Celestial Bodies as Dark Matter Detectors

Tim Linden

Stockholms universitet

Celestial Bodies vs. Direct Detection

Xenon-1T

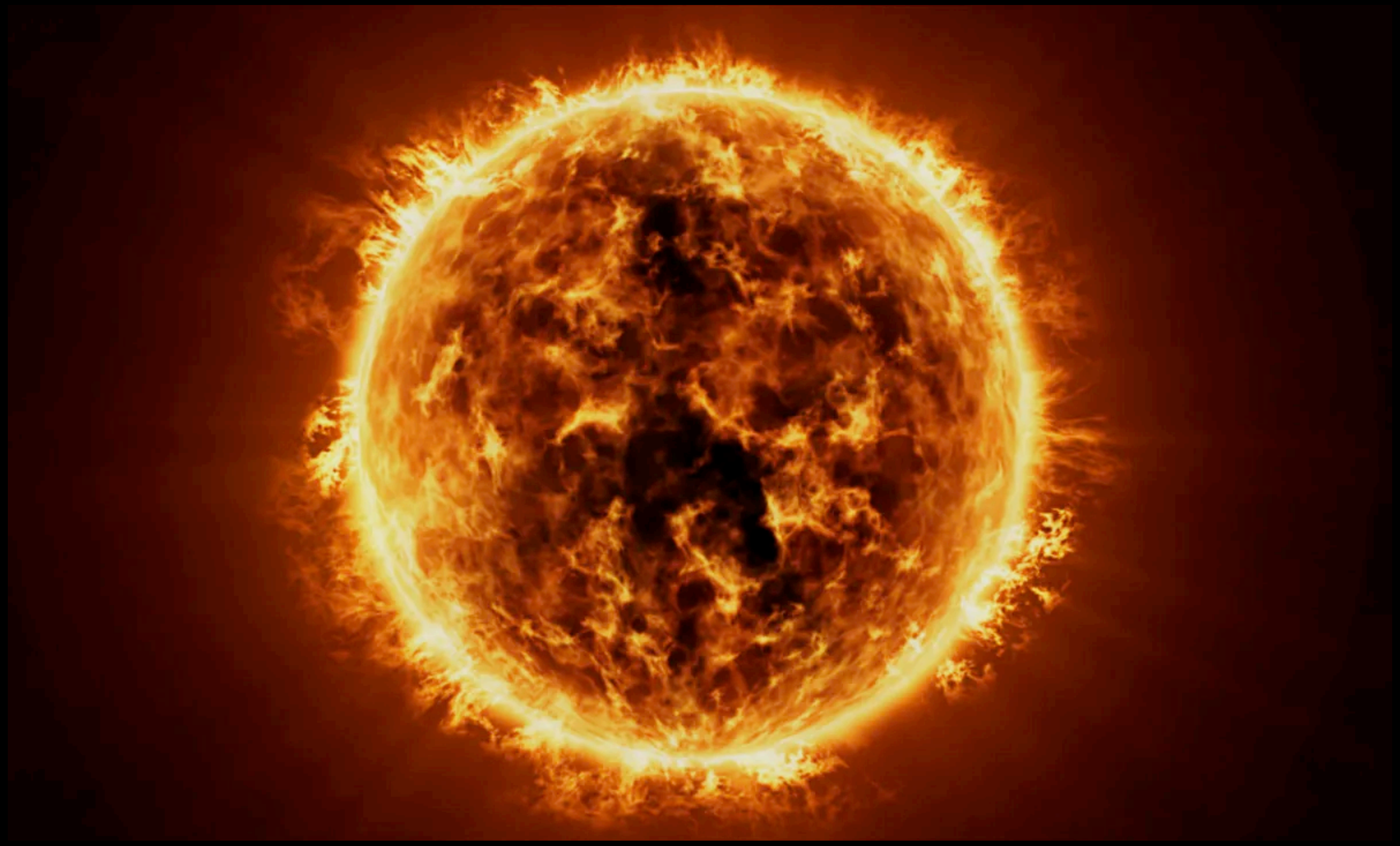
- 1000 kg
- 700 days

7×10^{5} kg day

Celestial Body

- 3×10^{30} kg
- 2×10^{10} days

6×10^{40} kg day



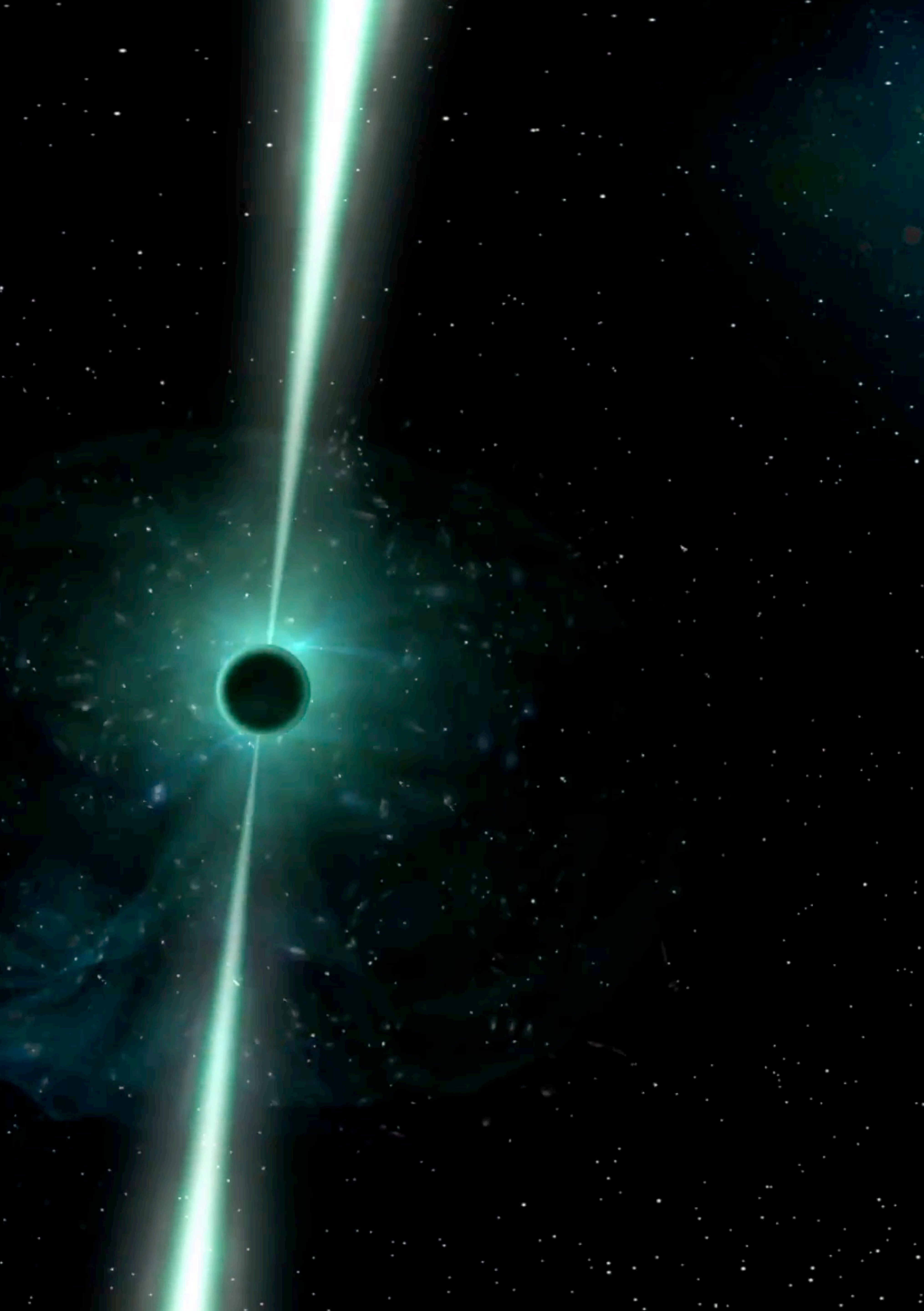
Precision Physics is Possible

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

PSR J1713+0747

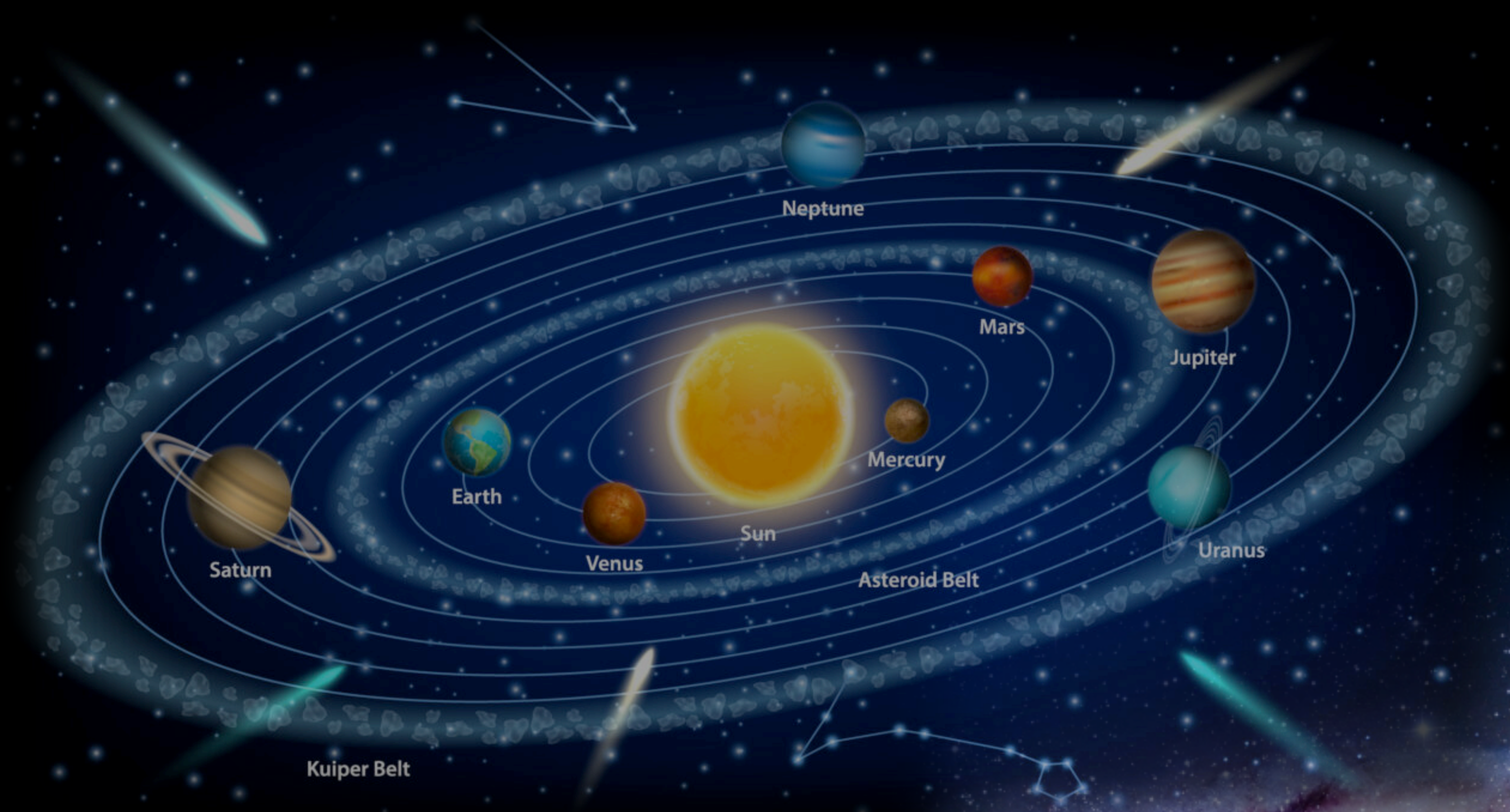
$F = 218.8118437960826270 \pm 0.0000000000000988\ s^{-1}$

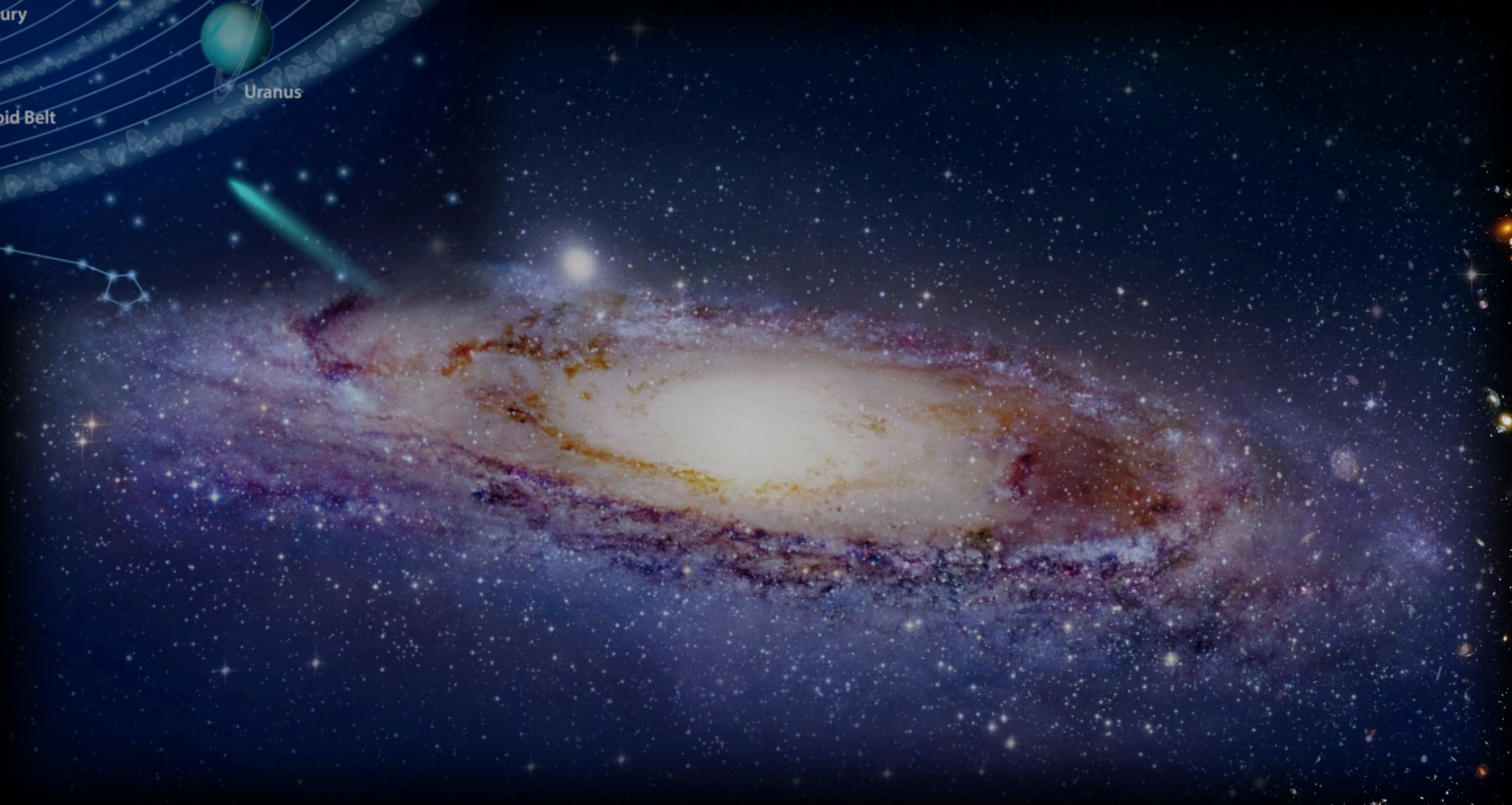
$F' = -4.083888637248 \pm 0.0000143324982645 \times 10^{-16}\ s$



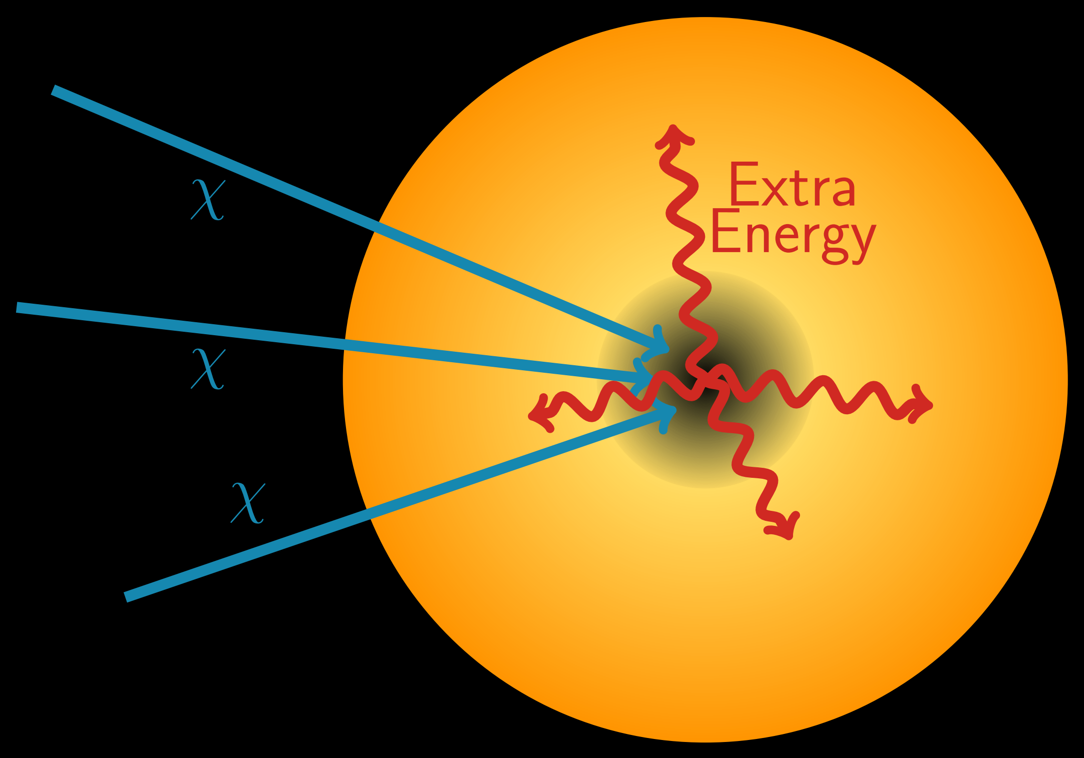
NANOGrav Collaboration (1801.02617)

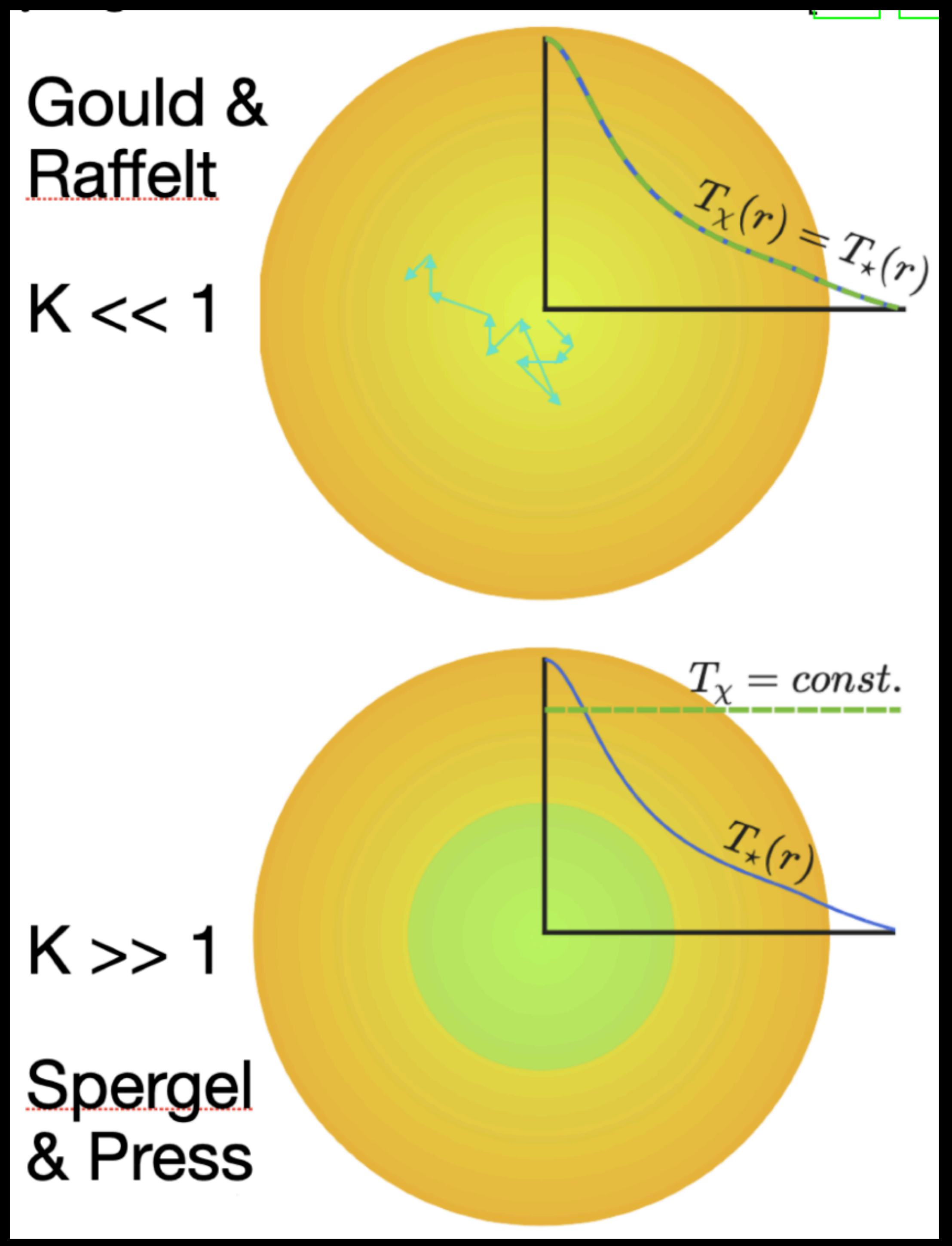
A Multitude of Targets

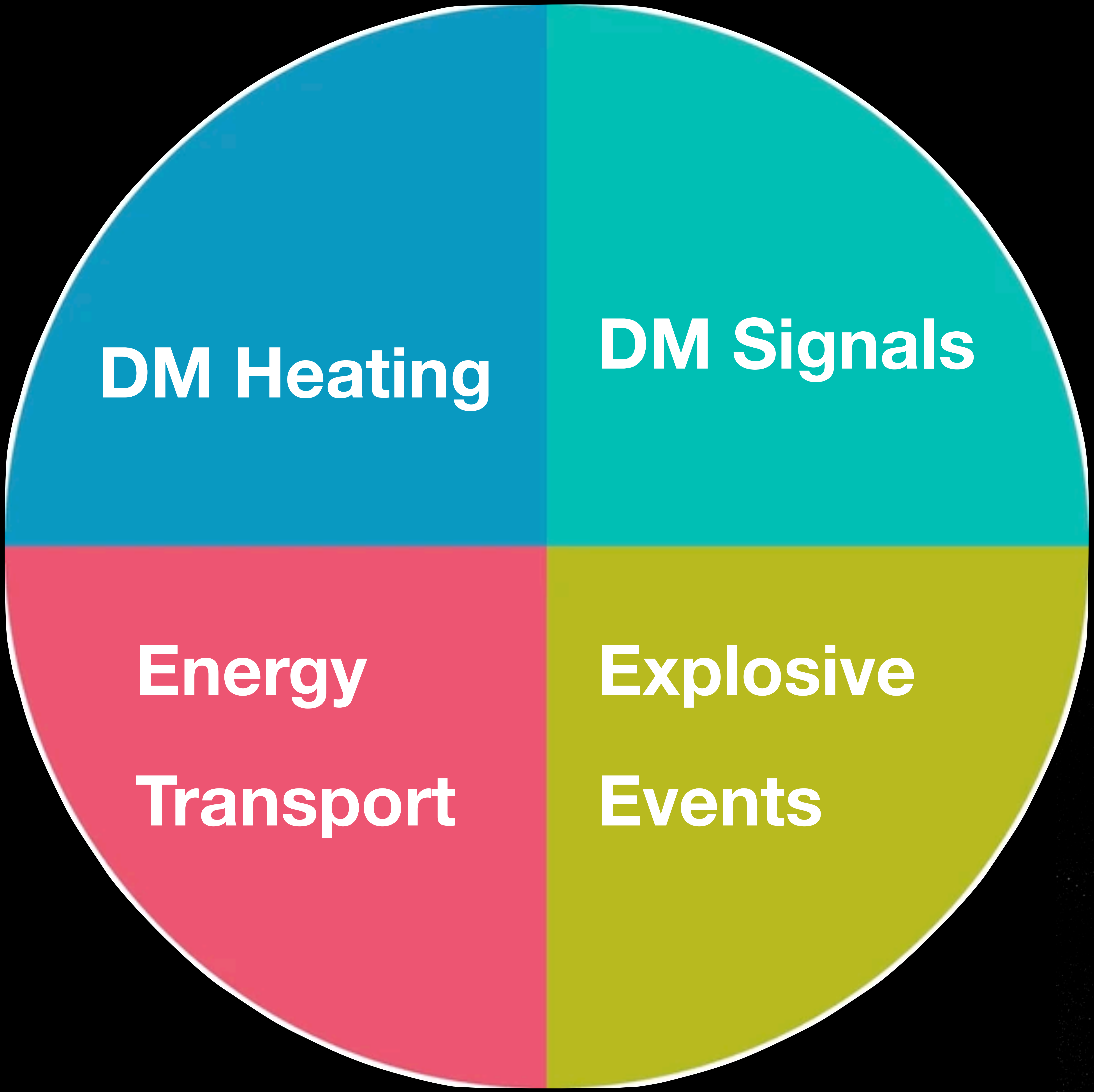


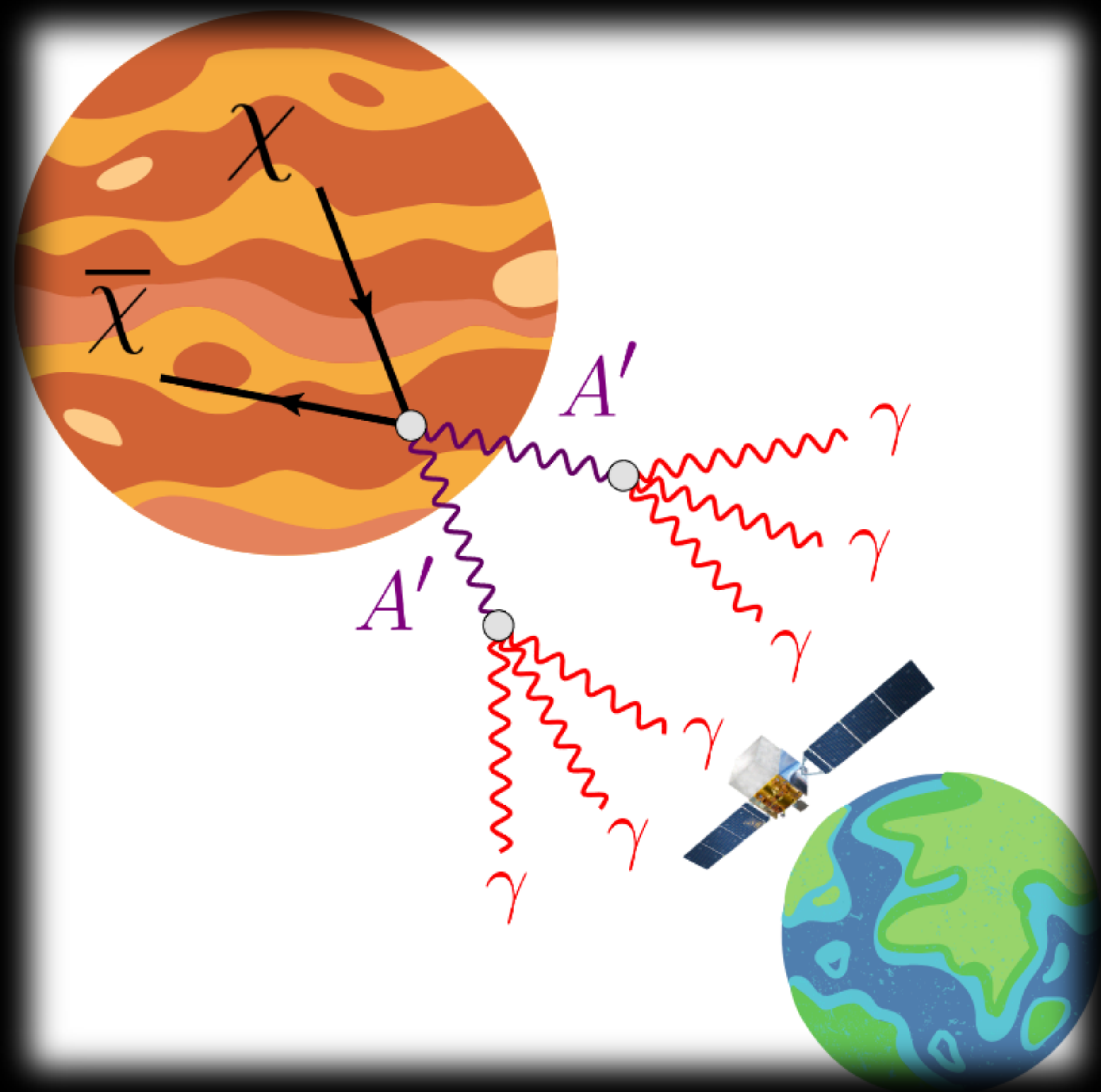


A Multitude of Signatures





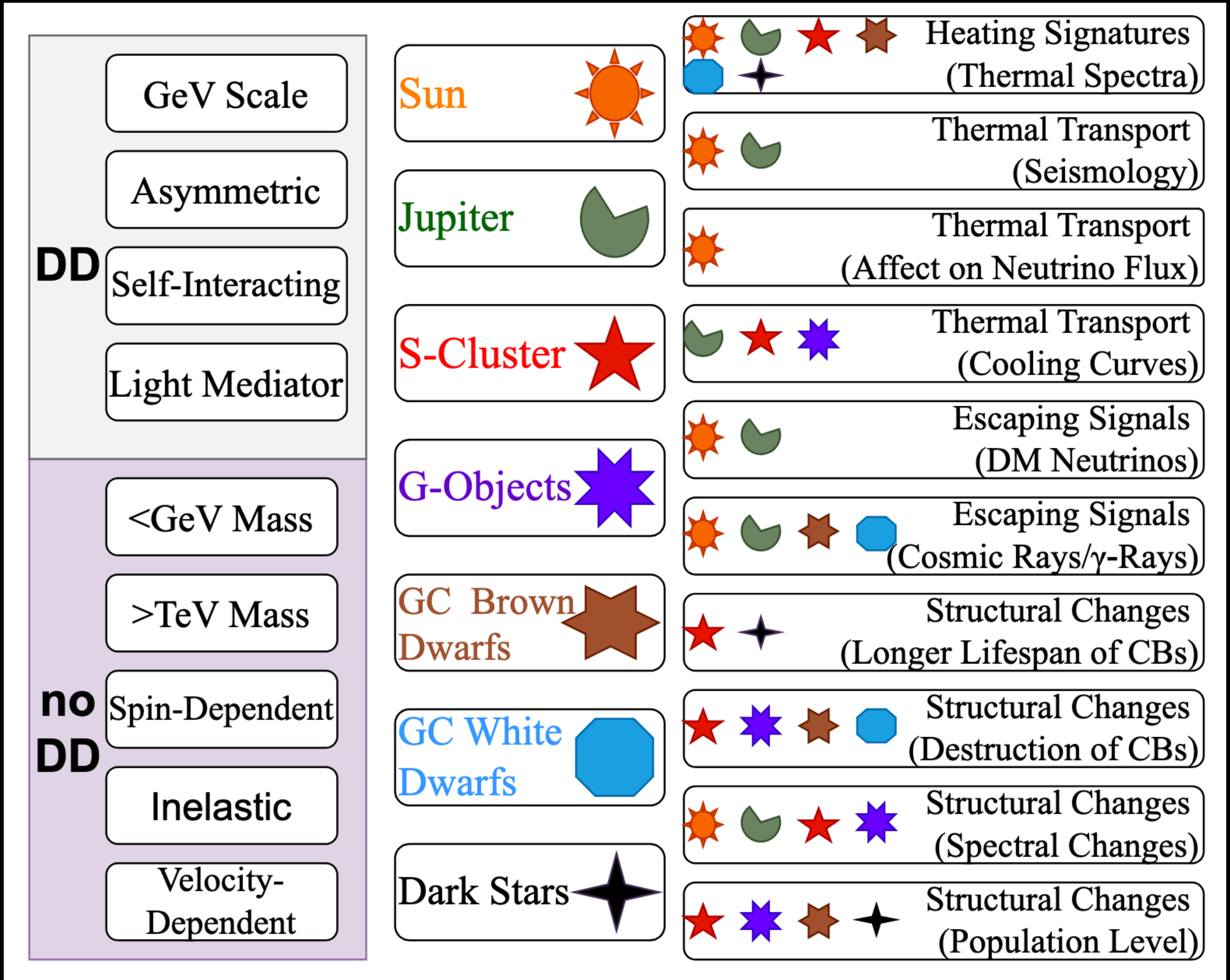




A Multitude of Dark Matter Models

A Multitude of Dark Matter Models

A Cacophony Of Studies



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

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

- Every individual study is individually unlikely.

A Few Recent Studies

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

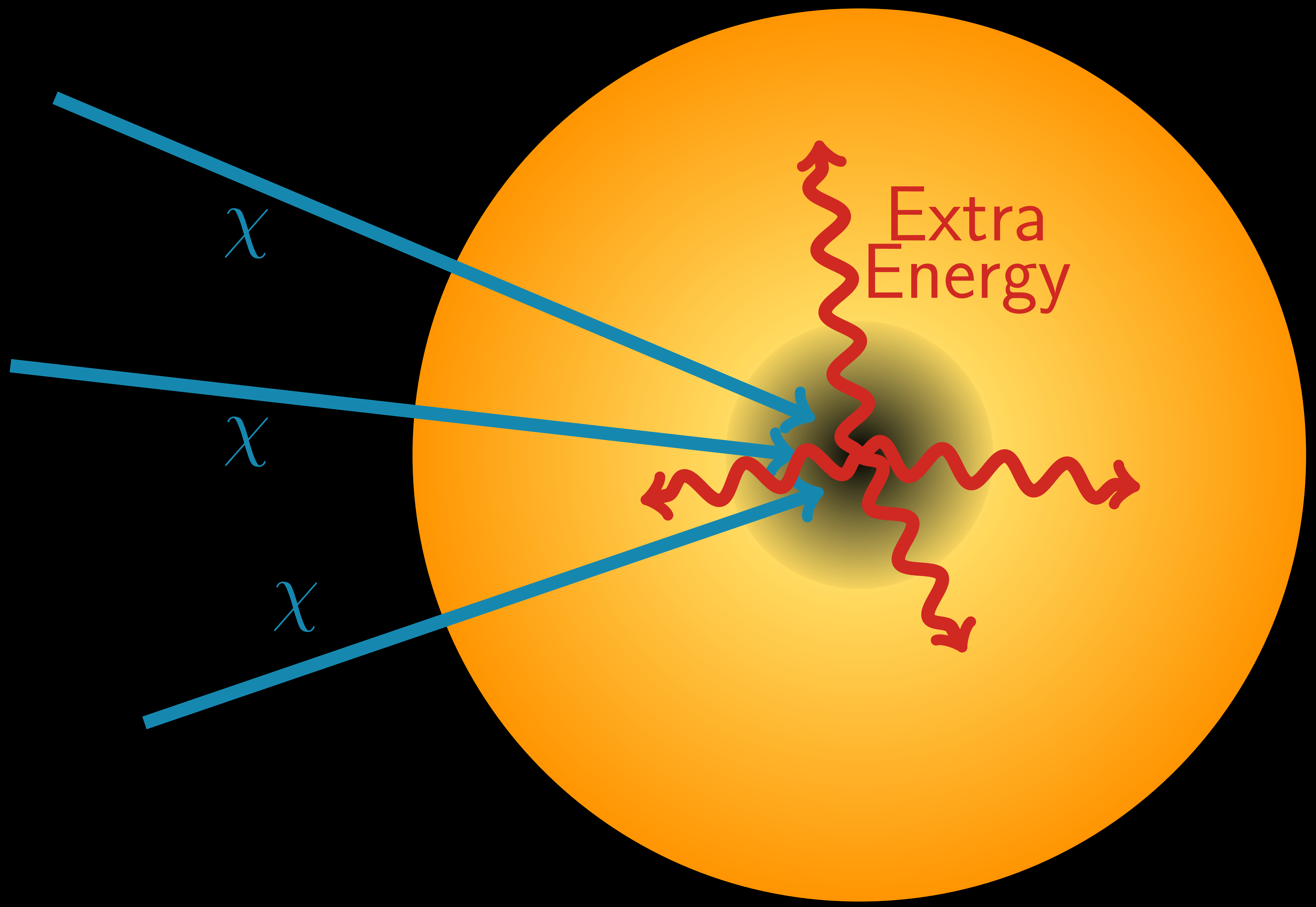
2.) SuperK Neutrino Searches in the Sun (2501.14864)

3.) Unusual Supernovae (2211.00013)

Immortal Stars at the Galactic Center

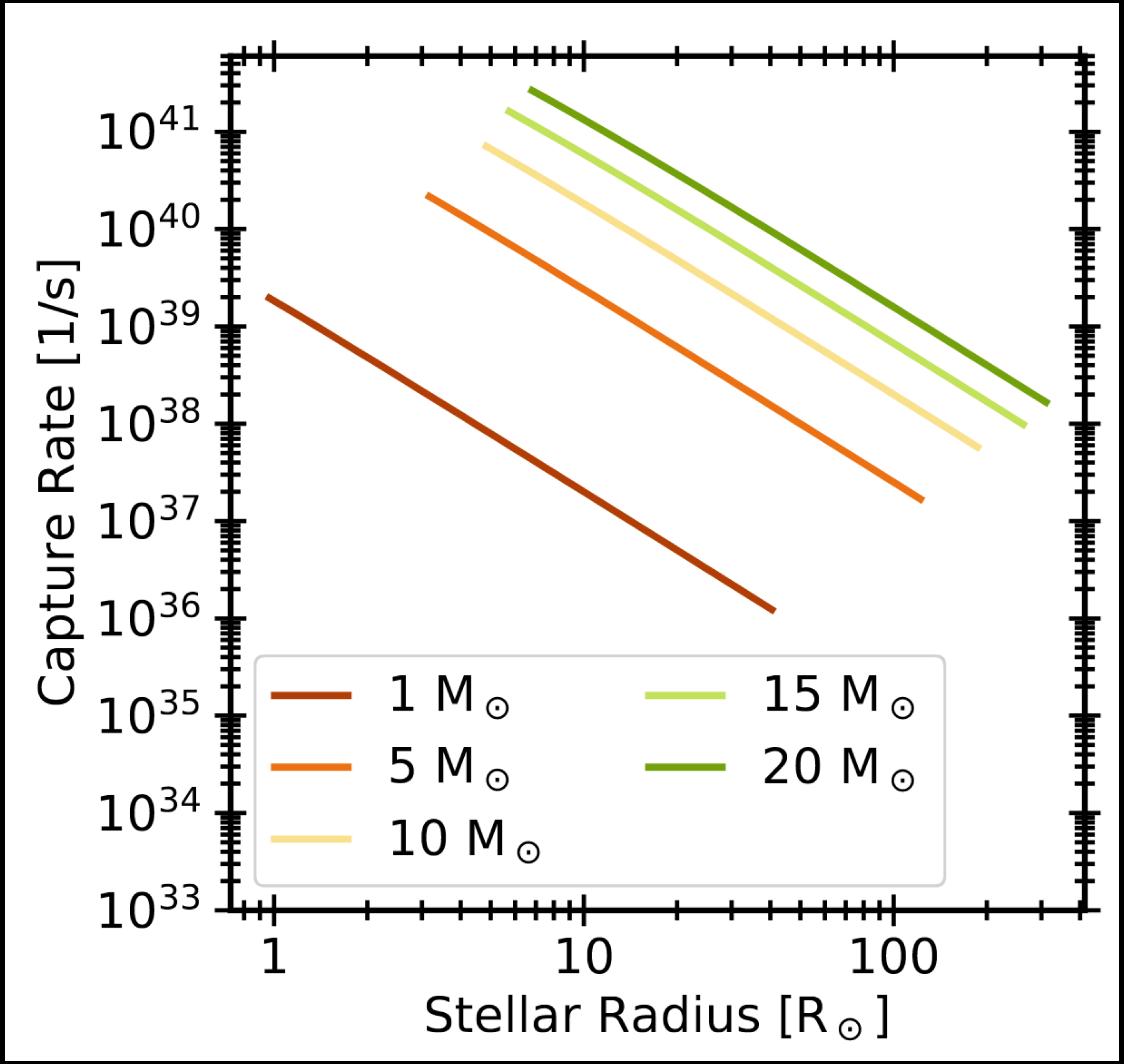
See also: work on Dark Stars (e.g., Spolyar & Freese)

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.

Immortal Stars at the Galactic Center



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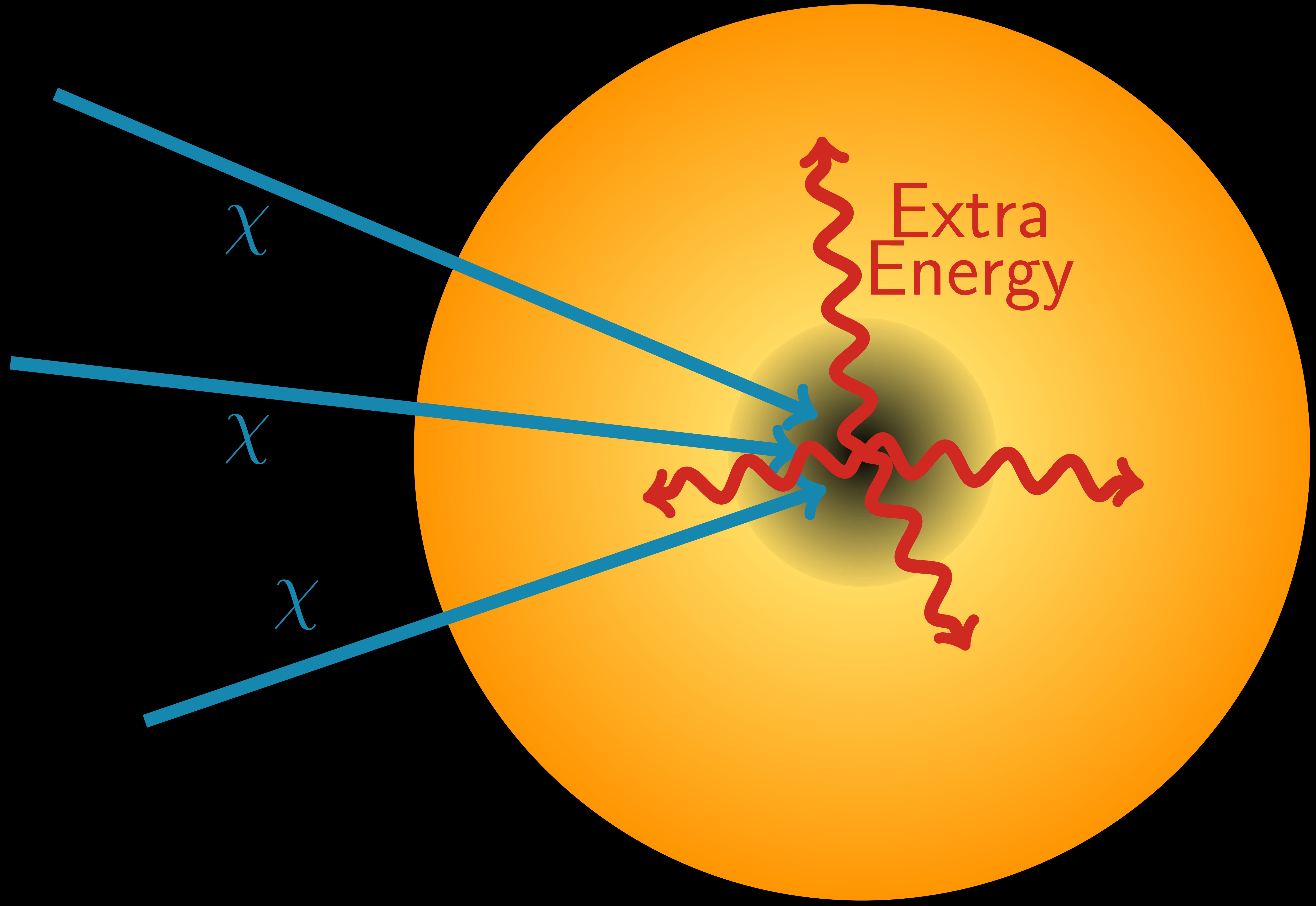
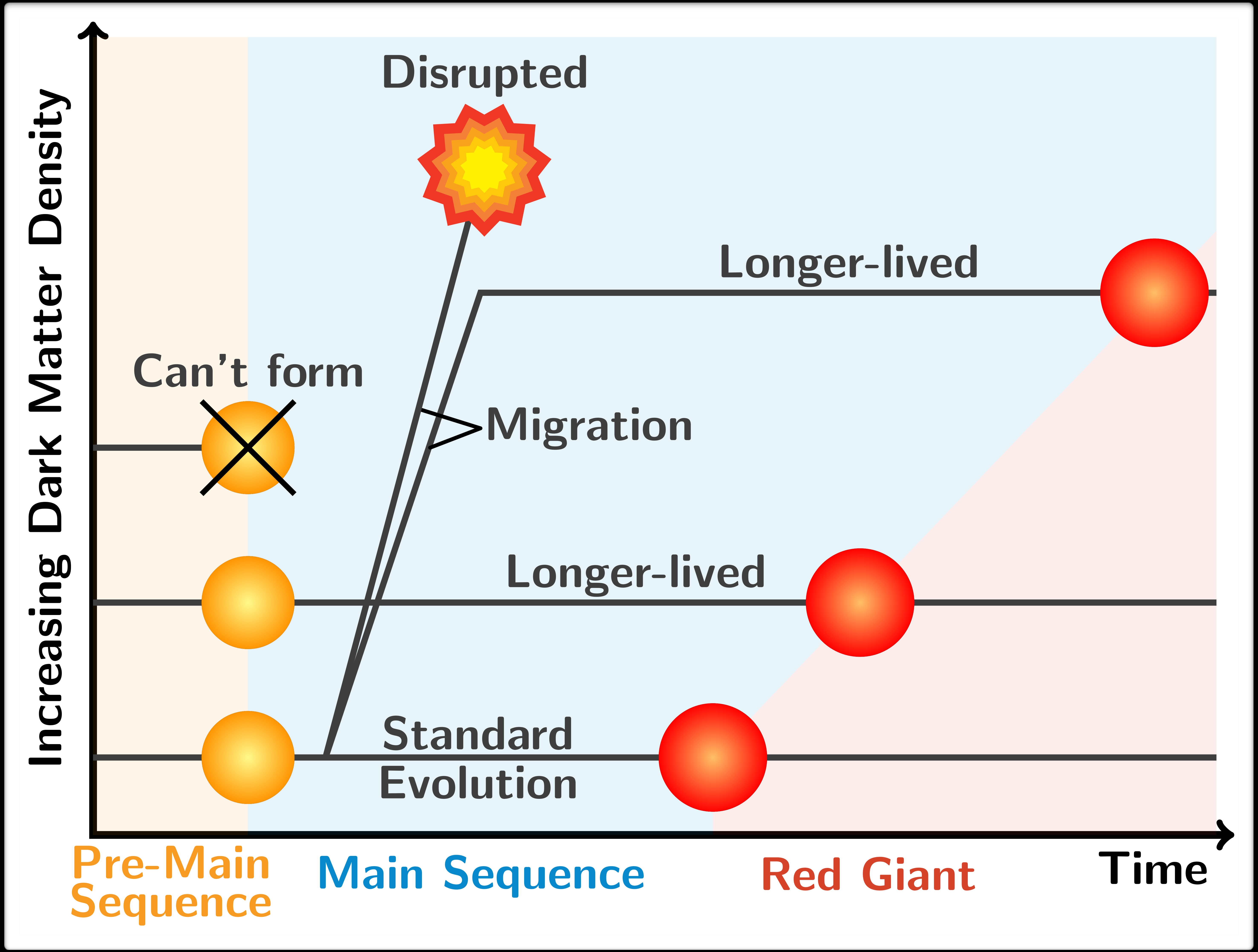


- "Miracle" - Very high dark matter densities at the galactic center.
- Standard WIMP DM
- Standard (though relatively high) dark matter density (low mass WIMPs)

Immortal Stars at the Galactic Center



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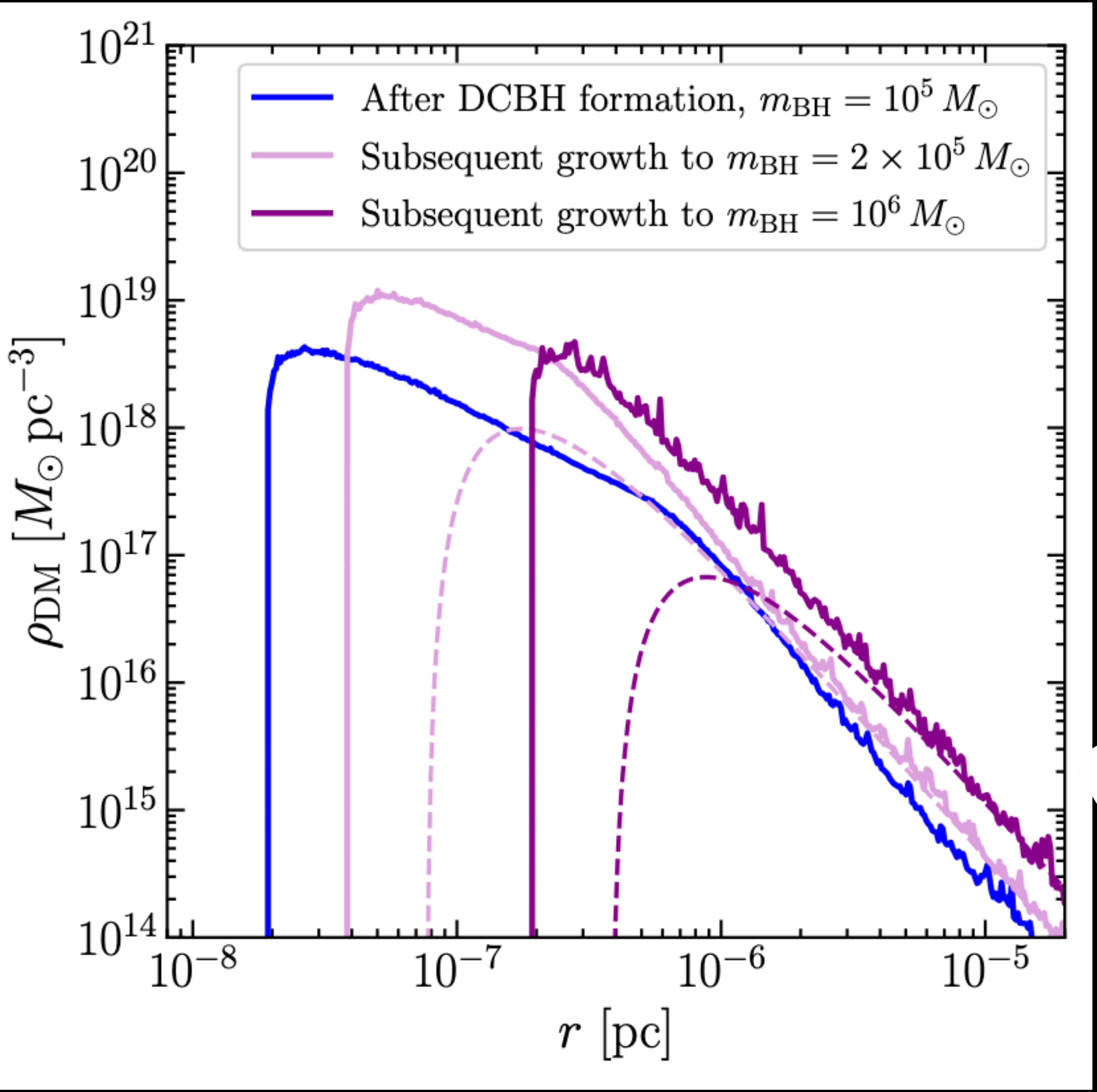


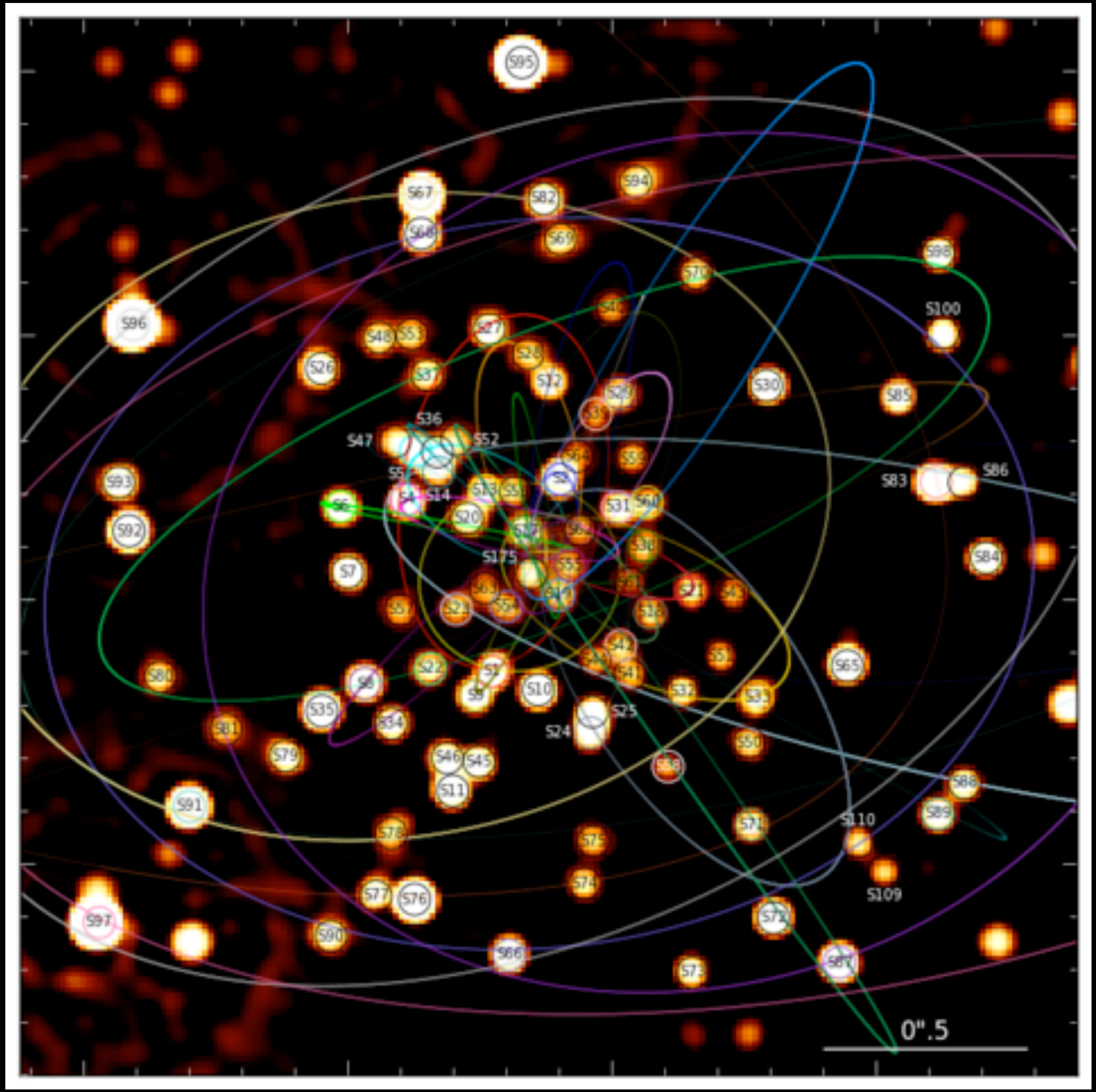
Dark Matter Mounds: towards a realistic description of dark matter overdensities around black holes

Gianfranco Bertone[1], A. Renske A. C. Wierda[1,2] Daniele Gaggero[3], Bradley J. Kavanagh[4] Marta Volonteri[1,5] and Naoki Yoshida[6,7]

[1] Gravitation Astroparticle Physics Amsterdam (GRAPPA), University of Amsterdam, Amsterdam, 1098 XH, Netherlands
[2] Department of Physics, KTH Royal Institute of Technology, The Oskar Klein Centre, AlbaNova, SE-106 91 Stockholm, Sweden
[3] INFN Sezione di Pisa, Polo Fibonacci, Largo B. Pontecorvo 3, 56127 Pisa, Italy
[4] Instituto de Física de Cantabria (IFCA, UC-CSIC), Avenida de Los Castros s/n, 39005 Santander, Spain
[5] Institut d'Astrophysique de Paris, Sorbonne Université, CNRS, UMR 7095, 98 bis bd Arago, 75014 Paris, France
[6] Department of Physics, The University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan
[7] Kavli Institute for the Physics and Mathematics of the Universe (WPI), UT Institute for Advanced Study, The University of Tokyo, Kashiwa, Chiba 277-8583, Japan

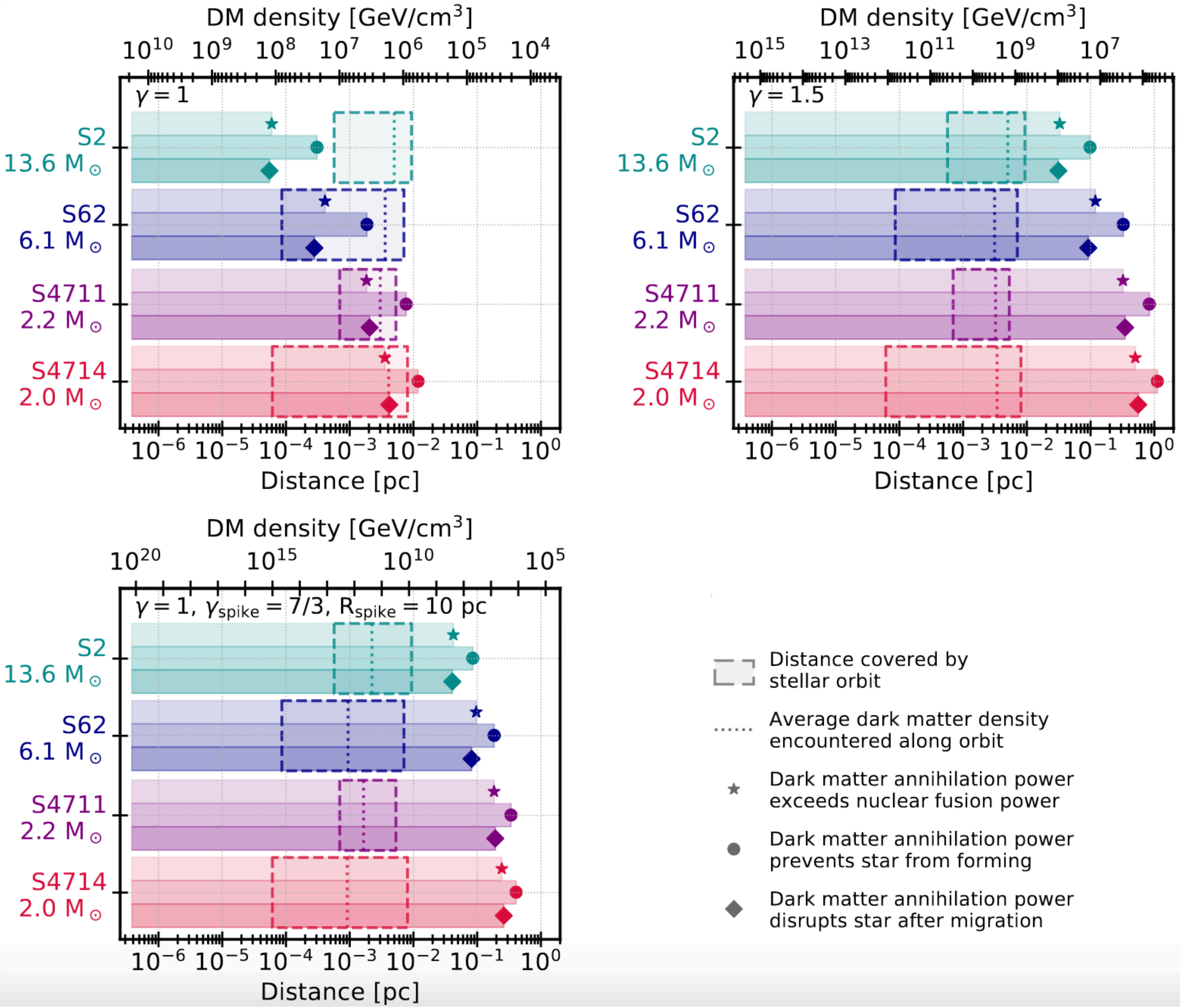
Dark matter overdensities around black holes can be searched for by looking at the characterist
imprint they leave on the gravitational waveform of binary black hole mergers. Current theoret
predictions of the density profile of dark matter overdensities are based on highly idealised form
scenarios, in which black holes are assumed to grow adiabatically from an infinitesimal seed t

Immortal Stars at the Galactic Center

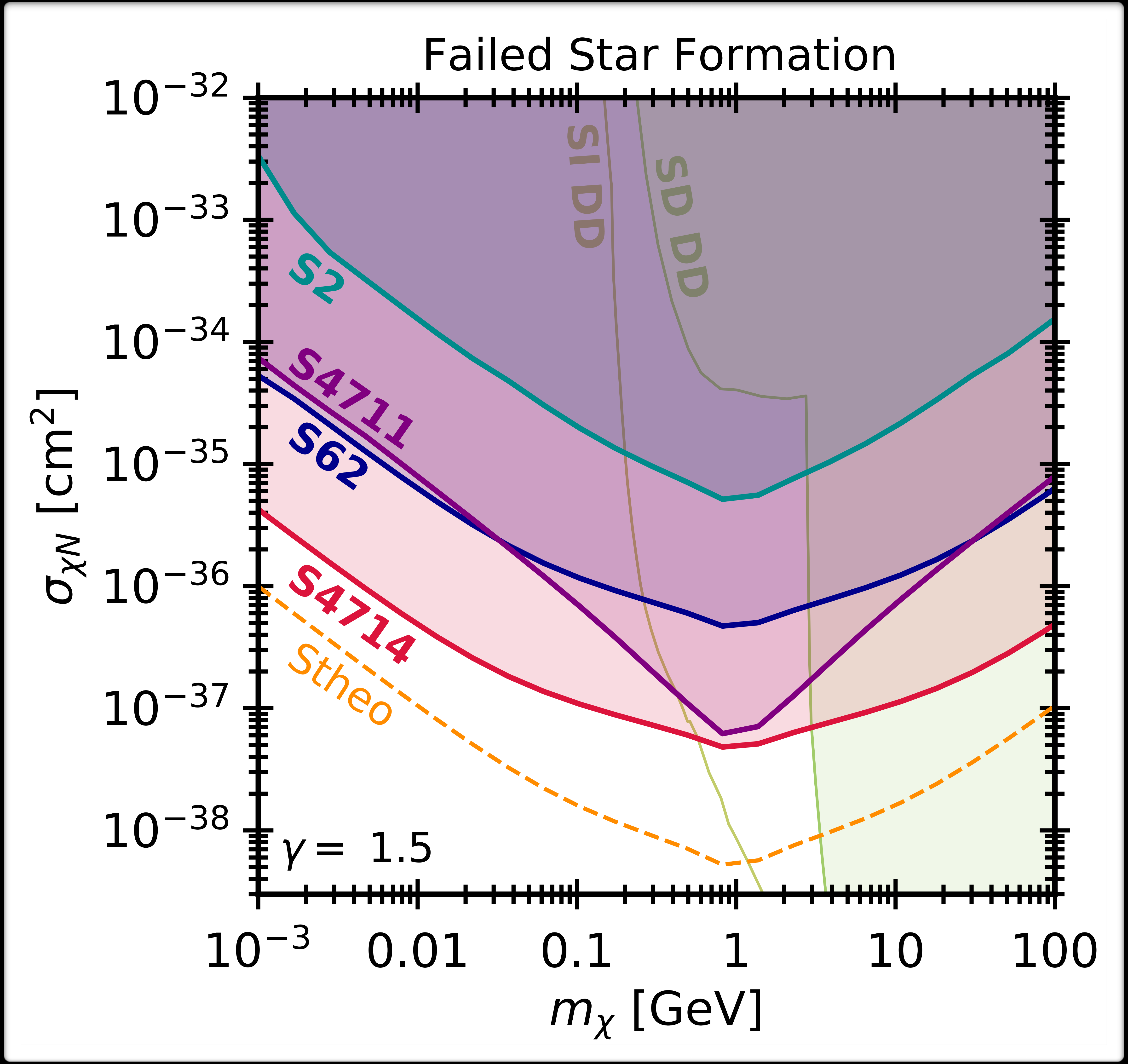


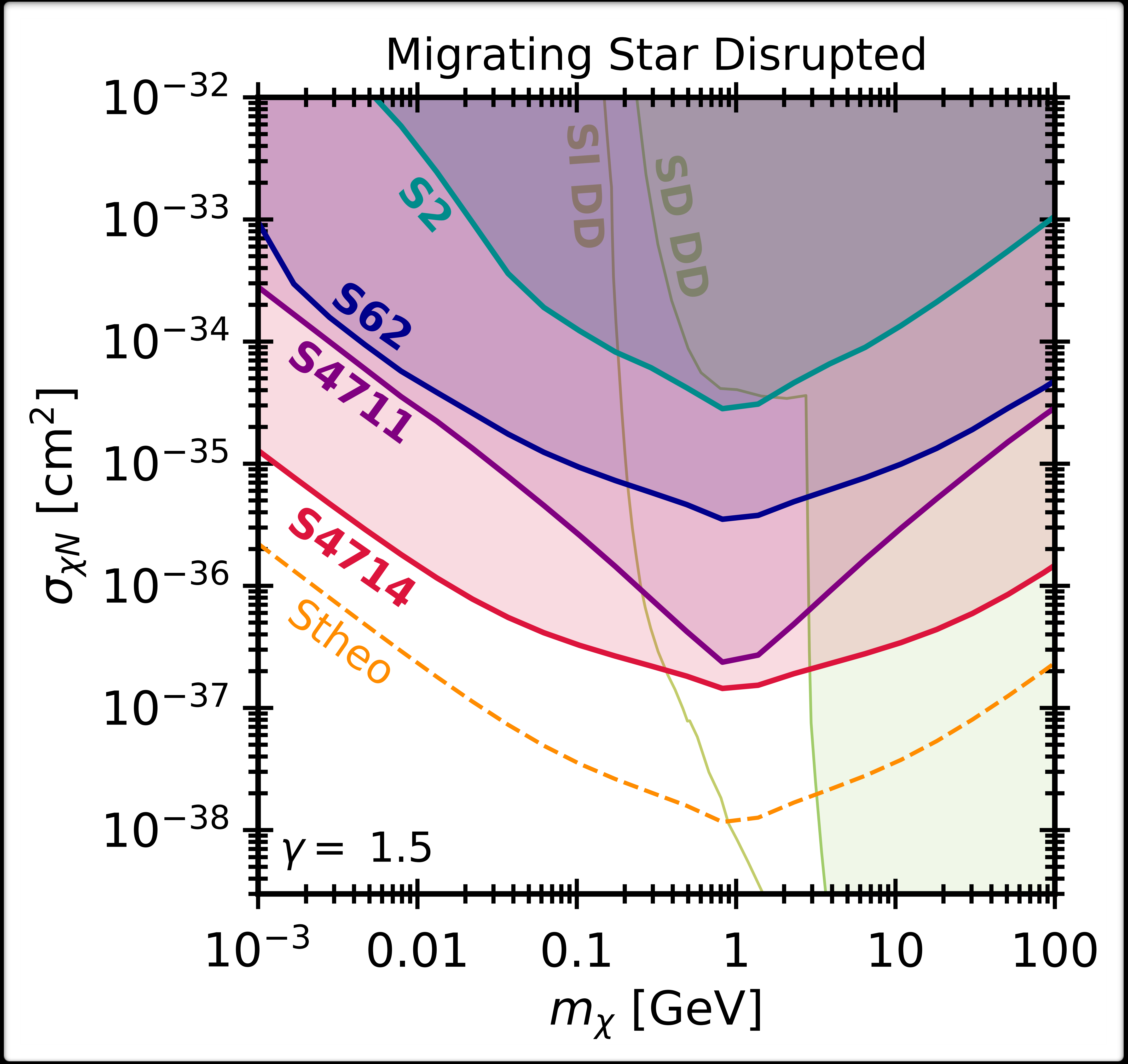
Many stars

within 0.016 pc


DM density [GeV/cm^3]
$\gamma = 1$
$\gamma = 1.5$
$\gamma = 1$, $\gamma_{spike} = 7/3$, $R_{spike} = 10$ pc
S2
13.6 M$_\odot$
S62
6.1 M$_\odot$
S4711
2.2 M$_\odot$
S4714
2.0 M$_\odot$
Distance [pc]
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





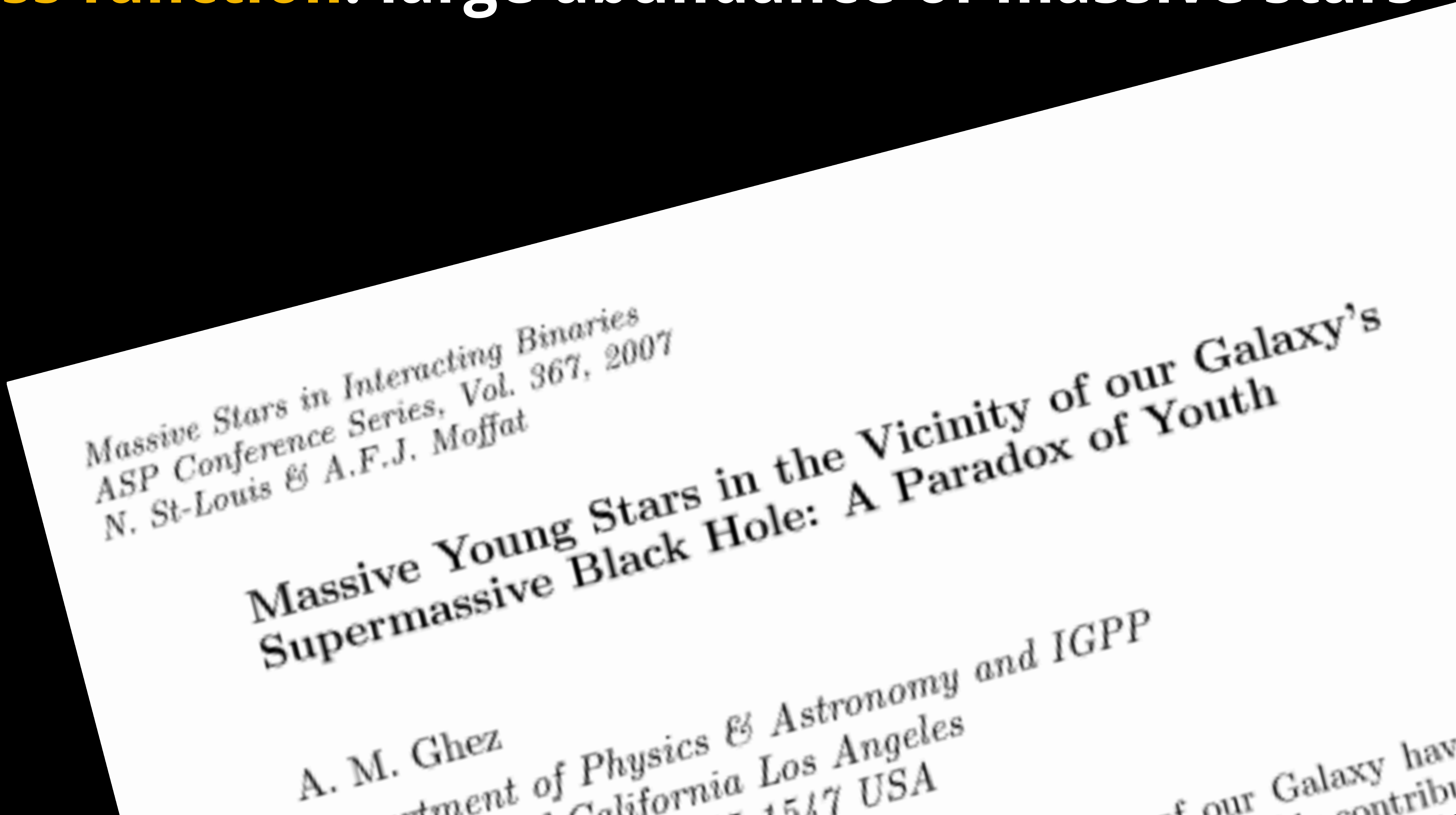
Immortal Stars at the Galactic Center

Origin not well understood: in situ formation or migration?

Paradox of Youth: Spectroscopically old but bright as young stars

Conundrum of Old Age: Lack of old stars

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



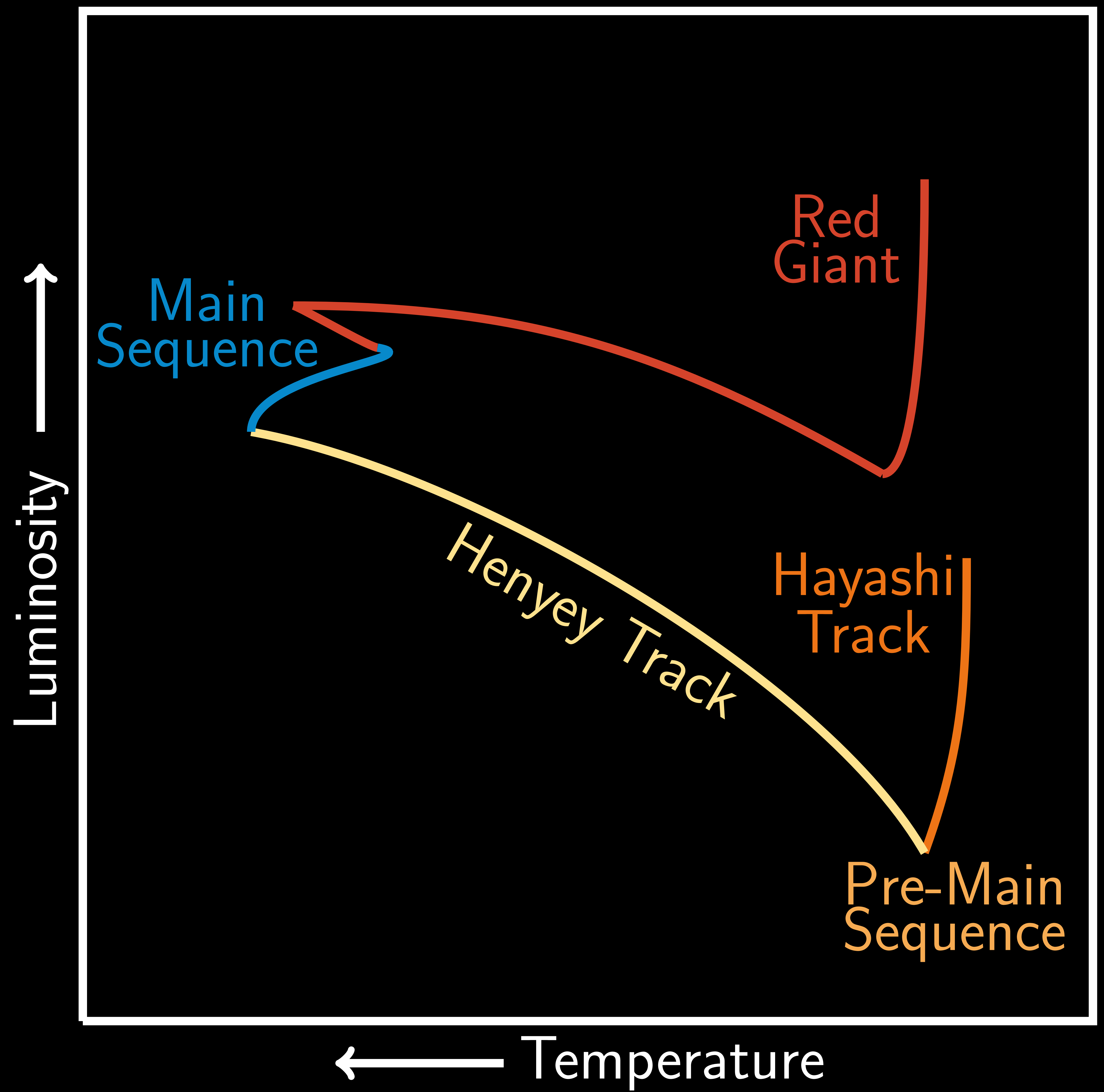
Massive Stars in Interacting Binaries
ASP Conference Series, Vol. 367, 2007
N. St-Louis & A.F.J. Moffat

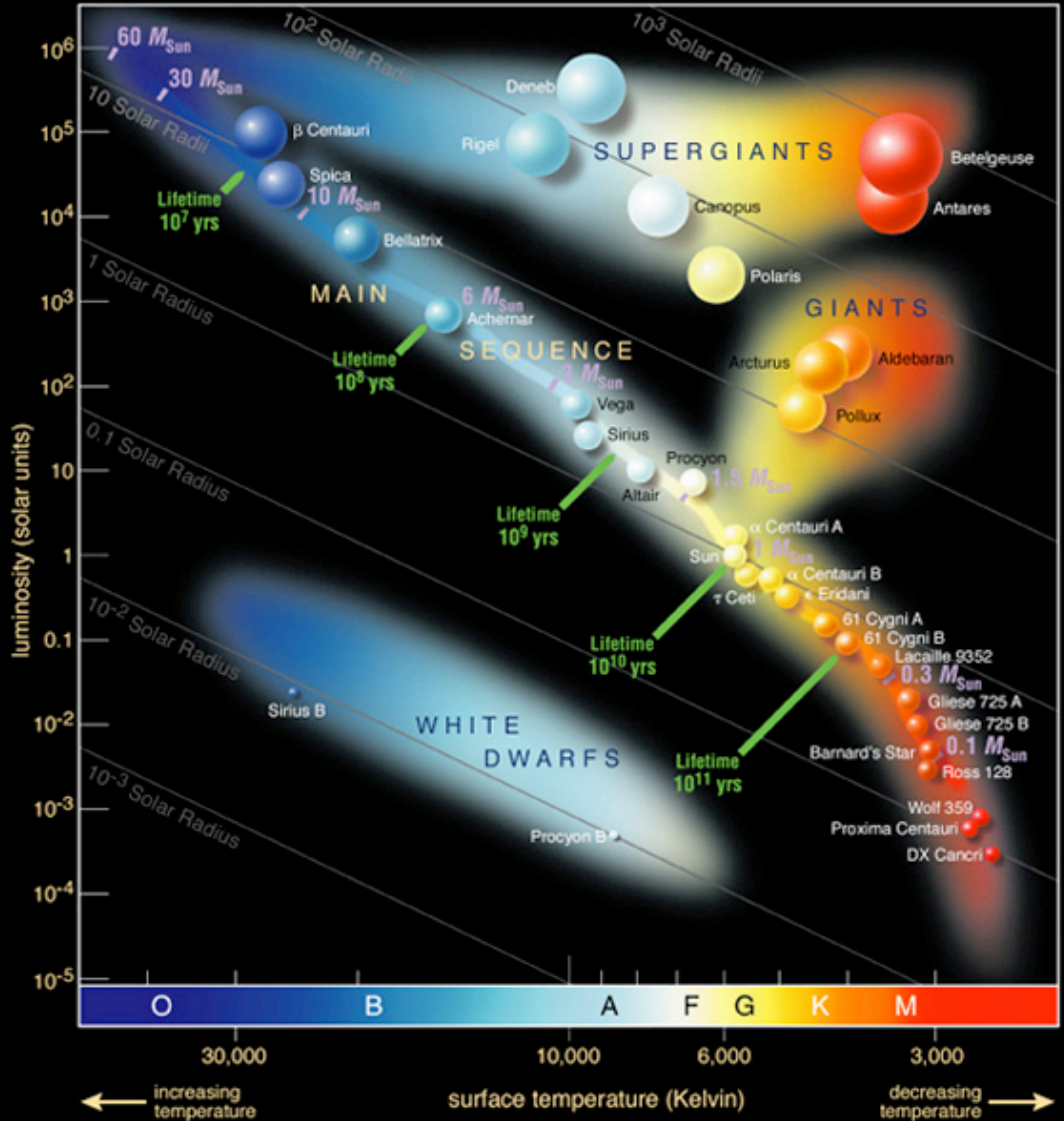
Massive Young Stars in the Vicinity of our Galaxy's Supermassive Black Hole: A Paradox of Youth

A. M. Ghez

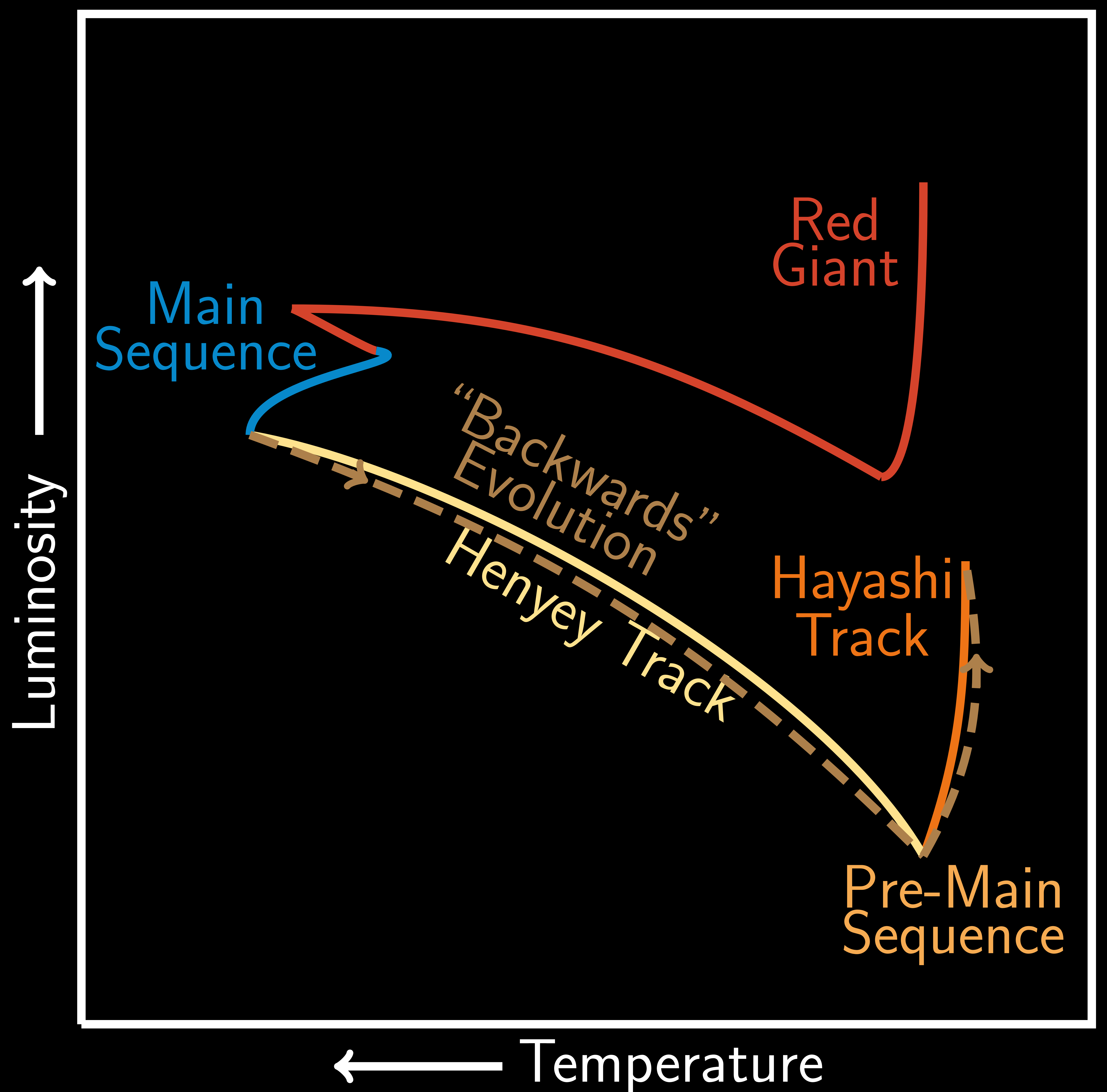
of Physics & Astronomy and IGPP
California Los Angeles
USA

Immortal Stars

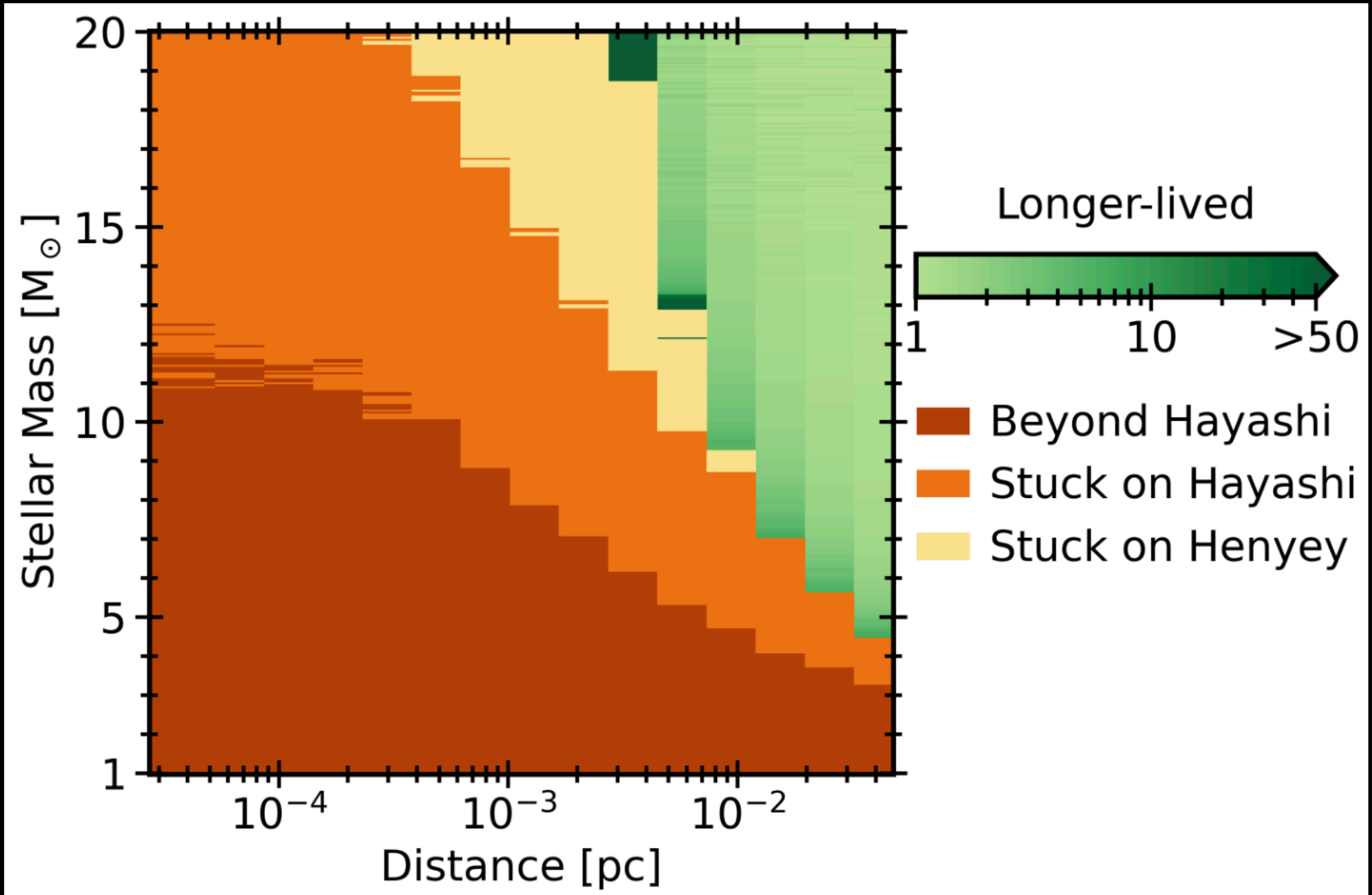


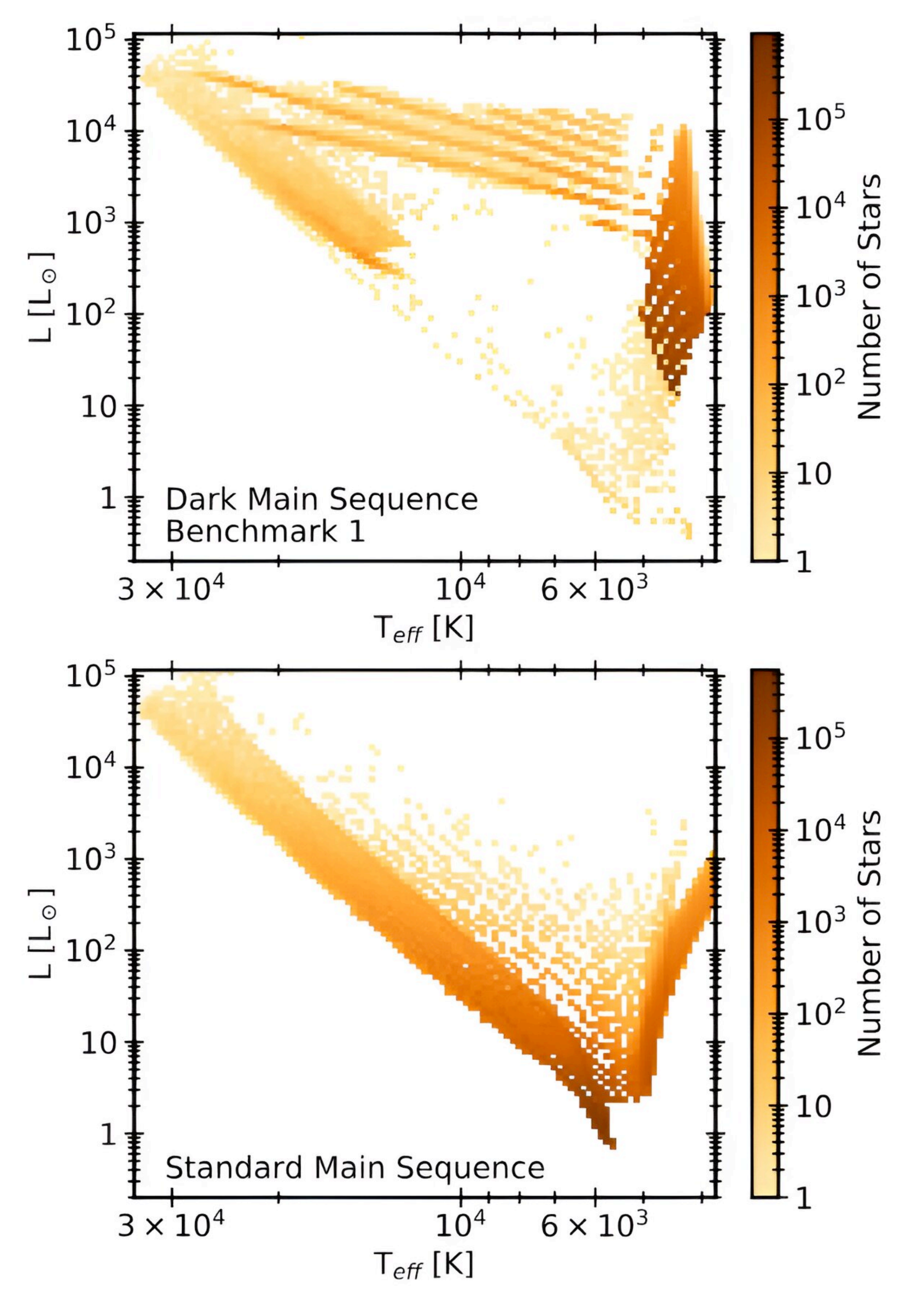


luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^-2
10^-3
10^-4
10^-5
60 M_Sun
30 M_Sun
10 M_Sun
6 M_Sun
3 M_Sun
1.5 M_Sun
1 M_Sun
0.3 M_Sun
0.1 M_Sun
10^2 Solar Radii
10^3 Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^-2 Solar Radius
10^-3 Solar Radius
β Centauri
Spica
Bellatrix
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
SUPERGIANTS
GIANTS
MAIN
SEQUENCE
WHITE
DWARFS
Sirius B
Procyon B
Lifetime 10^7 yrs
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^10 yrs
Lifetime 10^11 yrs
O
B
A
F
G
K
M
30,000
10,000
6,000
3,000
increasing temperature
surface temperature (Kelvin)
decreasing temperature


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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- Every individual study is individually unlikely.

Super-Kamiokande


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}.

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 ...f the large background. ... scattering of dark

DAMA/LIBRA and leptonically interacting Dark Matter

CERN-PH-TH/2009-116

...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

Abstra...

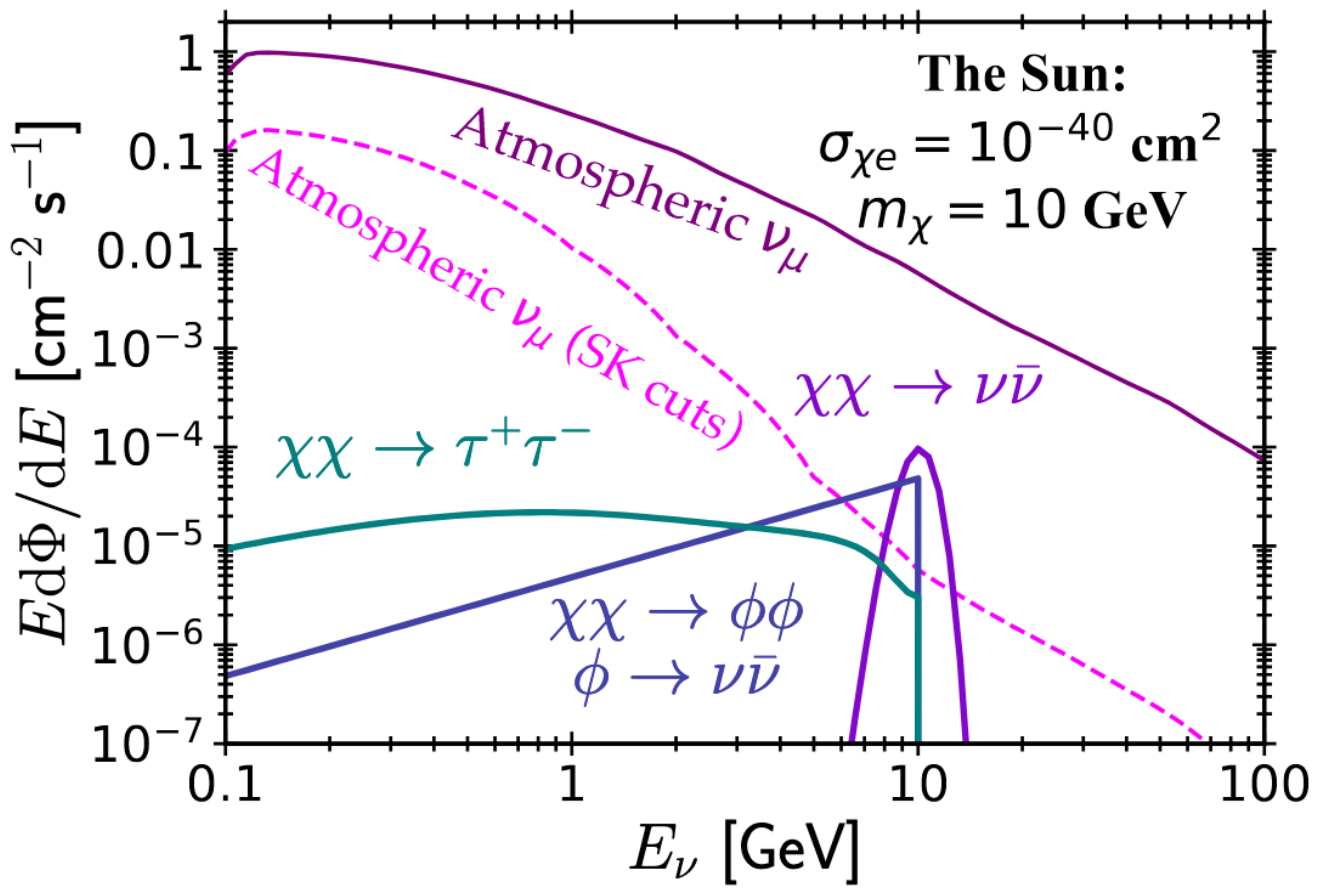
HRI-RECAPP-2023-03

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,§]

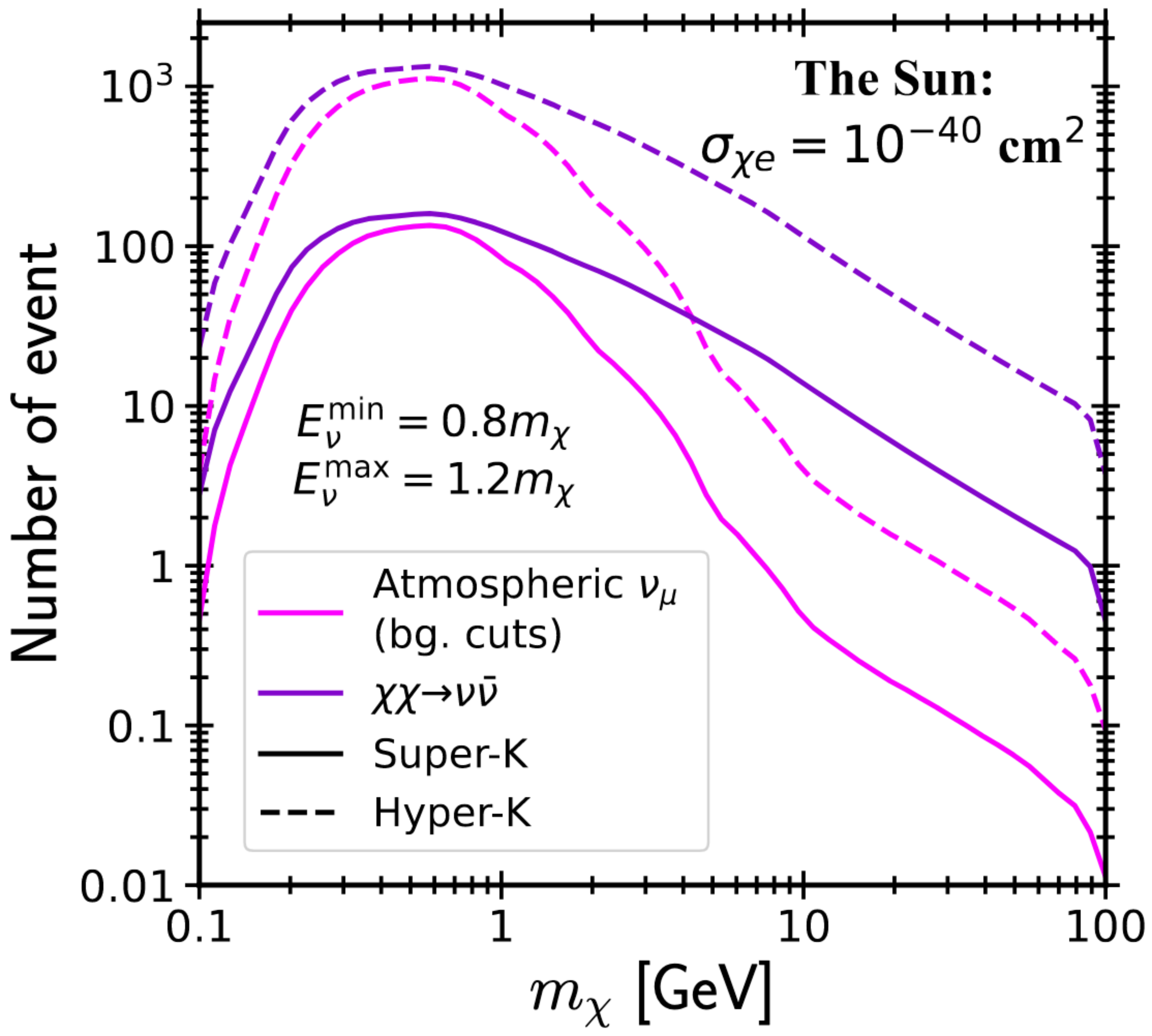
[1] Harish-Chandra Research Institute, A CI of Homi Bhabha National Institute, Chhatnag Road, Jhunsi, Prayagraj (Allahabad) 211019, India
[2] Regional Centre for Accelerator-based Particle Physics, Harish-Chandra Research Institute, Prayagraj (Allahabad) 211019, India
...ay Physics, Indian Institute of Science, C. V. Raman Avenue, Bengaluru 560012, ...
(Dated: August 25, 2023)

Super-Kamiokande



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

Super-Kamiokande



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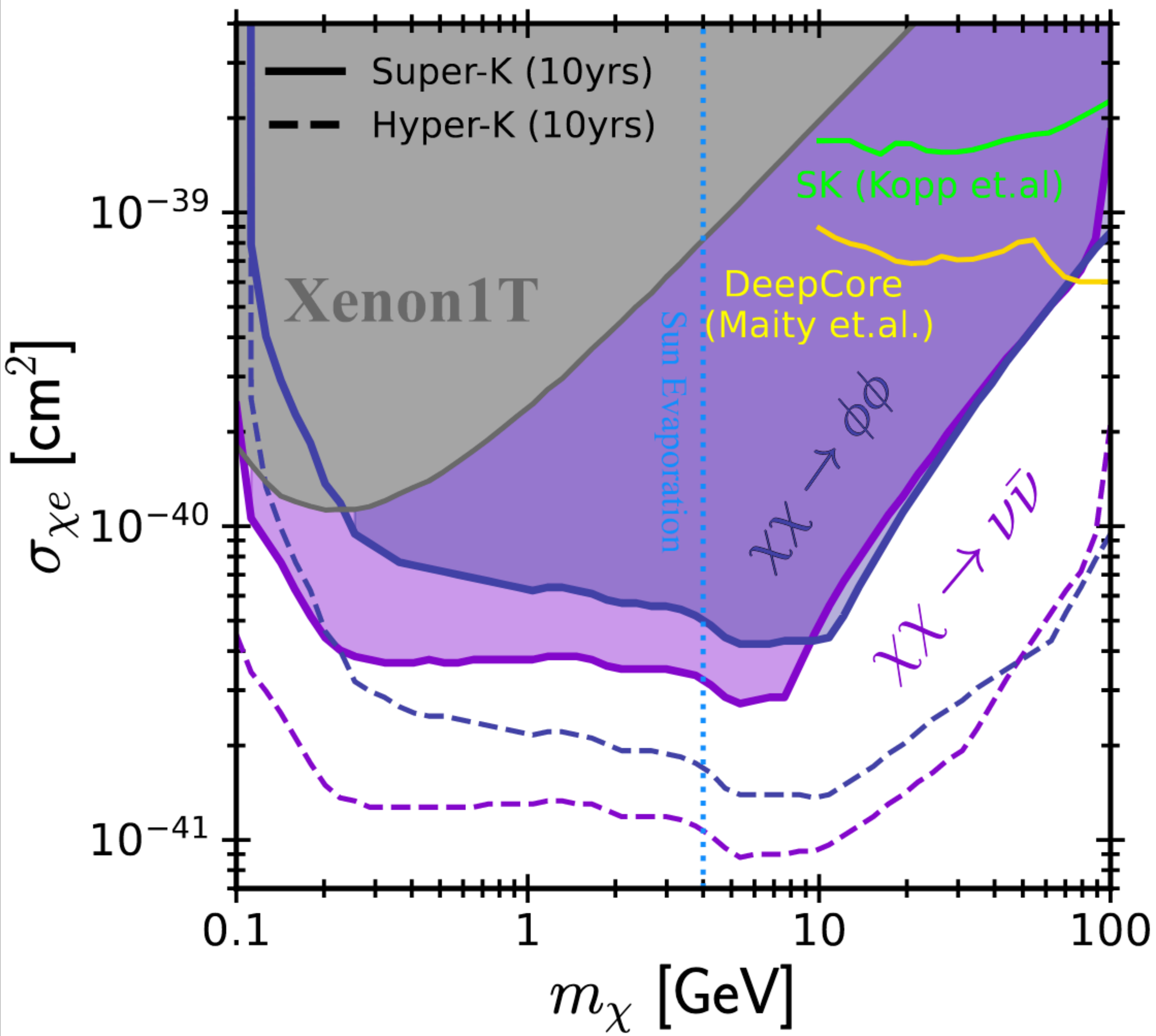
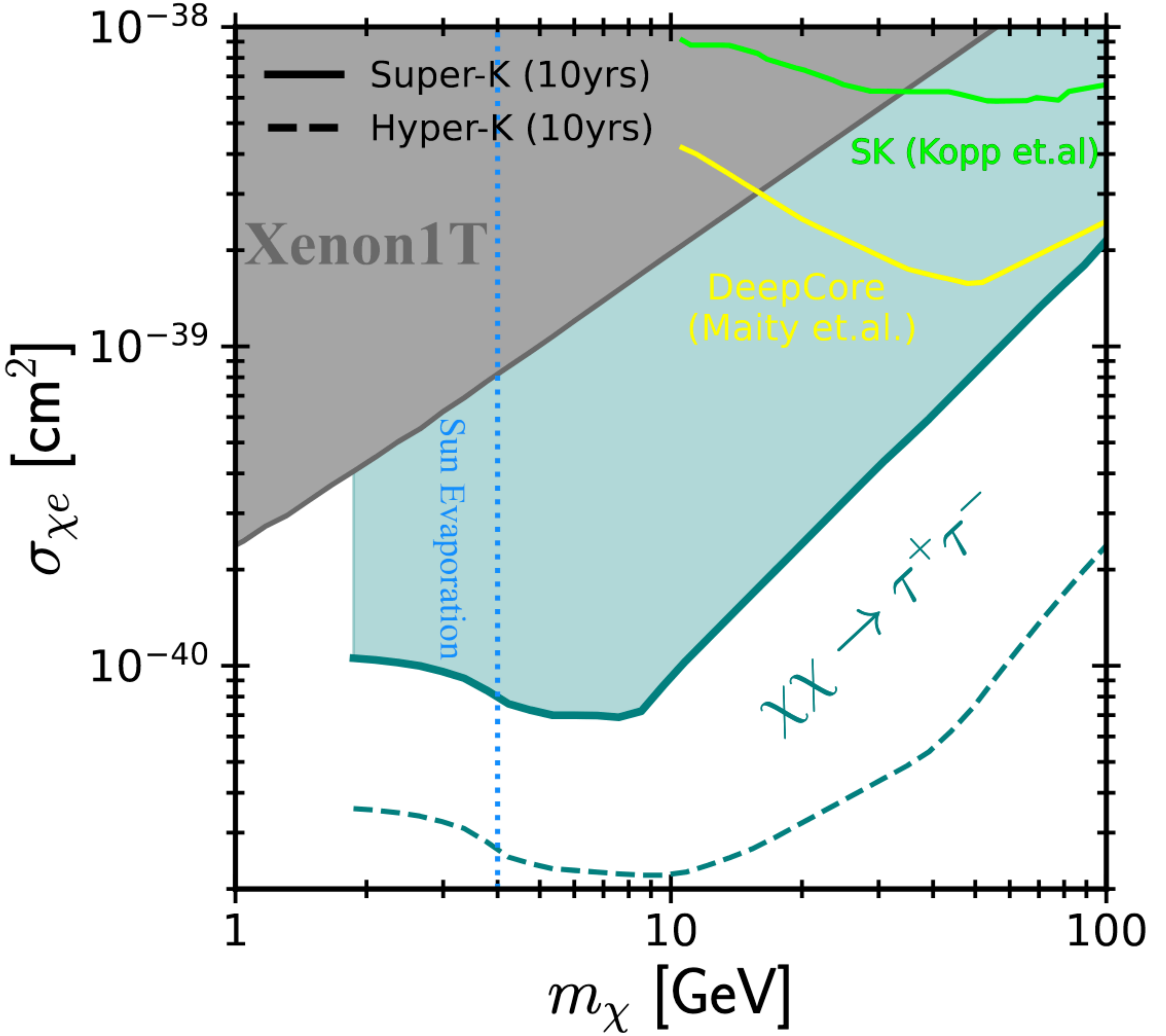
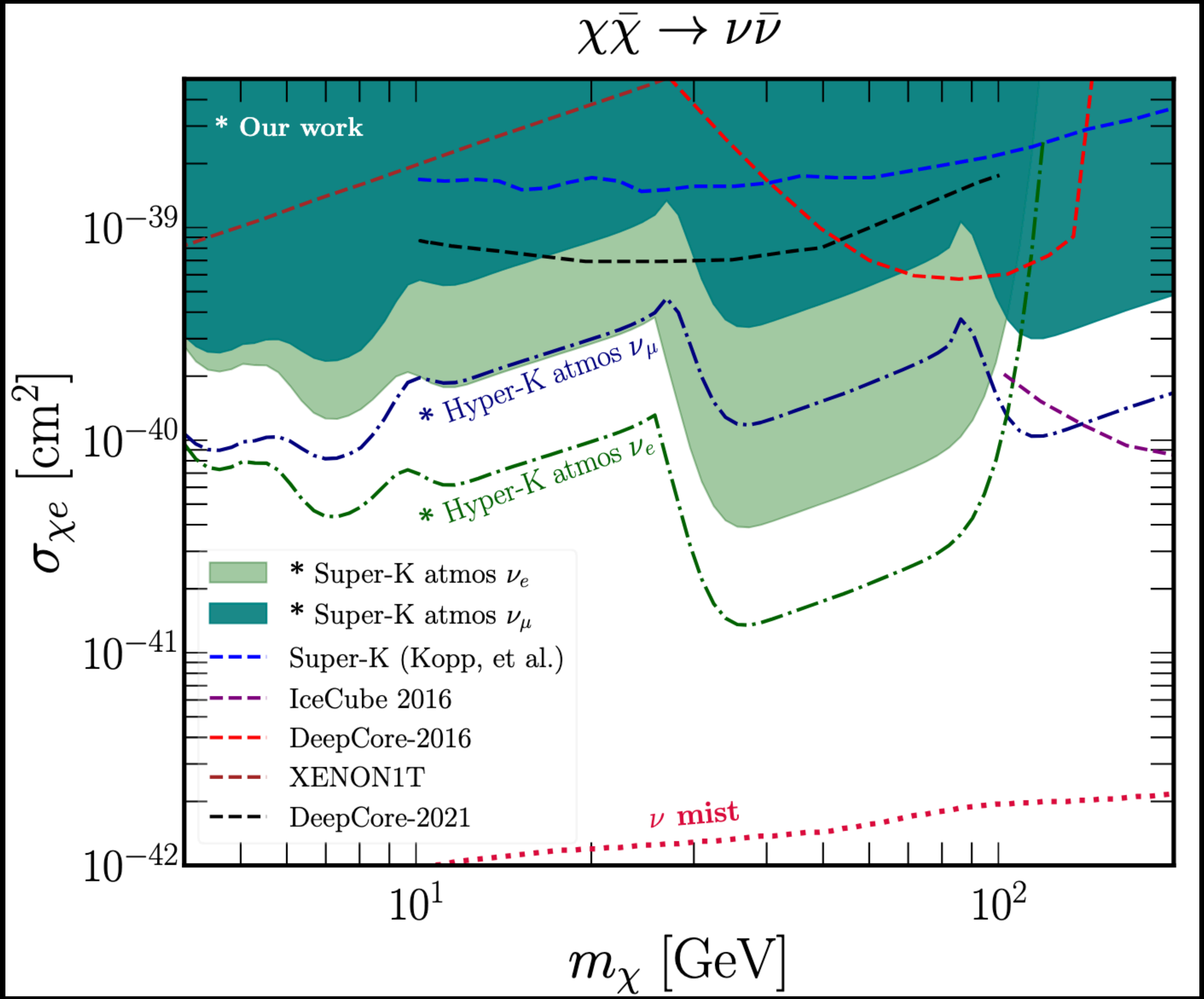


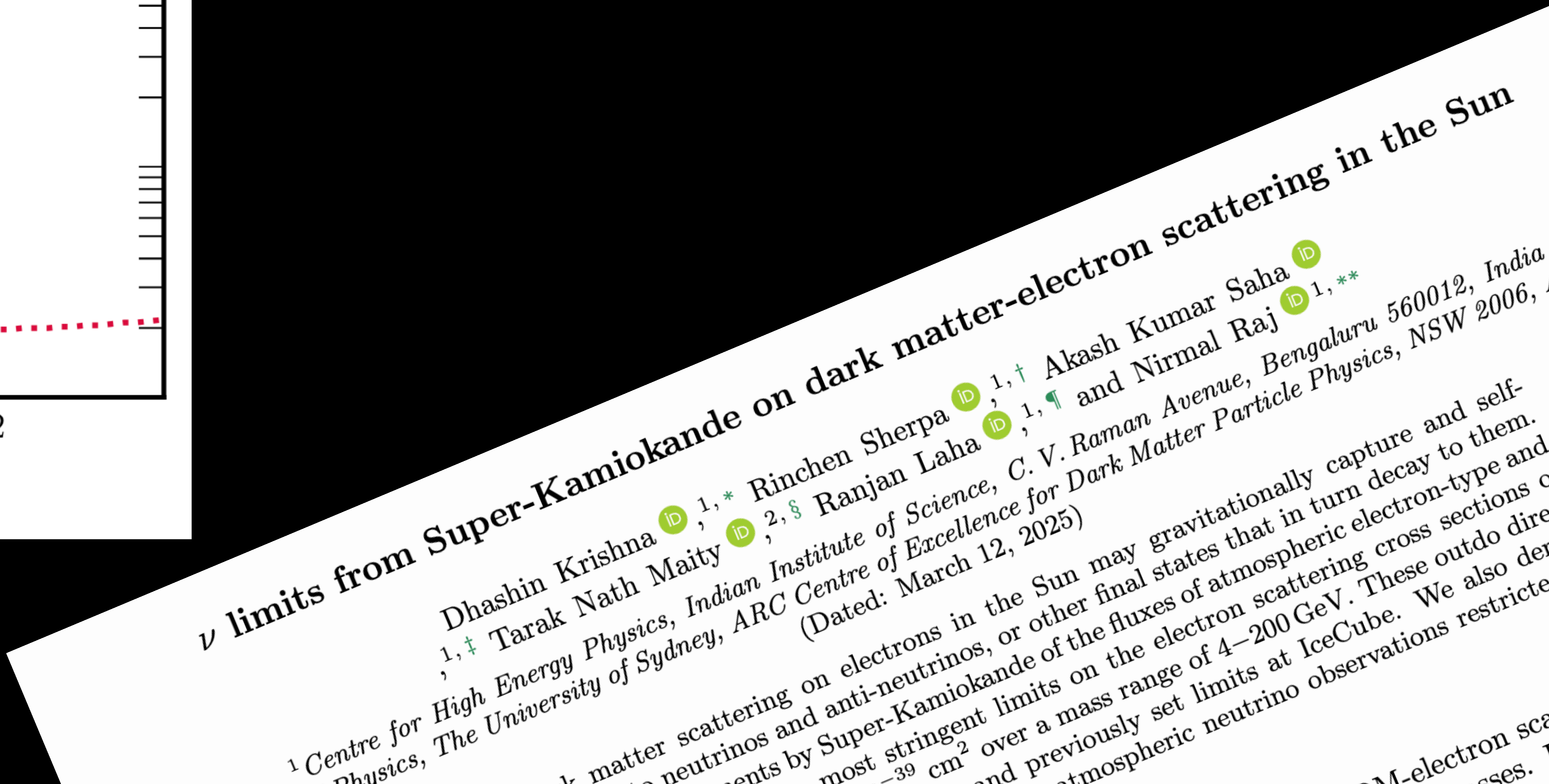


Super-Kamiokande

- 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)

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

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

Garani & Palomares-Ruiz (1702.02768)

$$R_i(w \to v) = \int n_i(r) \frac{\mathrm{d}\sigma_i}{\mathrm{d}v} |\boldsymbol{w} - \boldsymbol{u}| f_i(\boldsymbol{u}, r) \, \mathrm{d}^3\boldsymbol{u}$$

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

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,

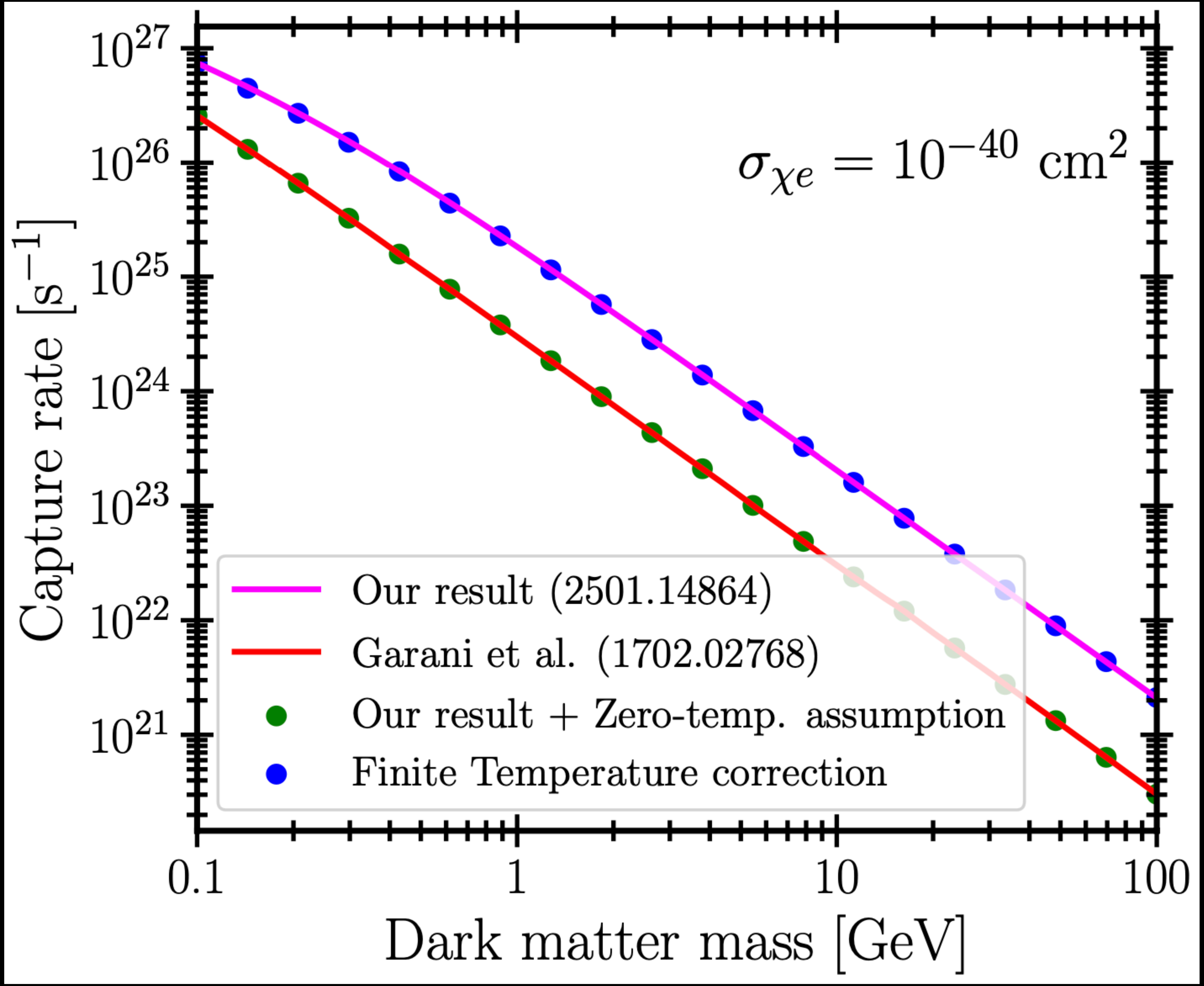
$$\Omega_v^-(w) = \frac{\sigma n}{w}\left(v^2 - \frac{\mu_-^2}{\mu} u^2\right) \theta\left(v^2 - \frac{\mu_-^2}{\mu} u^2\right). \tag{2.13}$$

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.**



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LTH-1321

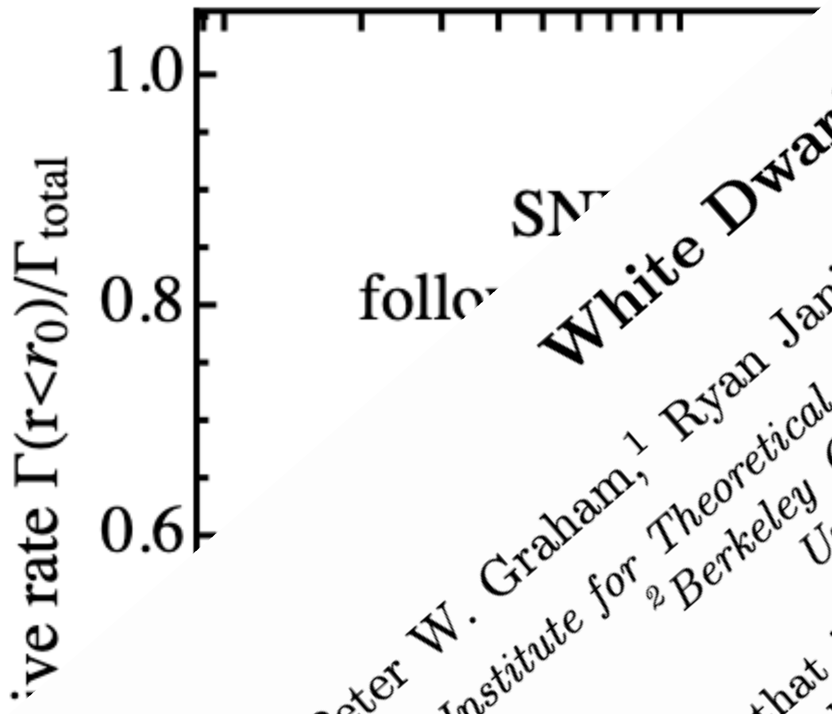
White Dwarfs in Dwarf Spheroidal Galaxies: A New Class of Compact-Dark-Matter Detectors

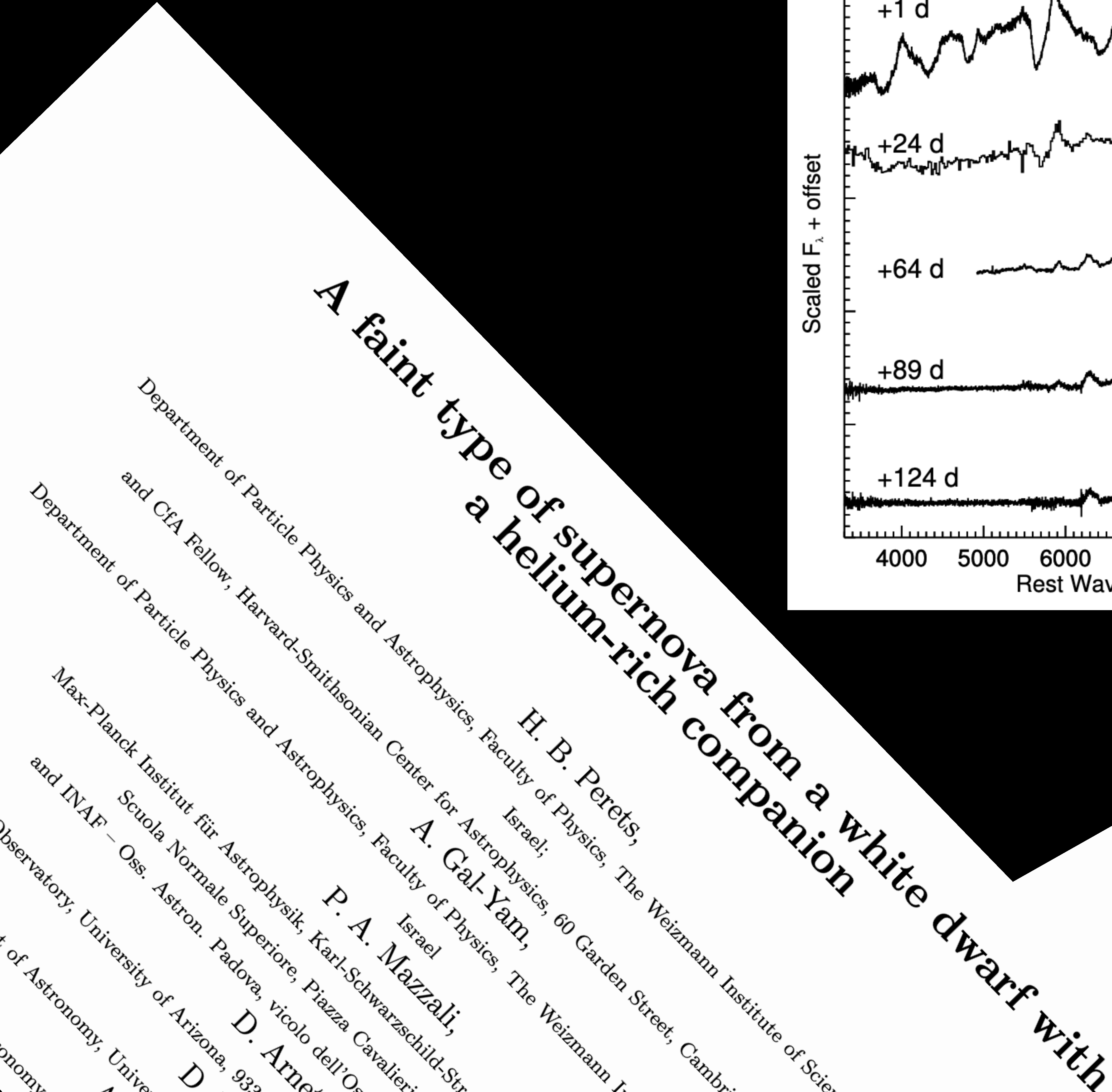
Juri Smirnov,[1,2,*] Ariel Goobar,[2,†] Tim Linden,[2,‡] and Edvard Mörtsell[2,§]

[1]*Department of Mathematical Sciences, University of Liverpool, Liverpool, L69 7ZL, United Kingdom*
[2]*The Oskar Klein Centre, Department of Physics, Stockholm University, AlbaNova, SE-10691 Stockholm, Sweden*

Recent surveys have discovered a population of faint supernovae, known as Ca-rich gap transients, inferred to originate from explosive ignitions of white dwarfs. In addition to their unique spectra and luminosities, these supernovae have an unusual spatial distribution and are predominantly found at large distances from their presumed host galaxies. We show that the locations of Ca-rich gap transients are well matched to the distribution ... dwarf spheroidal galaxies surrounding large galaxies, in accordance with a scenario where dark matter inter... ...s induce thermonuclear explosions among low-mass white dwarfs that may be otherwise difficult to ig... ...ndard stellar or binary evolution mechanisms. A plausible candidate to explain the observed eve... ...dial black holes with masses above 10^{21} grams.

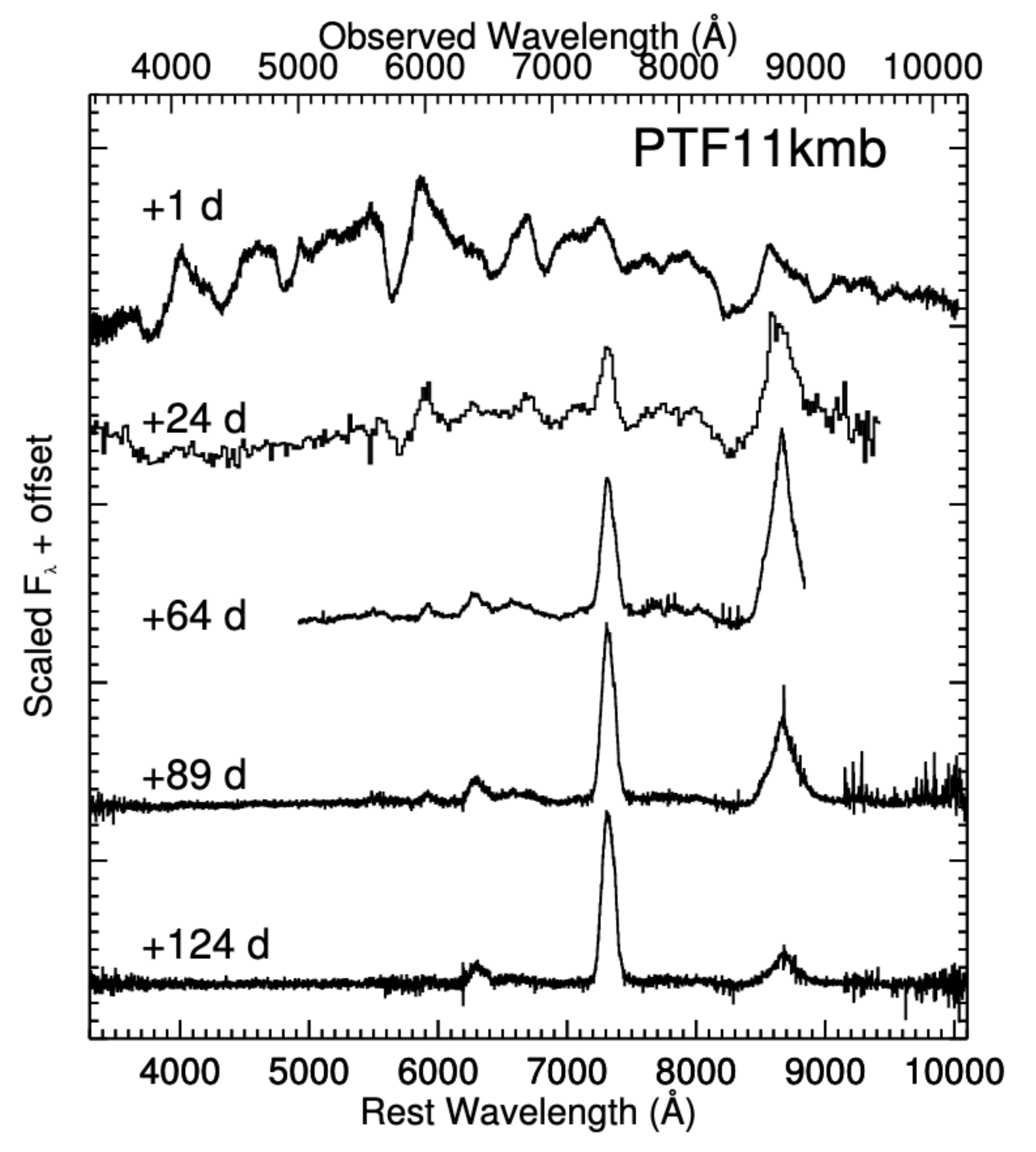
...ed a new population of super- ... [1, 2], called Ca-Rich Gap ... ype Ia SN, which trace ... ed at a much larger ... ies. Additionally, ... originate from ... sekhar limit, ... minantly

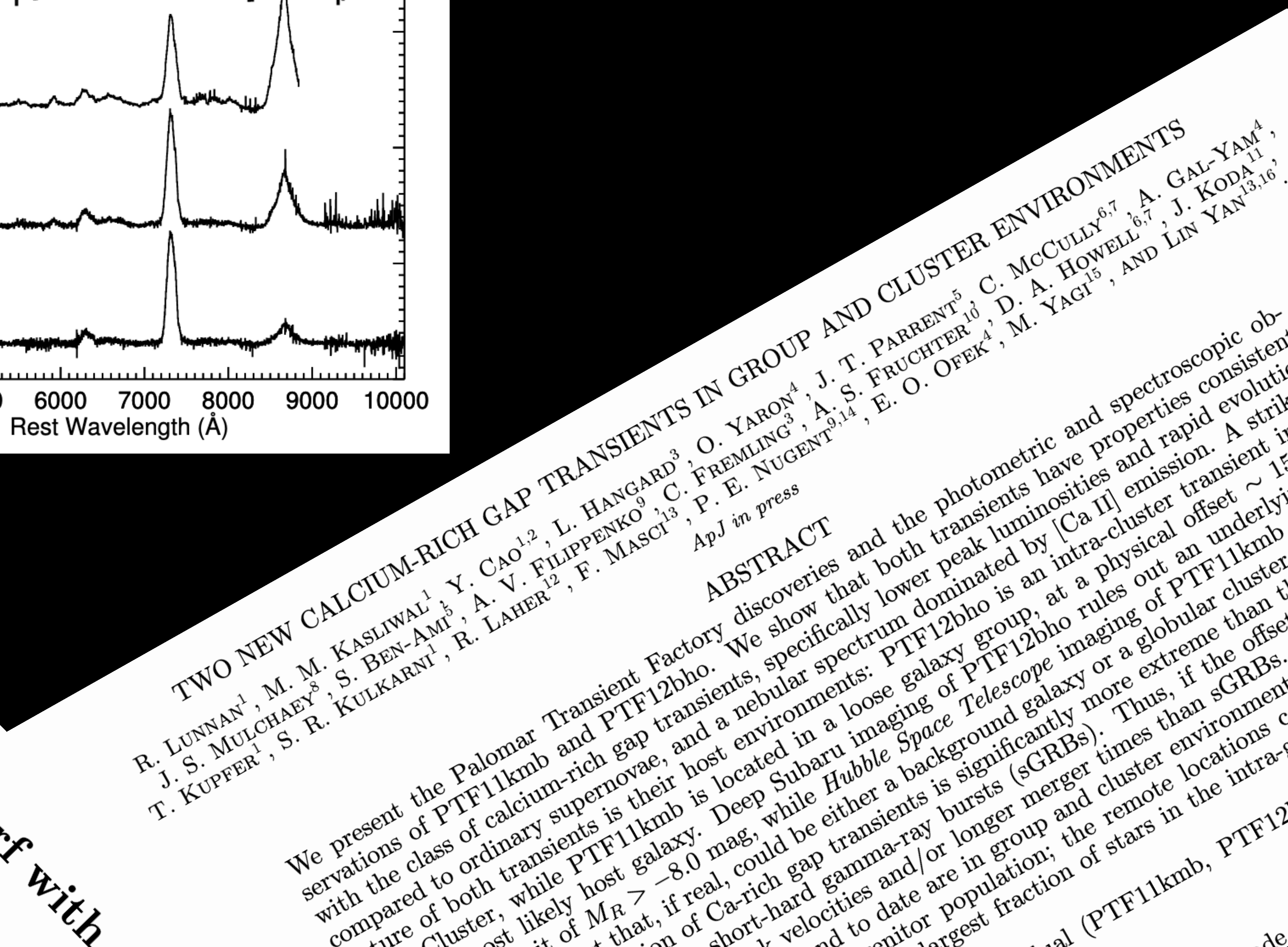




A faint type of supernova from a white dwarf with a helium-rich companion

H. B. Perets,
Department of Particle Physics and Astrophysics, Faculty of Physics, The Weizmann Institute of Scie
Israel;
and CfA Fellow, Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambri
A. Gal-Yam,
Department of Particle Physics and Astrophysics, Faculty of Physics, The Weizmann I
Israel
P. A. Mazzali,
Max-Planck Institut für Astrophysik, Karl-Schwarzschild-Str
Scuola Normale Superiore, Piazza Cavalieri
and INAF – Oss. Astron. Padova, vicolo dell'Os
D. Arne
Observatory, University of Arizona, 933
t of Astronomy, Unive





TWO NEW CALCIUM-RICH GAP TRANSIENTS IN GROUP AND CLUSTER ENVIRONMENTS

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ApJ in press

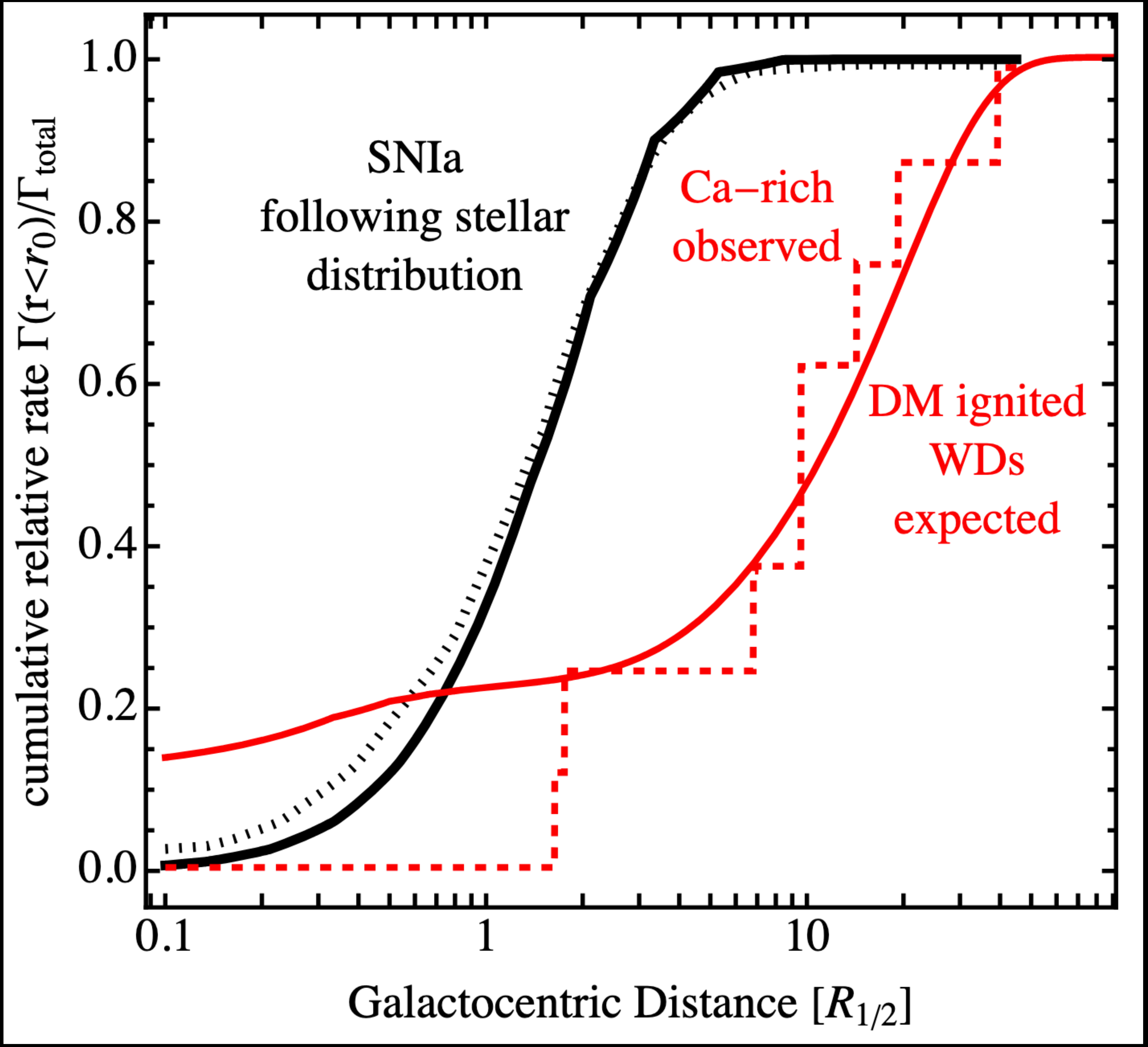
ABSTRACT

We present the Palomar Transient Factory discoveries and the photometric and spectroscopic ob-
servations of PTF11kmb and PTF12bho. We show that both transients have properties consistent
with the class of calcium-rich gap transients, specifically lower peak luminosities and rapid evolutio
compared to ordinary supernovae, and a nebular spectrum dominated by [Ca II] emission. A strik
ture of both transients is their host environments: PTF12bho is an intra-cluster transient in
Cluster, while PTF11kmb is located in a loose galaxy group, at a physical offset ∼ 15
ost likely host galaxy. Deep Subaru imaging of PTF12bho rules out an underlyi
it of $M_R > -8.0$ mag, while *Hubble Space Telescope* imaging of PTF11kmb
t that, if real, could be either a background galaxy or a globular cluster
ion of Ca-rich gap transients is significantly more extreme than th
short-hard gamma-ray bursts (sGRBs). Thus, if the offse
k velocities and/or longer merger times than sGRBs.
nd to date are in group and cluster environment
nitor population; the remote locations o
largest fraction of stars in the intra-
ial (PTF11kmb, PTF12

Fitting both the Number and Distribution of Ca-Rich Transients

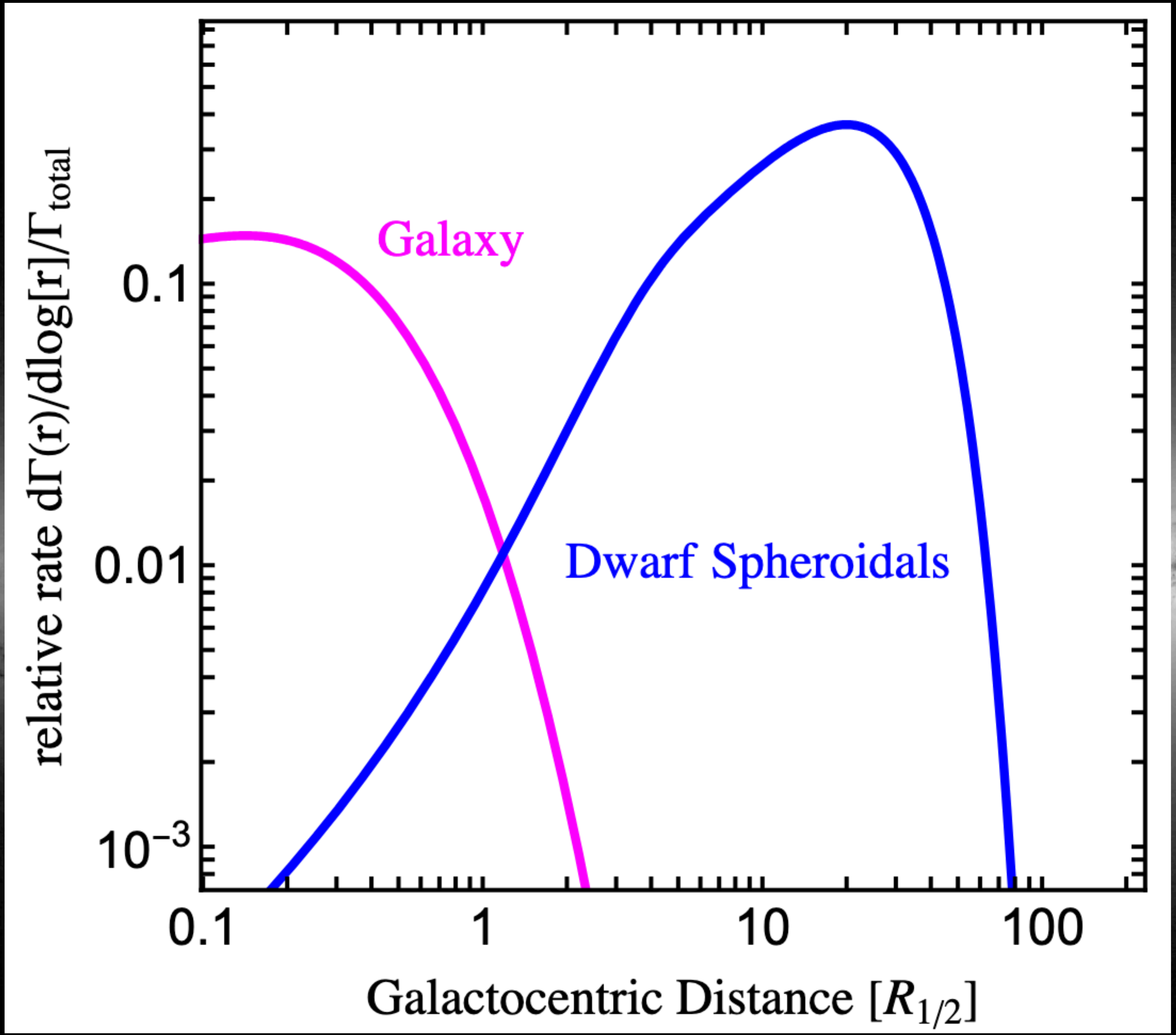
- **Low-luminosity and high-calcium content of Ca-rich population indicates low-mass progenitors (~0.6 $M_{\odot}$, far below the Chandrasekhar mass)**

- **Distribution of events in galactic center radius is also unusual.**

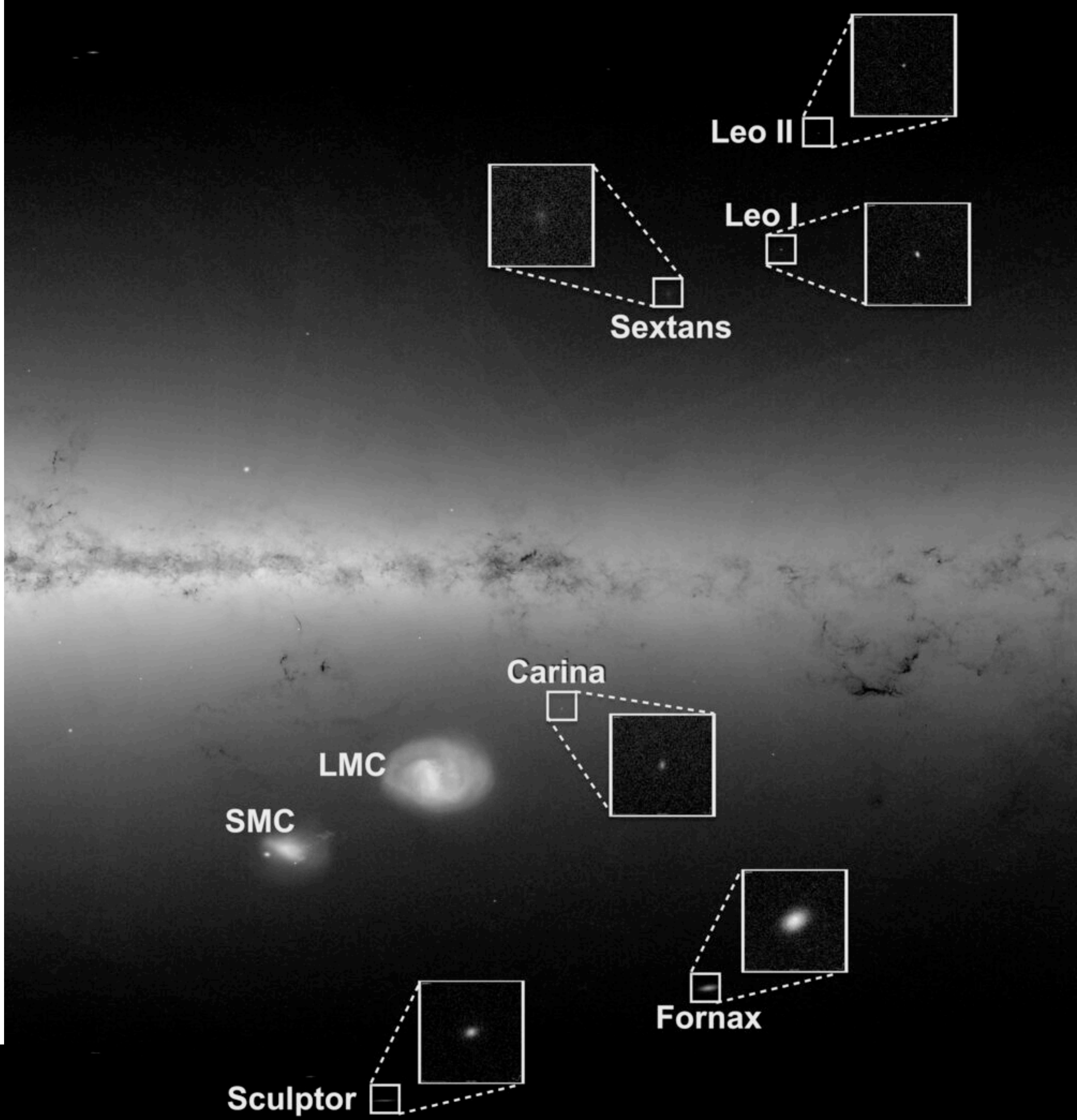


$$C_X \simeq \sqrt{\frac{6}{\pi}} \left(\frac{\rho_X}{\bar{v}_X}\right) \frac{\xi N_B v_{\rm esc}^2}{m_X} \left[1 - \frac{1 - \exp(-B^2)}{B^2}\right] f\left(\sigma_{nX}\right) \tag{1}$$

$$v_{esc} = 10.9 \left(\frac{M}{10^7 M_\odot}\right)^{1/3} \left[\frac{1+z}{9.5}\right]^{1/2} \frac{\rm km}{\rm s}$$



Galaxy
Dwarf Spheroidals
relative rate dΓ(r)/dlog[r]/Γ total
0.1
0.01
10^−3
0.1
1
10
100
Galactocentric Distance [R 1/2]

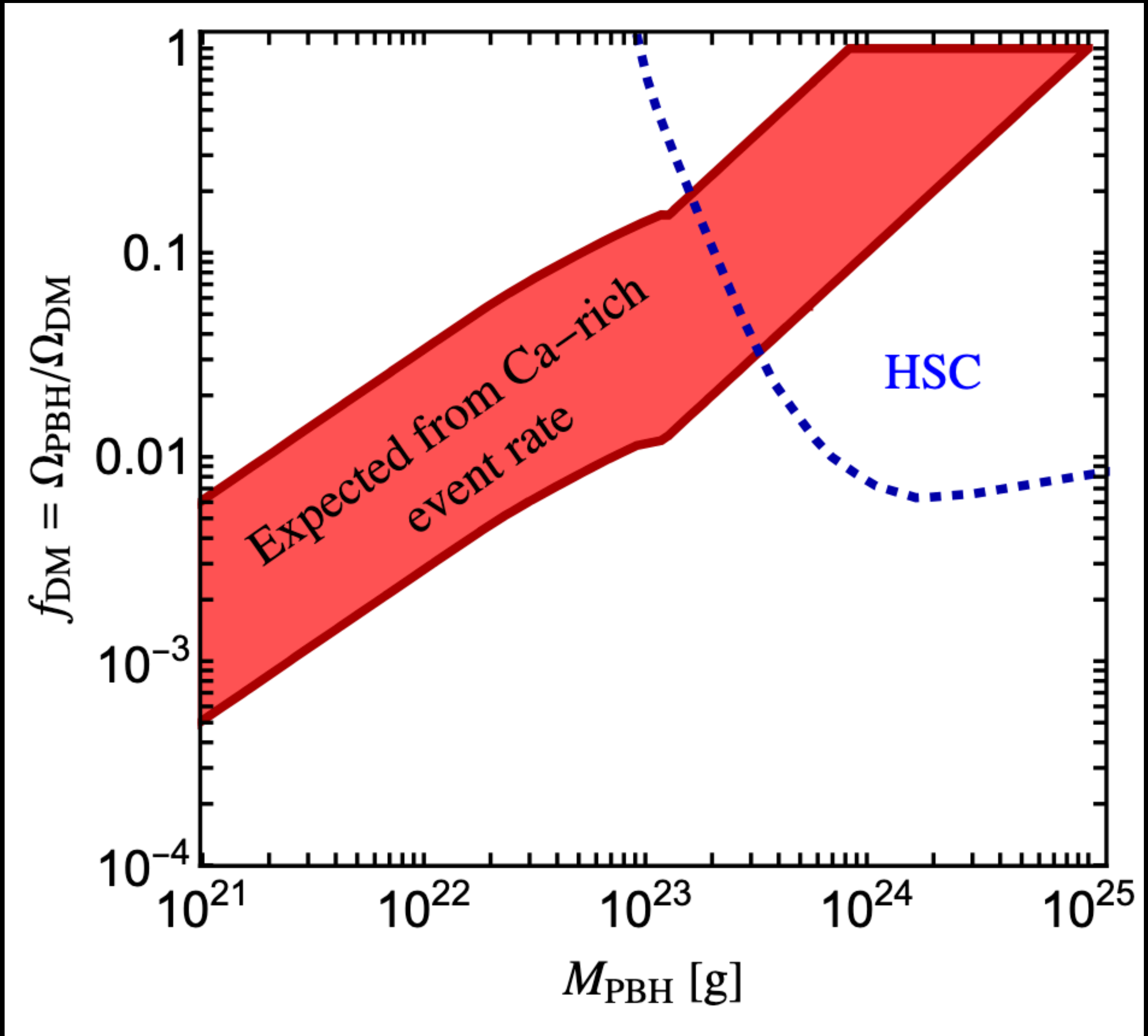


Leo II
Leo I
Sextans
Carina
LMC
SMC
Fornax
Sculptor

Fitting both the Number and Distribution of Ca-Rich Transients

- “Miracle” - Dark Matter must be relatively low-mass black holes (but can be a subdominant portion of the total dark matter density).

- Standard kinematic interactions rates and dark matter abundance.



Observational Follow-Ups are Motivated

- Searches for Ca-Rich SNe are a key science component for upcoming LSST analyses.

- JWST follow-ups of these sources can potentially detect nearby dwarf galaxies.

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

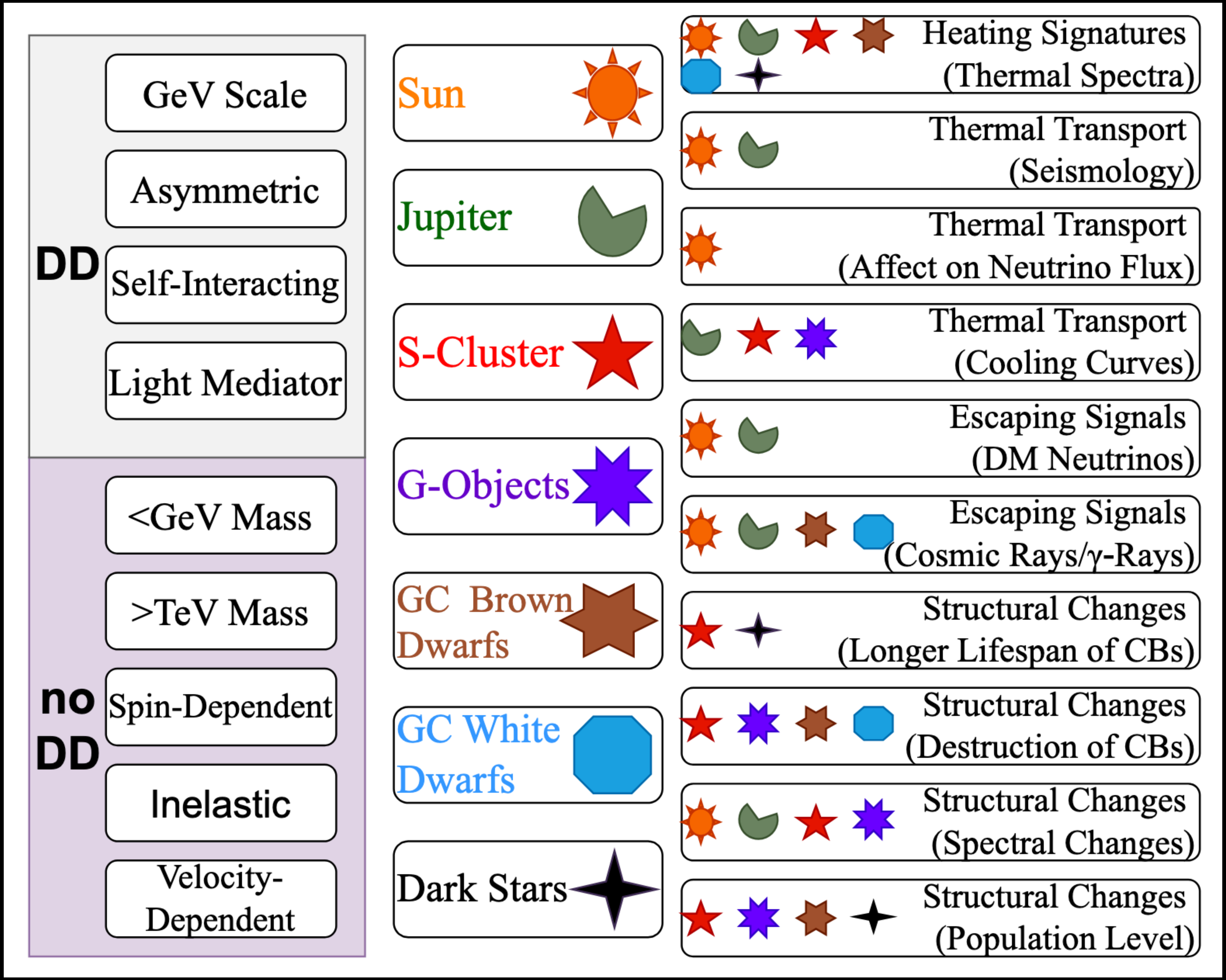
2.) Focus on observables

- 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