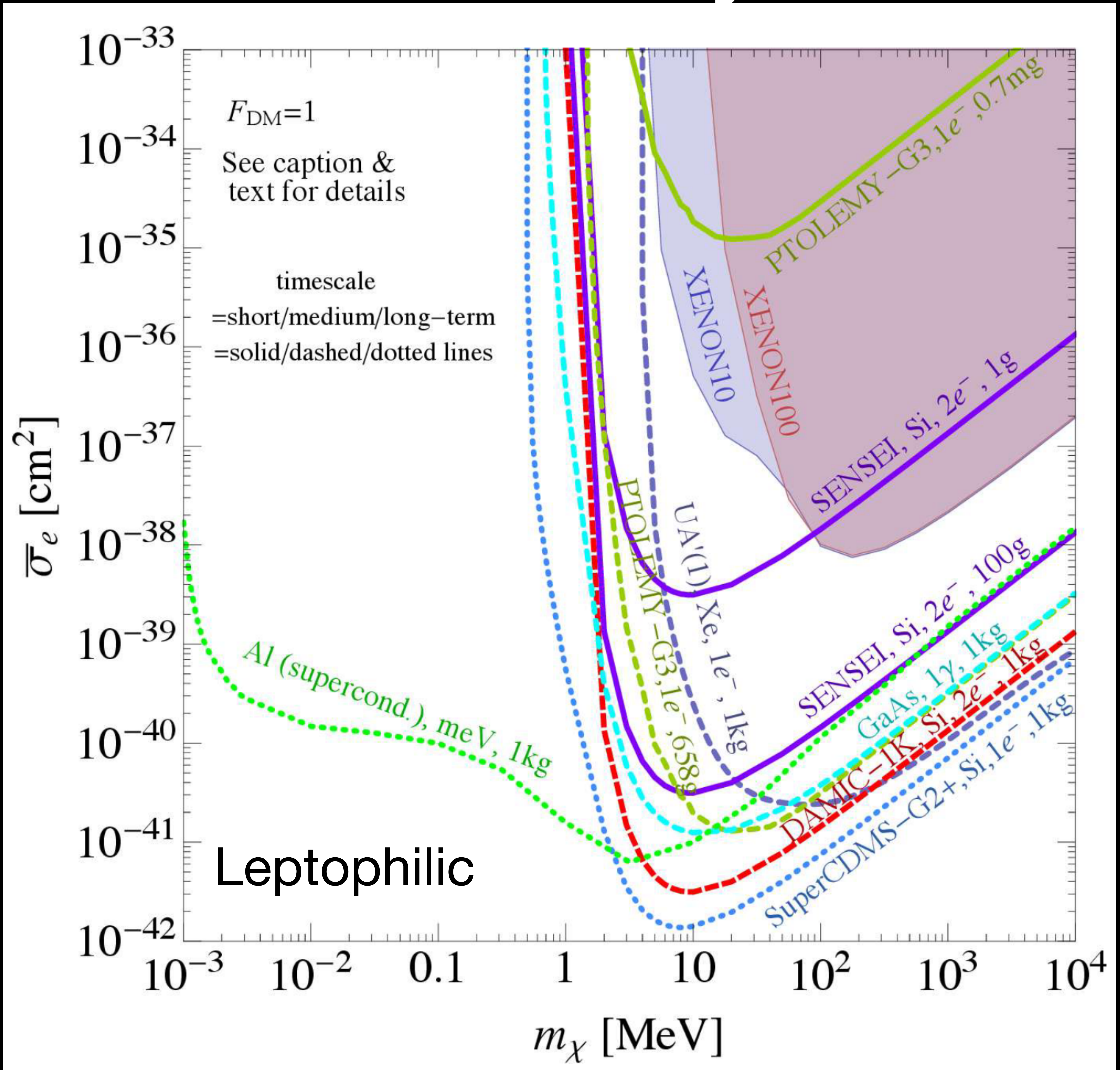
(Dated: August 25, 2023)

...k matter-electron scattering using high-energy neut... ...) interacting with electrons can get captured ... ...roduce different Standard Model (SM) ... ...erved in IceCube and DeepCore. ... ...find that the current data... ...on scattering cross secti... ...servations of the ...

Dark matter in the Sun: scattering off electrons vs nucleons

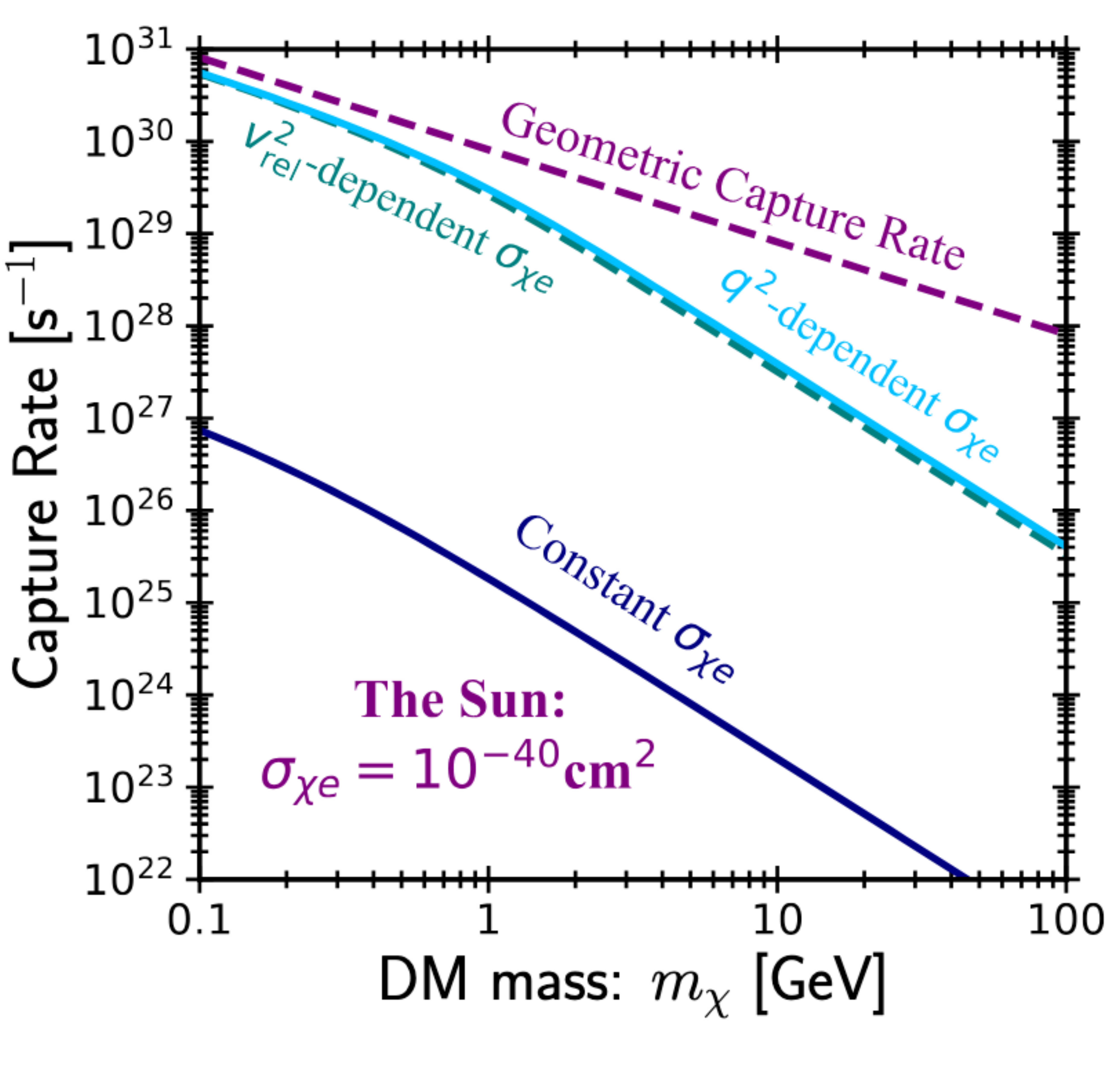
...i[1] and Sergio Palomares-Ruiz[2]
...hysics and Physikalisches Institut, Universität ...
...CSIC-Universitat de València, ... Spain
...y.es

Standard Searches Fail in Many of These Scenarios

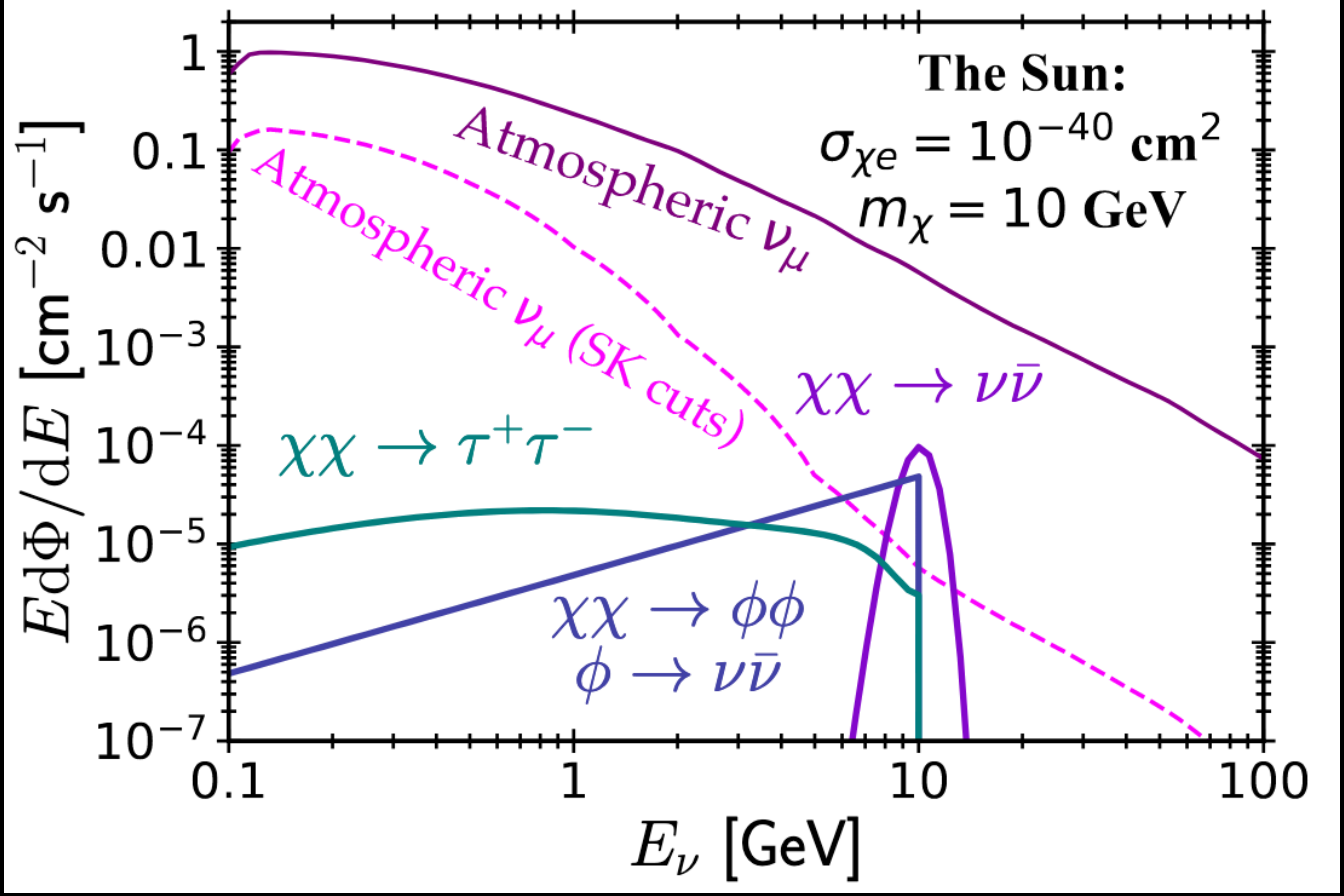


Super-Kamiokande Searches for the Sun

Dark Matter Capture in the Sun

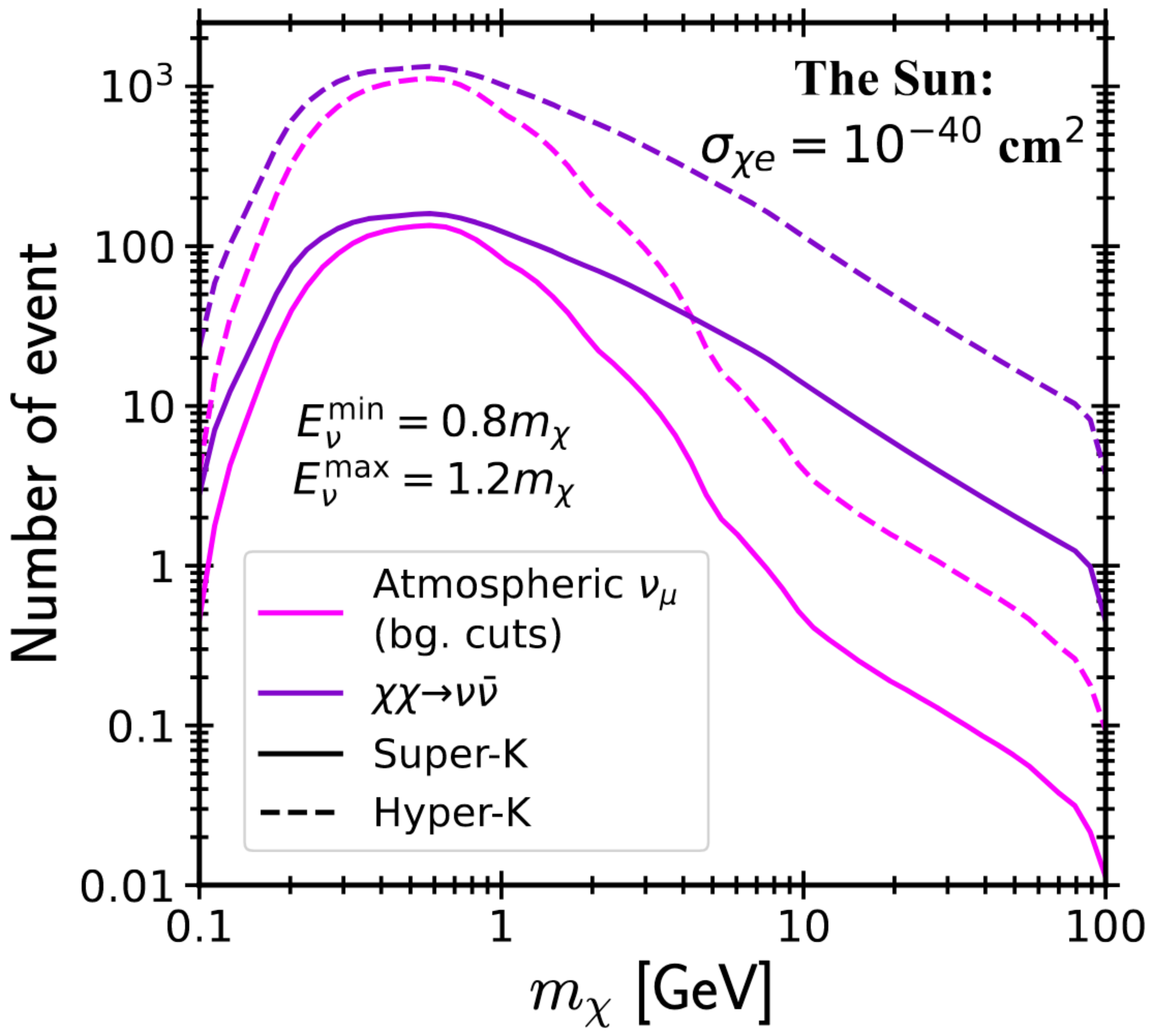


Super-Kamiokande



- **"Miracle" - Dark Matter must be leptophilic.**
- **Standard annihilation cross-sections and unconstrained scattering rate.**
- **Significant annihilation rate to neutrinos (or taus).**

Super-Kamiokande



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Super-Kamiokande

Super-Kamiokande

- When the cross-sections are velocity or momentum dependent, the high velocity of electrons makes constraints much stronger, probing the theoretical targets for leptophilic DM.

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- Every individual study is individually unlikely.

Immortal Stars at the Galactic Center

See also: work on Dark Stars (e.g., Spolyar & Freese)

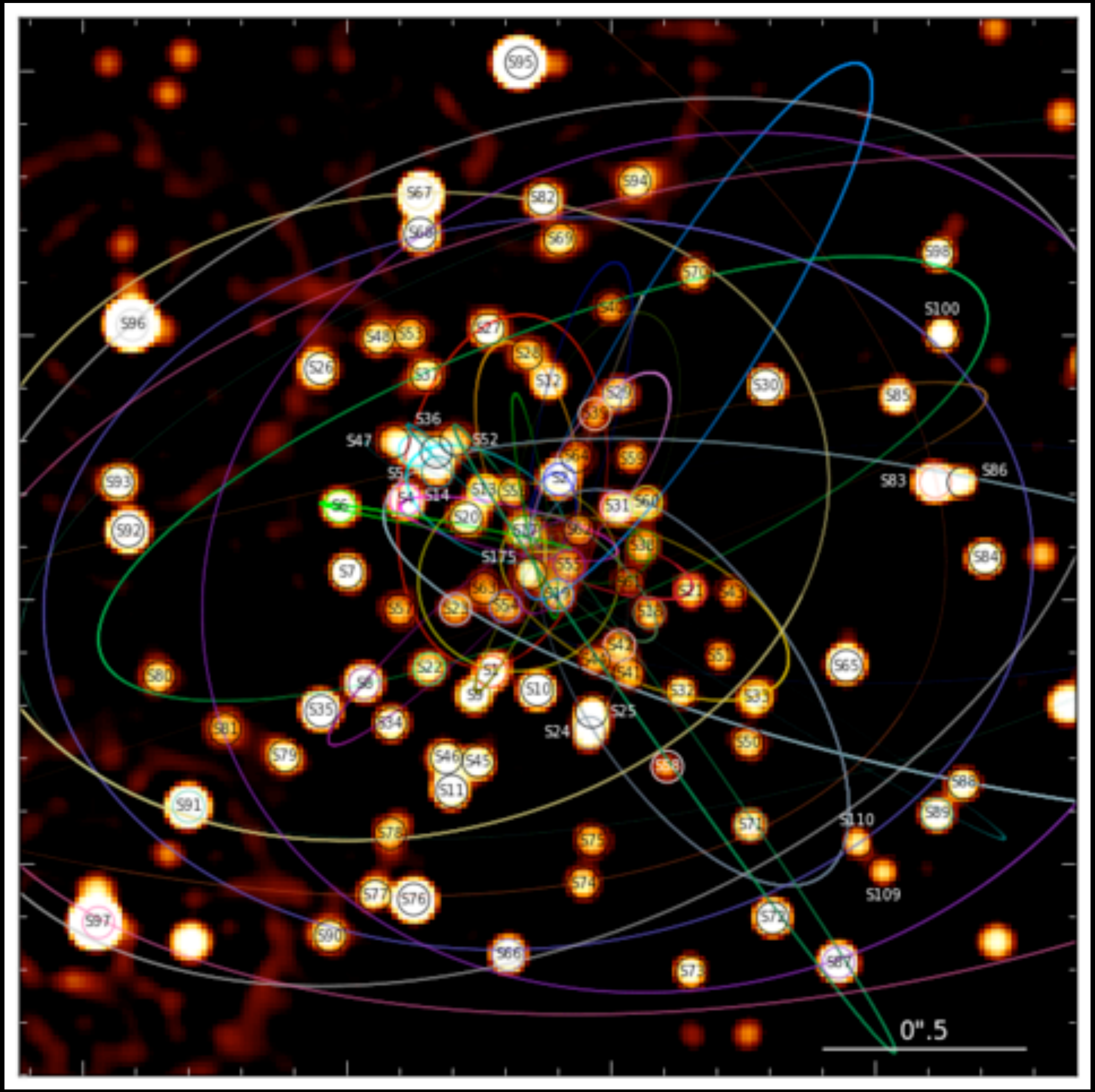
Immortal Stars at the Galactic Center

1.) Astrophysical Target: Galactic Center Stars

2.) Dark Matter Target: DM with Scattering and Annihilation Cross-Section

3.) Detection Technique: Stellar Heating (Optical)

Immortal Stars at the Galactic Center



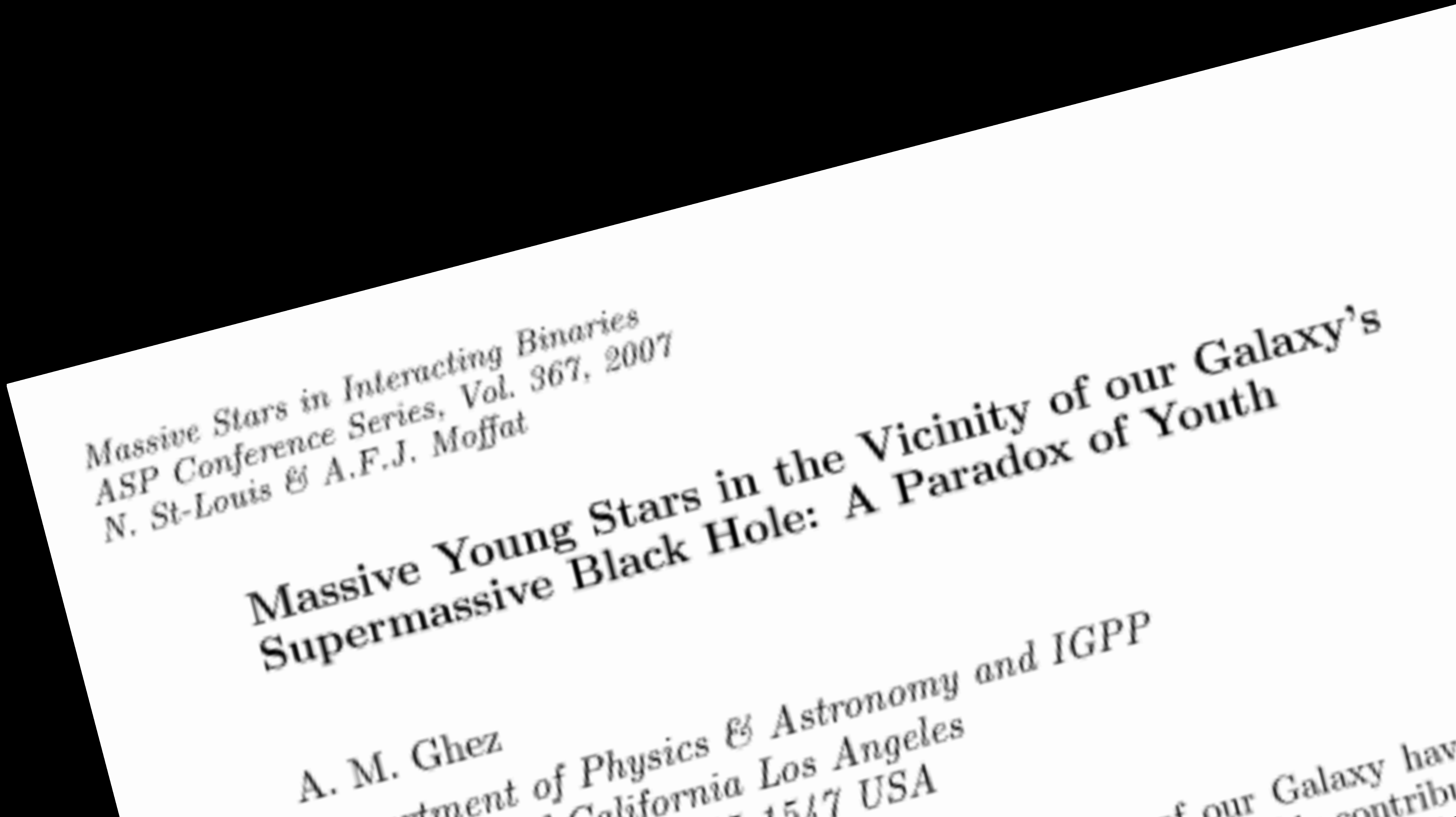
Many stars within 0.016 pc

Immortal Stars at the Galactic Center

Paradox of Youth: Spectroscopically middle-aged but bright as young stars

Conundrum of Old Age: Lack of very old stars

Top-heavy initial mass function: large abundance of massive stars

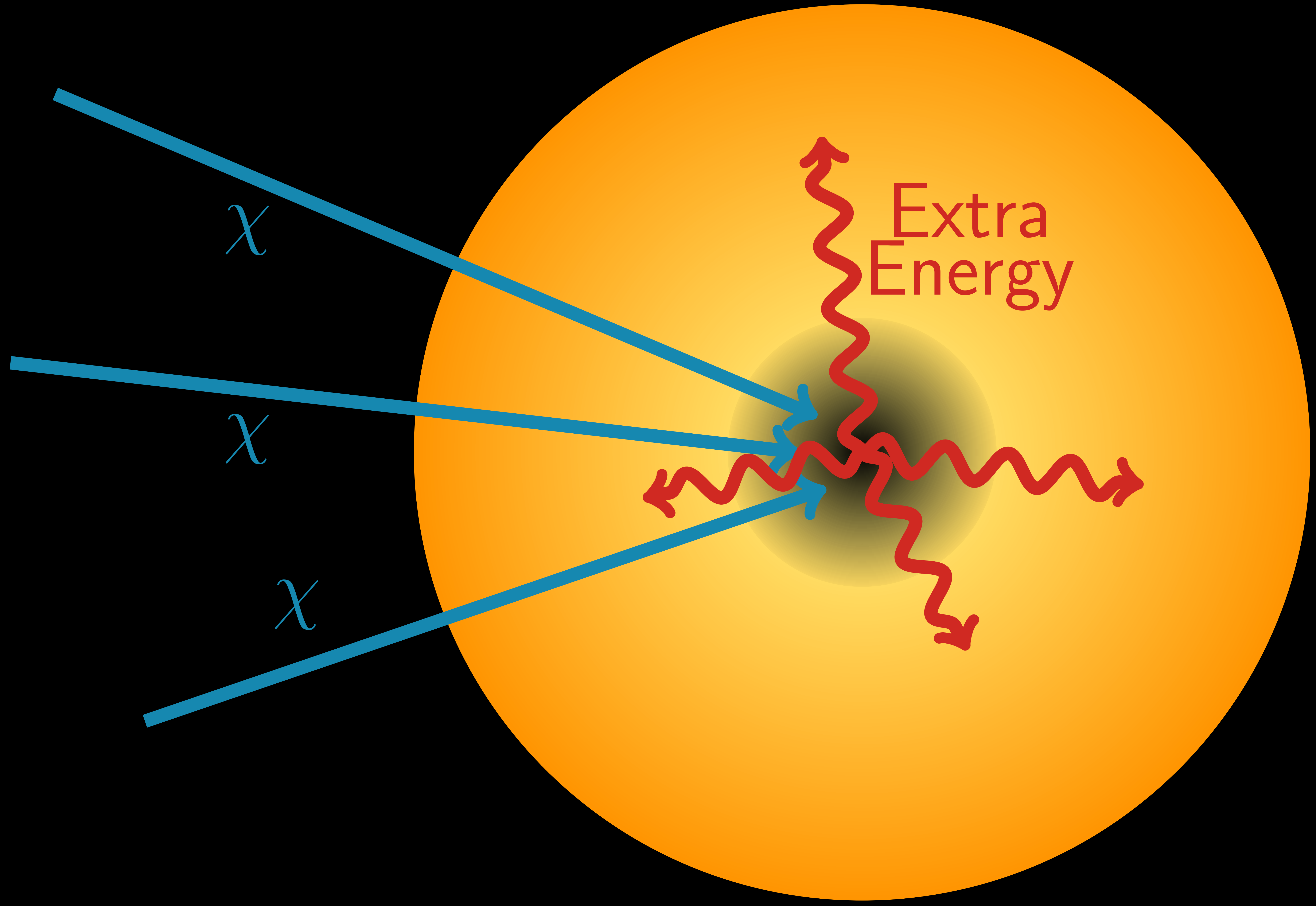


Massive Stars in Interacting Binaries
ASP Conference Series, Vol. 367, 2007
N. St-Louis & A.F.J. Moffat

Massive Young Stars in the Vicinity of our Galaxy's Supermassive Black Hole: A Paradox of Youth

A. M. Ghez

Immortal Stars at the Galactic Center



- **Dark Matter annihilation provides an additional power source that heats the star.**
- **The star maintains equilibrium - it expands if too much power is injected.**

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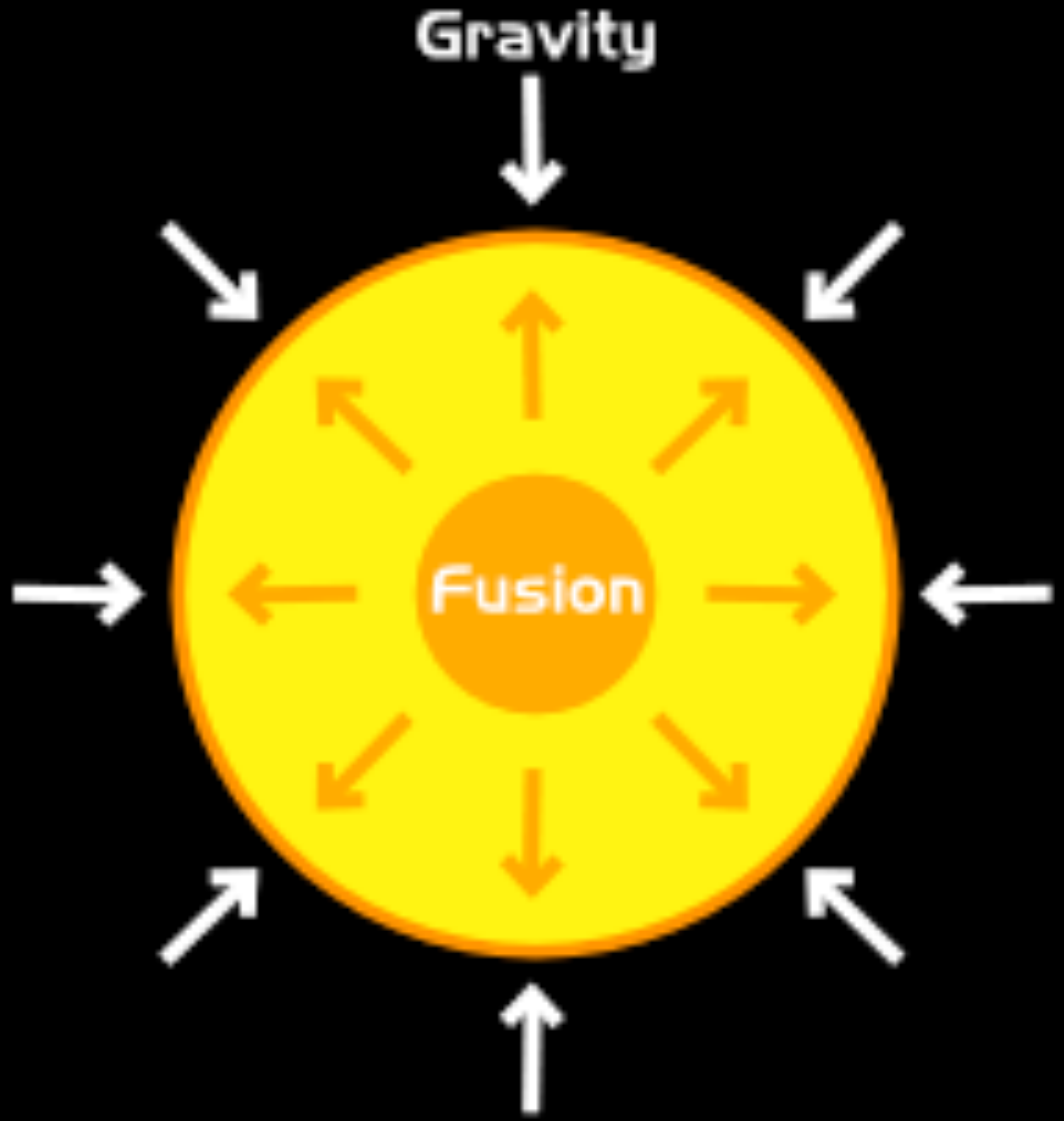
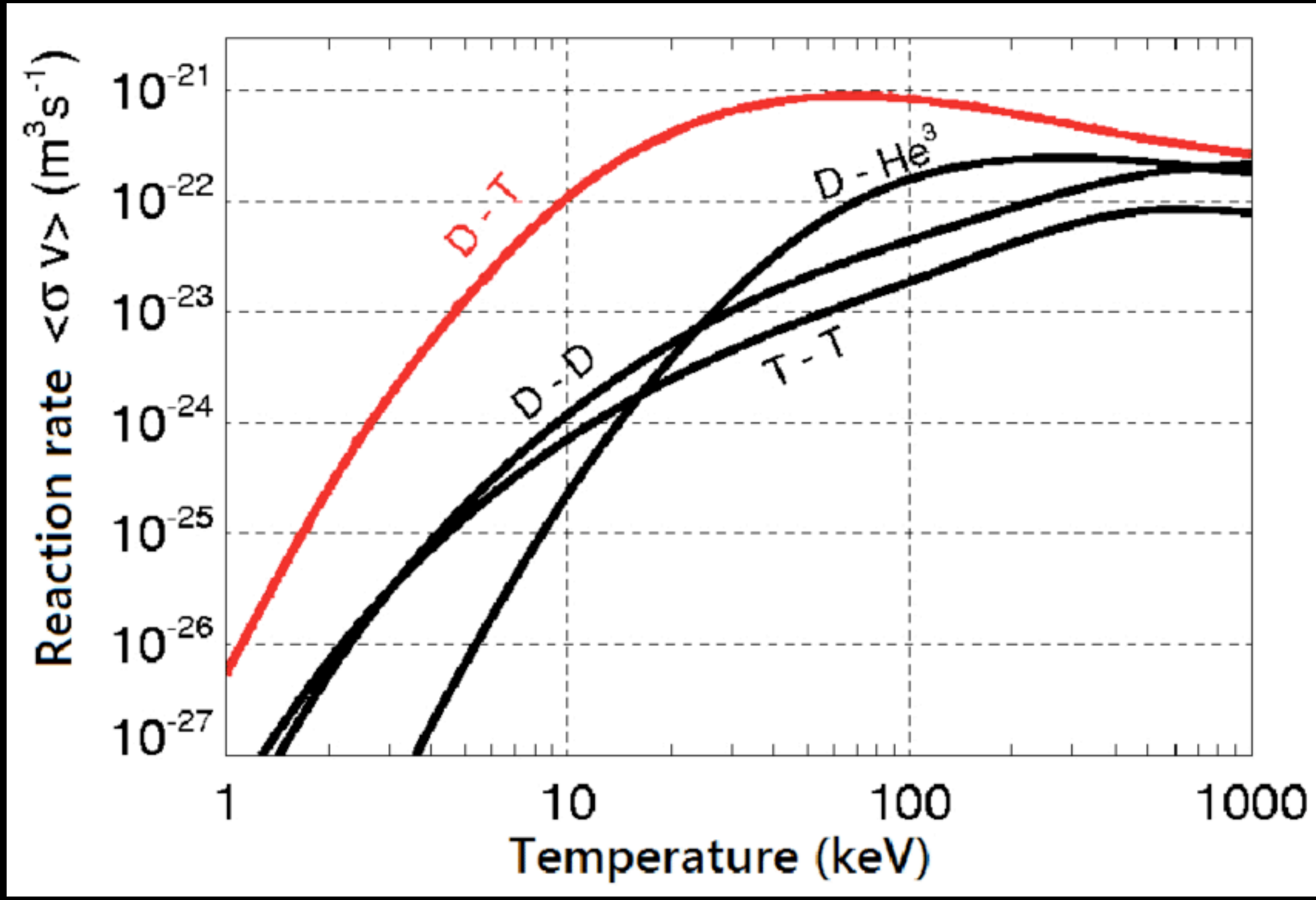
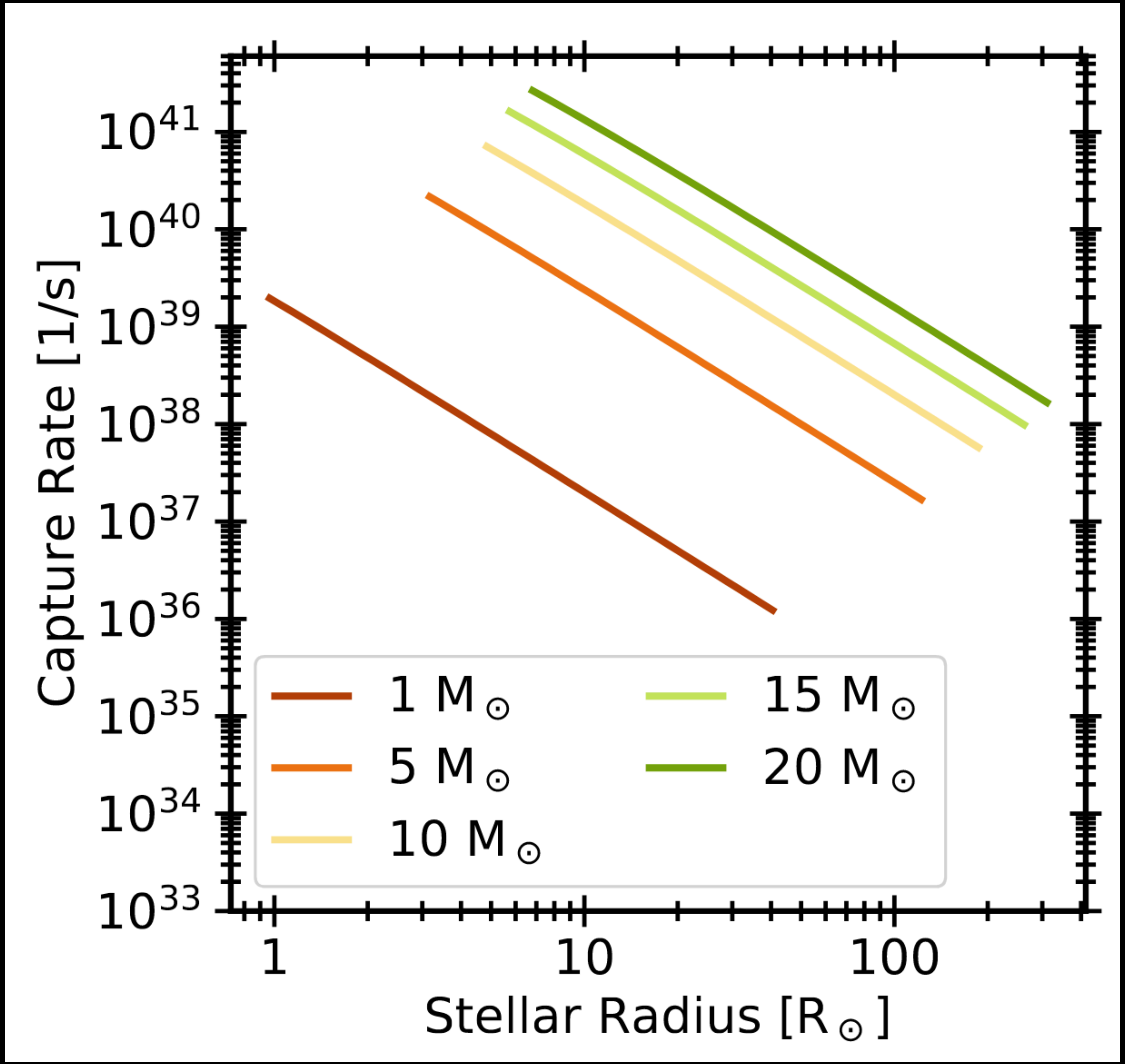




Immortal Stars at the Galactic Center



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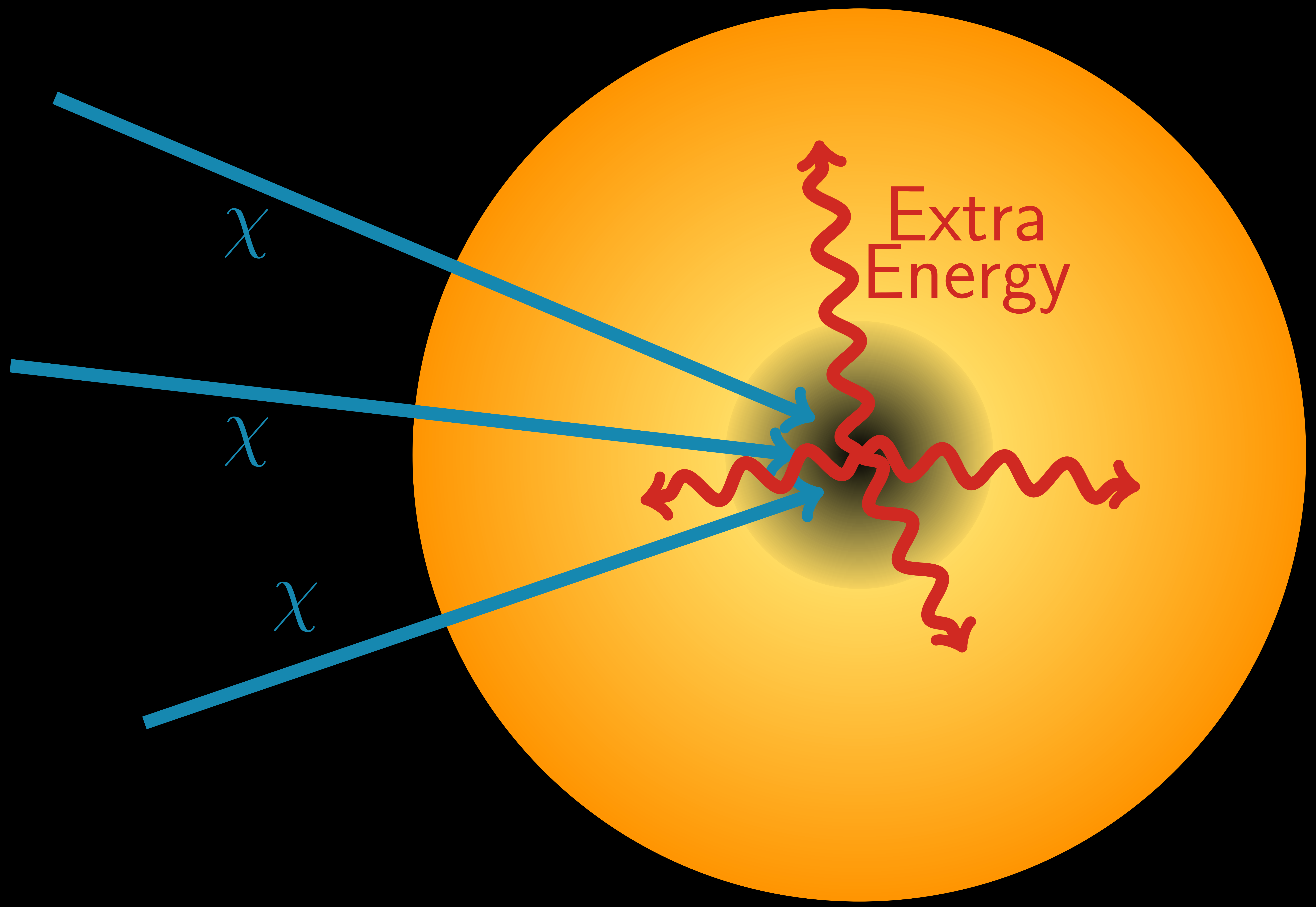
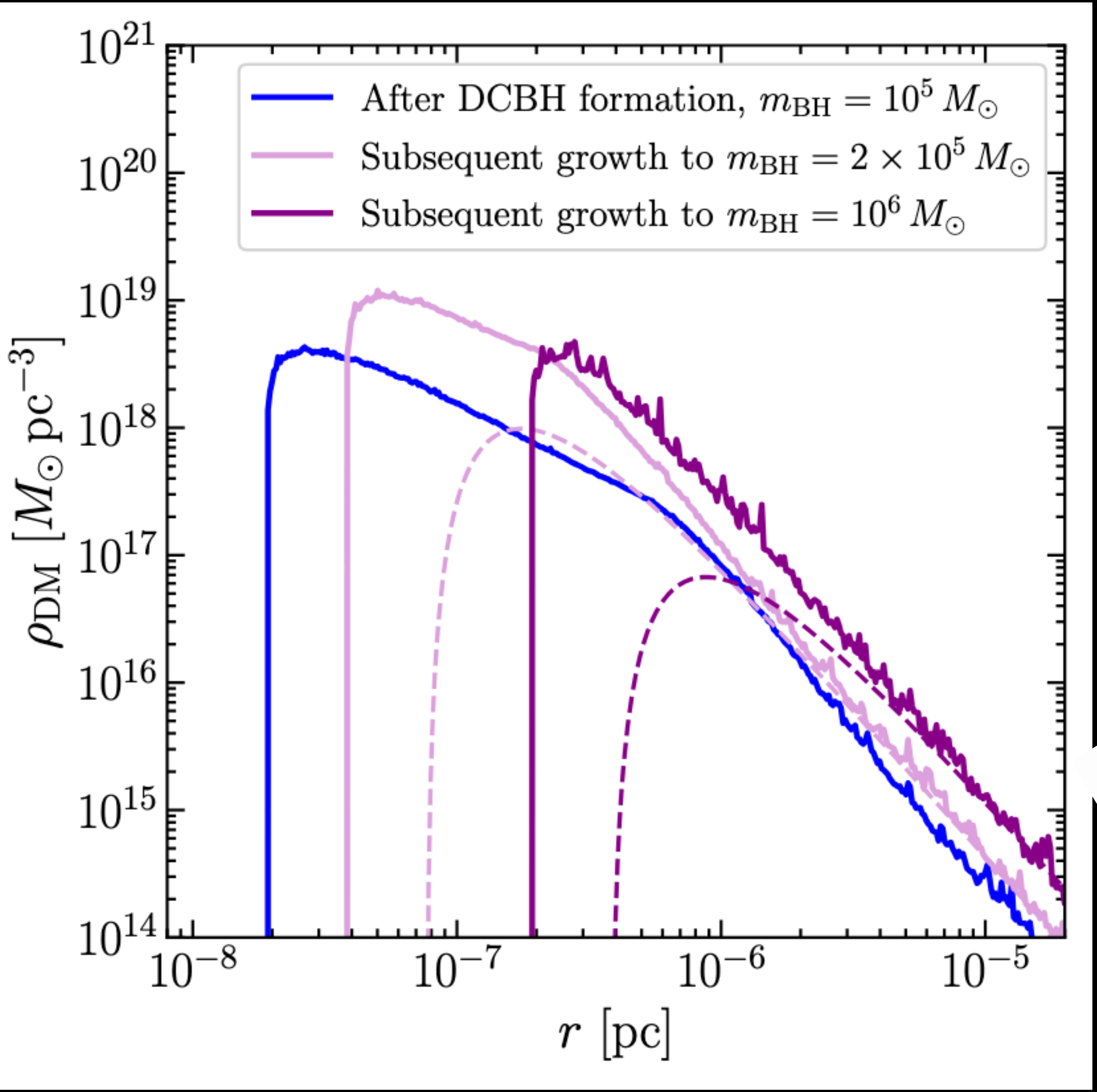
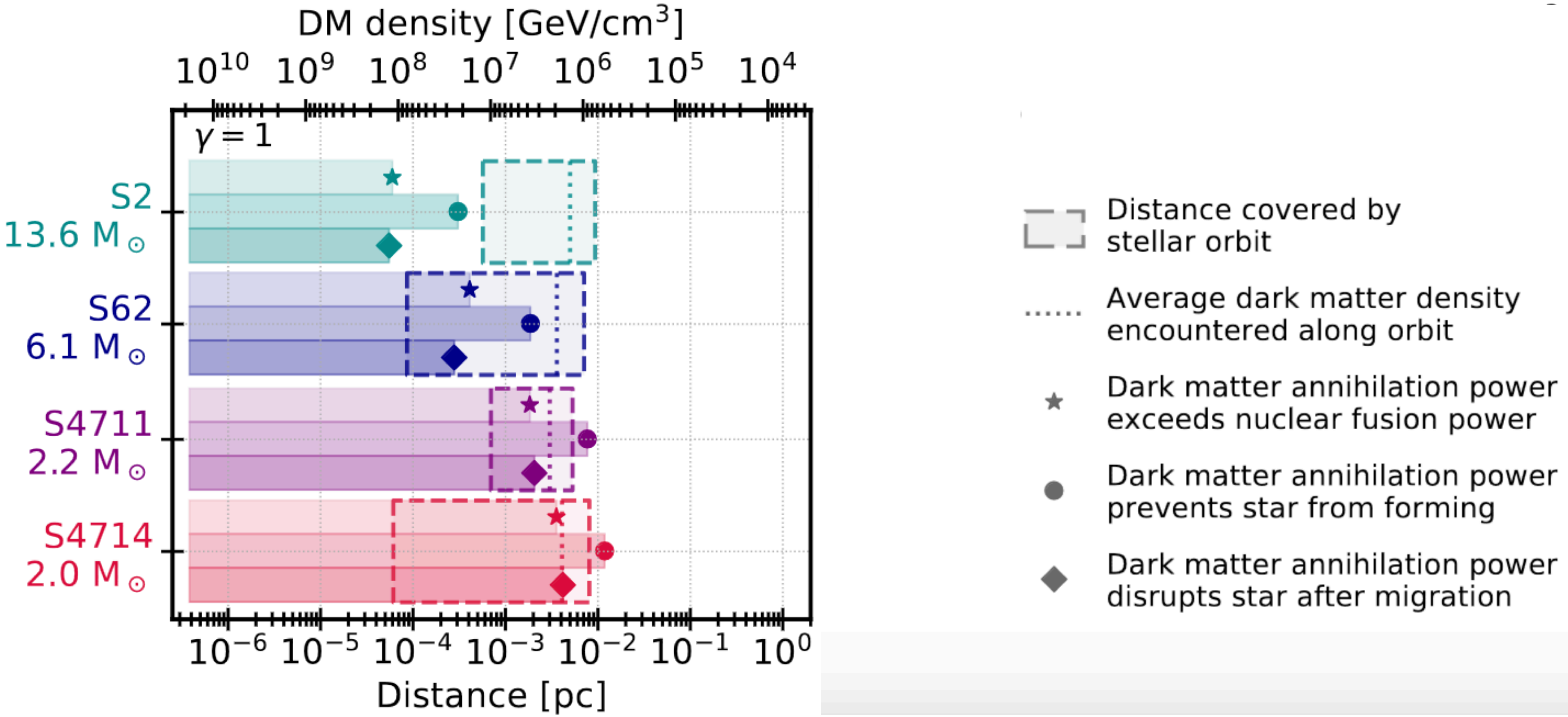


- "Miracle" - Very high dark matter densities at the galactic center.
- Standard WIMP DM
- Lower Mass WIMPs (to avoid direct detection constraints)

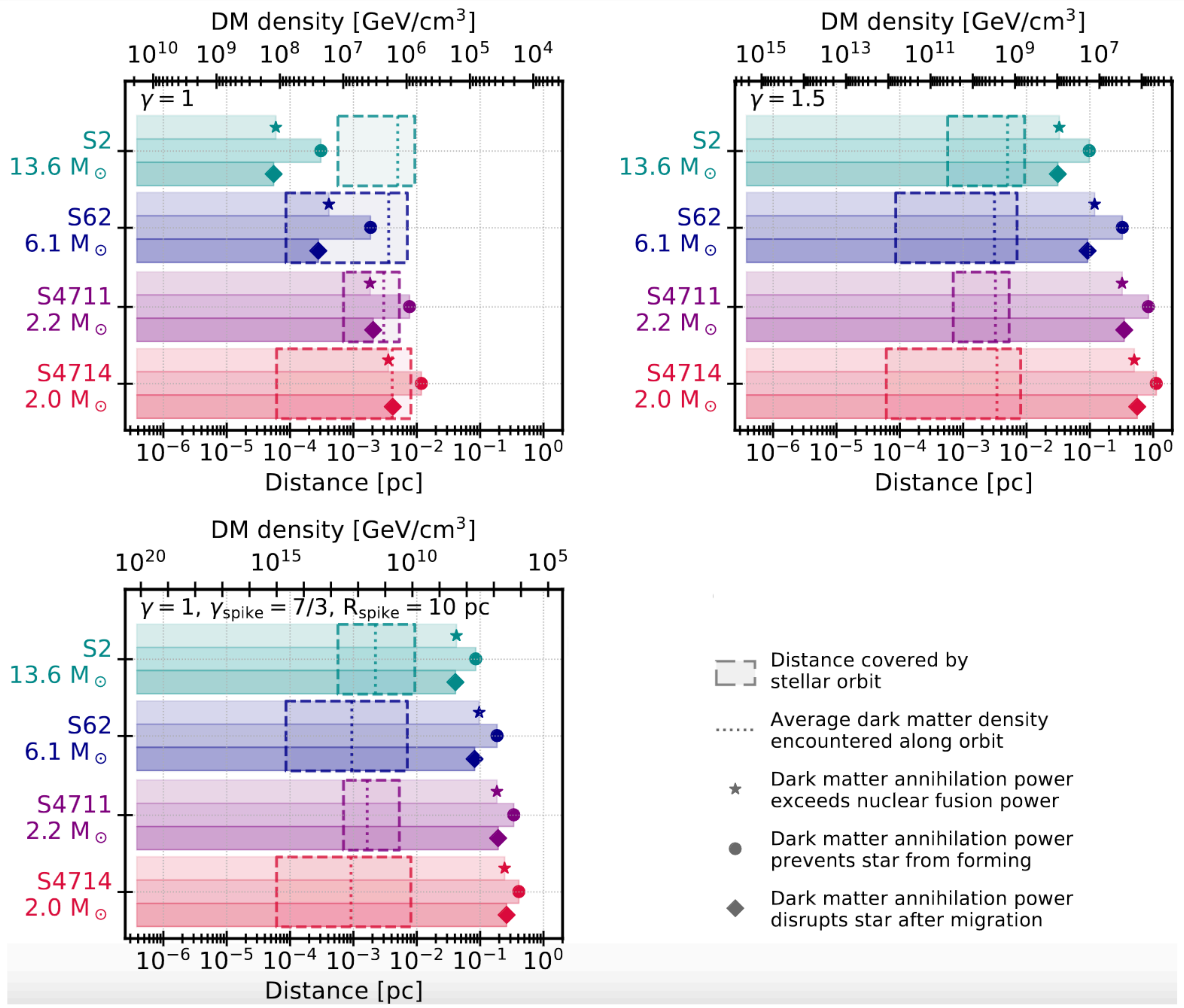
Immortal Stars at the Galactic Center



Multiple Stars in DM-Dense Regions

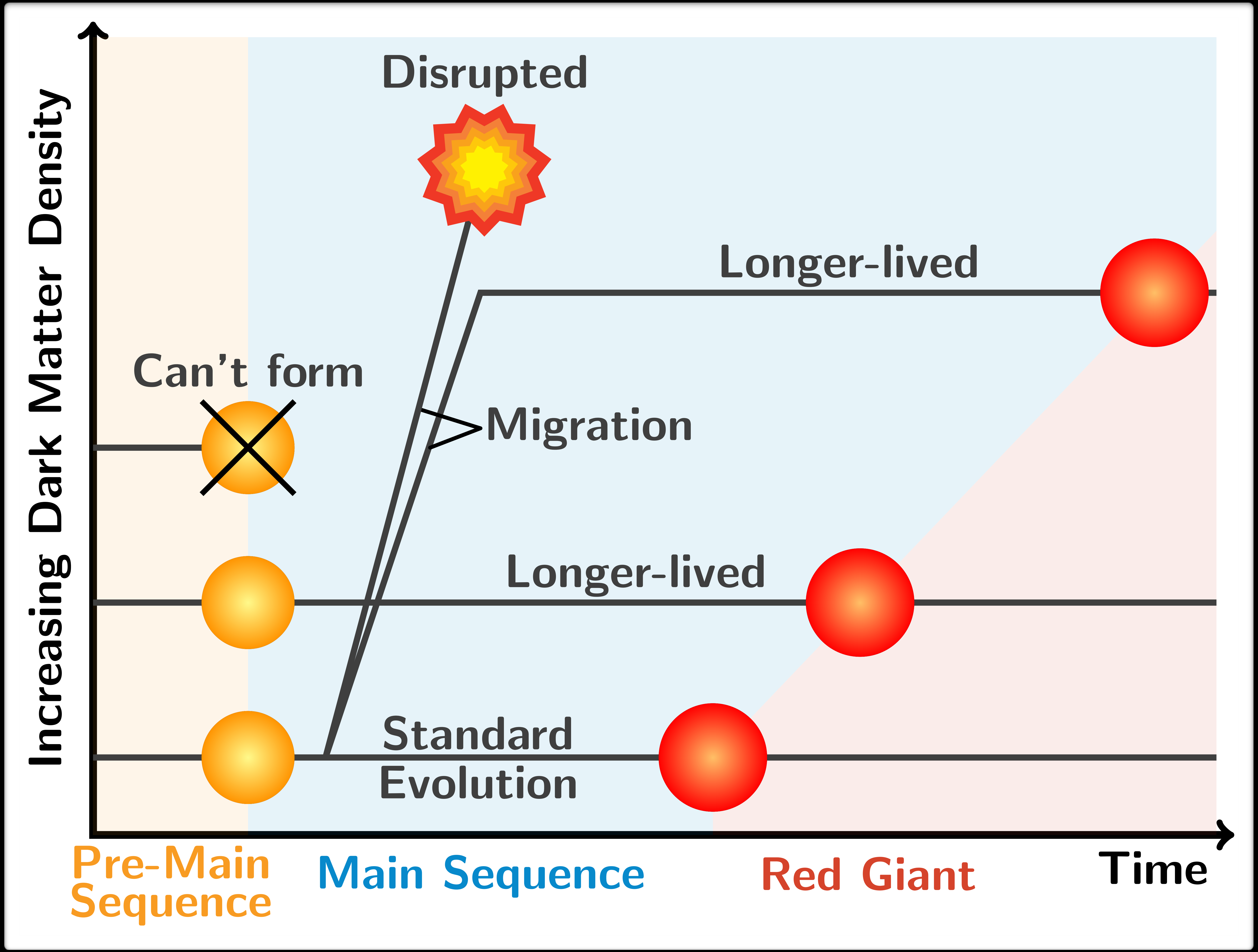


- (Assuming Geometric Capture cross-sections)



DM density [GeV/cm^3]
Distance [pc]
$\gamma = 1$
$\gamma = 1.5$
$\gamma = 1$, $\gamma_{spike} = 7/3$, $R_{spike} = 10$ pc
S2
13.6 $M_\odot$
S62
6.1 $M_\odot$
S4711
2.2 $M_\odot$
S4714
2.0 $M_\odot$
Distance covered by stellar orbit
Average dark matter density encountered along orbit
Dark matter annihilation power exceeds nuclear fusion power
Dark matter annihilation power prevents star from forming
Dark matter annihilation power disrupts star after migration

Immortal Stars at the Galactic Center



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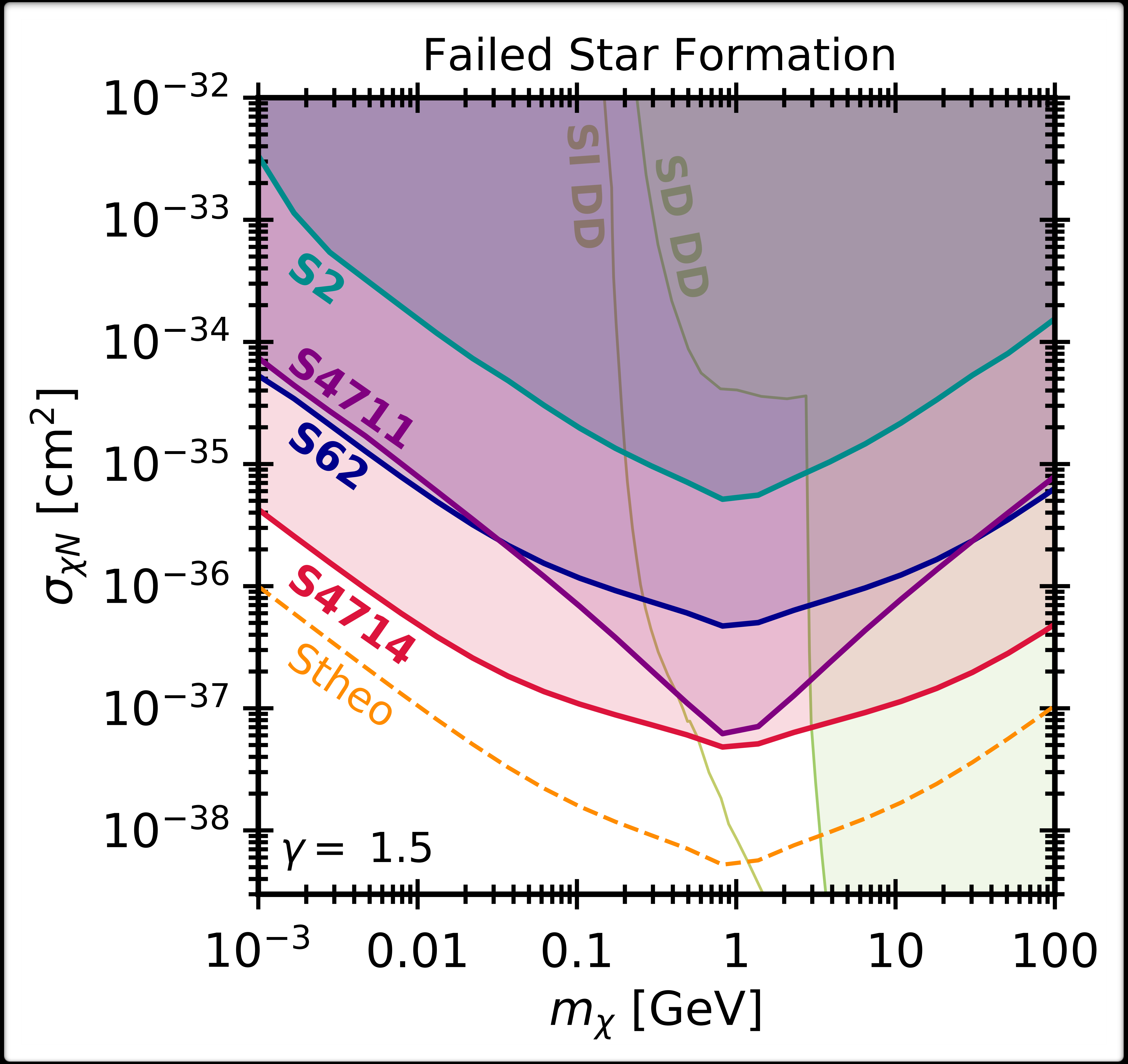
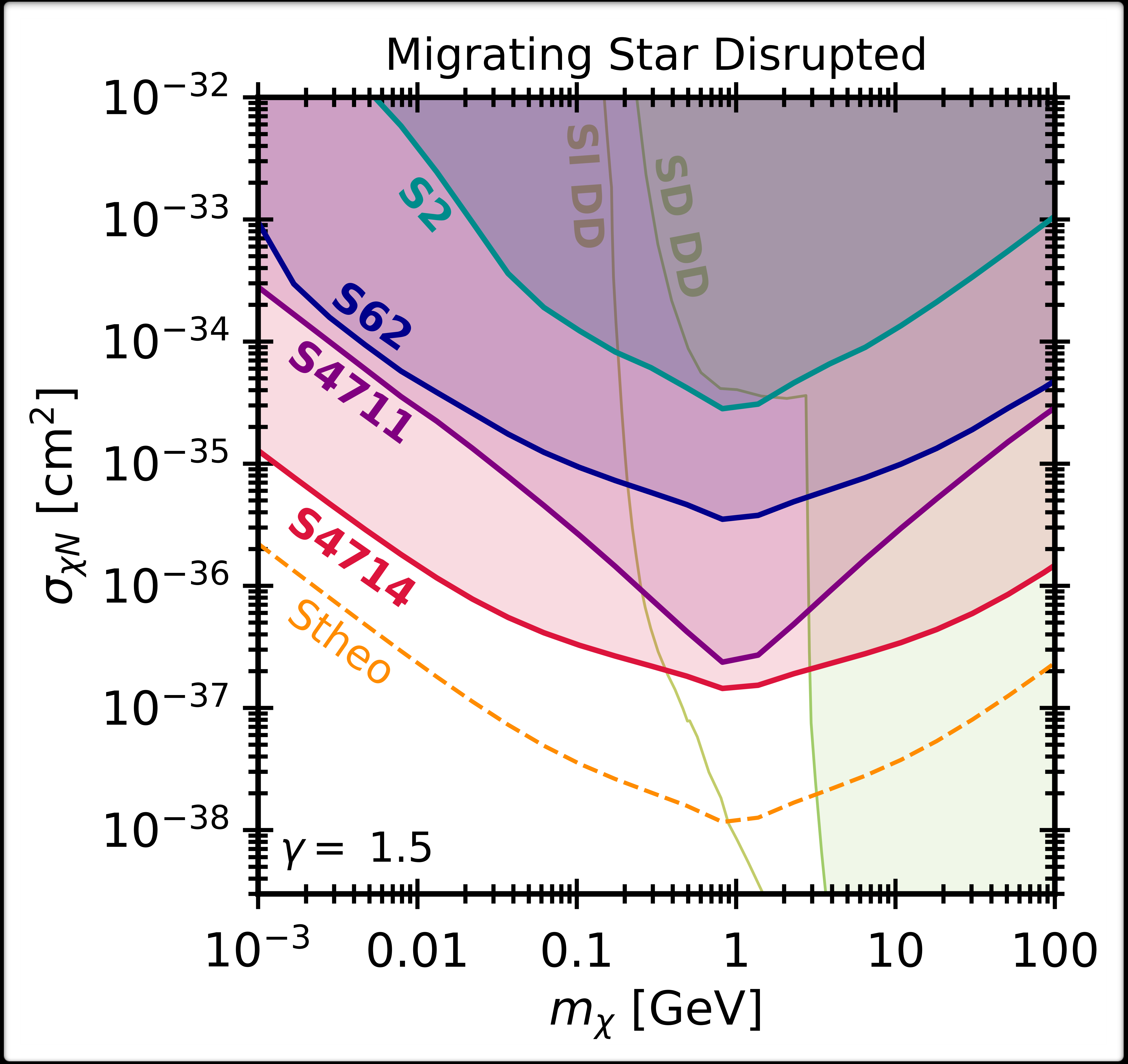
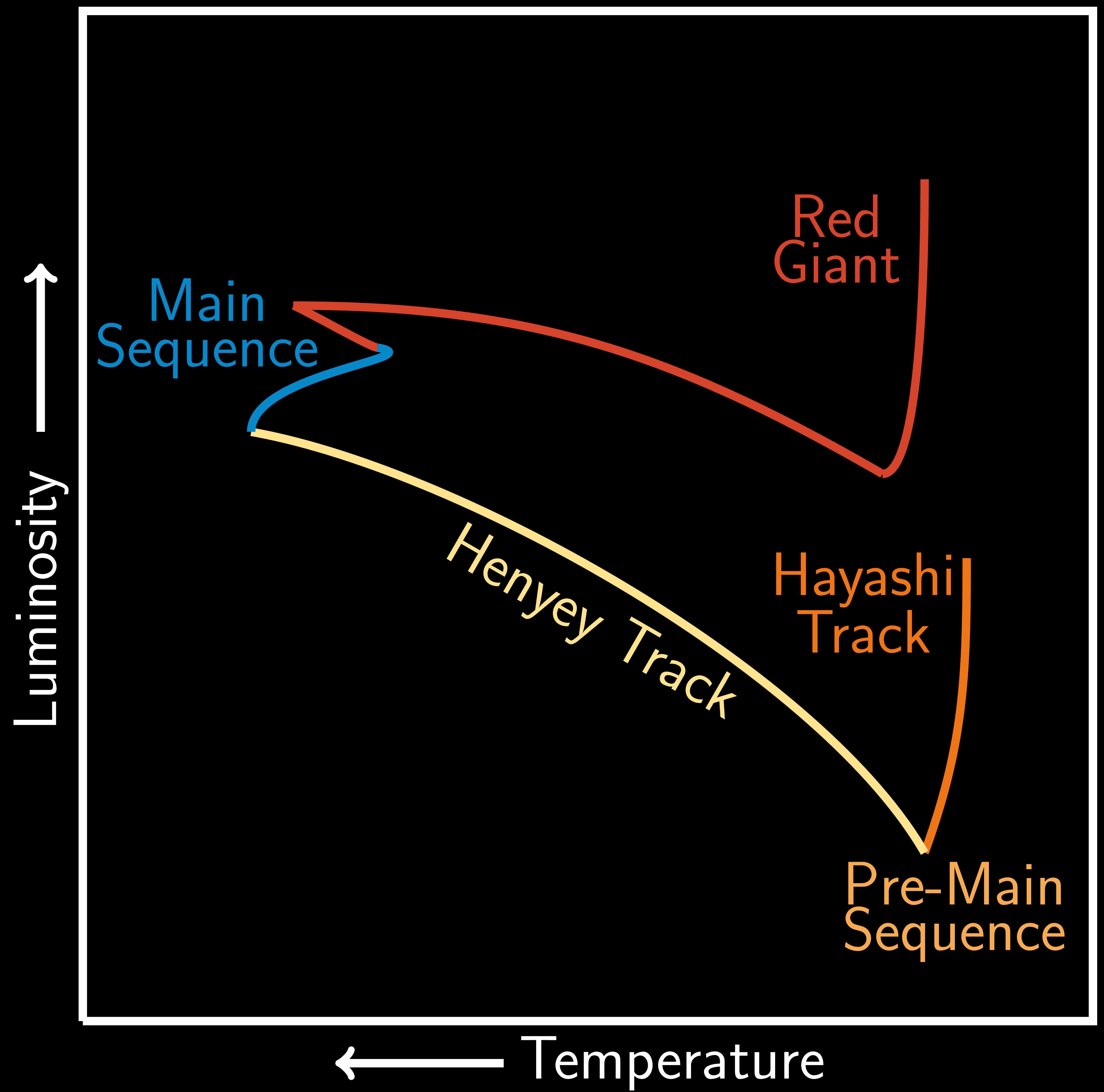


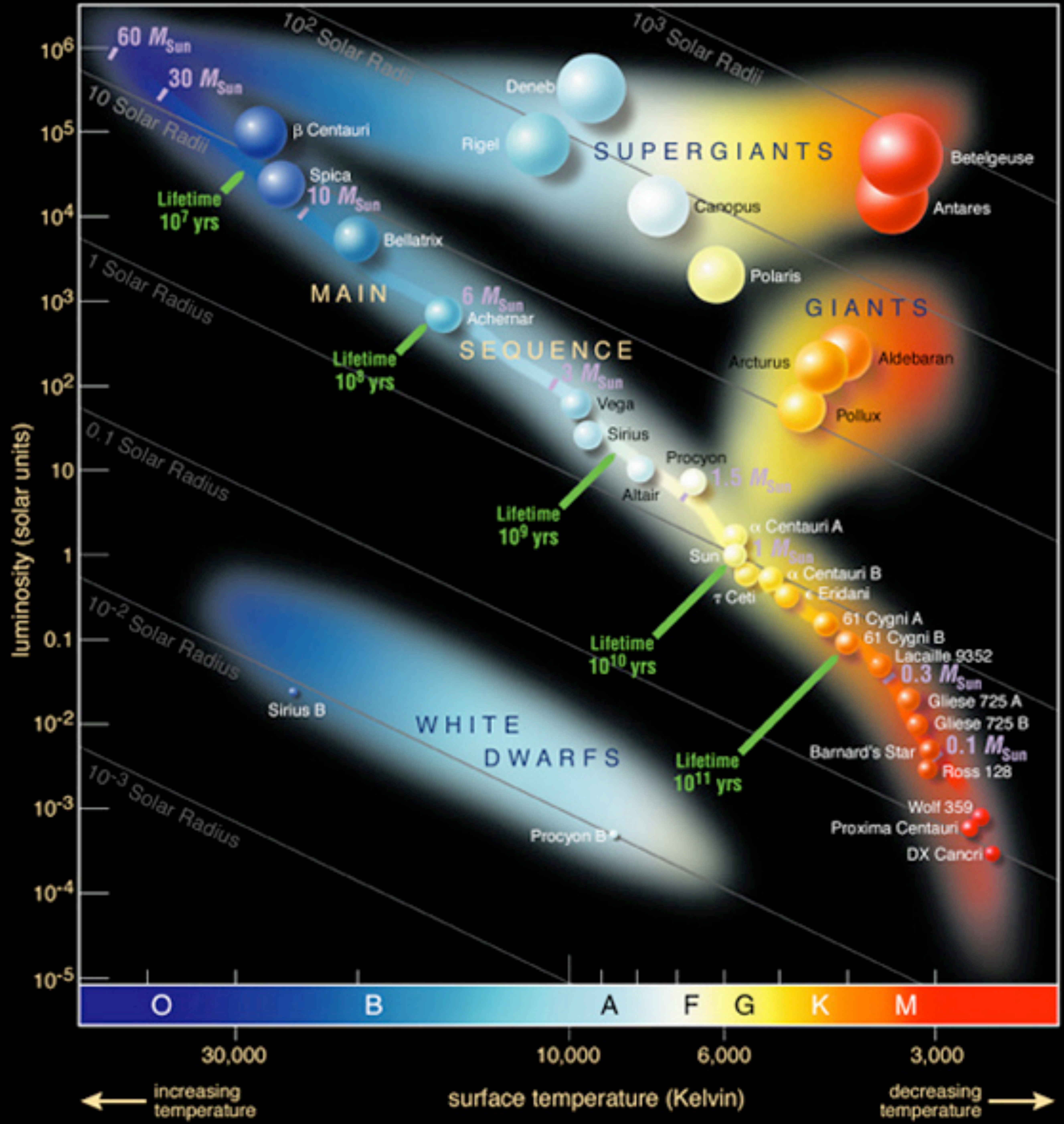


But:

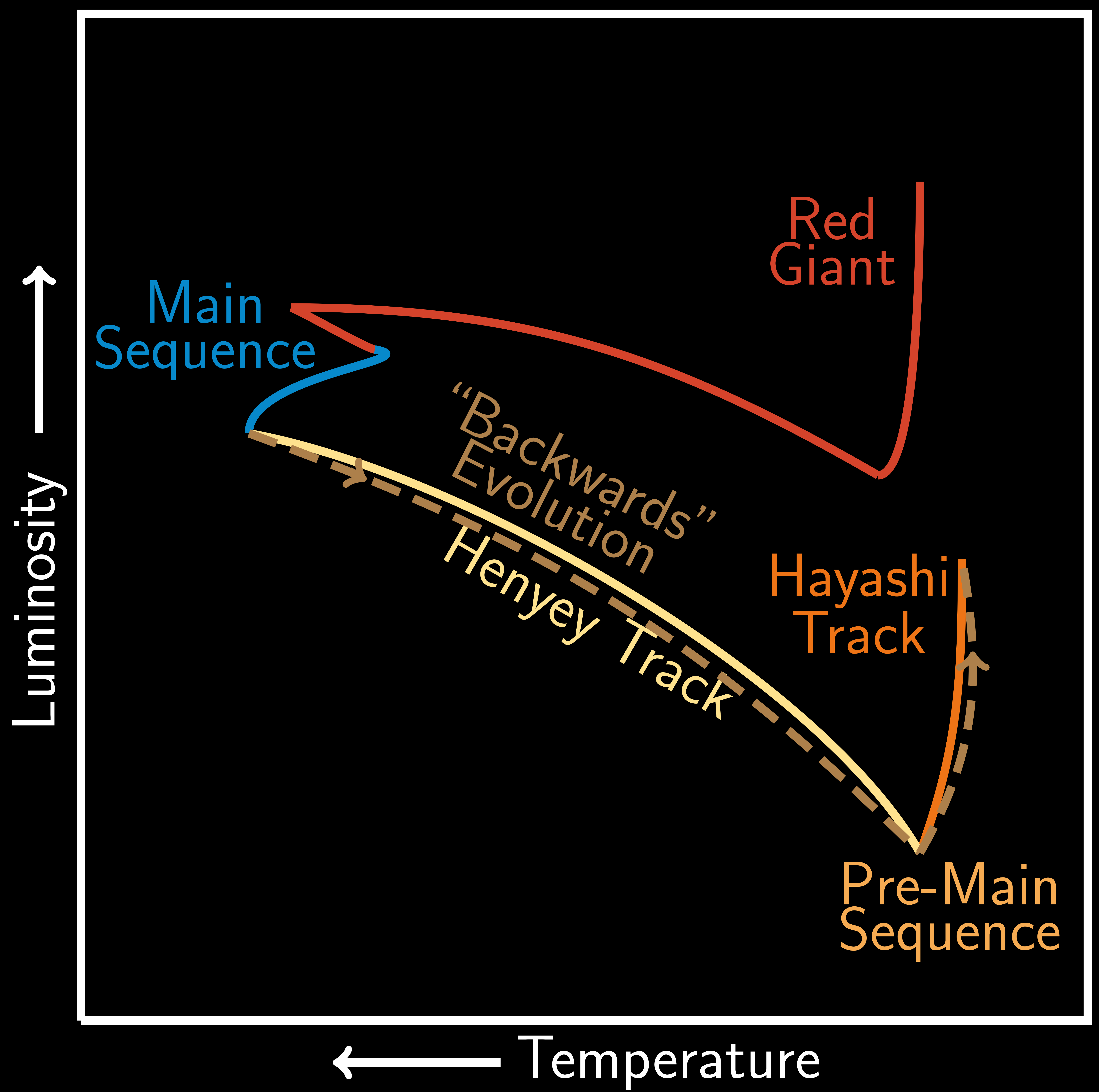
How Can You Use the Absence of a Star to Detect Something?

Immortal Stars

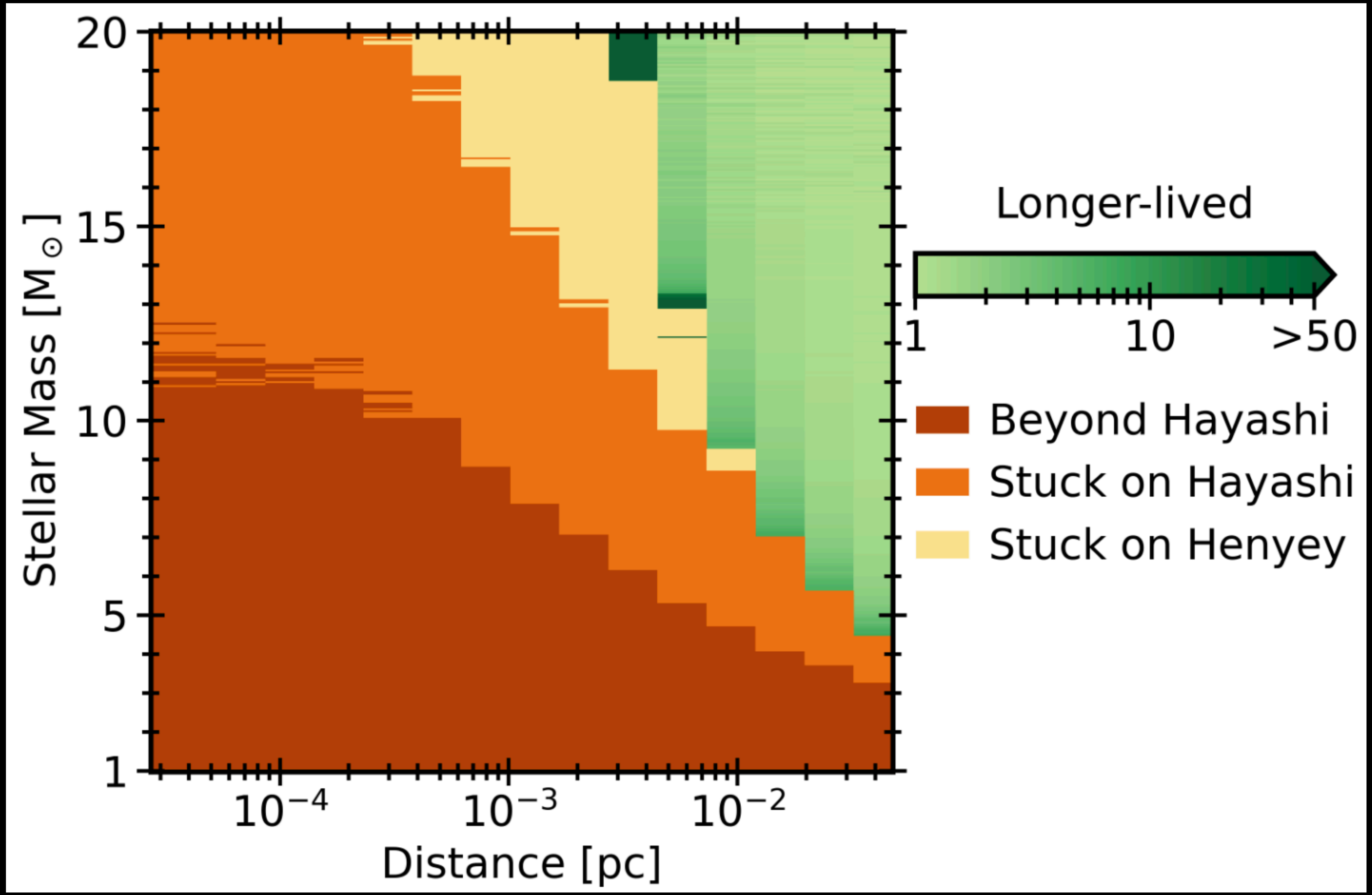


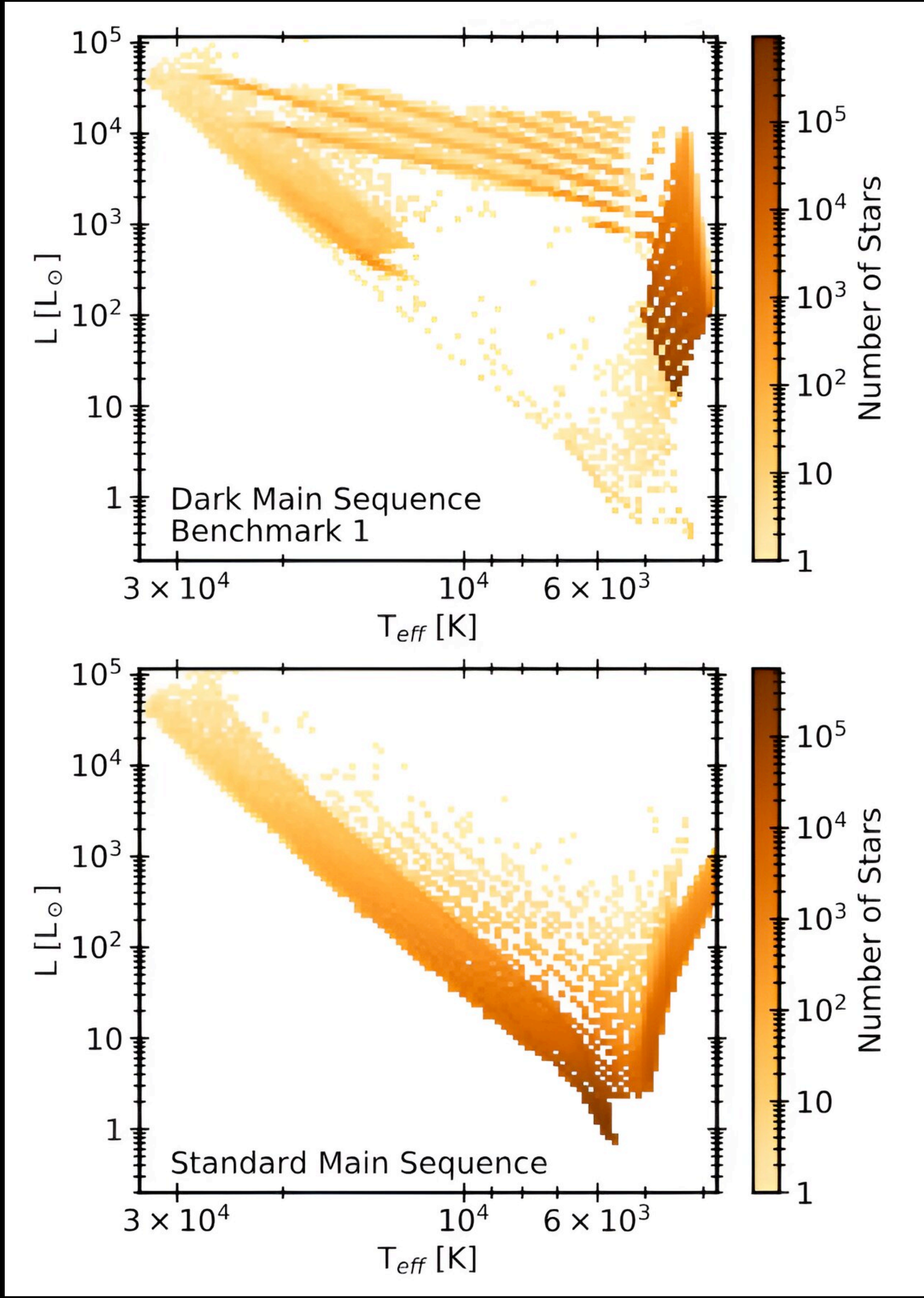


luminosity (solar units)
surface temperature (Kelvin)
increasing temperature
decreasing temperature
30,000
10,000
6,000
3,000
O
B
A
F
G
K
M
10 Solar Radii
10^2 Solar Radii
10^3 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^{-2} Solar Radius
10^{-3} Solar Radius
SUPERGIANTS
GIANTS
MAIN SEQUENCE
WHITE DWARFS
60 M_{Sun}
30 M_{Sun}
10 M_{Sun}
6 M_{Sun}
3 M_{Sun}
1.5 M_{Sun}
1 M_{Sun}
0.3 M_{Sun}
0.1 M_{Sun}
Lifetime 10^7 yrs
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^{10} yrs
Lifetime 10^{11} yrs
β Centauri
Spica
Bellatrix
Achernar
Vega
Sirius
Altair
Procyon
α Centauri A
Sun
α Centauri B
τ Ceti
ε Eridani
61 Cygni A
61 Cygni B
Lacaille 9352
Gliese 725 A
Gliese 725 B
Barnard's Star
Ross 128
Wolf 359
Proxima Centauri
DX Cancri
Deneb
Rigel
Canopus
Polaris
Betelgeuse
Antares
Arcturus
Aldebaran
Pollux
Sirius B
Procyon B


Red
Giant
Main
Sequence
"Backwards"
Evolution
Henyey Track
Hayashi
Track
Pre-Main
Sequence
Luminosity
Temperature

Immortal Stars





The type of signature observers can actually search for.

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Super-Kamiokande Searches for the Sun

Super-Kamiokande Strongly Constrains Leptophilic Dark Matter Capture in the Sun

Thong T.Q. Nguyen,[1,*] Tim Linden,[1,†] Pierluca Carenza,[1,‡] and Axel Widmark[1,2,§]

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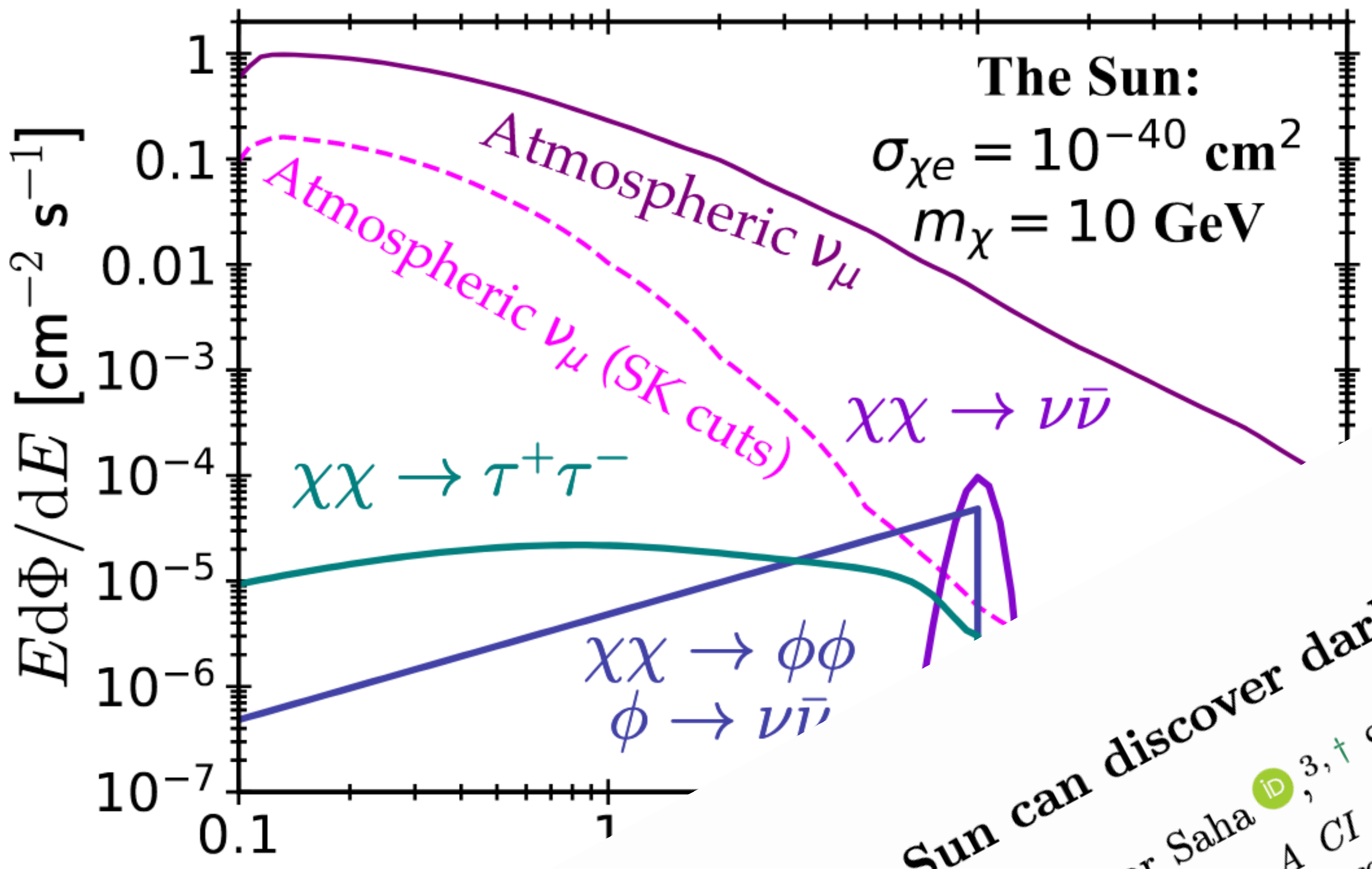
Introduction. — Detecting the particle interactions of dark matter is a cornerstone in our efforts to study beyond the standard model physics [1–3]. Many of the most ...nsitive constraints depend on searching for rare scat... interactions between the dark matter particle and ... model particles [4–11].
...rate strategies motivate current searches. ...ar, used in terrestrial detectors, uses un... to avoid astrophysical backgrounds ...o single dark matter interactions. ...een an effort to "go big", us... objects to constrain rare ...the large background. ... scattering of dark



DAMA/LIBRA and leptonically interacting Dark Matter

...him Kopp,[1,*] Viviana Niro,[1,†] Thomas Schwetz,[1,‡] and Jure Z...
[1] Max-Planck-Institute for Nuclear Physi...
PO Box 103980, 69029 Heidelberg, G...
[2] Theory Division, Physics Dep...
CERN, CH-1211 Geneva 23

CERN-PH-TH/2009-116

Abstra...

HRI-RECAPP-2023-03

Neutrinos from the Sun can discover dark matter-electron scattering

Tarak Nath Maity[1,2,3,*] Akash Kumar Saha[3,†] Sagnik Mondal[3,‡] and Ranjan Laha[3,§]
[1] Harish-Chandra Research Institute, A CI of Homi Bhabha National Institute, Chhatnag Road, Jhunsi, Prayagraj (Allahabad) 211019, India
[2] Regional Centre for Accelerator-based Particle Physics, Harish-Chandra Research Institute, Prayagraj (Allahabad) 211019, India
...ay Physics, Indian Institute of Science, C. V. Raman Avenue, Bengaluru 560012,
(Dated: August 25, 2023)


Detecting Dark Matter with Imploding Pulsars in the Galactic Center
Joseph Bramante
Department of Physics, 225 Nieuwland Science Hall,
University of Notre Dame, Notre Dame, IN 46556, USA
Tim Linden
Kavli Institute for Cosmological Physics 5640 South Ellis Avenue
University of Chicago Chicago, IL 60637
THE PECULIAR PULSAR POPULATION OF THE CENTRAL PARSEC
Jason Dexter
Department of Astronomy, University of California, Berkeley, CA 94720-3411, USA
Ryan M. O'Leary
Department of Astronomy, University of California, Berkeley, CA 94720-3411, USA
Draft version April 14, 2018
ABSTRACT
The Galactic centre pulsar population
Jayanth Chennamangalam and D. R. Lorimer
Department of Physics and Astronomy, West Virginia University, PO Box 6315, Morgantown, WV 26506, USA
National Radio Astronomy Observatory, PO Box 2, Green Bank, WV 24944, USA
ABSTRACT

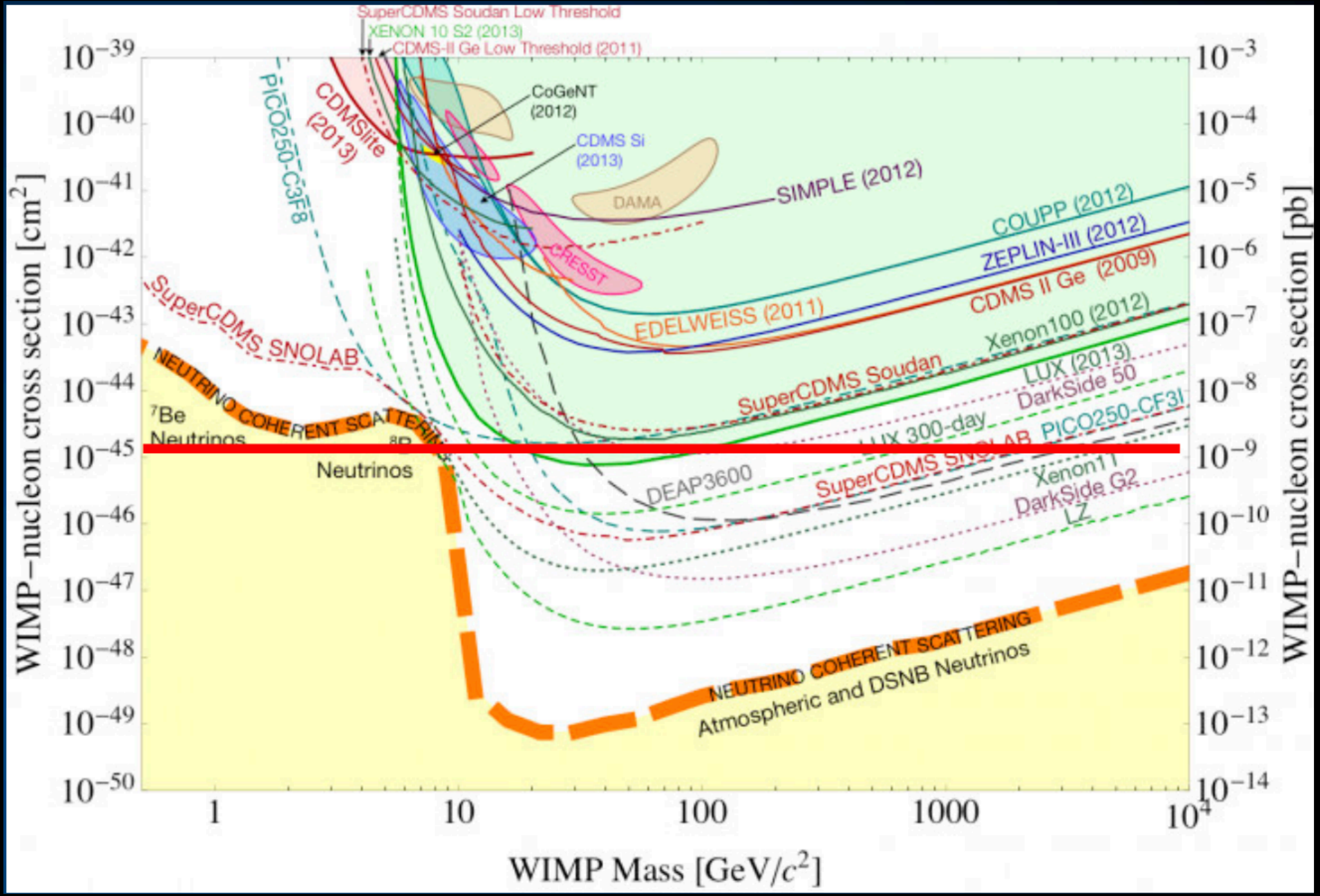
Neutron Stars are the Coolest Object in Physics

- $1.4\ M_{\odot}$ compressed into a 10 km radius
- Spinning up to $700\ s^{-1}$ (42000 rpm) -> velocity of 0.2c at the equator.
- Oblate spheroid to within 0.1 part in a million and spin-down power known to a part in 10^{20}.
- Magnetic field of 10^{10} T at the surface, electric field produces a potential of 1000 PV.

Neutron Stars as the Optimal Dark Matter Detectors

- **Direct detection cross-sections near 10^{-46} cm^2 produce ~1 event/(ton yr)**

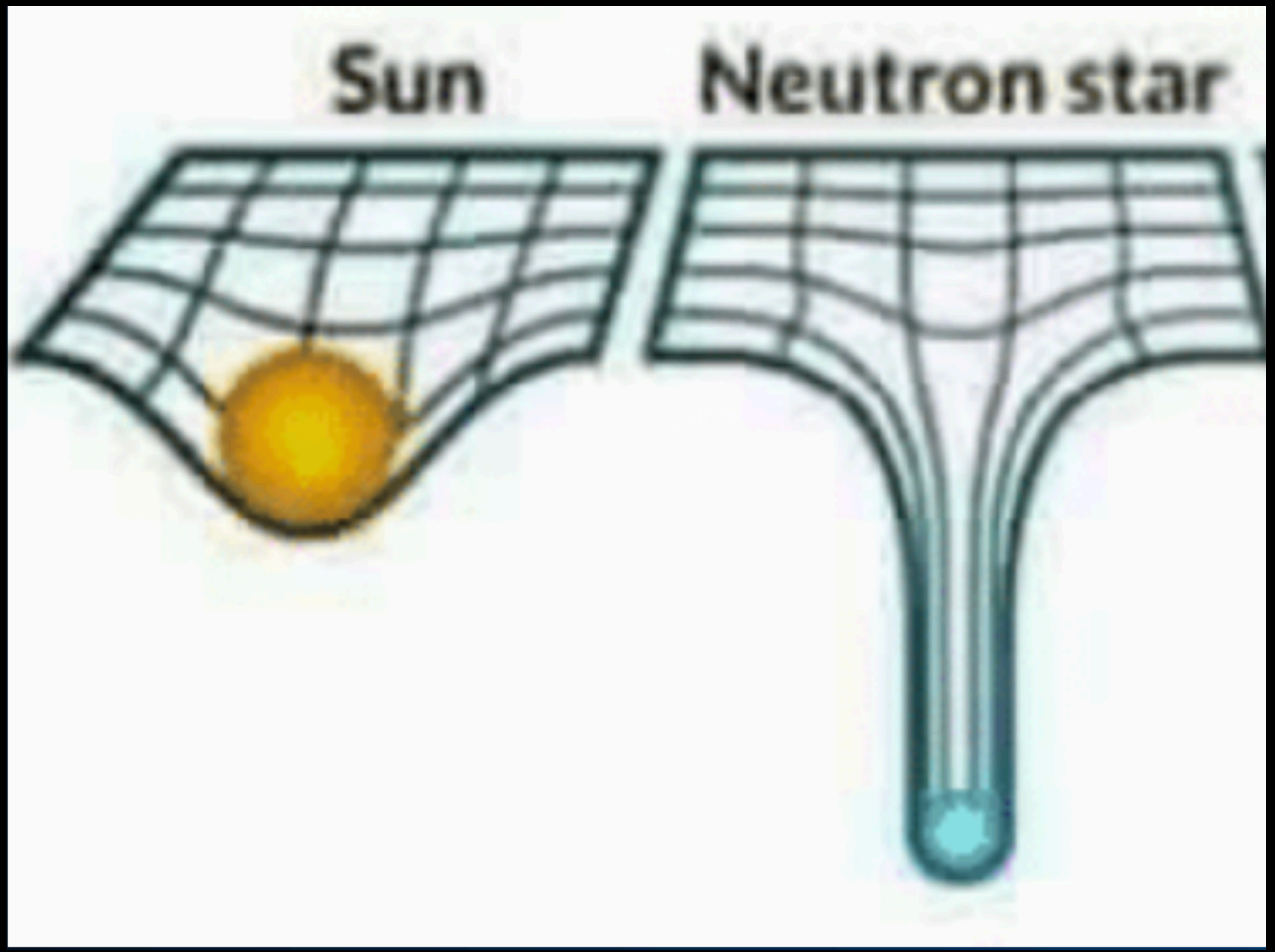
- **Sensitivity peaks near Xenon mass, and falls off significantly at higher or lower masses.**

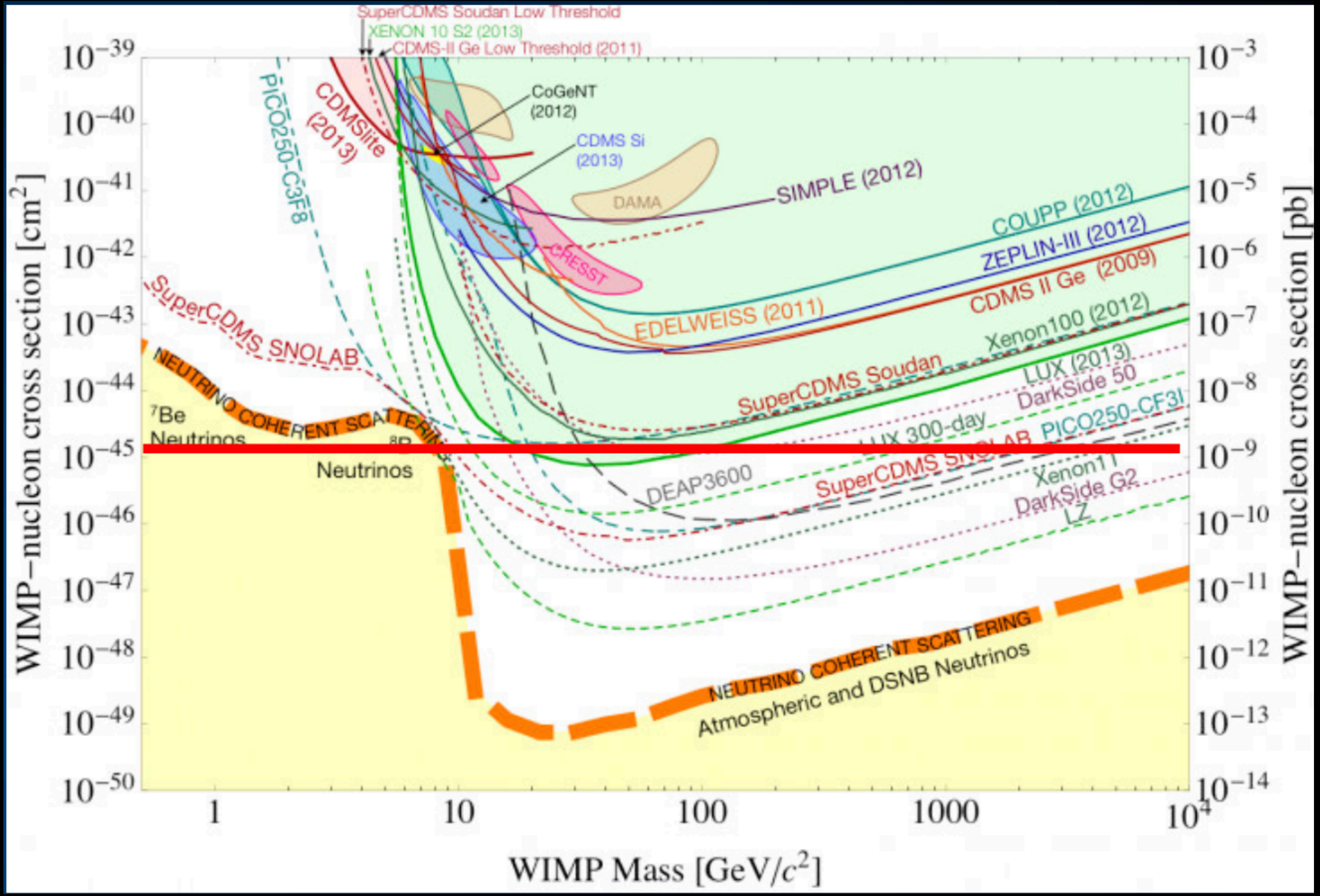


$$\sigma_{\rm sat}^{\rm single} \simeq \pi R^2 m_{\rm n}/M \simeq 2\times 10^{-45}\ {\rm cm}^2\ \left(\frac{1.5\ {\rm M}_\odot}{M}\right)\left(\frac{R}{10\ {\rm km}}\right)^2$$

Neutron Stars as the Optimal Dark Matter Detectors

- **Direct detection cross-sections near 10^{-46} cm^2 produce ~1 event/(ton yr)**





$$b_{\rm max} = \left(\frac{2GMR}{v_x^2}\right)^{1/2}\left(1 - \frac{2GM}{R}\right)^{-1/2}$$

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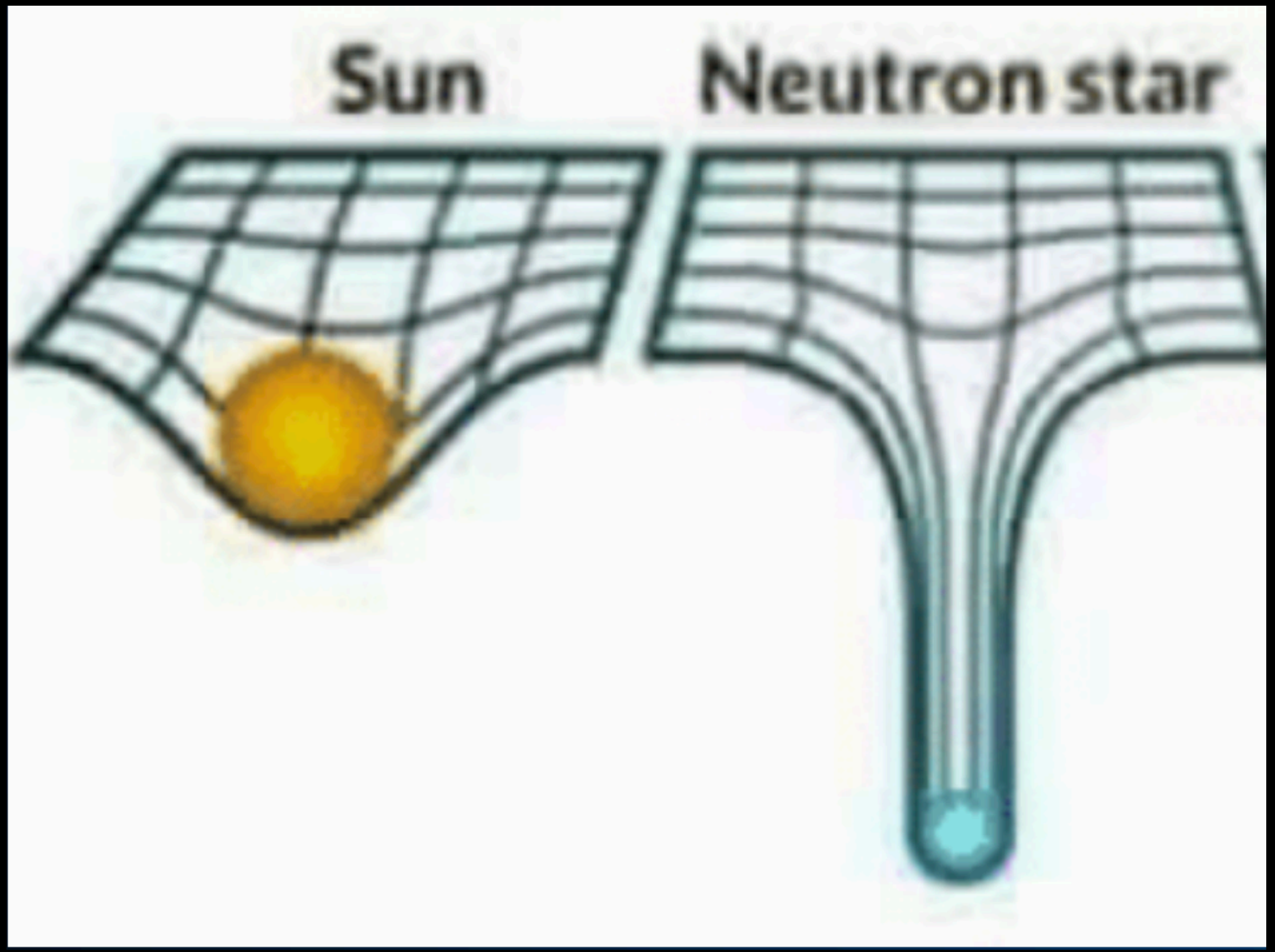
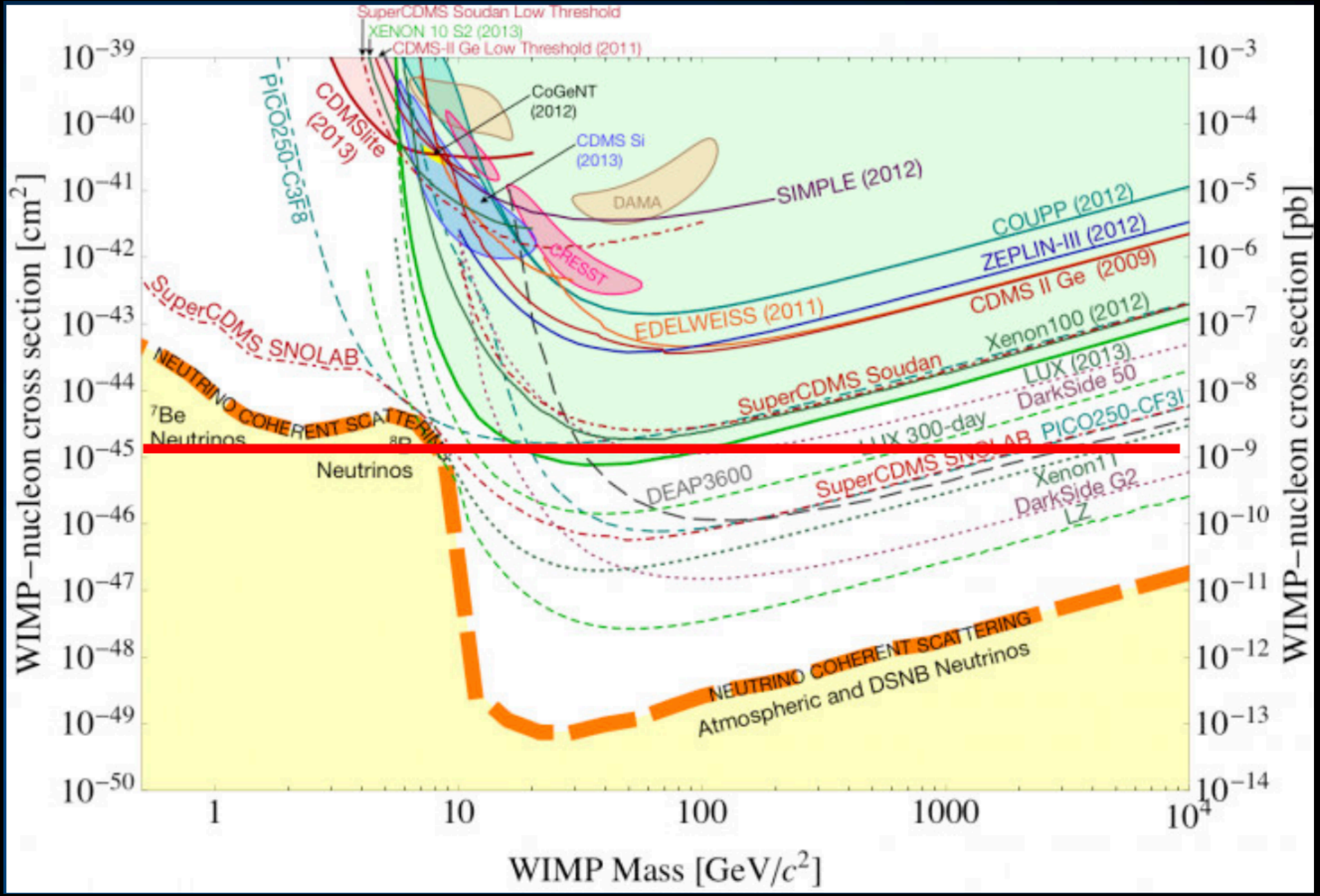
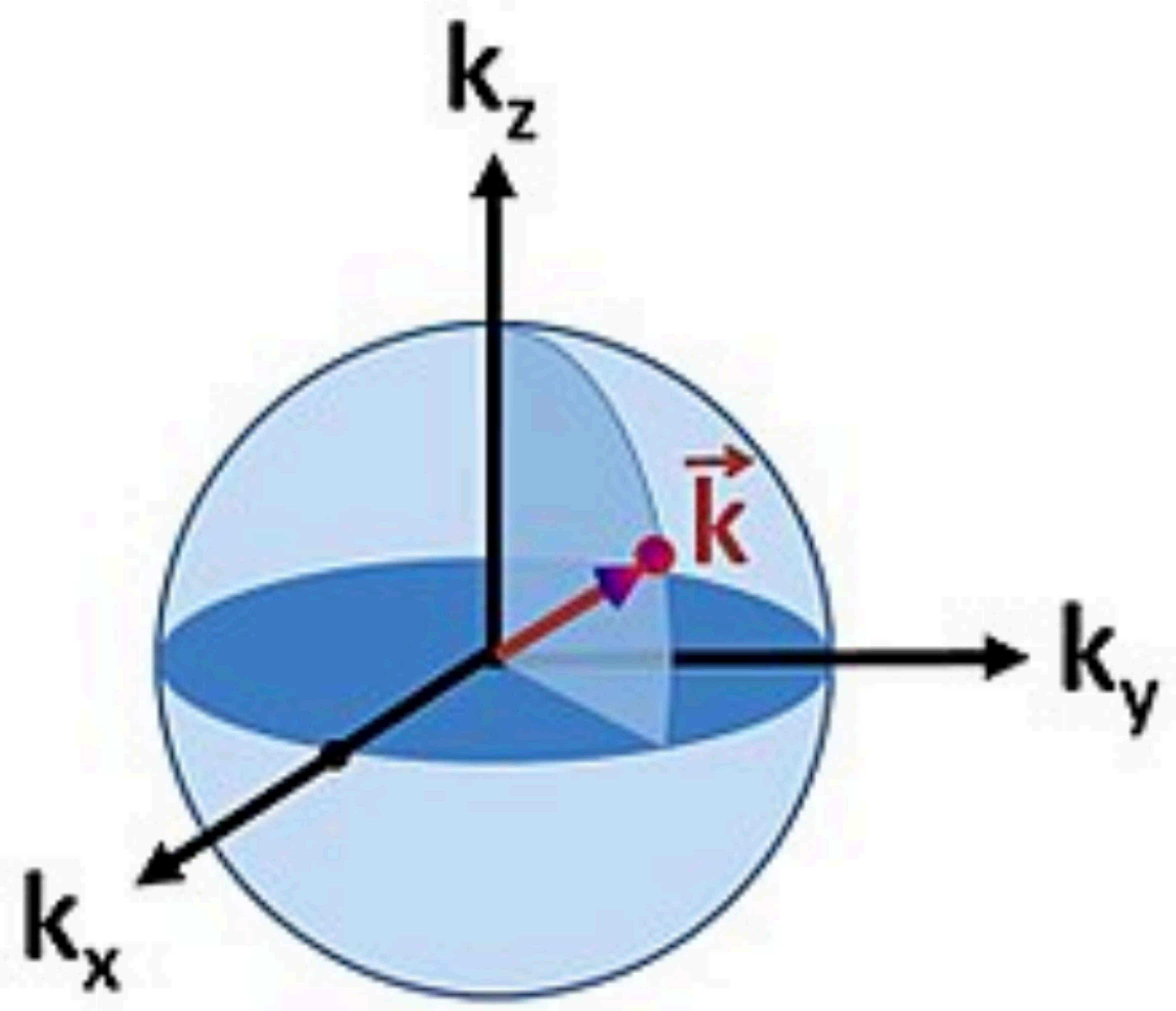




$$v_{esc} = \sqrt{\frac{2GM}{r}} \sim 0.7c$$

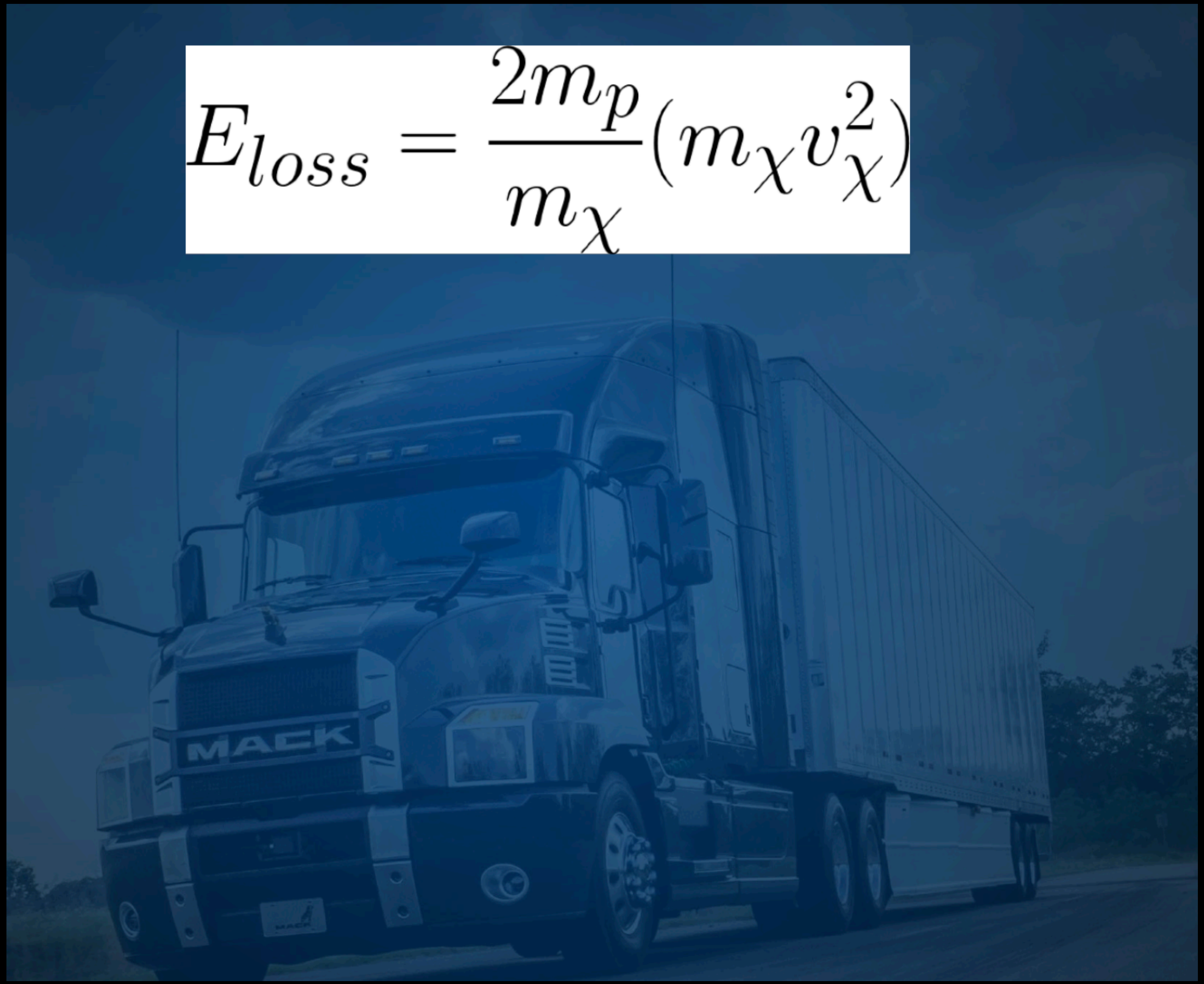
Energy Injection is Roughly Independent of Mass

Paul Blocking (< 1 GeV)



$$p_{\mathrm{F,n}} \simeq 0.45 \ \mathrm{GeV} \ (\rho_{NS}/(4 \times 10^{38} \ \mathrm{GeV \ cm^{-3}}))$$

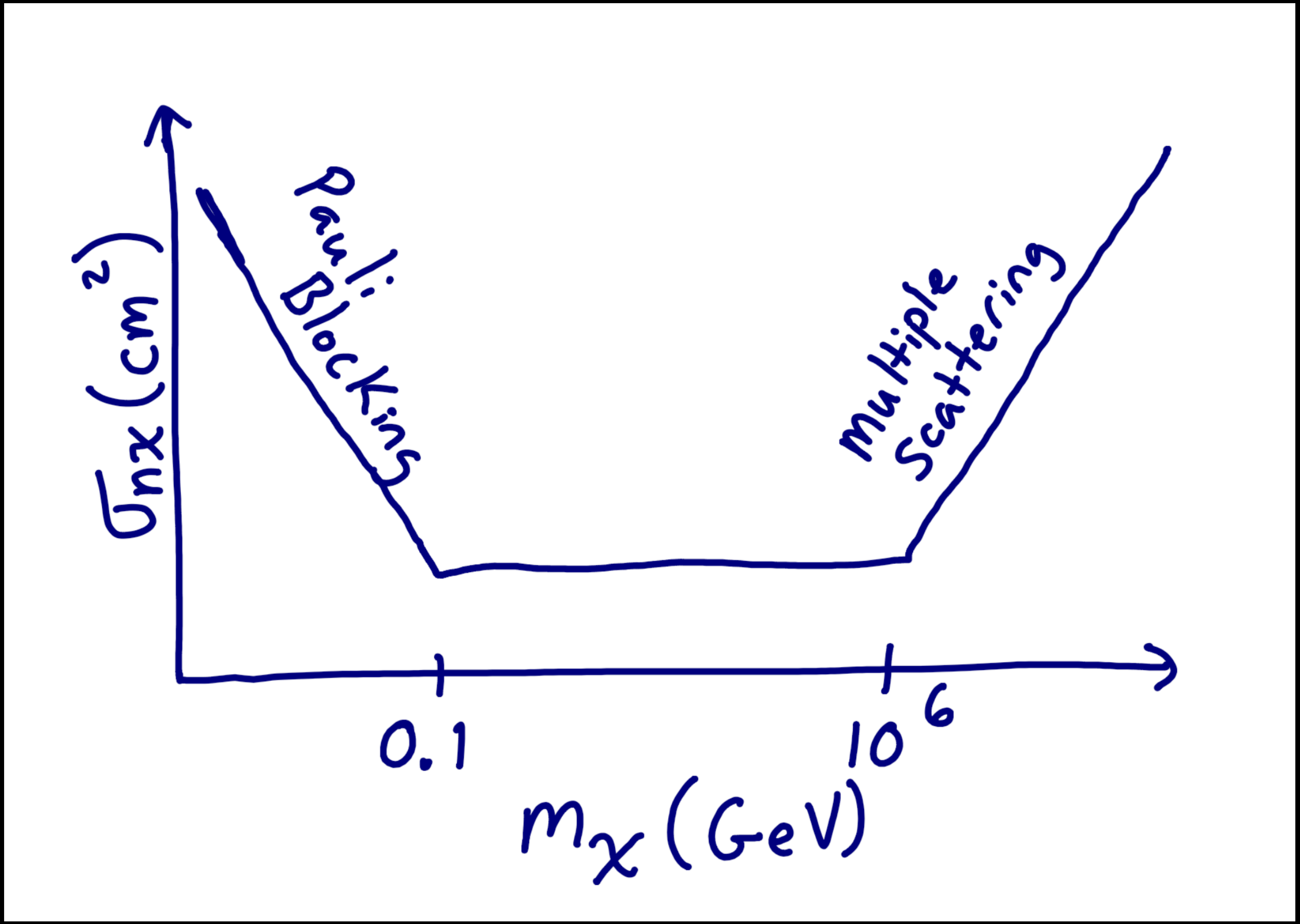
Multi-Scattering (>1 PeV)



$$E_{loss} = \frac{2m_p}{m_\chi}(m_\chi v_\chi^2)$$

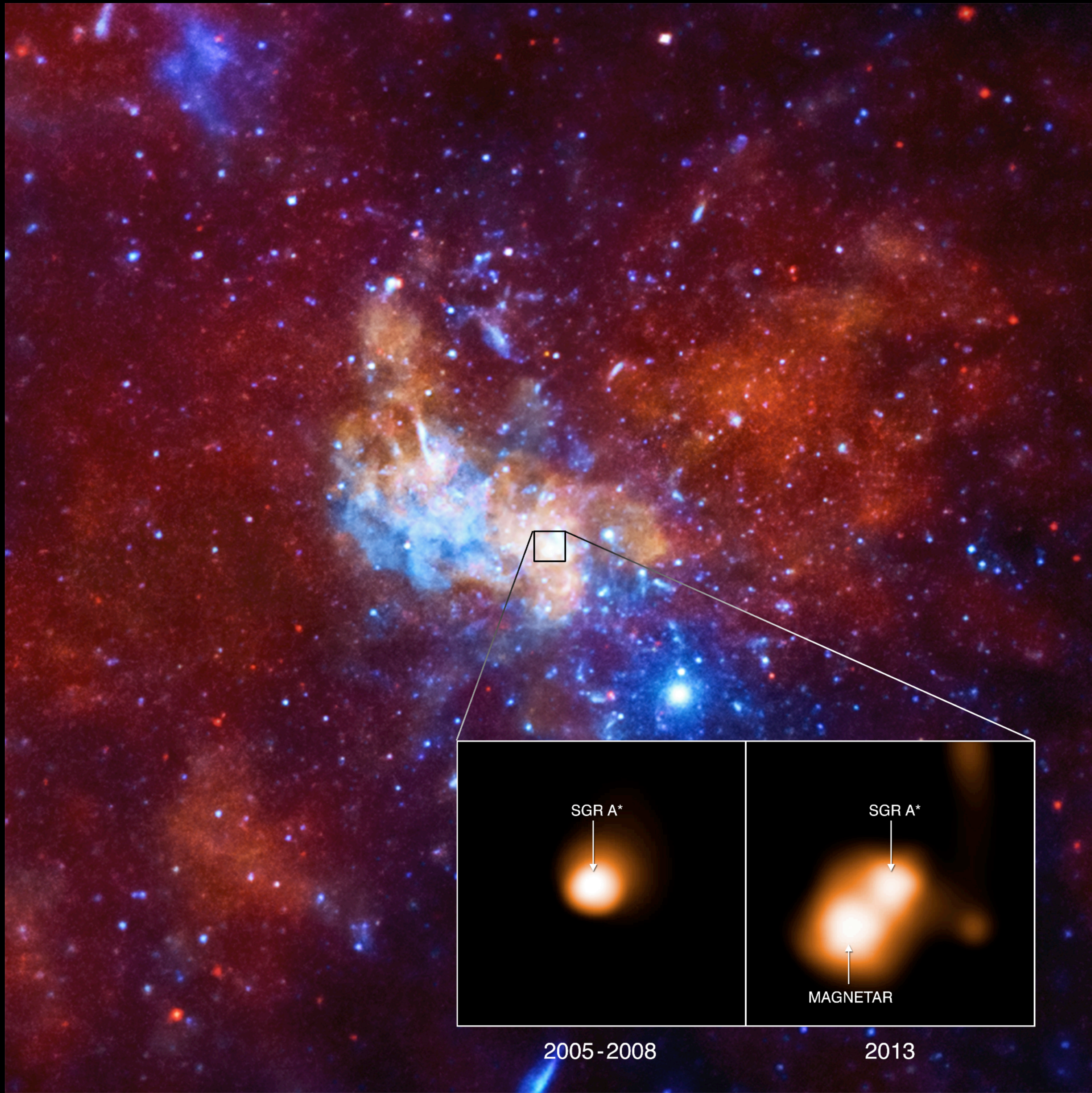
$$\sigma_{\mathrm{sat}}^{\mathrm{multi}} \simeq 2 \times 10^{-45} \ \mathrm{cm}^2 \left(\frac{m_x}{\mathrm{PeV}}\right)\left(\frac{1.5 \ \mathrm{M}_\odot}{M}\right)\left(\frac{R}{10 \ \mathrm{km}}\right)^2$$

Energy Injection is Roughly Independent of Mass



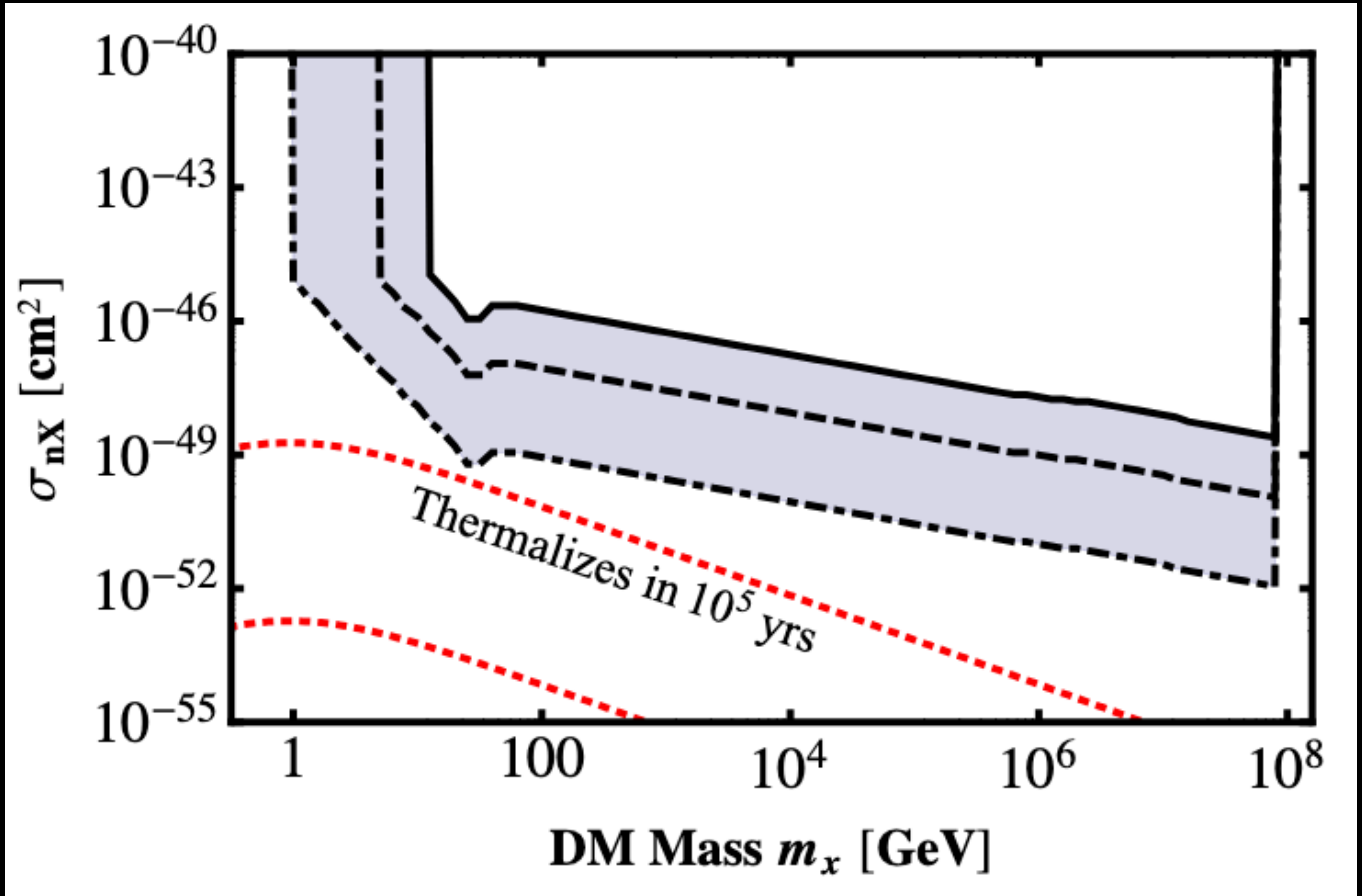
The 2013 GC Magnetar Detection

- Before 2013, it was thought that pulse dispersion made GC pulsars invisible.
- Magnetar observed (First in X-rays!) in 2013.
- Largest pulse dispersion of any existing pulsar, but not sufficient to make GC pulsars invisible.



Dark Matter interactions in NS

- Dark Matter accumulation can eliminate these pulsars:
- Need DM to either be non-annihilating massive fermions or bosons (to avoid Fermi degeneracy pressure)

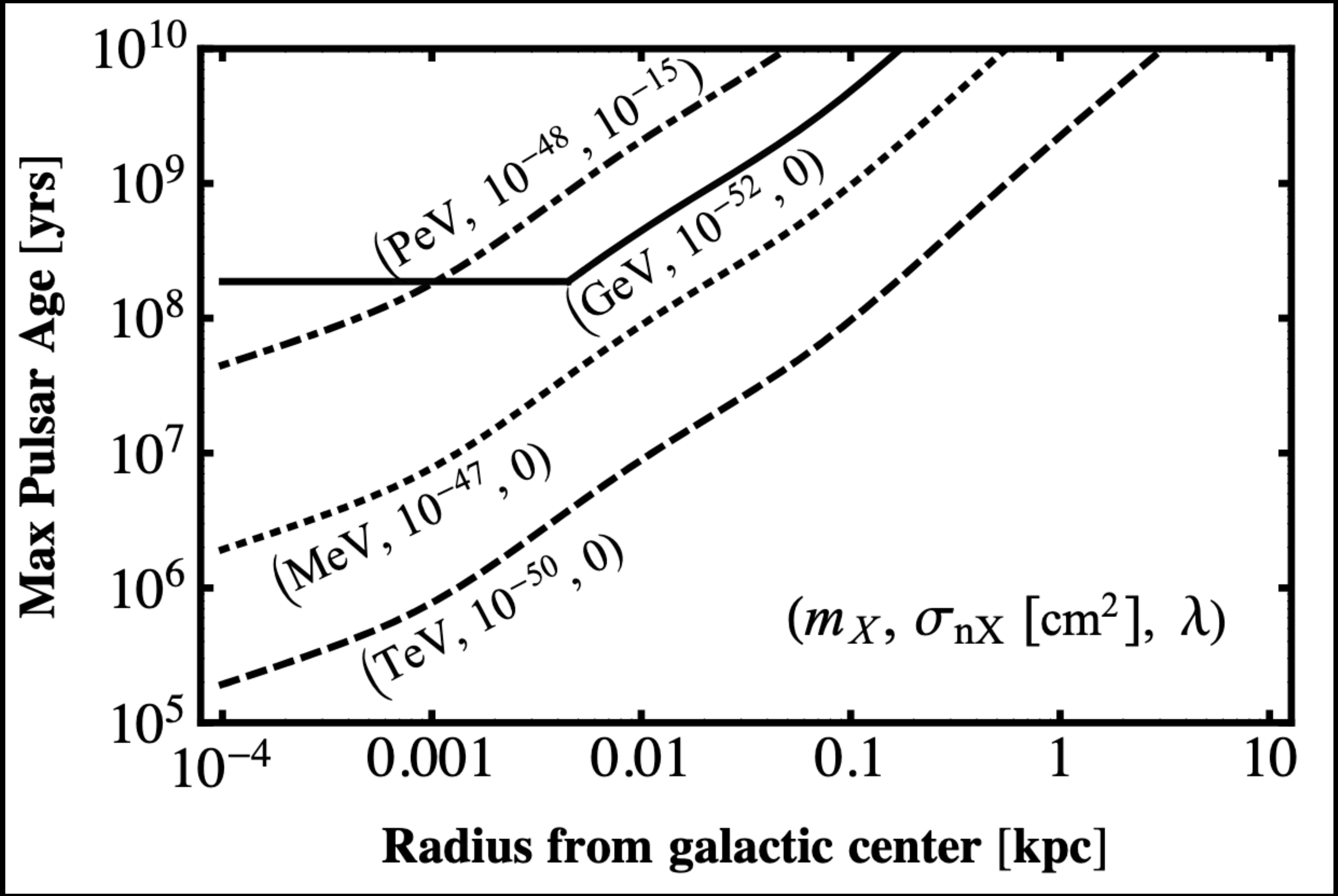


But:

How Can You Use the Absence of a Star to Detect Something?

Dark Matter interactions in NS

- Dark Matter accumulation can eliminate these pulsars:
- Need DM to either be non-annihilating massive fermions or bosons (to avoid Fermi degeneracy pressure)
- A New Astrophysical observable! A maximum age for pulsars that depends on GC radius.



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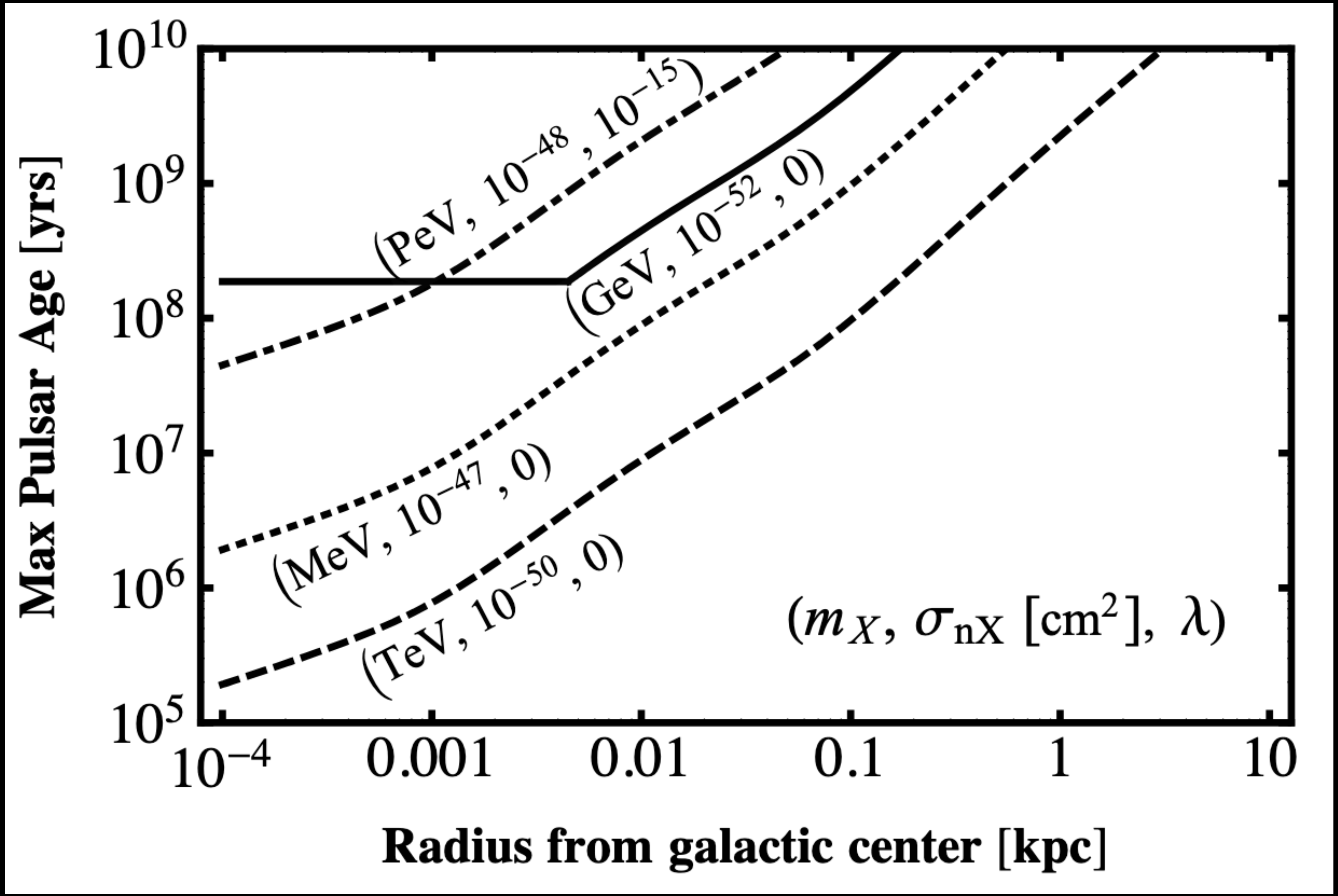
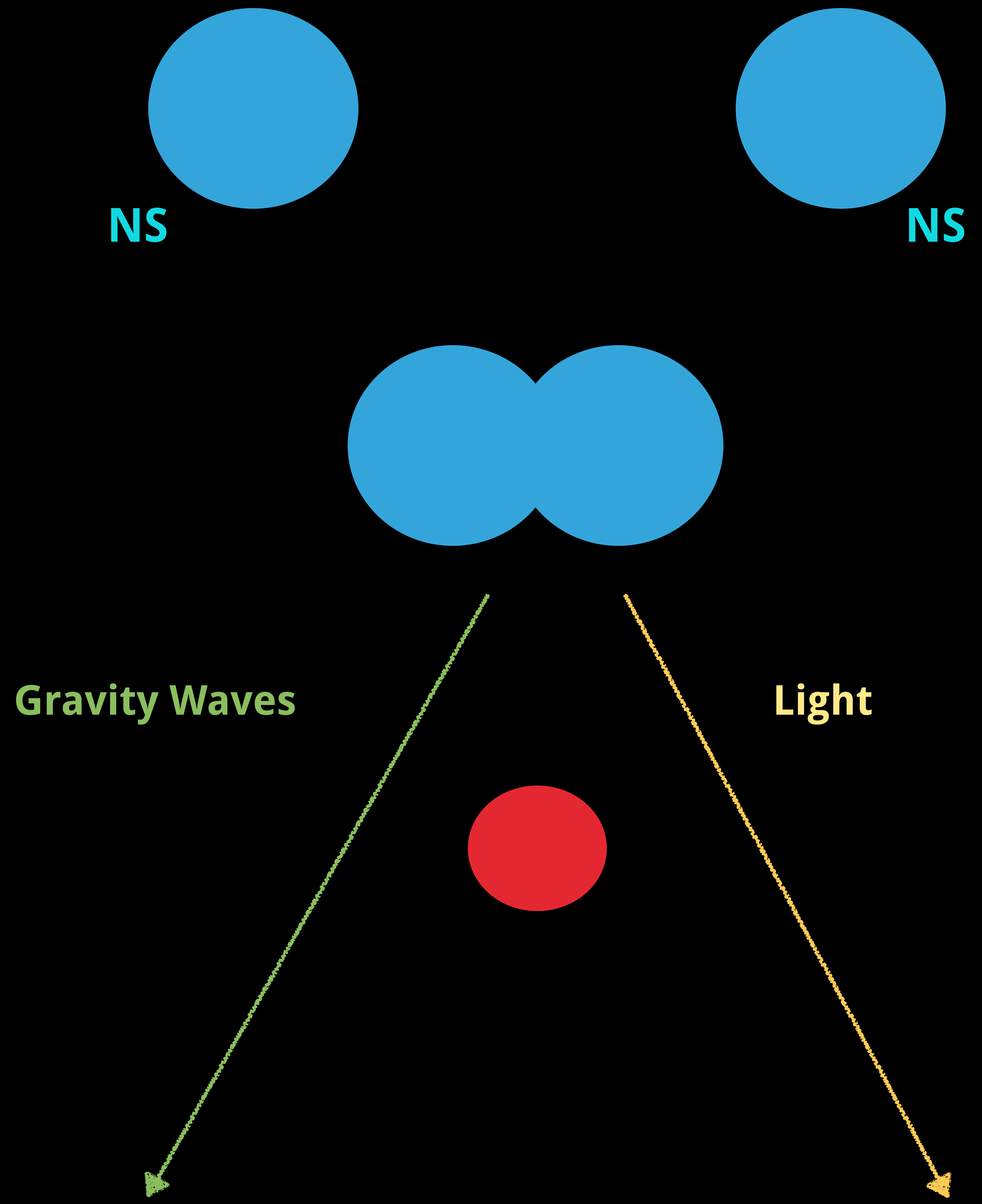
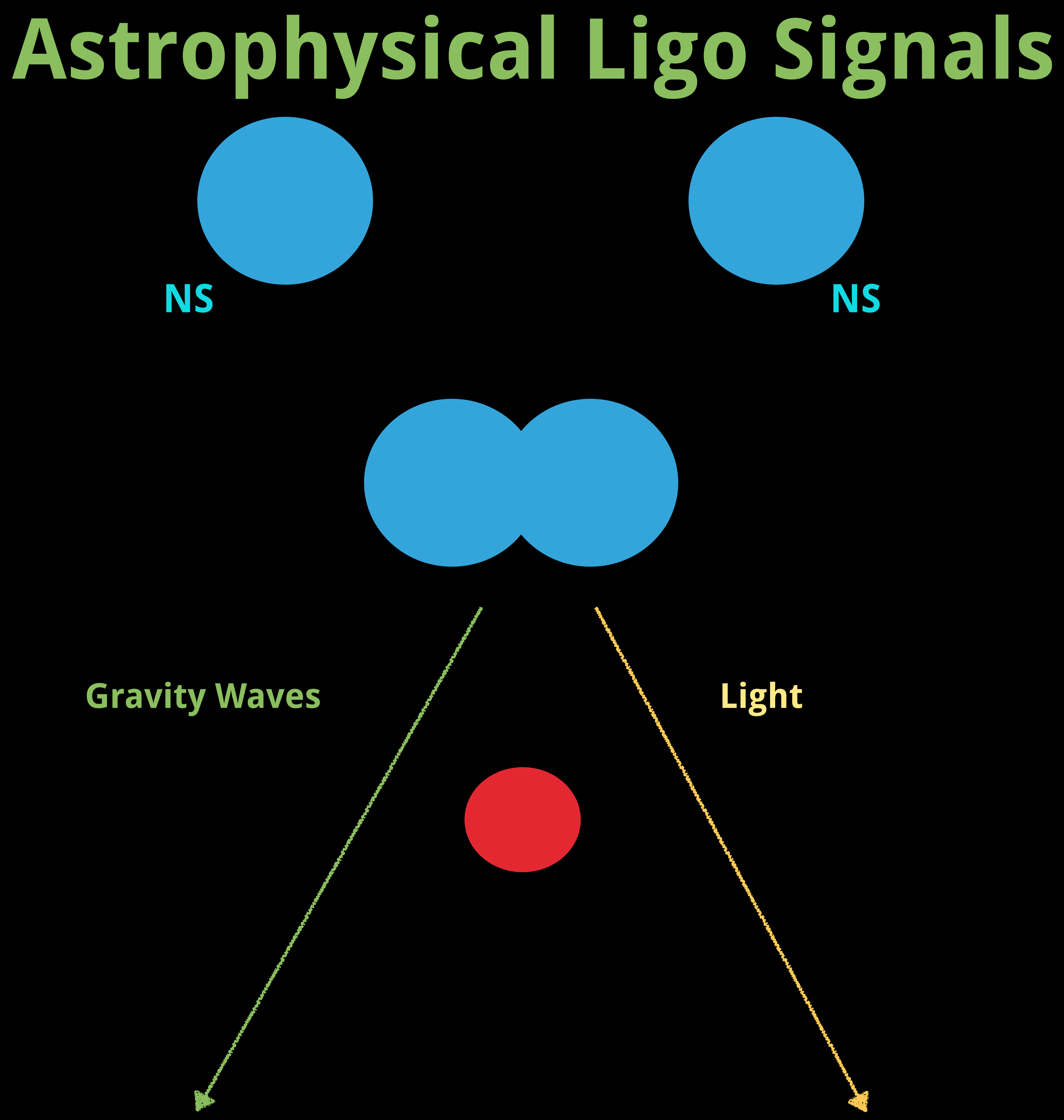


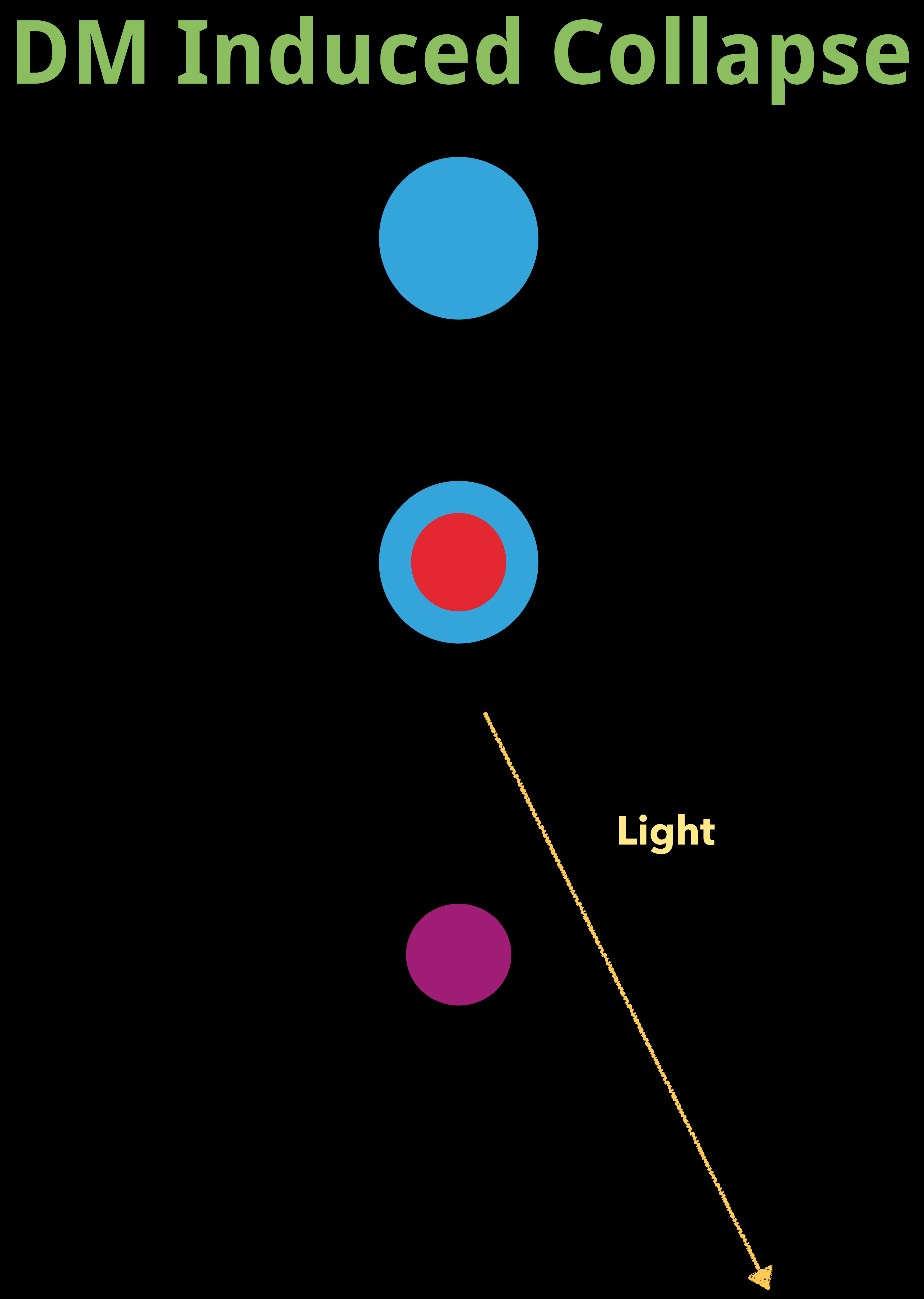
Separation of Electromagnetic and Gravitational Signals

Astrophysical Ligo Signals

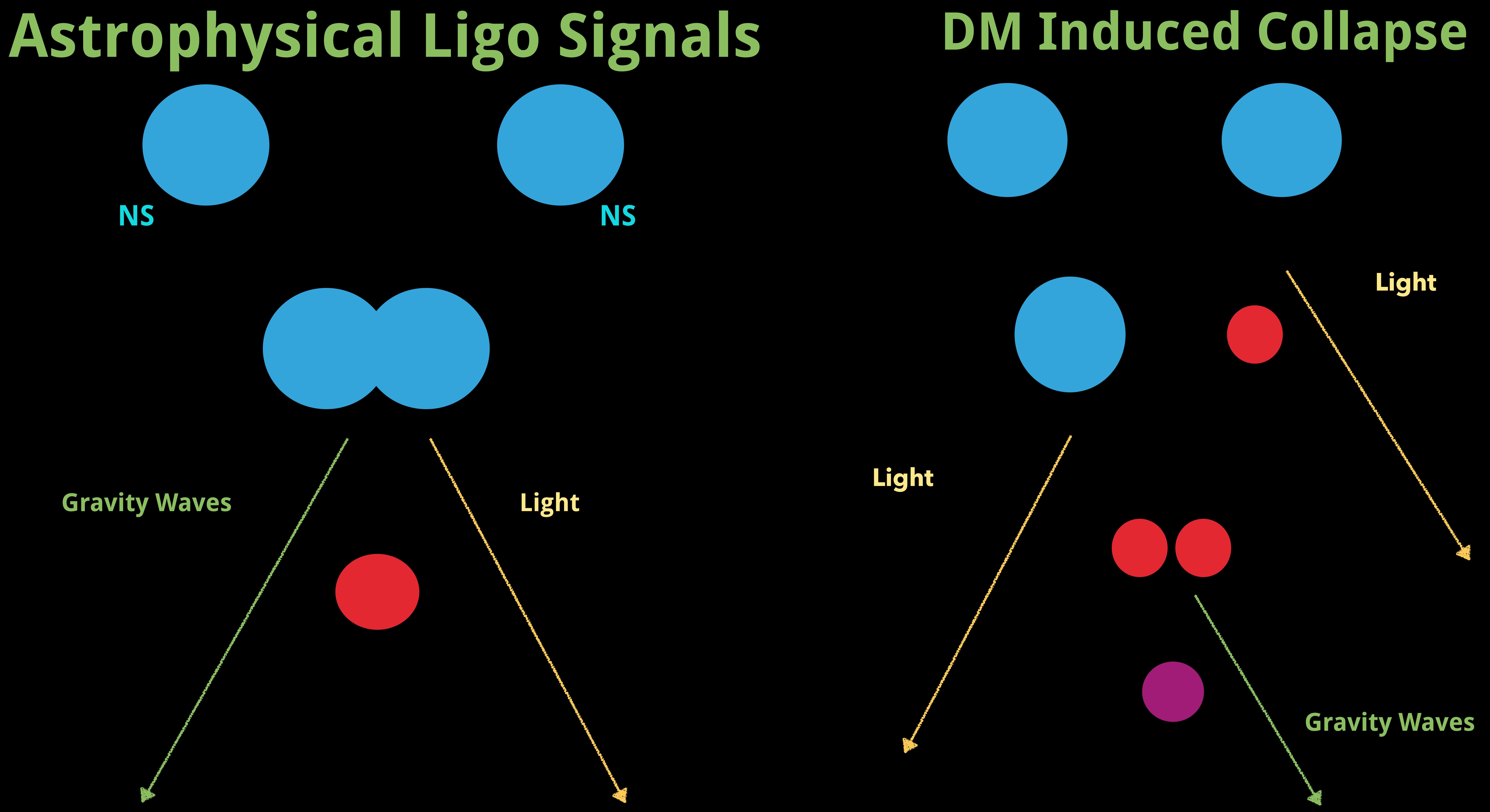


Separation of Electromagnetic and Gravitational Signals





Separation of Electromagnetic and Gravitational Signals



How to Do Science in the High-Risk High-Reward Regime

1.) Avoid Two-Miracle Studies

- Standard model miracles cost half. ✅
- Miracles can be correlated

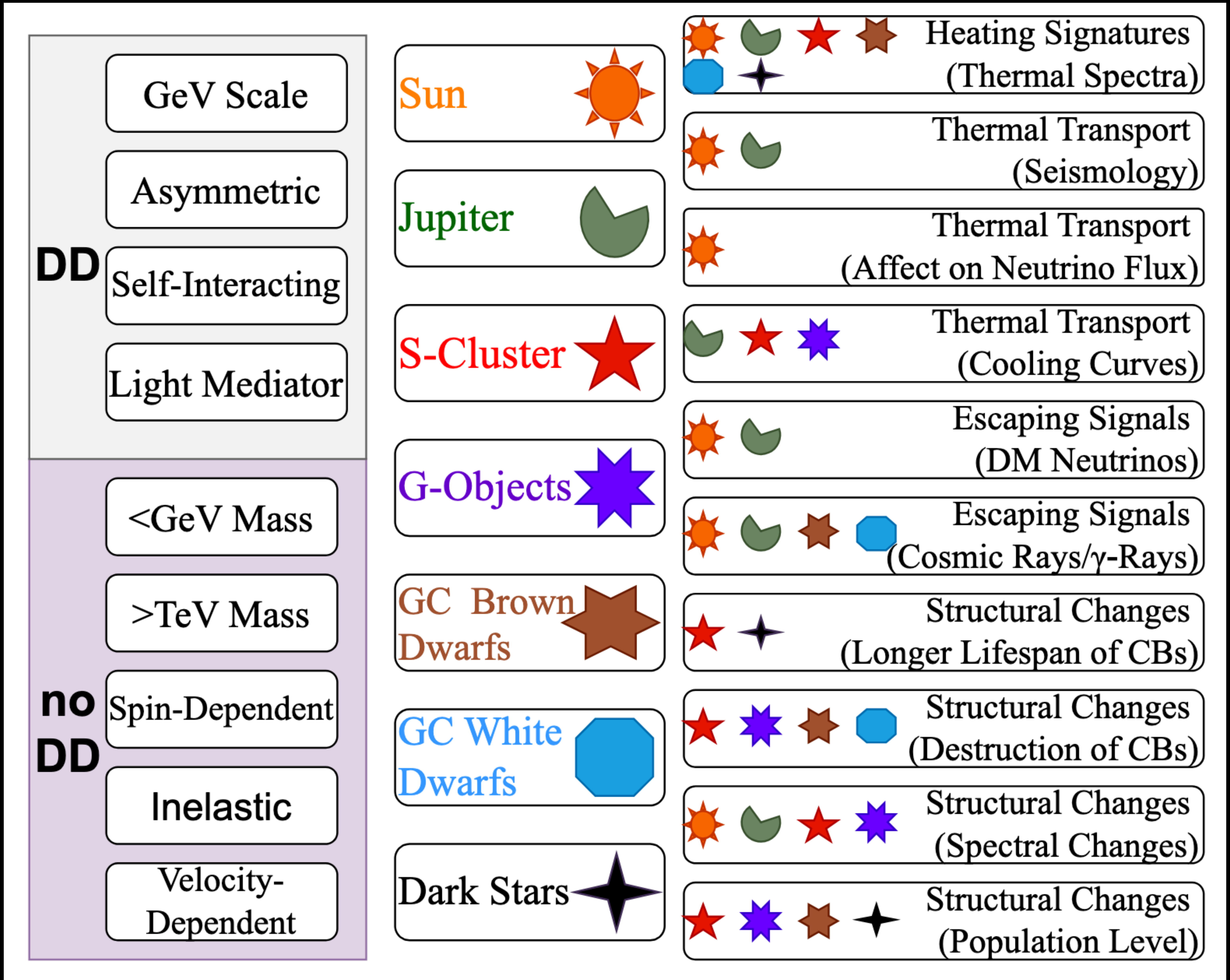
2.) Focus on observables

- When the risk is high, observers will not spend effort on studies. ✅

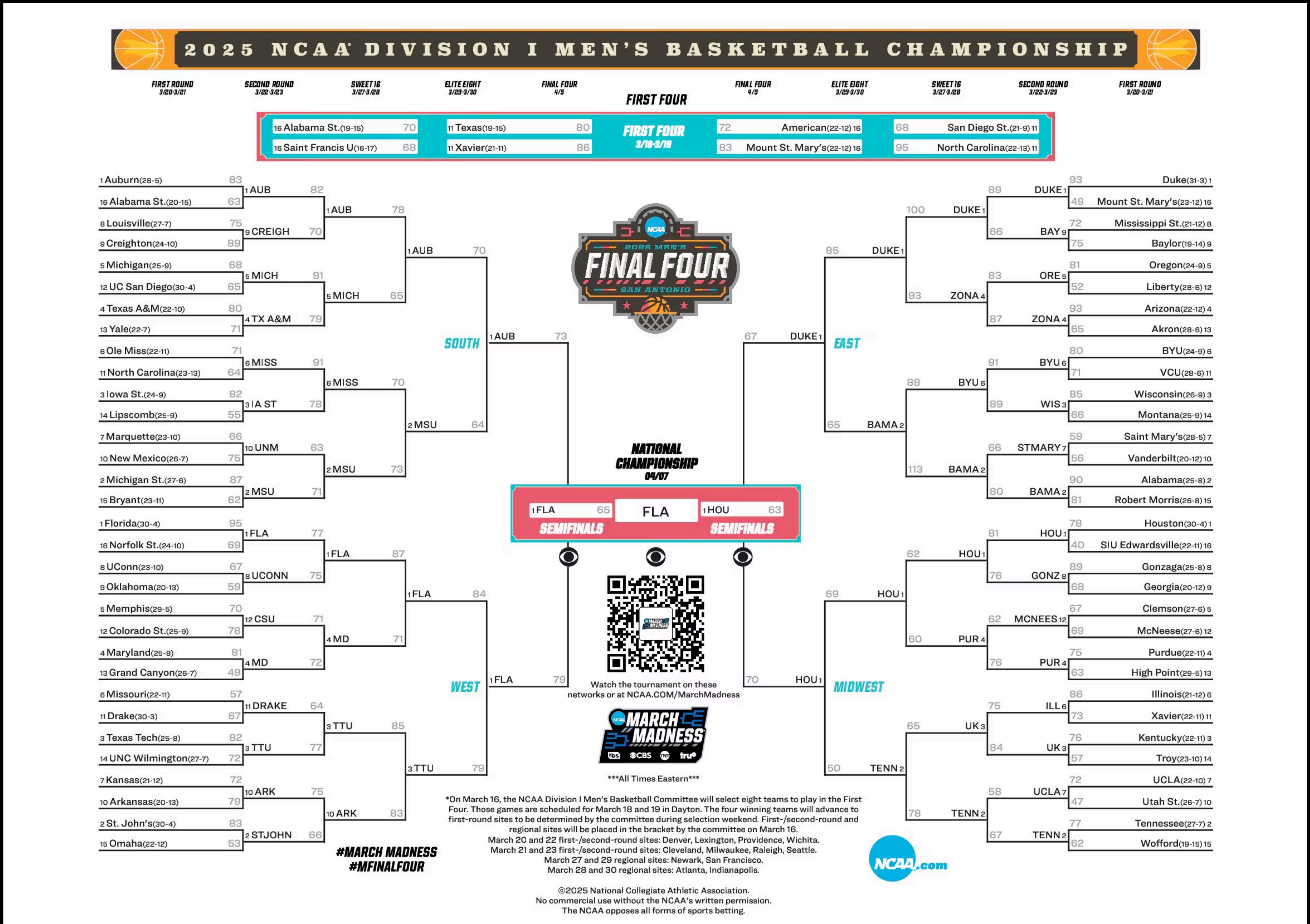
3.) Attack the biggest uncertainty, and then move on. ✅

- Every individual study is individually unlikely.

Conclusions



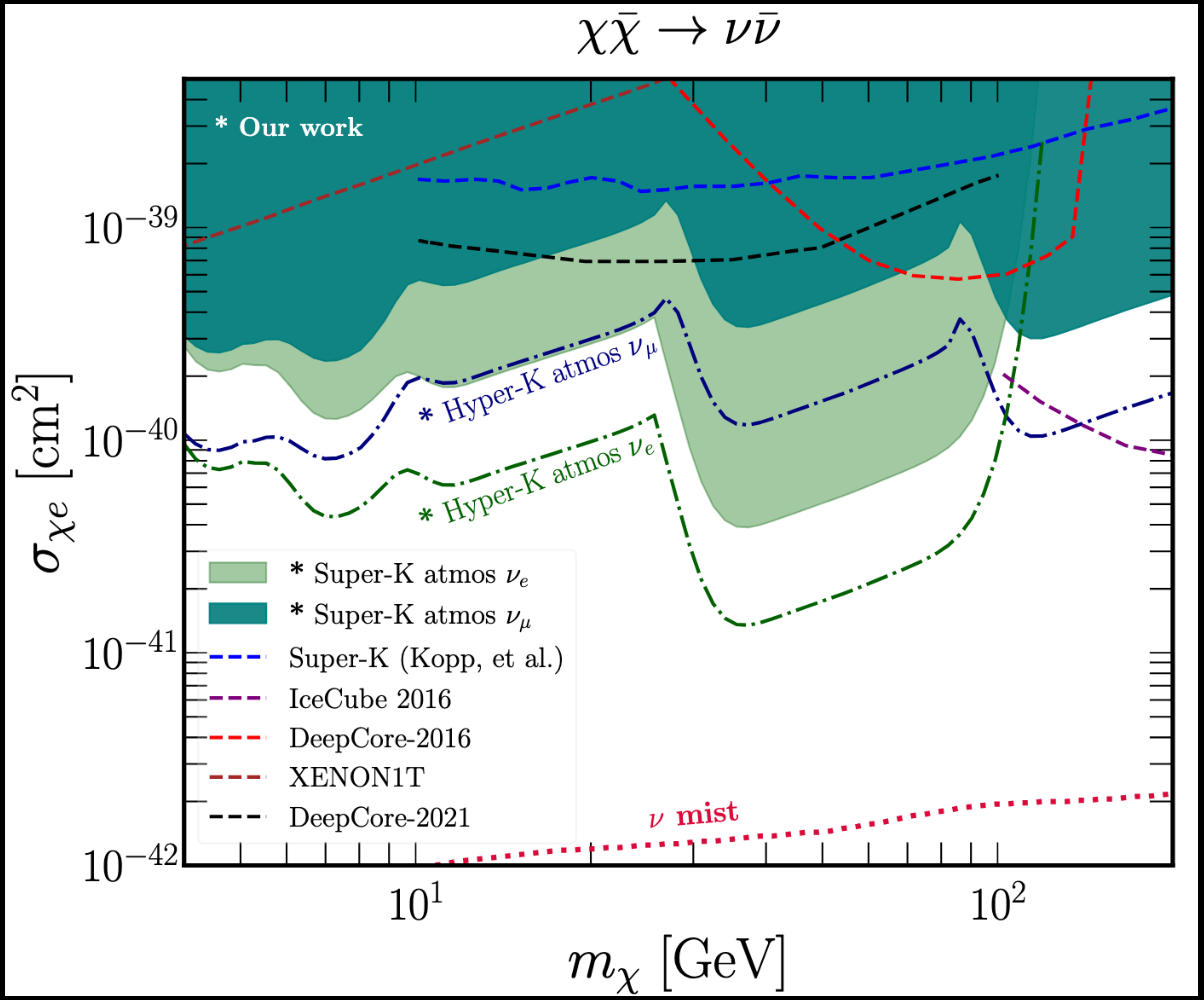
Conclusions

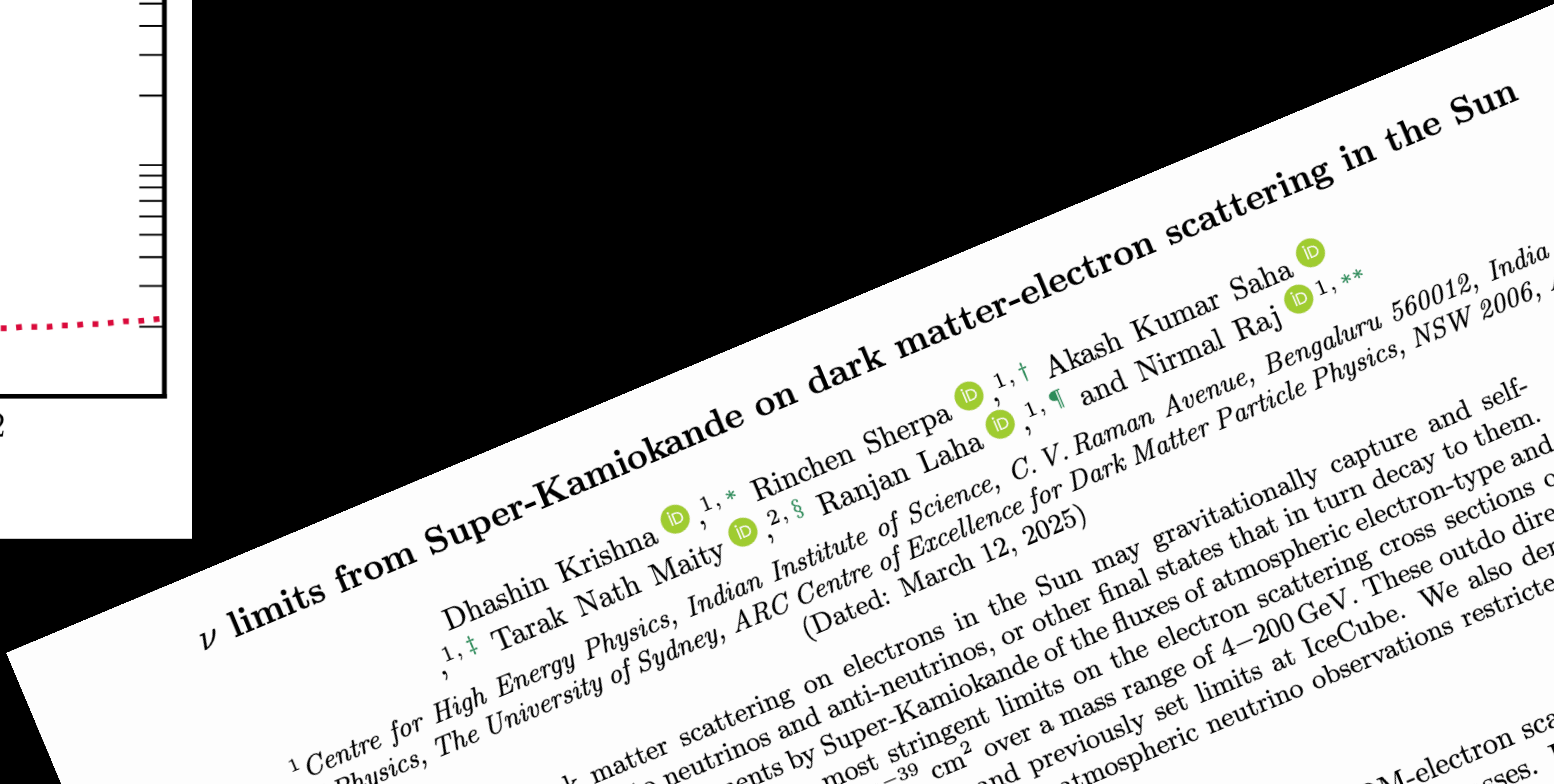


Super-Kamiokande

- When the cross-sections are velocity or momentum dependent, the high velocity of electrons makes constraints much stronger, probing the theoretical targets for leptophilic DM.

A Note Regarding 2503.07713





A Note Regarding 2503.07713

Gould, 1987a (Astrophys.J. 321 (1987) 560)

$$R(w \to v) = \frac{4\mu_+^4}{\pi^{\frac{1}{2}}} N\sigma \frac{v}{w} \int_0^\infty dx \int_{-\infty}^\infty dy \kappa^3 (x+y) e^{-\kappa^2 u^2} \theta(v - |y|) \theta(x - w) \quad \text{(A11)}$$

$$= \frac{2}{\pi^{\frac{1}{2}}} \frac{\mu_+^2}{\mu} N\sigma \frac{v}{w} [\chi(-\alpha_-, \alpha_+) + \chi(-\beta_-, \beta_+) e^{-\frac{M}{2T}(v^2 - w^2)}]. \quad \text{(A15)}$$

Garani & Palomares-Ruiz (1702.02768)

$$\begin{aligned} R_i(w \to v) &= \int n_i(r) \frac{\mathrm{d}\sigma_i}{\mathrm{d}v} |\boldsymbol{w} - \boldsymbol{u}| f_i(\boldsymbol{u}, r) \, \mathrm{d}^3\boldsymbol{u} \\ &= \frac{2}{\sqrt{\pi}} \frac{n_i(r)}{u_i^3(r)} \int_0^\infty \mathrm{d}u \, u^2 \int_{-1}^1 \mathrm{d}\cos\theta \frac{\mathrm{d}\sigma_i}{\mathrm{d}v} |\boldsymbol{w} - \boldsymbol{u}| \, e^{-u^2/u_i^2(r)} , \end{aligned} \quad \text{(A.1)}$$

A Note Regarding 2503.07713

$$C = \left[\left(\frac{8}{3\pi}\right)^{\frac{1}{2}}\sigma n_W \bar{v}\right]\left[\frac{M_B}{m}\right]\left[\frac{3{v_{\rm esc}}^2}{2\bar{v}^2}\left\langle\hat{\phi}\right\rangle\right]\left[\xi_\eta(\infty)\right]\left\langle\frac{\hat{\phi}}{\left\langle\hat{\phi}\right\rangle}\left(1-\frac{1-e^{-A^2}}{A^2}\right)\frac{\xi_1(A)}{\xi_\eta(\infty)}\right\rangle, \tag{2.31}$$

Moreover, the distribution of energy loss is uniform over this interval. On the other hand, scattering from velocity w to a velocity less than v, requires an energy loss of *at least*

$$\frac{\Delta E}{E} \geq \frac{w^2 - v^2}{w^2} = \frac{u^2}{w^2}. \tag{2.11}$$

Combining expressions (2.9) and (2.11) gives the probability that a given scattering will leave the WIMP with less than escape energy,

$$\frac{\mu_+^2}{\mu}\cdot\left(\frac{\mu}{\mu_+^2} - \frac{u^2}{w^2}\right)\ \theta\left(\frac{\mu}{\mu_+^2} - \frac{u^2}{w^2}\right). \tag{2.12}$$

The rate of scattering from w to less than v is just the product of the total rate of scattering, $\sigma n w$, with the conditional probability (2.12). This result may be written,

$$\Omega_v^-(w) = \frac{\sigma n}{w}\left(v^2 - \frac{\mu_-^2}{\mu}u^2\right)\ \theta\left(v^2 - \frac{\mu_-^2}{\mu}u^2\right). \tag{2.13}$$

Gould, 1987b (Astrophys.J. 321 (1987) 571)

A Note Regarding 2503.07713

- Incorrectly adding a zero-temperature kinematic cutoff significantly suppresses the leptophilic dark matter capture rate in the Sun (by a factor of ~7).

- Correcting this error leads to stronger limits in many studies.