

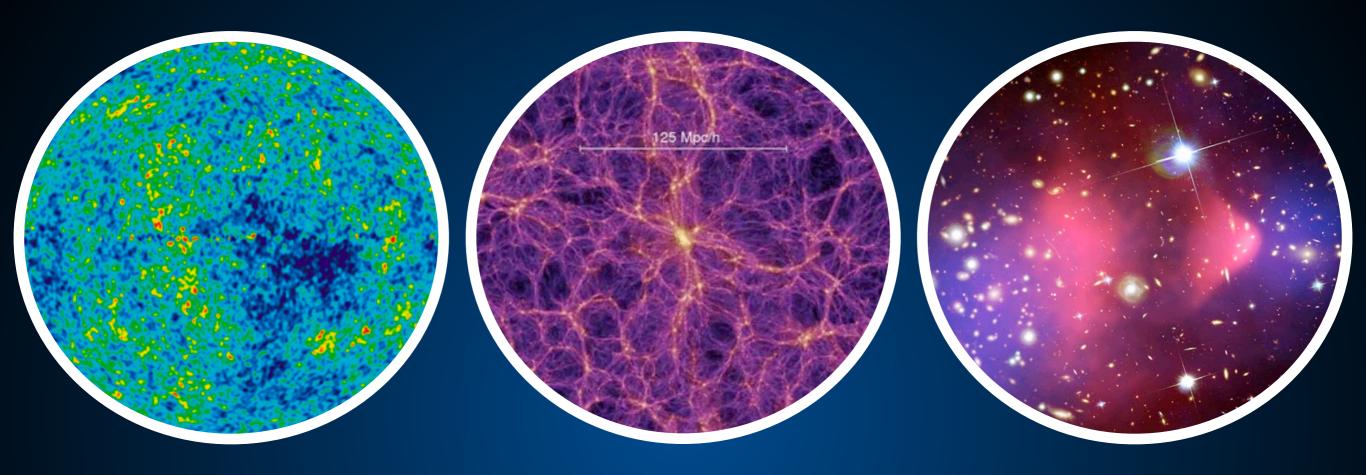
Unlocking Neutron Stars as Sensitive Probes of Dark Matter Tim Linden

Physics Colloquium Penn State University December 6, 2018



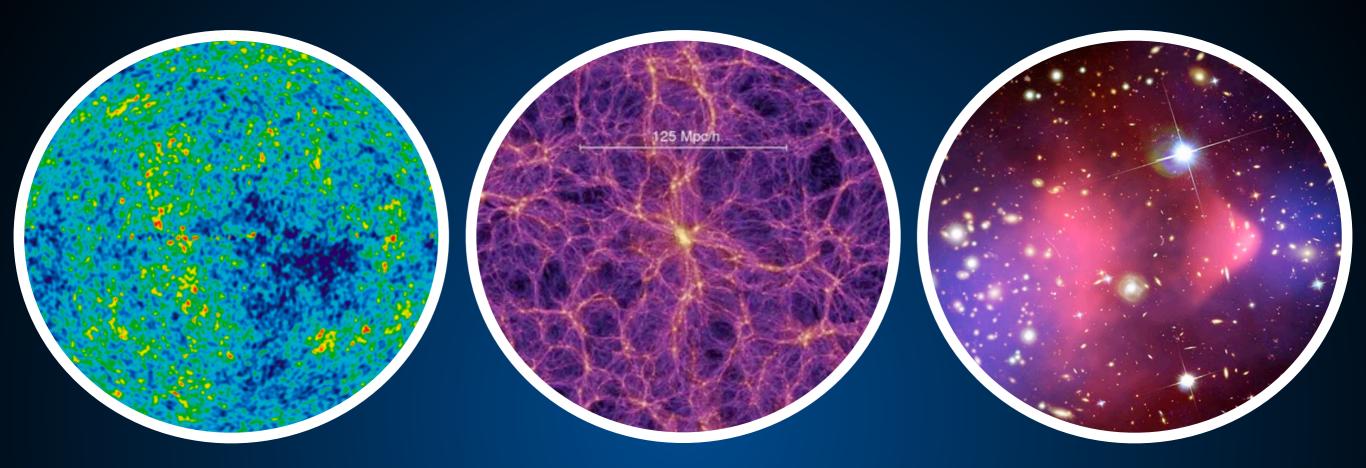
ROPARTICLE PHYSICS

Gravitational Dark Matter



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

Gravitational Probes of Dark Matter





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

 $F = 218.8118437960826270 + - 0.0000000000000988 s^{-1}$

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

NANOGrav Collaboration (1801.02617)

A Dipole Model

Can precisely measure the magnetic field:

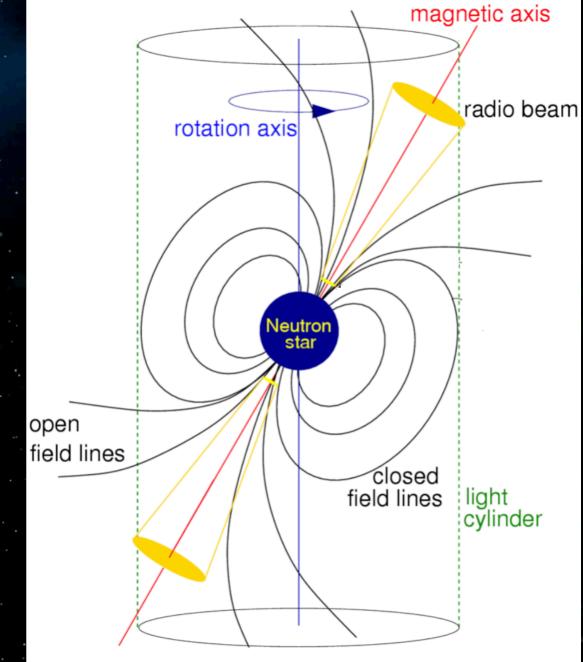
$$\frac{dE}{dt} \propto -\omega^4 R^6 B^2 \sin^2 \alpha$$
$$B \sim 3.3 \times 10^{19} \left[P^2 \left(\frac{1}{P} \frac{dP}{dt} \right) \right]^{1/2} \,\mathrm{G}$$

And approximately measure

the age:

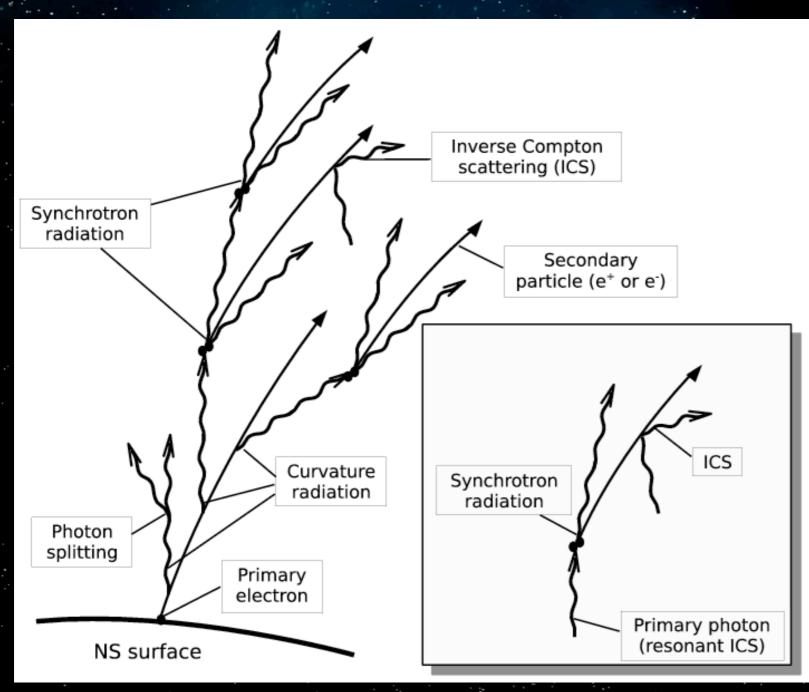
 $\frac{P}{2(dP/dt)}$

2(a1 / ac)



Curvature Radiation

Changing magnetic field produces electric field

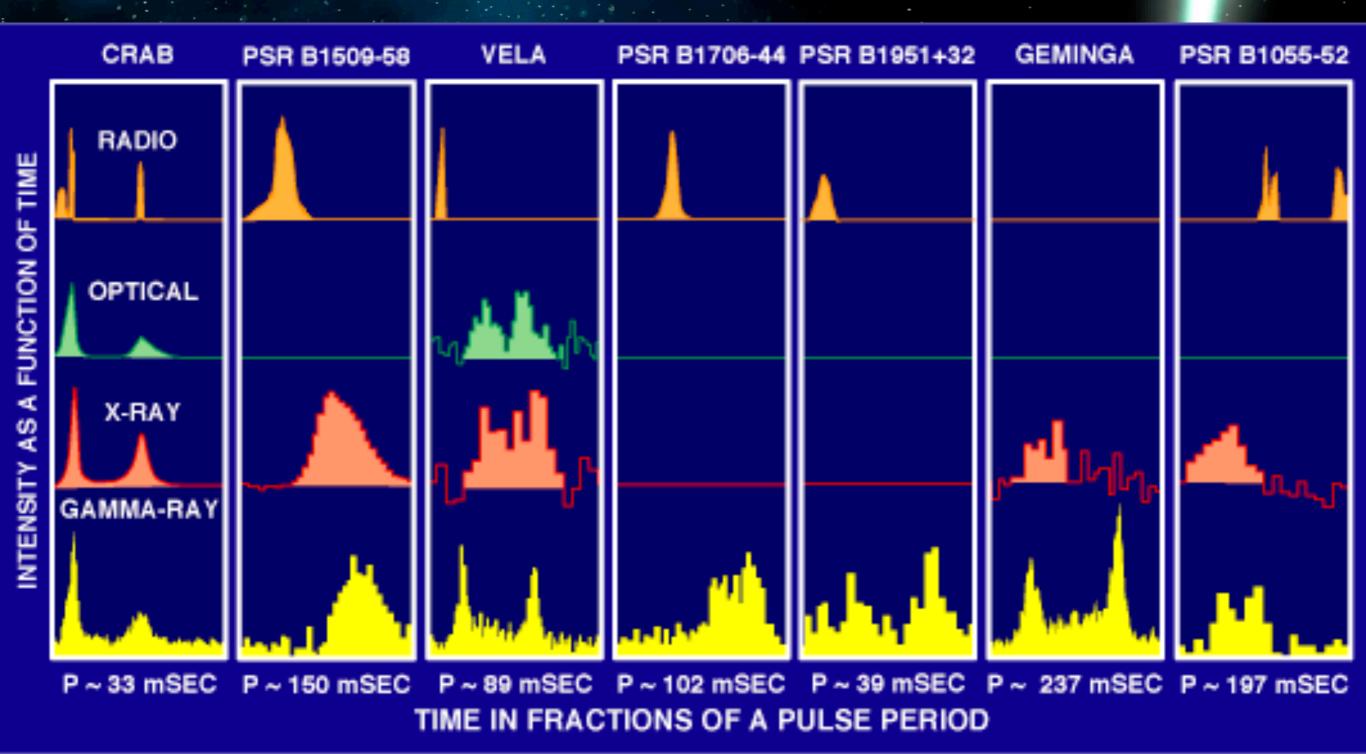


1000 PV potential available to accelerate particles

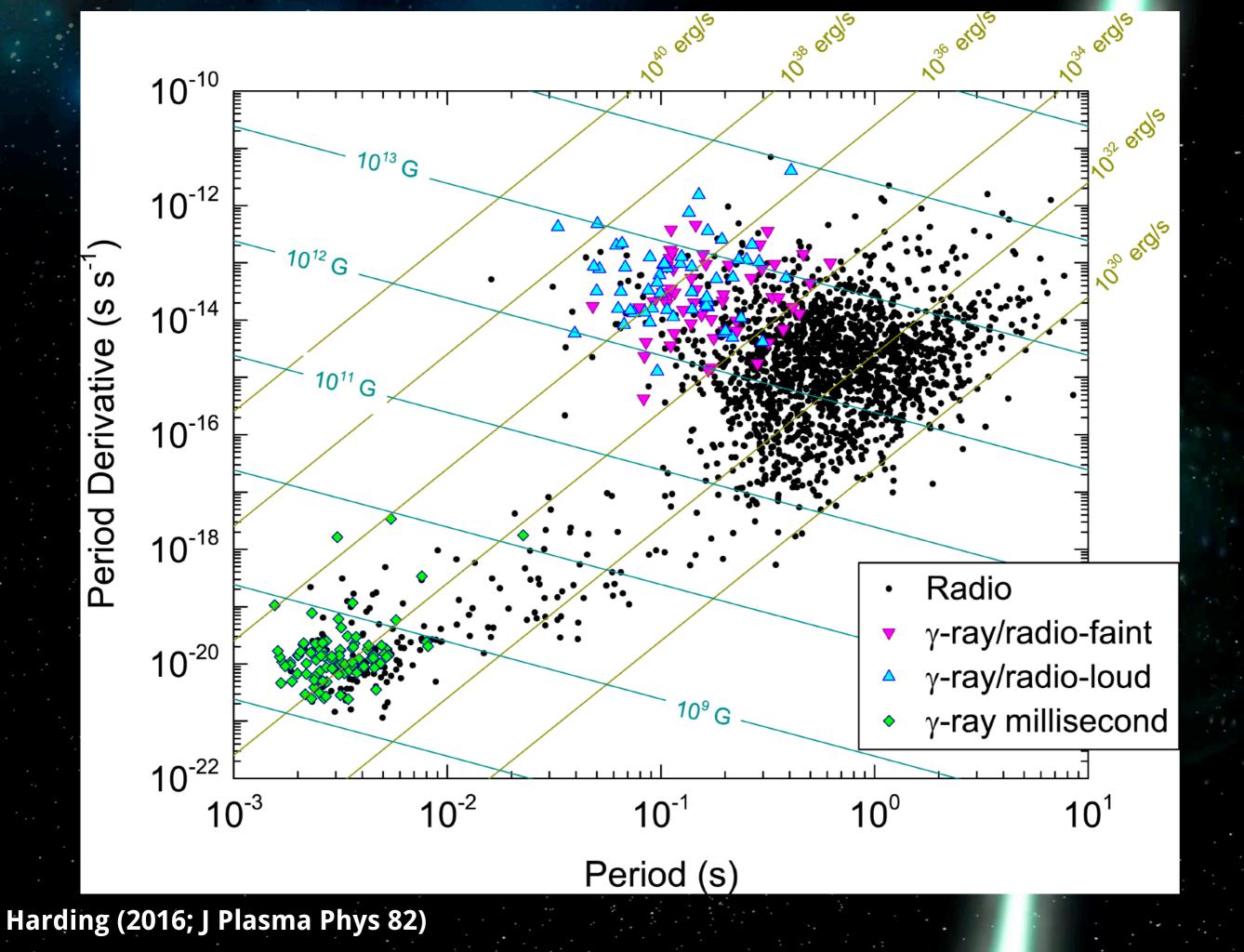
Ruderman & Sutherland (1975)



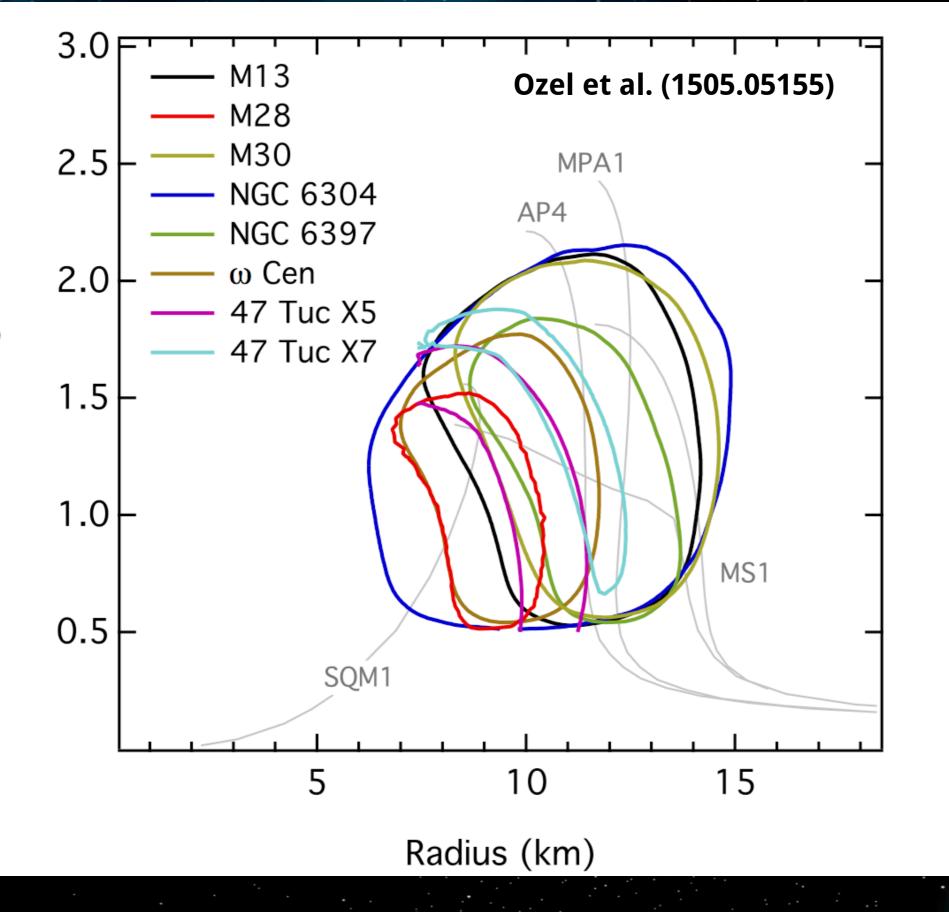
Multiwavelength Emission



credit: Dave Thompson



A Window Into Extreme Physics



Mass (M_☉)

A Window Into General Relativity

THE ASTROPHYSICAL JOURNAL LETTERS, 848:L12 (59pp), 2017 October 20 © 2017. The American Astronomical Society. All rights reserved. OPEN ACCESS

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, ALMA 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

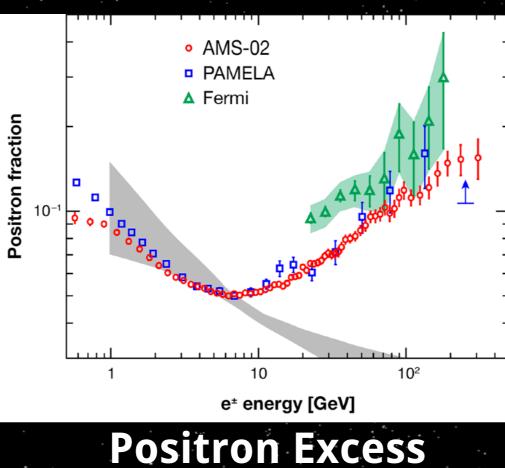
Abstract

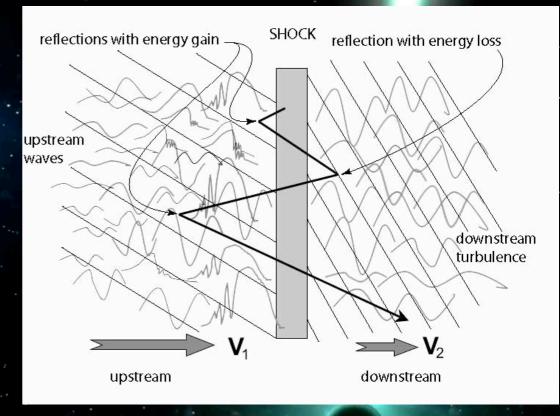
On 2017 August 17 a binary neutron star coalescence candidate (later designated GW170817) with merger time 12:41:04 UTC was observed through gravitational waves by the Advanced LIGO and Advanced Virgo detectors. The Fermi Gamma-ray Burst Monitor independently detected a gamma-ray burst (GRB 170817A) 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 deg² 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 ~ 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.

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

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

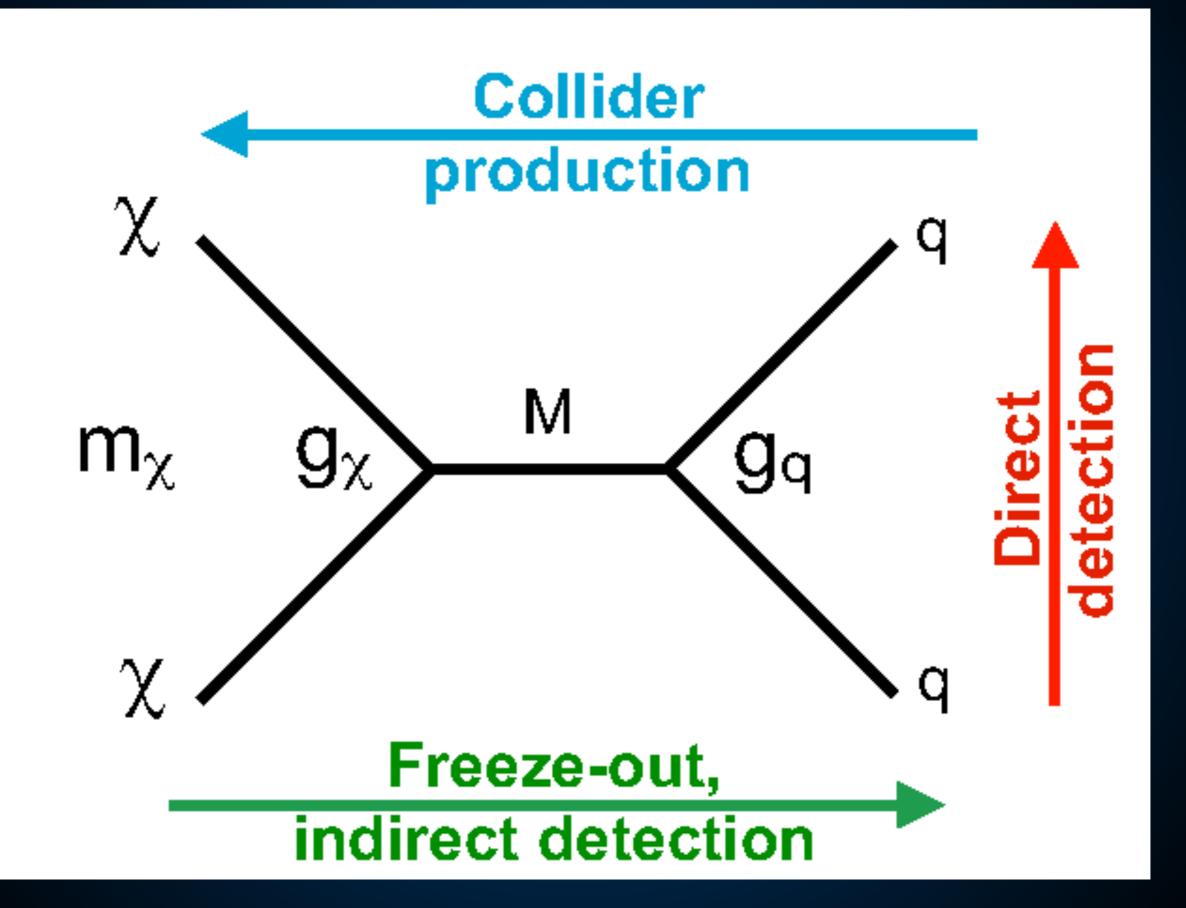
Sensitive probes of rare processes:

1. Nuclear densities over macroscopic distances

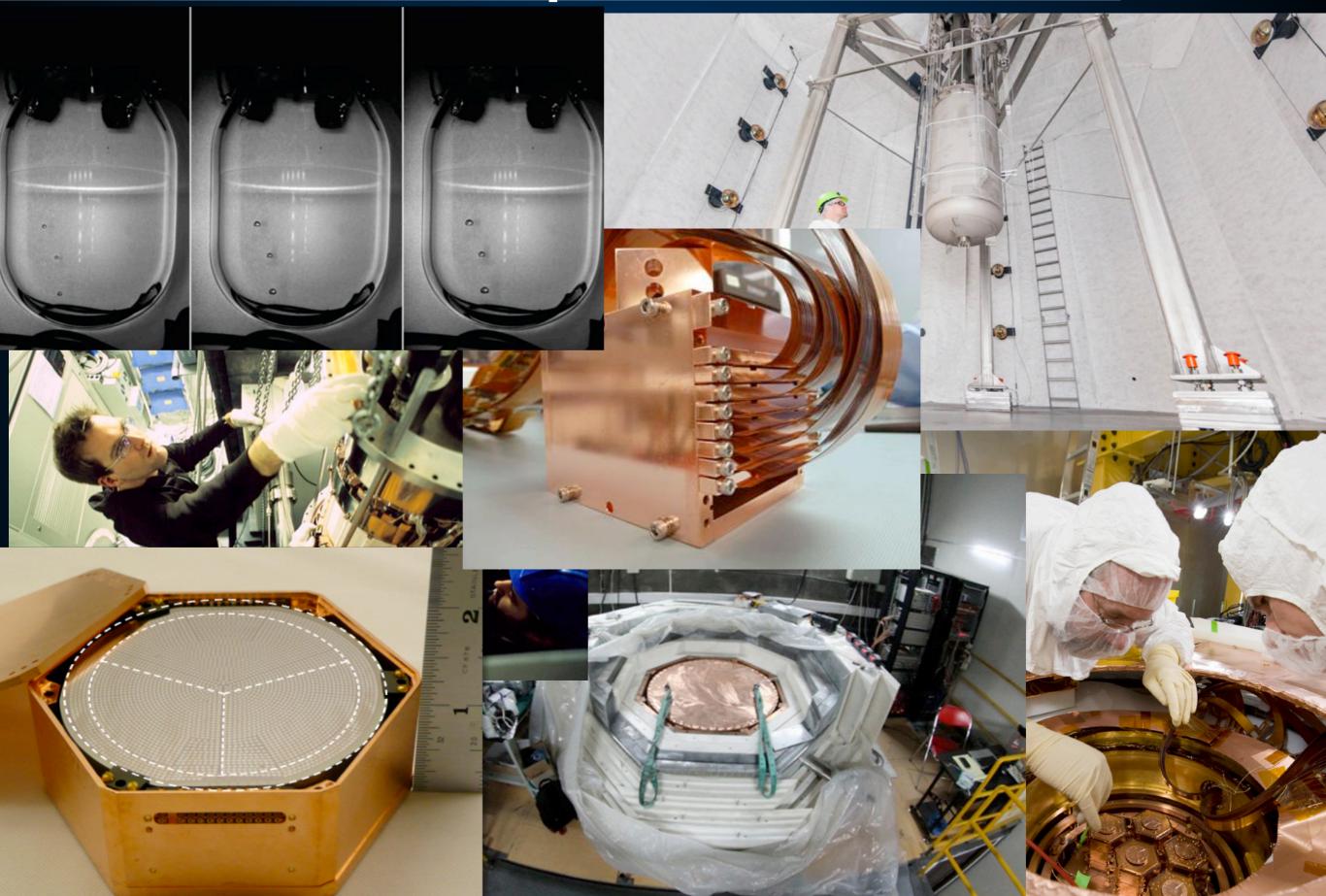
2. Strongest magnetic fields in the universe

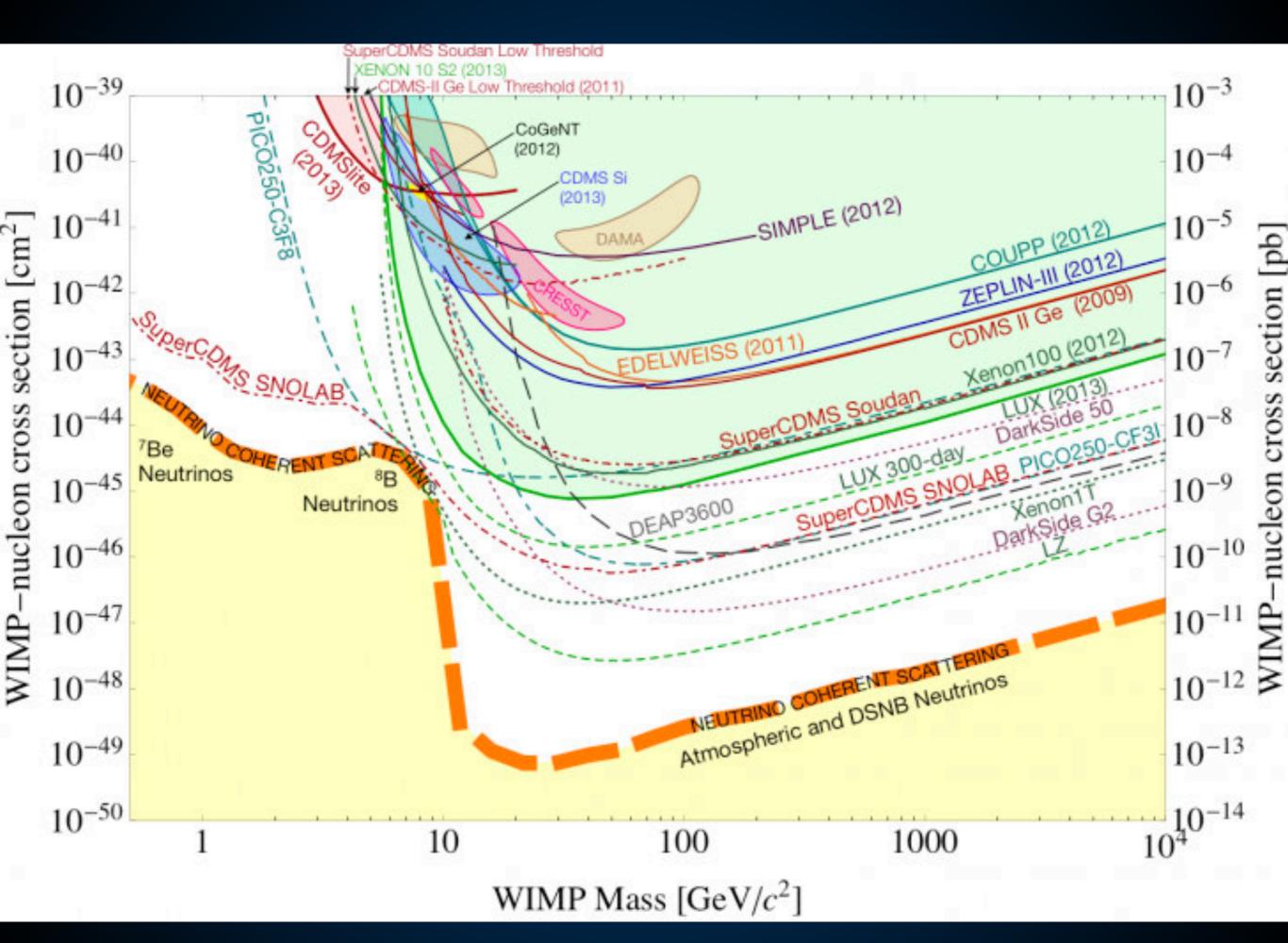
Precise measurements are possible

Searching for Dark Matter Interactions



Direct Detection: Experimental Efforts





Neutron Stars: The Optimal Direct Detection Experiment



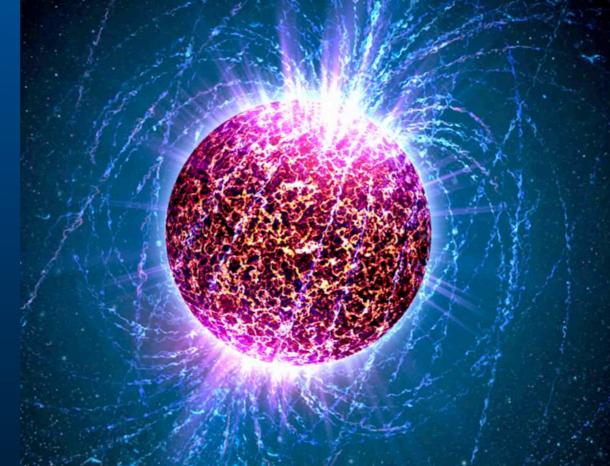
Neutron Star

- 10³⁰ kg
- 10¹² days

10⁴² kg day

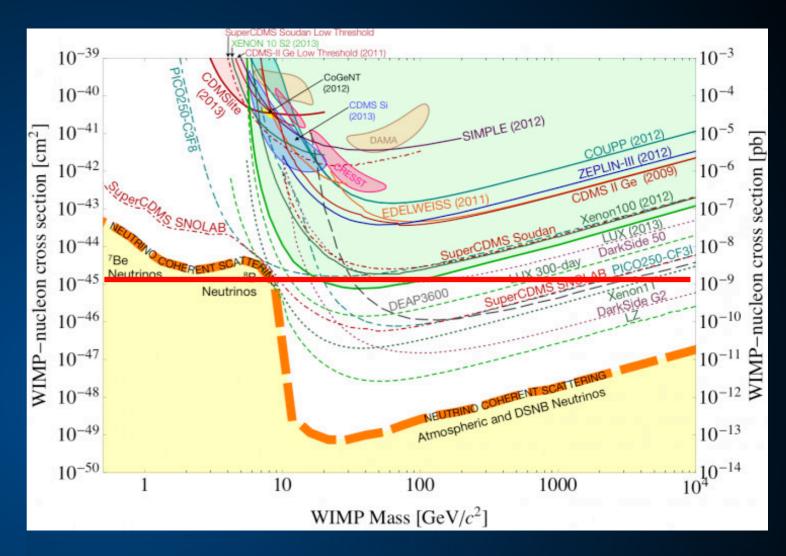
LUX

100 kg
 1000 days
 105 kg day



Neutron Stars: The Optimal Direct Detection Experiment

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

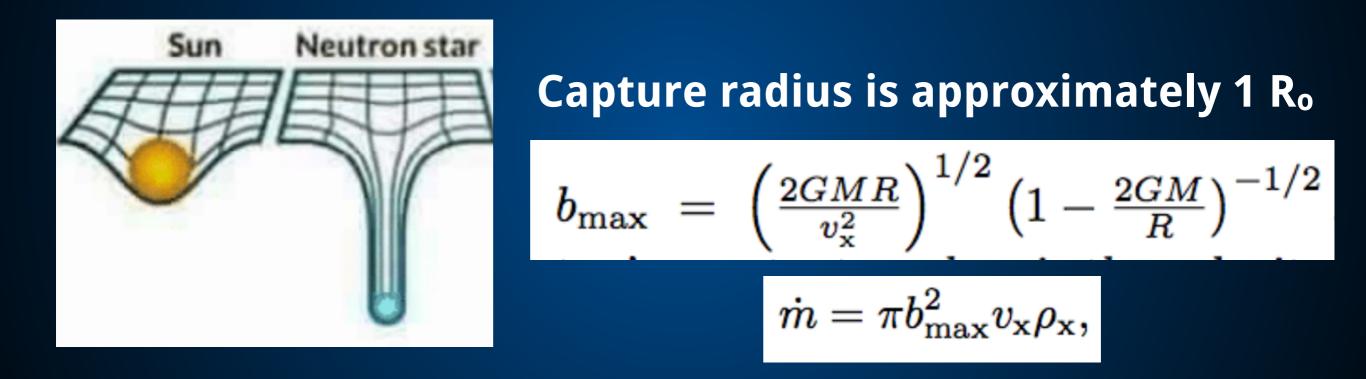


$$\sigma_{\rm sat}^{
m single} \simeq \pi R^2 m_{\rm n}/M \simeq 2 \times 10^{-45} \ {
m cm}^2 \ \left(\frac{1.5 \ {
m M}_{\odot}}{M}\right) \left(\frac{R}{10 \ {
m km}}\right)^2$$

This saturates the sensitivity of neutron stars to dark matter

Neutron Stars: Astrophysics Enhancements

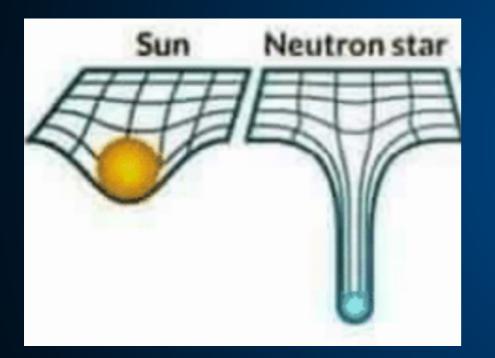
 Neutron stars gravitationally attract nearby dark matter



 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:

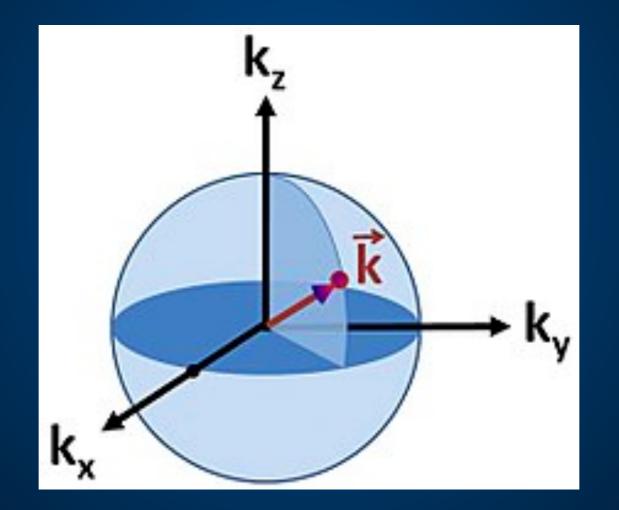
$$v_{esc} = \sqrt{\frac{2GM}{r}} \sim 0.7c$$

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

Neutron Stars: Particle Physics Complications

Typical NS neutron momentum is:

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



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

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

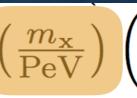
Neutron Stars: Particle Physics Complications

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

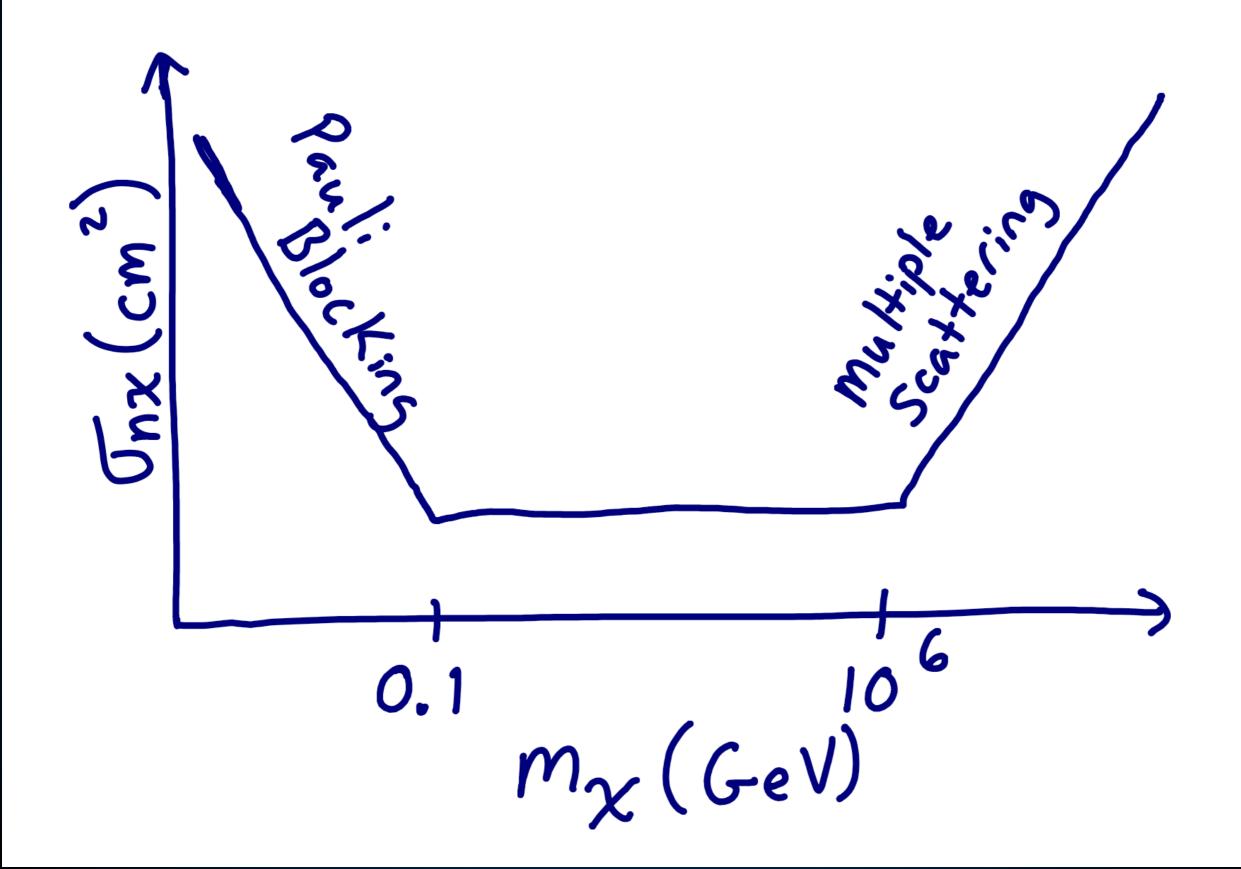
$$E_{loss} = \frac{2m_p}{m_\chi} (m_\chi v_\chi^2)$$

Very heavy dark matter requires multiple interactions:

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



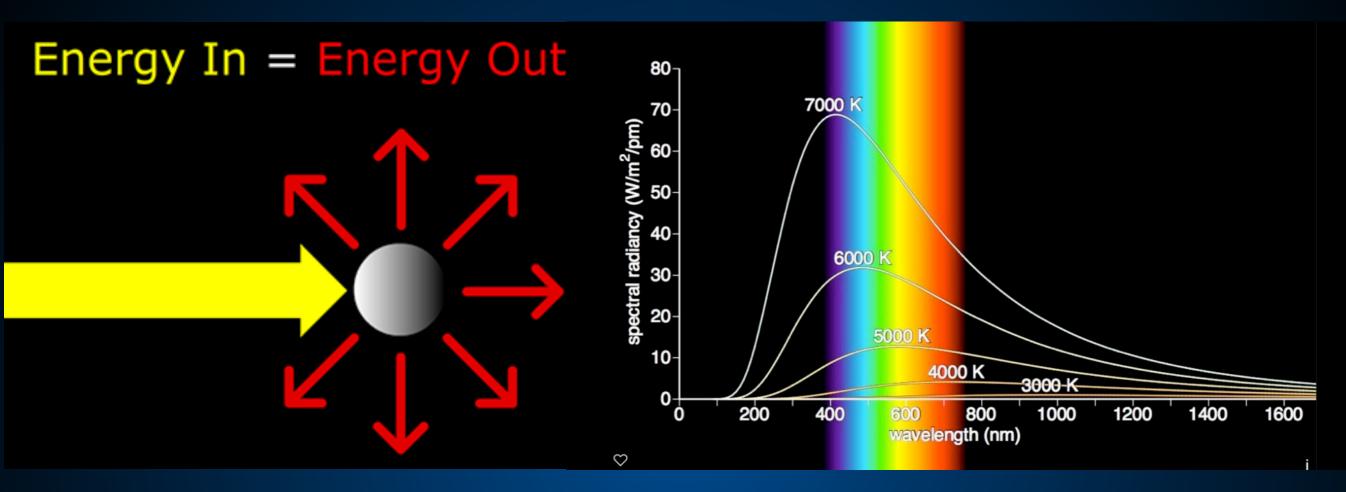
Neutron Stars: Particle Physics Complications



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:

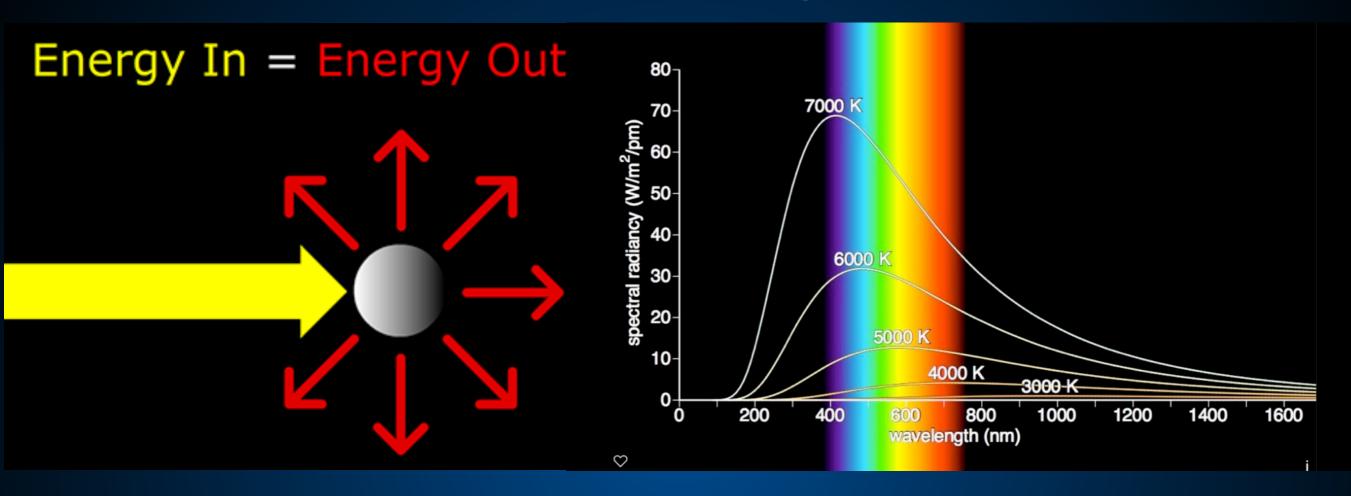
$$E_{\rm s} \simeq m_{\rm x} \left(\gamma - 1 \right)$$

This induces blackbody emission of luminosity:

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

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))

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

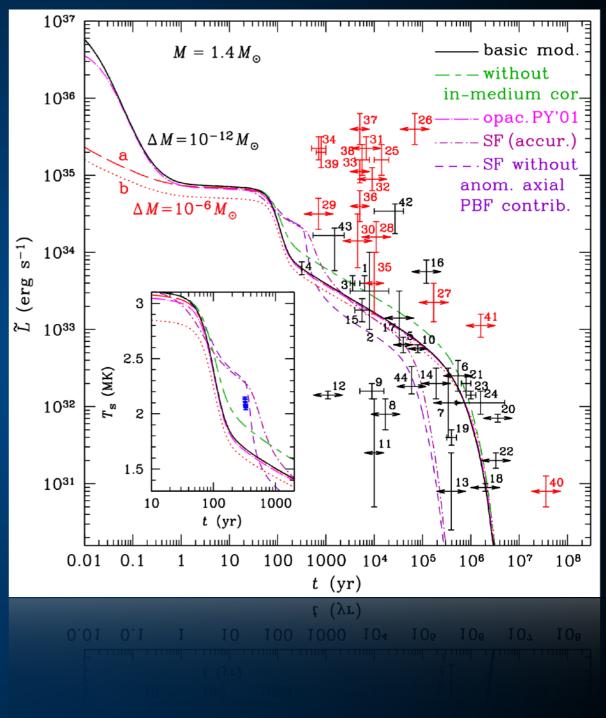
Baryakhtar, Bramante, Li, TL, Raj (1704.01577)

Detecting Hot Neutron Stars

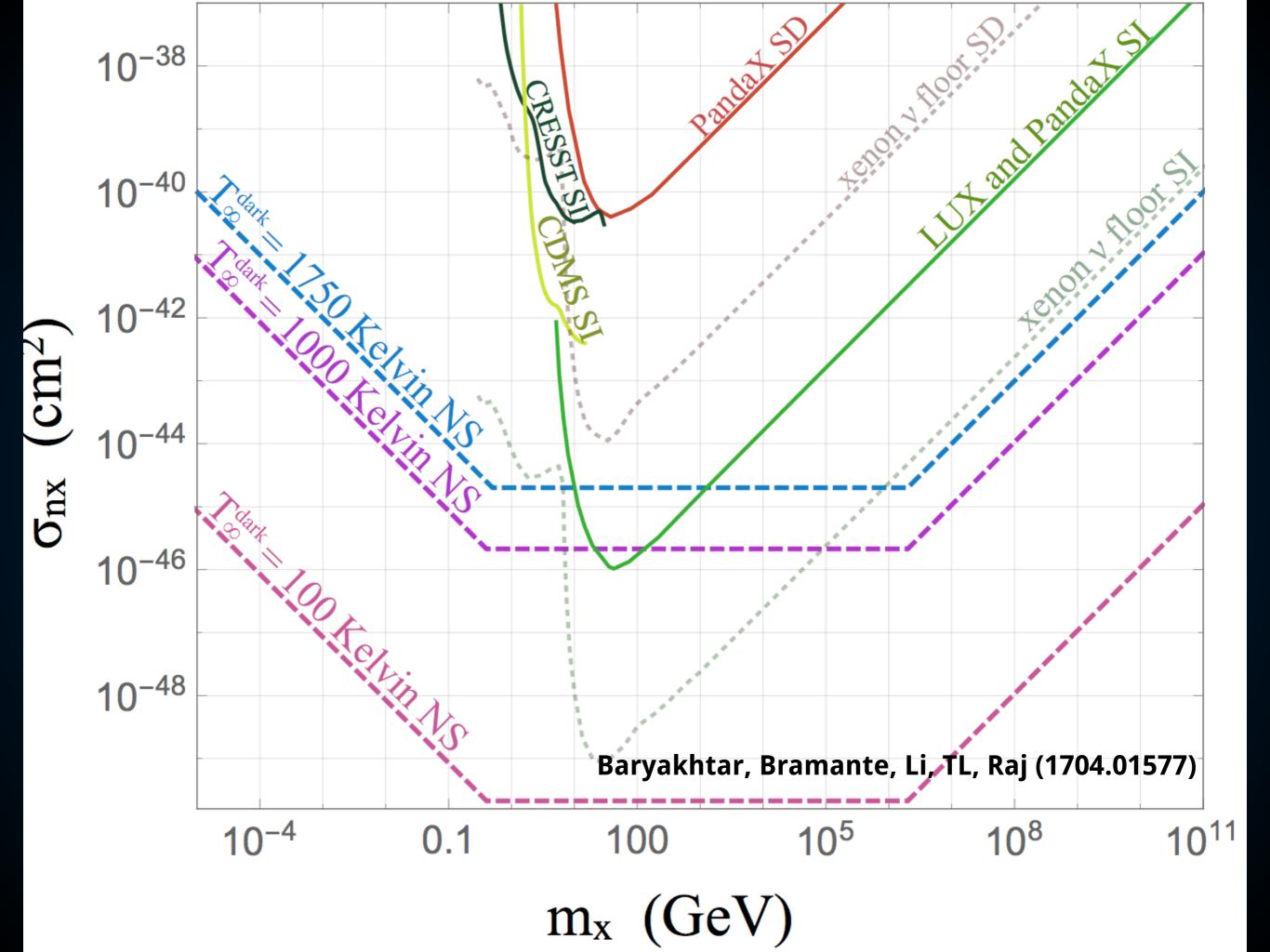
 Thermal emission detected from young neutron stars

 Older neutron stars continue cooling

 Dark matter sets a minimum temperature of ~2000 K (10²² erg)

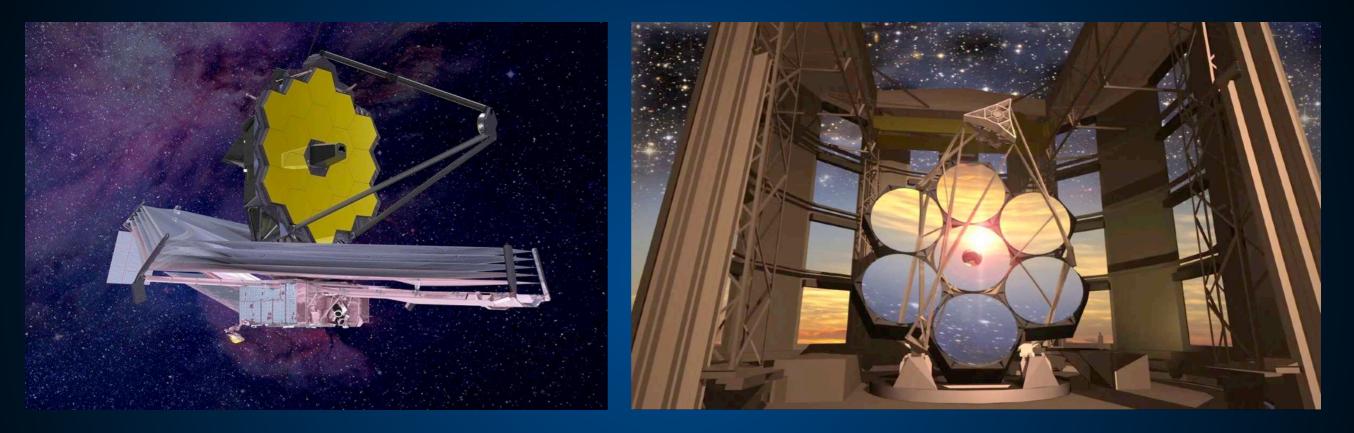


Potekhin & Chabrier (1711.07662)



Detecting Thermal Emission

Observations at 2000 K require infrared telescopes



JWST 10 nJy in 104 s GMT 0.5 nJy in 10⁵ 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

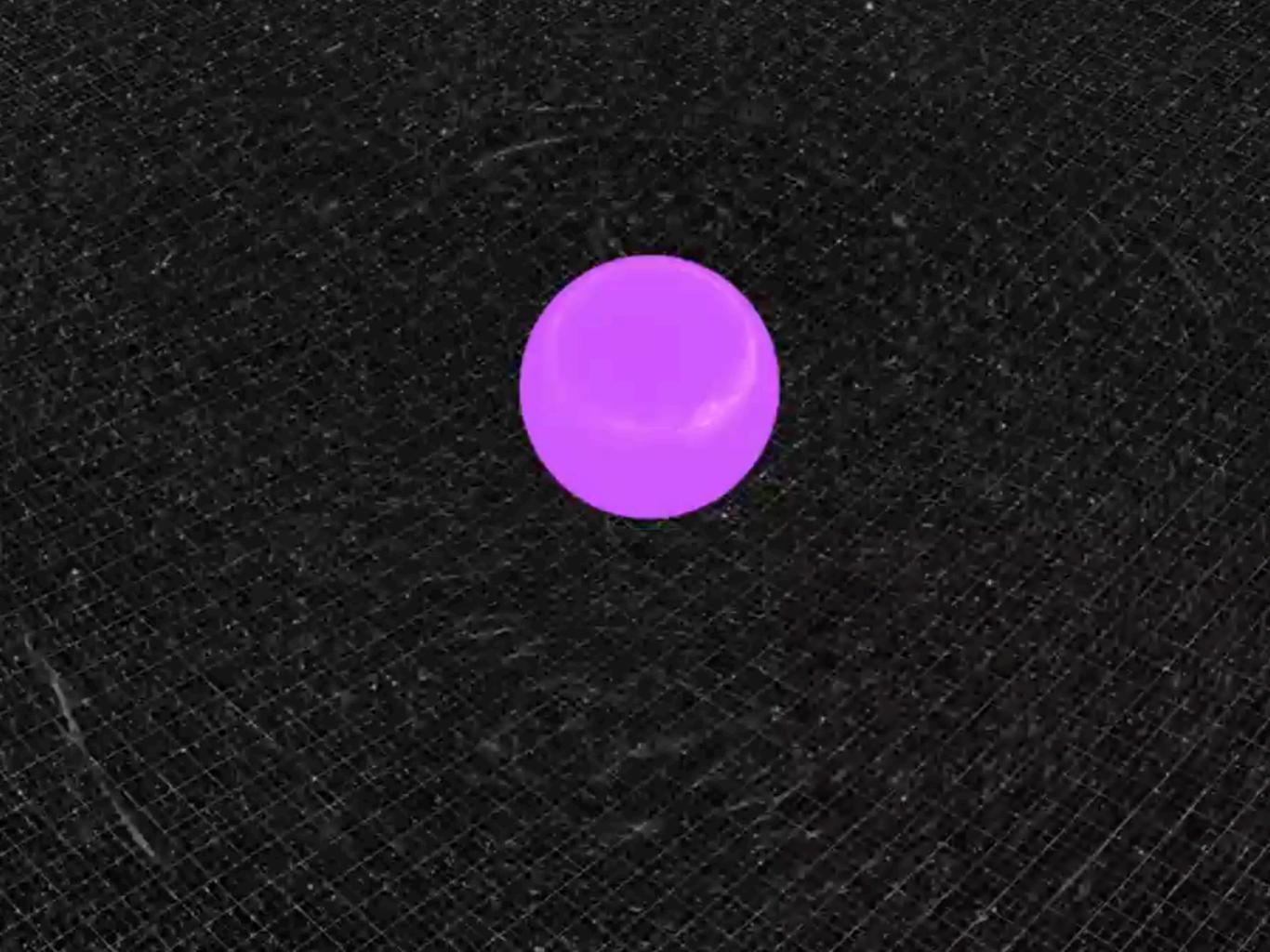
The Secret Life of Dark Matter Inside a Neutron Star

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

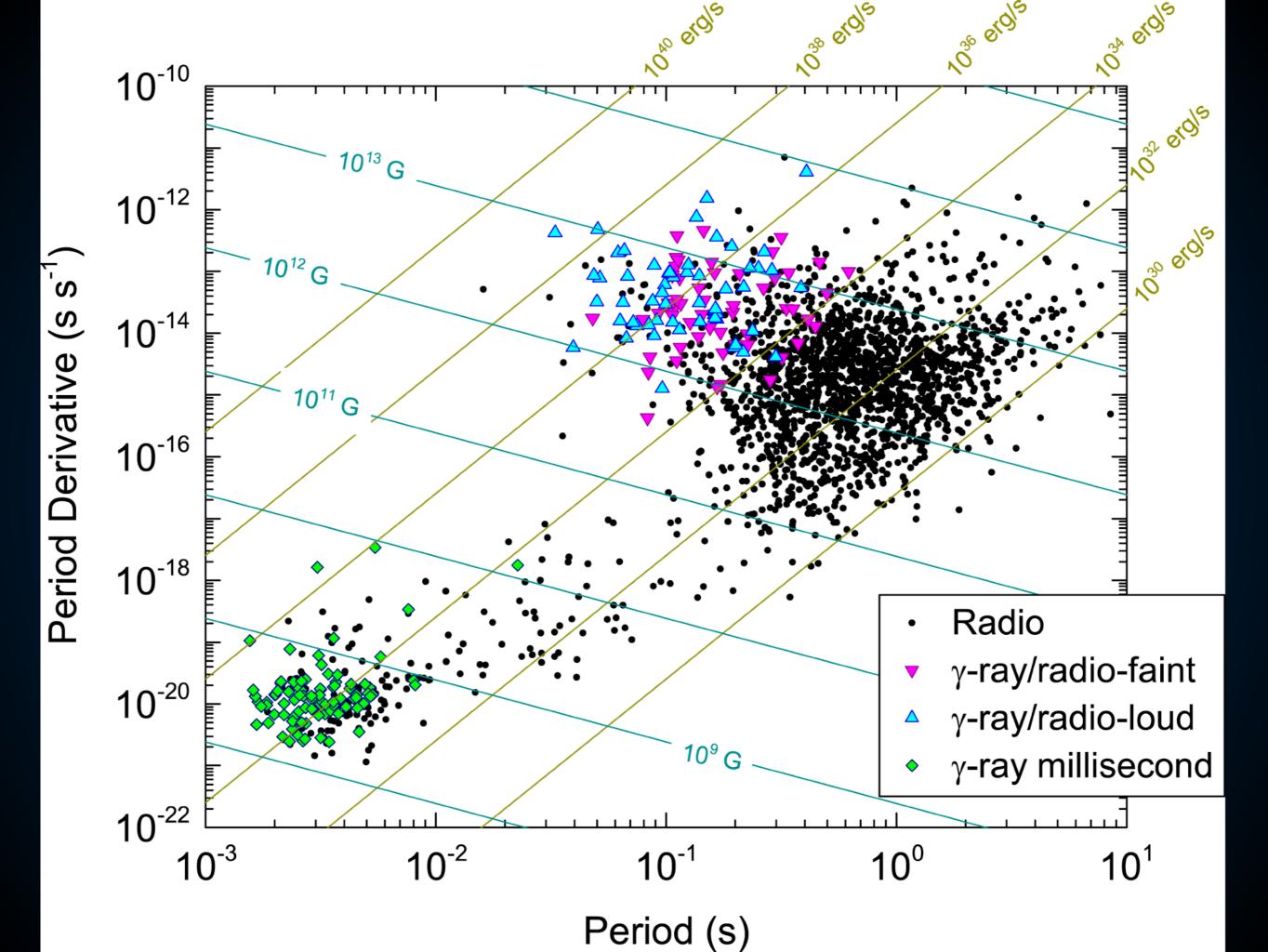
Requires dark matter to be non-annihilating.

PeV Fermionic Dark Matter

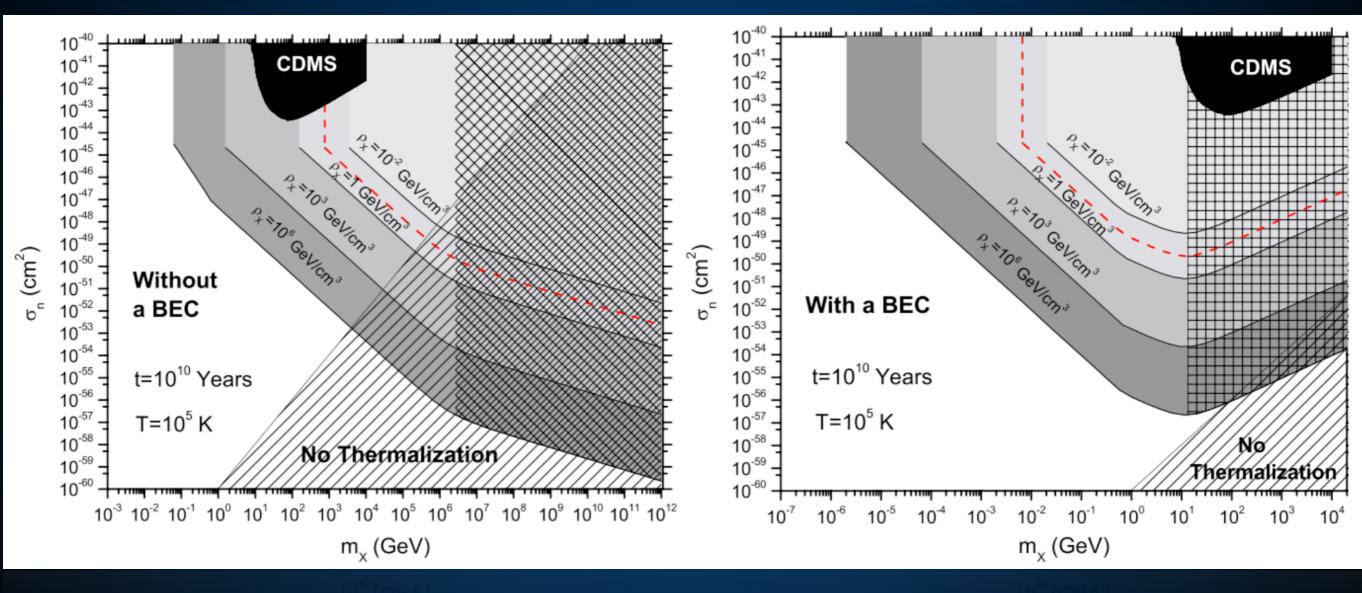
$$M_{crit}^{ferm} \simeq M_{pl}^3 / m_X^2$$

Bosonic Dark Matter

Attractive Self-Interacting Dark Matter



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!** THE PECULIAR PULSAR POPULATION OF THE CENTRAL PARSEC

Massive Star Formation

in the Galactic Center

Rochester Institute of Technology, Rochester, NY

The Galactic center is a hotbed of star formation activity of the most massive volume star of.

The Galactic center is a hotbed of star formation site and three of the most massive young activity of the integration of the most massive young star (c).

Iormation site and three of the most massive young stars with initial most sta a rich environment, it contains more stars with interact of the Galaxy. This review concerns the with initial in the volume stars formation in the volume stall of the volume stall in the volume stall in the volume stall in the volume stall. else in the Galaxy. This review concerns the stellar clusters, the nonulation in the region. The nonulation of volume stellar in the region. as it relates to massive star iomation in the stars surrounding the contral black hole of younger stars in the hole of the

massive stellar clusters, the population of younger stars in the central black hole, and the bulk of voinger stars in the calartic conter supposed the bulk of voinger stars in the calartic conter supposed the bulk of voinger stars in the rest of the voinger stars in the voinger stars in

the stars surrounding the central black hole, and the bulk of a lactic center suggests that the vertex of a similar nonnelations that must have been for The fossil record in the Galactic center suggests that the recently in the recently in the soft similar populations that must have been formed in the recently Department of Astronomy, University of California, Berkeley, CA 94720.3411, USA

Department of Astronomy, Universion April 14, 2018

ABSTRACT would be potential probes of i

A Signal

The Galactic center is a hol formation site and three of t

a rich environment, it containe else in the Galaxy. This review

as it relates to massive star form massive stellar clusters, the popula the stars surrounding the central bi The fossil record in the Galactic cente

resent-day examples of similar popula

isodes stretching back to the time pe

troduction

ralactic center (GC) is a

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

Only one (very young) pulsar detected **The Missing Pulsar problem!**

ALERT: THIS BIKE IS STOLEN

E CENTRAL PARSEC

Jrkeley, CA 94720.3411, USA

Via, Berkeley, CA 94720-3411, USA

A*, would be potential probes of it

emporal Scattering IS Inucu Weak

A*, would be potential probes of relativity center, predictions tempora relativity center, prome have been Galactic conter, perstrong tempora highlight that hyperstrong highlight s been that ions from a highlight radio pulsations from a mignly m emporal scattering is much weak has been stolen from Gautam Nagar area in New Delhi

5418

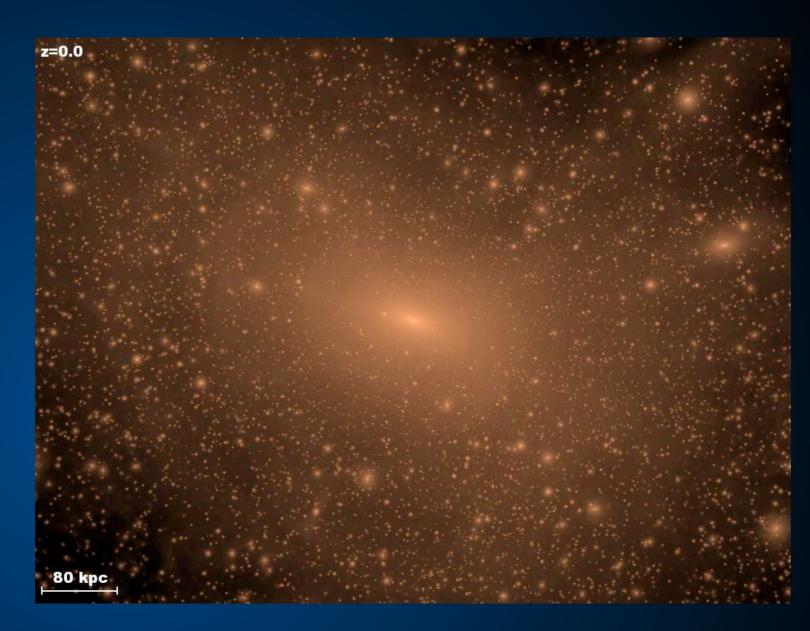
UP32 - CW -5418

The Missing Pulsar Problem

• High Dark Matter density near the GC.

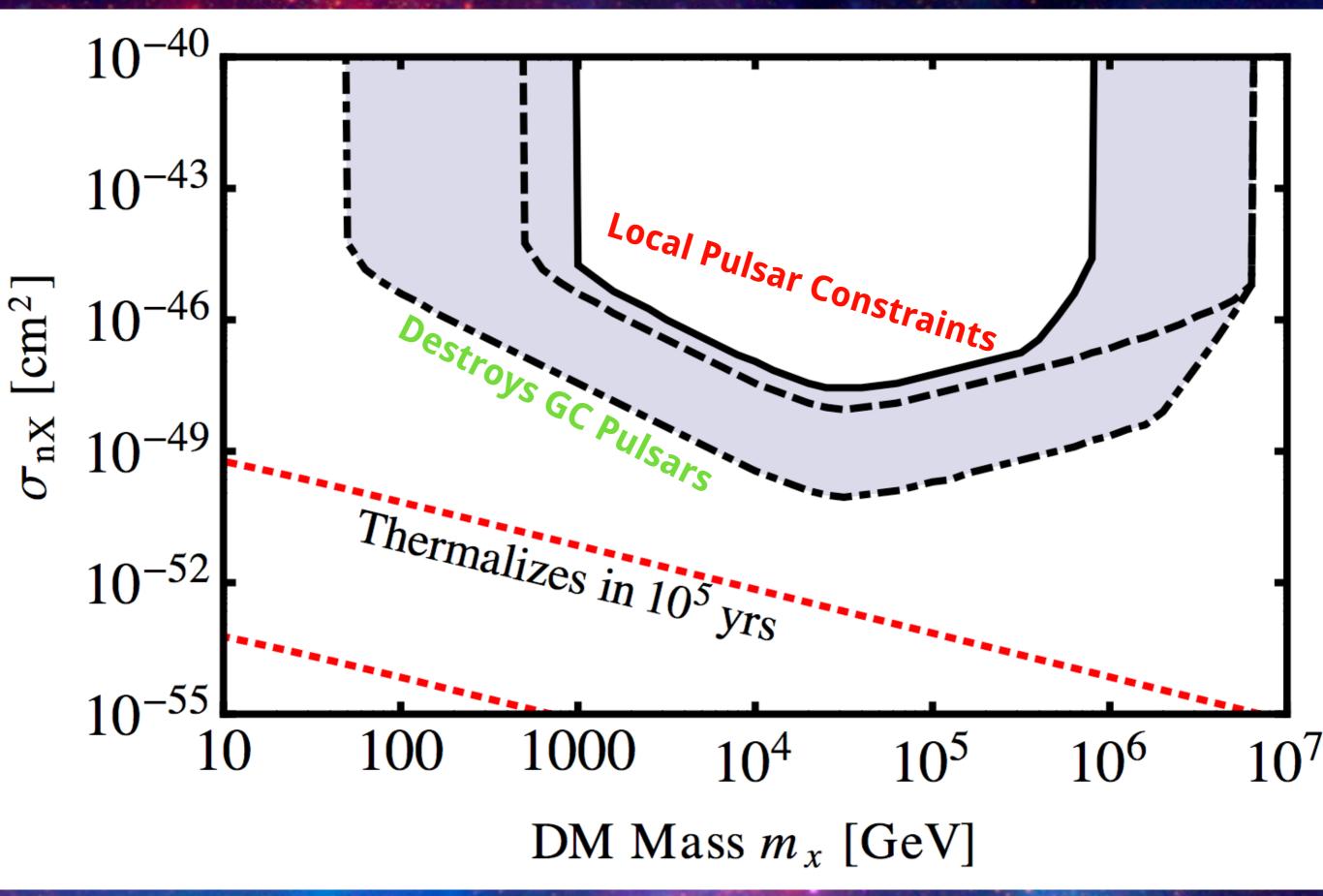
$$ho(r) = rac{
ho_0}{rac{r}{R_s} \Big(1 \ + \ rac{r}{R_s}\Big)^2}$$

 GC NS collapse in ~10⁵ yr while nearby NS remain.

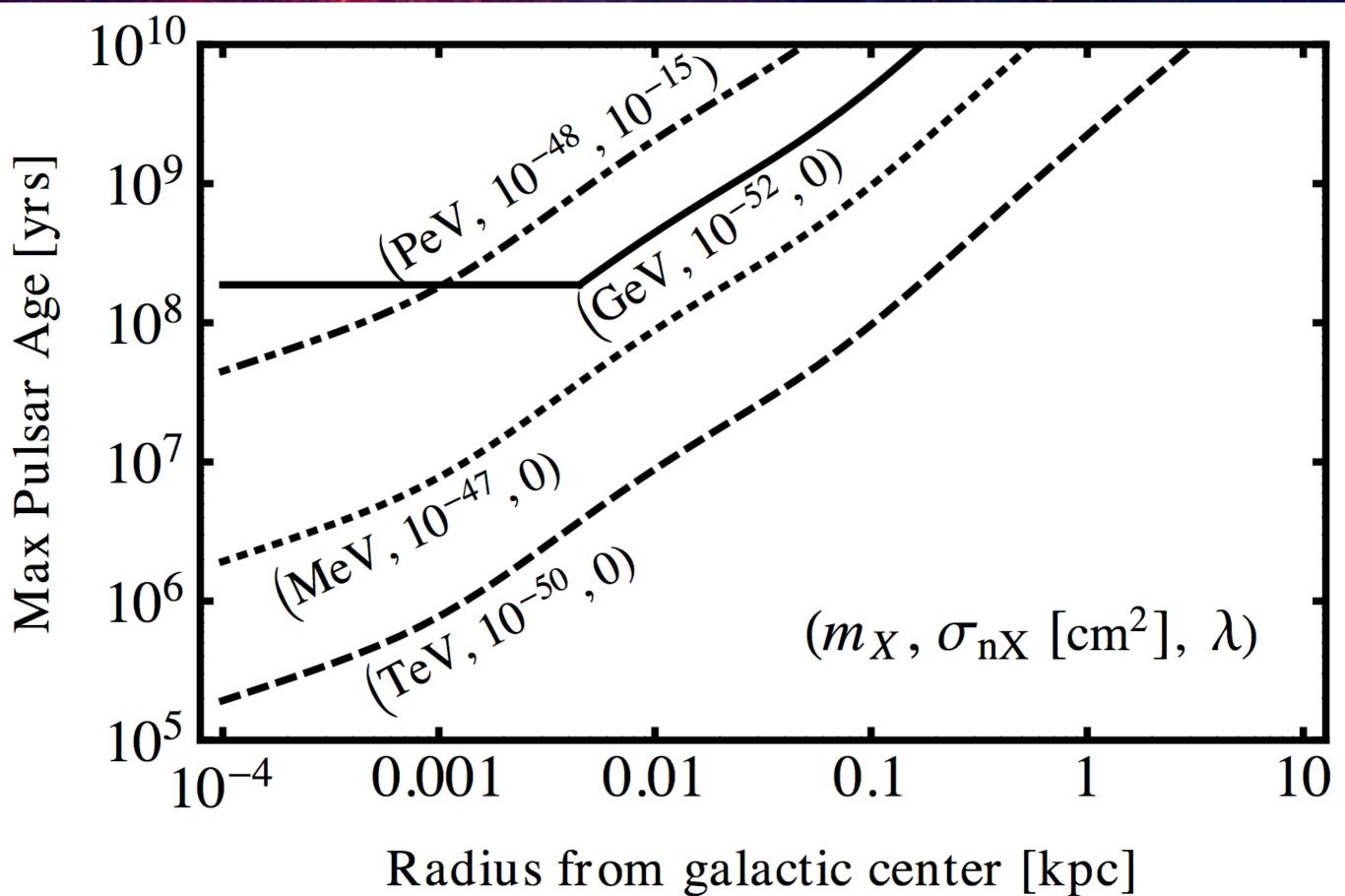


Constrains cross-section to within a few orders of magnitude.

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?

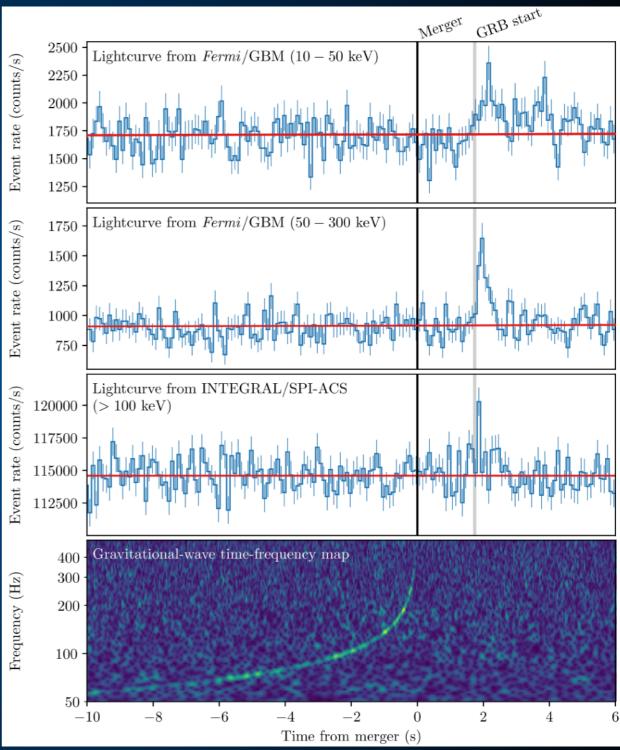
Bramante, TL, Tsai (1706.00001)

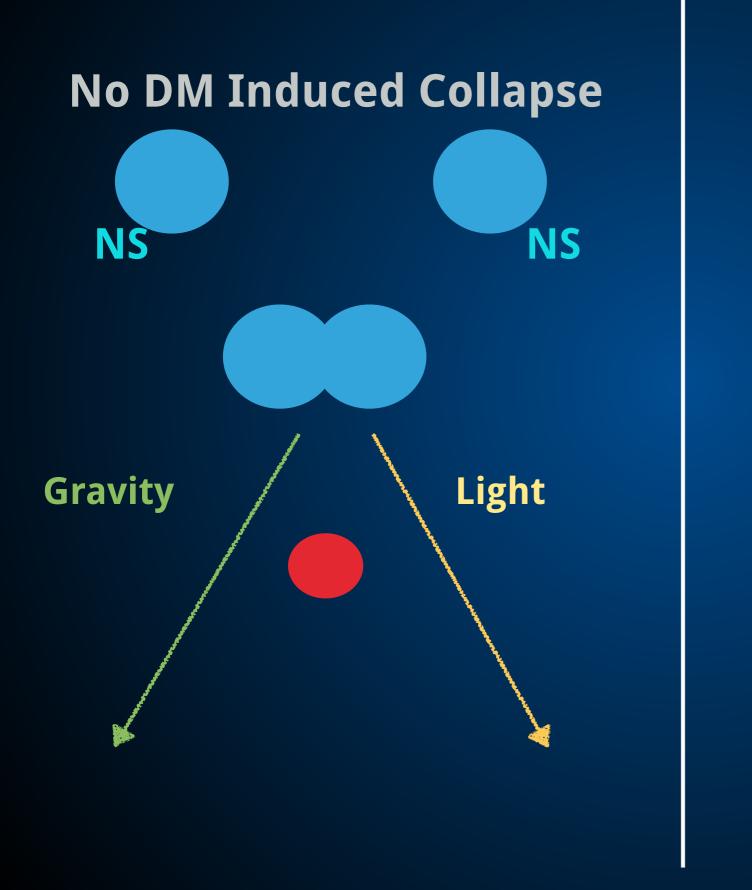
 Gamma-Ray Bursts (observed by Fermi)

 Optical emission from the decay of r-process elements

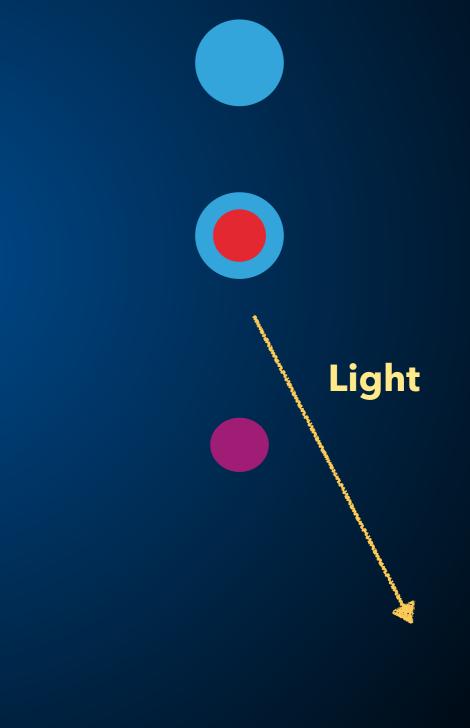
 Fast Radio Bursts are potentially correlated with NS mergers.

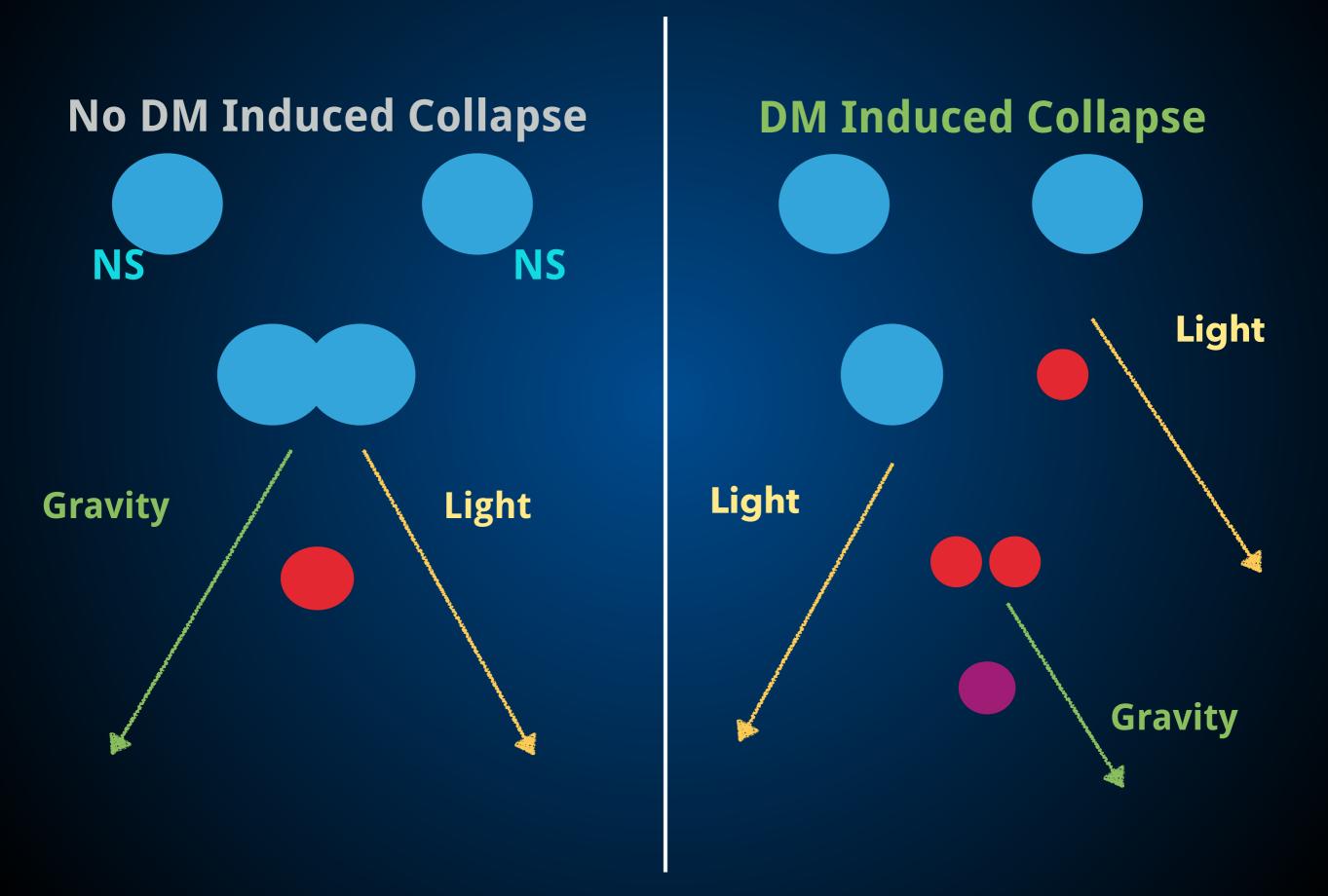
Fermi GBM Collaboration (1710.05834)



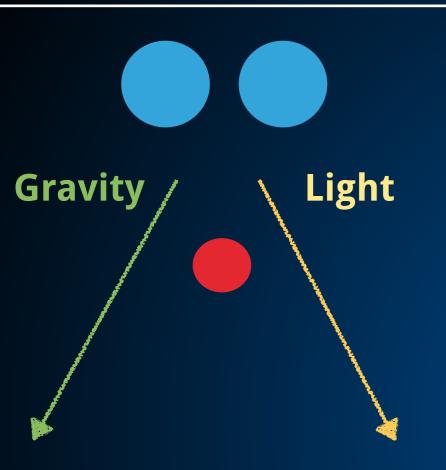


DM Induced Collapse





New Phenomena



<u>Merger Kilonovae</u>

Electromagnetic signals and gravitational waves jointly identified.

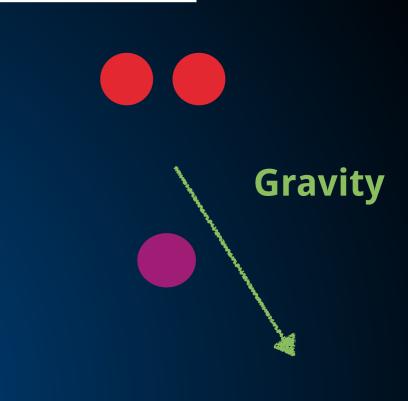
(proportional to ρ⁻¹DM)

<u>Quiet Kilonovae</u>

Light

Electromagnetic signals without gravitational waves.

(proportional to pdm).



Dark Mergers

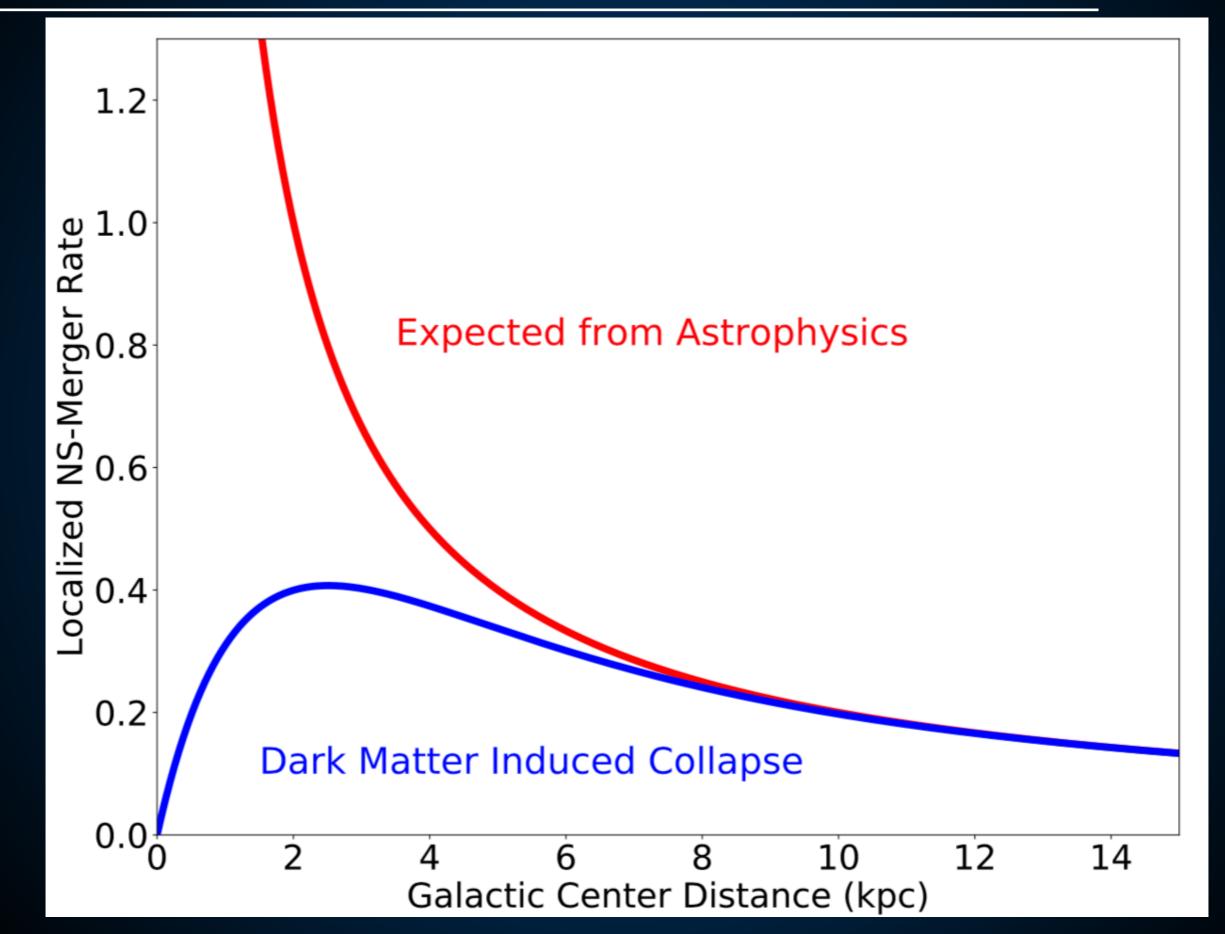
Gravitational waves without any electromagnetic signal. (proportional to ρ_{DM}).

Two Methods

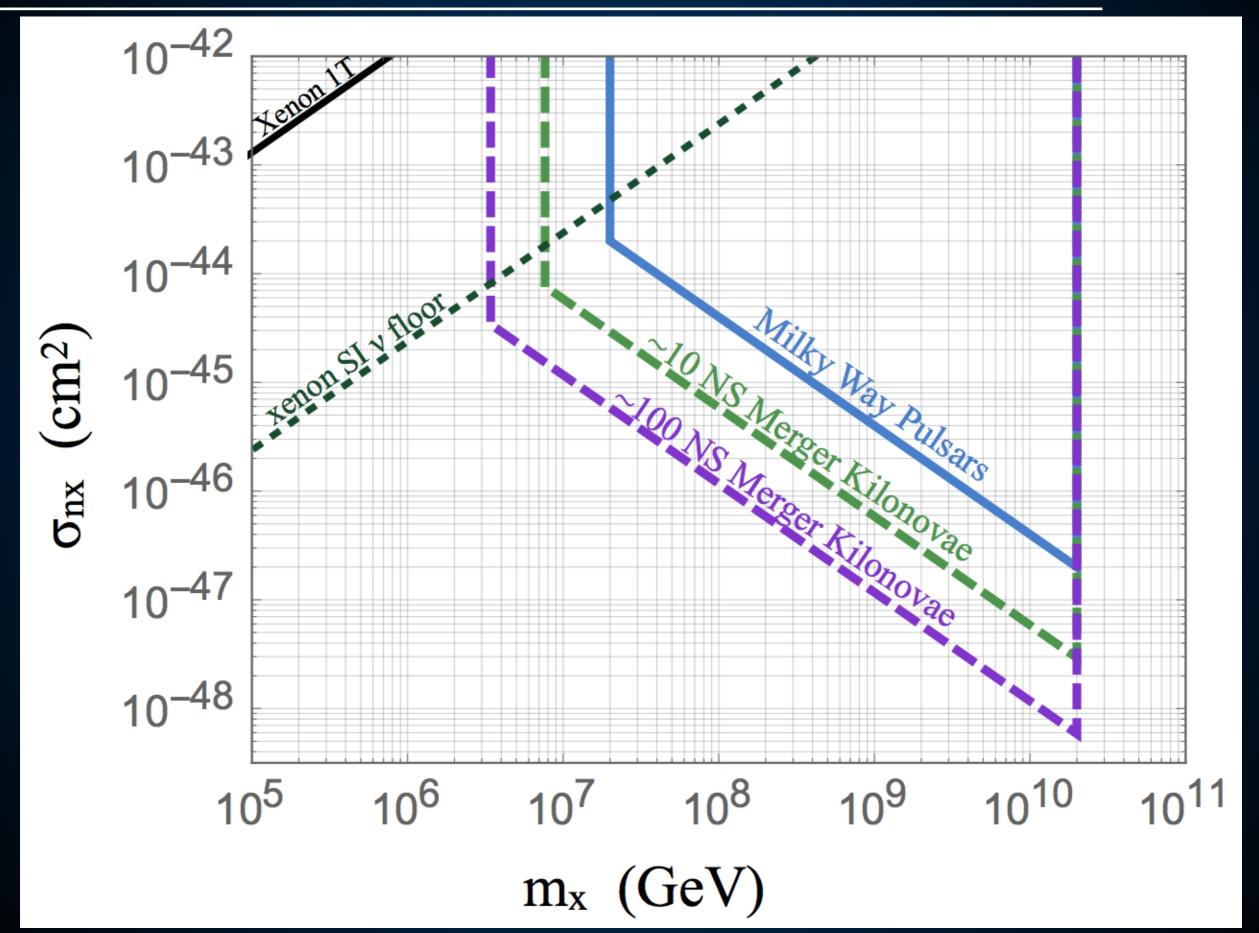
Two methods to isolate dark matter signal:

- 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.

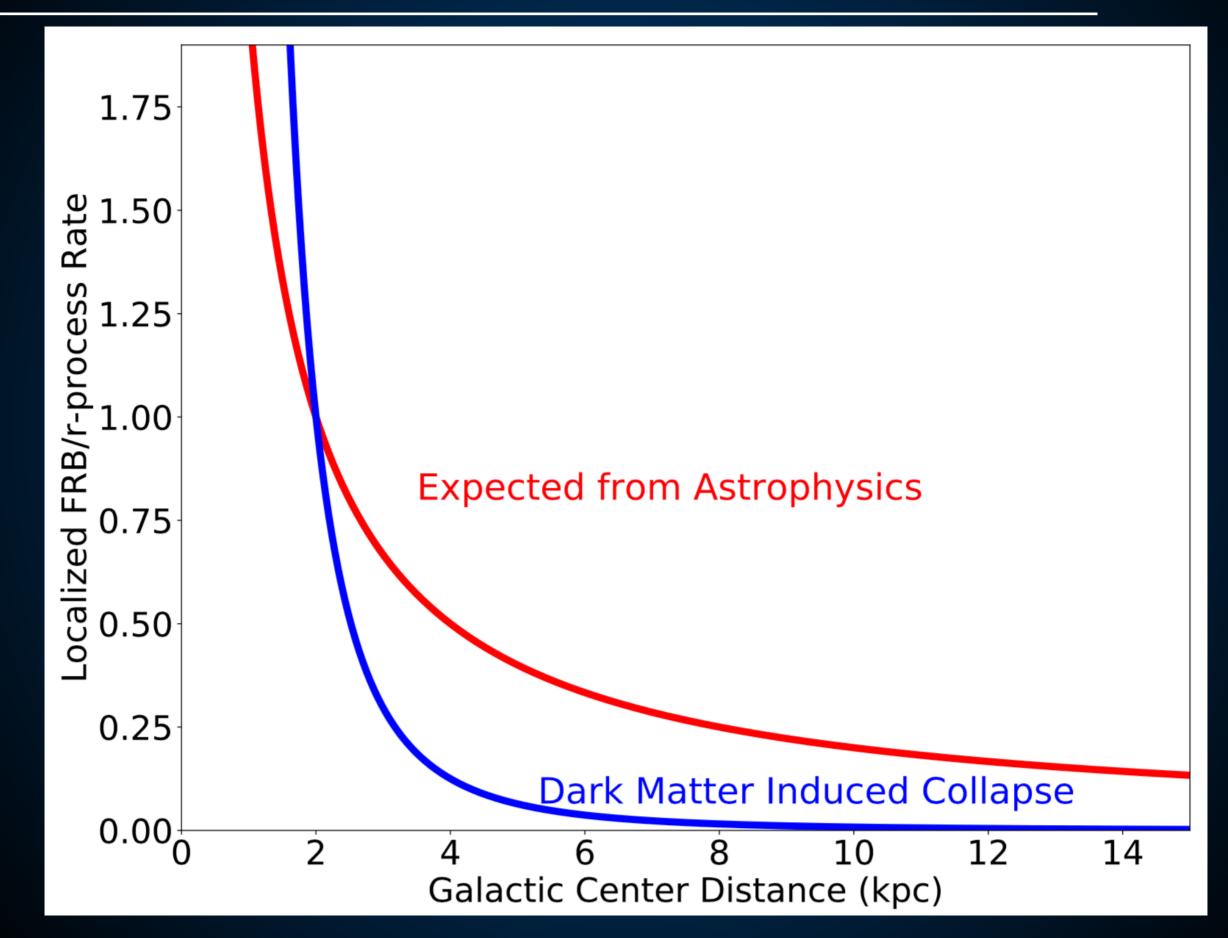
Merger Kilonovae



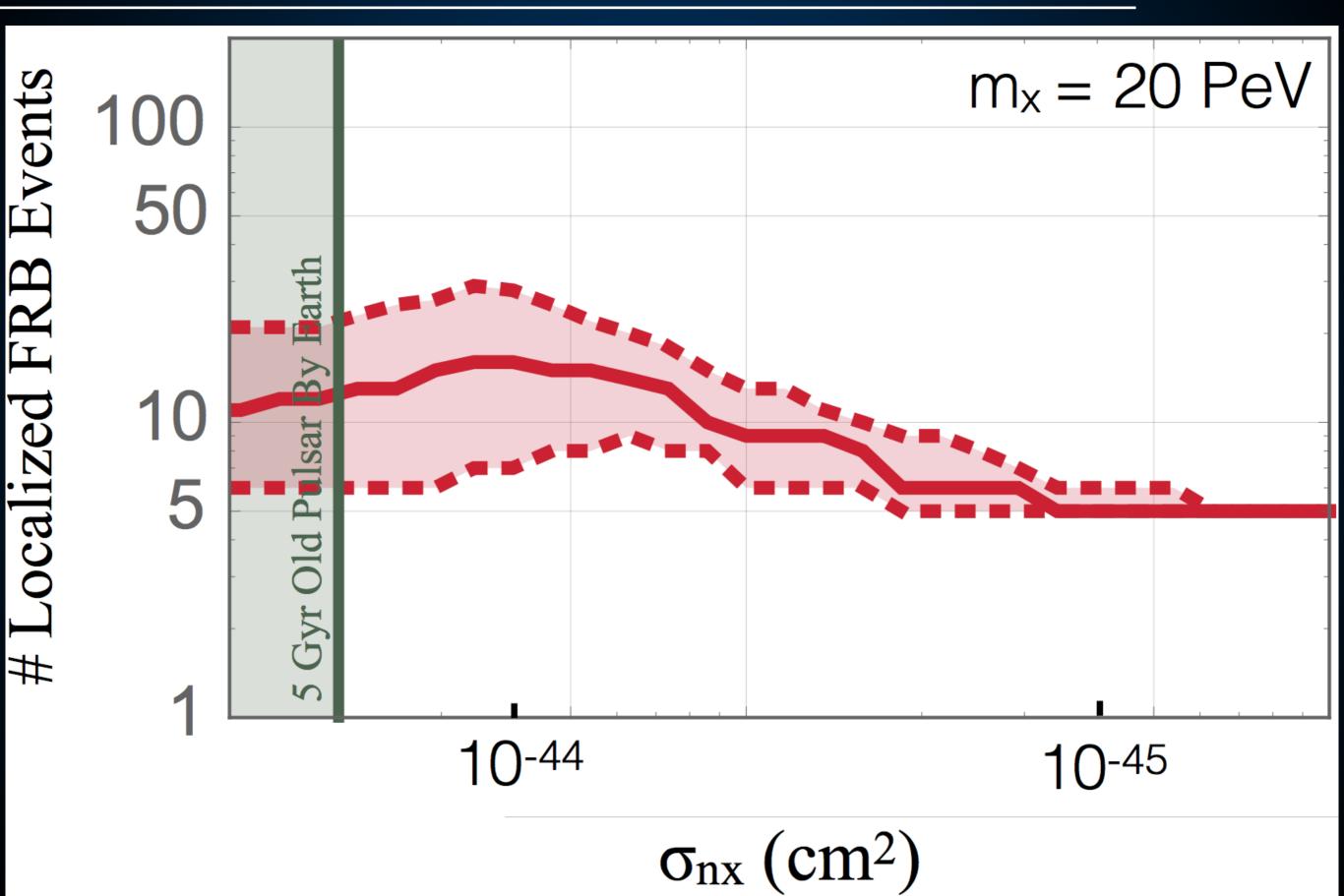
Constraining Dark Matter - Merger Kilonovae



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.

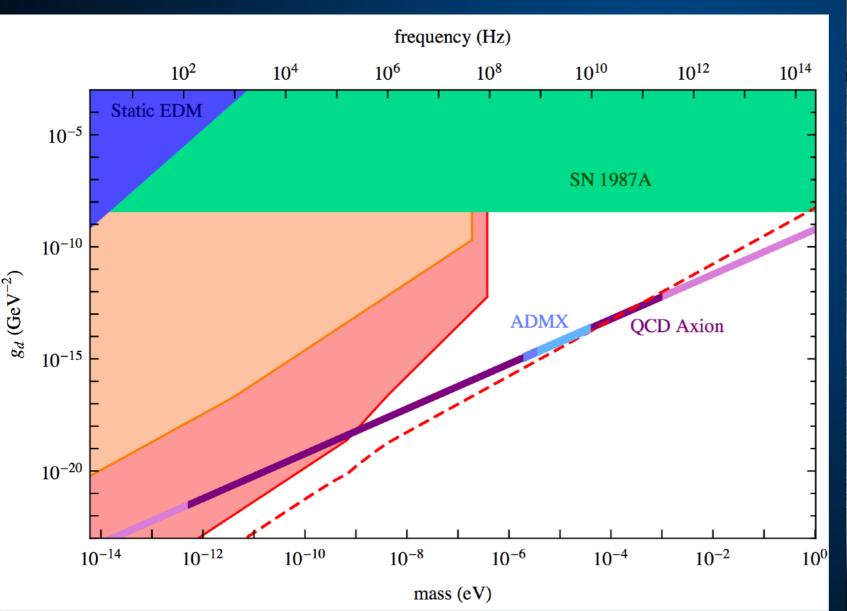
2. Strongest magnetic fields in the universe.

Precise measurements are possible.

Detecting Axion Dark Matter

• We can search for the resonant decay to photons:

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





Neutron Stars: The Optimal Axion Laboratory

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

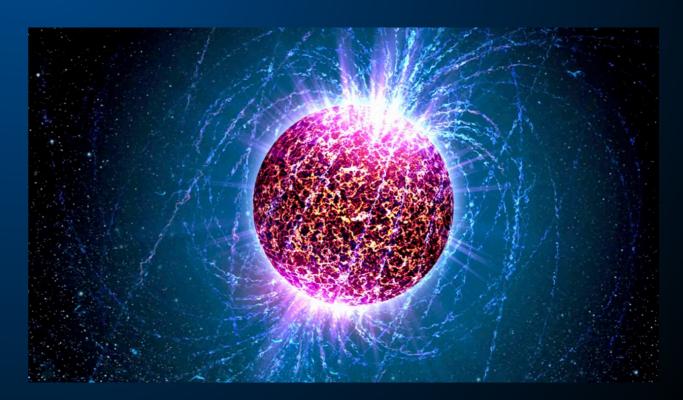


<u>ADMX</u>

- 10 T
- 1 m² 100 T² m²

Neutron Star

- 10¹⁰ T
- 10⁸ m²
 - 10²⁸ T² m²

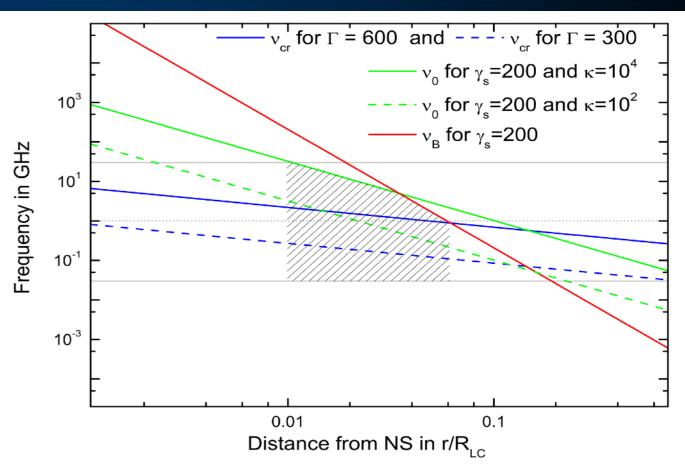


Neutron Stars: The Optimal Axion Laboratory

 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



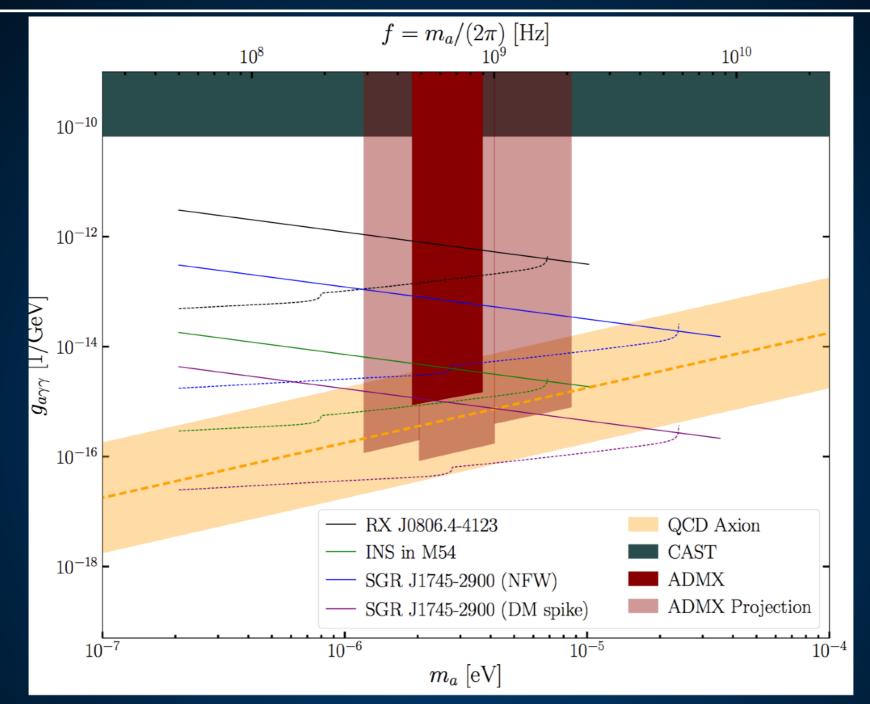
Need detailed model of NS magnetic fields.

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

Hook et al. (1804.03145)

Mitra et al. (1510.00103)

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).

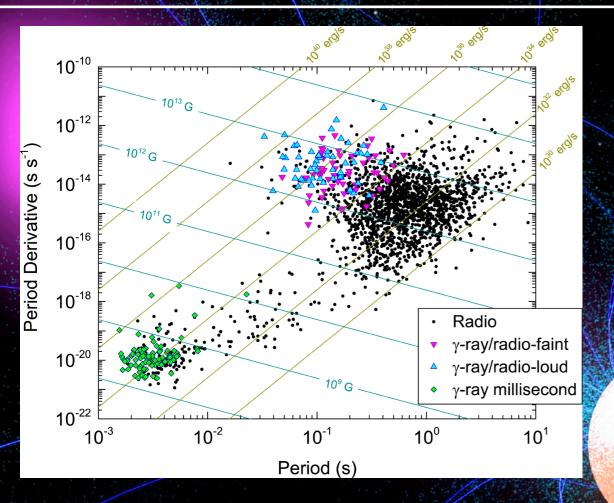
Finding the Right Neutron Star

DM-NS Interactions

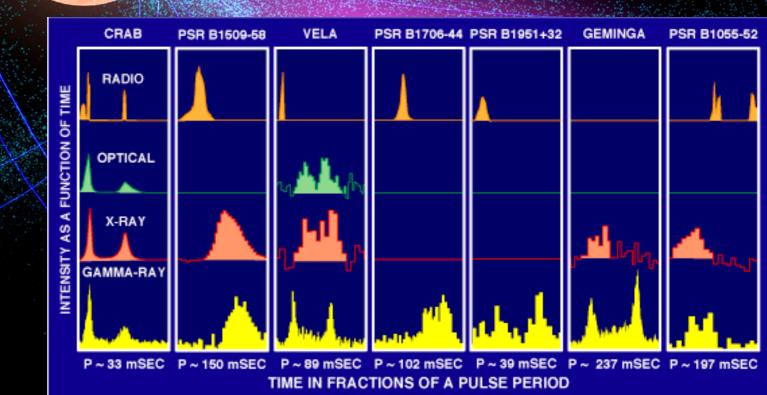
Constrain Astrophysics

Find Neutron Stars

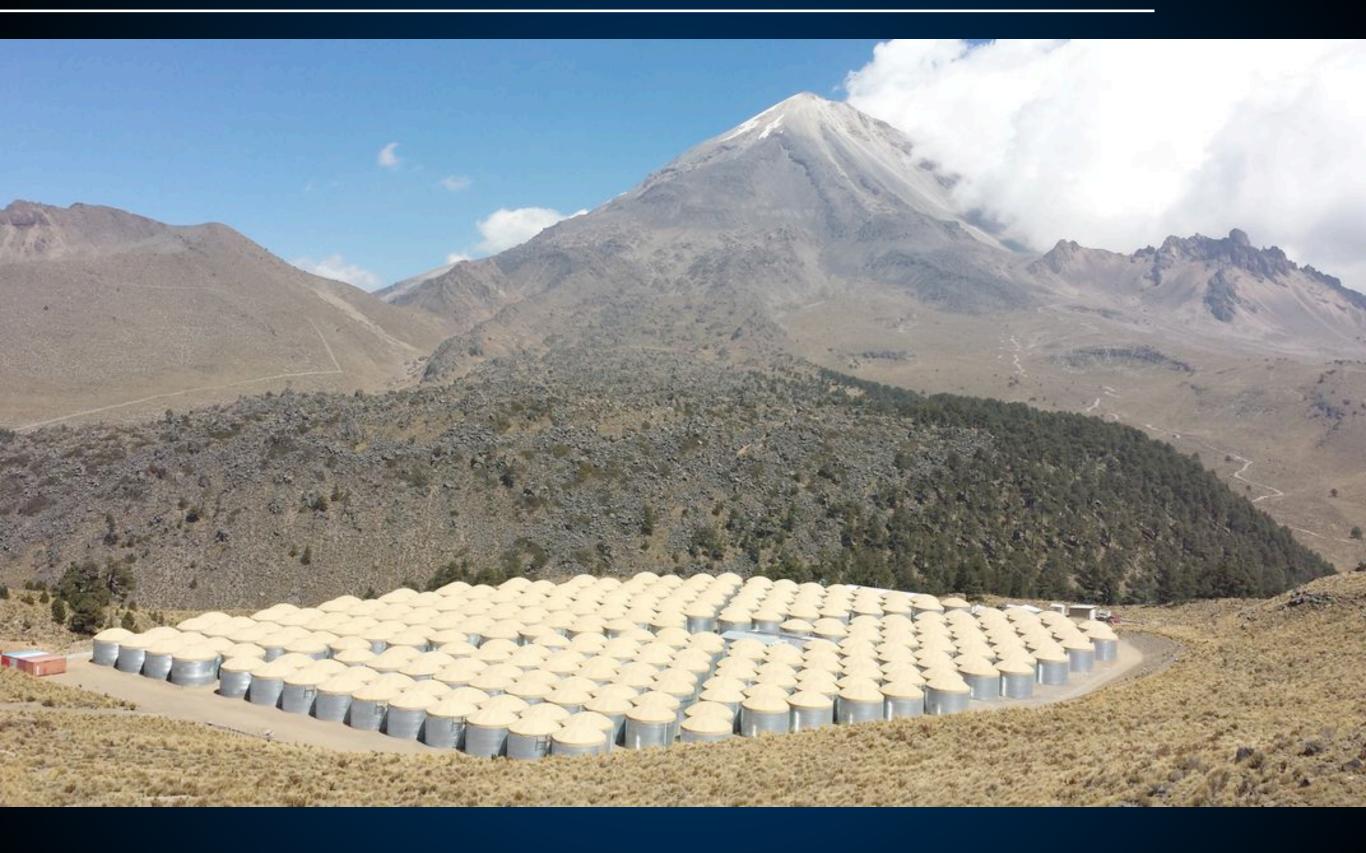
Radio Pulses: A Blessing and a Curse



Harding (2016; J Plasma Phys 82)



A New Method for Detecting Invisible Pulsars



A New Method for Detecting Invisible Pulsars

Moon (To Scale)

Geminga

2° ~ 10 pc



PSR B0656+14

(c) 3017 HANK Contrology Creative Community Attribution Share Alike 2 River Insure Int Community H. New

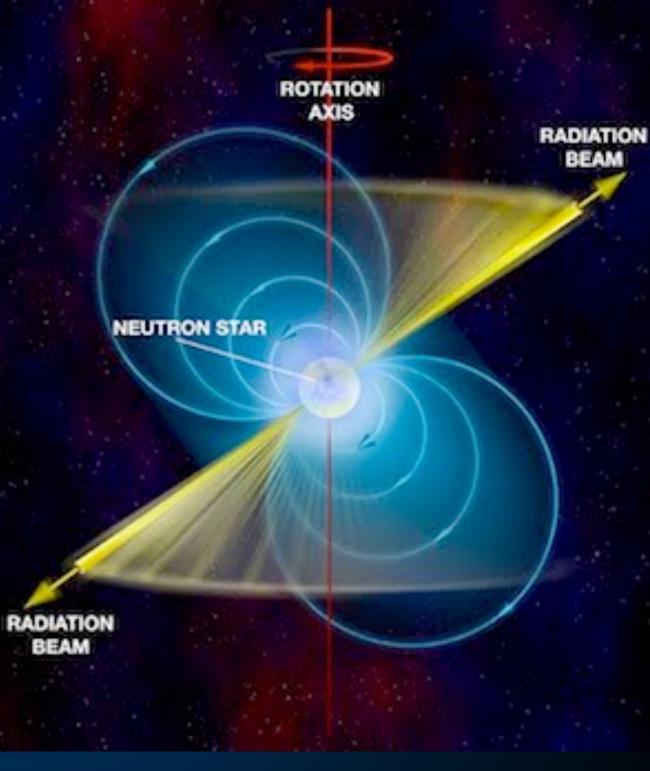
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Discovering Pulsars at TeV Energies

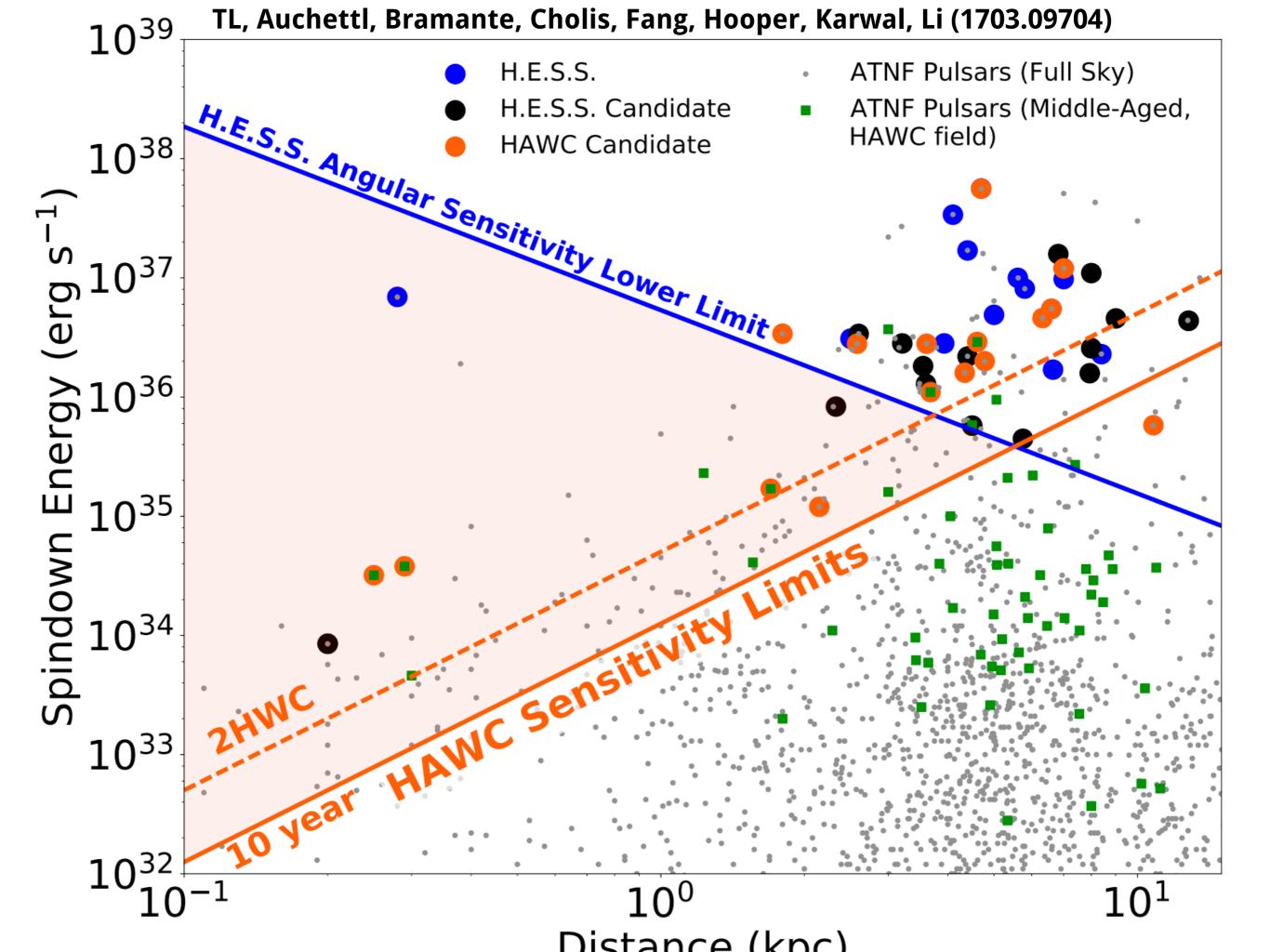
 Tauris and Manchester (1998) calculated the beaming angle from a population of young an middle-aged pulsars.

• This varies between 15-30%.

• 1/f pulsars are unseen in radio surveys.







What Do We Need?

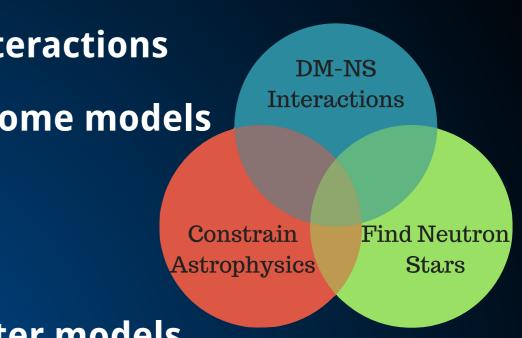
1. Continued observations of TeV halos.

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.

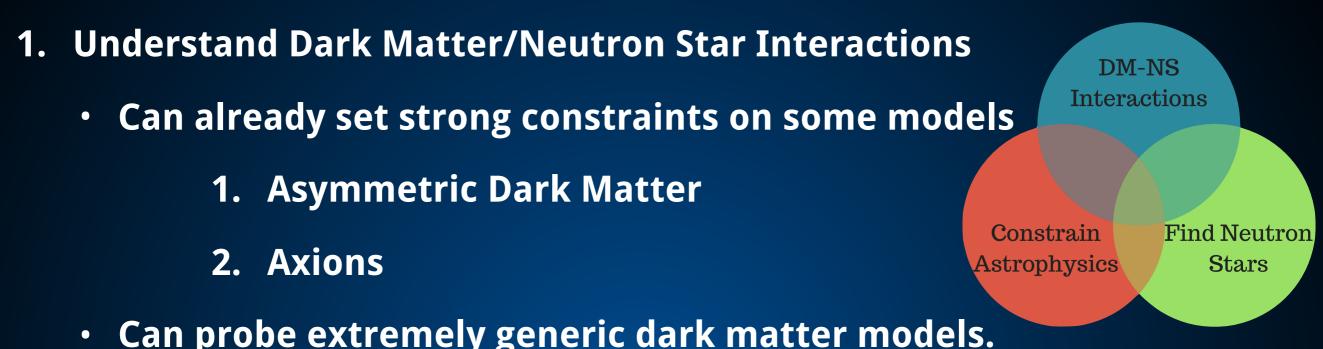
The Program

- 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

- 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** ullet
 - 1. Nearby
 - 2. Strong Magnetic Fields
 - 3. Not Beamed Towards Earth





Chawla et al. (1701.07457)

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10198

10 (16, 14)

ADDINET

1555(15)

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.

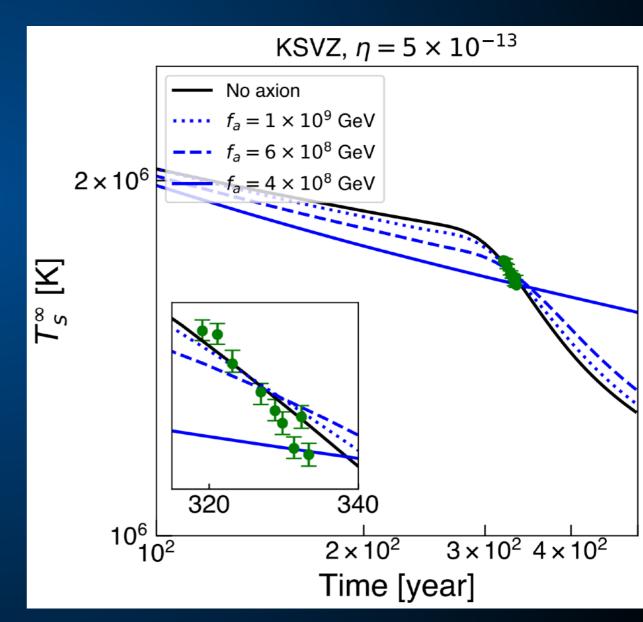
 Our observational techniques are in their infancy. The next decade will revolutionize the field in several directions.

Extra Slides

Particle Physics Mash-Up

 Can also use neutron star cooling curves to place limits on the axion crosssection.

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



Hamaguchi et al. (1806.07151)

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)

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

2HWC	ATNF	Distance	Angular	Projected	Expected	Actual	Flux	Expected	Actual	Age	Chance
Name	Name	(kpc)	Separation	Separation	Flux (× 10^{-15})	Flux (×10 ⁻¹⁵)	Ratio	Extension	Extension	(kyr)	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

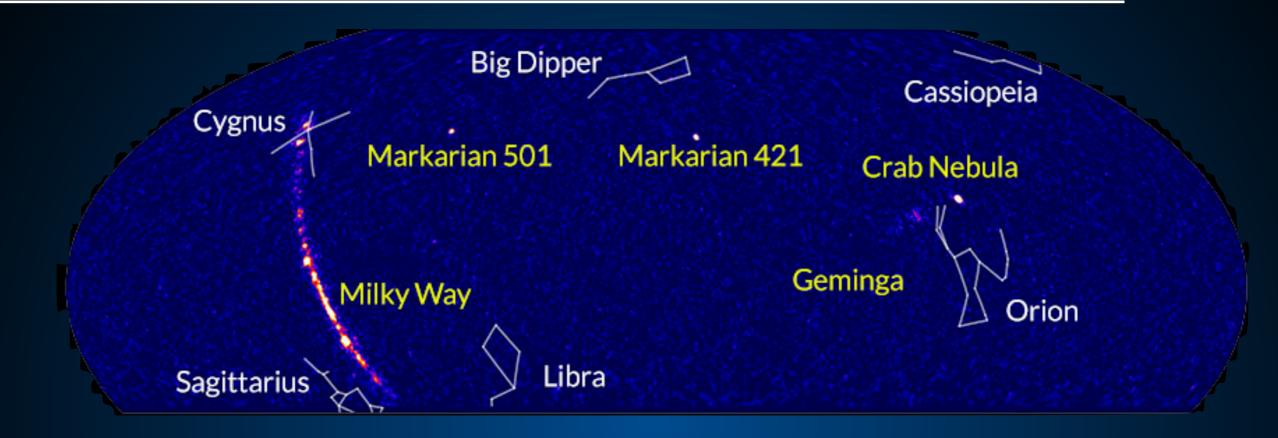
12 others with young pulsars

• 2.3 chance overlaps

• TeV emission may be contaminated by SNR

2HWC	ATNF	Distance	Angular	Projected	Expected	Actual	Flux	Expected	Actual	Age	Chance
Name	Name	(kpc)	Separation	Separation	Flux (×10 ⁻¹⁵)	Flux ($\times 10^{-15}$)	Ratio	Extension	Extension	(kyr)	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

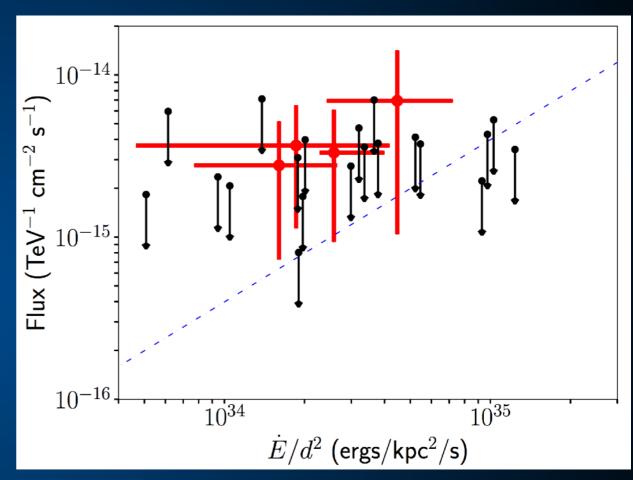
TL et al. (1703.09704)



- 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.

• Tentative Evidence that MSPs also produce these TeV halos.

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



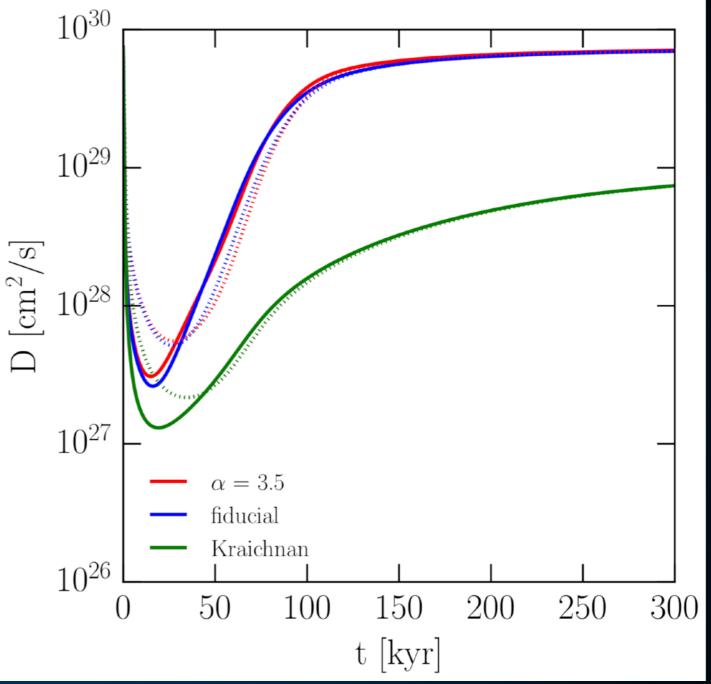
 Models indicate a MSP should exist within ~50 pc, but none has yet been found.

Hooper & TL (1803.08046)

A Model for TeV Halos

 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.

Evoli, TL, Morlino (TBS)

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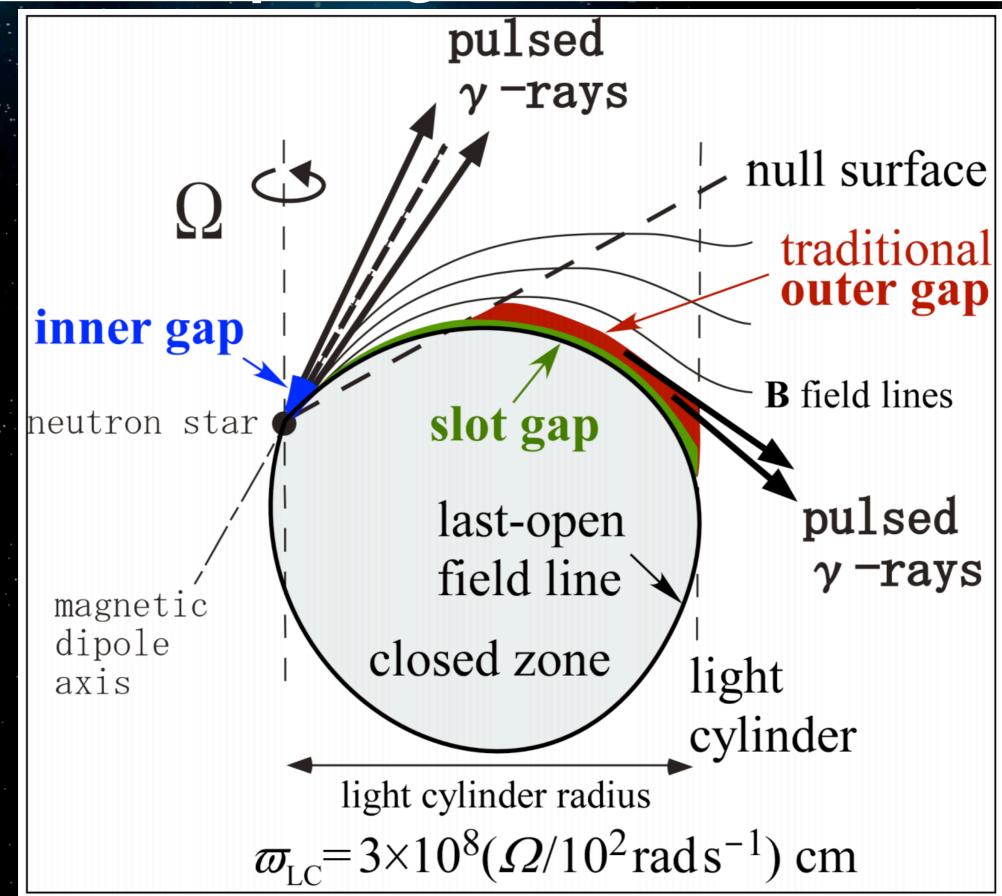
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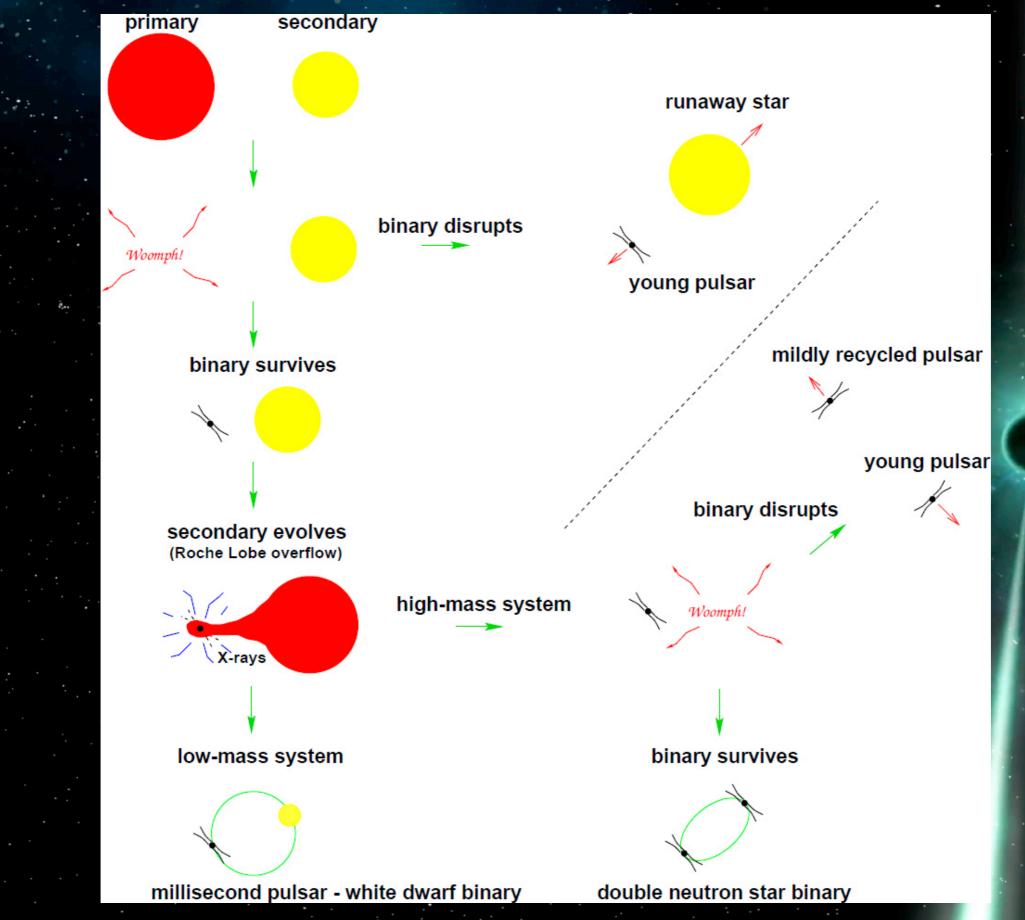
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TL et al. (1703.09704)

Emission Morphologies



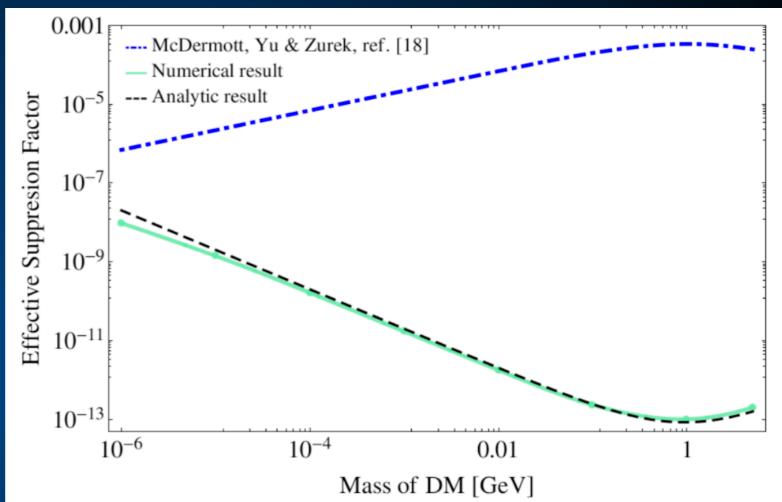
Evolutionary History of Millisecond Pulsars



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.



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

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

Bertoni et al. (2013; 1309.1721)

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:

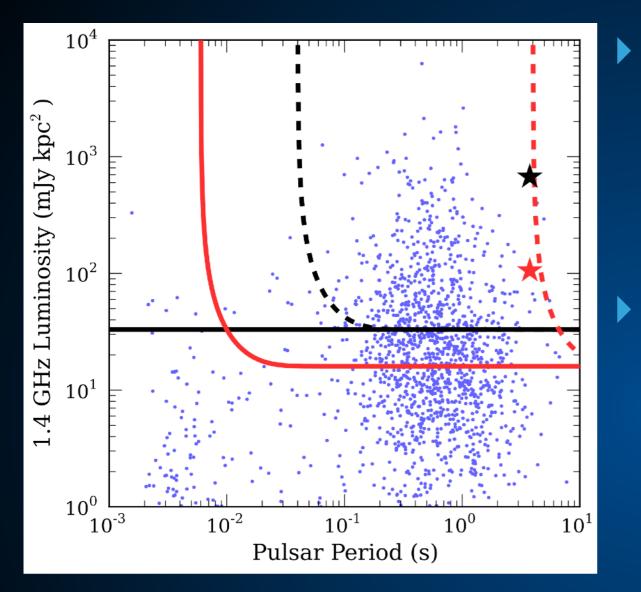
$$M_{crit}^{ferm} \simeq M_{pl}^3 / m_X^2$$

It then collapses on a timescale:

$$egin{split} & au_{
m co} \simeq rac{1}{n \sigma_{n {
m x}} v_{
m x}} \left(rac{p_F}{\Delta p}
ight) \left(rac{m_{
m x}}{2m_n}
ight) \ & \simeq 4 imes 10^5 \ {
m yrs} \left(rac{10^{-45} \ {
m cm}^2}{\sigma_{
m n {
m x}}}
ight) \left(rac{r_x}{r_0}
ight), \end{split}$$

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 !?

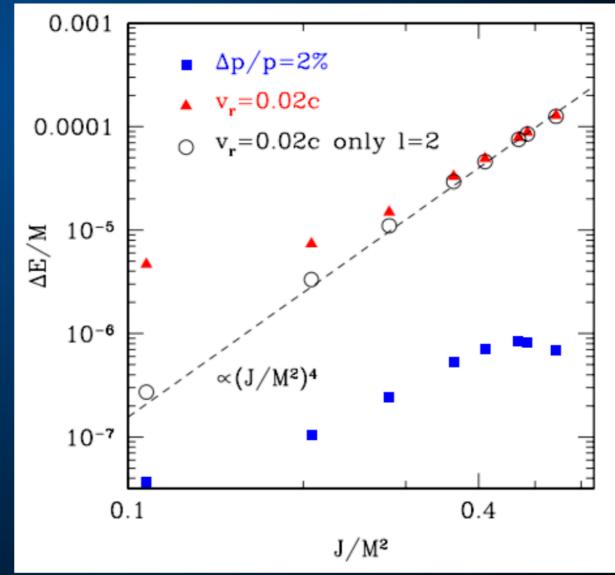
Gravitational Waves from NS Collapse

Gravitational Waves from DM induced collapse

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

- 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?)

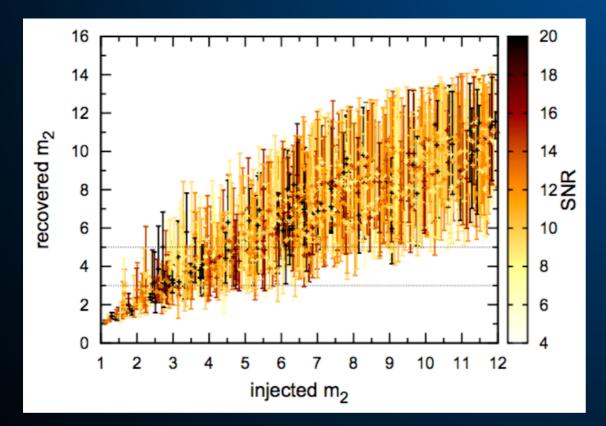
Baiotti et al. (gr-qc/0701043)

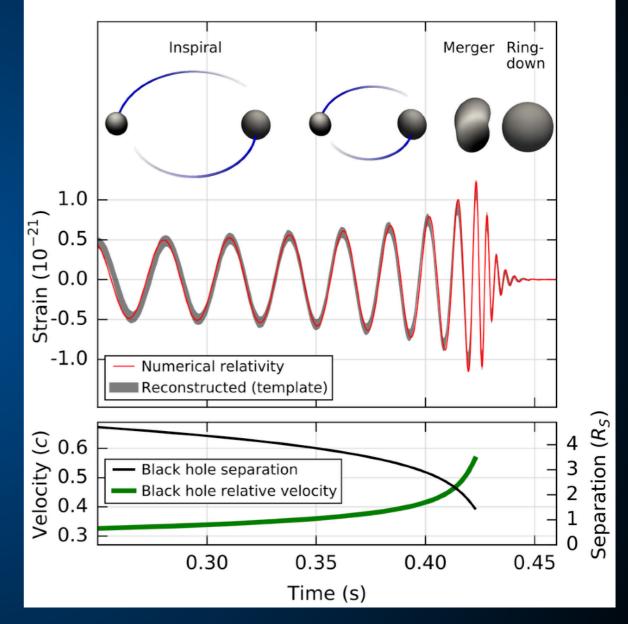


Differentiating Black Hole and NS Mergers

Anomalies in the tidal strain of binary neutron star mergers.

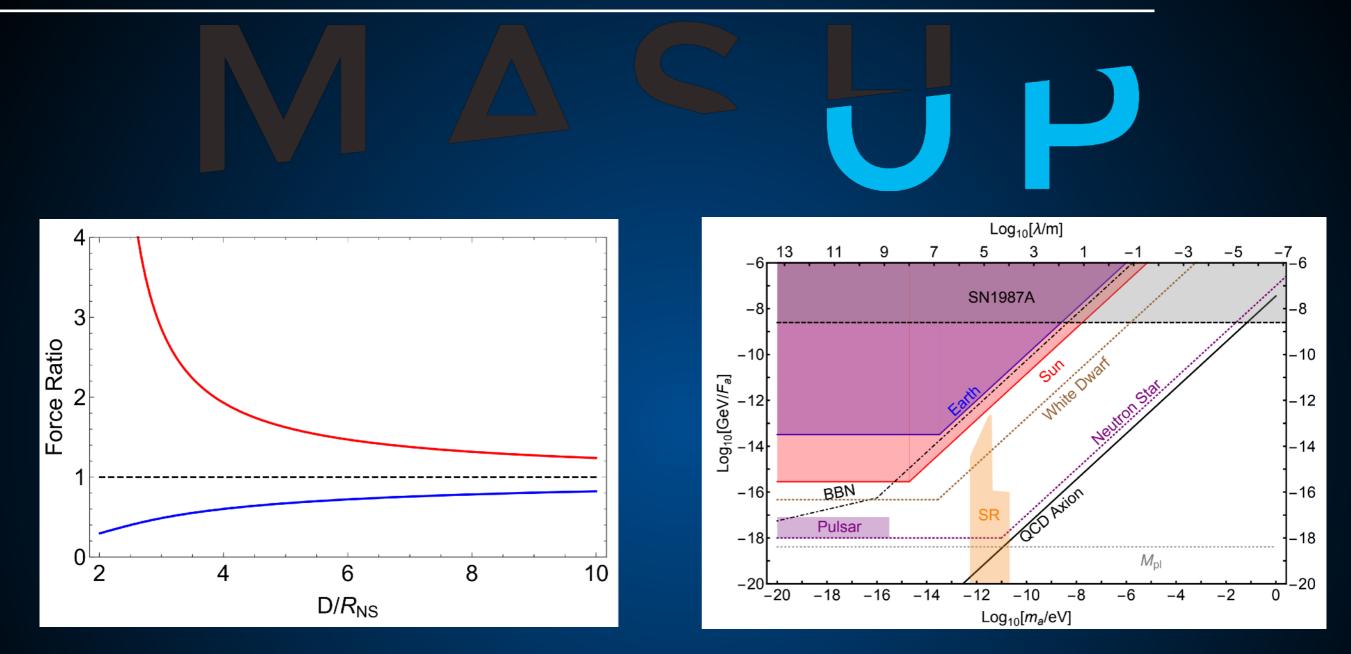
- DM induced NS collapse produces a population of 1.4 M_o black holes.
- Can potentially see differences in merger and ring-down, but not presently feasible.





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
	Physical baryon density parameter ^[a]	$\Omega_{\rm b} h^2$	0.022 30 ±0.000 14
	Physical dark matter density parameter ^[a]	$\Omega_{\rm c} h^2$	0.1188 ±0.0010
Indepen- dent	Age of the universe	t ₀	$13.799 \pm 0.021 \times 10^9$ years
para-	Scalar spectral index	ns	0.9667 ± 0.0040
meters	Curvature fluctuation amplitude, $k_0 = 0.002 \text{ Mpc}^{-1}$	Δ_R^2	$2.441 \stackrel{+0.088}{_{-0.092}} \times 10^{-9[17]}$
	Reionization optical depth	τ	0.066 ±0.012

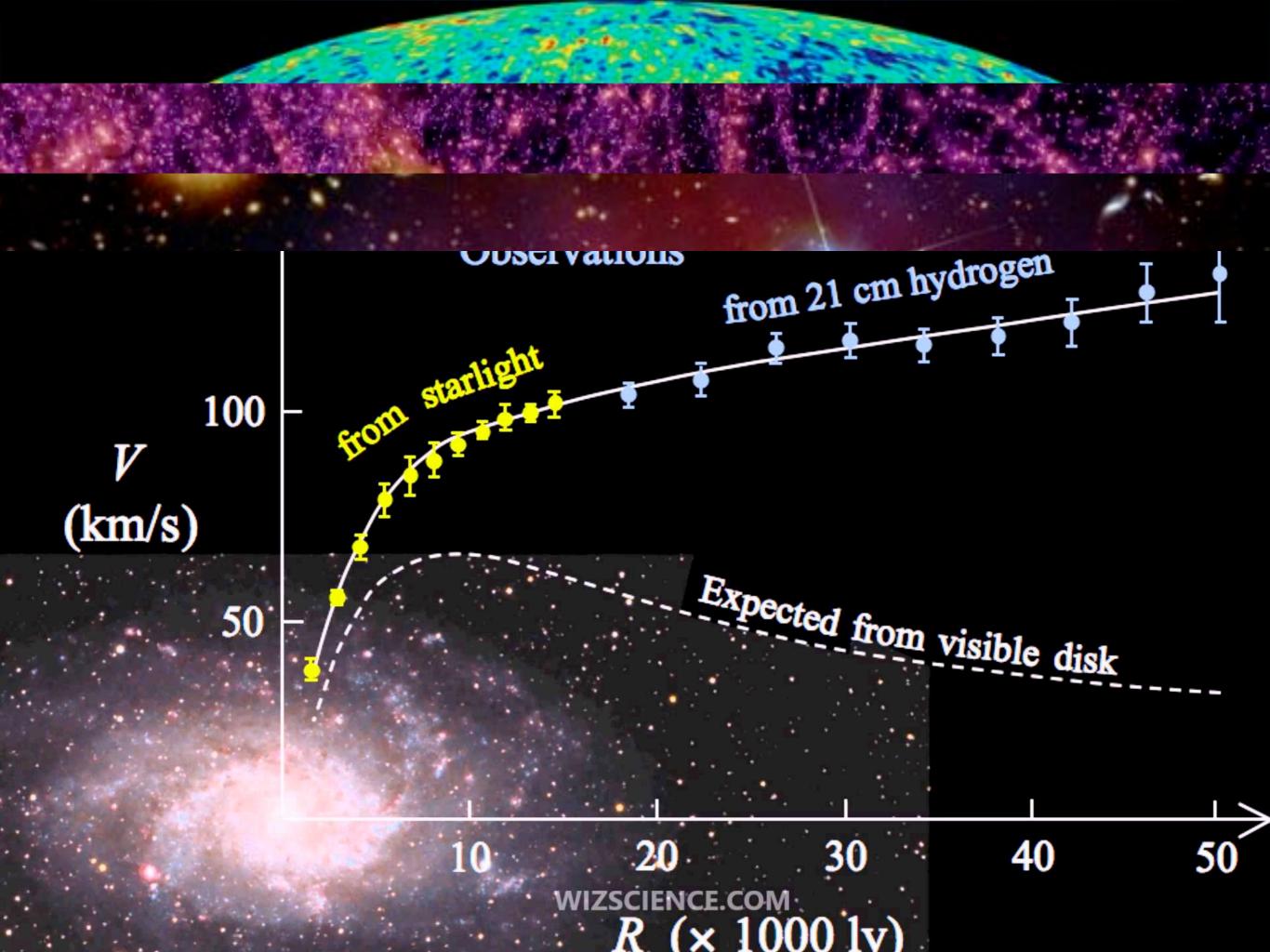
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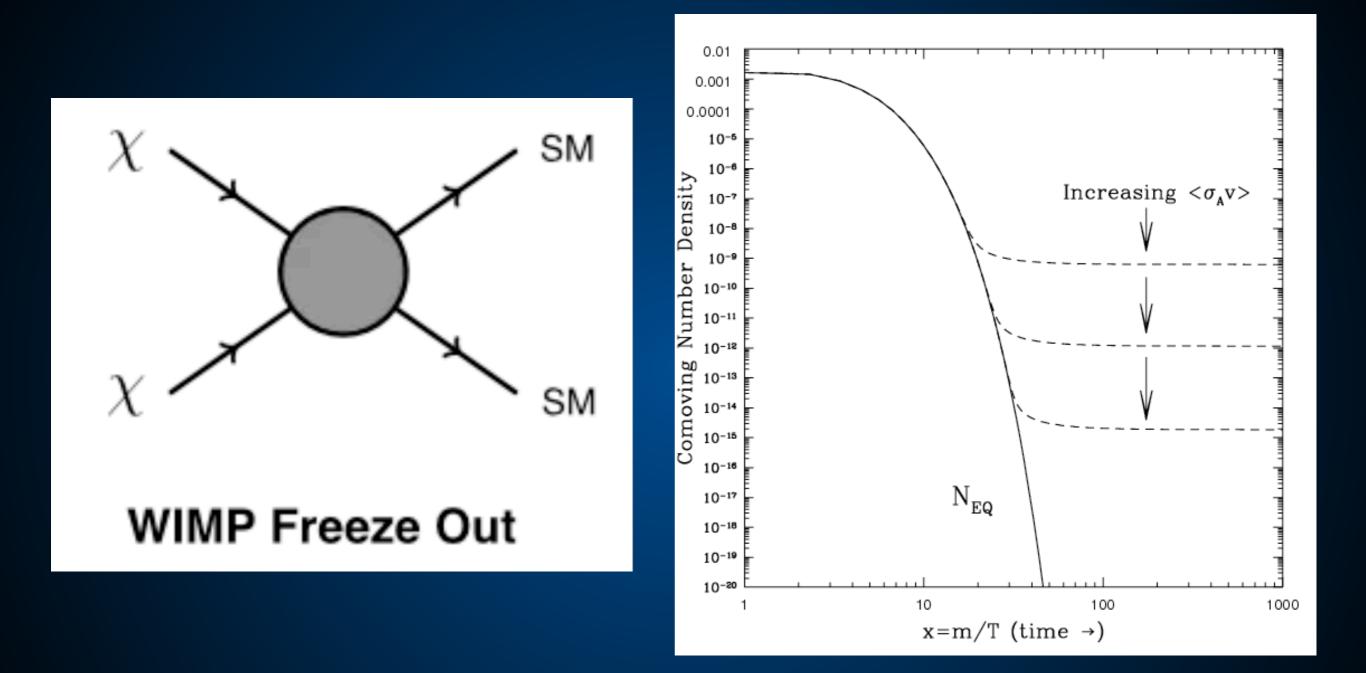
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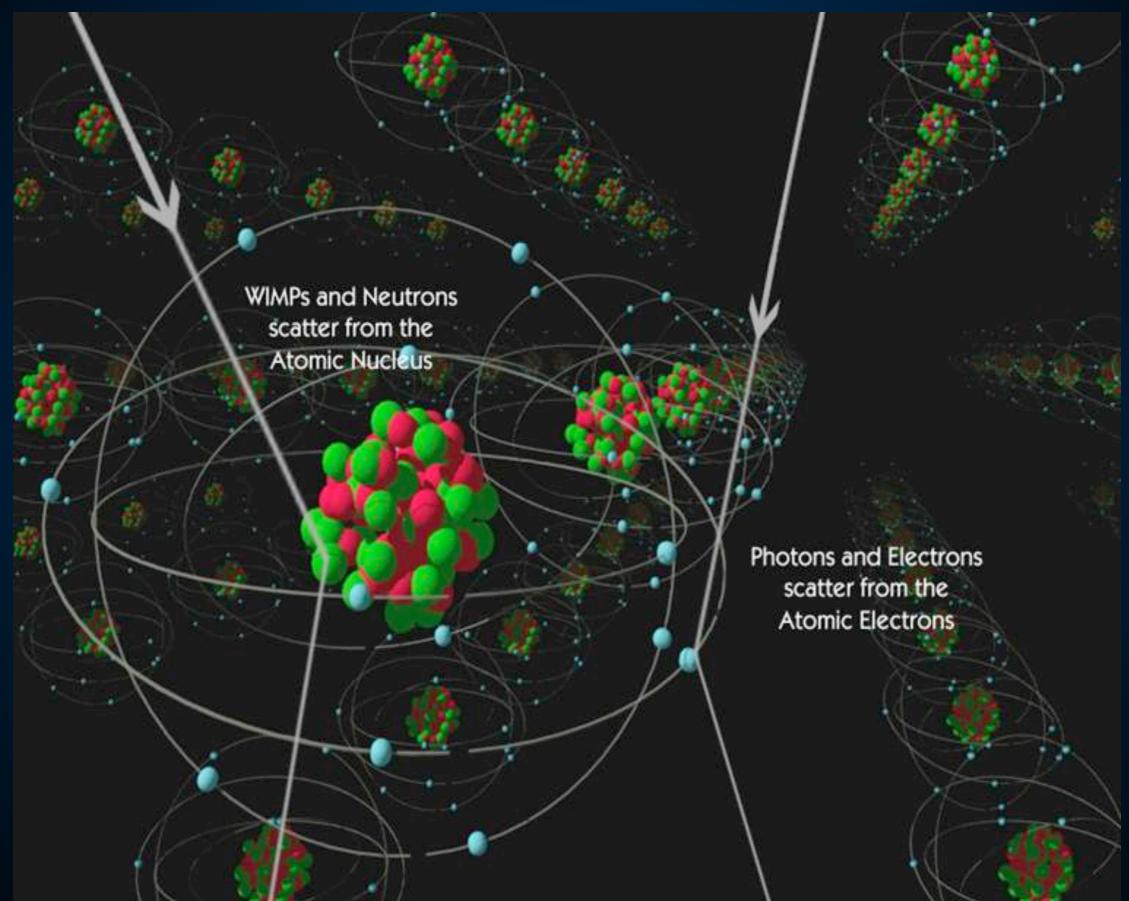


One Slide On WIMP Dark Matter

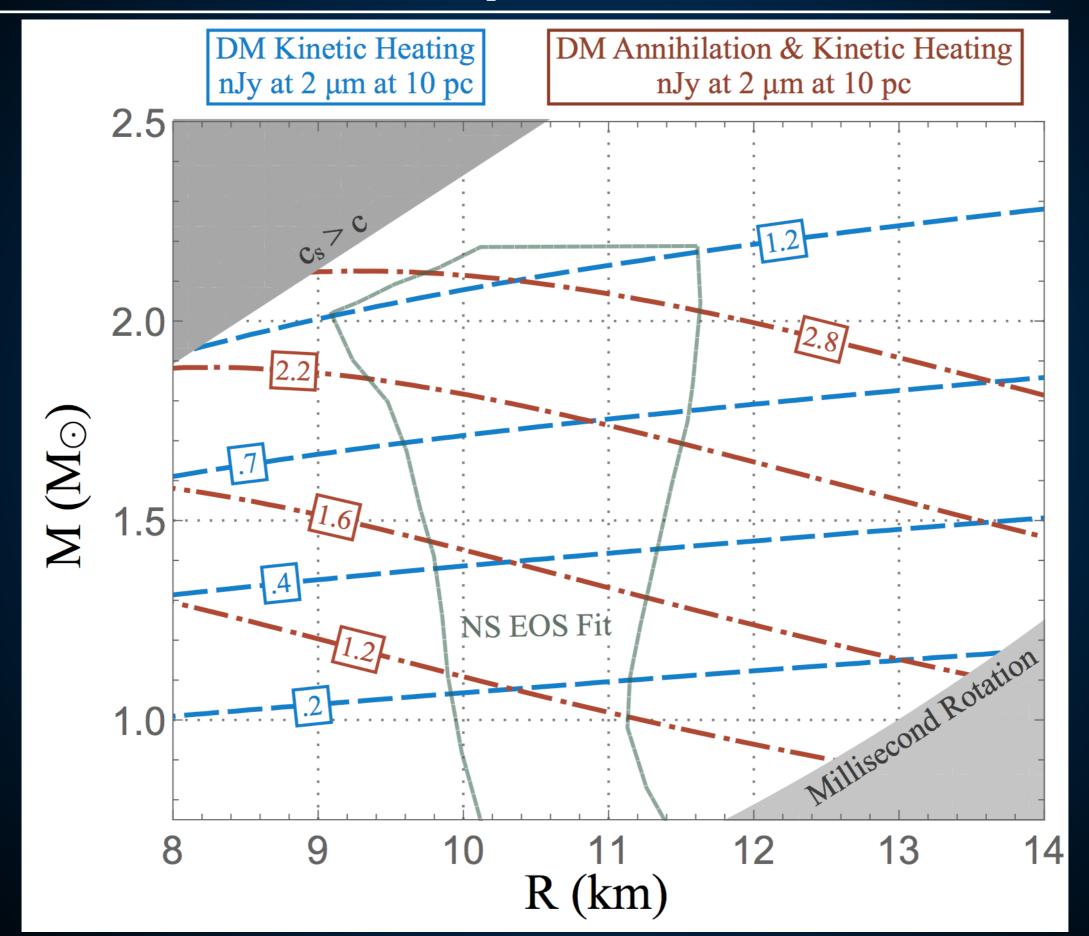


 The standard WIMP freeze-out scenario is still the bestmotivated model to explain the Dark Matter abundance.

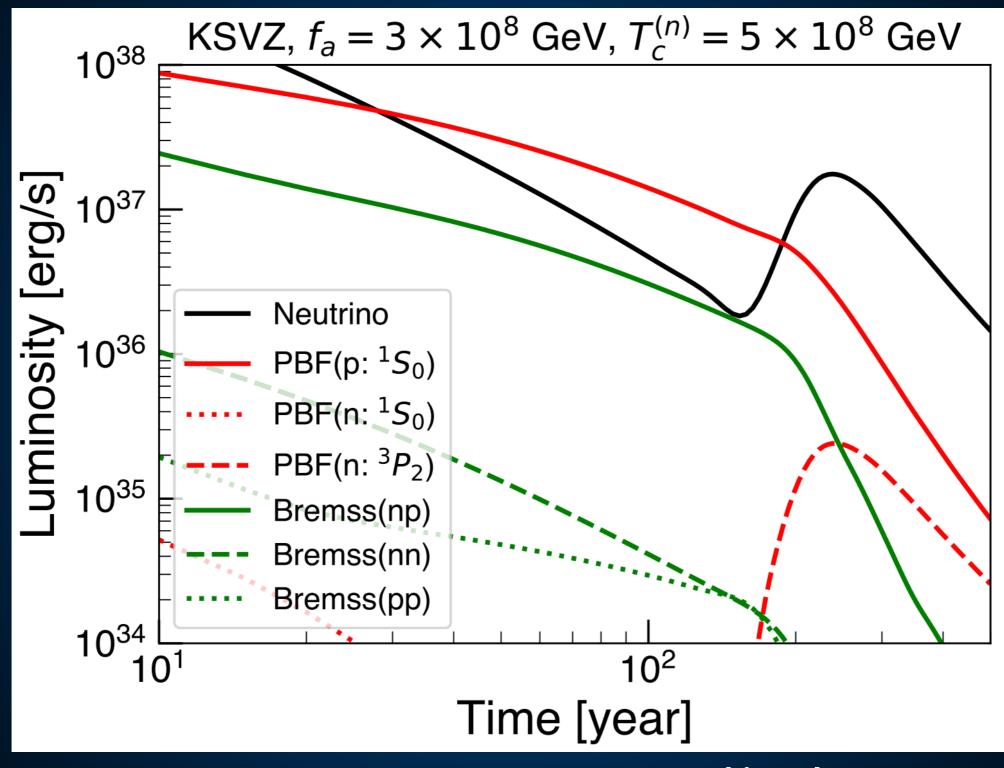
Direct Detection



Dark Matter Flux Depends on NS EOS



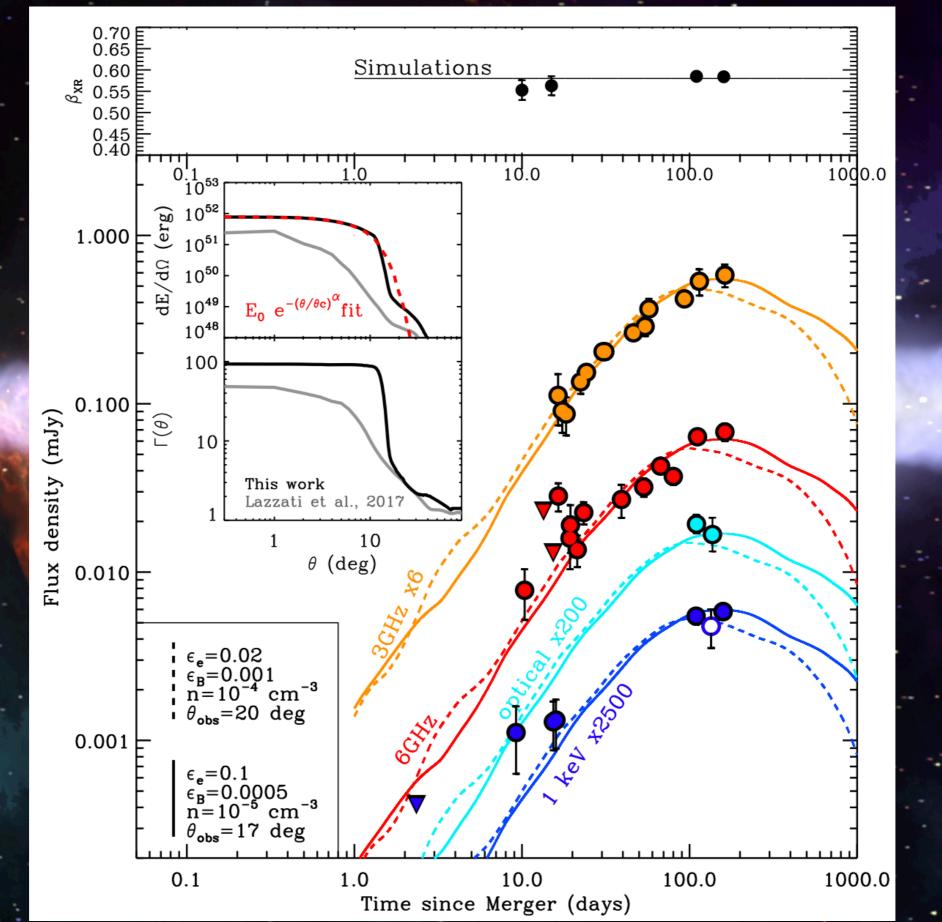
Axion and Neutrino Cooling in Neutron Stars



Hamaguchi et al. (1806.07151)

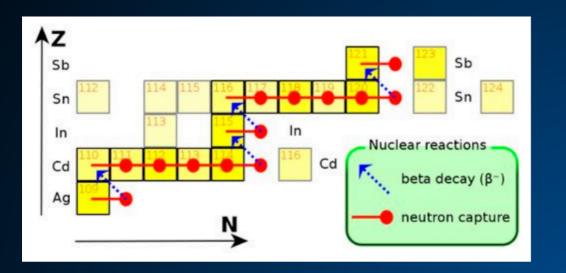
r-process Enrichment

<u>Margutti et al</u>. (1801.03531)

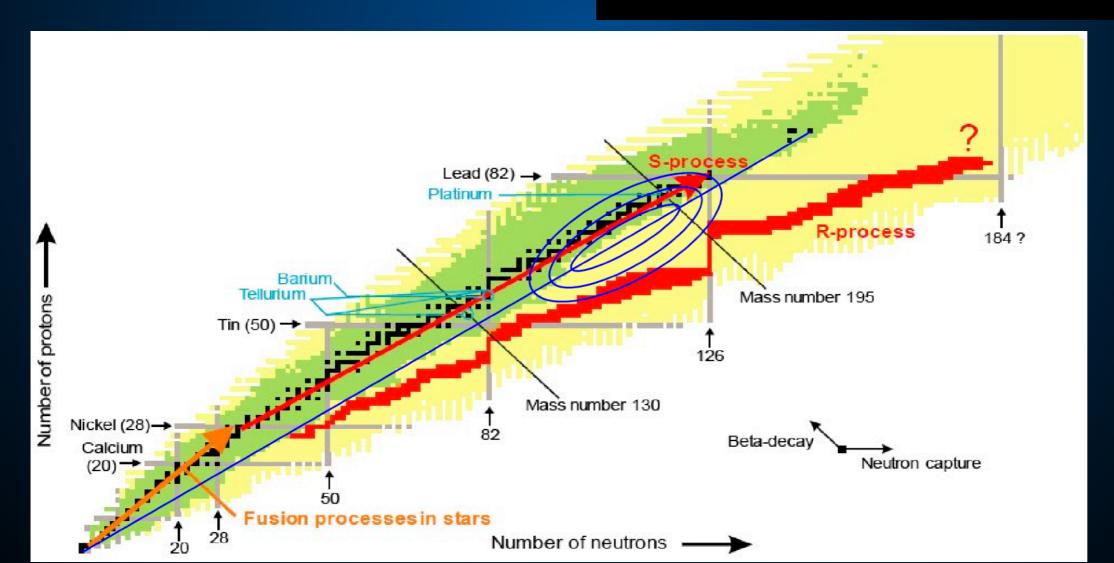


What is the r-process?

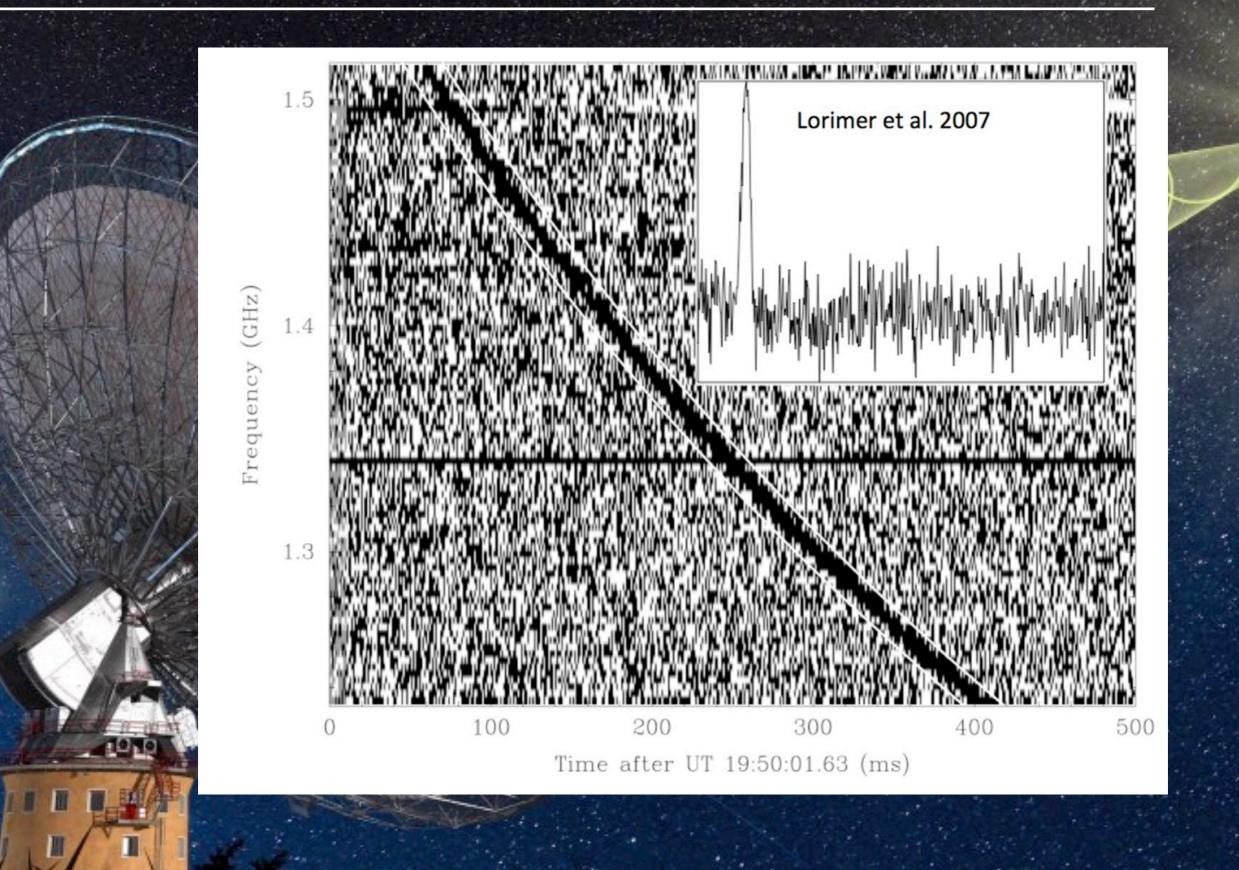
The Origin of the Solar System Elements



1 H		big	big bang fusion					cosmic ray fission									2 He
3 Li	4 Be	mer	merging neutron stars					exploding massive stars 📓					6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg	dyir	ng low	mass	stars	0	explo	exploding white dwarfs 🙋				13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 К	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 1	54 Xe
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 r	78 Pt	79 Au	80 Hg	81 TI	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra																
			57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
			La	Ce	Pr	Nd	Pm	Sm	Eu	Gđ	Tb	Dy	Но	Er	Tm	Yb	Lu
			89 Ac	90 Th	91 Pa	92 U											
hic cre	nic created by Jennifer Johnson													cal Im /AASN	0	redits	



Fast Radio Bursts



One More Slide on Axion Dark Matter

Axions proposed to solve the strong-CP problem

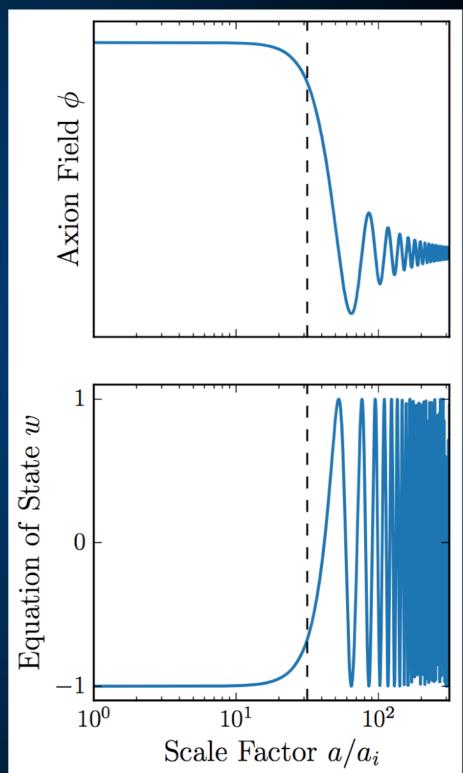
$$L_{\theta} = \theta \frac{g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu}$$

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

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

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).

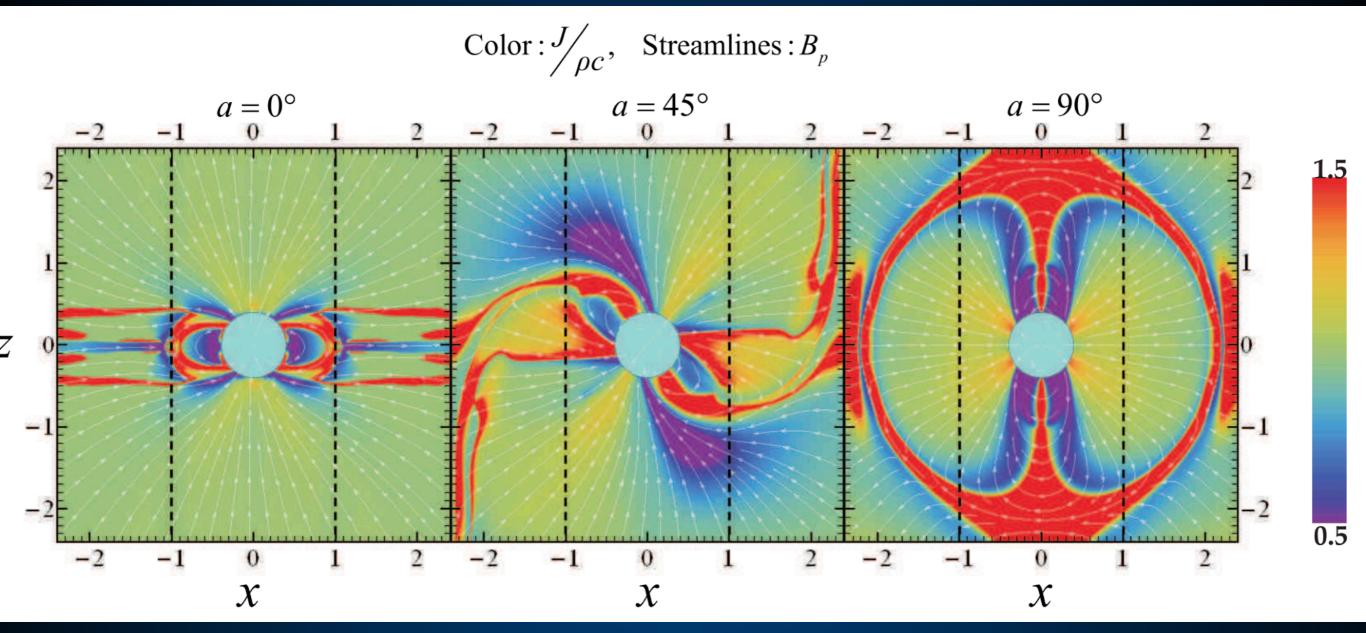
The low mass (high-fa) limit is set such that axions don't overclose the universe:

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

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

Massive Star Formation

in the Galactic Center

The Galactic center is a hotbed of star formation activity, containing the most massive young star clusters in the Galaxy. Given such The Galactic center is a hotbed of star formation activity containing the anxious massive young star clusters in the Galaxy. A start is containing more stars with initial masses above 100 Mo the assive star any with initial masses above 100 Mo the assive star any with any when a start with a start with a start with any when a start with a start formation site and three of the most massive young star of use of the falaxy. This review concerns the young star of uses in the Galaxy. This review concerns the young stellar population in the Galaxy. Given such as the young stellar population in the Galaxy. Given such as the young stellar population in the Galaxy and the Galaxy and the Galaxy. a rich environment, it contains more stars with initial masses above 100 Mo times to massive star formation in the region. The sample includes stars in the Galaxy with initial stars and the source of the sample includes stars are to mass the source of the sample includes stars are to mass the source of the sample includes stars are to mass the source of the sample includes stars in the same stars in the source of the same stars in the same stars else in the Galaxy. This review concerns the young stellar population in the region. The sample includes stage in the Galactic content of vormeer stars in the sample includes stage in the Galactic content of vormeer stars in the sample includes stage in the Galactic content of vormeer stars in the sample includes stage in the the same in the sample includes stage in the the same in the sample includes stage in the the same in the sample includes stage in the the same in the sample includes stage in the the same in the sample includes stage in the the same in the sample includes stage in the the same in the sample includes stage in the the same in the sample includes stage in the the same in th as it relates to massive star formation in the region. The sample includes stars in the population of younger stars in the present sites of stars in the present sites of star in the the the star in the present sites of star in the the star in the present sites of star in the the present sites of star in the the present sites of star in the the star in the present sites of star in the the star in the present sites of star in the the star in the present sites of star in the the star in the present sites of star in the the star in the present sites of star in the the star in the present sites of star in the star in the present sites of star in the star in the present sites of star in the star in the present sites of star in the star in the present sites of star in the star in the present sites of star in the star in the present sites of star in the star in the present sites of star in the star in the present sites of star in the star in the present sites of star in the star in the present sites of star in the star in the star in the star in the present sites of star in the star in the star in the present sites of star in the star in the star in the present sites of star in the star in the star in the present sites of star in the st

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)

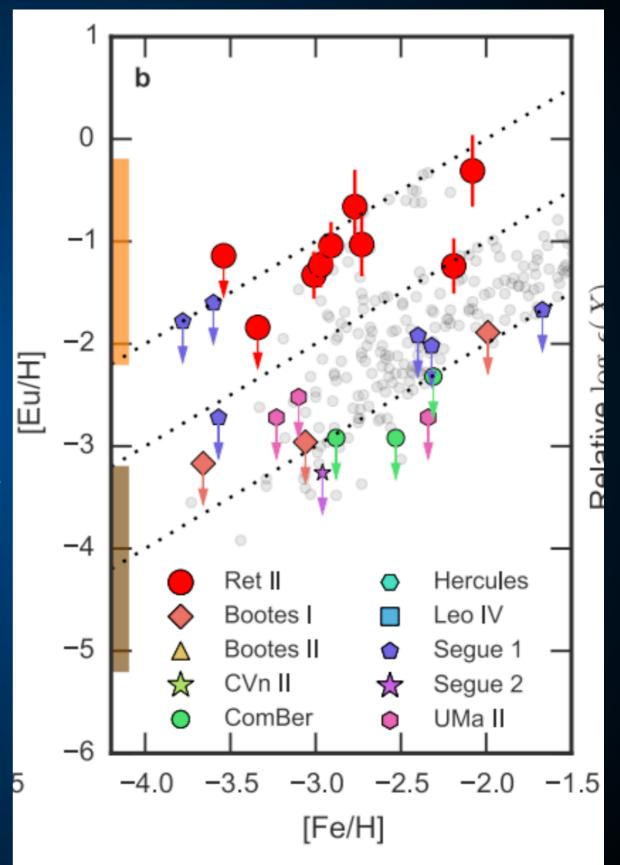
Dark matter accumulation rate scales inversely with velocity:

$$egin{split} \dot{m}_{\mathrm{x}} &= \pi
ho_{\mathrm{x}} rac{2GMR}{v_{\mathrm{x}}} \left(1 - rac{2GM}{R}
ight)^{-1} \ &\simeq rac{10^{26} \ \mathrm{GeV}}{\mathrm{s}} \left(rac{
ho_{\mathrm{x}}}{\mathrm{GeV/cm^3}}
ight) \left(rac{200 \ \mathrm{km/s}}{v_{\mathrm{x}}}
ight), \end{split}$$

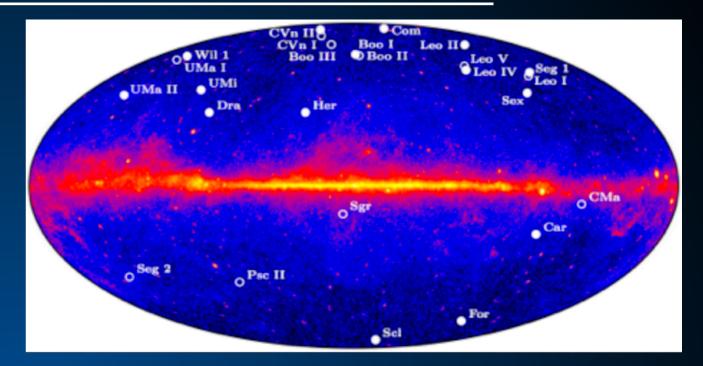
 Dwarf Spheroidal Galaxies are an optimal laboratory for asymmetric dark matter detection.

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

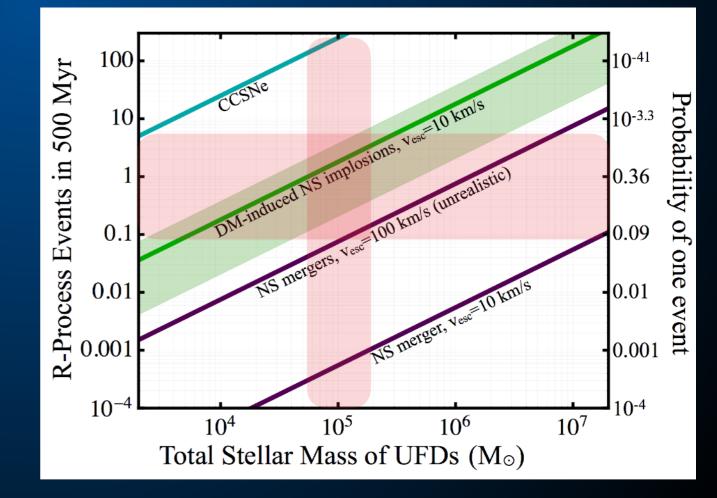
 Points to a rare formation channel (NS mergers)



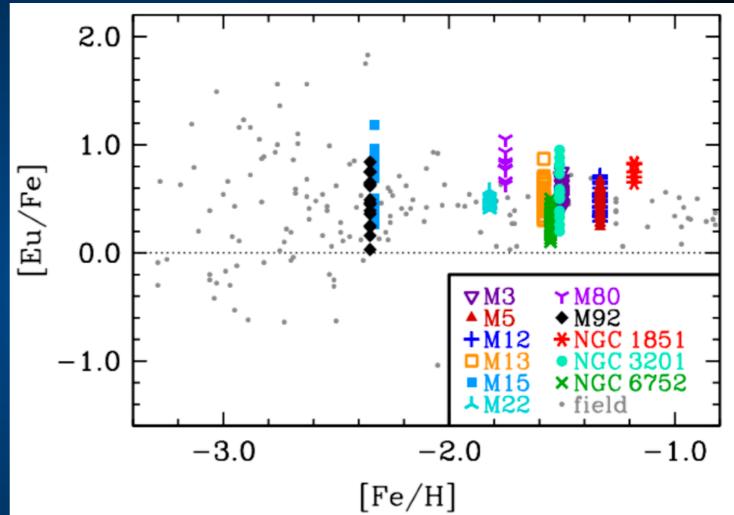
Normalize the nuclear cross-section to the missing pulsar problem.



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



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

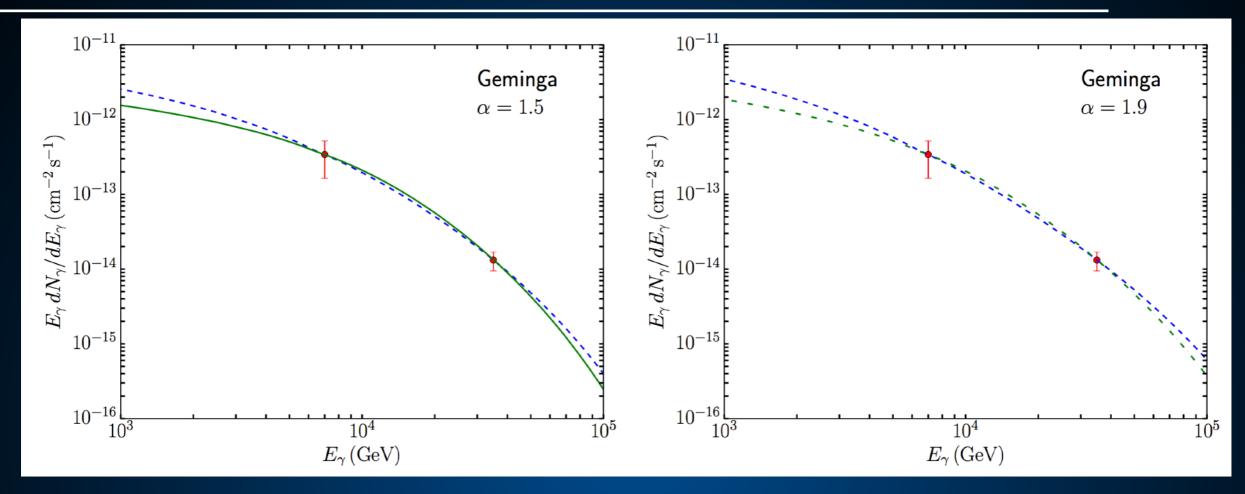


Roederer 2011 (1104.5056)

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

position dependent $M_{\rm DM} \propto \sigma_{\chi P} t_{\rm NS} \left(\frac{1}{V_{\chi}} \right)$ Particle physics timp (r) & Vy n Gry p.p. Model

Pulsars Produce the Positron Excess

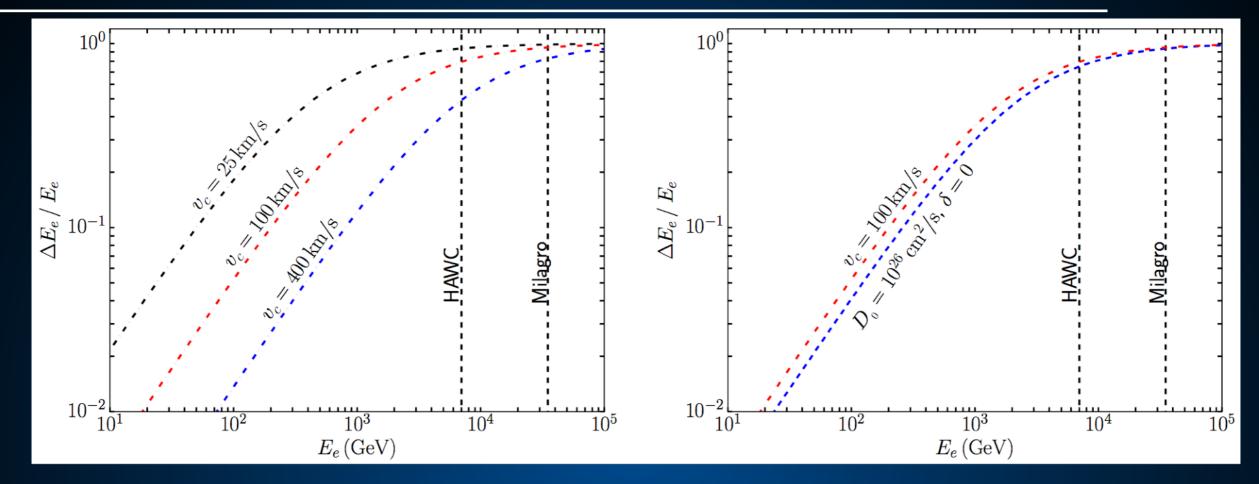


 Can calculate the gamma-ray spectrum necessary to fit the Geminga data from HAWC and Milagro

 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)

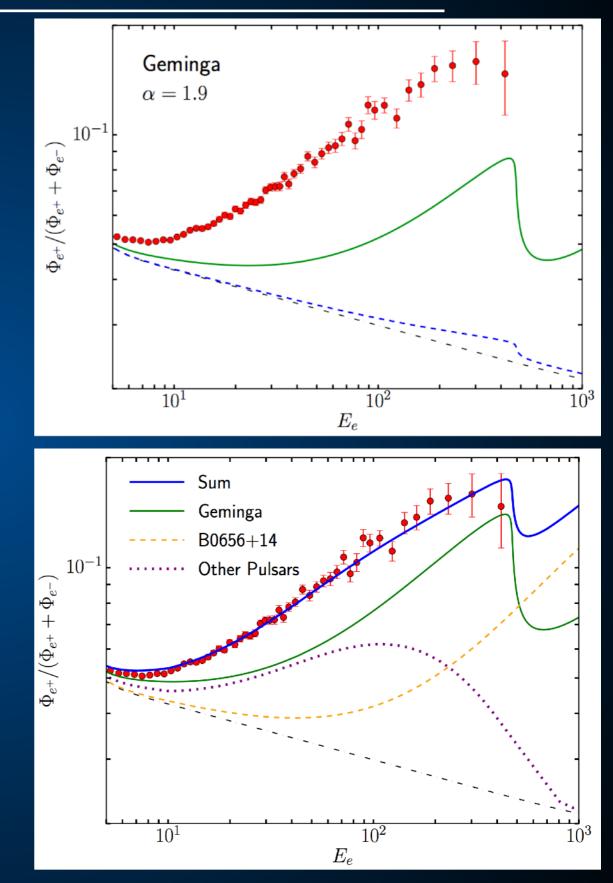
Pulsars Produce the Positron Excess

 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.

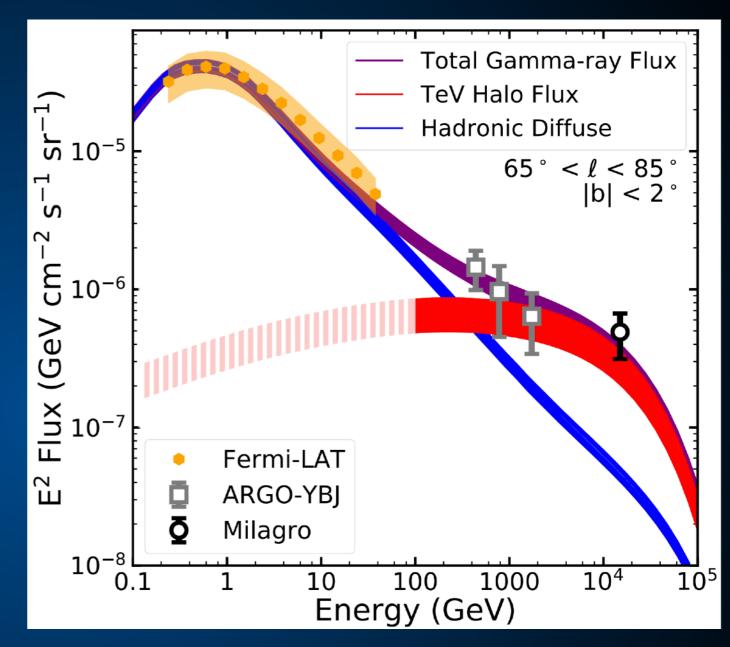
Hooper, Cholis, TL, Fang (1702.08436)



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.

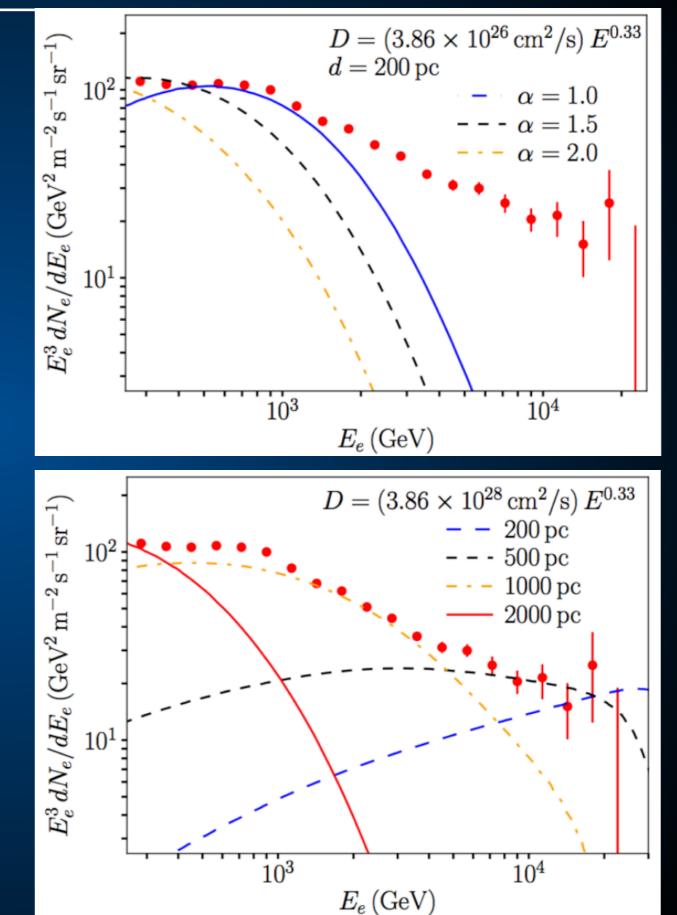


TL & Buckman (1707.01905)

 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!

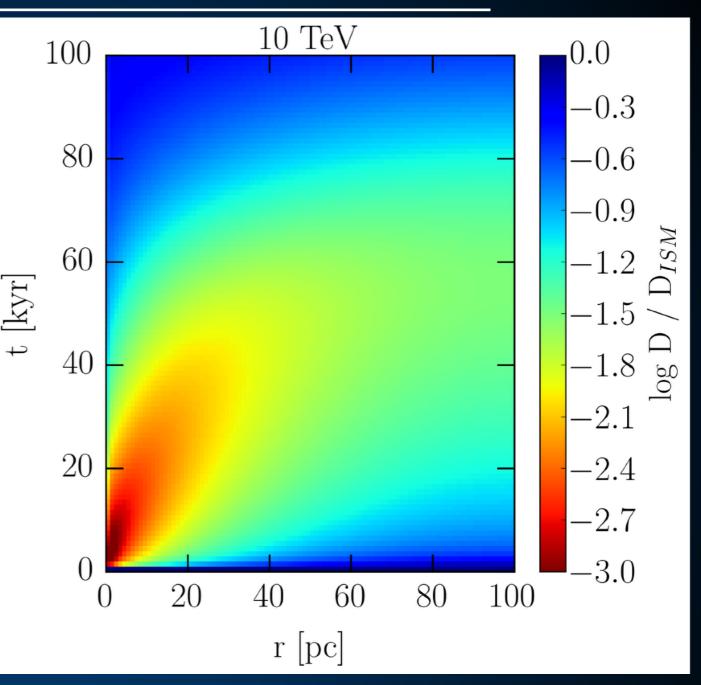


Hooper & TL (1711.07482)

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.

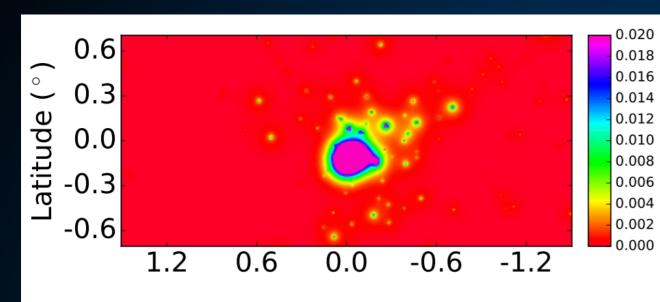
$$\Gamma_{\rm CR}(k) = \frac{2\pi}{3} \frac{c|v_A|}{k\mathcal{W}(k) U_0} \left[p^4 \frac{\partial f}{\partial z} \right]_{p_{\rm res}}$$

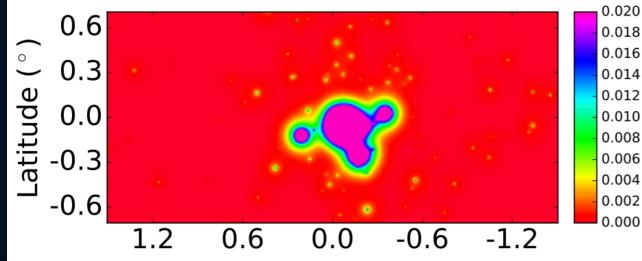


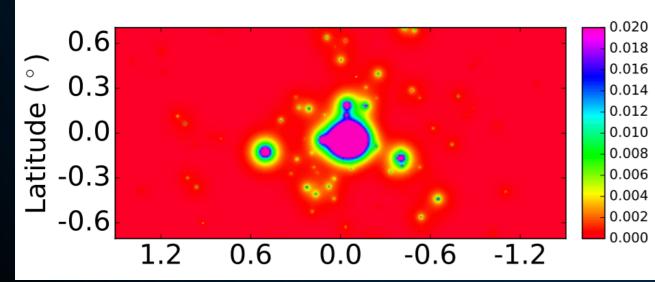
 These Alfven waves dominate cosmic-ray turbulence, because they are resonant with the electron energy leads to low diffusion

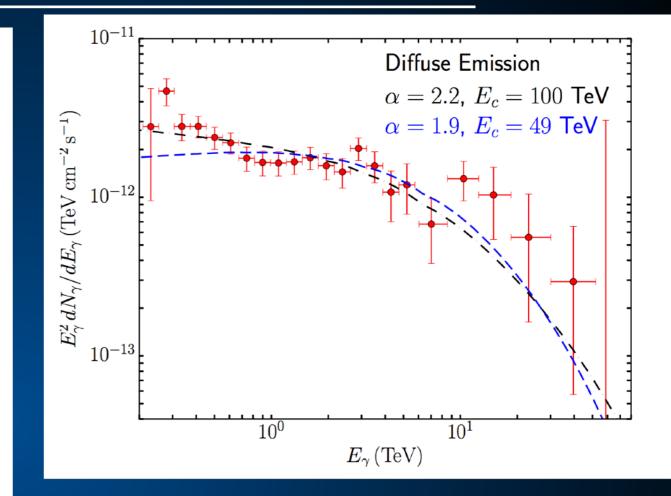
Evoli, TL & Morlino (TBS)

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)

One Slide on Axion Dark Matter

Axions proposed to solve the strong-CP problem

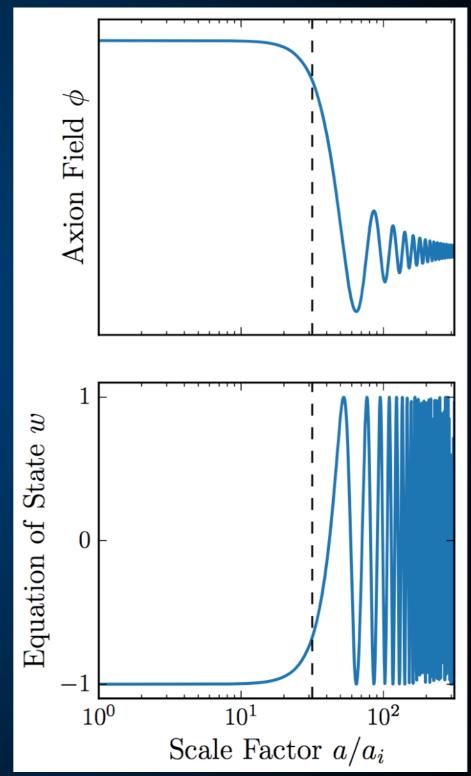
$$L_{\theta} = \theta \frac{g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu}$$

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

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

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

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



Marsh (2015; 1510.07633)