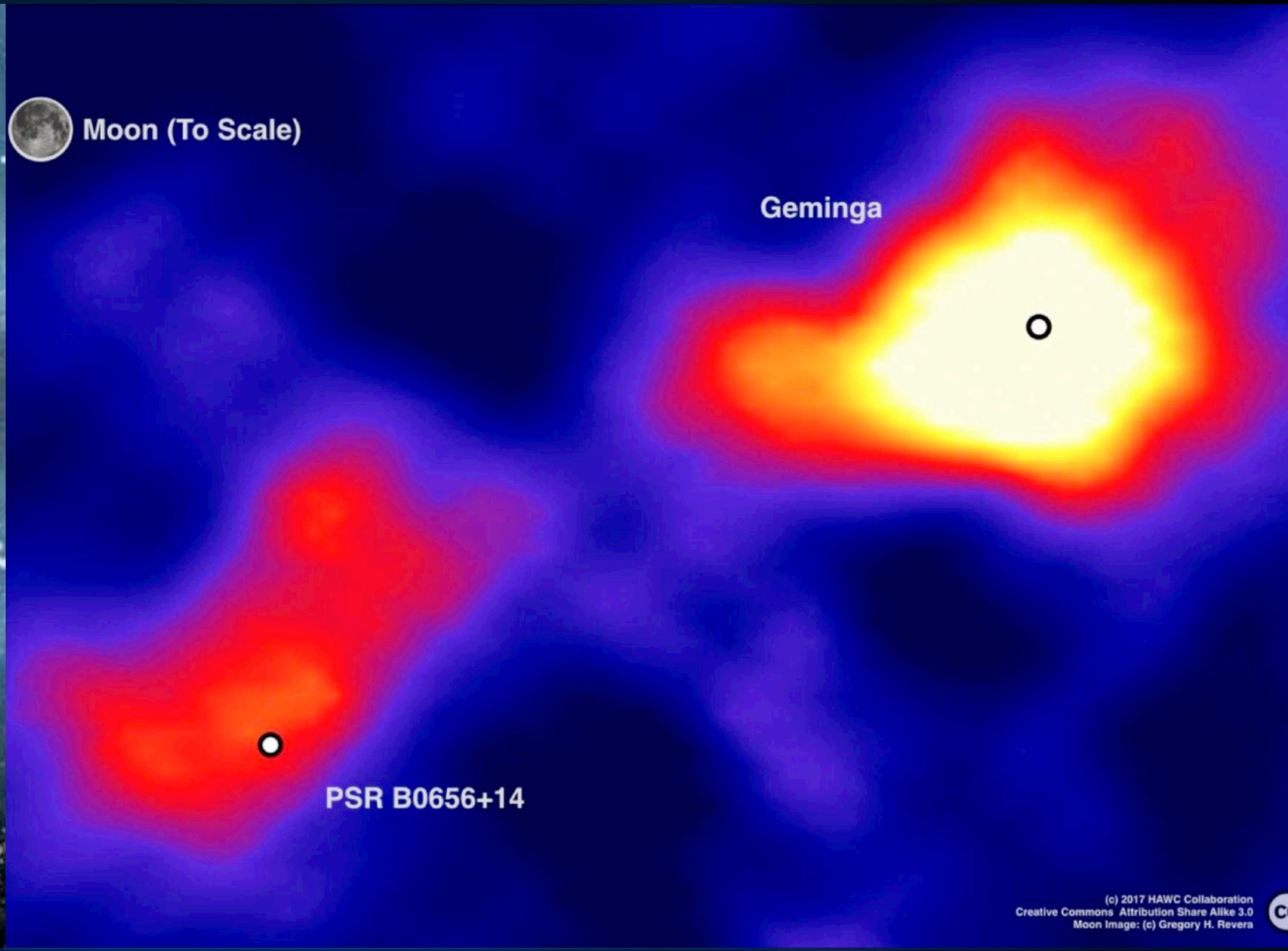


(c) 2017 HAWC Collaboration
Creative Commons Attribution Share Alike 3.0
Moon Image: (c) Gregory H. Revera

Fundamental Physics with Neutron Stars

Tim Linden

Harvard High Energy Theory Seminar
April 23, 2019

THE OHIO STATE UNIVERSITY
CENTER FOR COSMOLOGY AND
ASTROPARTICLE PHYSICS

Neutron Stars: The Big and the Small

- **Big**: ~1.4 M_o

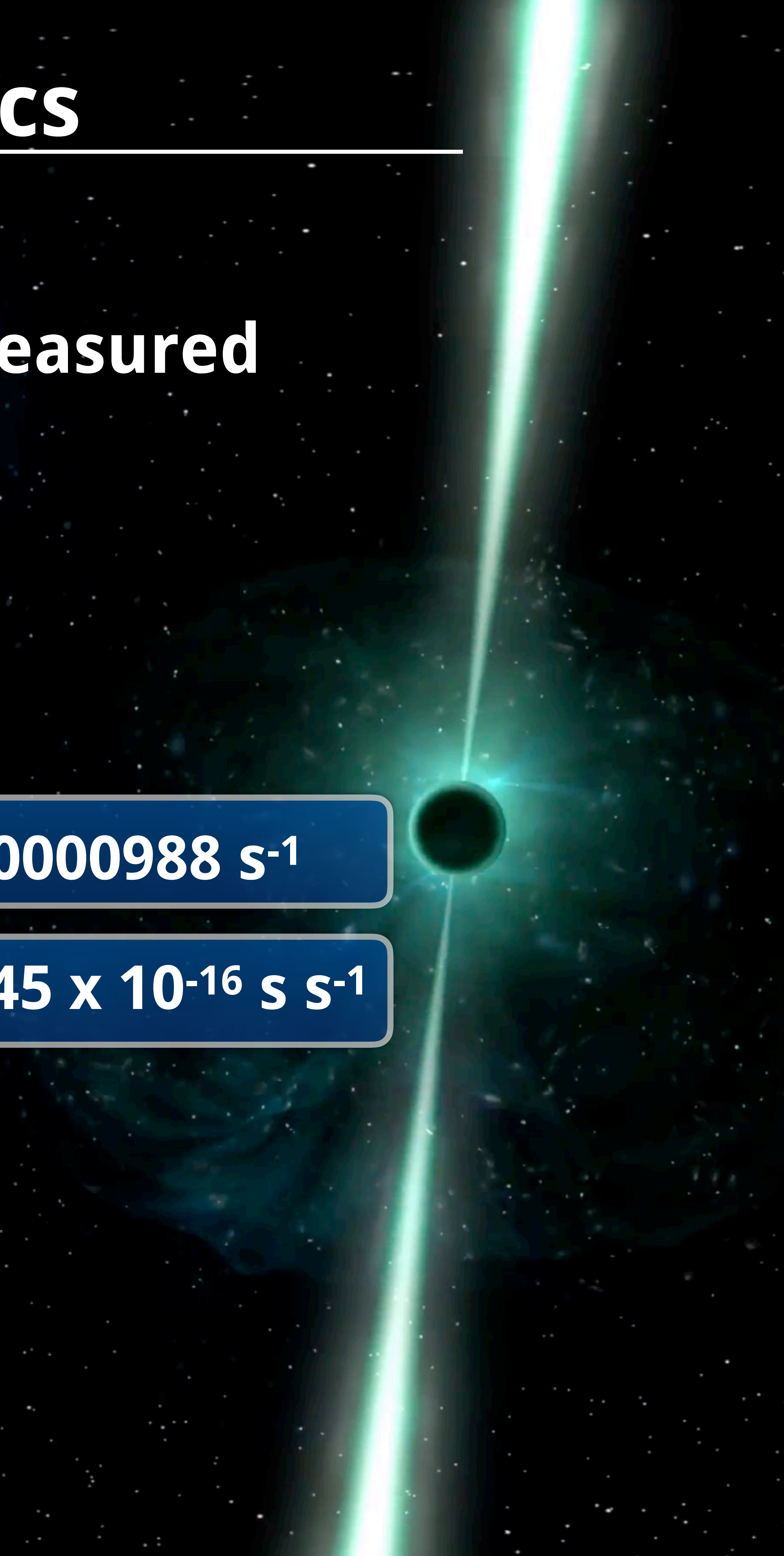
- **Small:** Compressed into 10 km

- **Big:** Can spin up to 700 s^{-1} (0.2 c at surface)

- **Small:** Oblate spheroid to < 1 part in a million

Neutron Stars: Precision Physics

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



PSR J1713+0747

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

$F' = -4.083888637248 \pm 0.0000143324982645 \times 10^{-16}\ s\ s^{-1}$

NANOGrav Collaboration (1801.02617)

A Dipole Model

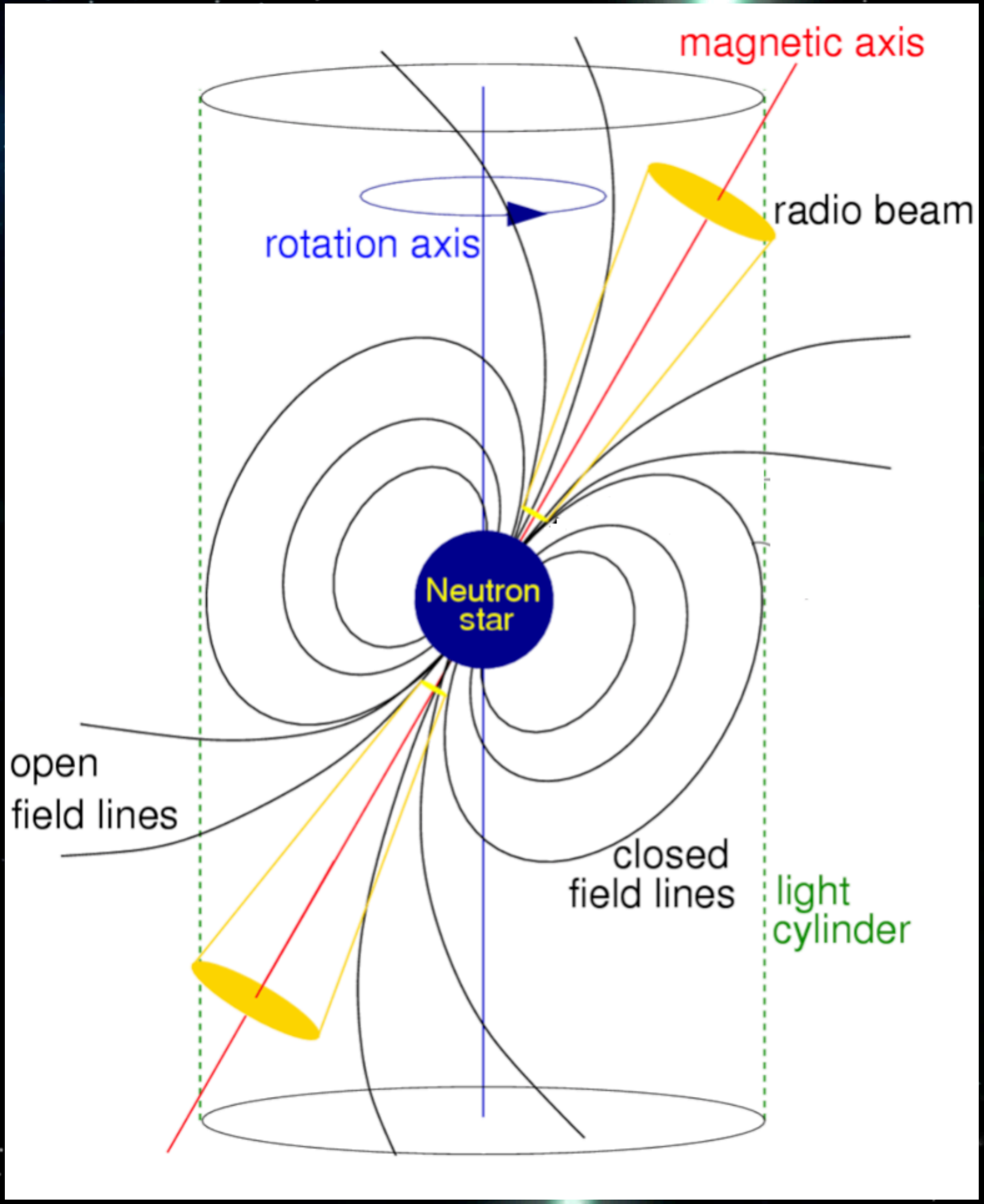
- Can precisely measure the magnetic field:

$$\frac{dE}{dt} \propto -\omega^4 R^6 B^2 \sin^2 \alpha$$

$$B \sim 3.3 \times 10^{19} \left[P^2 \left(\frac{1}{P} \frac{dP}{dt} \right) \right]^{1/2} \text{ G}$$

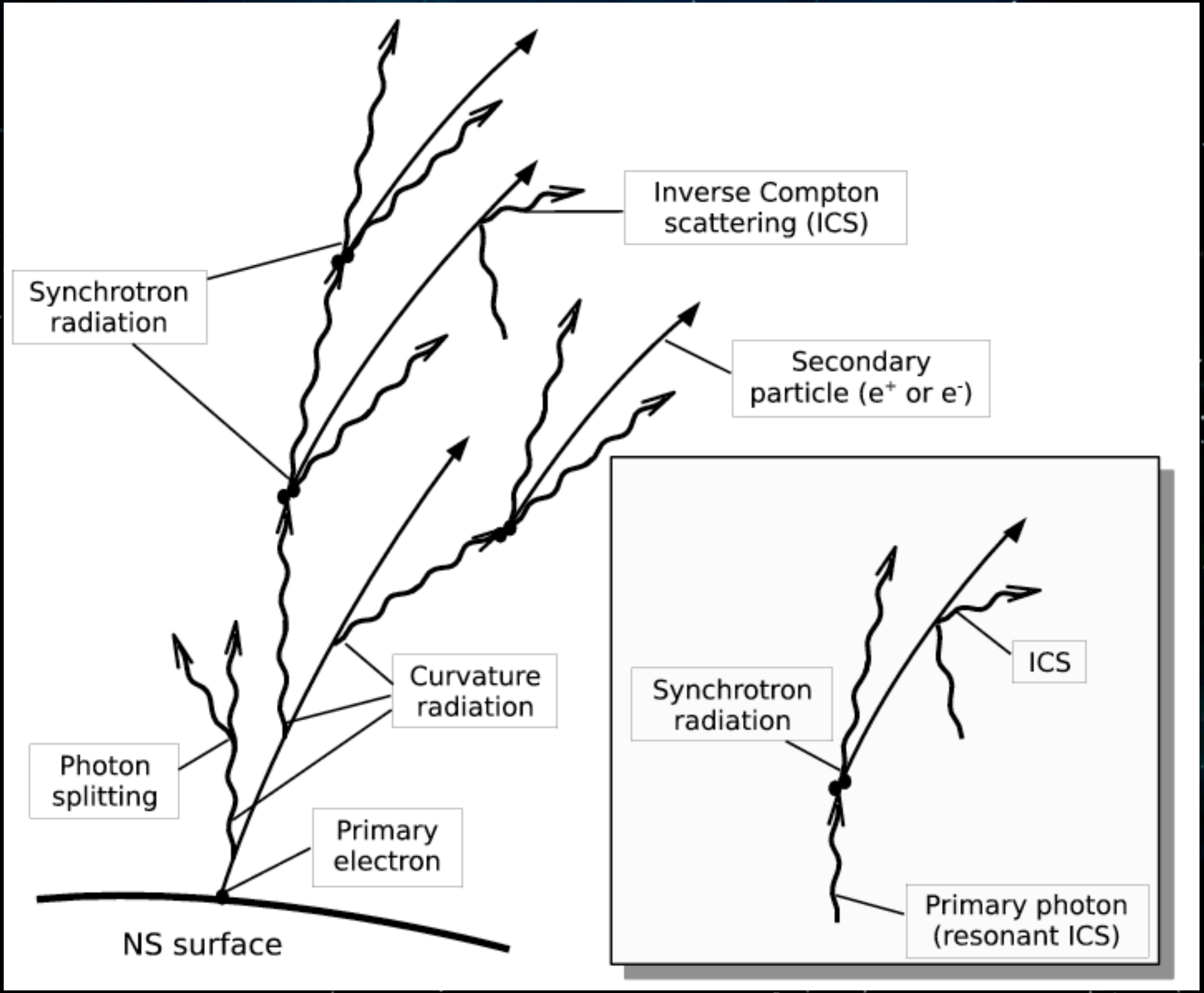
- And approximately measure the age:

$$\tau = \frac{P}{2(dP/dt)}$$



Curvature Radiation

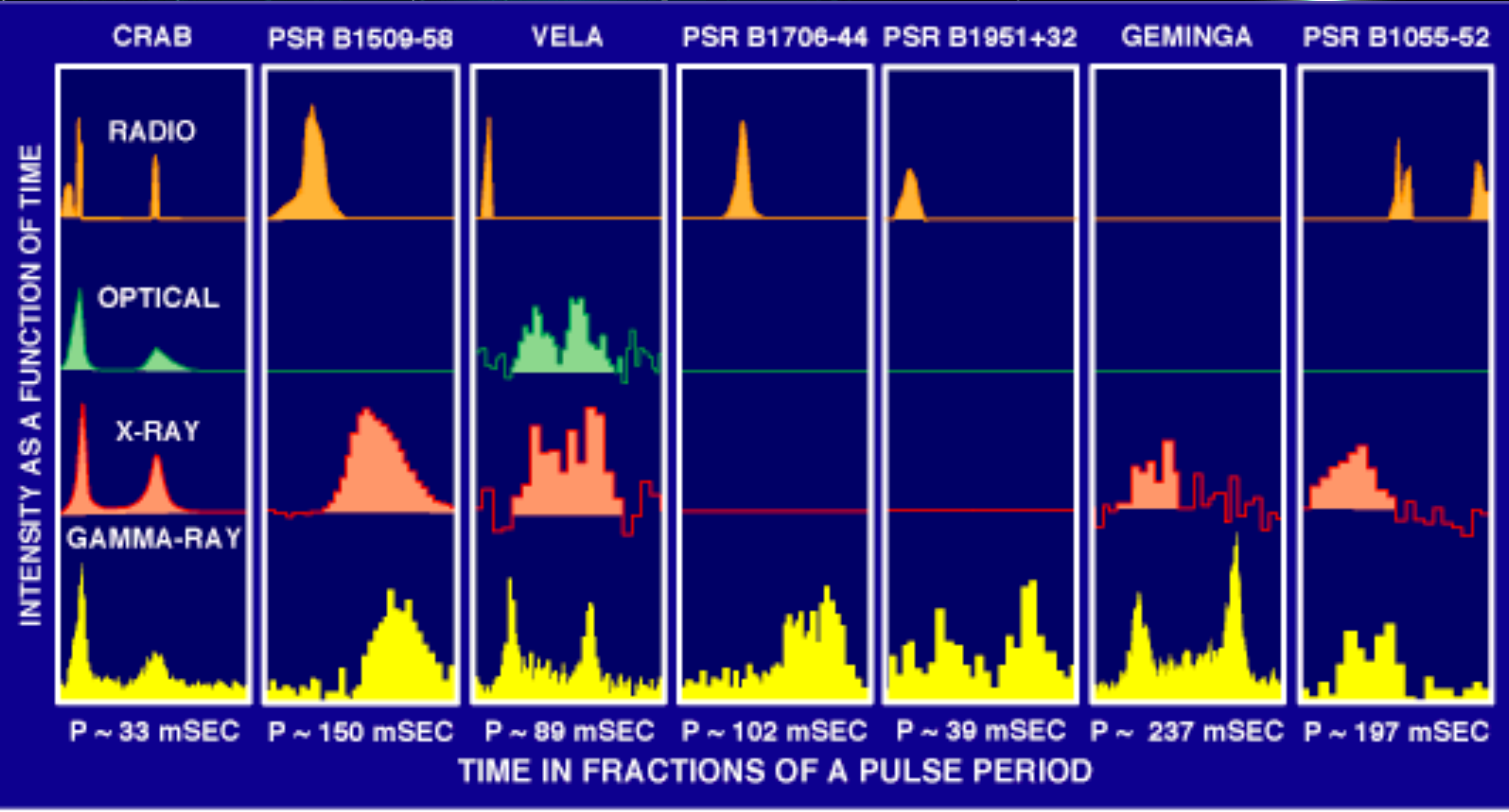
- **Changing magnetic field produces electric field**



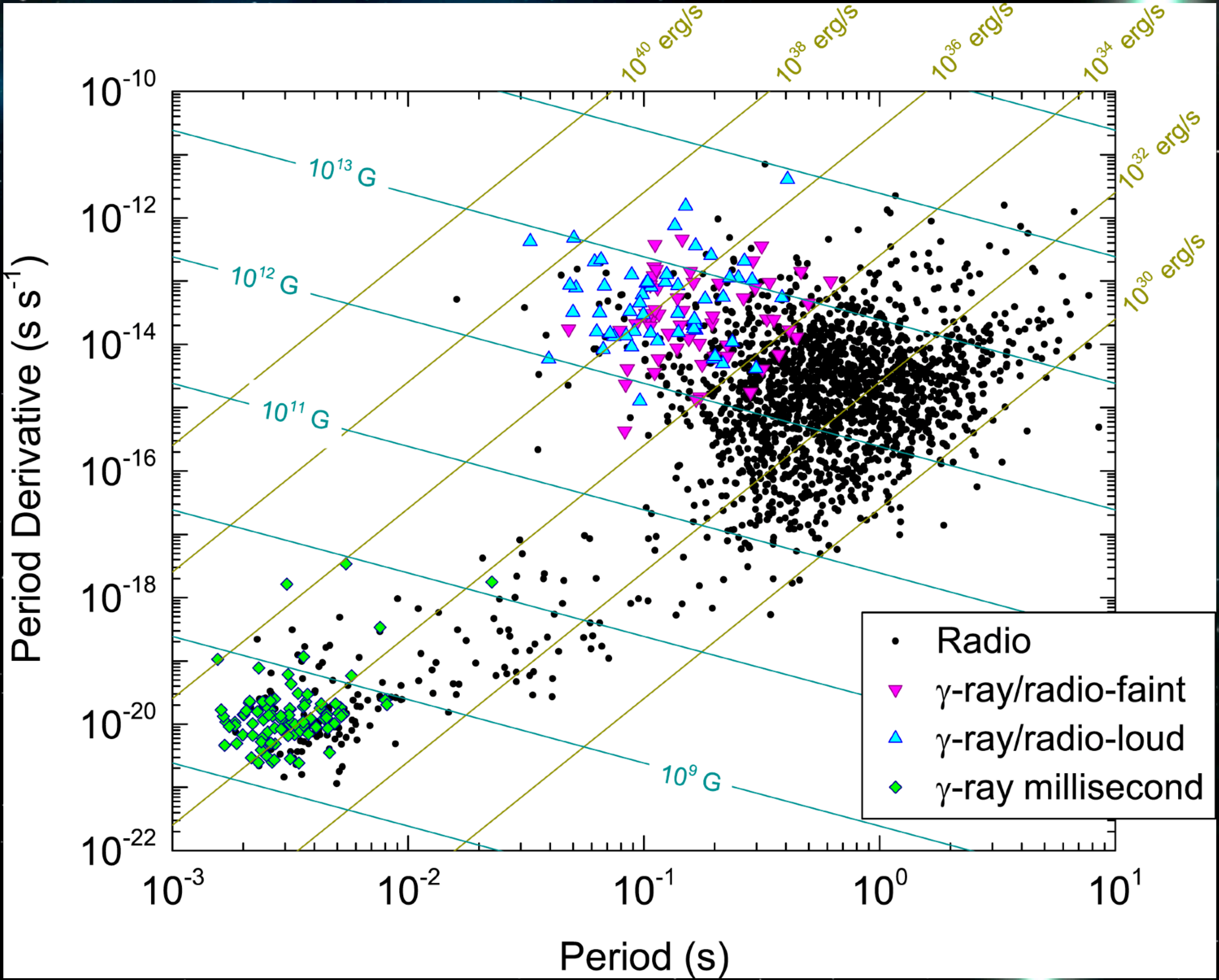
- **1000 PV potential available to accelerate particles**

Ruderman & Sutherland (1975)

Multiwavelength Emission

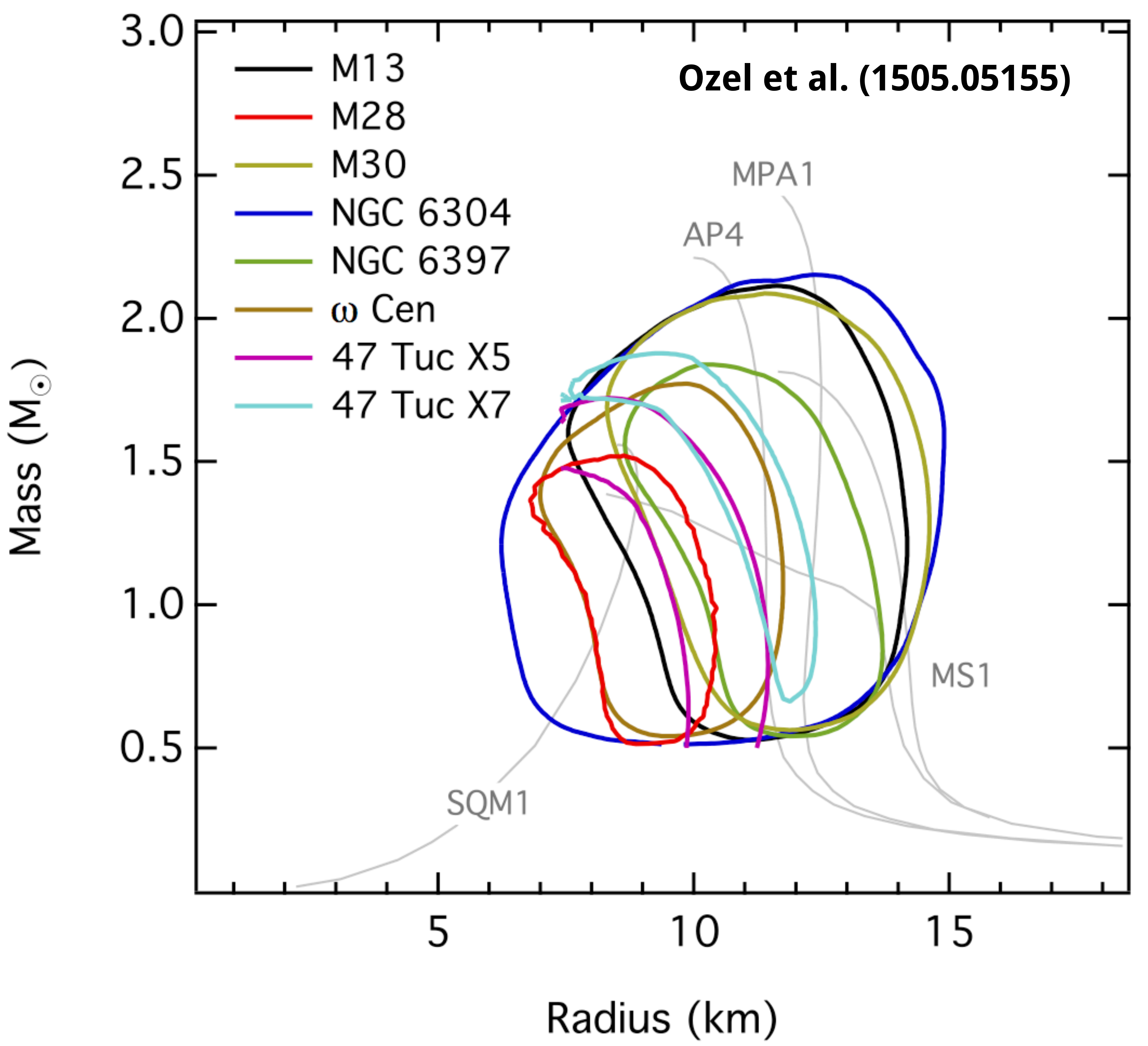


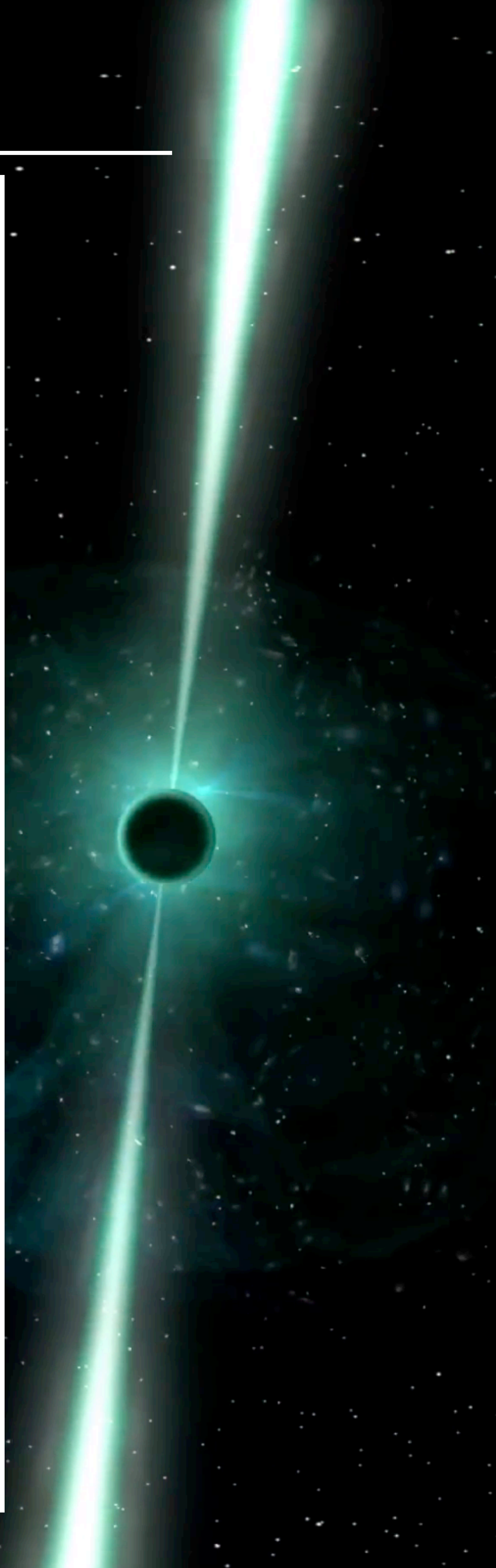
credit: Dave Thompson



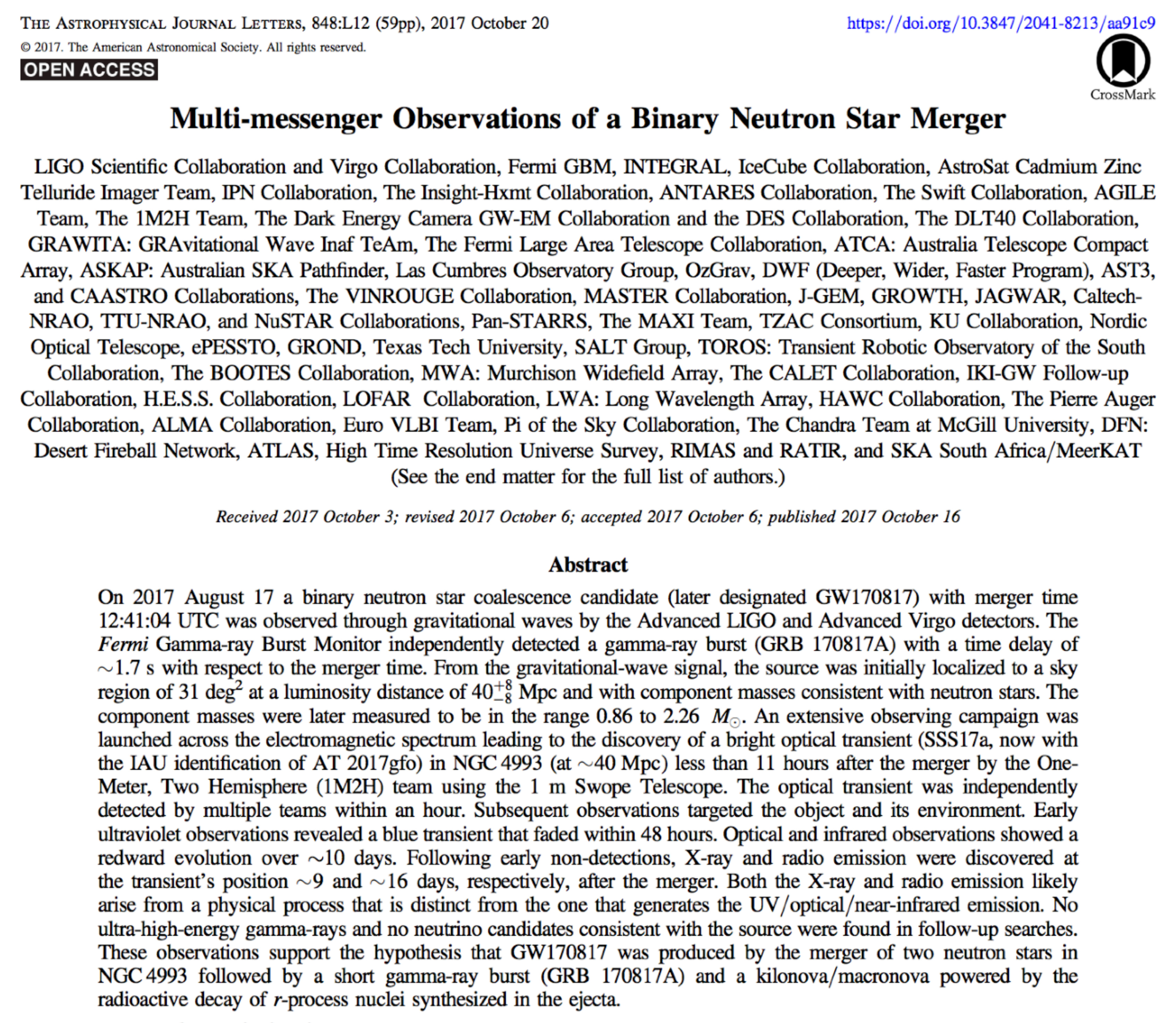
Harding (2016; J Plasma Phys 82)

A Window Into Extreme Physics


Ozel et al. (1505.05155)



A Window Into General Relativity



The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa91c9

Multi-messenger Observations of a Binary Neutron Star Merger

LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech-NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT
(See the end matter for the full list of authors.)

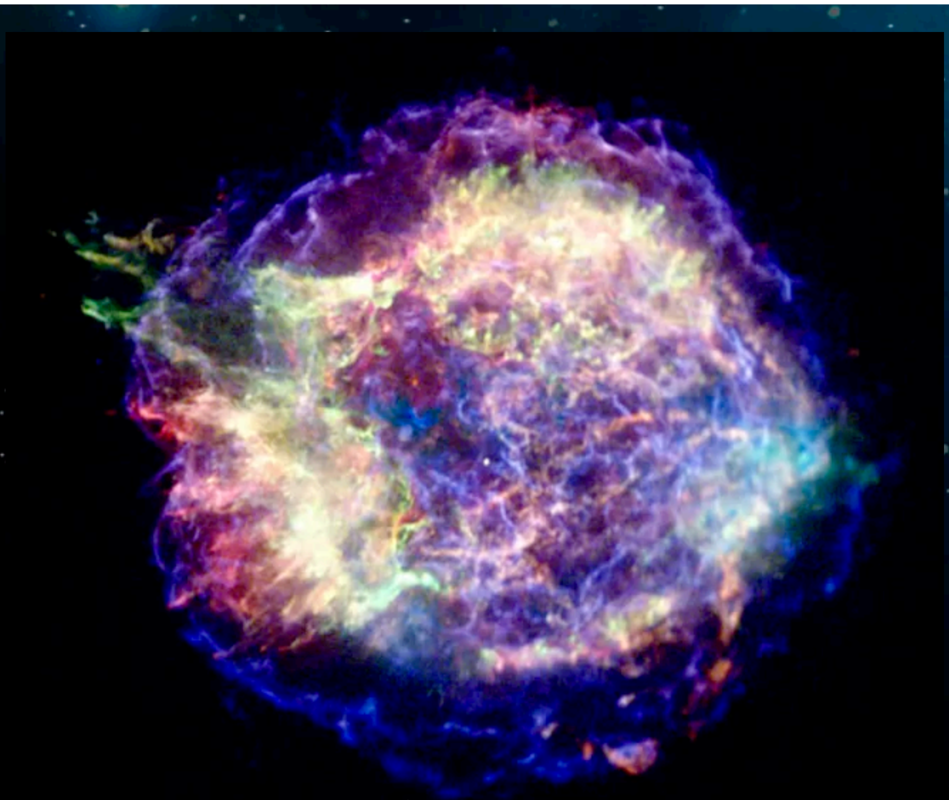
Received 2017 October 3; revised 2017 October 6; accepted 2017 October 6; published 2017 October 16

Abstract

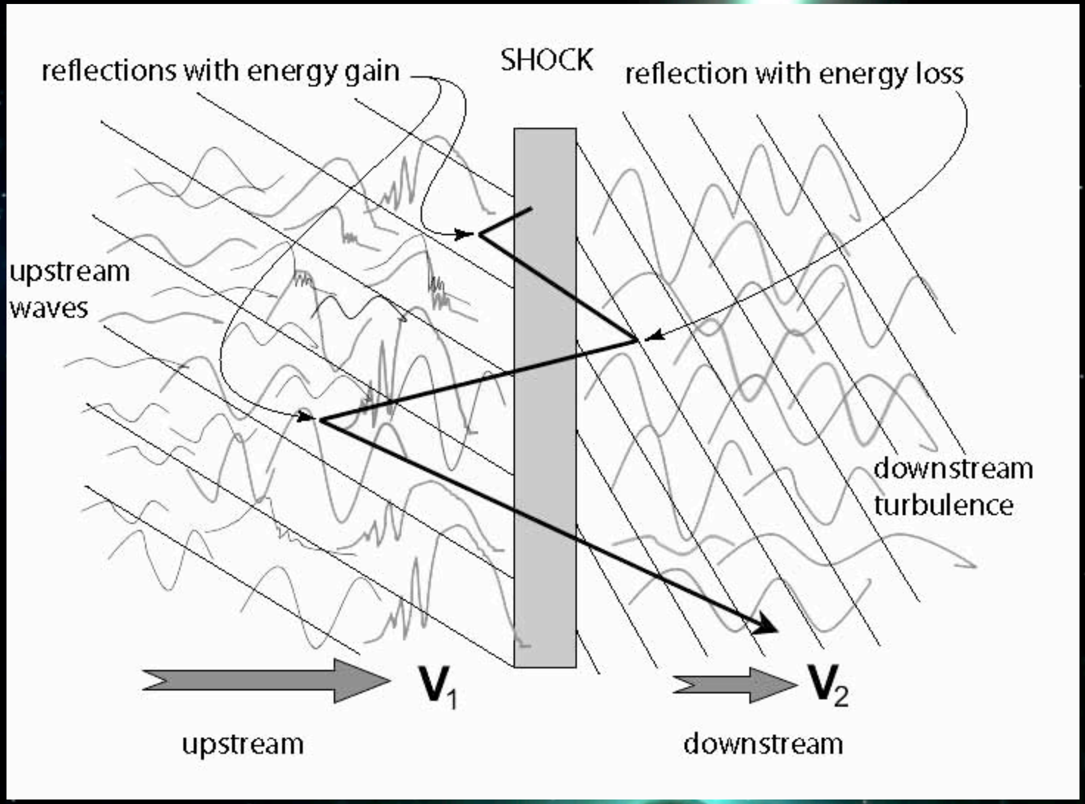
On 2017 August 17 a binary neutron star coalescence candidate (later designated GW170817) with merger time 12:41:04 UTC was observed through gravitational waves by the Advanced LIGO and Advanced Virgo detectors. The *Fermi* Gamma-ray Burst Monitor independently detected a gamma-ray burst (GRB 170817A) with a time delay of ~ 1.7 s with respect to the merger time. From the gravitational-wave signal, the source was initially localized to a sky region of 31 deg^2 at a luminosity distance of 40^{+8}_{-8} Mpc and with component masses consistent with neutron stars. The component masses were later measured to be in the range 0.86 to 2.26 $M_\odot$. An extensive observing campaign was launched across the electromagnetic spectrum leading to the discovery of a bright optical transient (SSS17a, now with the IAU identification of AT 2017gfo) in NGC 4993 (at ~ 40 Mpc) less than 11 hours after the merger by the One-Meter, Two Hemisphere (1M2H) team using the 1 m Swope Telescope. The optical transient was independently detected by multiple teams within an hour. Subsequent observations targeted the object and its environment. Early ultraviolet observations revealed a blue transient that faded within 48 hours. Optical and infrared observations showed a redward evolution over ~ 10 days. Following early non-detections, X-ray and radio emission were discovered at the transient's position ~ 9 and ~ 16 days, respectively, after the merger. Both the X-ray and radio emission likely arise from a physical process that is distinct from the one that generates the UV/optical/near-infrared emission. No ultra-high-energy gamma-rays and no neutrino candidates consistent with the source were found in follow-up searches. These observations support the hypothesis that GW170817 was produced by the merger of two neutron stars in NGC 4993 followed by a short gamma-ray burst (GRB 170817A) and a kilonova/macronova powered by the radioactive decay of *r*-process nuclei synthesized in the ejecta.

Key words: gravitational waves – stars: neutron

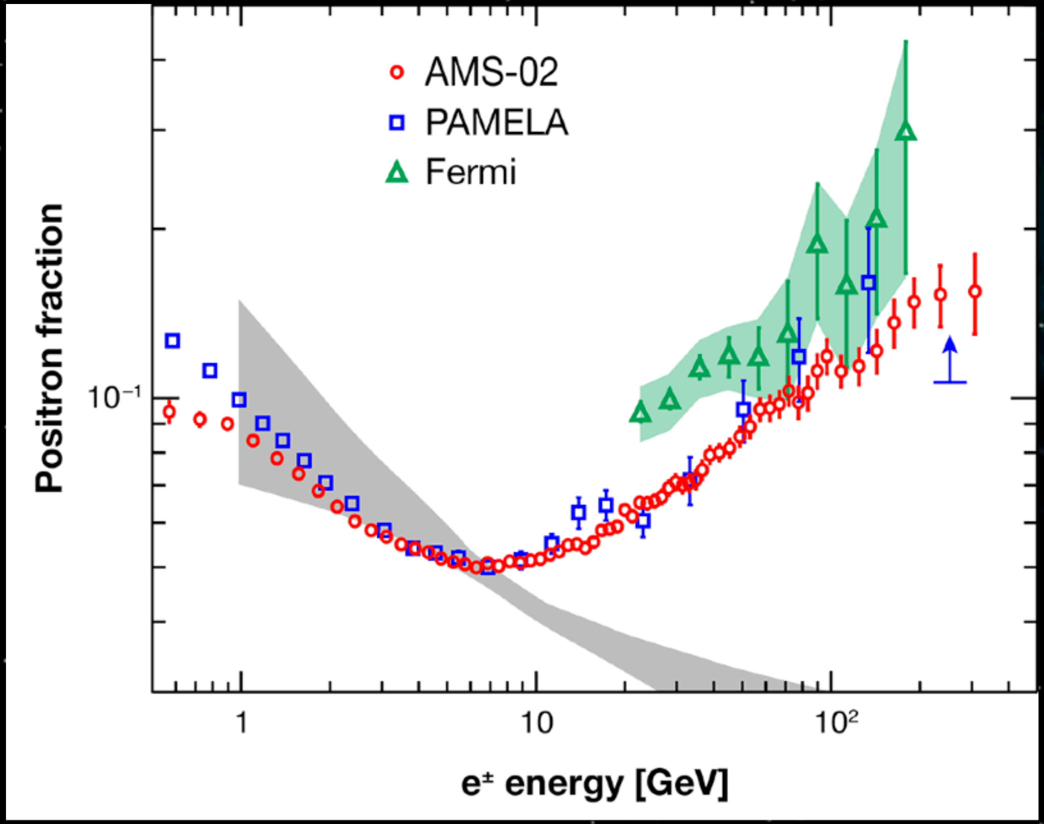
A Window Into Astrophysics



Massive Stars



Shock Acceleration



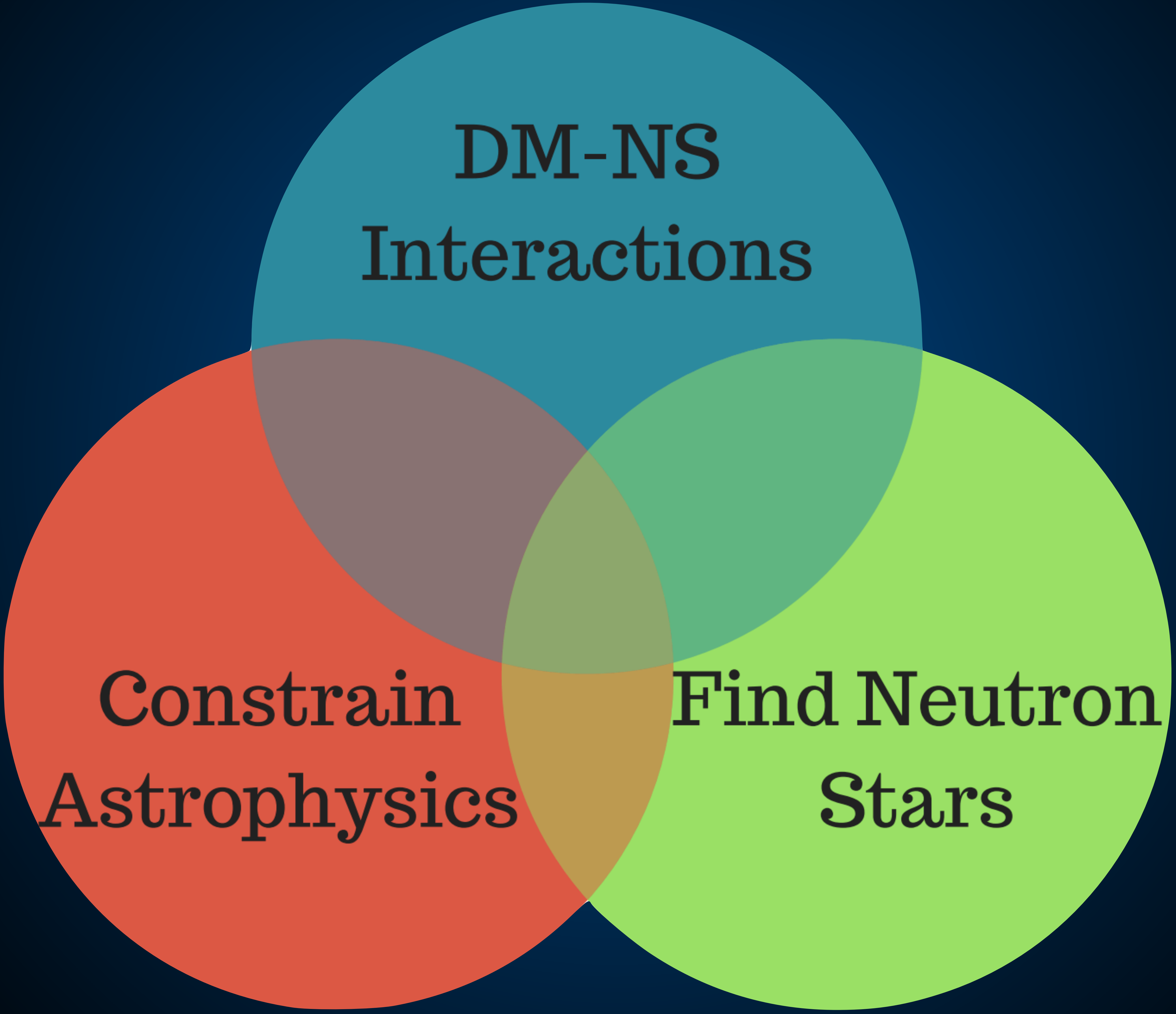
Positron Excess

A Window Into Fundamental Physics

- Sensitive probes of rare processes:
    1. Nuclear densities over macroscopic distances
    2. Strongest magnetic fields in the universe

- Precise measurements are possible

The Program



DM-NS Interactions

Constrain Astrophysics

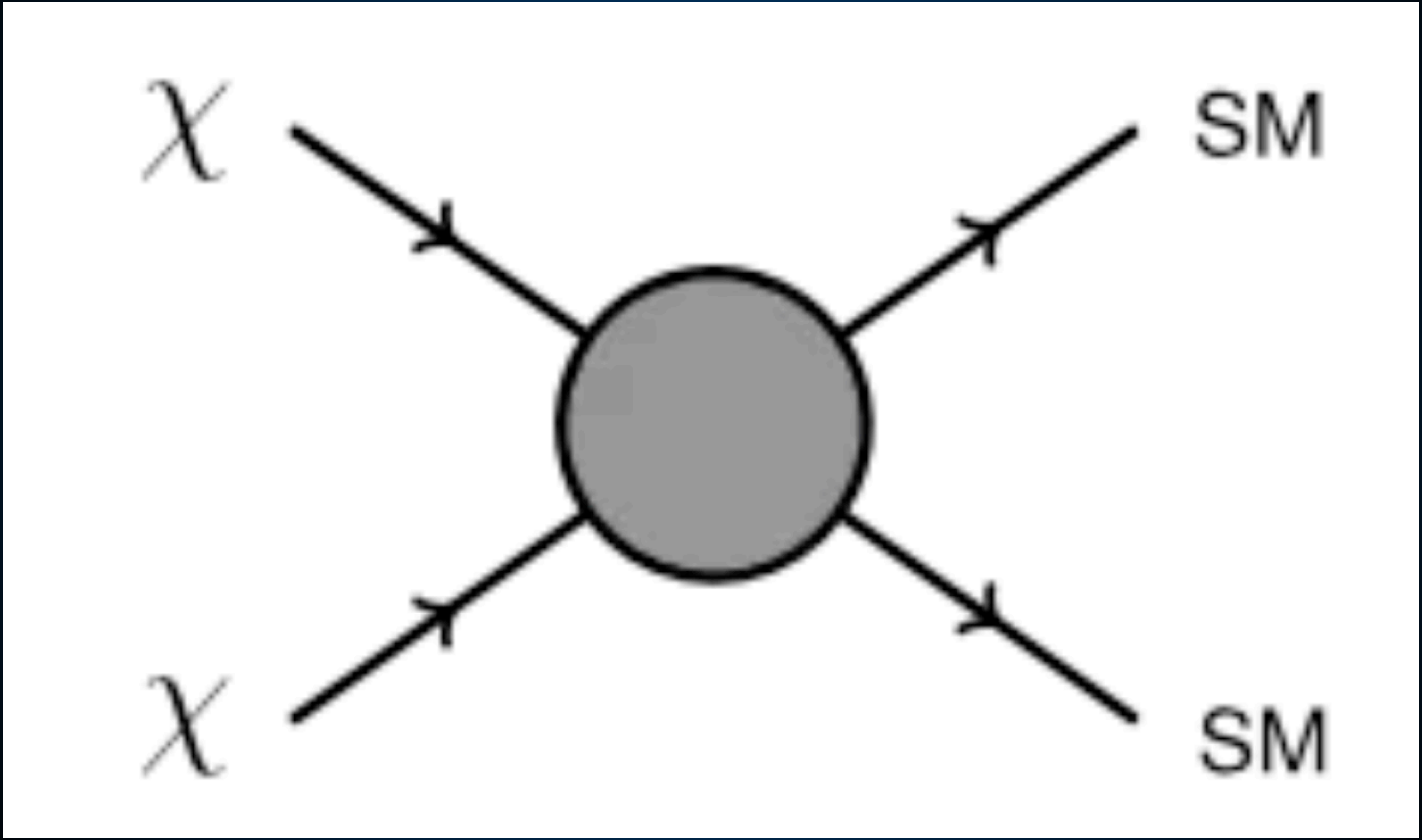
Find Neutron Stars

A Window Into Fundamental Physics

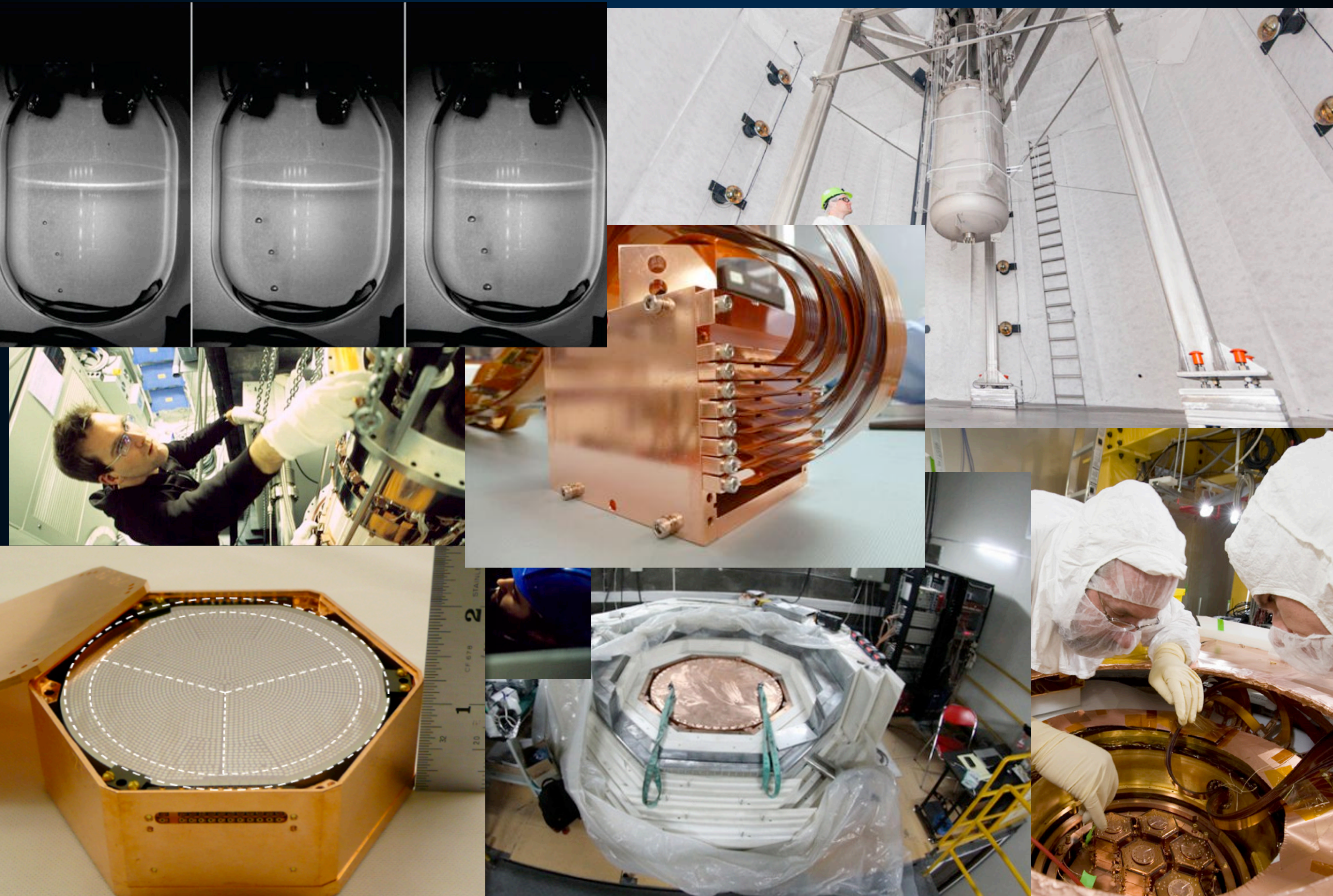
- Sensitive probes of rare processes:
    1. Nuclear densities over macroscopic distances
    2. Strongest magnetic fields in the universe

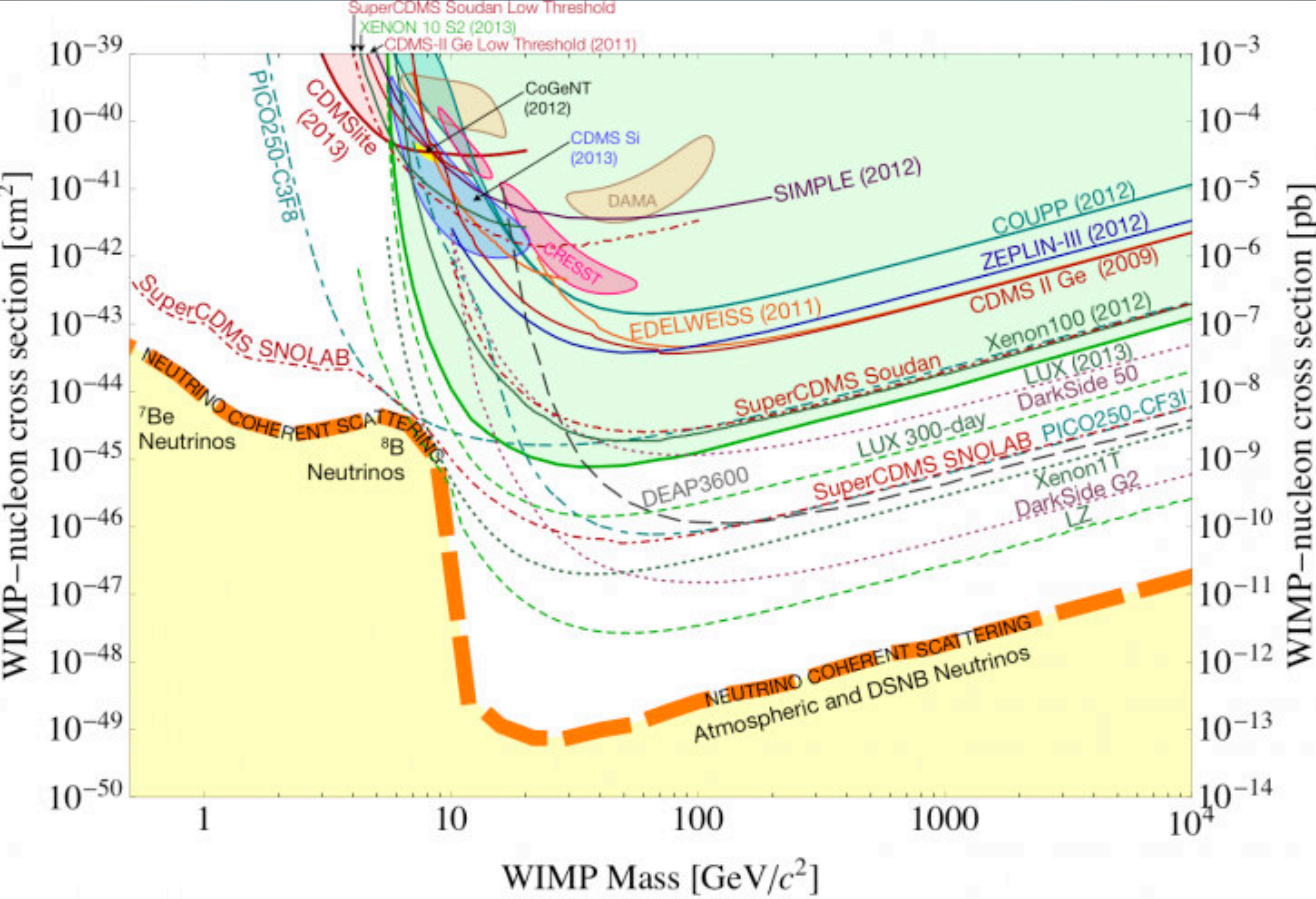
- Precise measurements are possible

Searching for Dark Matter Interactions



Direct Detection: Experimental Efforts




SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
PICO250-C3F8
CDMSlite (2013)
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
CRESST
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
Xenon100 (2012)
SuperCDMS Soudan
LUX (2013)
DarkSide 50
SuperCDMS SNOLAB
PICO250-CF3I
LUX 300-day
SuperCDMS SNOLAB
DEAP3600
Xenon1T
DarkSide G2
LZ
NEUTRINO COHERENT SCATTERING
⁷Be Neutrinos
⁸B Neutrinos
NEUTRINO COHERENT SCATTERING
Atmospheric and DSNB Neutrinos
WIMP–nucleon cross section [cm²]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c²]
10⁻³⁹
10⁻⁴⁰
10⁻⁴¹
10⁻⁴²
10⁻⁴³
10⁻⁴⁴
10⁻⁴⁵
10⁻⁴⁶
10⁻⁴⁷
10⁻⁴⁸
10⁻⁴⁹
10⁻⁵⁰
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³
10⁻¹⁴
1
10
100
1000
10⁴

Neutron Stars: The Optimal Direct Detection Experiment

Xenon-1T

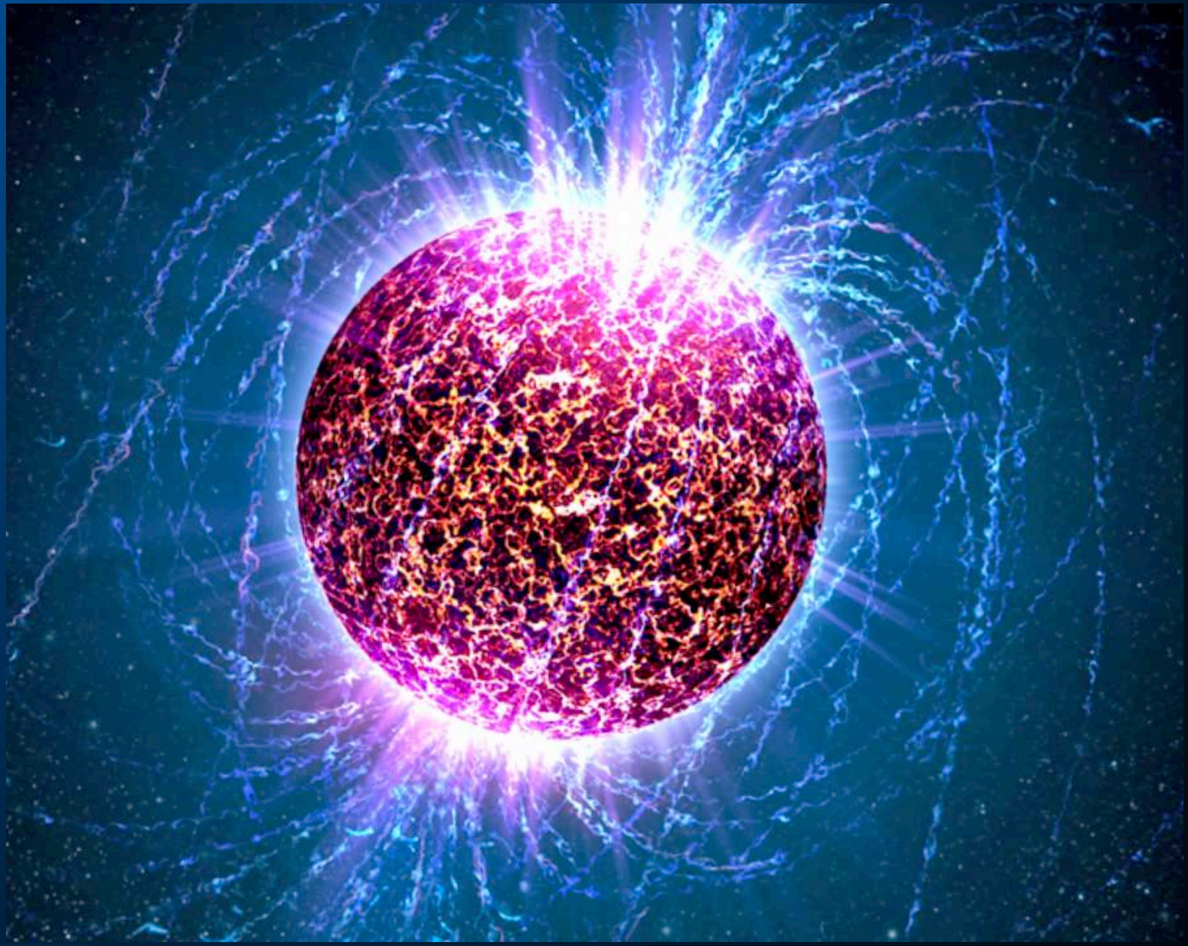
- 1000 kg
- 700 days

7×10^5 kg day

Neutron Star

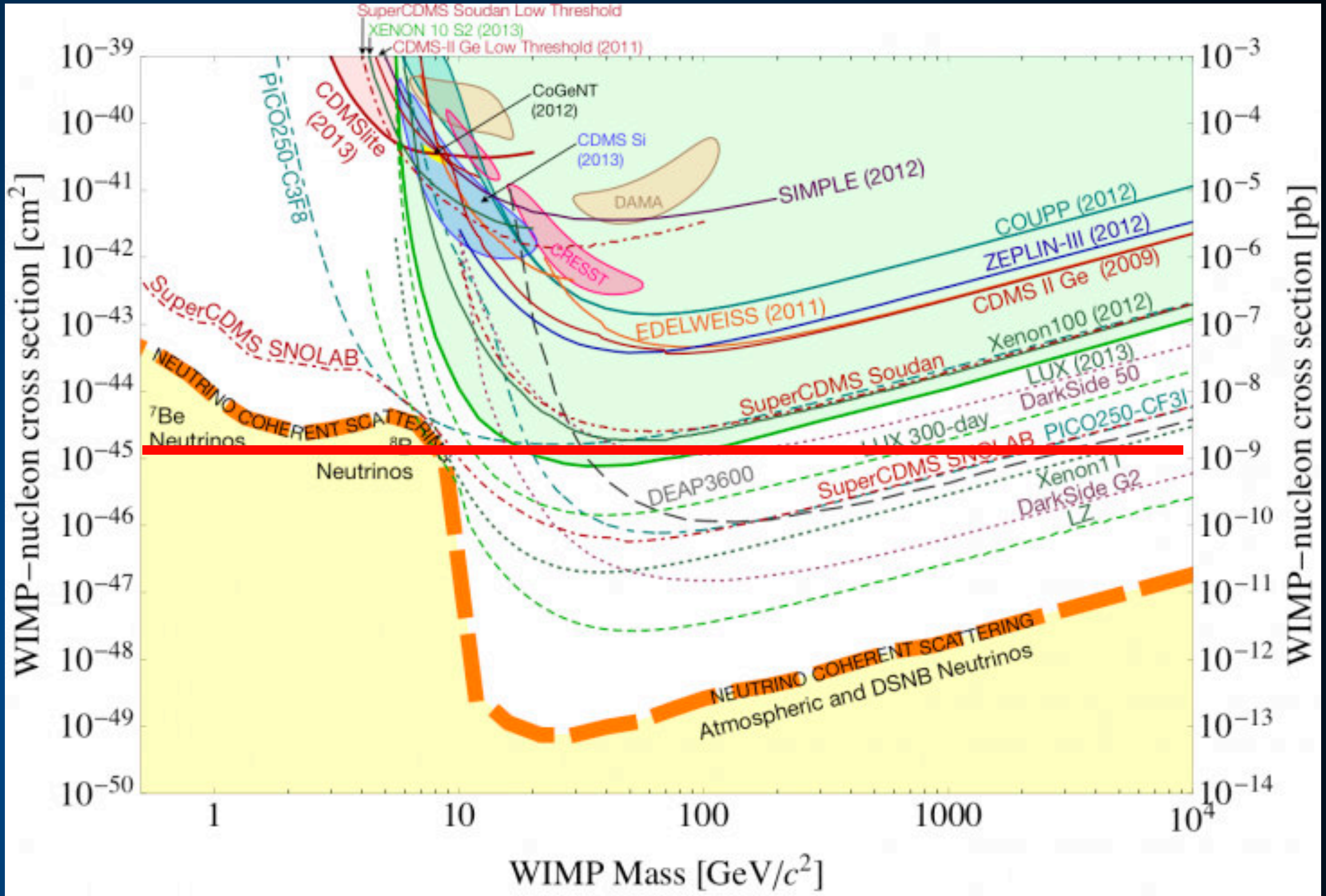
- 3×10^{30} kg
- 2×10^{10} days

6×10^{40} kg day



Neutron Stars: The Optimal Direct Detection Experiment

- **Neutron stars are so dense that they are optically thick to dark matter**

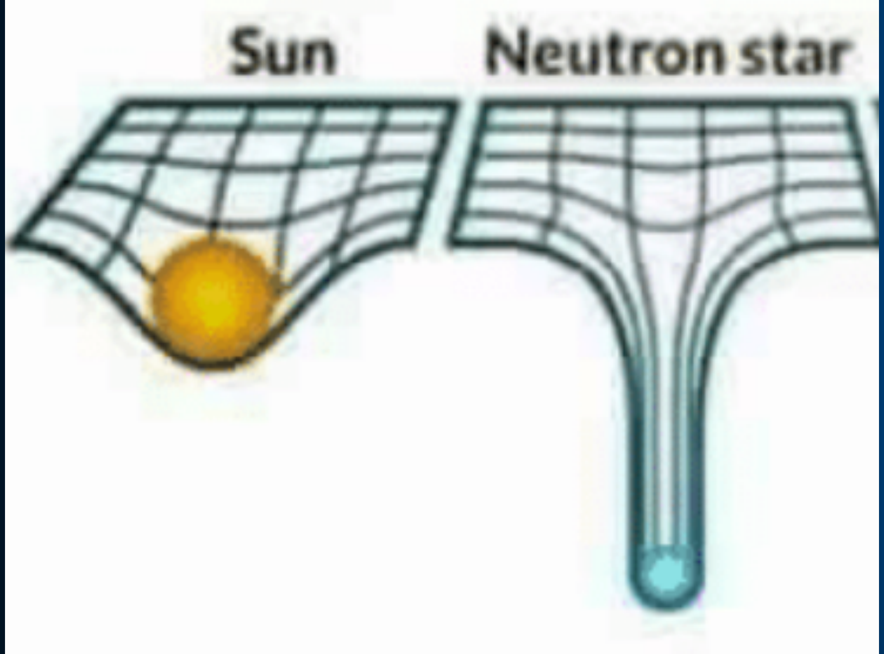


$$\sigma_{\rm sat}^{\rm single} \simeq \pi R^2 m_{\rm n}/M \simeq 2 \times 10^{-45}\ {\rm cm}^2 \ \left(\frac{1.5\ {\rm M}_\odot}{M}\right) \left(\frac{R}{10\ {\rm km}}\right)^2$$

- **This saturates the sensitivity of neutron stars to dark matter**

Neutron Stars: Astrophysics Enhancements

- Neutron stars gravitationally attract nearby dark matter



Capture radius is approximately 1 R_o

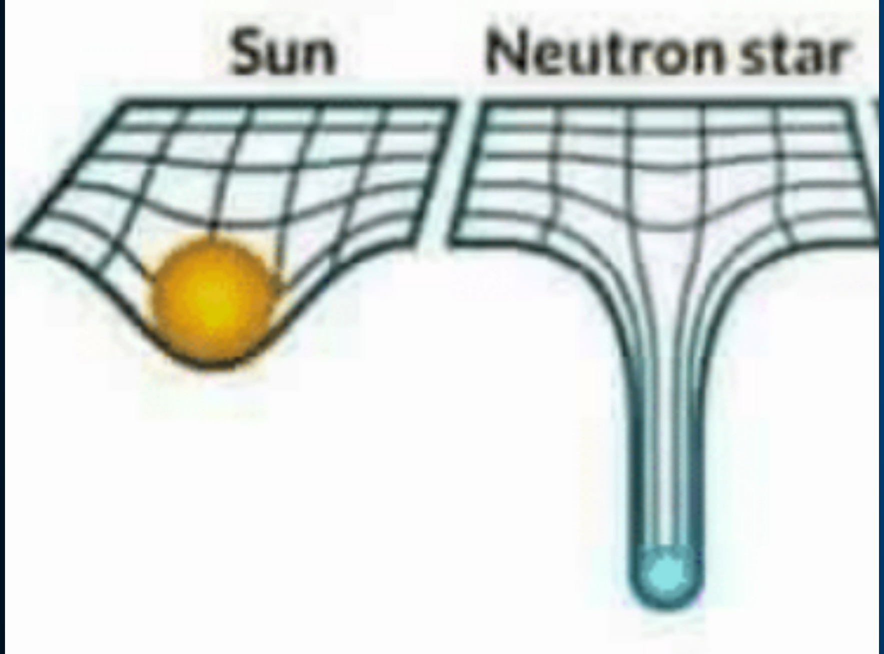
$$b_{\mathrm{max}} = \left(\frac{2GMR}{v_{\mathrm{x}}^2}\right)^{1/2}\left(1 - \frac{2GM}{R}\right)^{-1/2}$$

$$\dot{m} = \pi b_{\mathrm{max}}^2 v_{\mathrm{x}} \rho_{\mathrm{x}},$$

- Interaction scales as v_x^{-1}, very sensitive to slowly moving dark matter

Neutron Stars: Astrophysics Enhancements

- Neutron stars are a dark matter collider



When dark matter hits the neutron star surface it is moving relativistically:

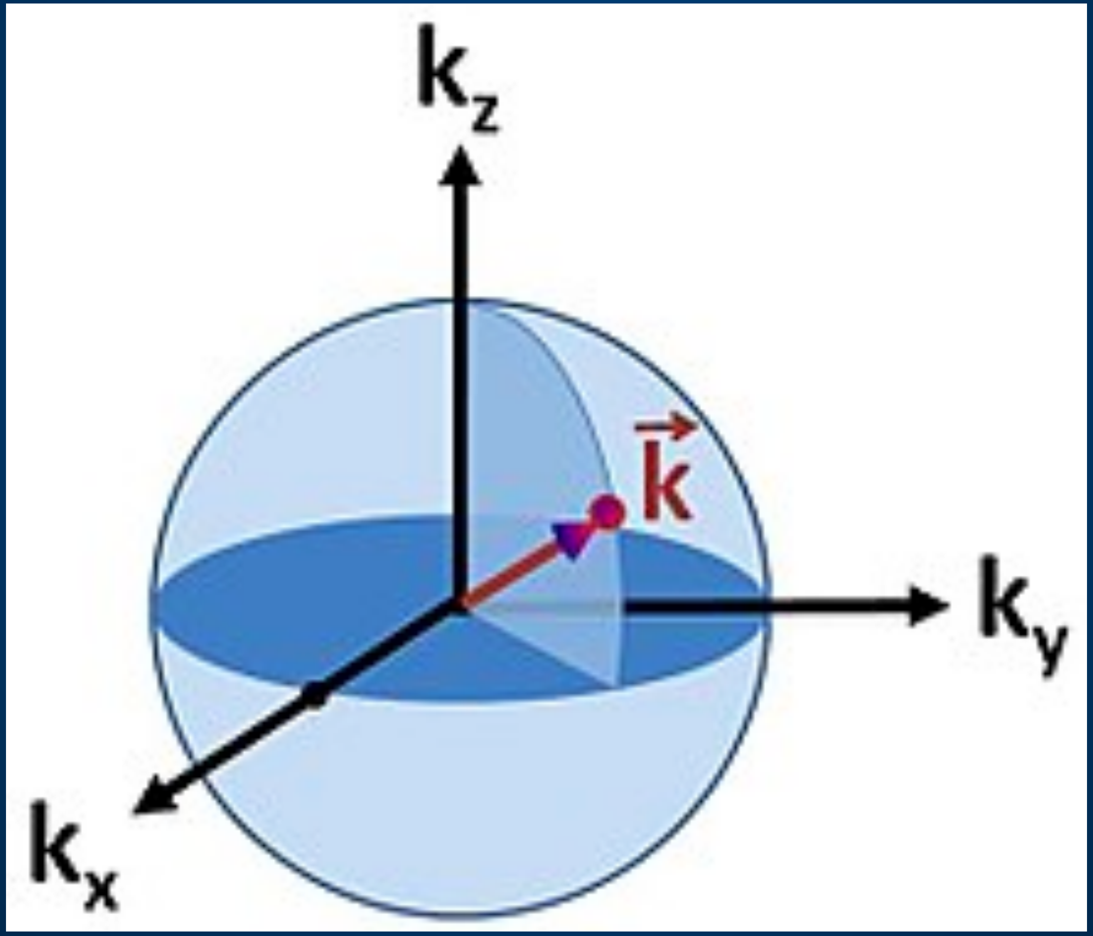
$$v_{esc} = \sqrt{\frac{2GM}{r}} \sim 0.7c$$

- Can probe p-wave suppressed dark matter or dark matter mass splittings

Neutron Stars: Particle Physics Complications

Typical NS neutron momentum is:

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



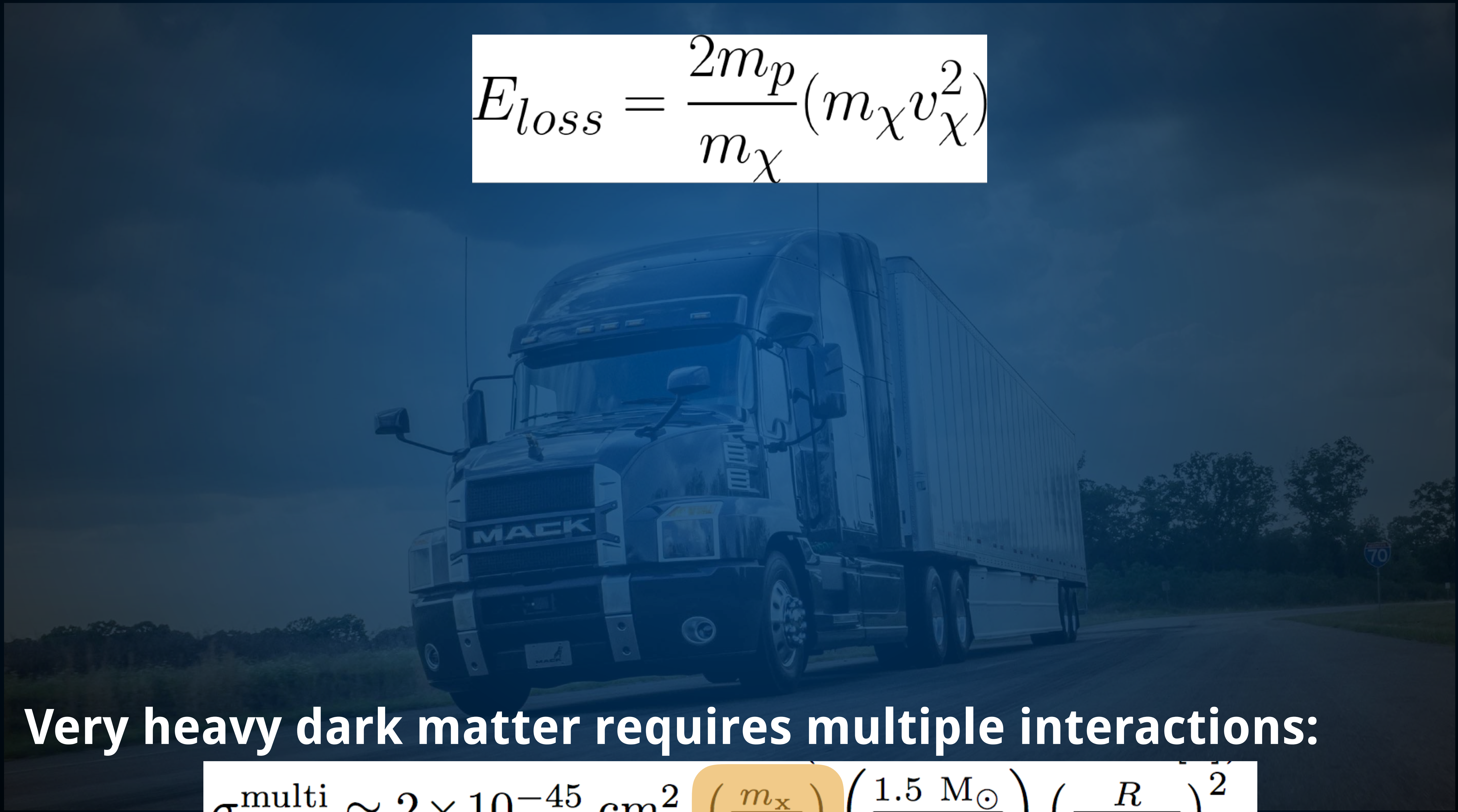
This suppresses the interaction cross-section for low mass DM:

$$\sigma_{\mathrm{sat}}^{\mathrm{Pauli}} \simeq \pi R^2 m_{\mathrm{n}} p_{\mathrm{f}} / (M \gamma m_{\mathrm{x}} v_{\mathrm{esc}} \simeq 2 \times 10^{-45} \ \mathrm{cm}^2 \ \left(\frac{\mathrm{GeV}}{m_{\mathrm{x}}}\right) \left(\frac{1.5 \ \mathrm{M}_{\odot}}{M}\right) \left(\frac{R}{10 \ \mathrm{km}}\right)^2 .$$

Neutron Stars: Particle Physics Complications

Dark Matter kinetic energy lost in a scatter with a proton is:

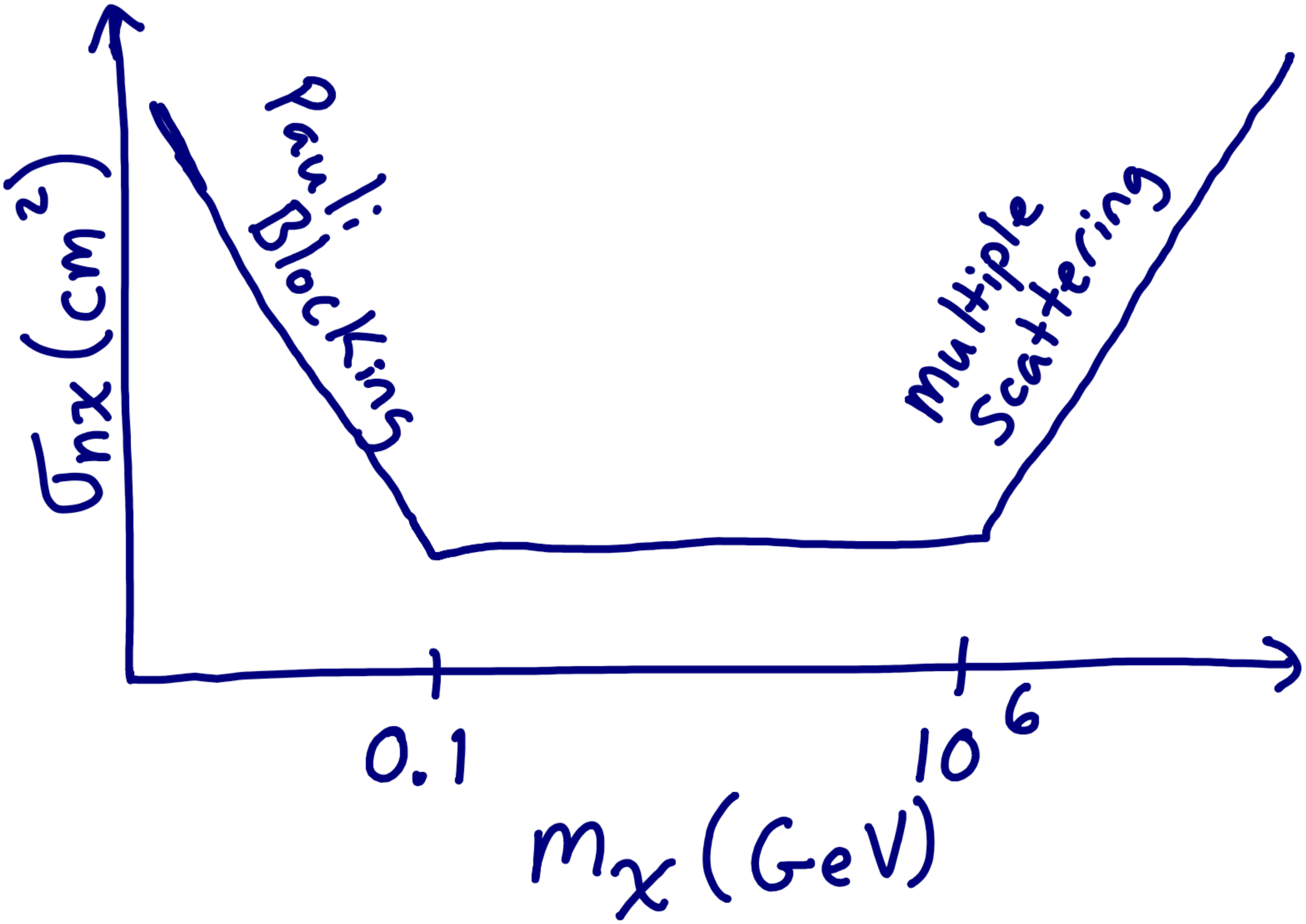
$$E_{loss} = \frac{2m_p}{m_\chi}(m_\chi v_\chi^2)$$



Very heavy dark matter requires multiple interactions:

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

Neutron Stars: Particle Physics Complications

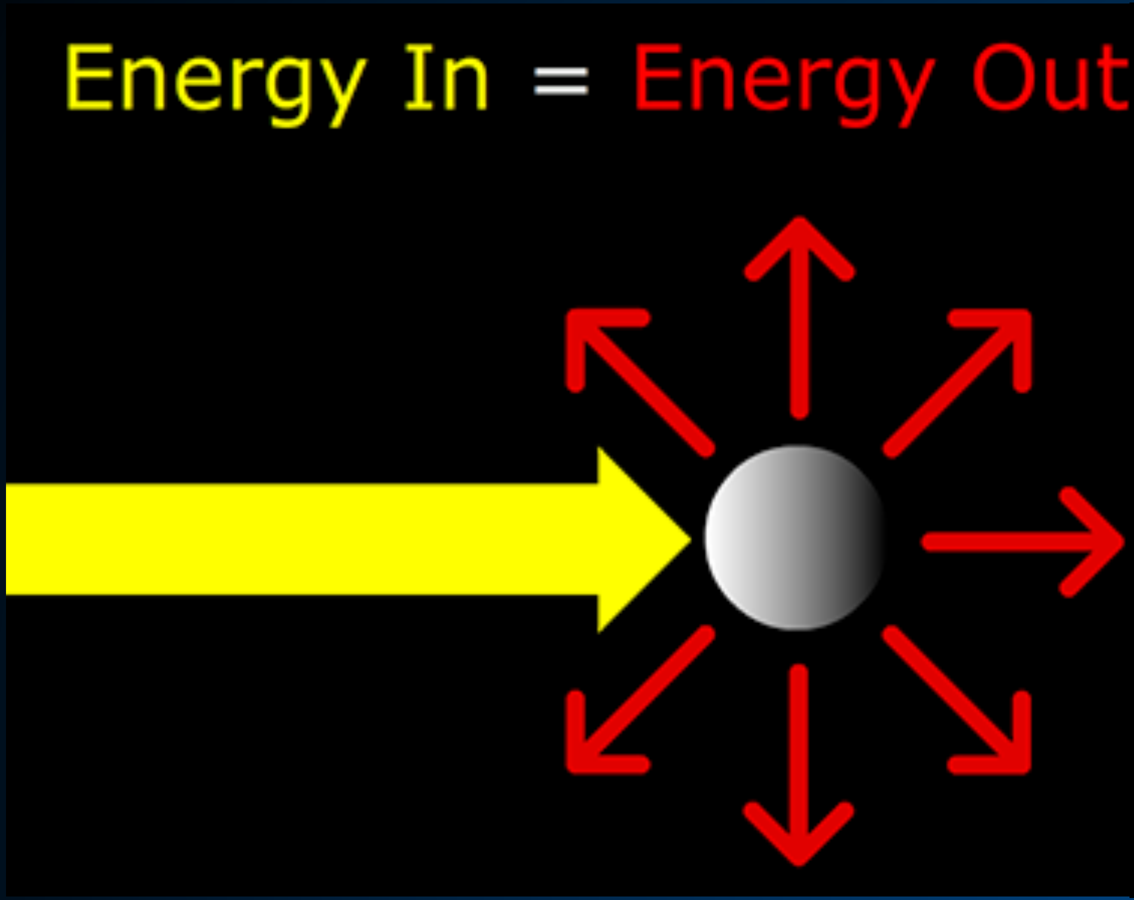


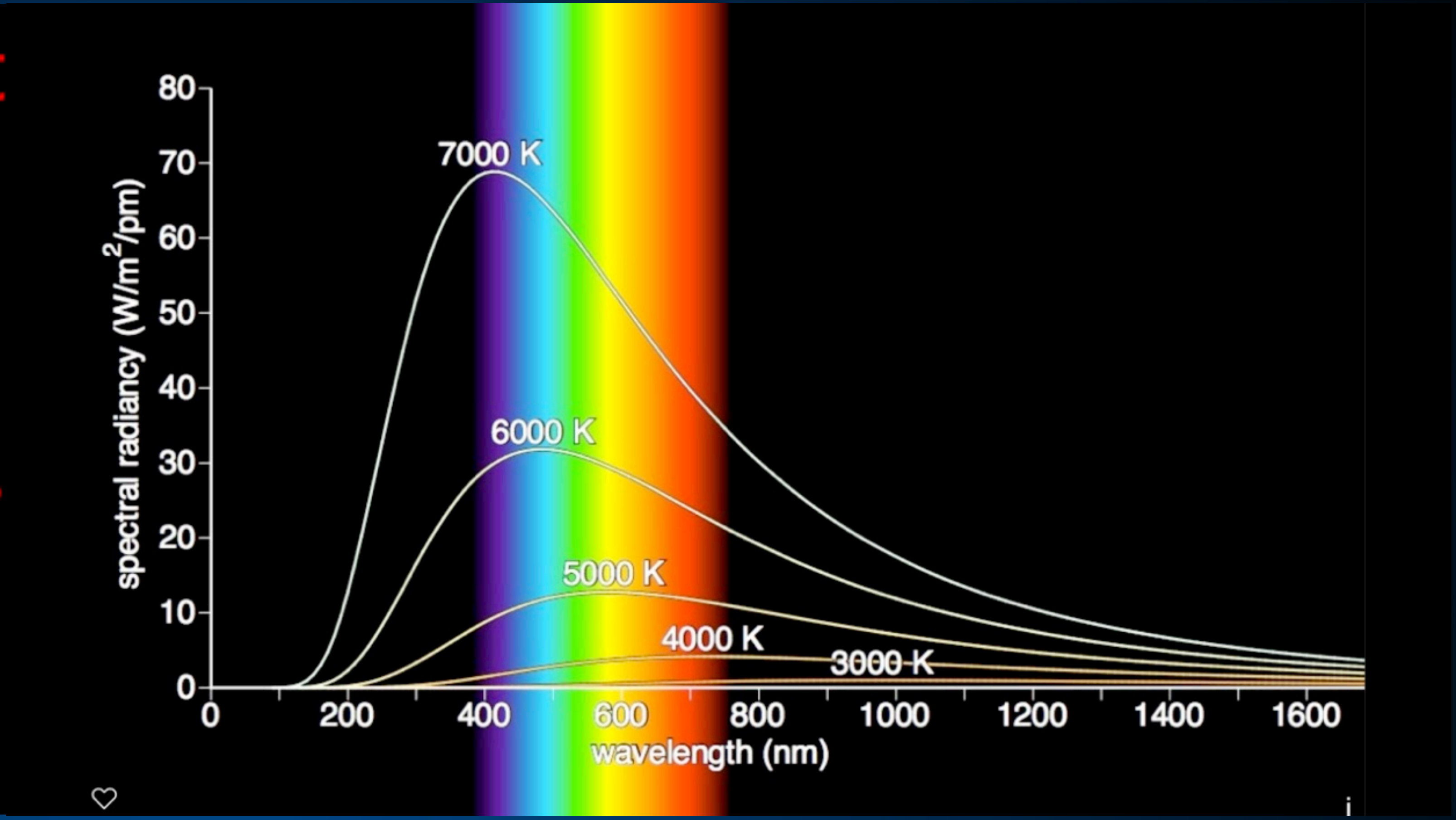
Detecting Dark Matter Scattering in Neutron Stars

Part I: Neutron Star Heating

Does the interaction produce an observable effect on the neutron star?

Dark Matter Induced Heating





DM-NS collisions impart significant energy into the NS:

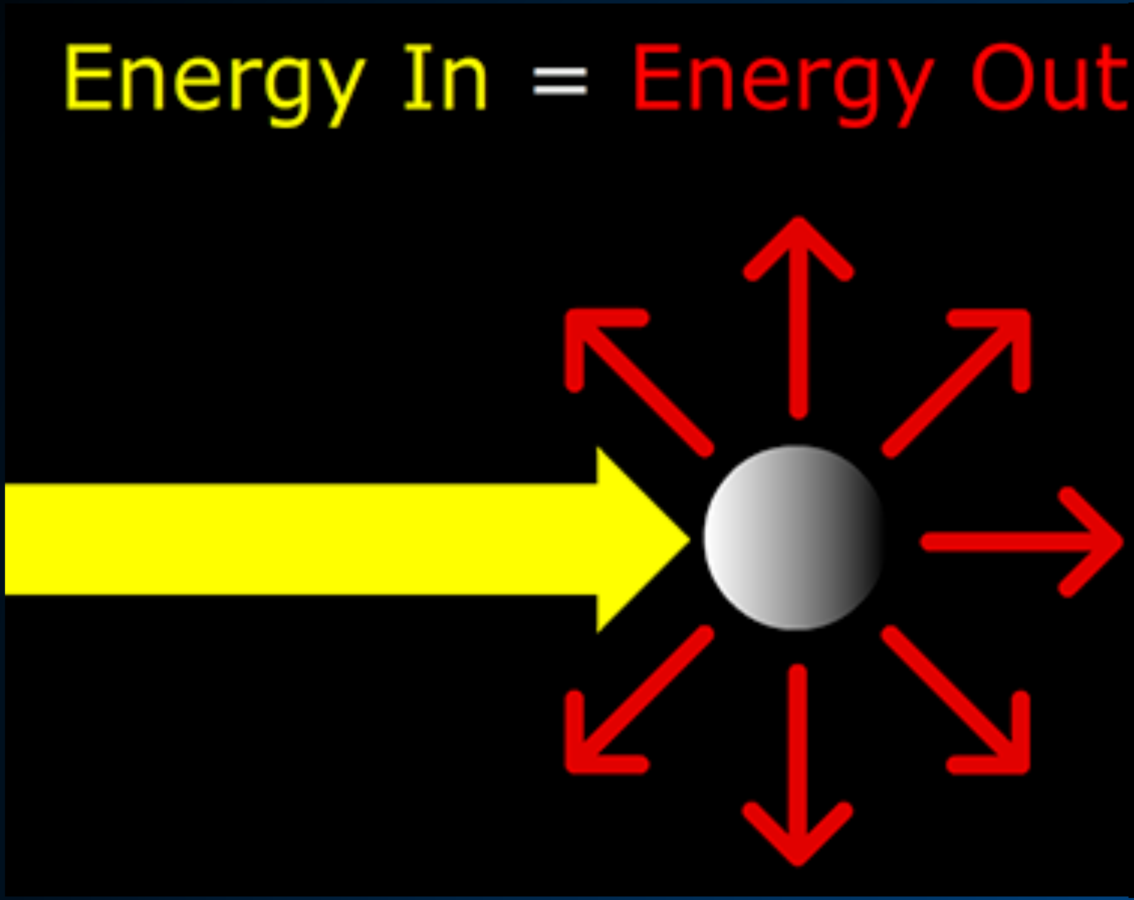
$$E_{\rm s} \simeq m_{\rm x} \left(\gamma - 1\right)$$

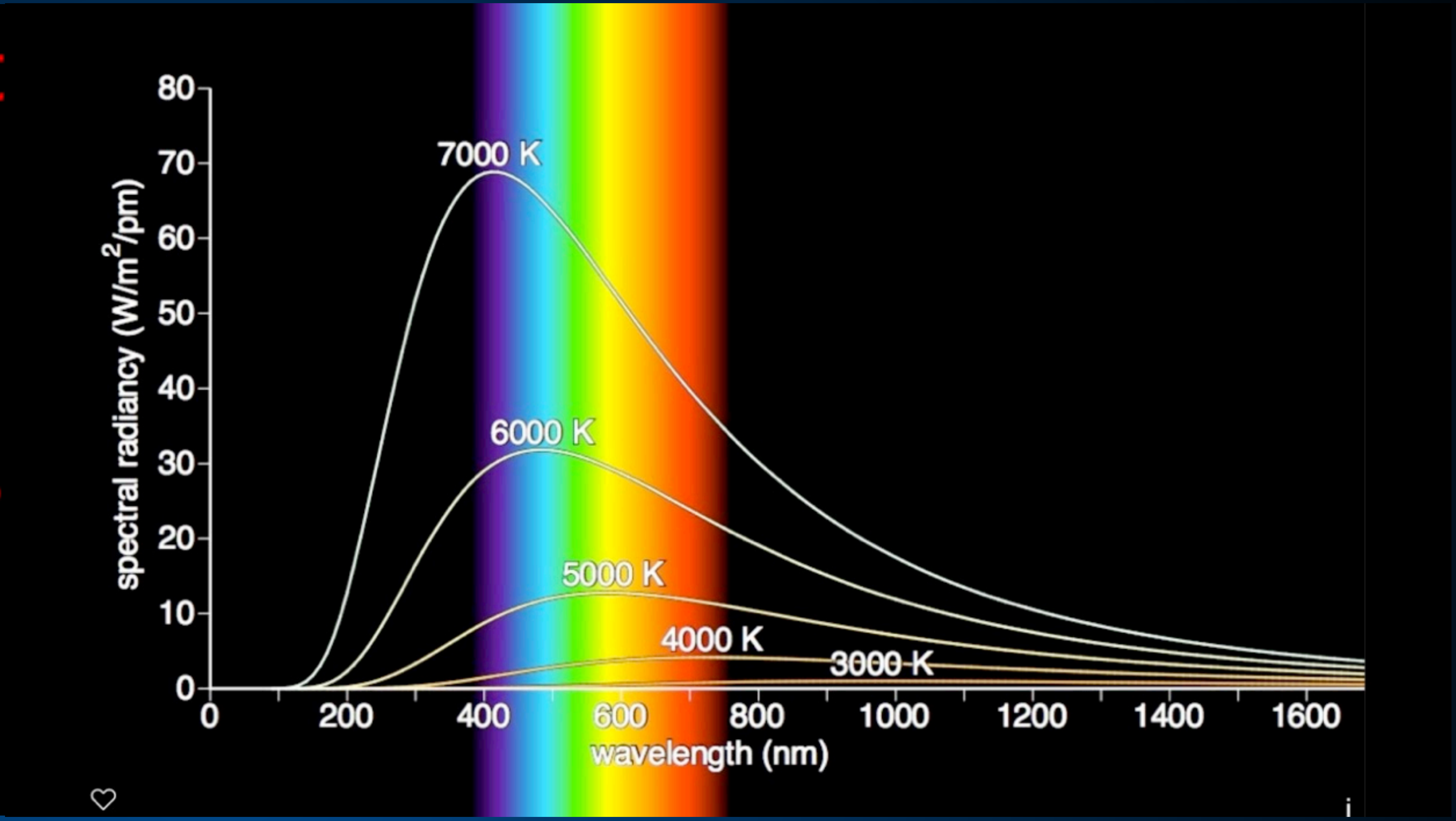
This induces blackbody emission of luminosity:

$$\dot{E}_{\rm k} = \frac{E_{\rm s} \dot{m}}{m_{\rm x}} f \simeq 1.4 \times 10^{25} \ {\rm GeV \ s^{-1}} \ \left(\frac{f}{1}\right),$$

Baryakhtar, Bramante, Li, TL, Raj (1704.01577)

Dark Matter Induced Heating





If Dark Matter subsequently annihilates, additional energy is injected (de Lavellez & Fairbairn (1004.0629))

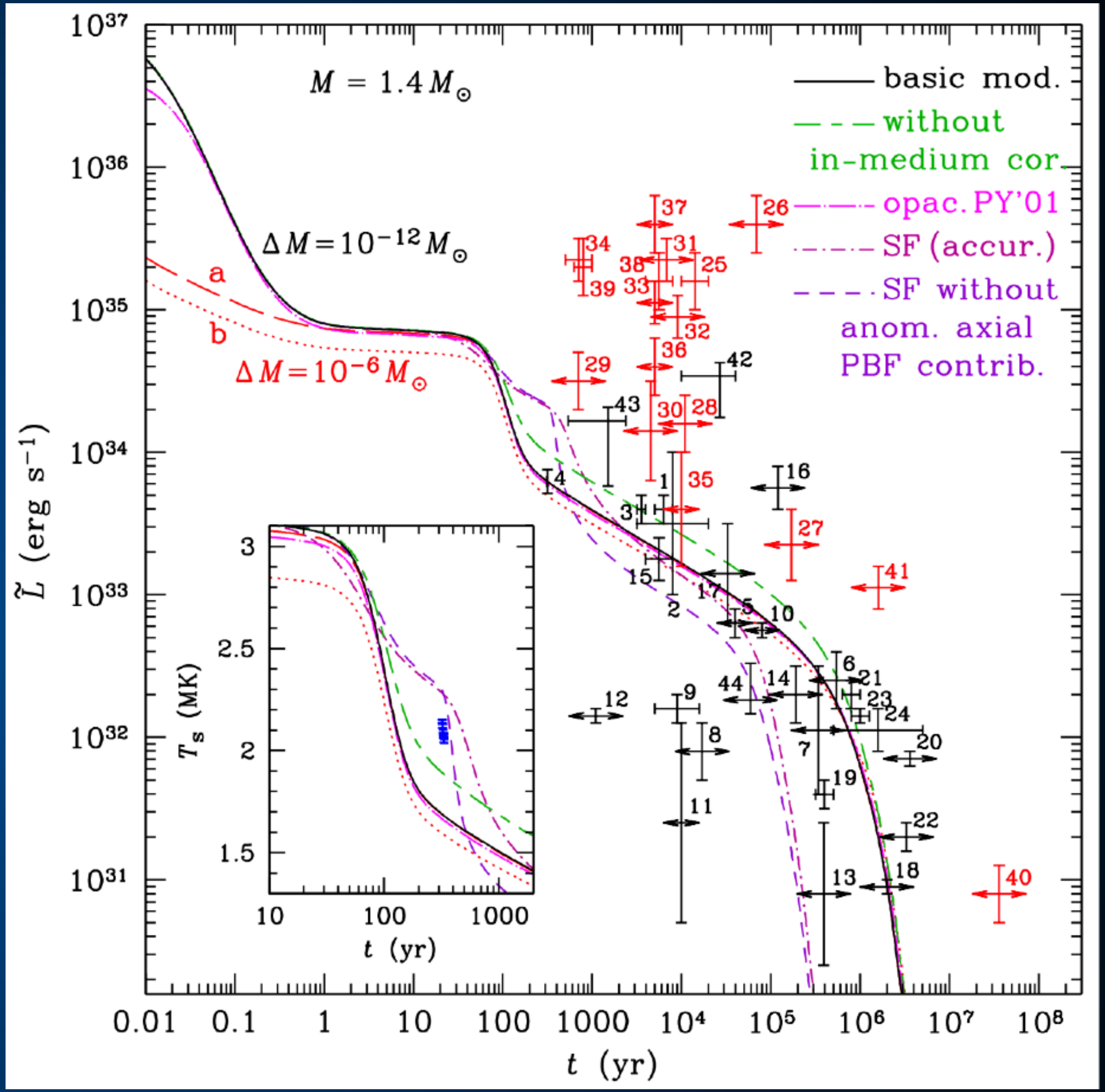
$$E_s \simeq m_x\,(\gamma - 1)$$

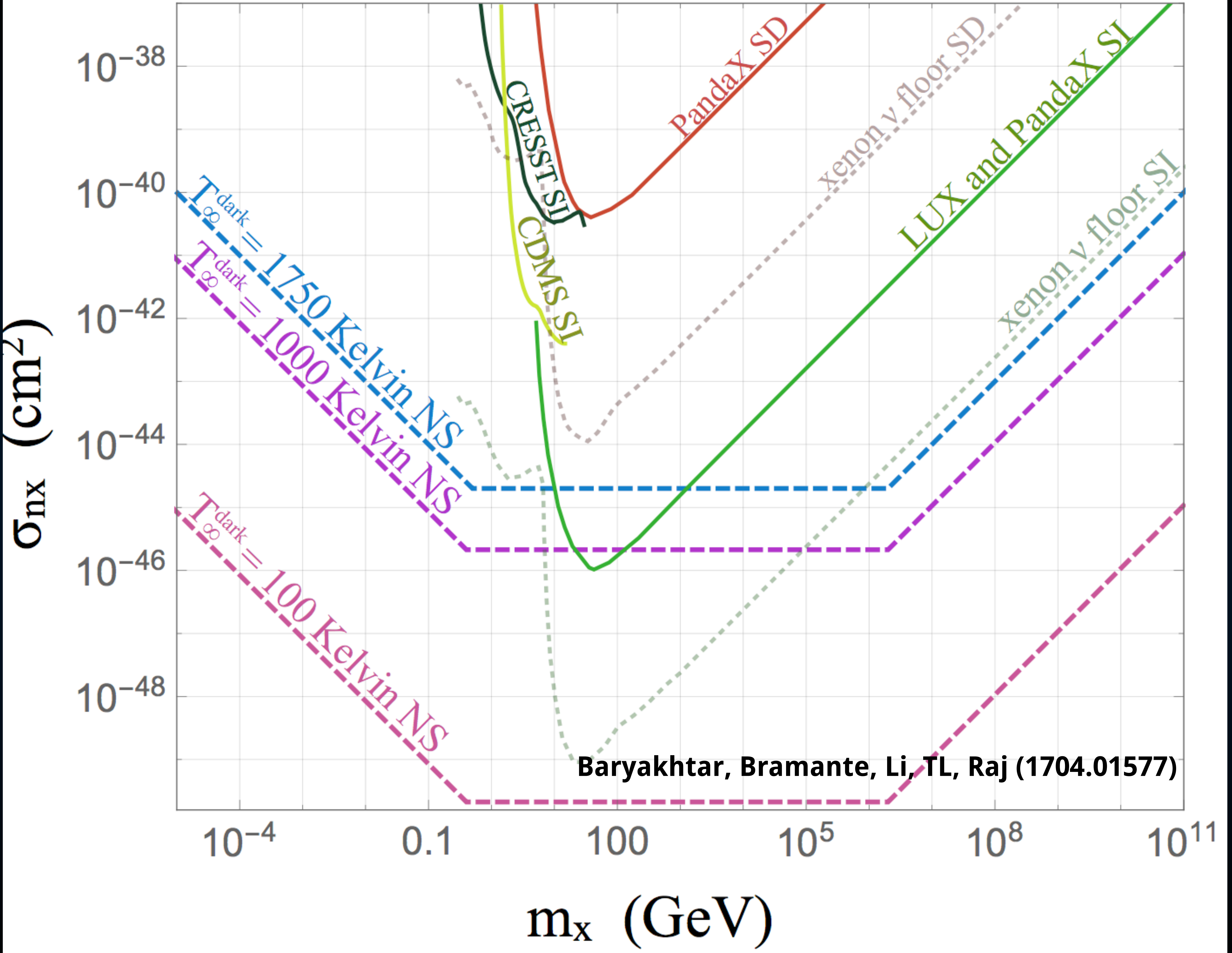
Baryakhtar, Bramante, Li, TL, Raj (1704.01577)

Detecting Hot Neutron Stars

- Thermal emission detected from young neutron stars
- Older neutron stars continue cooling
- Dark matter sets a minimum temperature of ~2000 K (10^{22} erg)

Potekhin & Chabrier (1711.07662)

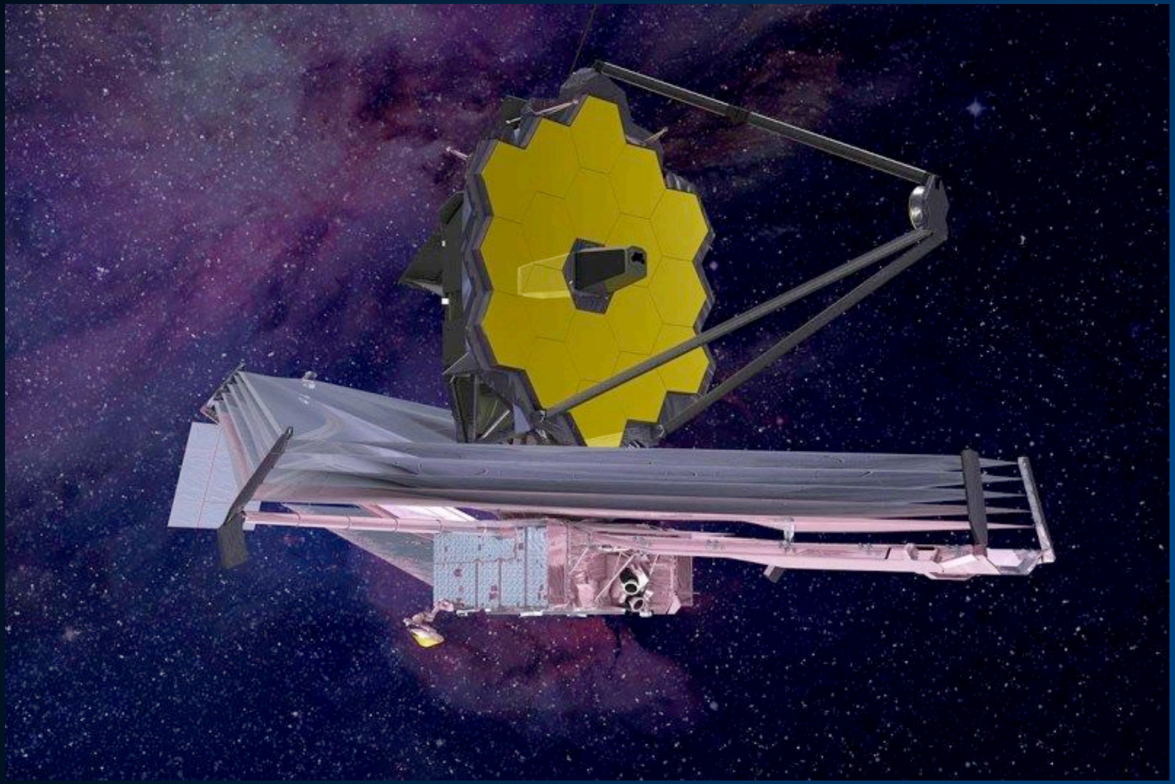




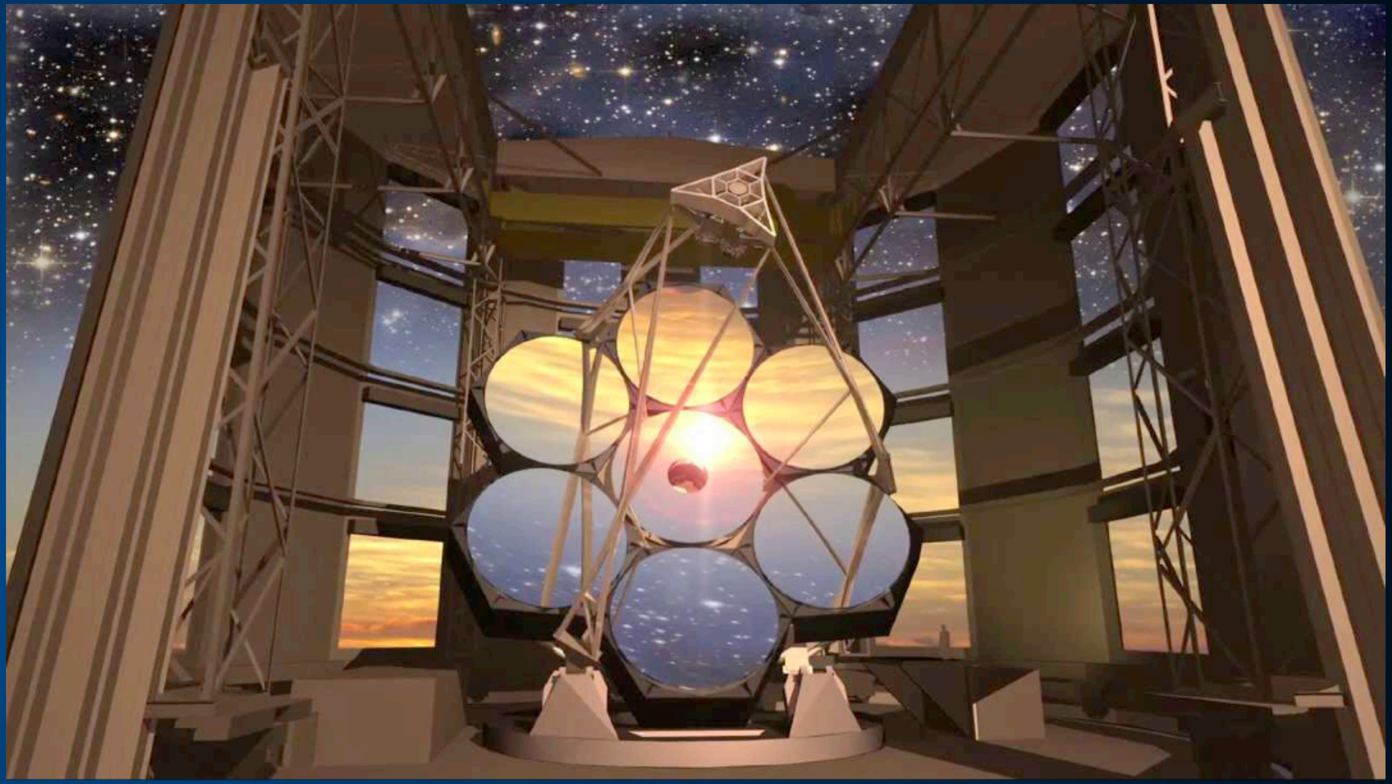
Baryakhtar, Bramante, Li, TL, Raj (1704.01577)

Detecting Thermal Emission

- Observations at 2000 K require infrared telescopes



JWST
10 nJy in 10^4 s



GMT
0.5 nJy in 10^5 s

- A pulsar at 10 pc would have a flux of ~2 nJy at 2 microns

Baryakhtar, Bramante, Li, TL, Raj (1704.01577)

What Do We Need?

1. A nearby pulsar (10-20 pc).
    - Closest observed pulsar: 90 pc (PSR B1055-52)
    - Average Distance to nearest NS: 10 pc (Sartore et al. 0908.3182)
2. A model to separate thermal from pulsed emission
3. Constraints on thermal injection sources, e.g. gas accretion and magnetic heating.

Detecting Dark Matter Scattering in Neutron Stars

Part II: Dark Matter Collapse

How does the interaction affect the dark matter?

The Secret Life of Dark Matter Inside a Neutron Star

- **Capture -** DM hits neutron and elastically scatters

- **Thermalization -** Trapped dark matter thermalizes with neutron superfluid. If dark matter can annihilate, it will.

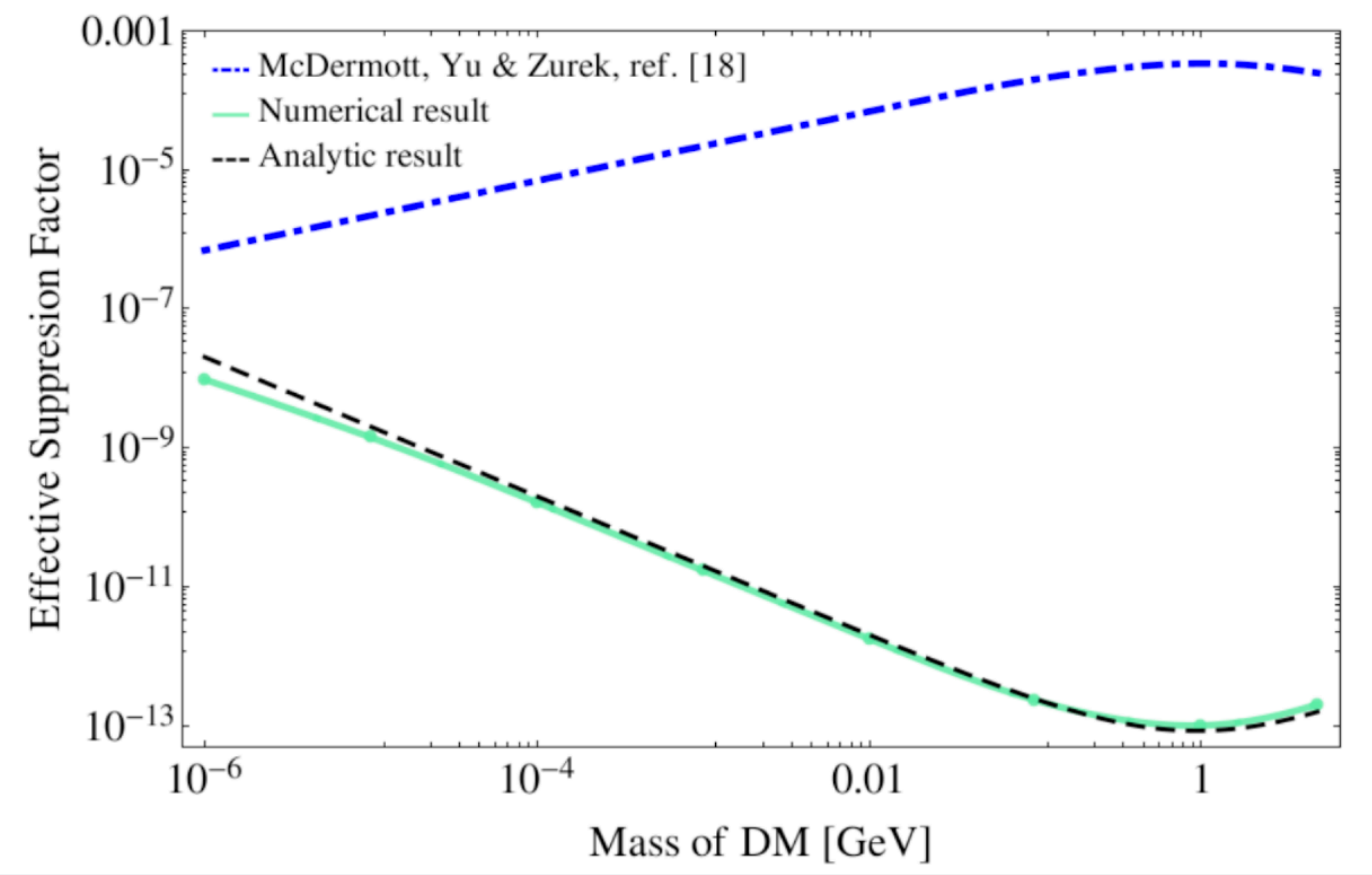
- **Collapse -** Dark matter degeneracy pressure not capable of preventing collapse.

Bramante & TL (1405.1031)
Bramante & TL (1601.06784)
Bramante, TL, Tsai (1706.00001)

Dark Matter Thermalization

- **Dark Matter thermalization is always suppressed by Pauli blocking.**

Bertoni et al. (2013; 1309.1721)



- **Superfluidity and superconductivity effects in the NS core also have a sizable effect.**

- **However, if DM is trapped within the NS, interactions are inevitable. in pessimistic scenarios, DM thermalizes in a timeframe:**

$$t_{th} \simeq 3.7 \text{ kyr} \frac{\frac{m_X}{m_B}}{(1+\frac{m_X}{m_B})^2} \left(\frac{2\times 10^{-45}\text{ cm}^2}{\sigma_{nX}}\right) \left(\frac{10^5\text{ K}}{T_{NS}}\right)^2$$

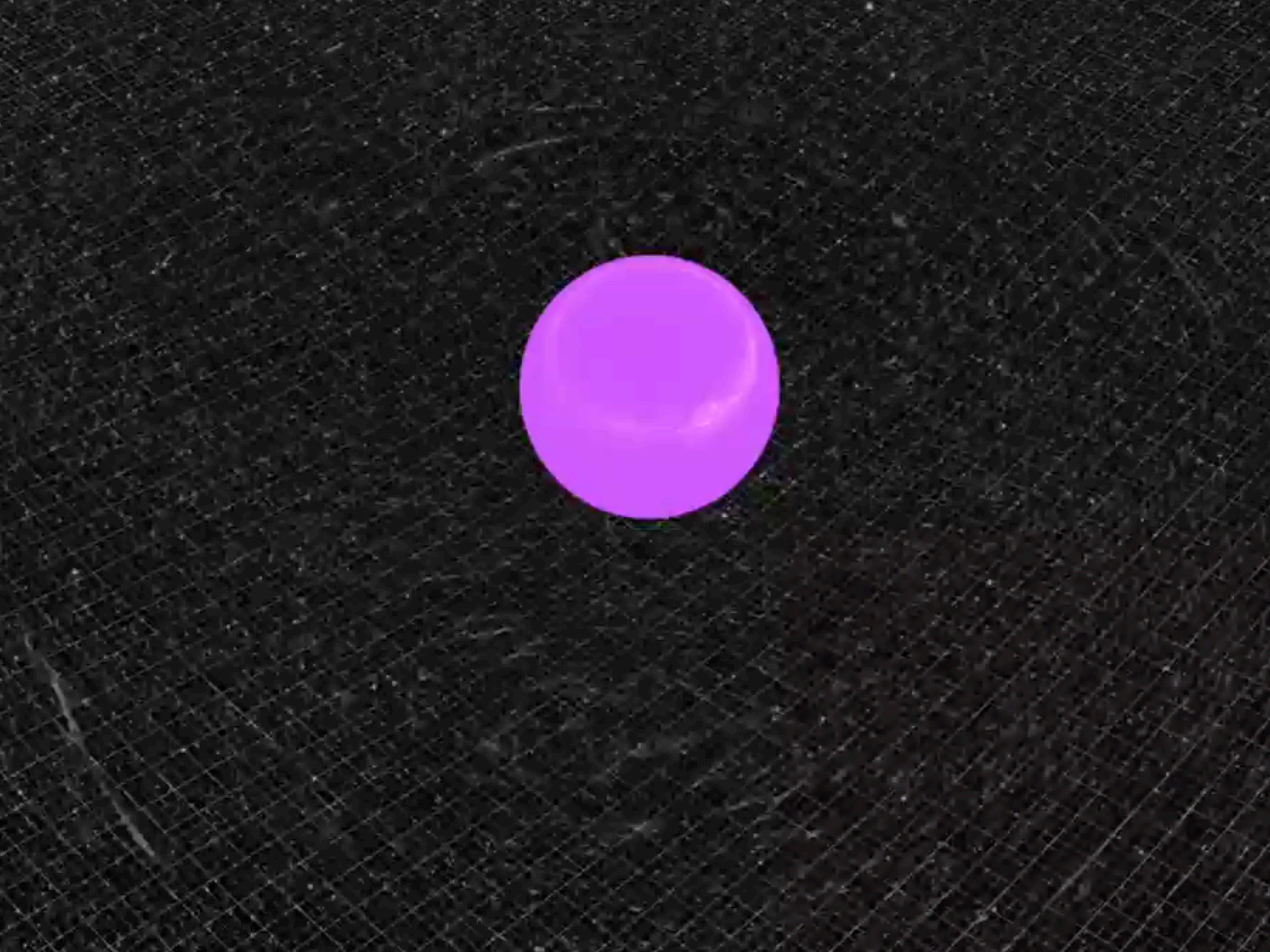
Dark Matter Collapse

- Two paths are possible:
  - If dark matter can annihilate, the large densities make annihilation inevitable.
  - If dark matter cannot annihilate, dark matter builds mass until it exceeds its own degeneracy pressure. For Fermionic dark matter this is:

$$M_{crit}^{ferm} \simeq M_{pl}^3/m_X^2$$

  - It then collapses on a timescale:

$$\begin{aligned}\tau_{\rm co} &\simeq \frac{1}{n\sigma_{n{\rm x}}v_{\rm x}}\left(\frac{p_F}{\Delta p}\right)\left(\frac{m_{\rm x}}{2m_n}\right)\\ &\simeq 4\times 10^5~{\rm yrs}\left(\frac{10^{-45}~{\rm cm}^2}{\sigma_{\rm nx}}\right)\left(\frac{r_x}{r_0}\right),\end{aligned}$$

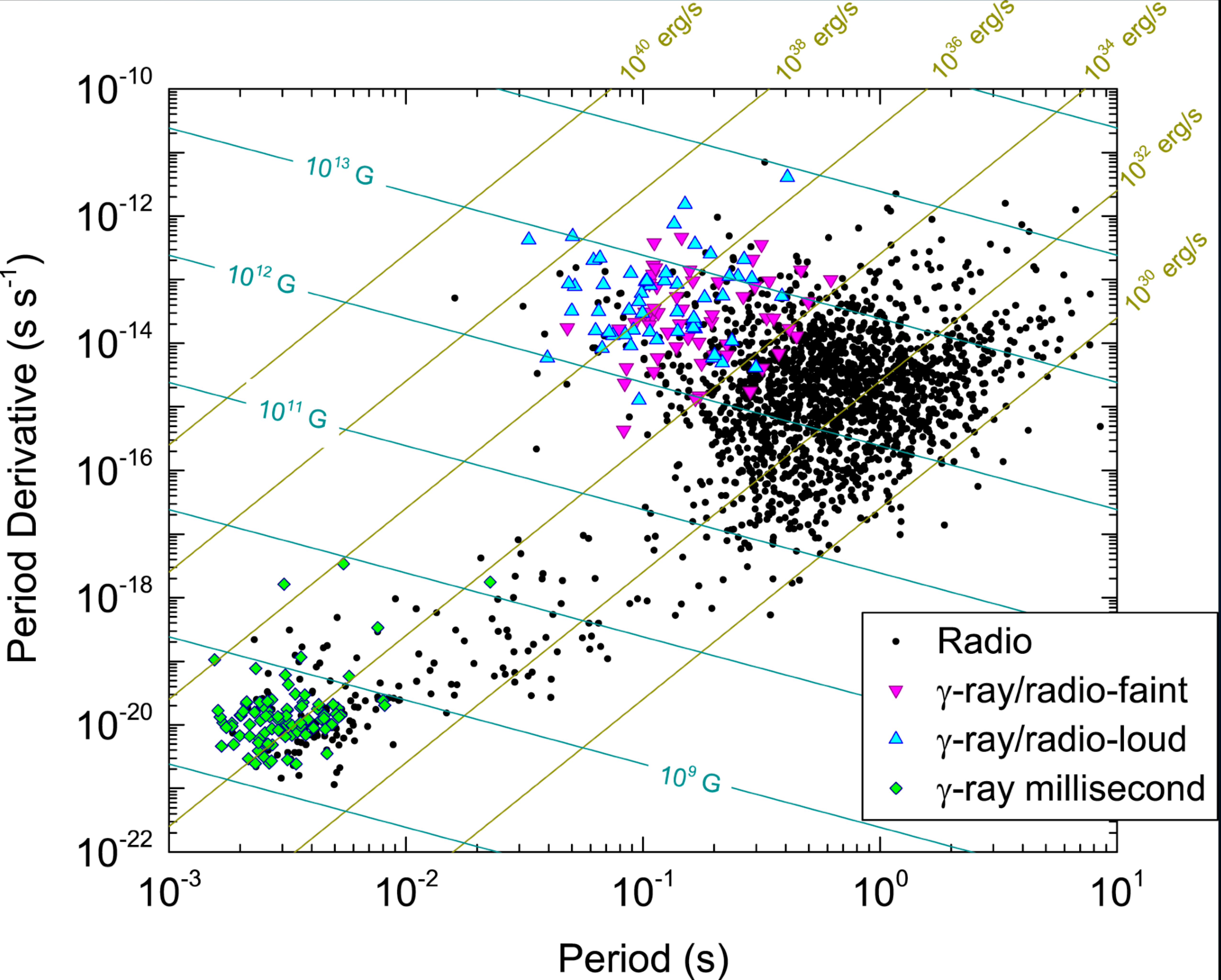


Dark Matter Parameter Space

- **Requires dark matter to be non-annihilating.**
  - **PeV Fermionic Dark Matter**

$$M_{crit}^{ferm} \simeq M_{pl}^{3}/m_{X}^{2}$$

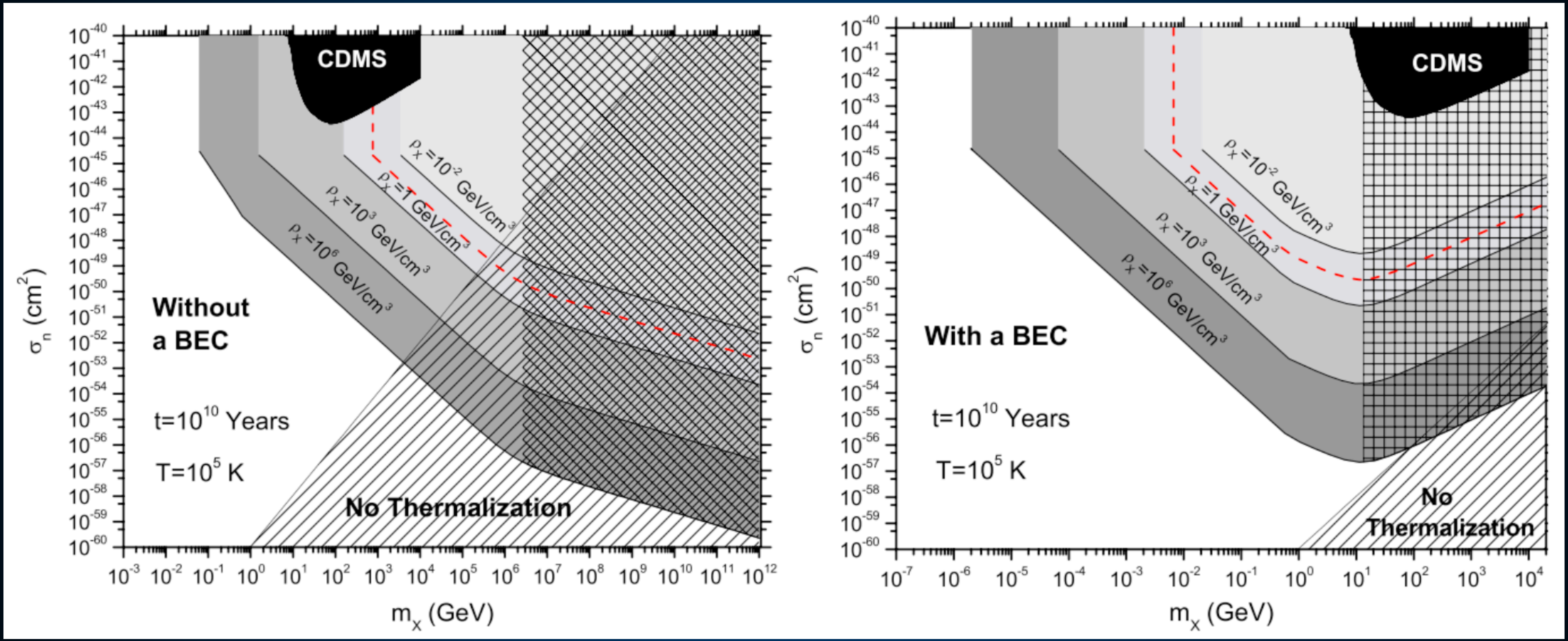
  - **Bosonic Dark Matter**
  - **Attractive Self-Interacting Dark Matter**



10^40 erg/s
10^38 erg/s
10^36 erg/s
10^34 erg/s
10^32 erg/s
10^30 erg/s
10^13 G
10^12 G
10^11 G
10^9 G
Period Derivative (s s^-1)
10^-10
10^-12
10^-14
10^-16
10^-18
10^-20
10^-22
10^-3
10^-2
10^-1
10^0
10^1
Period (s)
● Radio
▼ γ-ray/radio-faint
▲ γ-ray/radio-loud
◆ γ-ray millisecond

Strong Constraints are Possible

McDermott et al. (1103.5472)

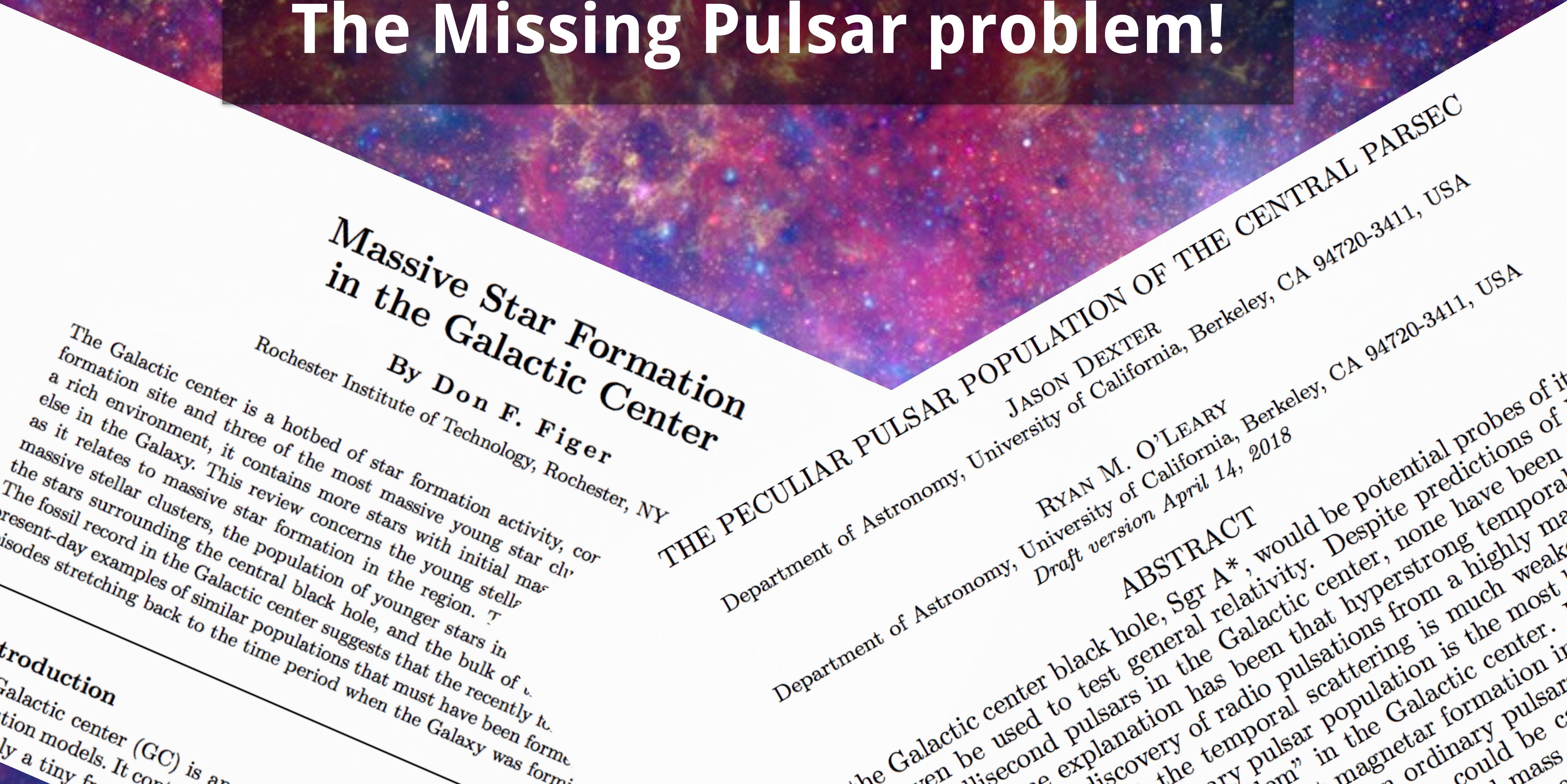


A Signal

10% of Star Formation in central 200 pc of Milky Way

Only one (very young) pulsar detected

The Missing Pulsar problem!



Massive Star Formation in the Galactic Center

By Don F. Figer

Rochester Institute of Technology, Rochester, NY

The Galactic center is a hotbed of star formation activity, cor
formation site and three of the most massive young star cl
a rich environment, it contains more stars with initial ma
else in the Galaxy. This review concerns the young stell
as it relates to massive star formation in the region. T
massive stellar clusters, the population of younger stars in
the stars surrounding the central black hole, and the bulk of
The fossil record in the Galactic center suggests that the recently fo
resent-day examples of similar populations that must have been forme
isodes stretching back to the time period when the Galaxy was form

troduction

Galactic center (GC) is an
tion models. It con
ly a tiny f

THE PECULIAR PULSAR POPULATION OF THE CENTRAL PARSEC

Jason Dexter
Department of Astronomy, University of California, Berkeley, CA 94720-3411, USA

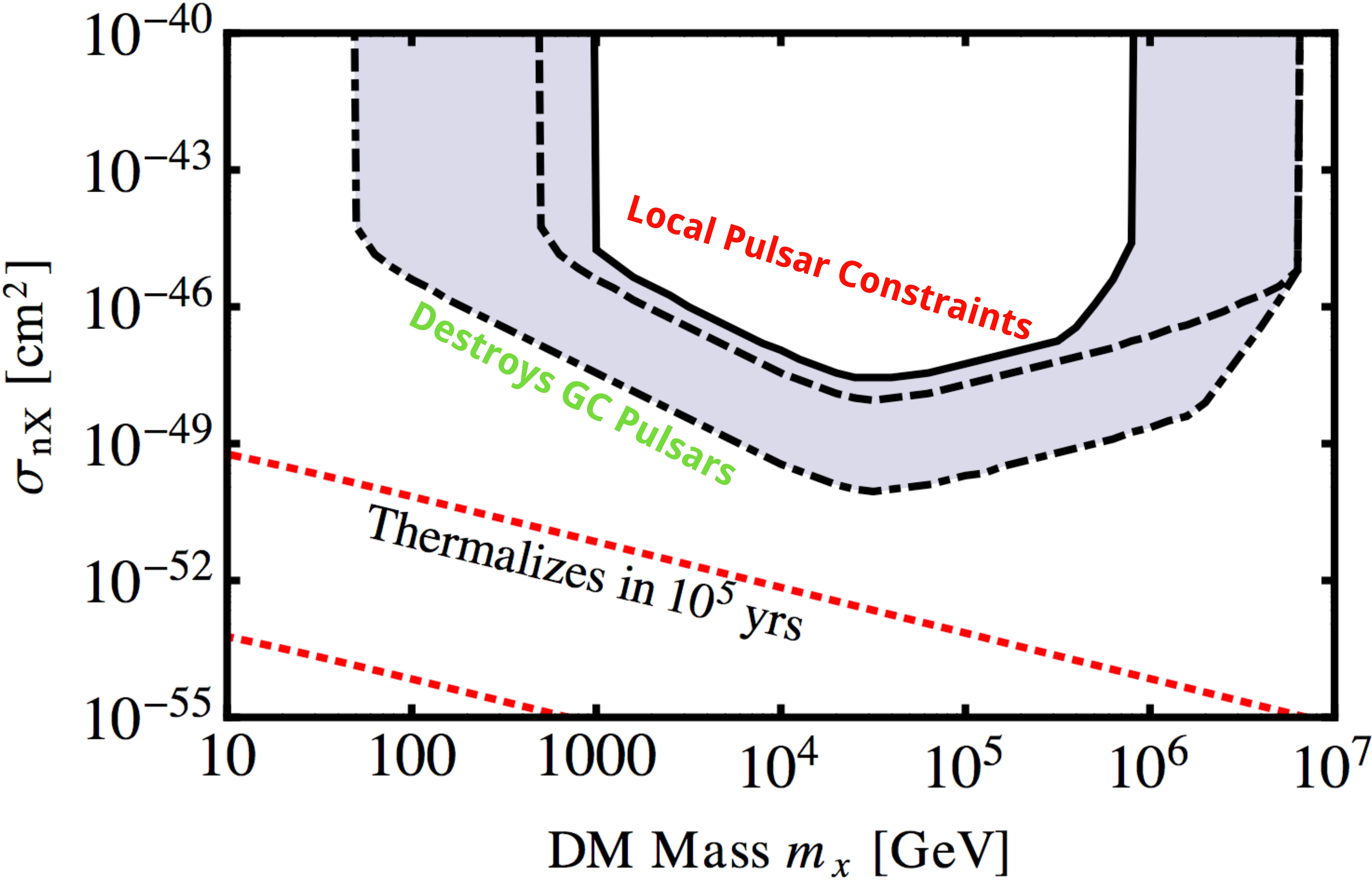
Ryan M. O'Leary
Department of Astronomy, University of California, Berkeley, CA 94720-3411, USA

Draft version April 14, 2018

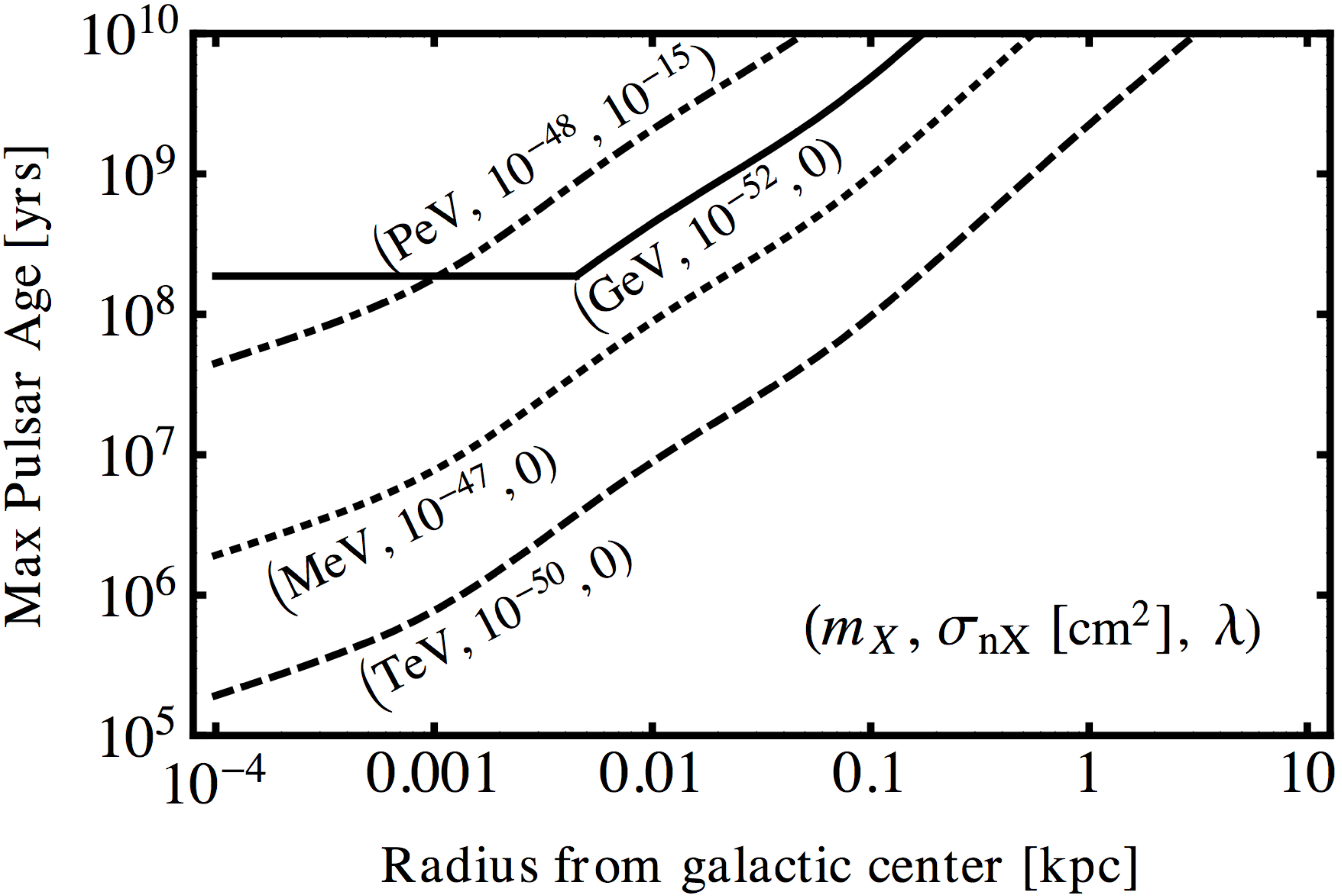
ABSTRACT

he Galactic center black hole, Sgr A*, would be potential probes of it
ven be used to test general relativity. Despite predictions of
llisecond pulsars in the Galactic center, none have been
e explanation has been that hyperstrong temporal
discovery of radio pulsations from a highly ma
the temporal scattering is much weak
ry pulsar population is the most
m" in the Galactic center.
magnetar formation i
n ordinary pulsar
could be c
mass

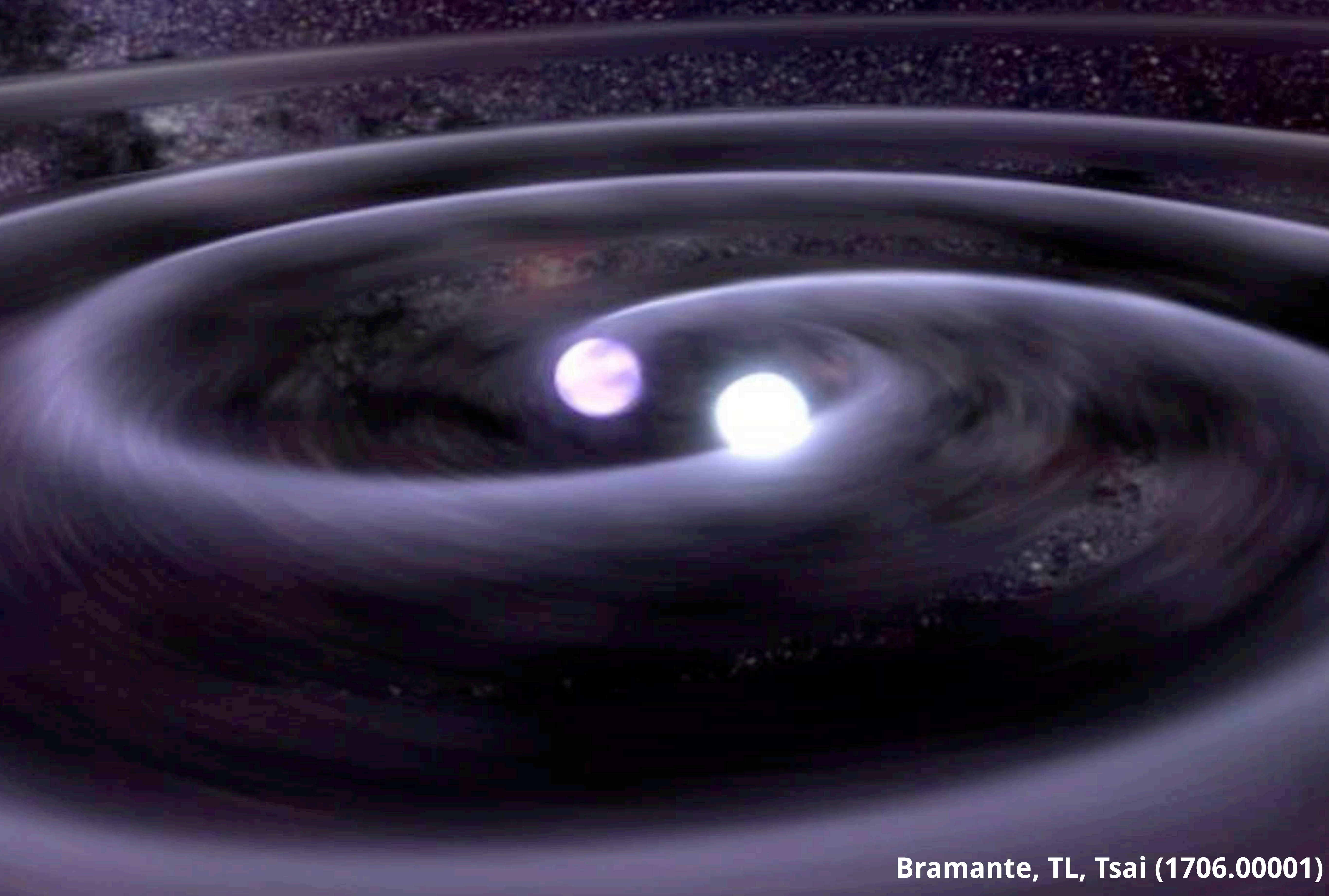
Bramante & TL (1405.1031)



Bramante & TL (1405.1031)



An Electromagnetic Signal

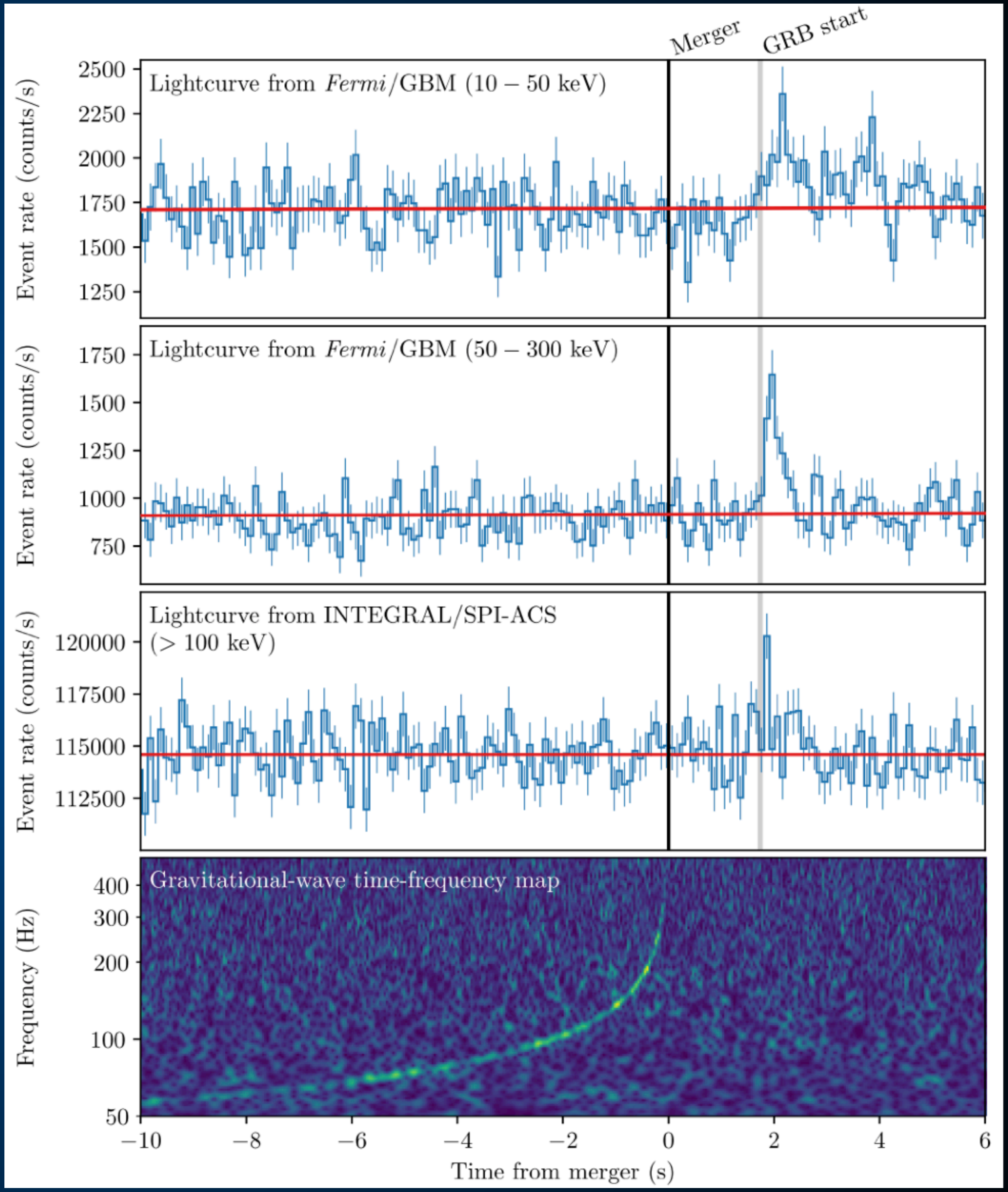


Bramante, TL, Tsai (1706.00001)

An Electromagnetic Signal

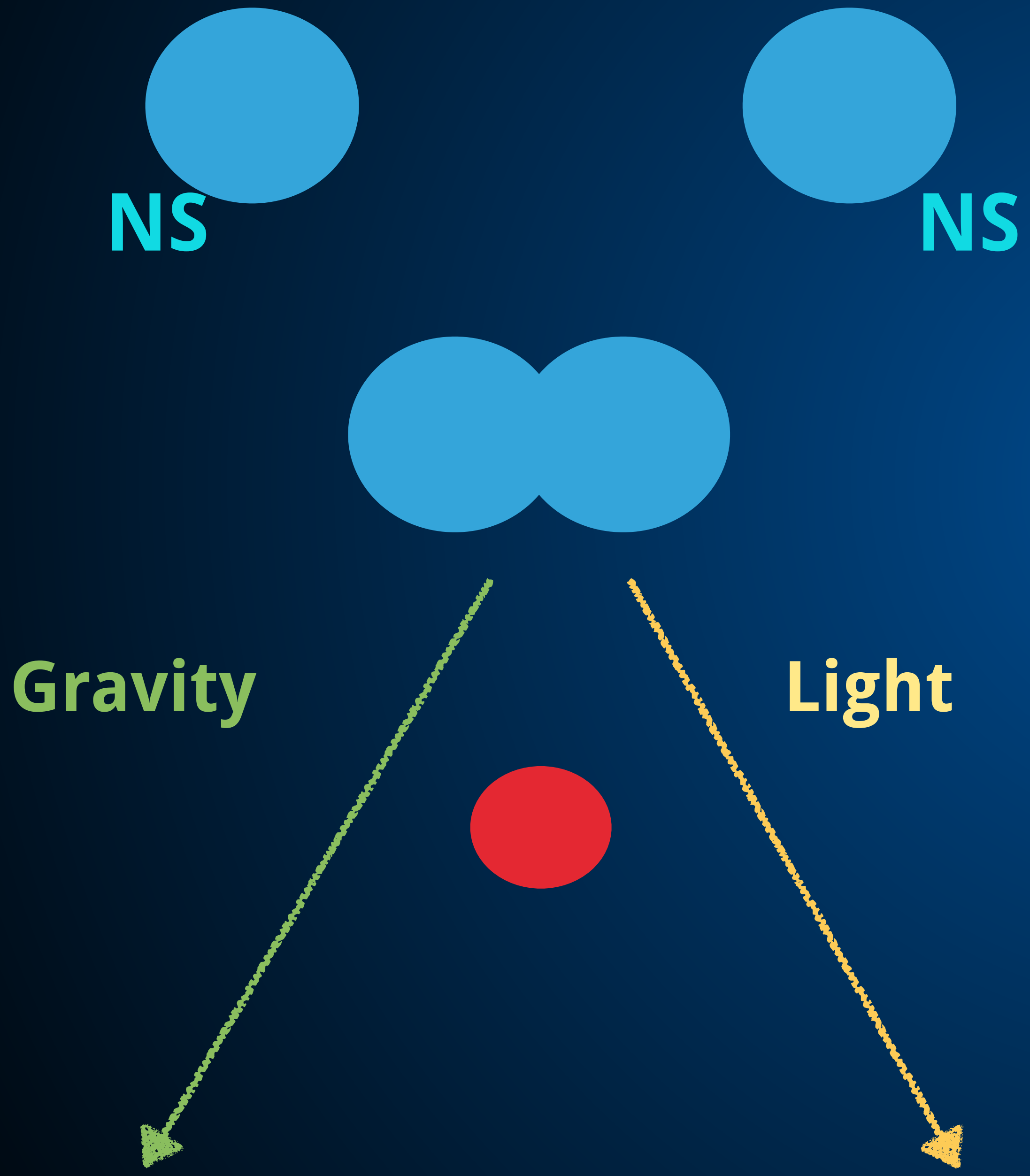
- **Gamma-Ray Bursts (observed by Fermi)**
- **Optical emission from the decay of r-process elements**
- **Fast Radio Bursts are potentially correlated with NS mergers.**

Fermi GBM Collaboration (1710.05834)

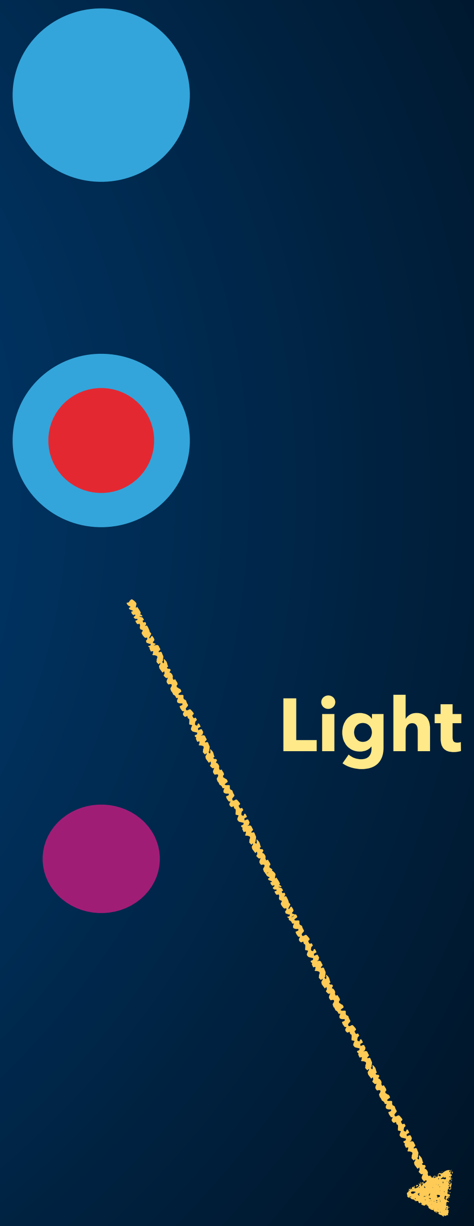


An Electromagnetic Signal

No DM Induced Collapse

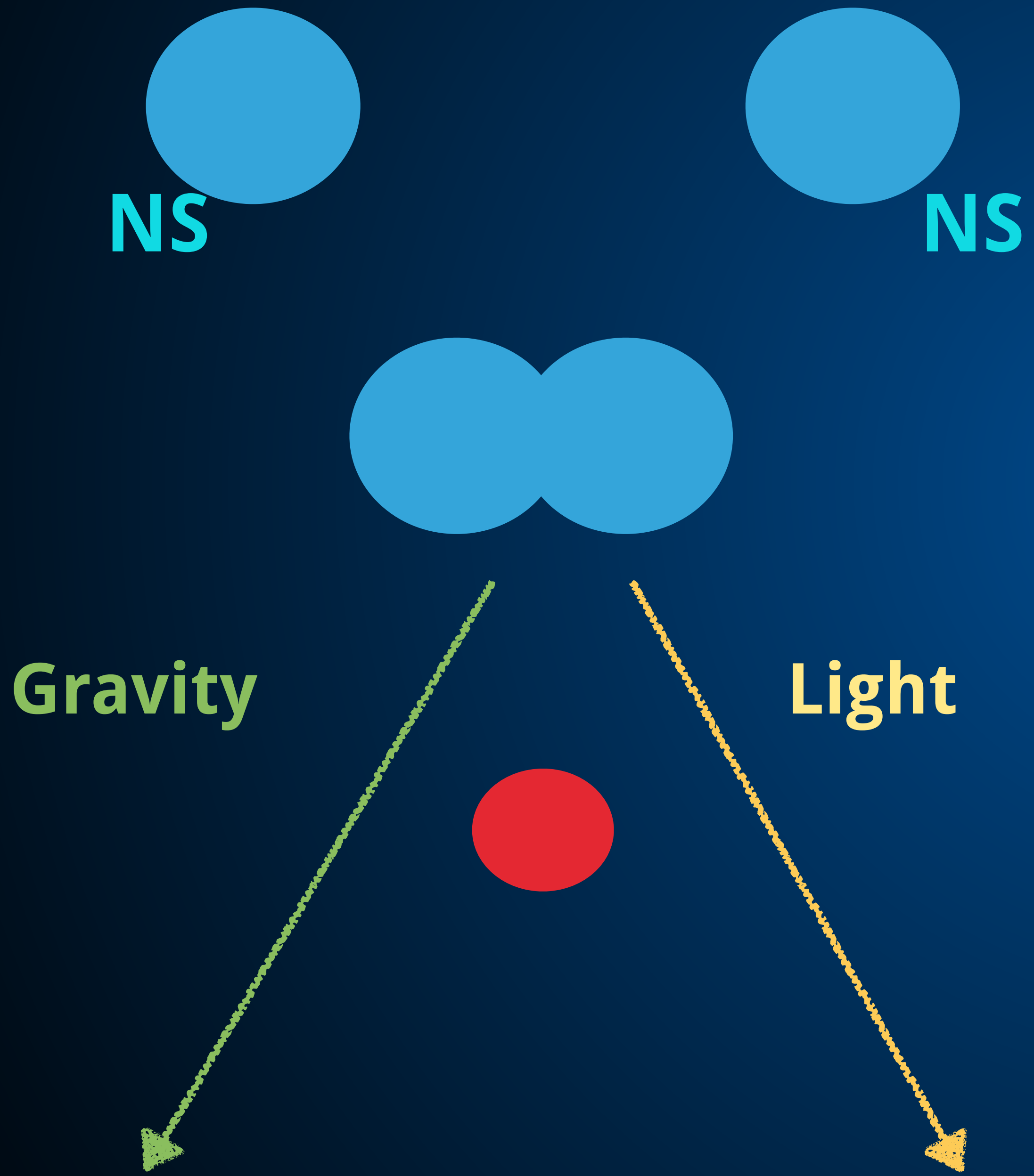


DM Induced Collapse

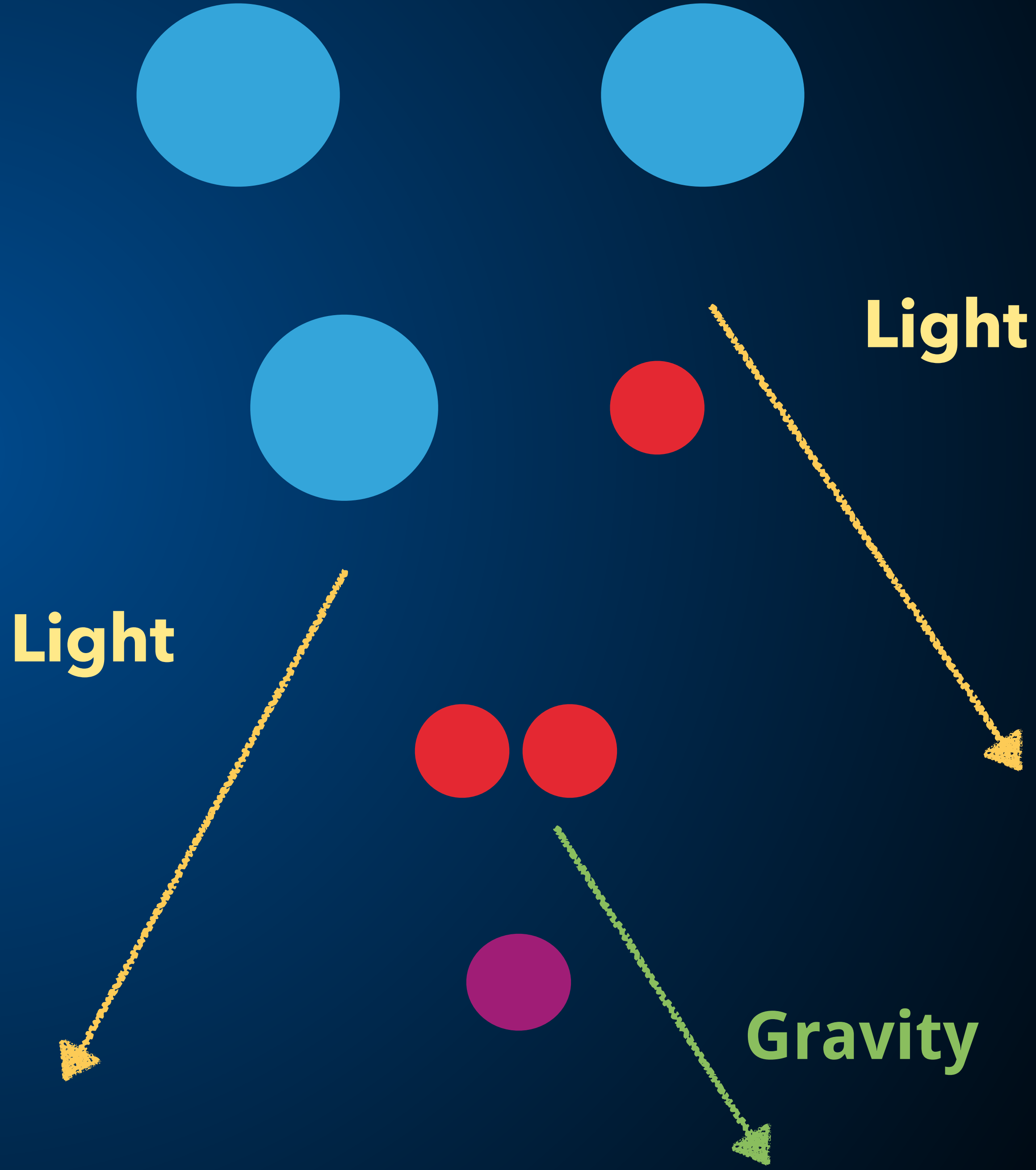


An Electromagnetic Signal

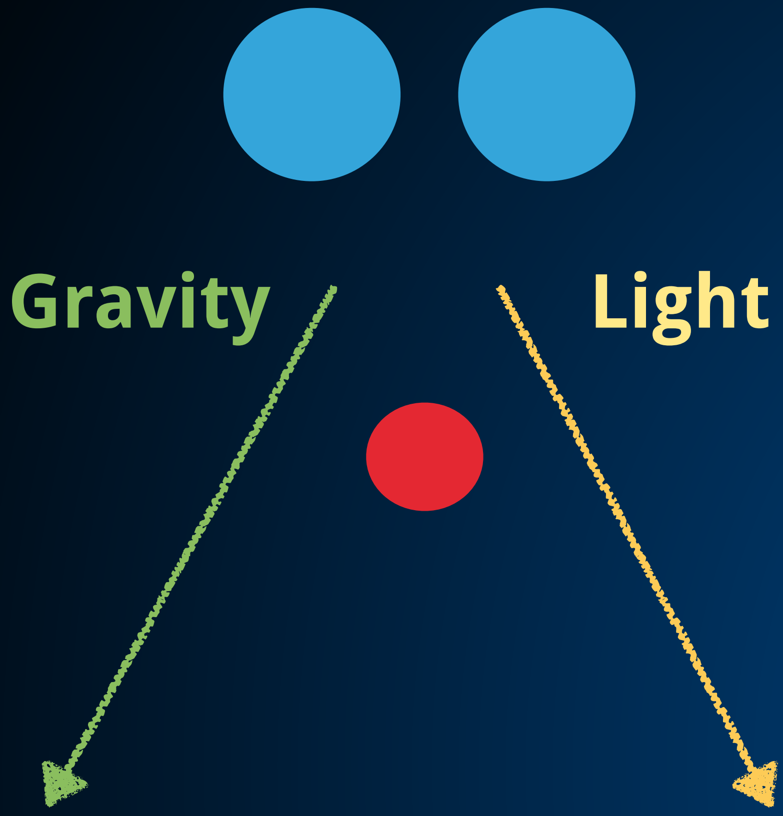
No DM Induced Collapse



DM Induced Collapse



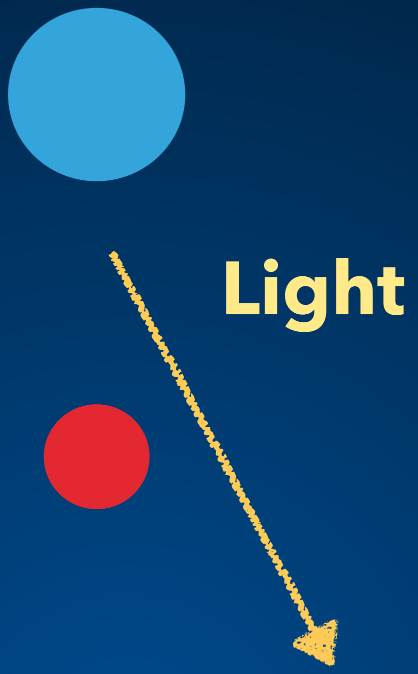
New Phenomena



Merger Kilonovae

Electromagnetic signals and gravitational waves jointly identified.

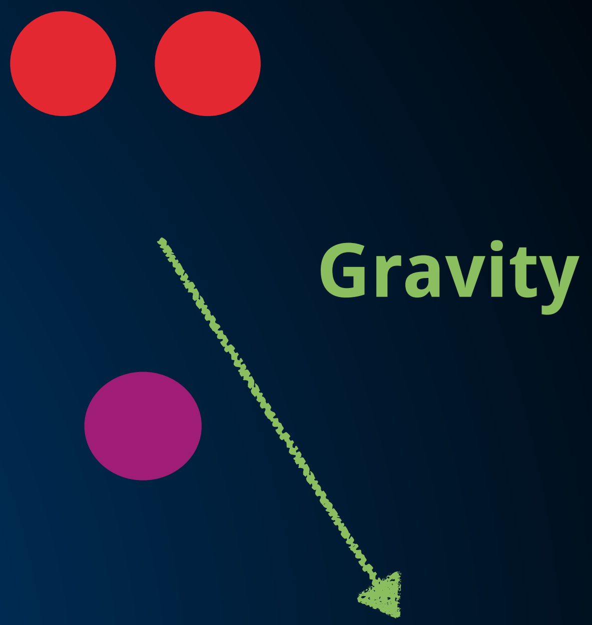
(proportional to ρ^{-1}_{DM})



Quiet Kilonovae

Electromagnetic signals without gravitational waves.

(proportional to ρ_{DM}).



Dark Mergers

Gravitational waves without any electromagnetic signal.

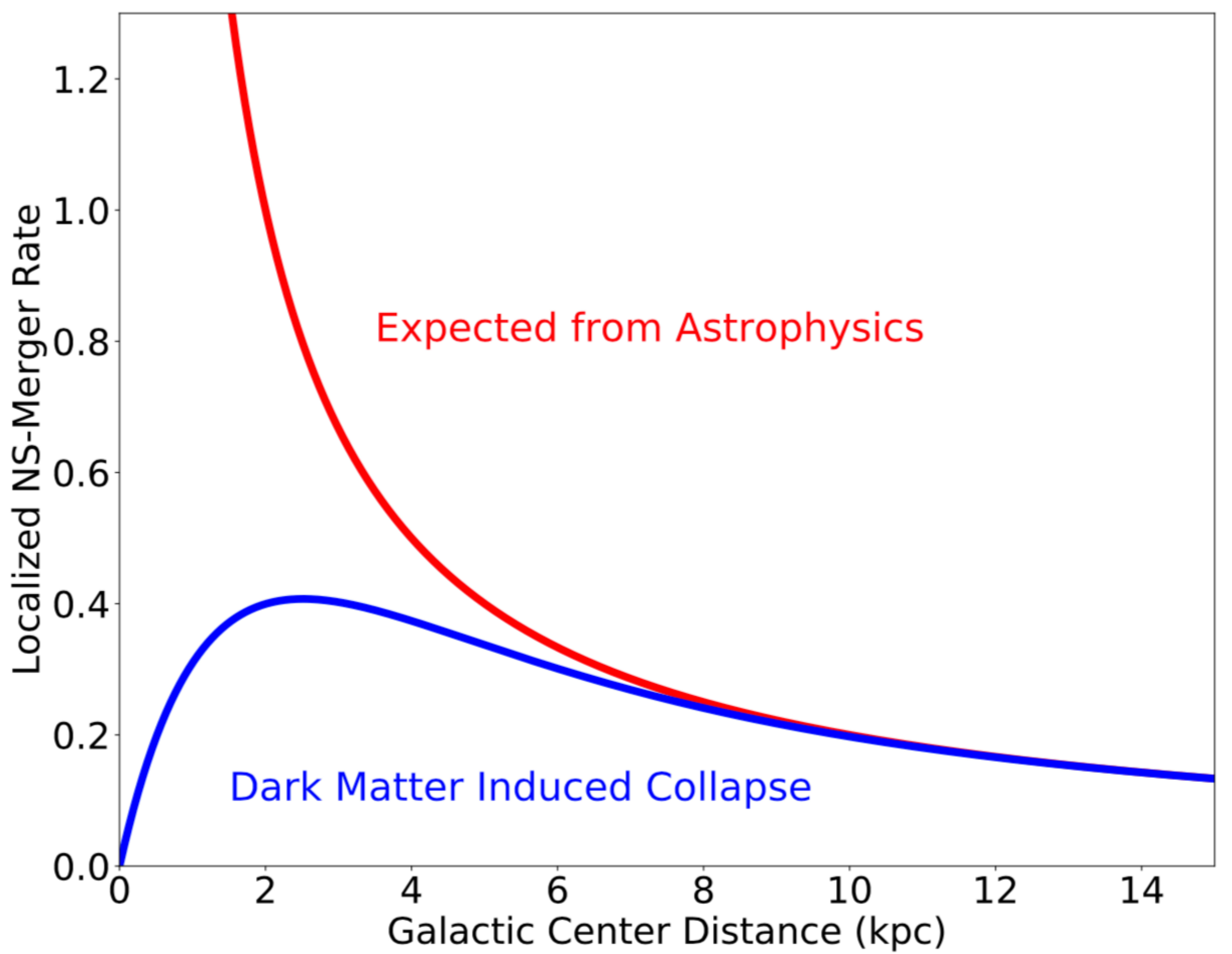
(proportional to ρ_{DM}).

Two Methods

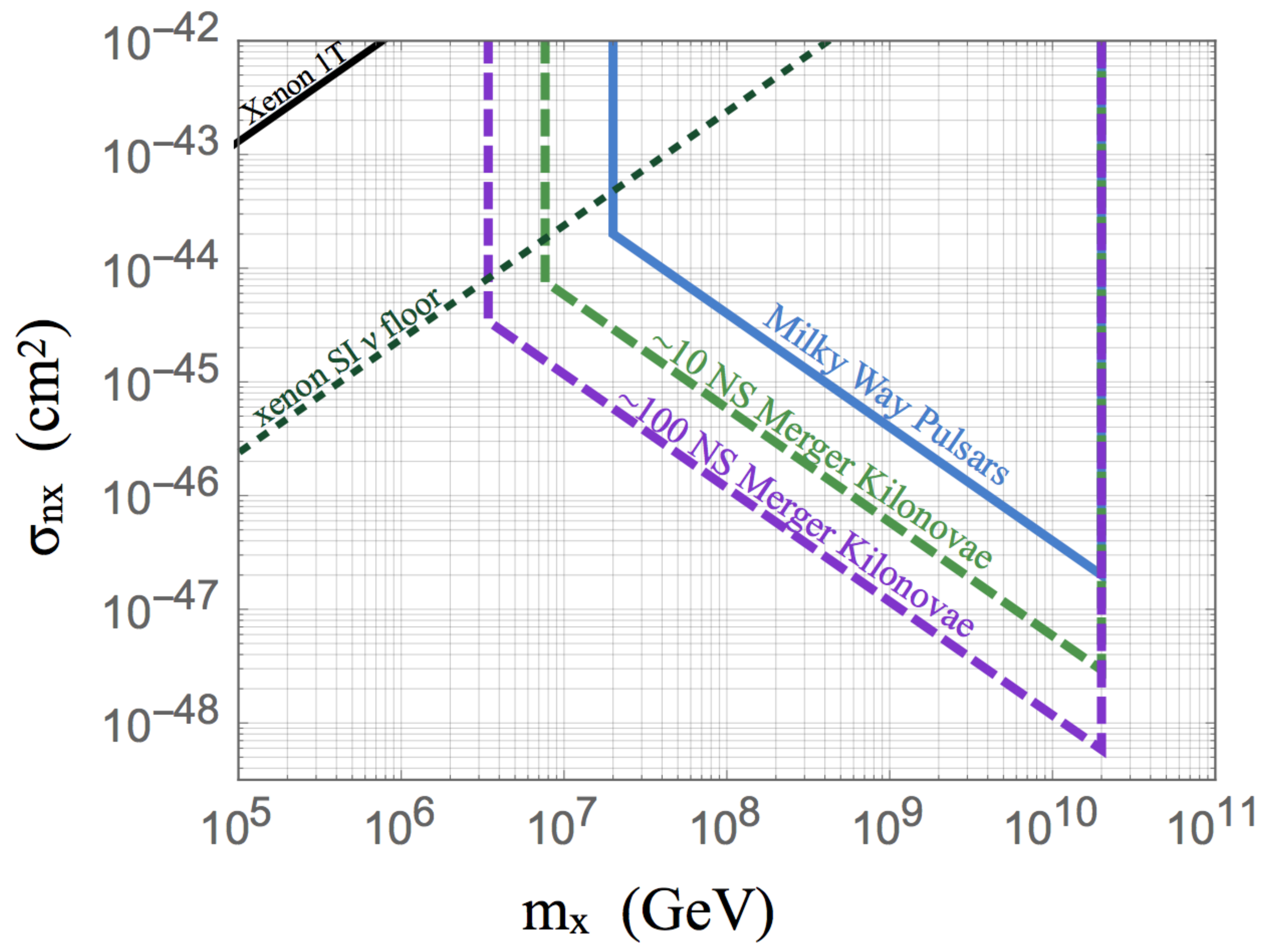
- **Two methods to isolate dark matter signal:**

  1. **Look in regions where dark matter induced signal is dominant (e.g. dwarf galaxies)**
  2. **Examine the spatial morphology of events in and extract dark matter density profile.**

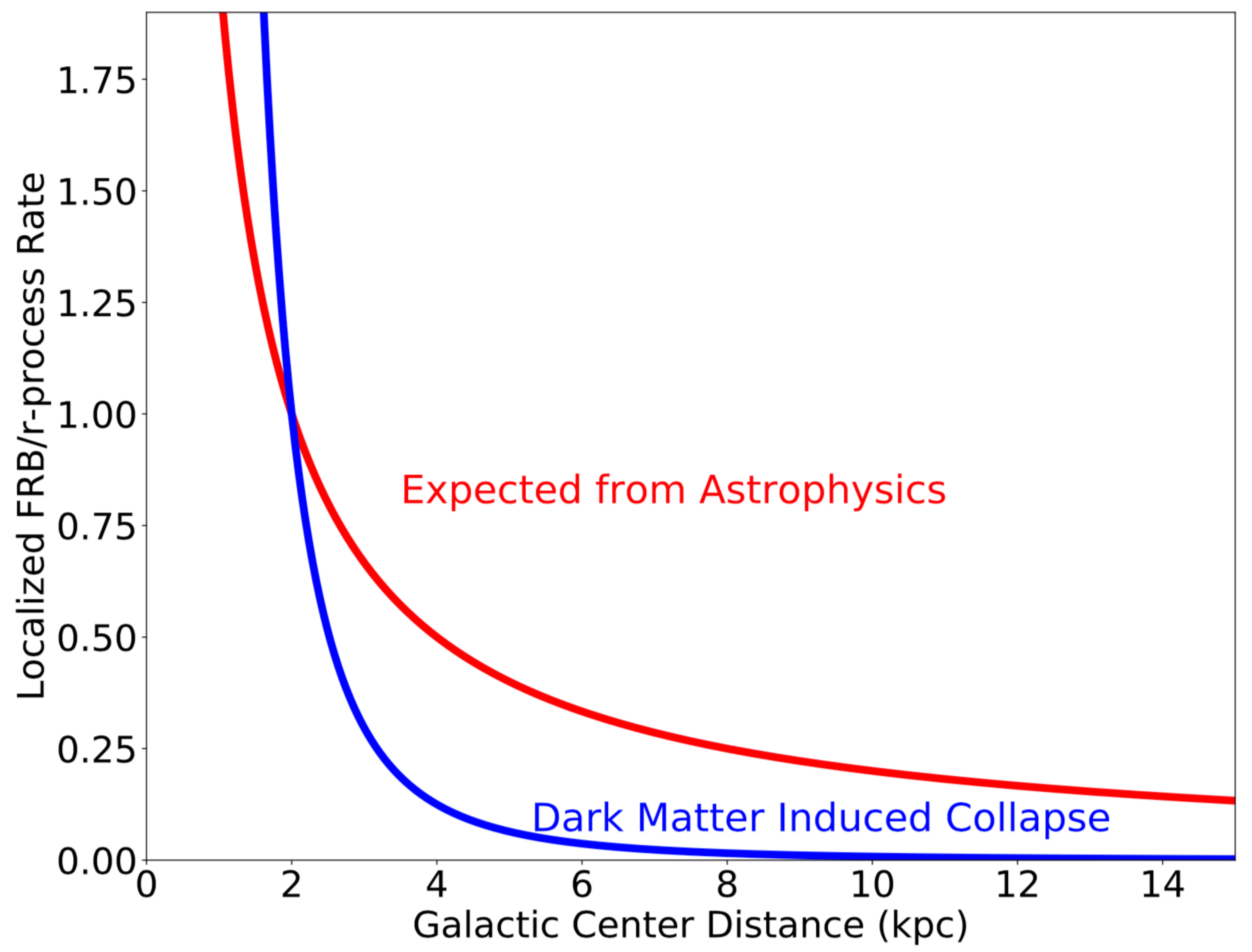
Merger Kilonovae



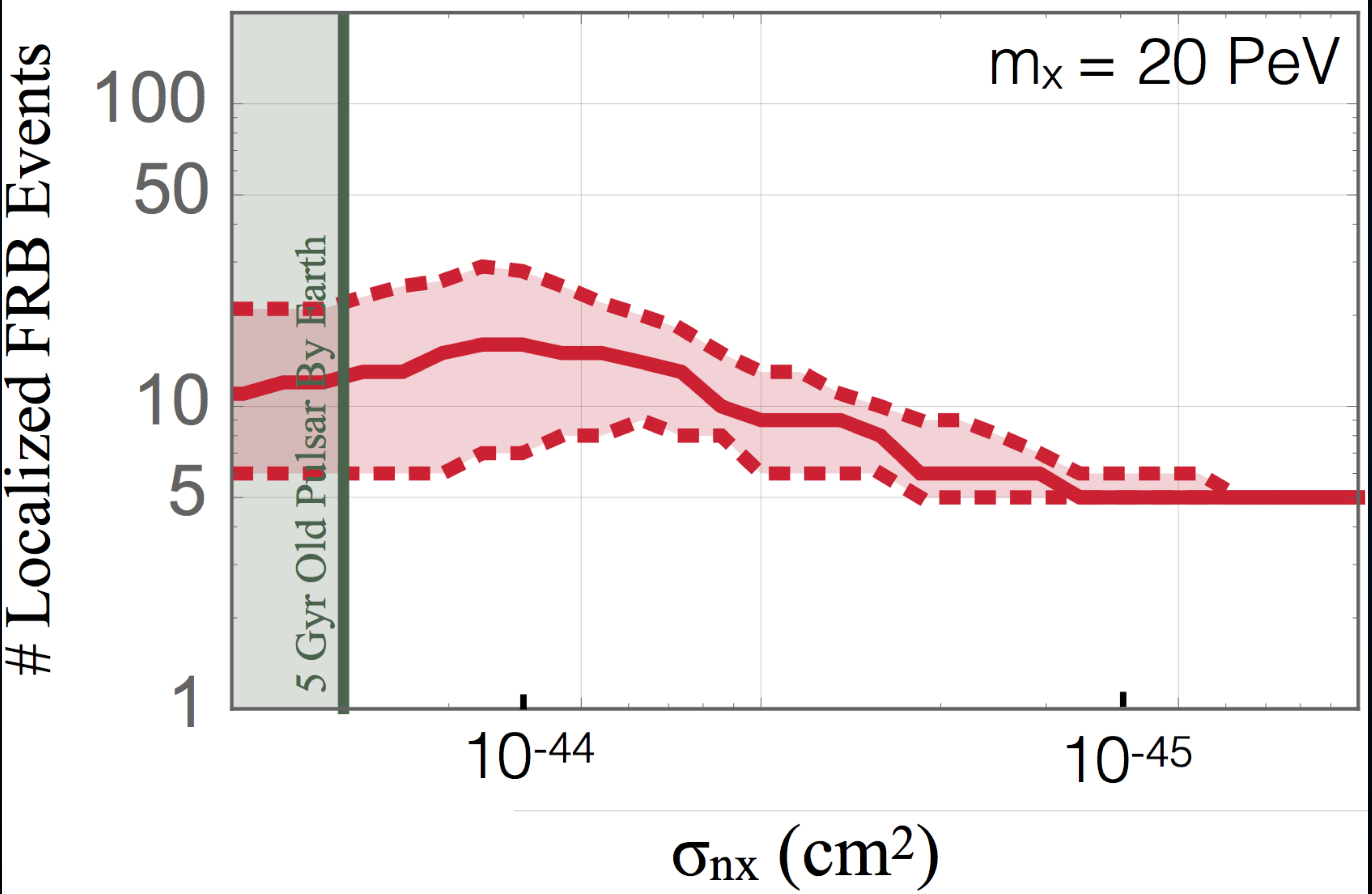
Constraining Dark Matter - Merger Kilonovae



Fast Radio Bursts or Quiet Kilonovae



Finding Dark Matter - Fast Radio Bursts



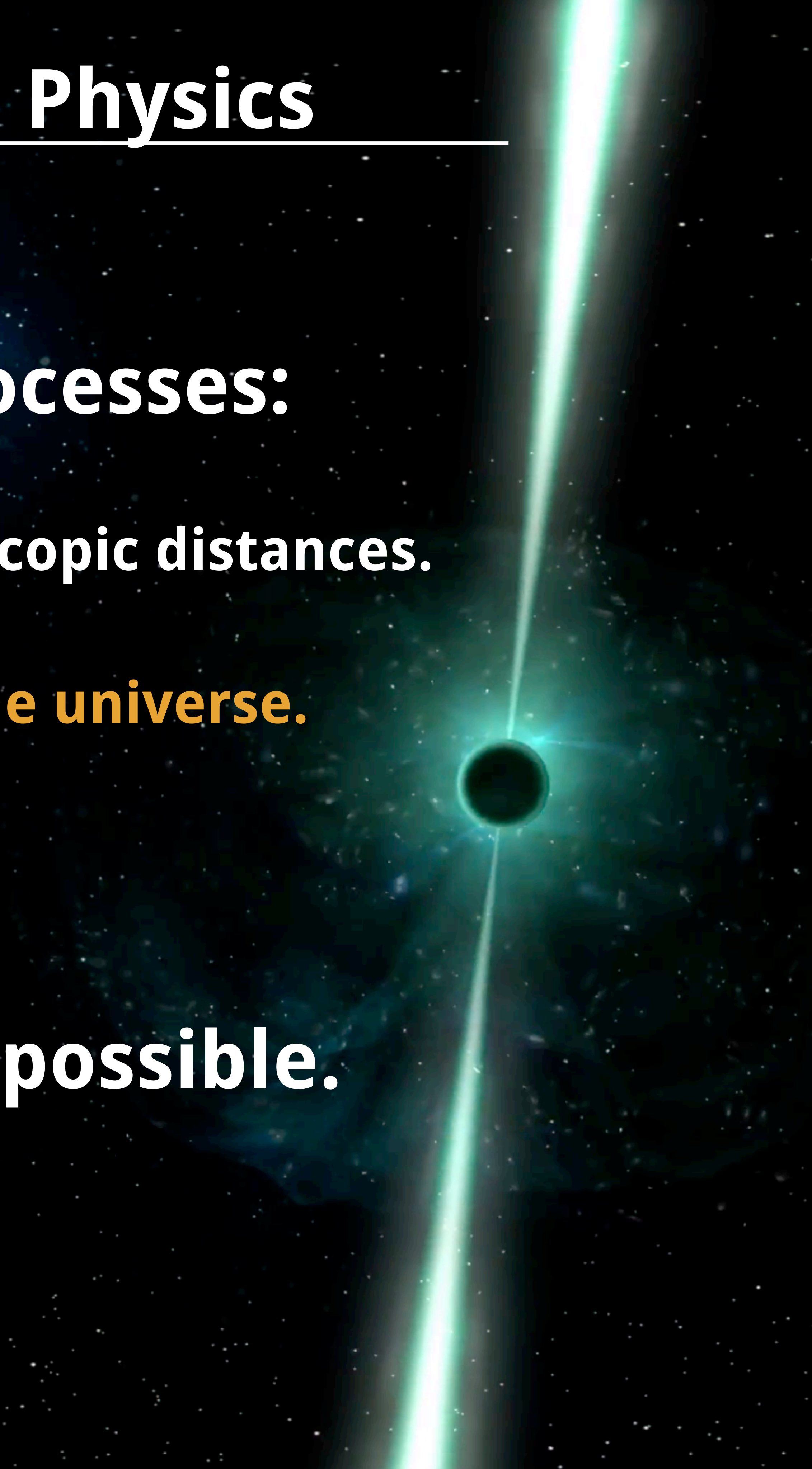
What Do We Need?

1. New Observations of NS Mergers (gravitational waves, electromagnetic emission, fast radio bursts).

2. Localization of the electromagnetic signatures within galaxies.

3. Improved models for the electromagnetic signals from dark matter induced NS collapse.

A Window Into Fundamental Physics



- Sensitive probes of rare processes:
  1. Nuclear densities over macroscopic distances.
  2. Strongest magnetic fields in the universe.

- Precise measurements are possible.

One Slide on Axion Dark Matter

Axions proposed to solve the strong-CP problem

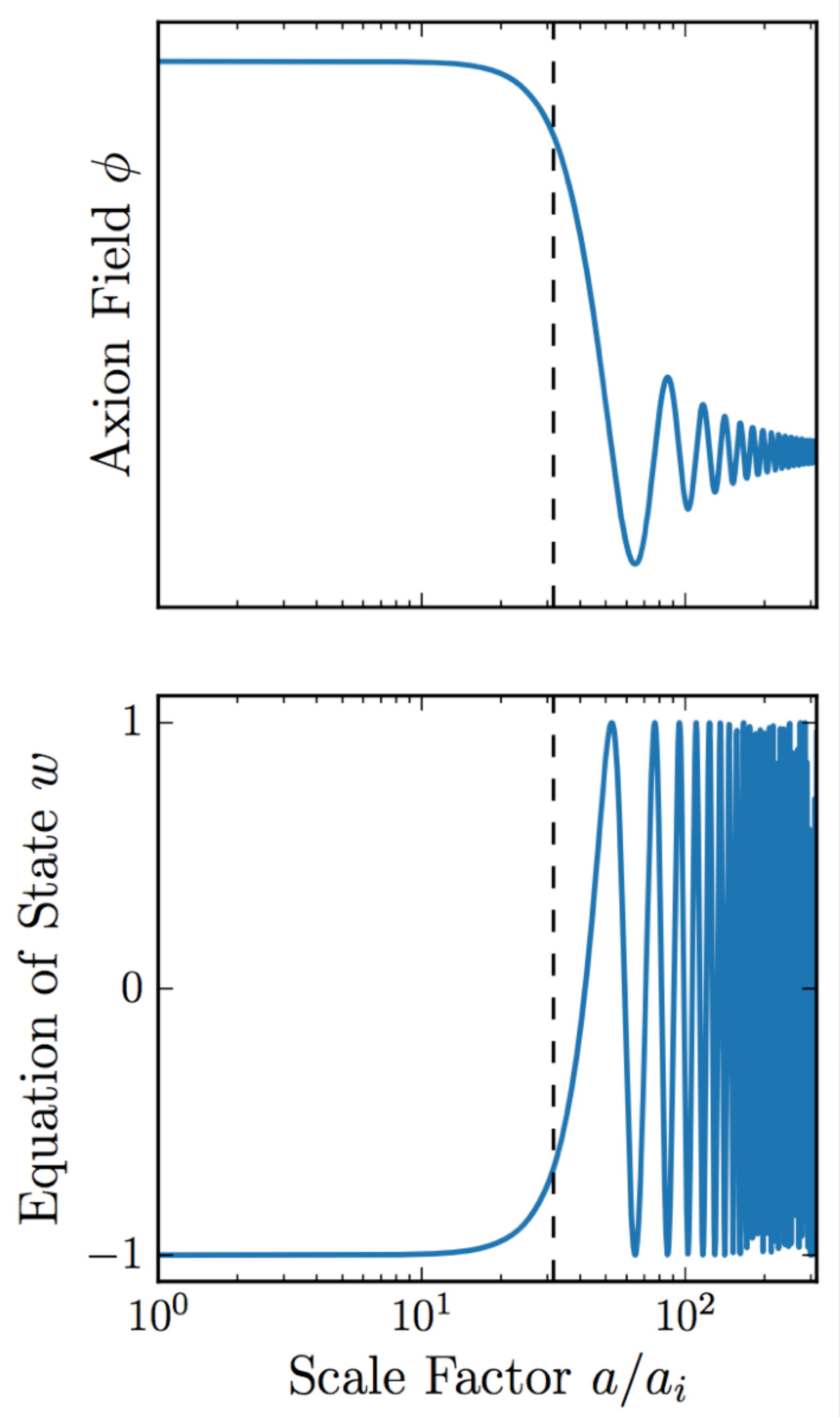
$$L_\theta = \theta \frac{g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu}$$

If this constant is promoted to a field, its self-interactions drive it to 0:

$$\mathcal{L}_\Theta \to \mathcal{L}_a = \tfrac{1}{2} (\partial_\mu a)^2 - \frac{\alpha_{\rm s}}{8\pi\, f_a}\, a\, G\widetilde{G}$$

This term must couple to the EM field, allowing for decays to photons:

$$\mathcal{L}_{\rm int} = -\tfrac{1}{4}\, g_{a\gamma} F_{\mu\nu} \widetilde{F}^{\mu\nu}\, a = g_{a\gamma} \mathbf{E} \cdot \mathbf{B}\, a$$

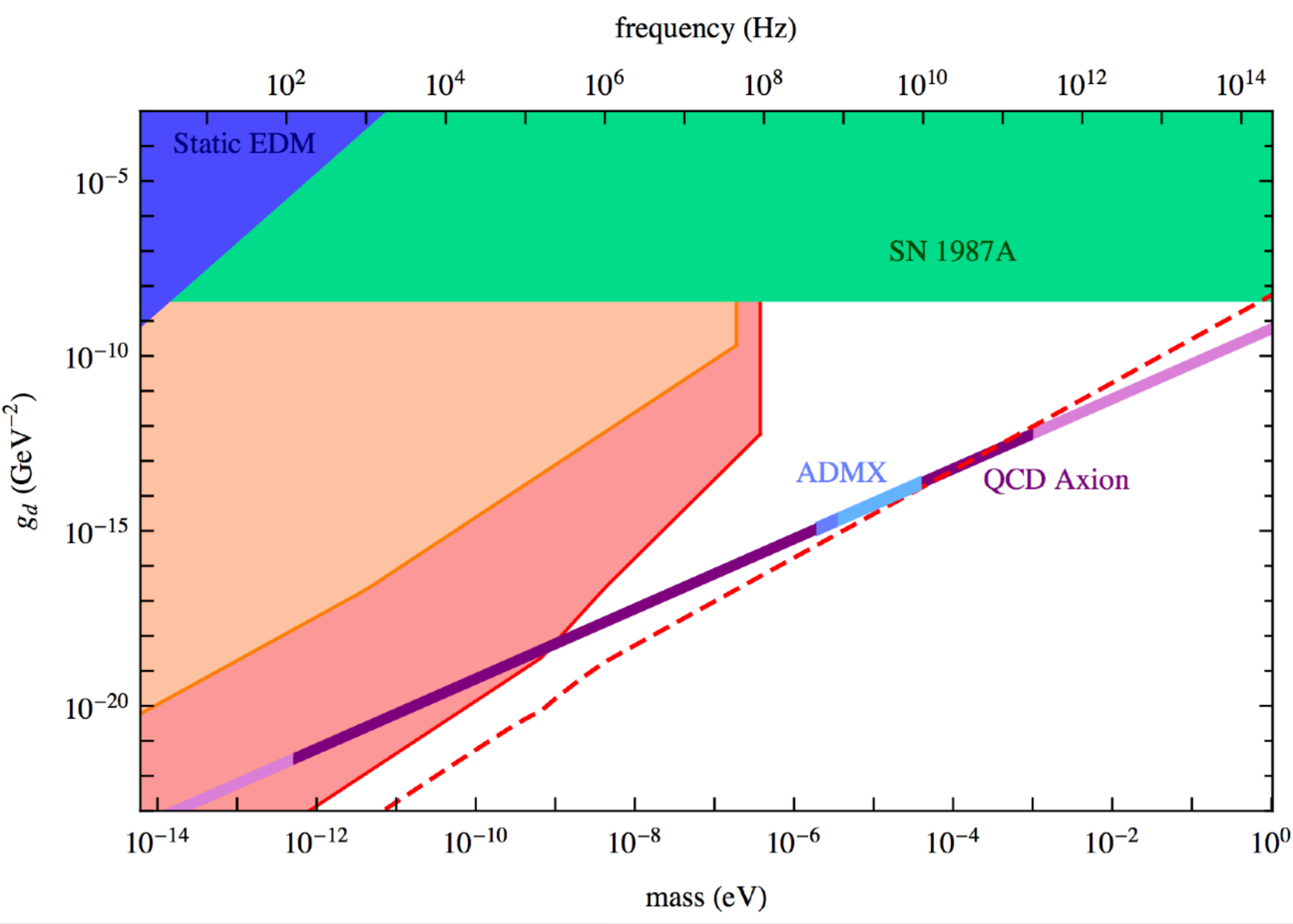


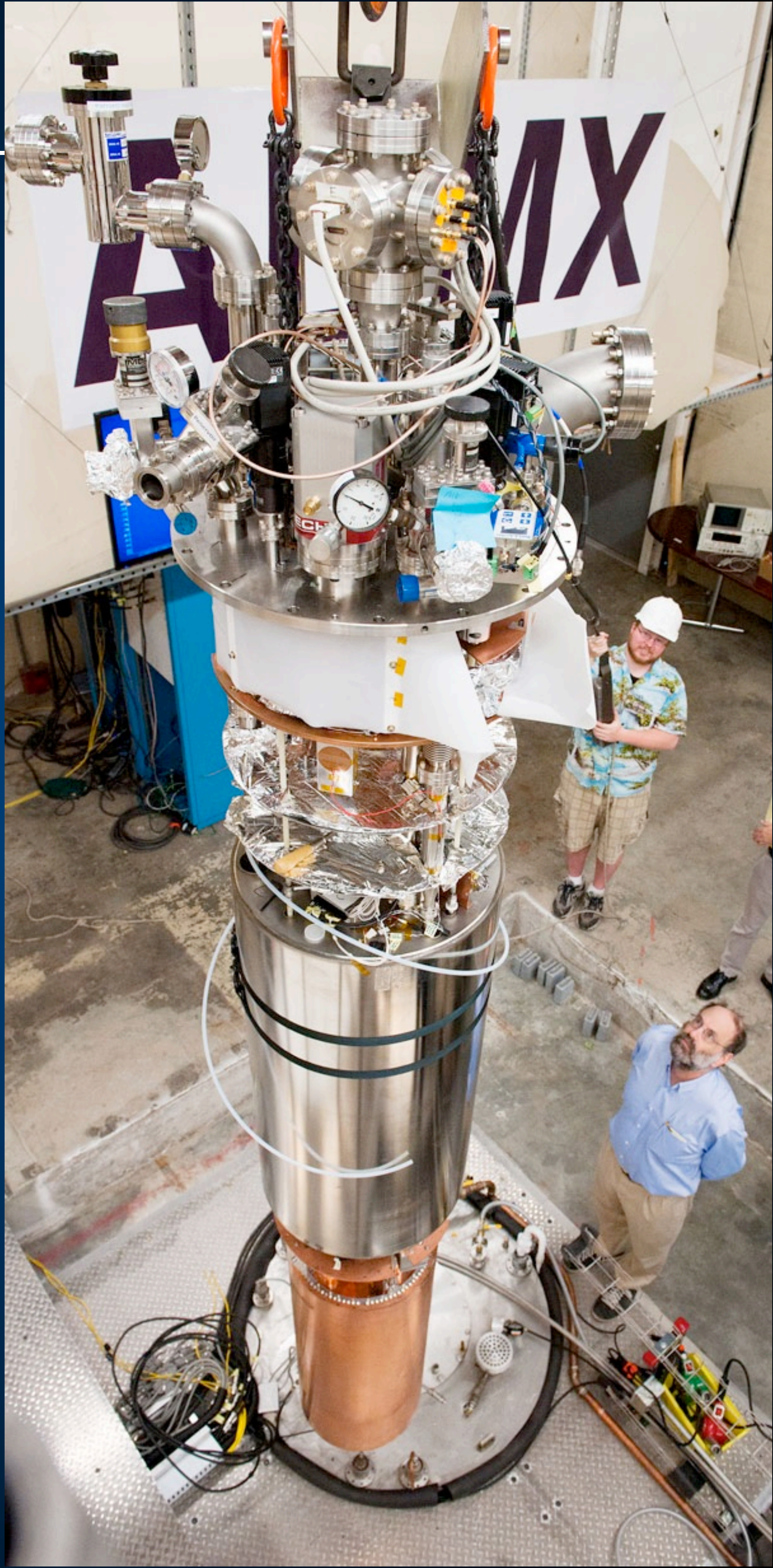
Marsh (2015; 1510.07633)

Detecting Axion Dark Matter

- We can search for the resonant decay to photons:

$$P_{\mathrm{SIG}} = \eta g_{a\gamma\gamma}^2 \left(\frac{\rho_a}{m_a}\right) B_0^2 V C Q_L$$





Neutron Stars: The Optimal Axion Laboratory

$$P_{a\gamma} \sim g_{a\gamma\gamma}^2 \mathbf{B}^2 L^2$$

ADMX

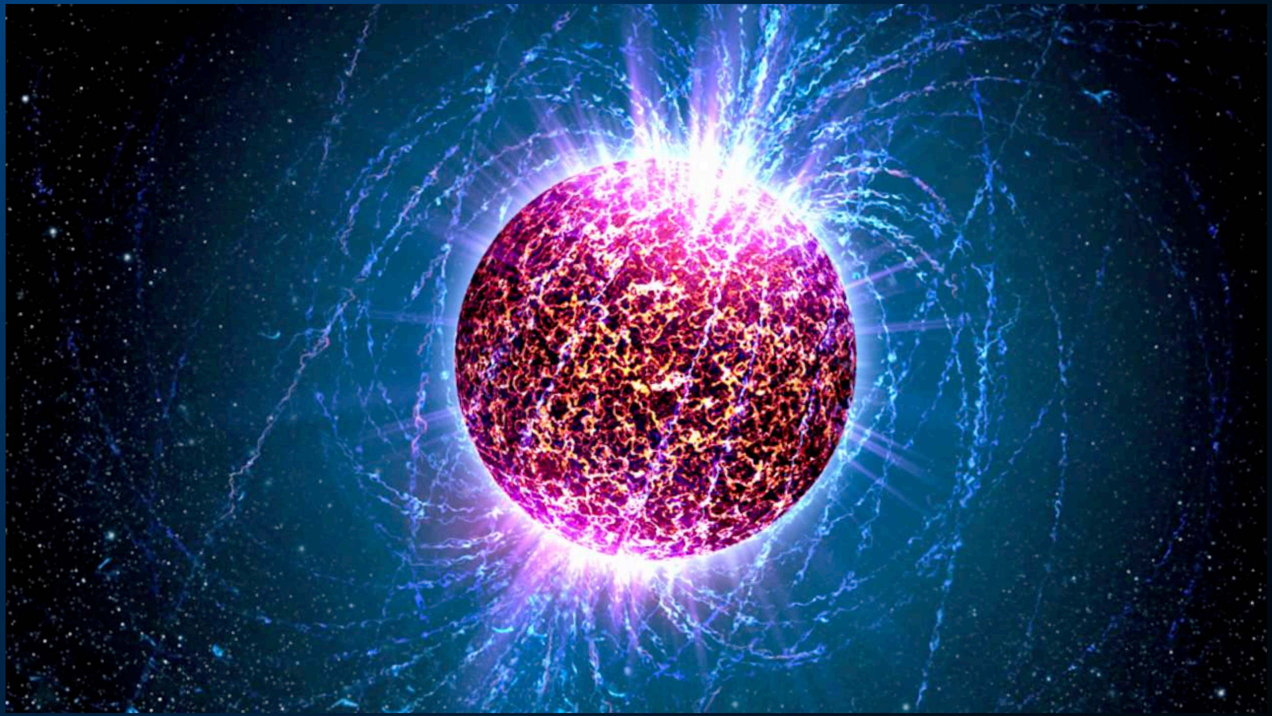
- 10 T
- 1 m^2

100 T^2 m^2

Neutron Star

- 10^{10} T
- 10^8 m^2

10^{28} T^2 m^2



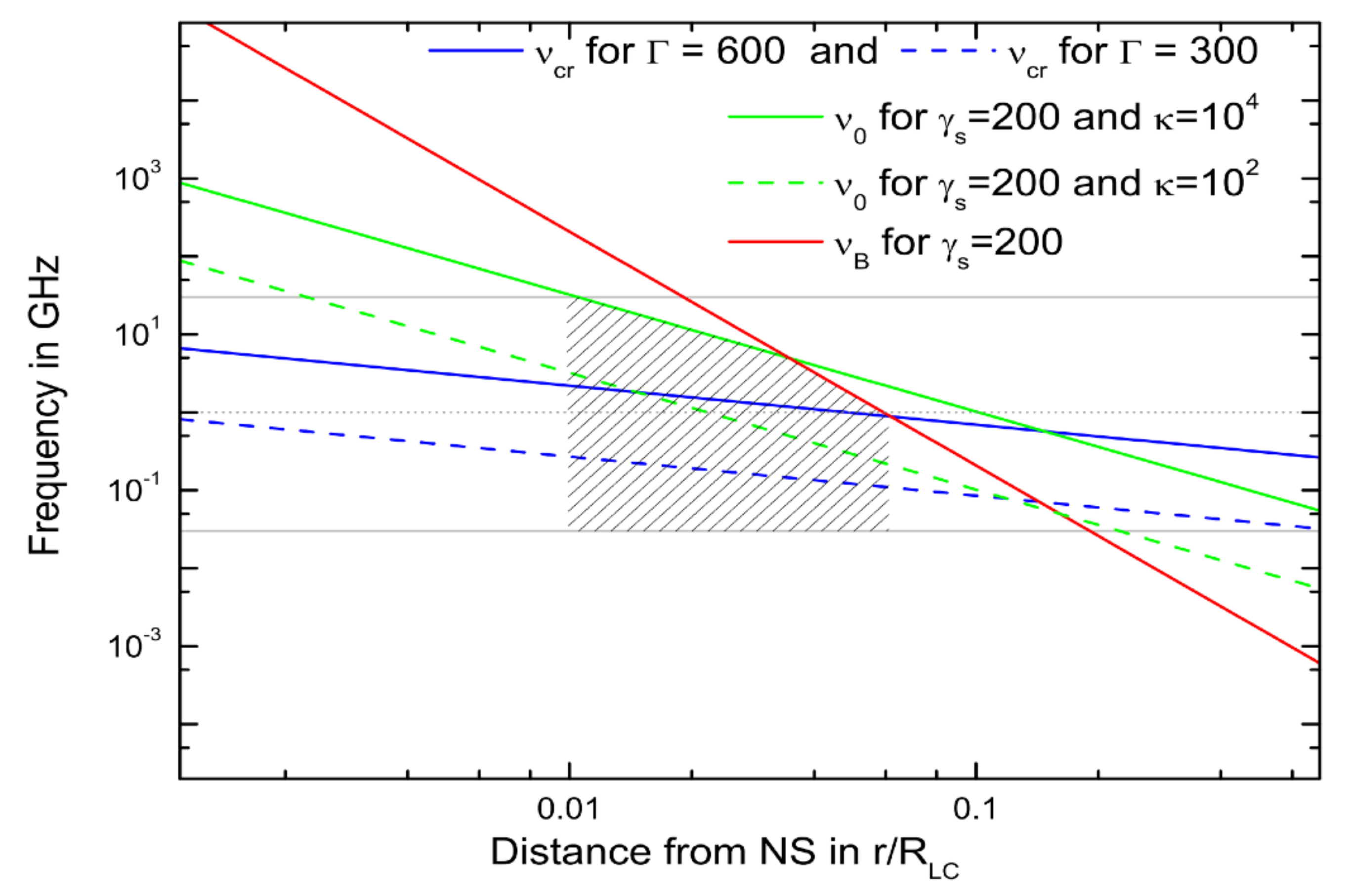
Neutron Stars: The Optimal Axion Laboratory

- **Resonant interactions occur when plasma frequency equals the axion mass:**

$$\omega_p \approx (1.5 \times 10^2 \text{ GHz}) \sqrt{\left(\frac{B_z}{10^{14} \text{ G}}\right)\left(\frac{1 \text{ sec}}{P}\right)}$$

= 6 x 10^{-4} eV

Mitra et al. (1510.00103)

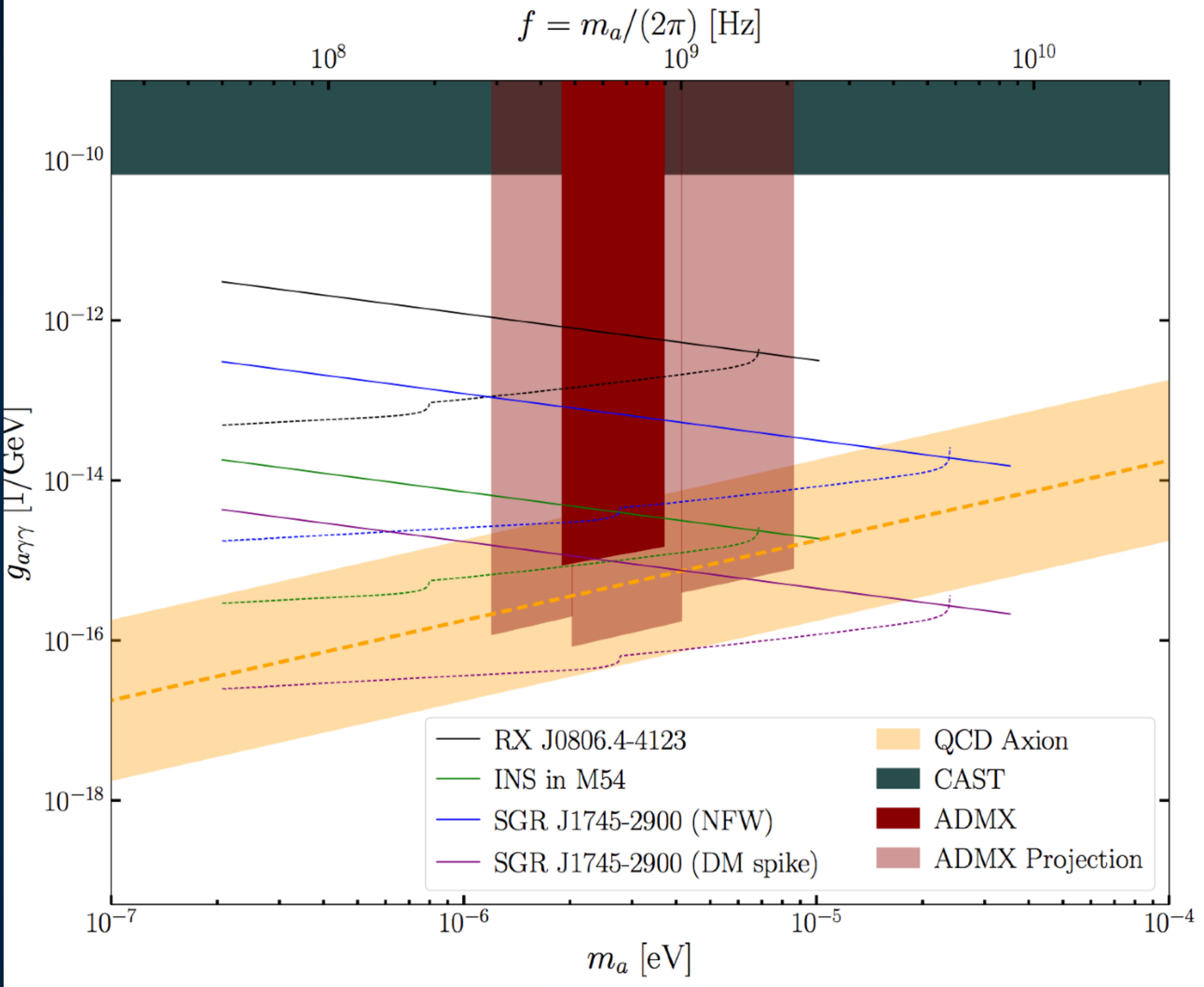


- **Need detailed model of NS magnetic fields.**

$$r_c(\theta, \theta_m, t) = 224 \text{ km} \times \left|3\cos\theta\, \hat{\mathbf{m}} \cdot \hat{\mathbf{r}} - \cos\theta_m\right|^{1/3} \times \left(\frac{r_0}{10 \text{ km}}\right) \times \left[\frac{B_0}{10^{14} \text{ G}} \frac{1 \text{ sec}}{P} \left(\frac{1 \text{ GHz}}{m_a}\right)^2\right]^{1/3} .$$

Hook et al. (1804.03145)

Neutron Stars: The Optimal Axion Laboratory



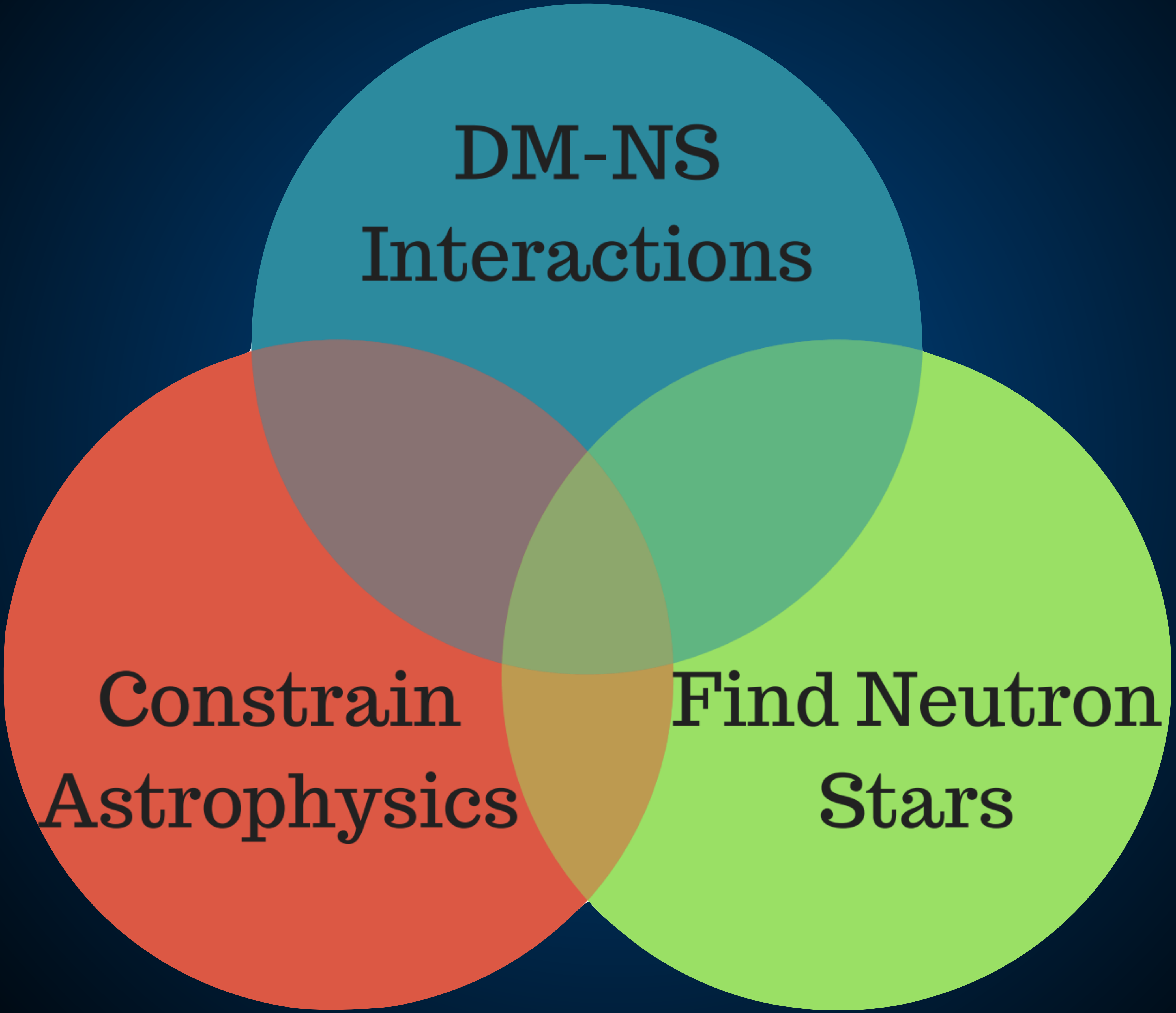
- **Can place complementary constraints on the QCD axion.**
- **Specific to models where axions are the dark matter.**

Hook et al. (1804.03145)

What Do We Need?

1. Nearby, highly-magnetized pulsar.
2. Better models of the pulsar magnetic field.
3. Sensitive observations of radio lines (different techniques than traditional pulsar searches).

Finding the Right Neutron Star

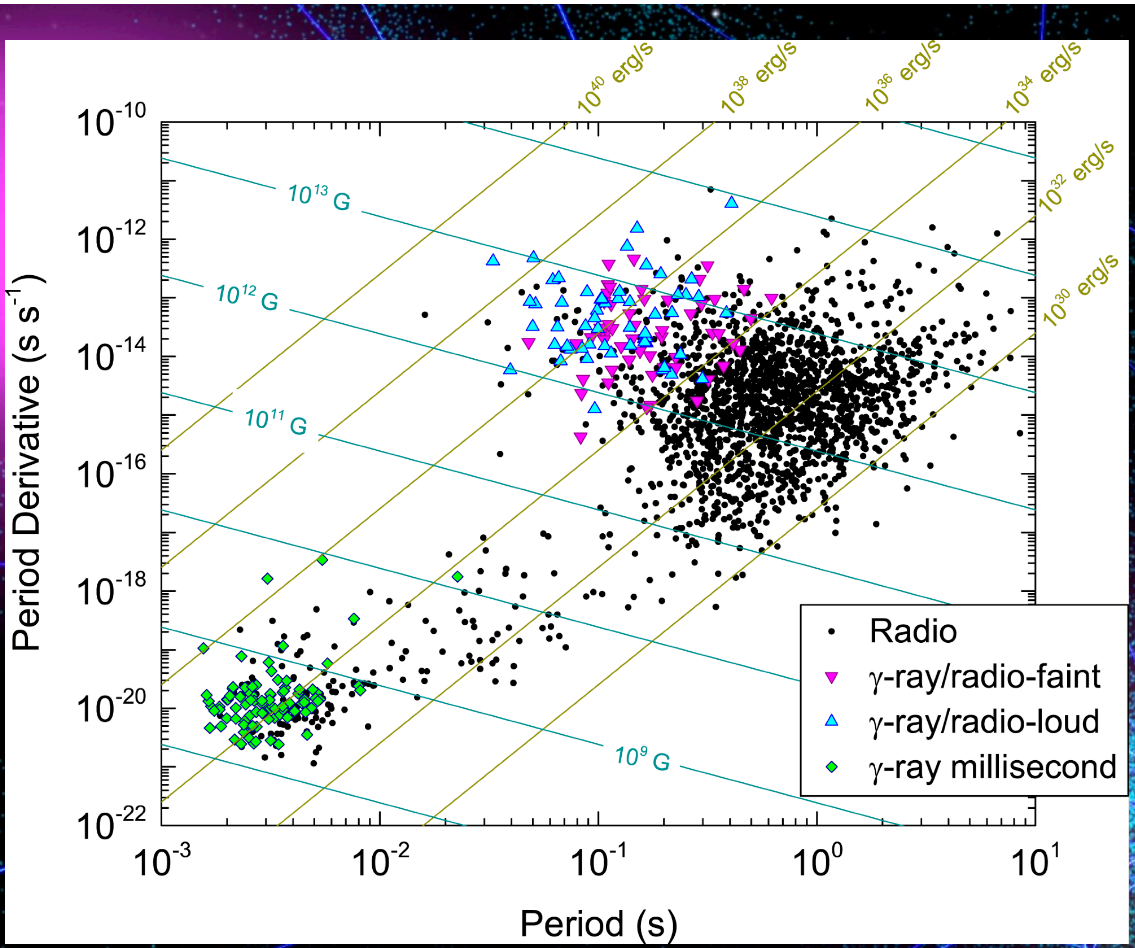


DM-NS Interactions

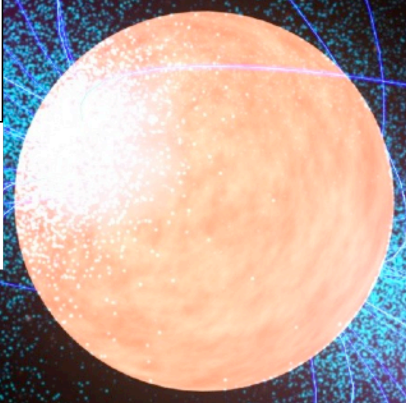
Constrain Astrophysics

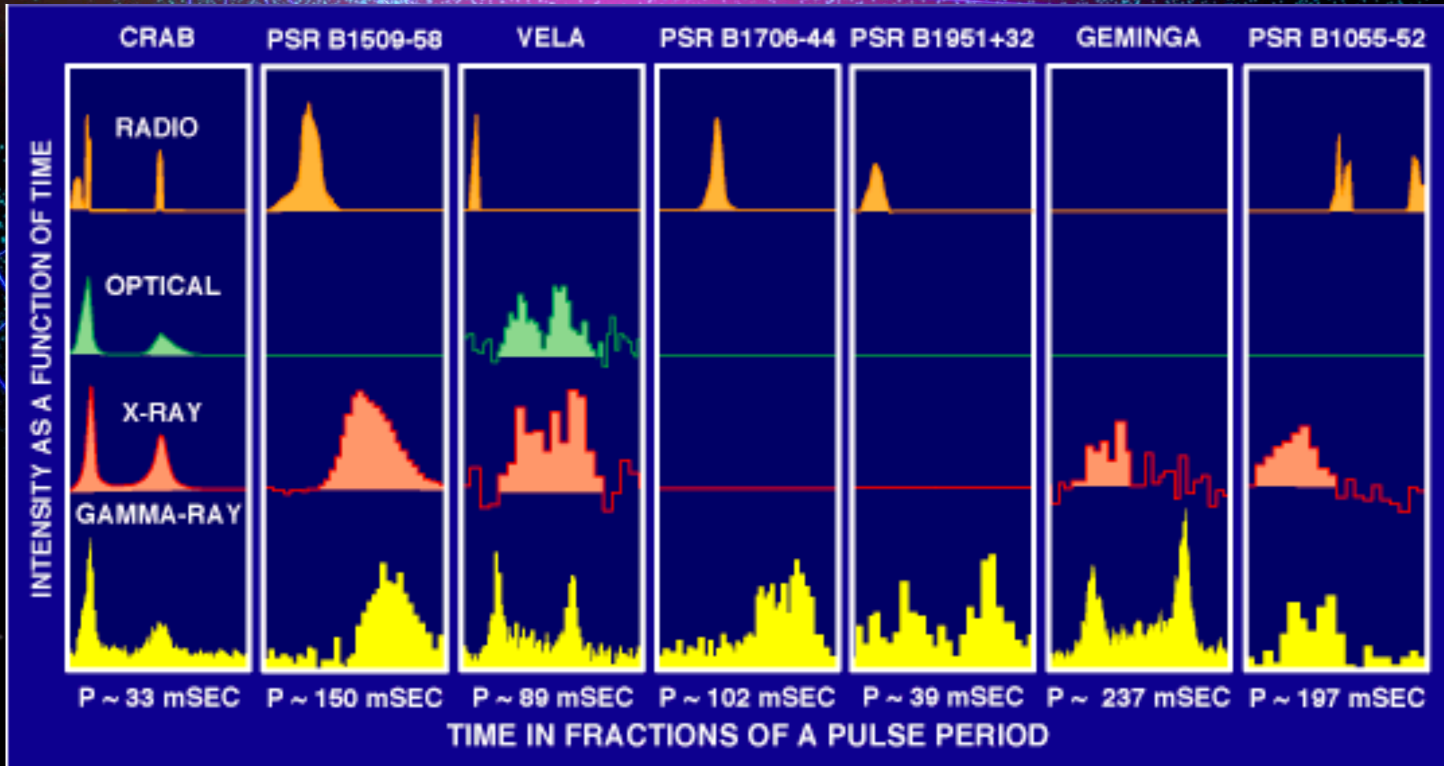
Find Neutron Stars

Radio Pulses: A Blessing and a Curse



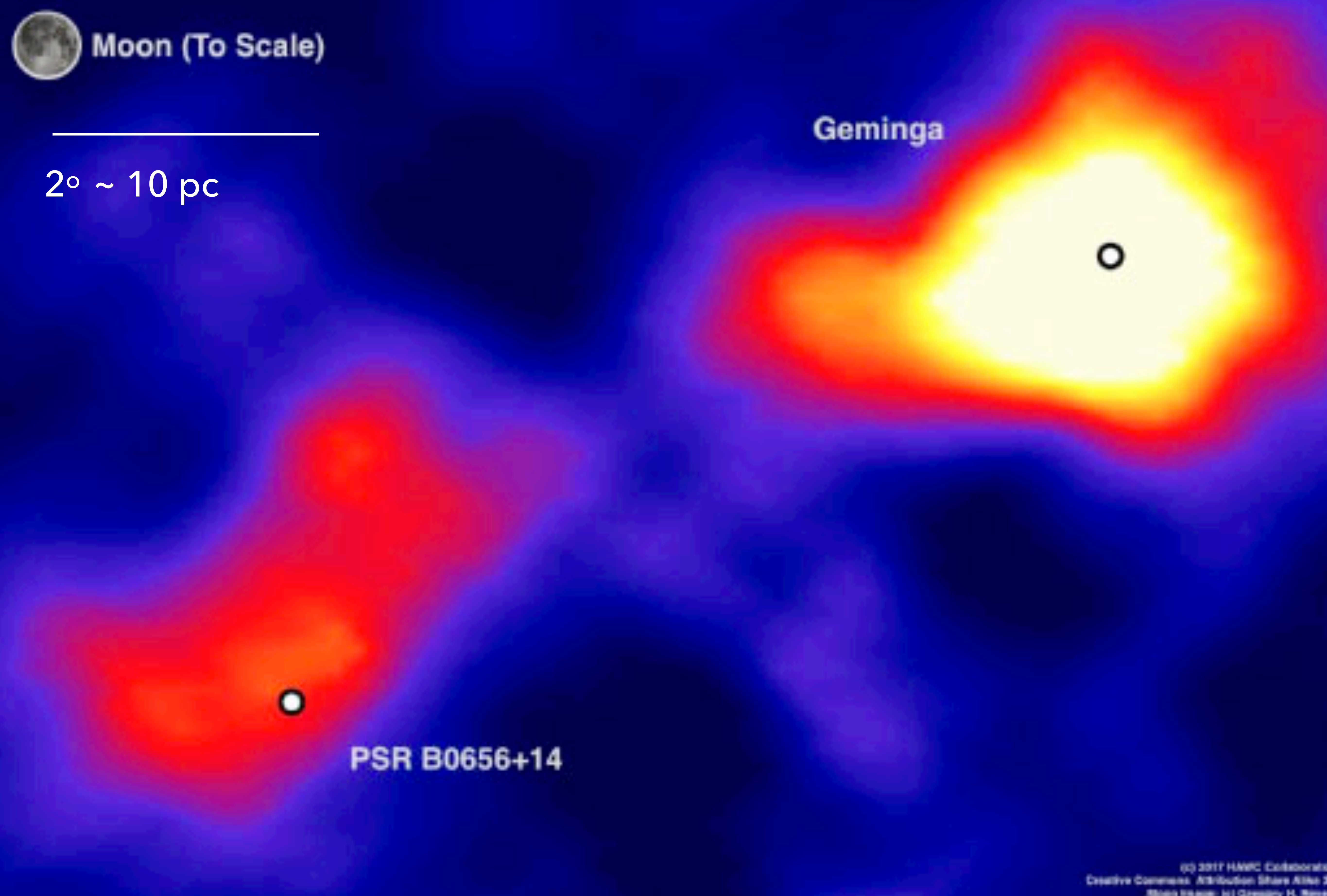
Harding (2016; J Plasma Phys 82)





A New Method for Detecting Invisible Pulsars

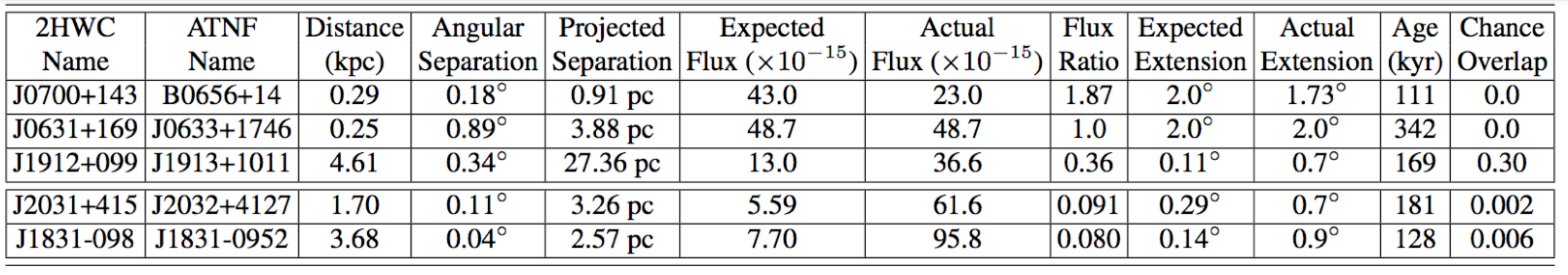
A New Method for Detecting Invisible Pulsars



2° ~ 10 pc

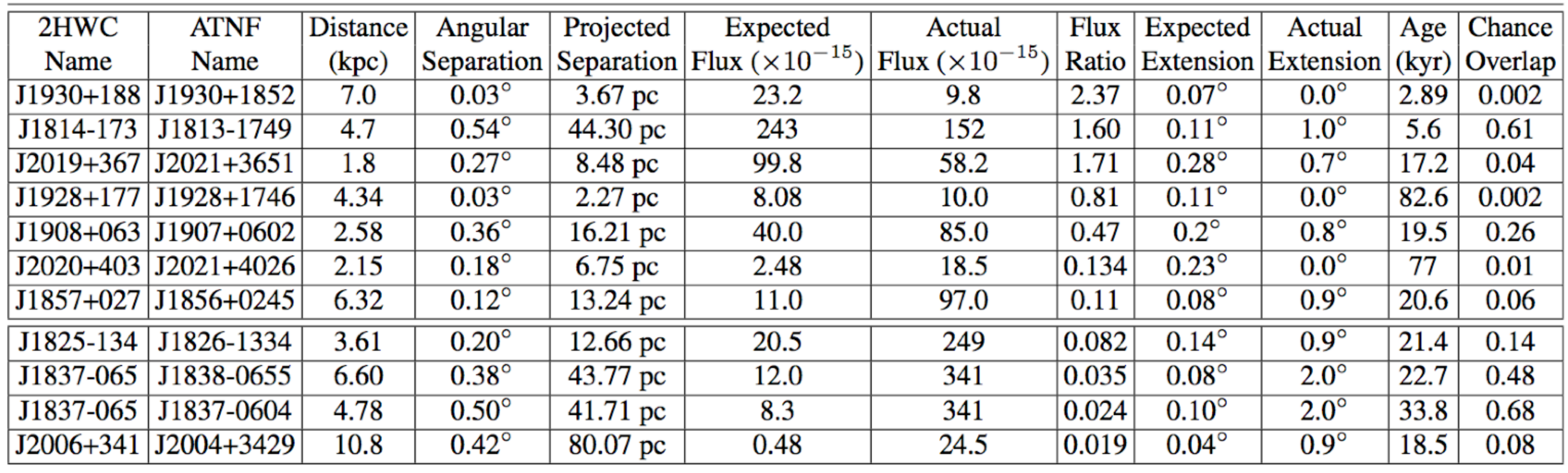
Discovering Pulsars at TeV Energies

- 5 / 39 sources in the 2HWC catalog are correlated with bright, middle-aged (100 — 400 kyr) pulsars.



2HWC Name	ATNF Name	Distance (kpc)	Angular Separation	Projected Separation	Expected Flux ($\times10^{-15}$)	Actual Flux ($\times10^{-15}$)	Flux Ratio	Expected Extension	Actual Extension	Age (kyr)	Chance Overlap
J0700+143	B0656+14	0.29	0.18°	0.91 pc	43.0	23.0	1.87	2.0°	1.73°	111	0.0
J0631+169	J0633+1746	0.25	0.89°	3.88 pc	48.7	48.7	1.0	2.0°	2.0°	342	0.0
J1912+099	J1913+1011	4.61	0.34°	27.36 pc	13.0	36.6	0.36	0.11°	0.7°	169	0.30
J2031+415	J2032+4127	1.70	0.11°	3.26 pc	5.59	61.6	0.091	0.29°	0.7°	181	0.002
J1831-098	J1831-0952	3.68	0.04°	2.57 pc	7.70	95.8	0.080	0.14°	0.9°	128	0.006

- 12 others with young pulsars
  - 2.3 chance overlaps
  - TeV emission may be contaminated by SNR



2HWC Name	ATNF Name	Distance (kpc)	Angular Separation	Projected Separation	Expected Flux ($\times10^{-15}$)	Actual Flux ($\times10^{-15}$)	Flux Ratio	Expected Extension	Actual Extension	Age (kyr)	Chance Overlap
J1930+188	J1930+1852	7.0	0.03°	3.67 pc	23.2	9.8	2.37	0.07°	0.0°	2.89	0.002
J1814-173	J1813-1749	4.7	0.54°	44.30 pc	243	152	1.60	0.11°	1.0°	5.6	0.61
J2019+367	J2021+3651	1.8	0.27°	8.48 pc	99.8	58.2	1.71	0.28°	0.7°	17.2	0.04
J1928+177	J1928+1746	4.34	0.03°	2.27 pc	8.08	10.0	0.81	0.11°	0.0°	82.6	0.002
J1908+063	J1907+0602	2.58	0.36°	16.21 pc	40.0	85.0	0.47	0.2°	0.8°	19.5	0.26
J2020+403	J2021+4026	2.15	0.18°	6.75 pc	2.48	18.5	0.134	0.23°	0.0°	77	0.01
J1857+027	J1856+0245	6.32	0.12°	13.24 pc	11.0	97.0	0.11	0.08°	0.9°	20.6	0.06
J1825-134	J1826-1334	3.61	0.20°	12.66 pc	20.5	249	0.082	0.14°	0.9°	21.4	0.14
J1837-065	J1838-0655	6.60	0.38°	43.77 pc	12.0	341	0.035	0.08°	2.0°	22.7	0.48
J1837-065	J1837-0604	4.78	0.50°	41.71 pc	8.3	341	0.024	0.10°	2.0°	33.8	0.68
J2006+341	J2004+3429	10.8	0.42°	80.07 pc	0.48	24.5	0.019	0.04°	0.9°	18.5	0.08

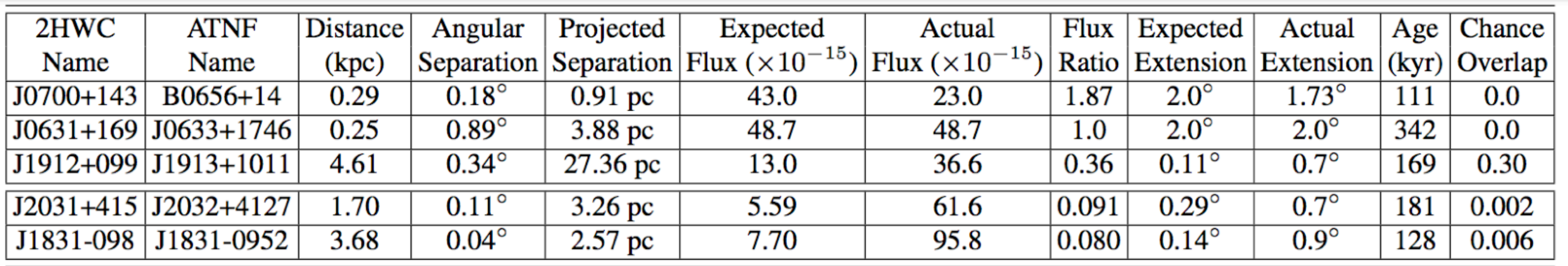
TL et al. (1703.09704)

Astrophysical Implications of TeV Halos

- TeV halo observations solve many astrophysical puzzles
    - Prove that pulsars produce the positron excess
      (Hooper, Cholis, TL, Fang 1702.08436)
    - Explain the TeV gamma-ray excess
      (TL & Buckman 1707.01905)
    - Explain inhomogeneities in cosmic-ray diffusion ,
      (Hooper & TL 1711.07482) (Evoli, TL, Morlino, TBS)
    - Explain TeV gamma-rays from the Galactic center
      (Hooper et al. 1705.09293)

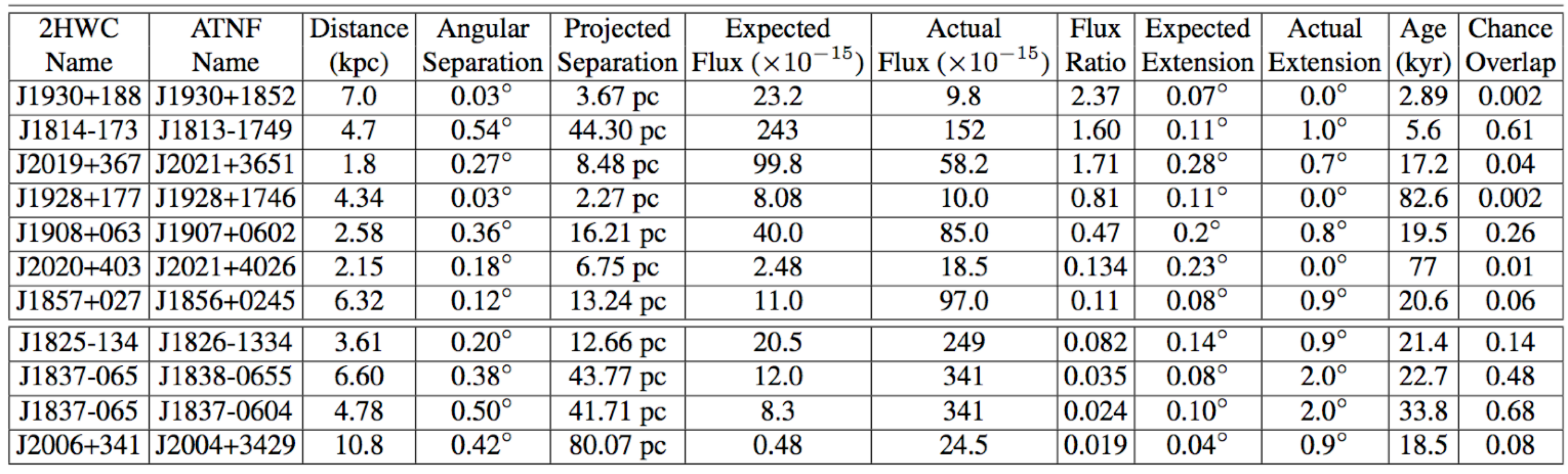
Discovering Pulsars at TeV Energies

- 5 / 39 sources in the 2HWC catalog are correlated with bright, middle-aged (100 — 400 kyr) pulsars.



2HWC Name	ATNF Name	Distance (kpc)	Angular Separation	Projected Separation	Expected Flux ($\times10^{-15}$)	Actual Flux ($\times10^{-15}$)	Flux Ratio	Expected Extension	Actual Extension	Age (kyr)	Chance Overlap
J0700+143	B0656+14	0.29	0.18°	0.91 pc	43.0	23.0	1.87	2.0°	1.73°	111	0.0
J0631+169	J0633+1746	0.25	0.89°	3.88 pc	48.7	48.7	1.0	2.0°	2.0°	342	0.0
J1912+099	J1913+1011	4.61	0.34°	27.36 pc	13.0	36.6	0.36	0.11°	0.7°	169	0.30
J2031+415	J2032+4127	1.70	0.11°	3.26 pc	5.59	61.6	0.091	0.29°	0.7°	181	0.002
J1831-098	J1831-0952	3.68	0.04°	2.57 pc	7.70	95.8	0.080	0.14°	0.9°	128	0.006

- 12 others with young pulsars
  - 2.3 chance overlaps
  - TeV emission may be contaminated by SNR

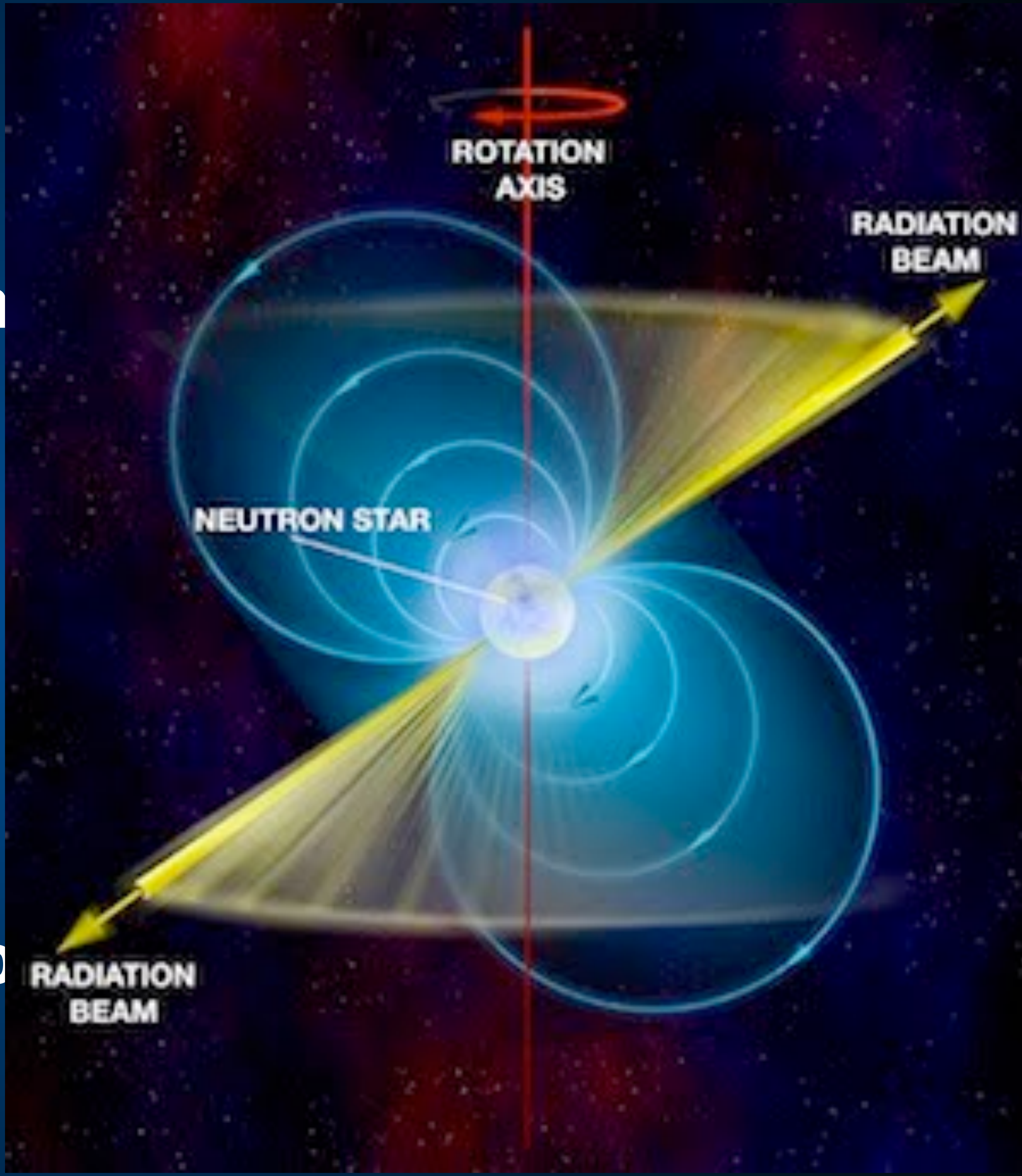


2HWC Name	ATNF Name	Distance (kpc)	Angular Separation	Projected Separation	Expected Flux ($\times10^{-15}$)	Actual Flux ($\times10^{-15}$)	Flux Ratio	Expected Extension	Actual Extension	Age (kyr)	Chance Overlap
J1930+188	J1930+1852	7.0	0.03°	3.67 pc	23.2	9.8	2.37	0.07°	0.0°	2.89	0.002
J1814-173	J1813-1749	4.7	0.54°	44.30 pc	243	152	1.60	0.11°	1.0°	5.6	0.61
J2019+367	J2021+3651	1.8	0.27°	8.48 pc	99.8	58.2	1.71	0.28°	0.7°	17.2	0.04
J1928+177	J1928+1746	4.34	0.03°	2.27 pc	8.08	10.0	0.81	0.11°	0.0°	82.6	0.002
J1908+063	J1907+0602	2.58	0.36°	16.21 pc	40.0	85.0	0.47	0.2°	0.8°	19.5	0.26
J2020+403	J2021+4026	2.15	0.18°	6.75 pc	2.48	18.5	0.134	0.23°	0.0°	77	0.01
J1857+027	J1856+0245	6.32	0.12°	13.24 pc	11.0	97.0	0.11	0.08°	0.9°	20.6	0.06
J1825-134	J1826-1334	3.61	0.20°	12.66 pc	20.5	249	0.082	0.14°	0.9°	21.4	0.14
J1837-065	J1838-0655	6.60	0.38°	43.77 pc	12.0	341	0.035	0.08°	2.0°	22.7	0.48
J1837-065	J1837-0604	4.78	0.50°	41.71 pc	8.3	341	0.024	0.10°	2.0°	33.8	0.68
J2006+341	J2004+3429	10.8	0.42°	80.07 pc	0.48	24.5	0.019	0.04°	0.9°	18.5	0.08

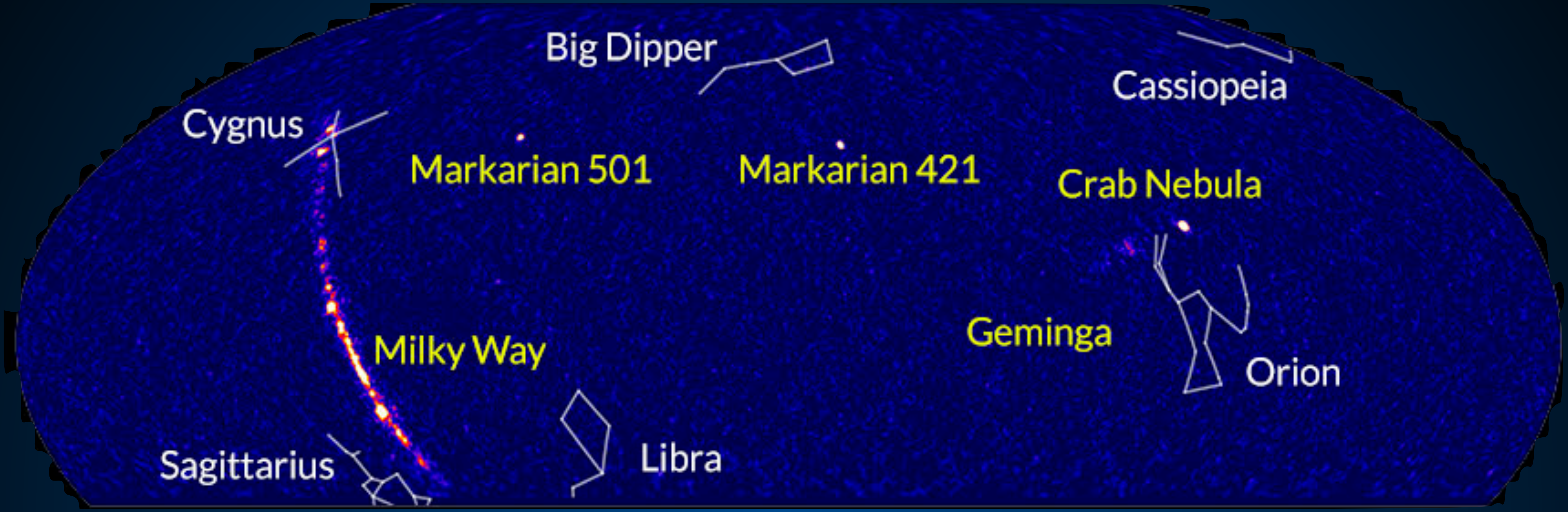
TL et al. (1703.09704)

Discovering Pulsars at TeV Energies

- Tauris and Manchester (1998) calculated the beaming angle from a population of young an middle-aged pulsars.
- This varies between 15-30%.
- 1/f pulsars are unseen in radio surveys.



Discovering Pulsars at TeV Energies



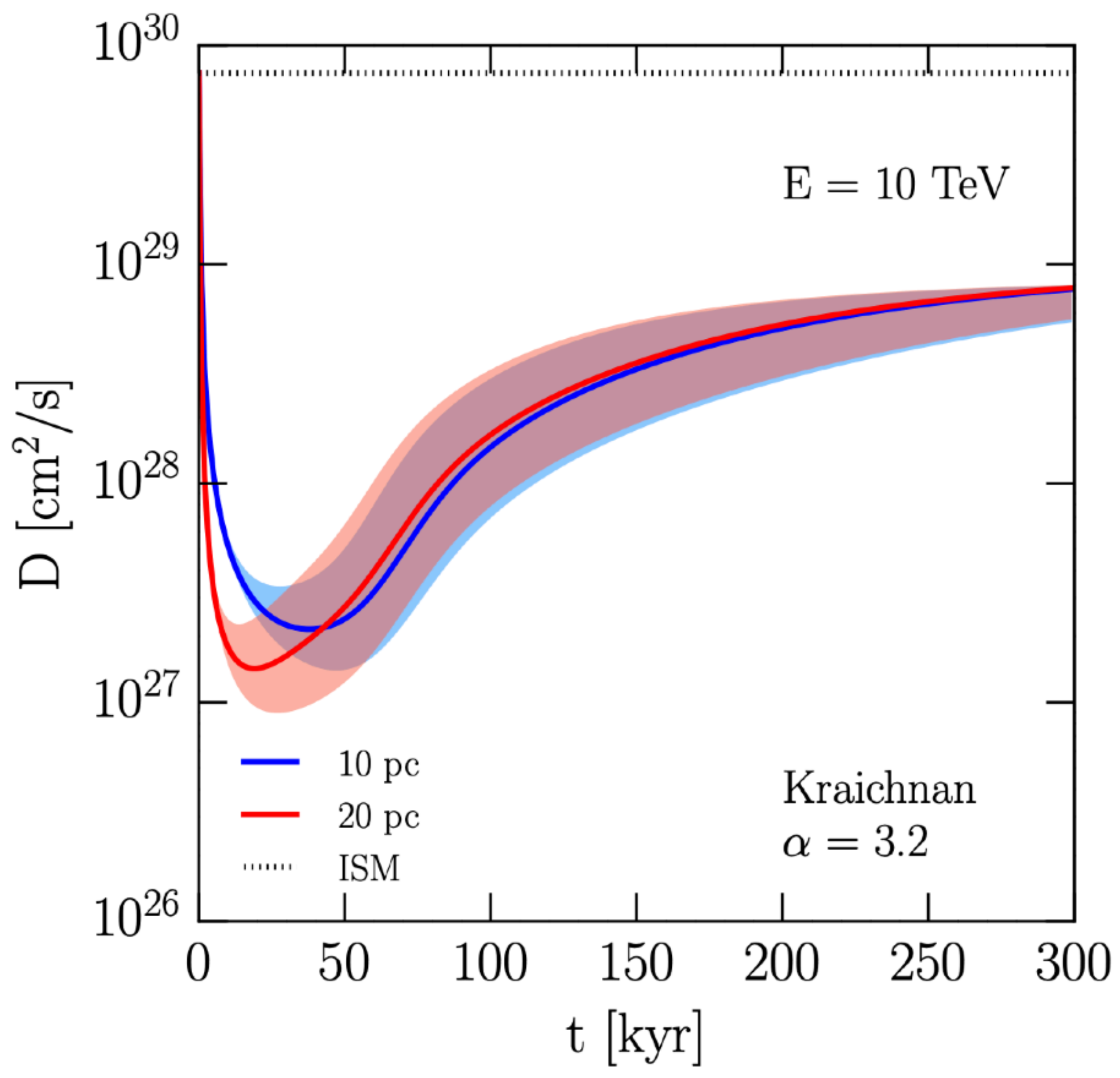
- **Correcting for the beaming fraction implies that 56^{+15}_{-11} TeV halos are currently observed by HAWC.**
- **However, <u>only 39 HAWC sources</u> total.**
- **Chance overlaps, SNR contamination must be taken into account.**

What Do We Need?

Evoli, TL, Morlino (1807.09263)

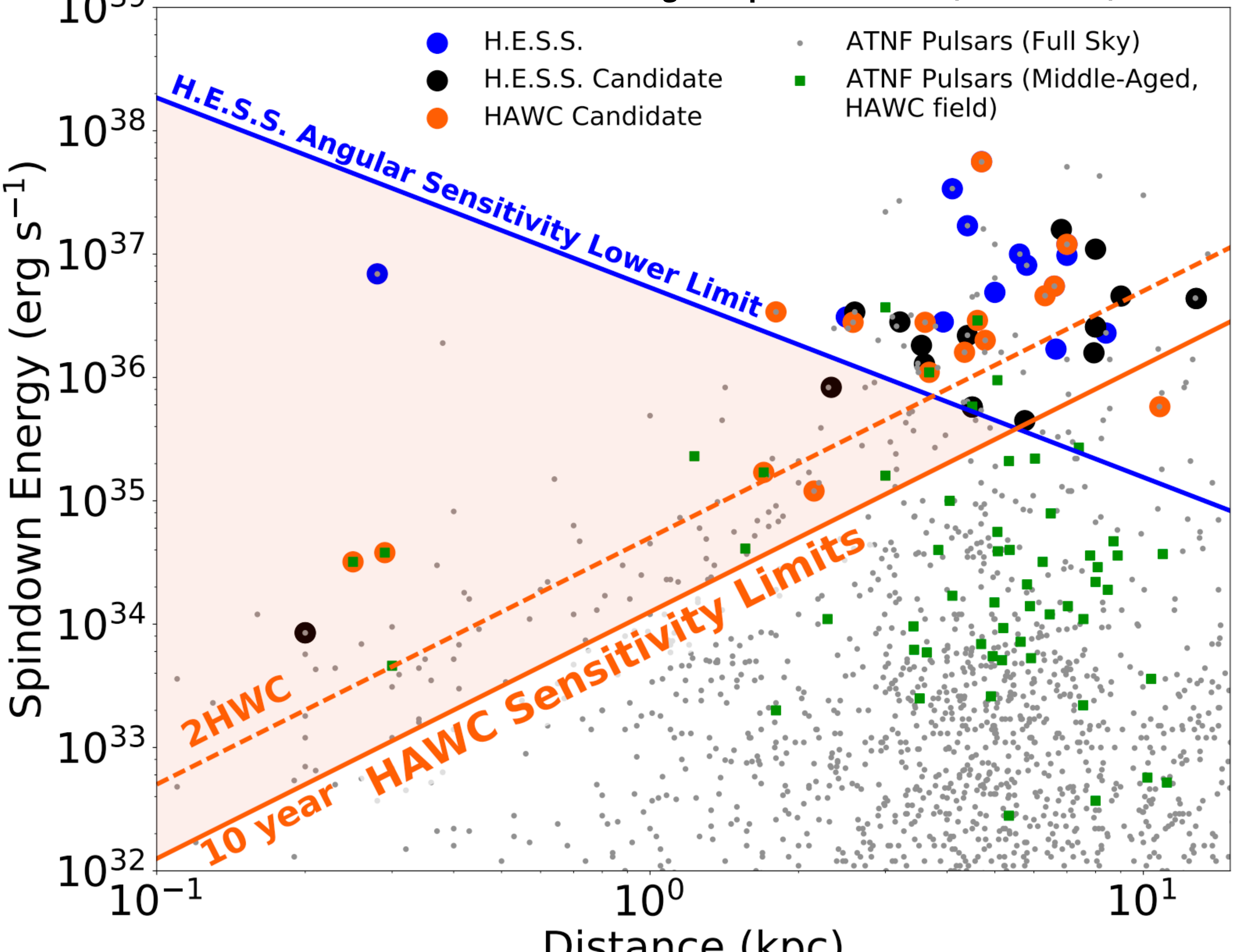
1. Continued observations of TeV halos.

2. A model for the confinement and emission of electrons in TeV halos.



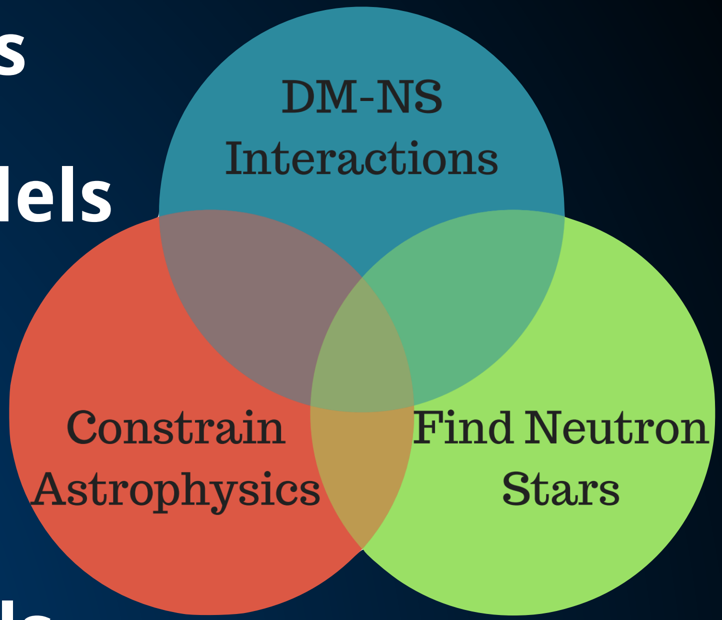
3. A method for precisely determining the pulsar position within the TeV halo.

TL, Auchettl, Bramante, Cholis, Fang, Hooper, Karwal, Li (1703.09704)



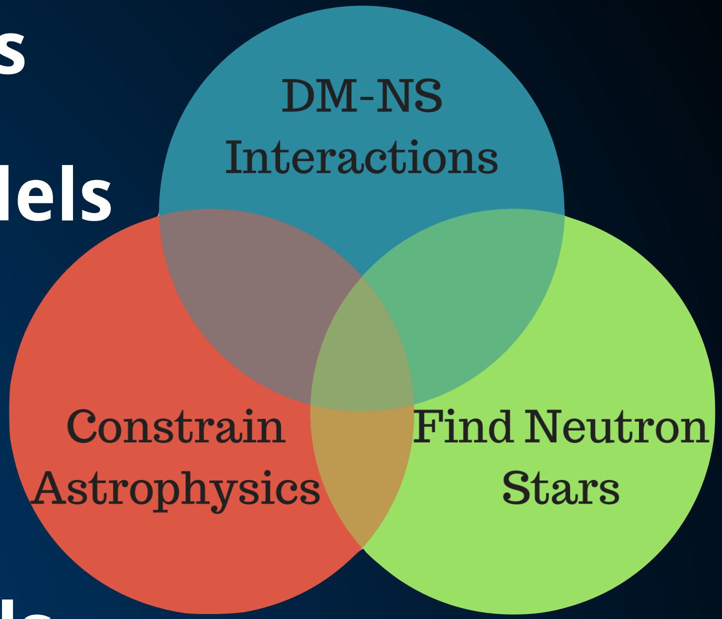
The Program

1. **Understand Dark Matter/Neutron Star Interactions**
   - **Can already set strong constraints on some models**
     1. **Asymmetric Dark Matter**
     2. **Axions**
   - **Can probe extremely generic dark matter models.**

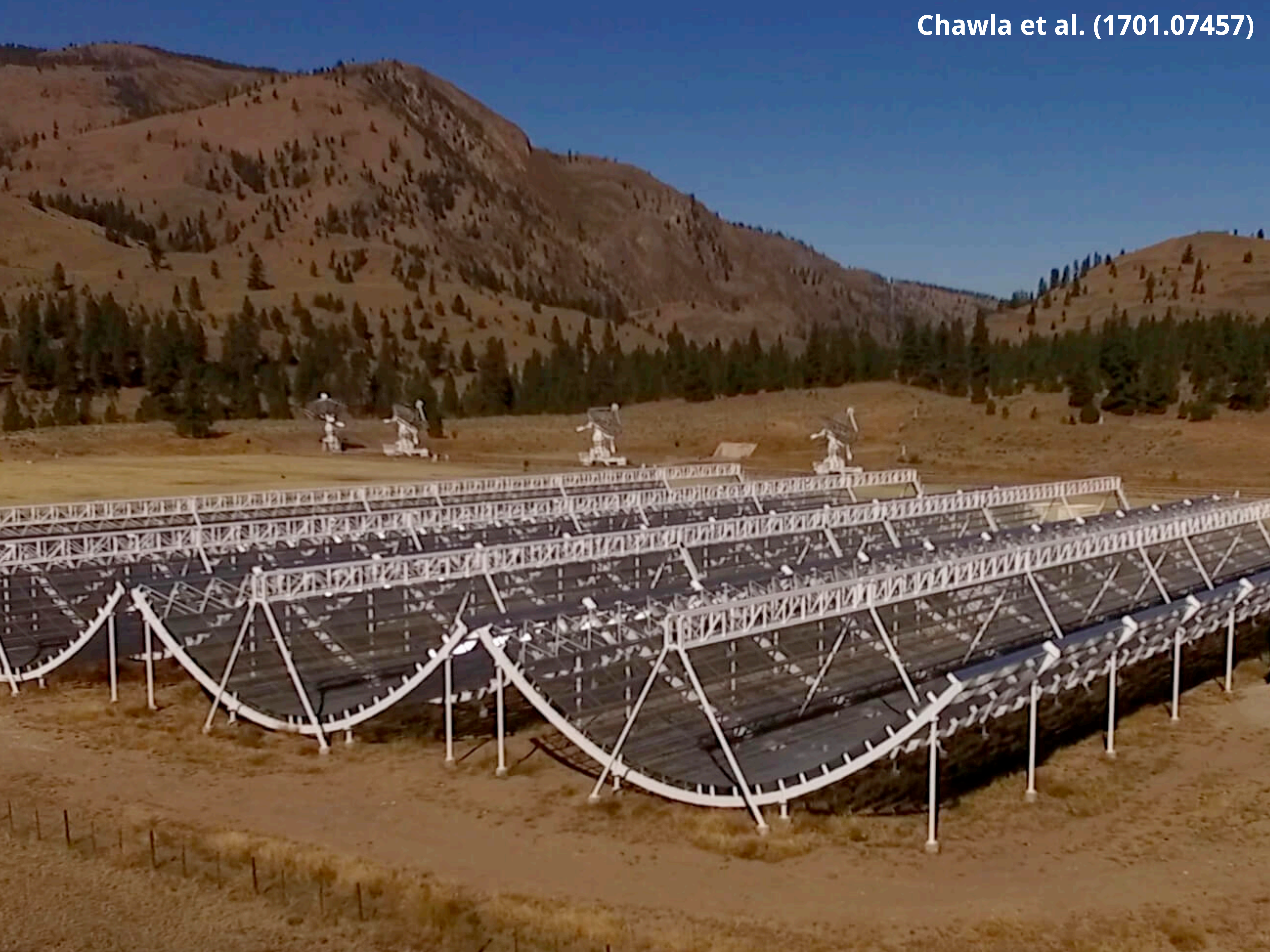


The Program

1. Understand Dark Matter/Neutron Star Interactions
   - Can already set strong constraints on some models
     1. Asymmetric Dark Matter
     2. Axions
   - Can probe extremely generic dark matter models.



2. Differentiate dim dark matter signals from astrophysics
   - Need detailed models of neutron star physics.
   - Requires observations of pulsars with “special” attributes
     1. Nearby
     2. Strong Magnetic Fields
     3. Not Beamed Towards Earth



Chawla et al. (1701.07457)

Keane et al. (1501.00056)


TL & Buckman (1707.01905)

Conclusions

- Pulsars have unique characteristics that are optimally suited for new physics searches.

- Early studies can set strong constraints on the asymmetric dark matter and axion parameter spaces.

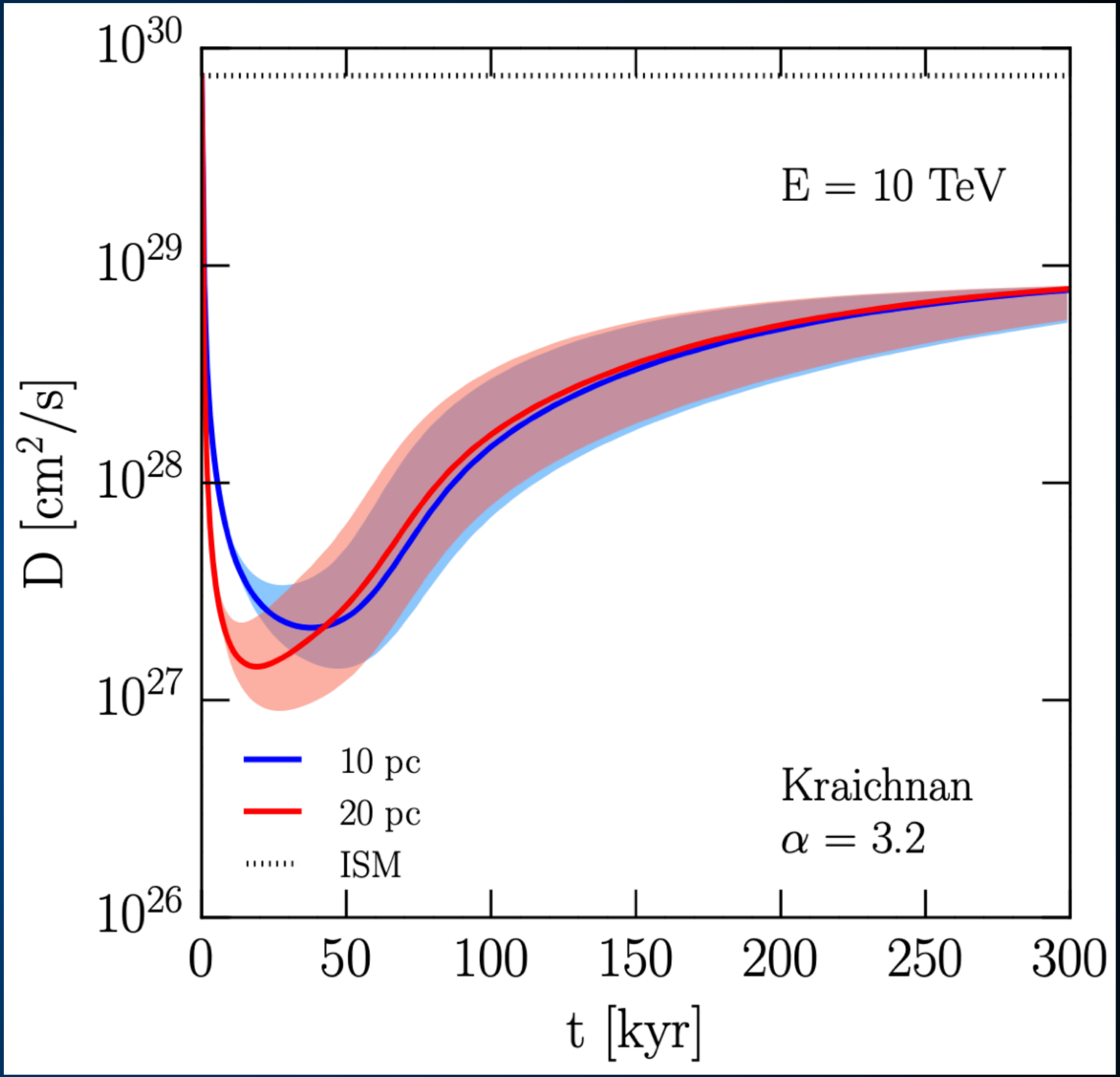
- Our observational techniques are in their infancy. The next decade will revolutionize the field in several directions.

Extra Slides

A Model for TeV Halos

Evoli, TL, Morlino (1807.09263)

- Early results indicate that pulsars themselves can confine electrons to produce TeV halo emission.



- Analog with cosmic-ray confinement in supernova remnants.

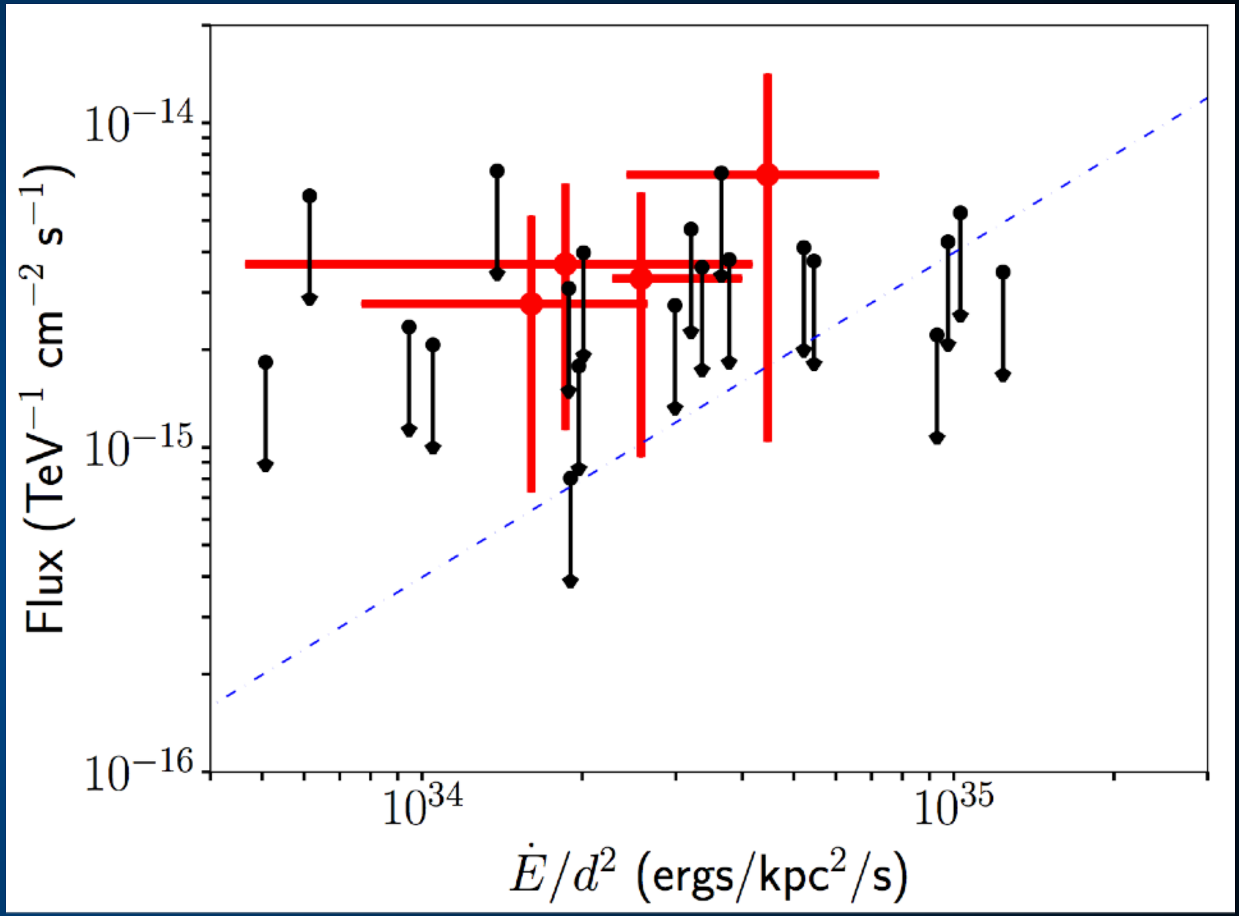
- More detailed models including reacceleration and joint supernova/pulsar emission are necessary.

Discovering Pulsars at TeV Energies

- Tentative Evidence that MSPs also produce these TeV halos.

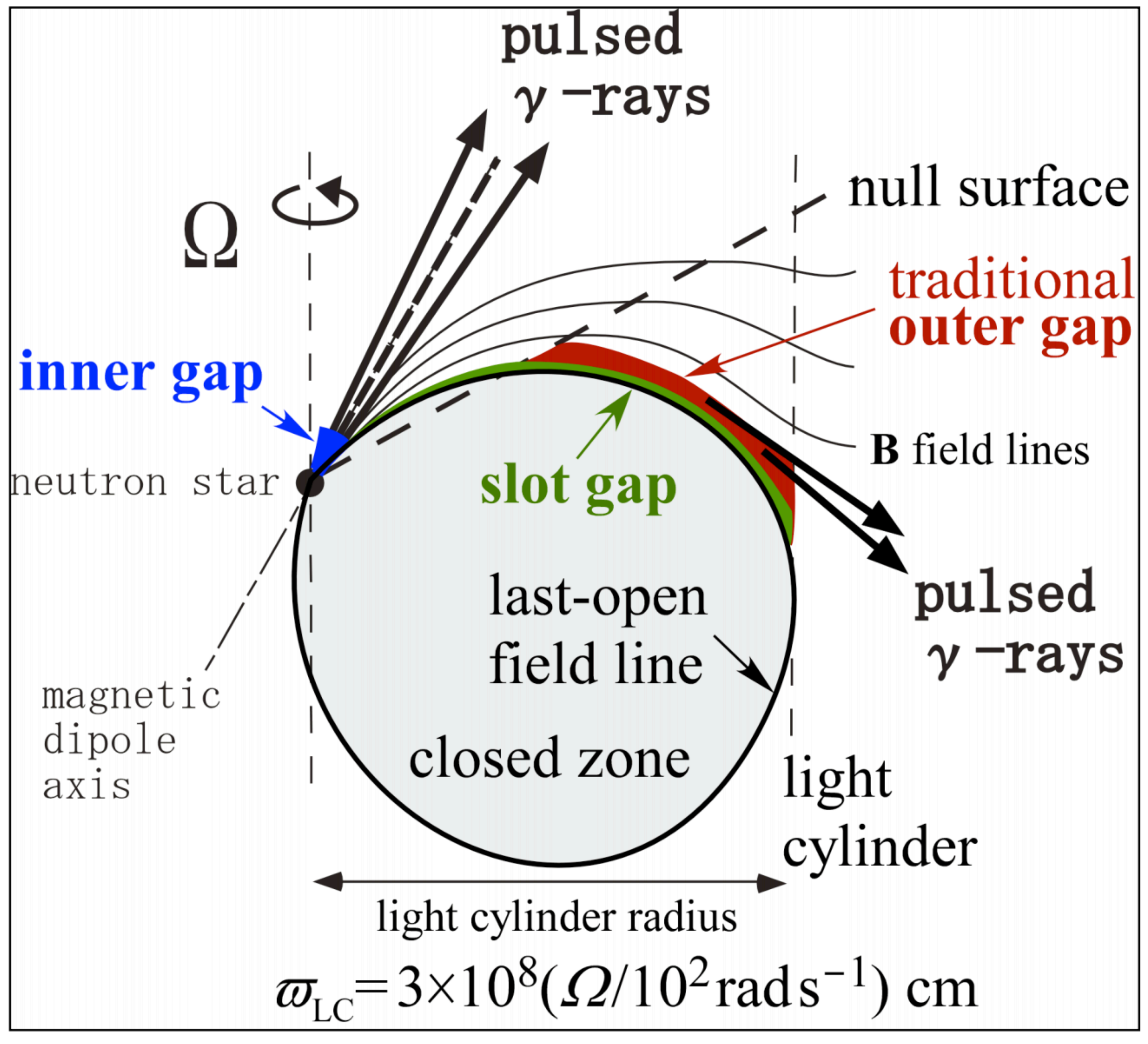
- MSPs are the coldest and oldest pulsars – important for DM heating.

- Models indicate a MSP should exist within ~50 pc, but none has yet been found.

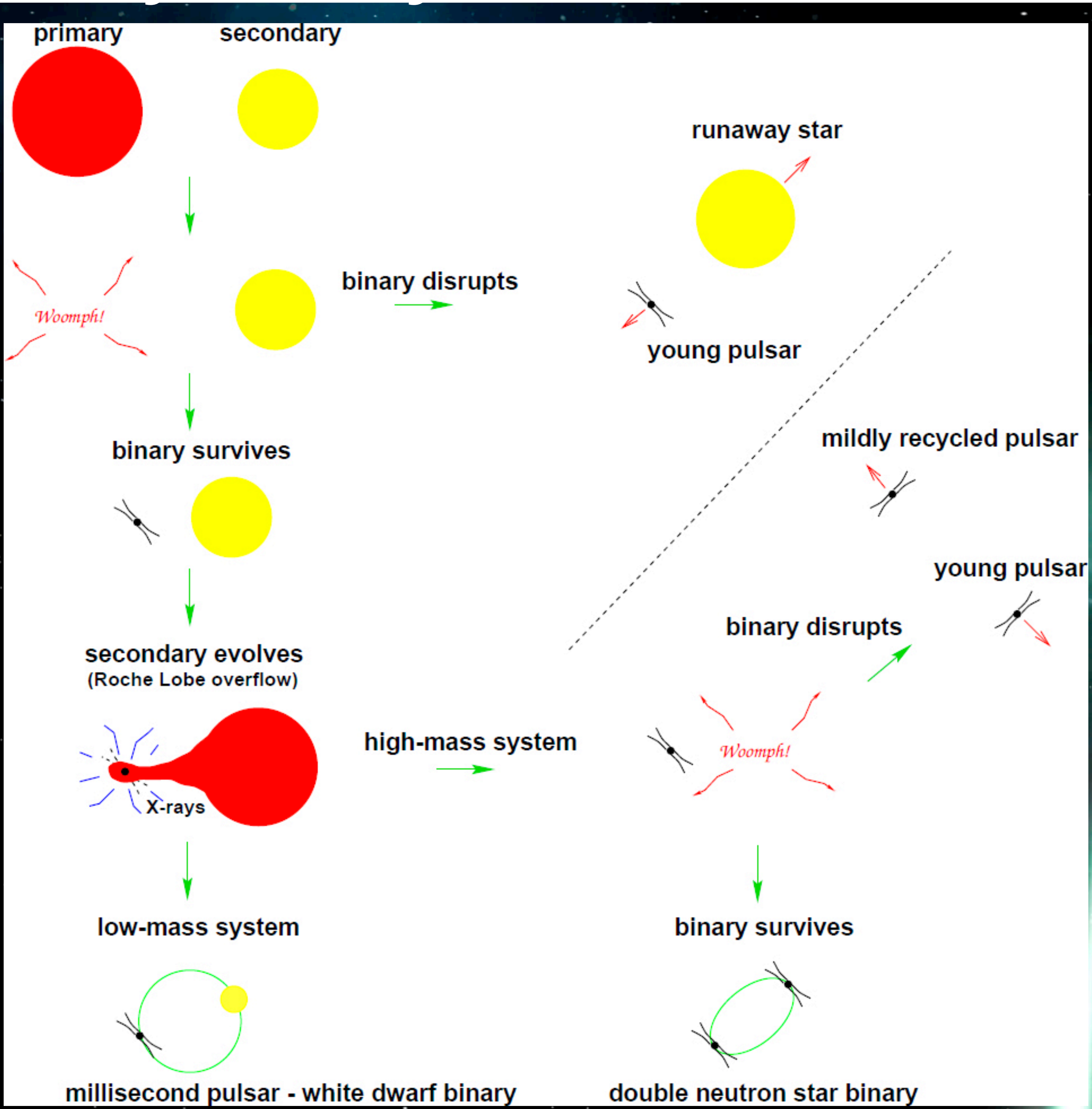


Hooper & TL (1803.08046)

Emission Morphologies



Evolutionary History of Millisecond Pulsars

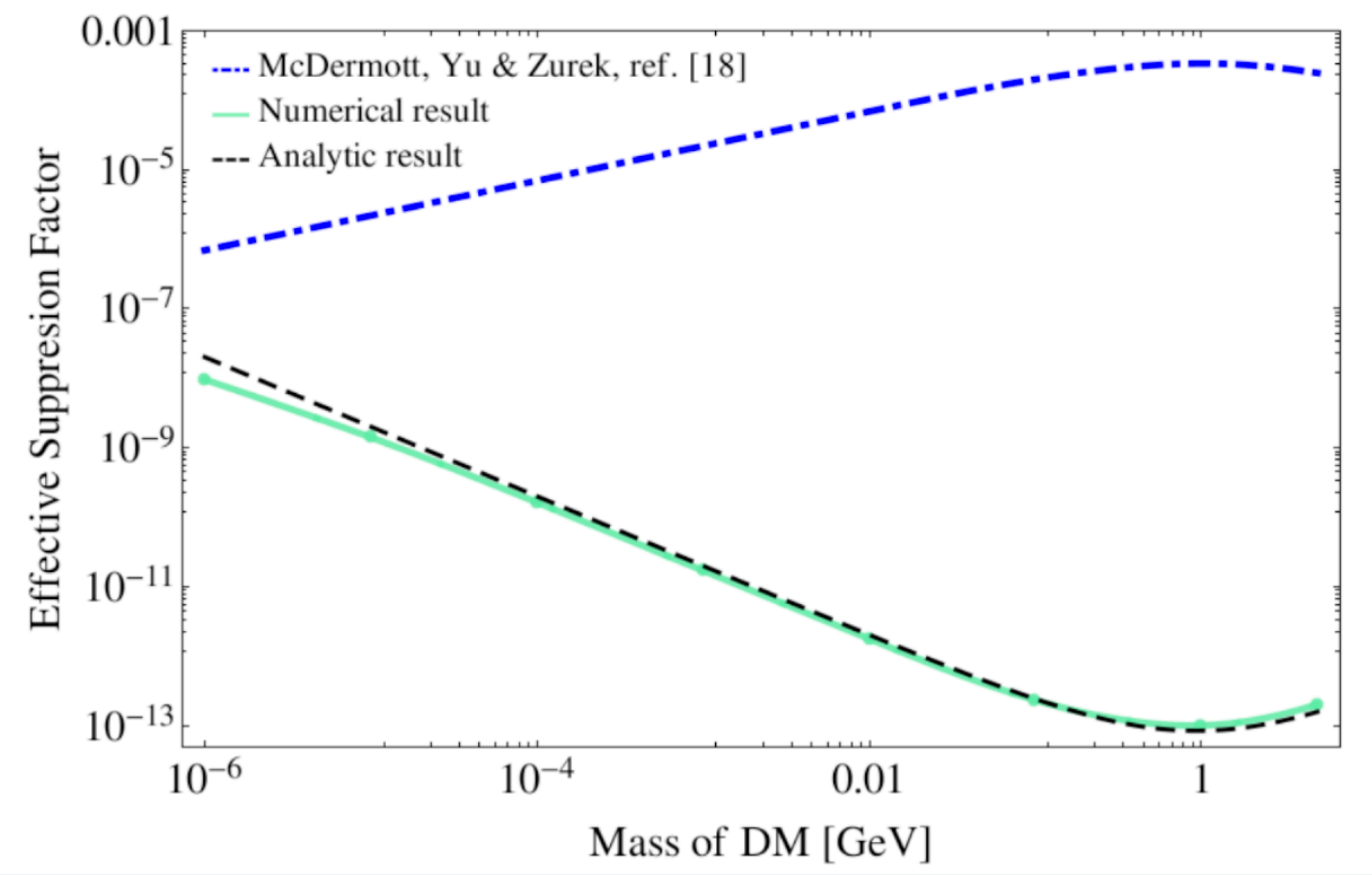


Dark Matter Thermalization

- **Dark Matter thermalization is always suppressed by Pauli blocking.**

- **Superfluidity and superconductivity effects in the NS core also have a sizable effect.**

Bertoni et al. (2013; 1309.1721)



- **However, if DM is trapped within the NS, interactions are inevitable. in pessimistic scenarios, DM thermalizes in a timeframe:**

$$t_{th} \simeq 3.7\ \mathrm{kyr} \frac{\frac{m_X}{m_B}}{(1+\frac{m_X}{m_B})^2} \left(\frac{2\times10^{-45}\ \mathrm{cm}^2}{\sigma_{nX}}\right) \left(\frac{10^5\ \mathrm{K}}{T_{NS}}\right)^2$$

Dark Matter Collapse

- Two paths are possible:
  - If dark matter can annihilate, the large densities make annihilation inevitable.
  - If dark matter cannot annihilate, dark matter builds mass until it exceeds its own degeneracy pressure. For Fermionic dark matter this is:

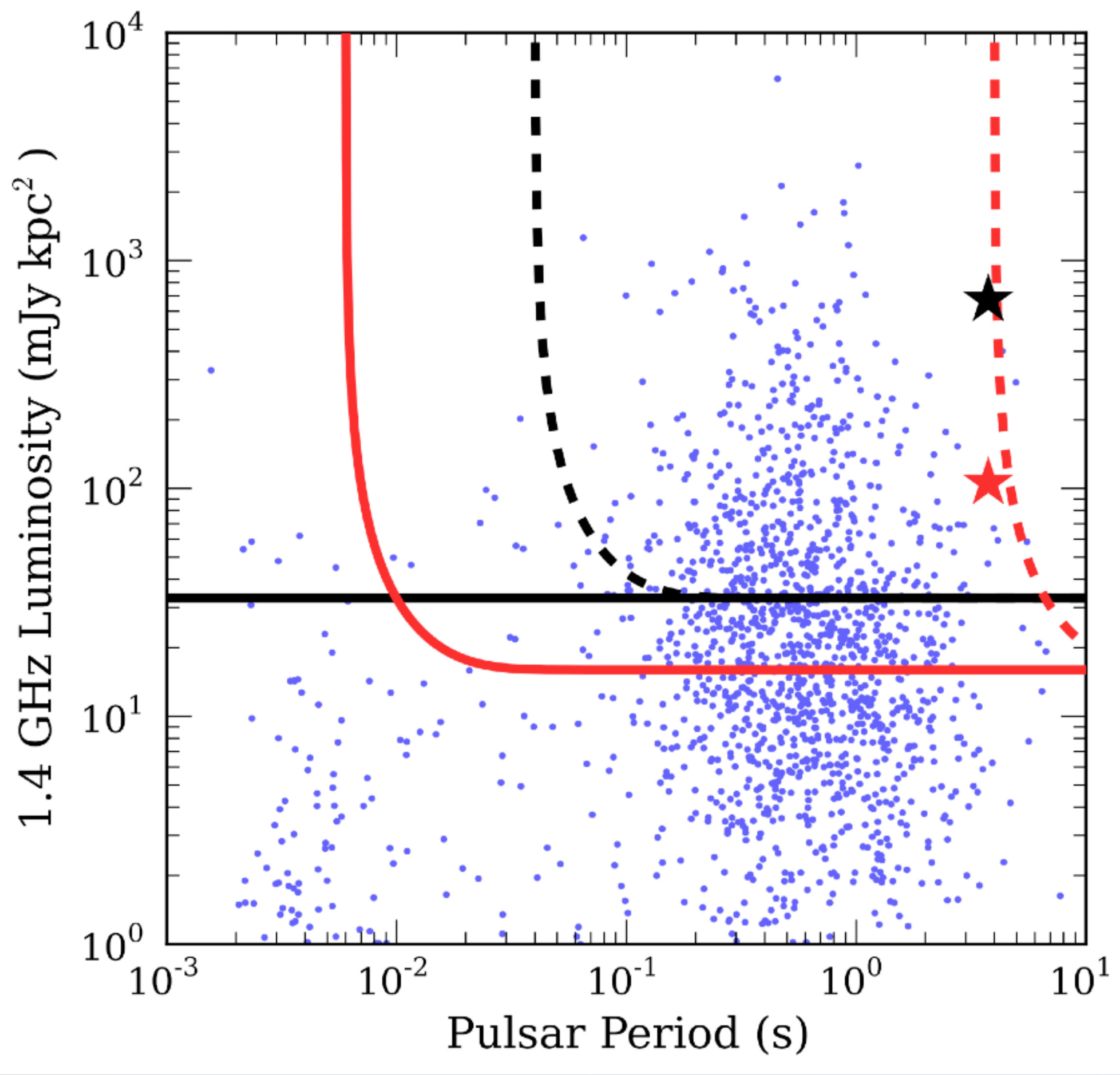
$$M_{crit}^{ferm} \simeq M_{pl}^3 / m_X^2$$

  - It then collapses on a timescale:

$$\begin{aligned} \tau_{\rm co} &\simeq \frac{1}{n\sigma_{n\rm x}v_{\rm x}}\left(\frac{p_F}{\Delta p}\right)\left(\frac{m_{\rm x}}{2m_n}\right) \\ &\simeq 4\times 10^5 \text{ yrs}\left(\frac{10^{-45}\text{ cm}^2}{\sigma_{\rm nx}}\right)\left(\frac{r_x}{r_0}\right), \end{aligned}$$

The Missing Pulsar Problem

Dexter, O'Leary (1310.7022)



- Large pulse dispersion was reasonable culprit

$$\Delta\tau \sim 1\ \mathrm{s}\left(\frac{\mathrm{Ghz}}{\nu}\right)^4$$

- Magnetar found in X-Ray observations in 2013.
  - No pulse dispersion in X-Rays
- Magnetar subsequently found in radio
- Pulse dispersion is small!
- Why aren't any other pulsars observed !?

Gravitational Waves from NS Collapse

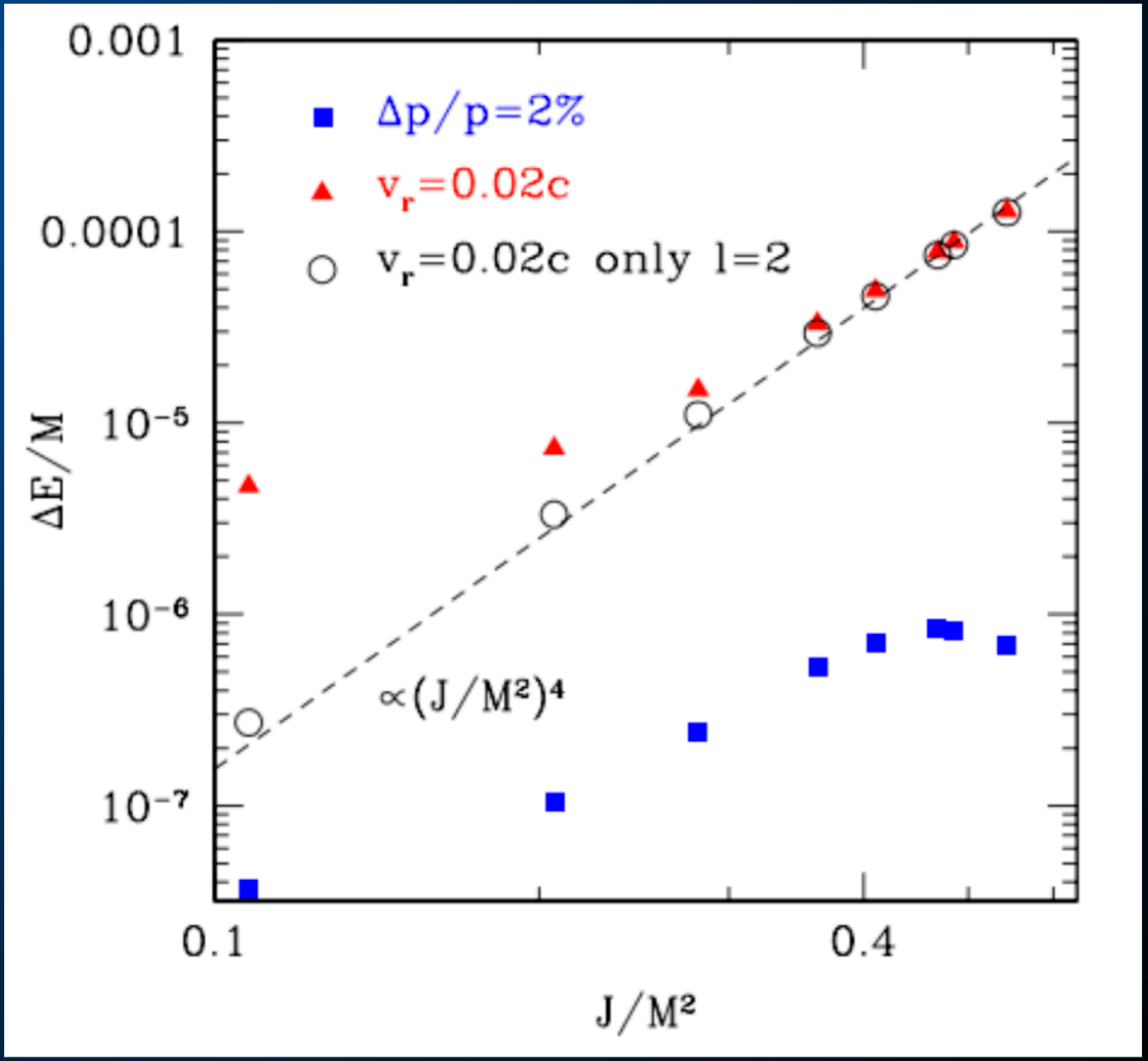
- **Gravitational Waves from DM induced collapse**

$$h_c \sim 5 \times 10^{-22} \left(\frac{M}{M_\odot}\right) \left(\frac{10\ \mathrm{kpc}}{D}\right) \quad @\ 531\ \mathrm{Hz},$$

Baiotti et al. (gr-qc/0701043)

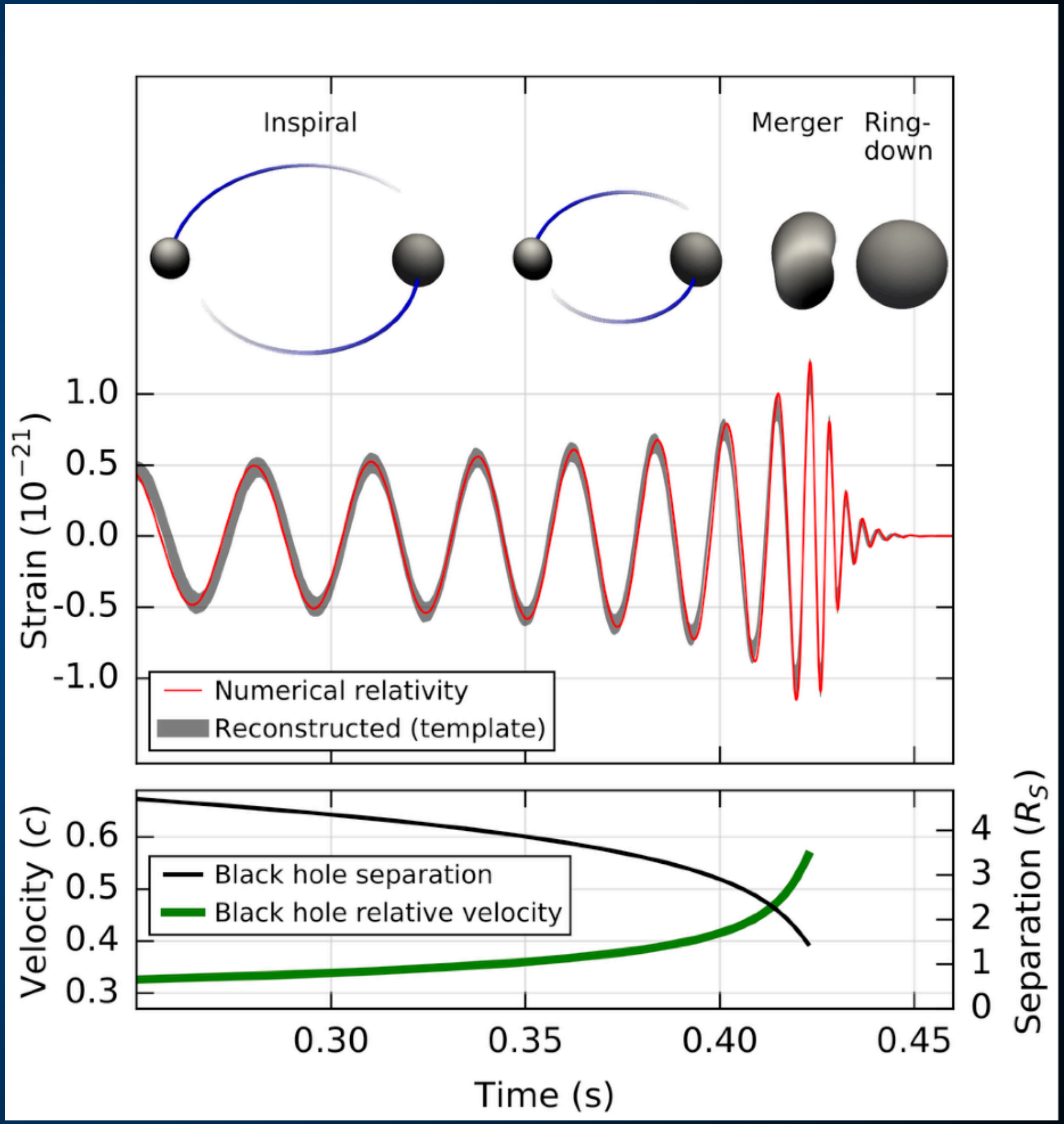
- **Single NS collapse models have been considered (primarily from accretion induced collapse).**

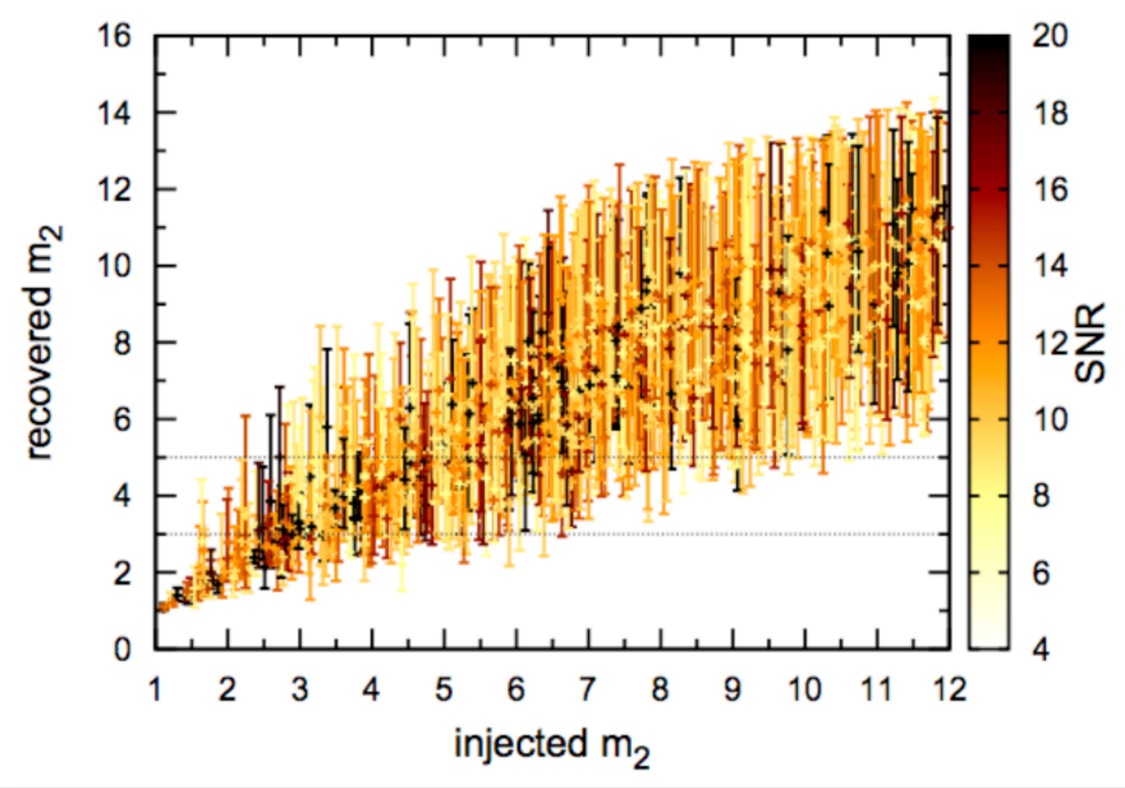
- **DM induced NS collapse observable throughout the Milky Way (0.01 yr^{-1} ?)**



Differentiating Black Hole and NS Mergers

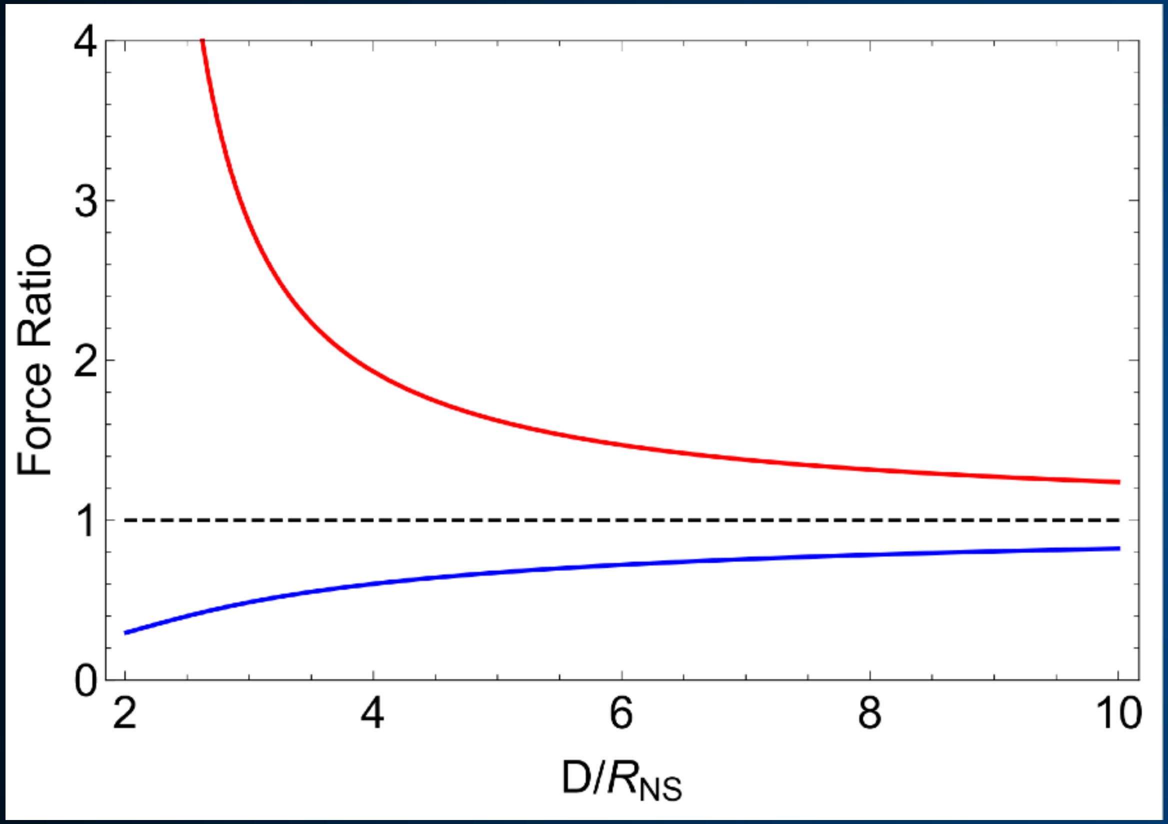
- **Anomalies in the tidal strain of binary neutron star mergers.**
  - **DM induced NS collapse produces a population of 1.4 $M_\odot$ black holes.**
  - **Can potentially see differences in merger and ring-down, but not presently feasible.**

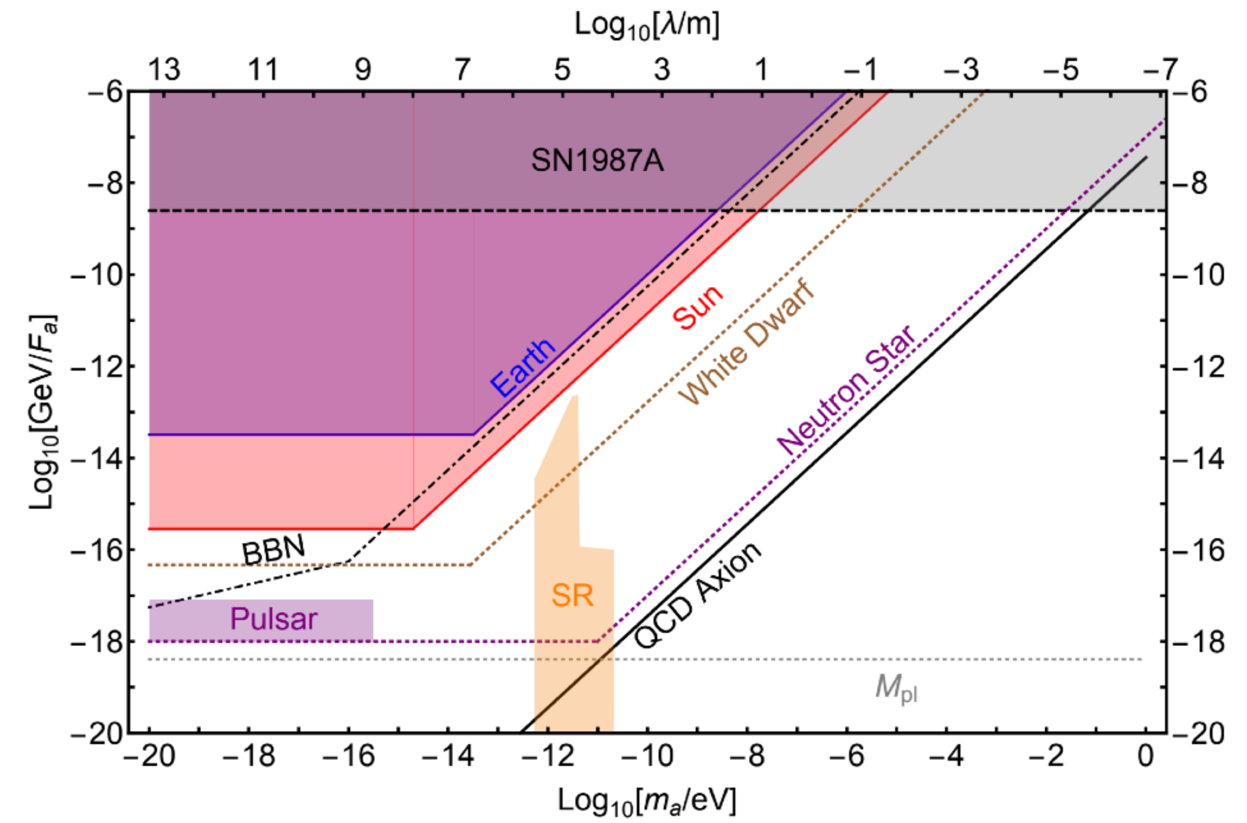




Littenburg et al. (1503.03179)

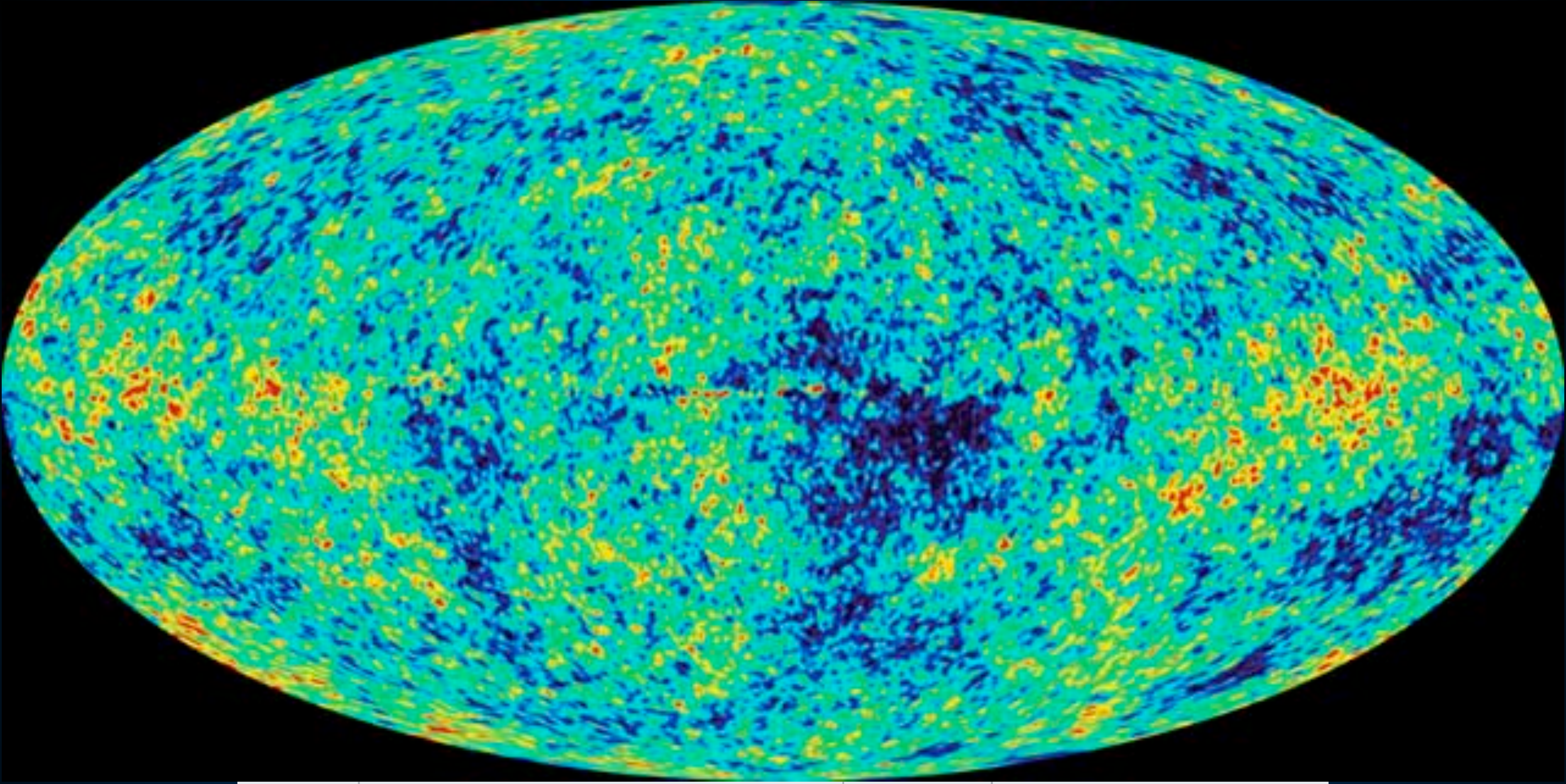
Particle Physics Mash-Up

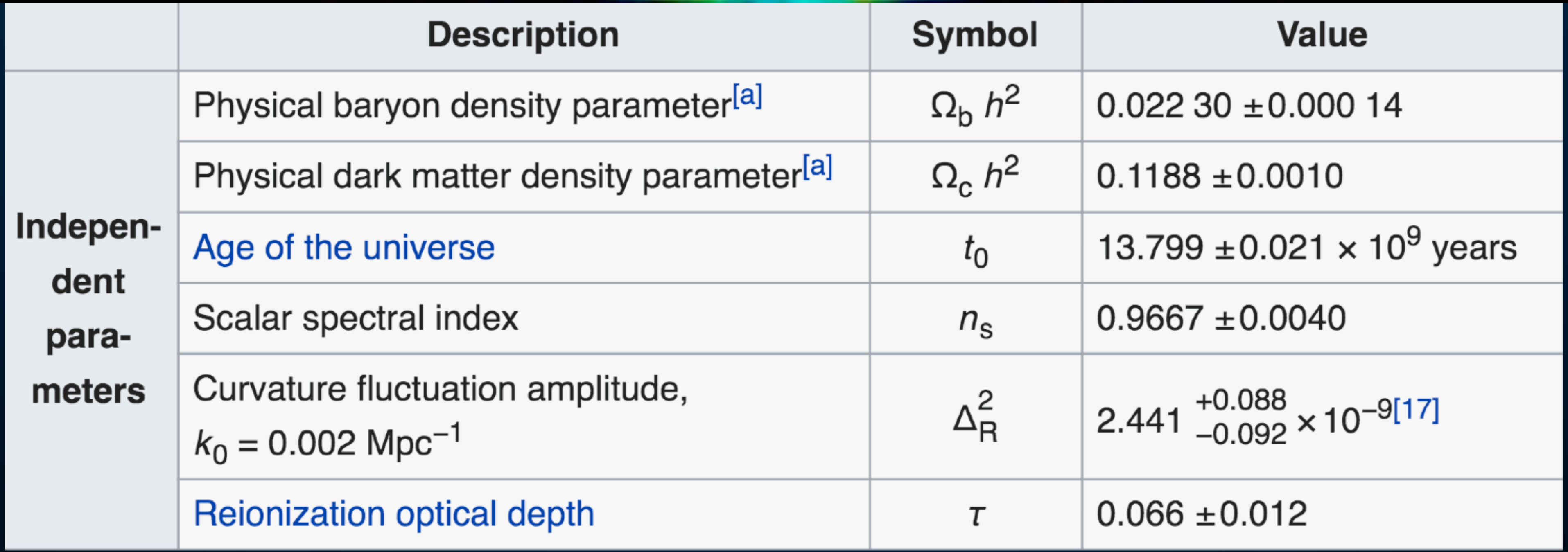




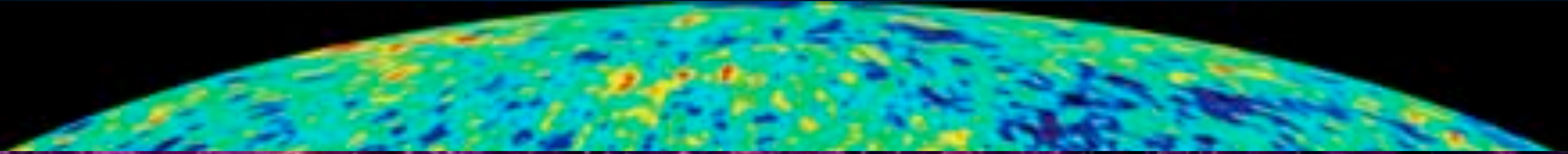
- **Low mass axions can mediate forces between inspiraling neutron stars, providing effects comparable to gravity.**
- **LIGO observations can probe the low-mass axion window.**

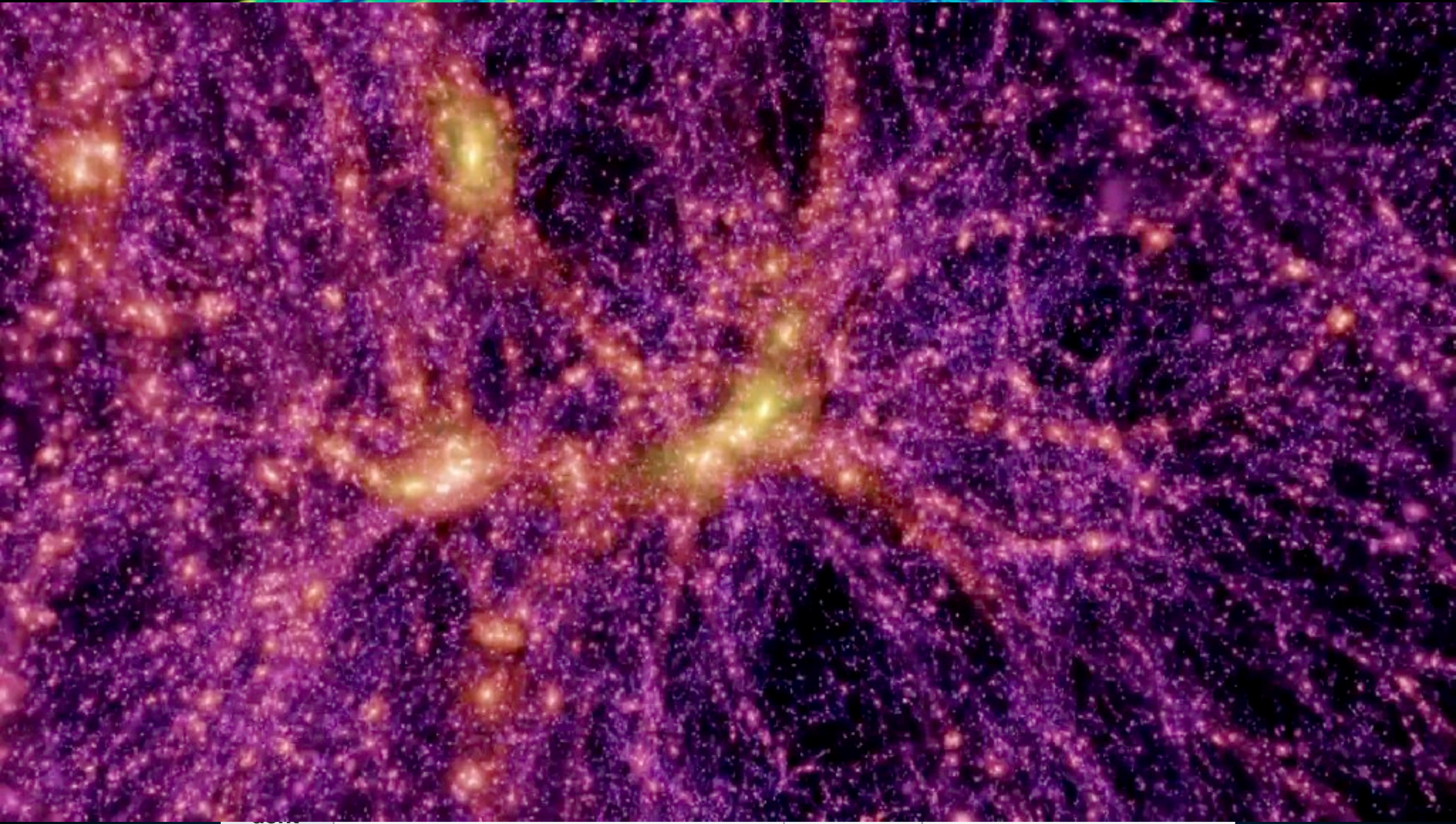
Hook et al. (1708.08464)

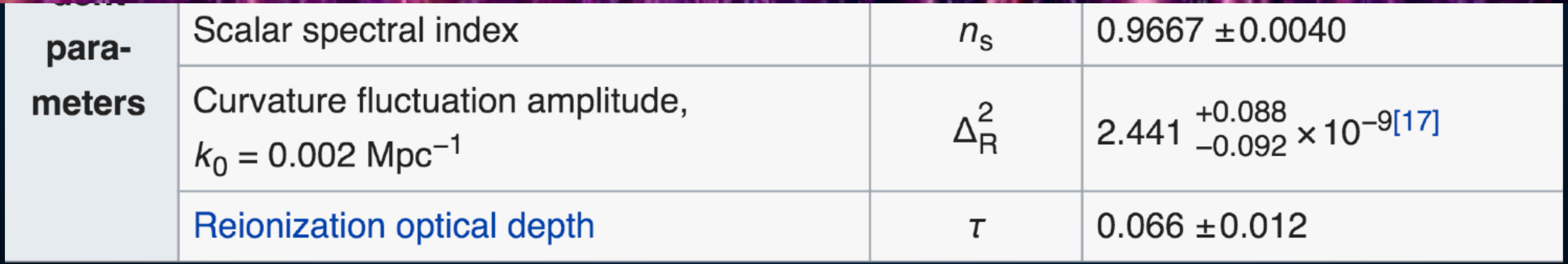




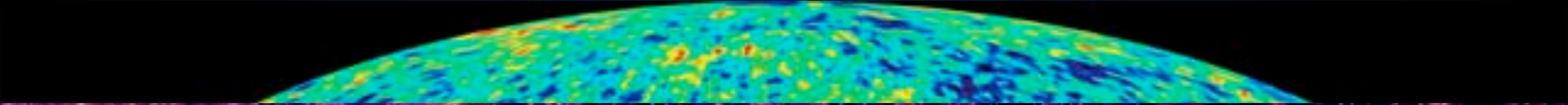
	Description	Symbol	Value
Independent parameters	Physical baryon density parameter[a]	$\Omega_b h^2$	0.022 30 ±0.000 14
	Physical dark matter density parameter[a]	$\Omega_c h^2$	0.1188 ±0.0010
	Age of the universe	t_0	13.799 ±0.021 × 10^9 years
	Scalar spectral index	n_s	0.9667 ±0.0040
	Curvature fluctuation amplitude, $k_0 = 0.002\ \mathrm{Mpc}^{-1}$	Δ^2_R	$2.441^{+0.088}_{-0.092} \times 10^{-9}$[17]
	Reionization optical depth	τ	0.066 ±0.012

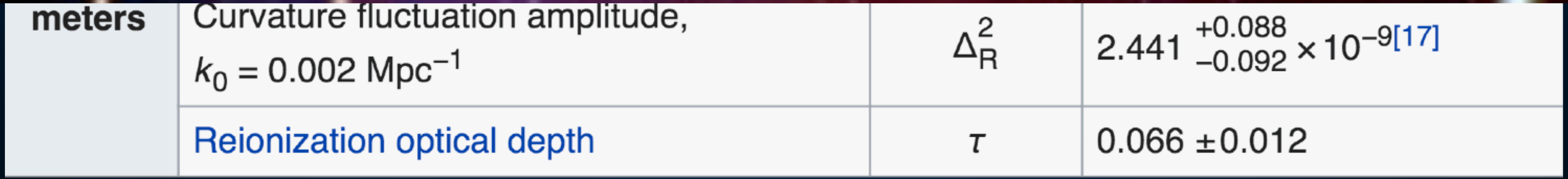




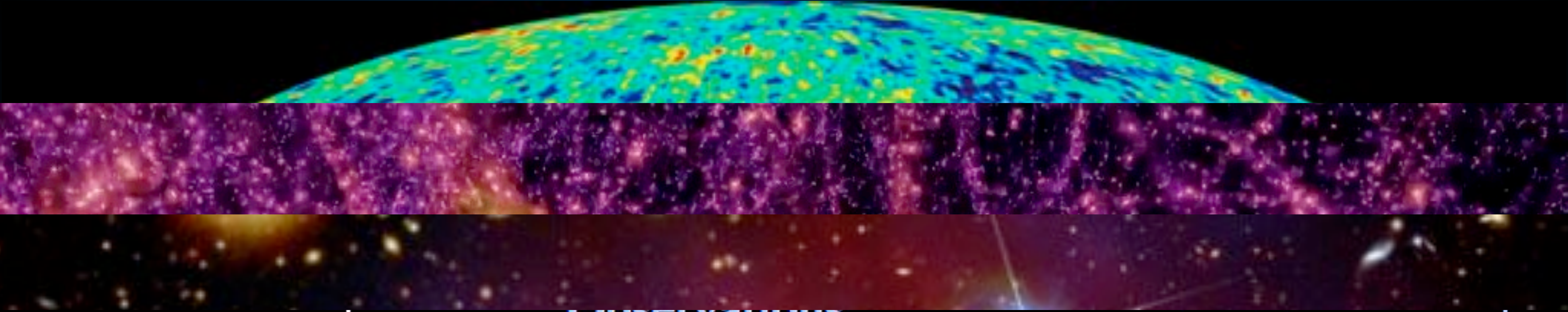


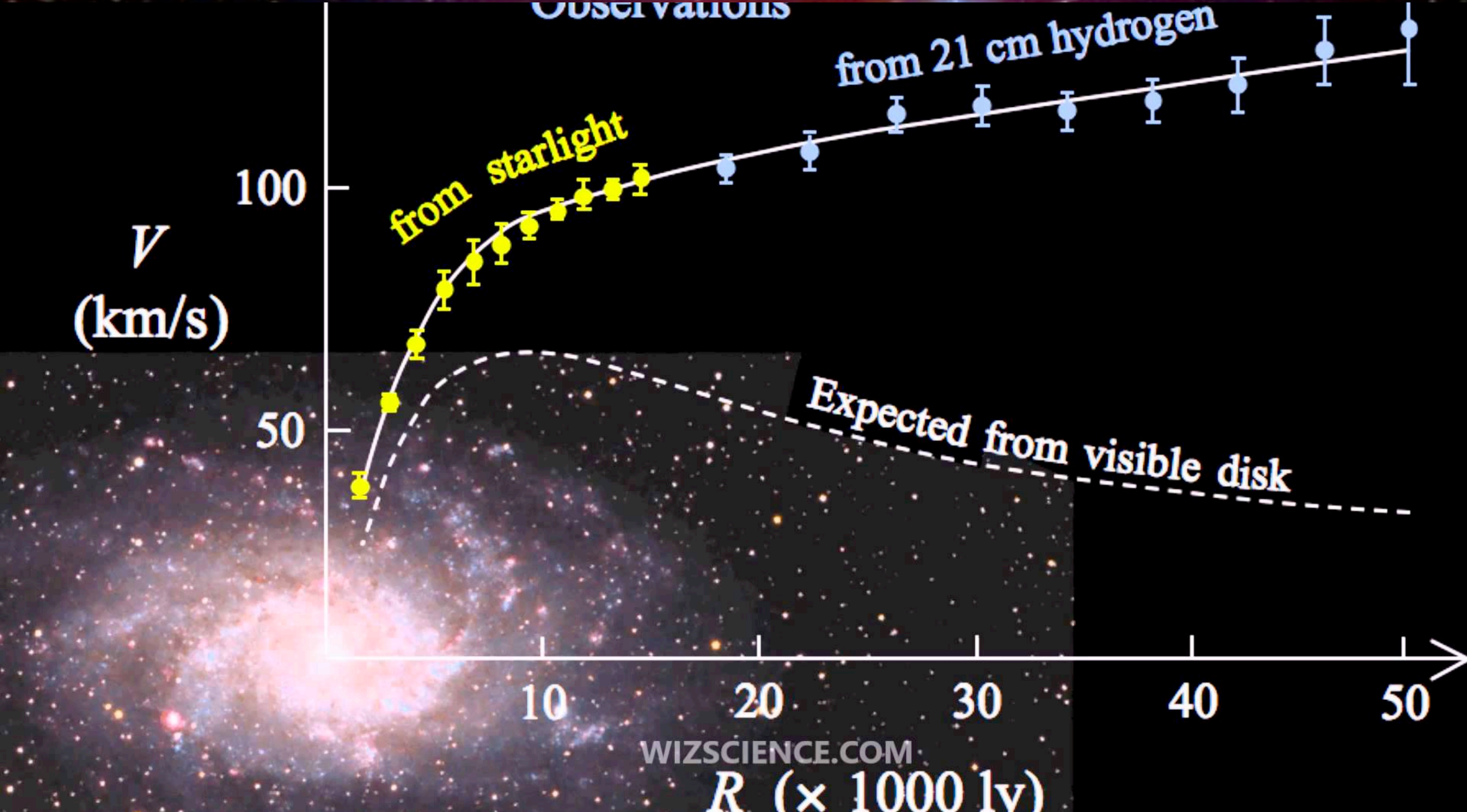
parameters	Scalar spectral index	n_s	0.9667 ±0.0040
	Curvature fluctuation amplitude, $k_0 = 0.002\ \mathrm{Mpc}^{-1}$	Δ^2_R	$2.441^{+0.088}_{-0.092} \times 10^{-9}$[17]
	Reionization optical depth	τ	0.066 ±0.012



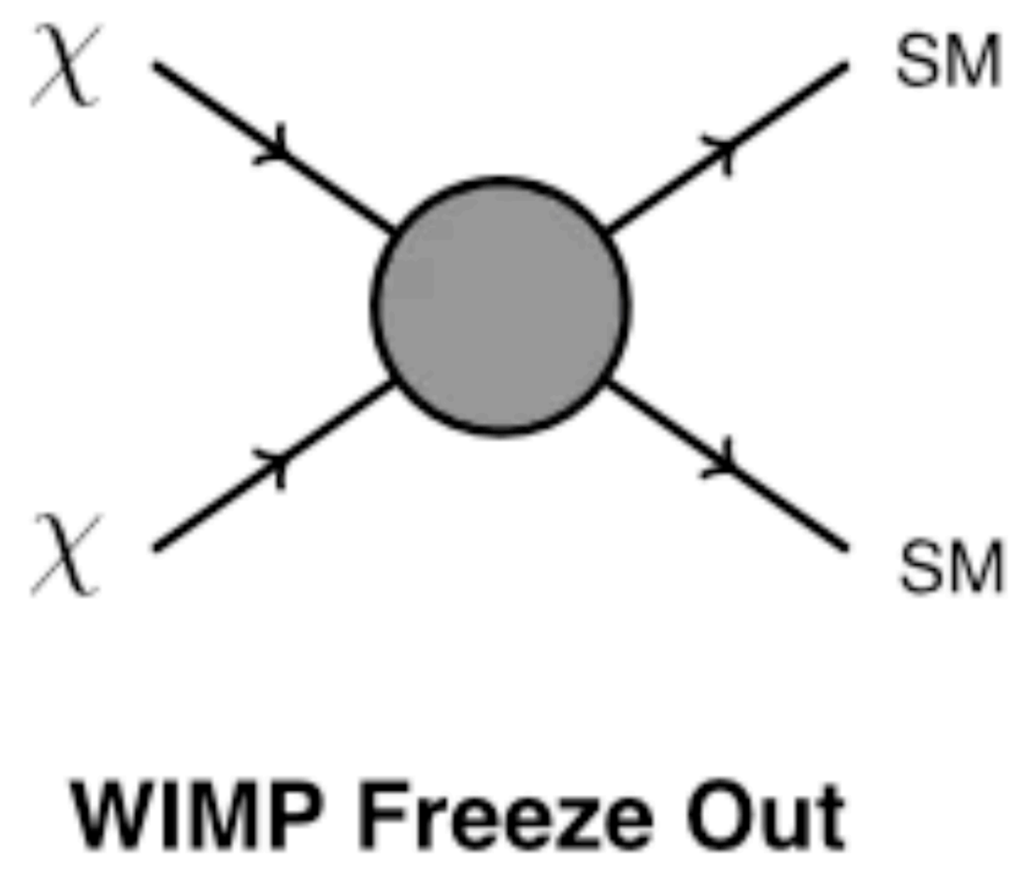


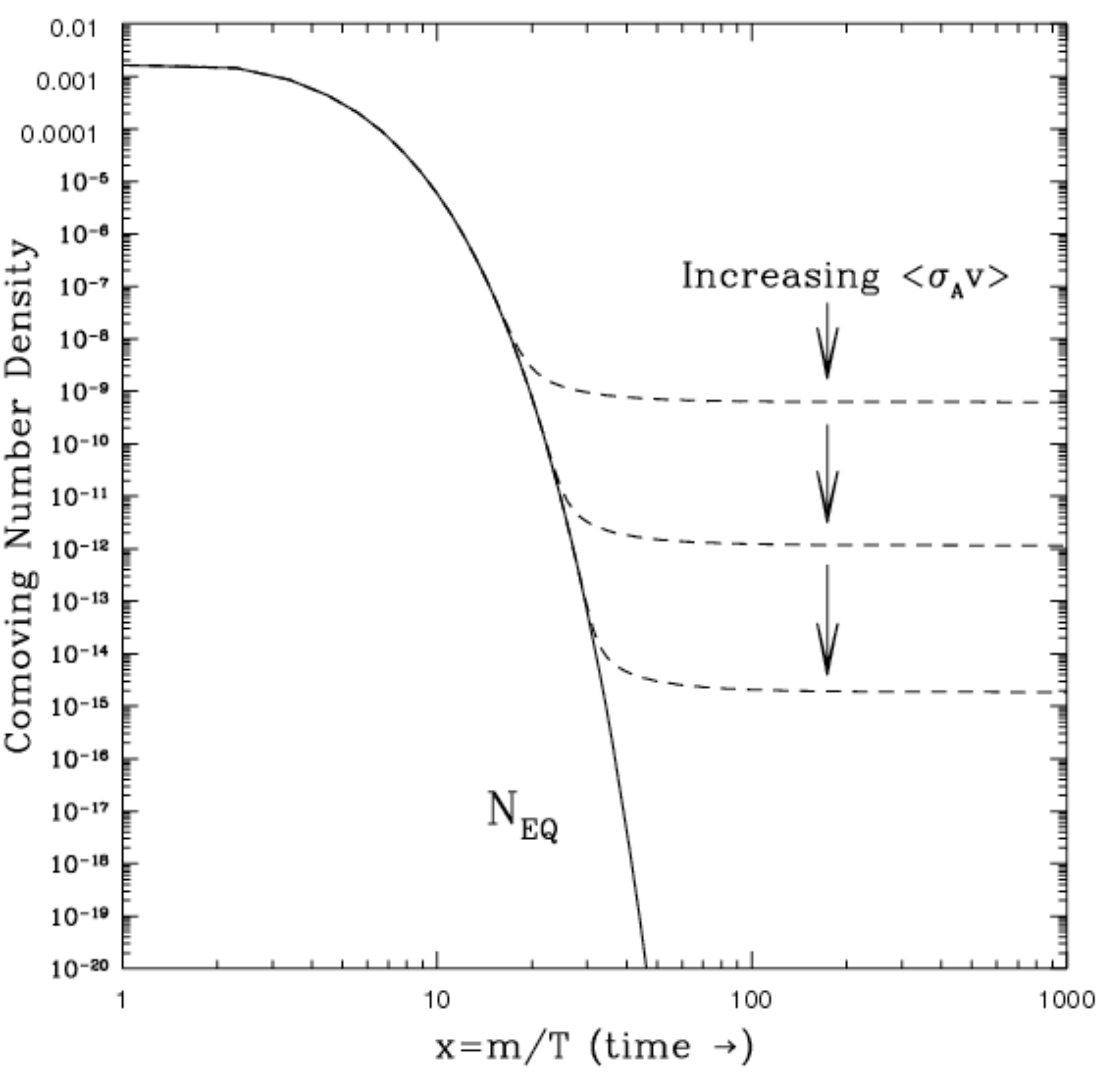
meters	Curvature fluctuation amplitude, $k_0 = 0.002\ \mathrm{Mpc}^{-1}$	Δ_R^2	$2.441\ ^{+0.088}_{-0.092} \times 10^{-9}$[17]
	Reionization optical depth	τ	0.066 ±0.012




Observations
from 21 cm hydrogen
from starlight
100
V
(km/s)
50
Expected from visible disk
10
20
30
40
50
R (× 1000 ly)

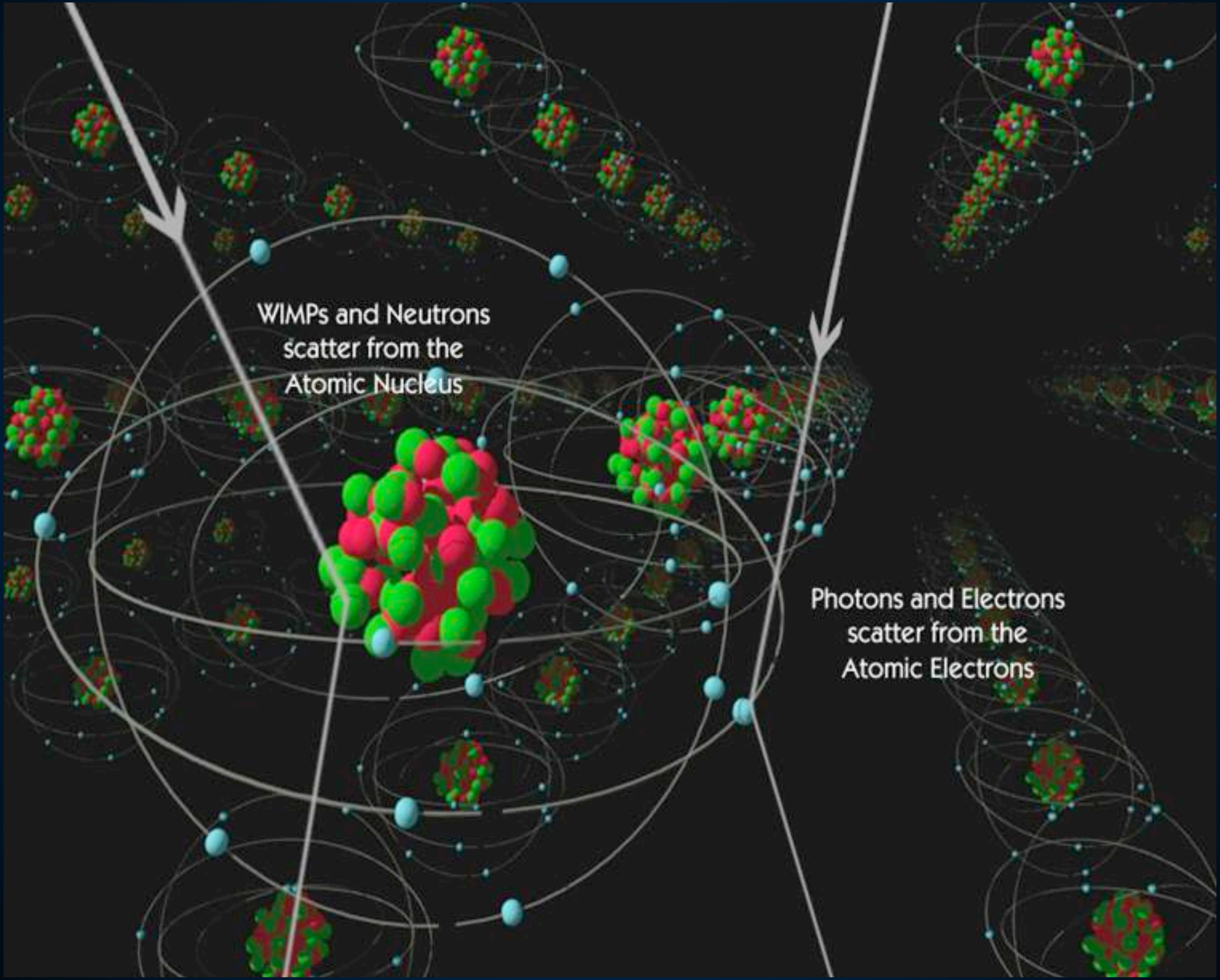
One Slide On WIMP Dark Matter



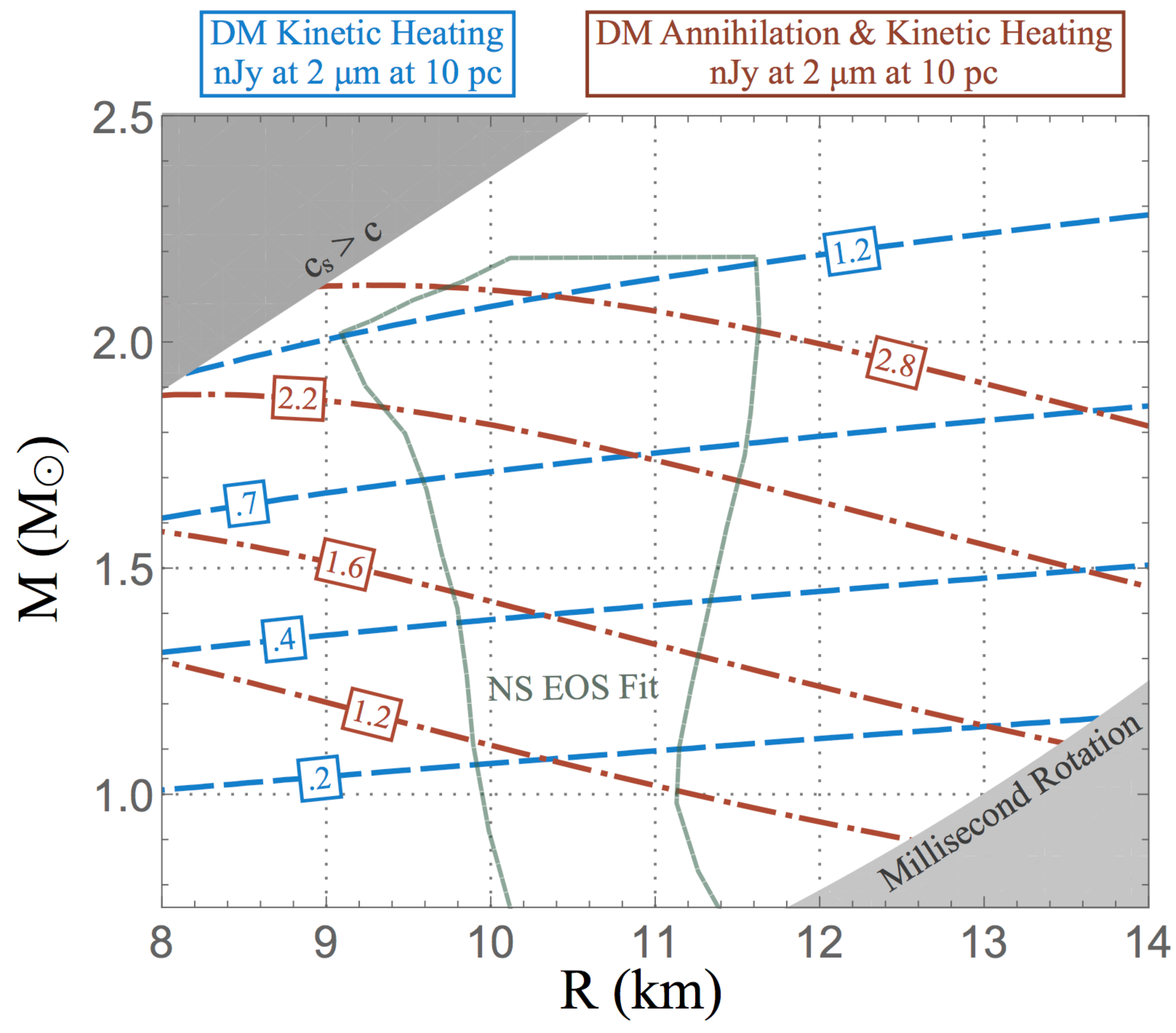


- **The standard WIMP freeze-out scenario is still the best-motivated model to explain the Dark Matter abundance.**

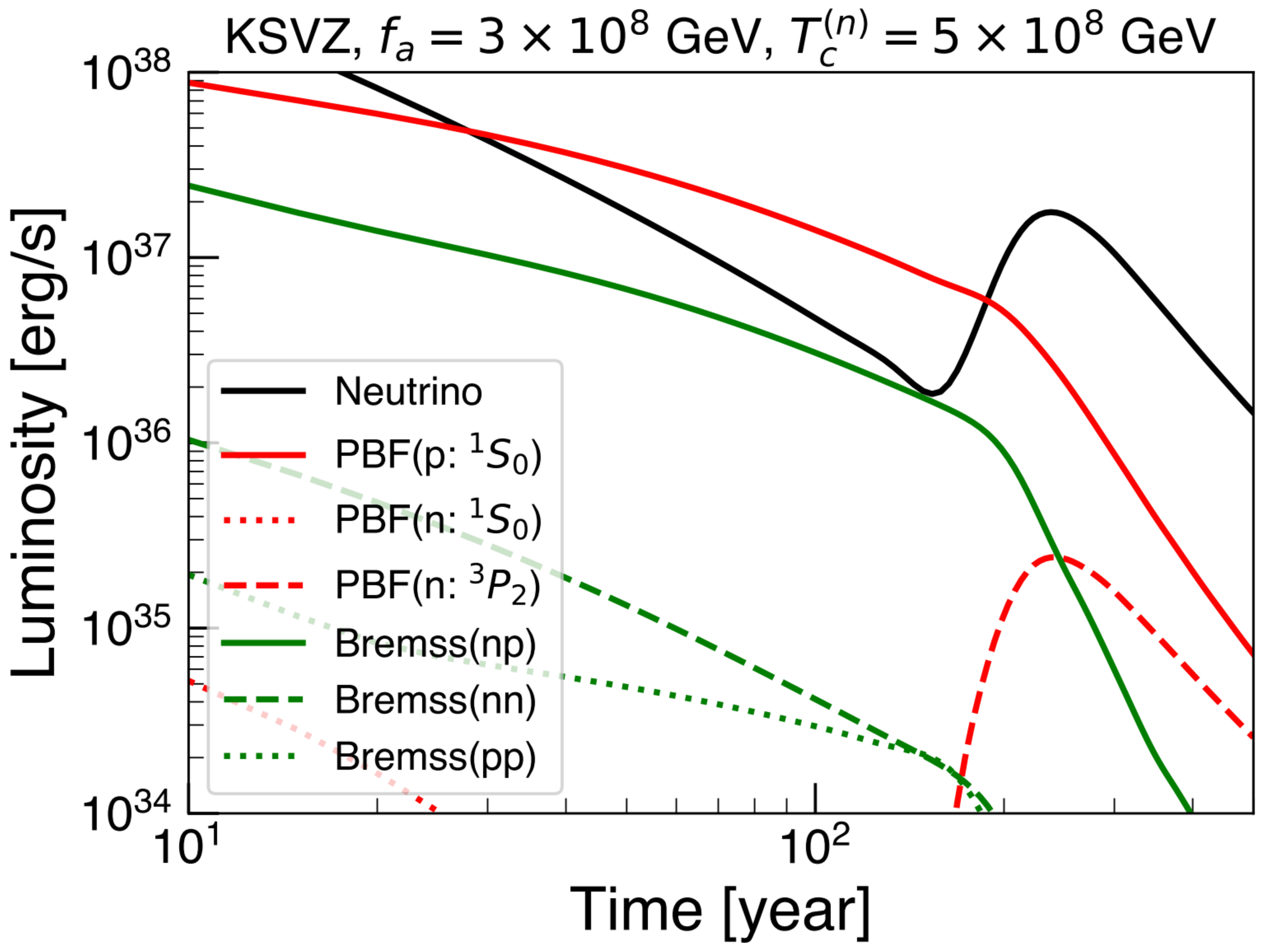
Direct Detection



Dark Matter Flux Depends on NS EOS



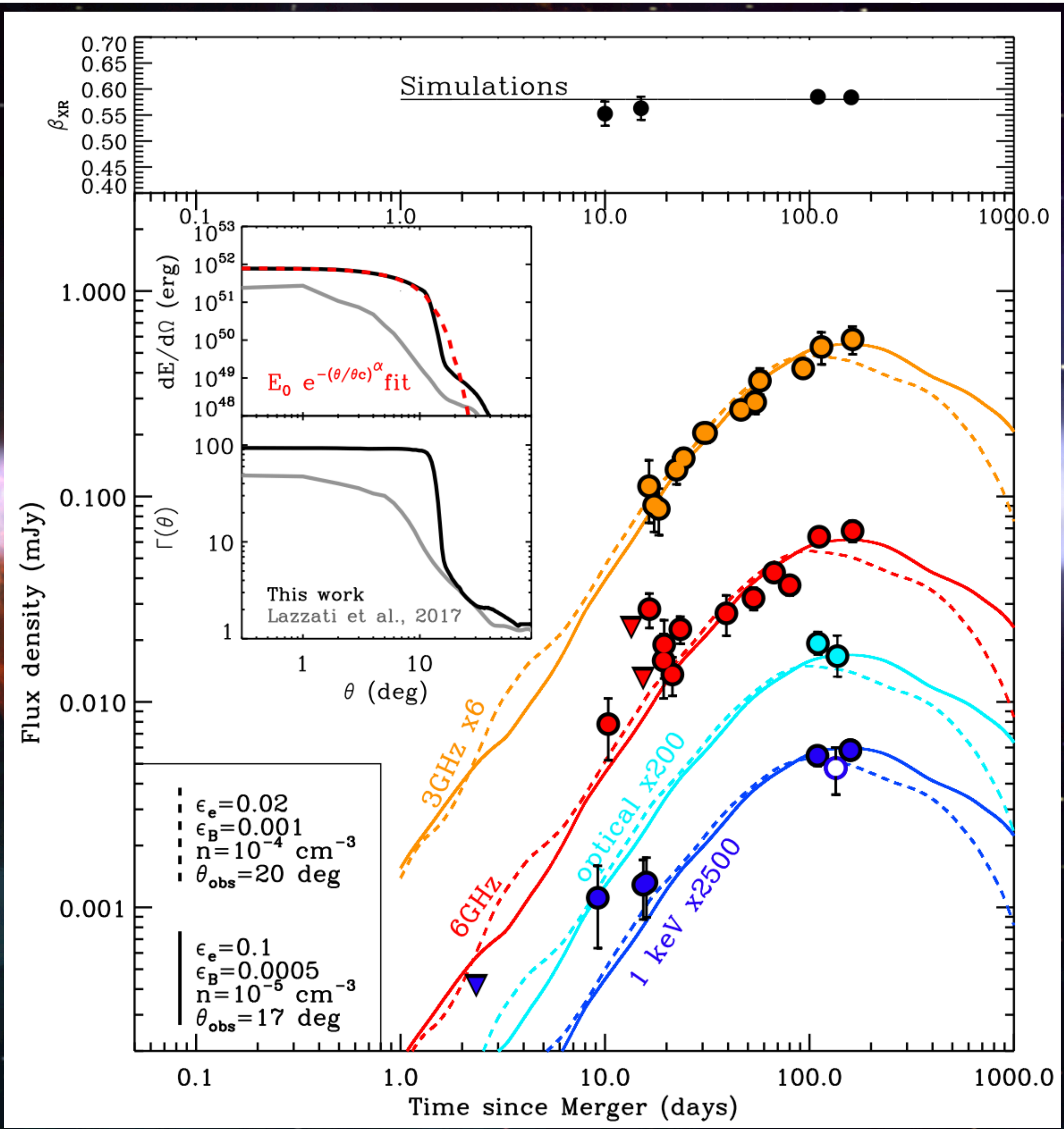
Axion and Neutrino Cooling in Neutron Stars



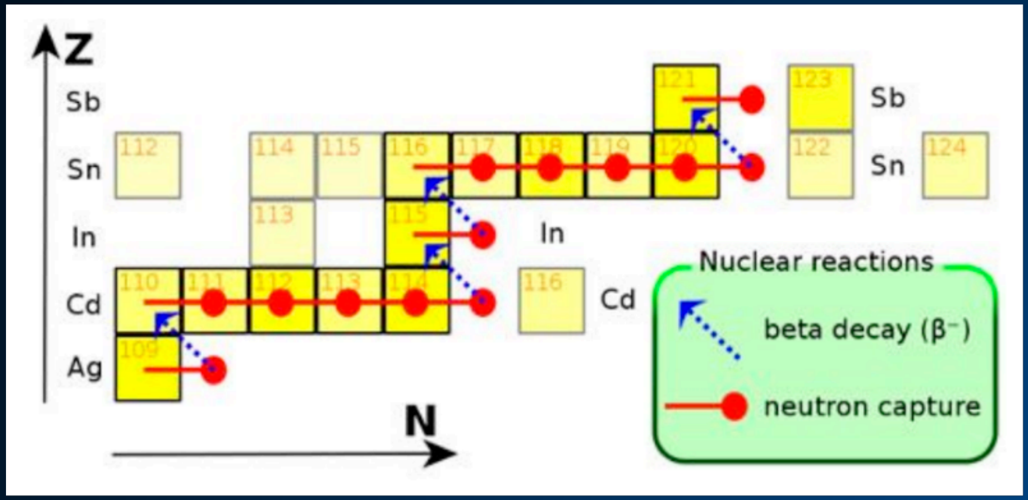
Hamaguchi et al. (1806.07151)

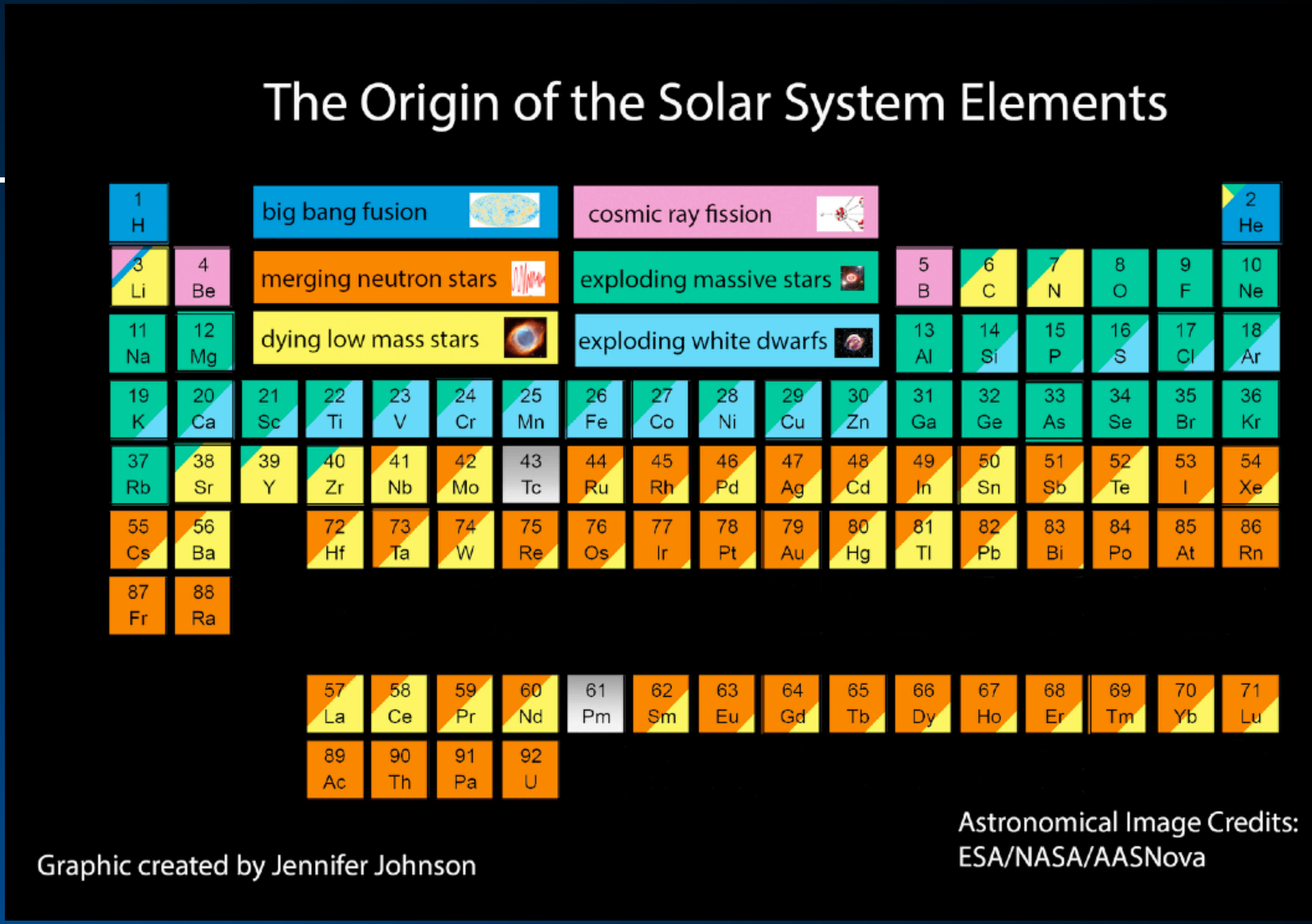
r-process Enrichment

Margutti et al. (1801.03531)



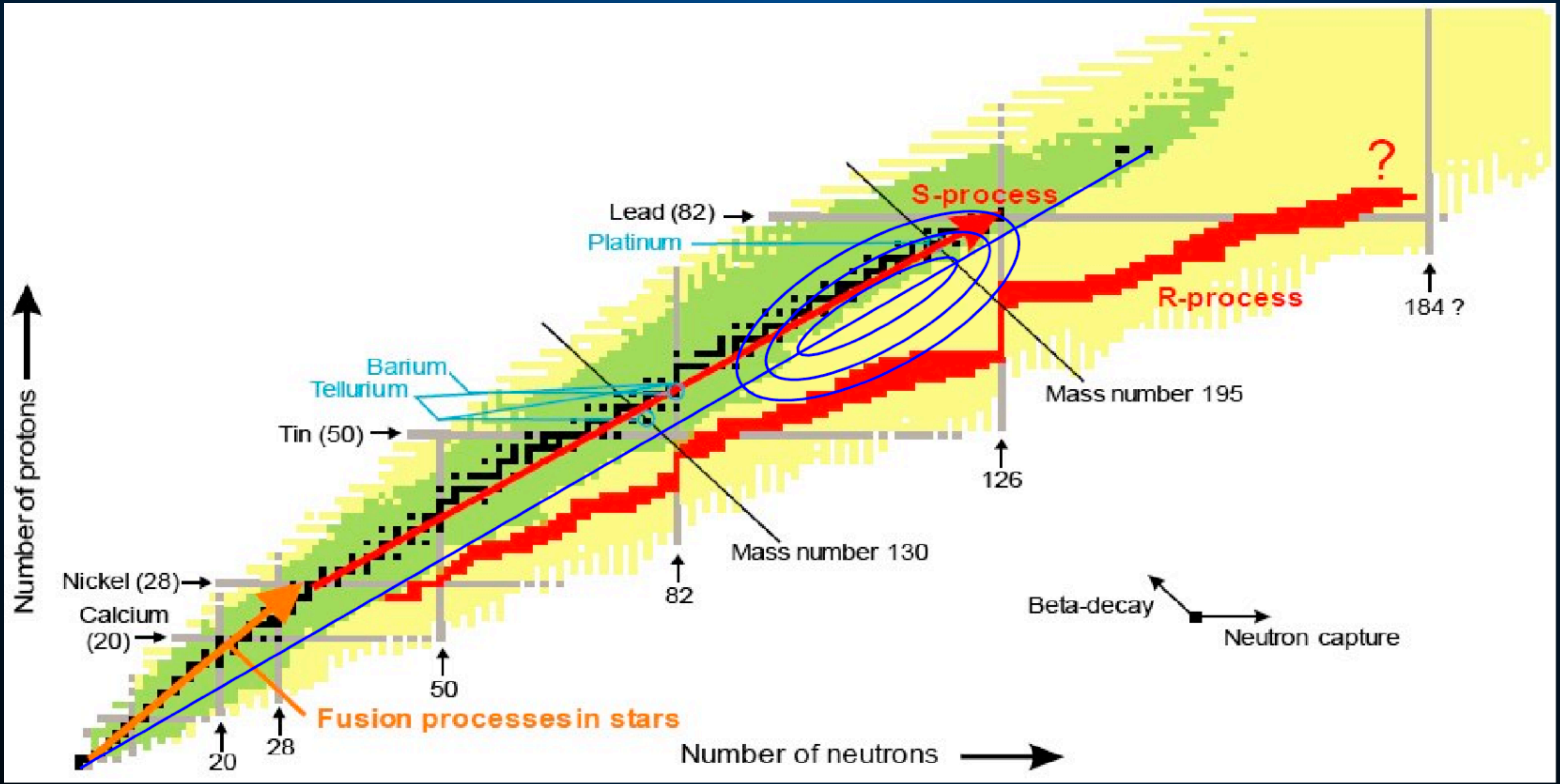
What is the r-process?



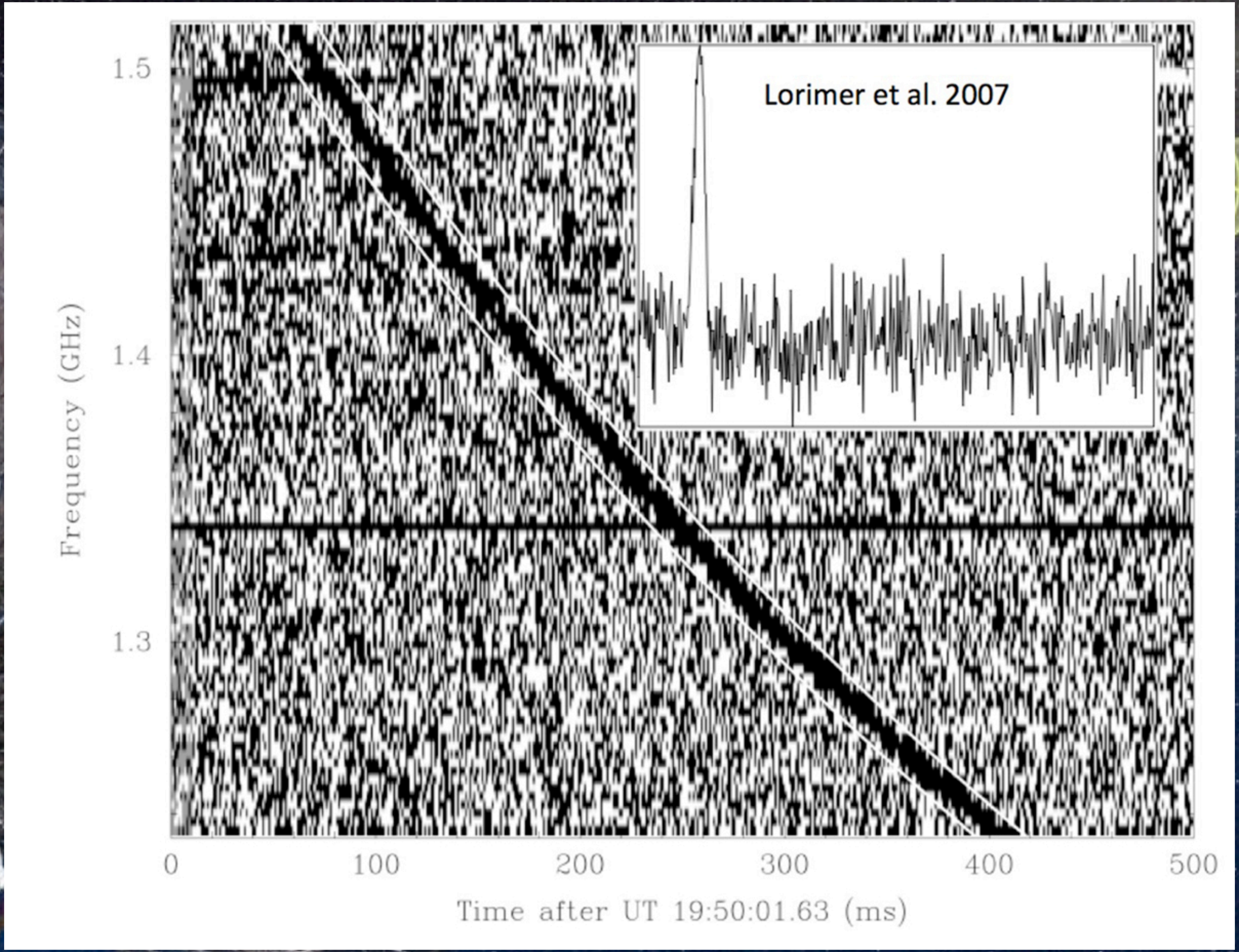

The Origin of the Solar System Elements

Graphic created by Jennifer Johnson

Astronomical Image Credits: ESA/NASA/AASNova



Fast Radio Bursts



Lorimer et al. 2007

One More Slide on Axion Dark Matter

Axions proposed to solve the strong-CP problem

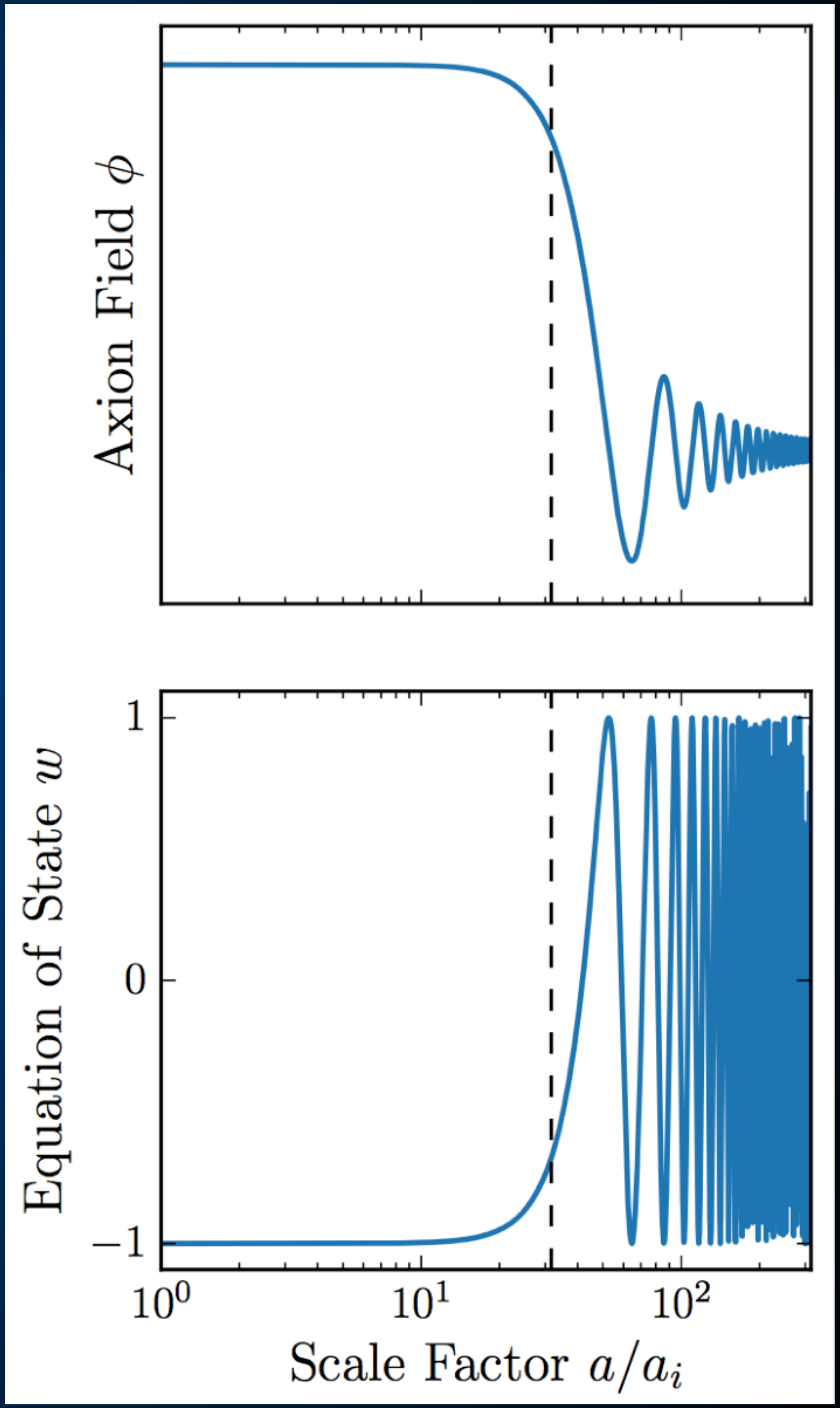
$$L_\theta = \theta \frac{g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu}$$

This is the sum of two different terms, that independently must be small.

$$\left| \Theta_{\mathrm{QCD}} + \arg \det M_q \right| \lesssim 10^{-9}$$

This provides you with an independent way to solve the strong-CP problem - by setting $m_u = 0$.

However, this appears to be at odds with experimental data.



Marsh (2015; 1510.07633)

QCD Axion Mass Bounds

QCD Axion obtains its mass from its decay constant and the coupling to quarks:

$$m_a = \frac{f_\pi m_\pi}{f_a}\left(\frac{z}{(1+z+w)(1+z)}\right)^{1/2}$$
$$= 0.60\,\mathrm{eV}\,\frac{10^7\,\mathrm{GeV}}{f_a},$$

The high-mass range of the QCD axion (low-f_a) is set by the constraint that the axion never comes into thermal equilibrium (and light-through a wall and astrophysical constraints).

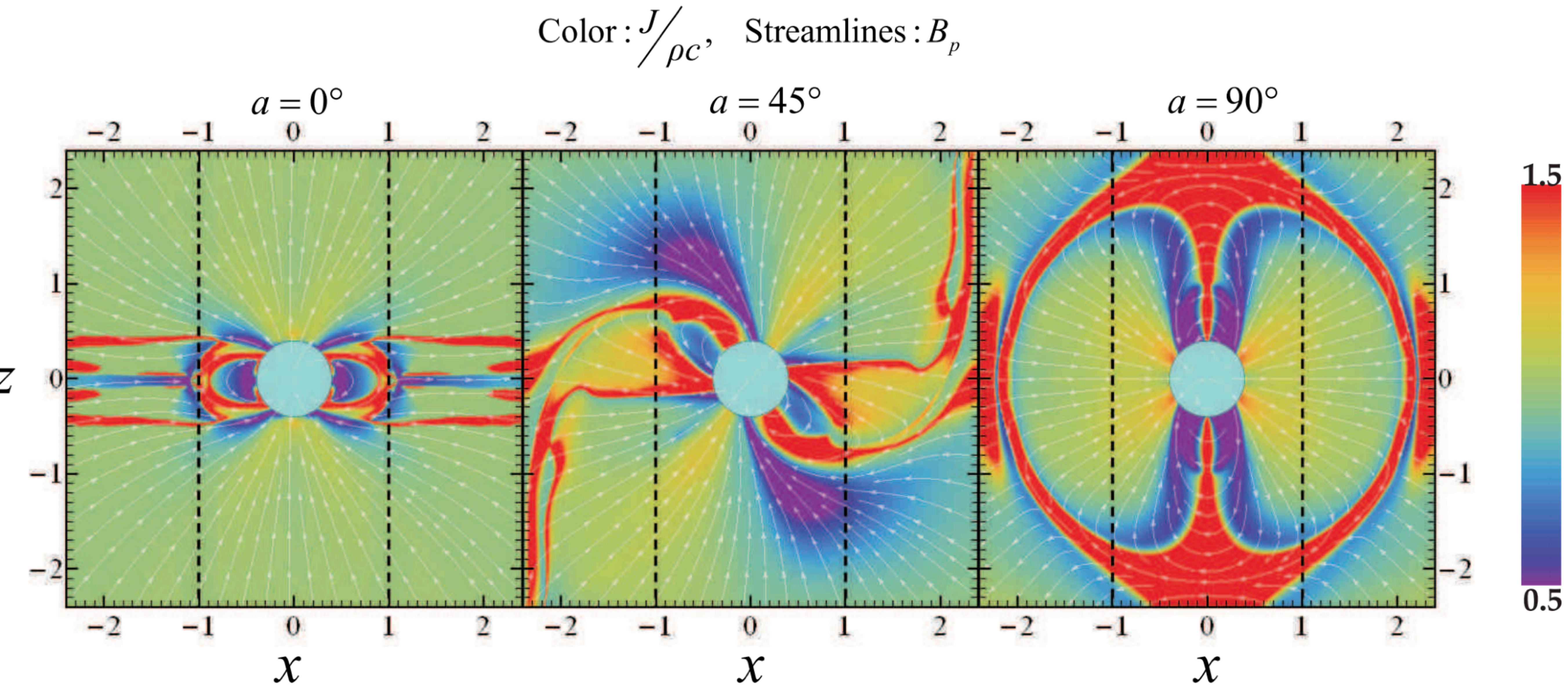
The low mass (high-fa) limit is set such that axions don't overclose the universe:

$$\Omega_a h^2 \approx 0.23\times10^{\pm0.6}(f_a/10^{12}\,\mathrm{GeV})^{1.175}\,\Theta_i^2\,F(\Theta_i)$$

Raffelt 1995

Goldreich-Julian Current

Kalapotharakos et al. (1108.2138)



$\text{Color}: J/\rho c, \quad \text{Streamlines}: B_p$

$a = 0°$ $a = 45°$ $a = 90°$

NS is a conductor with a strong rotating magnetic field. Thus, an electric field and current are formed.

In these simulations the NS is not a perfect dipole.

A Signal

10% of Star Formation in central 200 pc of Milky Way

Massive Star Formation in the Galactic Center

By Don F. Figer

Rochester Institute of Technology, Rochester, NY, USA

The Galactic center is a hotbed of star formation activity, containing the most massive star formation site and three of the most massive young star clusters in the Galaxy. Given such a rich environment, it contains more stars with initial masses above 100 $M_\odot$ than anywhere else in the Galaxy. This review concerns the young stellar population in the Galactic center, as it relates to massive star formation in the region. The sample includes stars in the three massive stellar clusters, the population of younger stars in the present sites of star formation, the stars surrounding the central black hole, and the bulk of the stars in the field popul
The fossil record in the Galactic center suggests that the recently formed massive sta
resent-day examples of similar populations that must have been formed throu
isodes stretching back to the time period when the Galaxy was formi

troduction

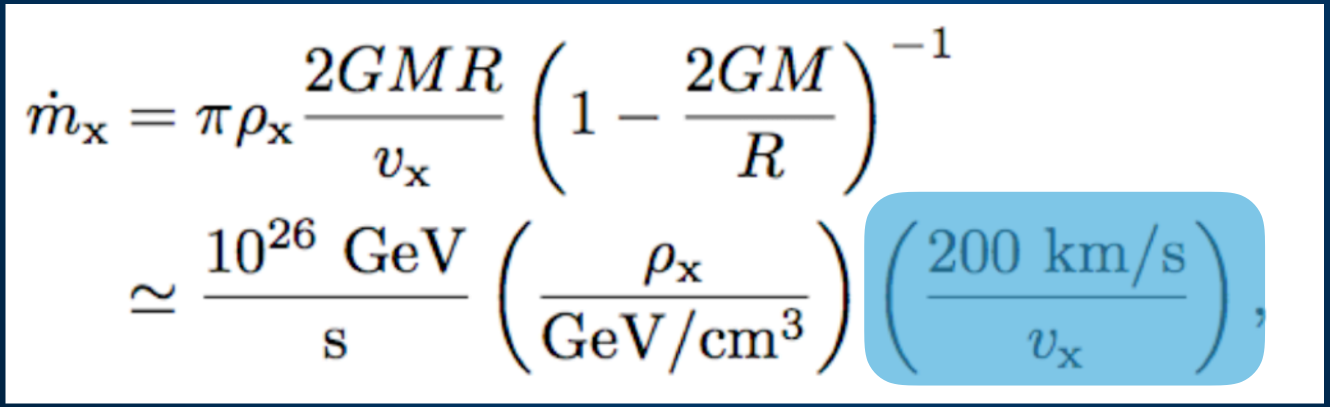
Galactic center (GC) is an
tion models. It con
ly a tiny f

Dark Matter Induced Collapse in dSphs

Bramante & TL (1601.06784)

- The dispersion velocity in dwarfs is also small.
  - Reticulum II: 3.3 +/- 0.7 km s^{-1} (Simon et al. 2015)

- Dark matter accumulation rate scales inversely with velocity:

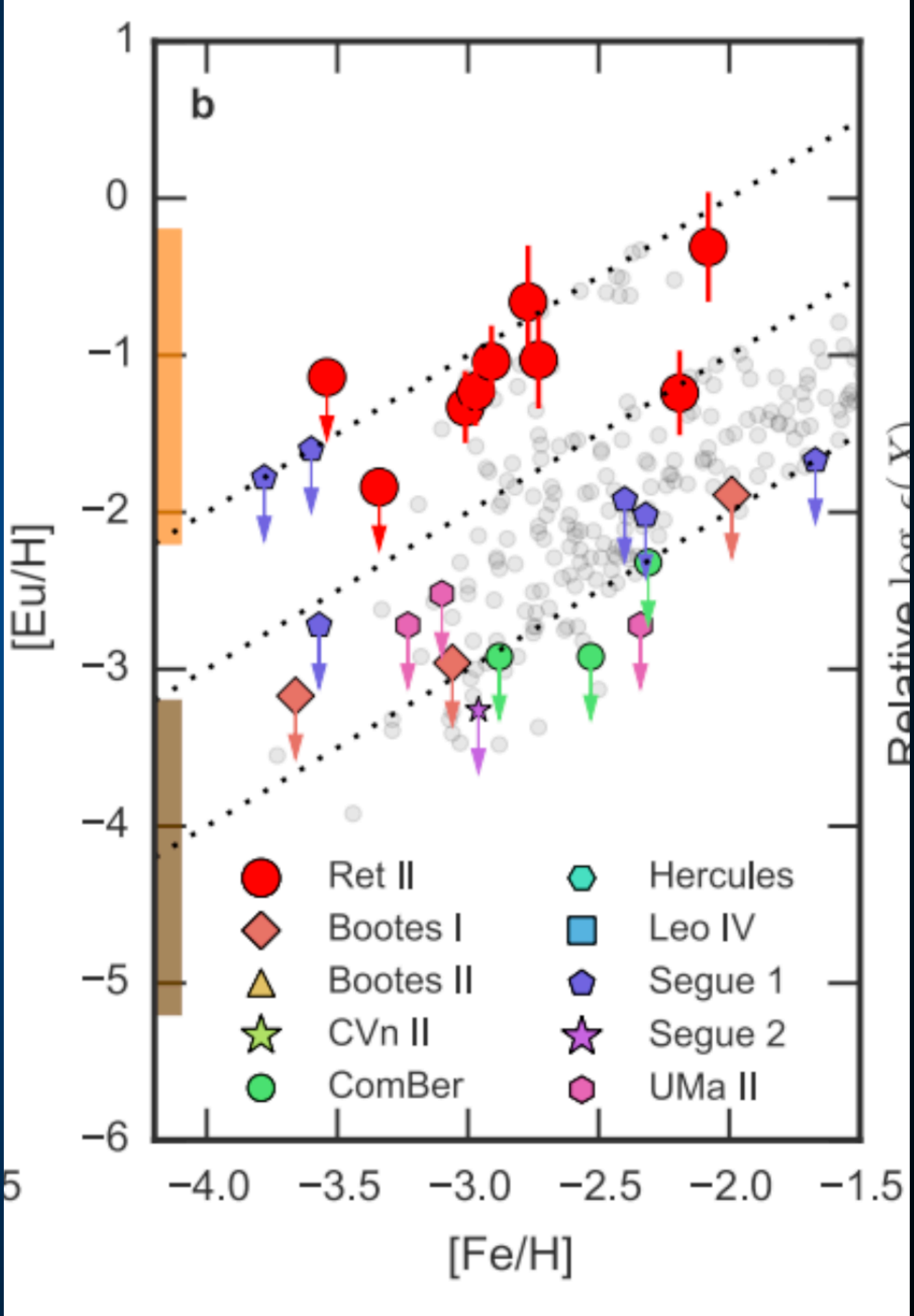


$$\dot{m}_{\rm x} = \pi \rho_{\rm x} \frac{2GMR}{v_{\rm x}} \left(1 - \frac{2GM}{R}\right)^{-1}$$
$$\simeq \frac{10^{26}\ {\rm GeV}}{\rm s} \left(\frac{\rho_{\rm x}}{{\rm GeV/cm^3}}\right) \left(\frac{200\ {\rm km/s}}{v_{\rm x}}\right),$$

- Dwarf Spheroidal Galaxies are an optimal laboratory for asymmetric dark matter detection.

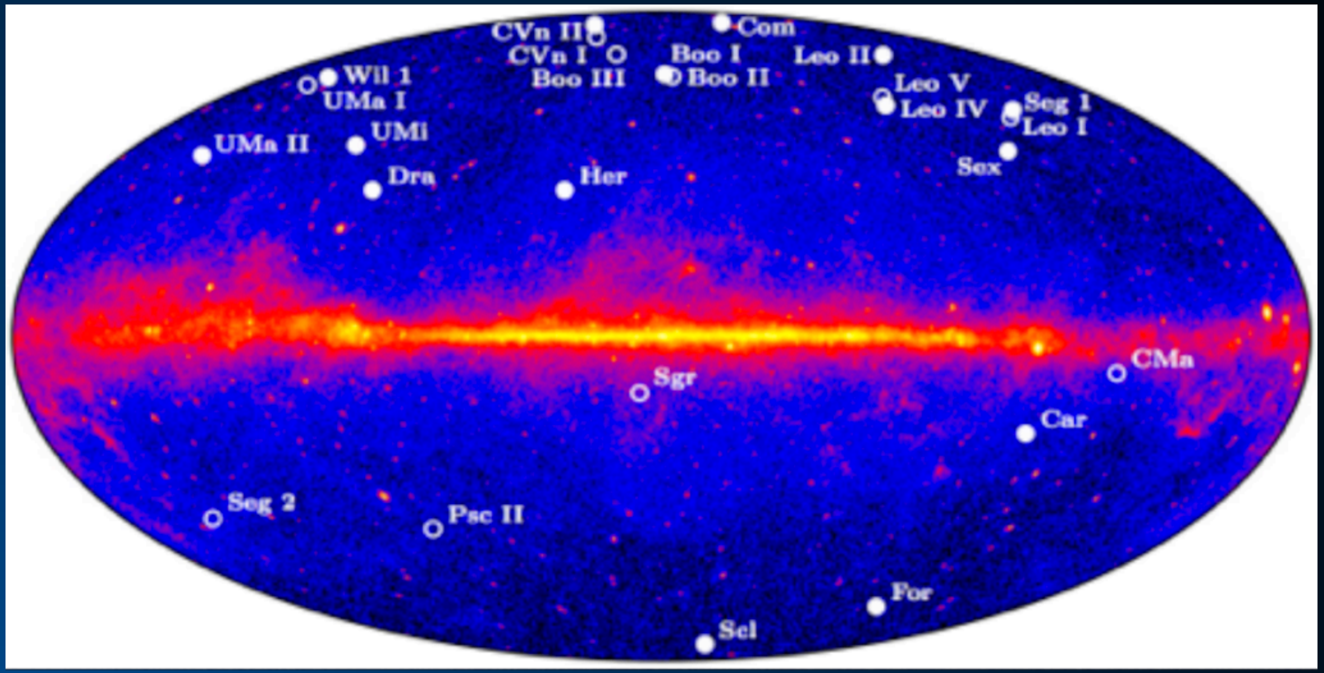
Dark Matter Induced Collapse in dSphs

- **Reticulum II dSph**
  - **Discovered by DES in 2015**
  - **Spectroscopic follow-up determined r-process abundances.**
  - **Large r-process abundance, but low metallicity!**
- **Points to a rare formation channel (NS mergers)**

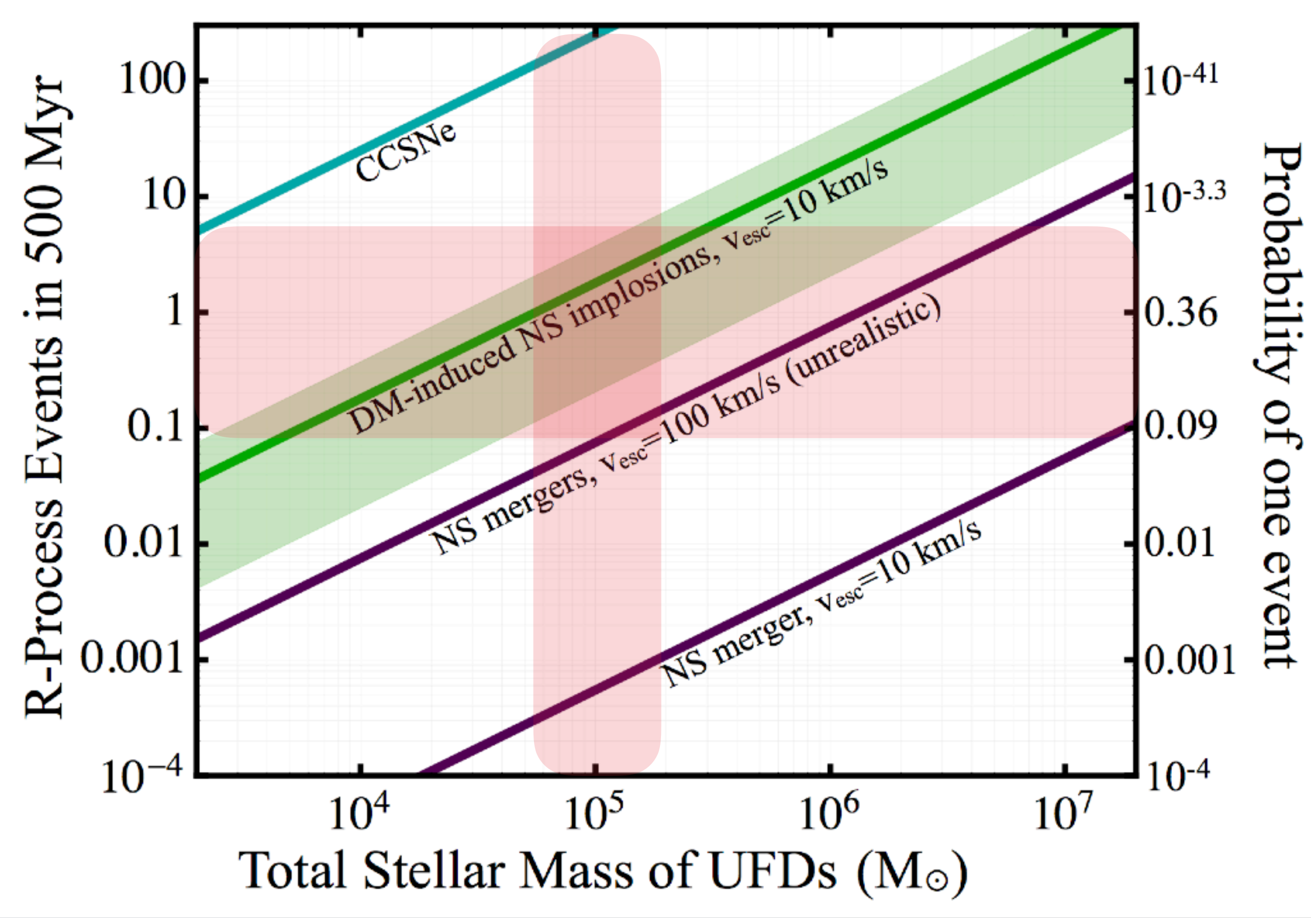


Dark Matter Induced Collapse in dSphs

- **Normalize the nuclear cross-section to the missing pulsar problem.**



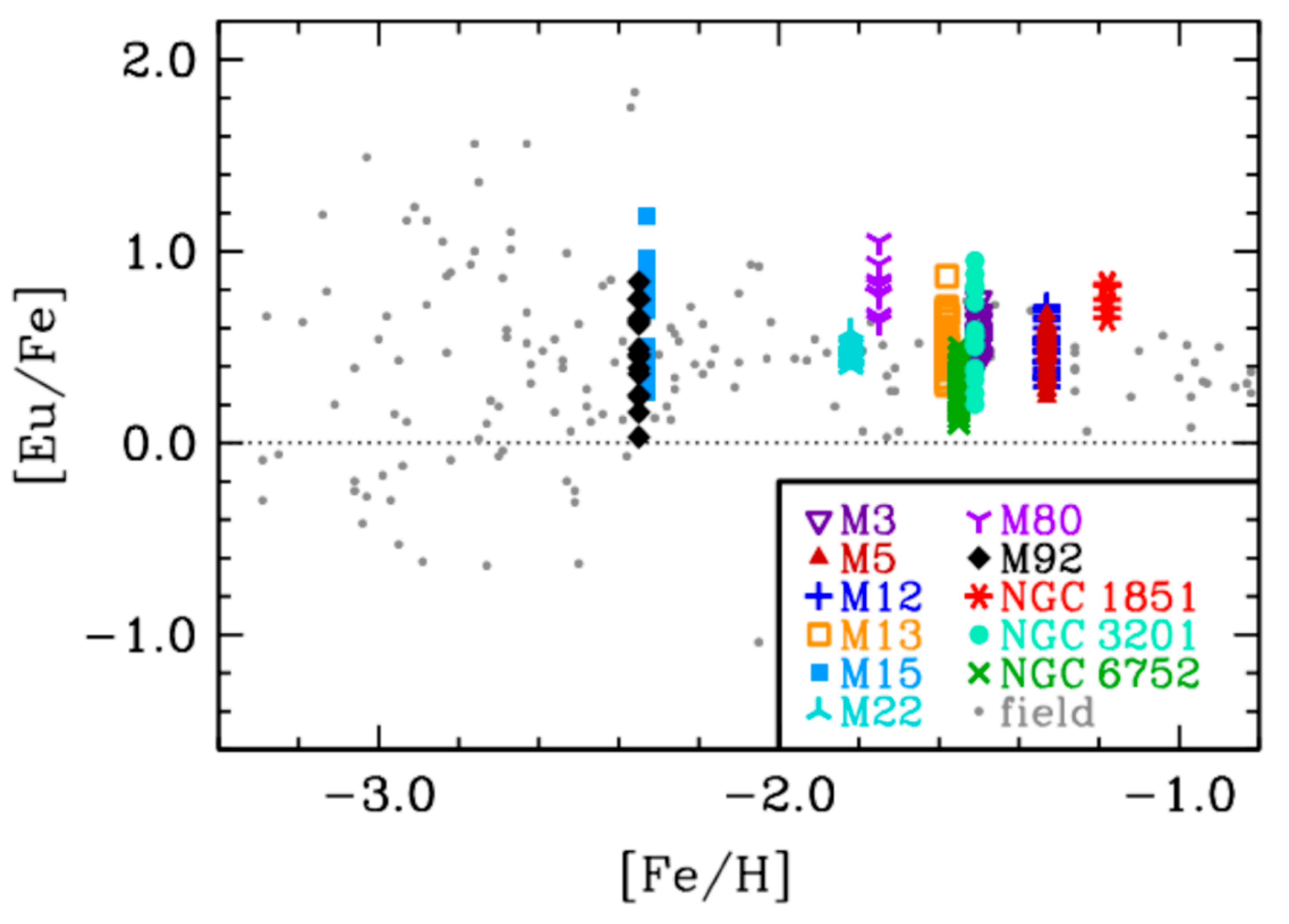
- **Supernovae produce ~100 events.**
- **Mergers produce ~0.0005 events**
- **DM induced collapse produces ~0.1-3 events.**



Dark Matter Induced Collapse in dSphs

Roederer 2011 (1104.5056)

- **Prediction: Globular Clusters should not be similarly r-process enriched.**
- **In fact, no globular cluster has been observed to have an r-process overabundance exceeding 1.2 dex.**



- **6 of 9 stars in Reticulum II have r-process enrichment exceeding 1.68 dex.**

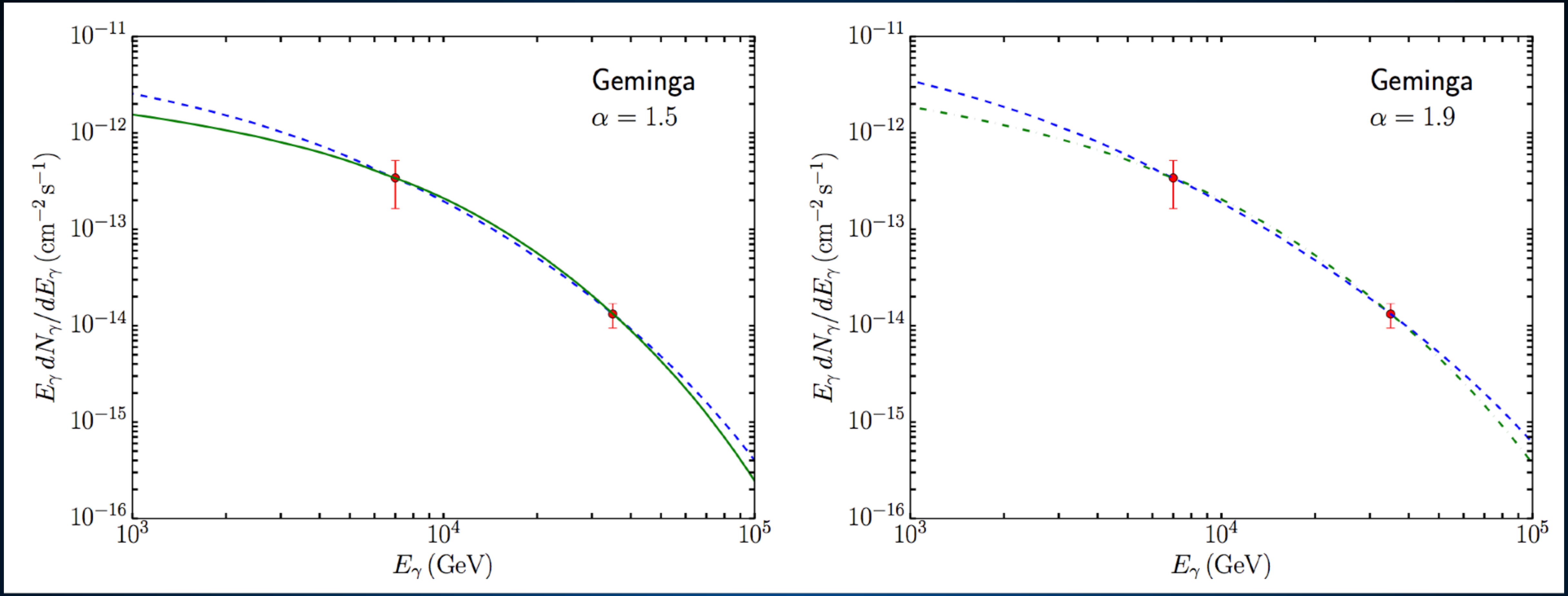
Dark Matter Induced Collapse in dSphs

$$M_{DM} \propto \underbrace{\sigma_{\chi p}}_{\text{particle physics}} \, t_{NS} \overbrace{\boxed{\left(\frac{\rho_\chi}{V_\chi}\right)}}^{\text{position dependent}}$$

in any p.p. model

$$t_{imp}(r) \propto \frac{\rho_\chi}{V_\chi}$$

Pulsars Produce the Positron Excess

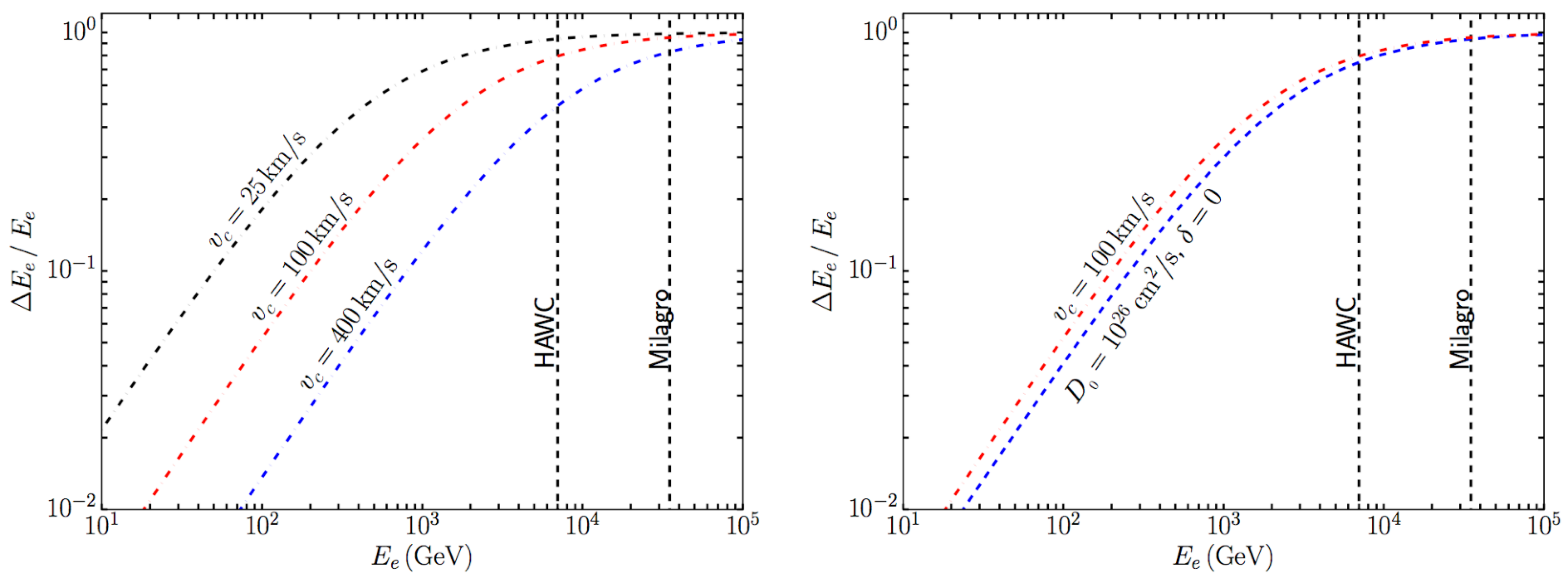


- **Can calculate the gamma-ray spectrum necessary to fit the Geminga data from HAWC and Milagro**

- **Can use this to calculate the underlying steady-state electron and positron spectrum**

Hooper, Cholis, TL, Fang (1702.08436)

Pulsars Produce the Positron Excess



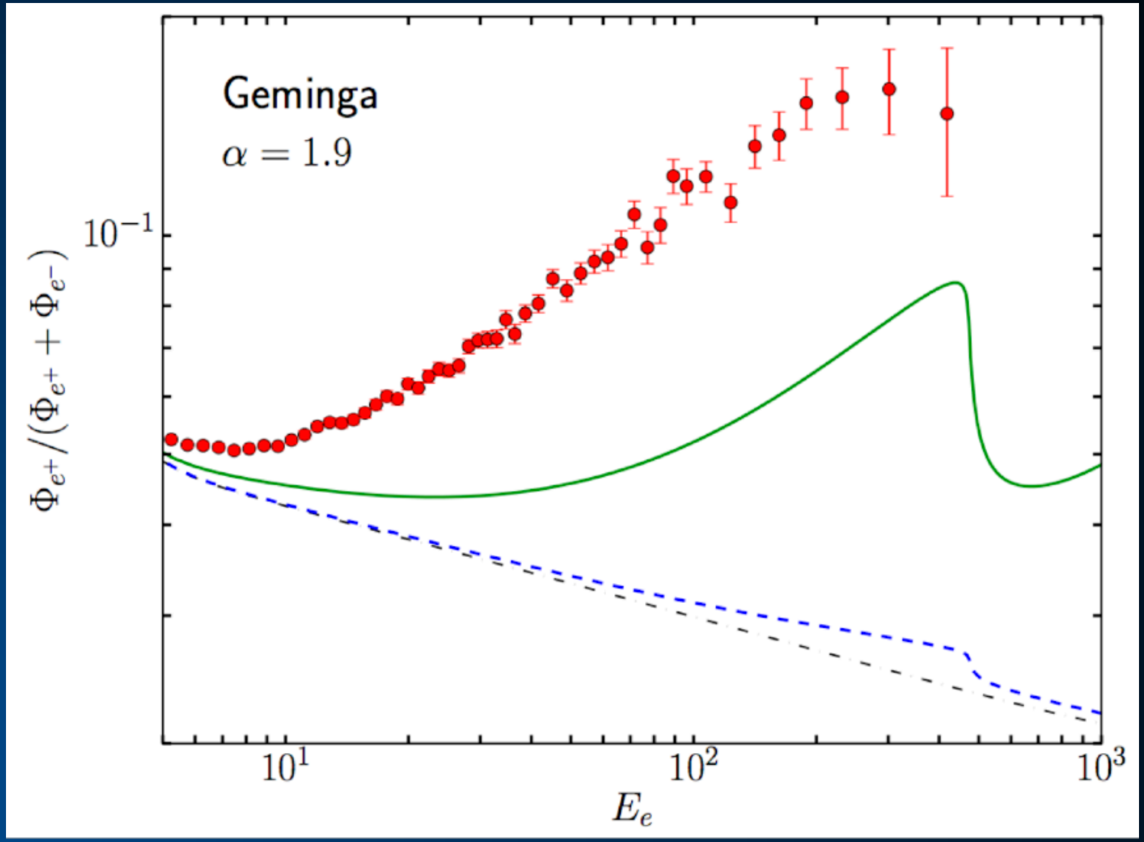
- **Utilizing a diffusion model, along with the steady state electron spectrum, and the morphology of the emission, can calculate the fraction of the electron energy lost before escaping the halo.**

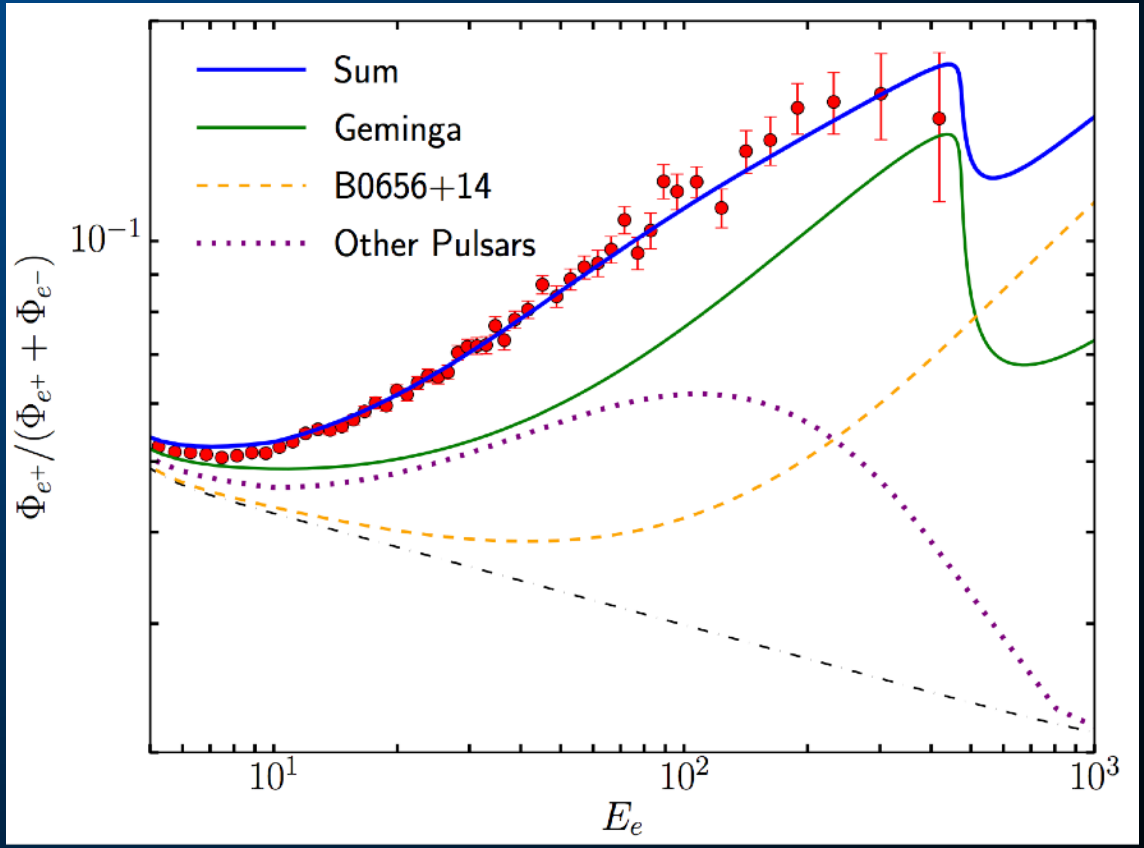
- **Less energetic electrons make it to the ISM!**

Hooper, Cholis, TL, Fang (1702.08436)

Pulsars Produce the Positron Excess

- **In these models, Geminga naturally produces ~50% of the positron excess.**
- **The total contribution from the remaining Milky Way pulsars produces the remaining emission.**
- **Difficult to understand TeV halo spectrum if pulsars <u>do not</u> make the positron excess.**



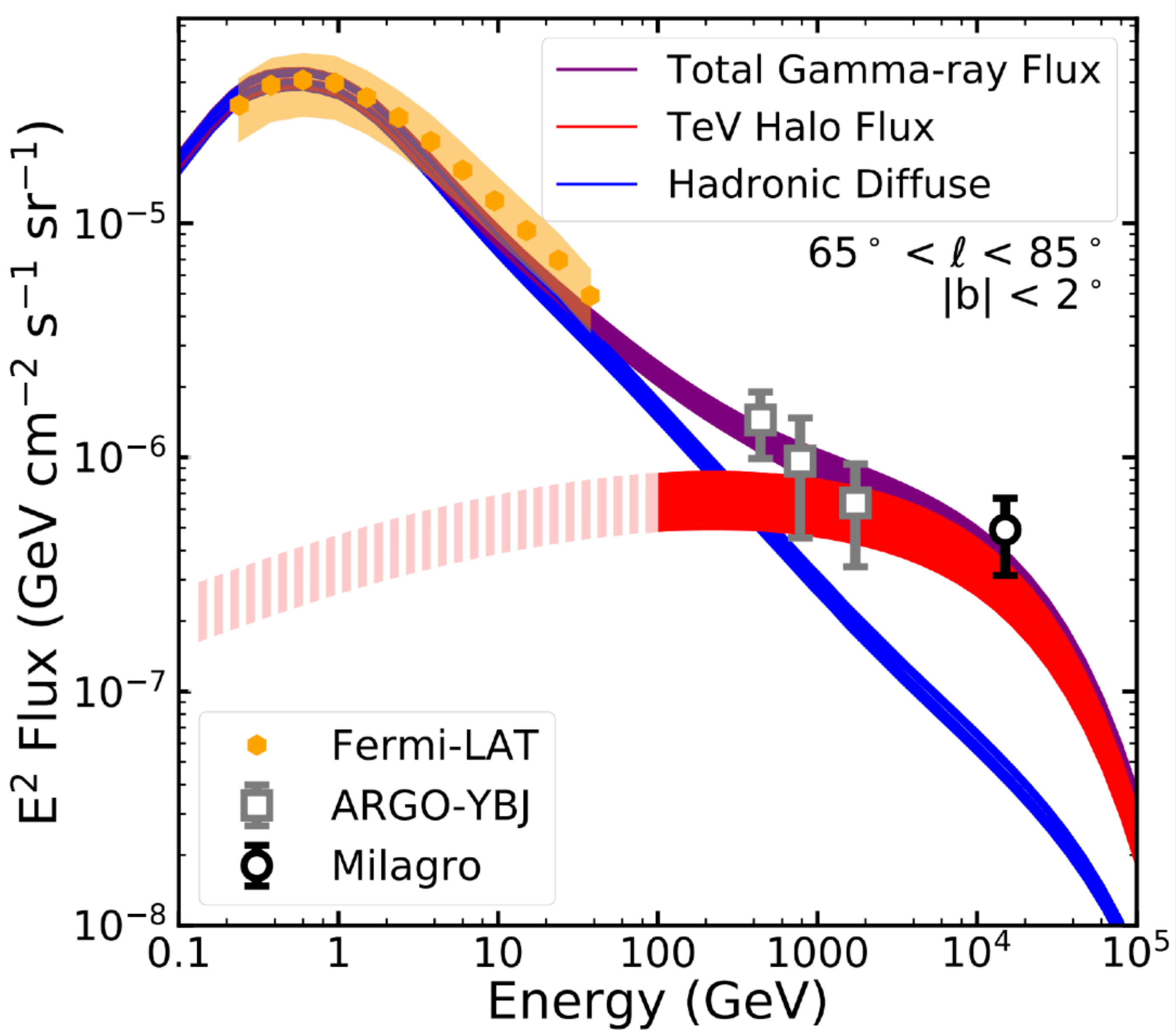


Hooper, Cholis, TL, Fang (1702.08436)

Pulsars Produce the TeV Excess

- **Milagro detected bright diffuse TeV emission along the Galactic plane.**

- **The intensity of this emission is incompatible with hadronic models constrained by Fermi and Argo-YBJ data.**



TL & Buckman (1707.01905)

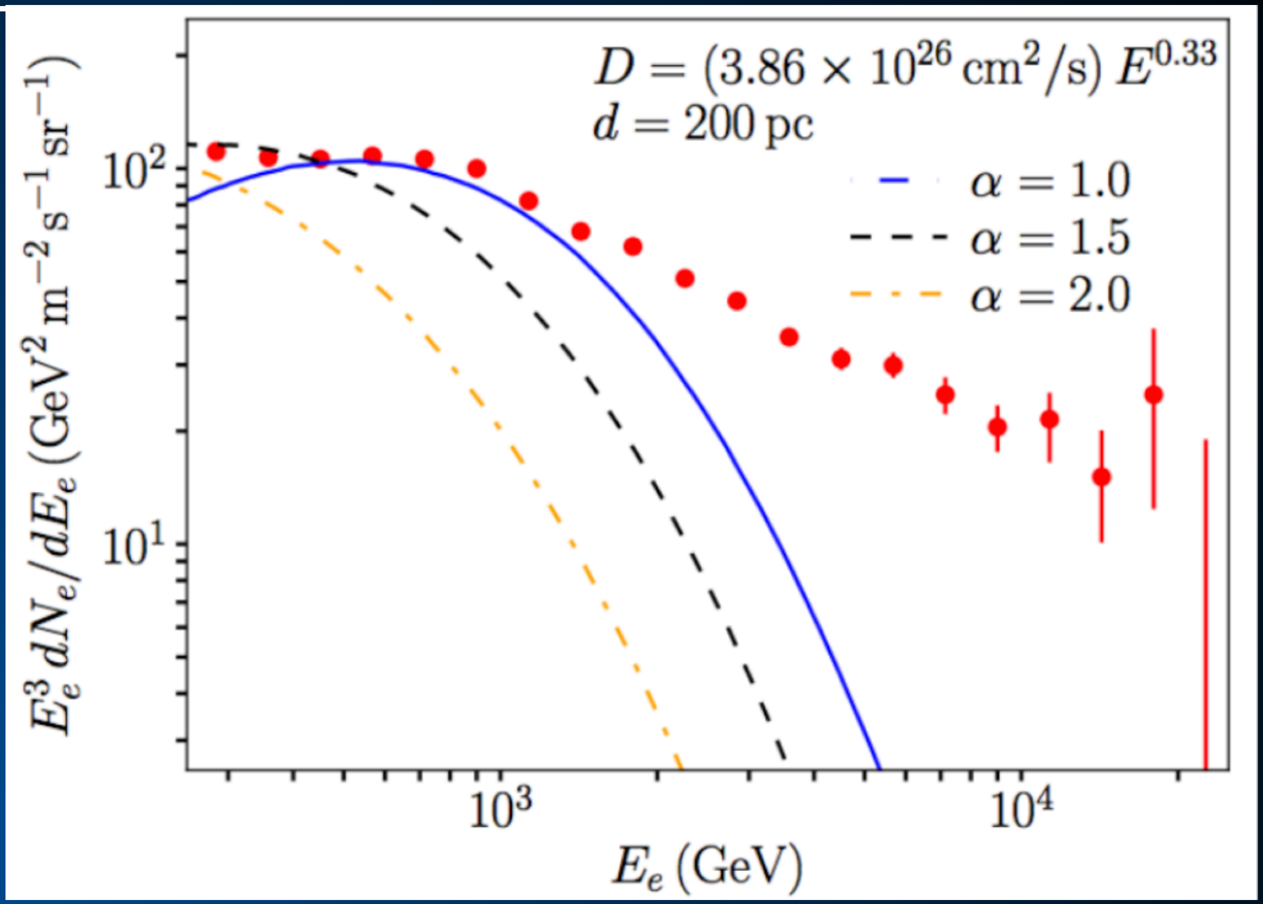
- **TeV halos produce a hard spectrum component that naturally explains the intensity and spectrum of this emission.**

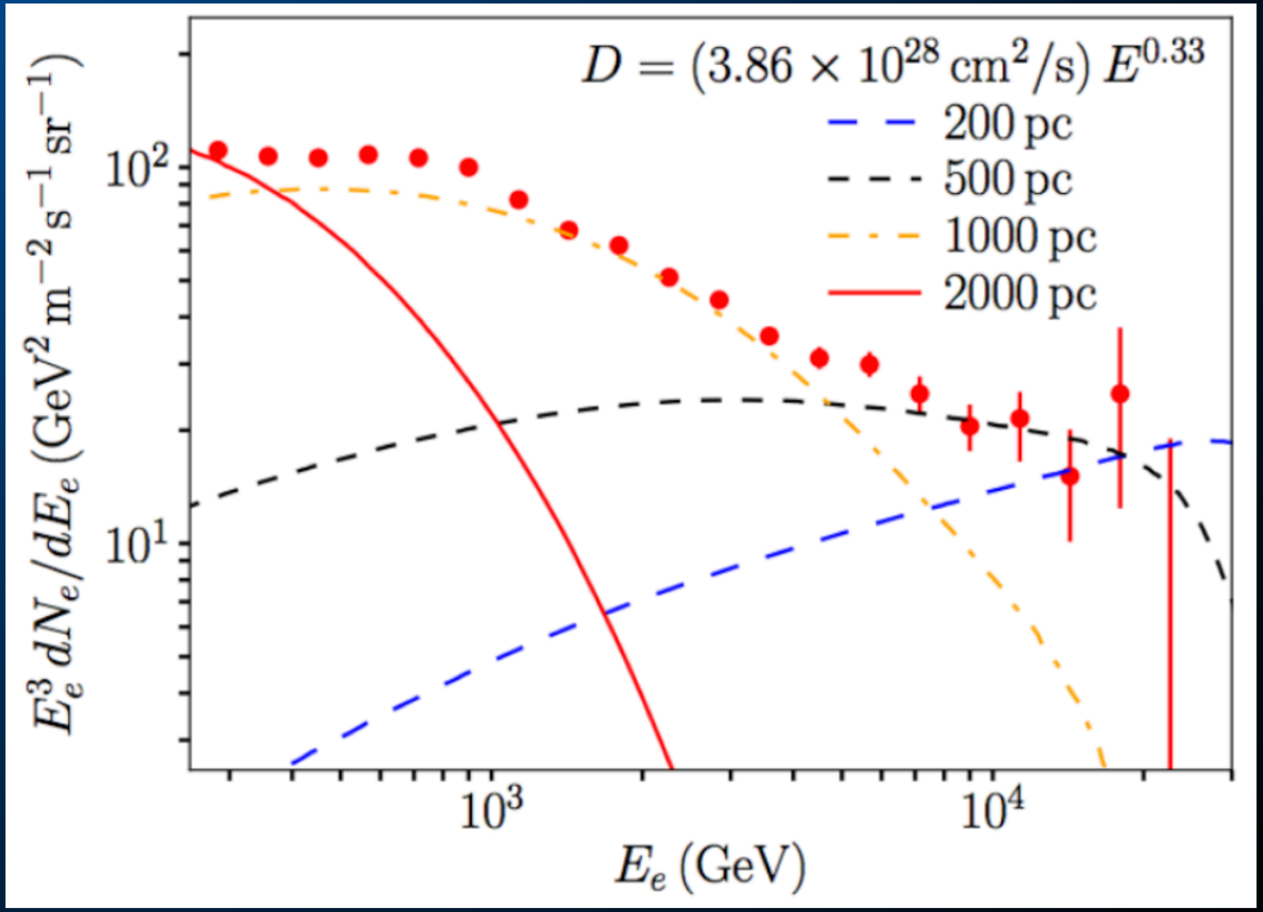
Pulsars Produce Anisotropic Diffusion

- **Diffusion near TeV halo is known to be suppressed - by two orders of magnitude!**

- **Diffusion constant near us must be high to explain observations of 10 TeV electrons.**

- **Pulsars produce regions of low-diffusion, where TeV halos shine!**



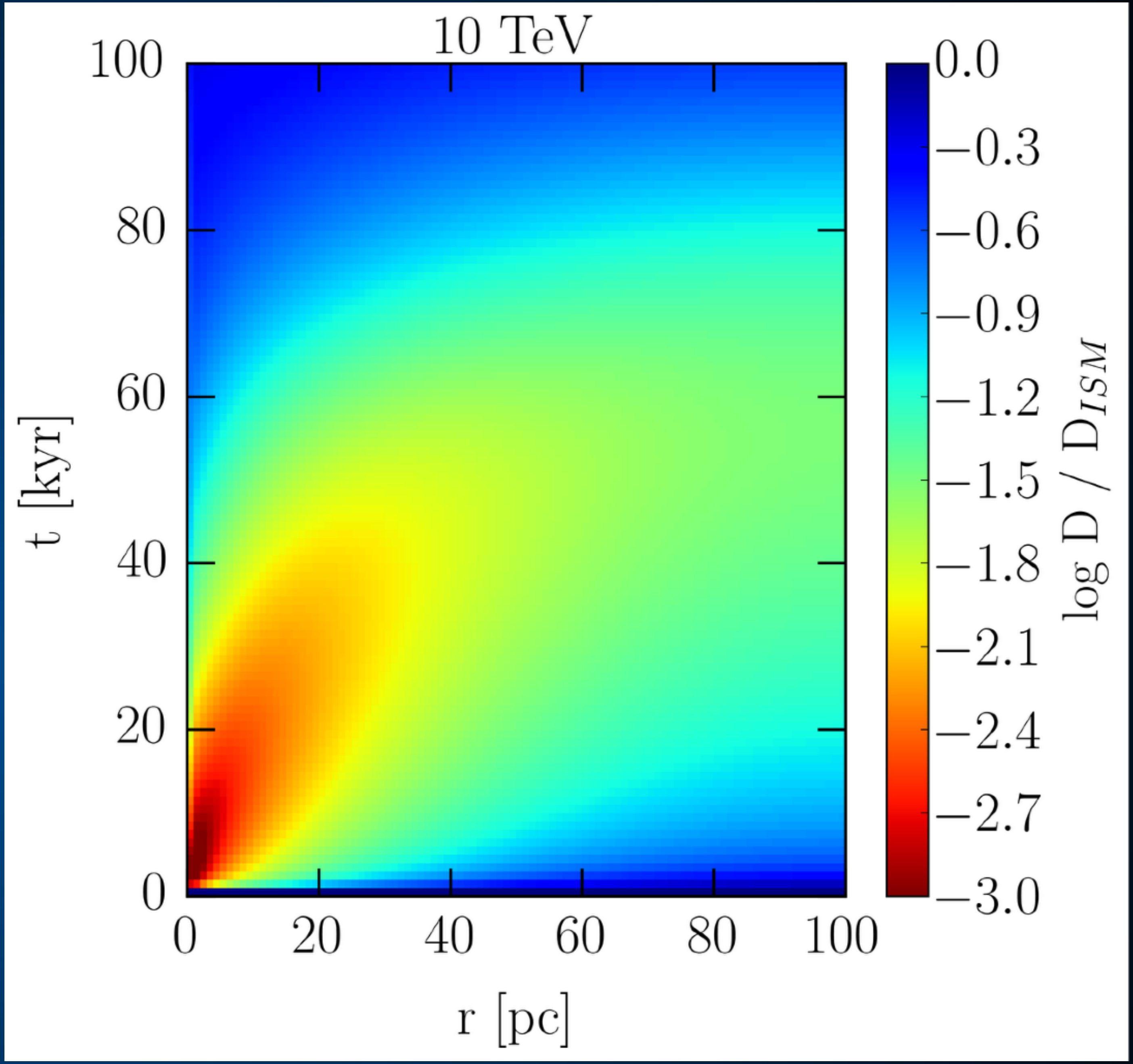


Hooper & TL (1711.07482)

Pulsars Produce Anisotropic Diffusion

- **Cosmic-Ray electrons produced by the pulsar obtain a steep gradient.**
- **This excites Alfven waves moving parallel to the electron gradient.**

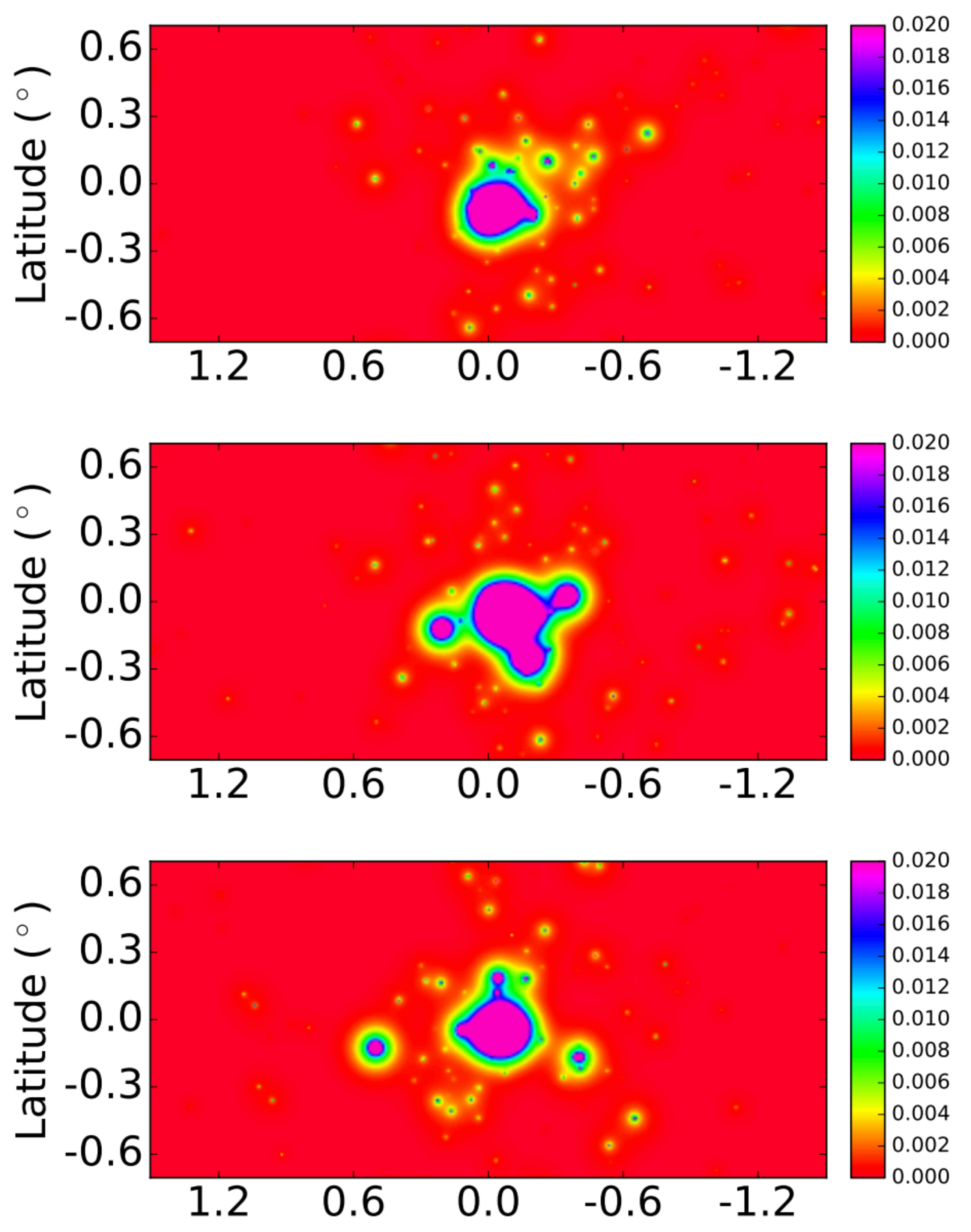
$$\Gamma_{\rm CR}(k) = \frac{2\pi}{3}\,\frac{c|v_A|}{k\mathcal{W}(k)\,U_0}\left[p^4\frac{\partial f}{\partial z}\right]_{p_{\rm res}}$$

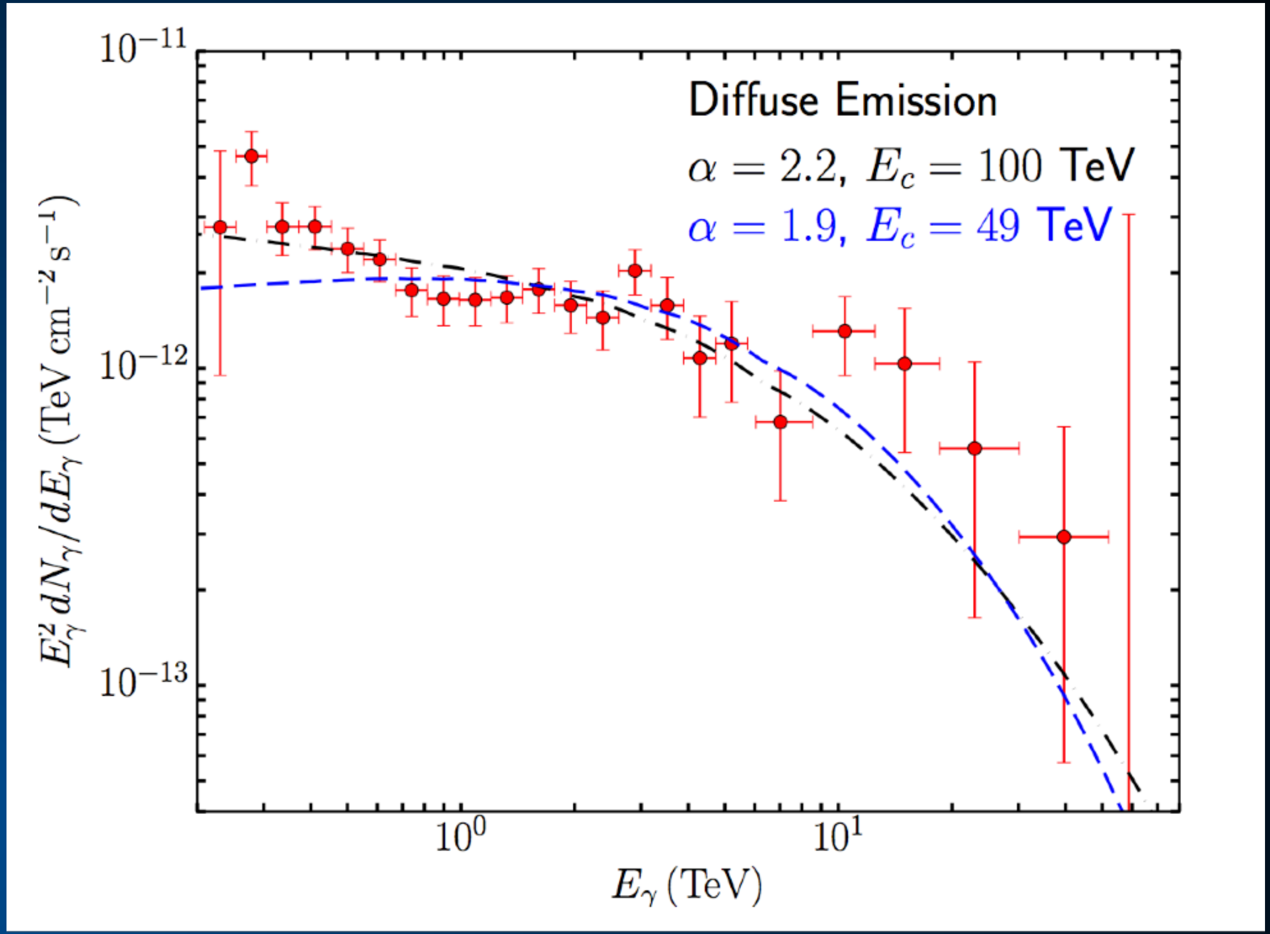


- **These Alfven waves dominate cosmic-ray turbulence, because they are resonant with the electron energy - leads to low diffusion**

Evoli, TL & Morlino (TBS)

Pulsars Produce Galactic Center Pevatron





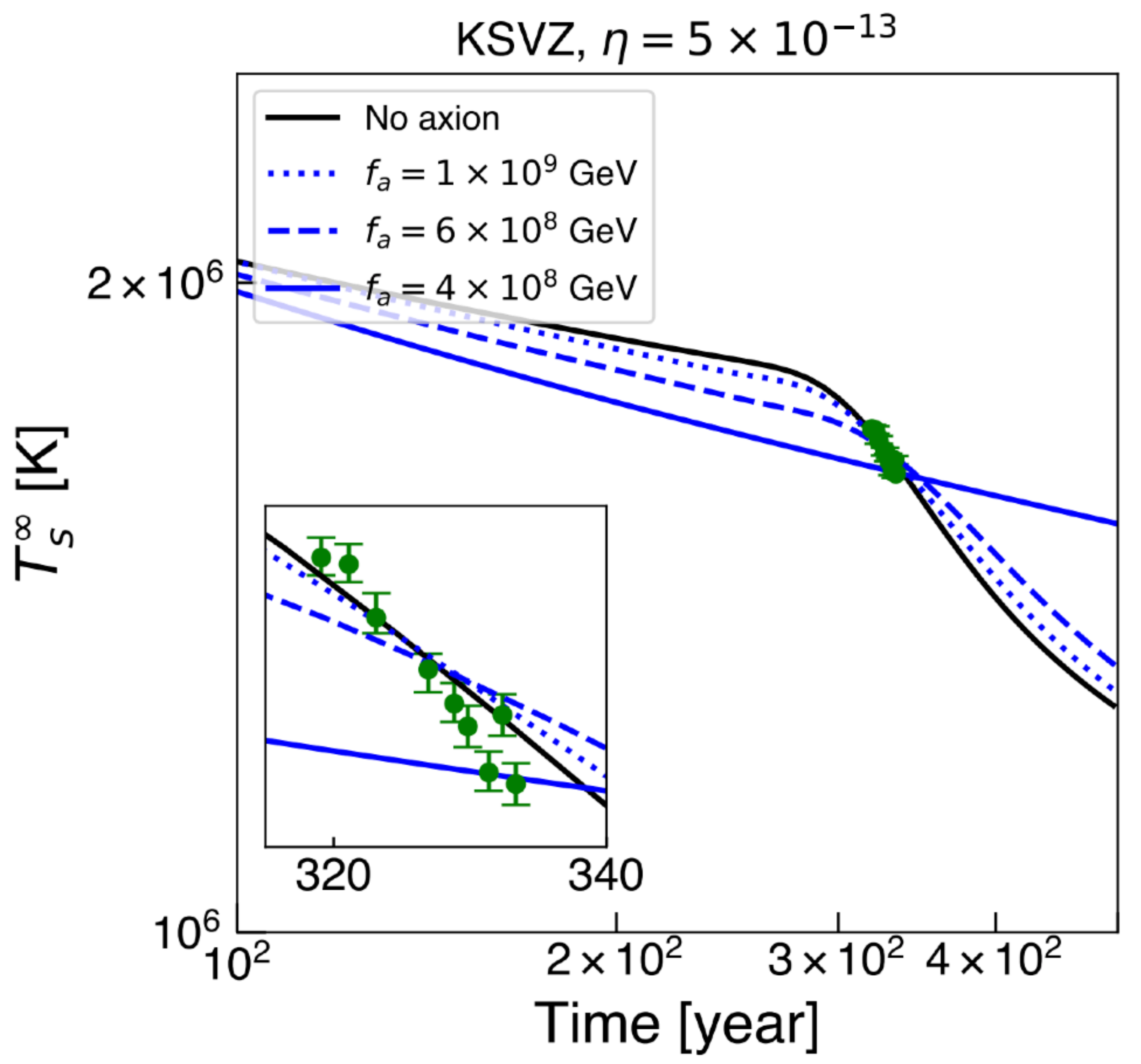
- **The spectrum of the HESS pevatron looks like the Geminga spectrum.**
- **Diffuse electrons can be made via pulsar natal kicks.**

Hooper, Cholis, TL (1705.09293)

Particle Physics Mash-Up

- Can also use neutron star cooling curves to place limits on the axion cross-section.

- Observations of the Cassiopeia A NS, with a known age of 337 years, rule out $f_a < 5 \times 10^8$ GeV.



Hamaguchi et al. (1806.07151)