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ASTROPHYSICAL SIGNATURES OF DARK MATTER ACCUMULATION IN NEUTRON STARS

Kings College Seminar

July 5, 2017

The Ohio State University

CENTER FOR COSMOLOGY AND ASTROPARTICLE PHYSICS

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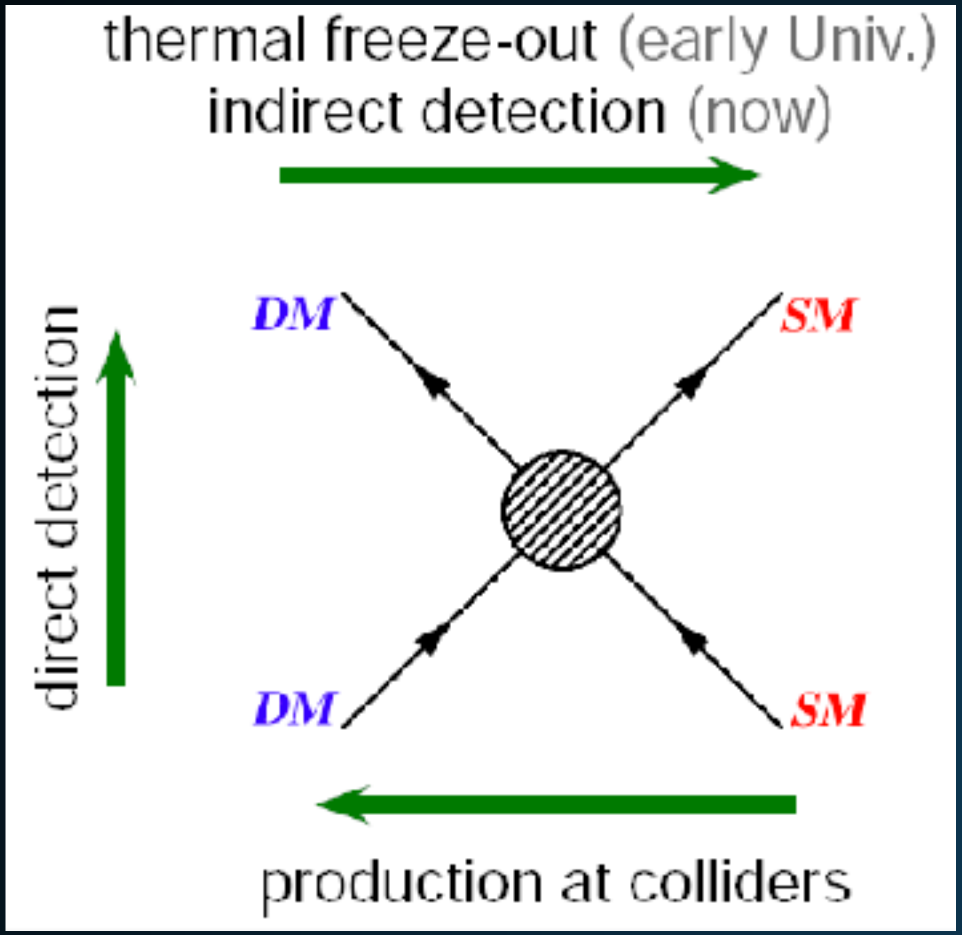
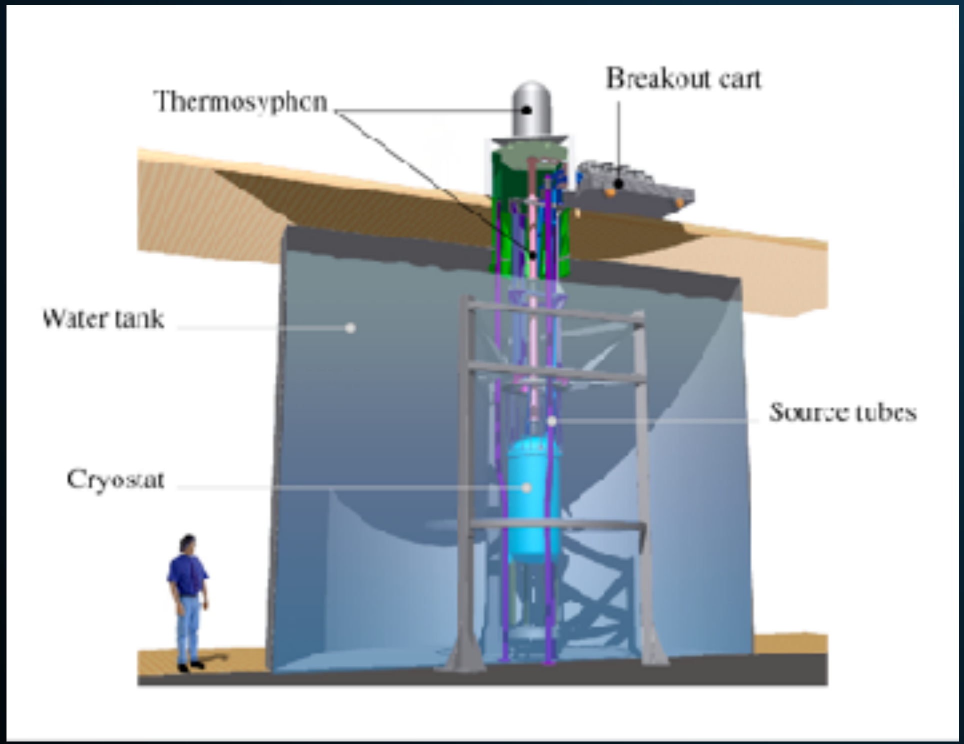
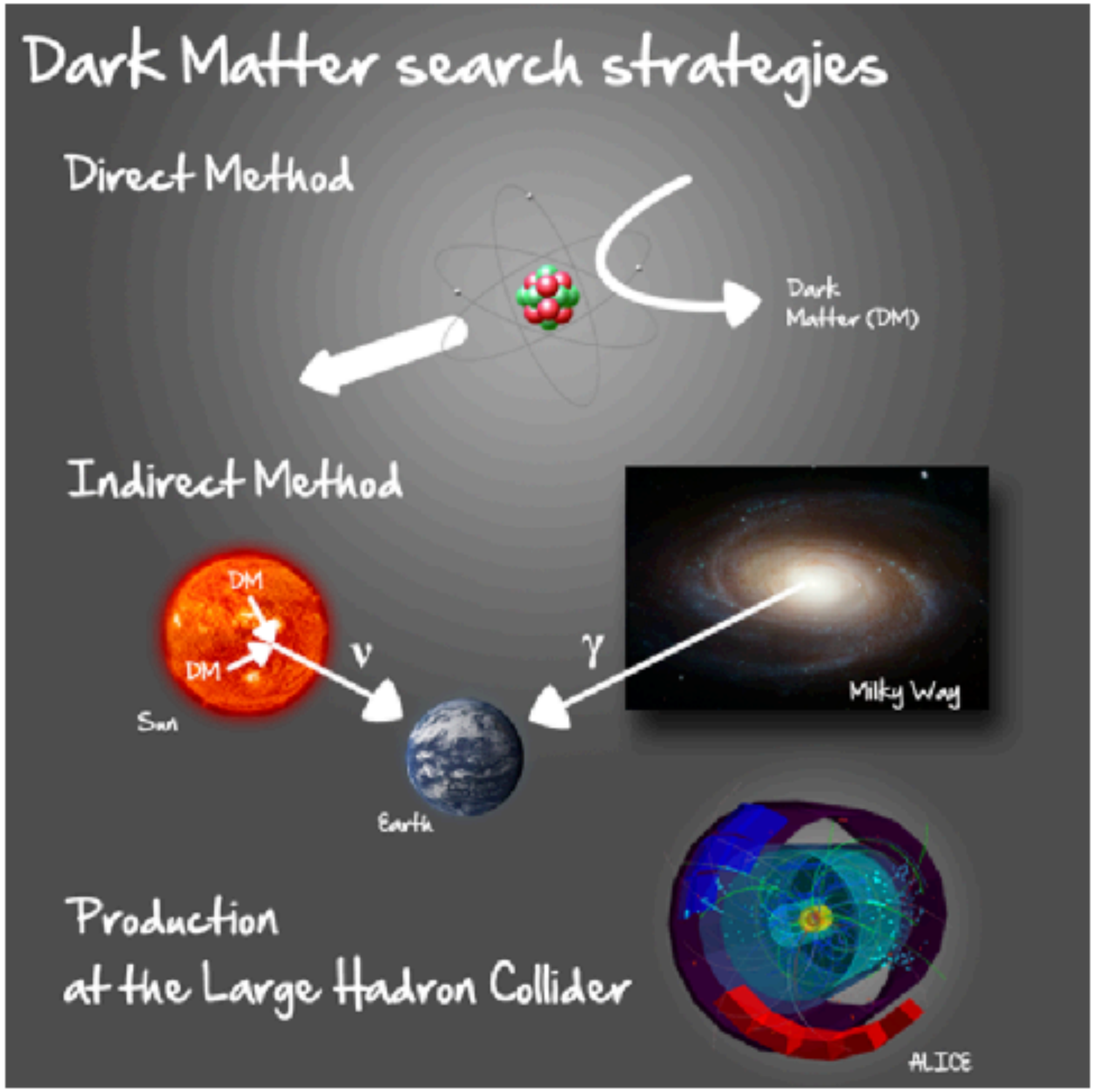
DARK MATTER DIRECT DETECTION



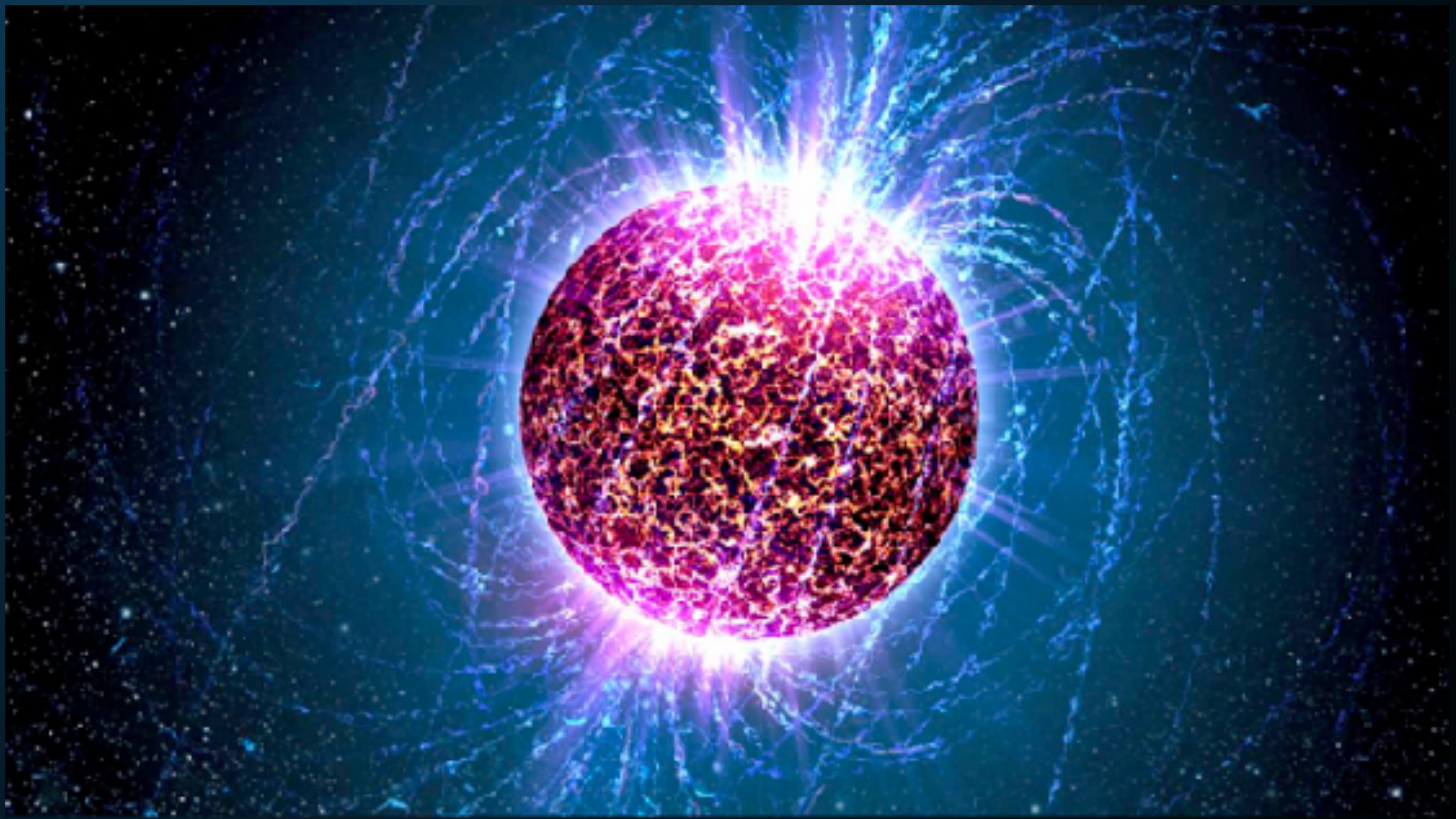




How to detect dark matter (credit: HAP / A. Chantelauze)

NEUTRON STARS AS DIRECT DETECTION LABORATORIES

- Xenon1T
  - 1000 kg
  - 730 day
- 7.3 x 10^5 kg day



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

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

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

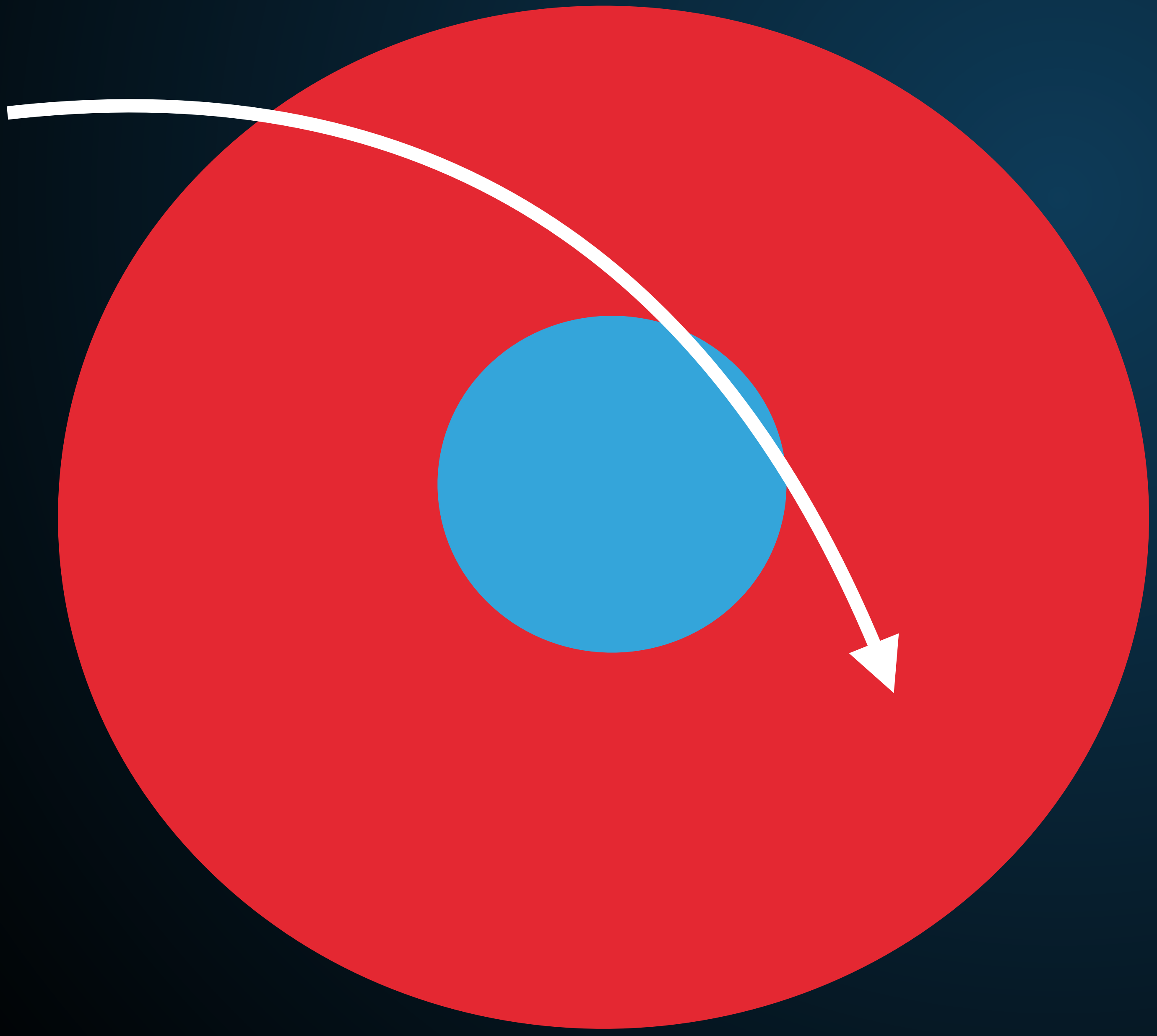
- **This saturates the sensitivity of neutron stars as dark matter detectors. Do not get additional sensitivity to higher cross-sections (in general).**

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

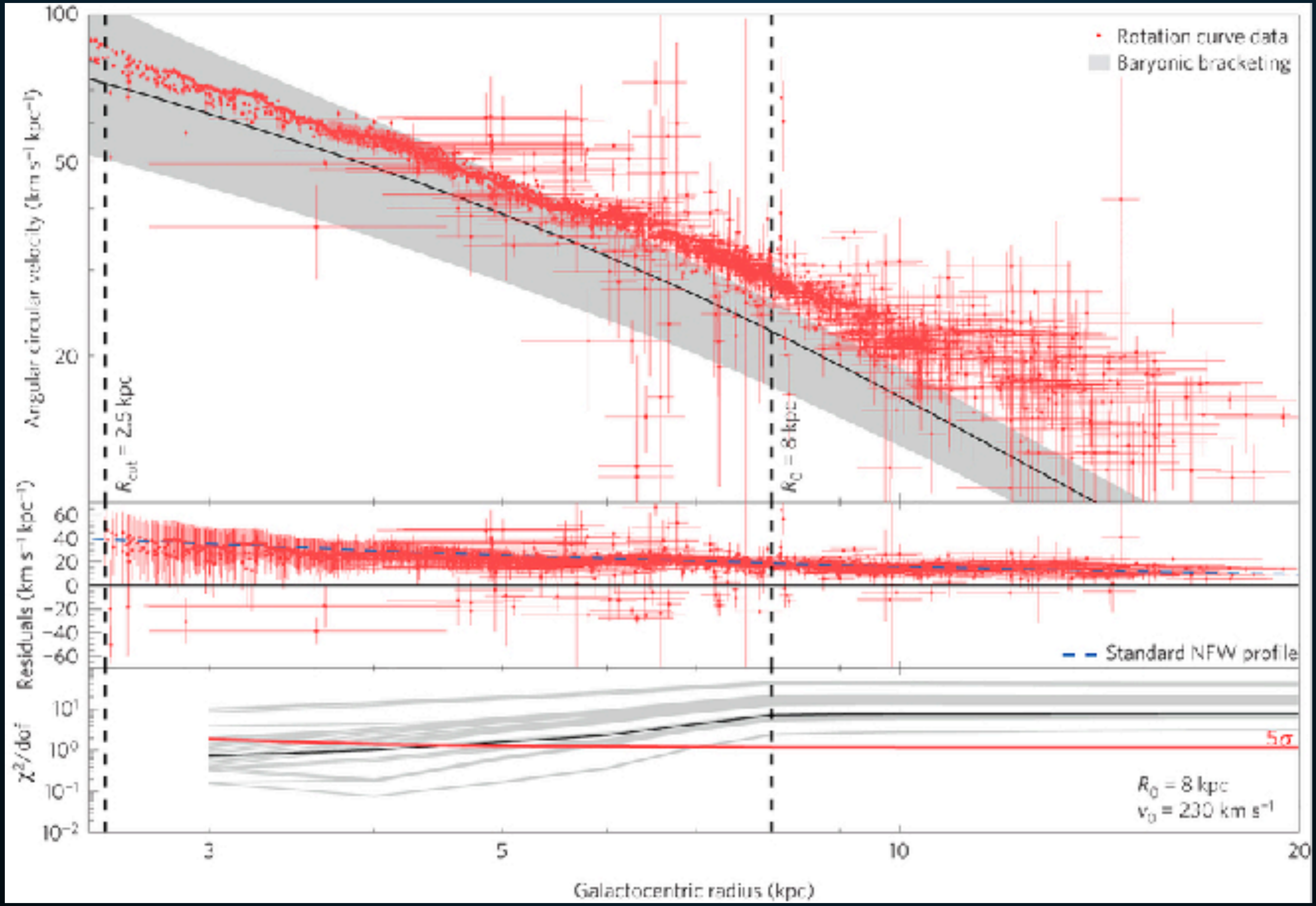


Potential well moves slowly moving dark matter particles into collisional orbit.

Interaction rate scales as v_X^{-1}.

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:

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

Typical NS proton momentum is:

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

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

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

- **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:

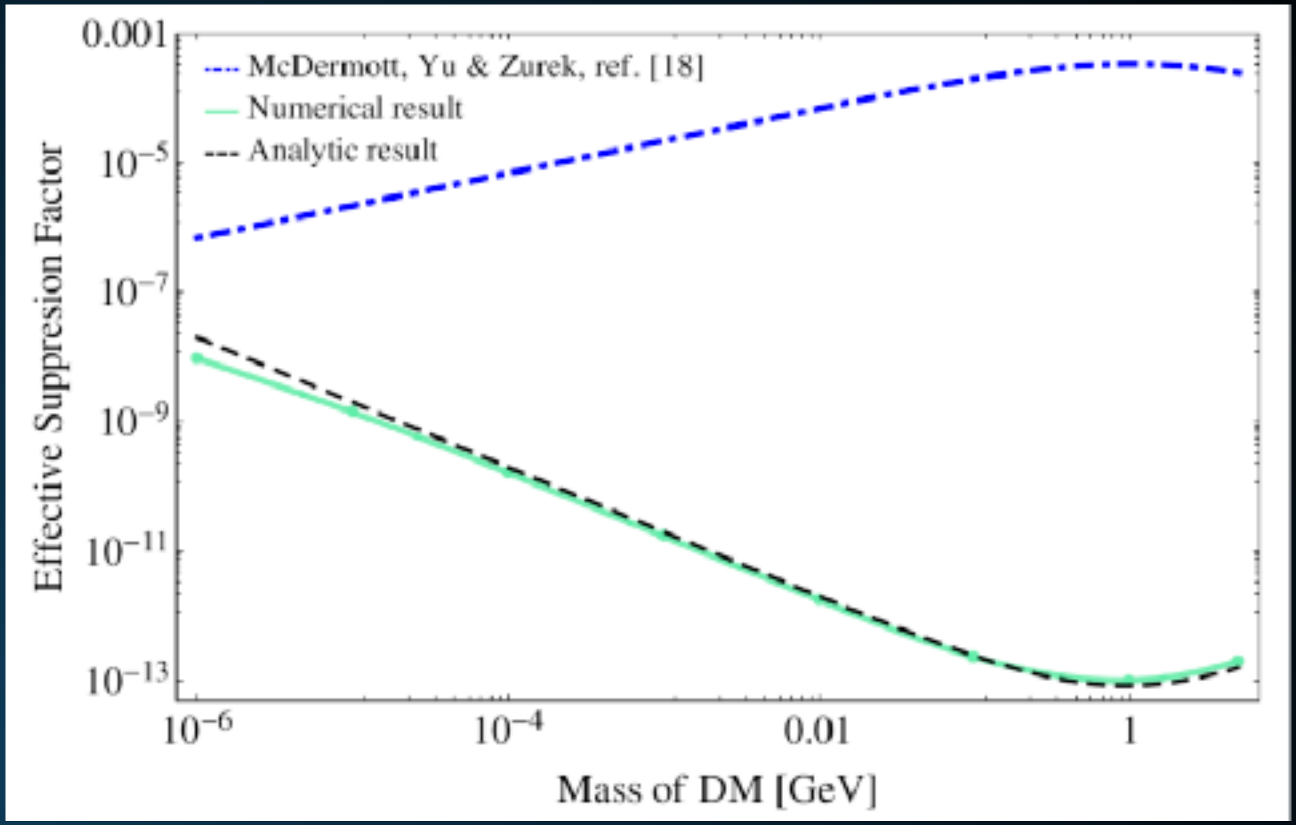
$$E_{loss} = \frac{2m_p}{m_\chi}(m_\chi v_\chi^2)$$

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

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

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:

$$\tau \approx 3750 \text{ yrs } \frac{\gamma}{(1+\gamma)^2}\left(\frac{2\times 10^{-45}\text{ cm}^2}{\sigma}\right)\left(\frac{10^5\text{ K}}{T}\right)^2 ,$$

- 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:

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

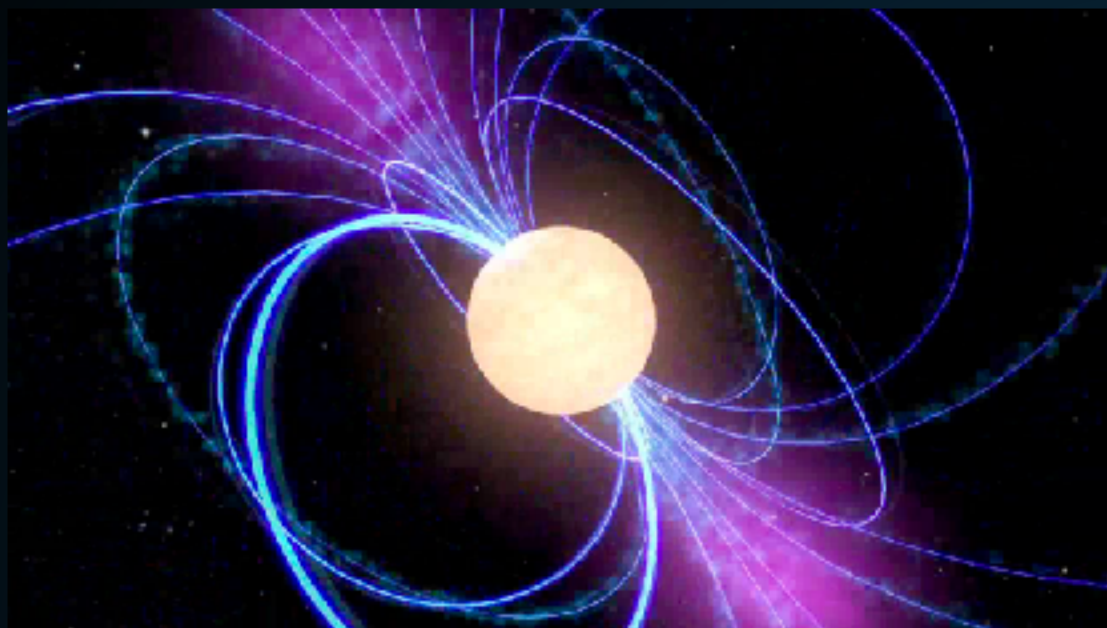
LOTS OF DARK MATTER MODELS (NO DETAILS HERE)

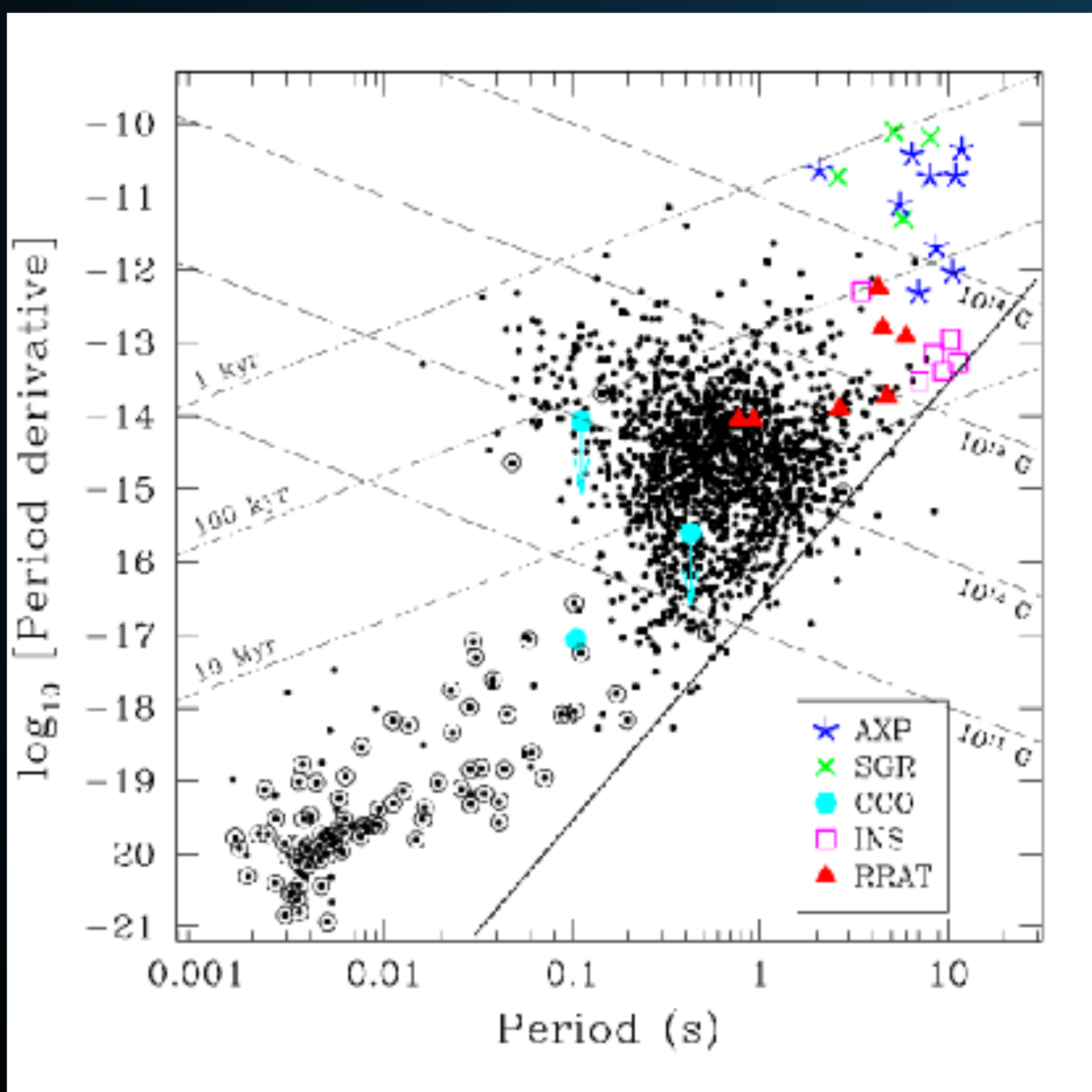
- Asymmetric Dark Matter is well-motivated
  - e.g. Baryon/Lepton Asymmetry through dark baryogengesis
- Some models do not work, e.g. GeV Fermions require ~1 $M_{\odot}$ of dark matter to be accreted

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

- <u>Many models do work:</u>
  - 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



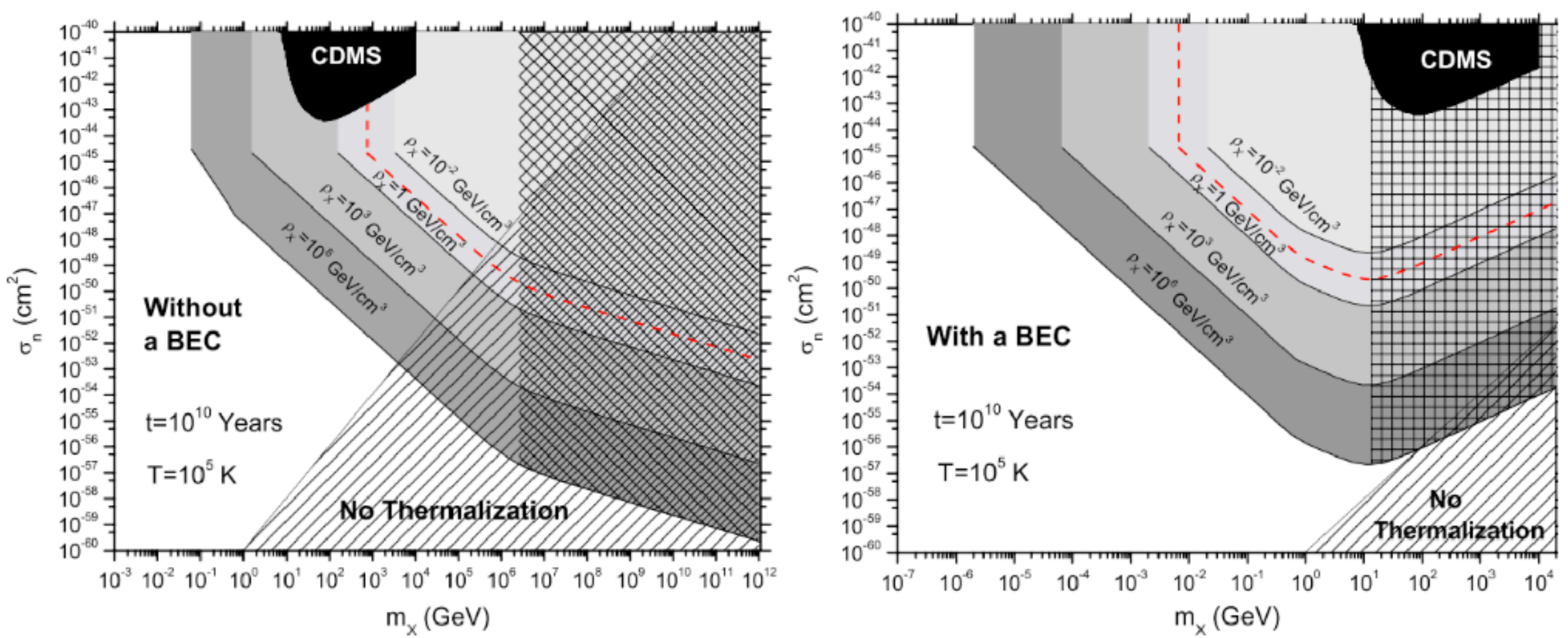


- **Pulsars = Quickly rotating NS with strong B-fields**
- **Rotation slows due to dipole radiation**
- **Can approximate age if period and period-derivative are known:**

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

PROBLEM: WE SEE OLD NEUTRON STARS

McDermott et al. (1103.5472)

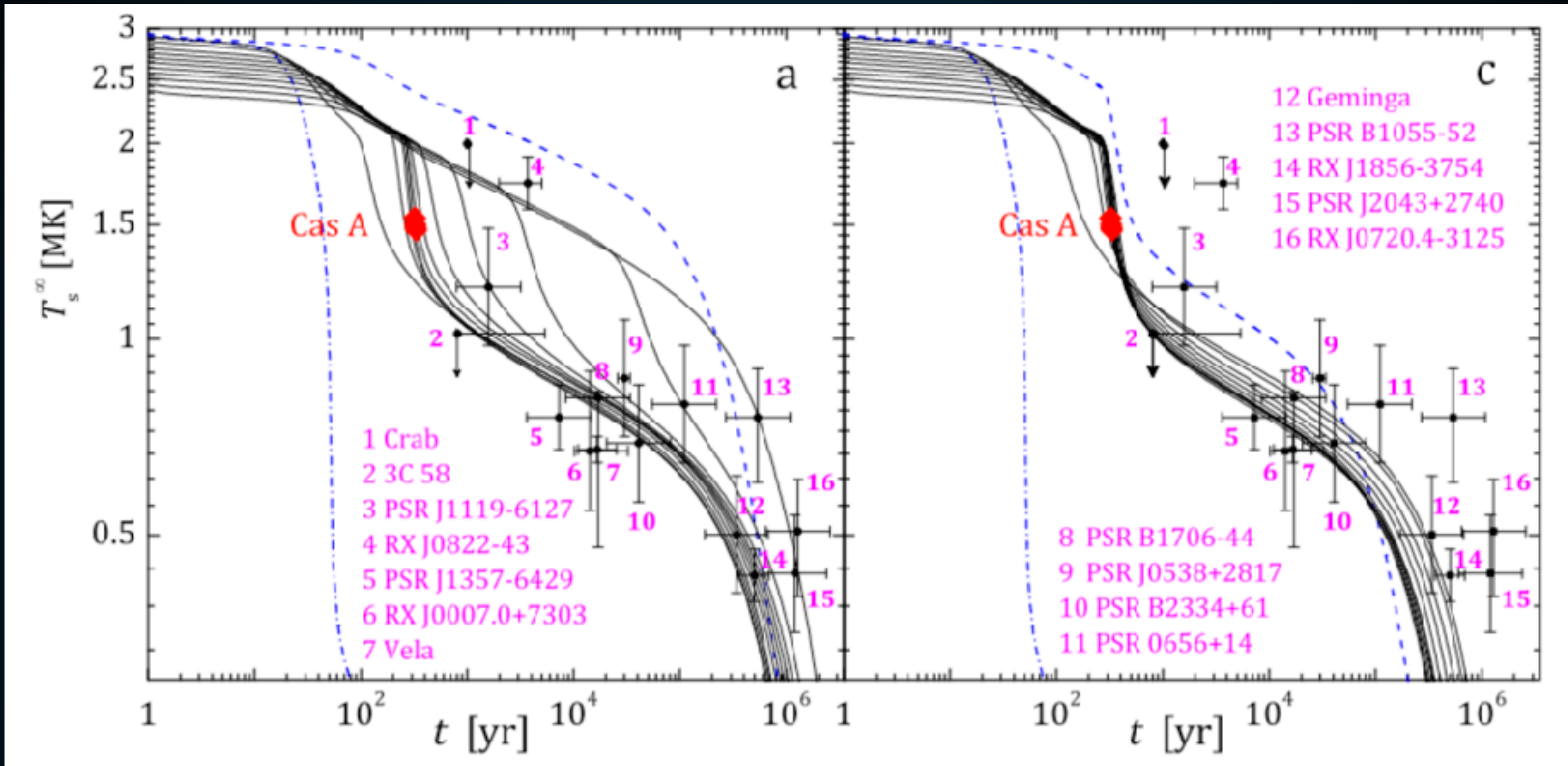


- We observe ~5 Gyr old neutron stars us.
- Thus dark matter must not collapse neutron stars too effectively.
- Sets strong constraints on dark matter that collapses neutron stars.

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

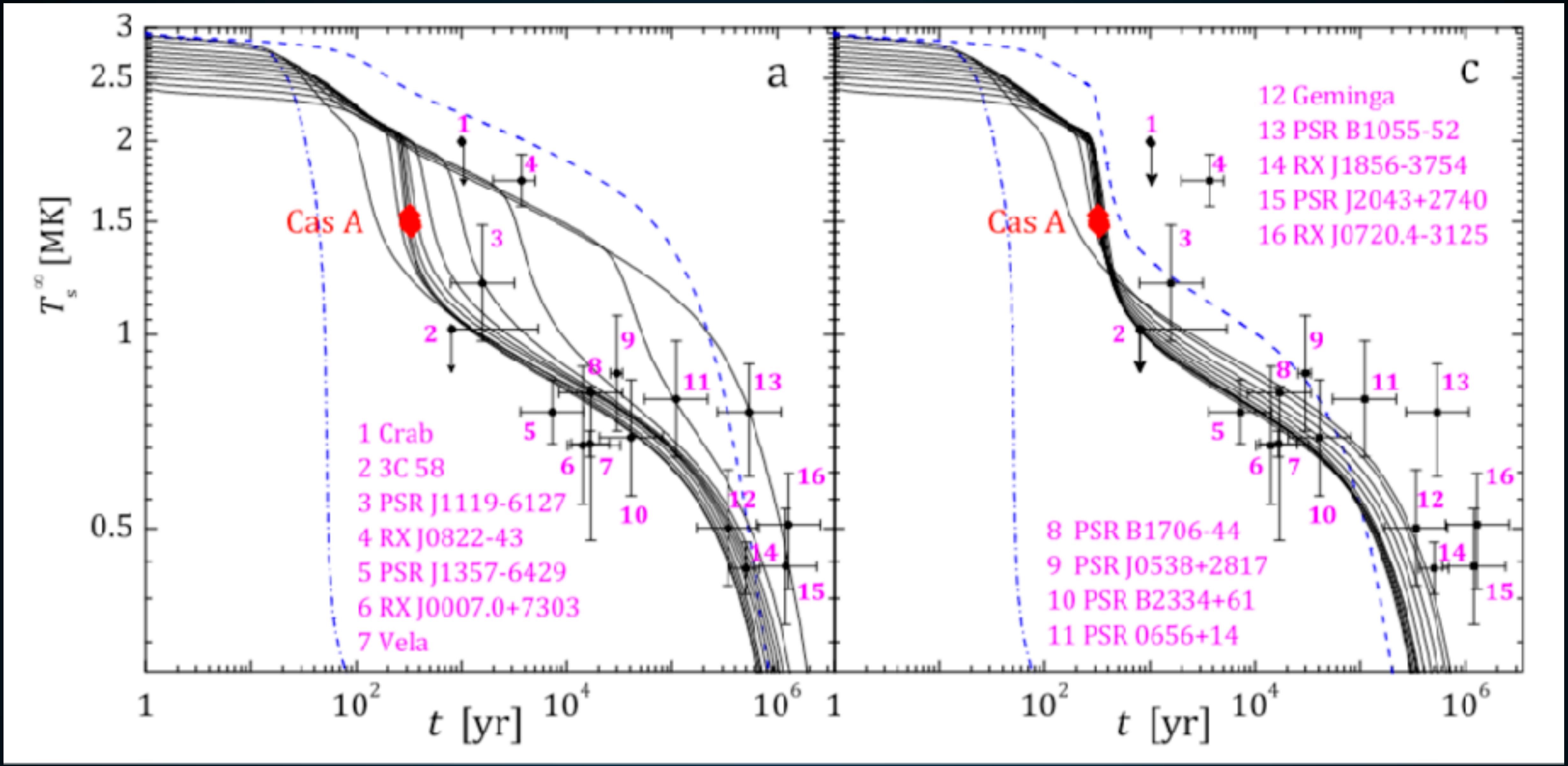
Shternin et al. (1012.0045)



- **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:**

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

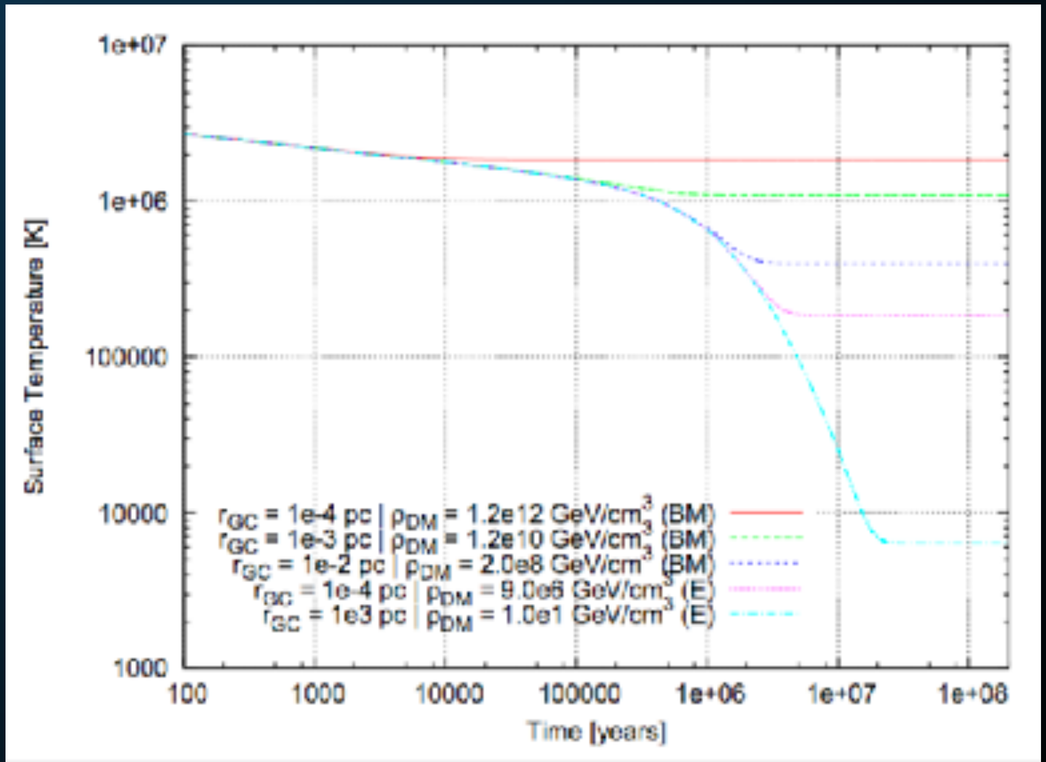
$$E_{\mathrm{s}} \simeq m_{\mathrm{x}} (\gamma - 1)$$

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

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

de Lavallez & Fairbairn (1004.0629)

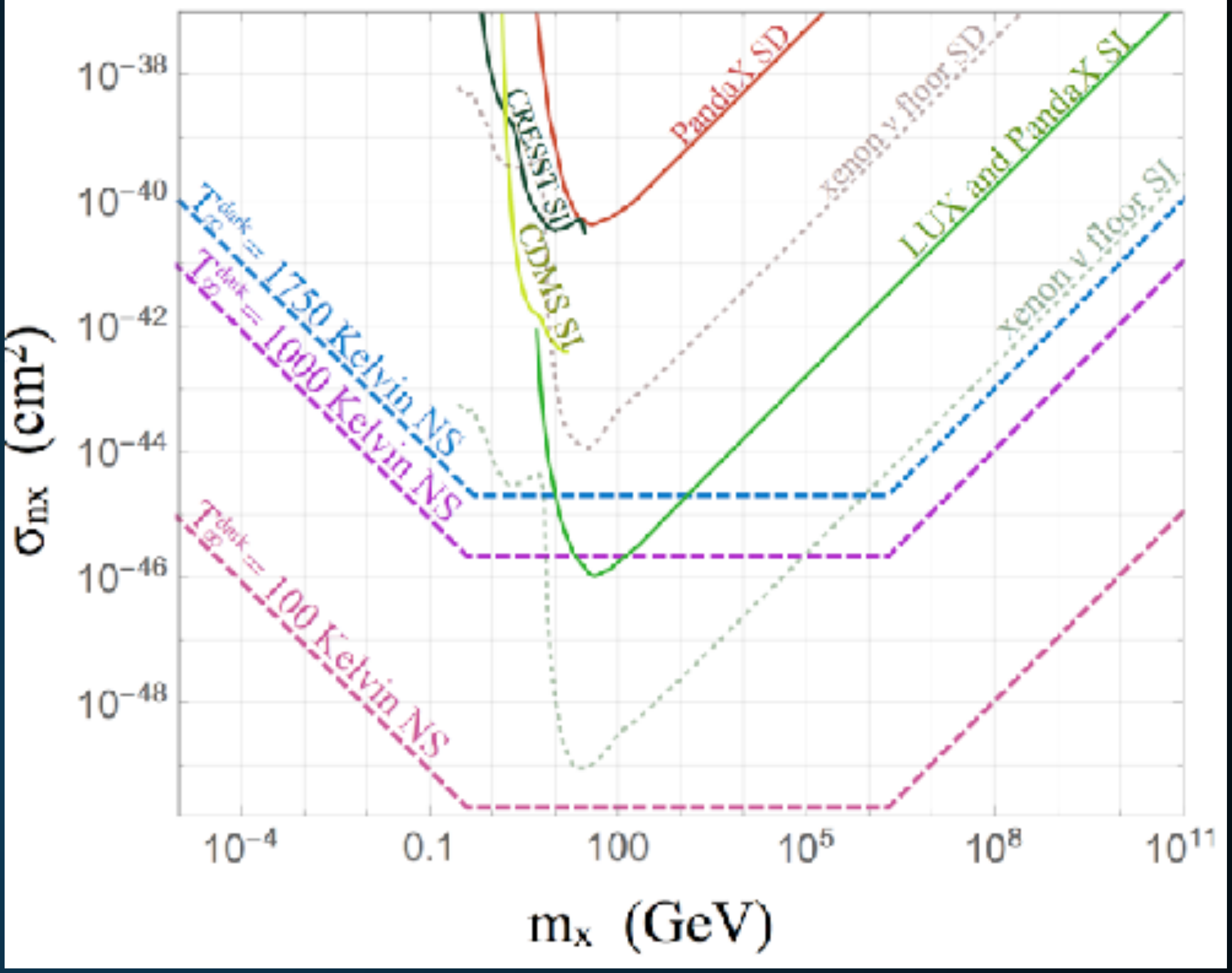
- **The dark matter particle does not need to annihilate, but if it does, more energy is injected ($E_s = \gamma m_X$).**



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:

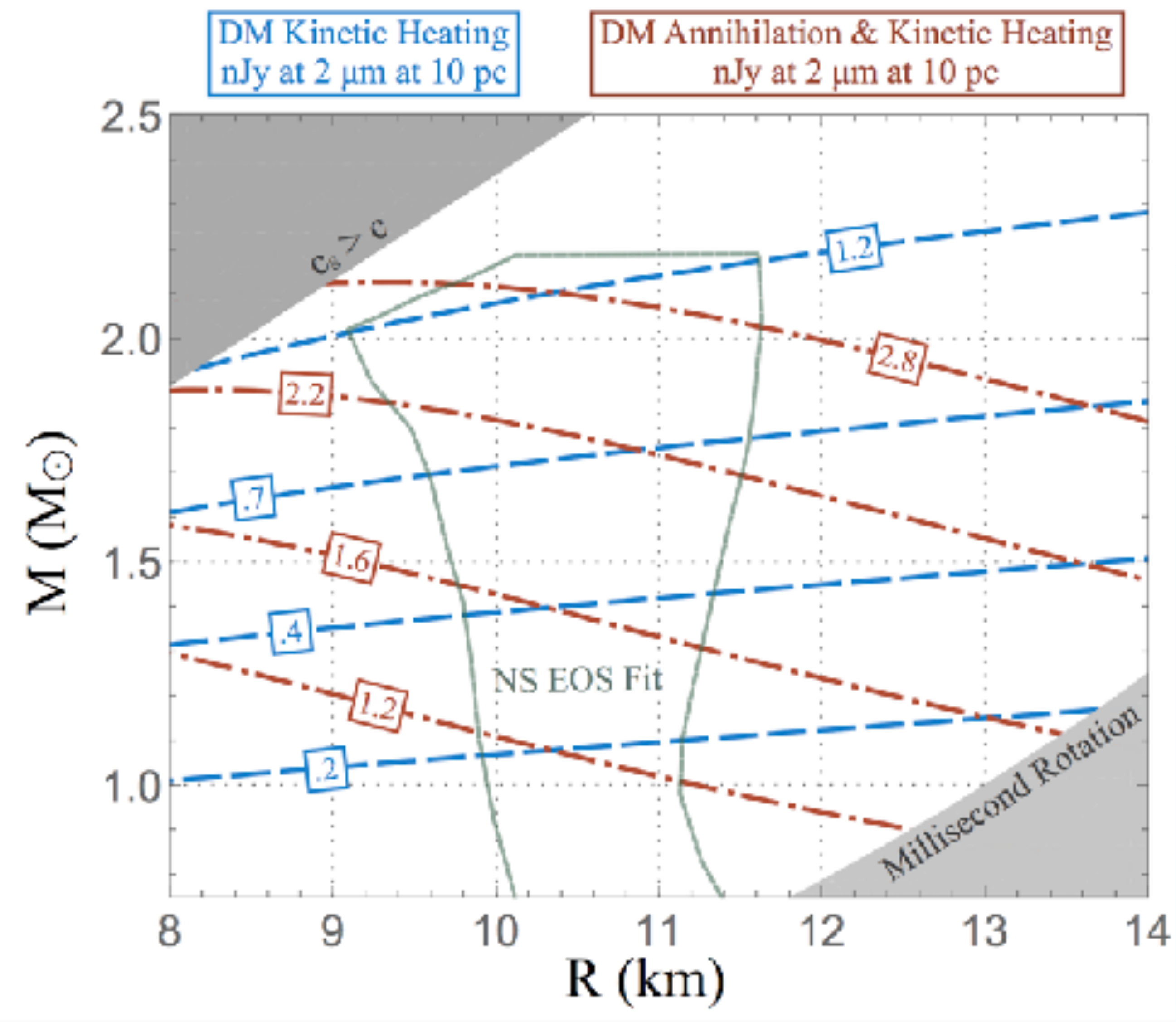


$$L_\infty^{\rm dark} = \dot{E}_{\rm k}\left(1-\frac{2GM}{R}\right) = 4\pi\sigma_{\rm B}R^2T_{\rm s}^4\left(1-\frac{2GM}{R}\right)$$

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

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

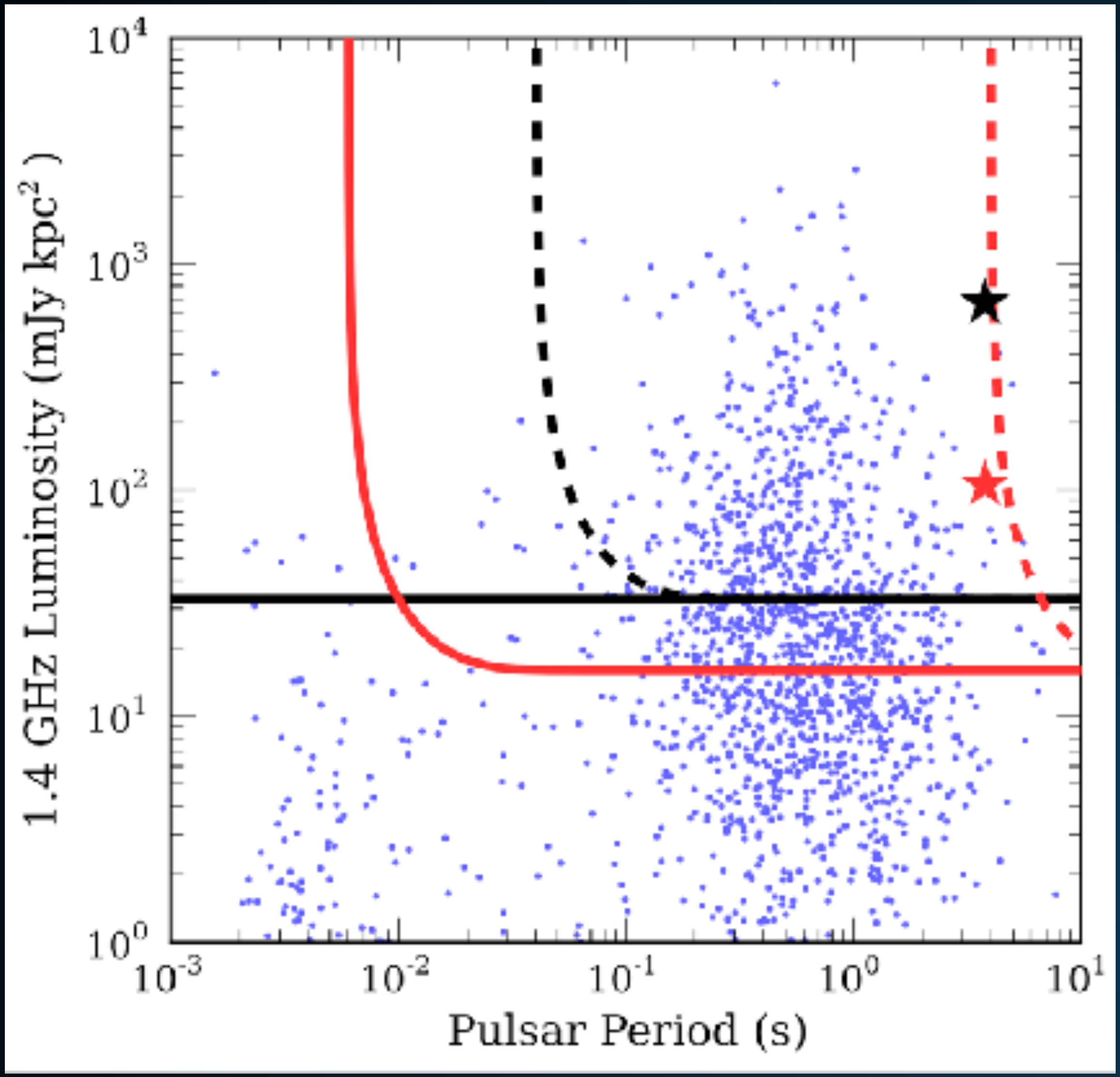
Baryakhtar, Bramante, Li, TL, Raj (1704.01577)

- 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

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

Dexter, O'Leary (1310.7022)

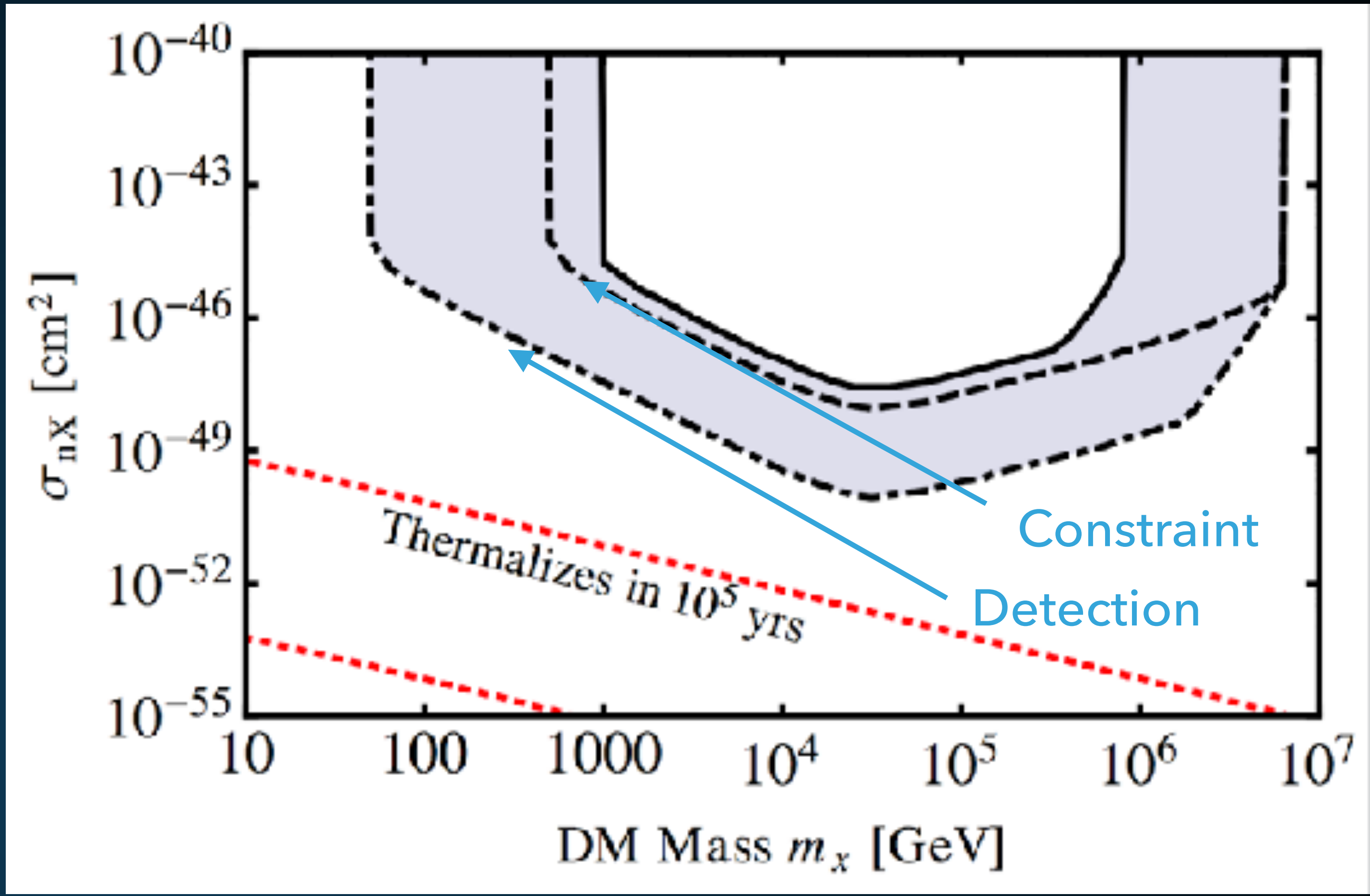


- Large pulse dispersion was reasonable culprit

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

- 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 !?

- High Dark Matter density near the GC.



Bosonic DM

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

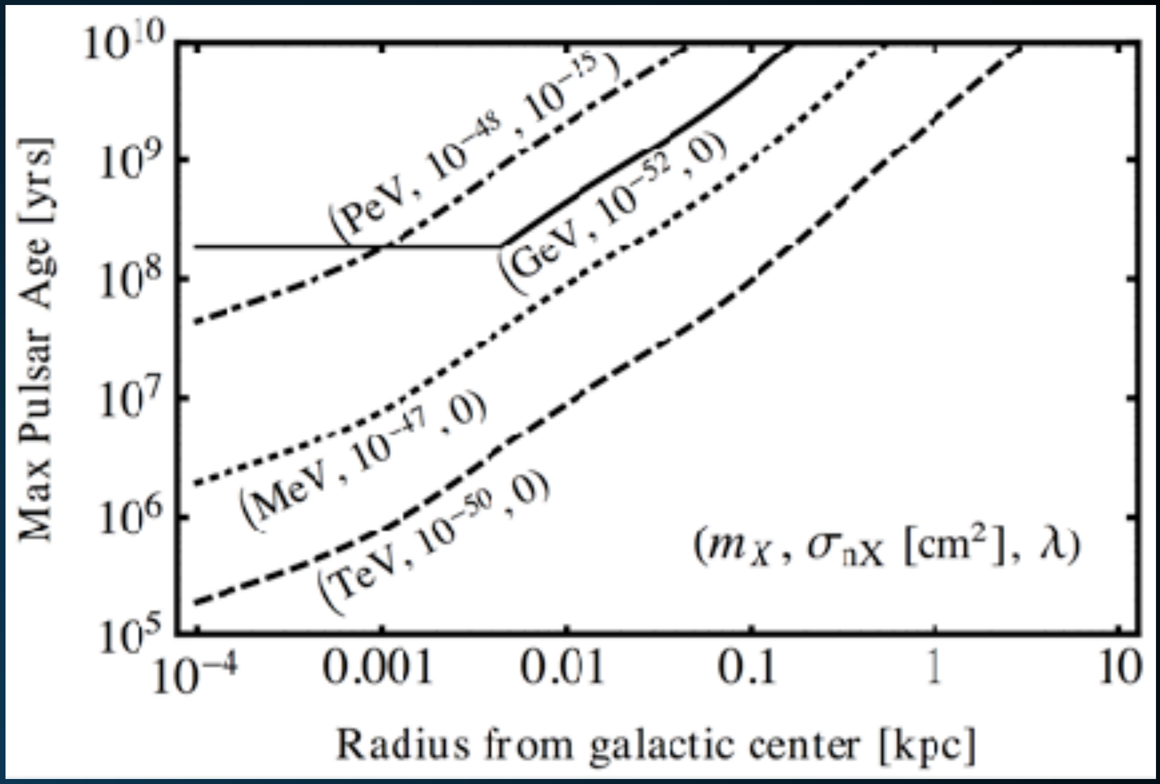
- GC NS collapse in ~10^5 yr while nearby NS remain.

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

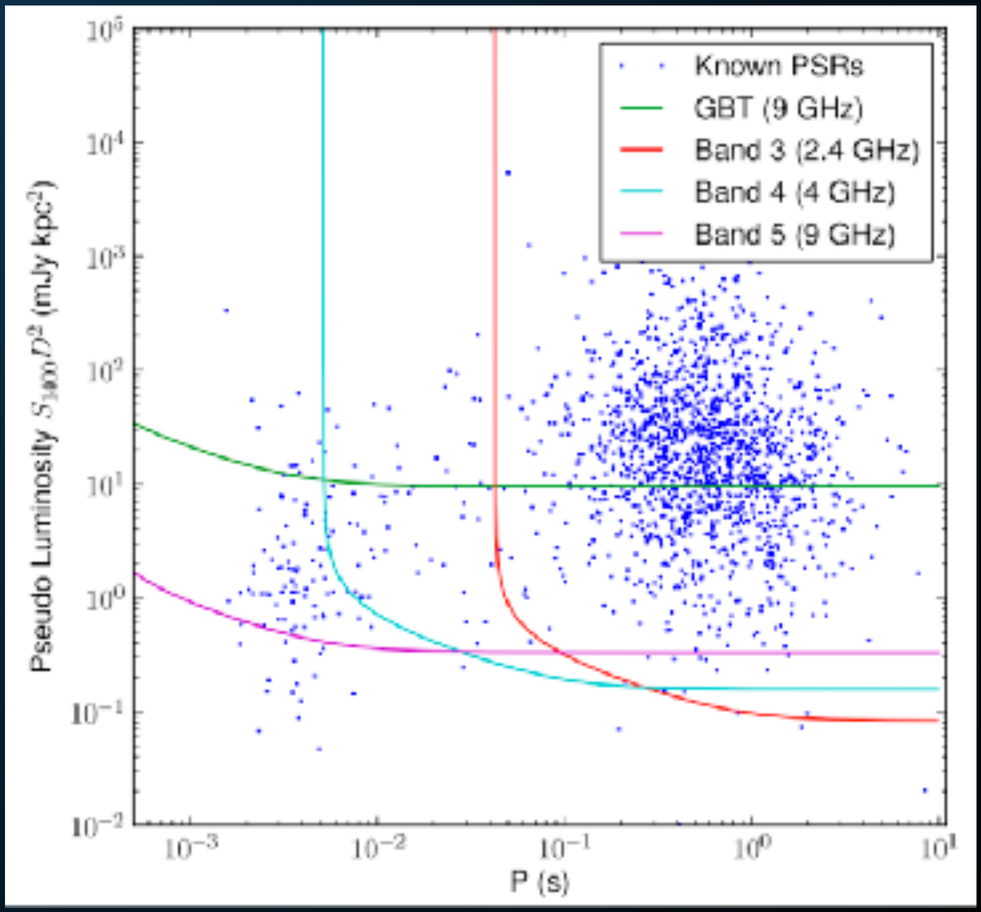
NEUTRON STAR COLLAPSE

Bramante, TL (1405.1031)

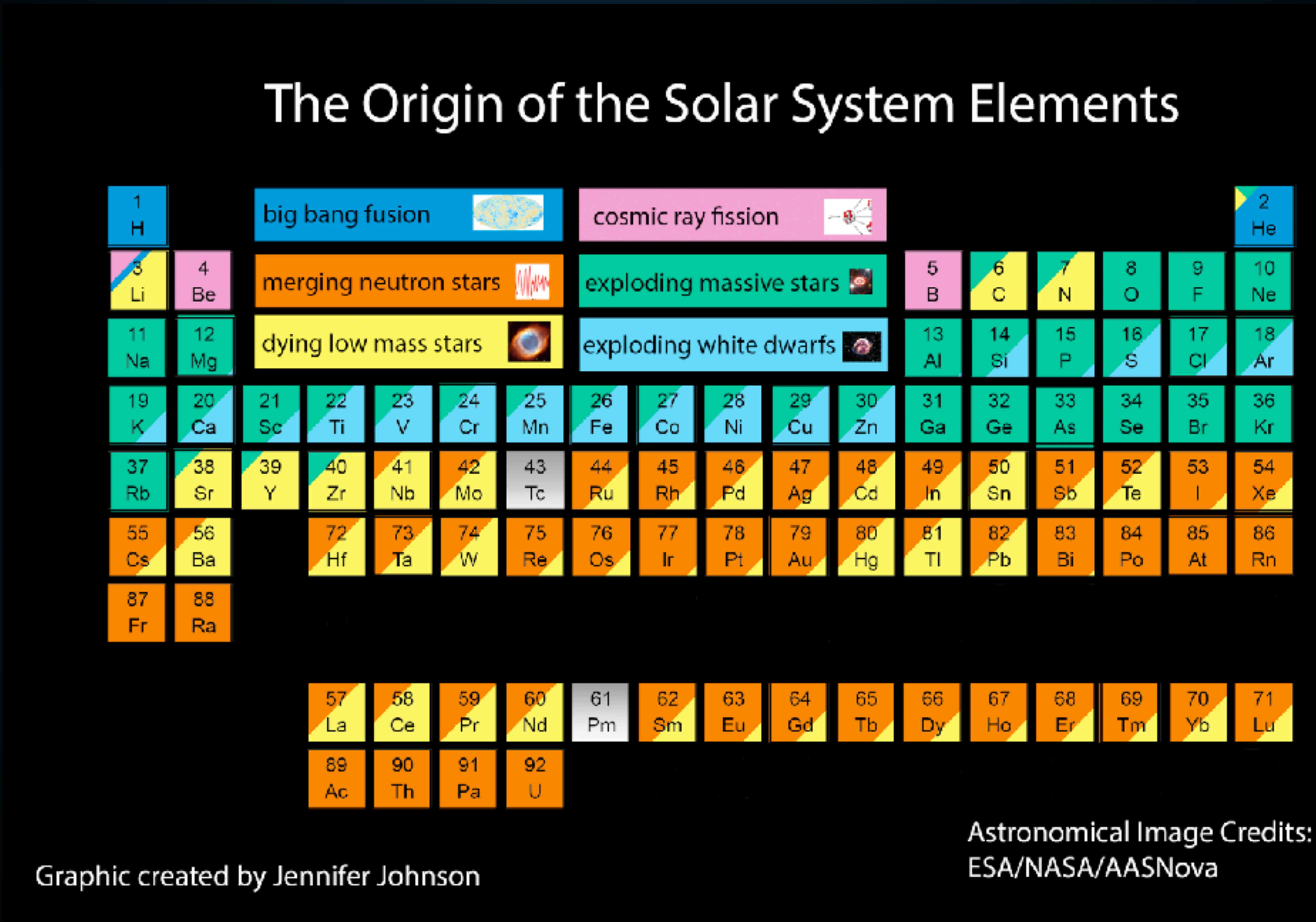
- **Potential Observation: A correlation between maximum NS age and GC radius.**
- **Can be confirmed or ruled out with one old pulsar observation near the GC.**
- **Upcoming radio instruments (e.g. MeerKat, SKA) will definitively test the missing pulsar problem.**



Eatough et al. (1501.00281)



R-PROCESS ENRICHMENT OF DWARF SPHEROIDAL GALAXIES



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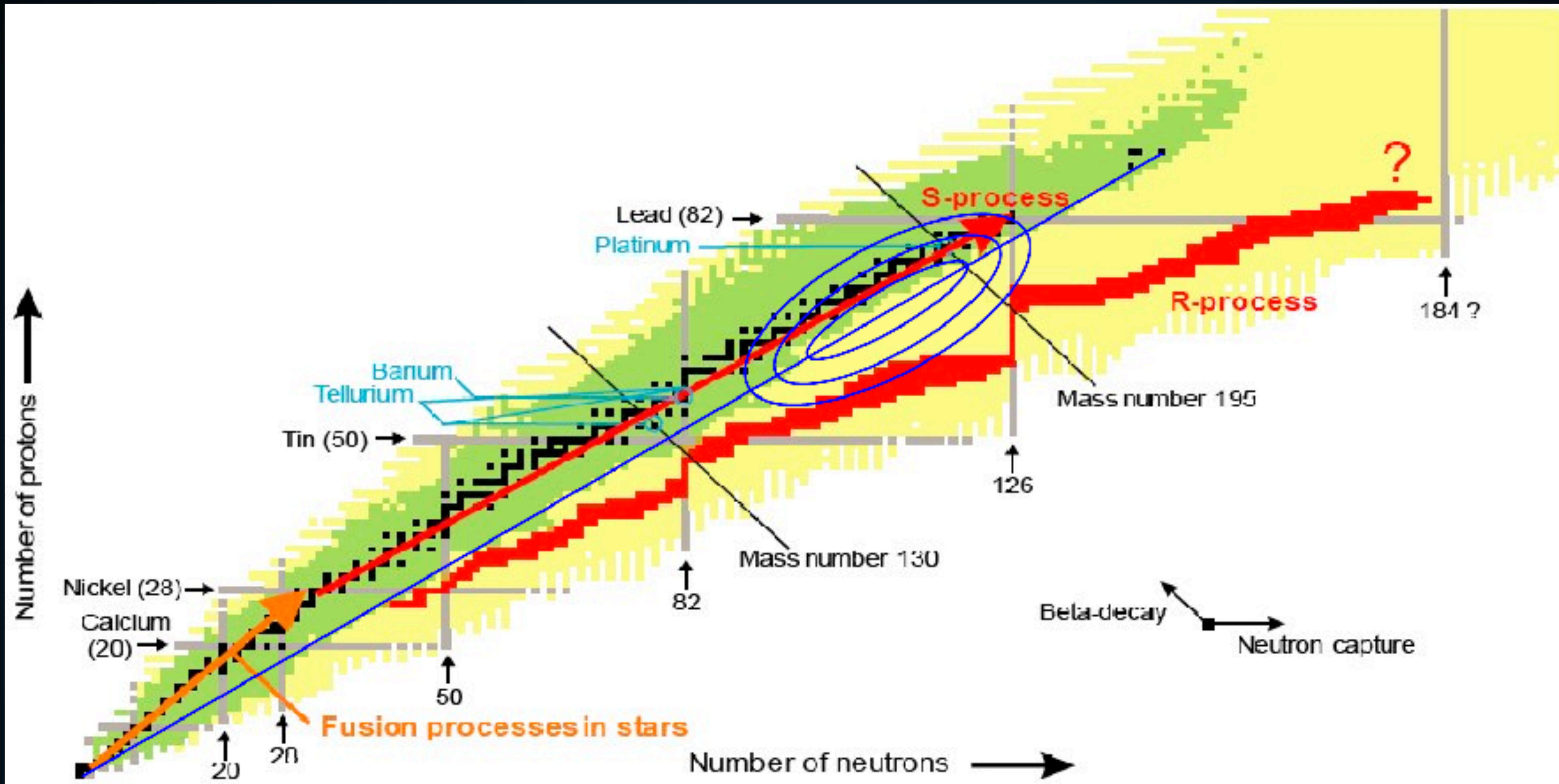
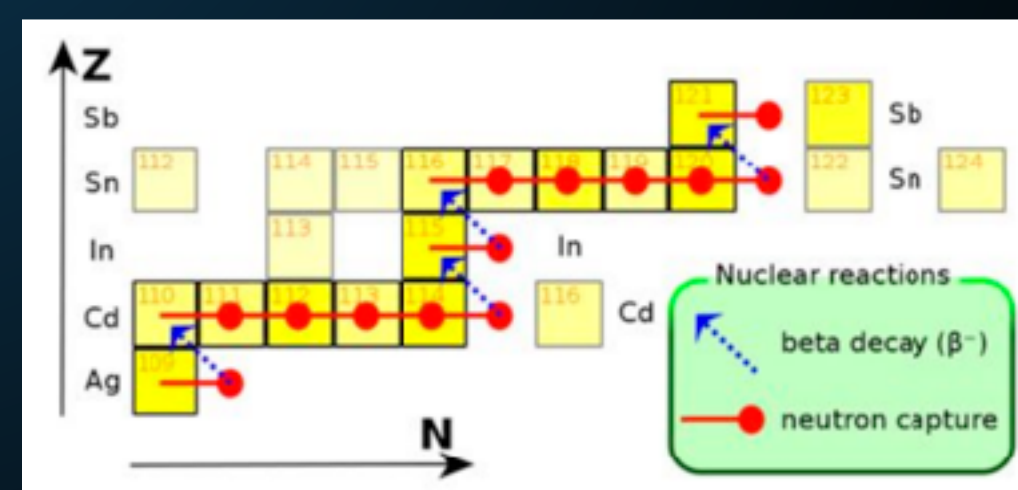
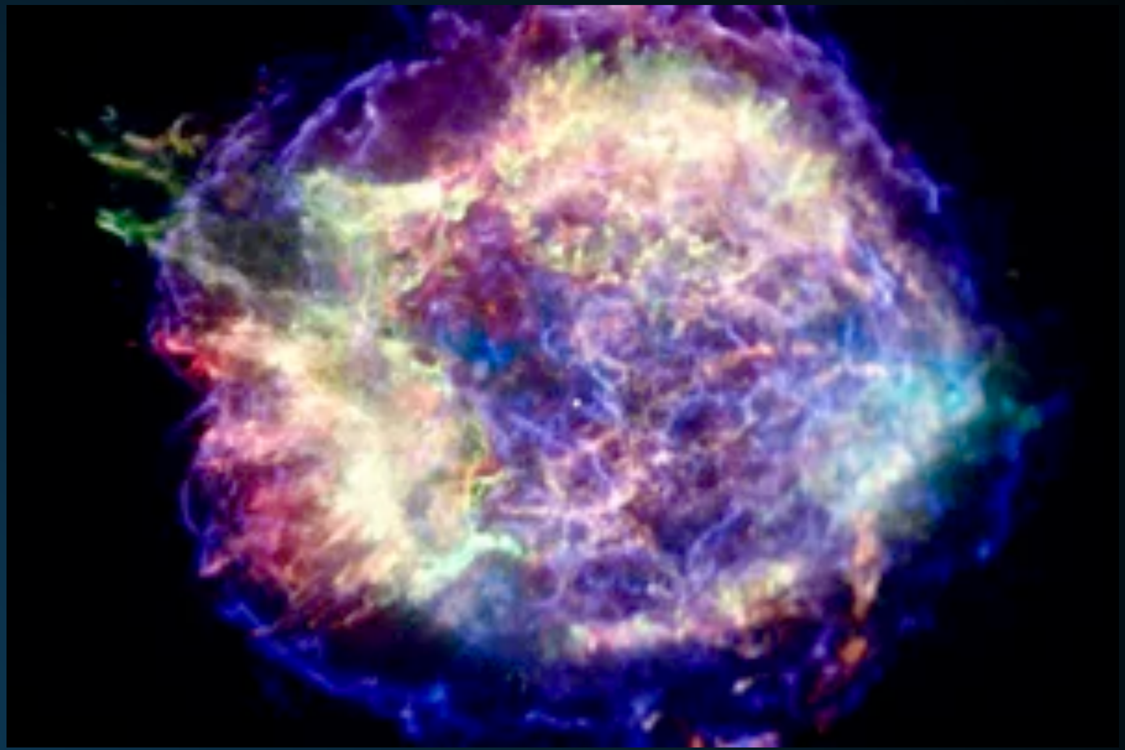


- Producing elements with large neutron over density requires extremely neutron-dense environment to avoid β-decay

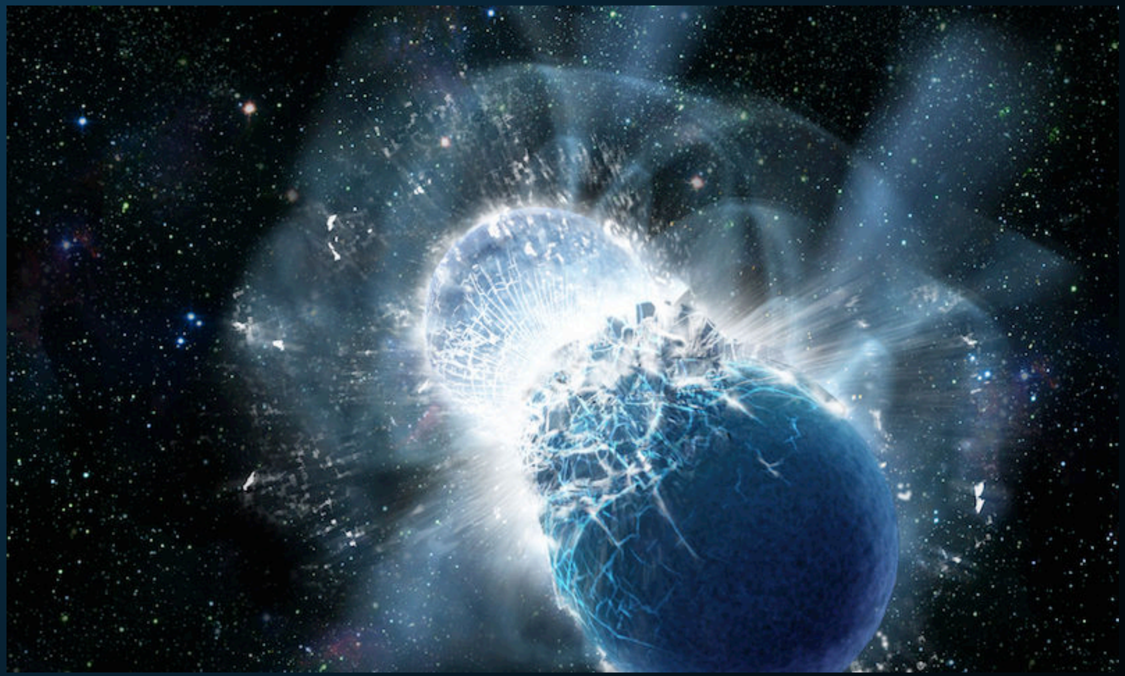


R-PROCESS ENRICHMENT OF DWARF SPHEROIDAL GALAXIES

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



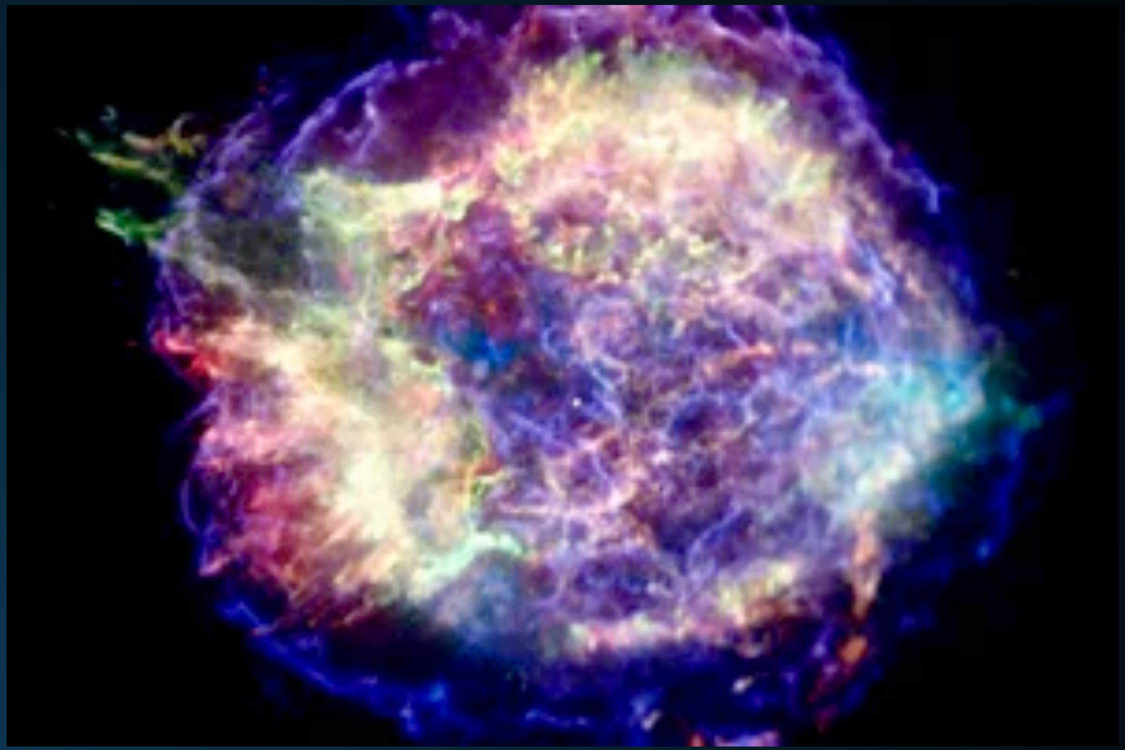
- **Supernovae are common: 0.02 SN yr^{-1} in Milky Way**
- **Neutron Star Mergers Rare: 10^{-4} yr^{-1} in Milky Way**



- **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
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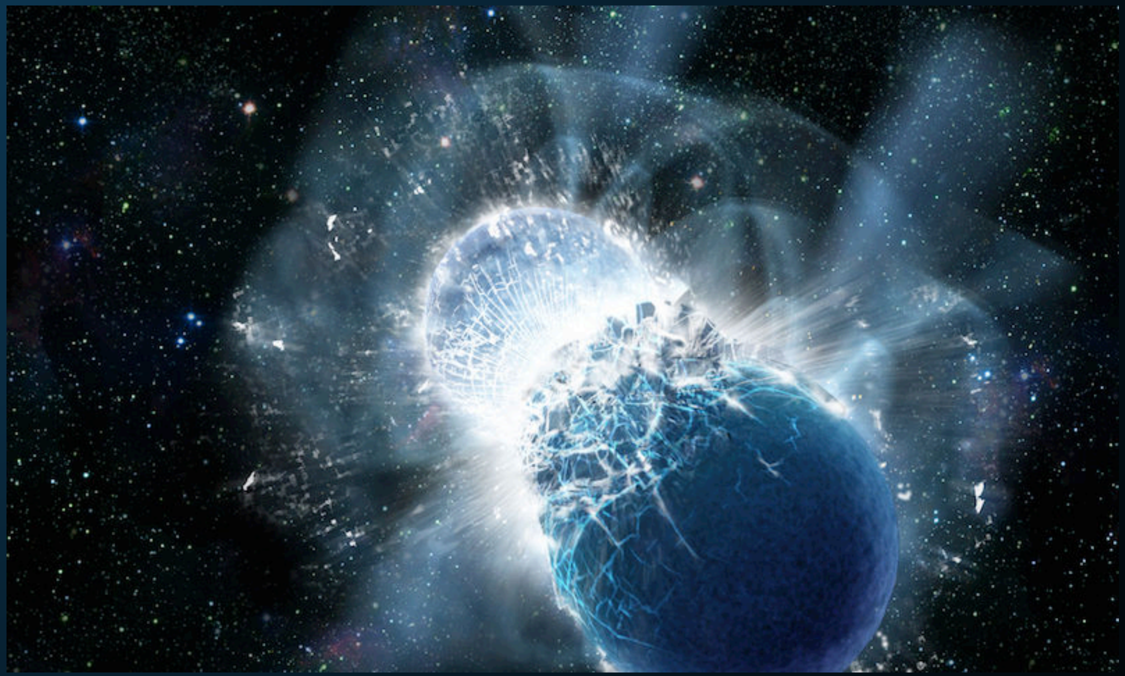


- Observe systems with small star-formation rates -> Poisson fluctuations in abundances!

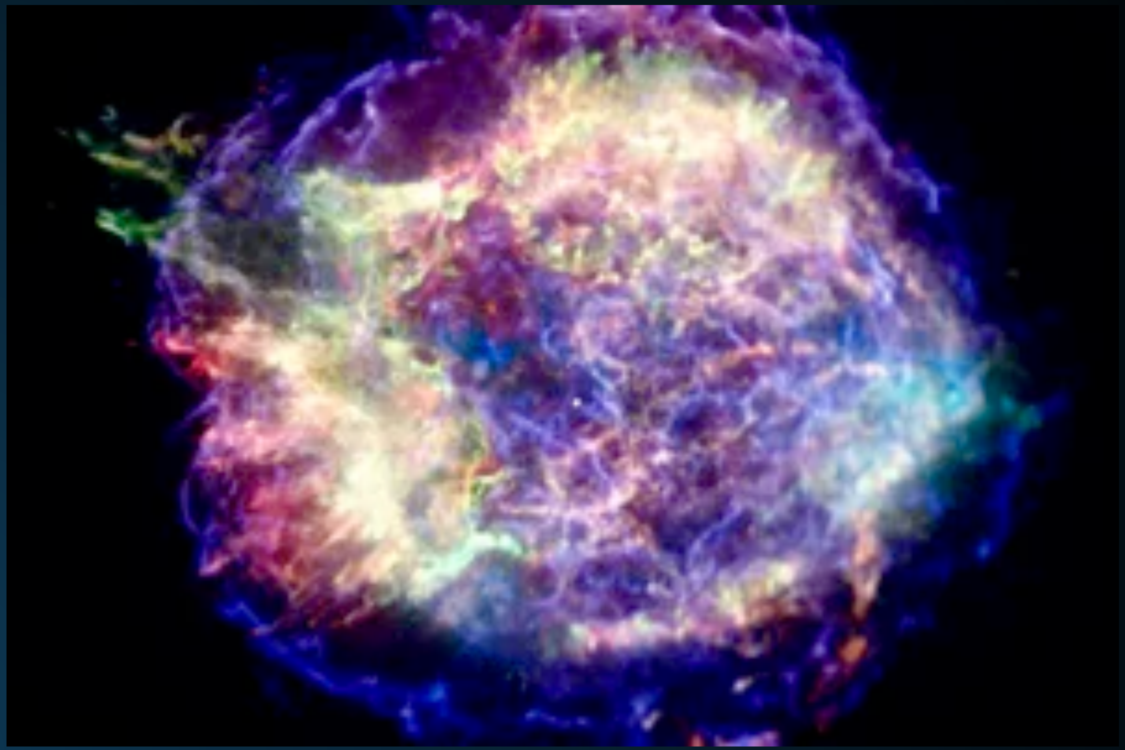
R-PROCESS ENRICHMENT OF DWARF SPHEROIDAL GALAXIES

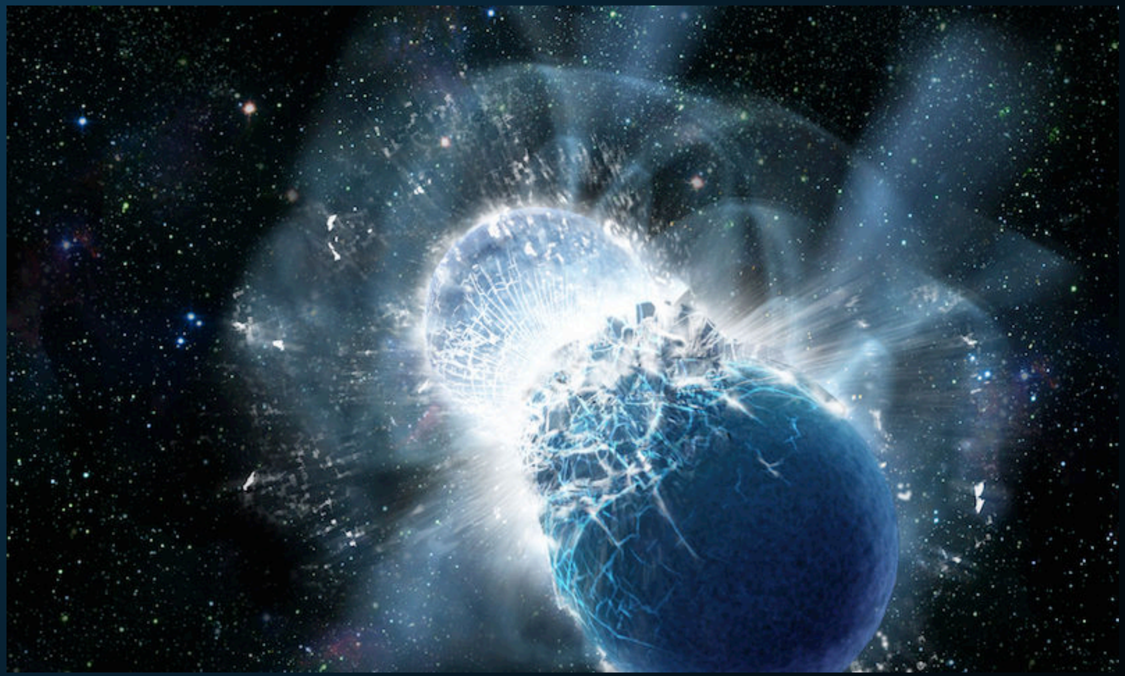
- **Differentiating supernovae and neutron star binary mergers**

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

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

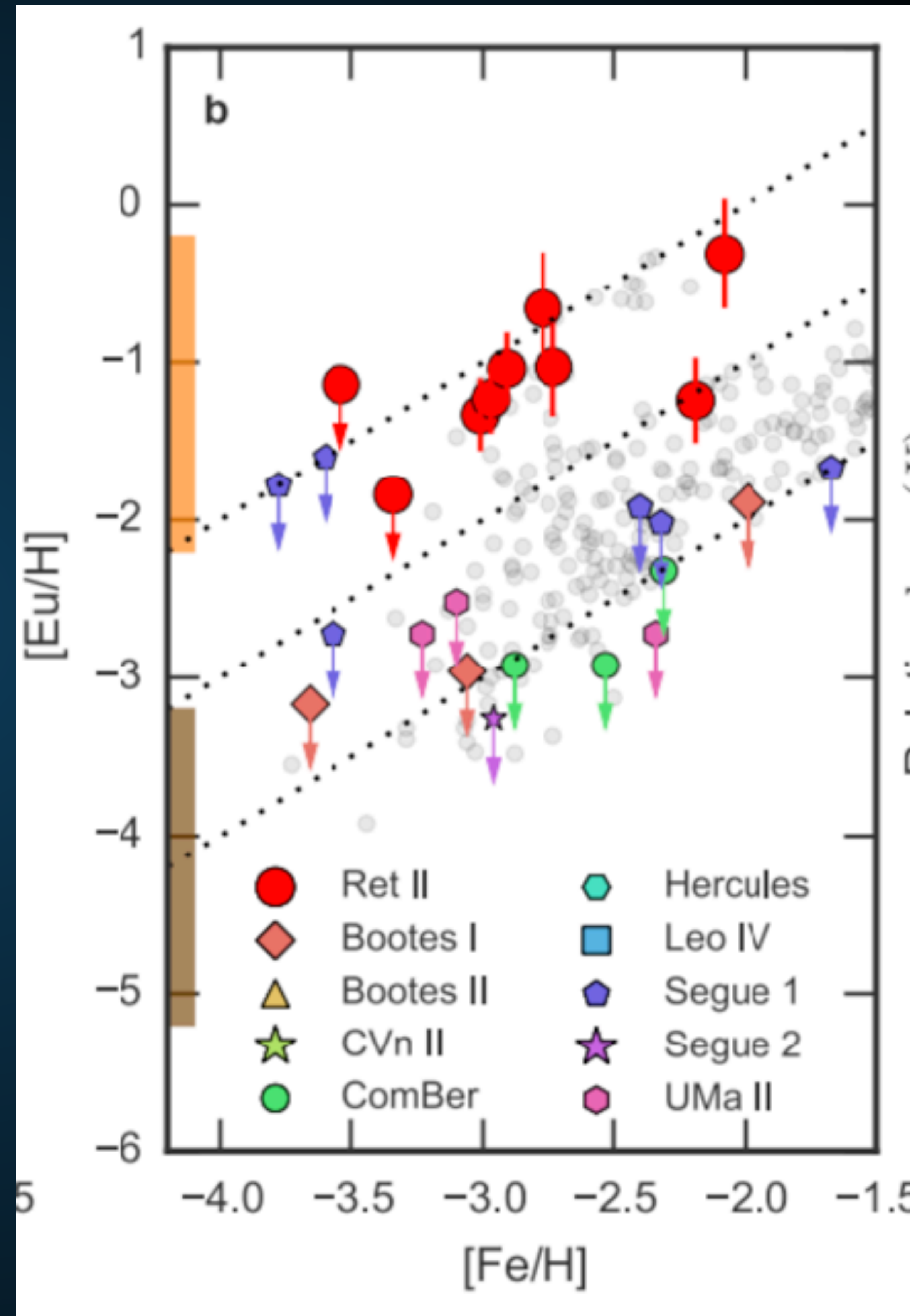
- **Can also cross-correlate with metallicity, which should track supernovae rate.**





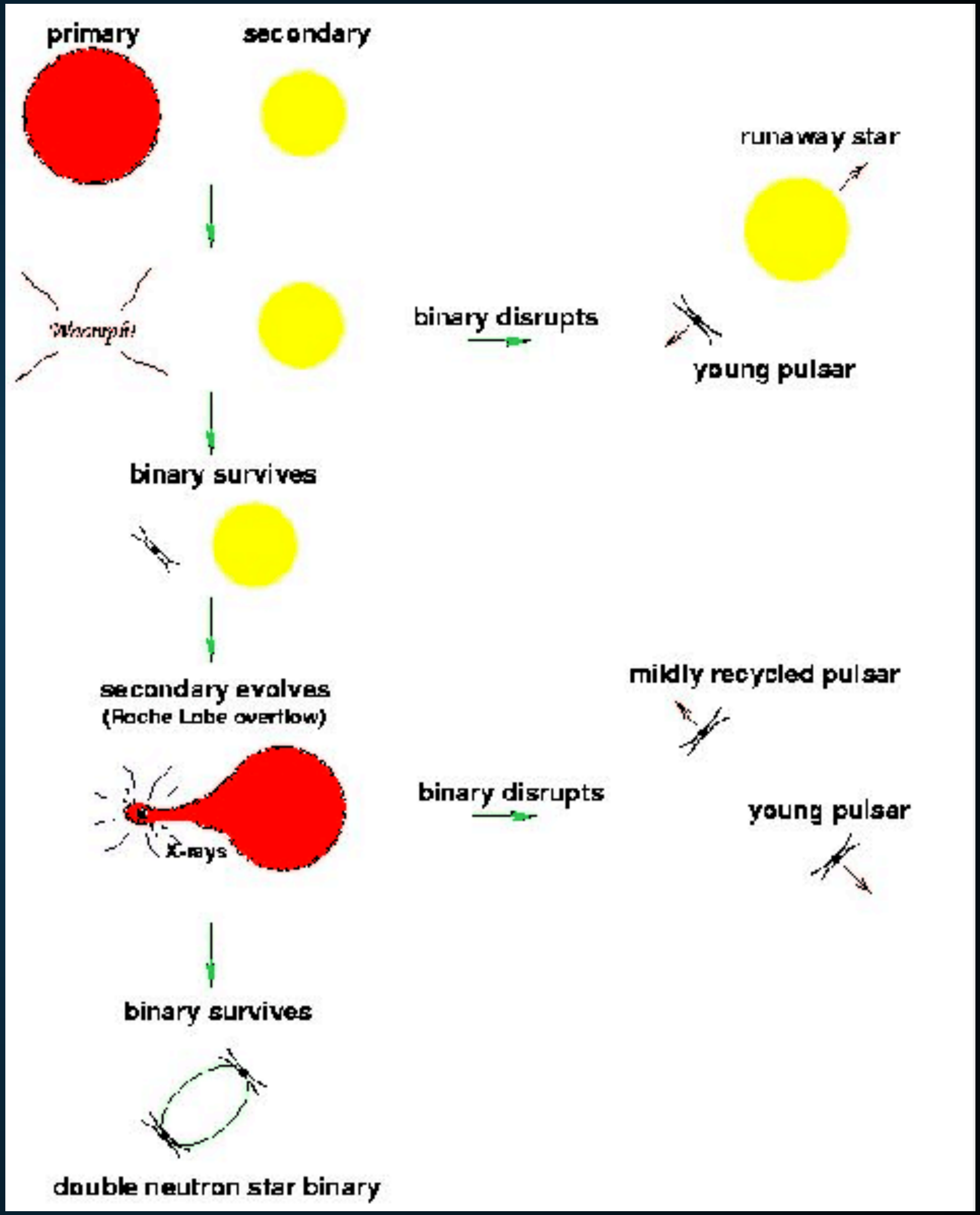
R-PROCESS ENRICHMENT OF DWARF SPHEROIDAL GALAXIES Ji et al. (1512.01558)

- 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)

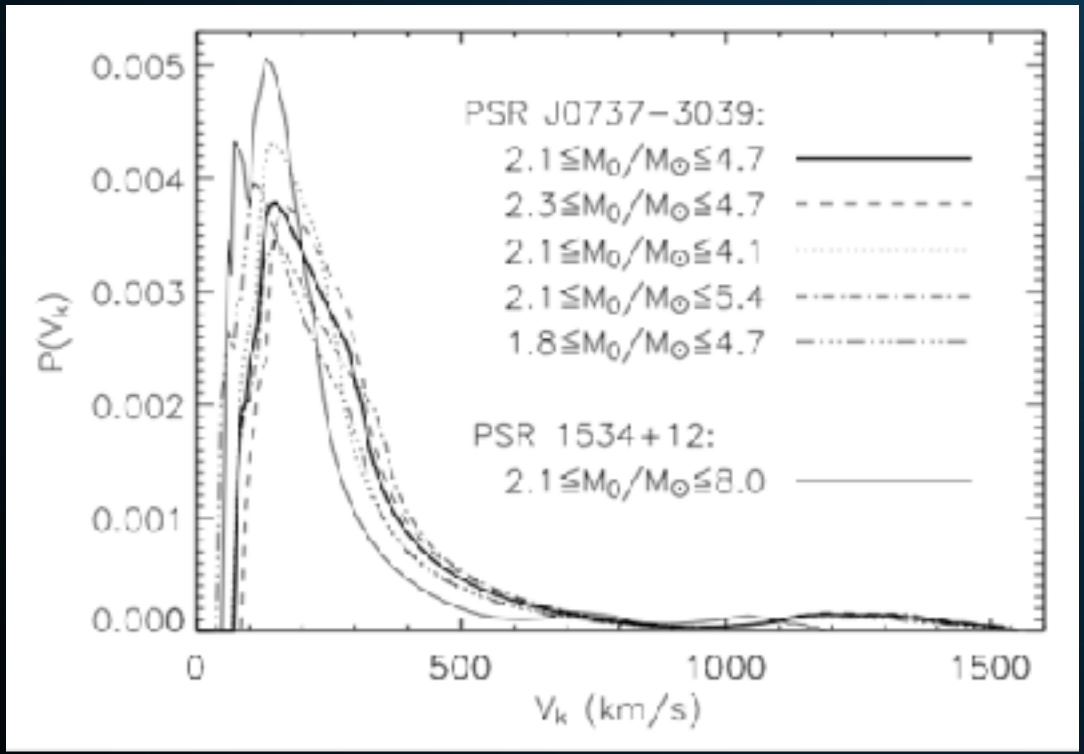


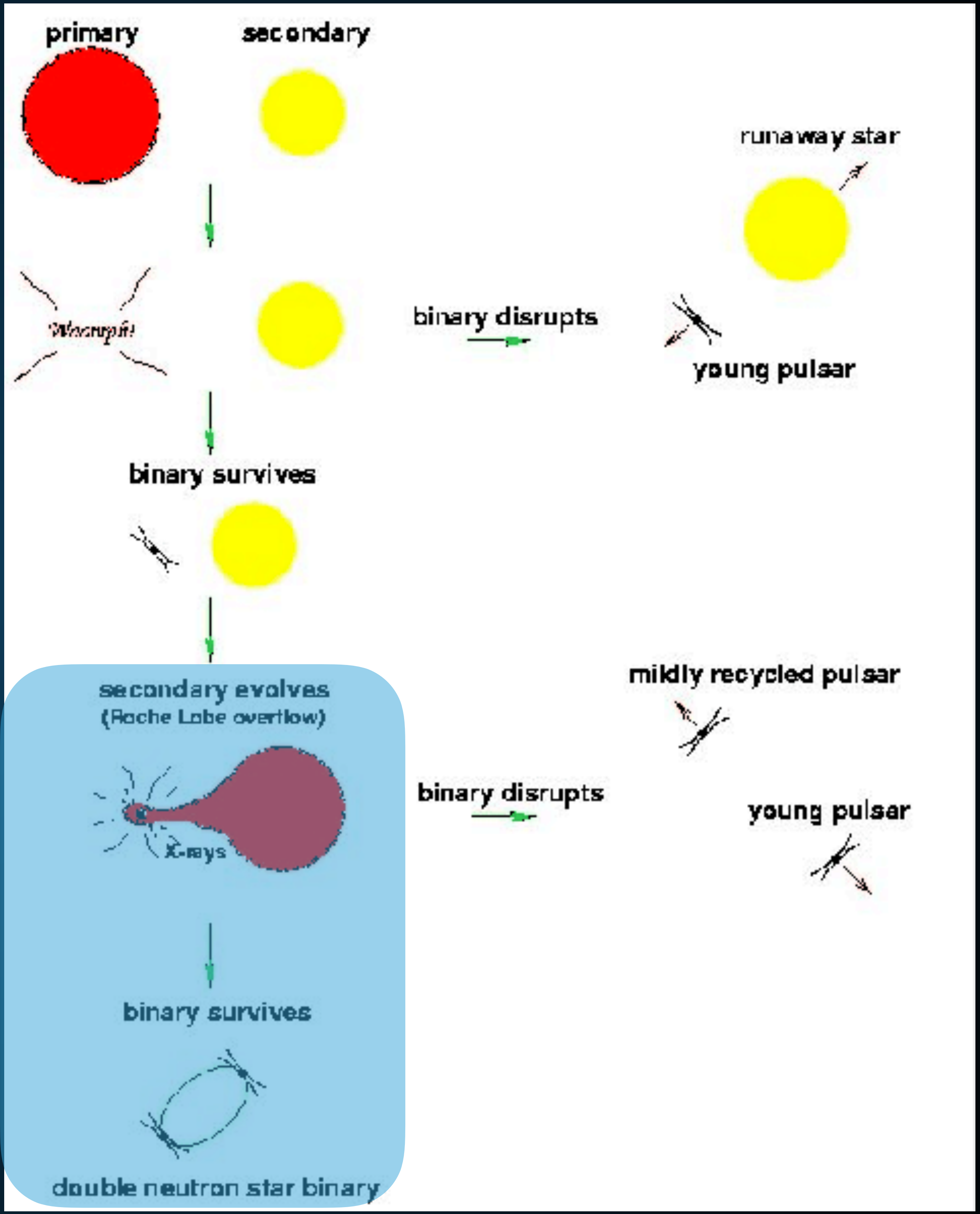
NEUTRON STAR KICKS IN BINARY MERGERS

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

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

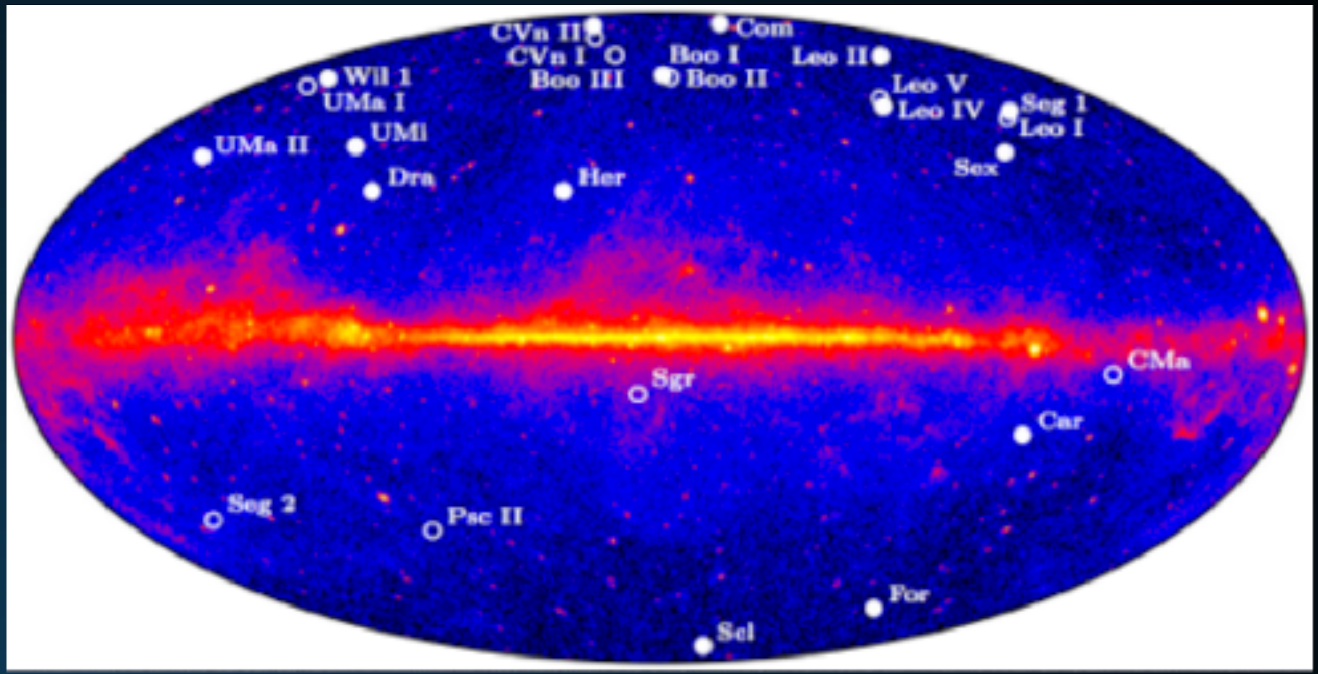
$$\dot{m}_x = \pi \rho_x \frac{2GMR}{v_x}\left(1 - \frac{2GM}{R}\right)^{-1}$$
$$\simeq \frac{10^{26}\ \mathrm{GeV}}{\mathrm{s}}\left(\frac{\rho_x}{\mathrm{GeV/cm^3}}\right)\left(\frac{200\ \mathrm{km/s}}{v_x}\right),$$

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

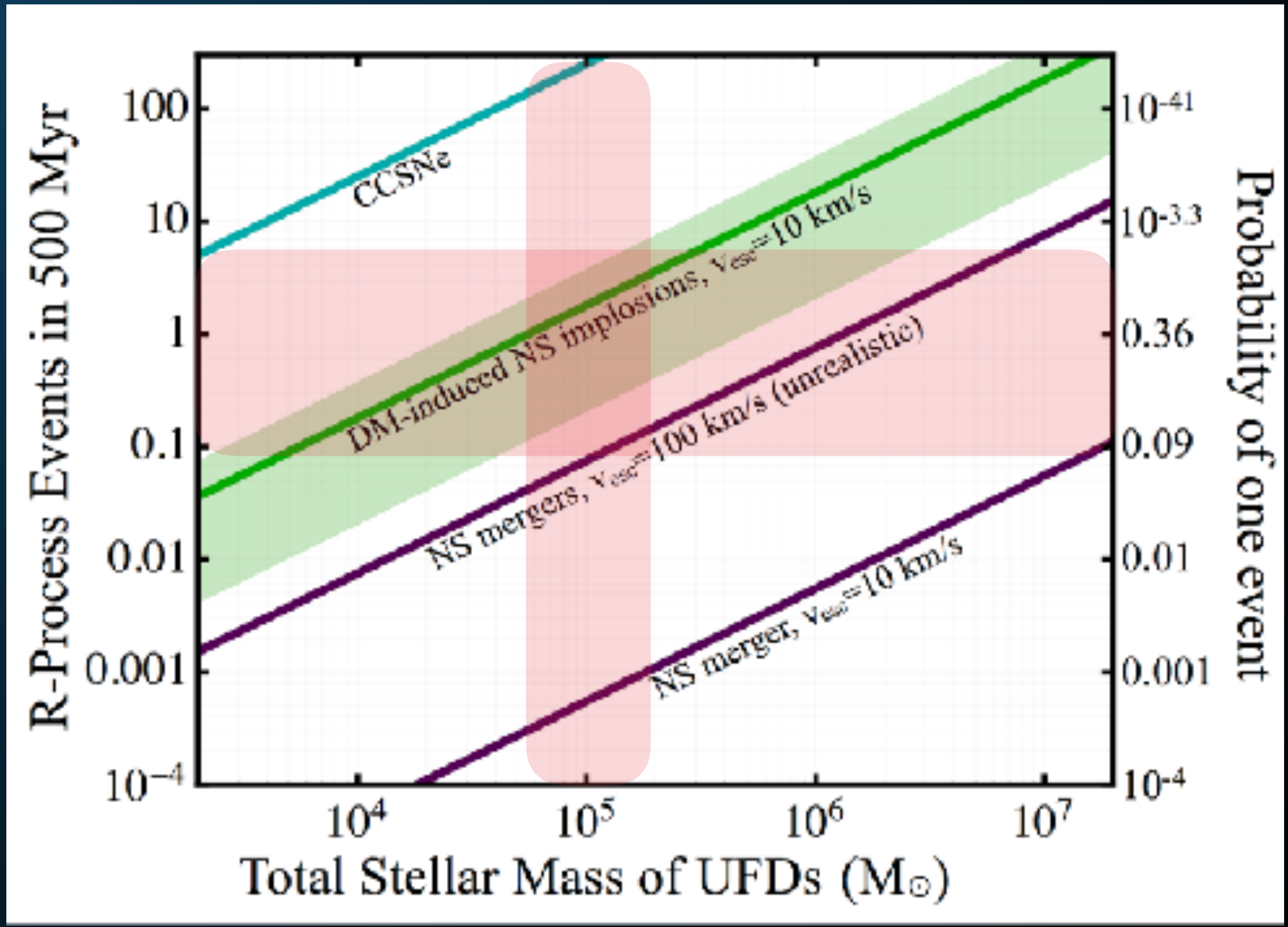
RATES FROM DARK MATTER INDUCED COLLAPSE

Bramante & TL (1601.06784)

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

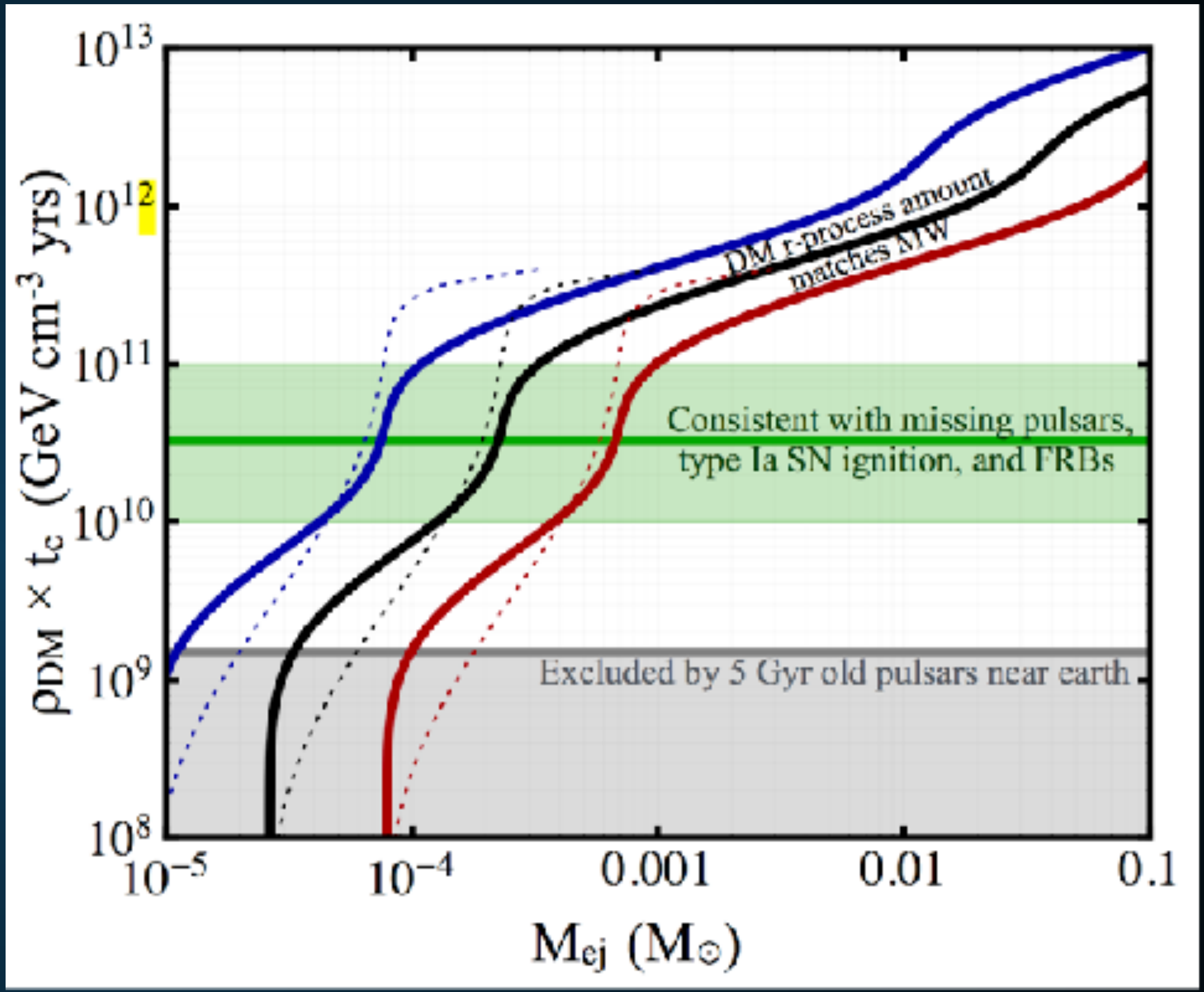


- Supernovae produce ~100 events.
- Mergers produce ~0.0005 events
- DM induced collapse produces ~0.1-3 events.



 Bramante & TL (1601.06784)

- How much r-process enrichment per dark matter induced collapse?



- Currently abundance
  - Yields between $5 \times 10^{-5}\ M_\circ$ and $10^{-3}\ M_\circ$ can explain Milky Way r-process abundance.

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

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

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

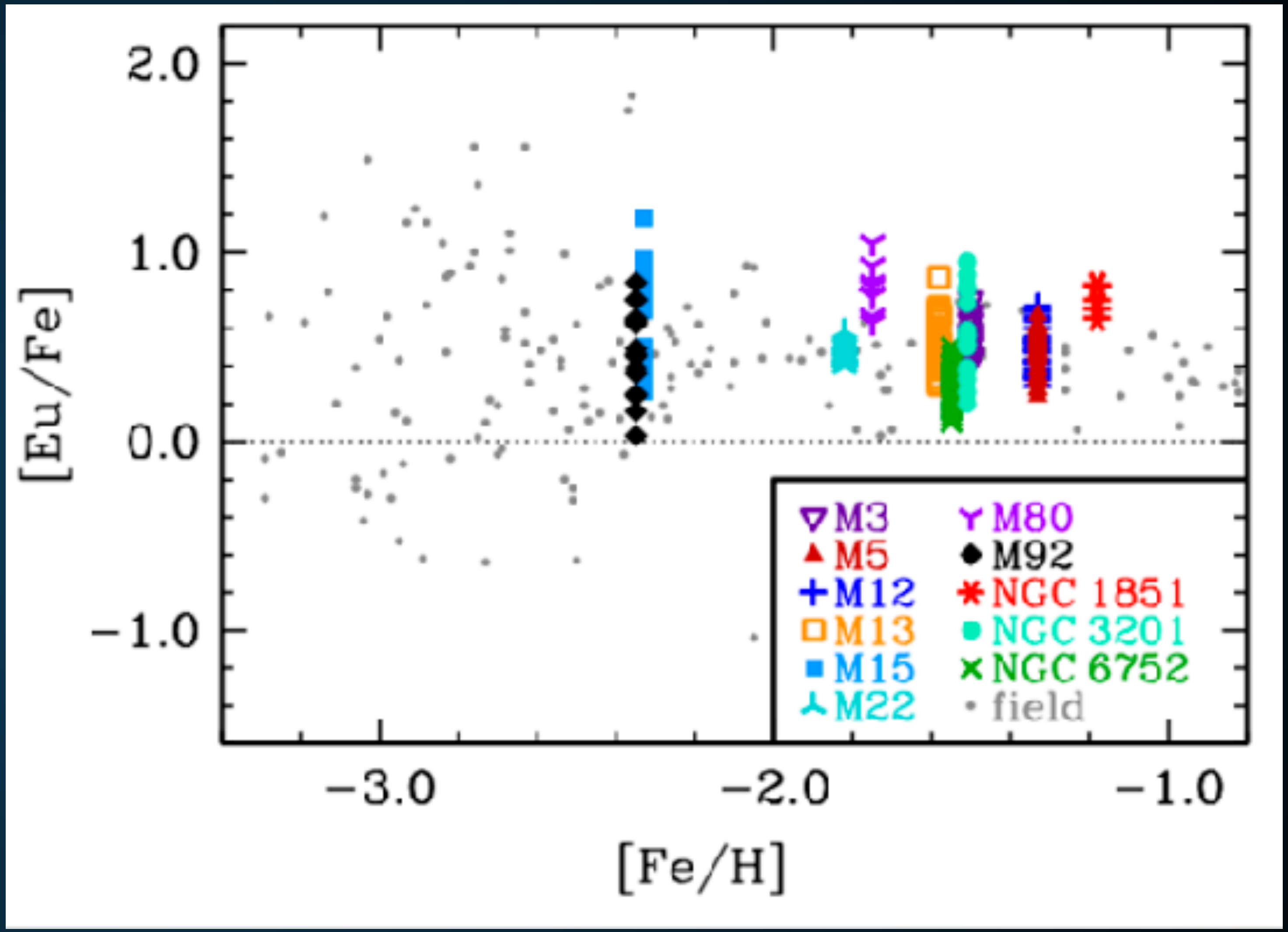
- **This energy can propel neutrons from the NS surface at v = 0.7c. The maximum mass that can be lost is:**

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

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

 Roederer 2011 (1104.5056)

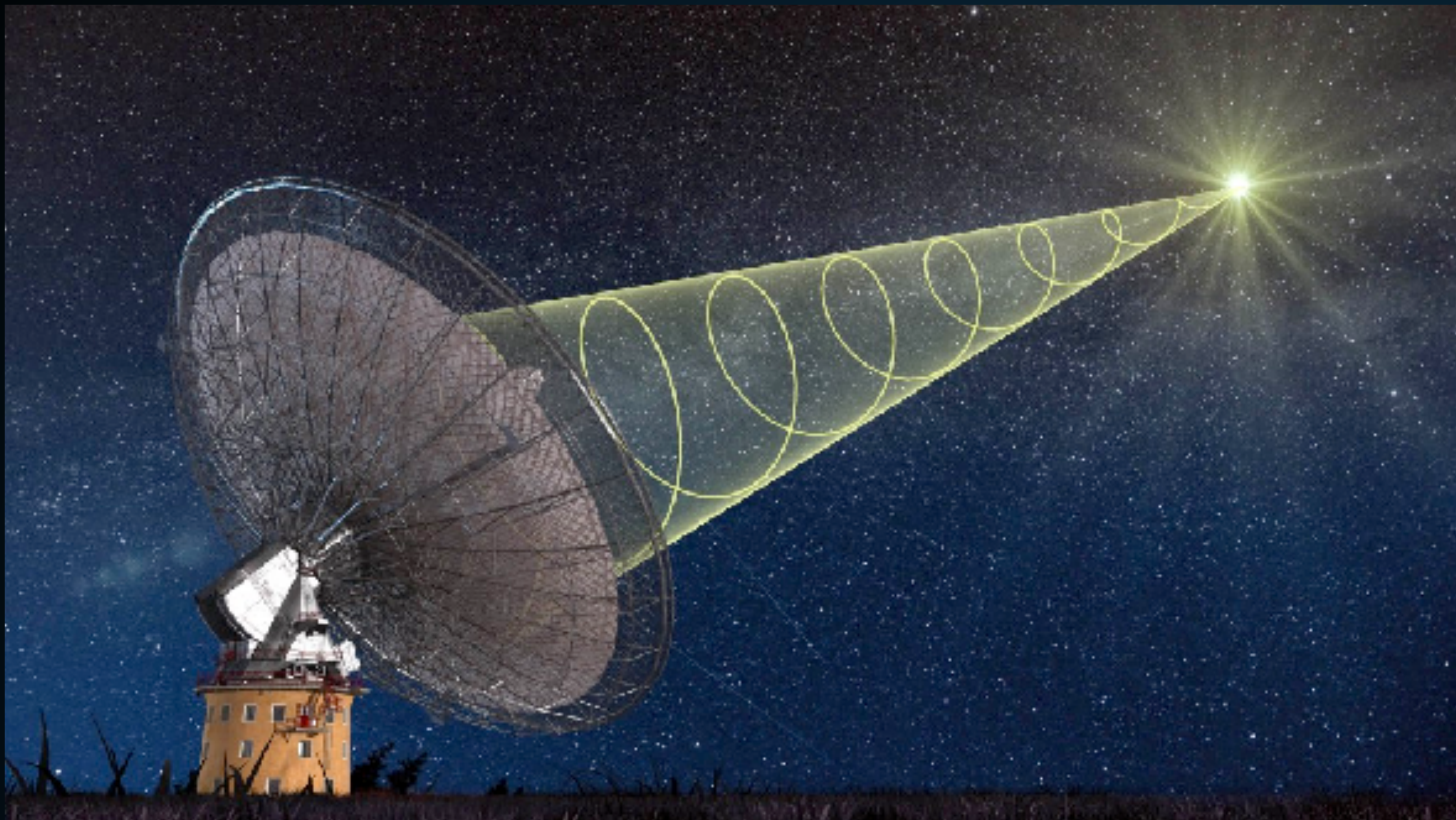
- **Prediction: Globular Clusters should not be similarly r-process enriched.**

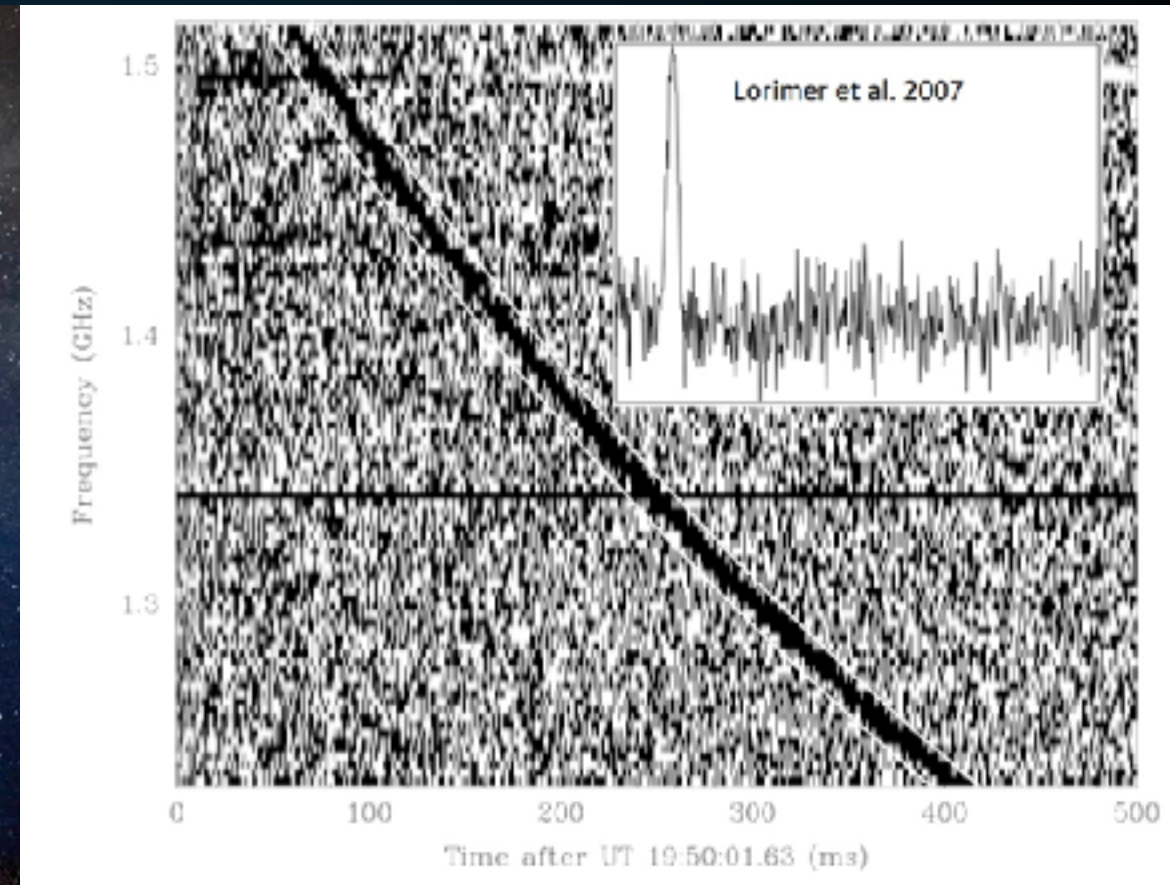


- **In fact, no globular cluster has been observed to have an r-process overabundance exceeding 1.2 dex.**

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

FAST RADIO BURSTS



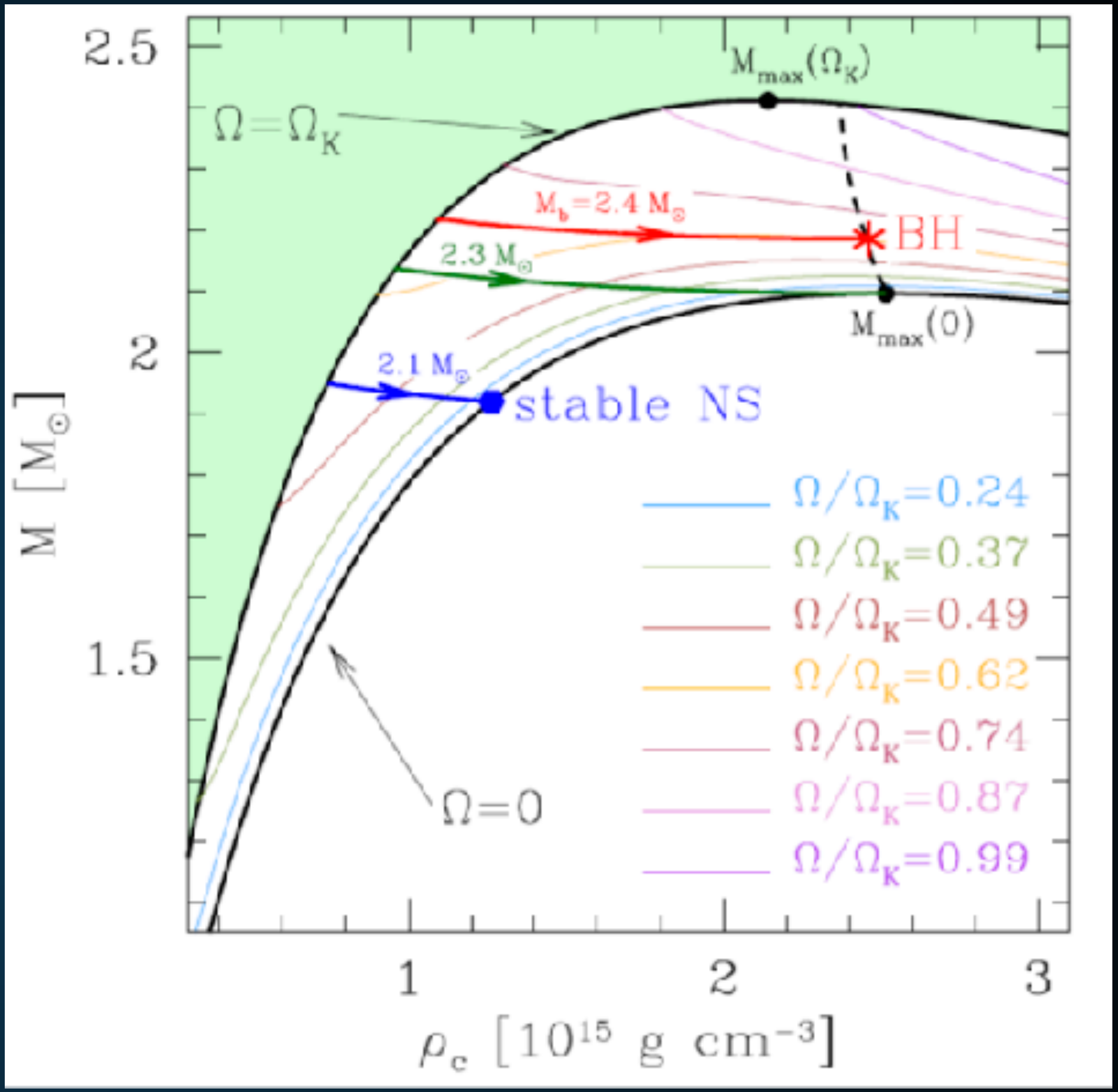


- **Short (~ms) radio bursts first discovered in 2007**
- **High dispersion measure indicates extragalactic origin.**
- **One repeating fast radio bursts, but others appear not to repeat.**
- **Origin unknown.**

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.

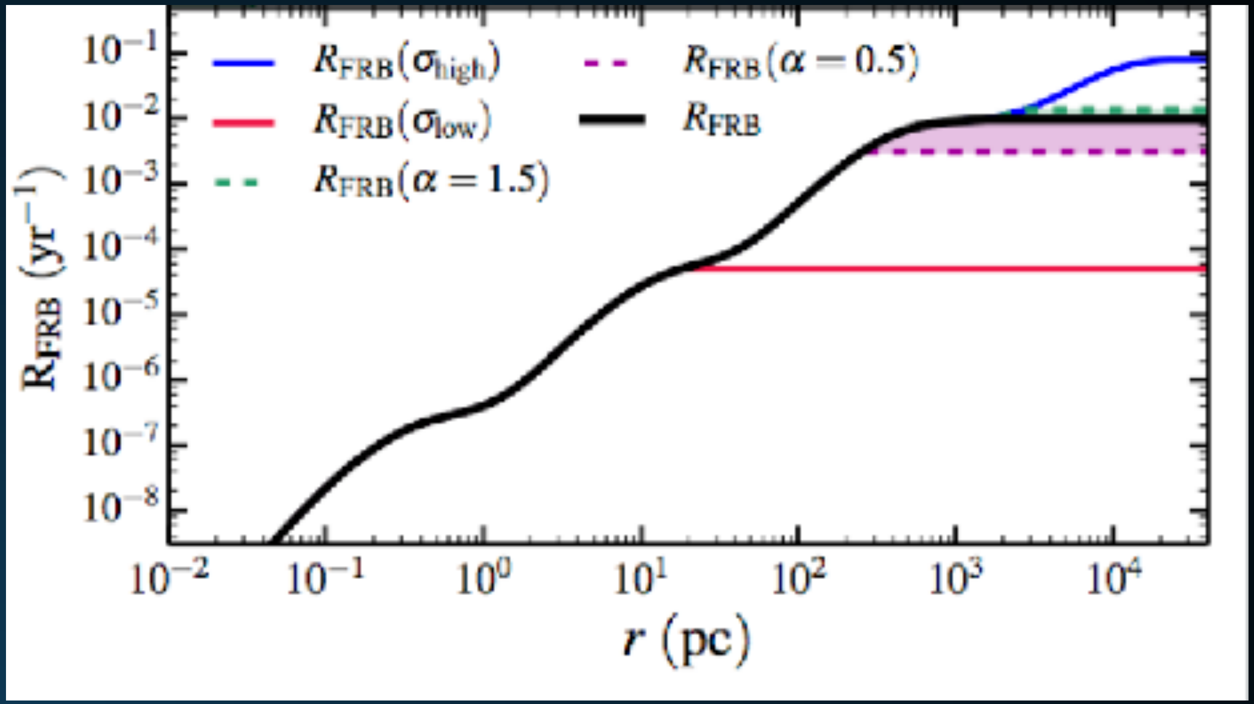


- Accretion induced collapse acts similarly to DM induced collapse.

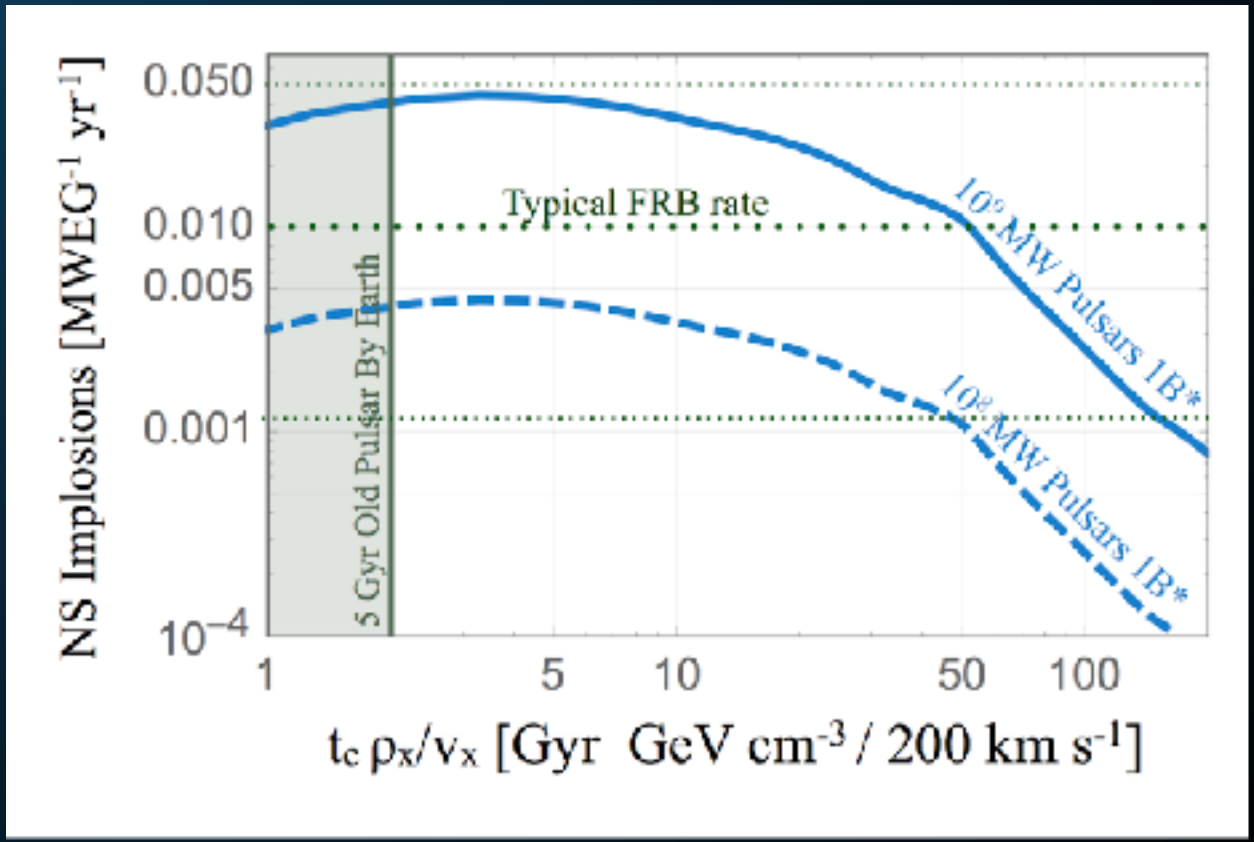
FAST RADIO BURSTS FROM PULSARS

Fuller & Ott (1412.6119)

- 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.



Bramante et al. (1706.00001)



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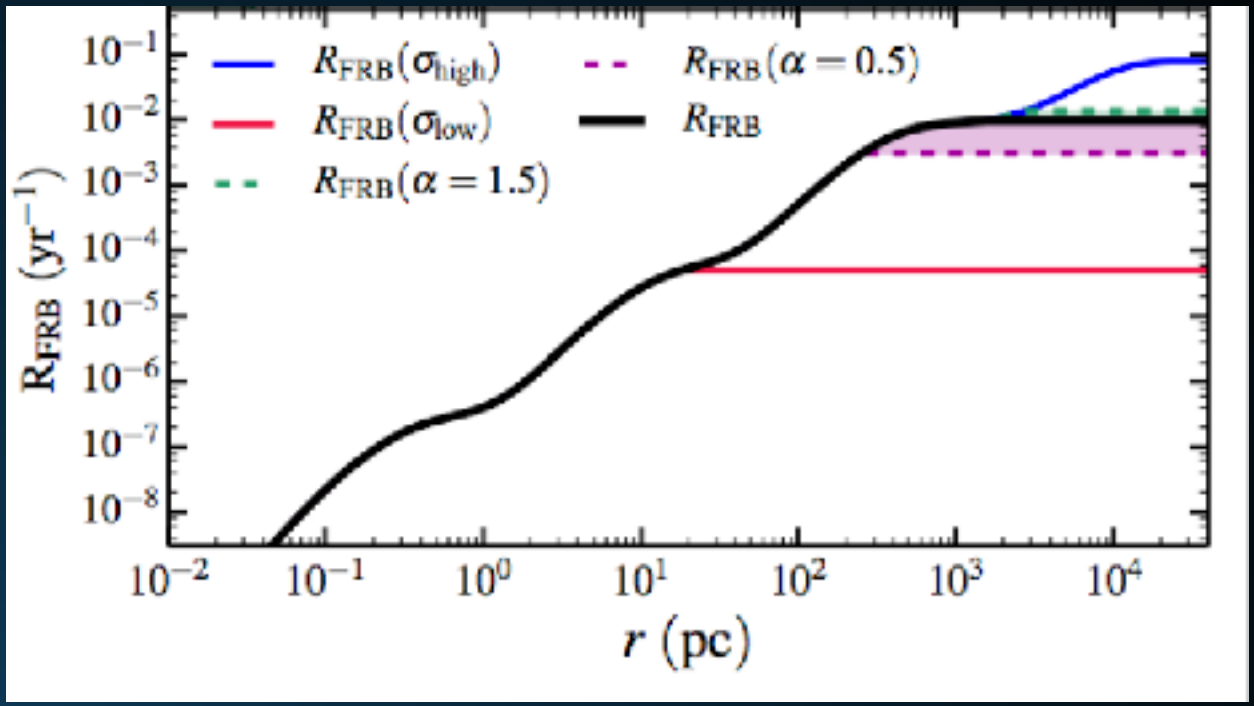
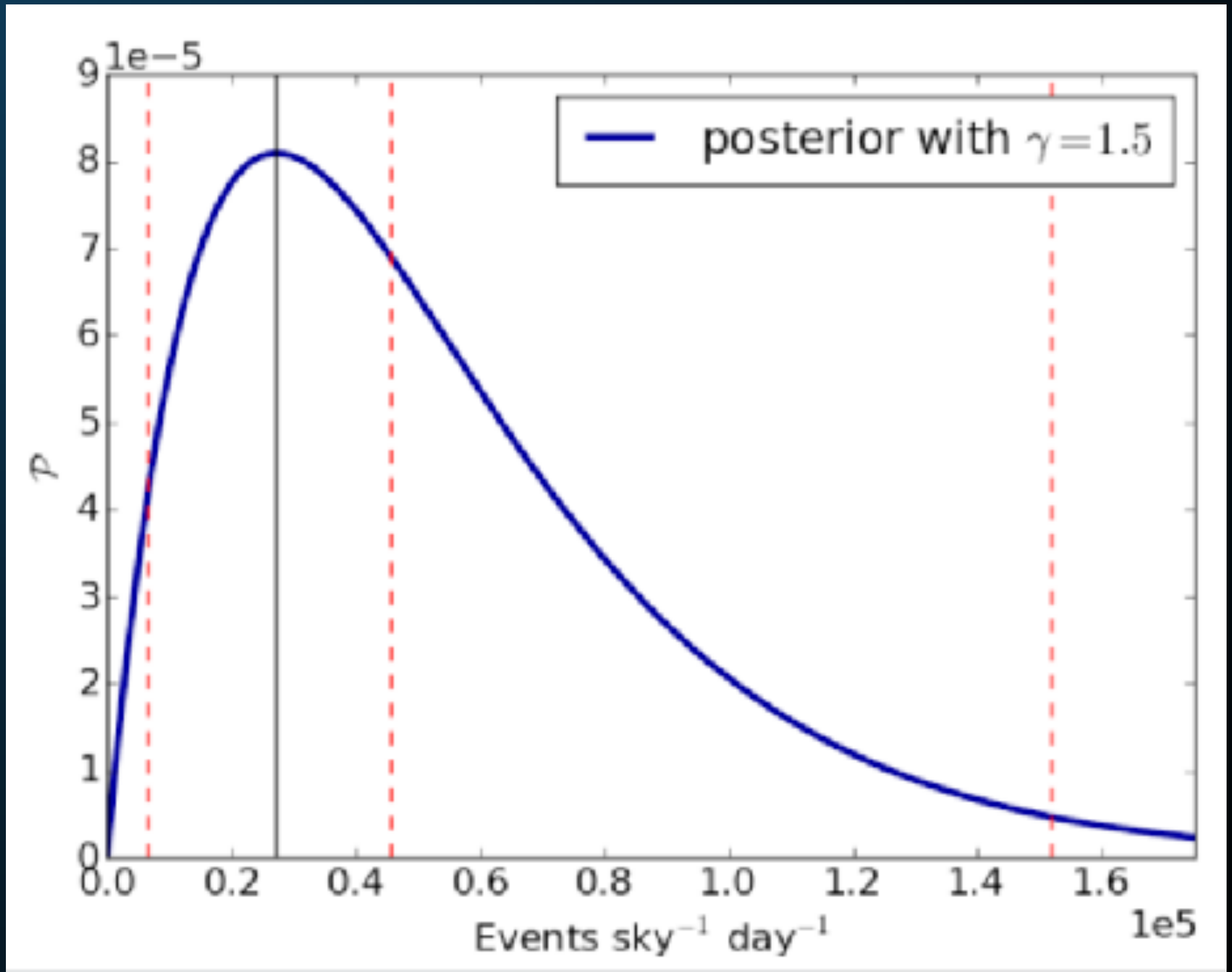
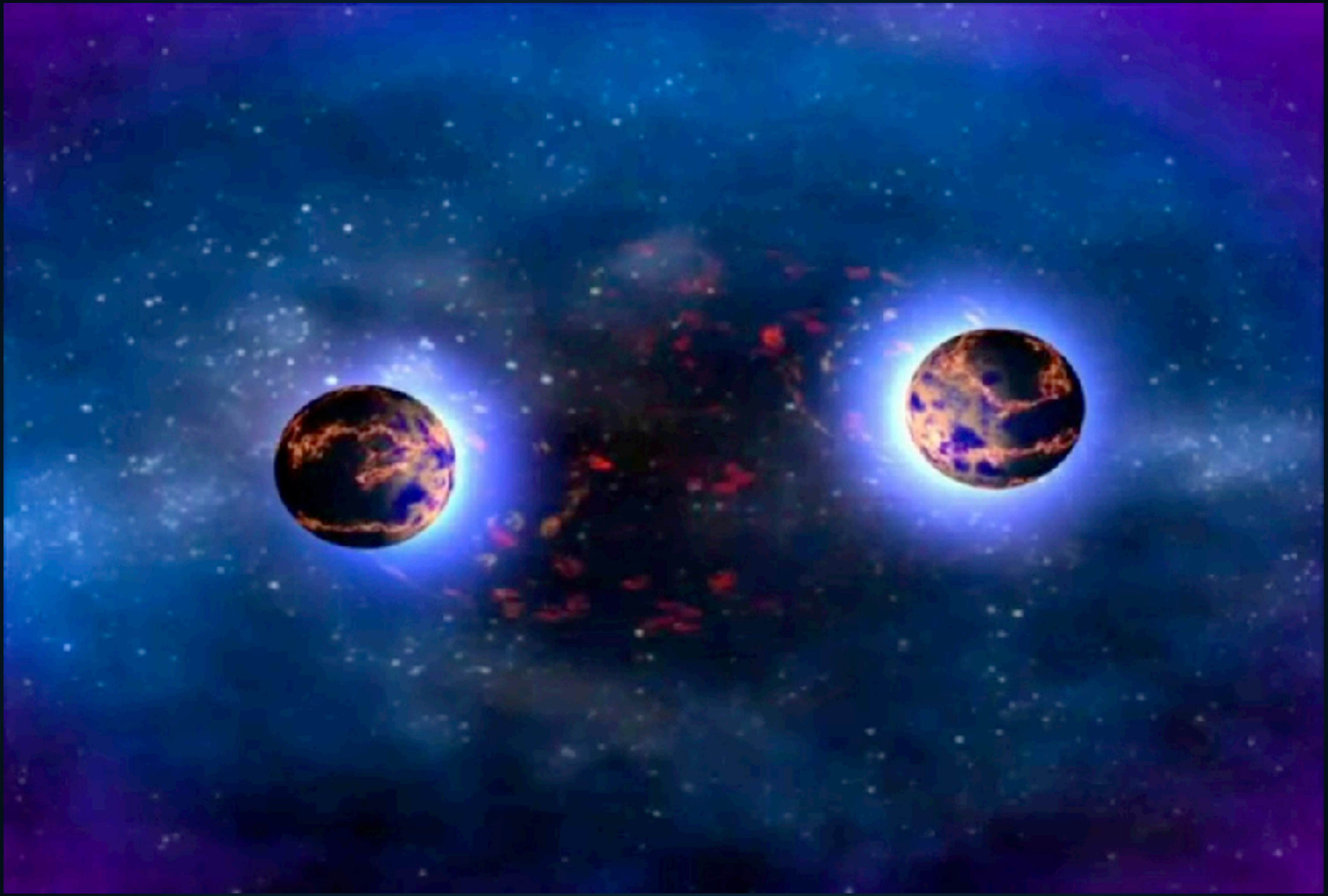


Connor et al. (1602.07292)



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

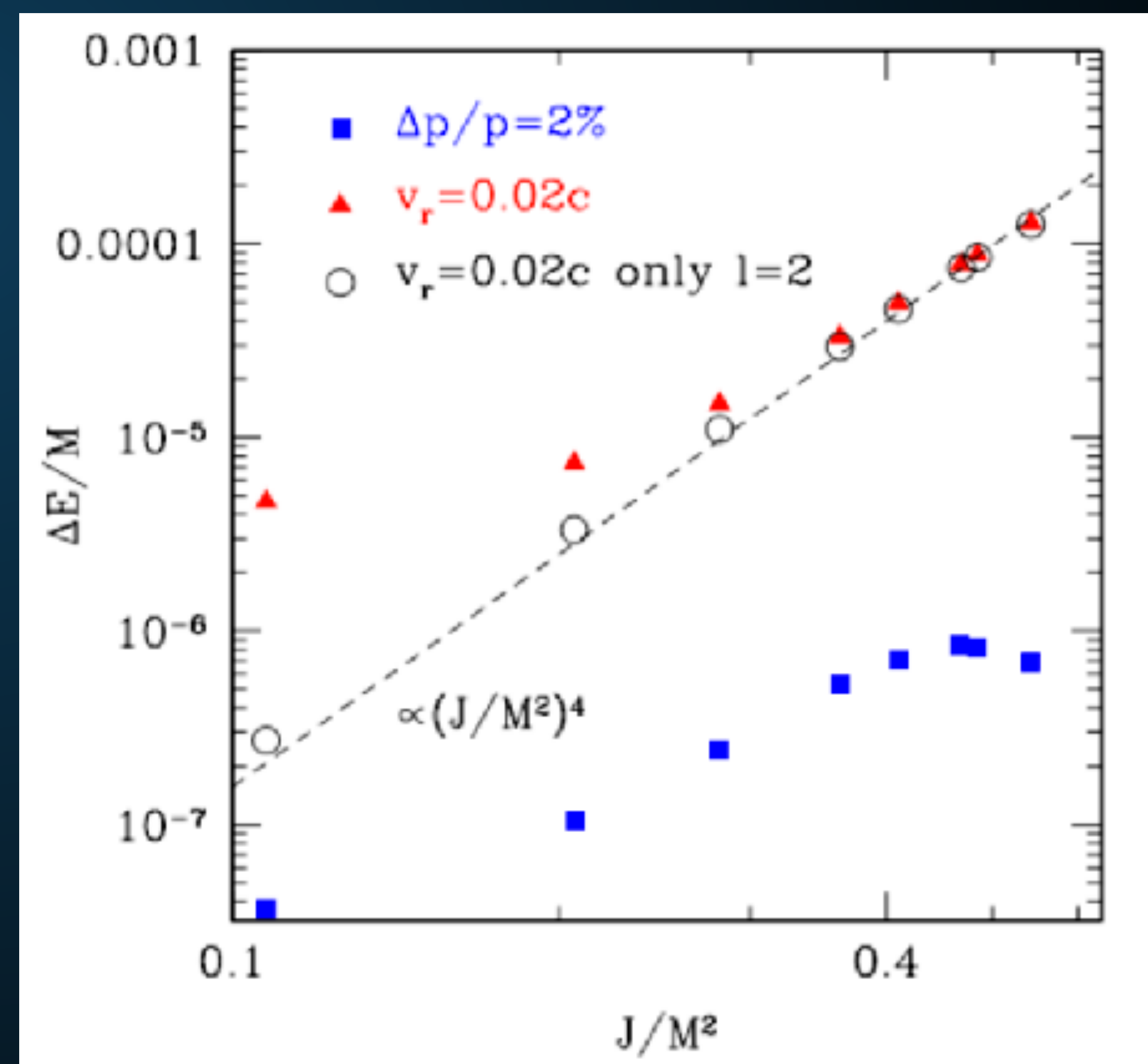
- **Gravitational Waves from DM induced collapse**

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

Baiotti et al. (gr-qc/0701043)

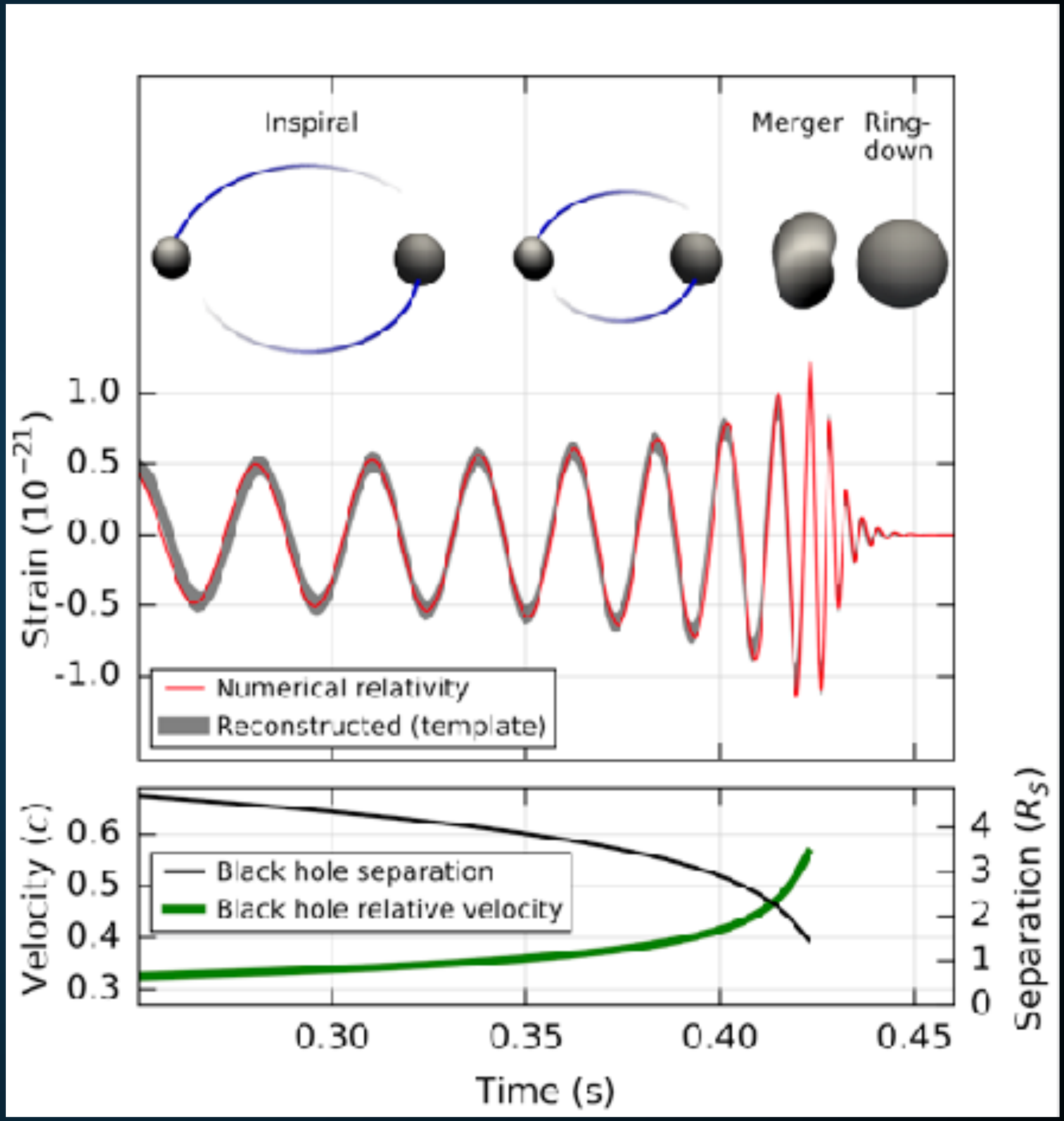
- **Single NS collapse models have been considered (primarily from accretion induced collapse).**

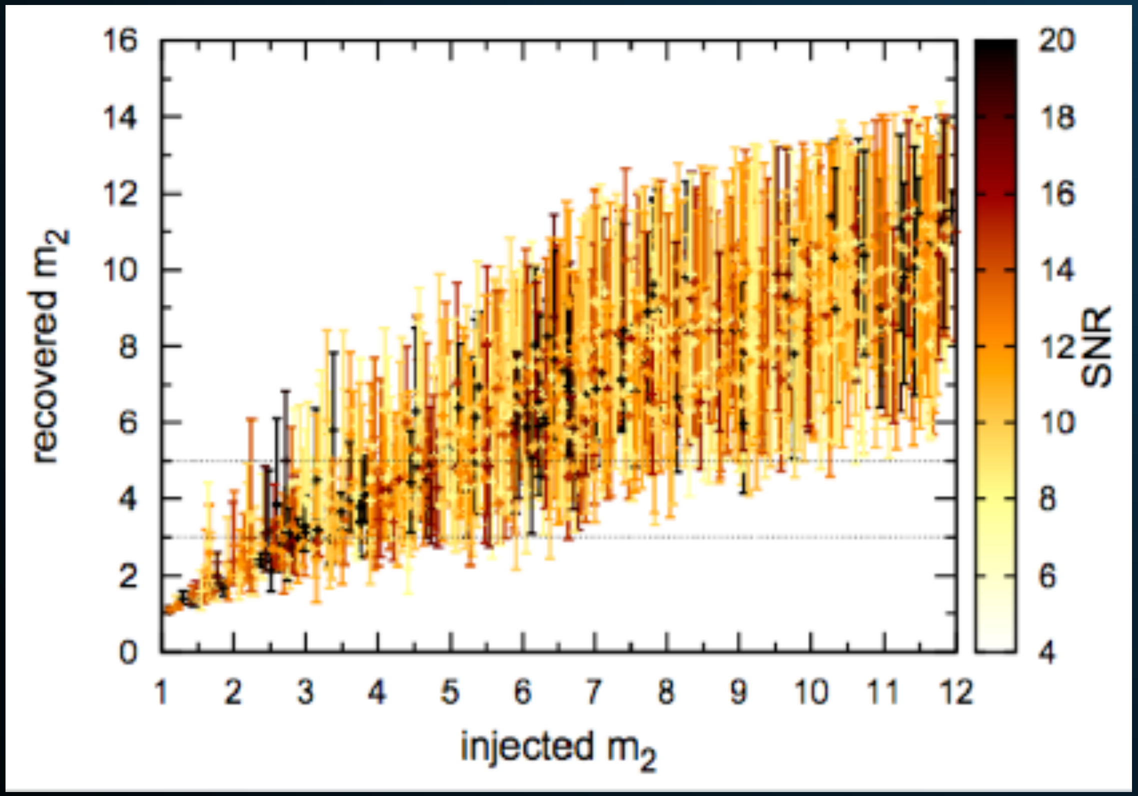
- **DM induced NS collapse observable throughout the Milky Way (0.01 yr^{-1} ?)**



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 $M_{\odot}$ black holes.
- Can potentially see differences in merger and ring-down, but not presently feasible.



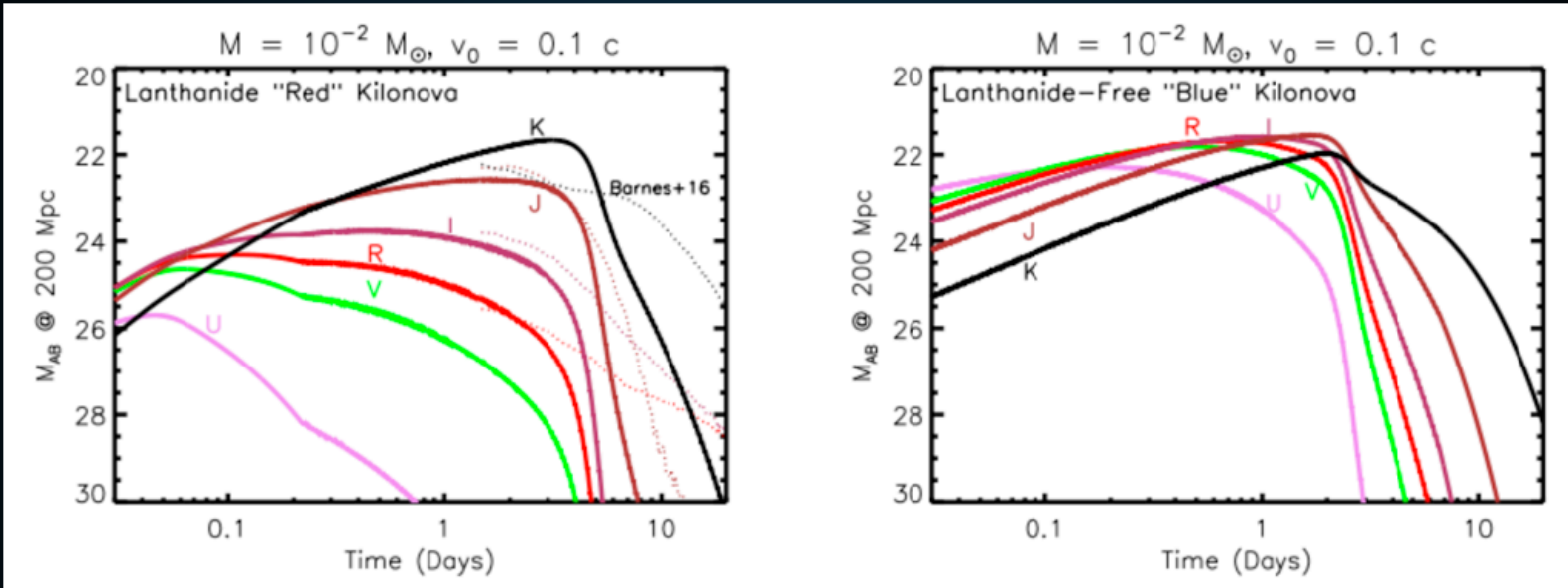


Littenburg et al. (1503.03179)

MERGER KILONOVAE

Metzger (1610.09381)

- Disassociation of electromagnetic and gravitational wave signatures



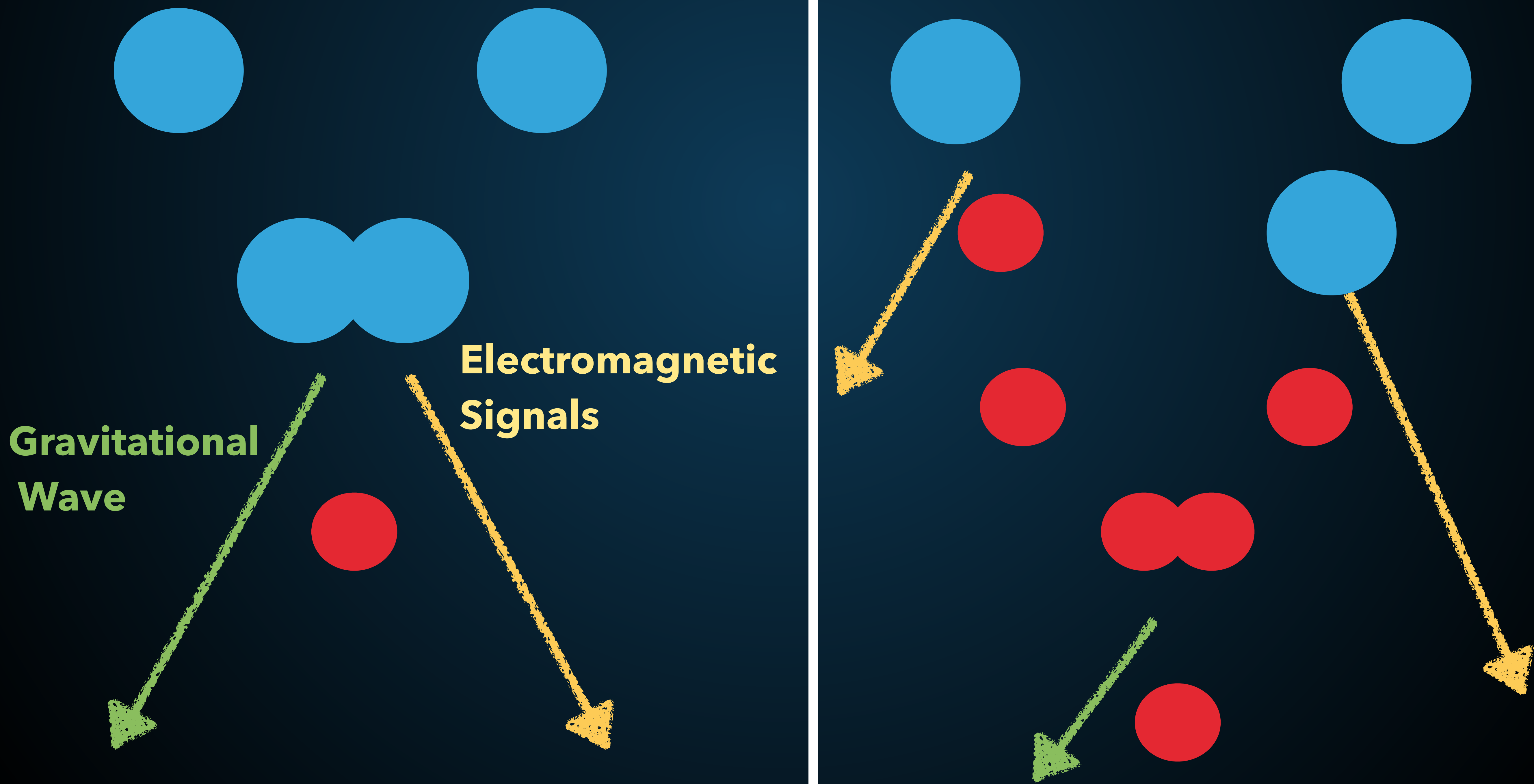
- **Kilonovae - Days long afterglows of NS-NS mergers formed primarily by beta-decay of r-process materials.**
- **Likely associated with sGRBs - but better localization.**

DISSOCIATION OF EM AND GRAVITATIONAL SIGNATURES

- Disassociation of electromagnetic and gravitational wave signatures

No DM Induced Collapse

DM Induced Collapse



Bramante, TL, Raj (1706.00001)

- <u>Merger Kilonovae</u> - Bright r-process afterglows of NS-NS binary mergers.
- <u>Quiet Kilonovae</u> - Possible r-process afterglows of DM induced neutron star collapse
- <u>Dark Mergers</u> - 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

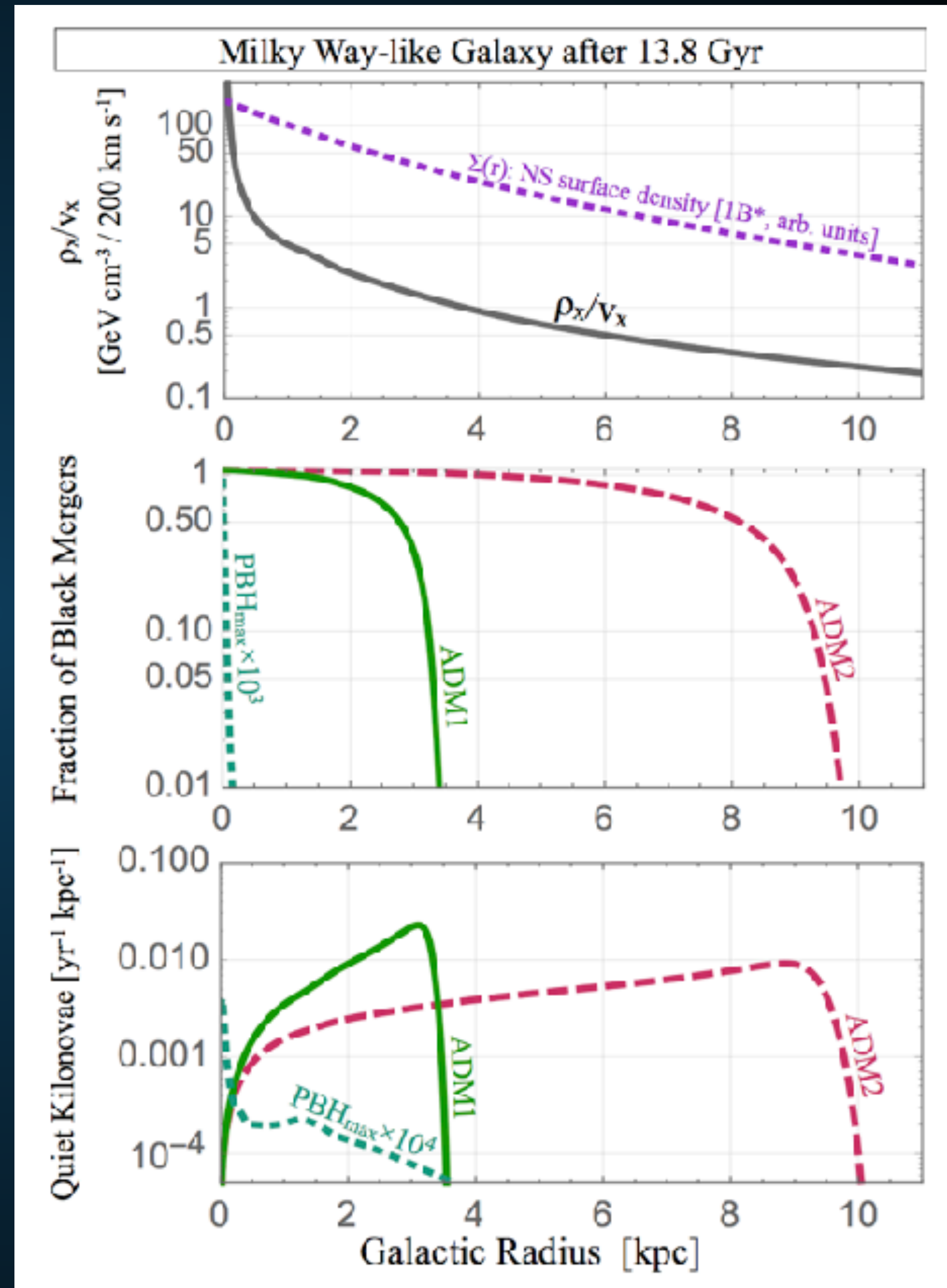
- **A reasonable fraction of all NS-NS mergers should actually be LM-LM mergers.**
- **LM-NS mergers occur in primordial black hole models.**
- **Difficult to argue that you have found dark matter by not seeing something that you should….**

RADIAL DEPENDENCE OF DM INDUCED COLLAPSE

Bramante, TL, Raj (1706.00001)

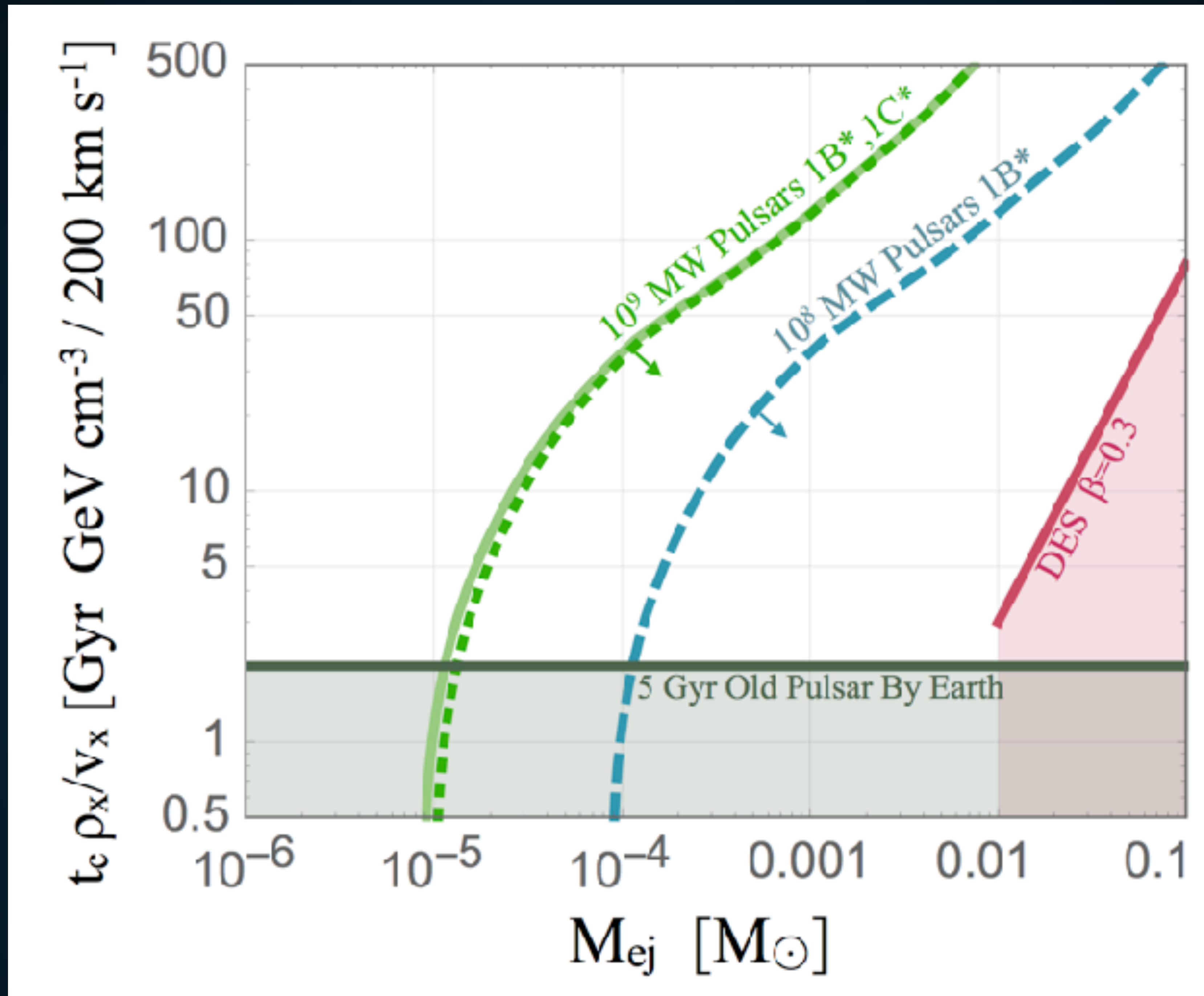
- This scenario does not happen equivalently through the galaxy.

- 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)

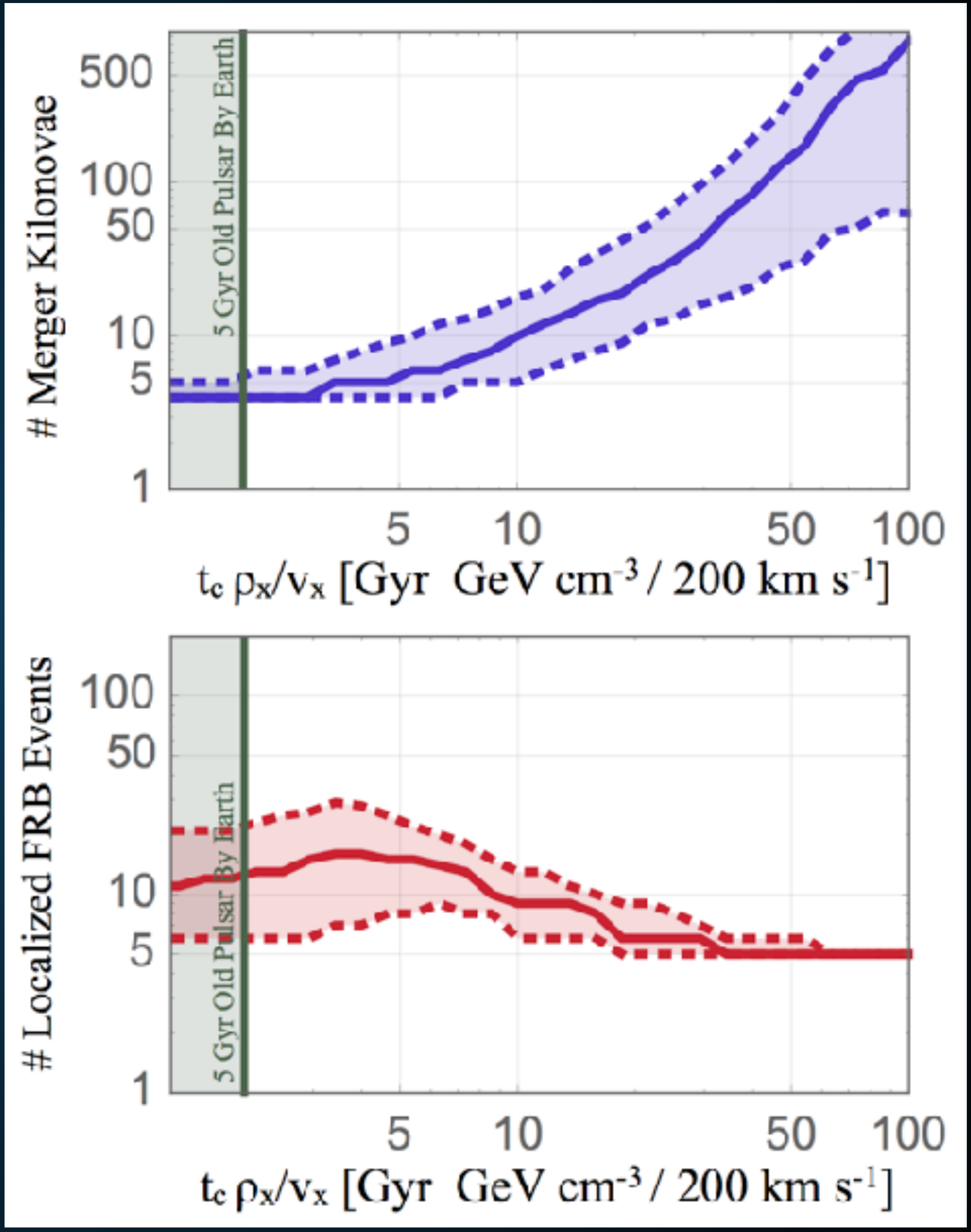


- These models reasonably re-produce the observed r-process abundance with "quiet kilonovae" that do not have a gravitational wave counterpart.

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.**



TeVPA 2017

tevpa2017.osu.edu

- August 7–11, Columbus, OH
- Registration and abstract submission are open
- Pre-meeting mini-workshops on Sunday, August 7

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.