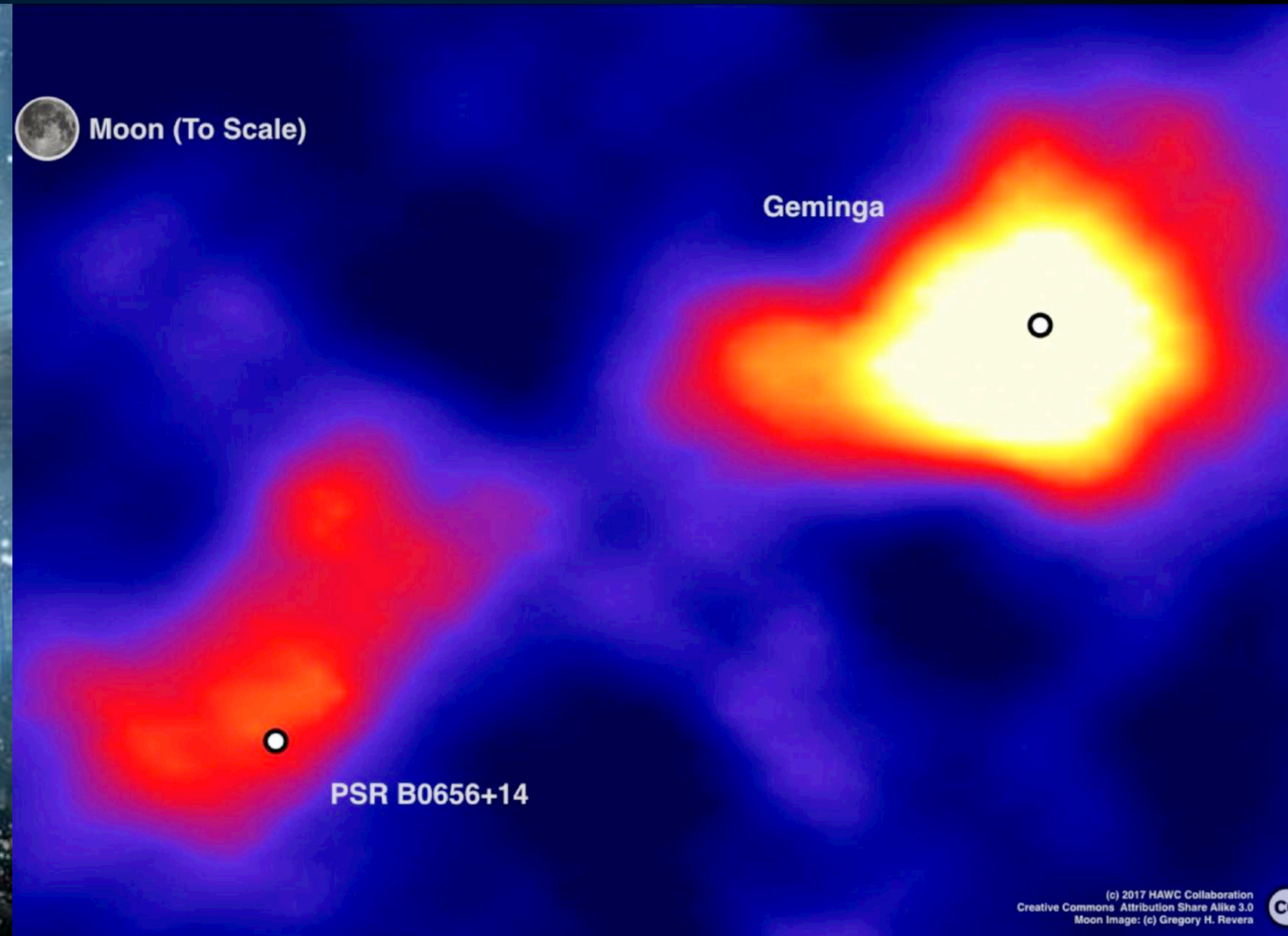


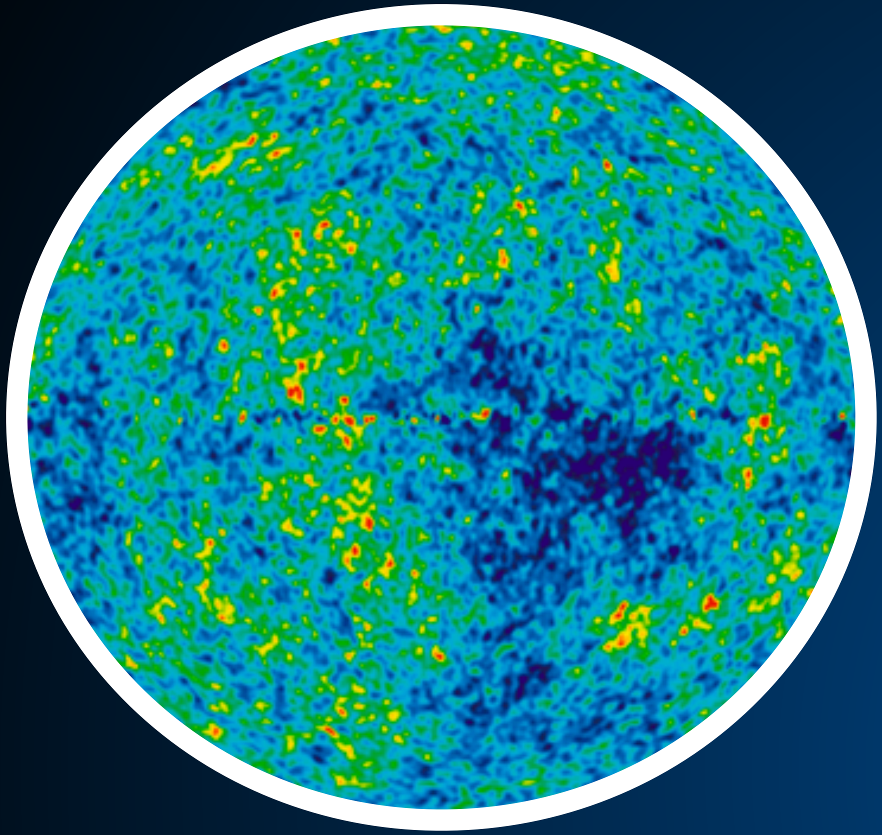
Unlocking Neutron Stars as Probes of Fundamental Physics

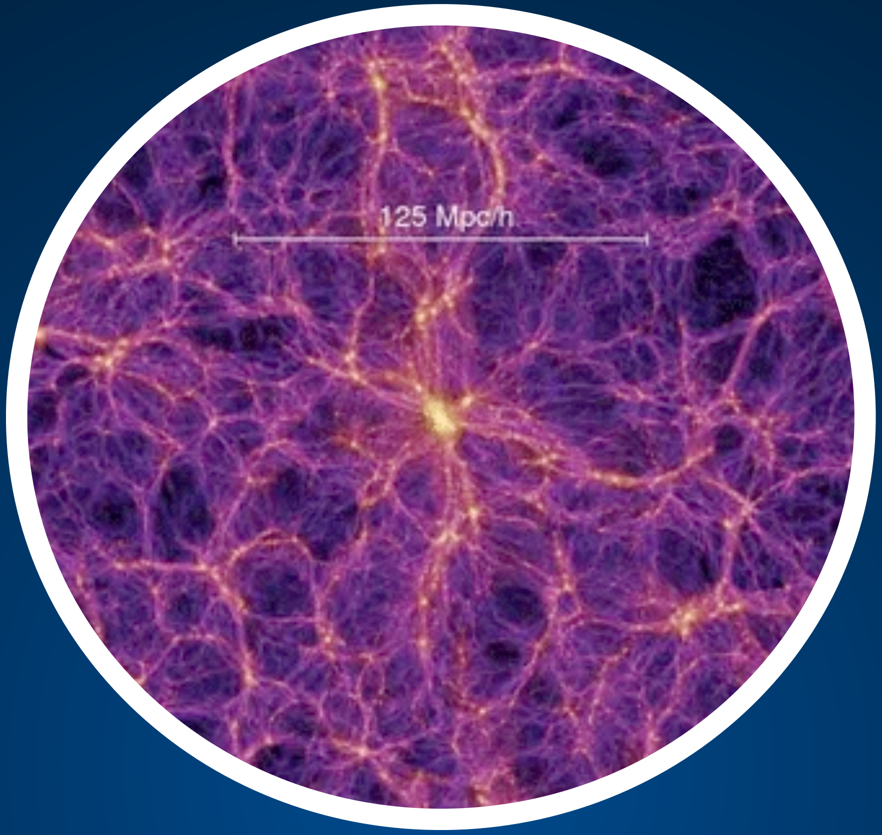
Tim Linden

High Energy Physics Seminar
University of Notre Dame
February 13, 2019

The Ohio State University
CENTER FOR COSMOLOGY AND ASTROPARTICLE PHYSICS

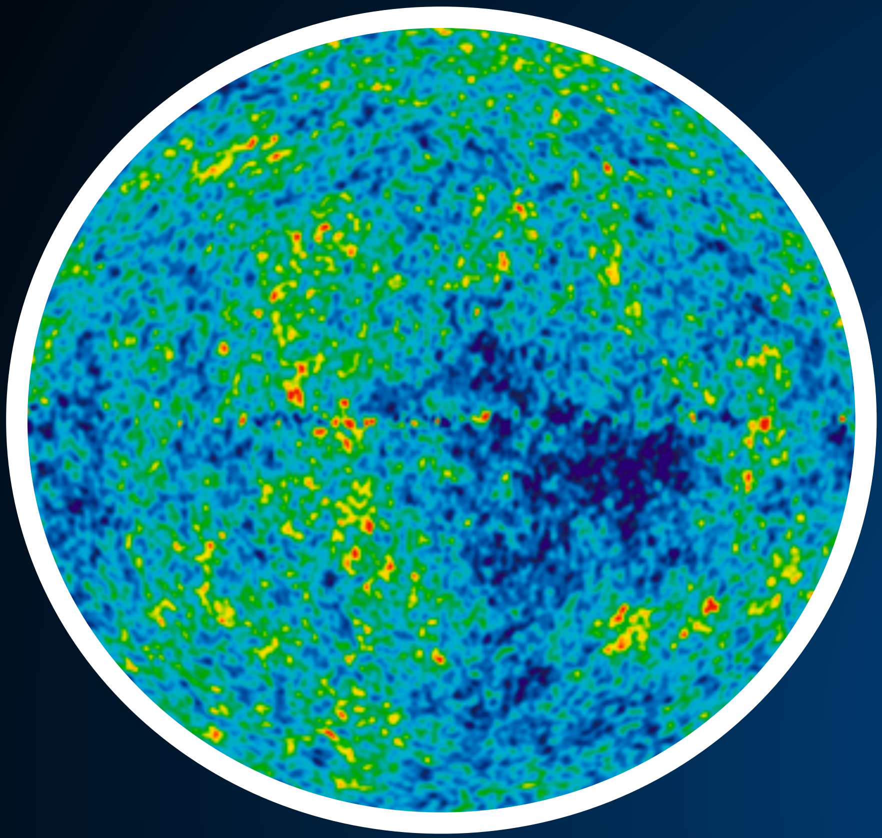
Gravitational Dark Matter

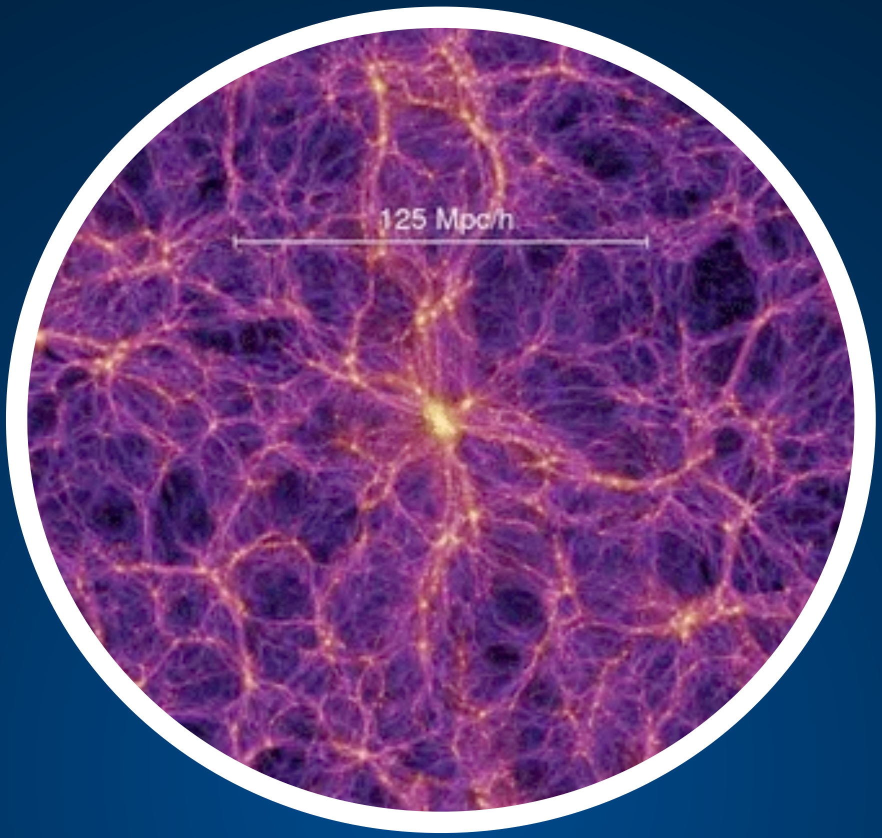




- Dark Matter is:
  - Dark
  - Cold
  - Stable
  - Prevalent

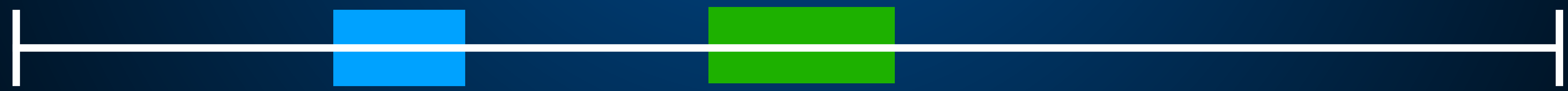
Gravitational Probes of Dark Matter





10^{-13} GeV

10^{2} GeV



10^{-25} GeV
$\sigma_X > R_{dwarfs}$

QCD Axion

WIMP Miracle!

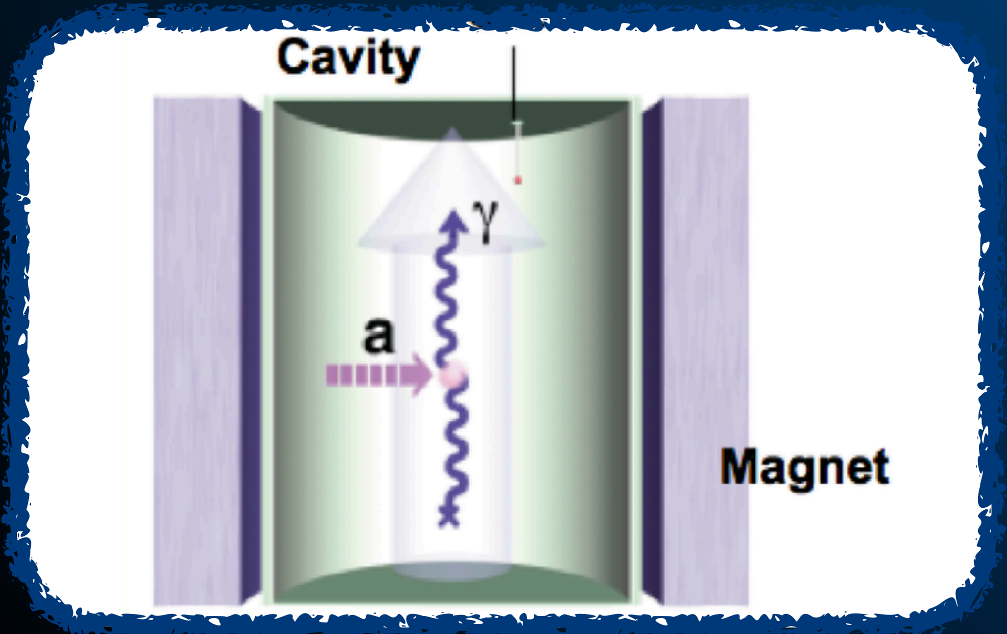
10^{62} GeV
$m_X > M_{dwarfs}$

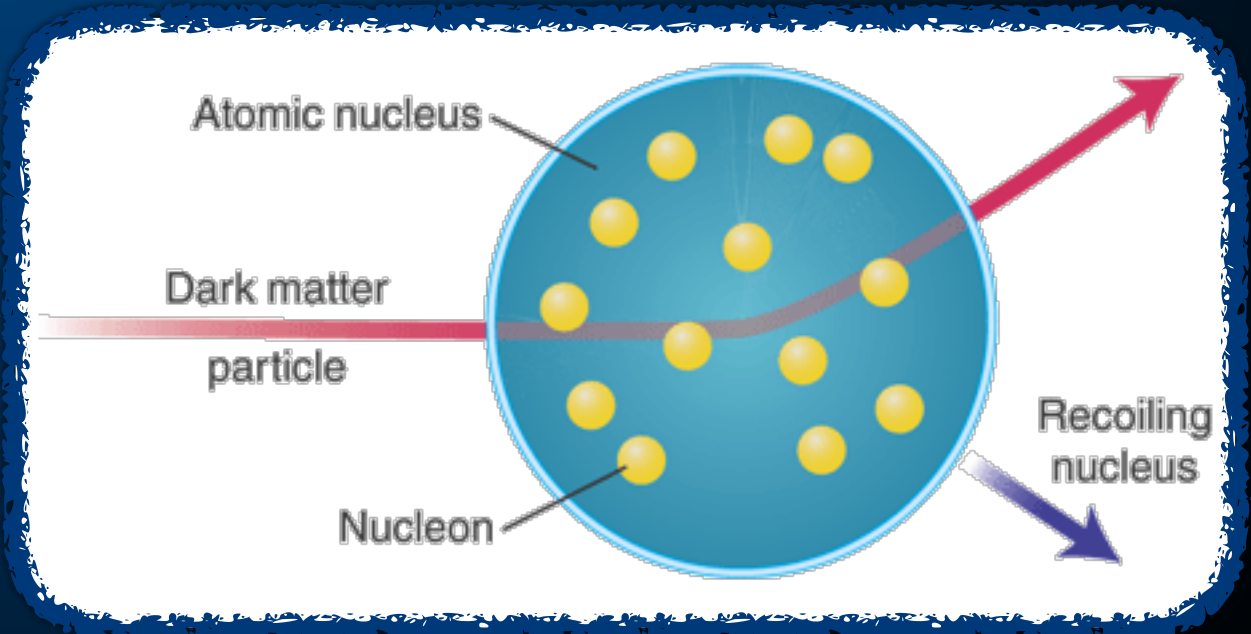
10^{-13} GeV

10^{2} GeV

QCD Axion

WIMP Miracle!





10^{-13} GeV

10^{2} GeV

QCD Axion

WIMP Miracle!

ADMX

Search for photon-axion conversion

Sensitivity ~ 10^{-24} W

Xenon 1T

Search for WIMP Scattering

Sensitivity ~ 1 keV yr^{-1}

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

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

$F' = -4.083888637248 \pm 0.000143324982645 \times 10^{-16}\ s\ s^{-1}$

NANOGrav Collaboration (1801.02617)

A Dipole Model

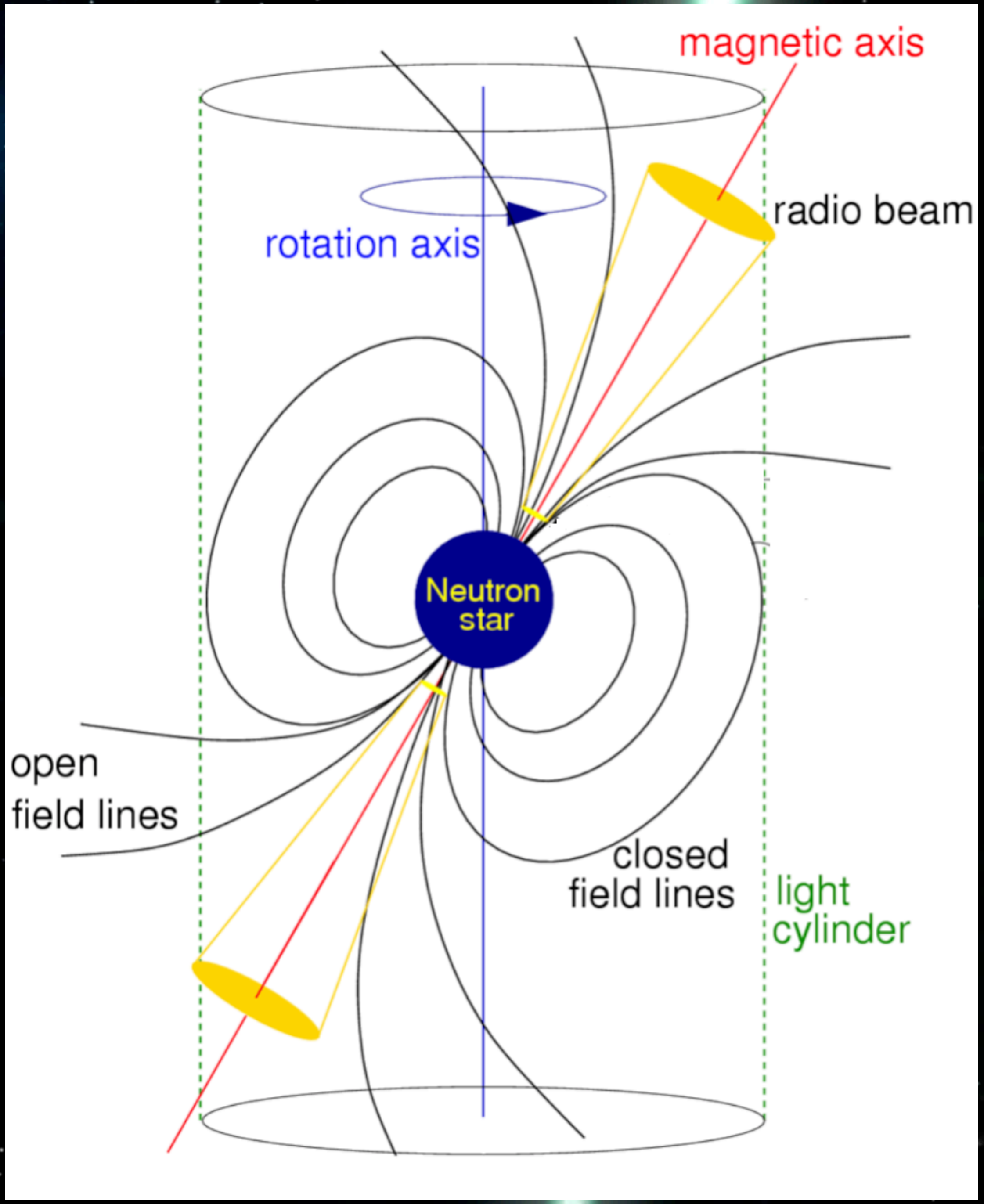
- Can precisely measure the magnetic field:

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

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

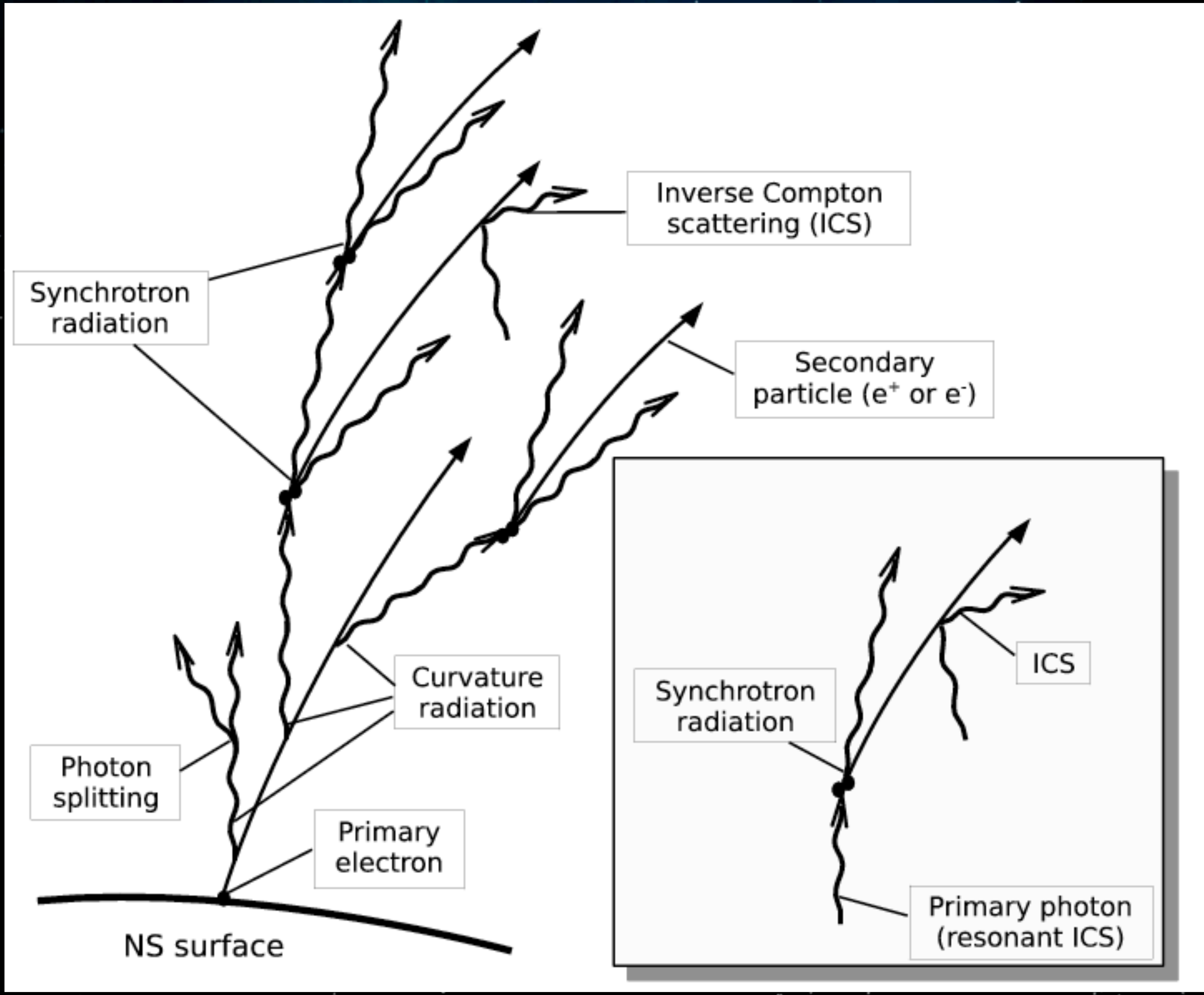
- And approximately measure the age:

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



Curvature Radiation

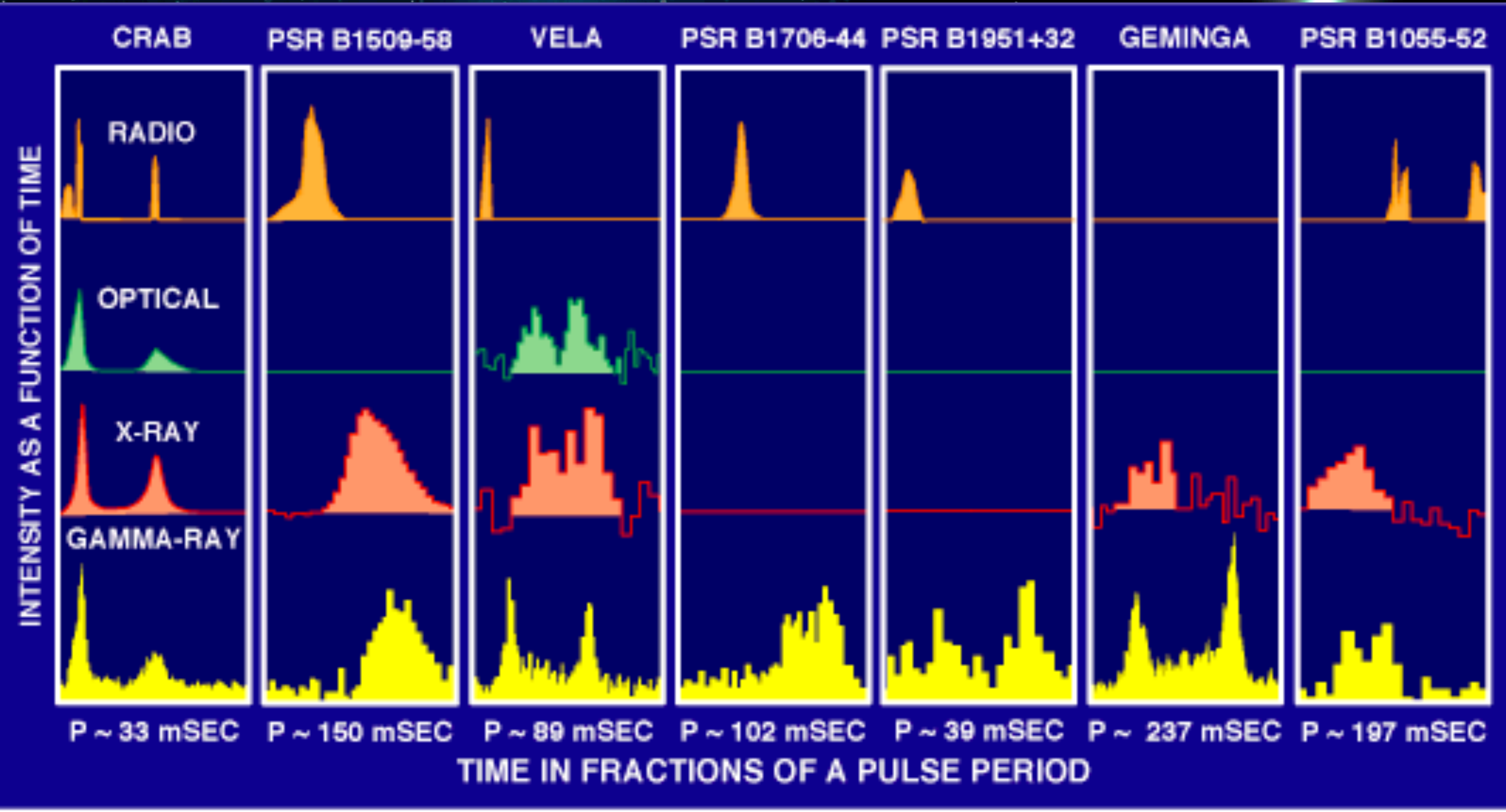
- Changing magnetic field produces electric field



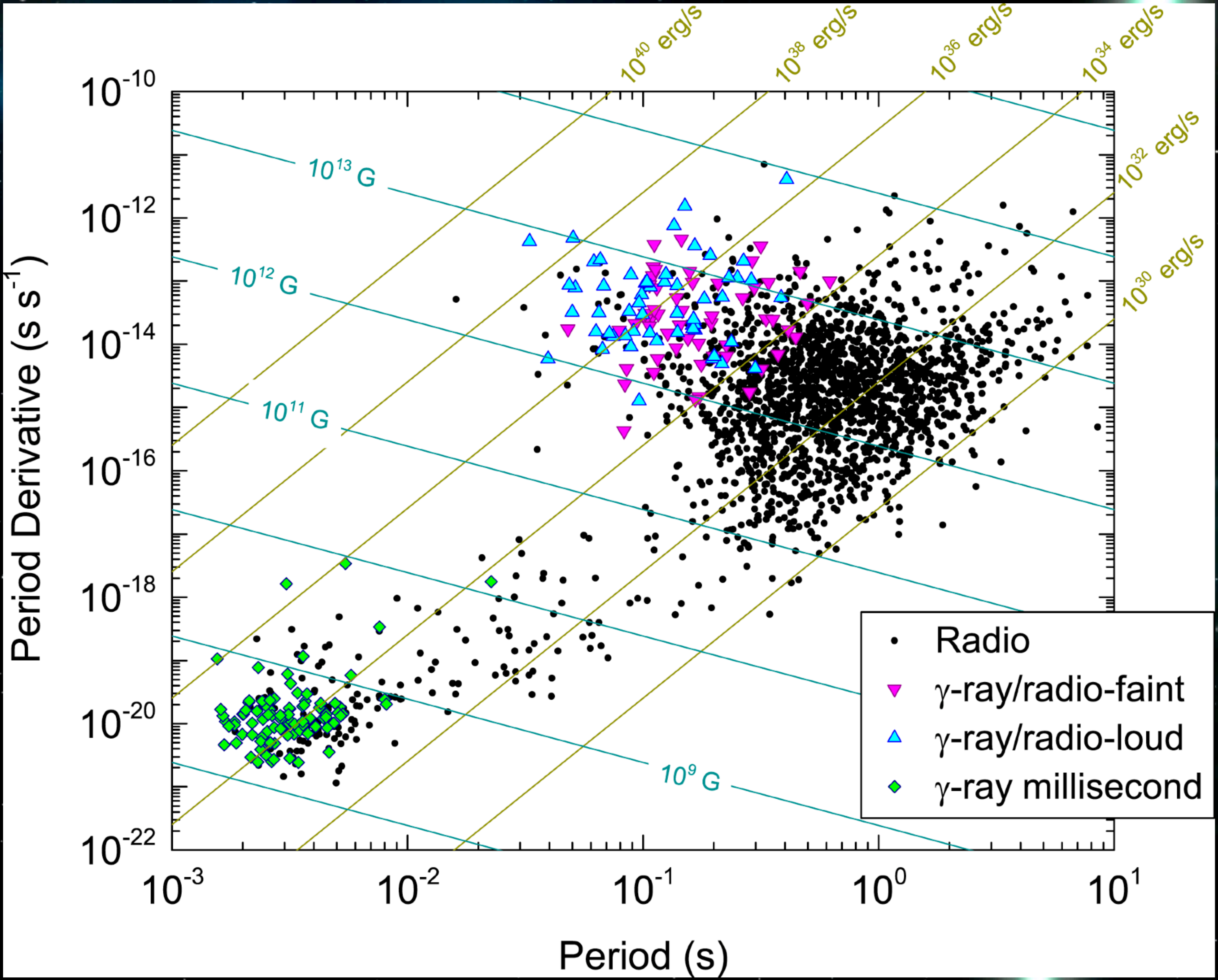
- 1000 PV potential available to accelerate particles

Ruderman & Sutherland (1975)

Multiwavelength Emission

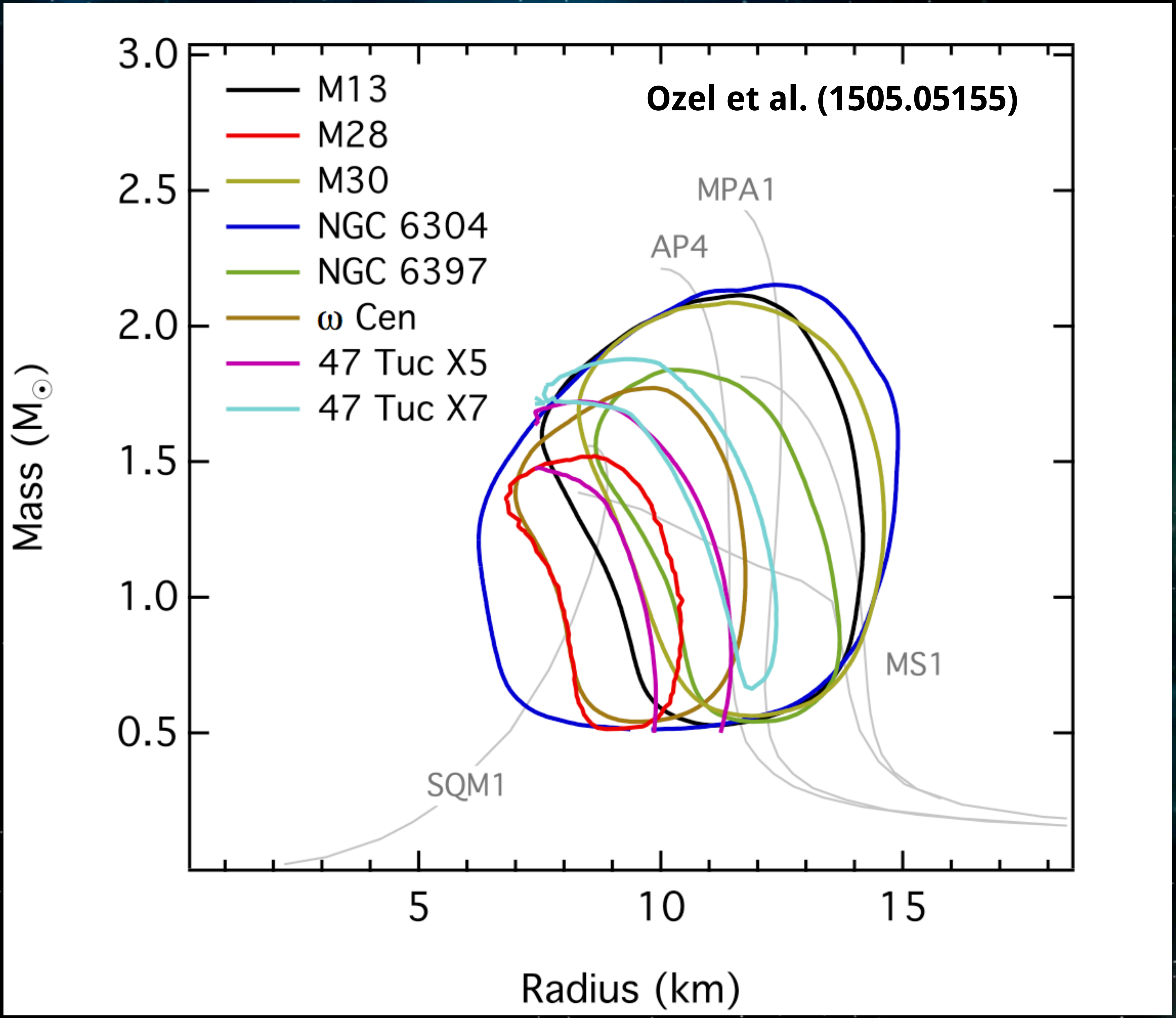


credit: Dave Thompson



Harding (2016; J Plasma Phys 82)

A Window Into Extreme Physics



A Window Into General Relativity

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

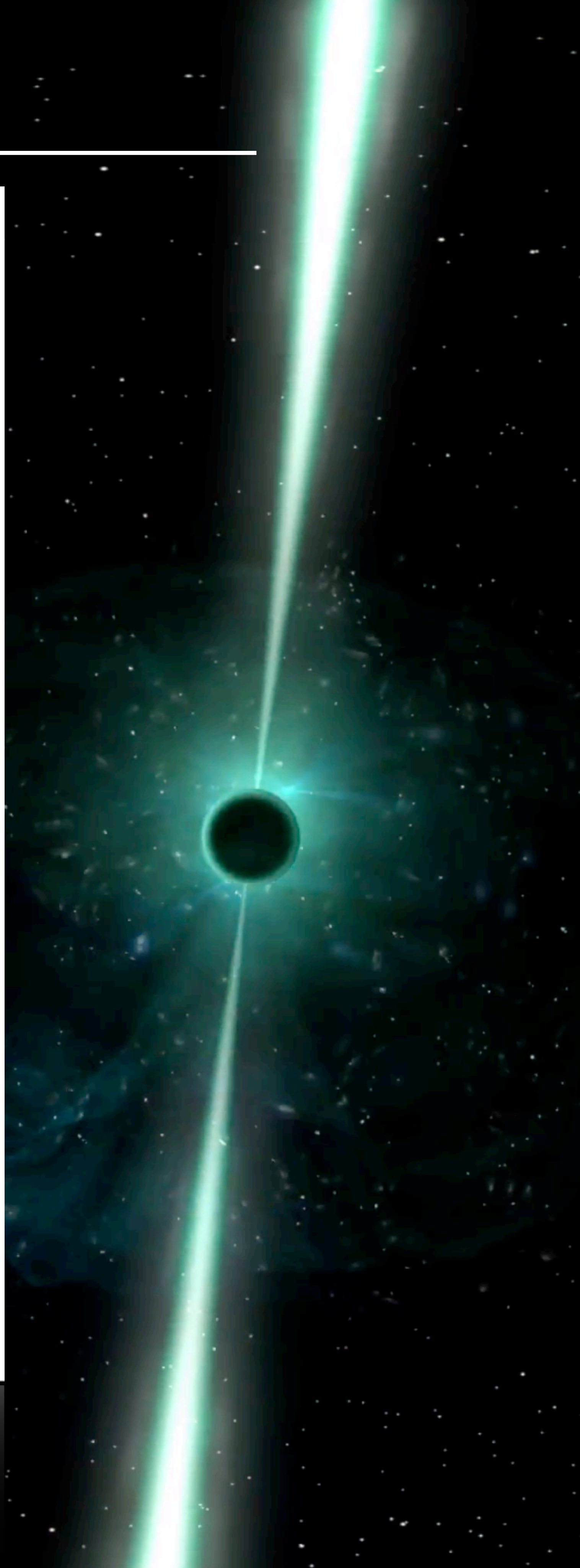
Multi-messenger Observations of a Binary Neutron Star Merger

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.)

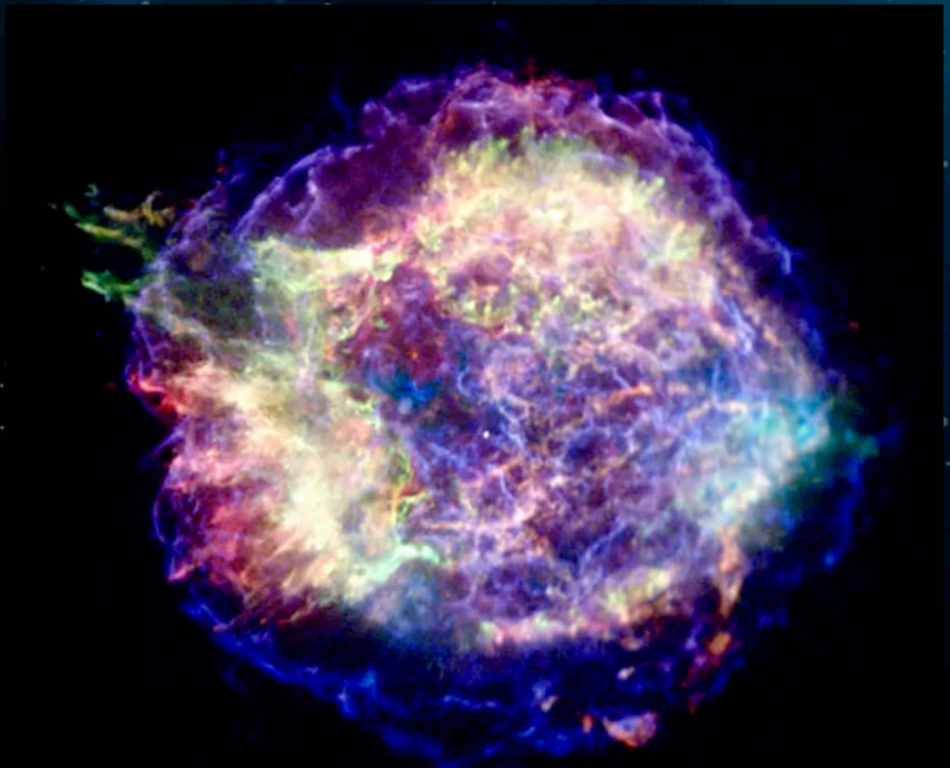
Received 2017 October 3; revised 2017 October 6; accepted 2017 October 6; published 2017 October 16

Abstract

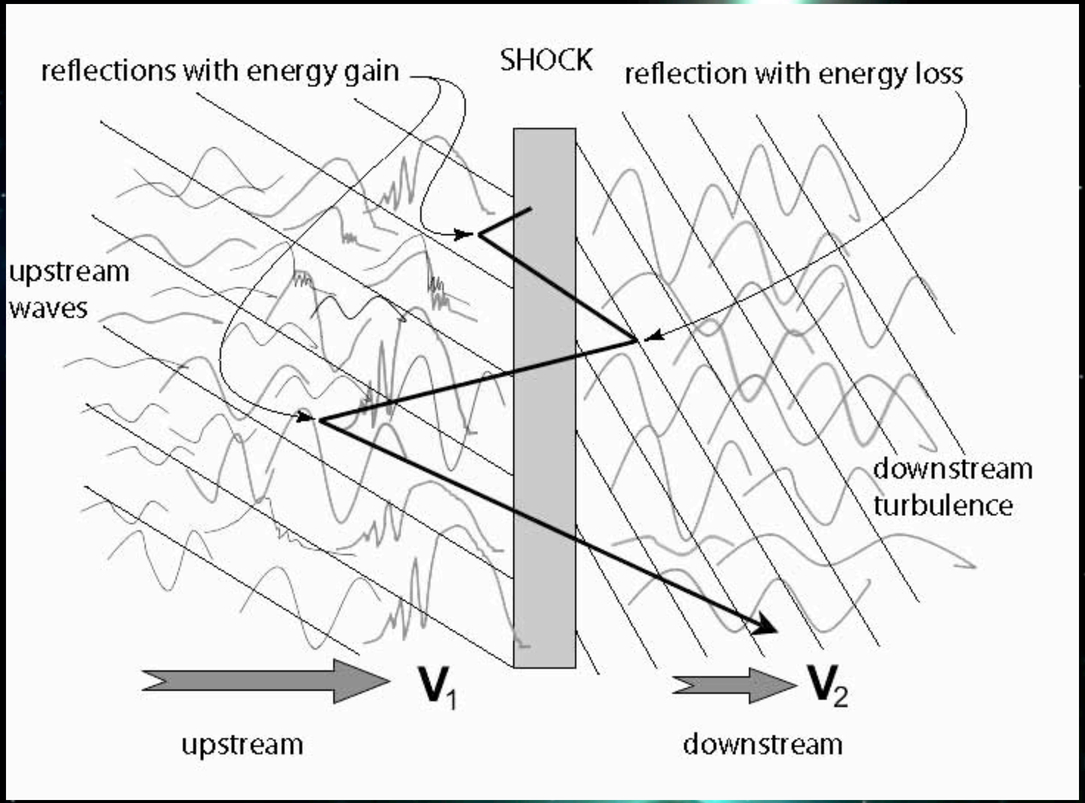
On 2017 August 17 a binary neutron star coalescence candidate (later designated GW170817) with merger time 12:41:04 UTC was observed through gravitational waves by the Advanced LIGO and Advanced Virgo detectors. The *Fermi* Gamma-ray Burst Monitor independently detected a gamma-ray burst (GRB 170817A) with a time delay of $\sim$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 $\sim$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 $\sim$10 days. Following early non-detections, X-ray and radio emission were discovered at the transient's position $\sim$9 and $\sim$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.



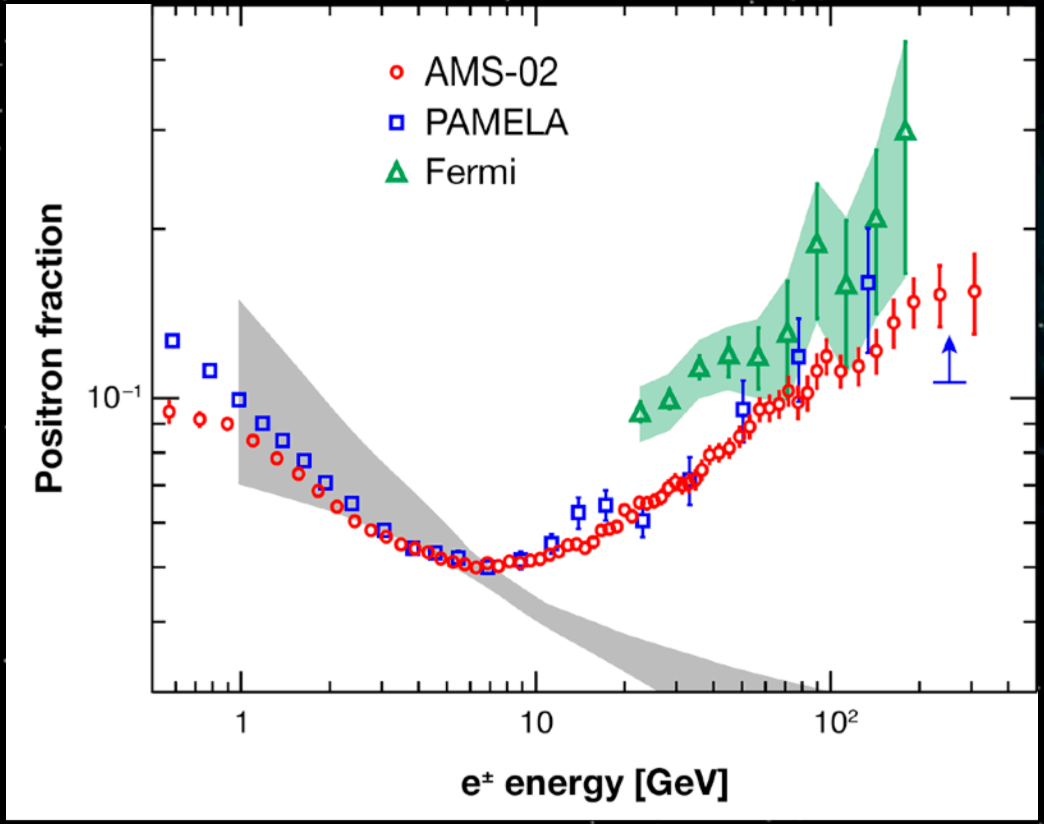
A Window Into Astrophysics



Massive Stars



Shock Acceleration



Positron Excess

A Window Into Fundamental Physics

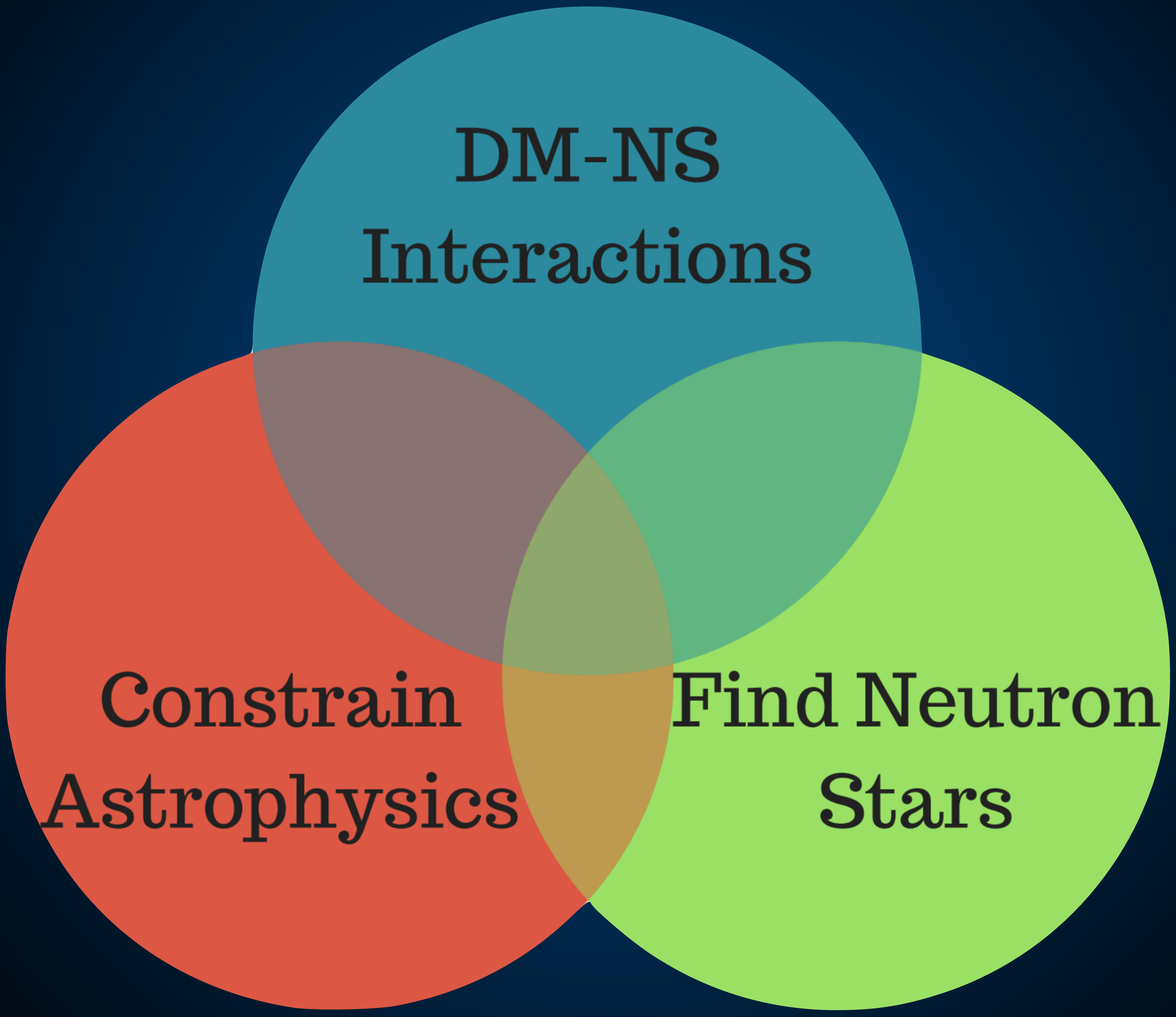
- Sensitive probes of rare processes:

  1. Nuclear densities over macroscopic distances

  2. Strongest magnetic fields in the universe

- Precise measurements are possible

The Program

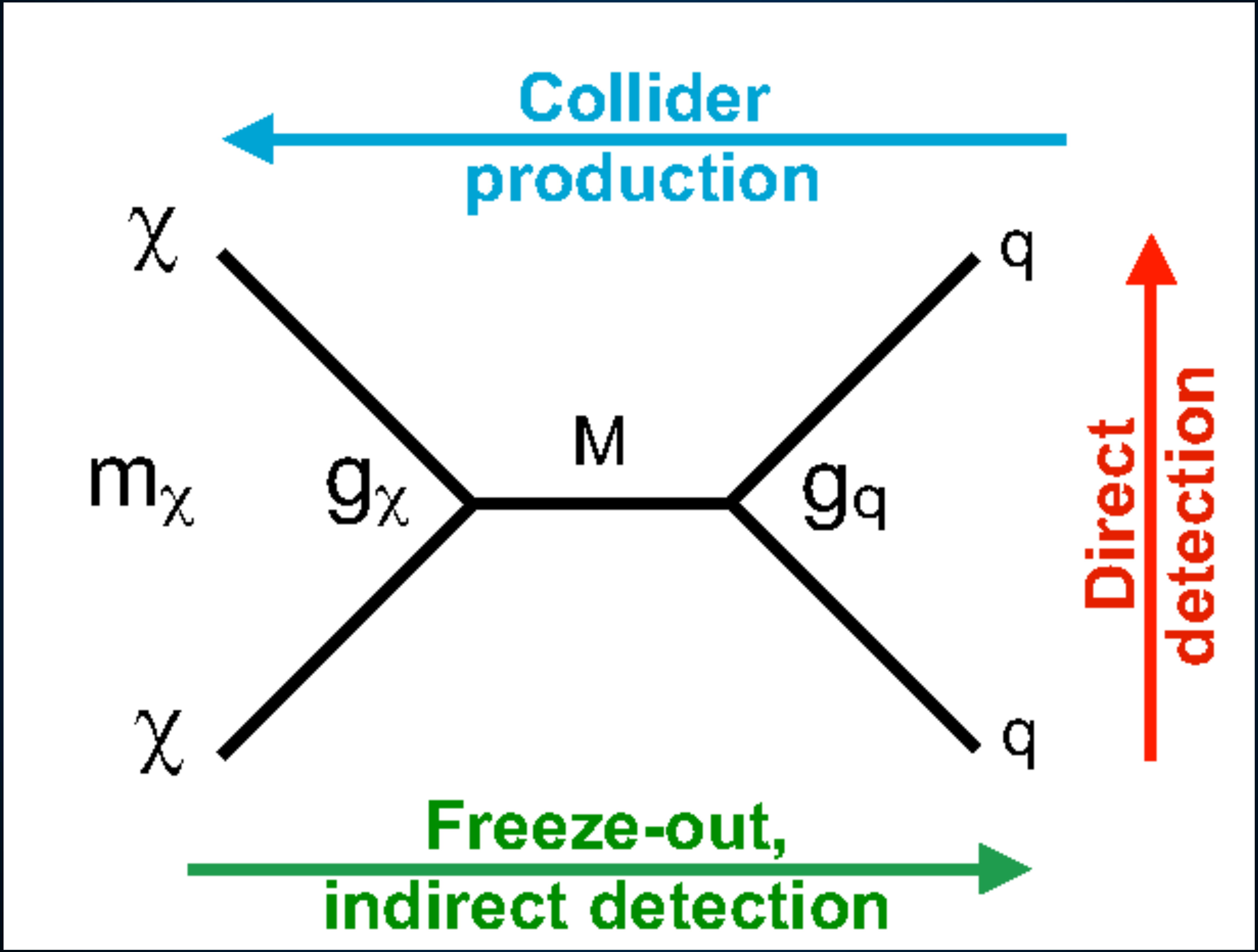

DM-NS
Interactions
Constrain
Astrophysics
Find Neutron
Stars

A Window Into Fundamental Physics

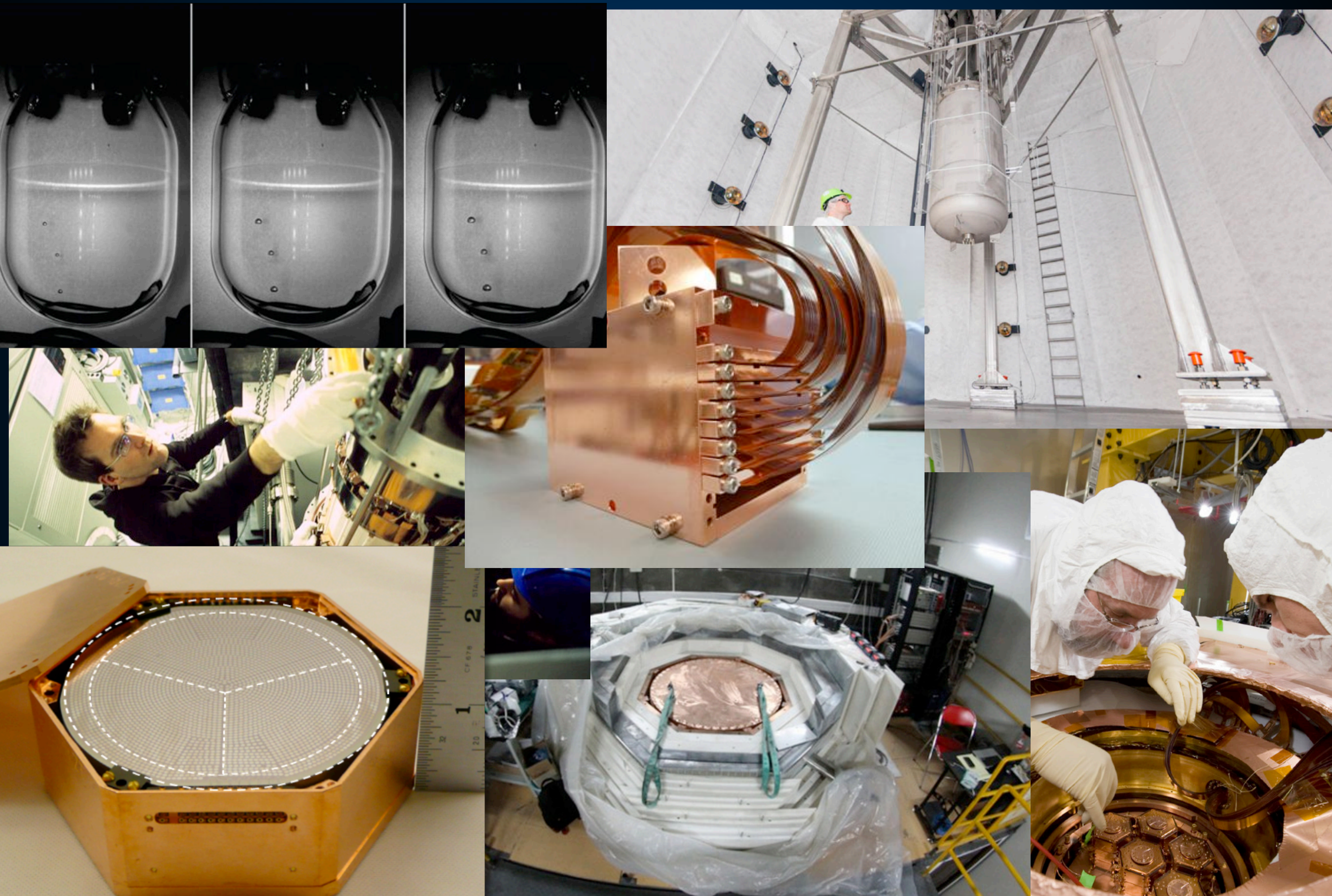
- **Sensitive probes of rare processes:**
  1. Nuclear densities over macroscopic distances
  2. Strongest magnetic fields in the universe

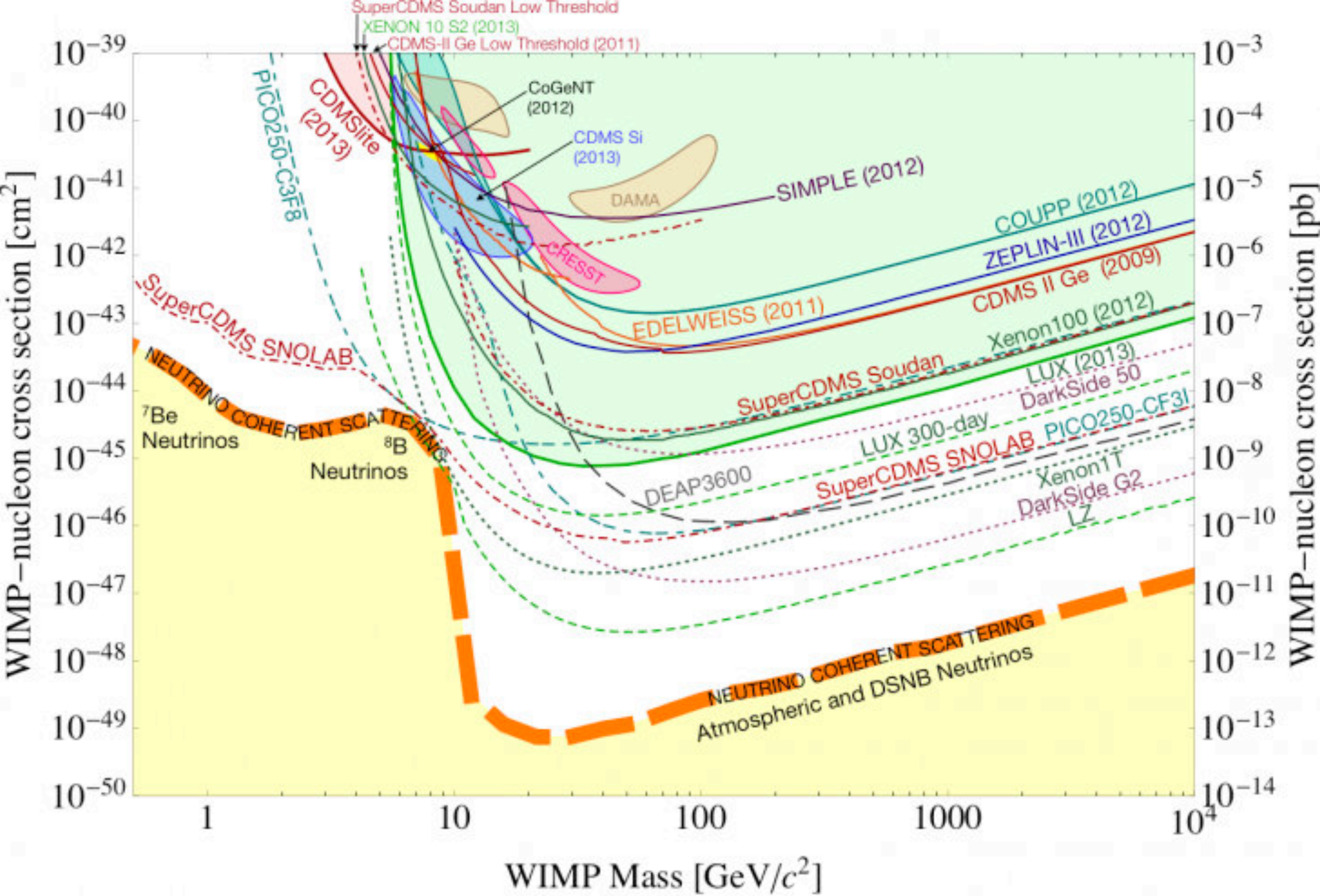
- **Precise measurements are possible**

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)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
CRESST
EDELWEISS (2011)
Xenon100 (2012)
LUX (2013)
DarkSide 50
SuperCDMS Soudan
SuperCDMS SNOLAB
PICO250-CF3I
LUX 300-day
DEAP3600
Xenon1T
DarkSide G2
LZ
NEUTRINO COHERENT SCATTERING
7Be Neutrinos
8B Neutrinos
Atmospheric and DSNB Neutrinos
WIMP–nucleon cross section [cm2]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c2]

Neutron Stars: The Optimal Direct Detection Experiment

Neutron Star

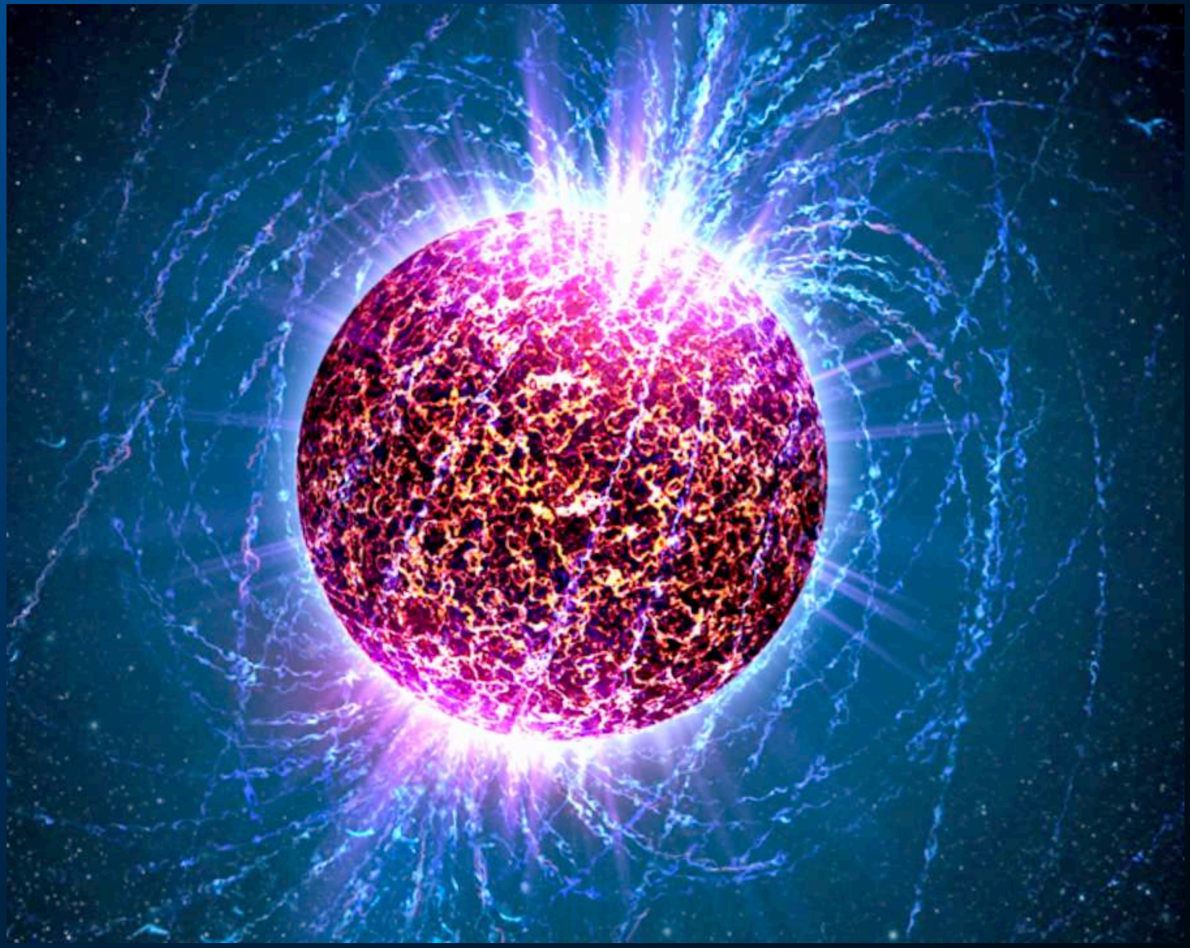
- 10^{30} kg
- 10^{12} days

10^{42} kg day

LUX

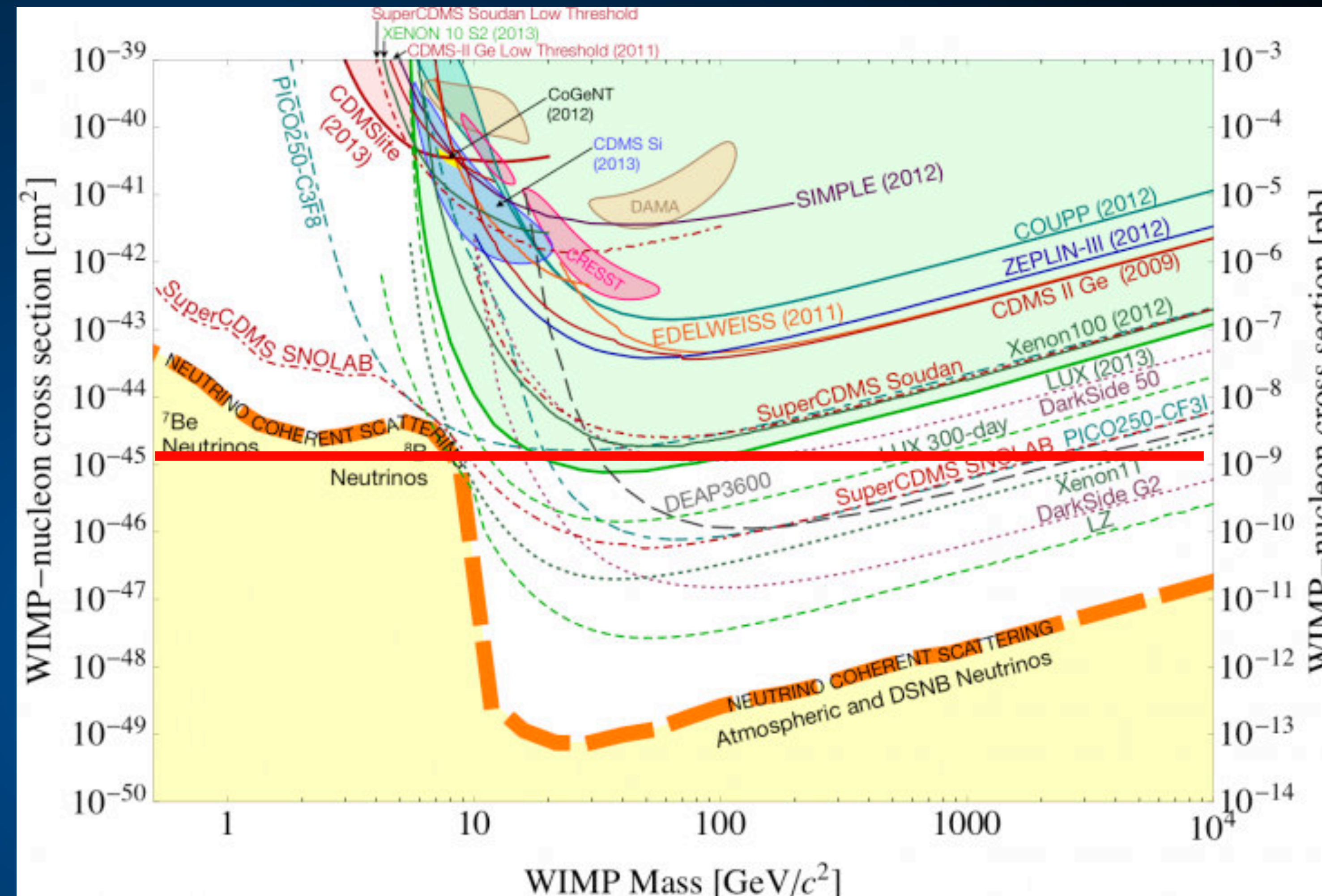
- 100 kg
- 1000 days

10^{5} kg day



Neutron Stars: The Optimal Direct Detection Experiment

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

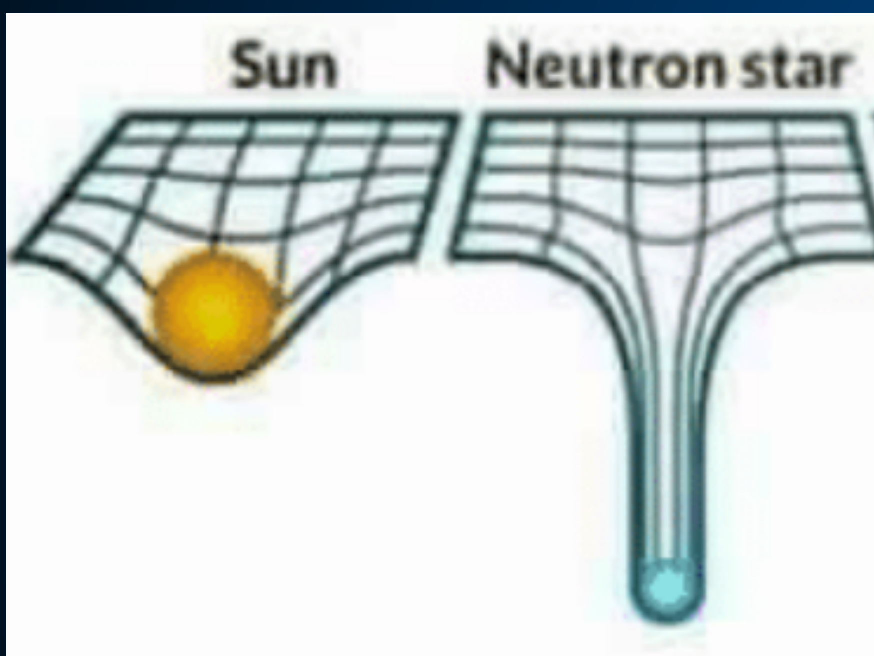


$$\sigma_{\mathrm{sat}}^{\mathrm{single}} \simeq \pi R^2 m_{\mathrm{n}}/M \simeq 2 \times 10^{-45}\ \mathrm{cm}^2 \left(\frac{1.5\ \mathrm{M}_\odot}{M}\right)\left(\frac{R}{10\ \mathrm{km}}\right)^2$$

- **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

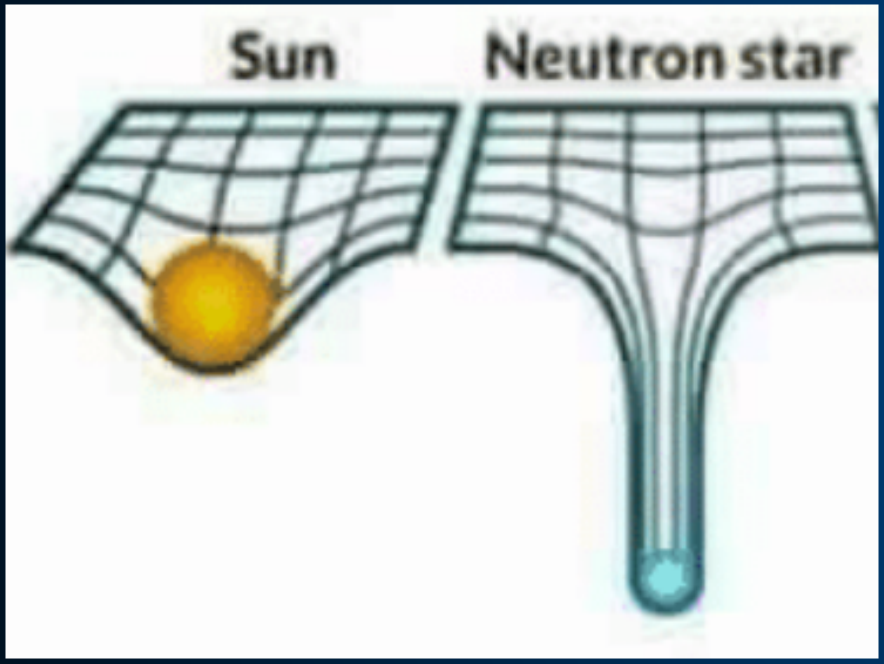
$$b_{\max} = \left(\frac{2GMR}{v_x^2}\right)^{1/2} \left(1 - \frac{2GM}{R}\right)^{-1/2}$$

$$\dot{m} = \pi b_{\max}^2 v_x \rho_x,$$

- 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:

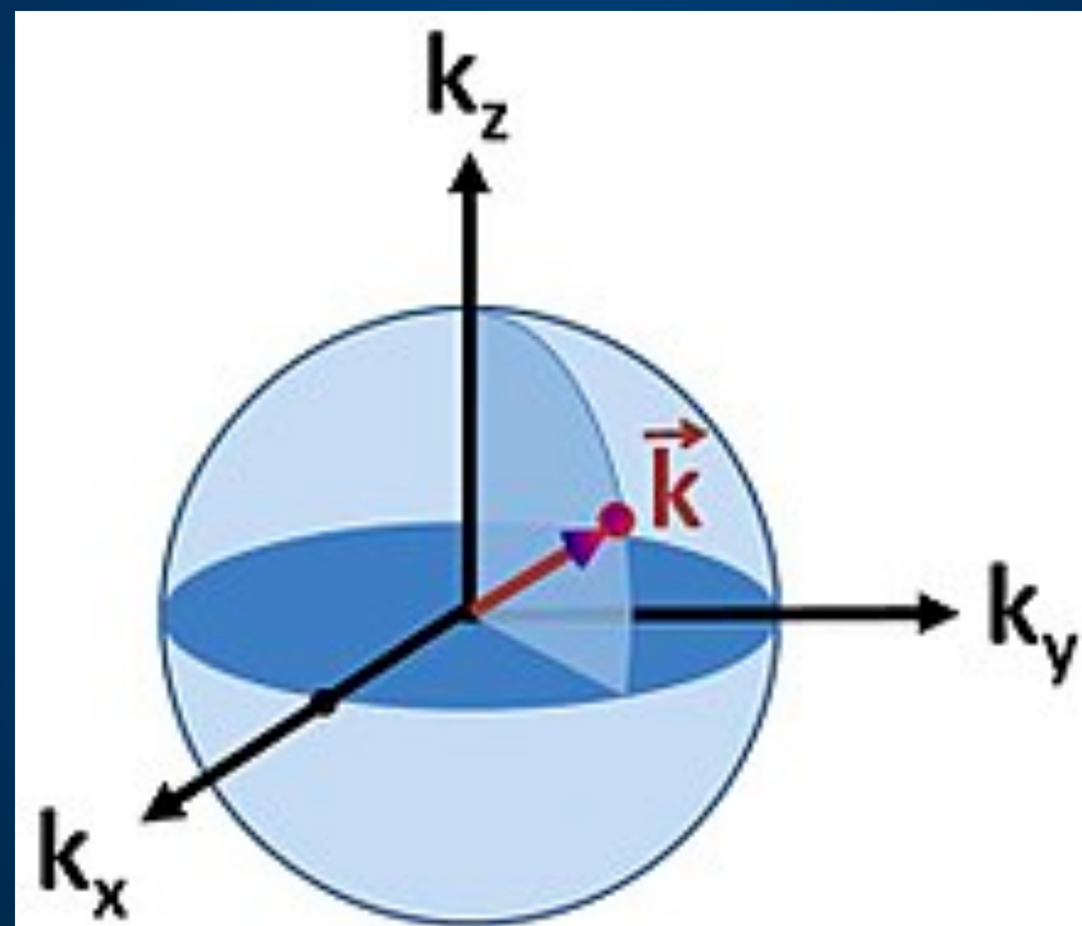
$$v_{esc} = \sqrt{\frac{2GM}{r}} \sim 0.7c$$

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

Neutron Stars: Particle Physics Complications

Typical NS neutron momentum is:

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



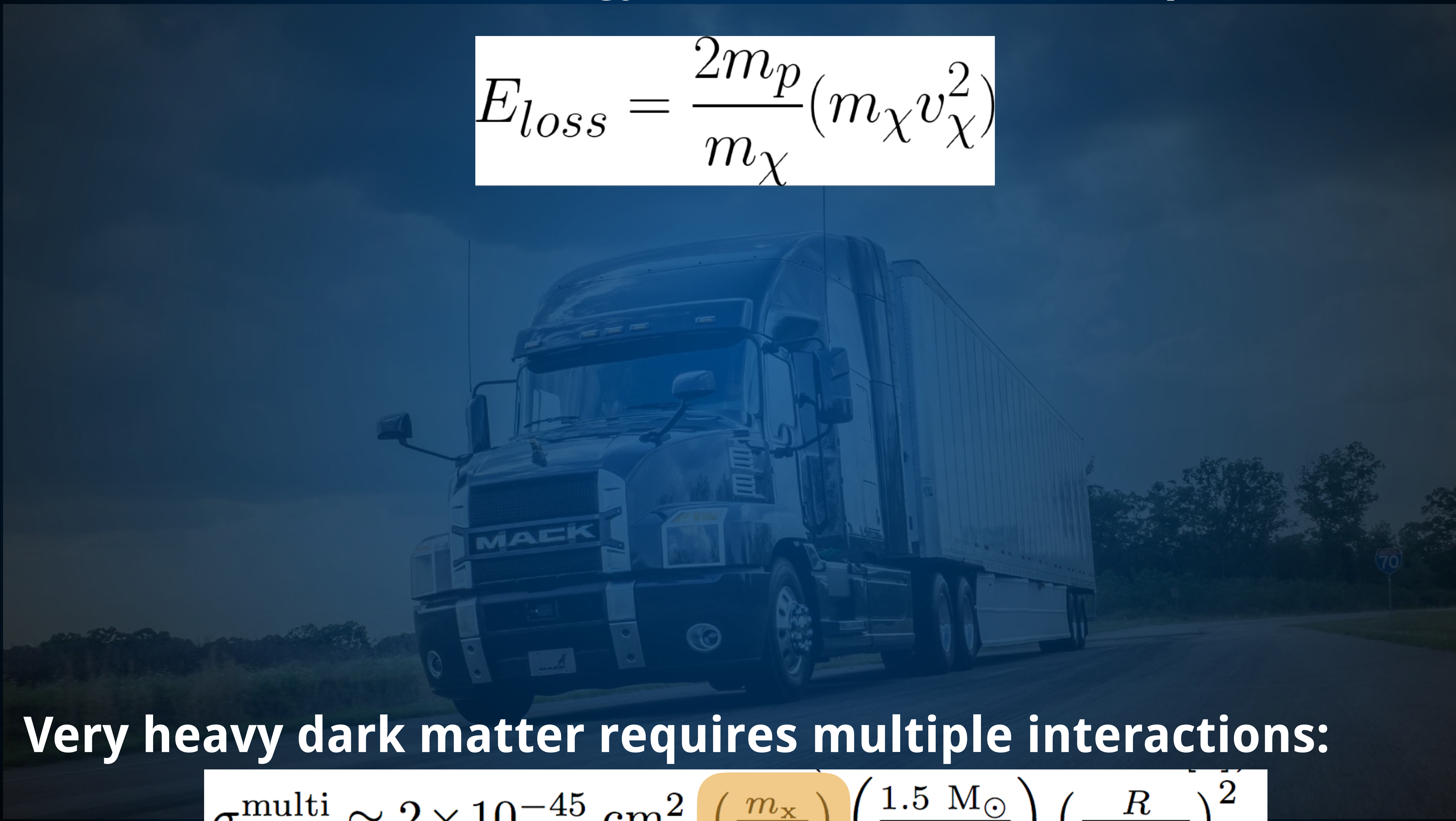
This suppresses the interaction cross-section for low mass DM:

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

Neutron Stars: Particle Physics Complications

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

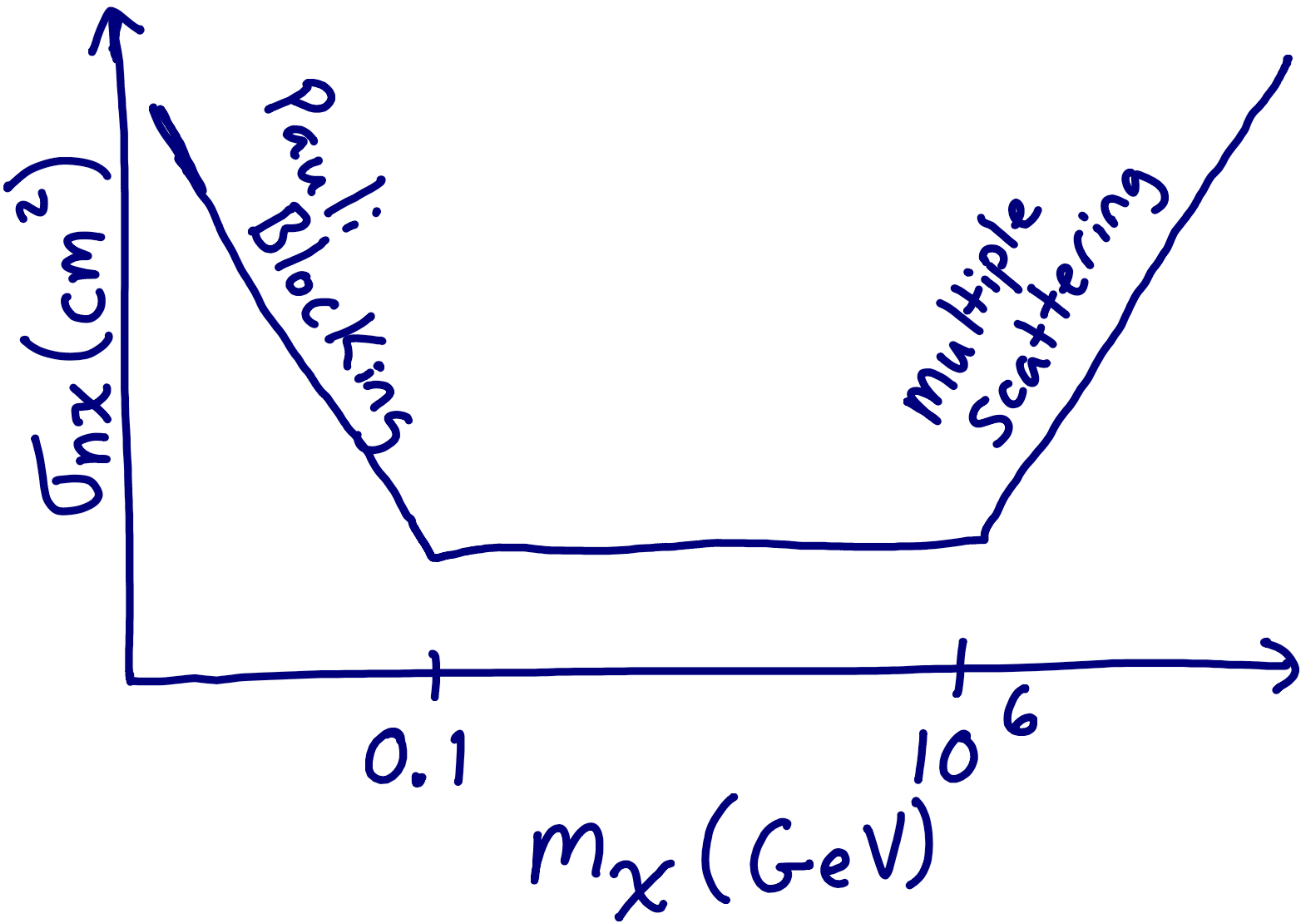
$$E_{loss} = \frac{2m_p}{m_\chi}(m_\chi v_\chi^2)$$



Very heavy dark matter requires multiple interactions:

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

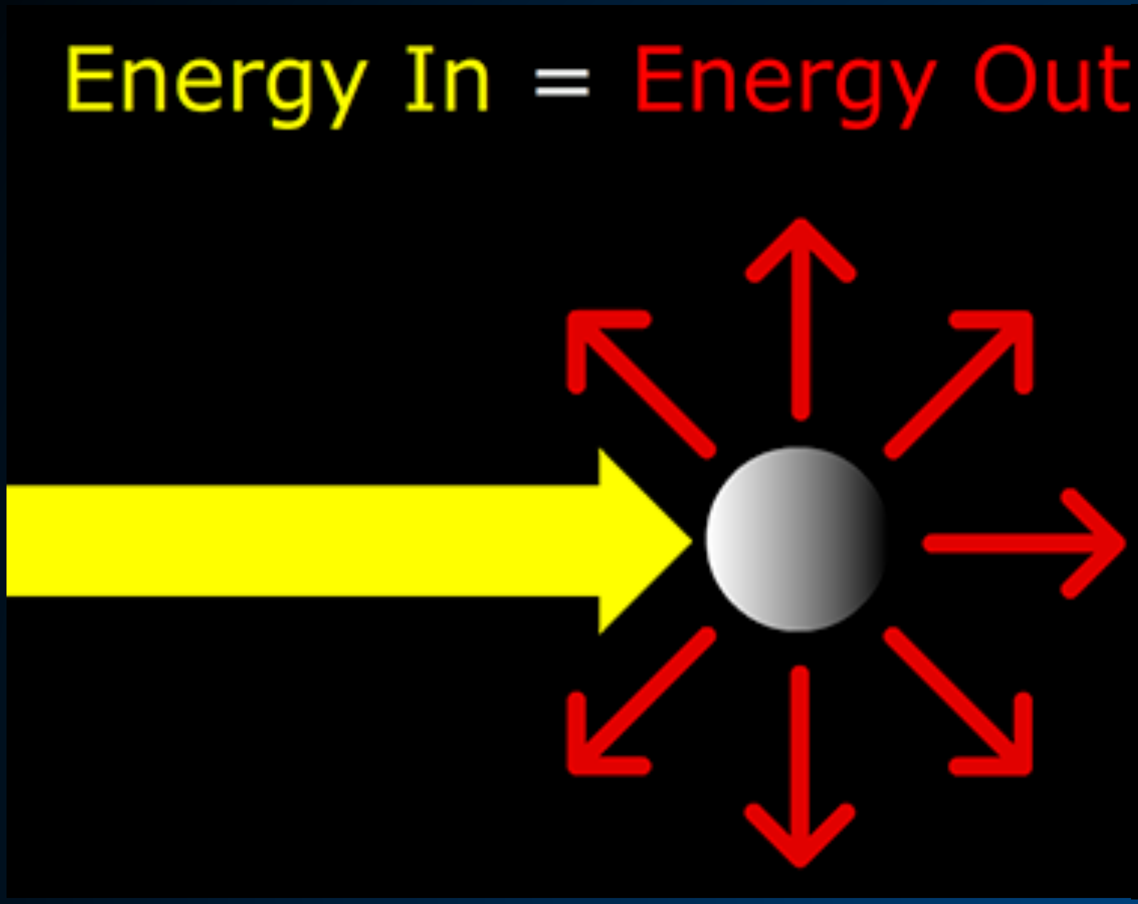
Neutron Stars: Particle Physics Complications

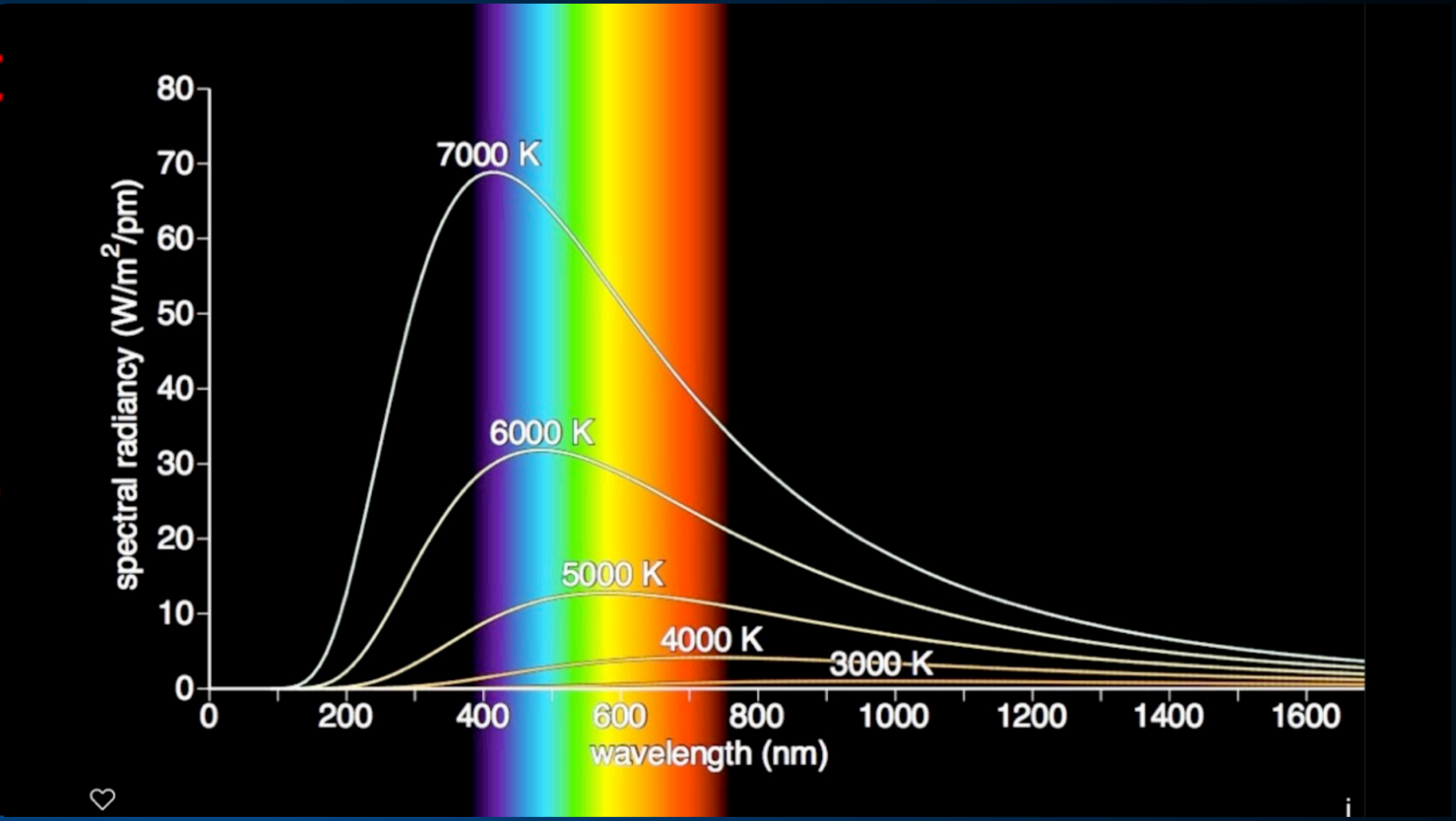


Detecting Dark Matter Scattering in Neutron Stars

Part I: Neutron Star Heating

Dark Matter Induced Heating





DM-NS collisions impart significant energy into the NS:

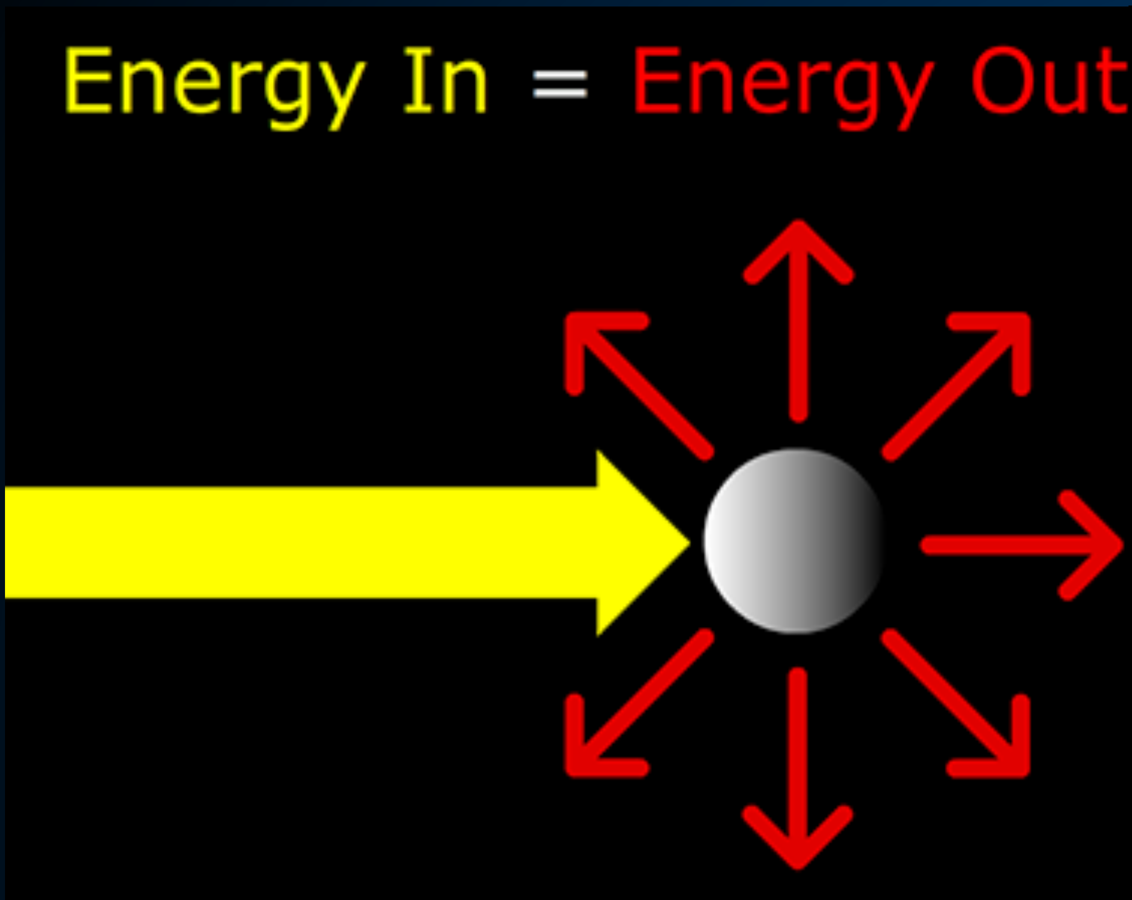
$$E_s \simeq m_x (\gamma - 1)$$

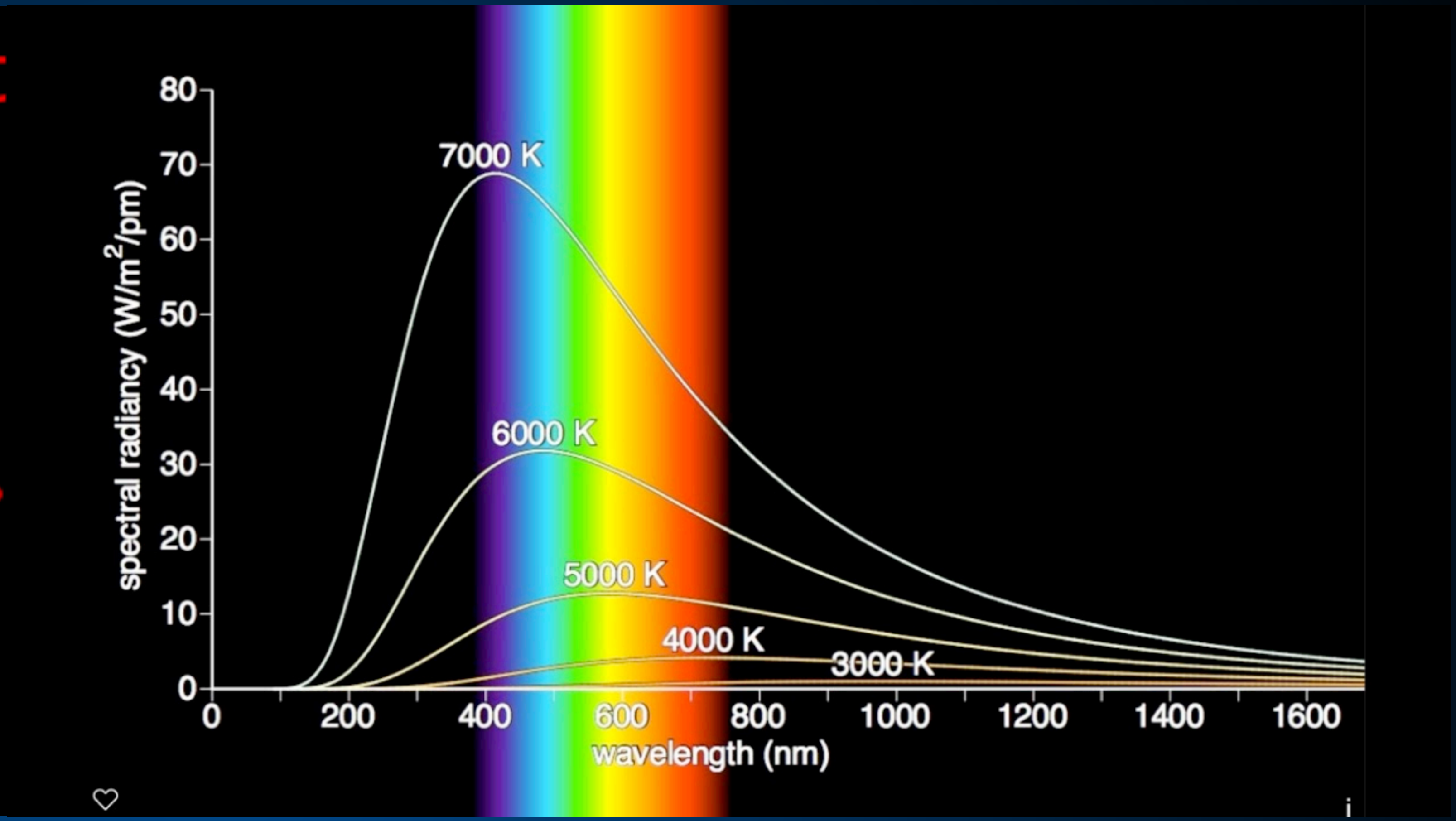
This induces blackbody emission of luminosity:

$$\dot{E}_k = \frac{E_s \dot{m}}{m_x} f \simeq 1.4 \times 10^{25} \ \mathrm{GeV\ s^{-1}} \ \left(\frac{f}{1}\right),$$

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))**

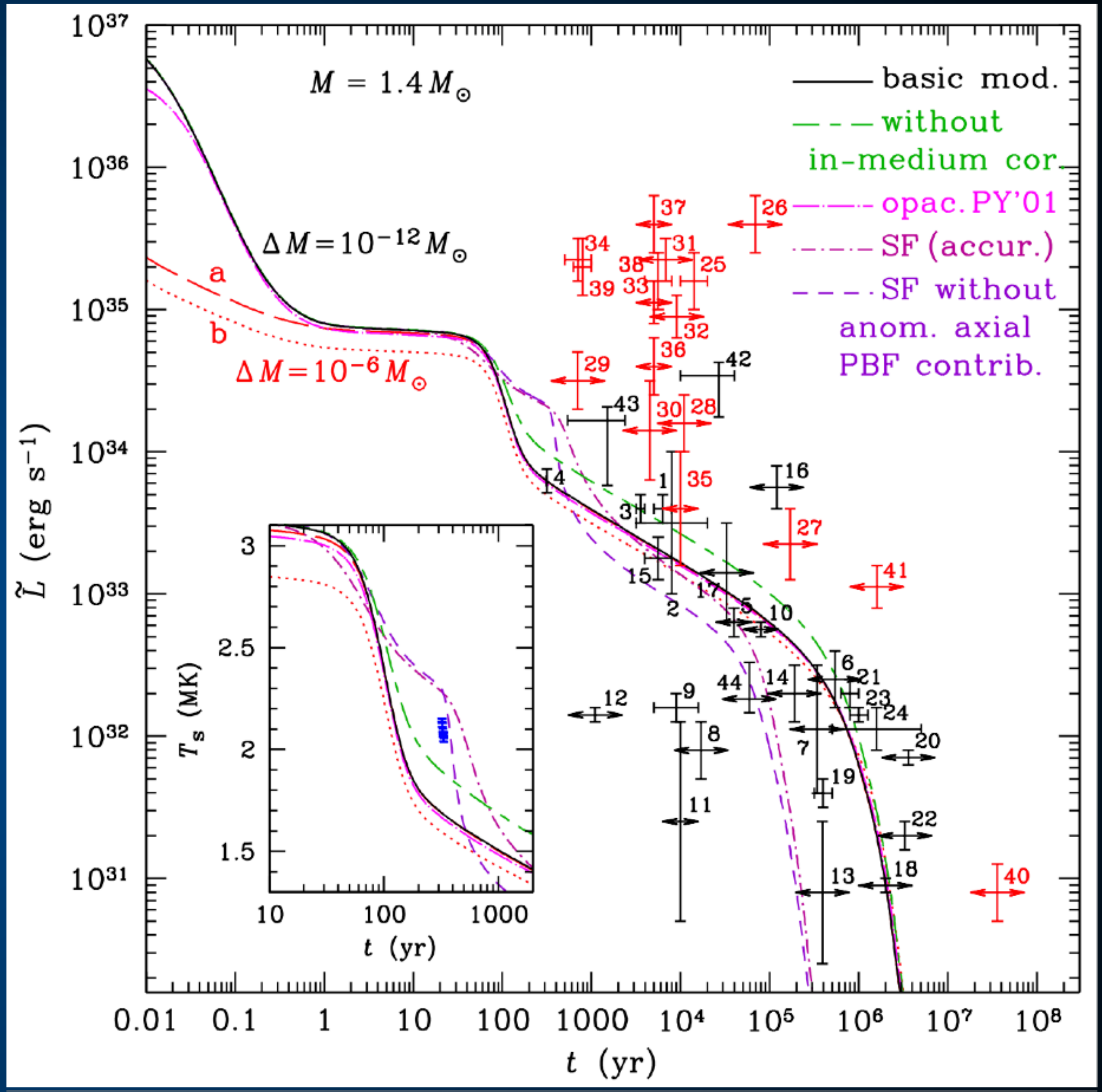
$$E_{\rm s} \simeq m_{\rm x} \left(\gamma - 1\right)$$

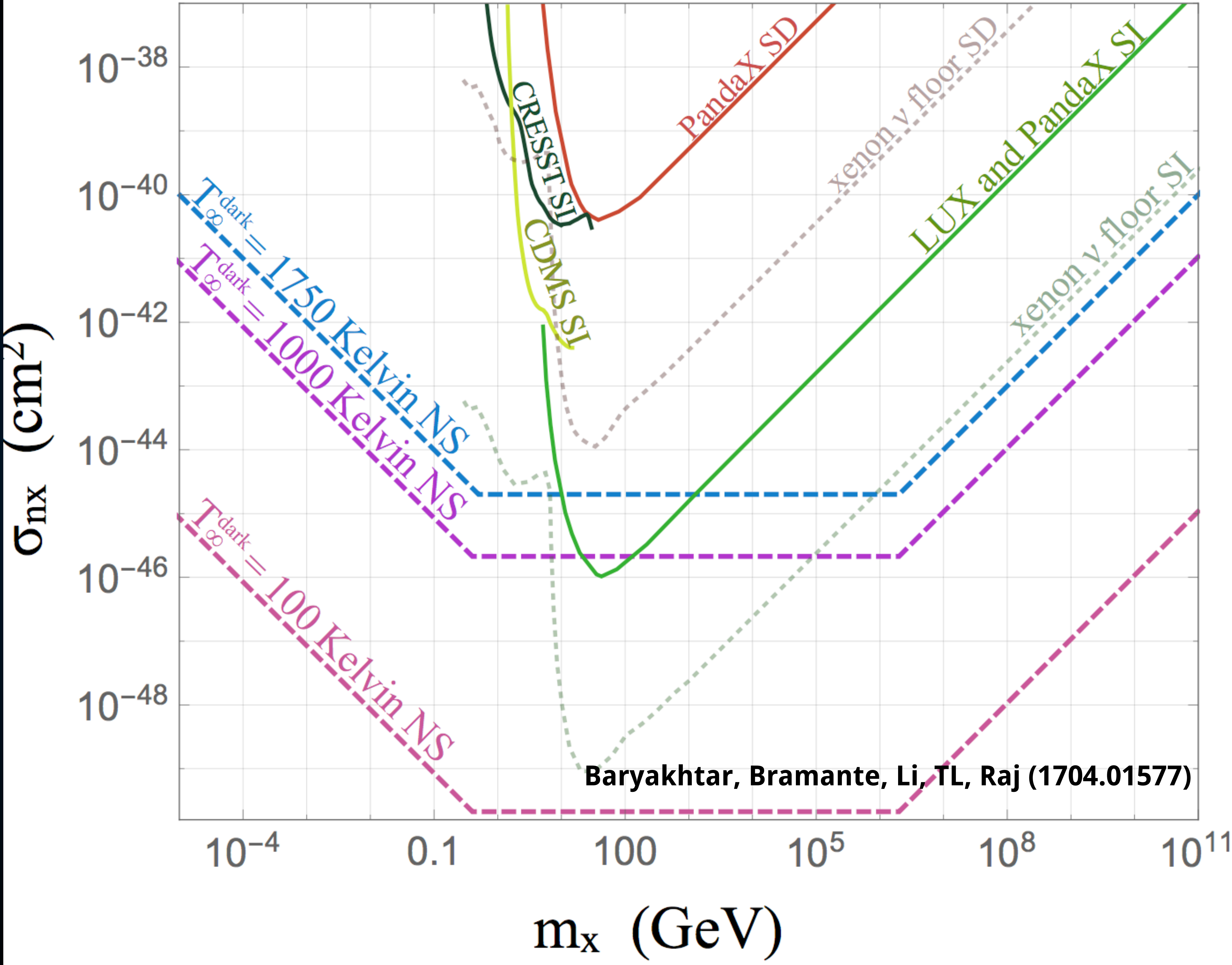
Baryakhtar, Bramante, Li, TL, Raj (1704.01577)

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)

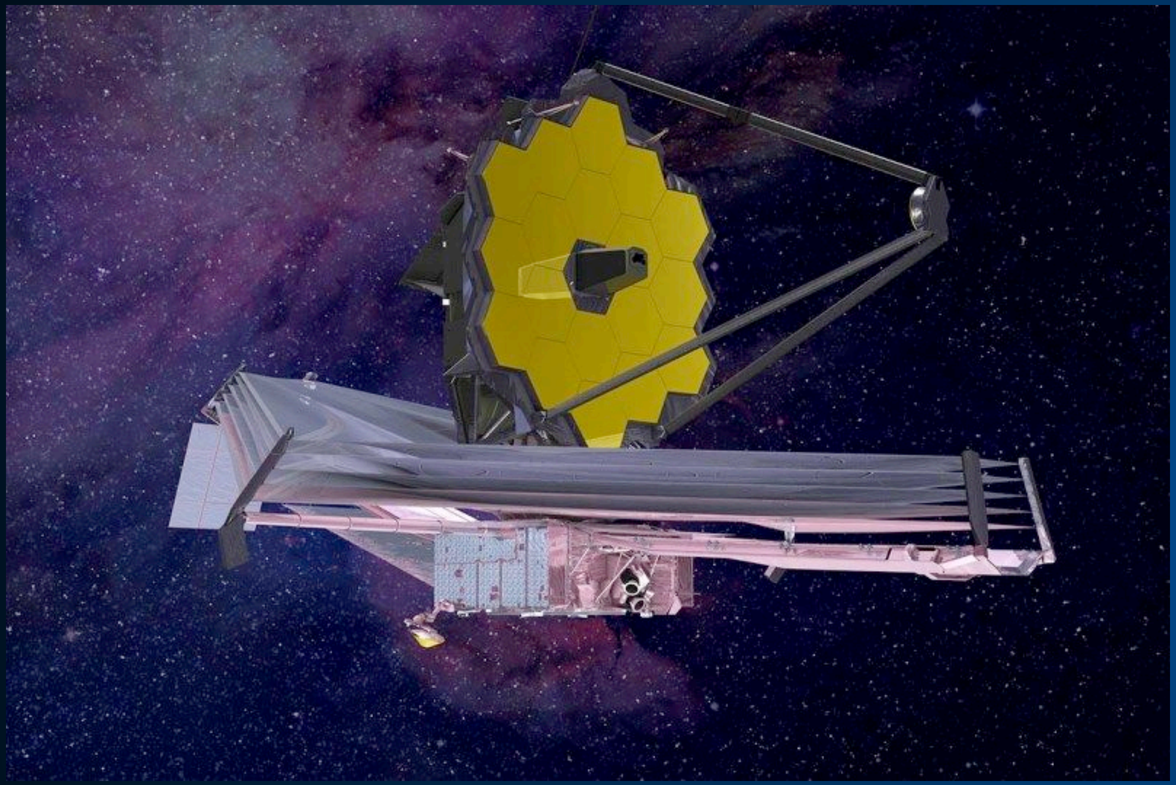




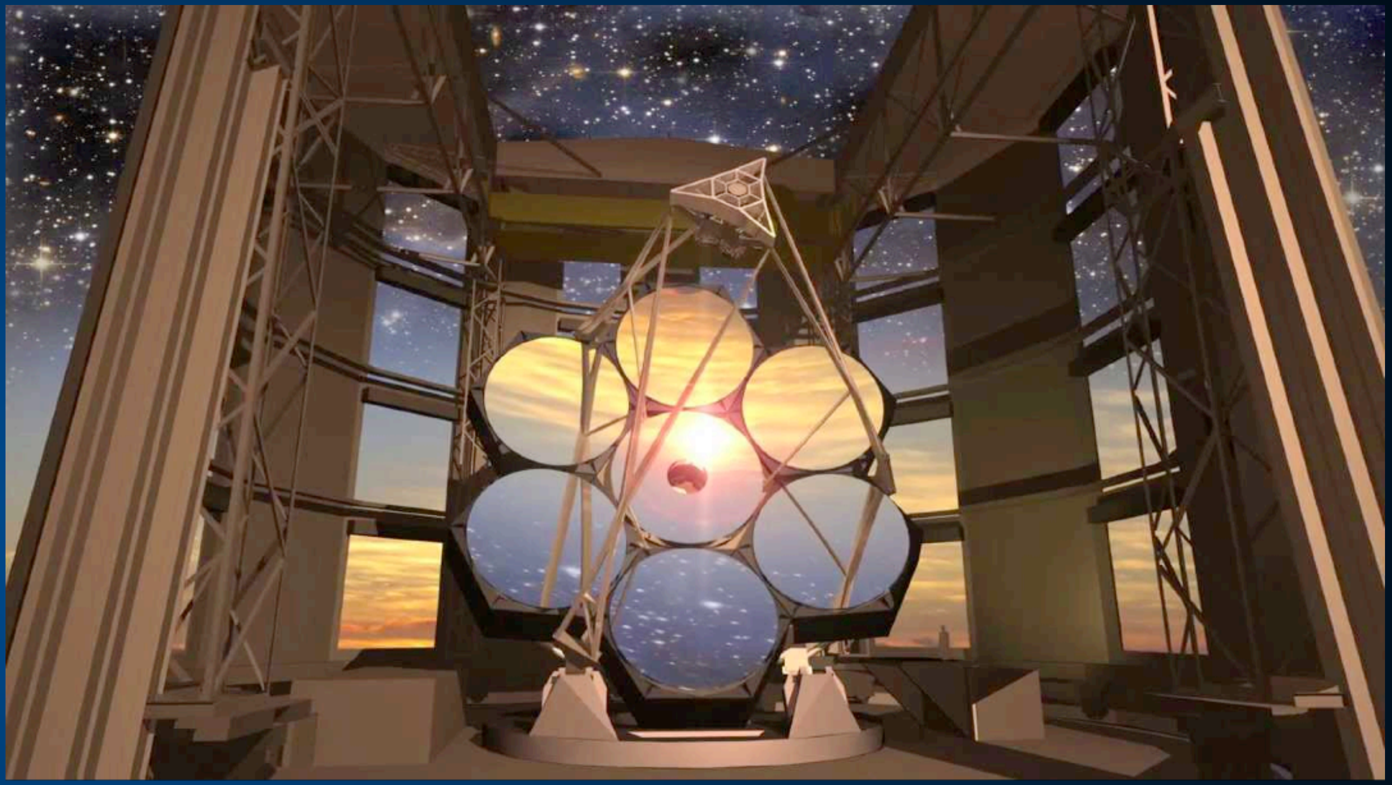
σnx (cm²)
mx (GeV)
10−38
10−40
10−42
10−44
10−46
10−48
10−4
0.1
100
10⁵
10⁸
10¹¹
PandaX SD
CRESST SI
CDMS SI
xenon ν floor SD
LUX and PandaX SI
xenon ν floor SI
T∞dark = 1750 Kelvin NS
T∞dark = 1000 Kelvin NS
T∞dark = 100 Kelvin NS
Baryakhtar, Bramante, Li, TL, Raj (1704.01577)

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.

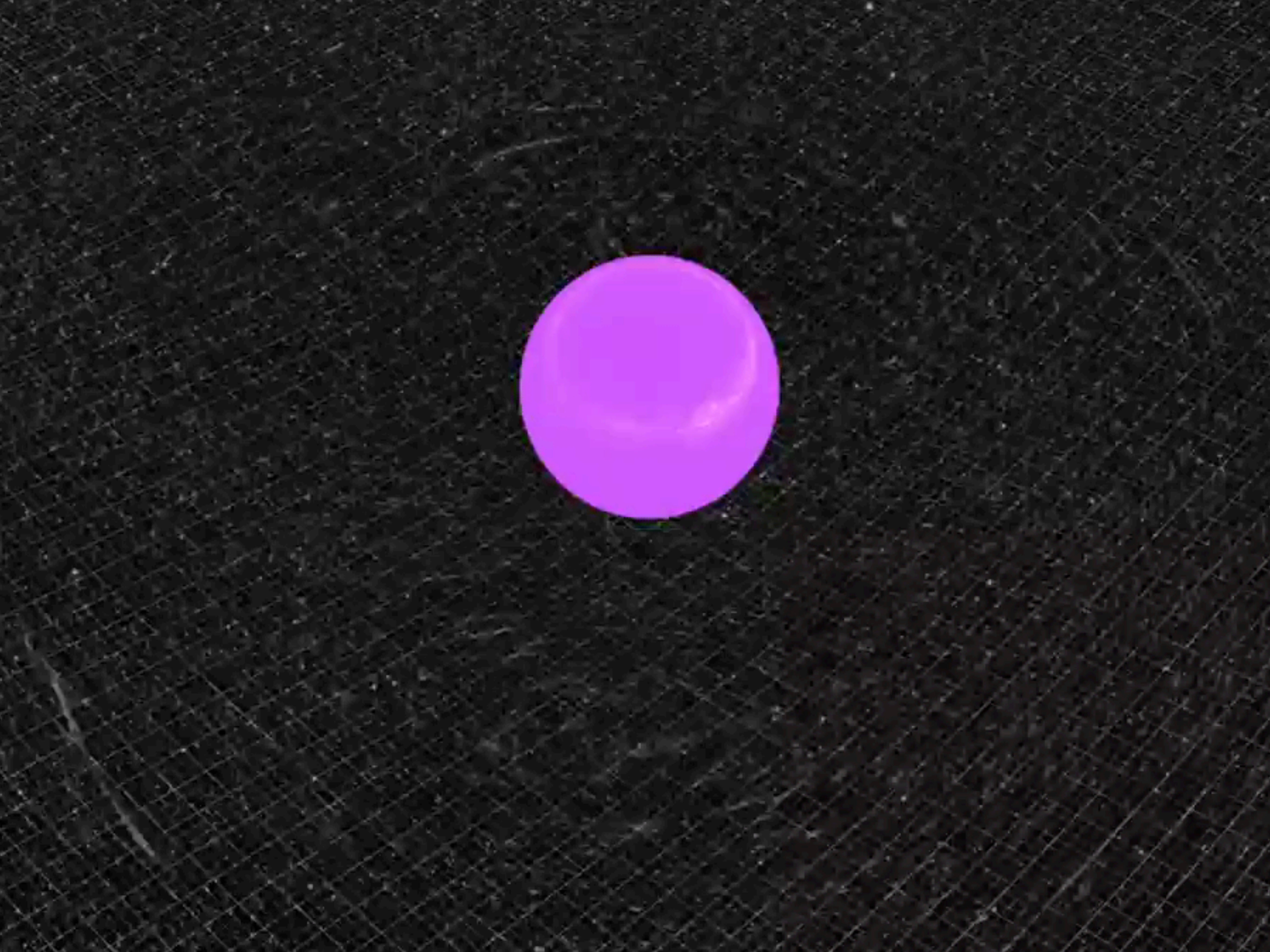
Detecting Dark Matter Scattering in Neutron Stars

Part II: Dark Matter Collapse

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 Parameter Space

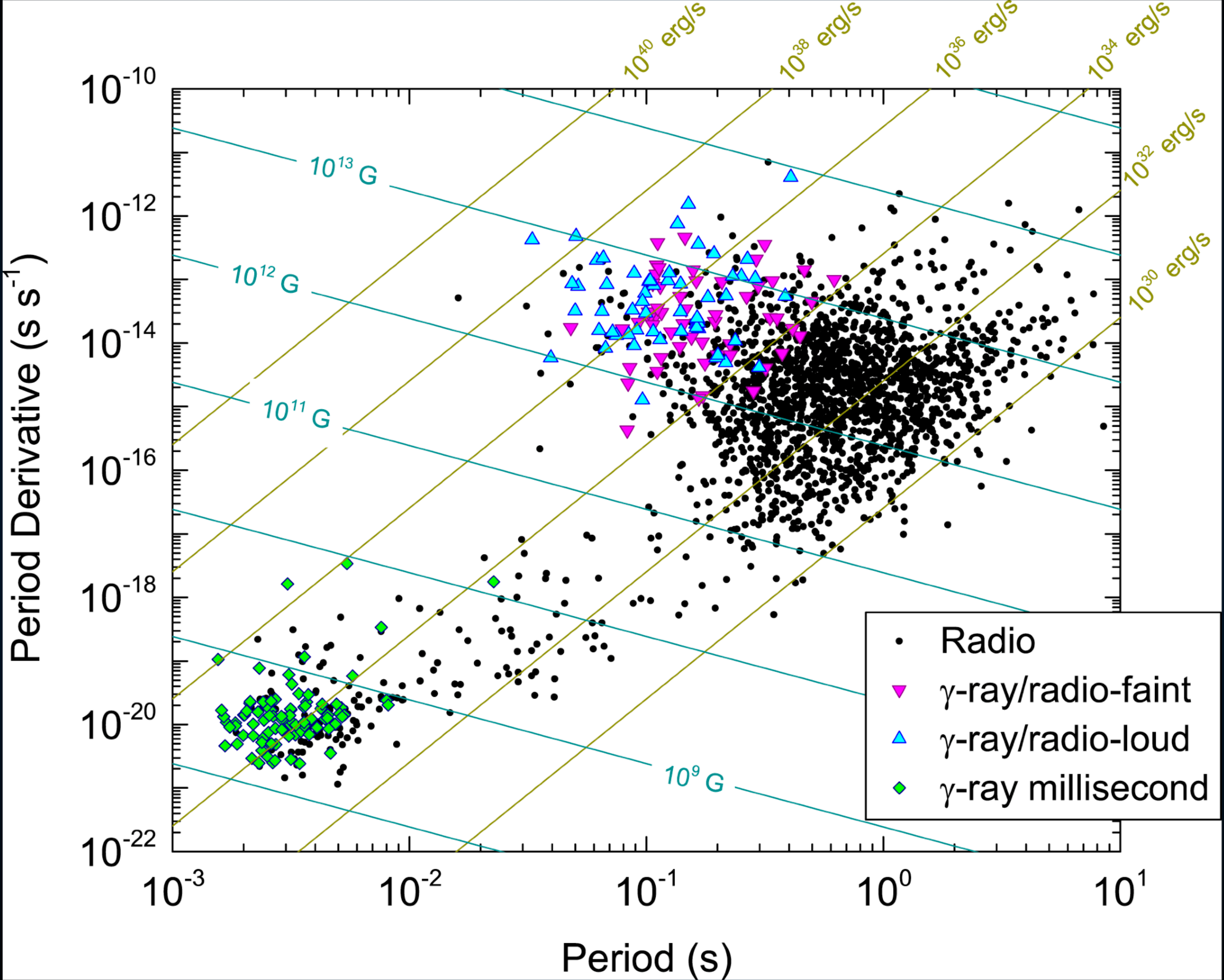
- Requires dark matter to be non-annihilating.

  - PeV Fermionic Dark Matter

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

  - Bosonic Dark Matter

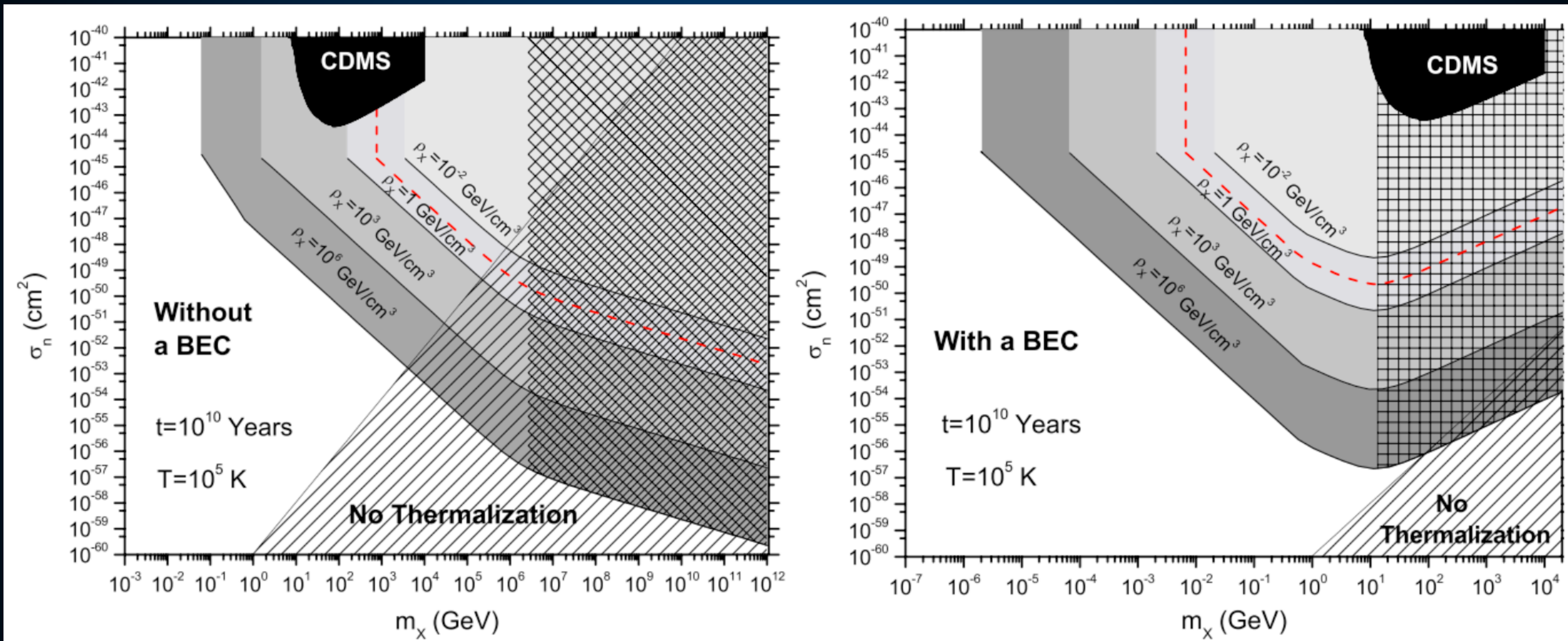
  - Attractive Self-Interacting Dark Matter



Period Derivative (s s^{-1})
Period (s)
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-22}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
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
Radio
γ-ray/radio-faint
γ-ray/radio-loud
γ-ray millisecond

Strong Constraints are Possible

McDermott et al. (1103.5472)

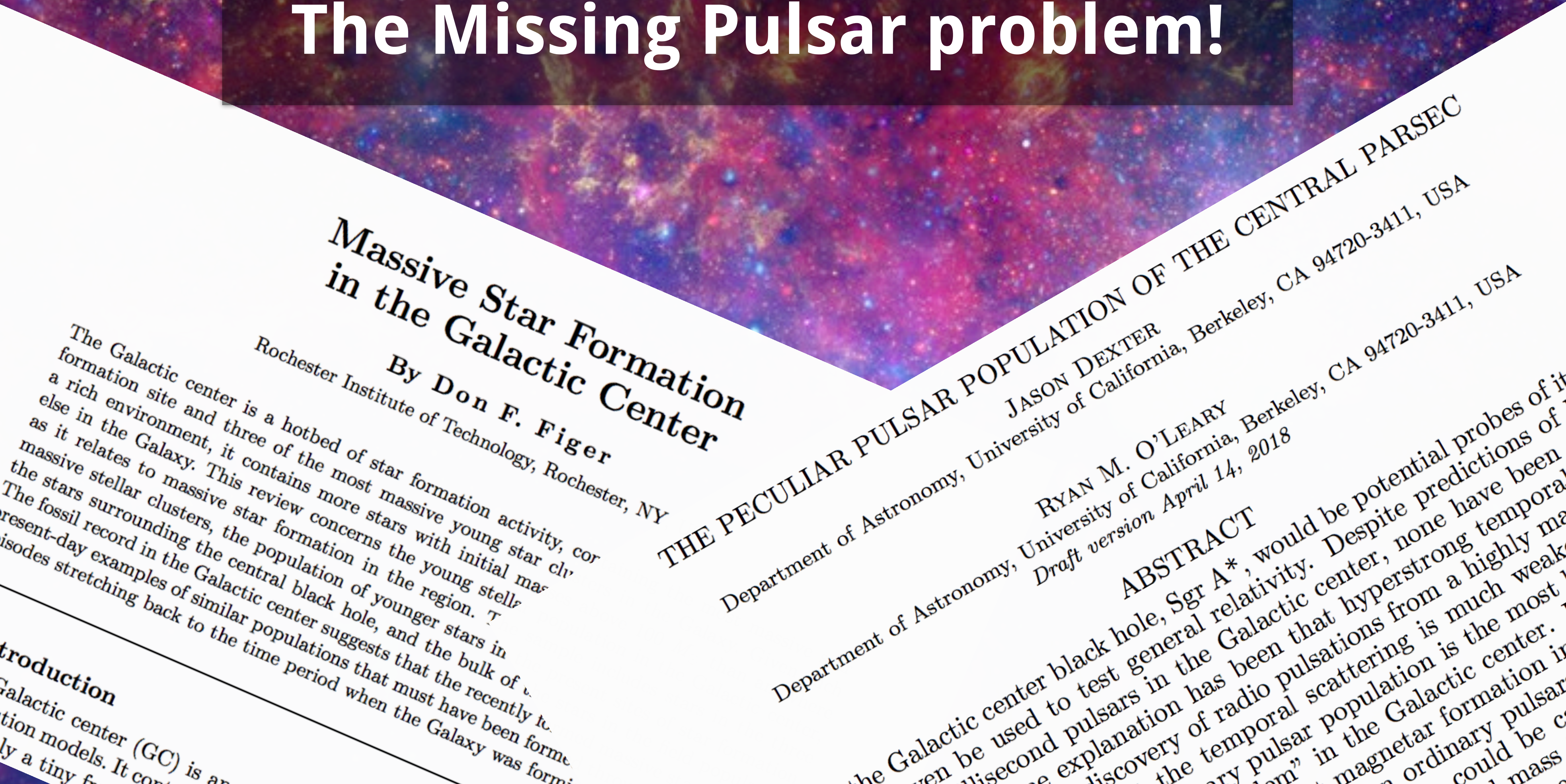


A Signal

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

Only one (very young) pulsar detected

The Missing Pulsar problem!



A Signal

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

Only one (very young) pulsar detected

The Missing Pulsar problem!

A Notre Dame Connection

Detecting Dark Matter with Imploding Pulsars in the Galactic Center

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The paucity of old millisecond pulsars observed at the galactic center of the Milky Way could be the result of dark matter accumulating in and destroying neutron stars. In regions of high dark matter density, dark matter clumped in a pulsar can exceed the Schwarzschild limit and collapse into a natal black hole which destroys the pulsar. We examine what dark matter models are consistent with this hypothesis and find regions of parameter space where dark matter accumulation can significantly degrade the neutron star population within the galactic center while remaining consistent with observations of old millisecond pulsars in globular clusters and near the solar position. We identify what dark matter couplings and masses might cause a young pulsar at the galactic center to unexpectedly extinguish. Finally, we find that pulsar collapse age scales inversely with the dark matter density and linearly with the dark matter velocity dispersion. This implies that maximum pulsar age is spatially dependent on position within the dark matter halo of the Milky Way. In turn, this pulsar age spatial dependence will be dark matter model dependent.

Dark matter (DM) is evident in the rotational velocities of galaxies, the equation of state of the primordial universe, and the gravitational lensing of colliding galactic clusters. Although its gravitational characteristics are well established, its other putative, impuissant interactions have only been constrained. Nevertheless, there are hints of DM couplings in gamma ray excesses from the galactic center (GC) [1–4] a keV photon line in galactic clusters [5, 6], and the cored out mass profiles of dwarf galaxies [7–10].

Recently, X-ray observations by the NuSTAR and Swift satellites observed pulsating emission from a magnetar located at an angular distance of only 3" from the dynamical center of the galaxy – corresponding to a three-dimensional separation of only ~ 0.1 pc [11, 12]. This finding was followed-up by several groups, who found radio pulsations from the same object [13, 14]. The radio data indicated that the temporal broadening of the

within the lifetime of GC pulsars, especially MSPs deed, many bounds have been placed on non-anni (a.k.a. Asymmetric) DM with the observation compact astrophysical objects [21–37]. We DM NS collapse mechanism requires tha hilation rate be nearly non-existent, a metry enforcing this remains valid d black hole. Otherwise the DM will an crossing the Schwarzschild radius [3

The bounds derived from pulsar quence of calculations in order to d rounding DM collapses pulsars: (the pulsar via gravitational infall fo scatter, (ii) the DM thermalizes i ter of the pulsar, (iii) for bosonic condensate forms, while for fermio attractive self-interaction permits c energy must be minimized at arbitra

The Missing Pulsar Problem

Bramante & TL (1405.1031)

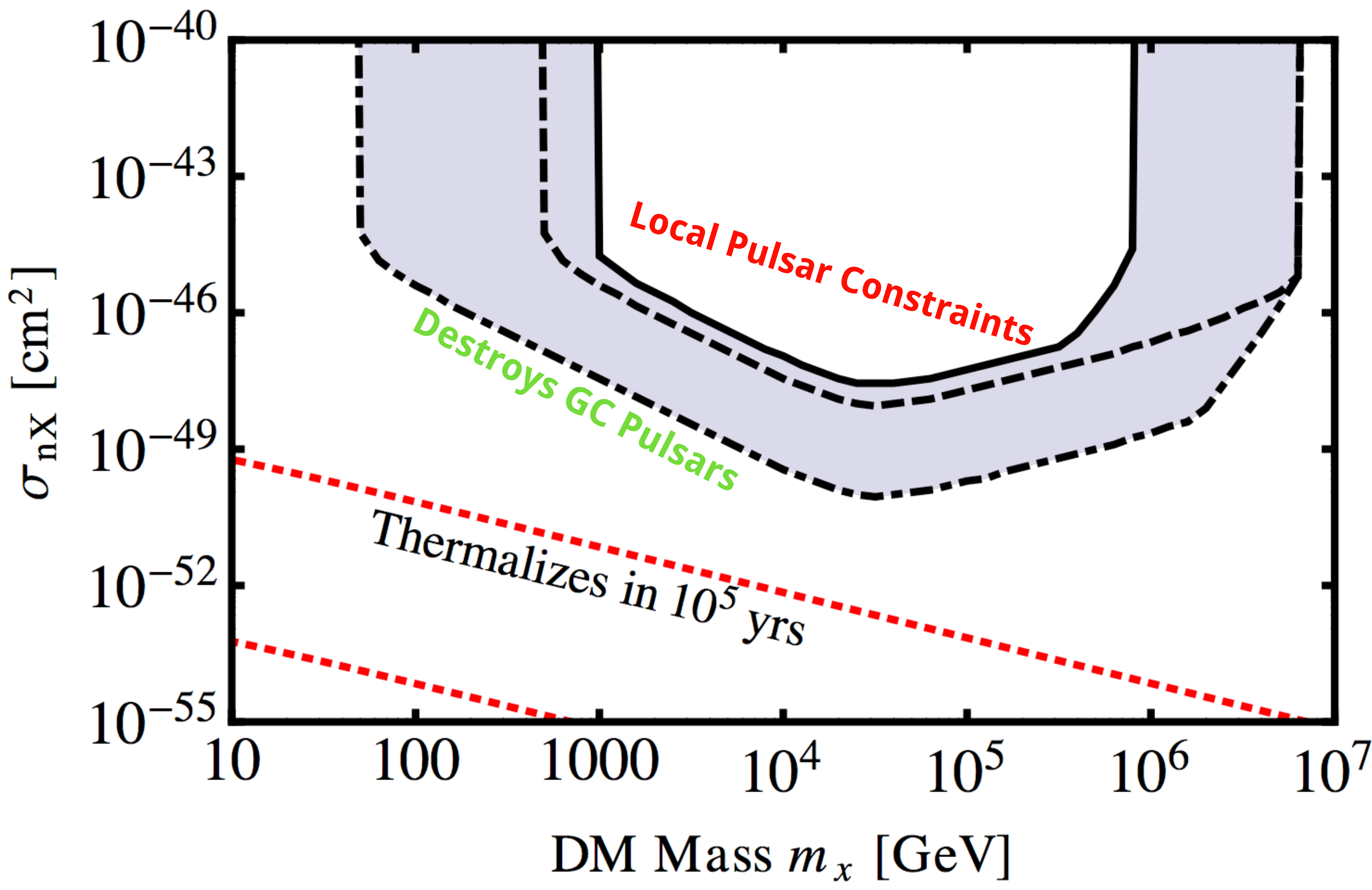
- High Dark Matter density near the GC.

$$\rho(r) = \frac{\rho_0}{\frac{r}{R_s}\left(1 + \frac{r}{R_s}\right)^2}$$

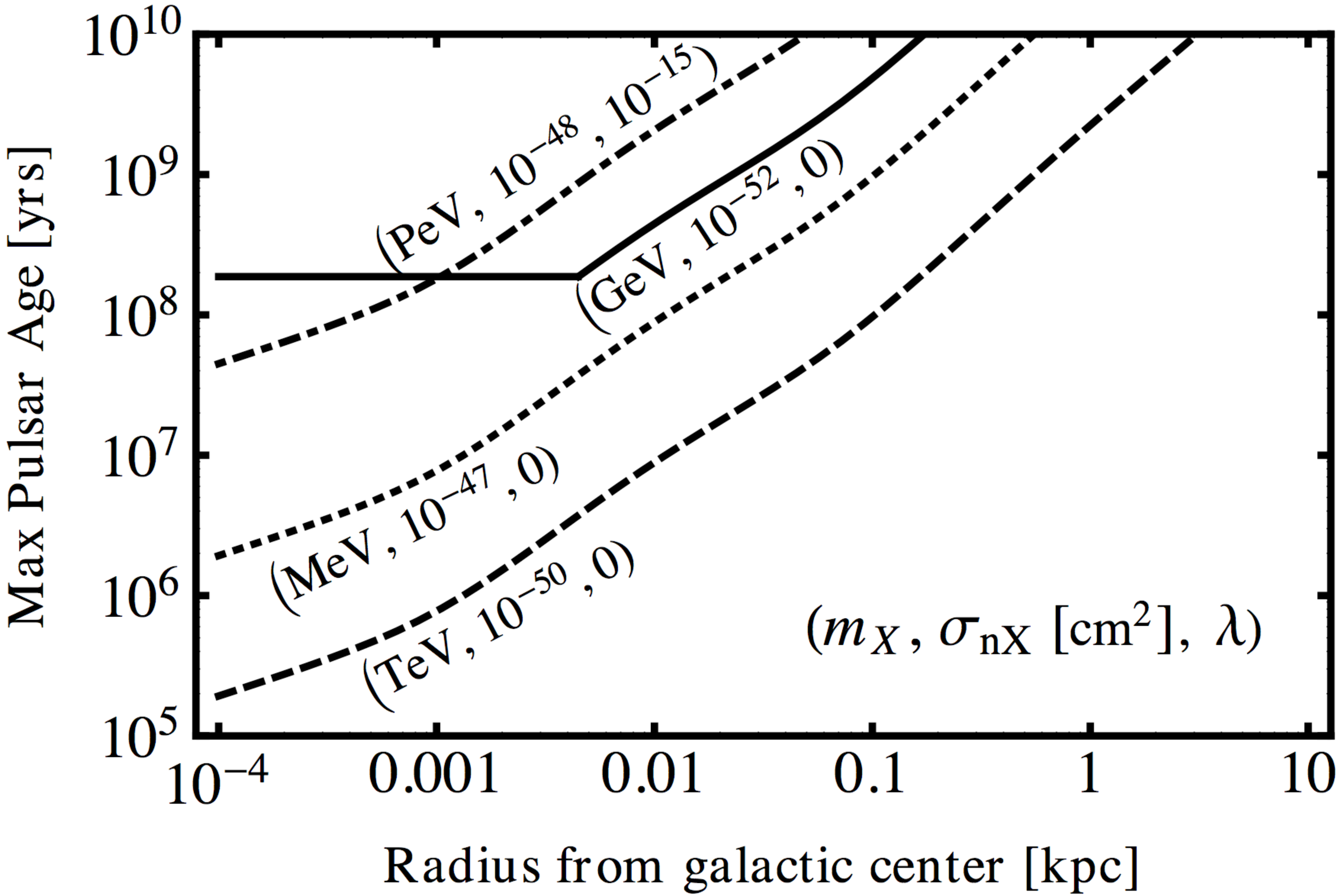
- GC NS collapse in ~10^5 yr while nearby NS remain.

- Constrains cross-section to within a few orders of magnitude.

Bramante & TL (1405.1031)



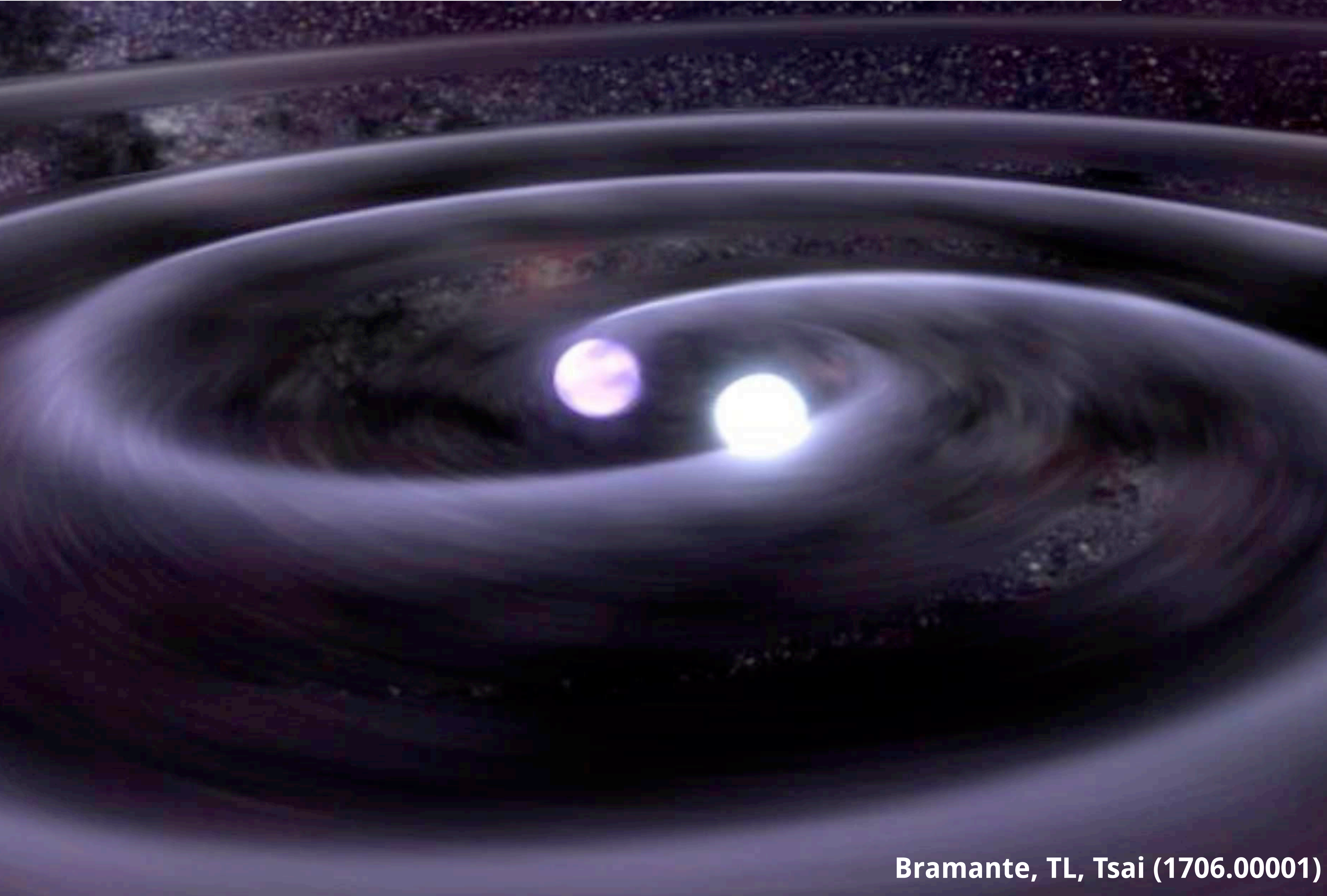
Bramante & TL (1405.1031)



Hard to detect dark matter through a null observation.

What observations stand as evidence of dark matter induced neutron star collapse?

An Electromagnetic Signal



Bramante, TL, Tsai (1706.00001)

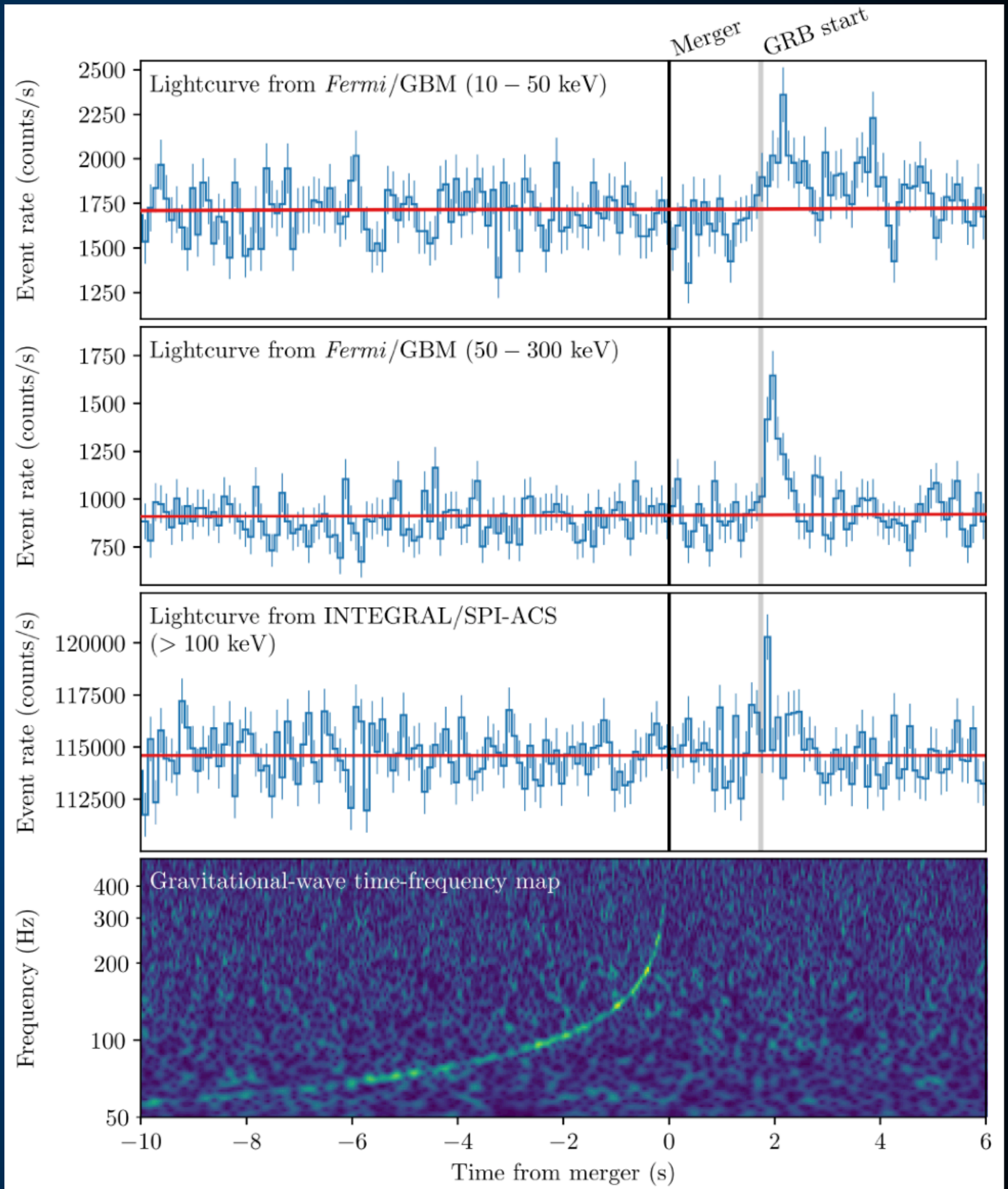
An Electromagnetic Signal

- **Gamma-Ray Bursts (observed by Fermi)**

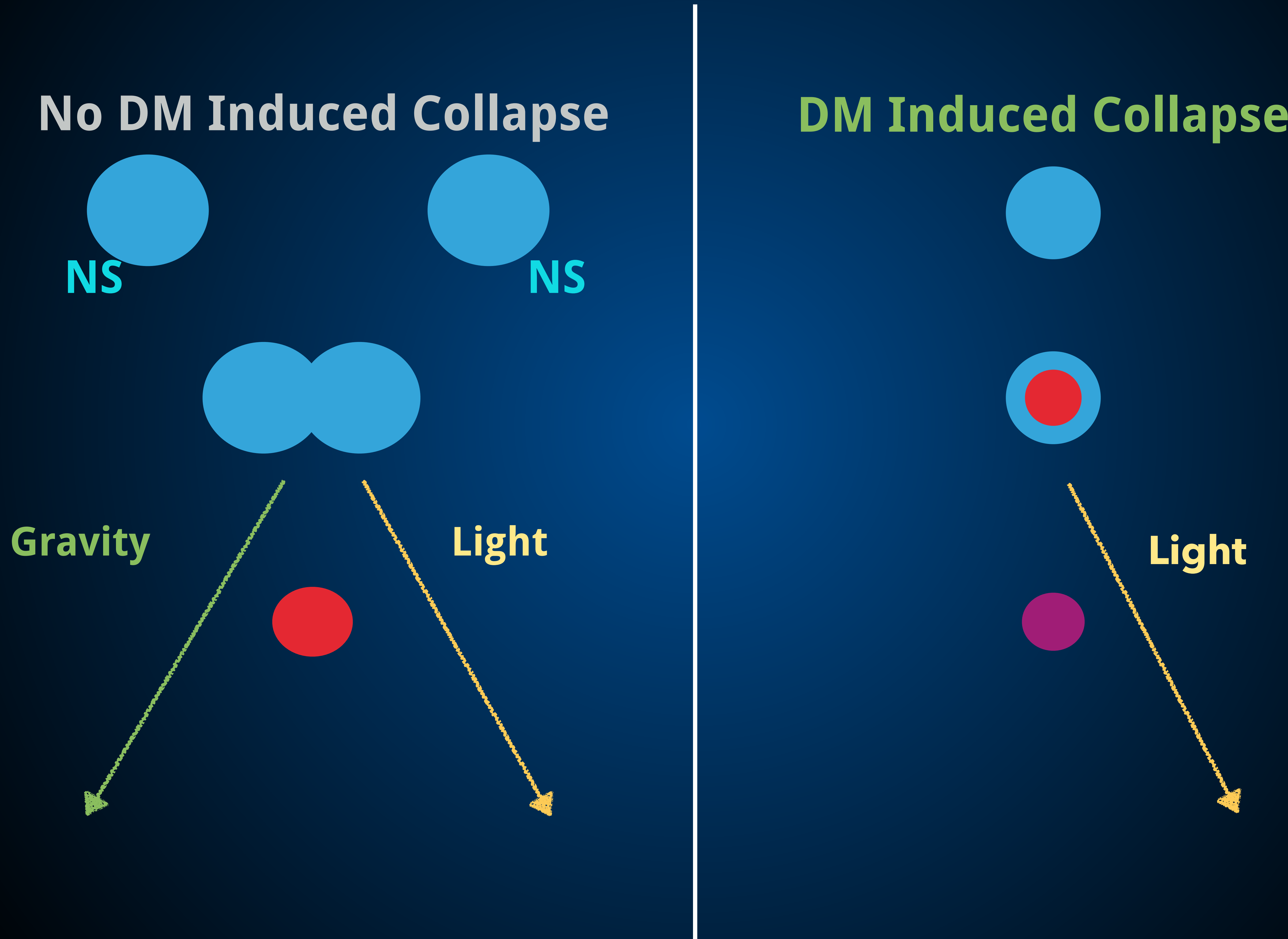
- **Optical emission from the decay of r-process elements**

- **Fast Radio Bursts are potentially correlated with NS mergers.**

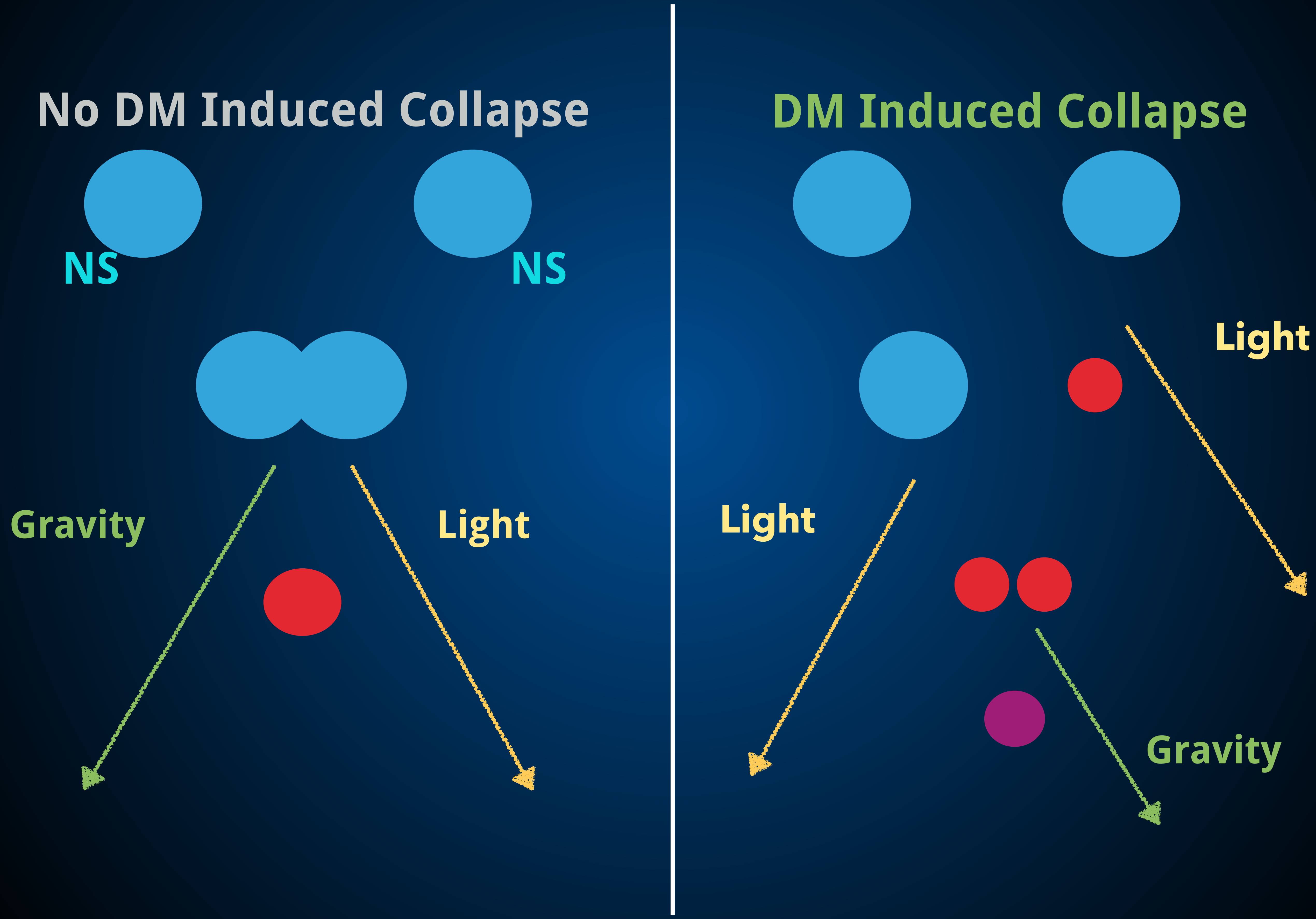
Fermi GBM Collaboration (1710.05834)



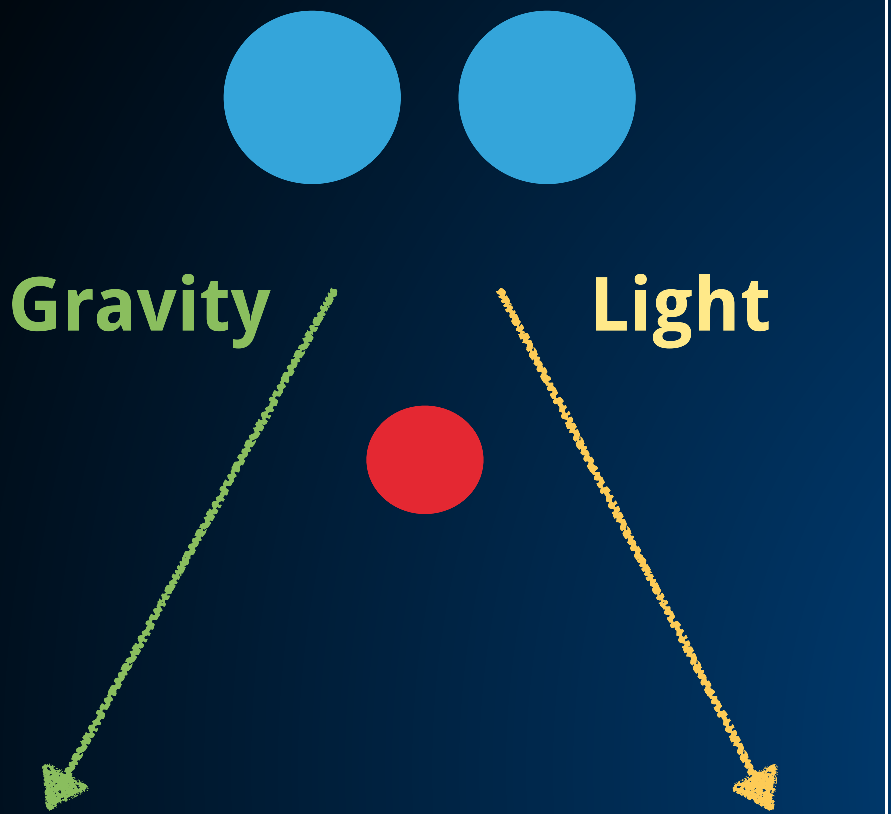
An Electromagnetic Signal



An Electromagnetic Signal



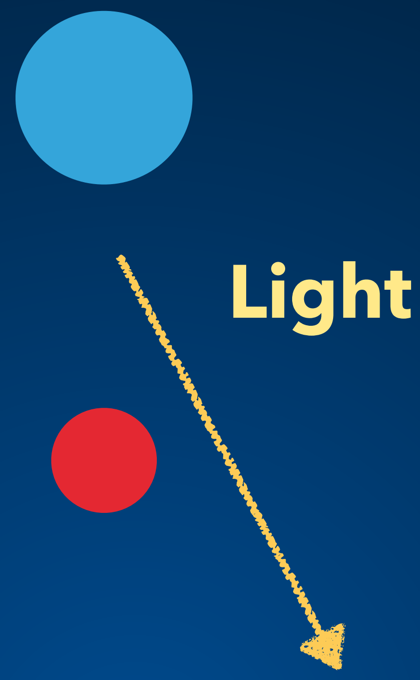
New Phenomena



Merger Kilonovae

Electromagnetic signals and gravitational waves jointly identified.

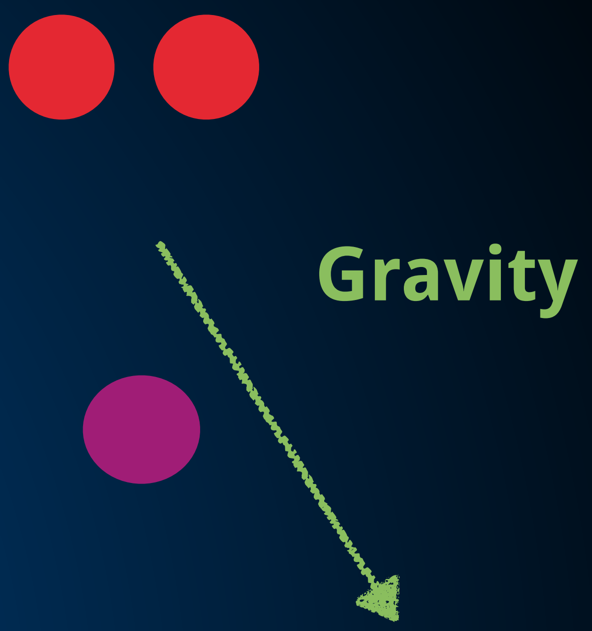
(proportional to ρ^{-1}_{DM})



Quiet Kilonovae

Electromagnetic signals without gravitational waves.

(proportional to ρ_{DM}).



Dark Mergers

Gravitational waves without any electromagnetic signal.

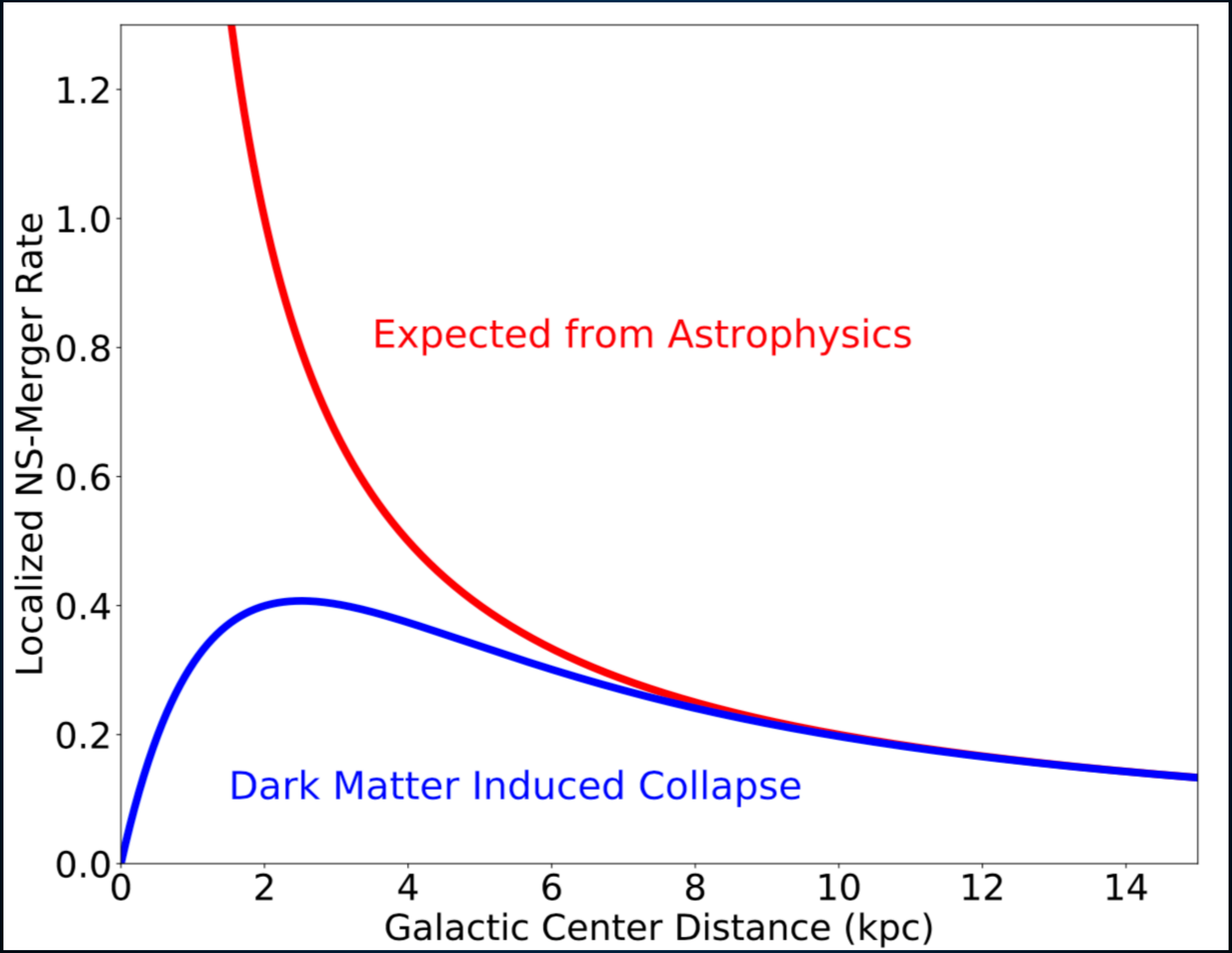
(proportional to ρ_{DM}).

Two Methods

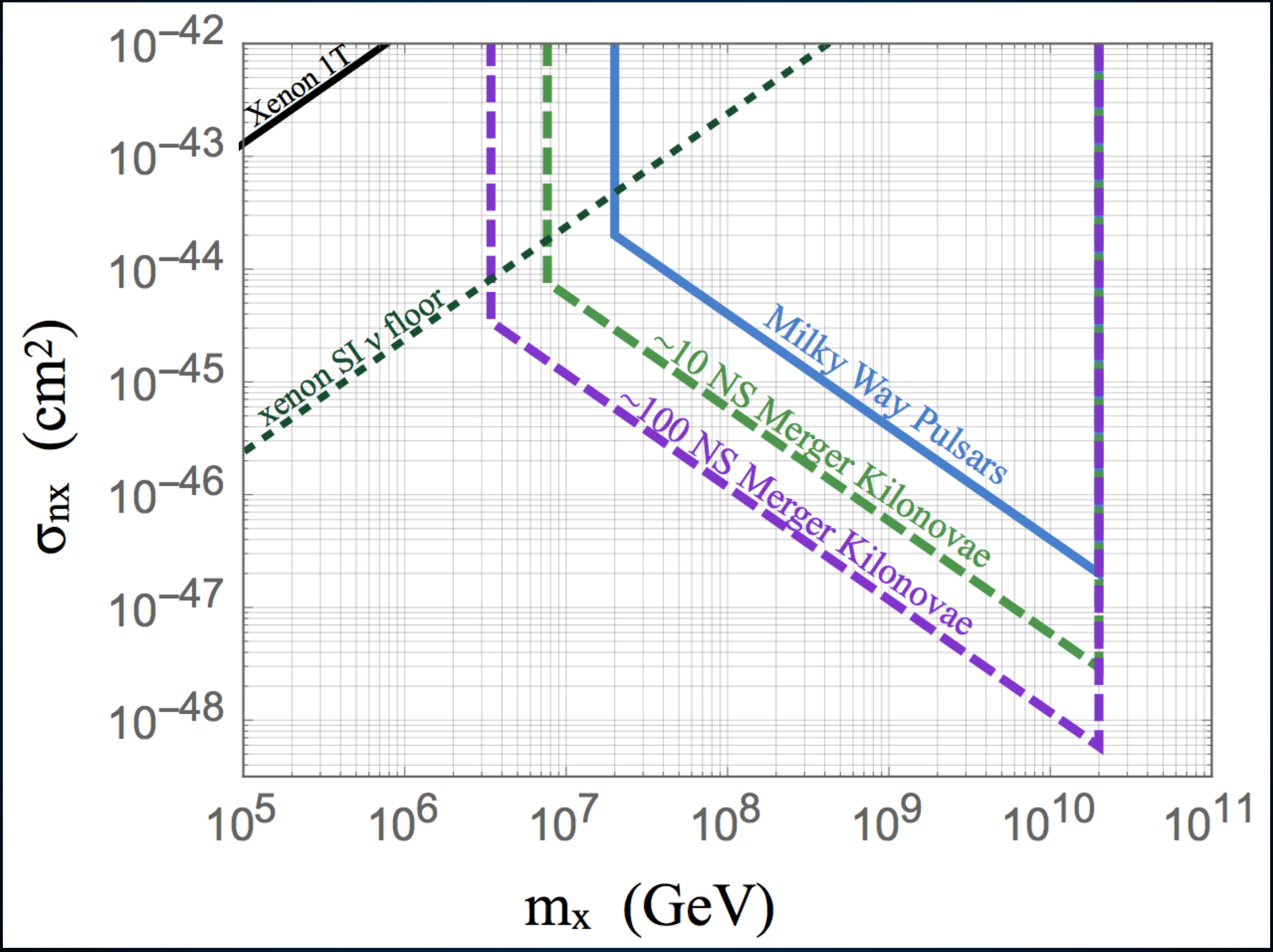
- Two methods to isolate dark matter signal:

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.

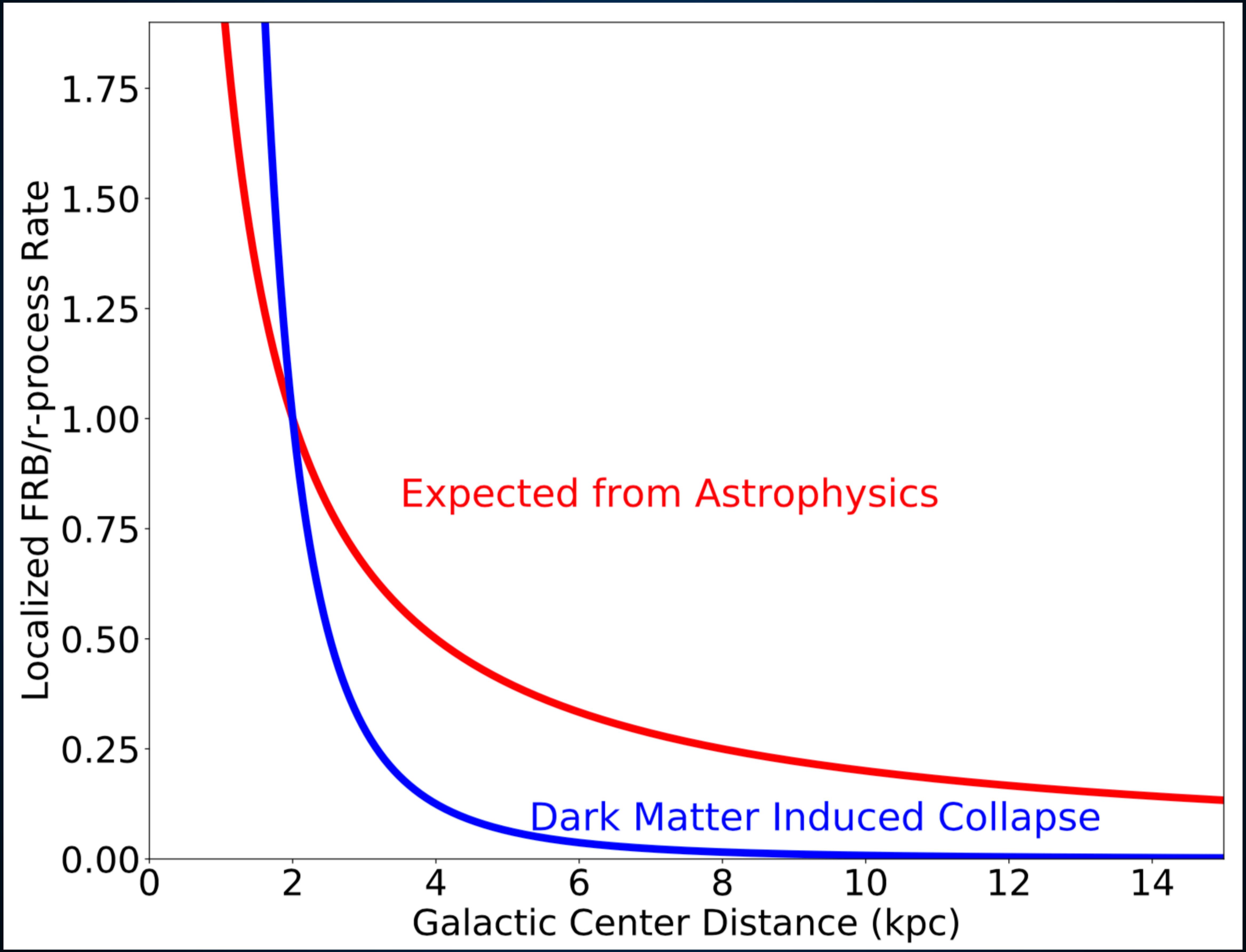
Merger Kilonovae



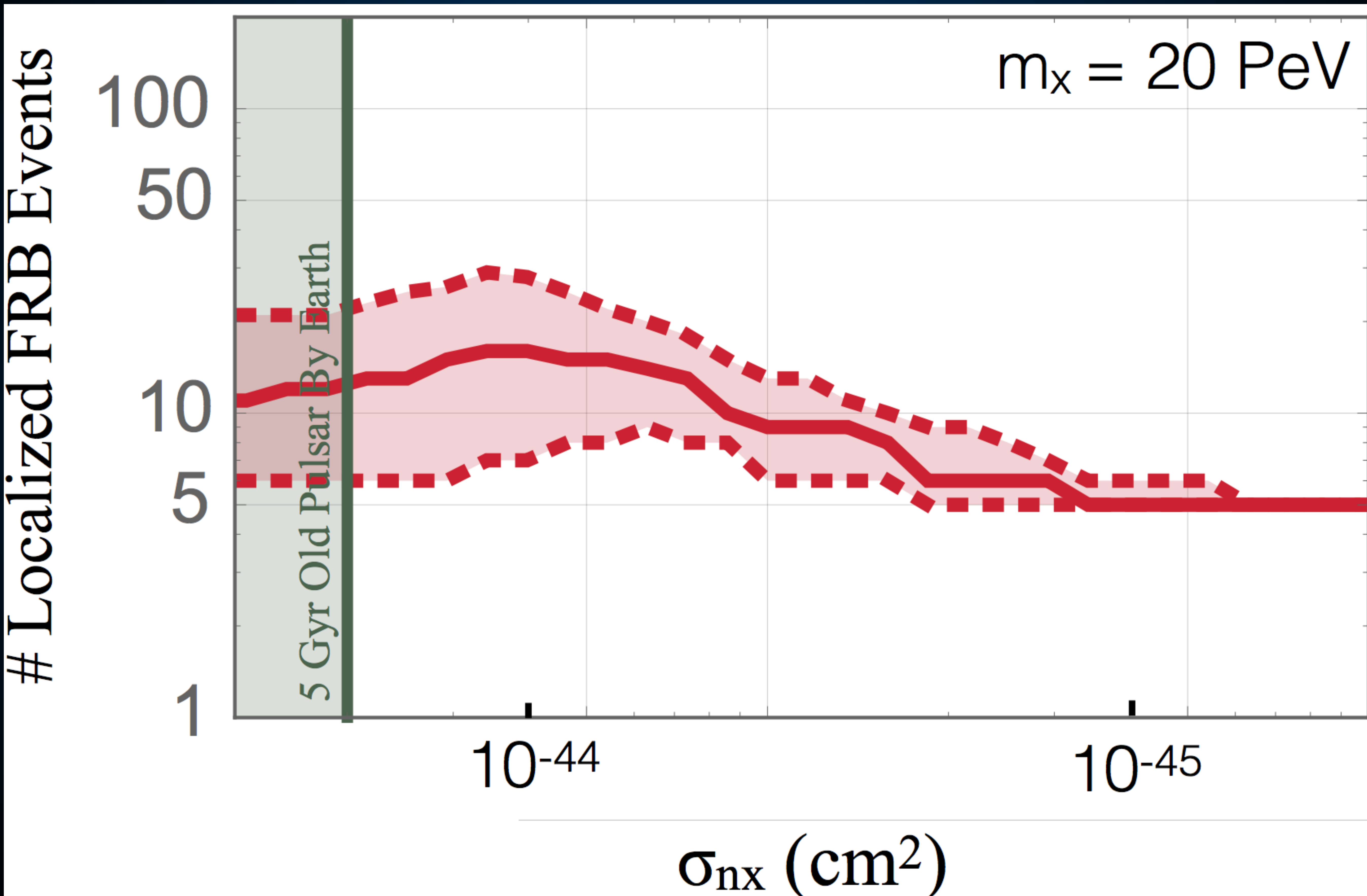
Constraining Dark Matter - Merger Kilonovae



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

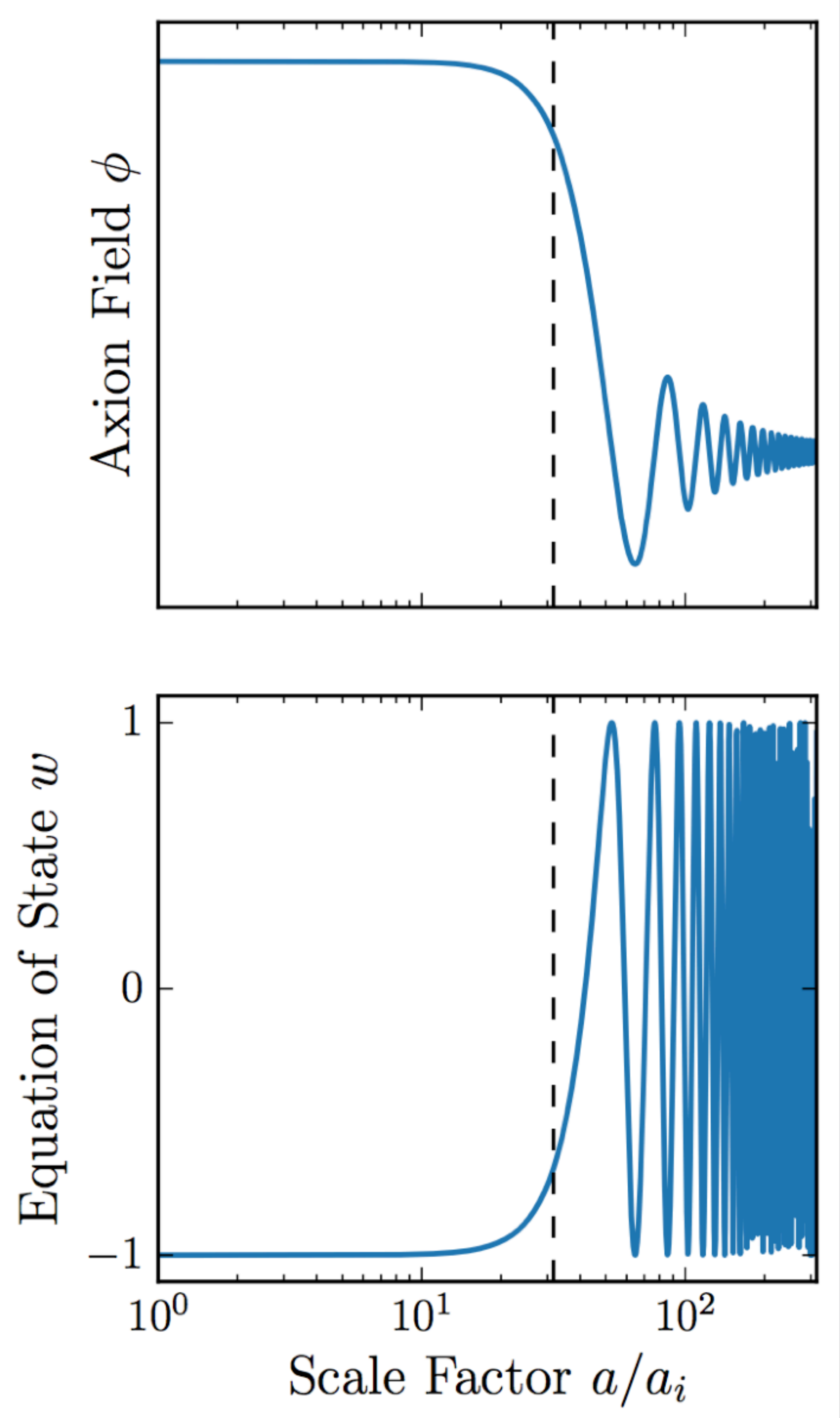
$$L_\theta = \theta \frac{g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu}$$

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

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

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

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

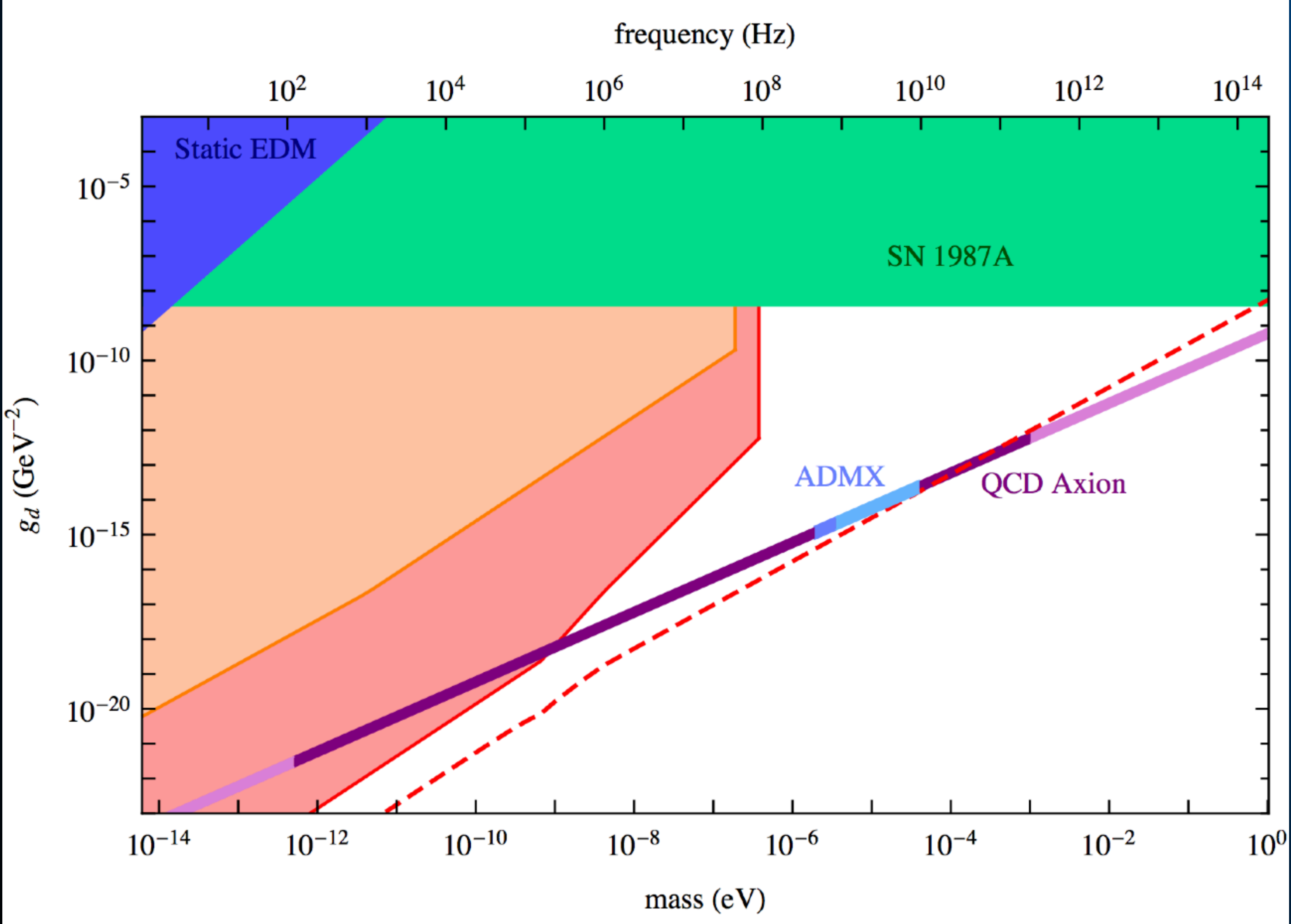


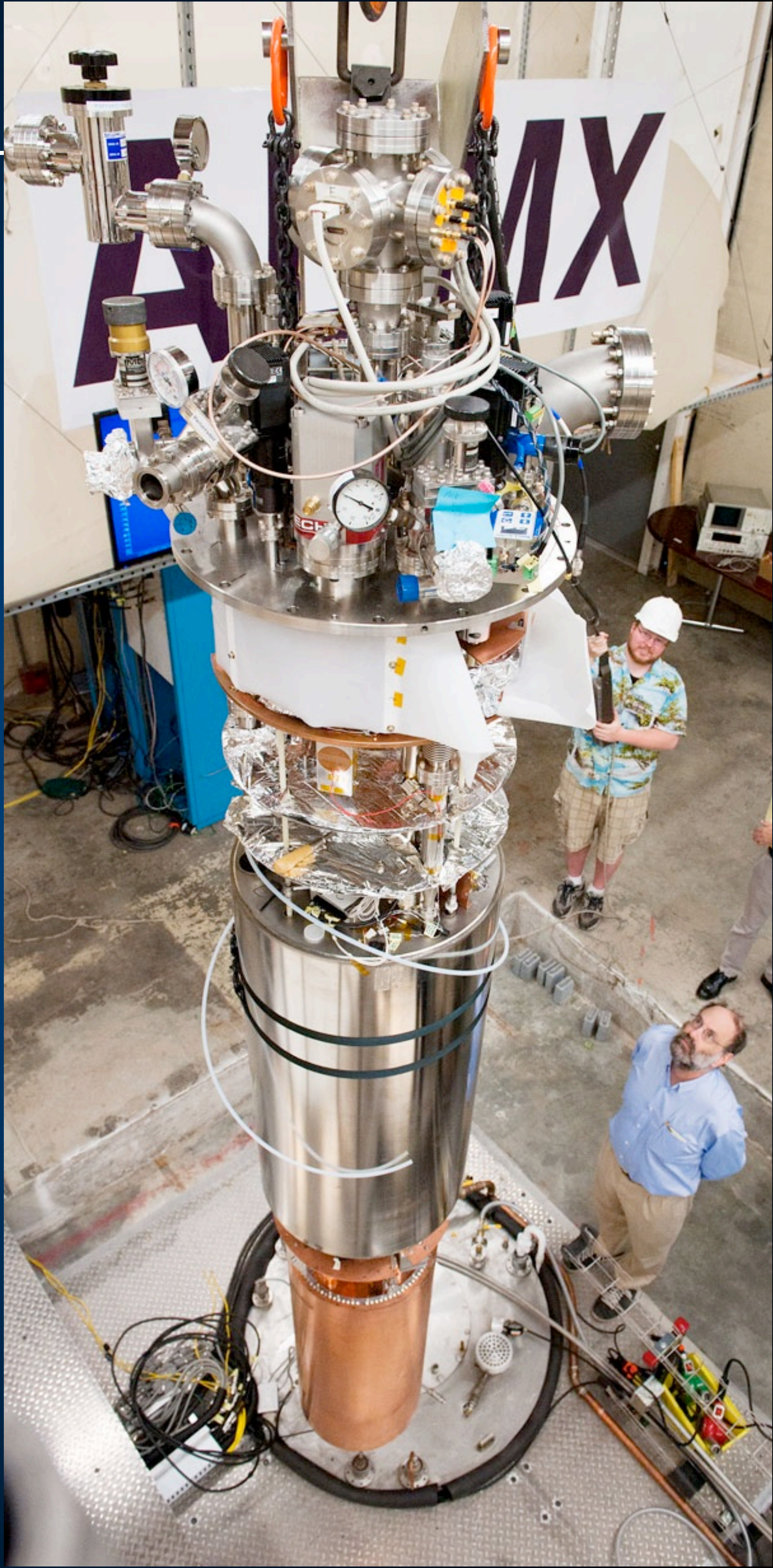
Marsh (2015; 1510.07633)

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

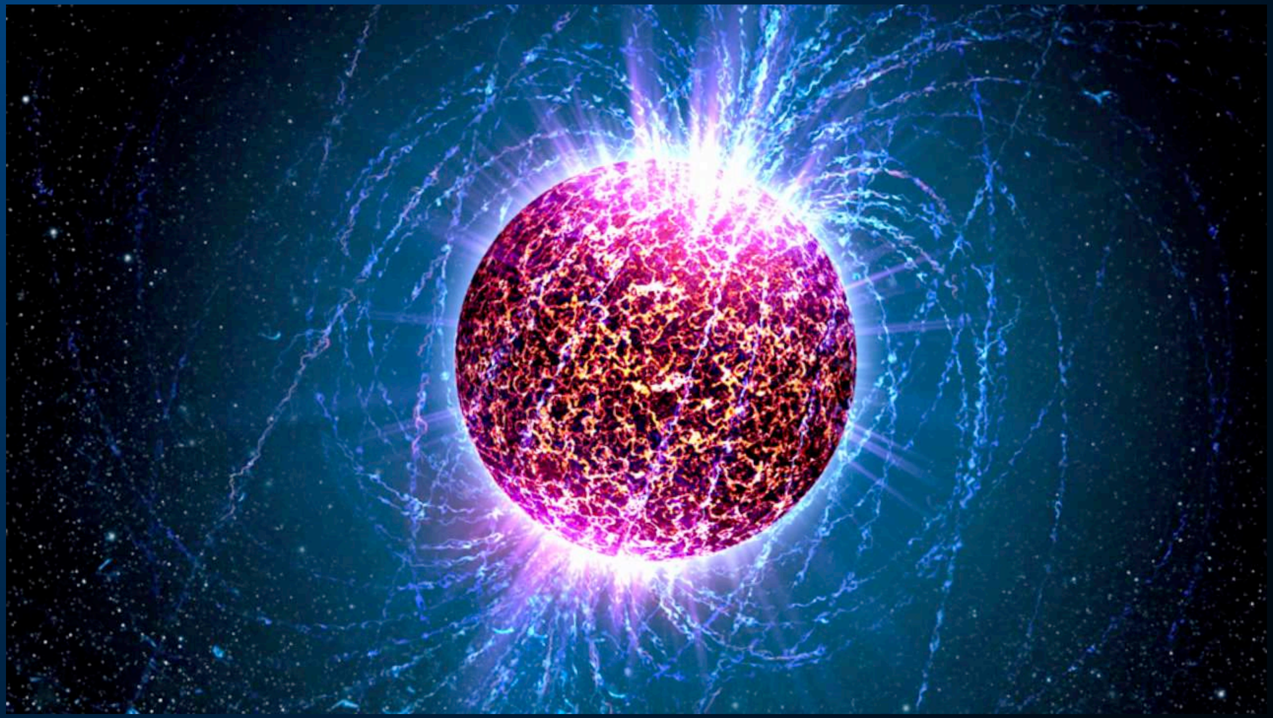
- 10 T
- 1 m^2

100 T^2 m^2

Neutron Star

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

10^{28} T^2 m^2



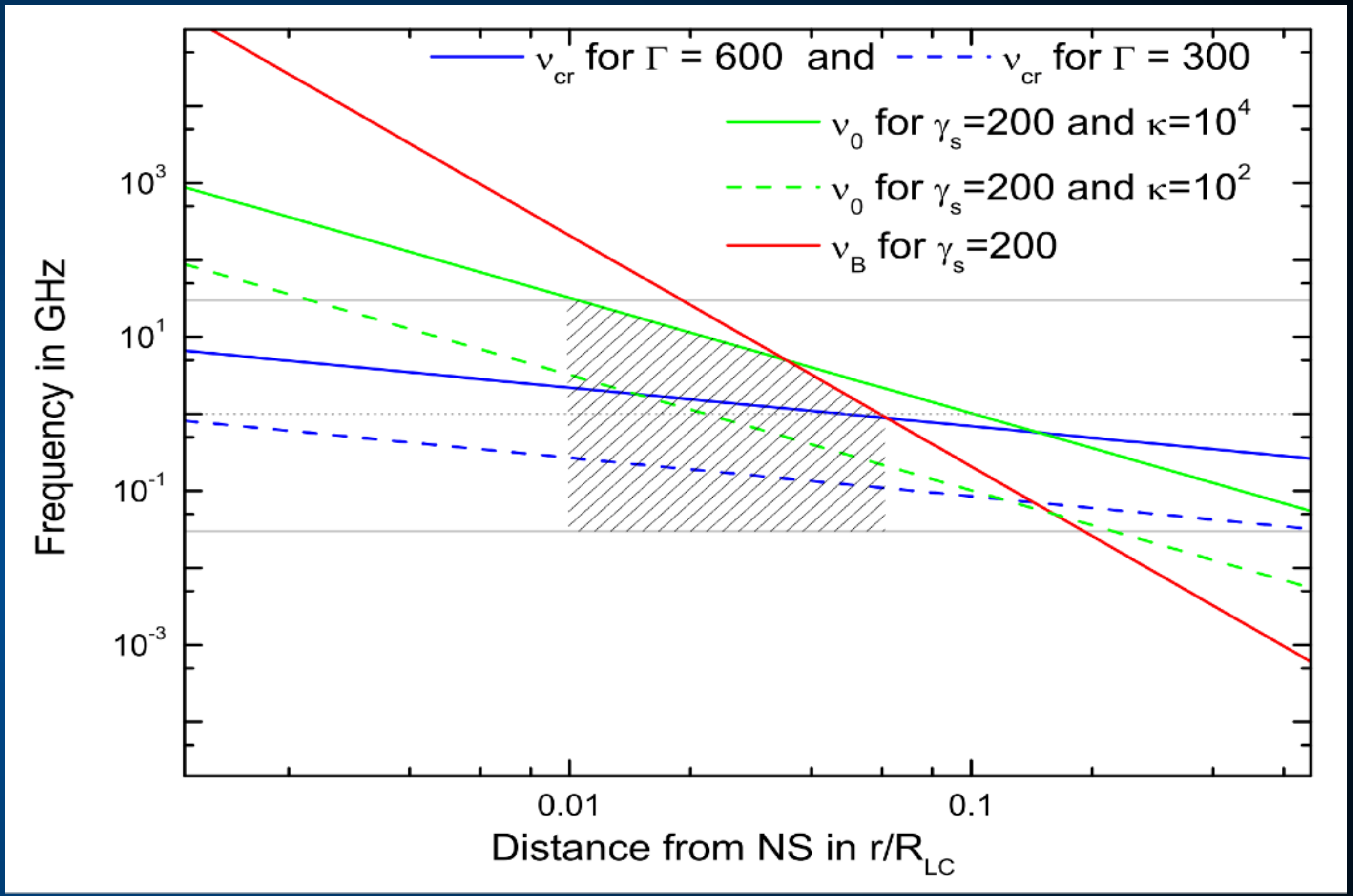
Neutron Stars: The Optimal Axion Laboratory

- **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)

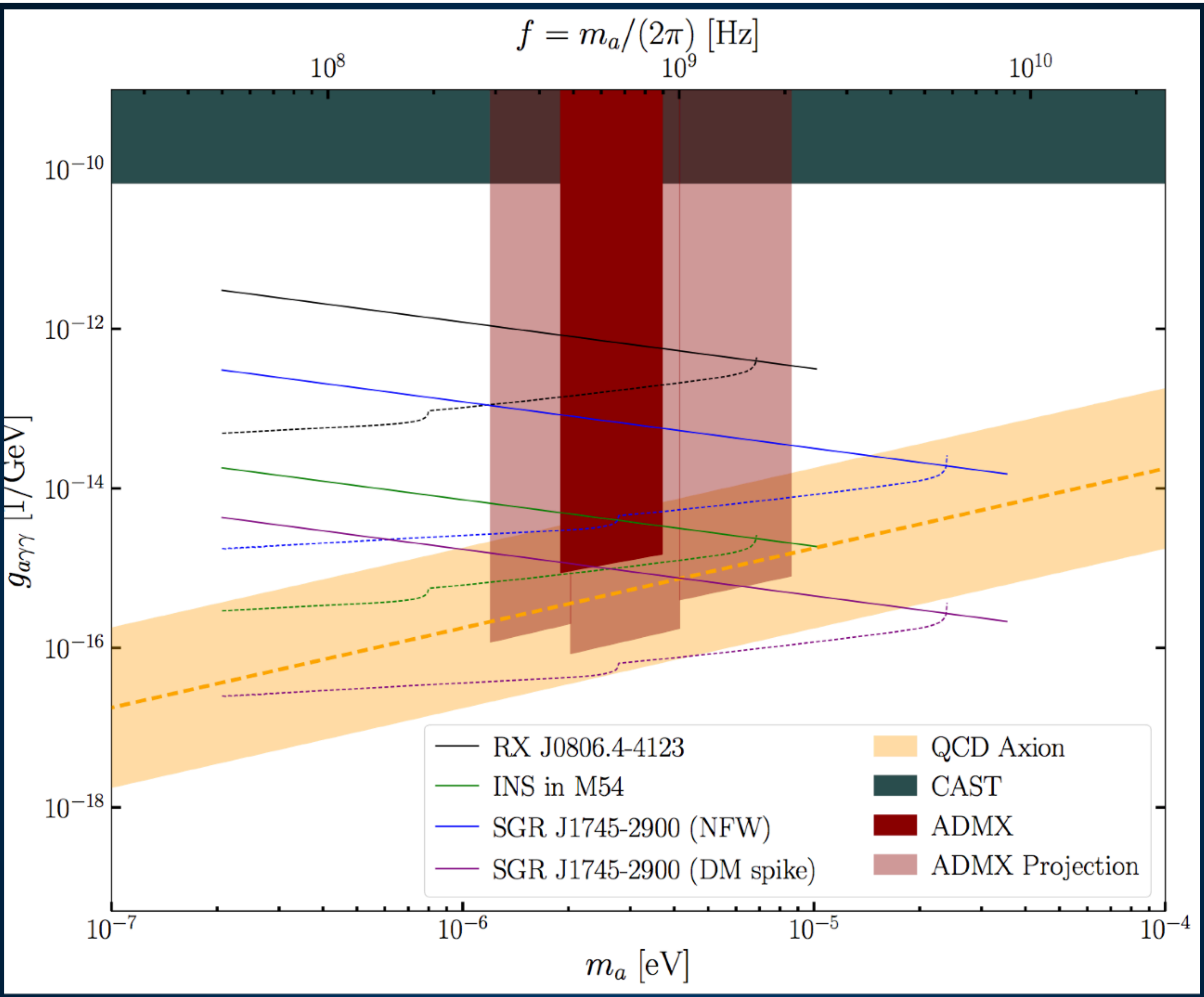


- **Need detailed model of NS magnetic fields.**

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

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)

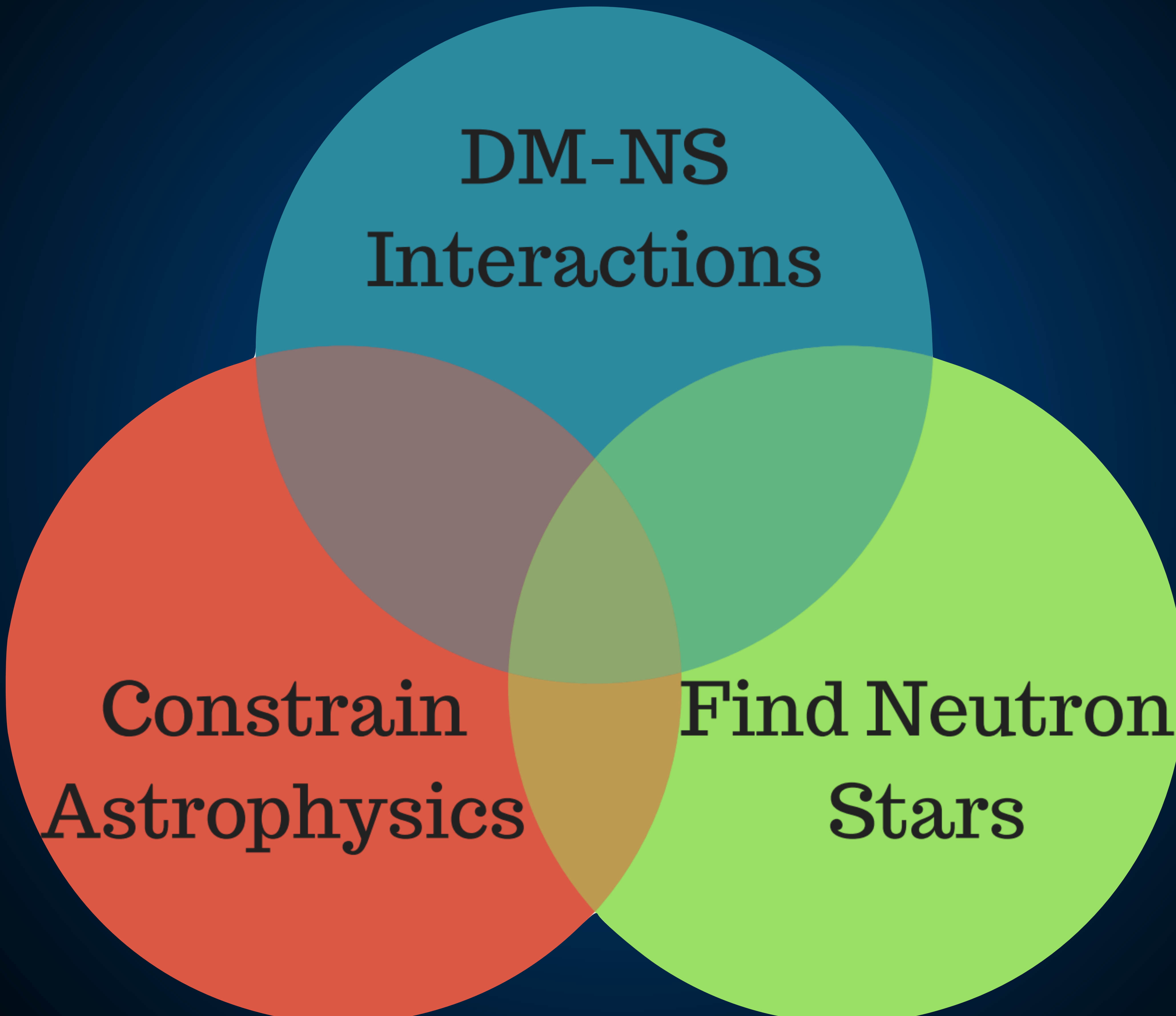
What Do We Need?

1. Nearby, highly-magnetized pulsar.

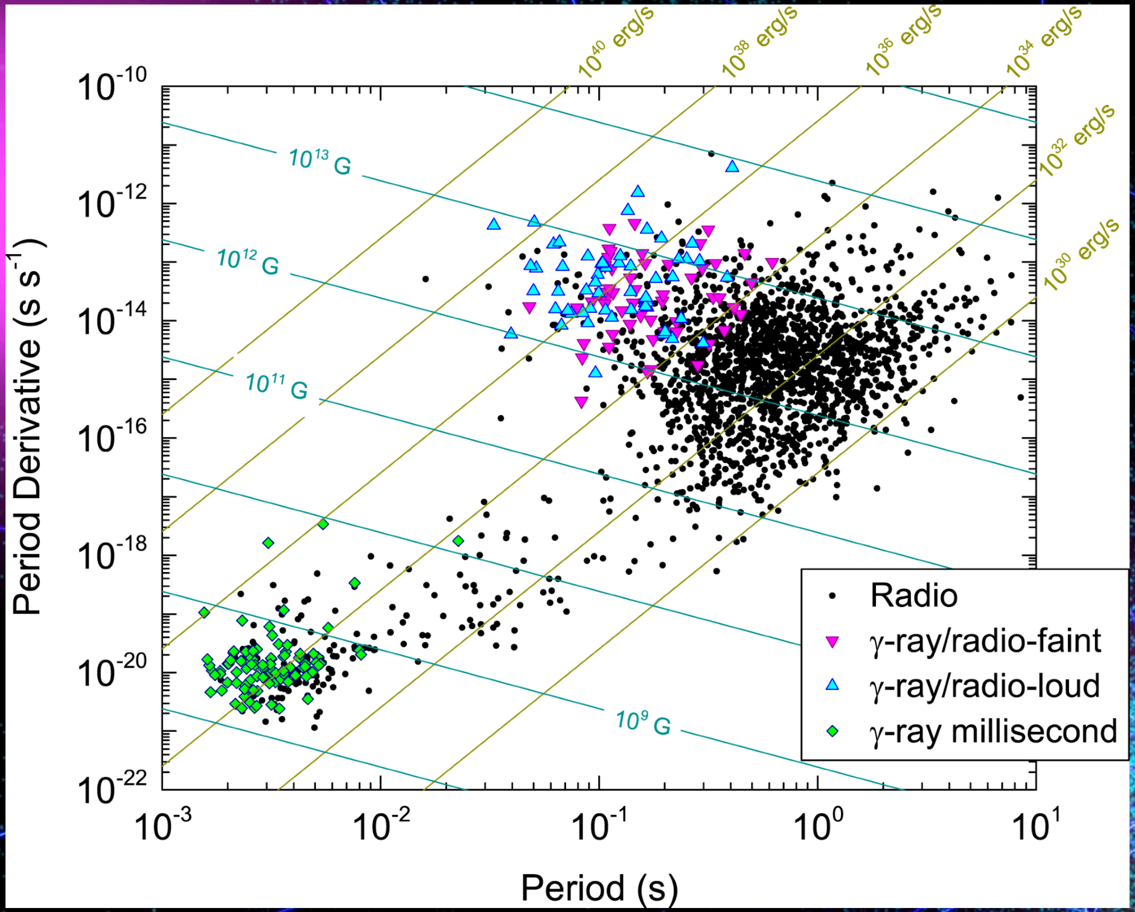
2. Better models of the pulsar magnetic field.

3. Sensitive observations of radio lines (different techniques than traditional pulsar searches).

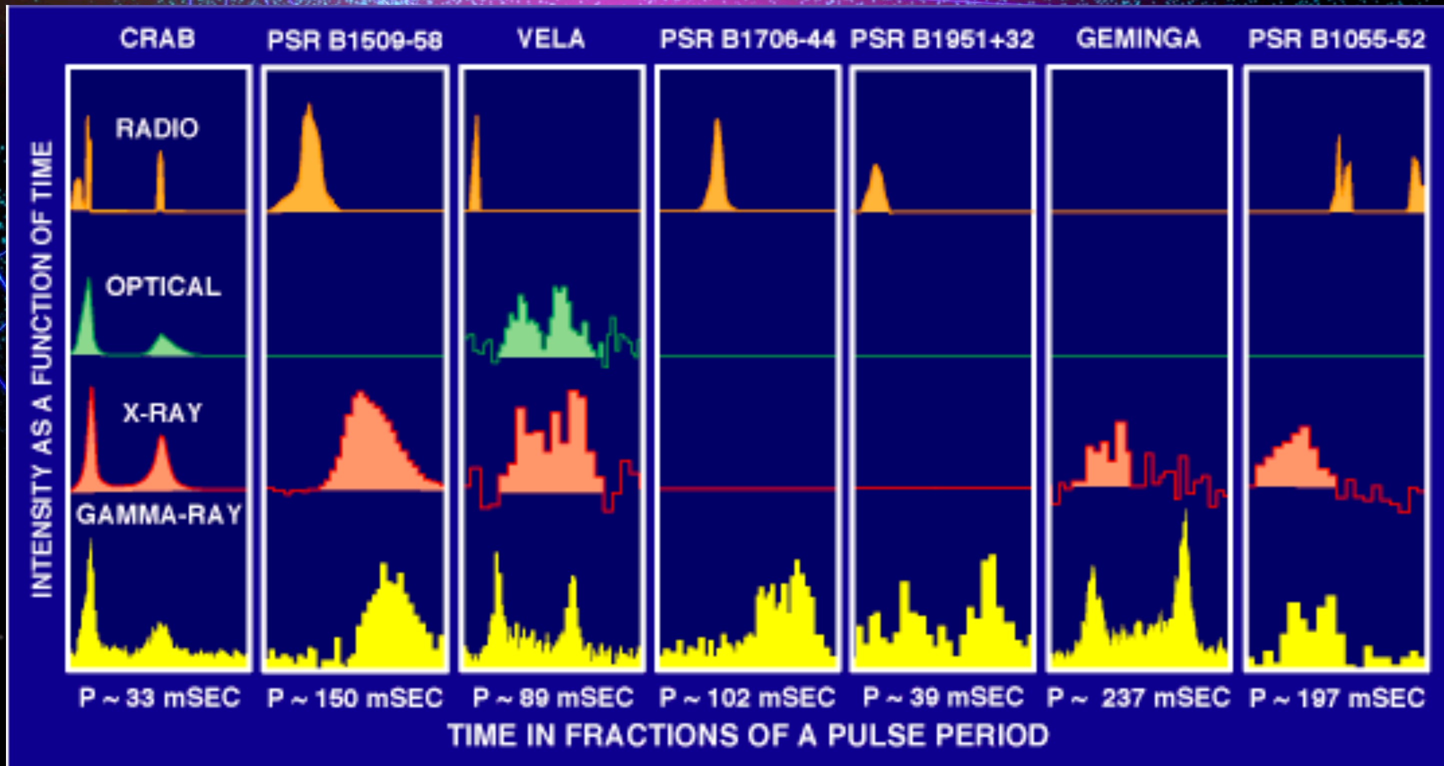
Finding the Right Neutron Star



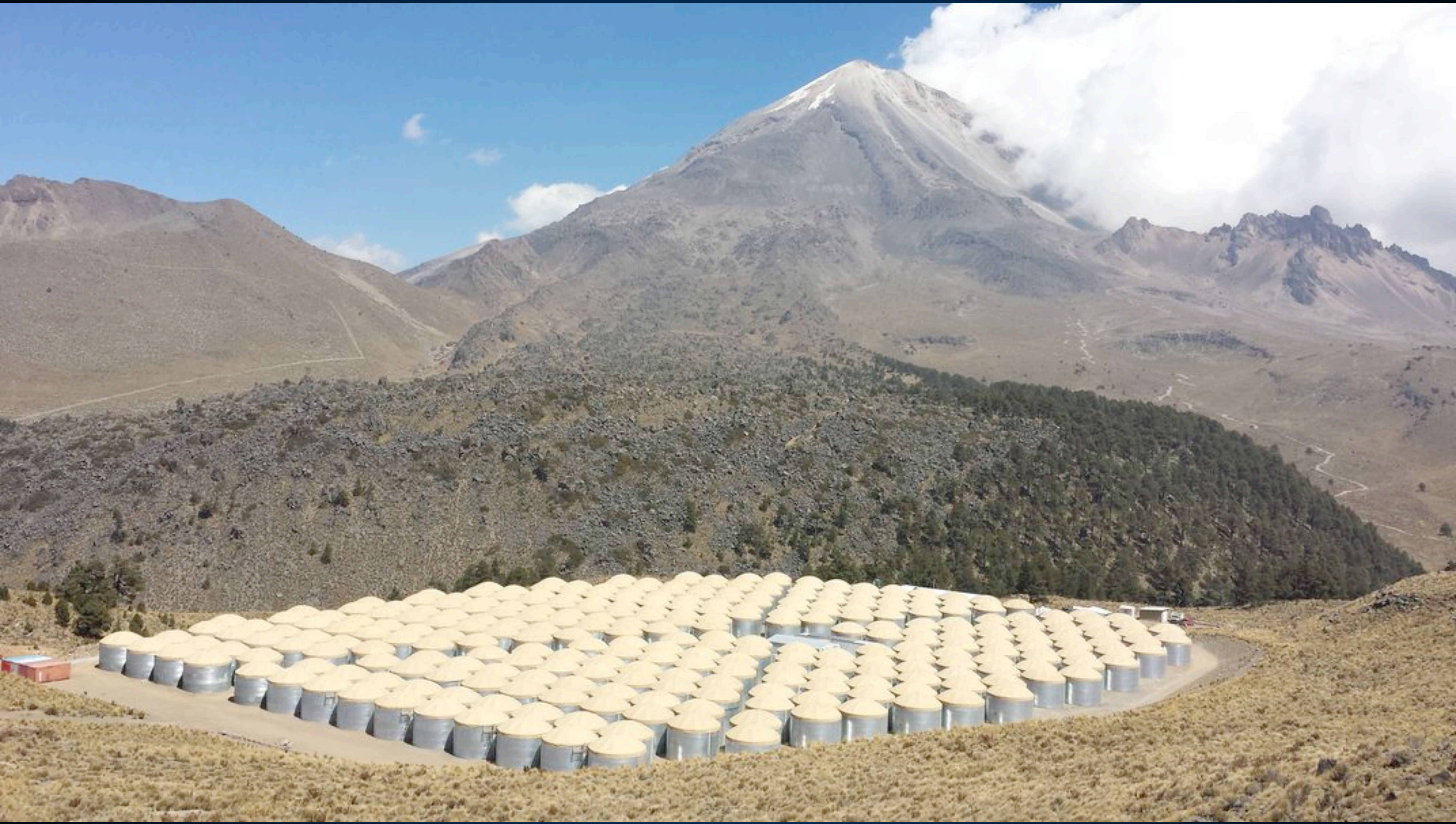
Radio Pulses: A Blessing and a Curse



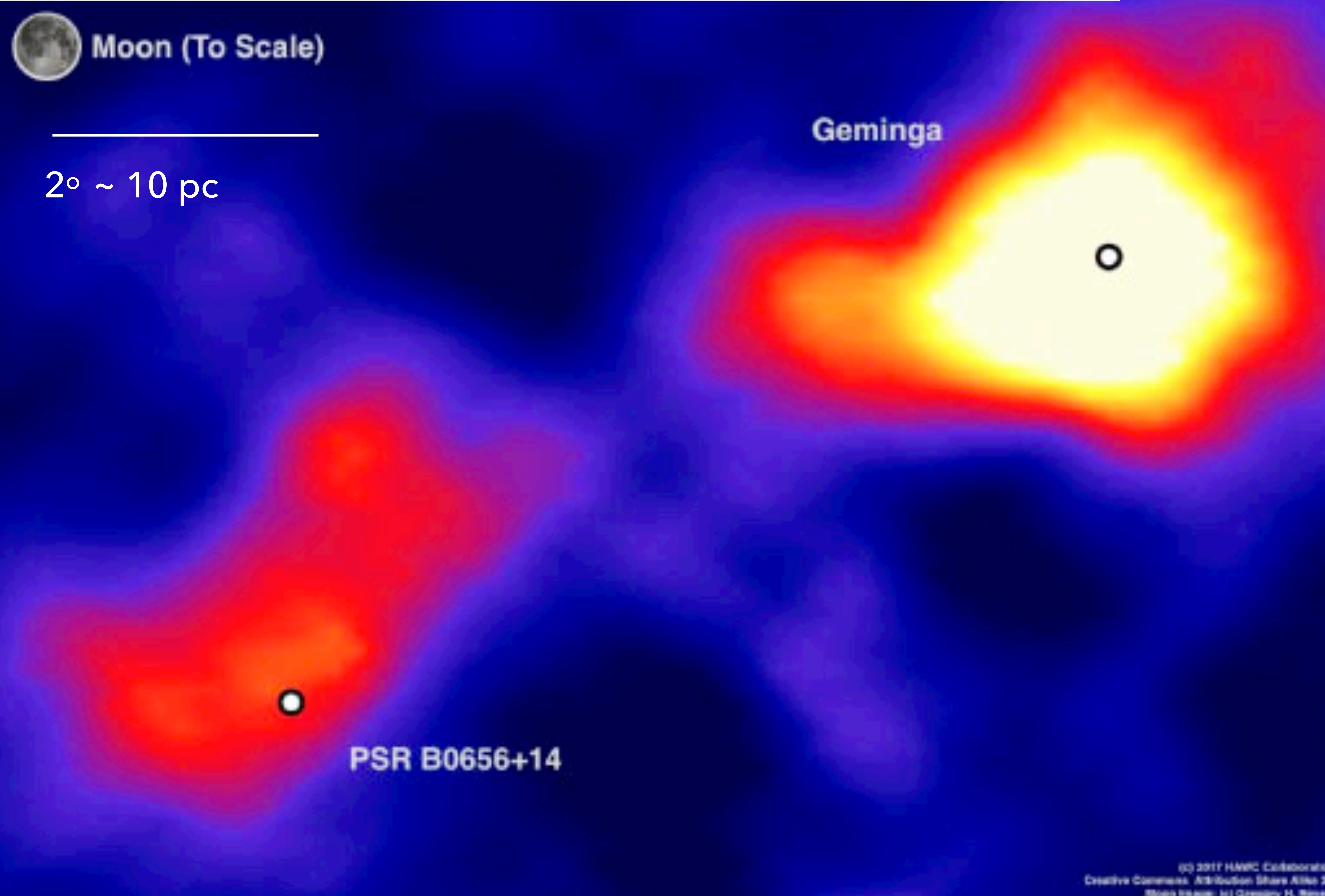
Harding (2016; J Plasma Phys 82)



A New Method for Detecting Invisible Pulsars



A New Method for Detecting Invisible Pulsars



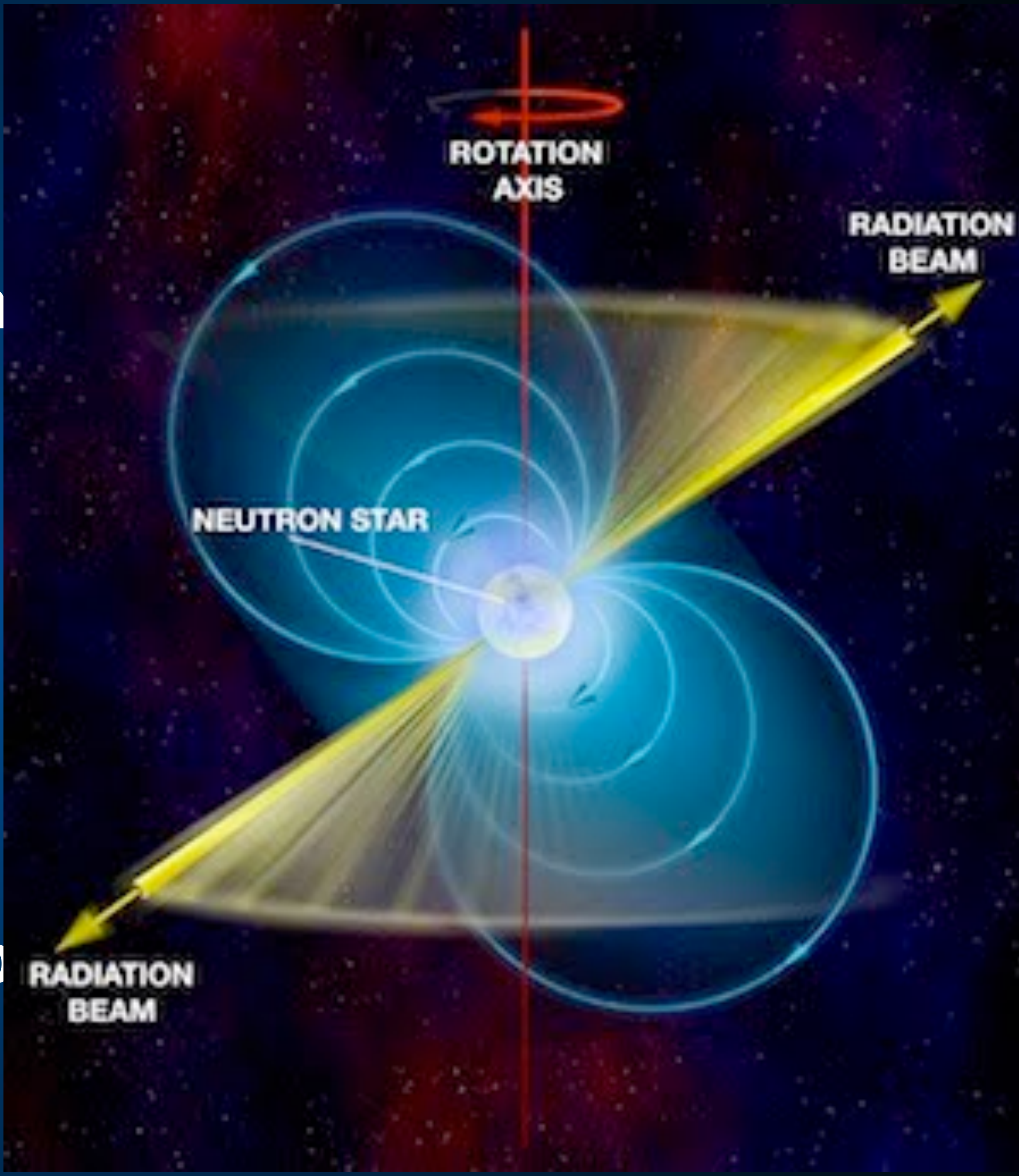
Astrophysical Implications of TeV Halos

- TeV halo observations solve many astrophysical puzzles

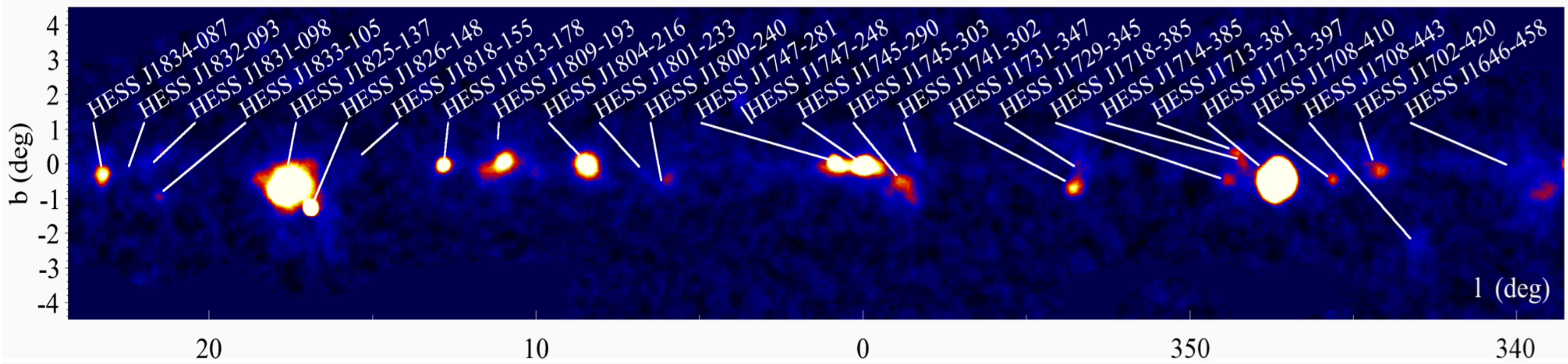
  - Prove that pulsars produce the positron excess
    (Hooper, Cholis, TL, Fang 1702.08436)
  - Explain the TeV gamma-ray excess
    (TL & Buckman 1707.01905)
  - Explain inhomogeneities in cosmic-ray diffusion ,
    (Hooper & TL 1711.07482) (Evoli, TL, Morlino, TBS)
  - Explain TeV gamma-rays from the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

Discovering Pulsars at TeV Energies

- 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 Invisible Pulsars at TeV Energies



The H.E.S.S. Galactic plane survey

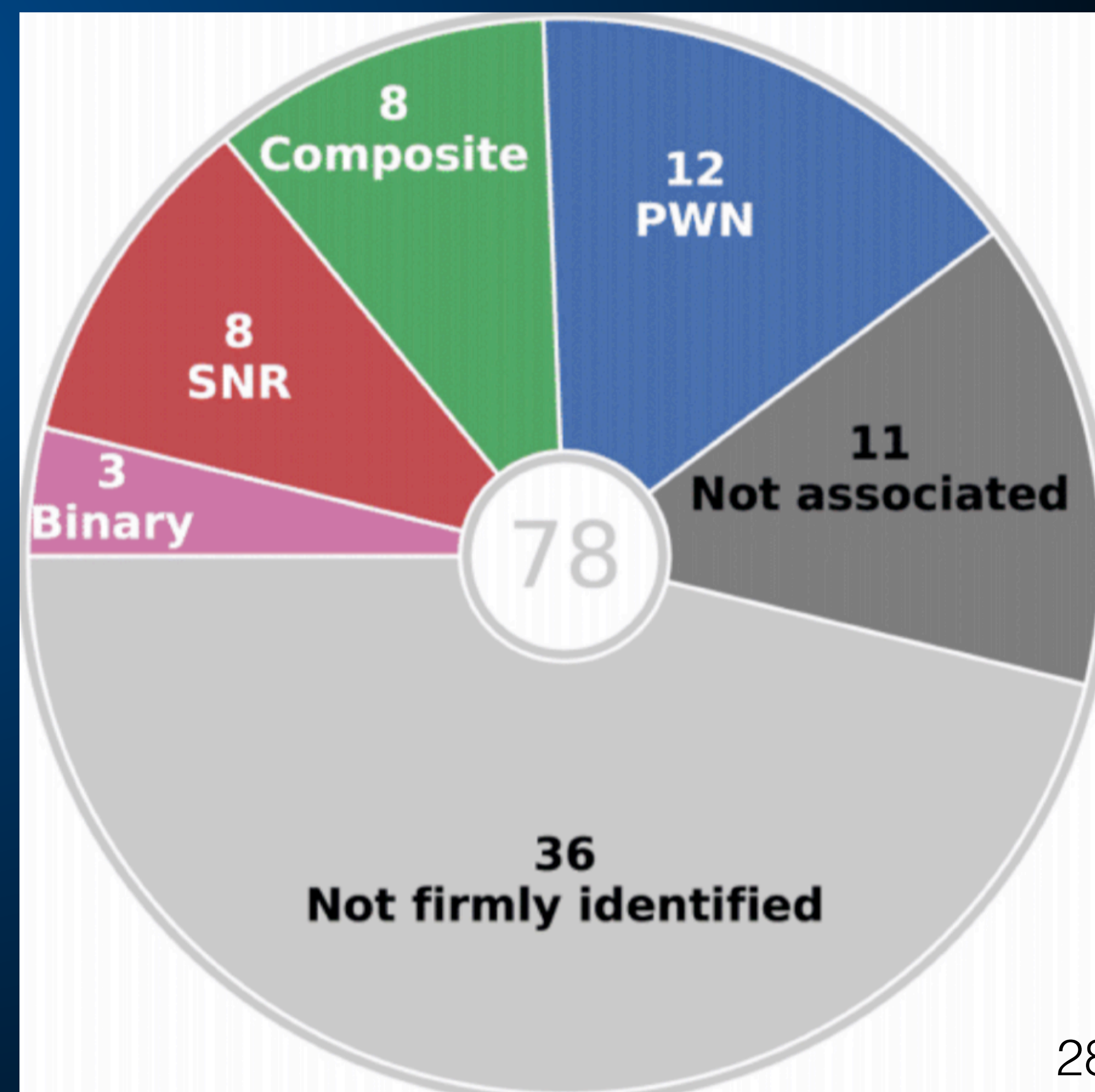
H.E.S.S. Collaboration, H. Abdalla[1], A. Abramowski[2], F. Aharonian[3,4,5], F. Ait Benkhali[3], E.O. Angüner[21], M. Arakawa[43], M. Arrieta[15], P. Aubert[24], M. Backes[8], A. Balzer[9], M. Barnard[1], Y. Becherini[10], J. Becker Tjus[11], D. Berge[12], S. Bernhard[13], K. Bernlöhr[3], R. Blackwell[14], M. Böttcher[1], C. Boisson[15], J. Bolmont[16], S. Bonnefoy[37], P. Bordas[3], J. Bregeon[17], F. Brun*[26], P. Brun[18], M. Bryan[9], M. Büchele[36], T. Bulik[19], M. Capasso[29], S. Carrigan[3,48], S. Caroff[30], A. Carosi[24], S. Casanova[21,3], M. Cerruti[16], N. Chakraborty[3], R.C.G. Chaves*[17,22], A. Chen[23], J. Chevalier[24], S. Colafrancesco[23], B. Condon[26], J. Conrad[27,28], I.D. Davids[8], J. Decock[18], C. Deil*[3], J. Devin[17], P. deWilt[14], L. Dirson[2], A. Djannati-Ataï[31], W. Domainko[3], A. Donath*[3], L.O'C. Drury[4], K. Dutson[33], J. Dyks[34], T. Edwards[3], K. Egberts[35], P. Eger[3], G. Emery[16], J.-P. Ernenwein[20], S. Eschbach[36], C. Farnier[27,10], S. Fegan[30], M.V. Fernandes[2], A. Fiasson[24], G. Fontaine[30], A. Förster[3], S. Funk[36], M. Füßling[37], S. Gabici[31], Y.A. Gallant[17], T. Garrigoux[1], H. Gast[3,49], F. Gaté[24], G. Giavitto[37], B. Giebels[30], D. Glawion[25], J.F. Glicenstein[18], D. Gottschall[29], M.-H. Grondin[26], J. Hahn[3], M. Haupt[37], J. Hawkes[14], G. Heinzelmann[2], G. Henri[32], G. Hermann[3], J.A. Hinton[3], W. Hofmann[3], C. Hoischen[35], T. L. Holch[7], M. Holler[13], D. Horns[2], A. Ivascenko[1], H. Iwasaki[43], A. Jacholkowska[16], M. Jamrozy[38], D. Jankowsky[36], F. Jankowsky[25], M. Jingo[23], L. Jouvin[31], I. Jung-Richardt[36], M.A. Kastendieck[2], K. Katarzyński[39], M. Katsuragawa[44], U. Katz[36], D. Kerszberg[16], D. Khangulyan[43], B. Khélifi[31], J. King[3], S. Klepser[37], D. Klochkov[29], W. Kluźniak[34], Nu. Komin[23], K. Kosack[18], S. Krakau[11], M. Kraus[36], P.P. Krüger[1], H. Laffon[26], G. Lamanna[24], J. Lau[14], J.-P. Lees[24], J. Lefaucheur[15], A. Lemière[31], M. Lemoine-Goumard[26], J.-P. Lenain[16], E. Leser[35], T. Lohse[7], M. Lorentz[18], R. Liu[3], R. López-Coto[3], I. Lypova[37], V. Marandon*[3], D. Malyshev[29], A. Marcowith[17], C. Mariaud[30], R. Marx[3], G. Maurin[24], N. Maxted[14,45], M. Mayer[7], P.J. Meintjes[40], M. Meyer[27], A.M.W. Mitchell[3], R. Moderski[34], M. Mohamed[25], L. Mohrmann[36], K. Morå[27], E. Moulin[18], T. Murach[37], S. Nakashima[44], M. de Naurois[30], H. Ndiyavala[1], F. Niederwanger[13], J. Niemiec[21], L. Oakes[7], P. O'Brien[33], H. Odaka[44], S. Ohm[37], M. Ostrowski[38], I. Oya[37], M. Padovani[17], M. Panter[3], R.D. Parsons[3], M. Paz Arribas[7], N.W. Pekeur[1], G. Pelletier[32], C. Perennes[16], P.-O. Petrucci[32], B. Peyaud[18], Q. Piel[24], S. Pita[31], V. Poireau[24], H. Poon[3], D. Prokhorov[10], H. Prokoph[12], G. Pühlhofer[29], M. Punch[31,10], A. Quirrenbach[25], S. Raab[36], R. Rauth[13], A. Reimer[13], O. Reimer[13], M. Renaud[17], R. de los Reyes[3], F. Rieger[3,41], L. Rinchiuso[18], C. Romoli[4], G. Rowell[14], B. Rudak[34], C.B. Rulten[15], S. Safi-Harb[50], V. Sahakian[6,5], S. Saito[43], D.A. Sanchez[24], A. Santangelo[29], M. Sasaki[36], M. Schandri[36], R. Schlickeiser[11], F. Schüssler[18], A. Schulz[37], U. Schwanke[7], S. Schwemmer[25], M. Seglar-Arroyo[18], M. Settimo[16], A.S. Seyffert[1], N. Shafi[23], I. Shilon[36], K. Shiningayamwe[8], R. Simoni[9], H. Sol[15], F. Spanier[1], M. Spir-Jacob[31], Ł. Stawarz[38], R. Steenkamp[8], C. Stegmann[35,37], C. Steppa[35], I. Sushch[1], T. Takahashi[44], J.-P. Tavernet[16], T. Tavernier[31], A.M. Taylor[37], R. Terrier[31], L. Tibaldo[3], D. Tiziani[36], M. Tluczykont[2], C. Trichard[20], M. Tsirou[17], N. Tsuji[43], R. Tuffs[3], Y. Uchiyama[43], D.J. van der Walt[1], C. van Eldik[36], C. van Rensburg[1], B. van Soelen[40], G. Vasileiadis[17], J. Veh[36], C. Venter[1], A. Viana[3,46], P. Vincent[16], J. Vink[9], F. Voisin[14], H.J. Völk[3], T. Vuillaume[24], Z. Wadiasingh[1], S.J. Wagner[25], P. Wagner[7], R.M. Wagner[27], R. White[3], A. Wierzcholska[21], P. Willmann[36], A. Wörnlein[36], D. Wouters[18], R. Yang[3], D. Zaborov[30], M. Zacharias[1], R. Zanin[3], A.A. Zdziarski[34], A. Zech[15], F. Zefi[30], A. Ziegler[36], J. Zorn[3], and N. Żywucka[38]

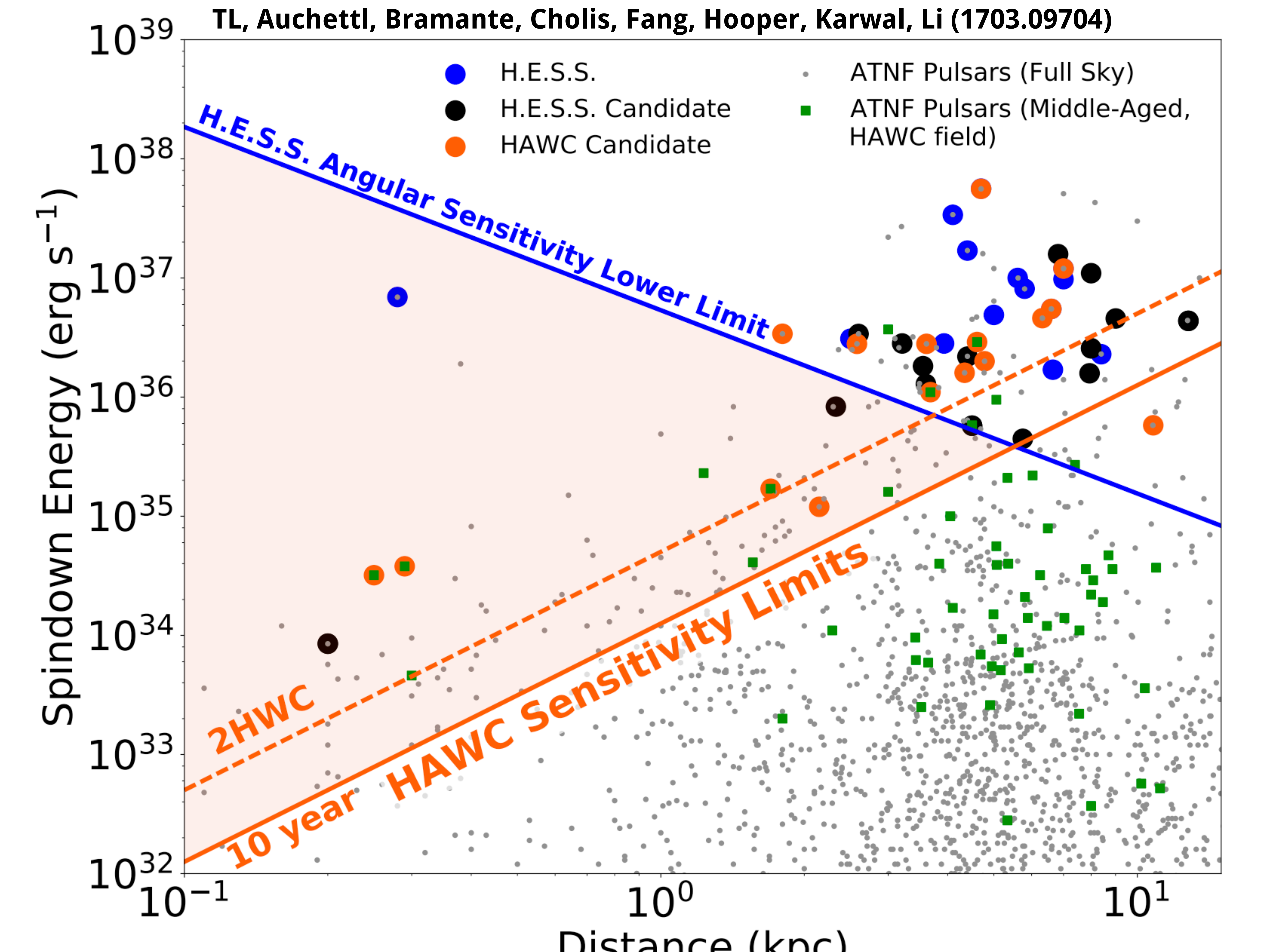
(Affiliations can be found after the references)

April 10, 2018

ABSTRACT

We present the results of the most comprehensive survey of the Galactic plane in very high-energy (VHE) γ-rays, including a public release of Galactic sky maps, a catalog of VHE sources, and the discovery of 16 new sources of VHE γ-rays. The High Energy Spectroscopic System (H.E.S.S.) Galactic plane survey (HGPS) was a decade-long observation program carried out by the H.E.S.S. I array of Cherenkov telescopes in Namibia from 2004 to 2013. The observations amount to nearly 2700 h of quality-selected data, covering the Galactic plane at longitudes from $\ell = 250^\circ$ to 65° and latitudes $|b| \leqslant 3^\circ$. In addition to the unprecedented spatial coverage, the HGPS also features a relatively high angular resolution ($0.08^\circ \approx 5$ arcmin mean point spread function 68% containment radius), sensitivity ($\lesssim 1.5\%$ Crab flux for point-like sources), and energy range (0.2 to 100 TeV). We constructed a catalog of VHE γ-ray sources from the HGPS data set with a systematic procedure for both source detection and characterization of morphology and spectrum. We present this likelihood-based method in detail, including the introduction of a model component to account for unresolved, large-scale emission along the Galactic plane. In total, the resulting HGPS catalog contains 78 VHE sources, of which 14 are not reanalyzed here, for example, due to their complex morphology, namely shell-like sources and the Galactic center region. Where possible, we provide a firm identification of the VHE source or plausible associations with sources in other astronomical catalogs. We also studied




TL, Auchettl, Bramante, Cholis, Fang, Hooper, Karwal, Li (1703.09704)
H.E.S.S.
H.E.S.S. Candidate
HAWC Candidate
ATNF Pulsars (Full Sky)
ATNF Pulsars (Middle-Aged, HAWC field)
H.E.S.S. Angular Sensitivity Lower Limit
2HWC
10 year HAWC Sensitivity Limits
Spindown Energy (erg s^{-1})
10^{39}
10^{38}
10^{37}
10^{36}
10^{35}
10^{34}
10^{33}
10^{32}
10^{-1}
10^{0}
10^{1}
Distance (kpc)

What Do We Need?

1. Continued observations of TeV halos.

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

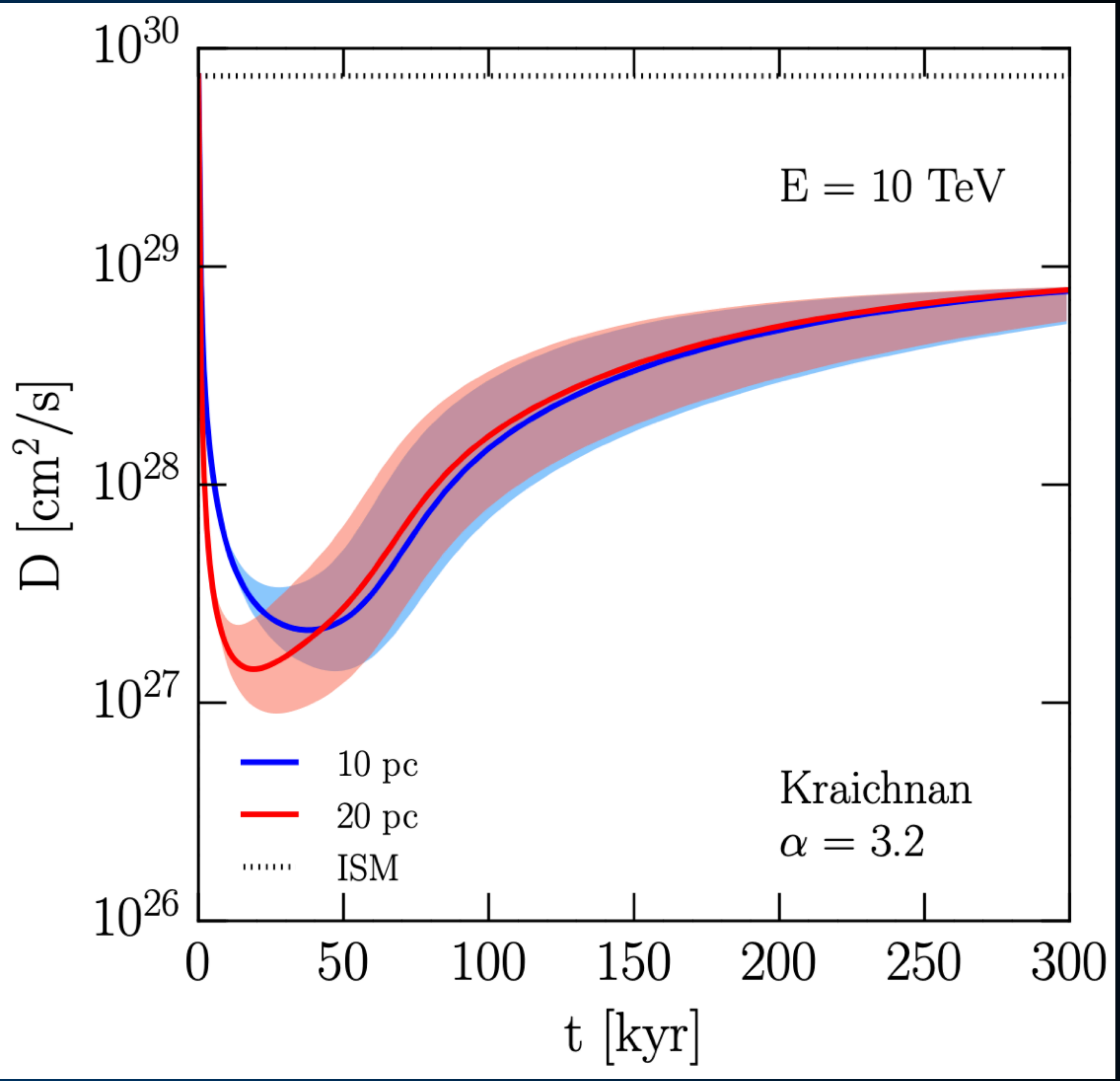
3. A method for precisely determining the pulsar position within the TeV halo.

A Model for TeV Halos

Evoli, TL, Morlino (1807.09263)

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

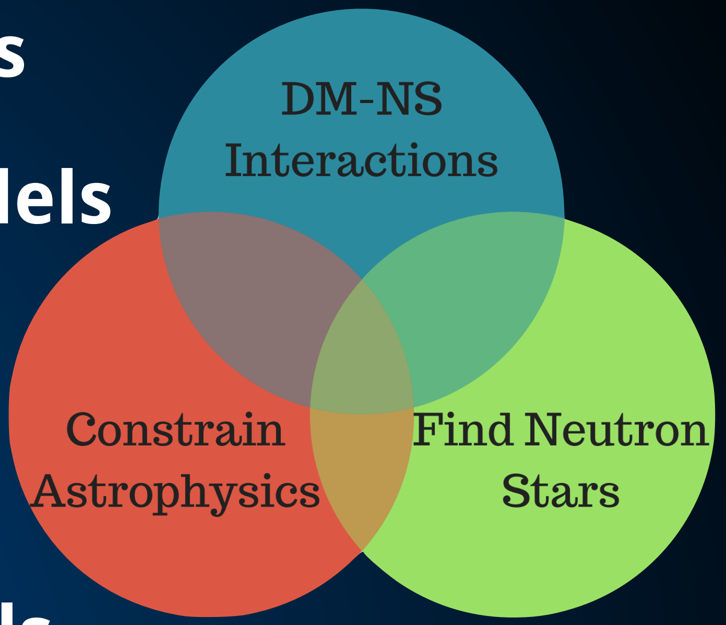
- Analog with cosmic-ray confinement in supernova remnants.



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

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.**



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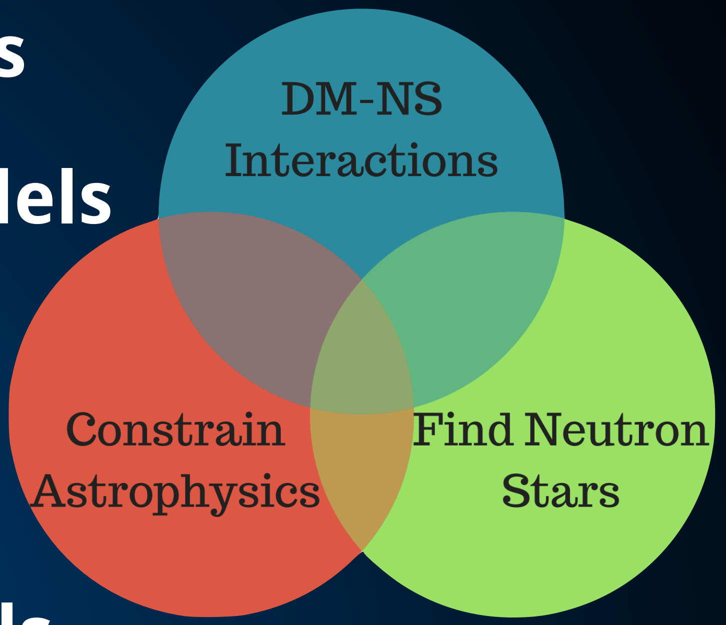
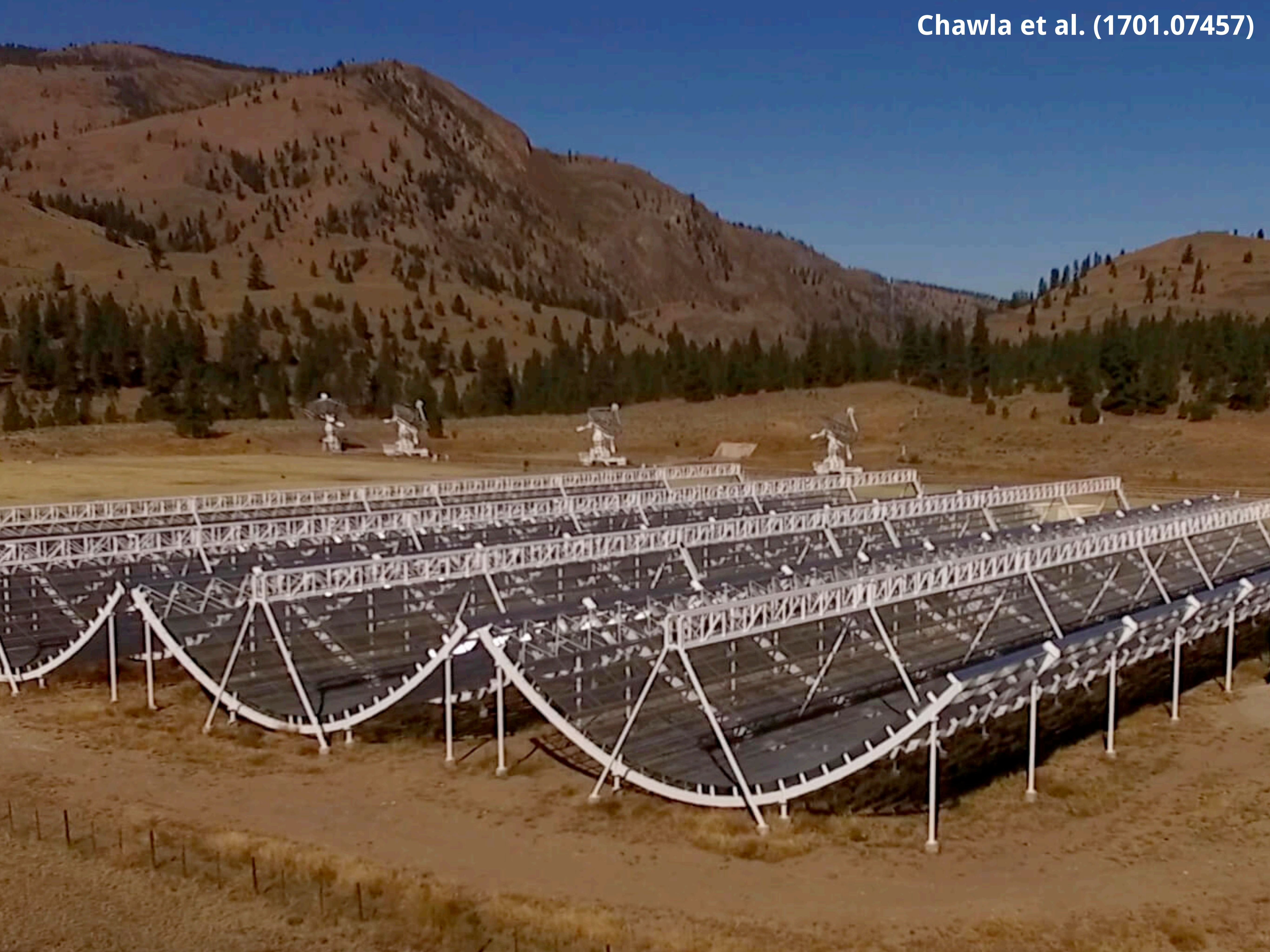


2. **Differentiate dim dark matter signals from astrophysics**
   - **Need detailed models of neutron star physics.**
   - **Requires observations of pulsars with “special” attributes**
     1. **Nearby**
     2. **Strong Magnetic Fields**
     3. **Not Beamed Towards Earth**

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.**

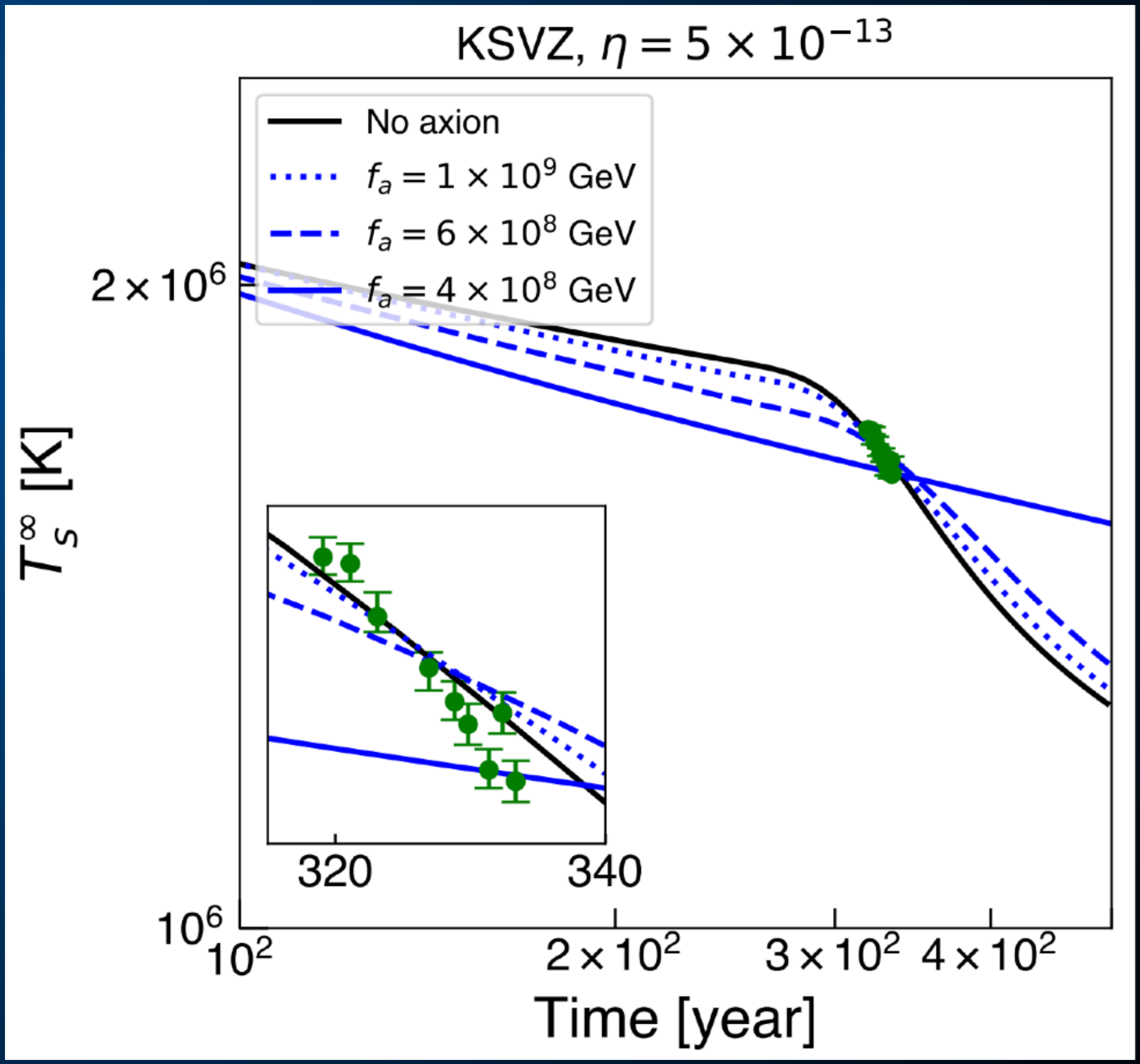
- **Early studies can set strong constraints on the asymmetric dark matter and axion parameter spaces.**

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

Extra Slides

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)

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 ($\times 10^{-15}$)	Actual Flux ($\times 10^{-15}$)	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

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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

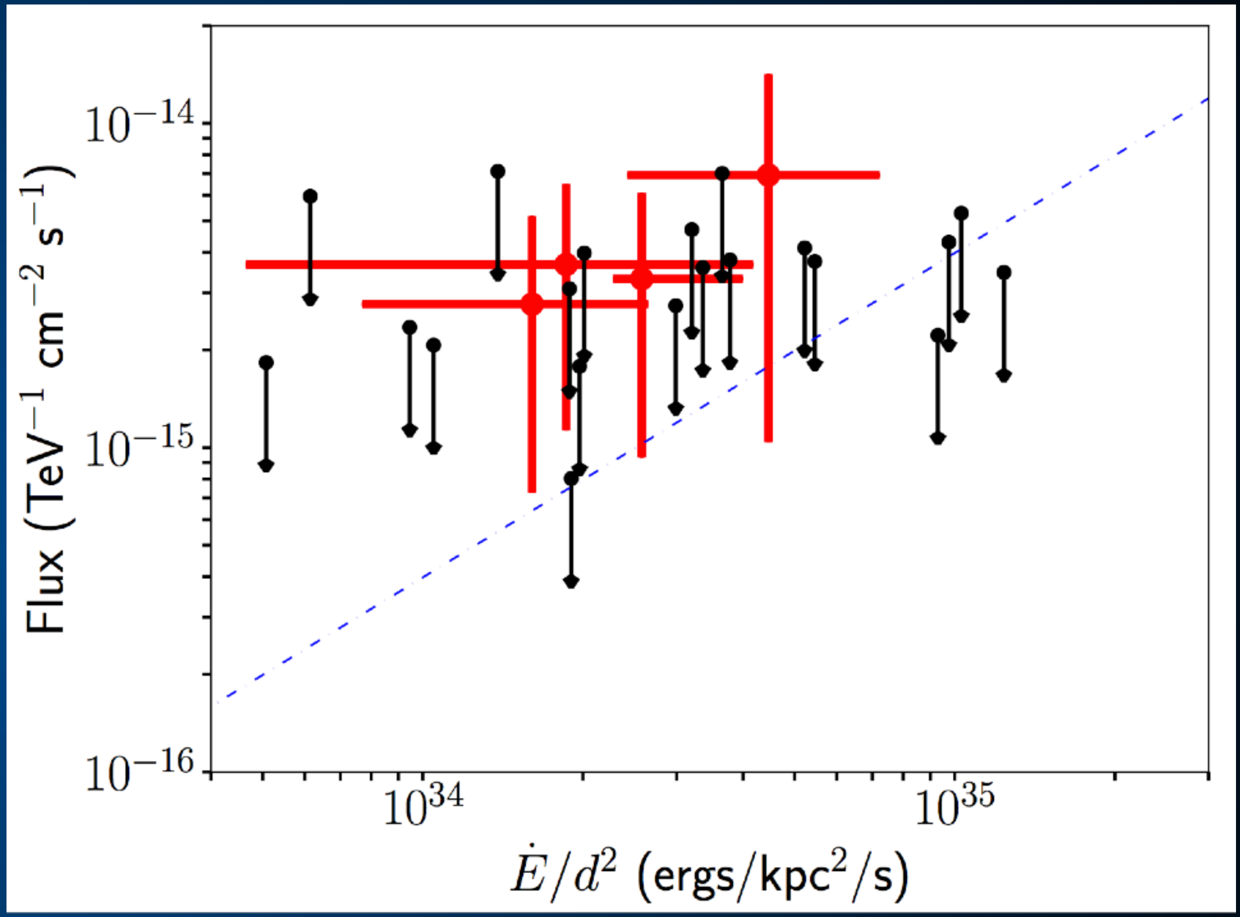
- **Correcting for the beaming fraction implies that 56^{+15}_{-11} TeV halos are currently observed by HAWC.**
- **However, <u>only 39 HAWC sources</u> total.**
- **Chance overlaps, SNR contamination must be taken into account.**

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)

Discovering Pulsars at TeV Energies

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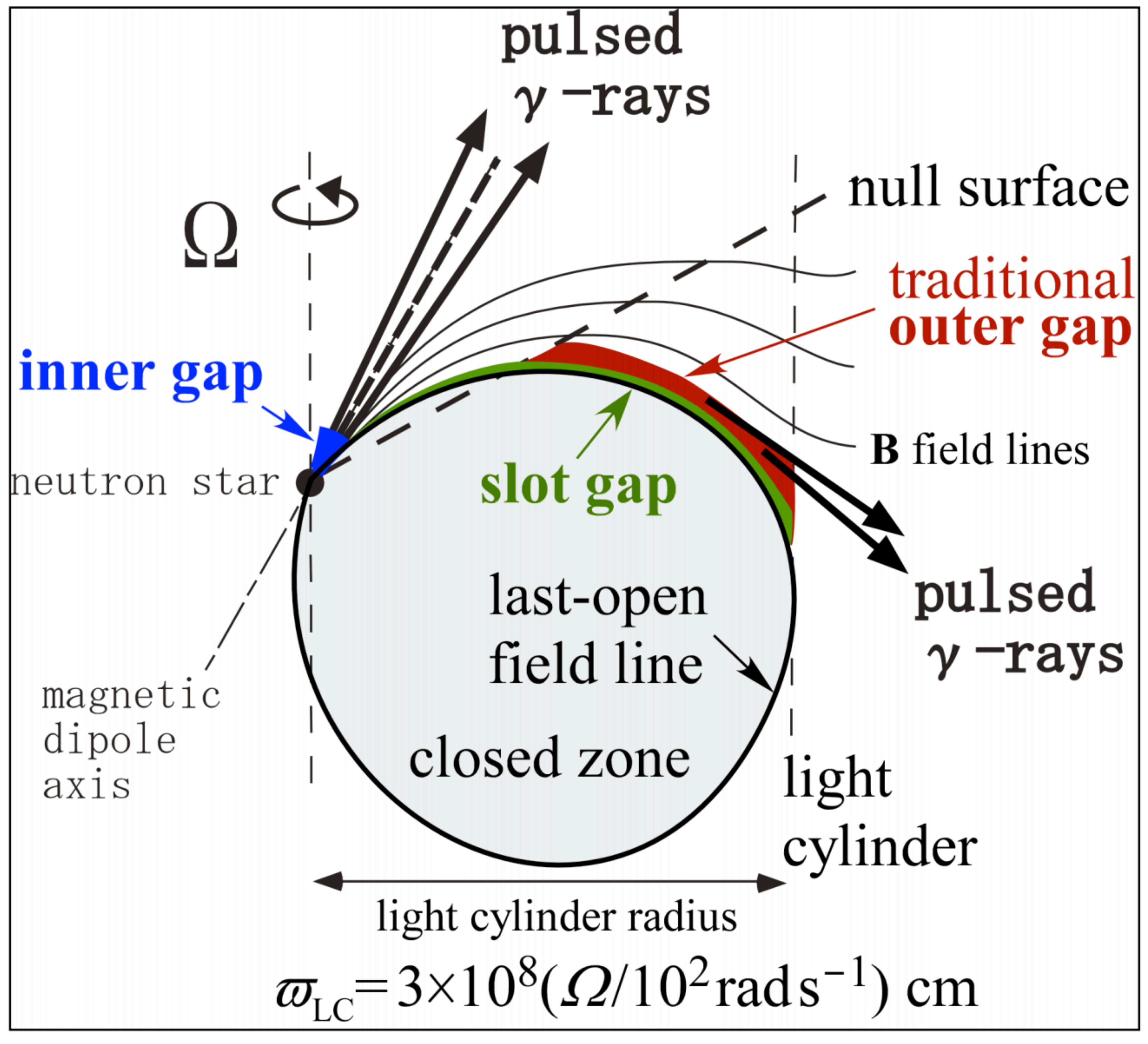
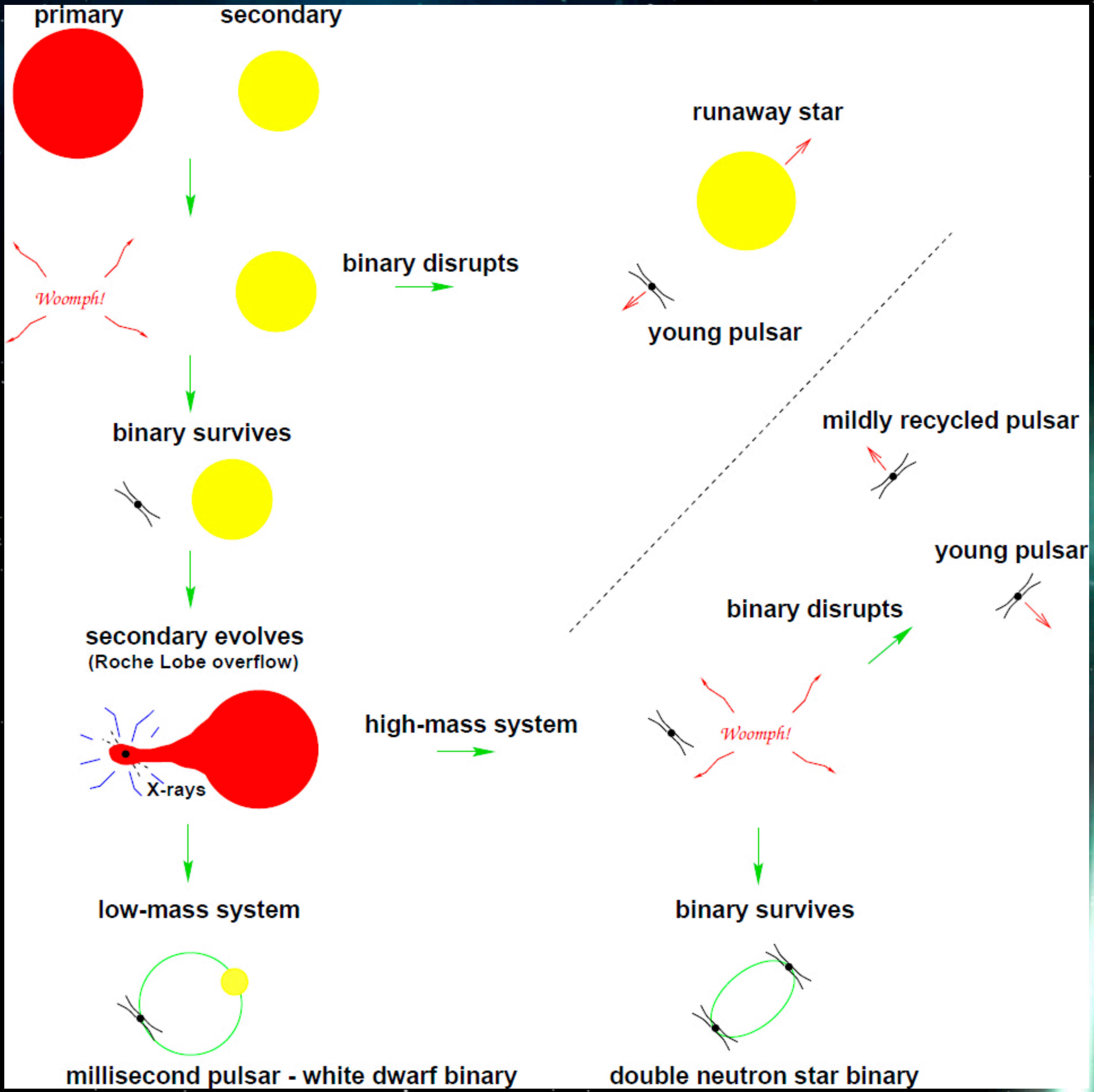
TL et al. (1703.09704)

Emission Morphologies



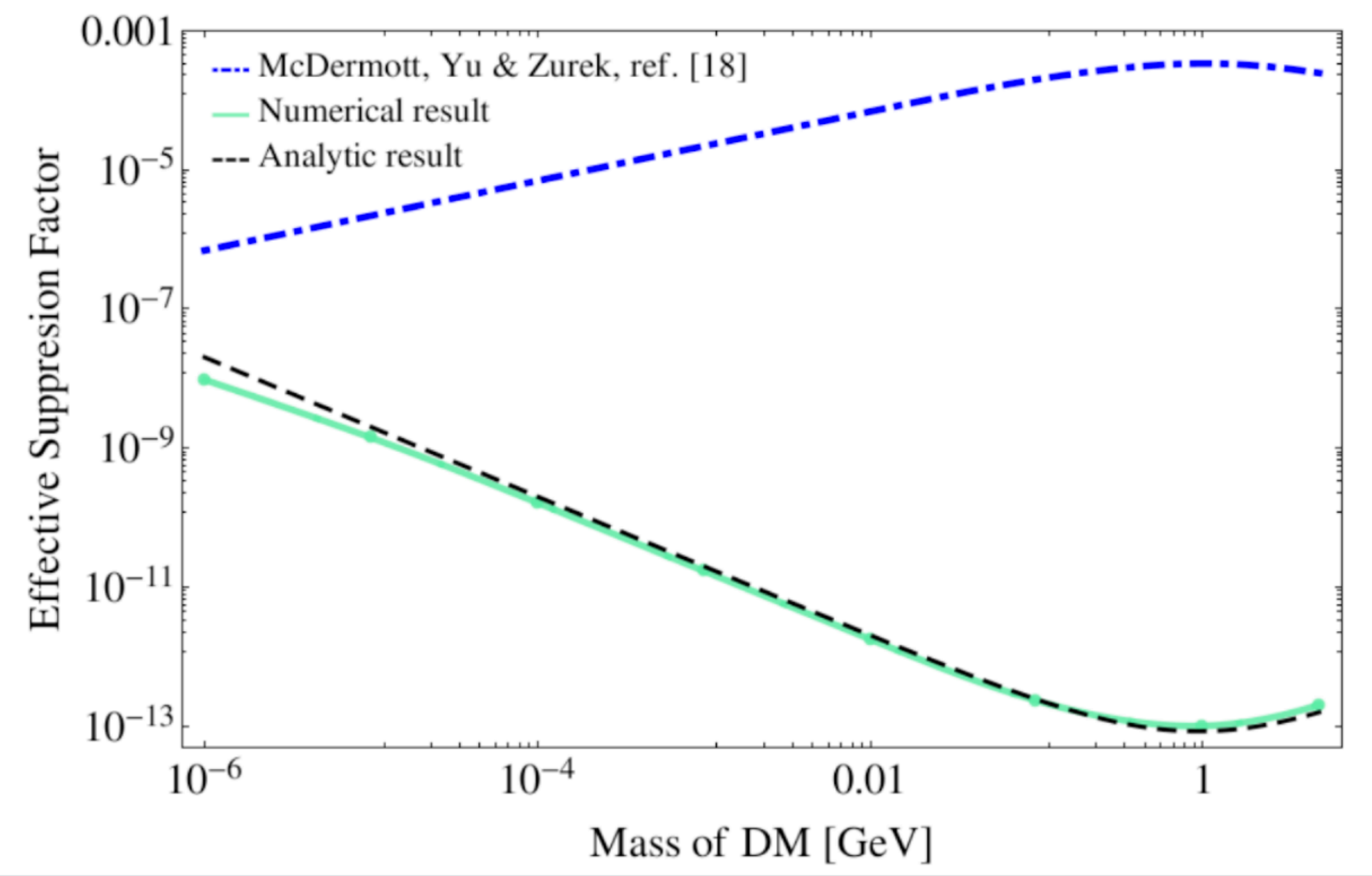
Evolutionary History of Millisecond Pulsars



Dark Matter Thermalization

Bertoni et al. (2013; 1309.1721)

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



- **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:**

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

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:

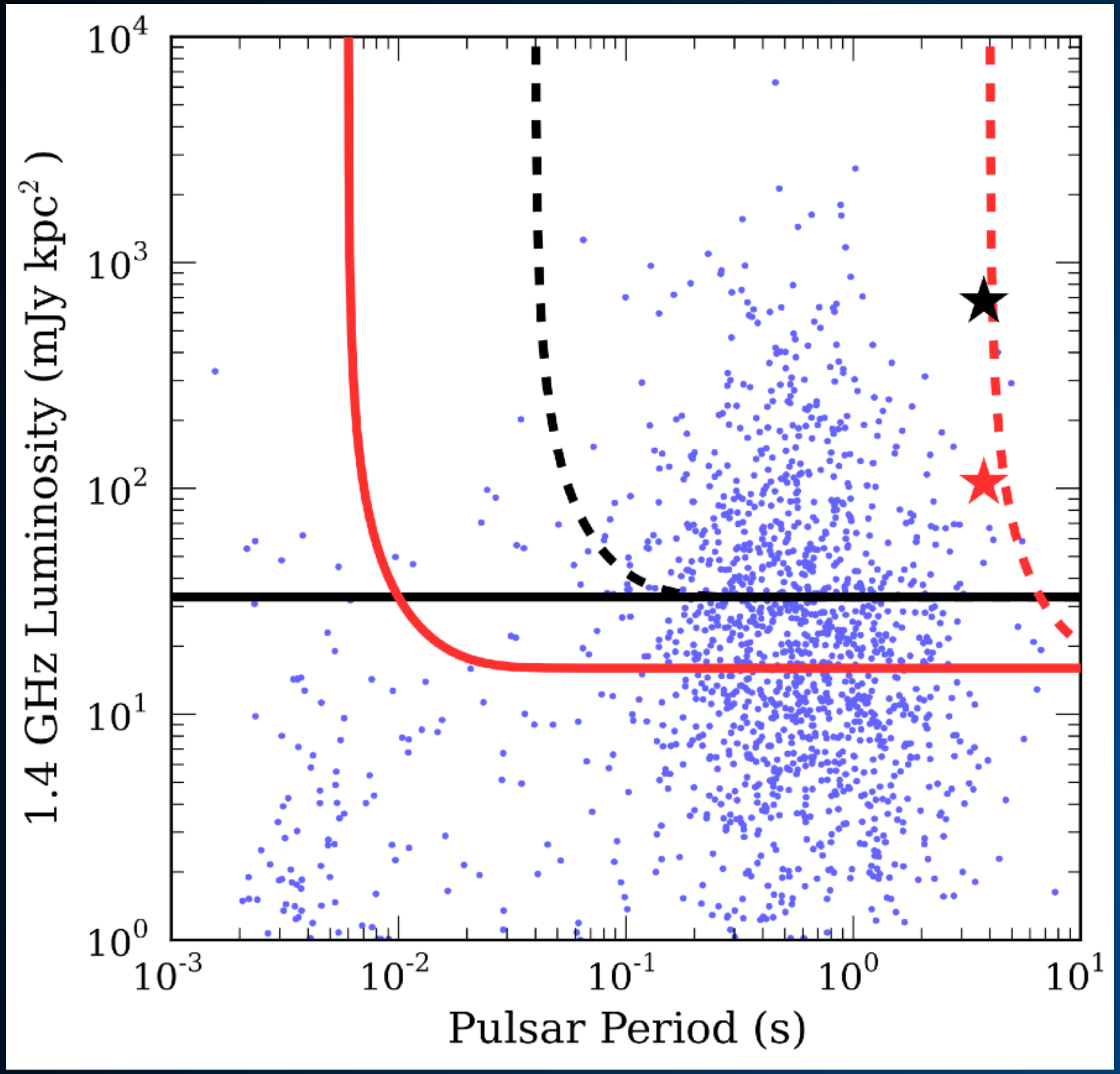
$$M_{crit}^{ferm} \simeq M_{pl}^3/m_X^2$$

  - It then collapses on a timescale:

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

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

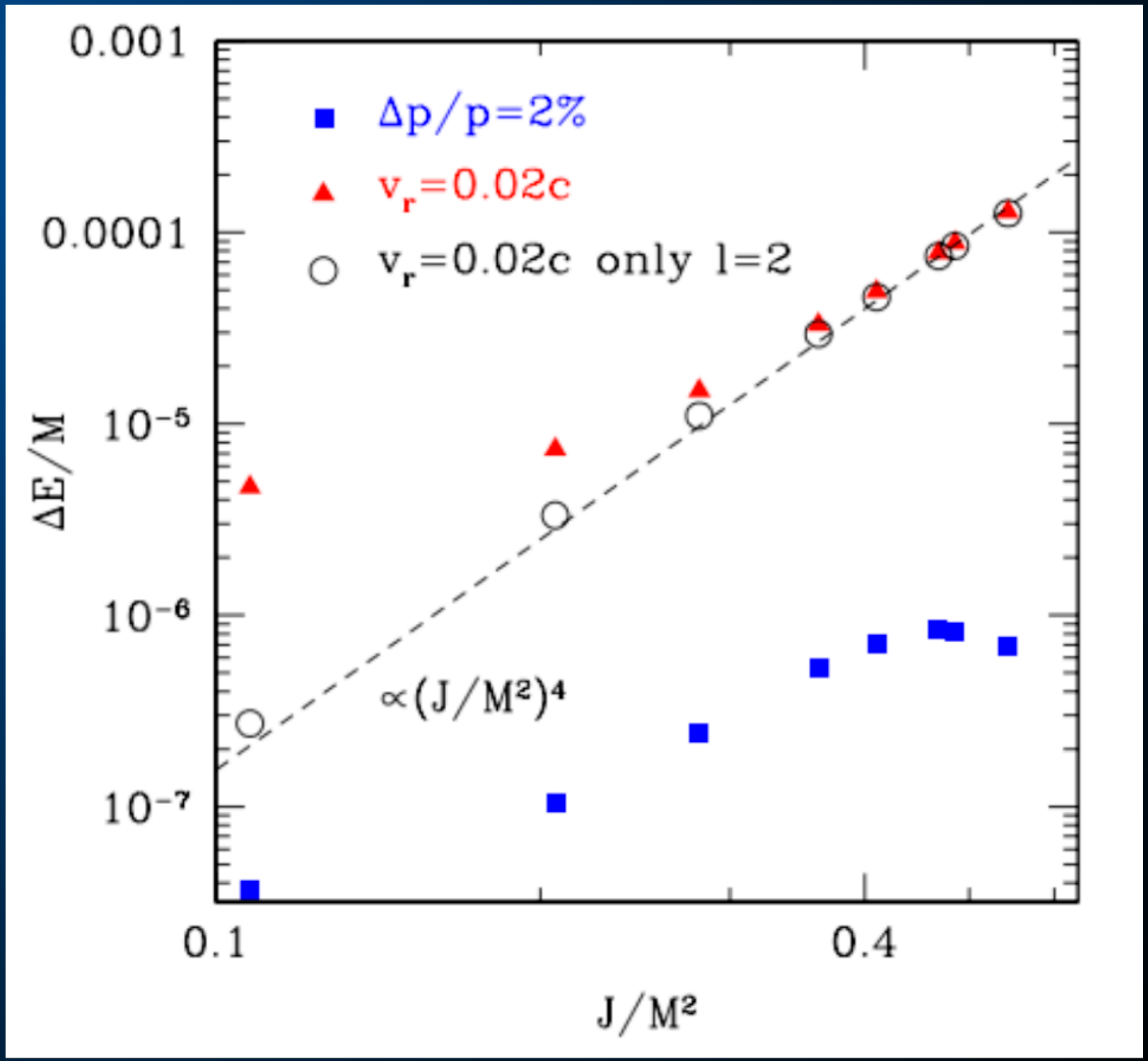
- **Gravitational Waves from DM induced collapse**

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

Baiotti et al. (gr-qc/0701043)

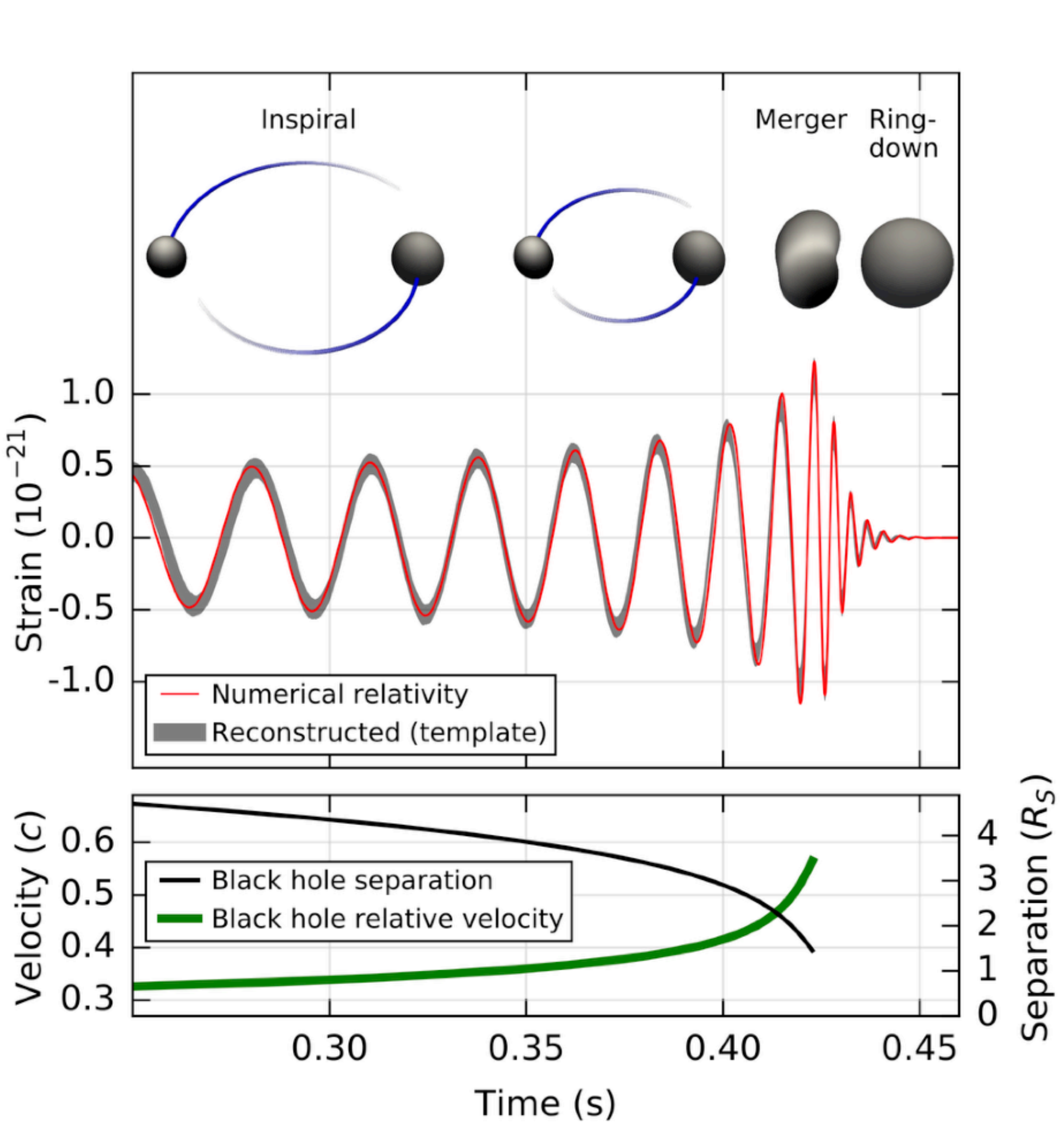
- **Single NS collapse models have been considered (primarily from accretion induced collapse).**

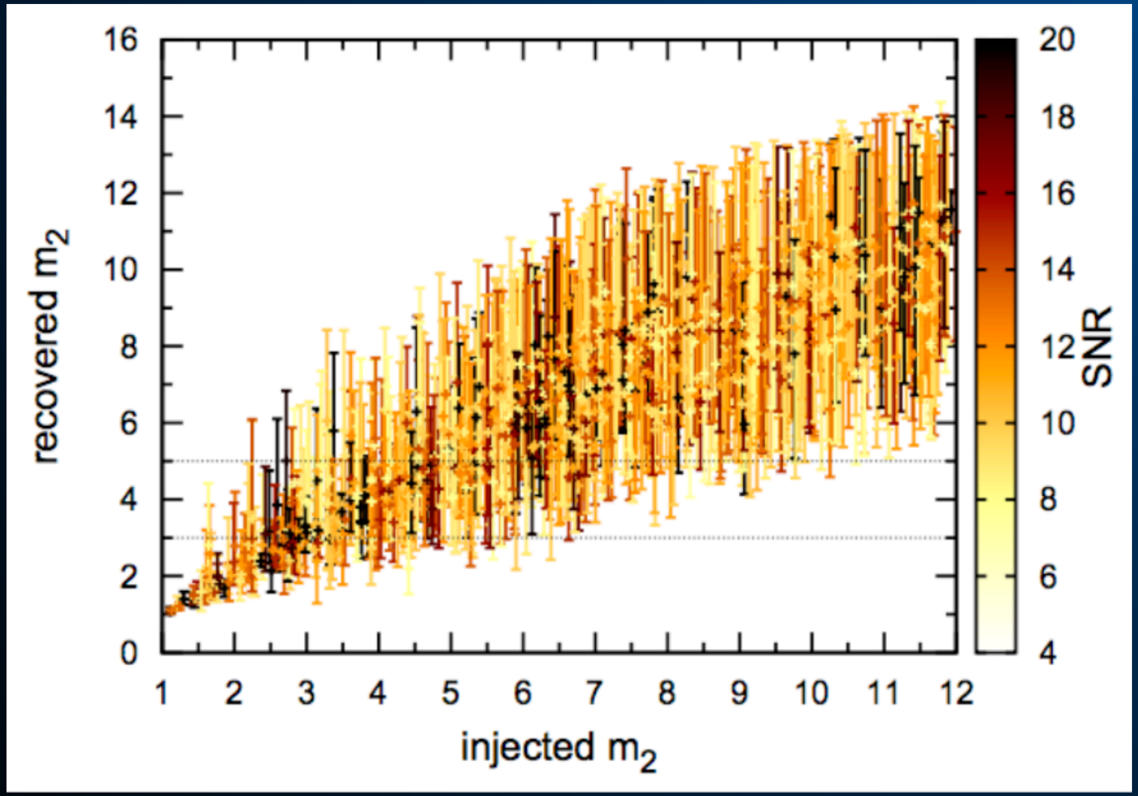
- **DM induced NS collapse observable throughout the Milky Way (0.01 yr^{-1} ?)**



Differentiating Black Hole and NS Mergers

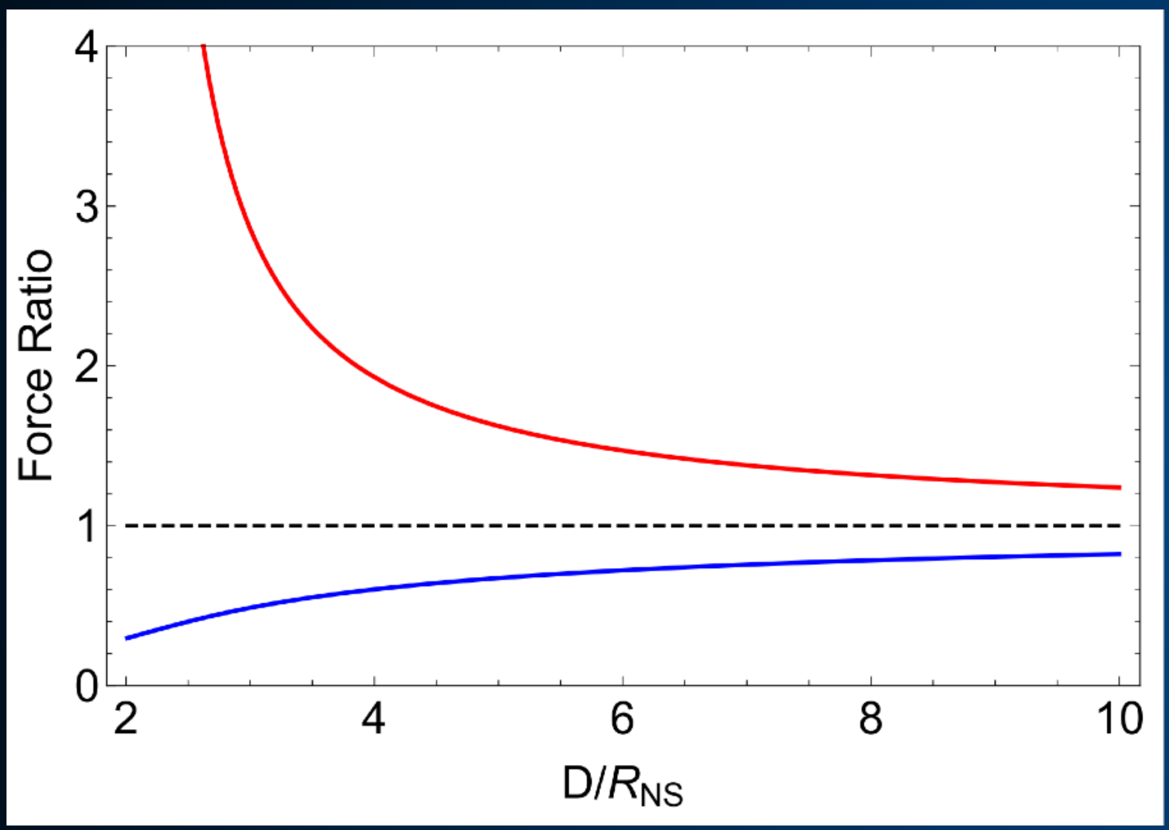
- **Anomalies in the tidal strain of binary neutron star mergers.**
  - **DM induced NS collapse produces a population of 1.4 $M_{\odot}$ black holes.**
  - **Can potentially see differences in merger and ring-down, but not presently feasible.**

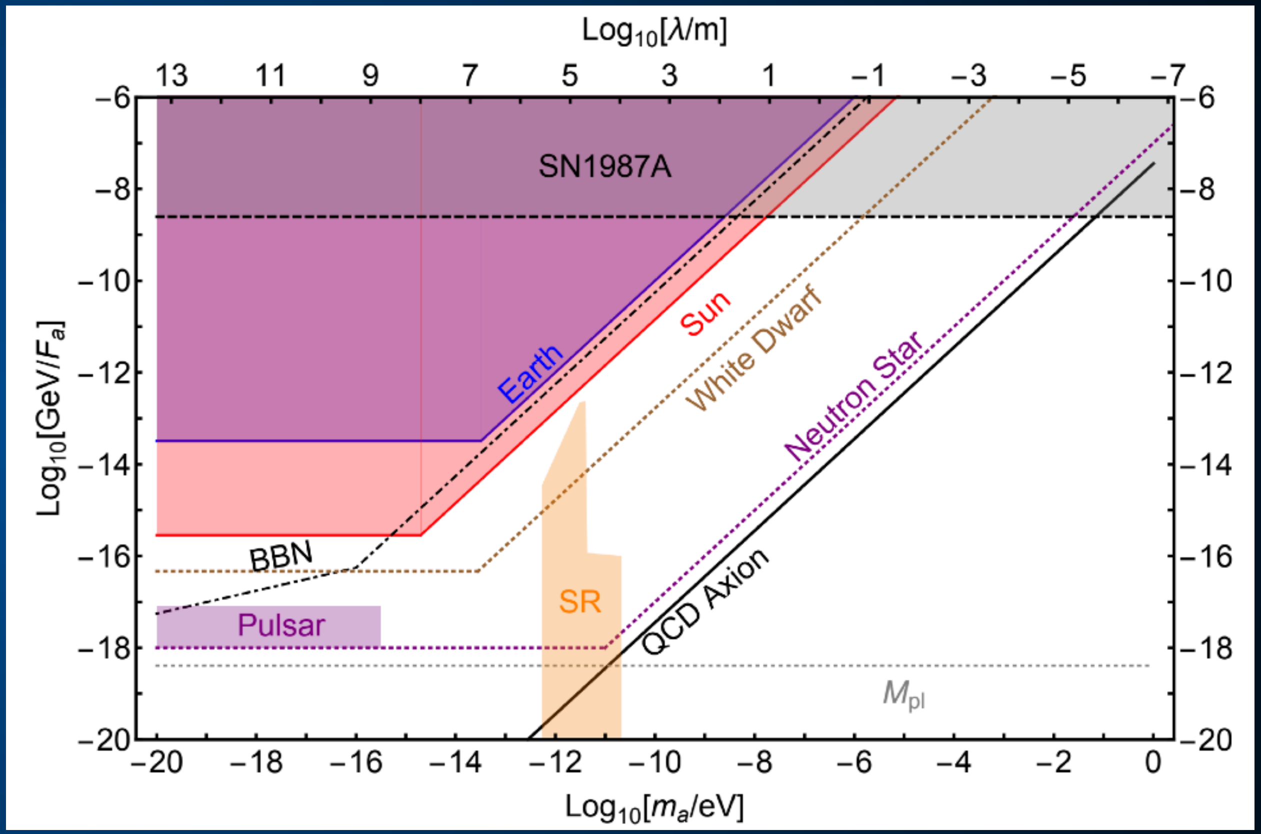




Littenburg et al. (1503.03179)

Particle Physics Mash-Up

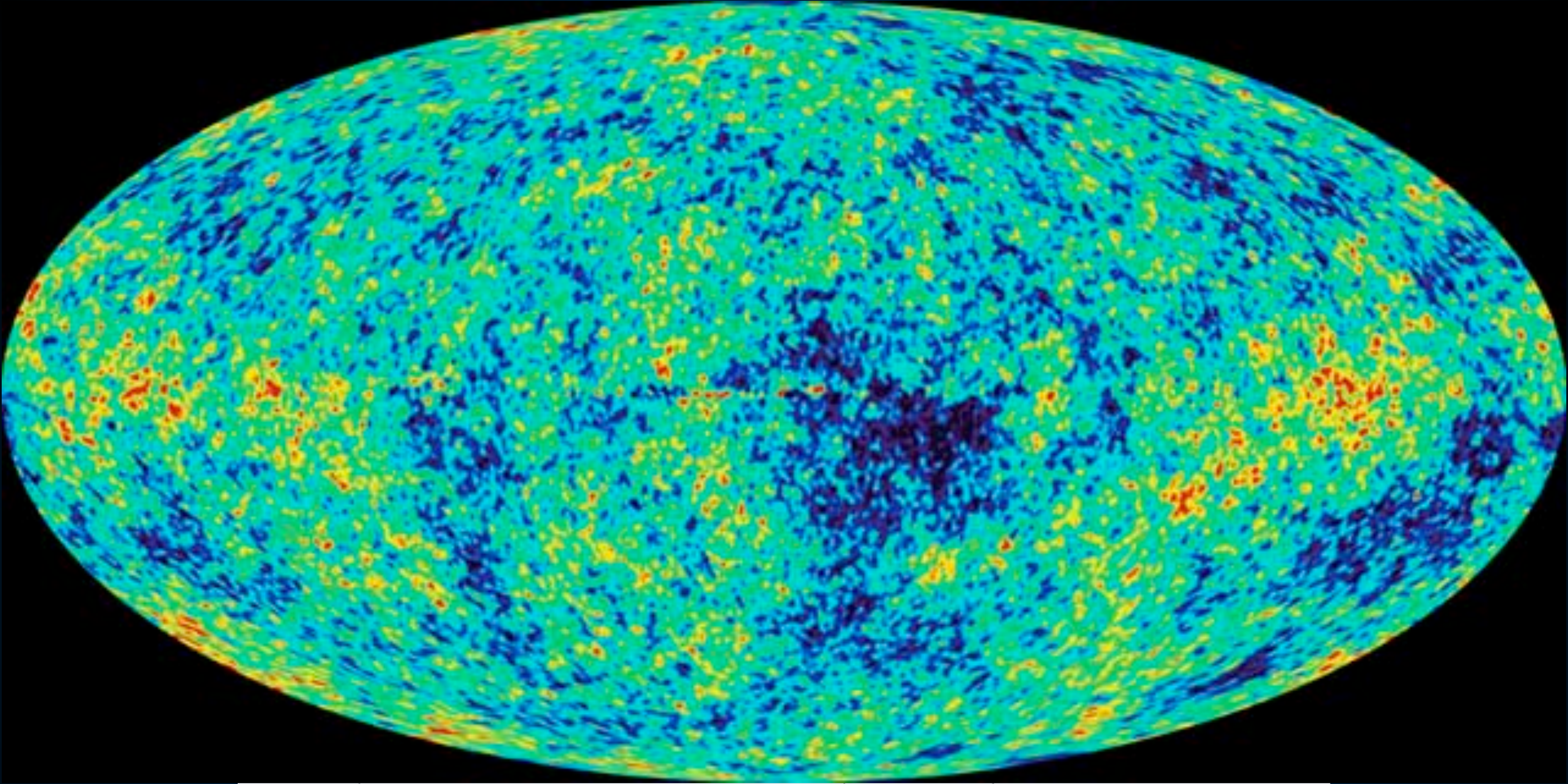




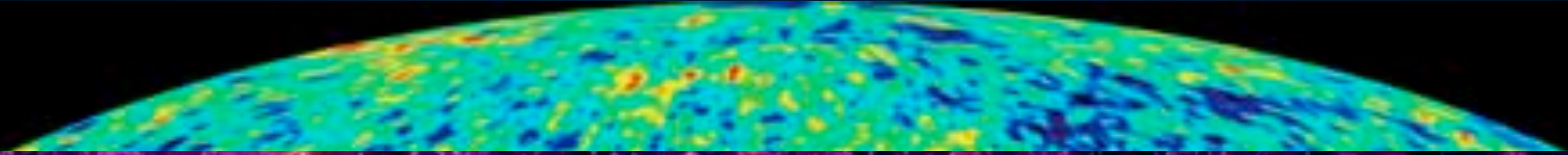
- **Low mass axions can mediate forces between inspiraling neutron stars, providing effects comparable to gravity.**

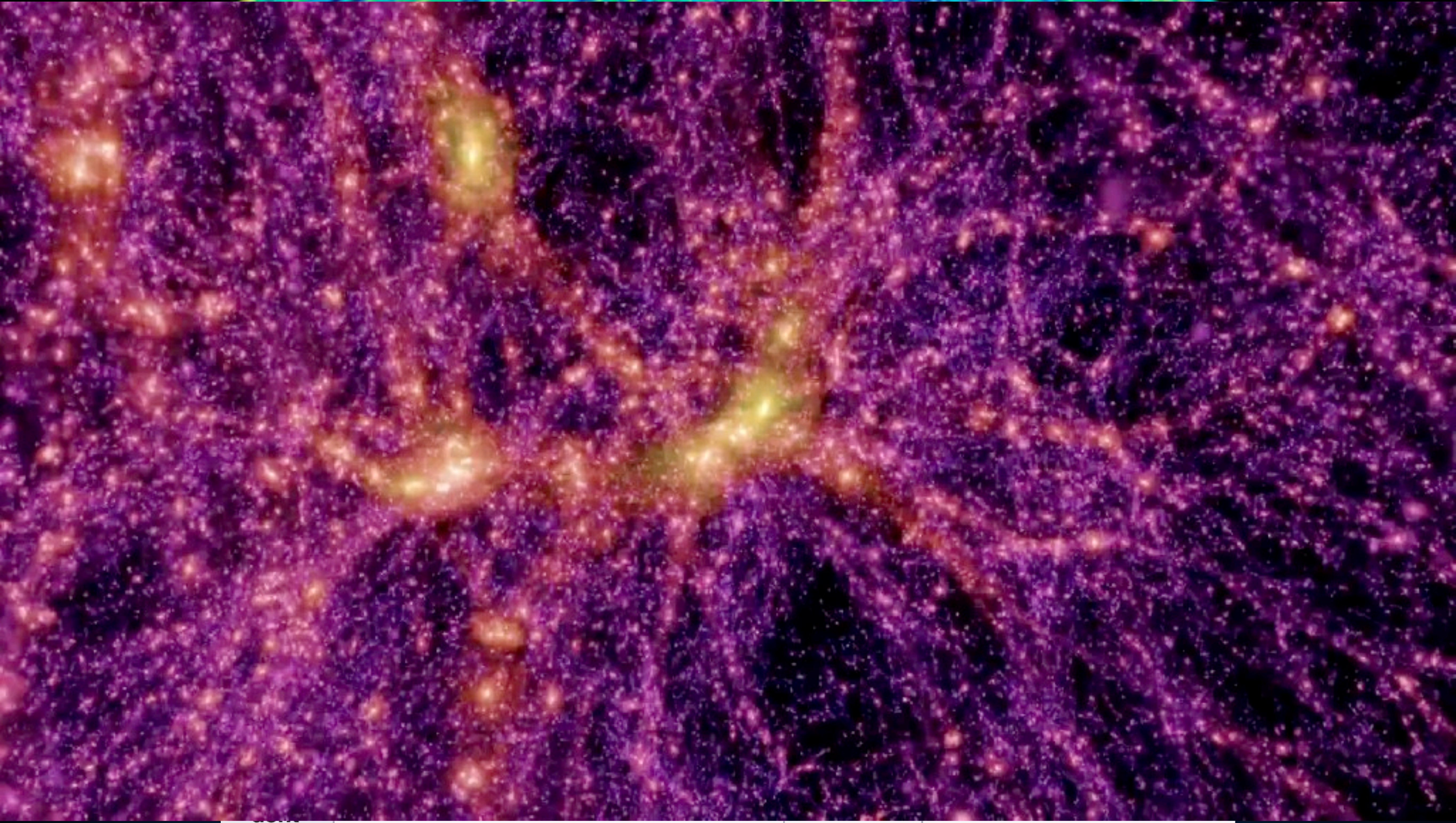
- **LIGO observations can probe the low-mass axion window.**

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





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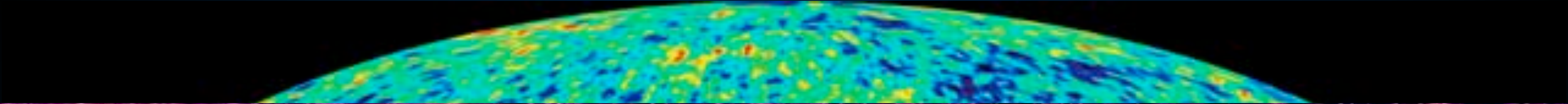

meters	Curvature fluctuation amplitude, $k_0 = 0.002\ \mathrm{Mpc}^{-1}$	Δ_R^2	$2.441\ ^{+0.088}_{-0.092} \times 10^{-9}$[17]
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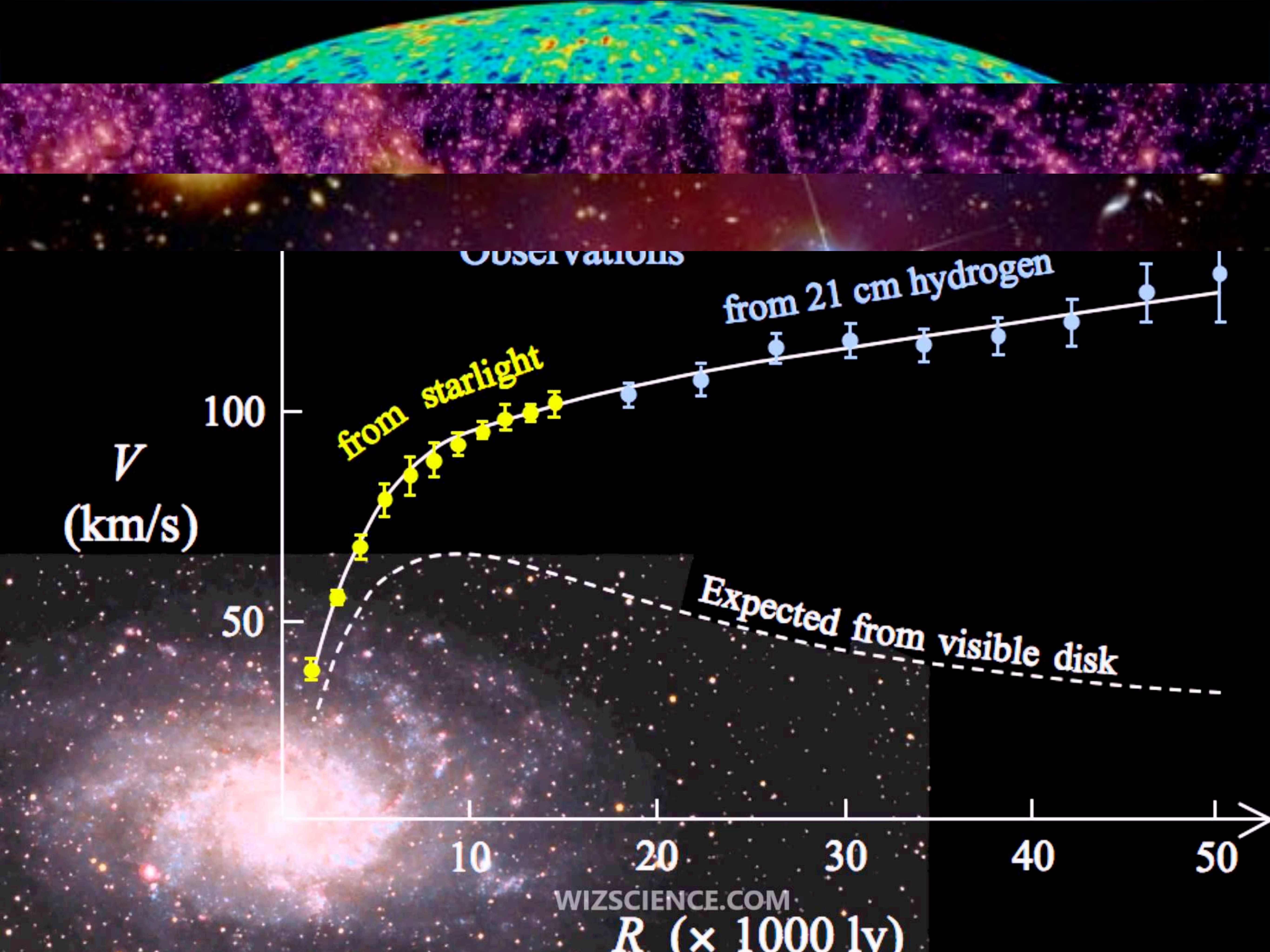
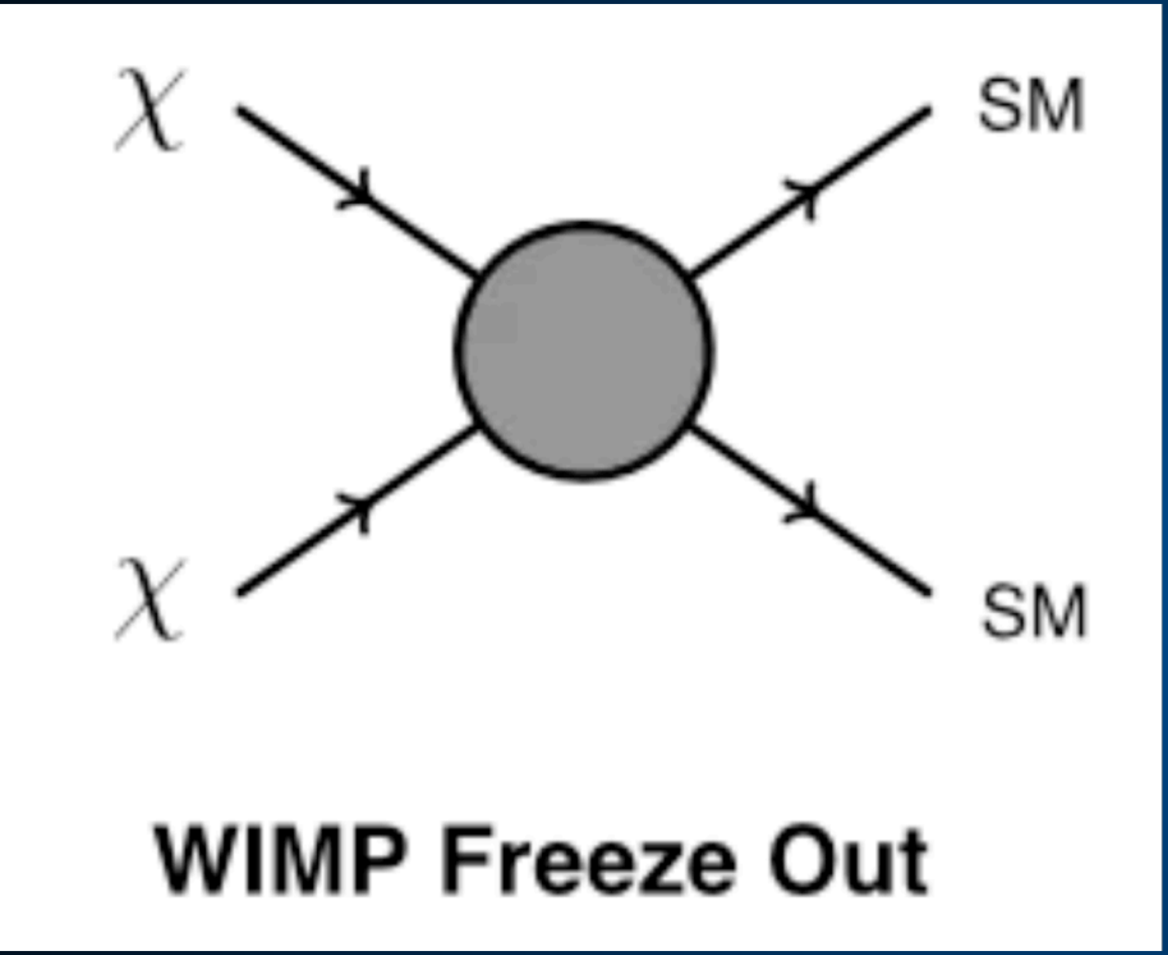
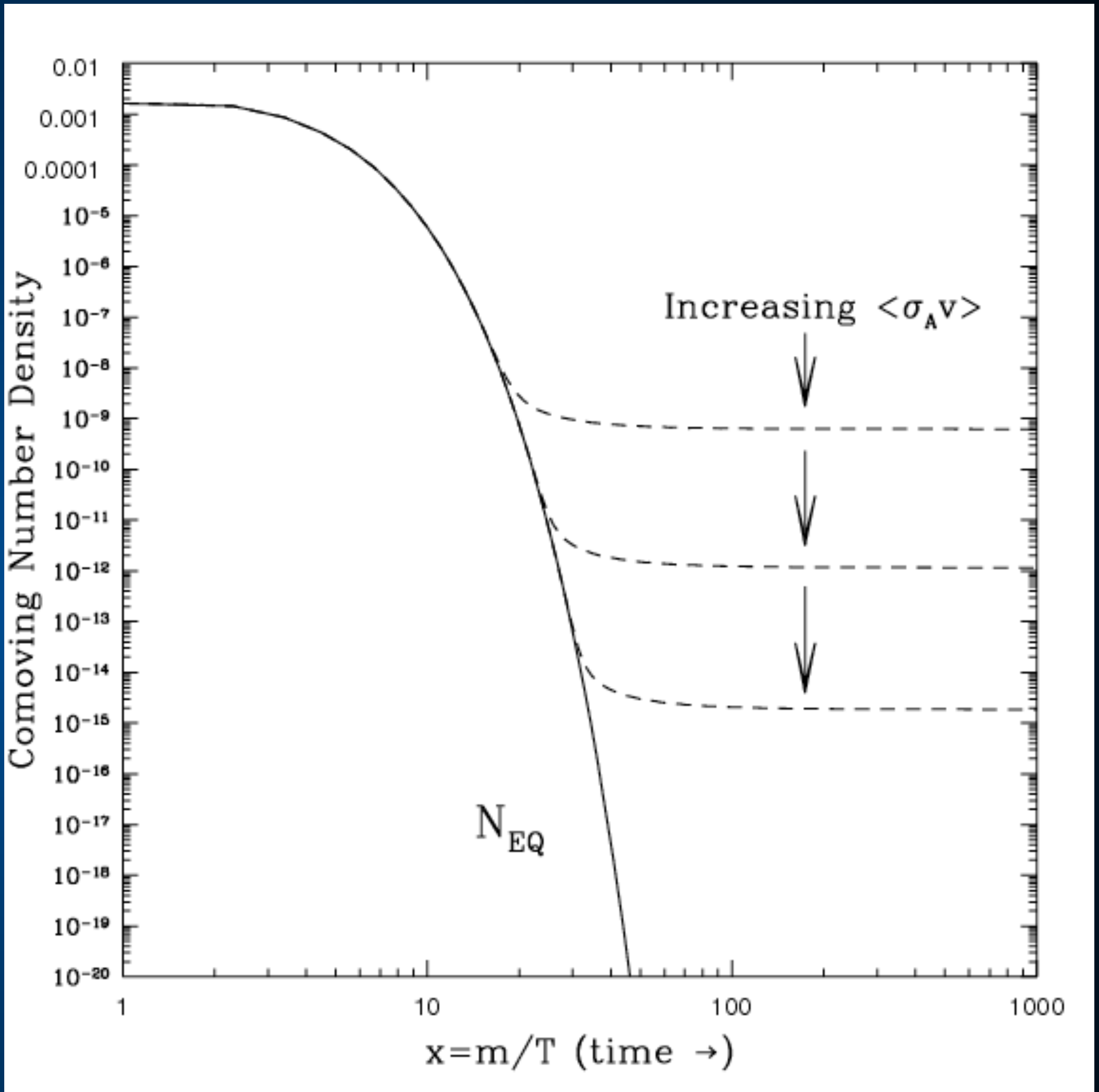

from 21 cm hydrogen
from starlight
100
50
V
(km/s)
Expected from visible disk
10
20
30
40
50
WIZSCIENCE.COM
R (× 1000 ly)

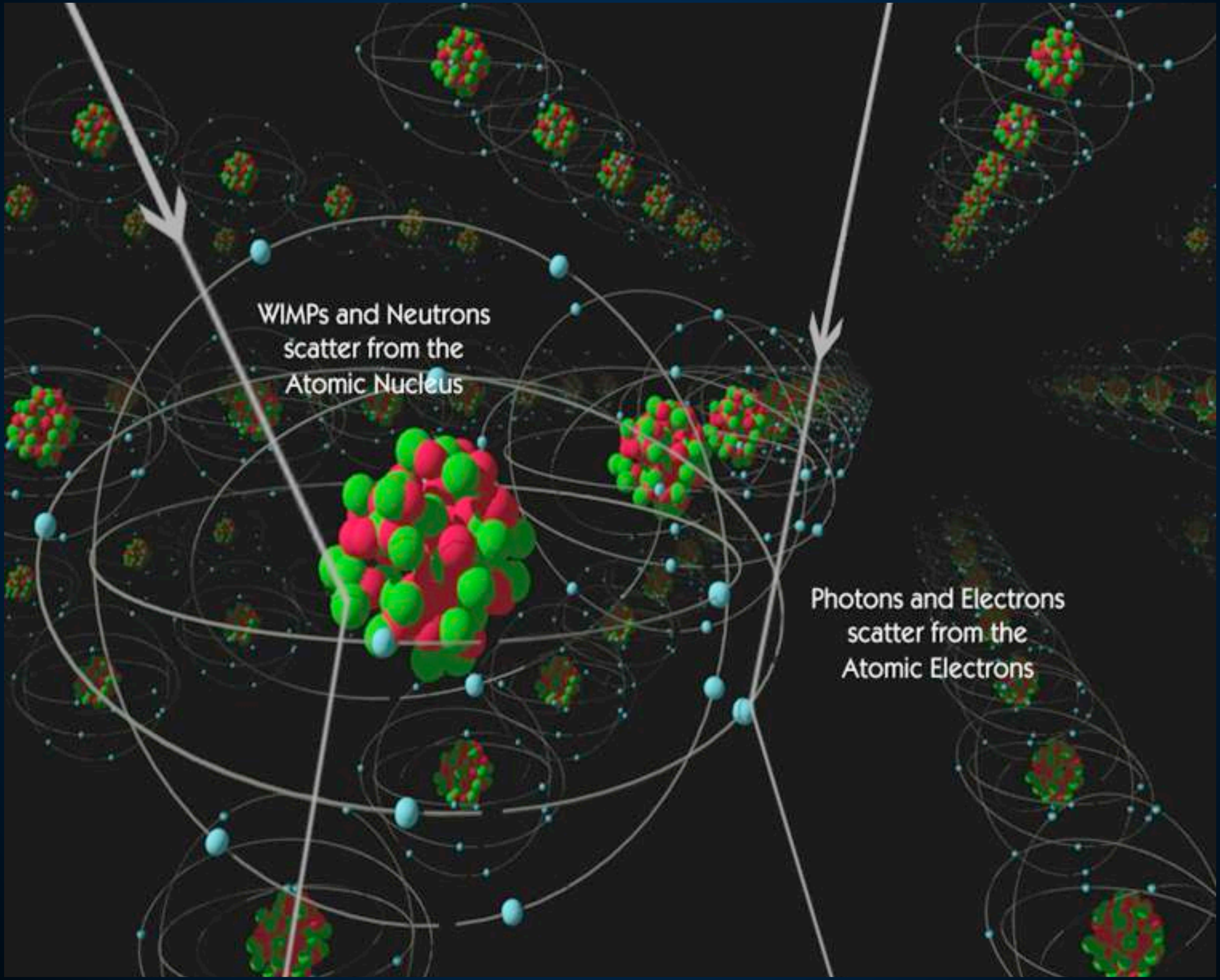
One Slide On WIMP Dark Matter



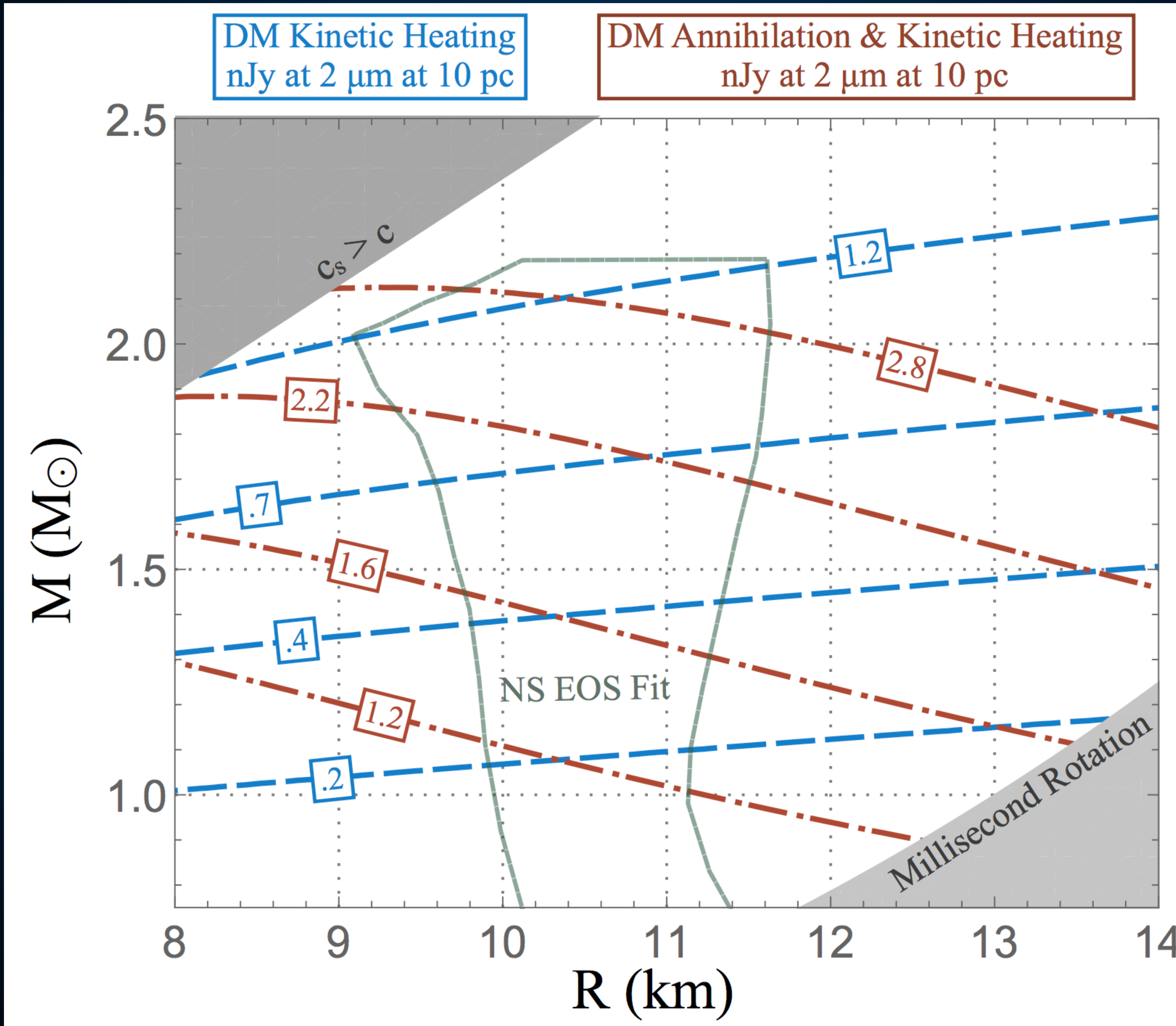


- **The standard WIMP freeze-out scenario is still the best-motivated model to explain the Dark Matter abundance.**

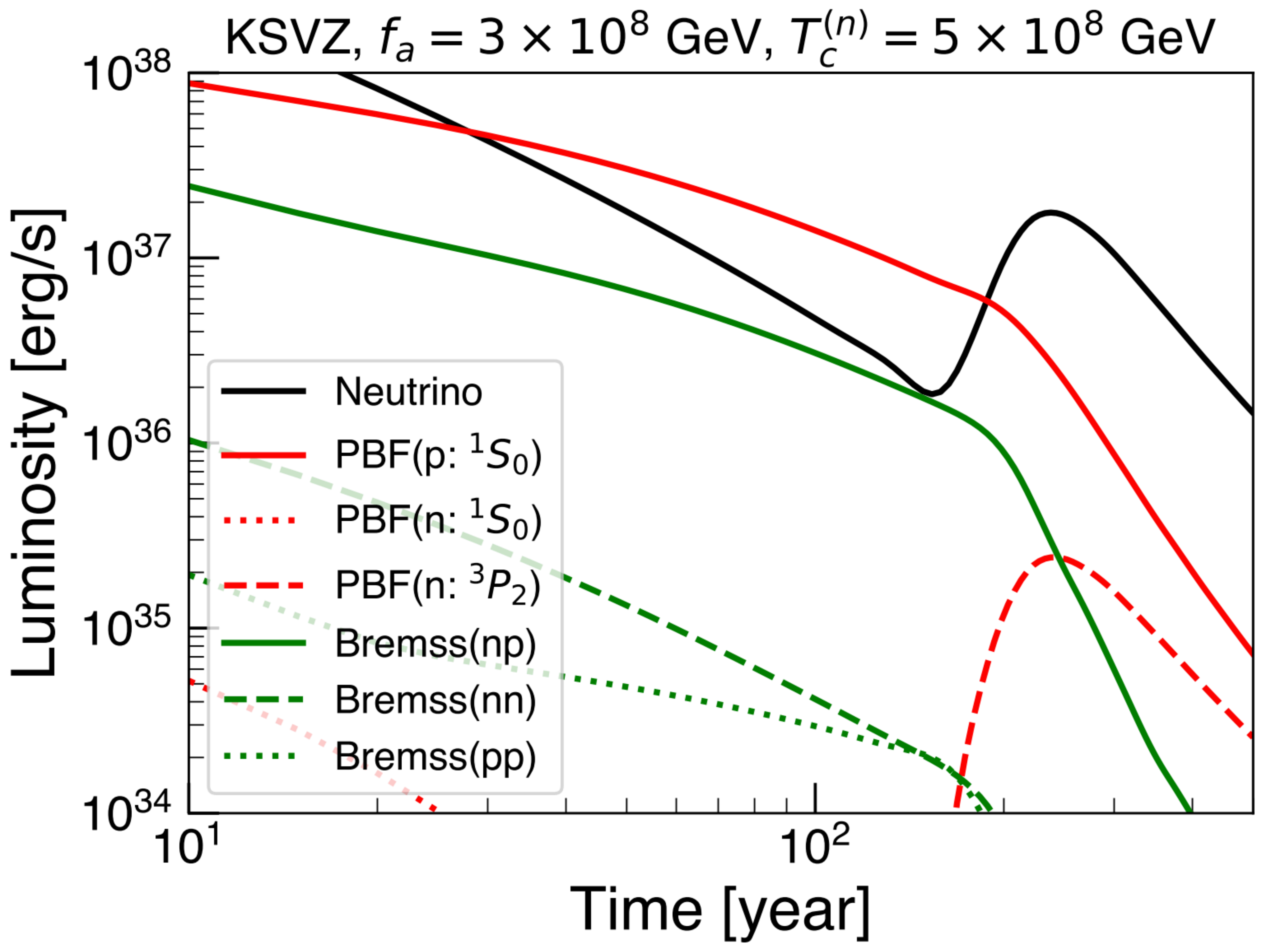
Direct Detection



Dark Matter Flux Depends on NS EOS



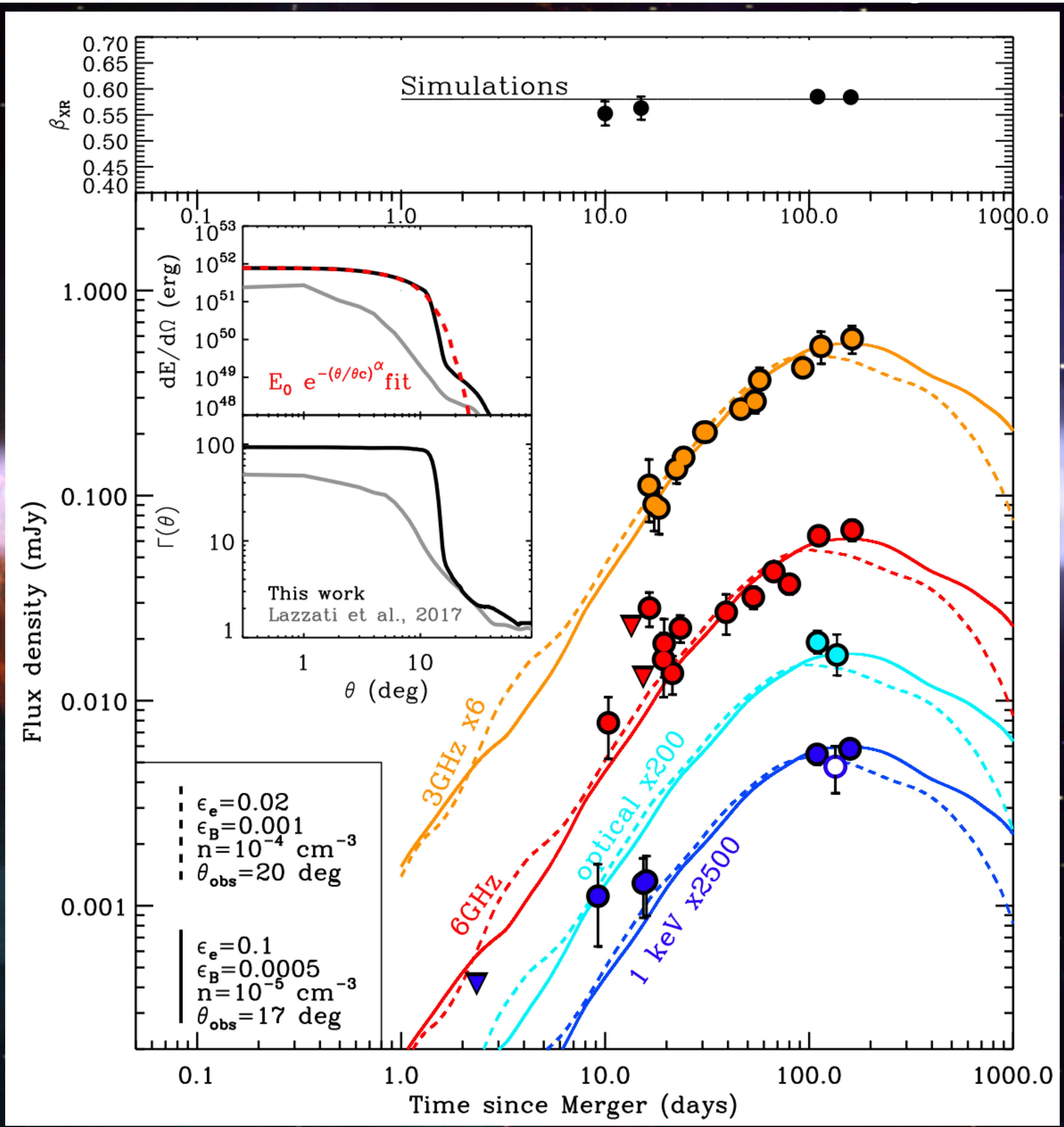
Axion and Neutrino Cooling in Neutron Stars



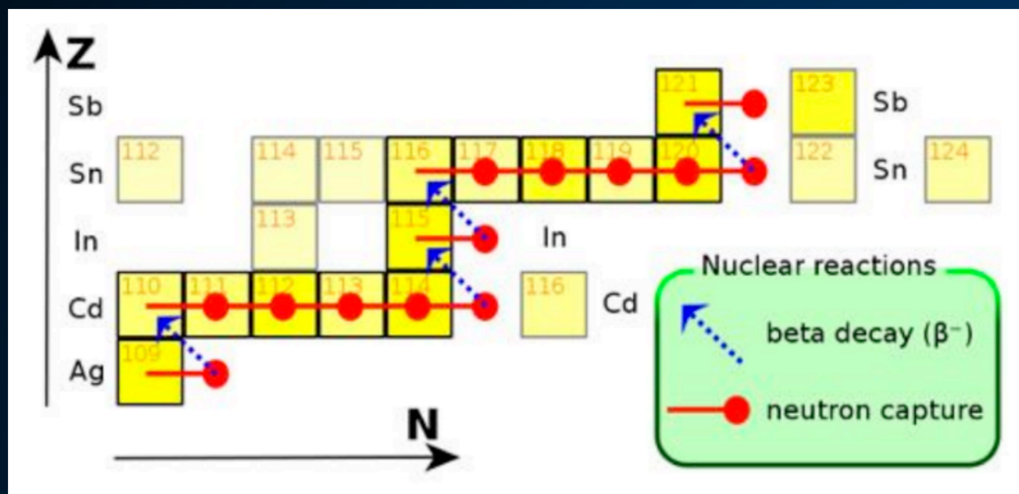
Hamaguchi et al. (1806.07151)

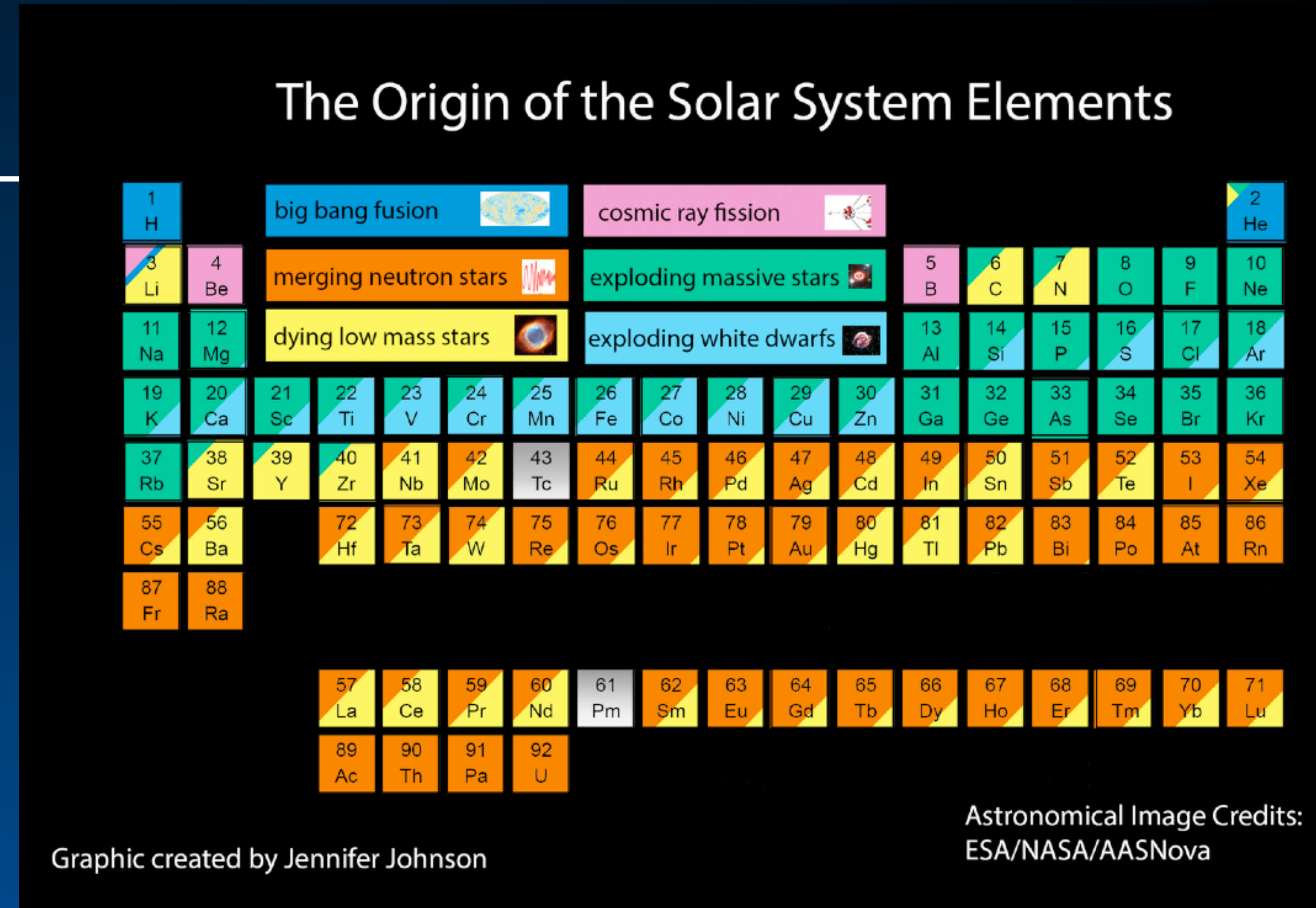
r-process Enrichment

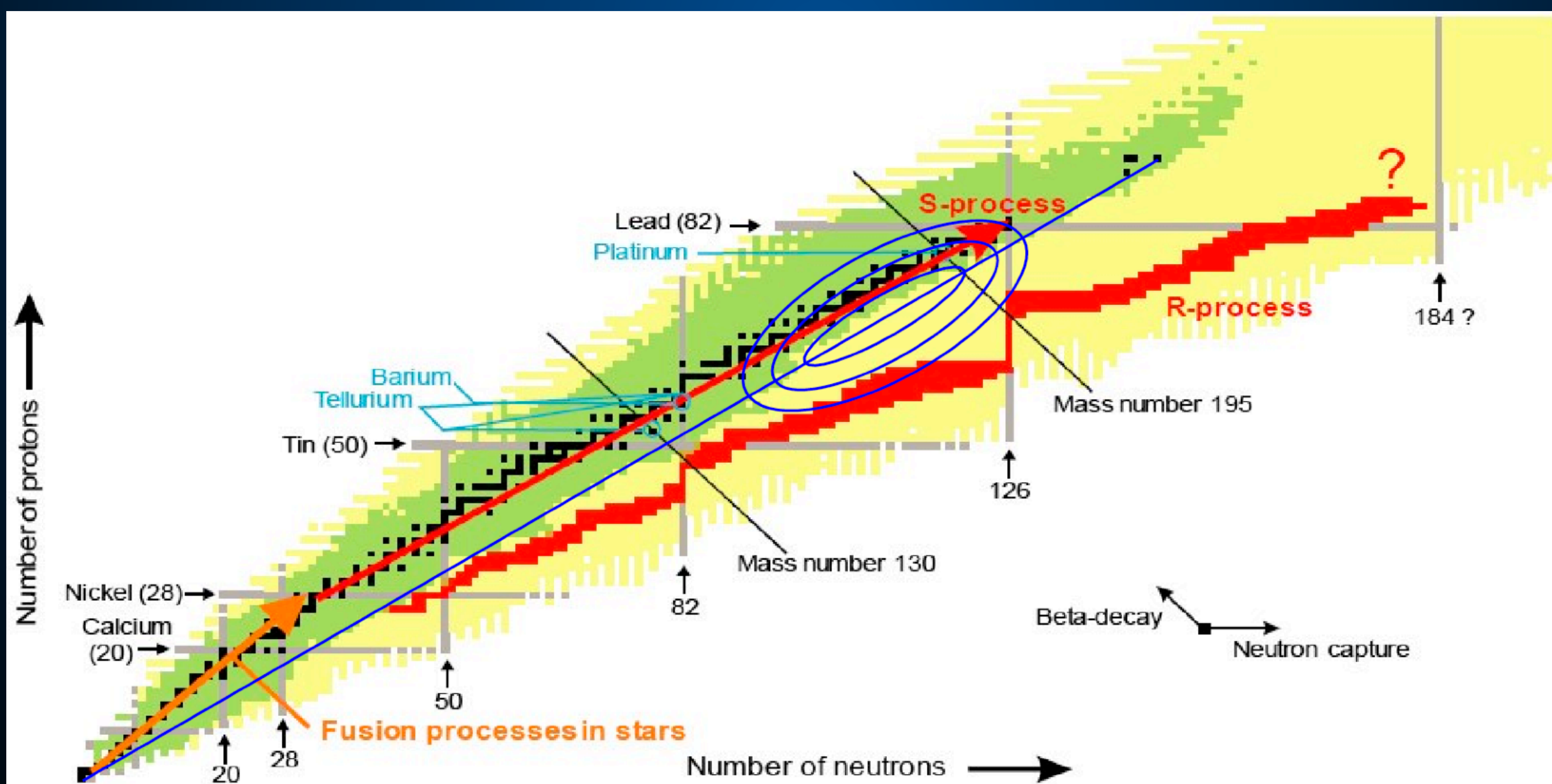
Margutti et al. (1801.03531)



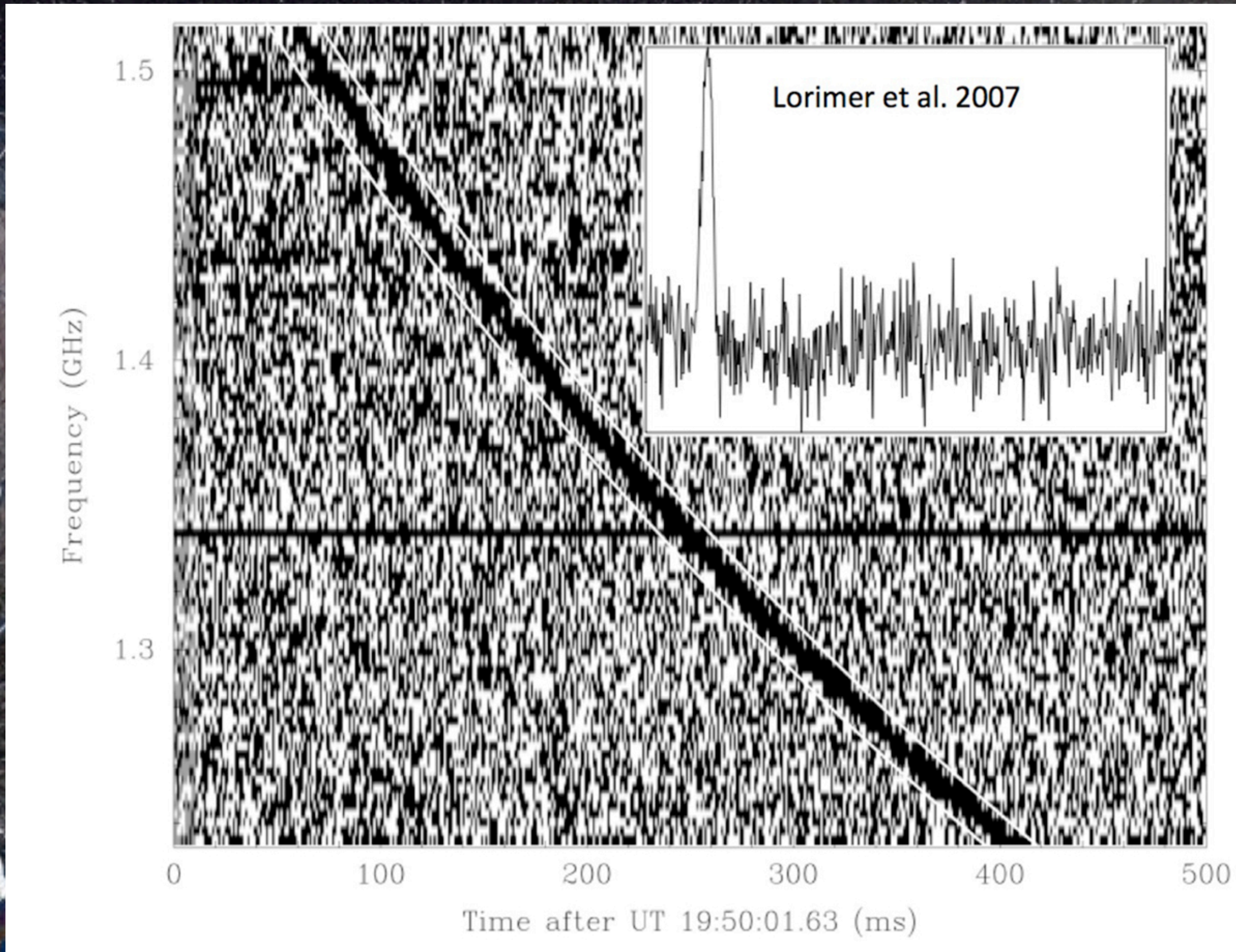
What is the r-process?







Fast Radio Bursts



One More Slide on Axion Dark Matter

Axions proposed to solve the strong-CP problem

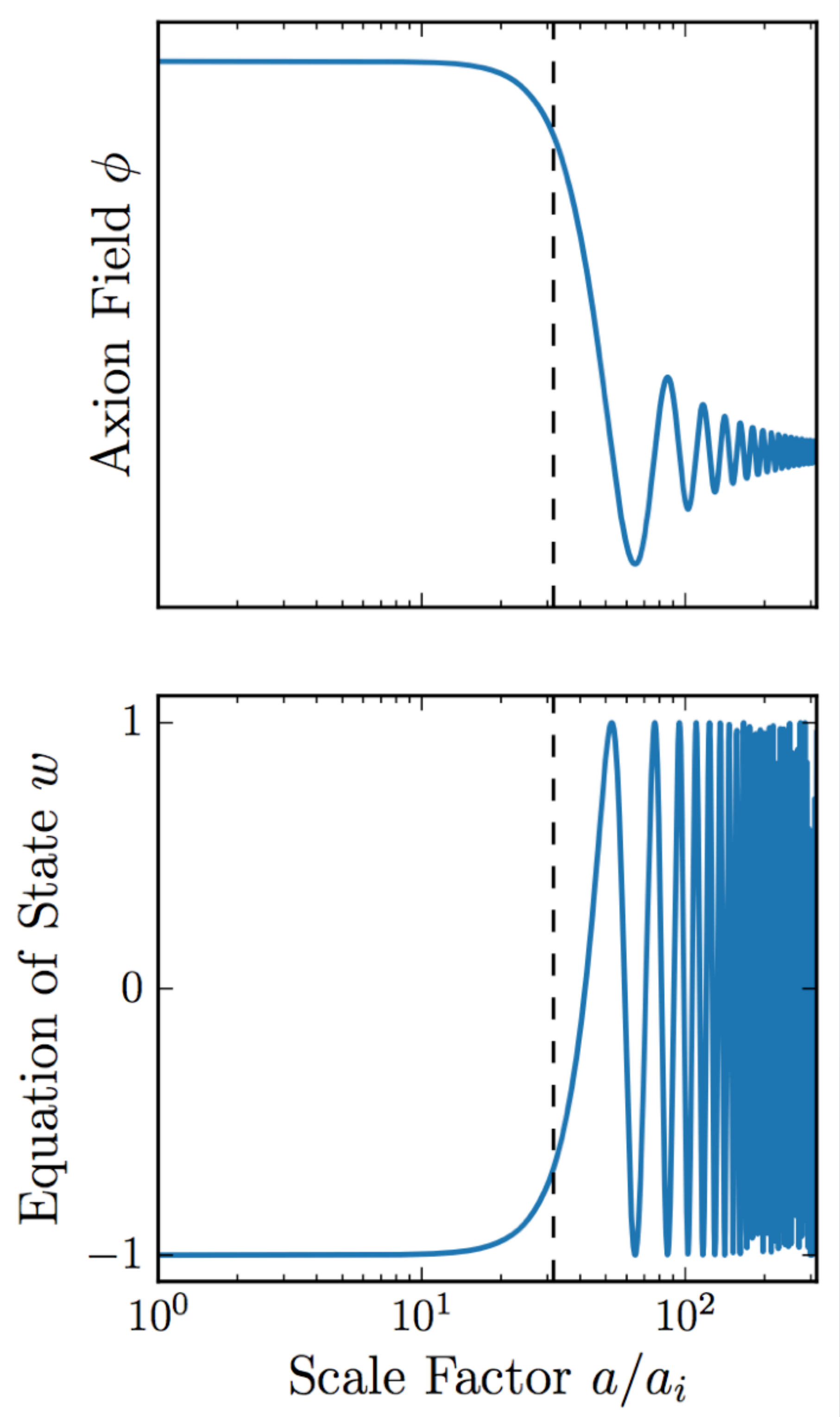
$$L_\theta = \theta \frac{g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu}$$

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

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

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).

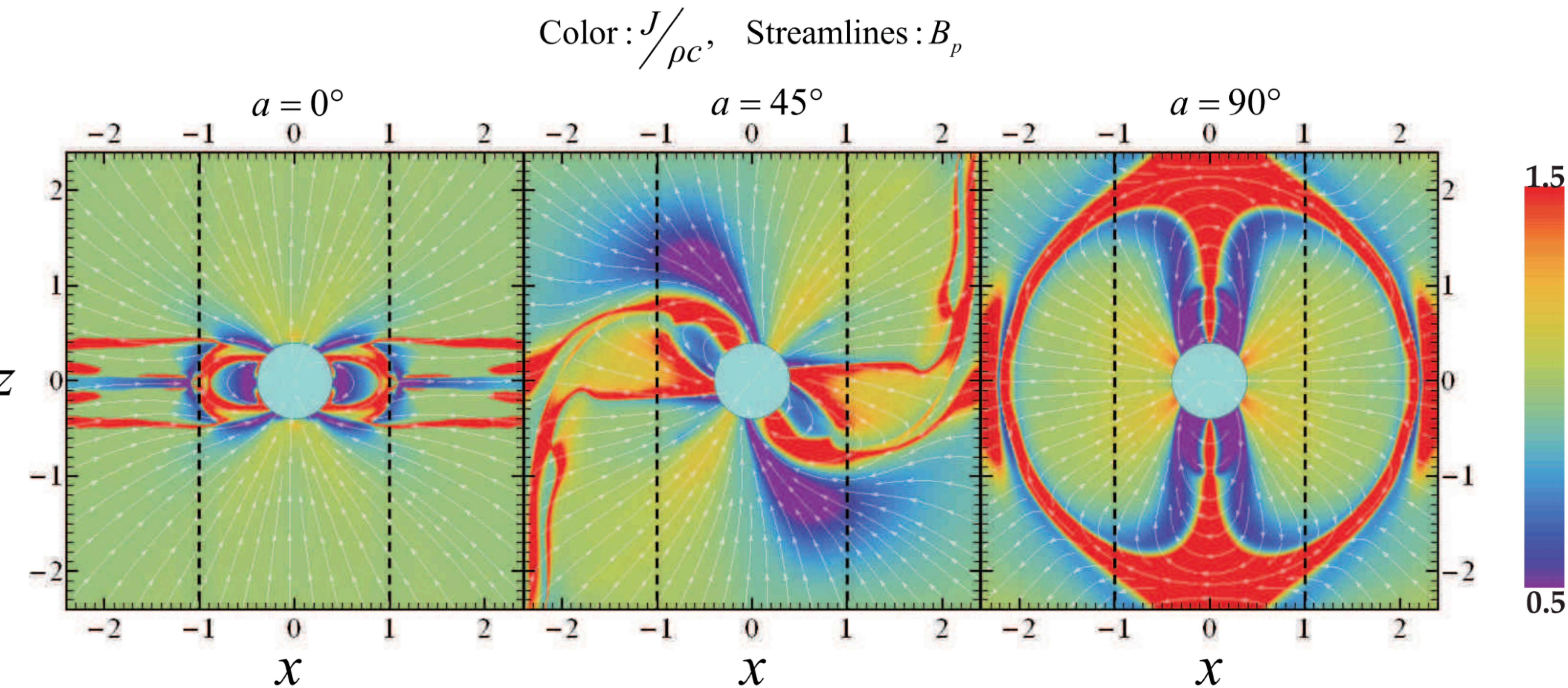
The low mass (high-fa) limit is set such that axions don't overclose the universe:

$$\Omega_a h^2 \approx 0.23\times 10^{\pm 0.6}(f_a/10^{12}\,\mathrm{GeV})^{1.175}\,\Theta_i^2\,F(\Theta_i)$$

Raffelt 1995

Goldreich-Julian Current

Kalapotharakos et al. (1108.2138)



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

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)**

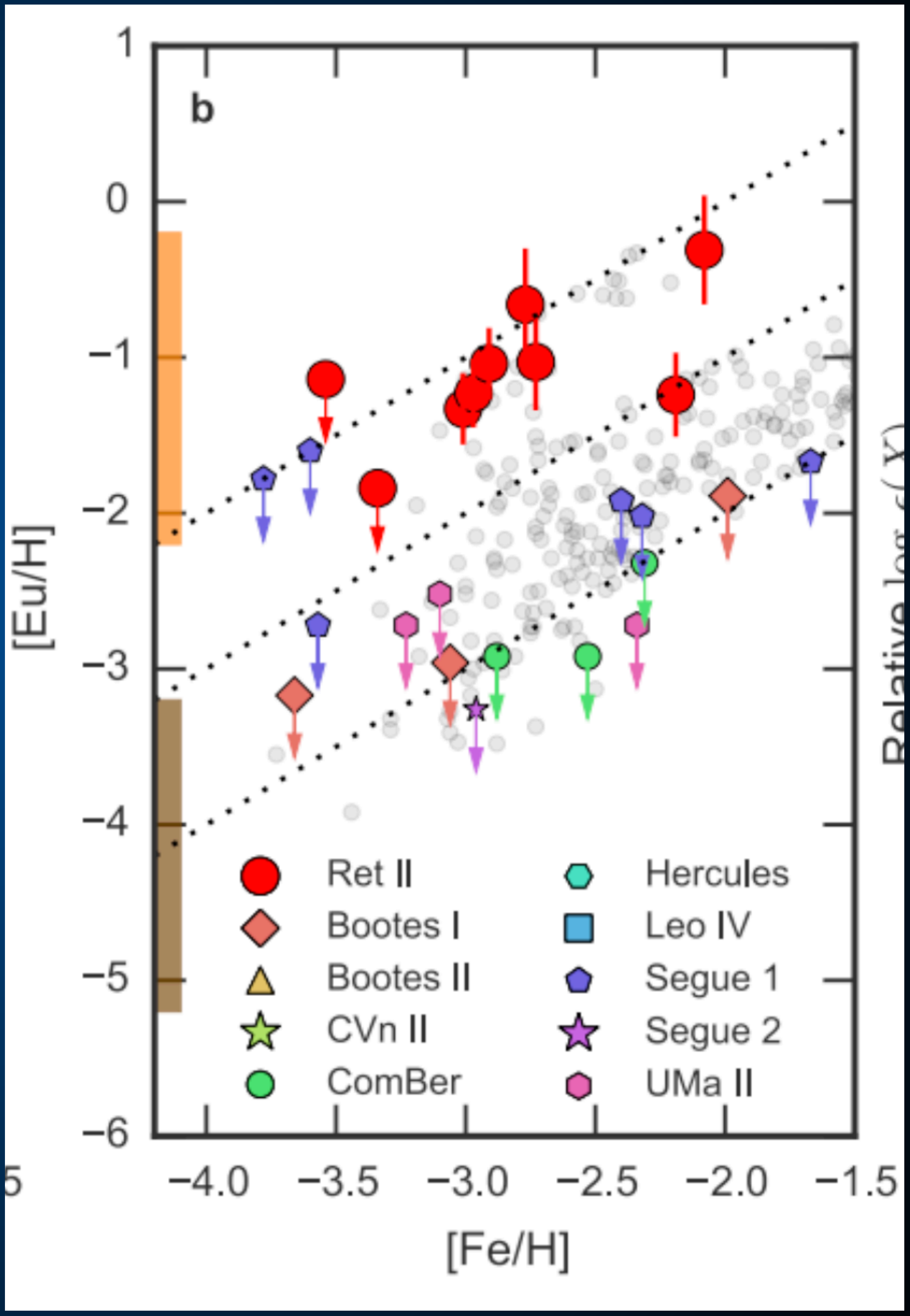
- **Dark matter accumulation rate scales inversely with velocity:**

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

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

Dark Matter Induced Collapse in dSphs

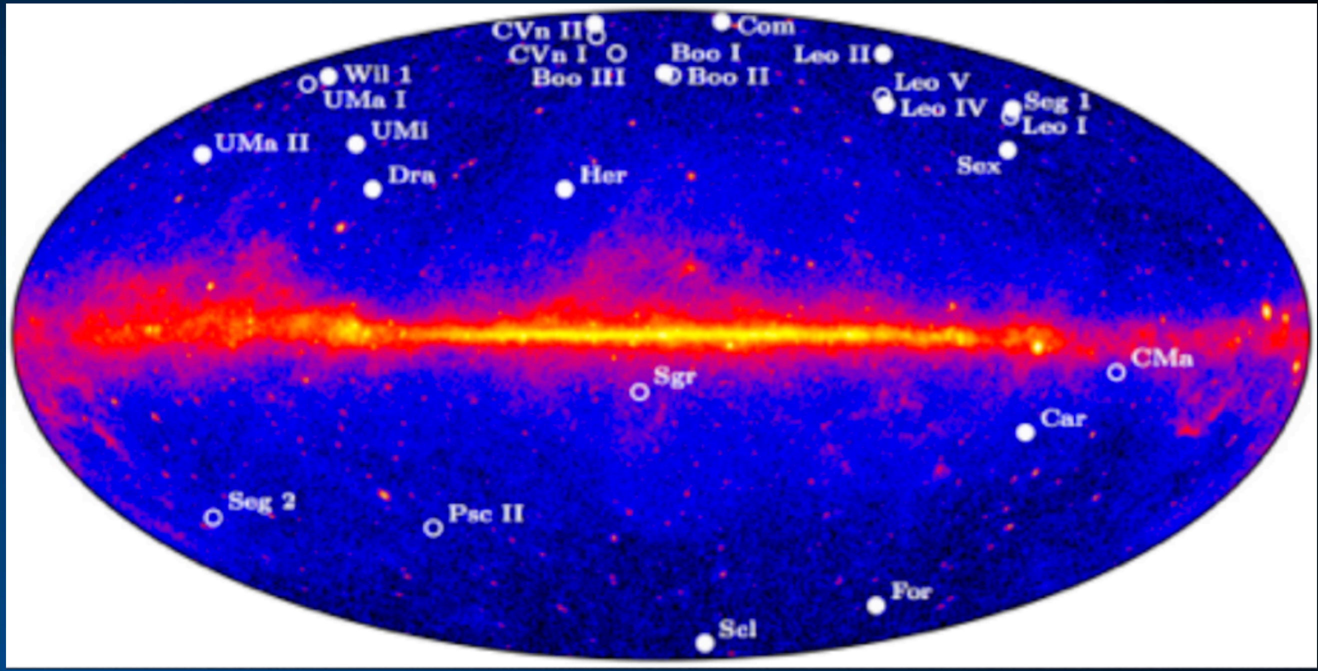
- **Reticulum II dSph**
  - **Discovered by DES in 2015**
  - **Spectroscopic follow-up determined r-process abundances.**
  - **Large r-process abundance, but low metallicity!**



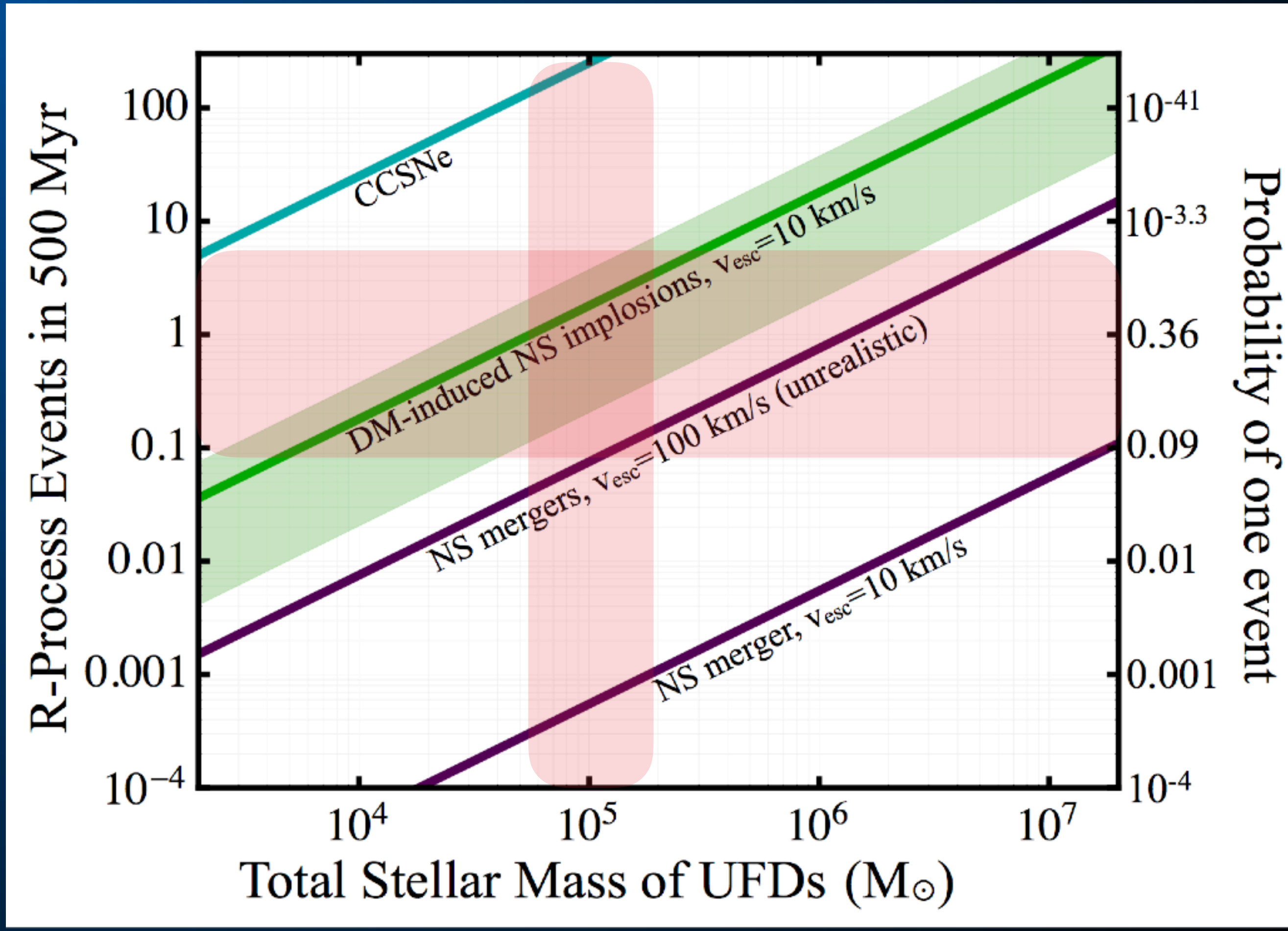
- **Points to a rare formation channel (NS mergers)**

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.**

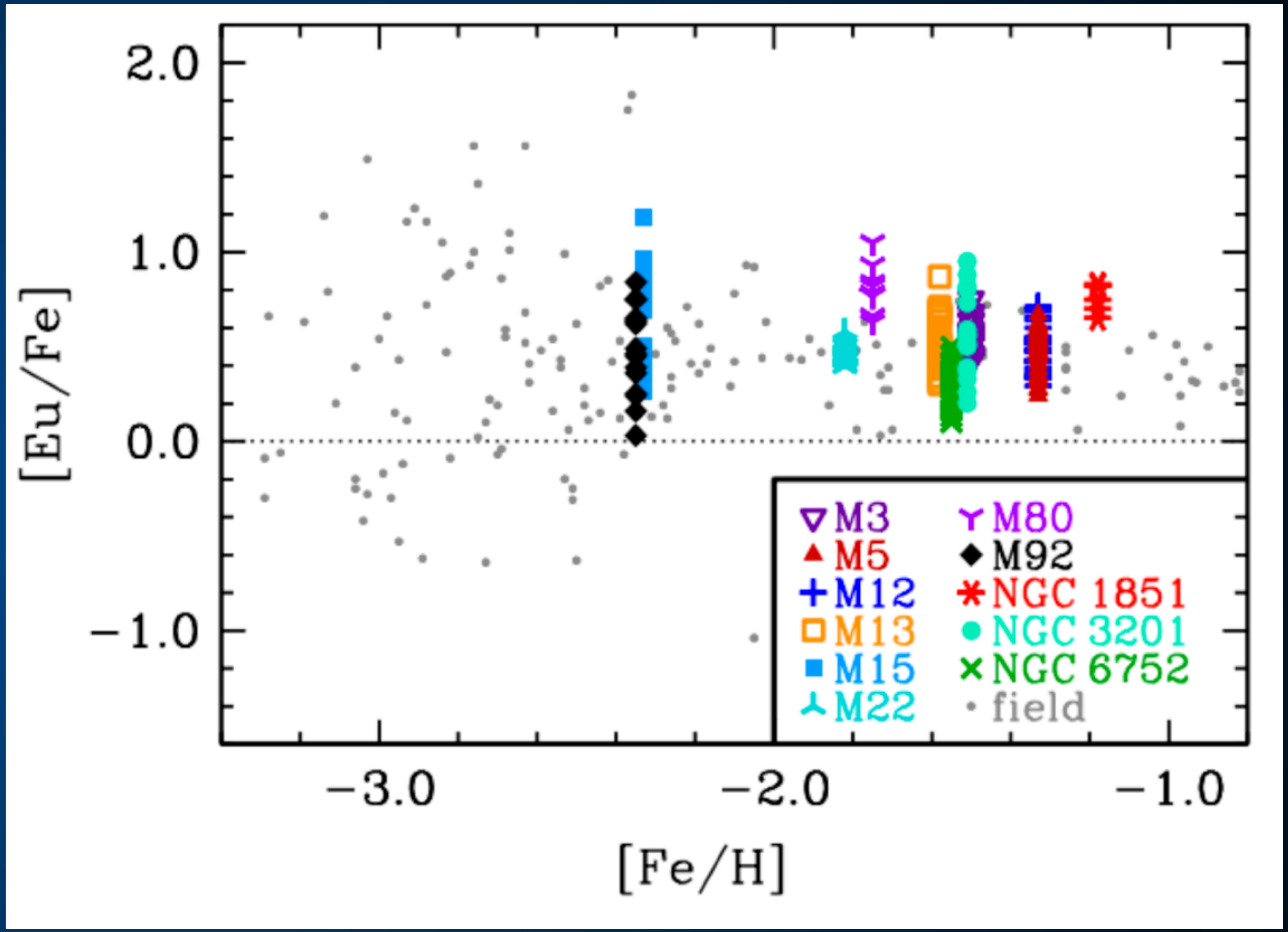


Dark Matter Induced Collapse in dSphs

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

$$M_{DM} \propto \sigma_{\chi p}\, t_{NS}\left(\frac{\rho_\chi}{v_\chi}\right)$$

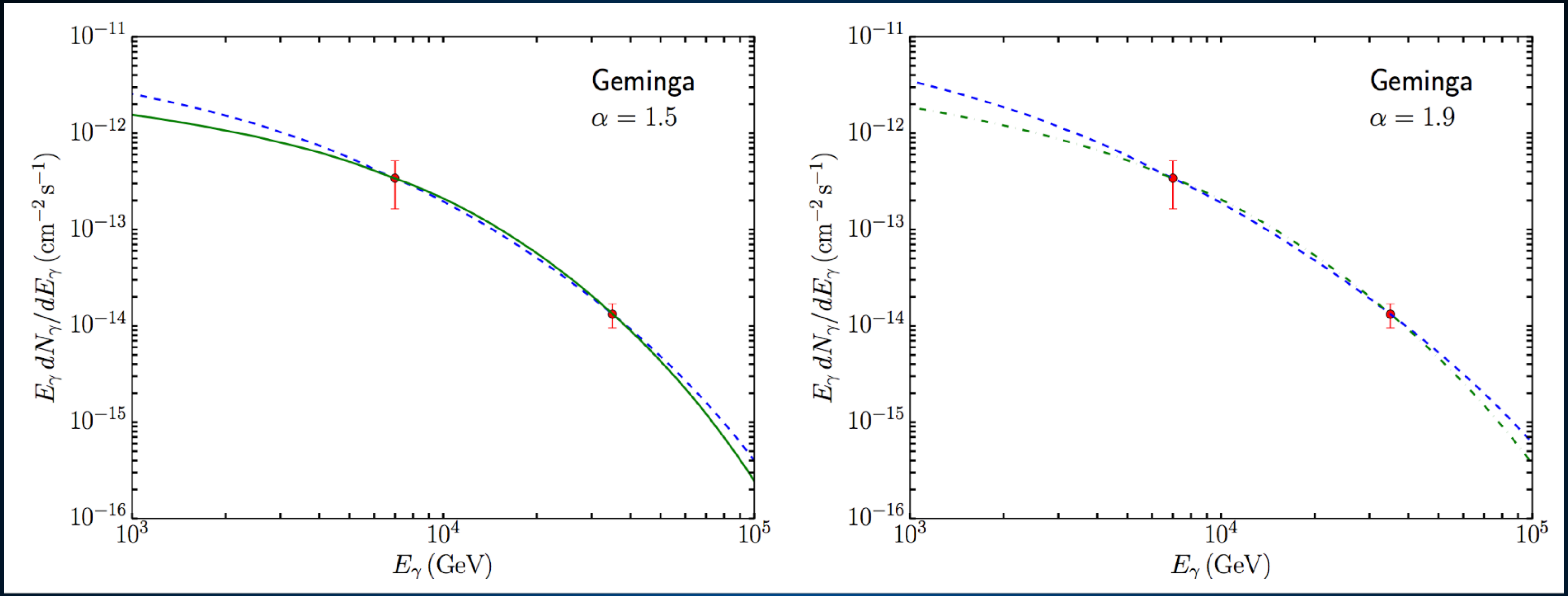
($\sigma_{\chi p}$: particle physics)

($\frac{\rho_\chi}{v_\chi}$: position dependent)

in any p.p. model

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

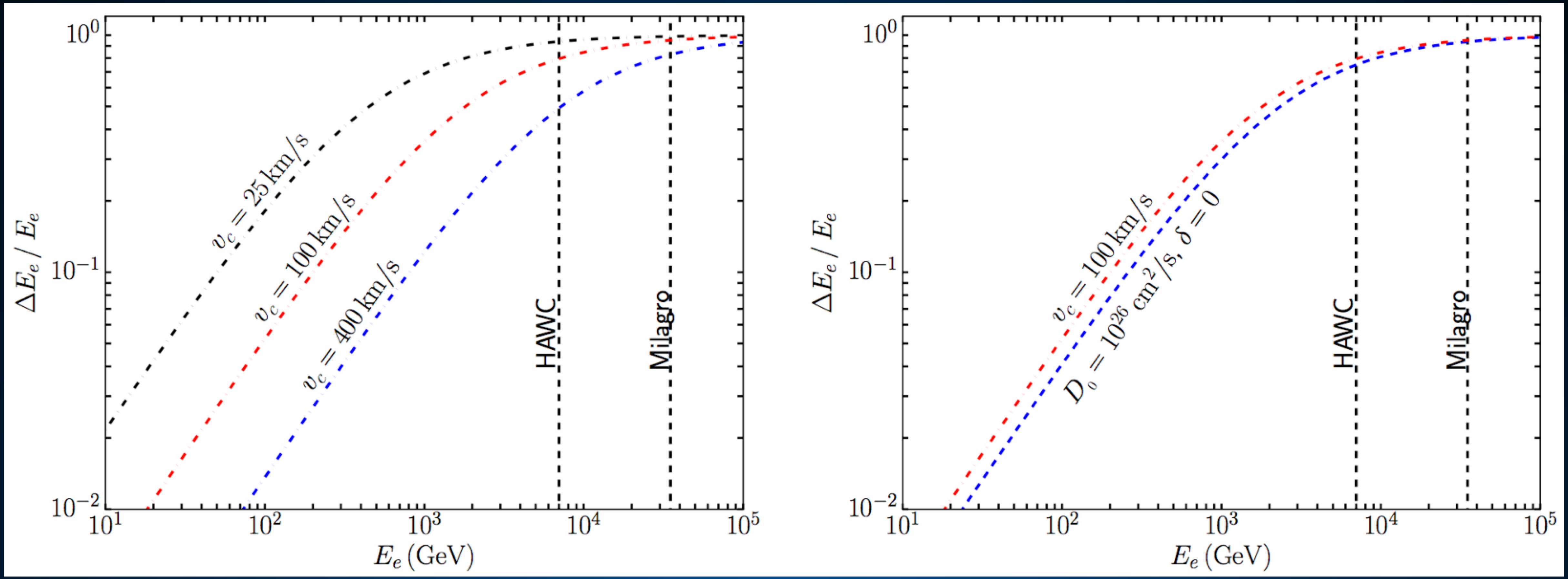
Pulsars Produce the Positron Excess



- **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



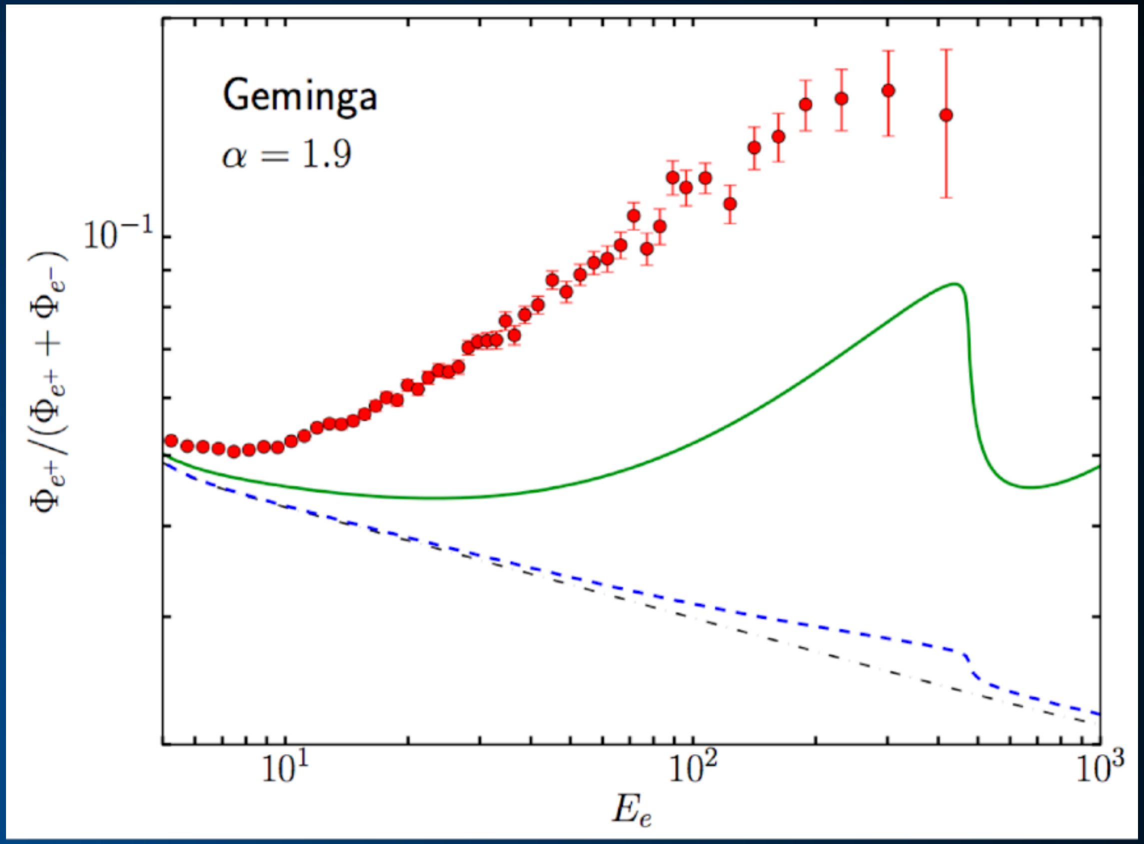
- **Utilizing a diffusion model, along with the steady state electron spectrum, and the morphology of the emission, can calculate the fraction of the electron energy lost before escaping the halo.**

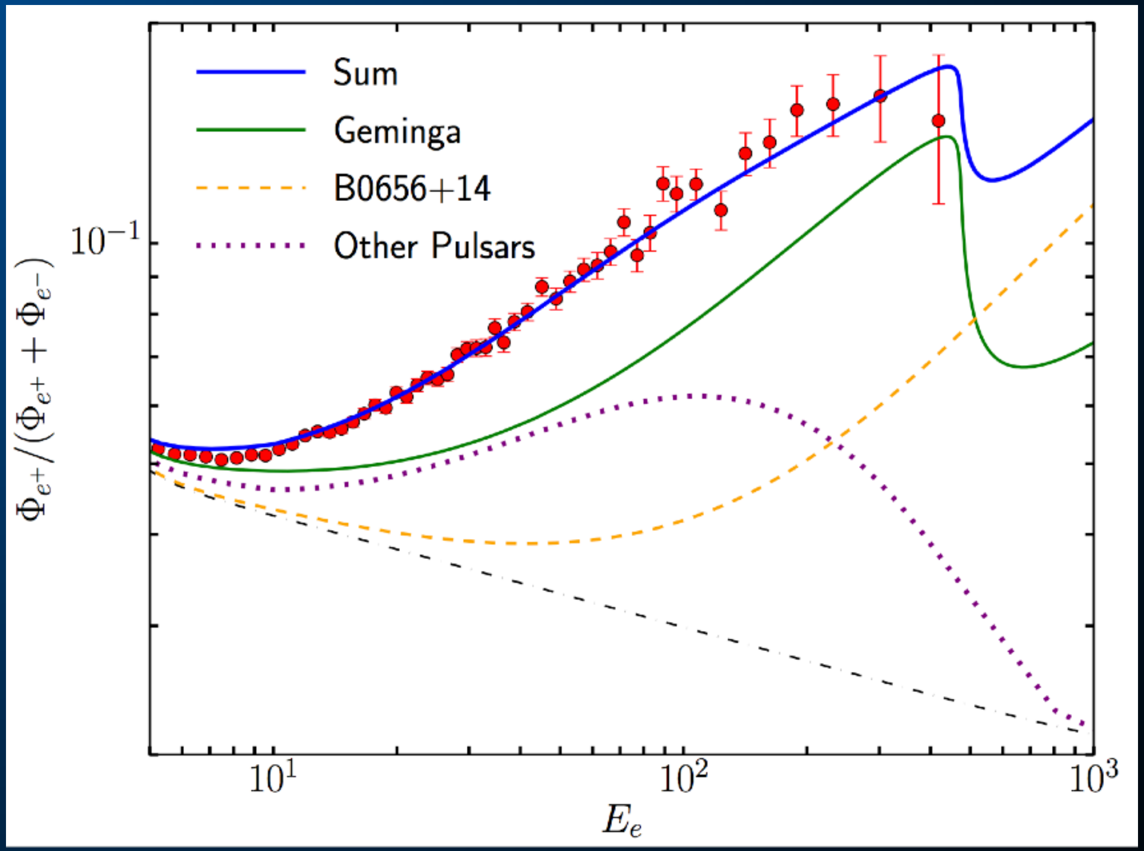
- **Less energetic electrons make it to the ISM!**

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.**

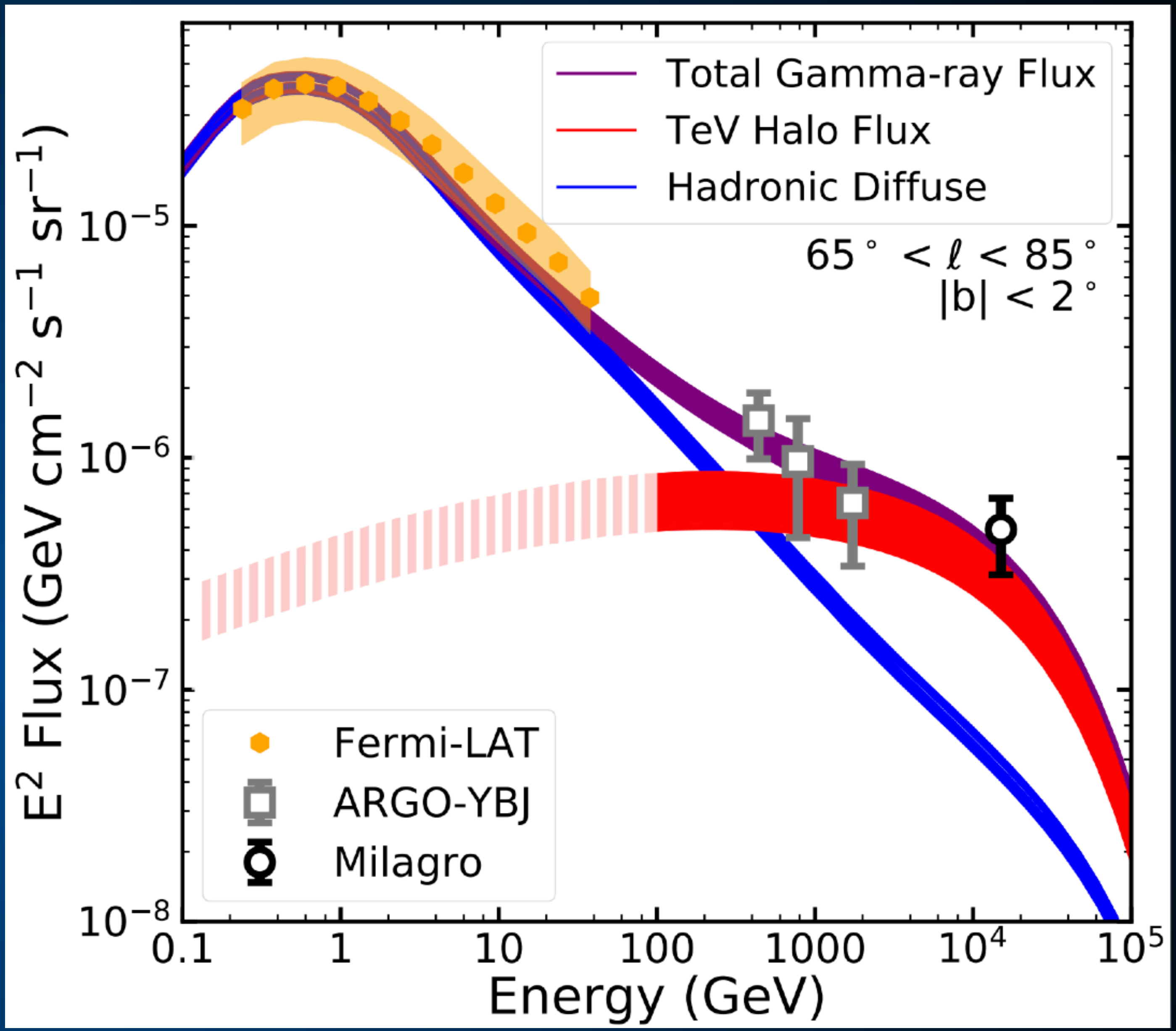




Hooper, Cholis, TL, Fang (1702.08436)

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.**

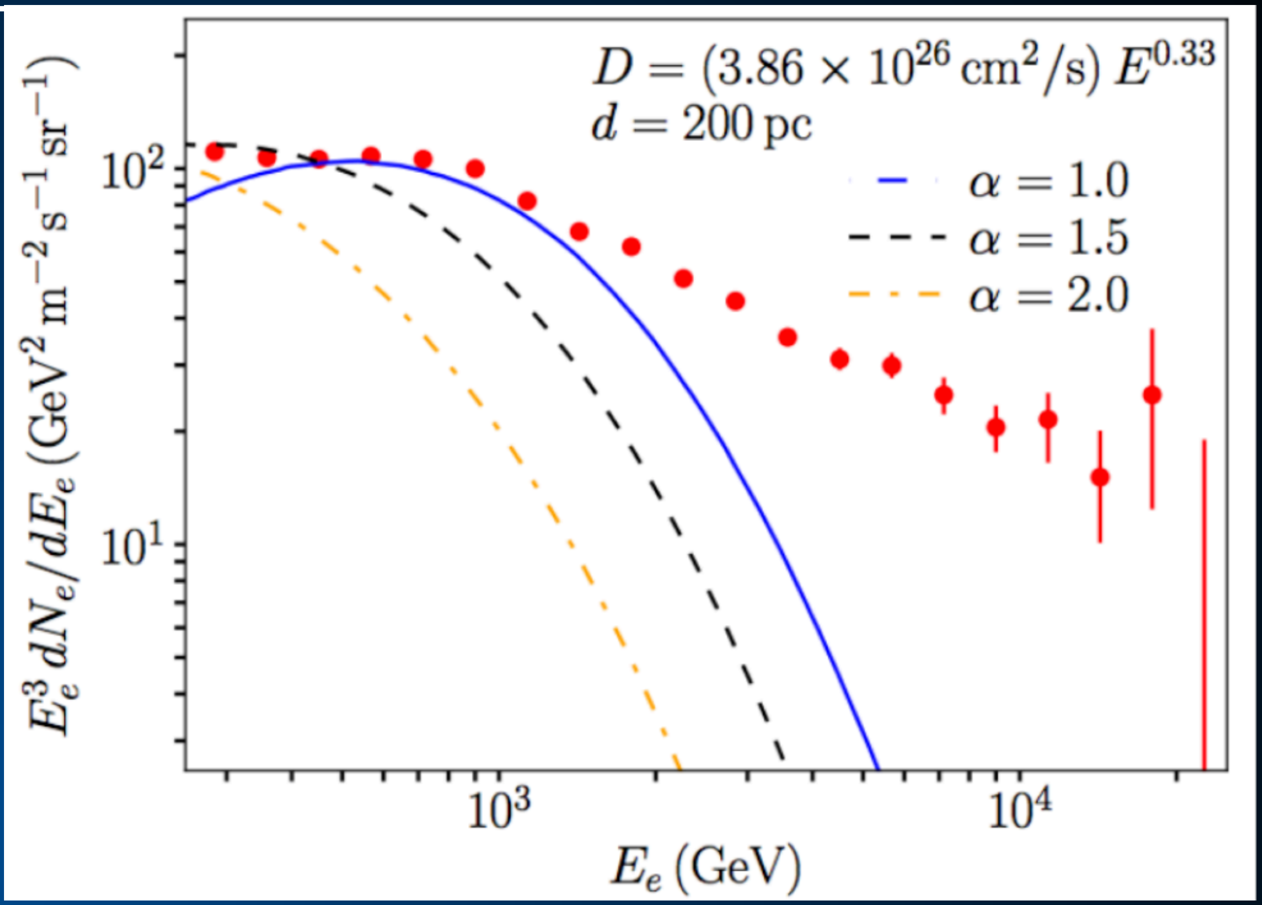


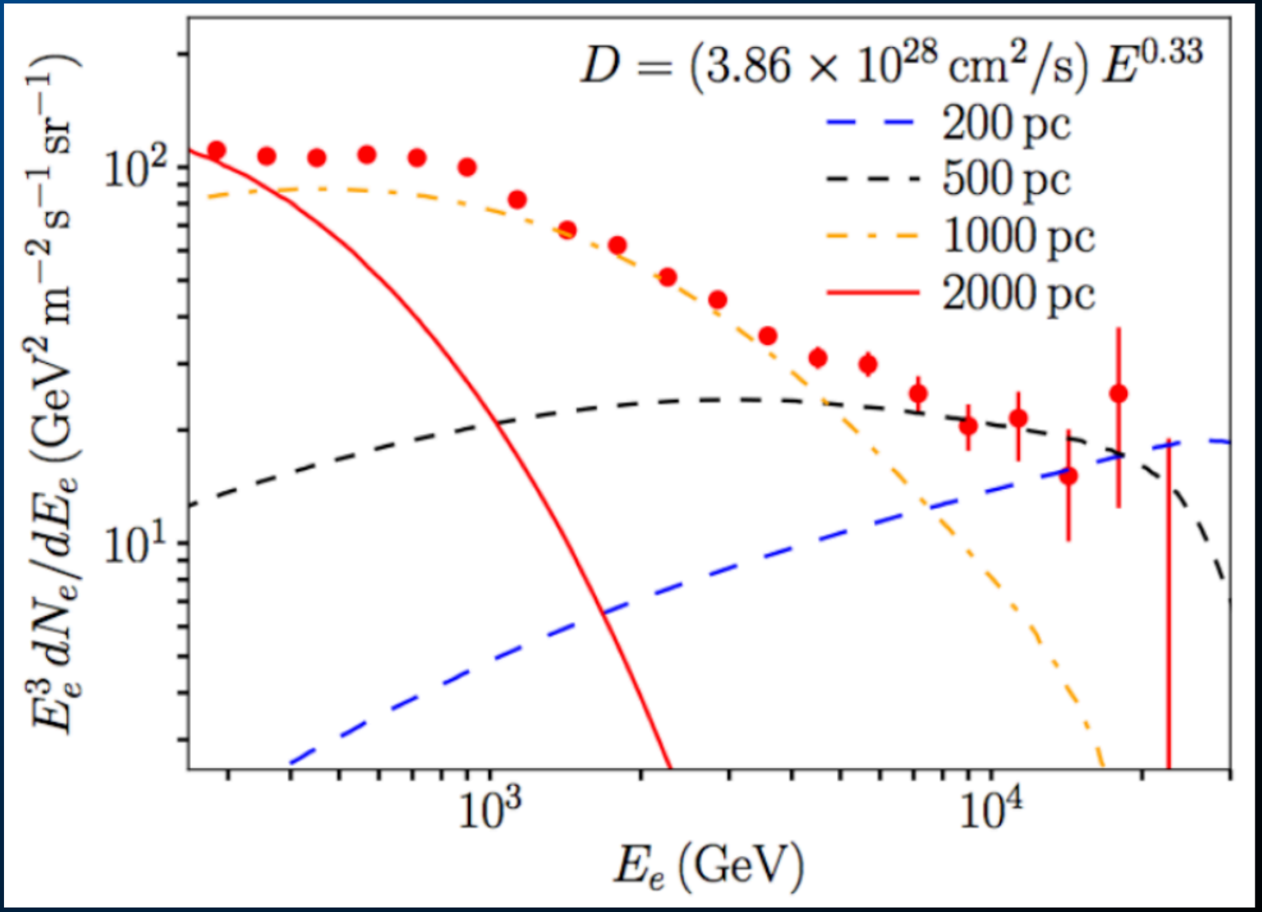
TL & Buckman (1707.01905)

- **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!**



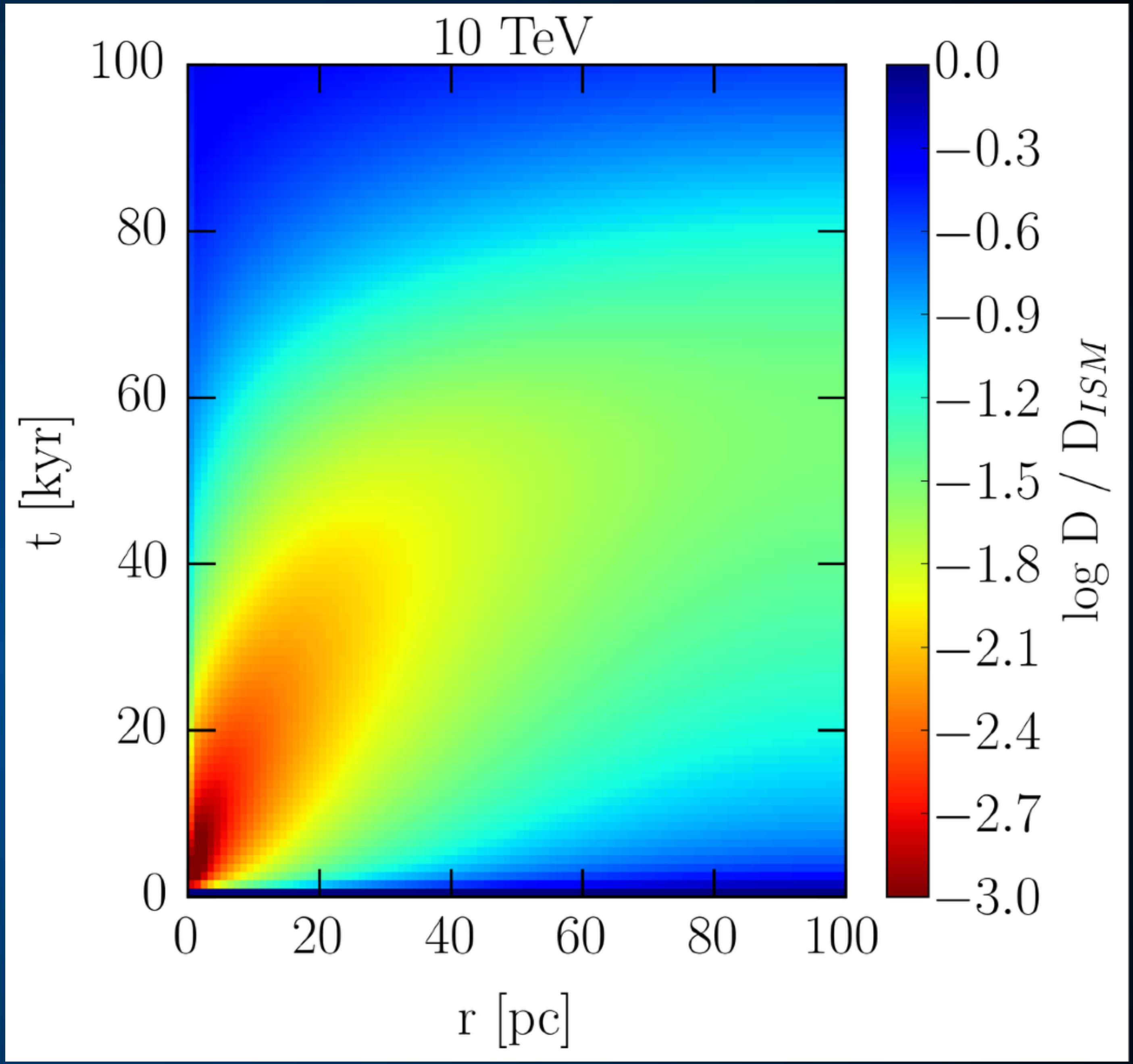


Hooper & TL (1711.07482)

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.**

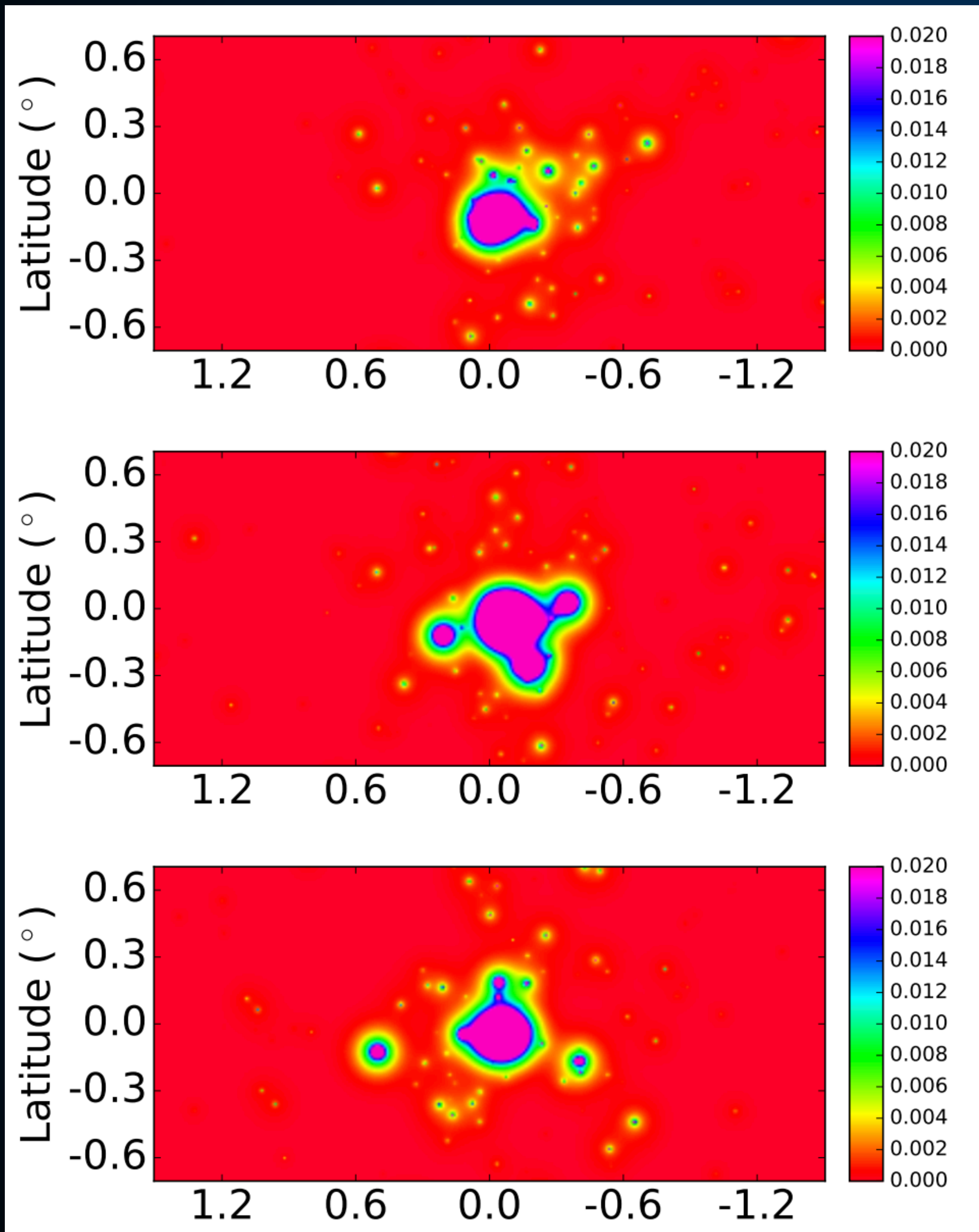
$$\Gamma_{\rm CR}(k) = \frac{2\pi}{3} \frac{c|v_A|}{k\mathcal{W}(k)\,U_0} \left[p^4 \frac{\partial f}{\partial z}\right]_{p_{\rm res}}$$

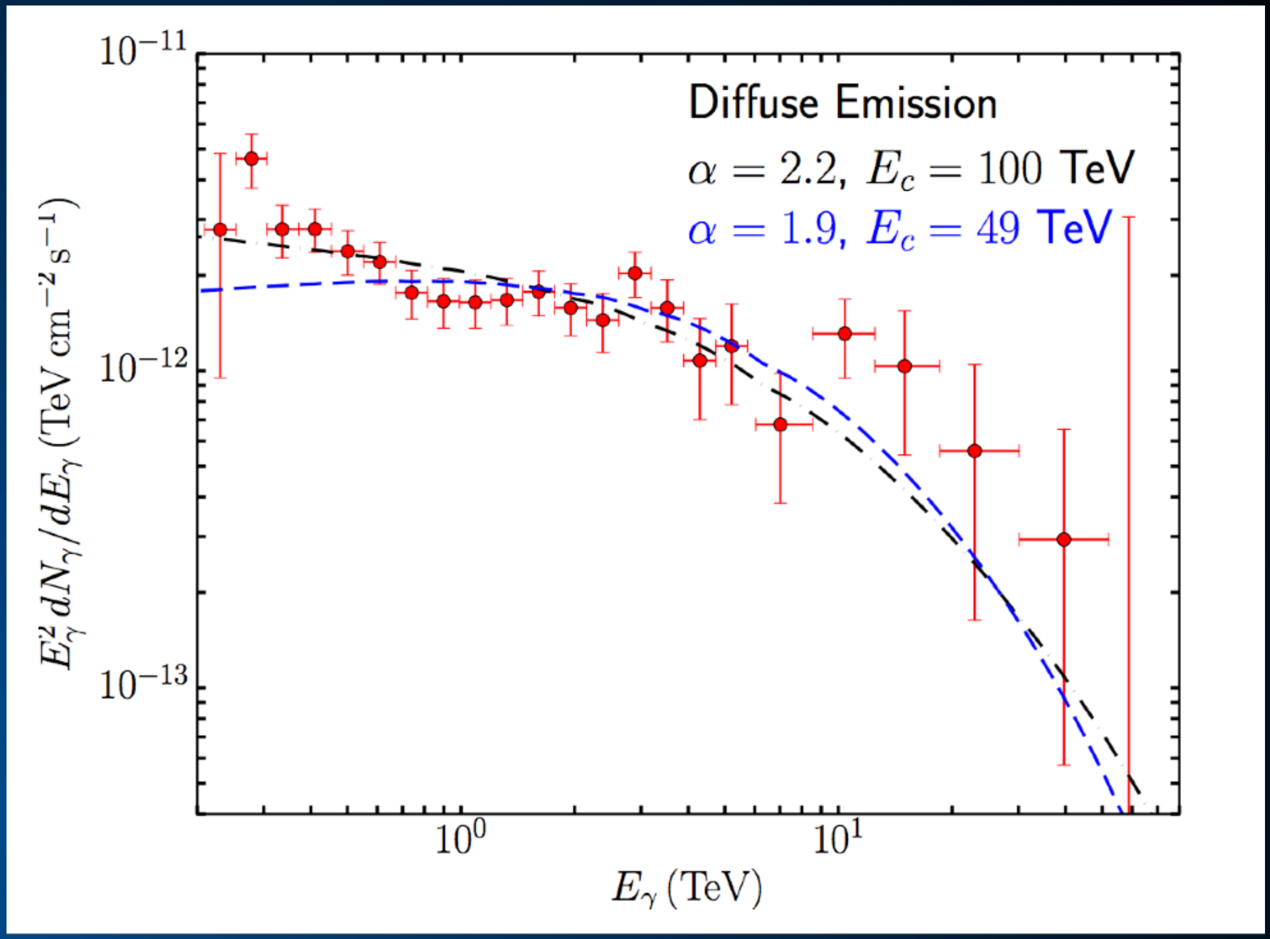


- **These Alfven waves dominate cosmic-ray turbulence, because they are resonant with the electron energy - leads to low diffusion**

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)