TIM LINDEN

ASTROPHYSICAL SIGNATURES OF DARK MATTER ACCUMULATION IN NEUTRON STARS

The Ohio State University - HEP/HET Seminar

November 20, 2017

THE OHIO STATE UNIVERSITY
CENTER FOR COSMOLOGY AND
ASTROPARTICLE PHYSICS

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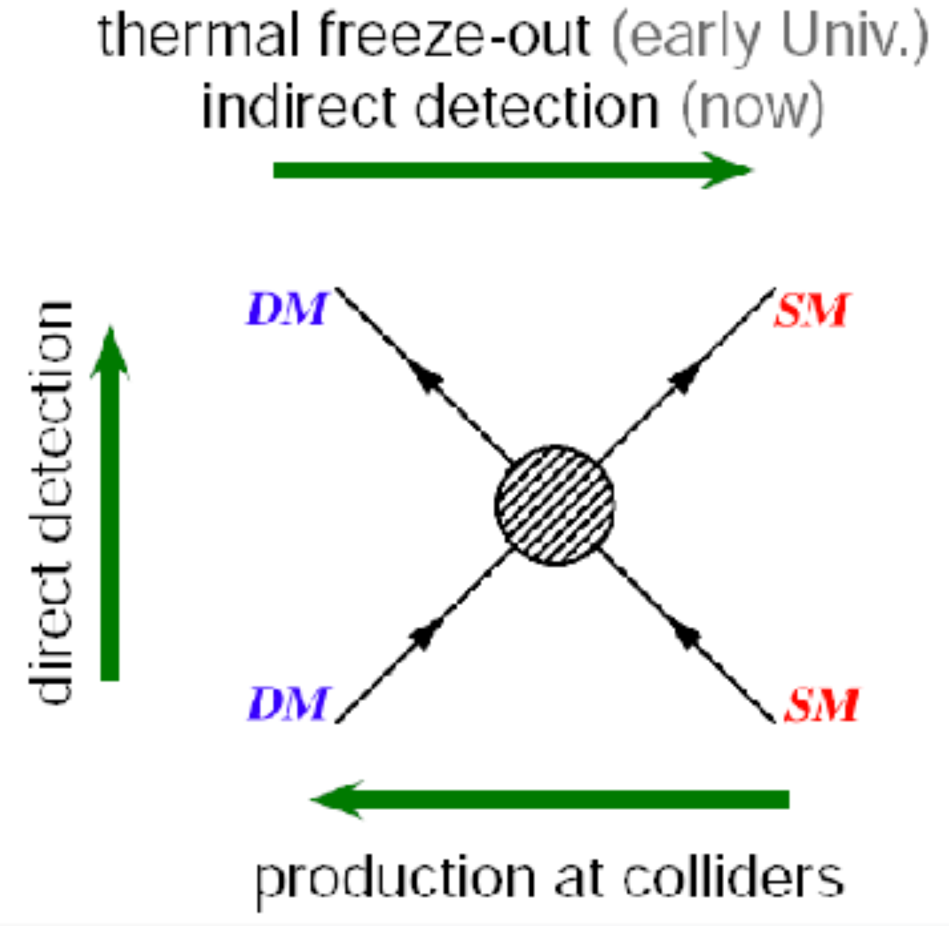
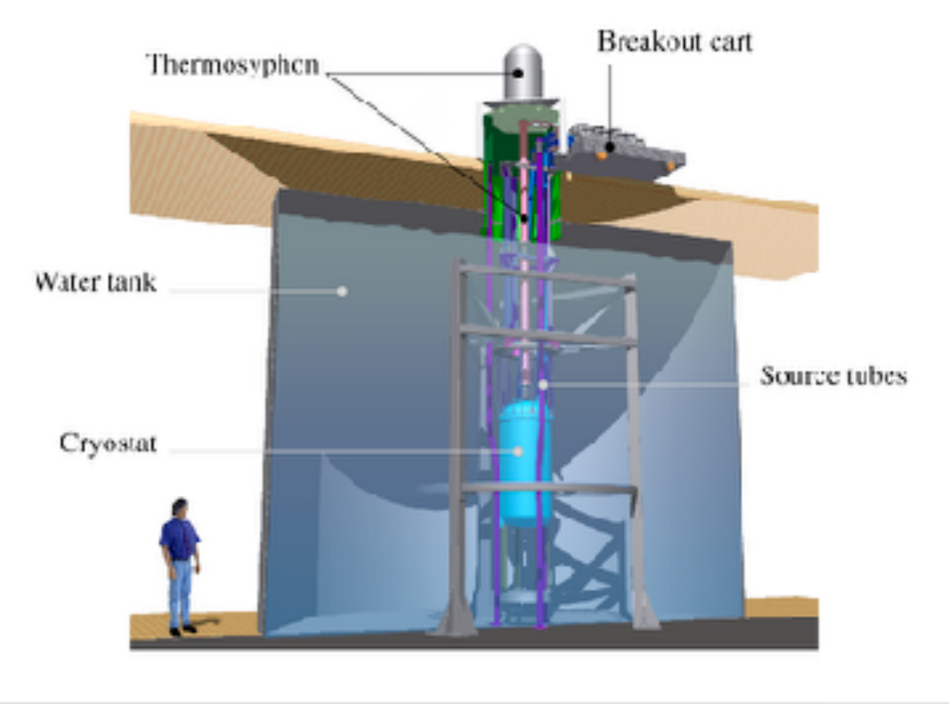
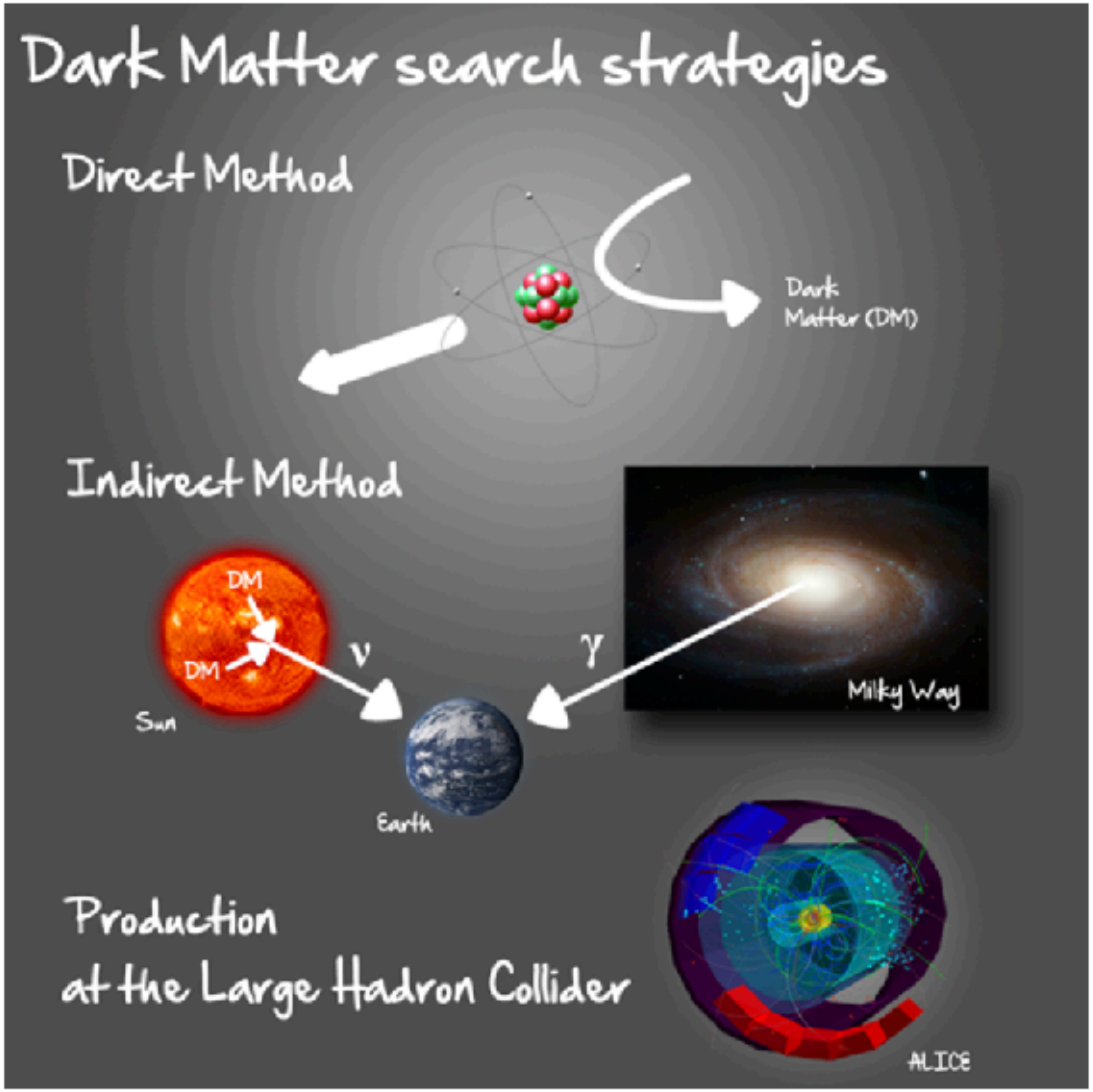
DARK MATTER DIRECT DETECTION

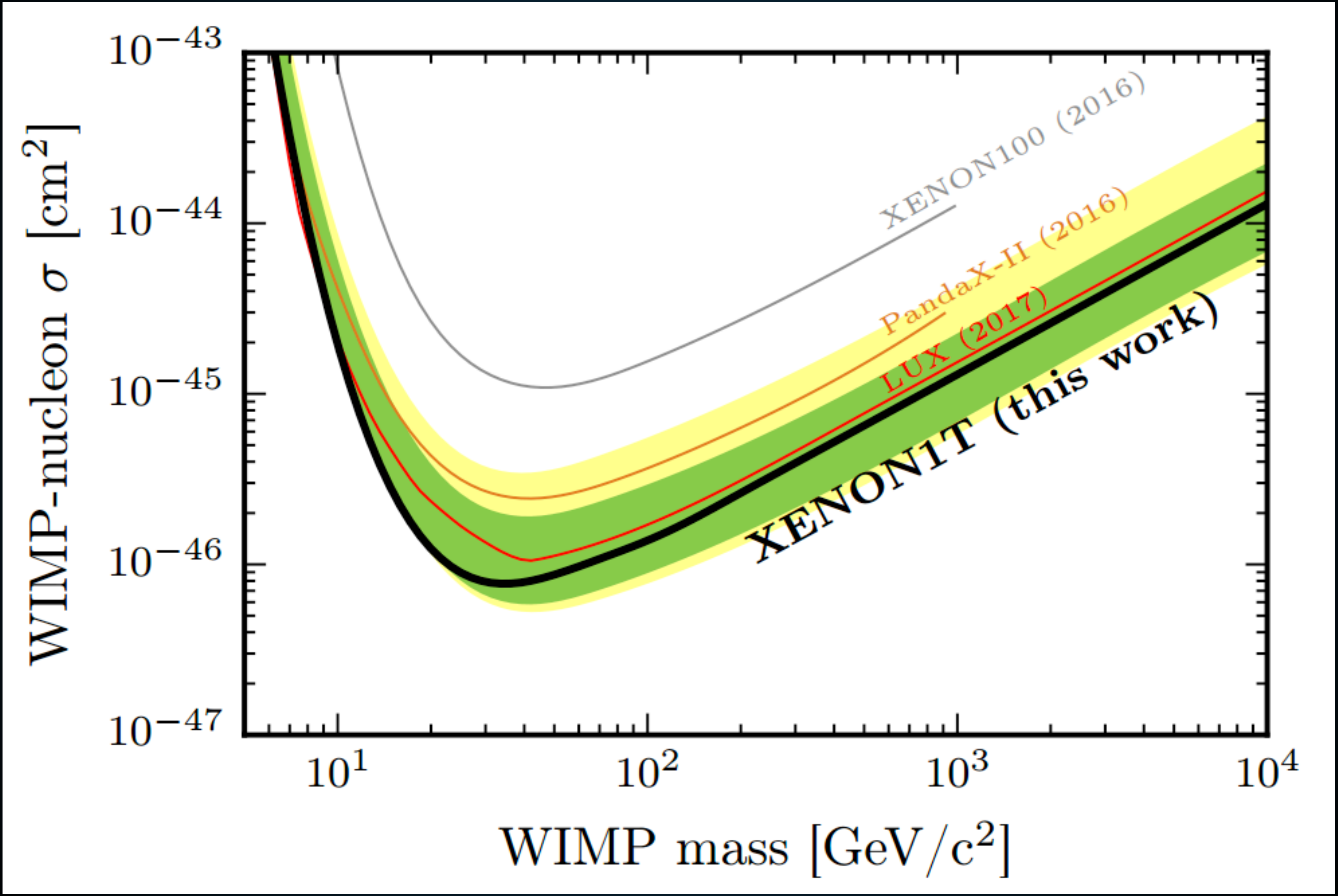






How to detect dark matter (credit: HAP / A. Chantelauze)

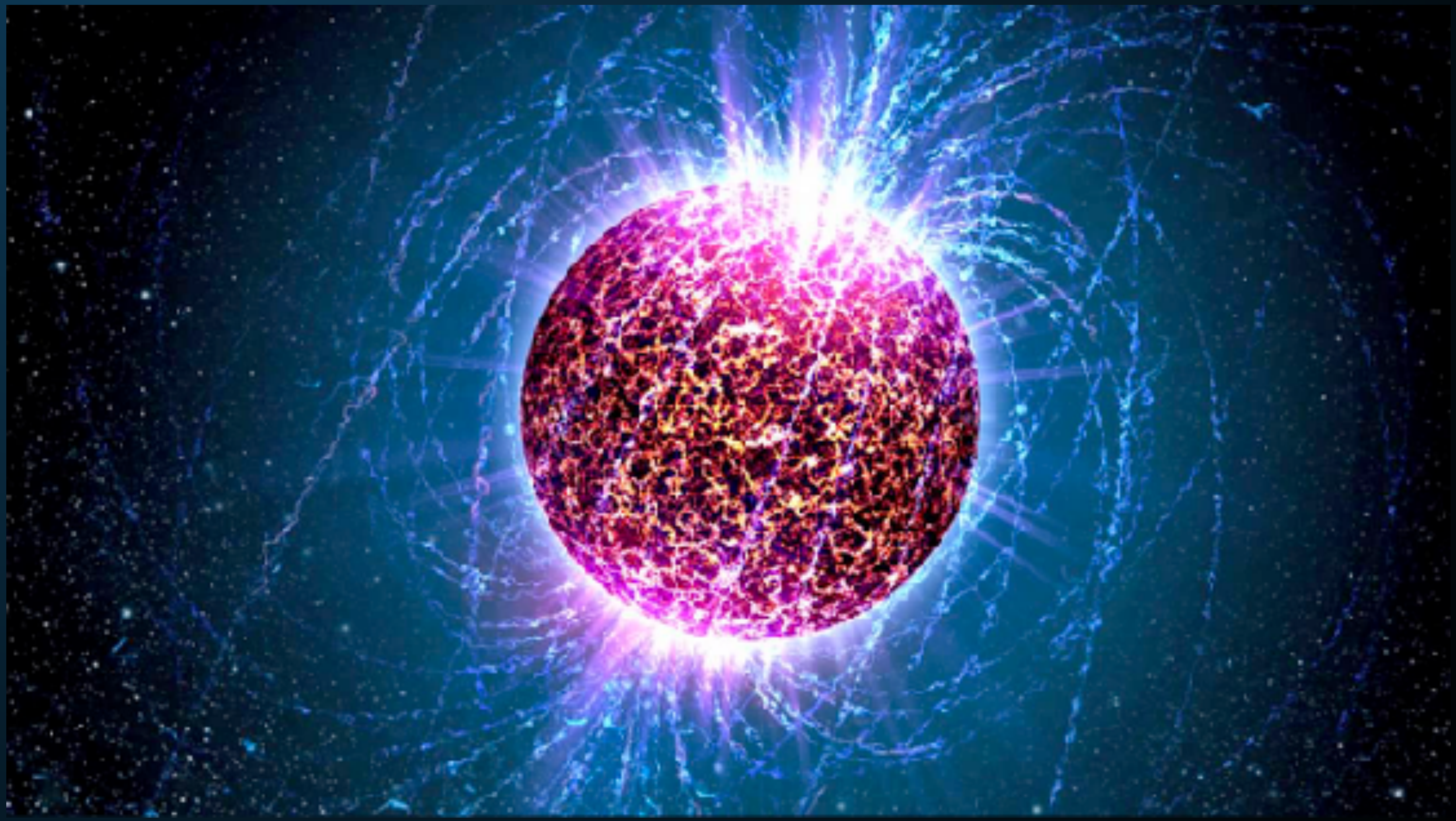
DARK MATTER DIRECT DETECTION



NEUTRON STARS AS DIRECT DETECTION LABORATORIES

- Xenon1T
  - 1000 kg
  - 730 day
- 7.3×10^{5} kg day

- Neutron Star
  - 2.8×10^{30} kg
  - 1.8×10^{10} day
- 5.0×10^{40} kg day



NEUTRON STARS AS DIRECT DETECTION LABORATORIES

- **Neutron stars are sensitive to very small interaction cross-sections:**

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

- **This saturates the sensitivity of neutron stars as dark matter detectors. Do not get additional sensitivity to higher cross-sections (in general).**

NEUTRON STARS AS DIRECT DETECTION LABORATORIES

Goal: Become sensitive to single dark matter nucleon scattering events in an energetic 1 $M_\odot$ neutron star that is 300 light years away.

NEUTRON STARS AS DIRECT DETECTION LABORATORIES

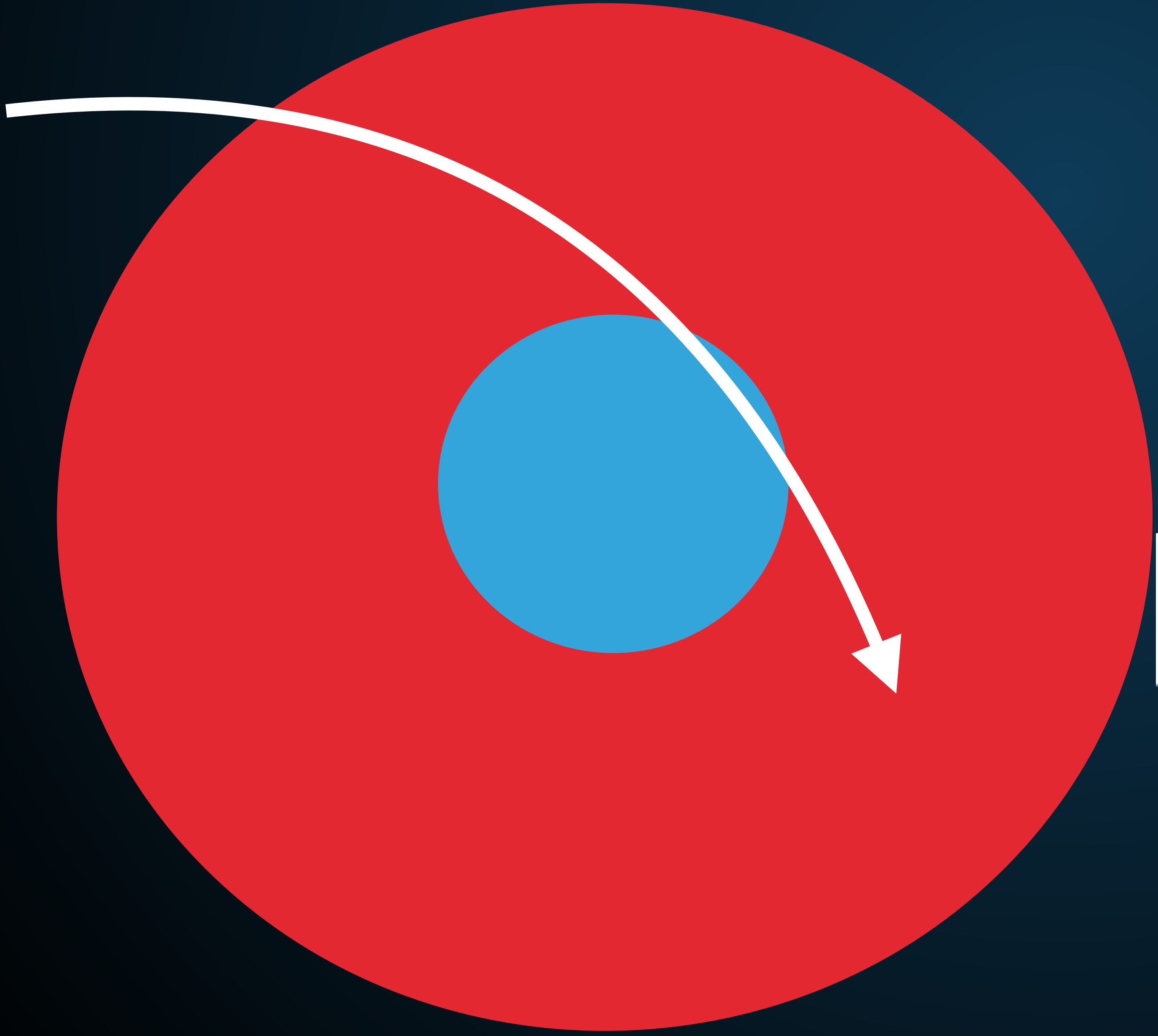
Reasonable Goal: Produce observations that would be sensitive to ~10^{35} dark matter neutron star interactions over the history of the universe.

DARK MATTER ACCUMULATION IN NEUTRON STARS

- Three Stages of Dark Matter Accumulation:
  - Dark Matter Capture
    - DM hits neutron and elastically scatters
  - Dark Matter Thermalization
    - Trapped dark matter interacts with nucleon fluid and achieves temperature equilibrium.
  - Dark Matter Collapse
    - Dark matter degeneracy pressure not capable of preventing collapse.

CAPTURE: ASTROPHYSICAL ENHANCEMENTS

- Two enhancements:
  - NS gravitational potential well
  - Regions with high dark matter density



Potential well moves slowly moving dark matter particles into collisional orbit.

Interaction rate scales as v_X^{-1}.

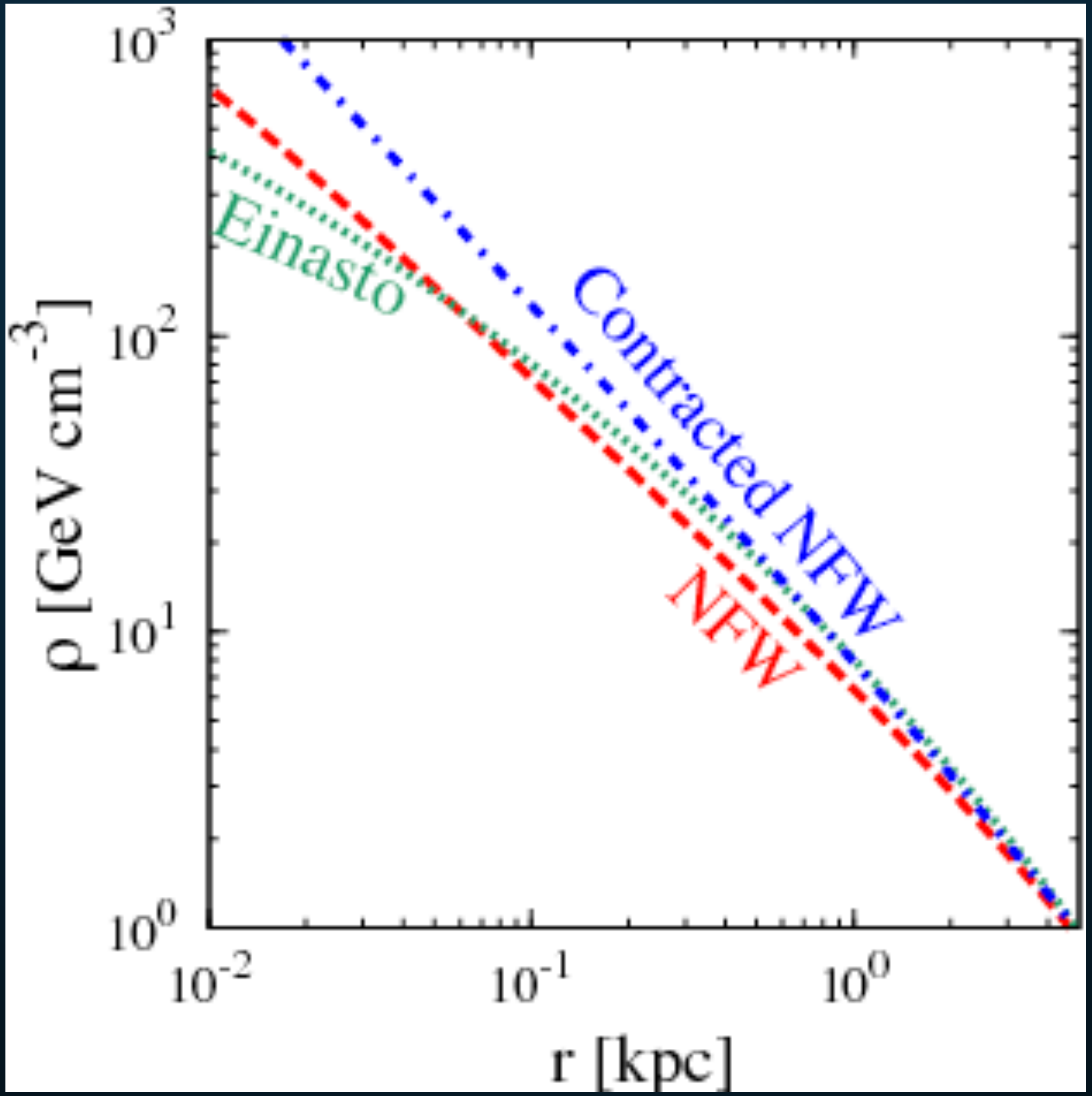
$$b_{\max} = \left(\frac{2GMR}{v_{\mathrm{x}}^2}\right)^{1/2}\left(1-\frac{2GM}{R}\right)^{-1/2}$$

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

CAPTURE: ASTROPHYSICAL ENHANCEMENTS

Iocco et al. (2015;1502.03821)

- **Two enhancements:**
  - **NS gravitational potential well**
  - **Regions with high dark matter density**



CAPTURE: PARTICLE PHYSICS ENHANCEMENTS

- Two enhancements:
    - Interactions are relativistic (p-wave)
    - Spin-Dependent Interactions

Neutron Stars are a dark matter collider:

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

Dark Matter interacts with a neutron star relativistically

Can probe p-wave suppressed or mass-split (e.g. Higgsino) DM

CAPTURE: PARTICLE PHYSICS ENHANCEMENTS

- Two enhancements:
  - Interactions are relativistic (p-wave)
  - Spin-Dependent Interactions

Models of Neutron Star equations of state indicate that the majority of the NS mass is composed of individual neutrons.

No difference between spin-independent and spin-dependent interactions.

CAPTURE: PARTICLE PHYSICS IMPEDIMENTS

- **Two impediments to dark matter interactions:**
  - **Pauli Blocking (low-mass dark matter)**
  - **Dark Matter Capture (high-mass dark matter)**

Dark Matter scattering imparts a momentum:

$$\delta p \sim \gamma m_{\mathrm{x}} v_{\mathrm{esc}},$$

Typical NS proton momentum is:

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

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

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

CAPTURE: PARTICLE PHYSICS IMPEDIMENTS

- Two impediments to dark matter interactions:
  - Pauli Blocking (low-mass dark matter)
  - Dark Matter Capture (high-mass dark matter)

Dark Matter energy lost in a scatter with a GeV proton is approximately:

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

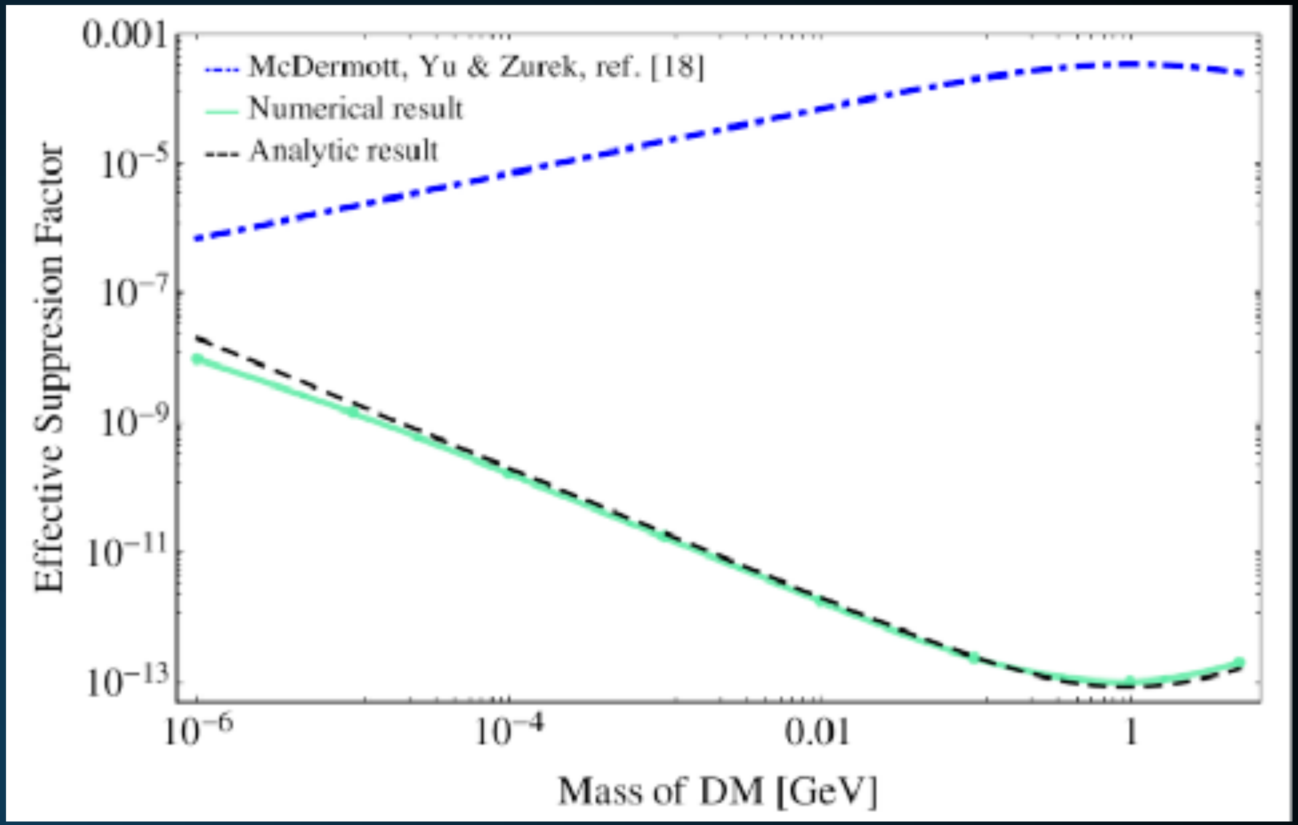
If this is smaller than the DM kinetic energy at infinity the dark matter will not remain bound after a single interaction:

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

THERMALIZATION

Bertoni et al. (2013; 1309.1721)

- **Dark Matter thermalization is always suppressed by Pauli blocking.**
- **Analytical and numerical models have very different predictions.**



- **However, if DM is trapped within the NS, interactions are still inevitable, and dark matter thermalizes on a significantly smaller timescale than DM capture:**

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

COLLAPSE

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

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

  - It then collapses on a timescale:

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

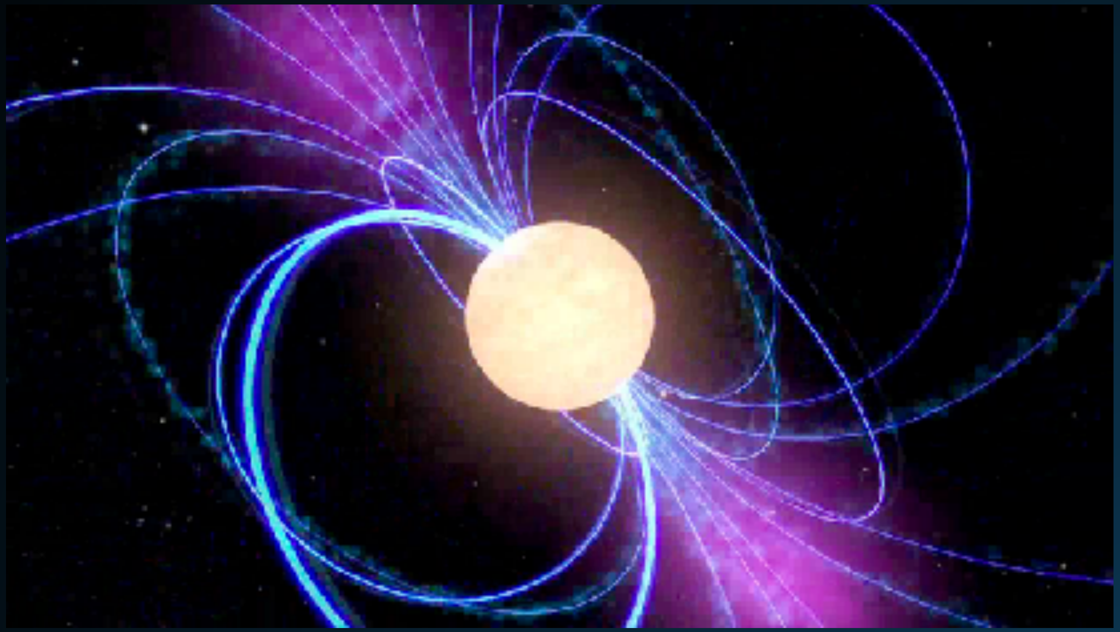
LOTS OF DARK MATTER MODELS (NO DETAILS HERE)

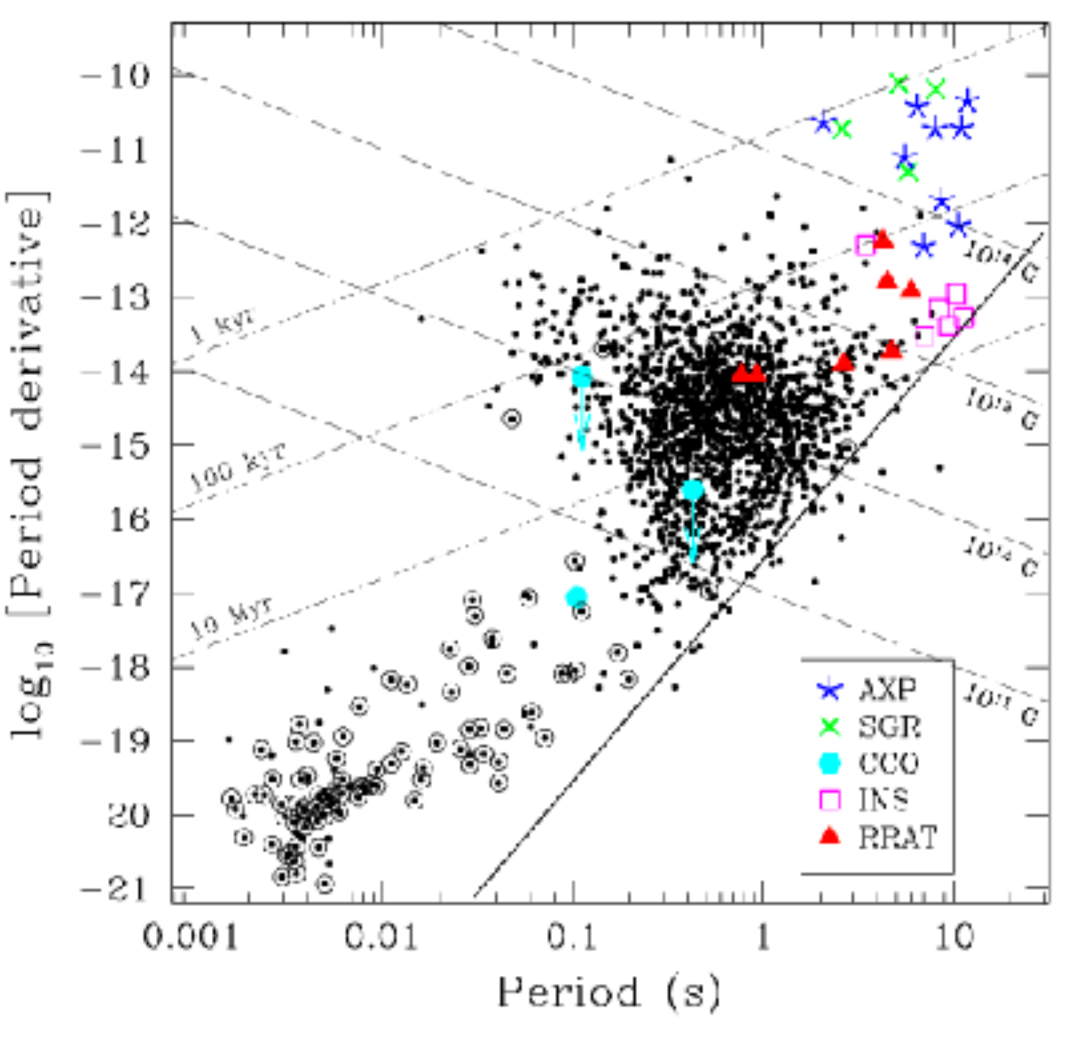
- Asymmetric Dark Matter is well-motivated
  - e.g. Baryon/Lepton Asymmetry through dark baryogengesis
- Some models do not work, e.g. GeV Fermions require ~1 $M_\odot$ of dark matter to be accreted

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

- Many models do work:
  - PeV Fermionic DM (~10^{-10} $M_\odot$)
  - Bosonic DM (MeV - PeV) with small quartic
  - MeV-PeV DM with attractive potential (e.g. Scalar Higgs Portal)

PROBLEM: WE SEE OLD NEUTRON STARS



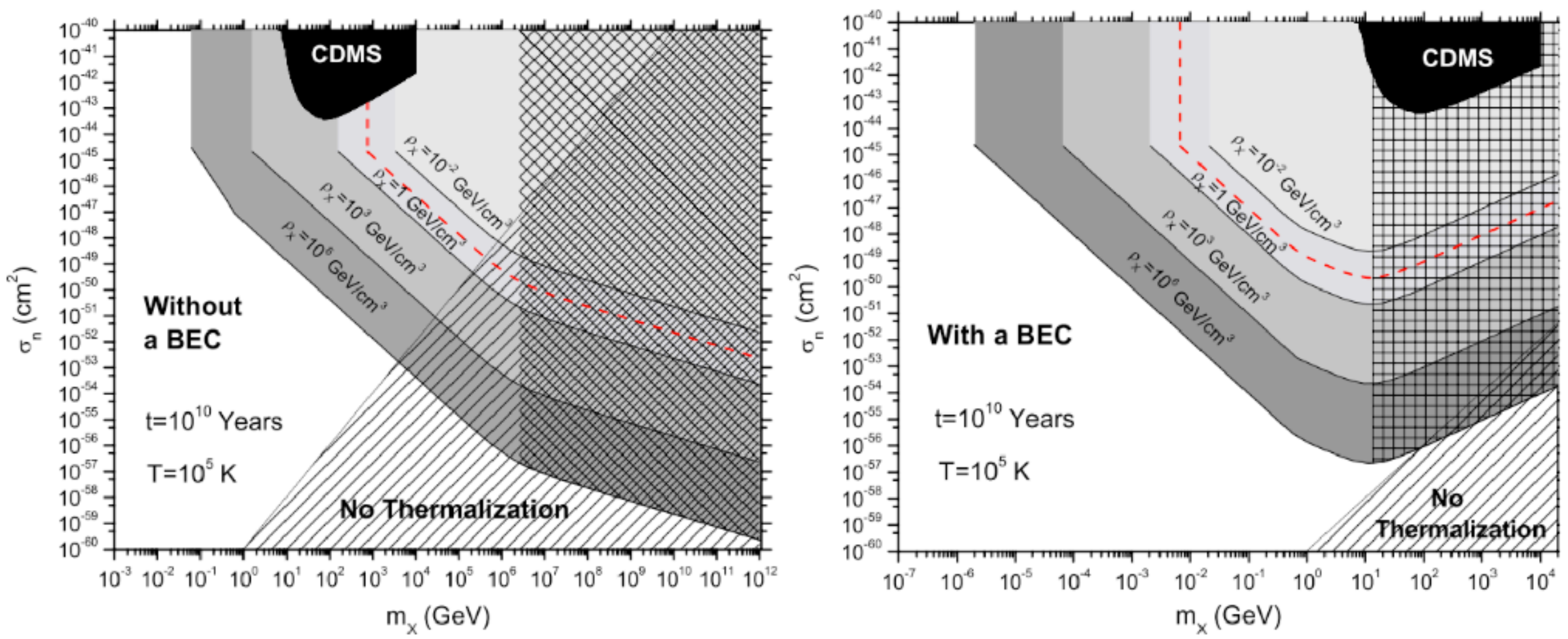


- Pulsars = Quickly rotating NS with strong B-fields
- Rotation slows due to dipole radiation
- Can approximate age if period and period-derivative are known:

$$\tau \approx P/(2\dot{P})$$

PROBLEM: WE SEE OLD NEUTRON STARS

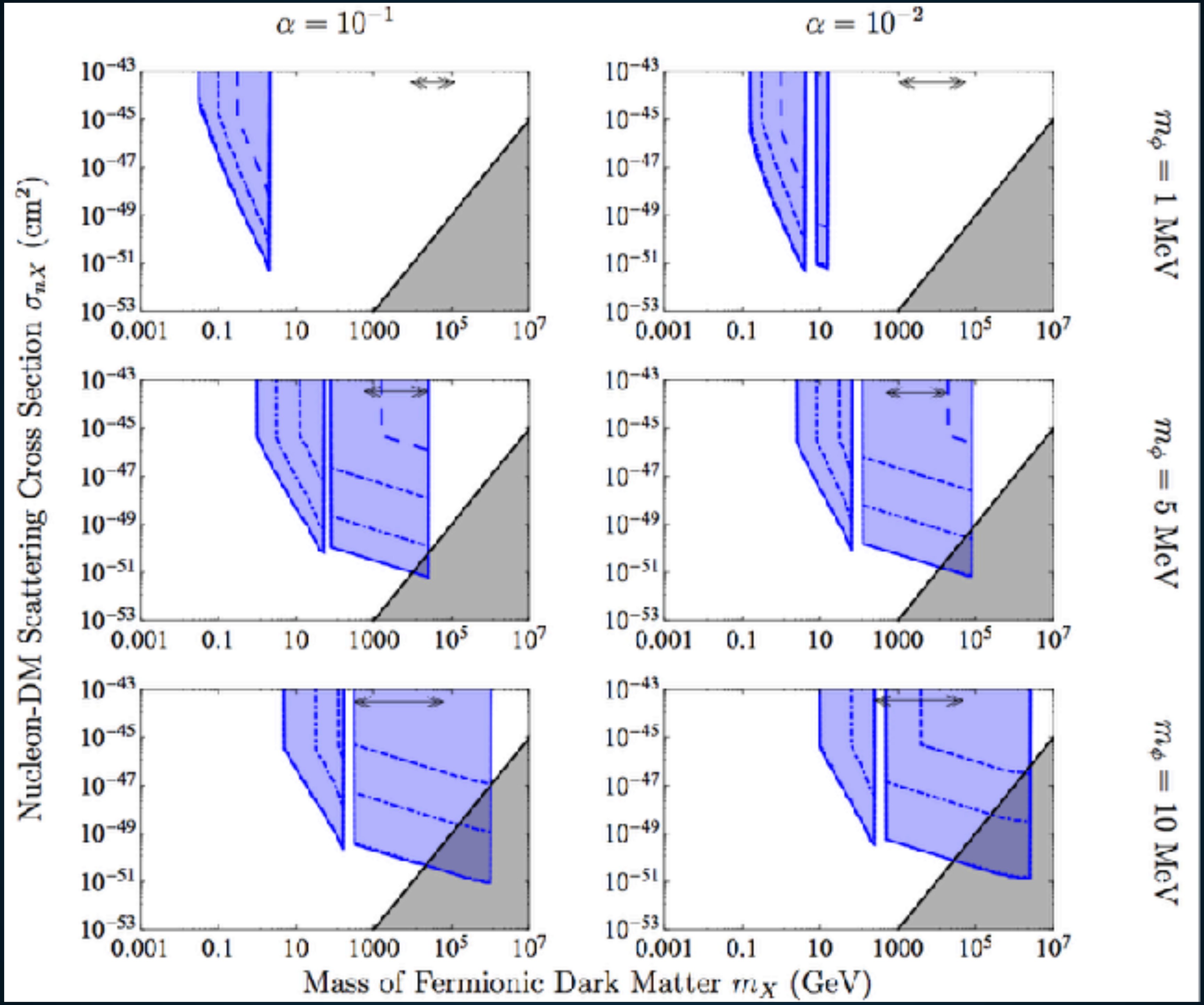
McDermott et al. (1103.5472)



- We observe ~5 Gyr old neutron stars us.
- Thus dark matter must not collapse neutron stars too effectively.
- Sets strong constraints on dark matter that collapses neutron stars - e.g. here in the case of scalar dark matter.

PROBLEM: WE SEE OLD NEUTRON STARS

Bramante et al. (1310.3509)



- Or Fermionic Dark matter with an attractive self-interaction cross-section.

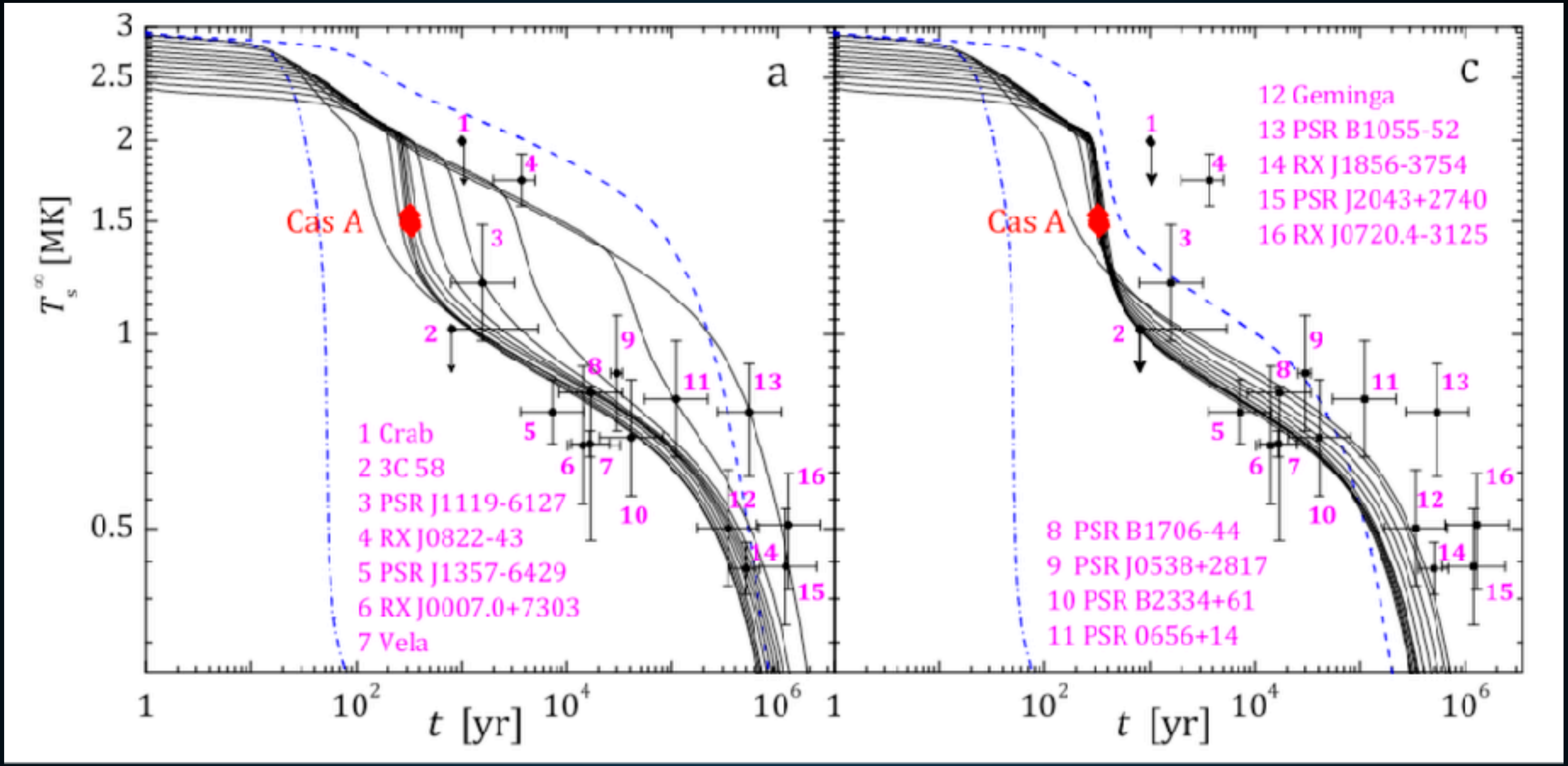
POSSIBLE SIGNATURES OF DARK MATTER INTERACTIONS

- Neutron star heating

- Neutron star collapse
  - Missing neutron stars
  - Electromagnetic signatures
    - Fast Radio Bursts
    - Kilonovae
    - r-process enrichment
  - Gravitational wave signatures

DARK KINETIC HEATING

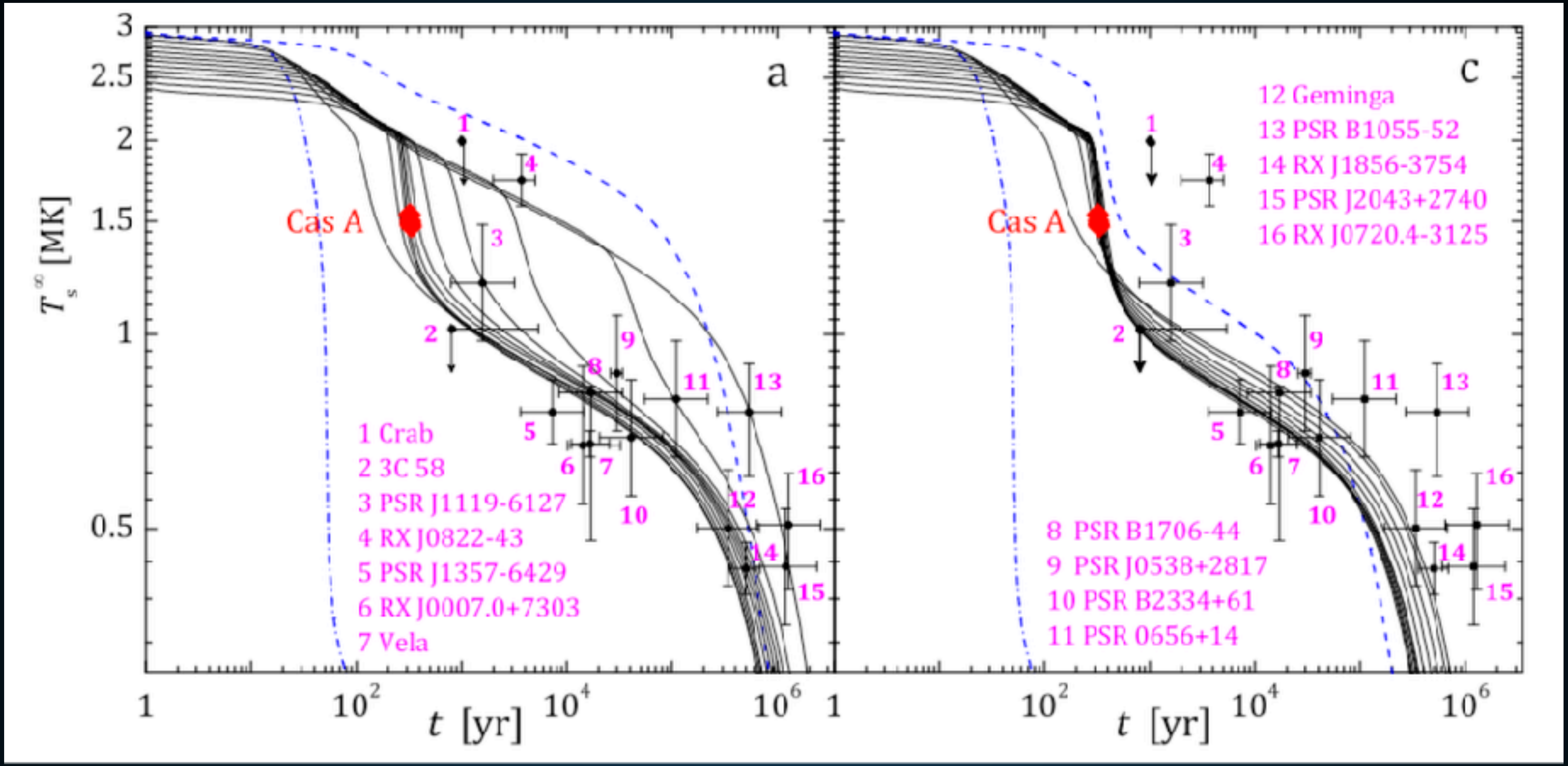
Shternin et al. (1012.0045)



- In addition to pulsations, a handful of pulsars have been detected via blackbody radiation.
- Primarily at temperatures ~10^6 K.

DARK KINETIC HEATING

Shternin et al. (1012.0045)



- **Older neutron stars are expected to cool effectively.**
- **20 Myr neutron stars are believed to have temperatures < 1000 K.**

DARK KINETIC HEATING

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

- **A dark matter particle impacts a neutron star surface with significant kinetic energy:**

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

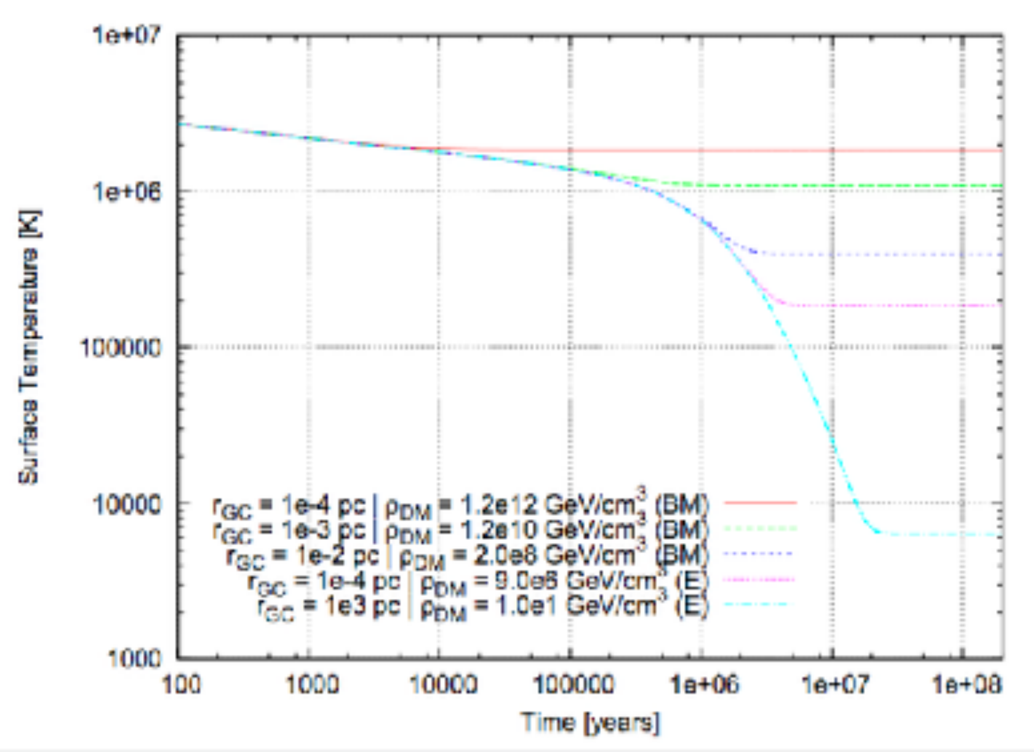
$$E_{\rm s} \simeq m_{\rm x} (\gamma - 1)$$

- **This sets a minimum energy input to the neutron star:**

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

de Lavallez & Fairbairn (1004.0629)

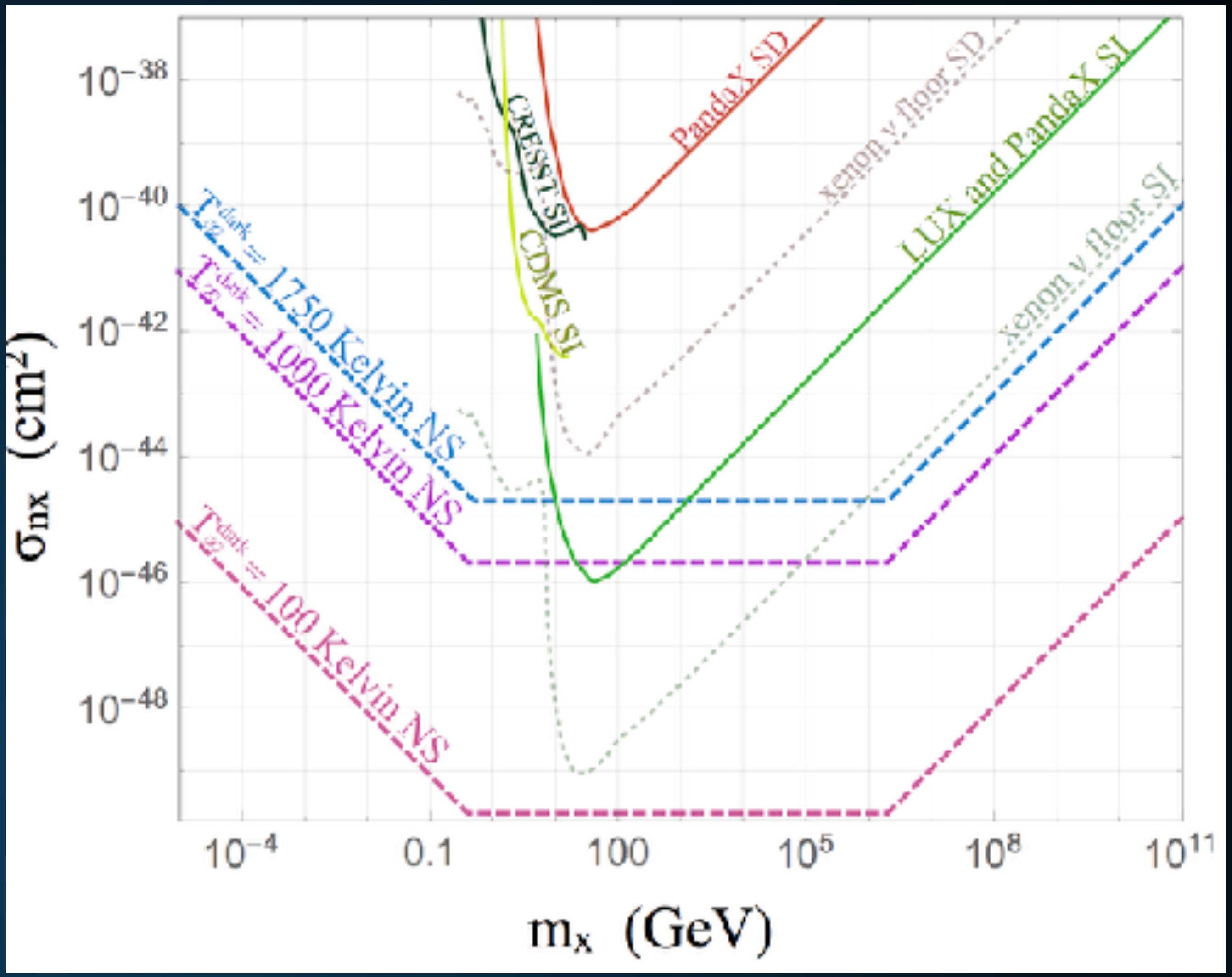
- **The dark matter particle does not need to annihilate, but if it does, more energy is injected ($E_s = \gamma m_X$).**



DARK KINETIC HEATING

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

- Dark matter then thermalizes with the NS.
- Energy transferred into nucleon kinetic energy.
- Neutron star emits as a blackbody with luminosity:



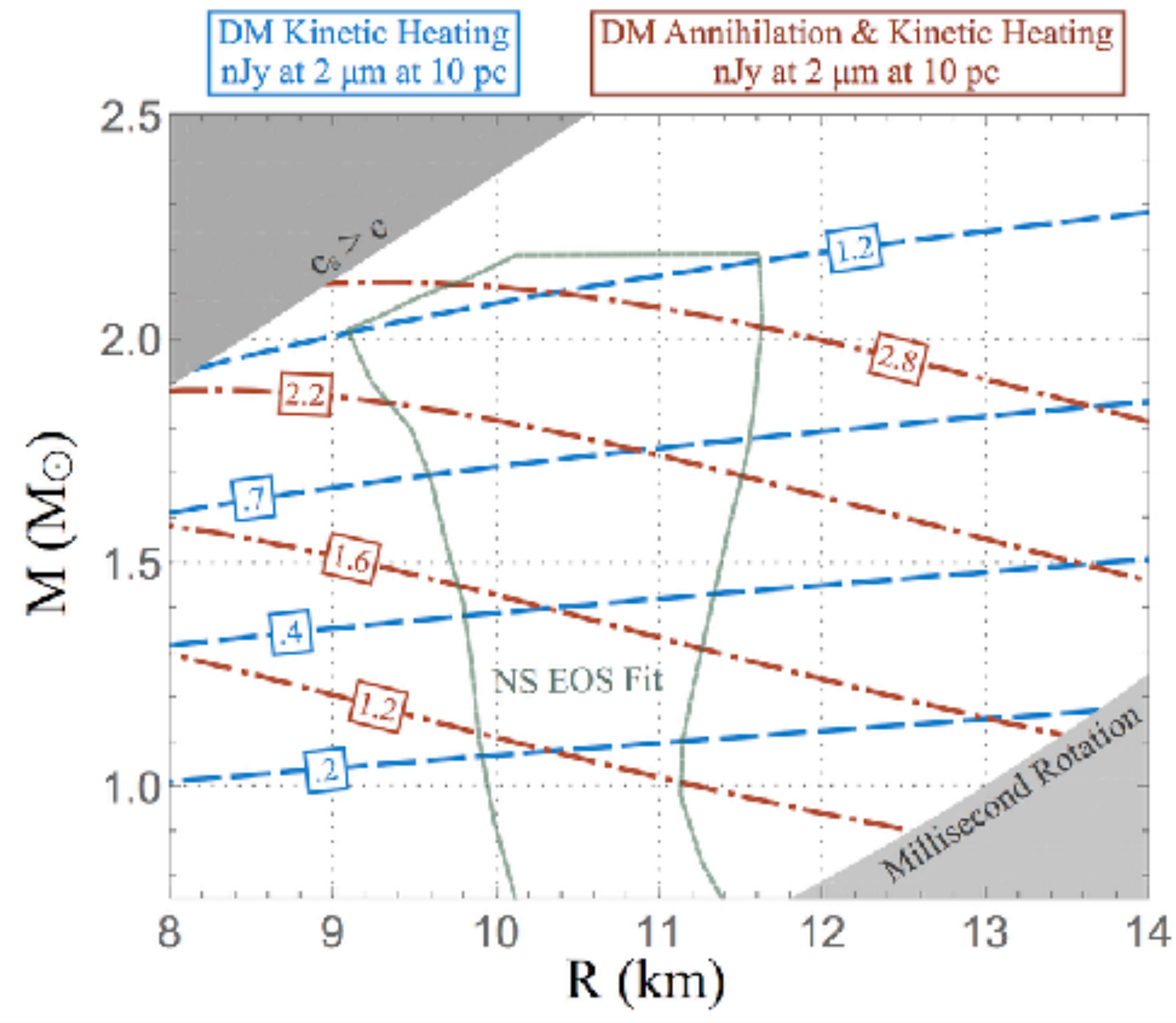
$$L_\infty^{\rm dark} = \dot{E}_{\rm k}\left(1 - \frac{2GM}{R}\right) = 4\pi\sigma_{\rm B}R^2T_{\rm s}^4\left(1 - \frac{2GM}{R}\right)$$

- This corresponds to a temperature ~1750 K for dark matter saturating the direct detection cross-section.
- Exceeds the sensitivity of standard direct detection.

DARK KINETIC HEATING

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

- **Seeing this signal requires extremely sensitive infrared observations.**
- **Fortunately, such telescopes are coming online:**
  - **James Webb**
  - **Thirty Meter Telescope**



- **Nominal JWST sensitivity is ~10 nJy at 10^4 s.**
- **TMT can reach 0.5 nJy in ~10^5 s, if backgrounds can be controlled.**

SOME COMPLEXITIES

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

- Neutron star needs to be a pulsar, so it can be located in radio observations.
  - Closest pulsar ~90 pc, but models indicate a pulsar with distance ~10-20 pc should exist.
- Alternative heating mechanisms:
  - Baryonic Heating on interstellar medium?
  - Heating powered by magnetic turbulence?

THE MISSING PULSAR PROBLEM

ALERT: THIS BIKE IS STOLEN

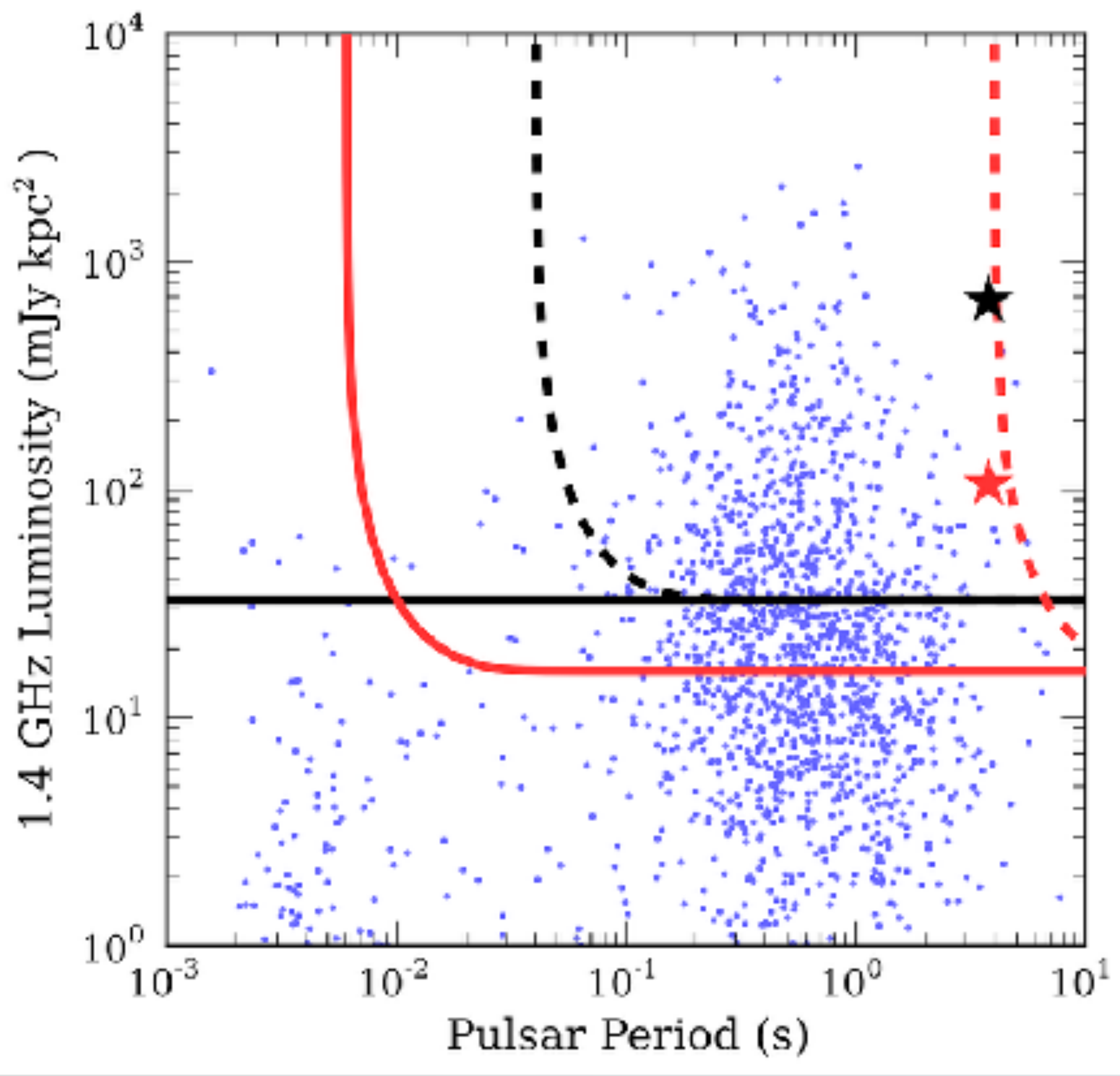
UP32 CW 5418

This N.O.W. bikers group bike has been stolen from Gautam Nagar area in New Delhi on 10th December 2010. Any one who sees or have any info about this bike, please contact Delhi Police on 100 or the vehicle owner Aditya Ratti at 9582128004. Many Thanks

- Lots of star-formation in the Galactic center
- Should produce lots of pulsars, but we haven’t seen them.

THE MISSING PULSAR PROBLEM

Dexter, O'Leary (1310.7022)



- Large pulse dispersion was reasonable culprit

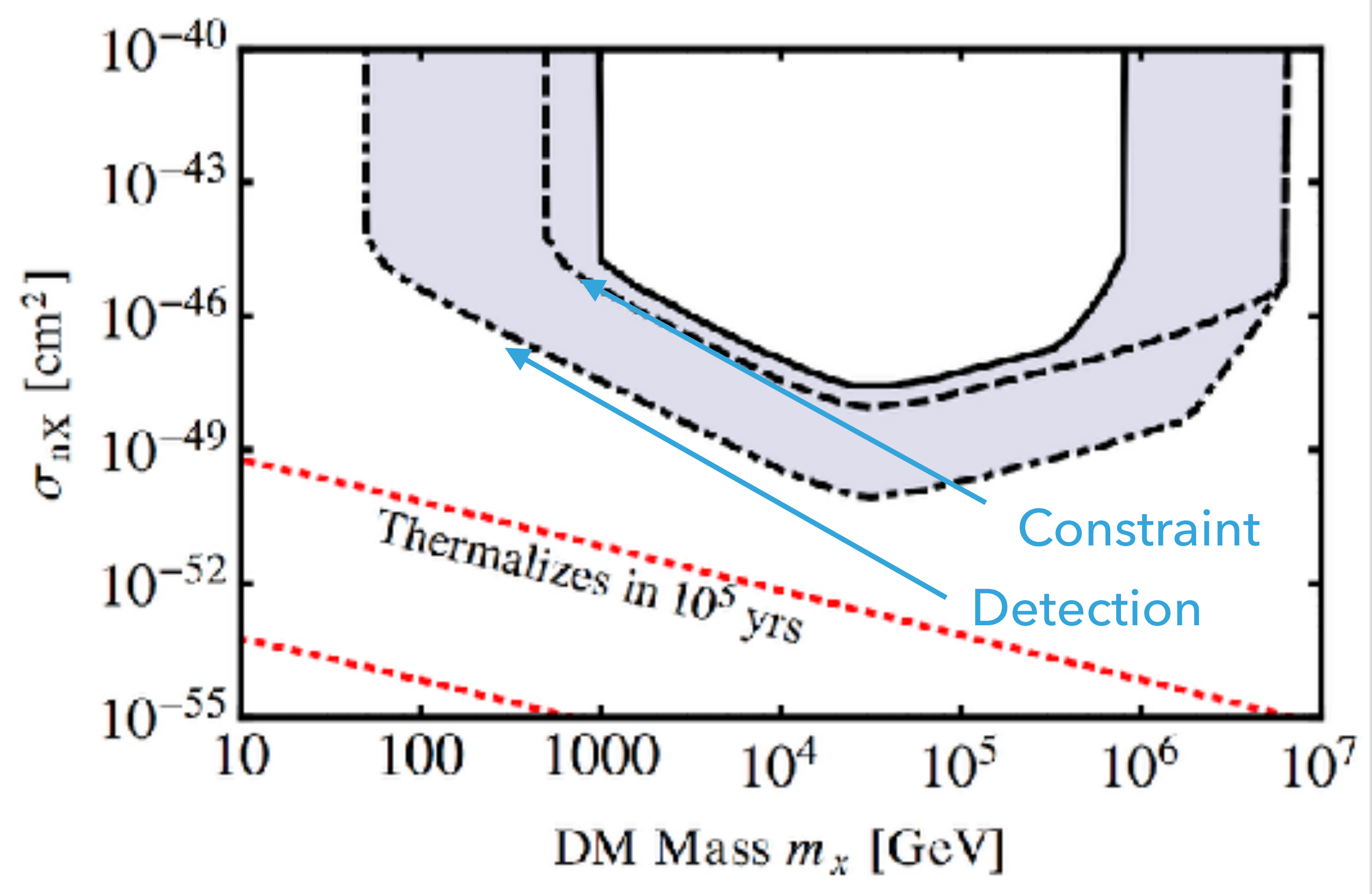
$$\Delta\tau \sim 1\ \mathrm{s}\left(\frac{\mathrm{Ghz}}{\nu}\right)^4$$

- 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 !?

DARK MATTER INDUCED NEUTRON STAR COLLAPSE

Bramante, TL (1405.1031)

- High Dark Matter density near the GC.
- GC NS collapse in ~10^5 yr while nearby NS remain.



Bosonic DM

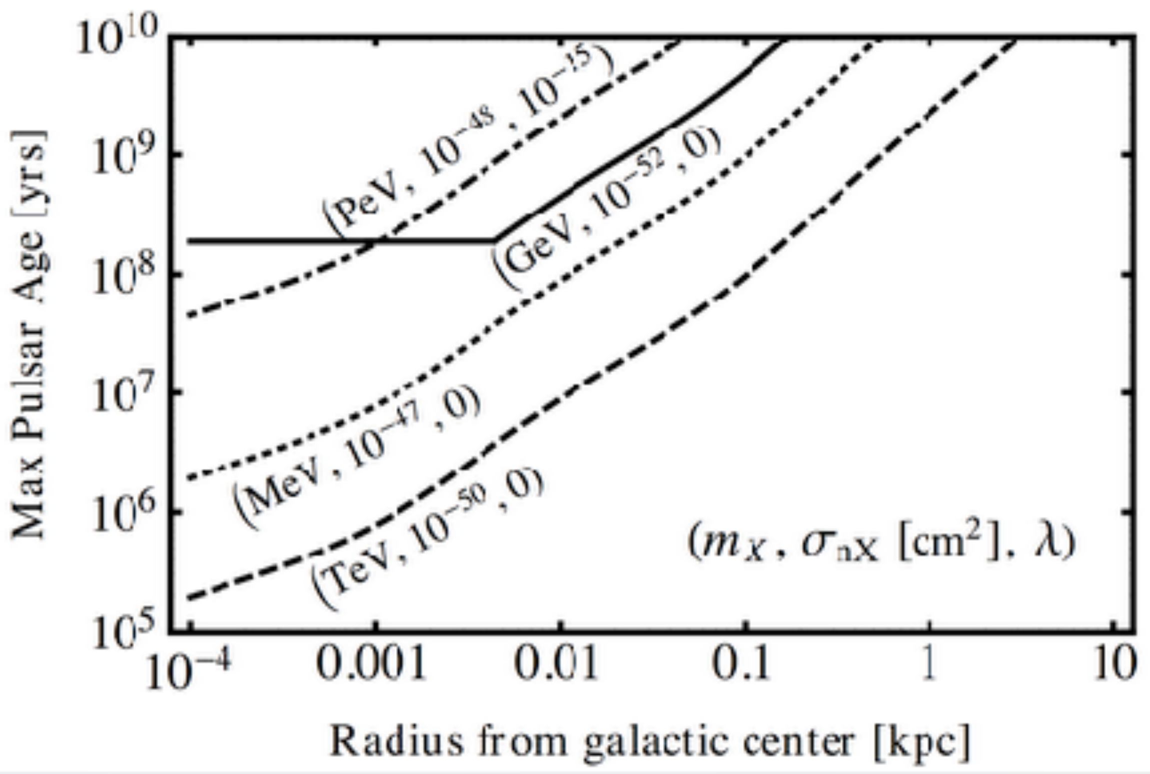
$\lambda|\phi|^4 = 10^{-15}$.

- GC NS collapse in ~10^4 - 10^5 yr while nearby NS remain.

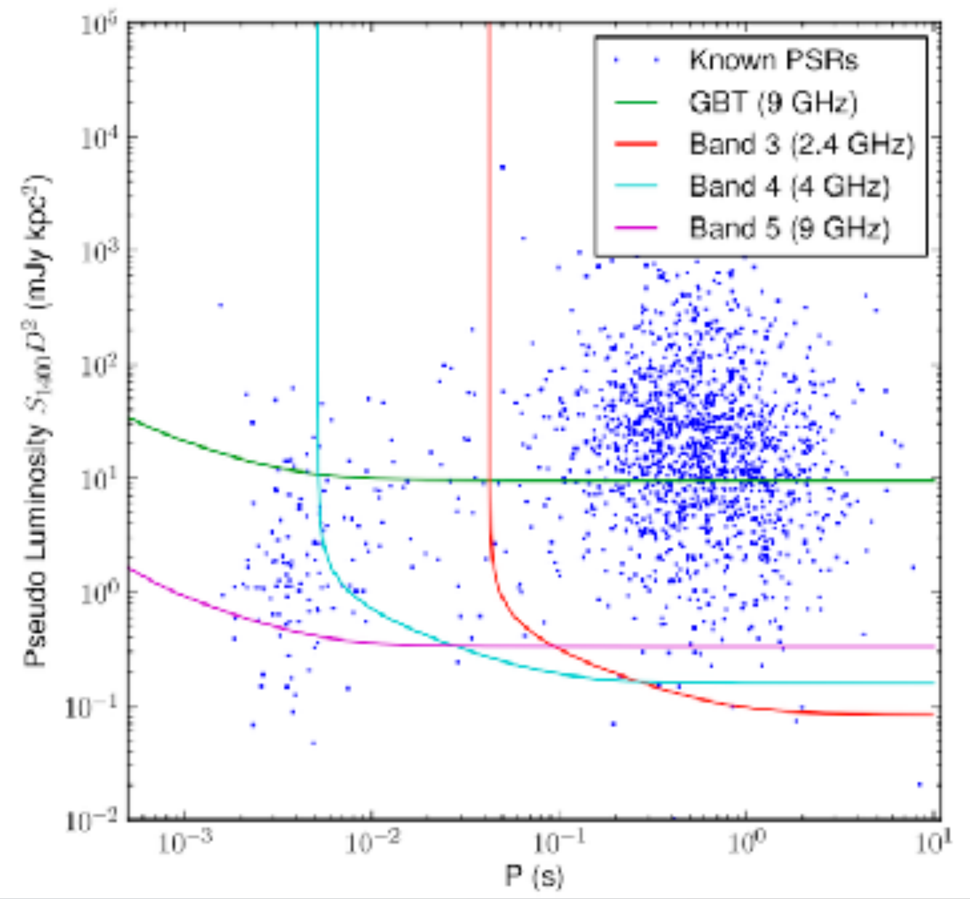
NEUTRON STAR COLLAPSE

- **Potential Observation: A correlation between maximum NS age and GC radius.**
- **Can be confirmed or ruled out with one old pulsar observation near the GC.**
- **Upcoming radio instruments (e.g. MeerKat, SKA) will definitively test the missing pulsar problem.**

Bramante, TL (1405.1031)

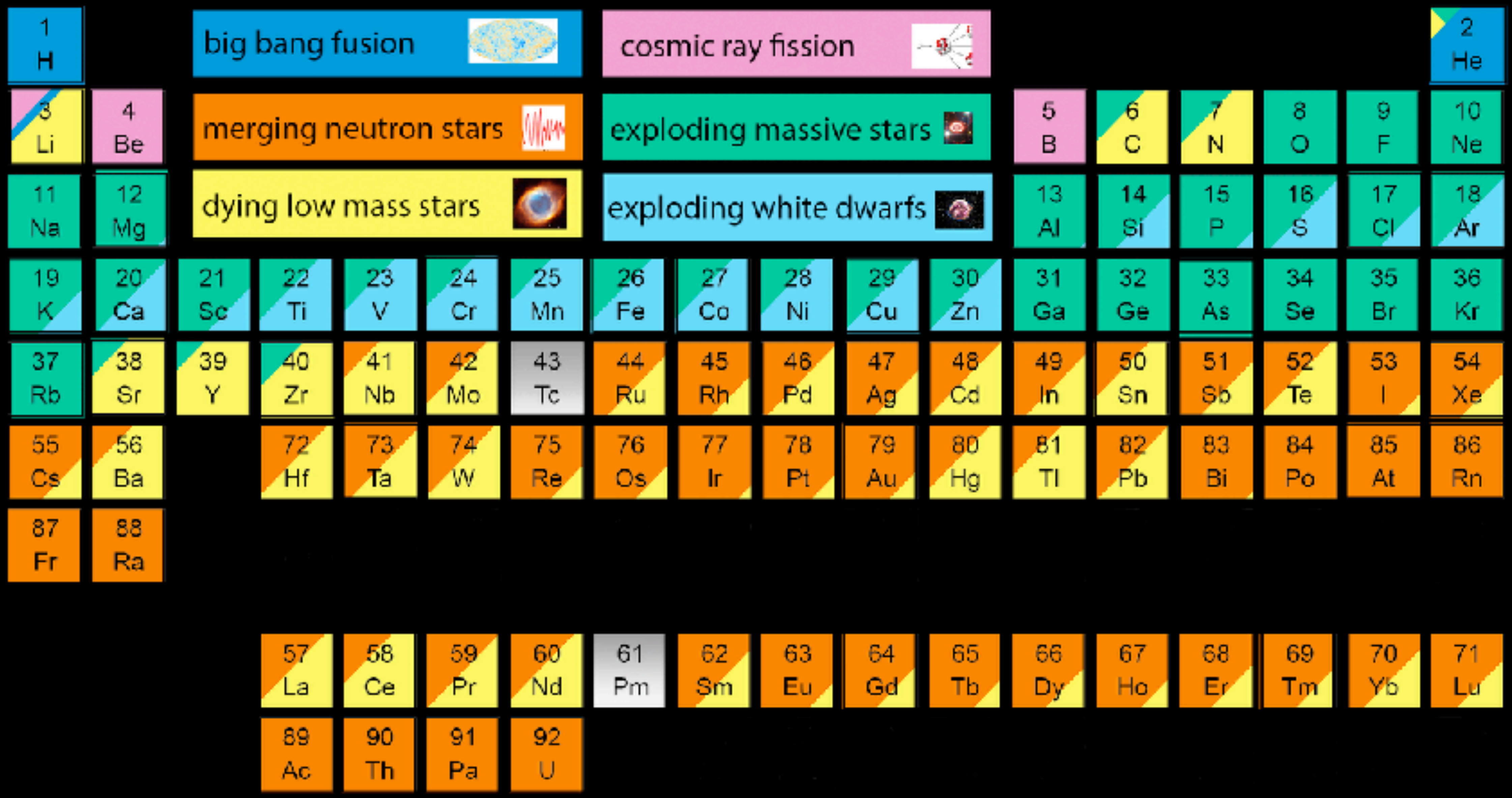


Eatough et al. (1501.00281)



R-PROCESS ENRICHMENT OF DWARF SPHEROIDAL GALAXIES

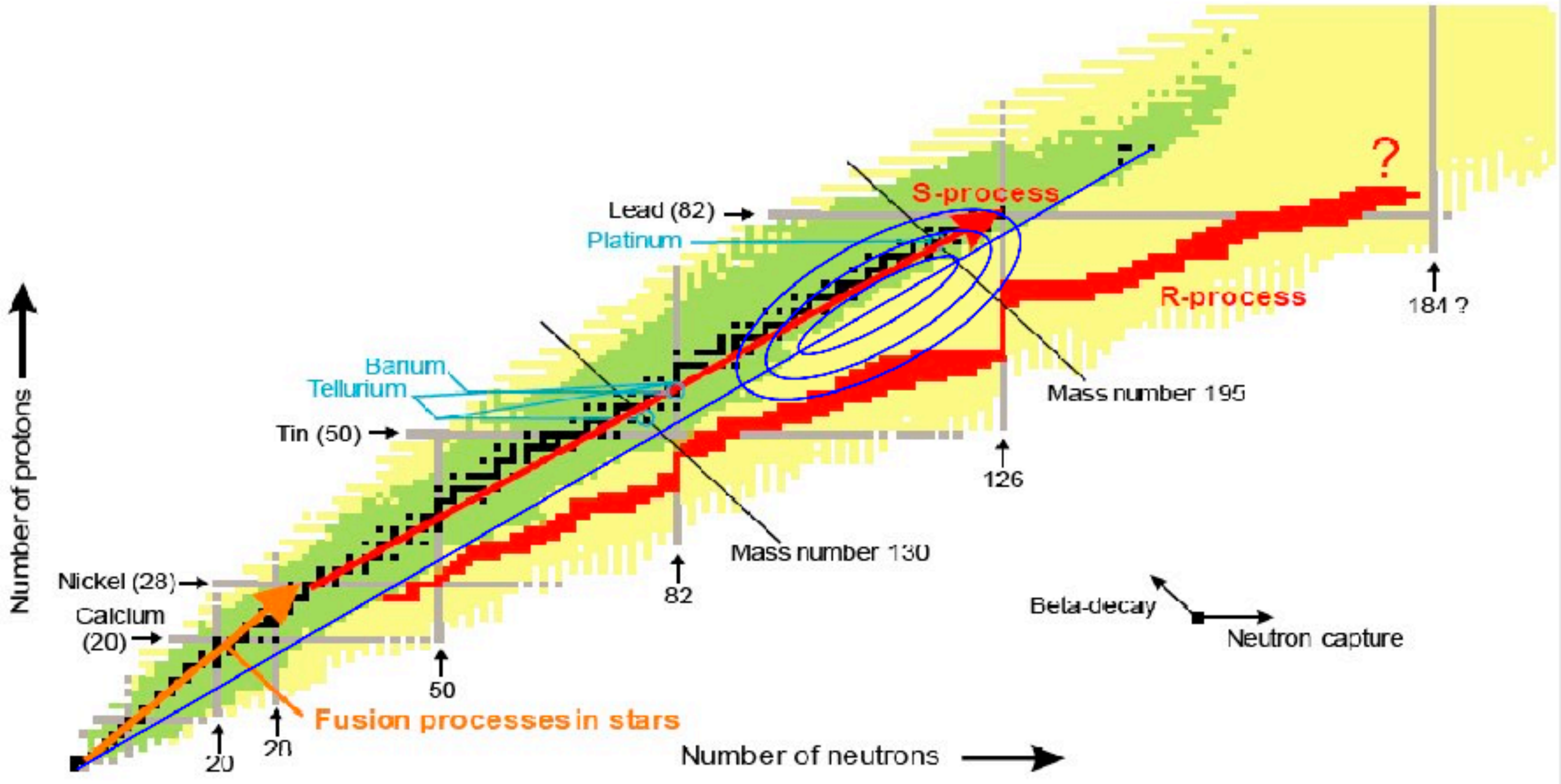
The Origin of the Solar System Elements



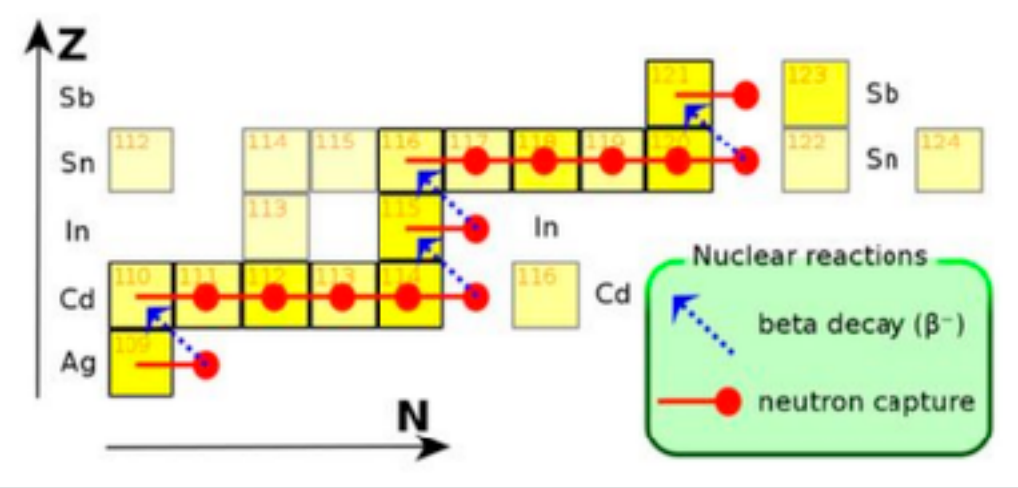
Astronomical Image Credits:
ESA/NASA/AASNova

Graphic created by Jennifer Johnson

R-PROCESS ENRICHMENT OF DWARF SPHEROIDAL GALAXIES

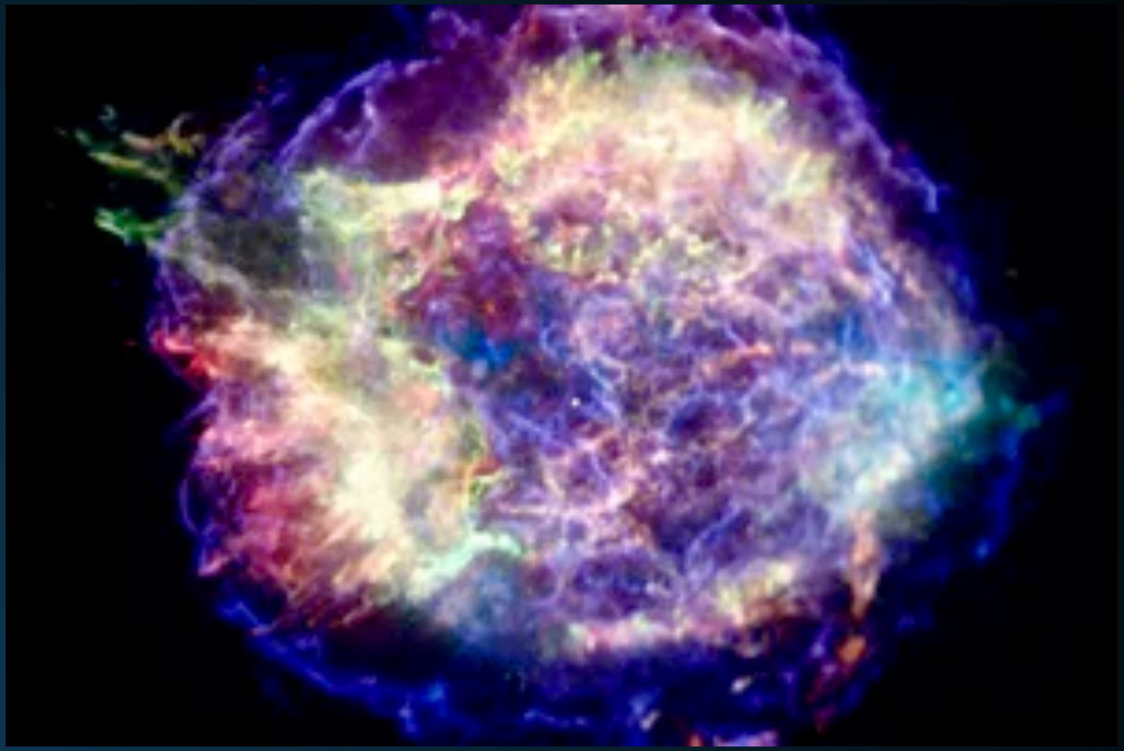


- **Producing elements with large neutron over density requires extremely neutron-dense environment to avoid β-decay**

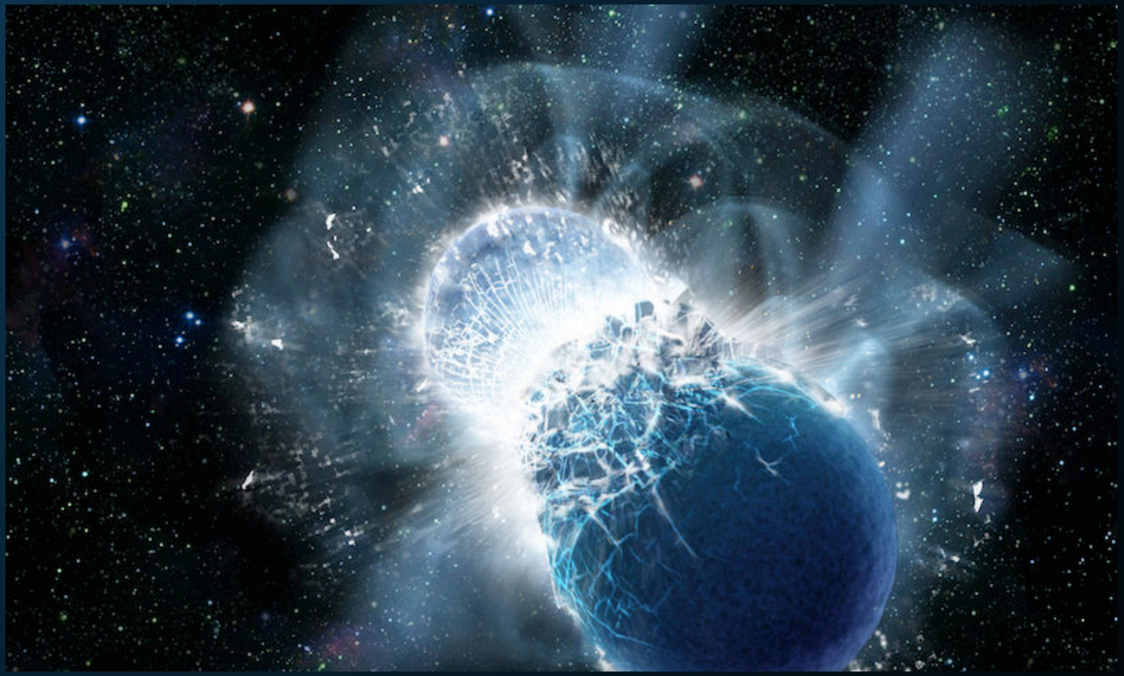


R-PROCESS ENRICHMENT OF DWARF SPHEROIDAL GALAXIES

- **Differentiating supernovae and neutron star binary mergers**

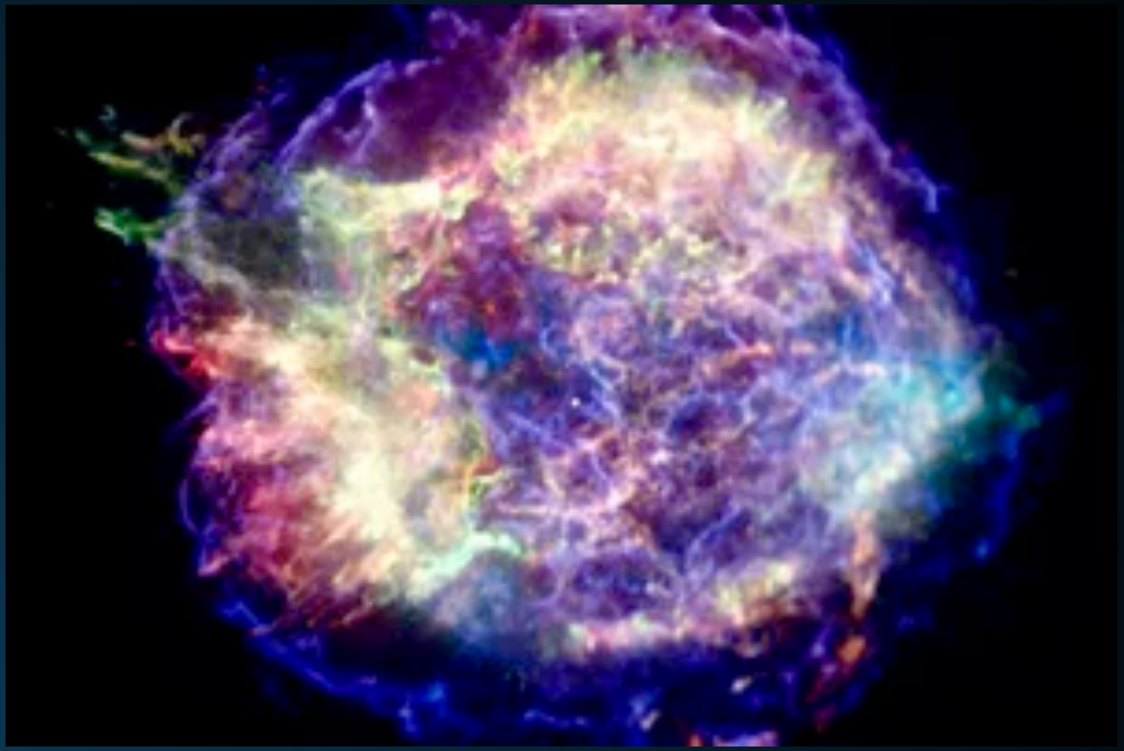


- **Supernovae are common: 0.02 SN yr^{-1} in Milky Way**
- **Neutron Star Mergers Rare: 10^{-4} yr^{-1} in Milky Way**



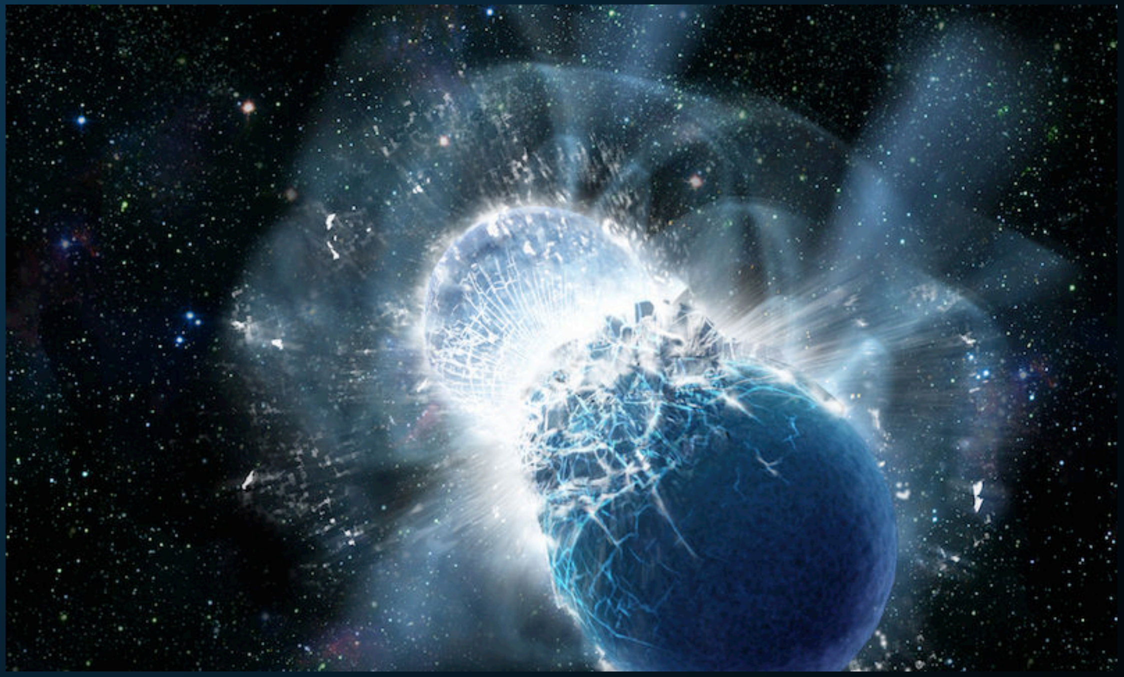
- **But r-process yields for each unknown - degenerate with rate!**

R-PROCESS ENRICHMENT OF DWARF SPHEROIDAL GALAXIES



- Differentiating supernovae and neutron star binary mergers

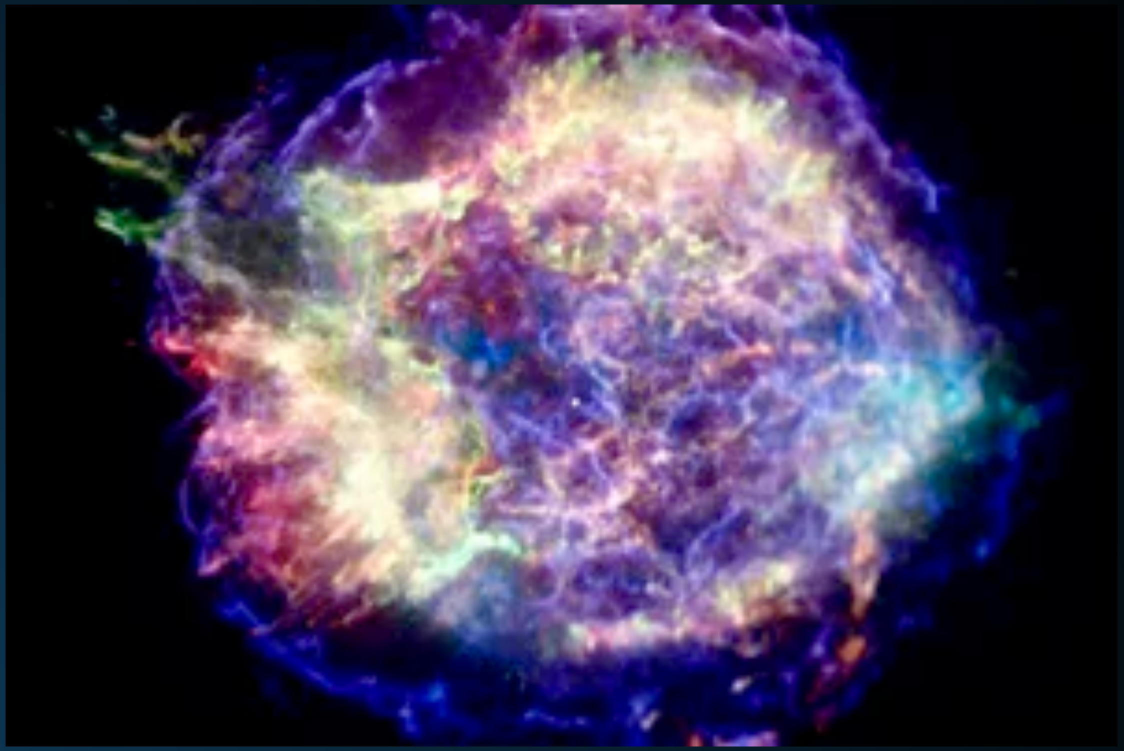
- Supernovae are common: 0.02 SN yr^{-1} in Milky Way



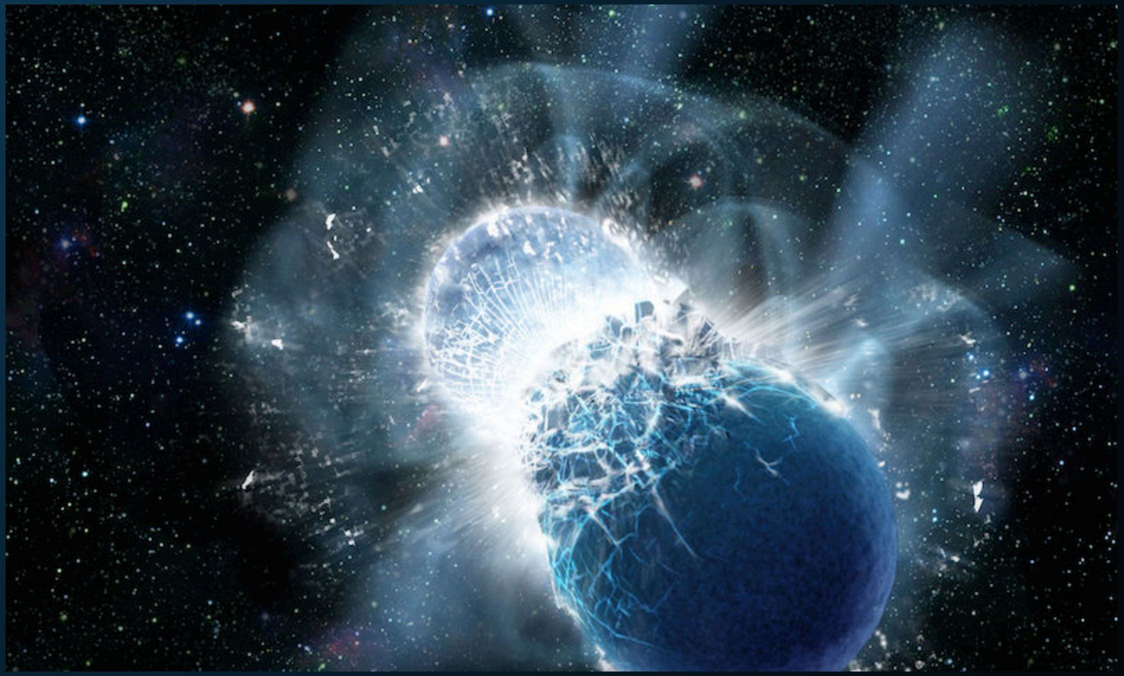
- Neutron Star Mergers Rare: 10^{-4} yr^{-1} in Milky Way

- Observe systems with small star-formation rates -> Poisson fluctuations in abundances!

R-PROCESS ENRICHMENT OF DWARF SPHEROIDAL GALAXIES

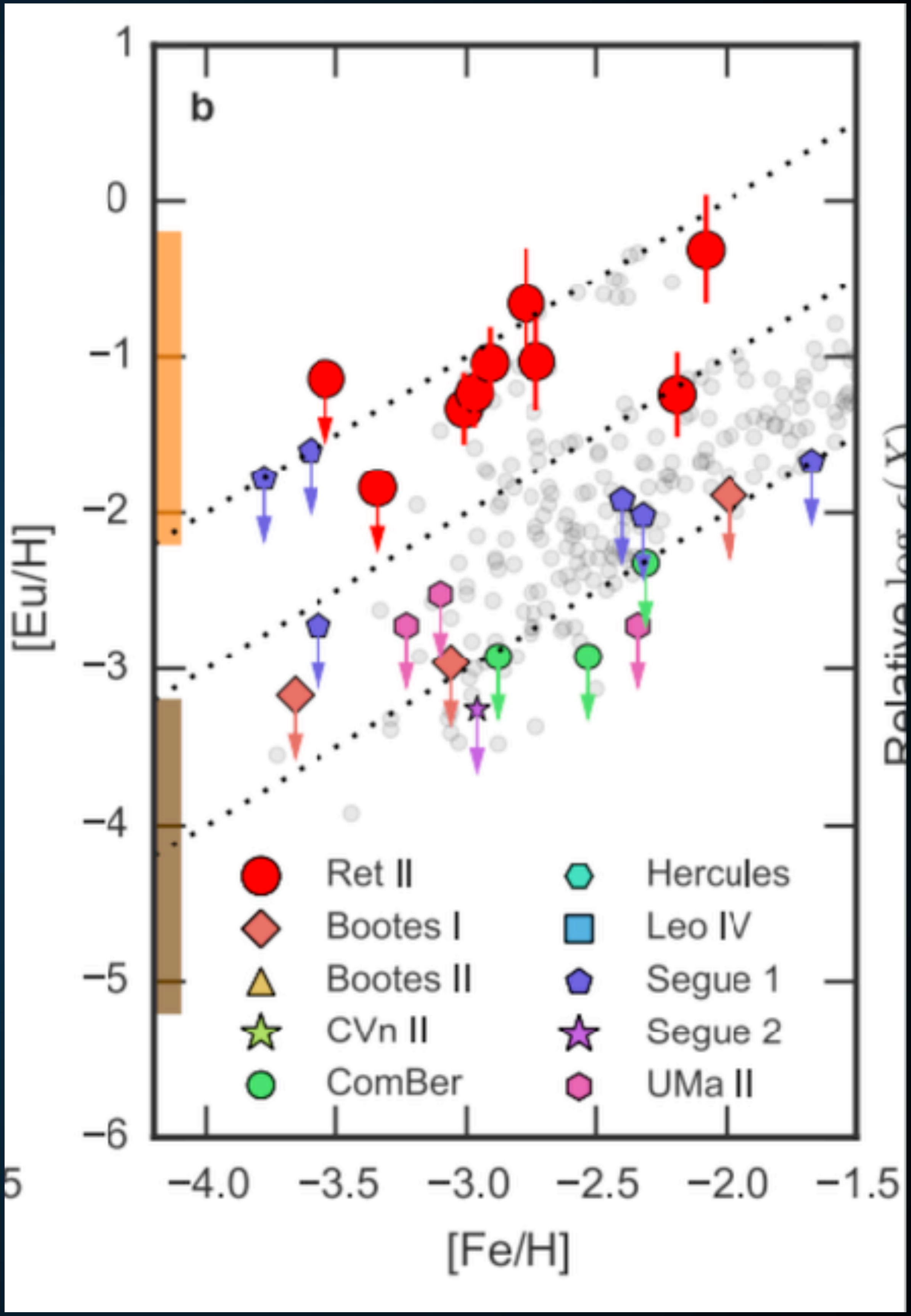


- Differentiating supernovae and neutron star binary mergers
- Supernovae are common: 0.02 SN yr^{-1} in Milky Way
- Neutron Star Mergers Rare: 10^{-4} yr^{-1} in Milky Way
- Can also cross-correlate with metallicity, which should track supernovae rate.



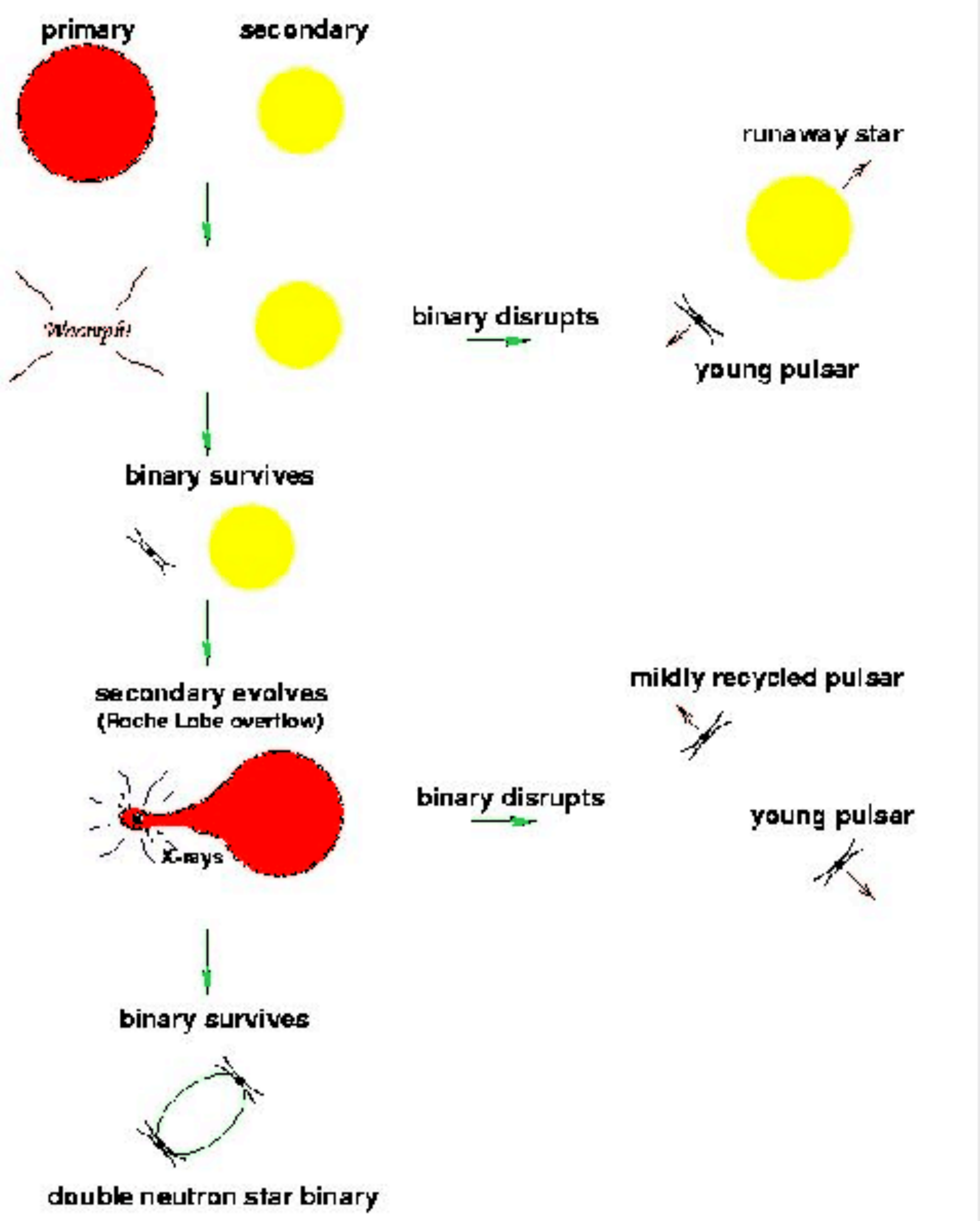
R-PROCESS ENRICHMENT OF DWARF SPHEROIDAL GALAXIES Ji et al. (1512.01558)

- 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)



BINARY STELLAR EVOLUTION

- Neutron stars receive large natal kicks due to asymmetries in the supernovae explosion.
- v_{kick} ~ 400 km s^{-1}.
- Escape velocity of dSph ~10 km s^{-1}.
- Low kick neutron star populations are possible (e.g. globular clusters)

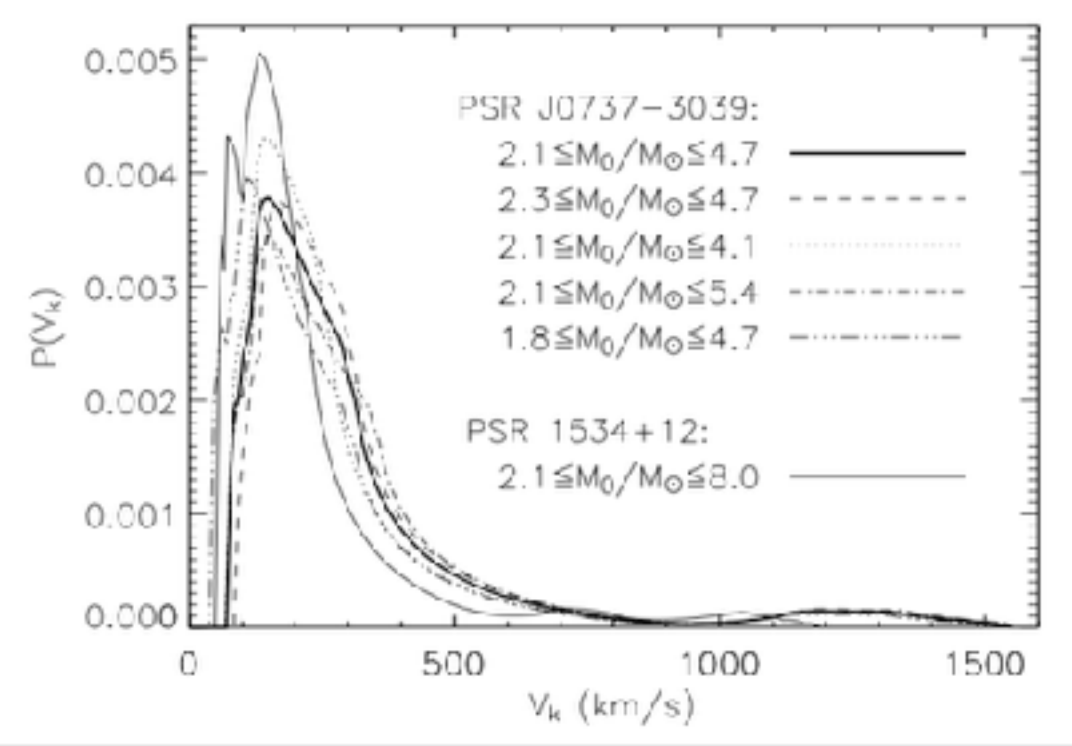


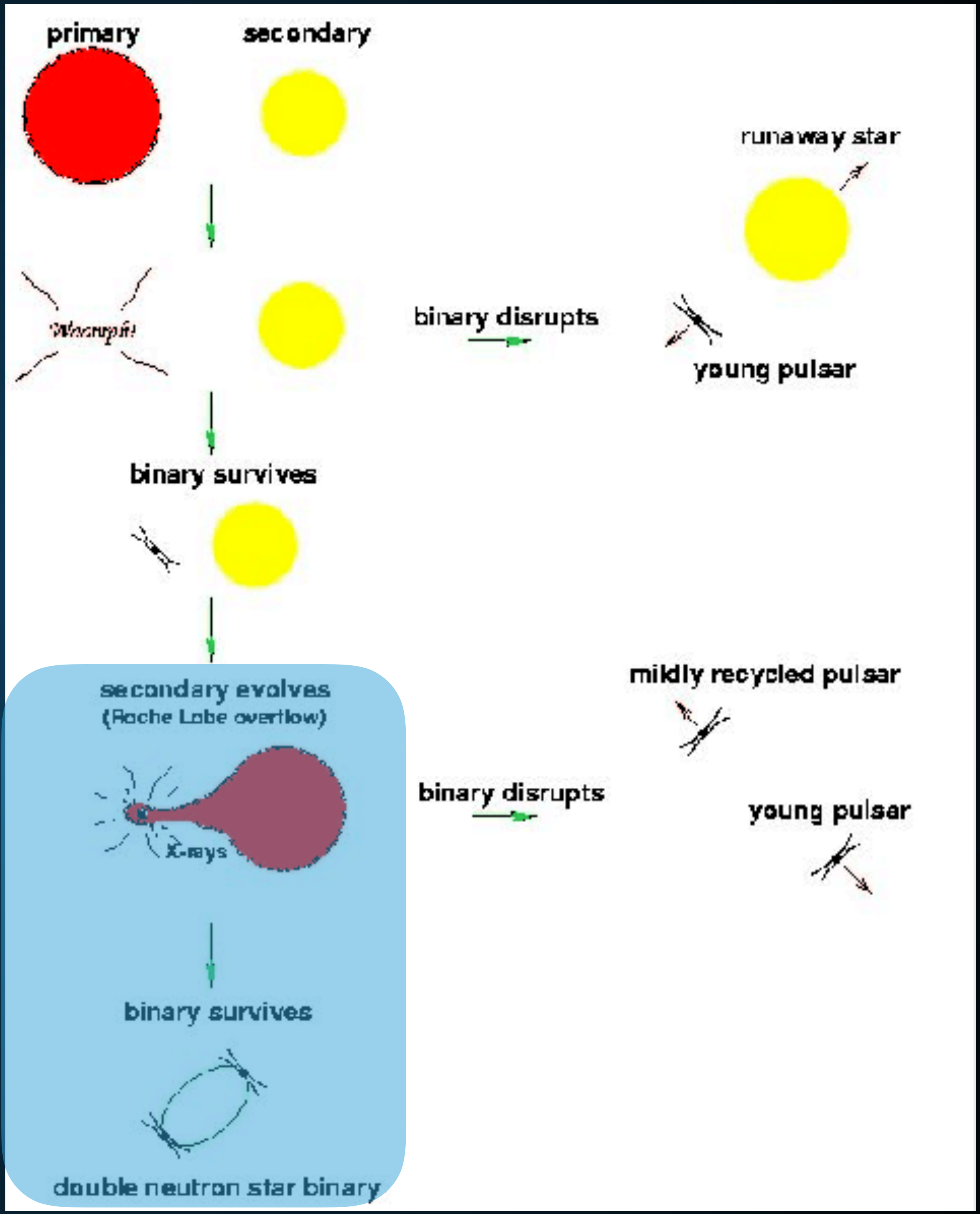
NEUTRON STAR KICKS IN BINARY MERGERS

Willems & Kalogera (astro-ph/0312426)

- **Mergers require kicks to move binary from widely separated supergiant system to tightly bound NS-NS binary.**

$$\tau_m(m_1, m_2, w, b) = \frac{3}{85}\,\frac{a_0^4}{m_{\rm tot}^3\,\eta}\,\left(1 - e_0^2\right)^{7/2}.$$

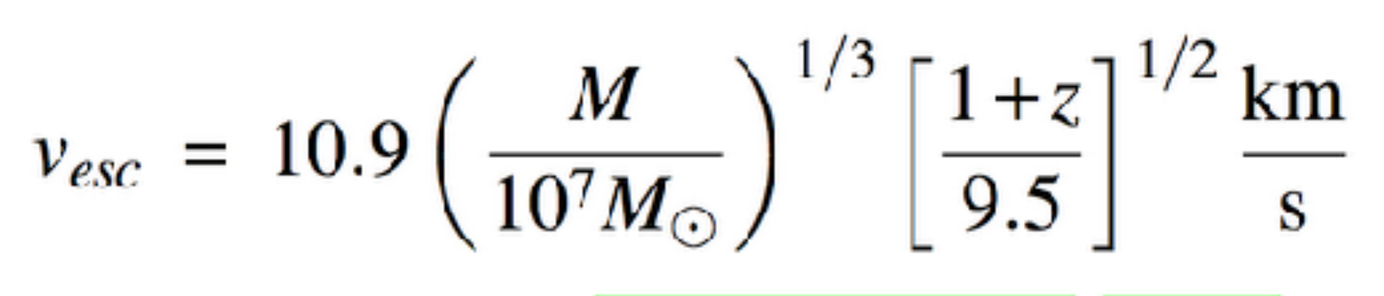




DOUBLE NEUTRON STAR ESCAPE FROM DSPHS

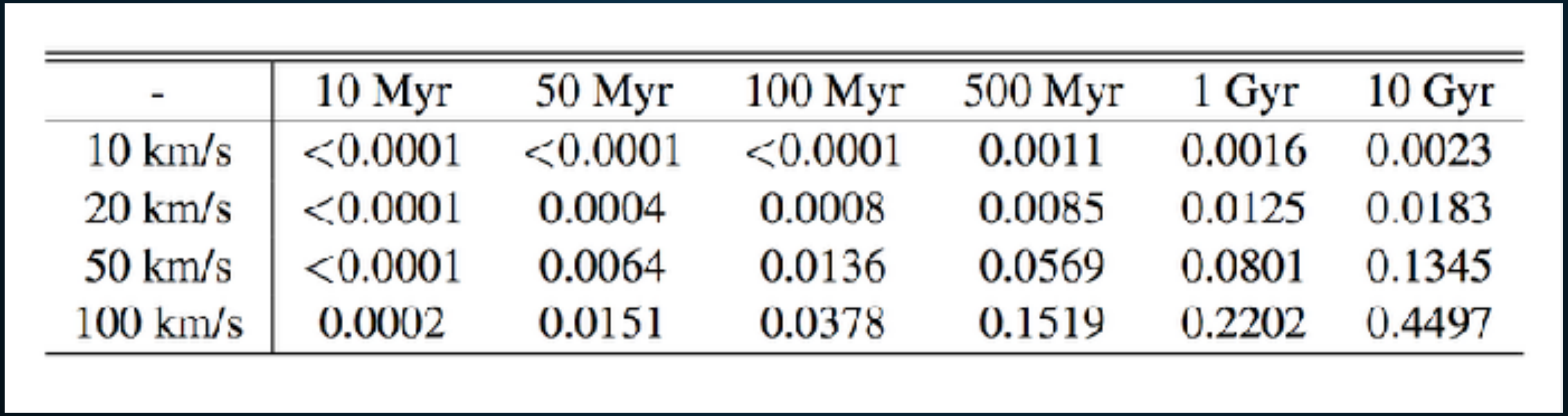
Bramante & TL (1601.06784)

- The escape velocity from a dwarf spheroidal galaxy is small:



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

- Natal kicks remove >99% of all binaries from the dwarf spheroidal galaxy.

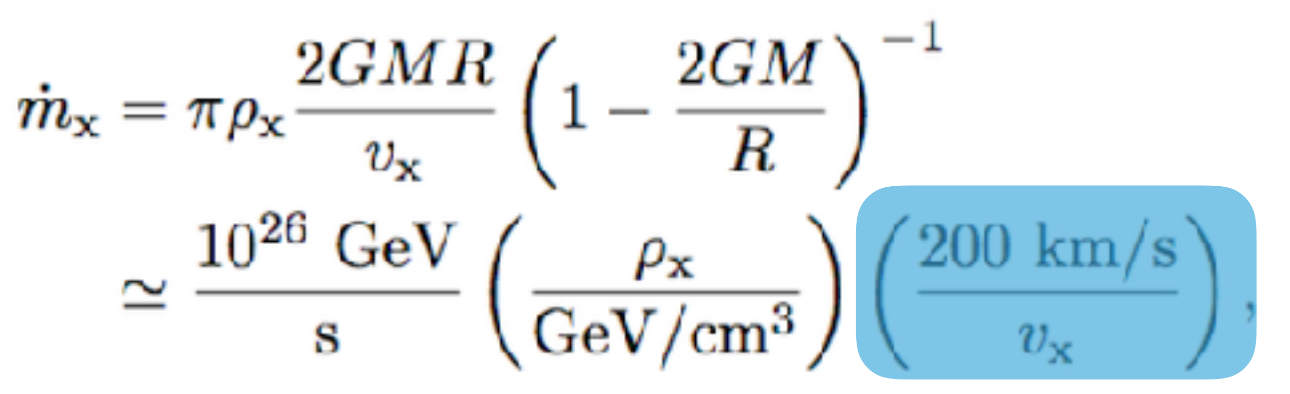


-	10 Myr	50 Myr	100 Myr	500 Myr	1 Gyr	10 Gyr
10 km/s	<0.0001	<0.0001	<0.0001	0.0011	0.0016	0.0023
20 km/s	<0.0001	0.0004	0.0008	0.0085	0.0125	0.0183
50 km/s	<0.0001	0.0064	0.0136	0.0569	0.0801	0.1345
100 km/s	0.0002	0.0151	0.0378	0.1519	0.2202	0.4497

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:**



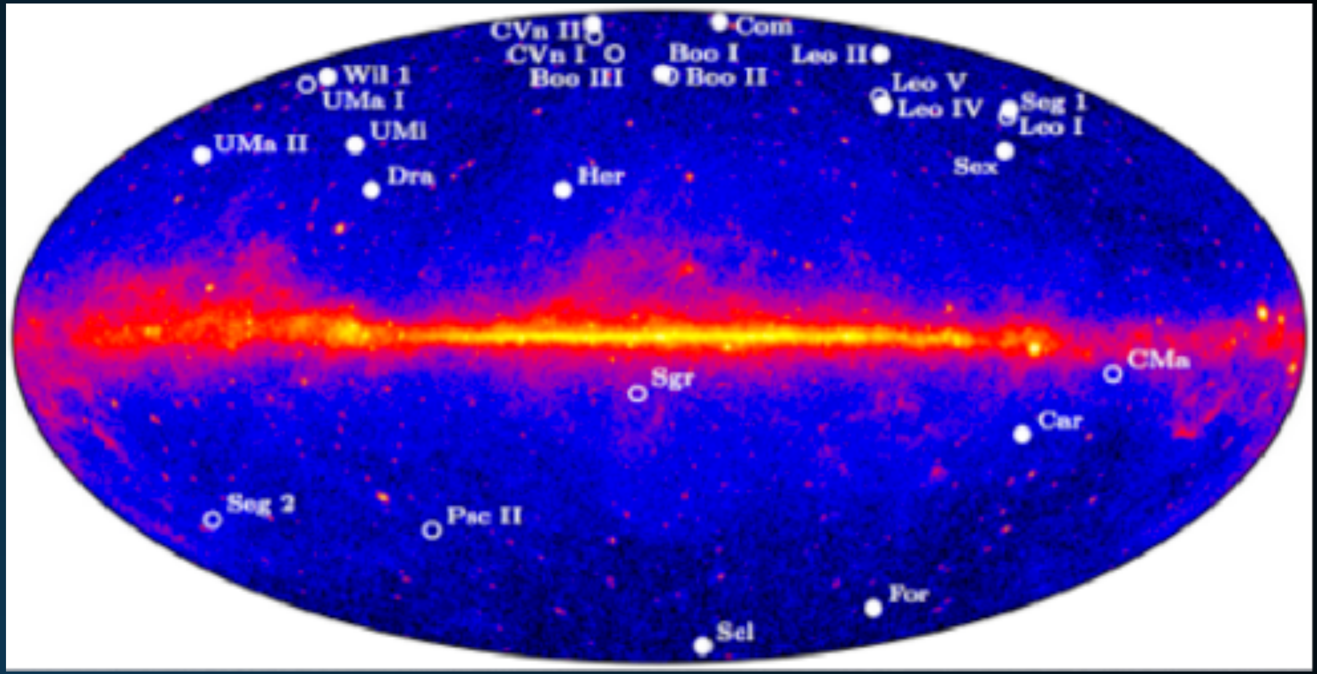
$$\begin{aligned}\dot{m}_{\mathrm{x}} &= \pi \rho_{\mathrm{x}} \frac{2GMR}{v_{\mathrm{x}}}\left(1-\frac{2GM}{R}\right)^{-1} \\ &\simeq \frac{10^{26}\ \mathrm{GeV}}{\mathrm{s}}\left(\frac{\rho_{\mathrm{x}}}{\mathrm{GeV/cm^3}}\right)\left(\frac{200\ \mathrm{km/s}}{v_{\mathrm{x}}}\right),\end{aligned}$$

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

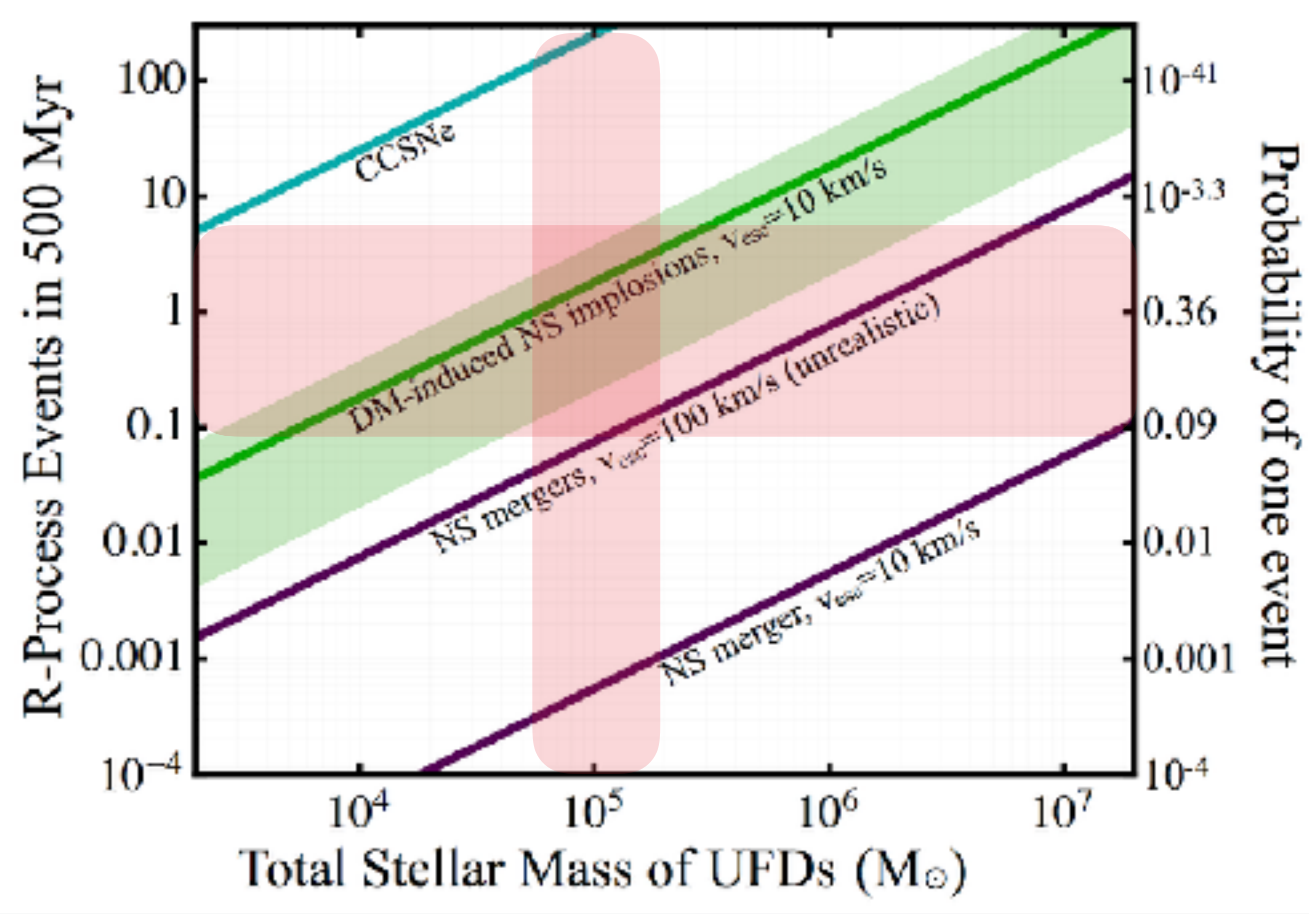
RATES FROM DARK MATTER INDUCED COLLAPSE

Bramante & TL (1601.06784)

- We expect ~1 r-process event over all ultra-faint dwarf galaxies (total 10^5 $M_\odot$.



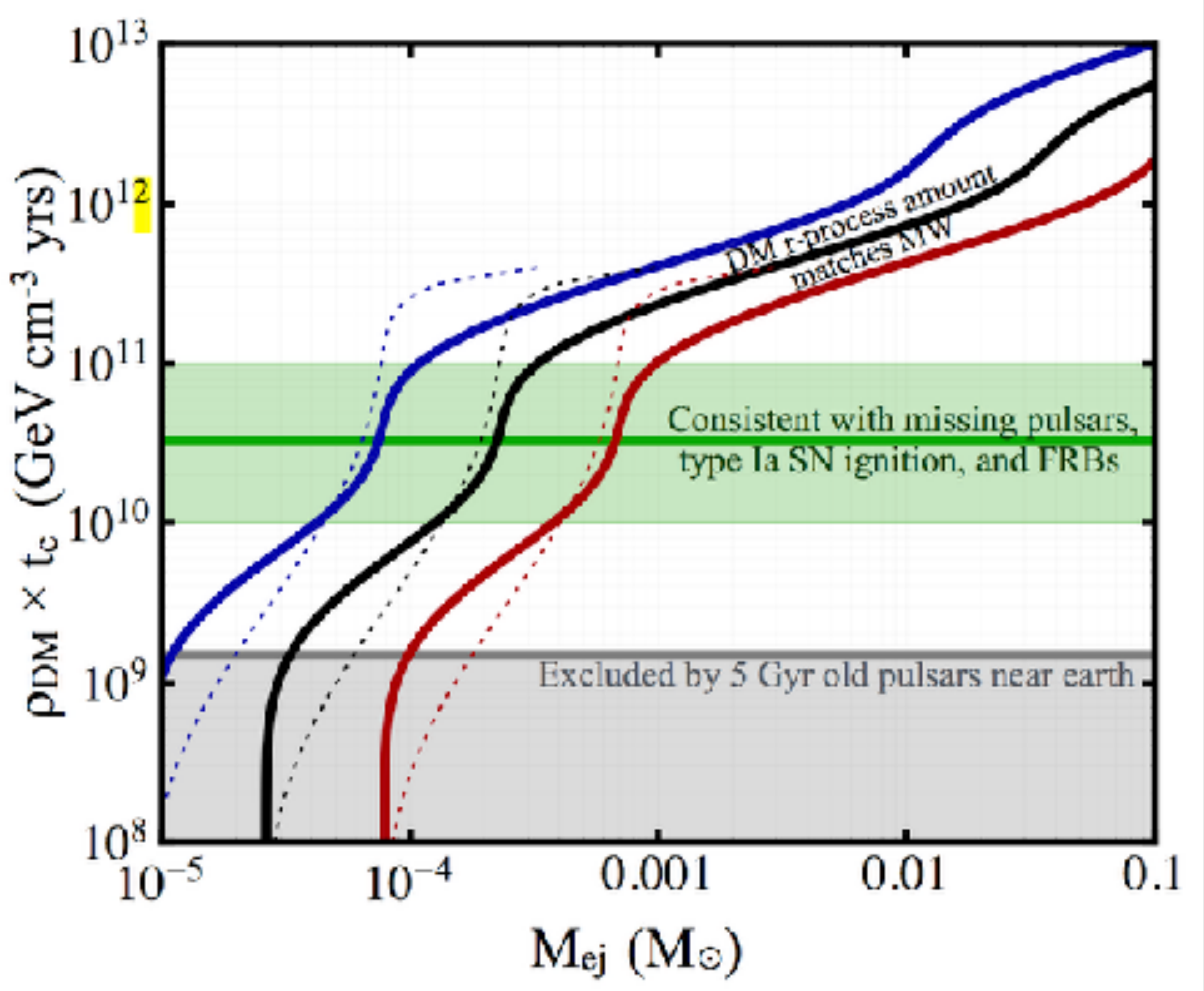
- Supernovae produce ~100 events.
- Mergers produce ~0.0005 events
- DM induced collapse produces ~0.1-3 events.



R-PROCESS ENRICHMENT OF THE MILKY WAY

Bramante & TL (1601.06784)

- How much r-process enrichment per dark matter induced collapse?
- Currently abundance
  - Yields between 5 x 10^{-5} $M_\odot$ and 10^{-3} $M_\odot$ can explain Milky Way r-process abundance.

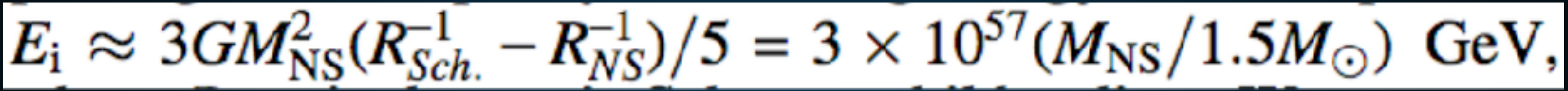


- Significant uncertainties in r-process element transport throughout the Milky Way.

R-PROCESS ENRICHMENT OF THE MILKY WAY

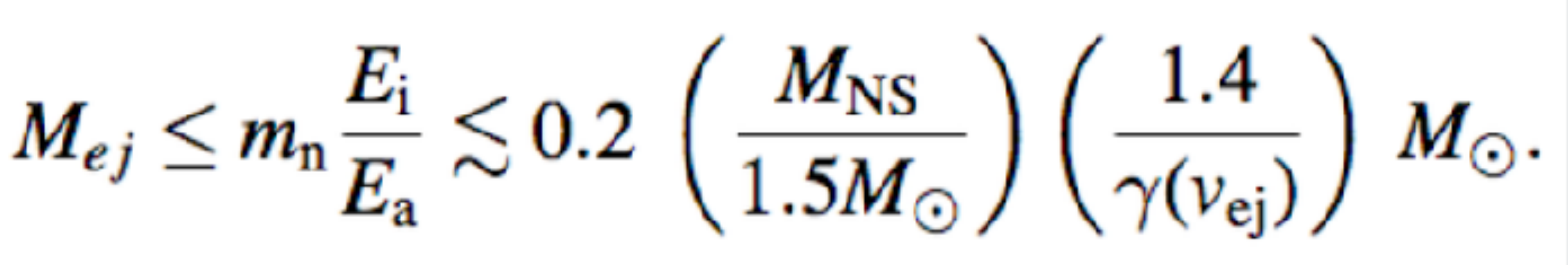
Bramante & TL (1601.06784)

- Can roughly estimate the maximal r-process production rate via energetics:



$$E_{\rm i} \approx 3GM_{\rm NS}^2(R_{Sch.}^{-1} - R_{NS}^{-1})/5 = 3 \times 10^{57}(M_{\rm NS}/1.5M_\odot)\ \text{GeV},$$

- This energy can propel neutrons from the NS surface at v = 0.7c. The maximum mass that can be lost is:



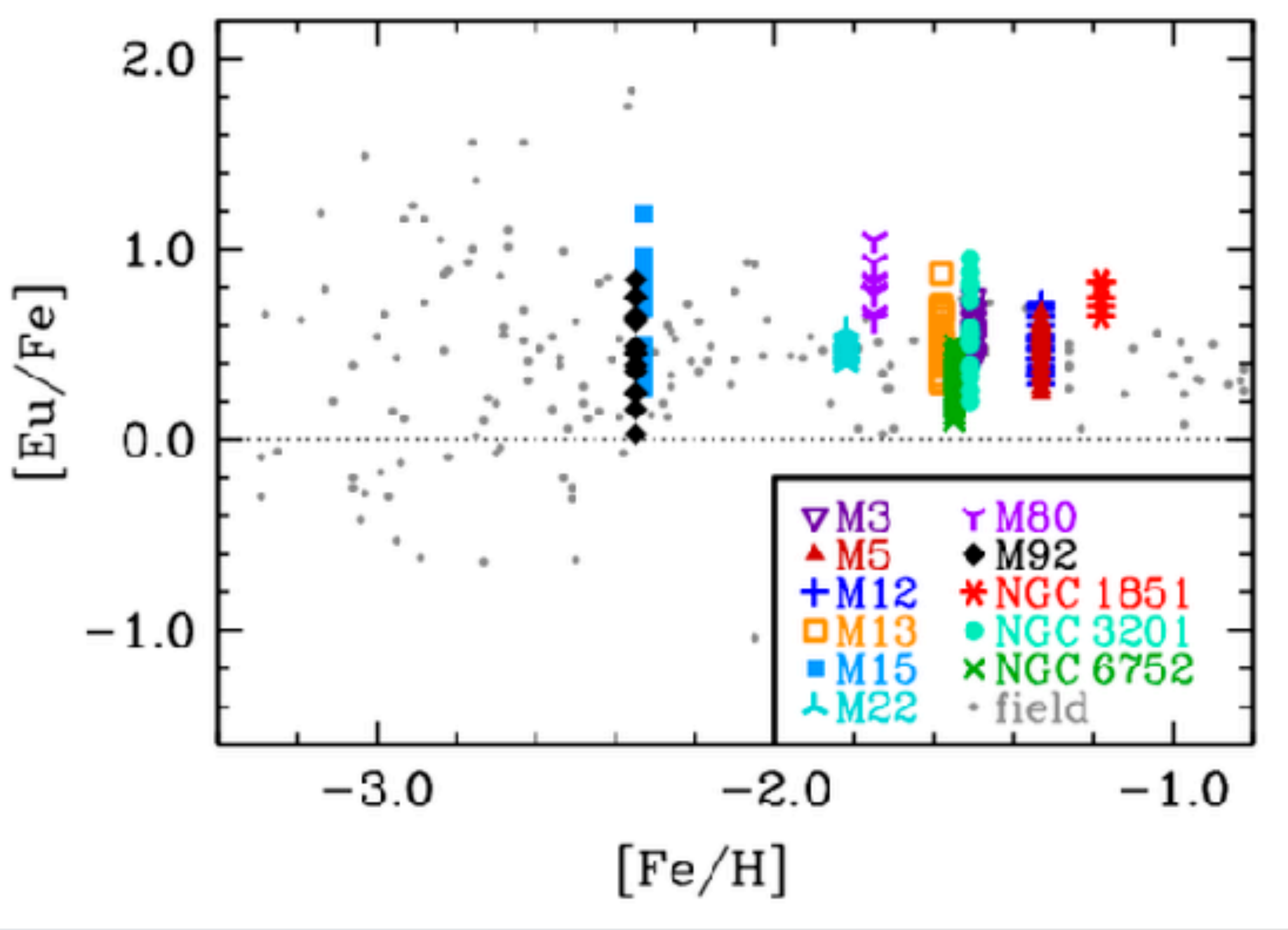
$$M_{ej} \leq m_{\rm n}\frac{E_{\rm i}}{E_{\rm a}} \lesssim 0.2\left(\frac{M_{\rm NS}}{1.5M_\odot}\right)\left(\frac{1.4}{\gamma(v_{\rm ej})}\right)M_\odot .$$

- The actual r-process enrichment depends on the quantity and density of neutrons which escape in the implosion. Computational models are needed.

R-PROCESS ENRICHMENT IN GLOBULAR CLUSTERS

Roederer 2011 (1104.5056)

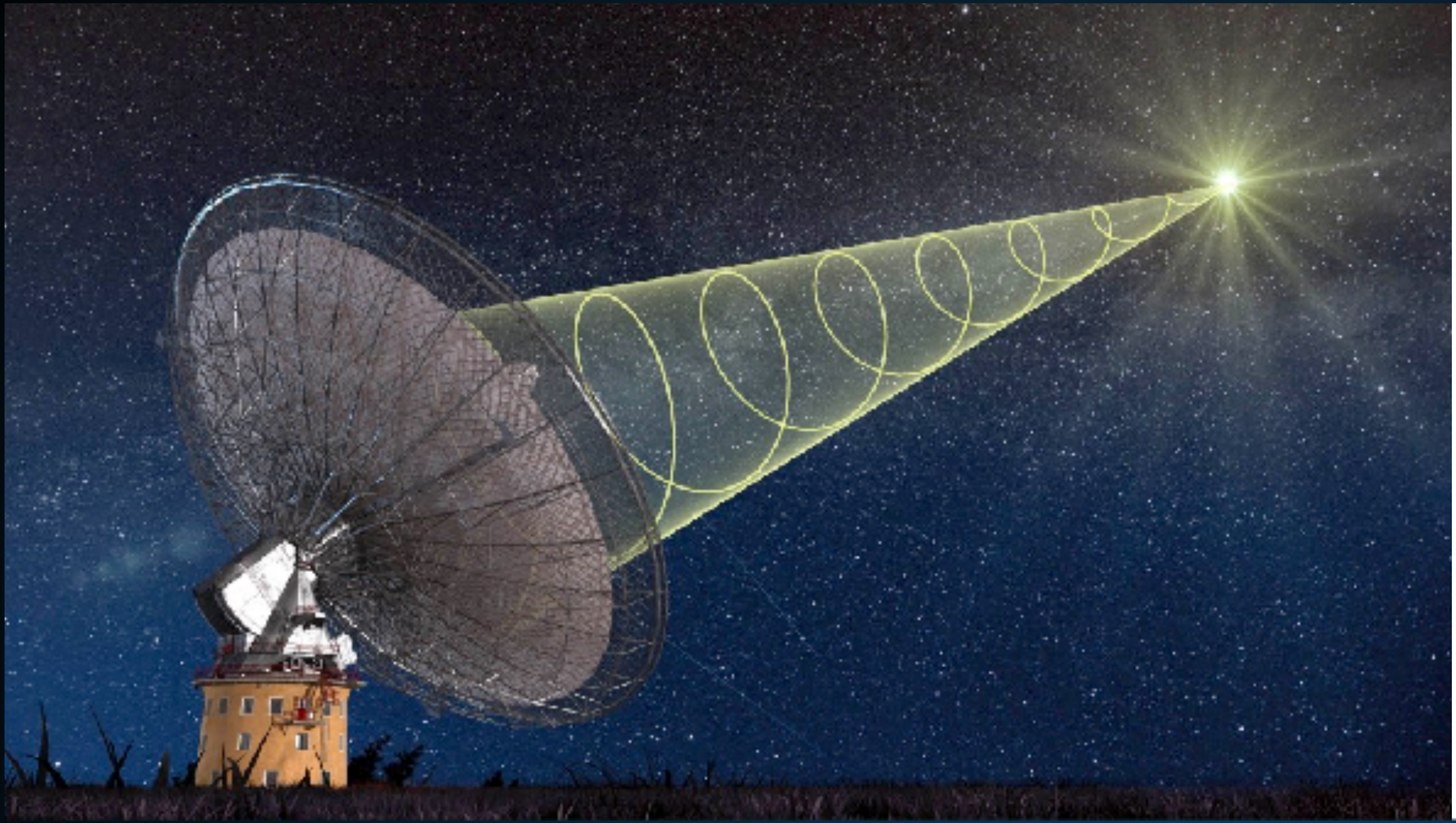
- Prediction: Globular Clusters should not be similarly r-process enriched.

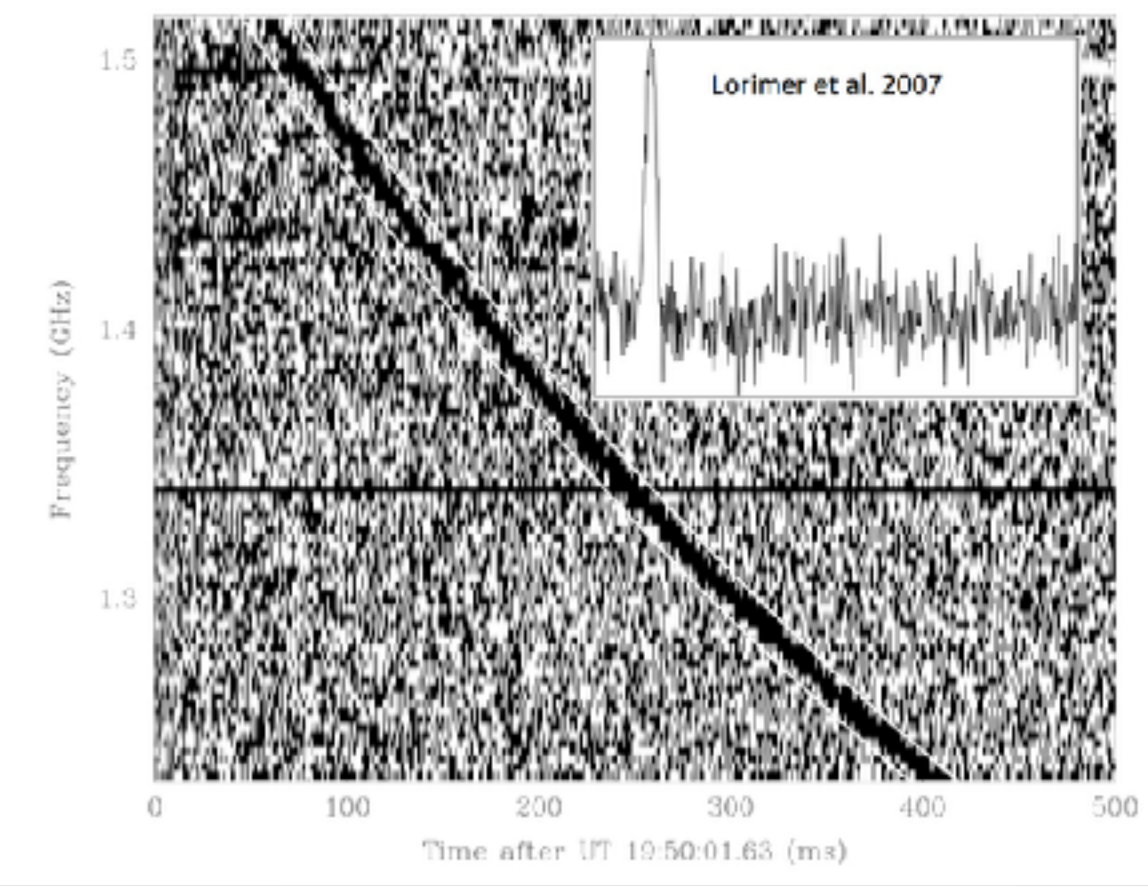


- In fact, no globular cluster has been observed to have an r-process overabundance exceeding 1.2 dex.

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

FAST RADIO BURSTS



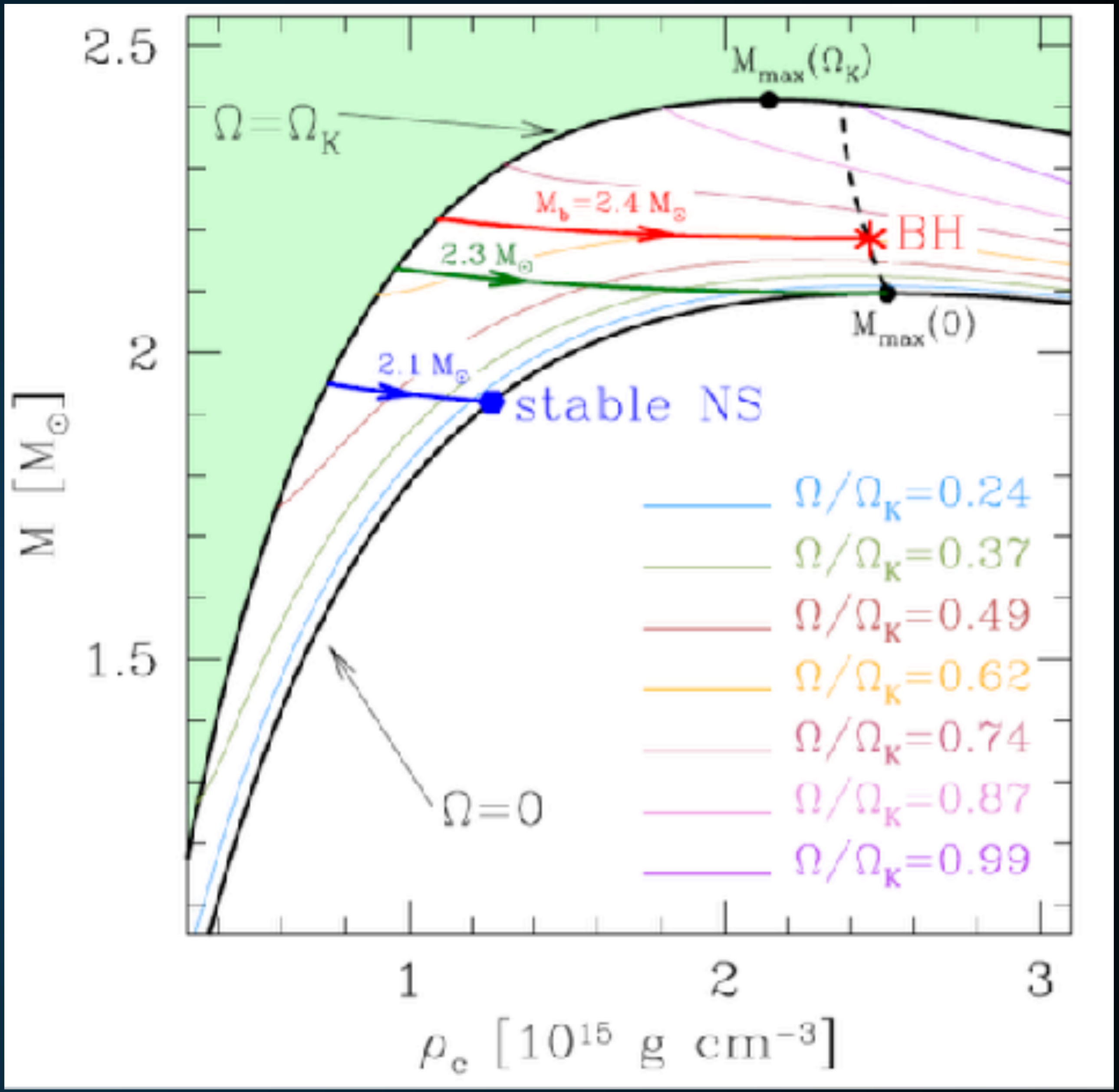


- Short (~ms) radio bursts first discovered in 2007
- High dispersion measure indicates extragalactic origin.
- One repeating fast radio bursts, but others appear not to repeat.
- Origin unknown.

FAST RADIO BURSTS FROM PULSARS

Falcke & Rezzolla (1307.1409)

- Millisecond timescale indicates size < 300 km.
- Radio pulsar magnetic fields have energetics and cooling timescales needed to produce emission.
- Models of neutron star mergers and accretion induced collapse have been proposed.

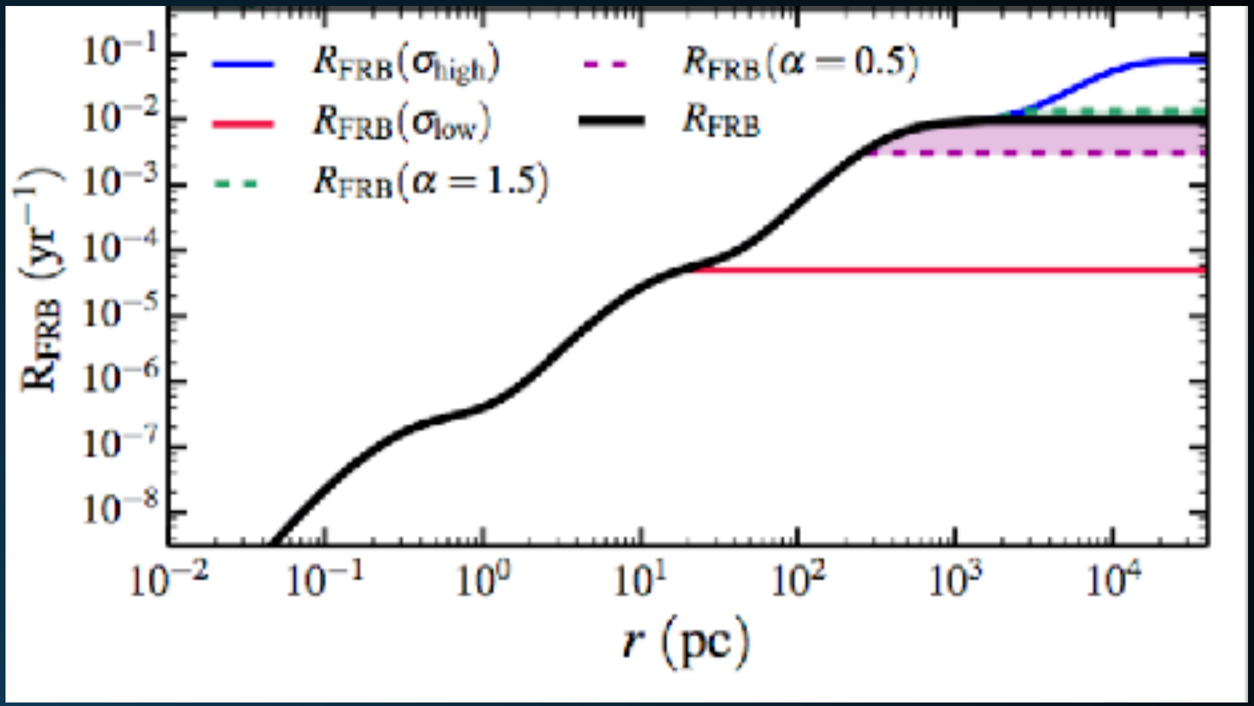


- Accretion induced collapse acts similarly to DM induced collapse.

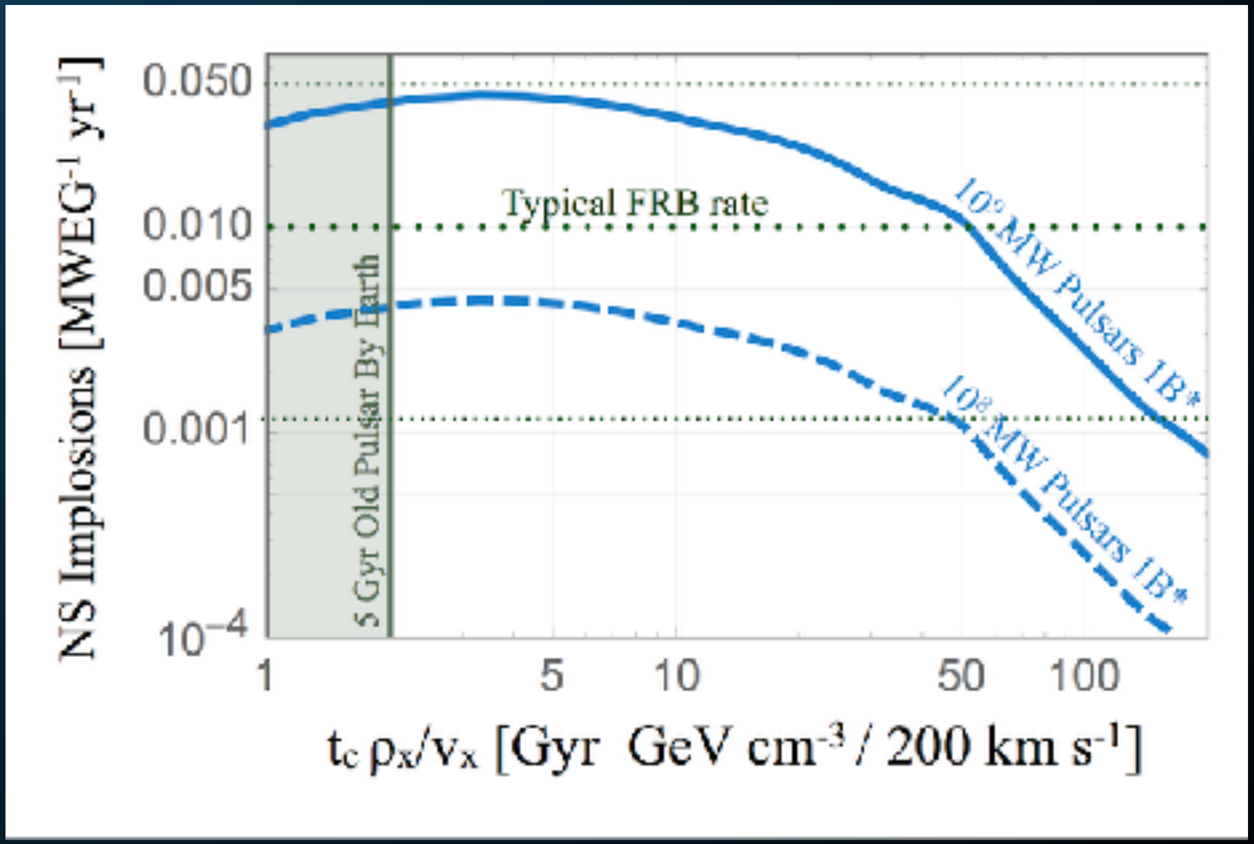
FAST RADIO BURSTS FROM PULSARS

- FRB rates may be as high as 10^5 day^{-1}.
- Consistent with a galactic FRB rate of 10^{-2} yr^{-1} and with the SN rate.
- Consistent with the cross-sections needed to explain the missing pulsar problem.

Fuller & Ott (1412.6119)



Bramante et al. (1706.00001)



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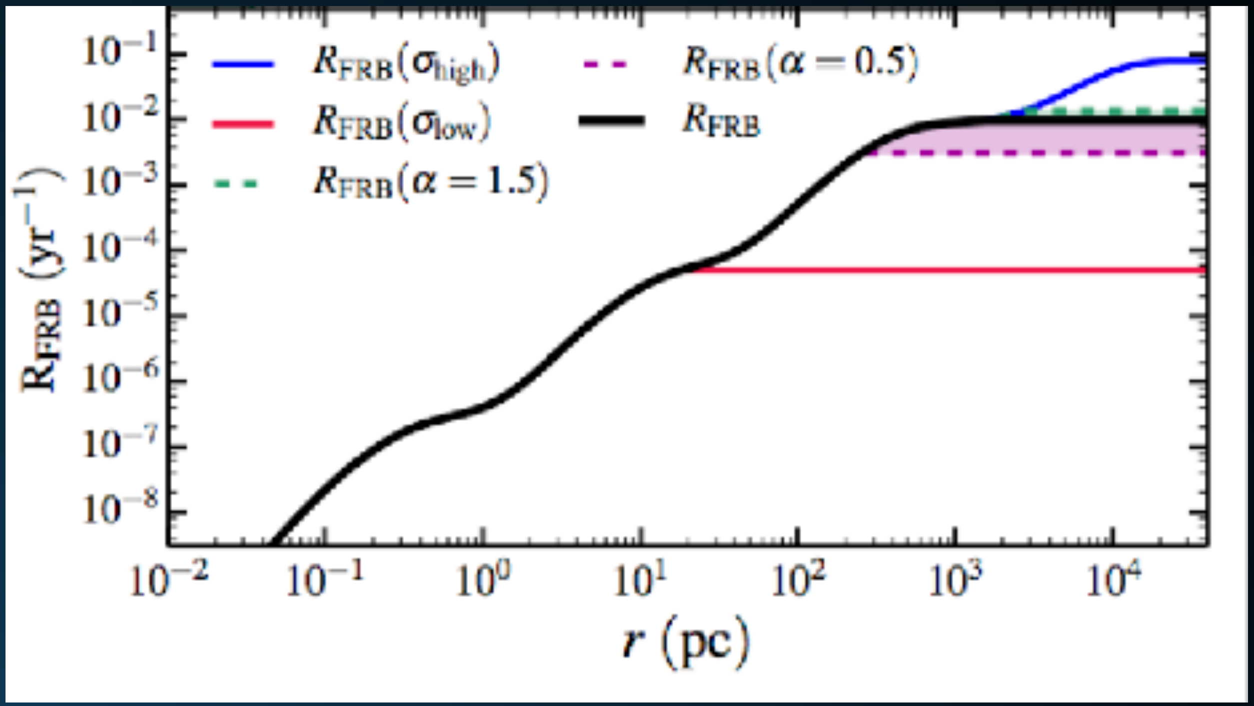
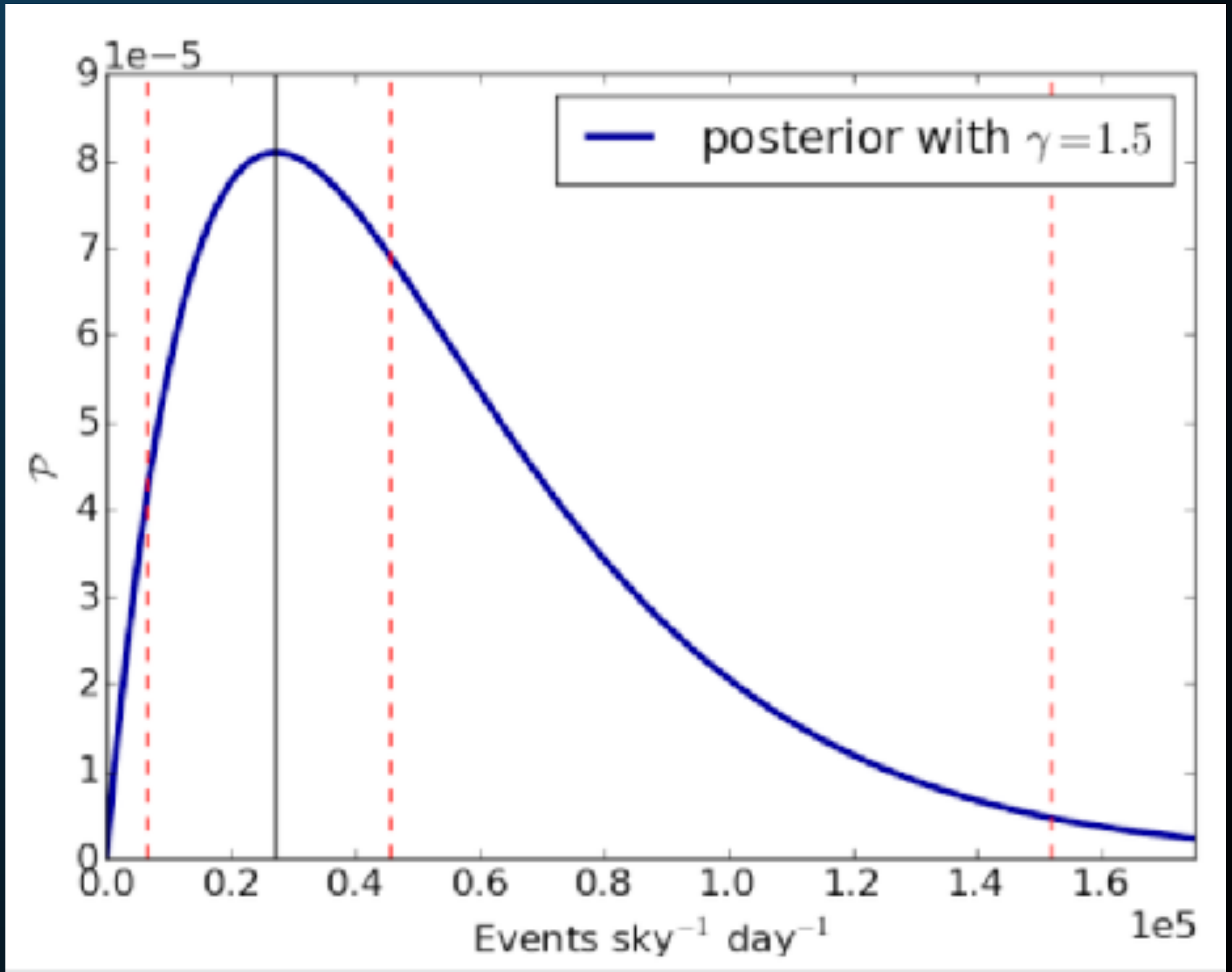
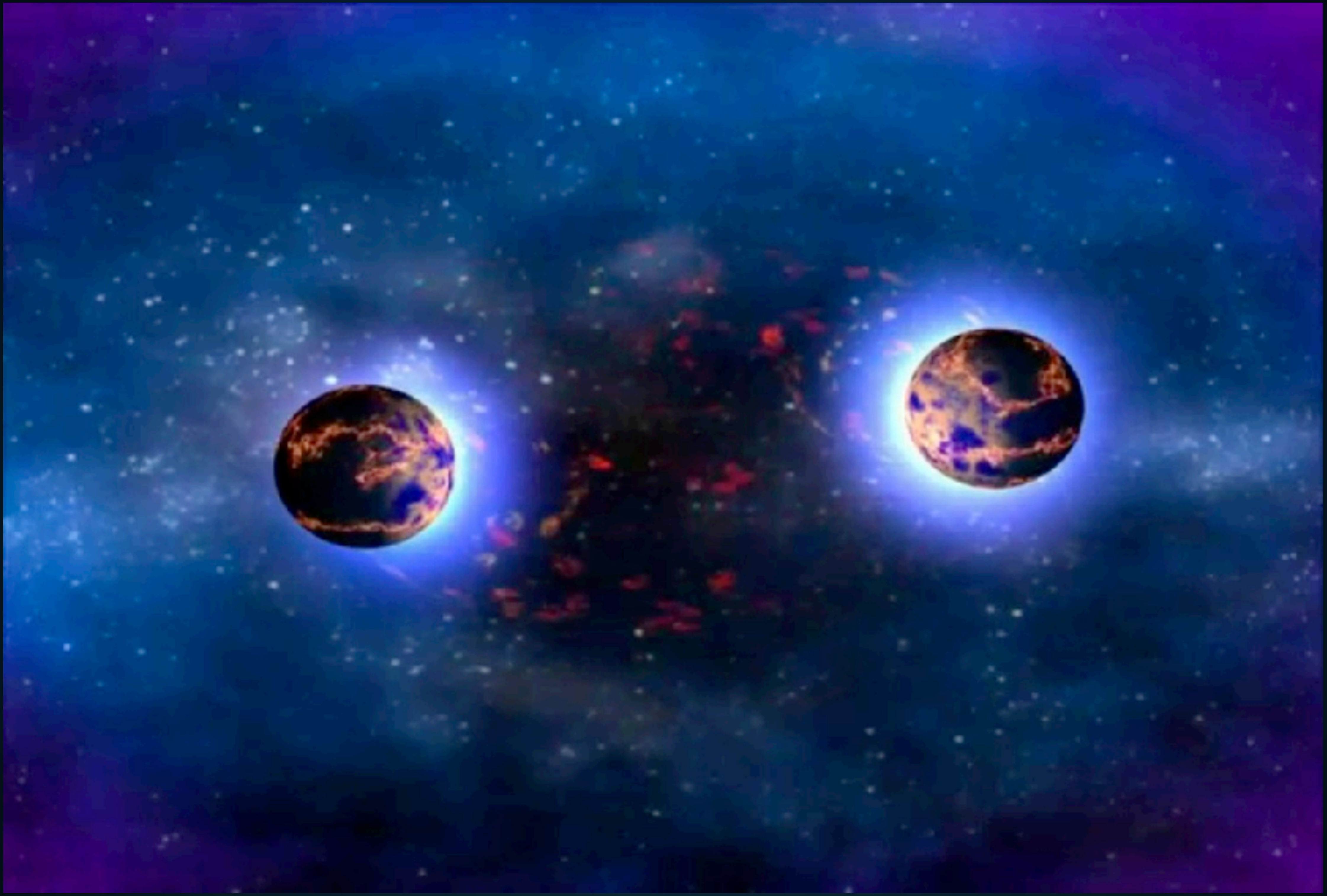


Connor et al. (1602.07292)



NS IMPLOSIONS AND DOUBLE COMPACT OBJECTS



- **Dark Matter induced implosions can affect the signals expected from LIGO.**

GRAVITATIONAL WAVE SIGNATURES OF DM INDUCED COLLAPSE

- Three Potential Signals:
  - Gravitational Waves from DM induced collapse
  - Anomalies in the tidal strain of binary neutron star mergers.
  - Disassociation of electromagnetic and gravitational wave signatures

GRAVITATIONAL WAVE SIGNATURES OF DM INDUCED COLLAPSE

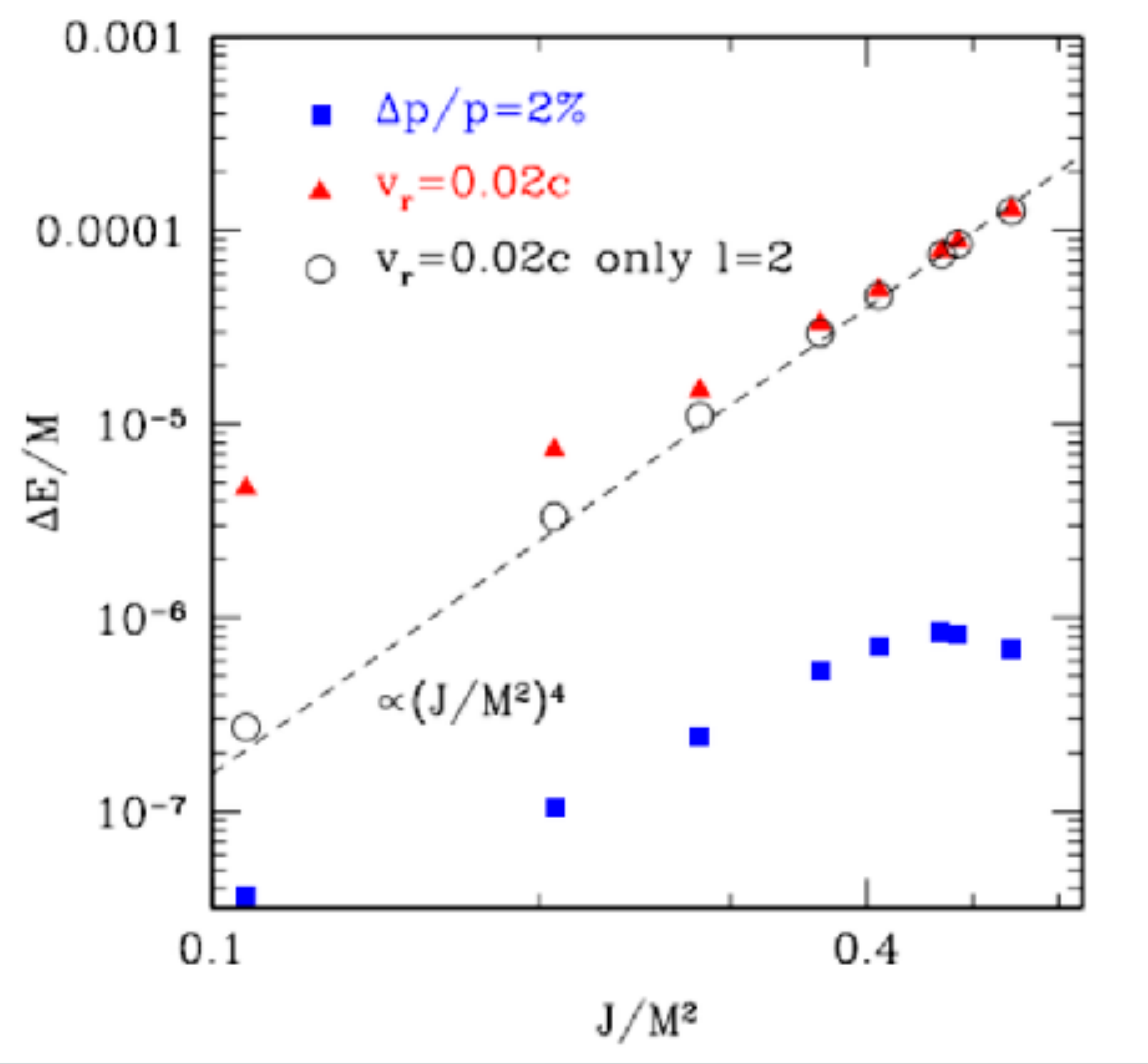
- **Gravitational Waves from DM induced collapse**

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

Baiotti et al. (gr-qc/0701043)

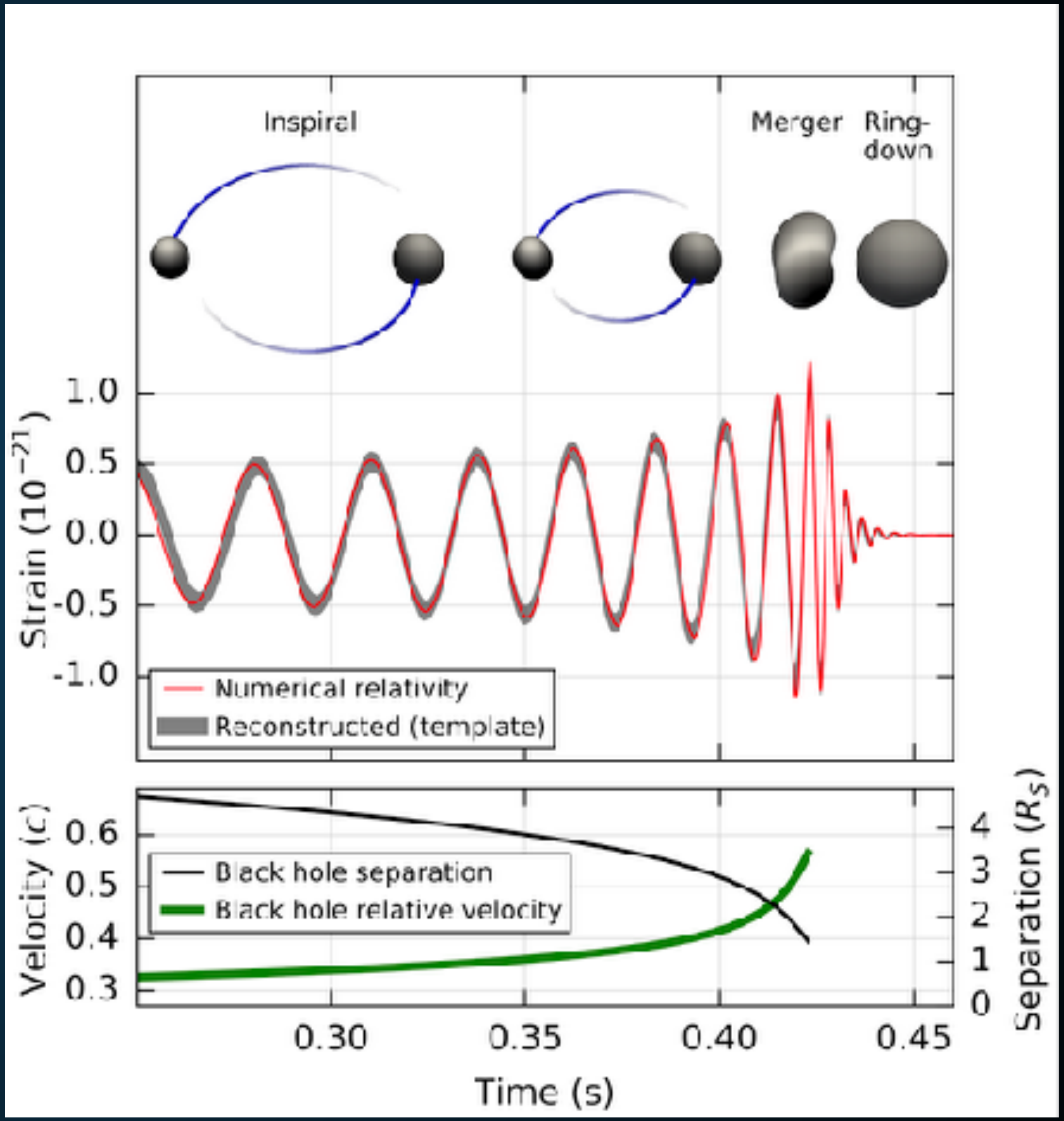
- **Single NS collapse models have been considered (primarily from accretion induced collapse).**

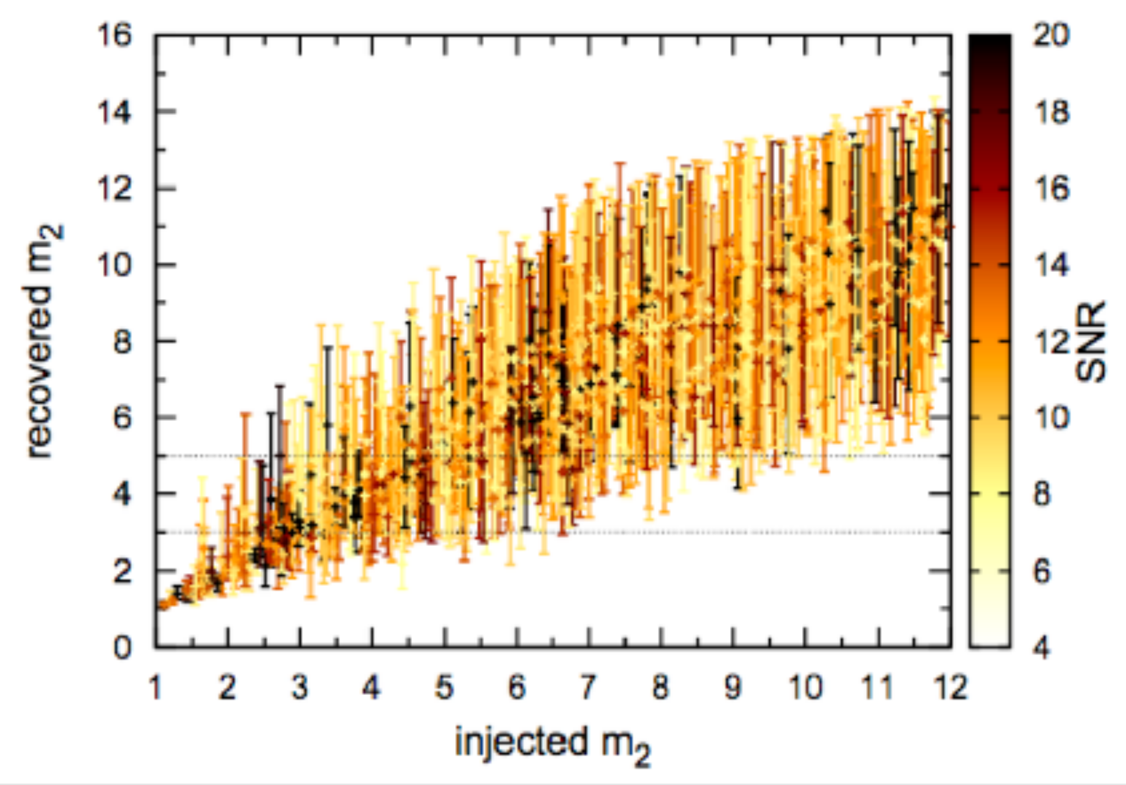
- **DM induced NS collapse observable throughout the Milky Way (0.01 yr^{-1} ?)**



GRAVITATIONAL WAVE SIGNATURES OF DM INDUCED COLLAPSE

- 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.



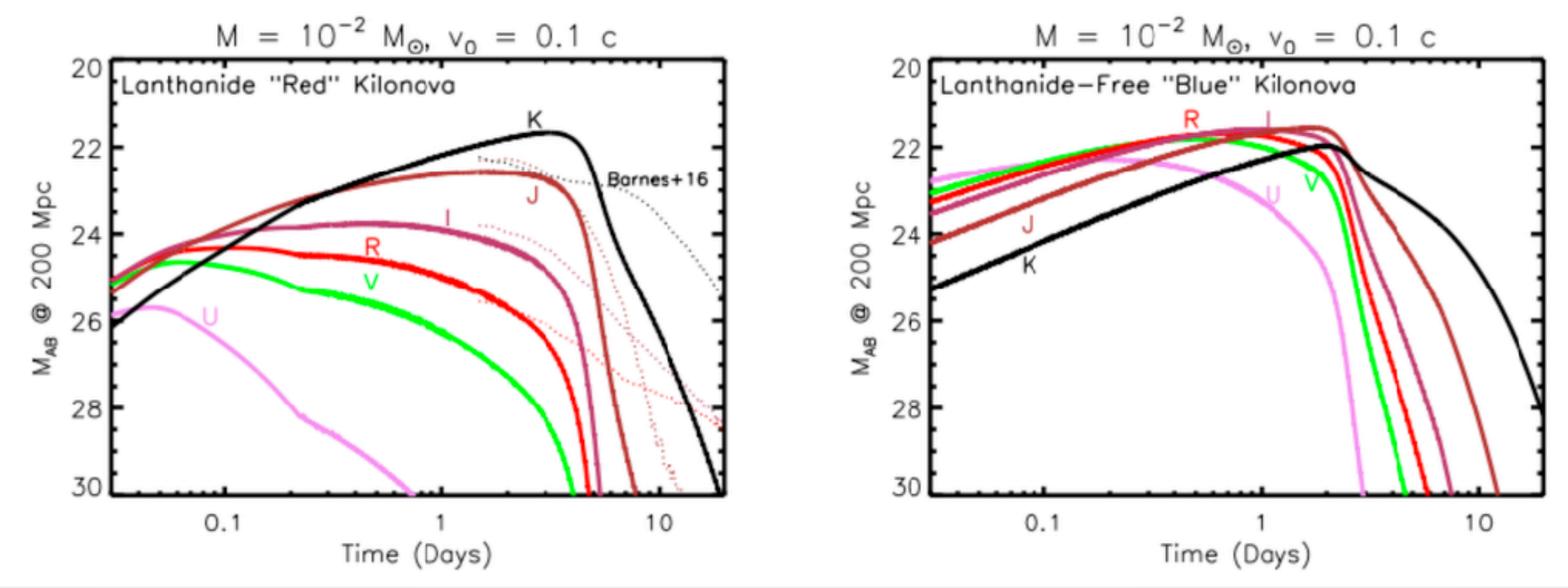


Littenburg et al. (1503.03179)

MERGER KILONOVAE

Metzger (1610.09381)

- Disassociation of electromagnetic and gravitational wave signatures

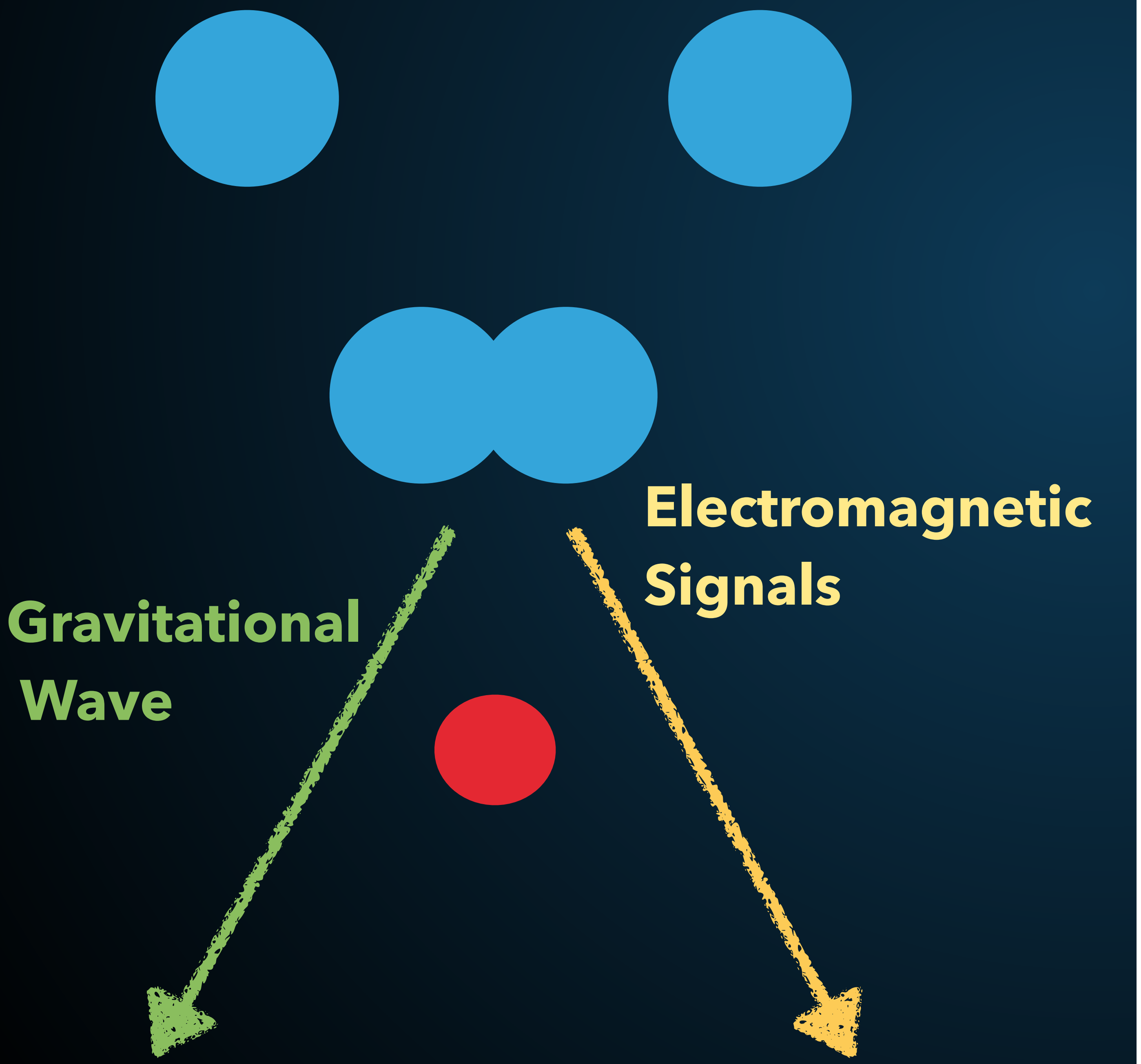


- Kilonovae - Days long afterglows of NS-NS mergers formed primarily by beta-decay of r-process materials.
- Likely associated with sGRBs - but better localization.

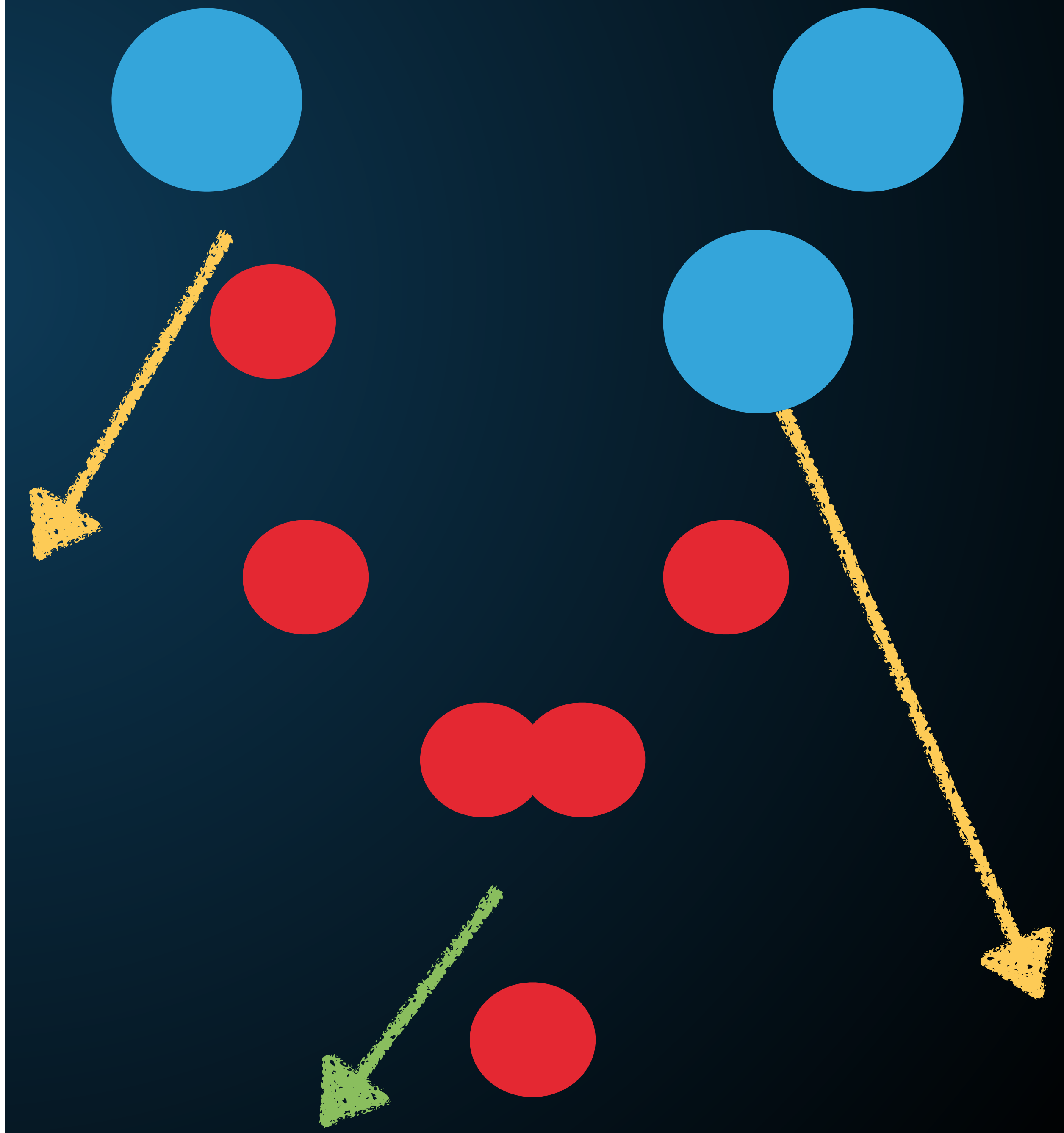
DISSOCIATION OF EM AND GRAVITATIONAL SIGNATURES

- Disassociation of electromagnetic and gravitational wave signatures

No DM Induced Collapse



DM Induced Collapse



IN CASE YOU'VE BEEN ASLEEP (NOW OR IN THE LAST 3 MONTHS)

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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.)

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Abstract

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

SOME TERMS

Bramante, TL, Raj (1706.00001)

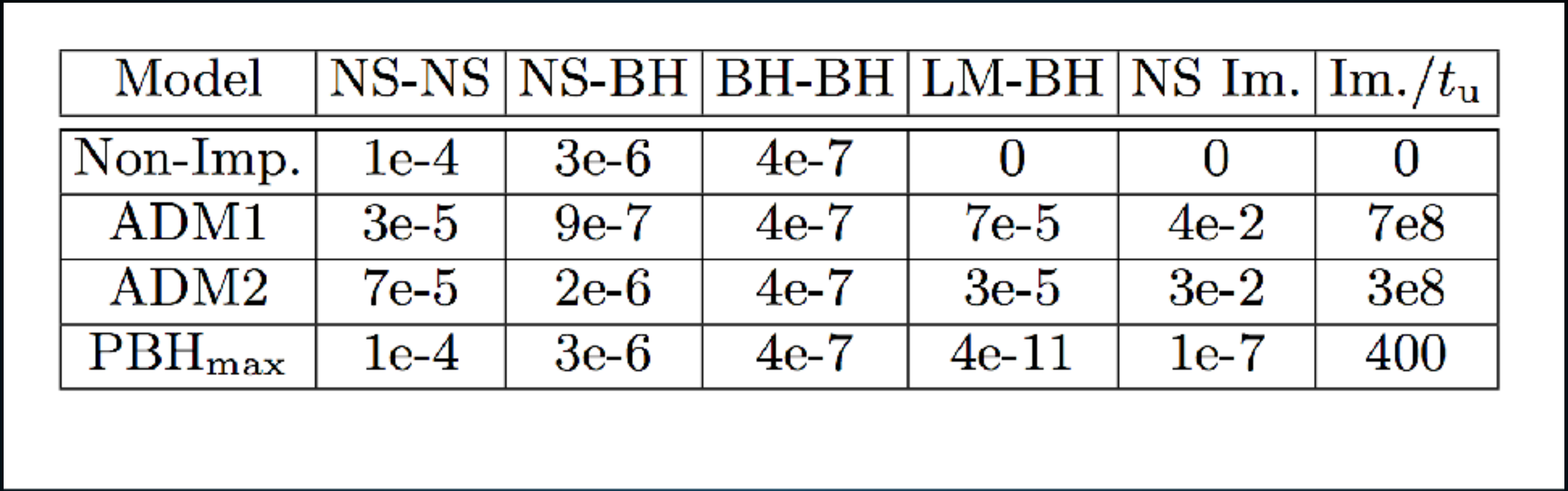
- **Merger Kilonovae** - Bright r-process afterglows of NS-NS binary mergers.

- **Quiet Kilonovae** - Possible r-process afterglows of DM induced neutron star collapse

- **Dark Mergers** - Interactions that look like NS-NS binaries to LIGO, but both NS have already collapsed, and thus no electromagnetic counterpart is found.

RADIAL DEPENDENCE OF DM INDUCED COLLAPSE

Bramante, TL, Raj (1706.00001)



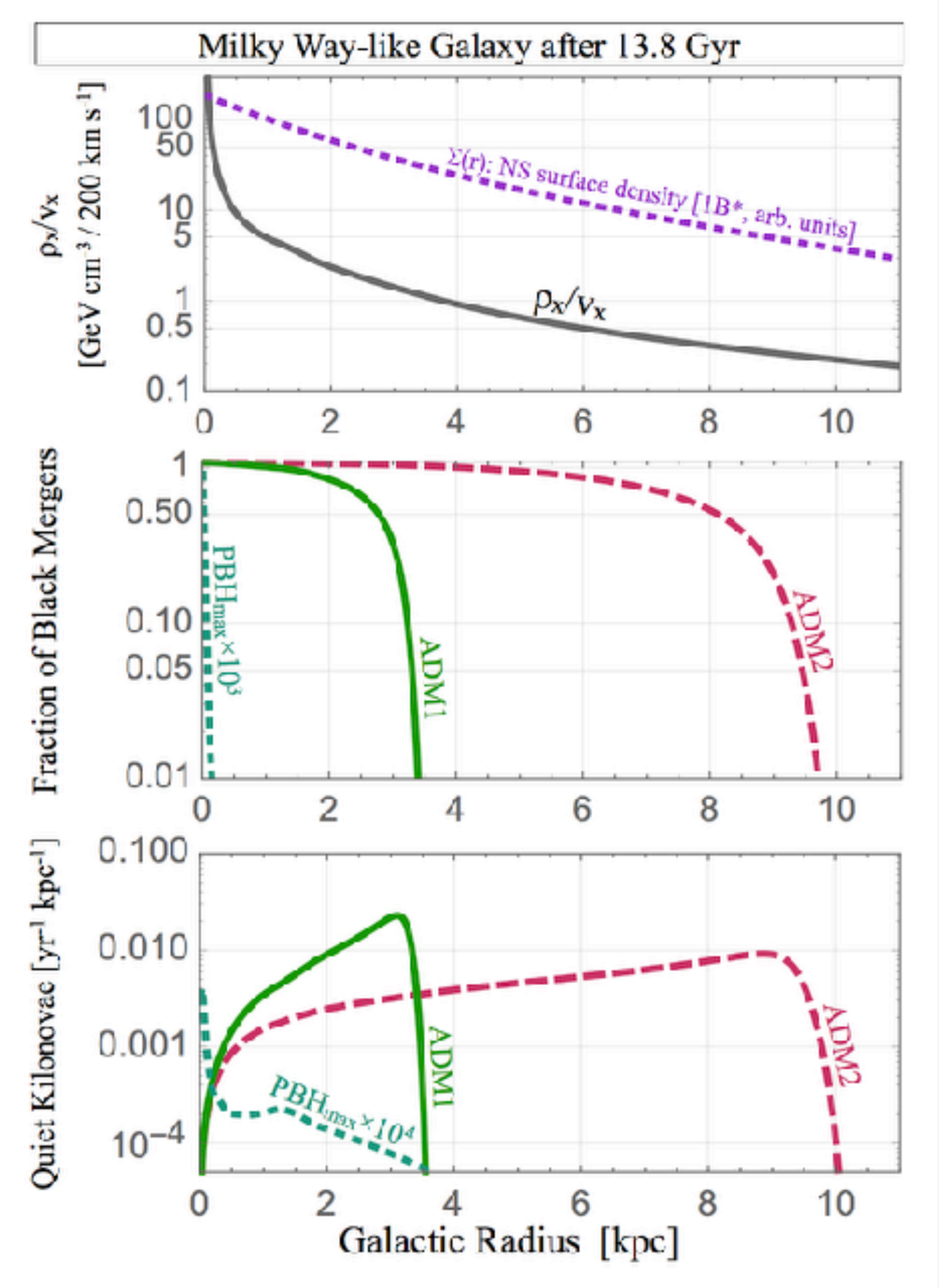
Model	NS-NS	NS-BH	BH-BH	LM-BH	NS Im.	Im./t_u
Non-Imp.	1e-4	3e-6	4e-7	0	0	0
ADM1	3e-5	9e-7	4e-7	7e-5	4e-2	7e8
ADM2	7e-5	2e-6	4e-7	3e-5	3e-2	3e8
PBH_{max}	1e-4	3e-6	4e-7	4e-11	1e-7	400

- A reasonable fraction of all NS-NS mergers should actually be LM-LM mergers.
- LM-NS mergers occur in primordial black hole models.
- Difficult to argue that you have found dark matter by not seeing something that you should….

RADIAL DEPENDENCE OF DM INDUCED COLLAPSE

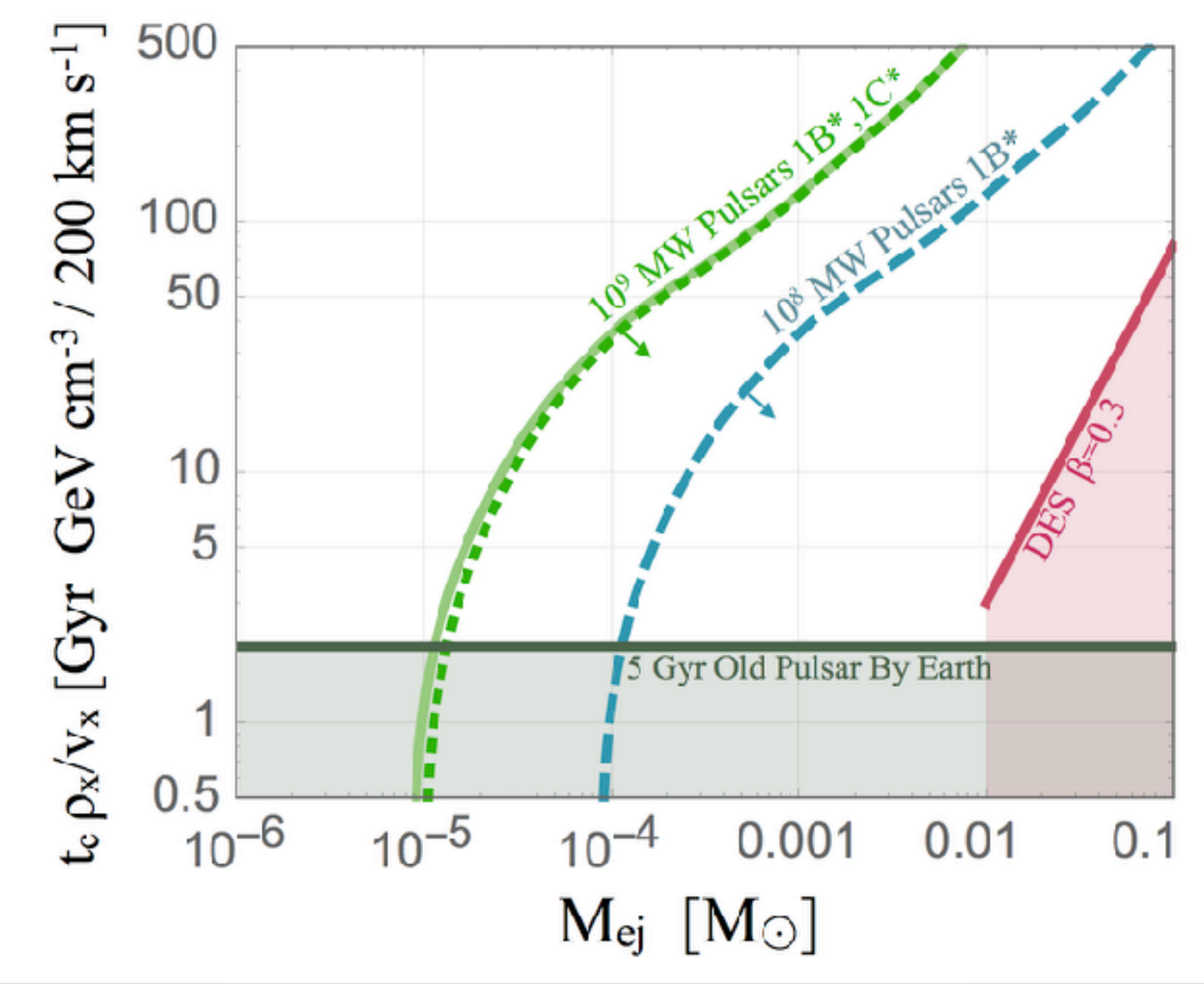
Bramante, TL, Raj (1706.00001)

- **This scenario does not happen equivalently through the galaxy.**
- **Bright kilo novae associated with NS-NS mergers should be detected, but only in the outskirts of galaxies.**



CONSISTENCY WITH R-PROCESS AND FRB RATES

Bramante, TL, Raj (1706.00001)

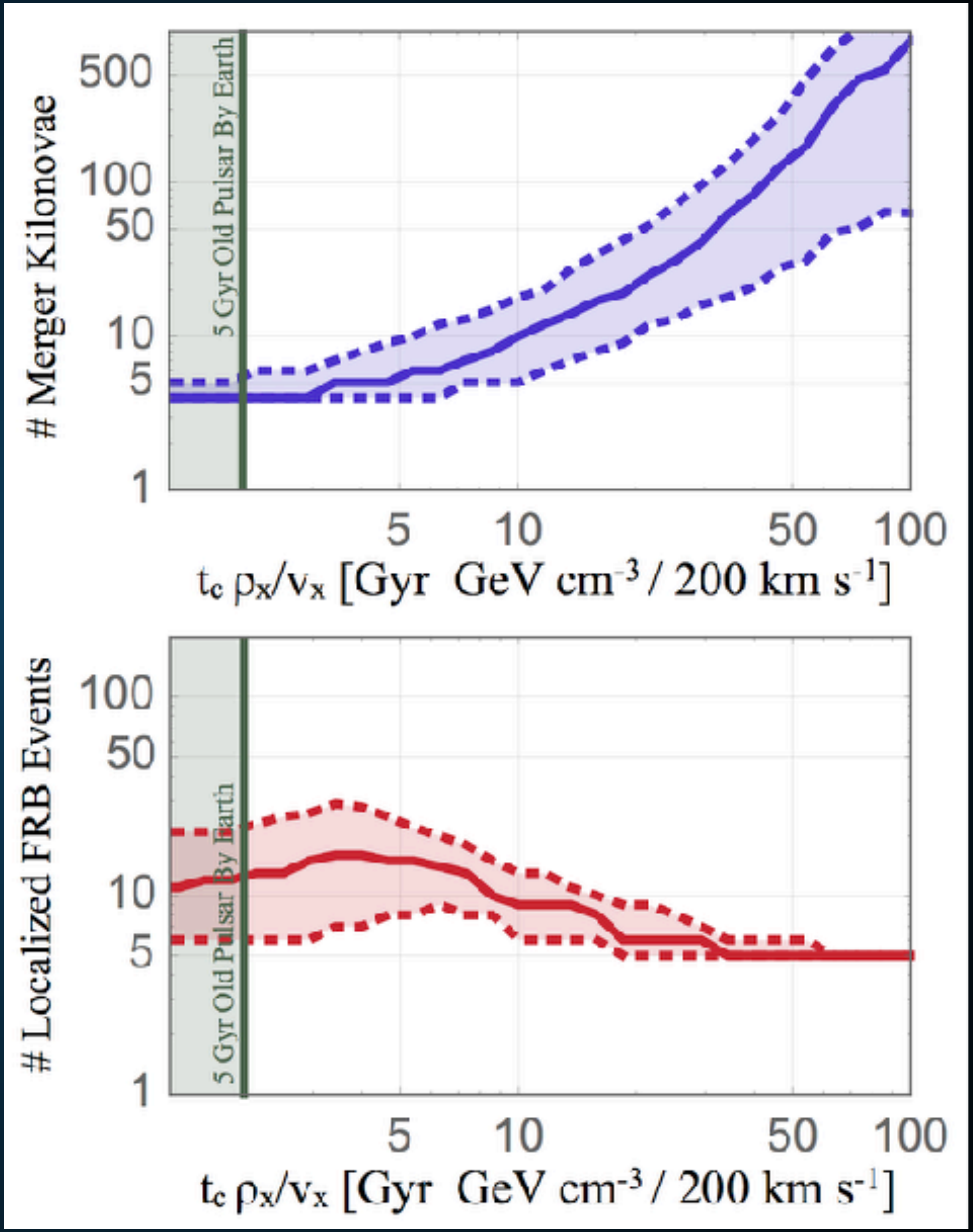


- **These models reasonably re-produce the observed r-process abundance with “quiet kilonovae” that do not have a gravitational wave counterpart.**

USING SPATIAL INFORMATION TO FIND DM

Bramante, TL, Raj (1706.00001)

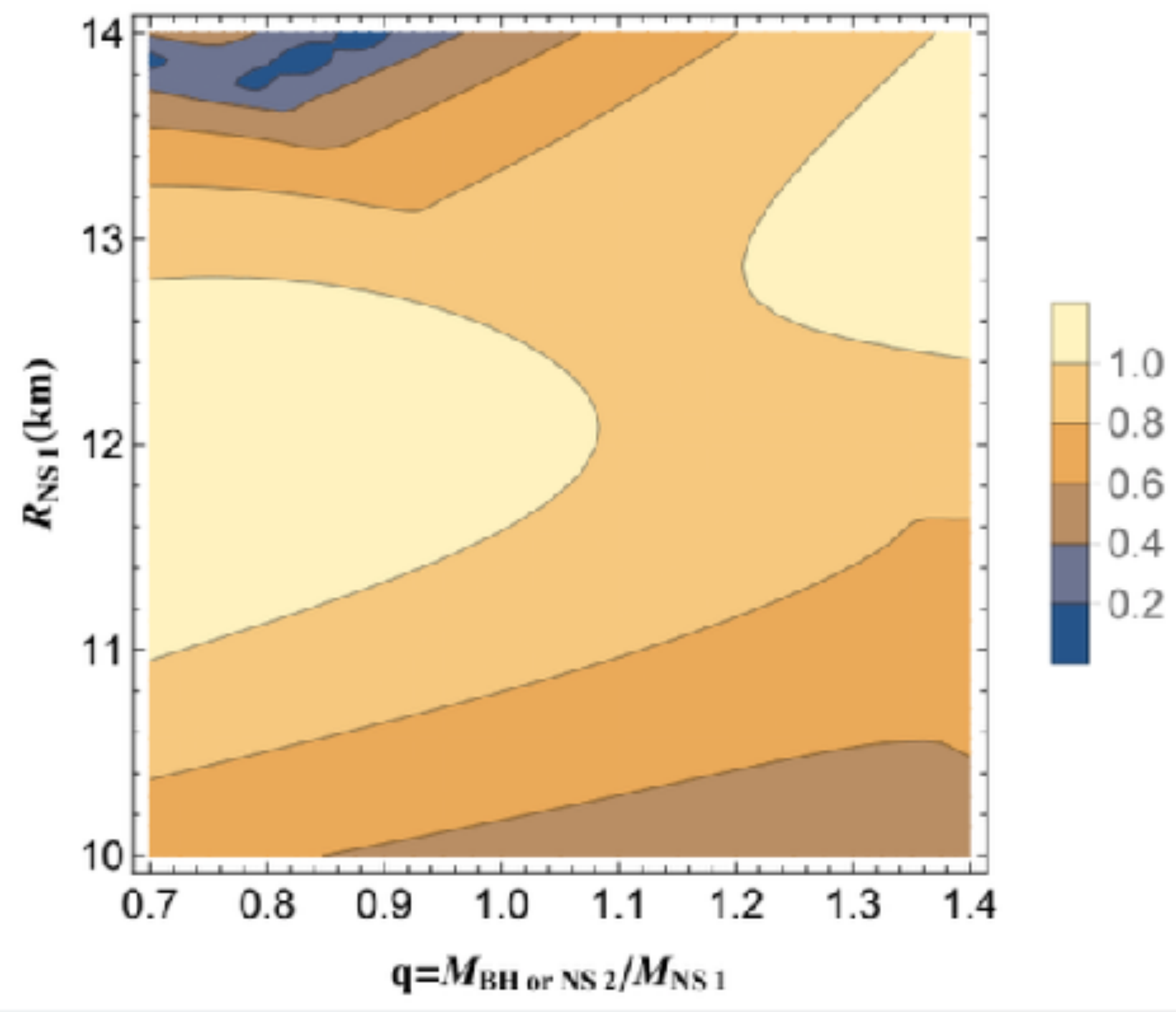
- By localizing either merger kilonovae or fast-radio bursts, can differentiate models where DM collapses NS.
- FRB instruments such as CHIME expected to detect ~1000 FRBs in the next few years.



USING SPATIAL INFORMATION TO FIND DM

Yang et al. (1710.05891)

- **Can also potentially differentiate low-mass BH mergers from NS-NS mergers.**
- **Will require stacking a large number of LIGO events, or more sensitive gravitational wave detectors.**



DISCUSSION AND CONCLUSIONS

- Asymmetric dark matter models naturally produce neutron star collapse in regions with high dark matter density and low velocity dispersion.
- There are a number of astrophysical signals (and hints!) of such interactions.
- Future observations are likely to definitively prove, or rule out, this class of models.