Dark Matter Accumulation in Neutron Stars

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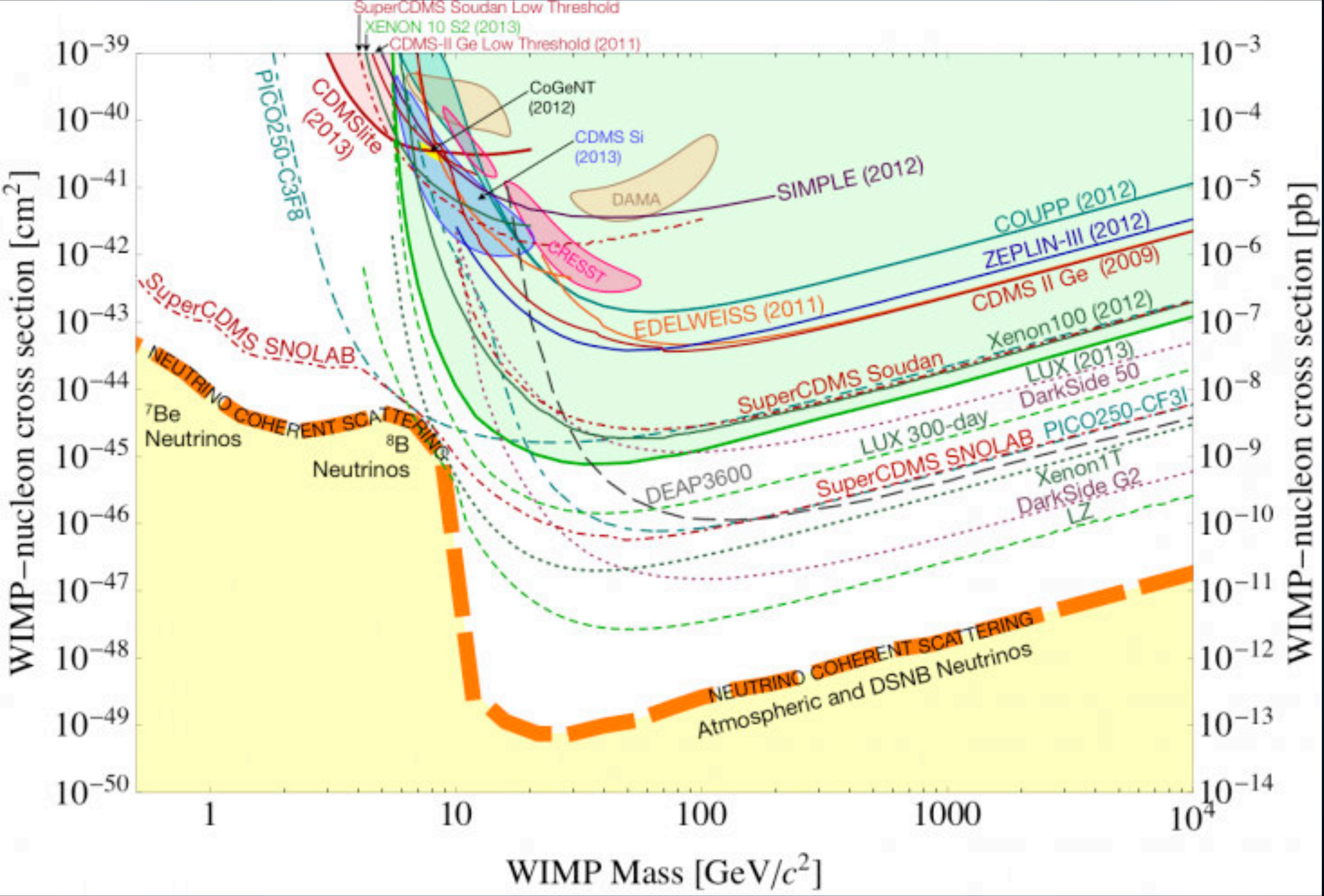
Direct Dark Matter Detection: Experimental Efforts



SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
CDMSlite (2013)
PICO250-C3F8
DAMA
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
CRESST
EDELWEISS (2011)
Xenon100 (2012)
SuperCDMS Soudan
LUX (2013)
DarkSide 50
SuperCDMS SNOLAB
LUX 300-day
PICO250-CF3I
SuperCDMS SNOLAB
Xenon1T
DEAP3600
DarkSide G2
LZ
NEUTRINO COHERENT SCATTERING
^{7}Be Neutrinos
^{8}B Neutrinos
NEUTRINO COHERENT SCATTERING
Atmospheric and DSNB Neutrinos
WIMP–nucleon cross section [cm^2]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c^2]

Neutron Stars: The Optimal Direct Detection Laboratory

Xenon-1T

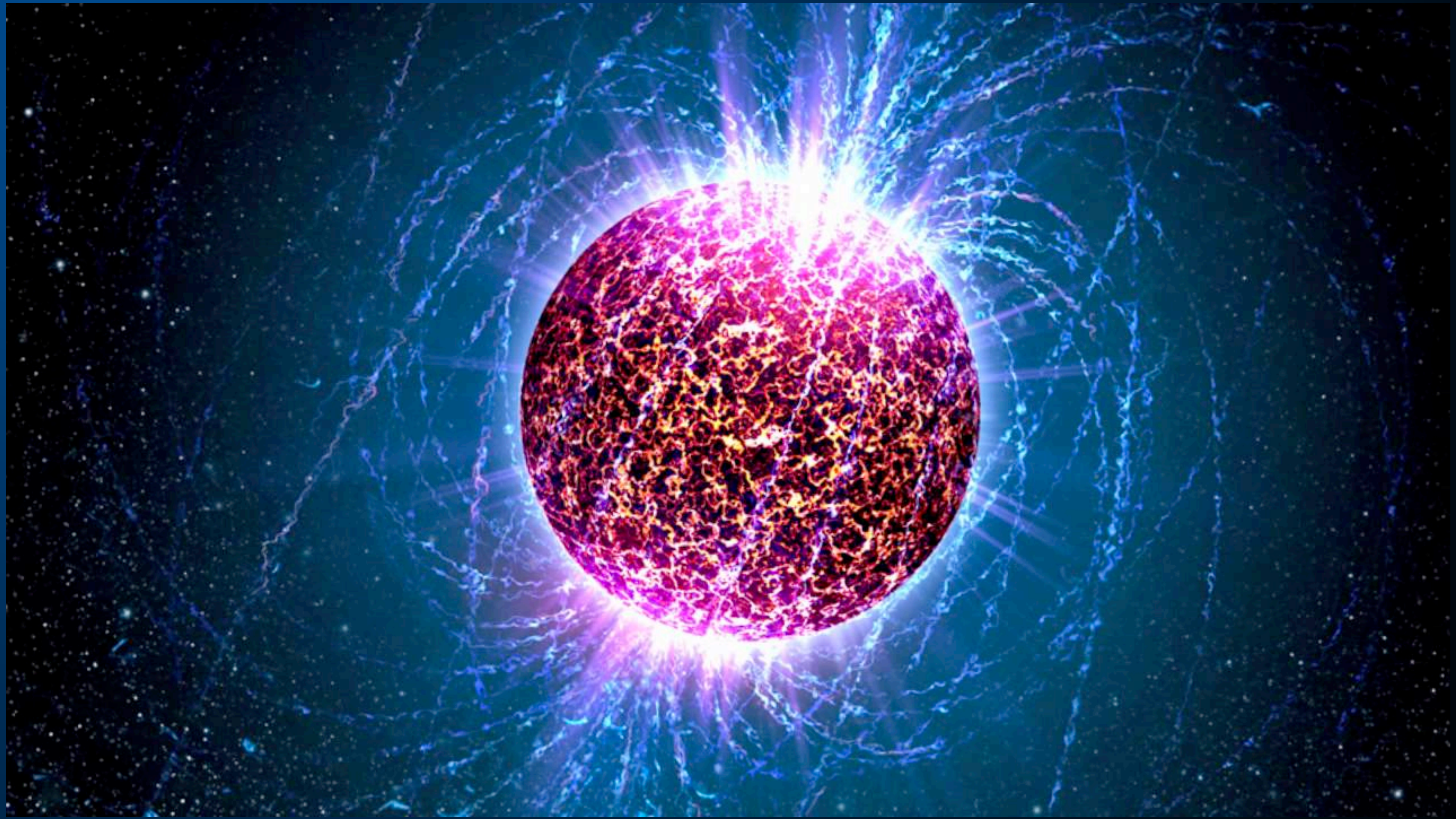
- 1000 kg
- 700 days

7×10^{5} kg day

Neutron Star

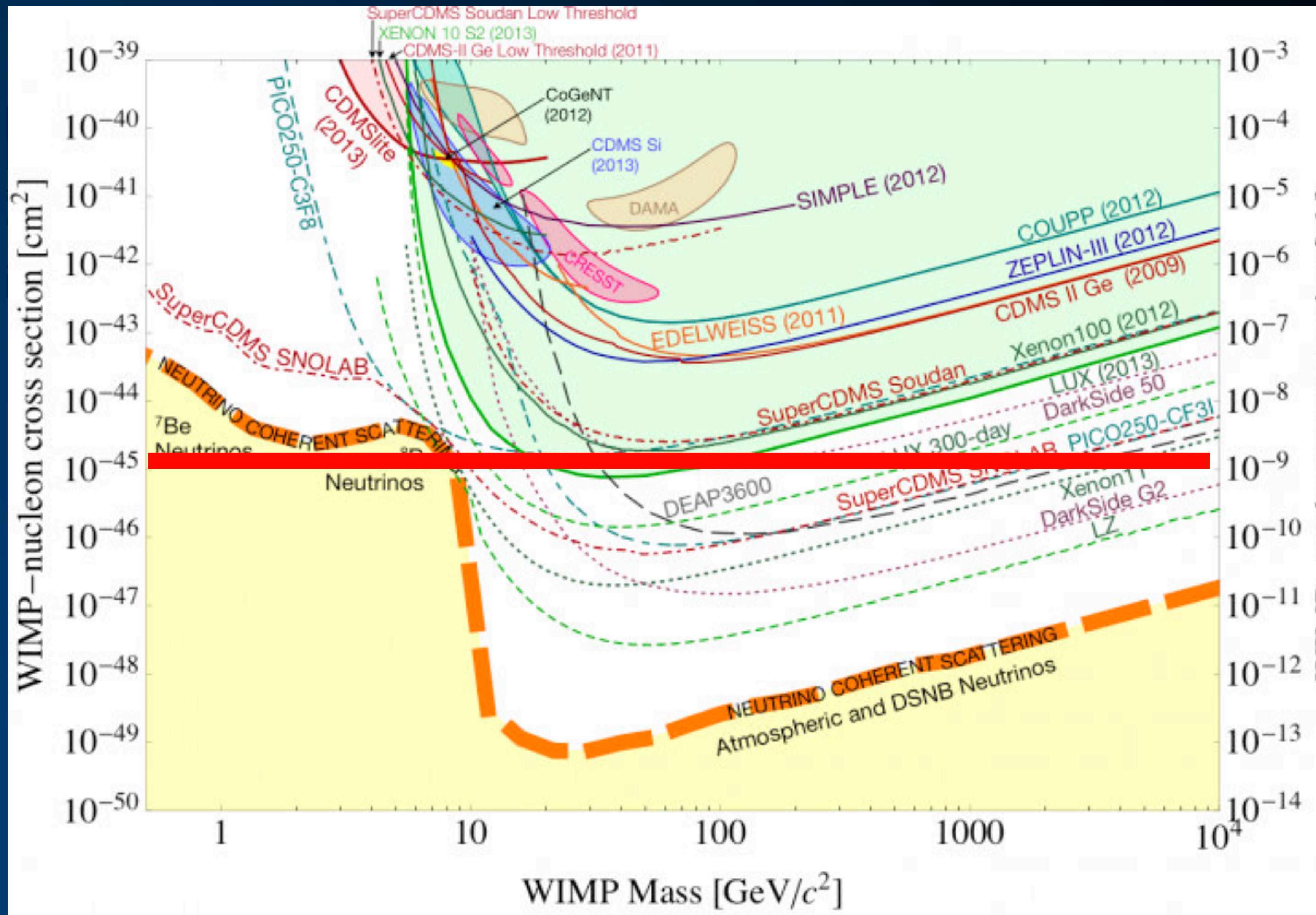
- 3×10^{30} kg
- 2×10^{10} days

6×10^{40} kg day



Neutron Stars: The Optimal Direct Detection Laboratory

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



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

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

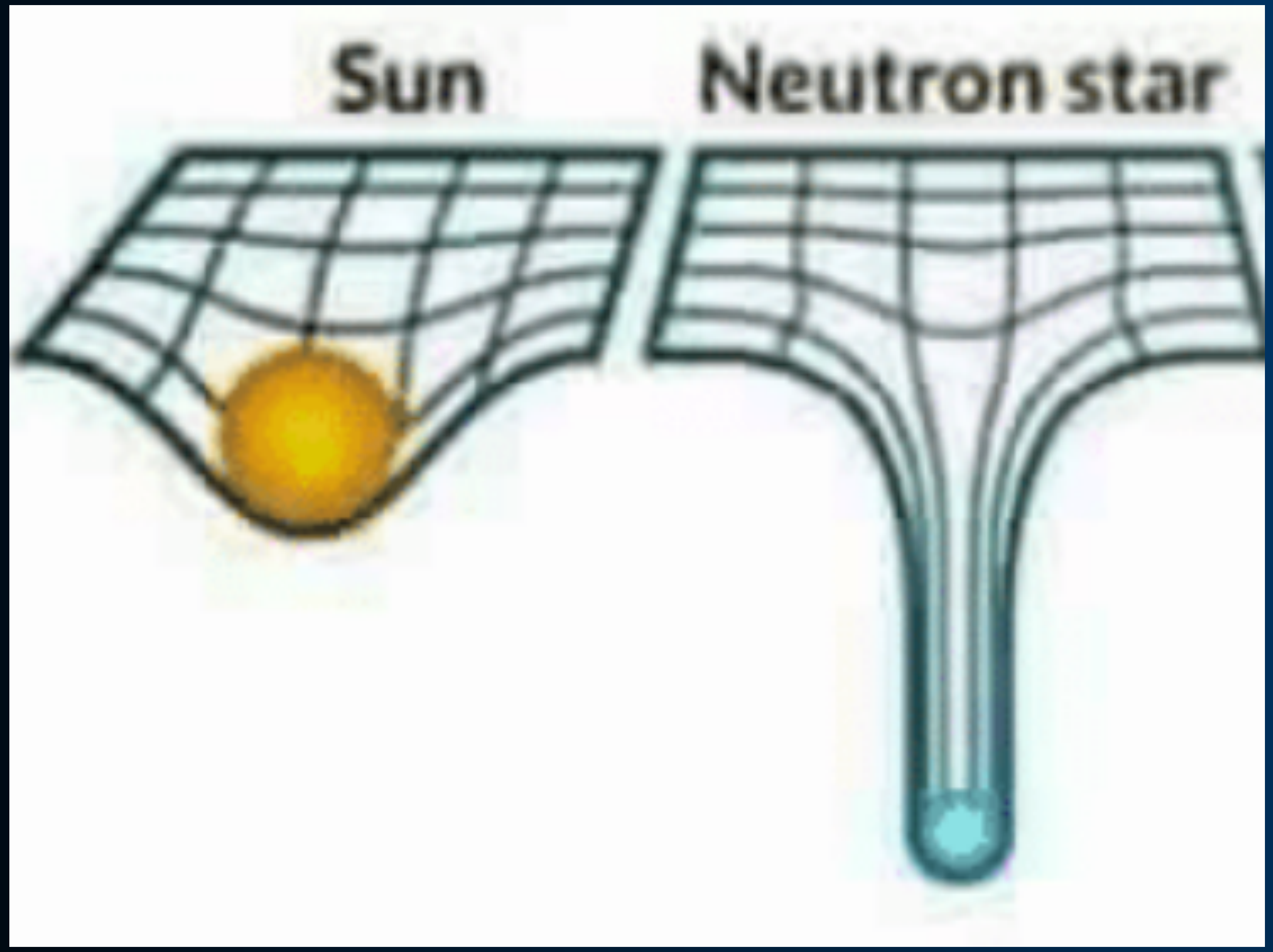
How Do We Observe These Interactions?

Detecting DM-NS Interactions

- What about the dark matter itself?
  - Capture - DM hits neutron and elastically scatters - injects energy into the neutron star (Baryakhtar et al. 1704.01577)
  - 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.

Neutron Stars: A Direct Detection Collider

- **Neutron stars gravitationally attract nearby dark matter particles.**



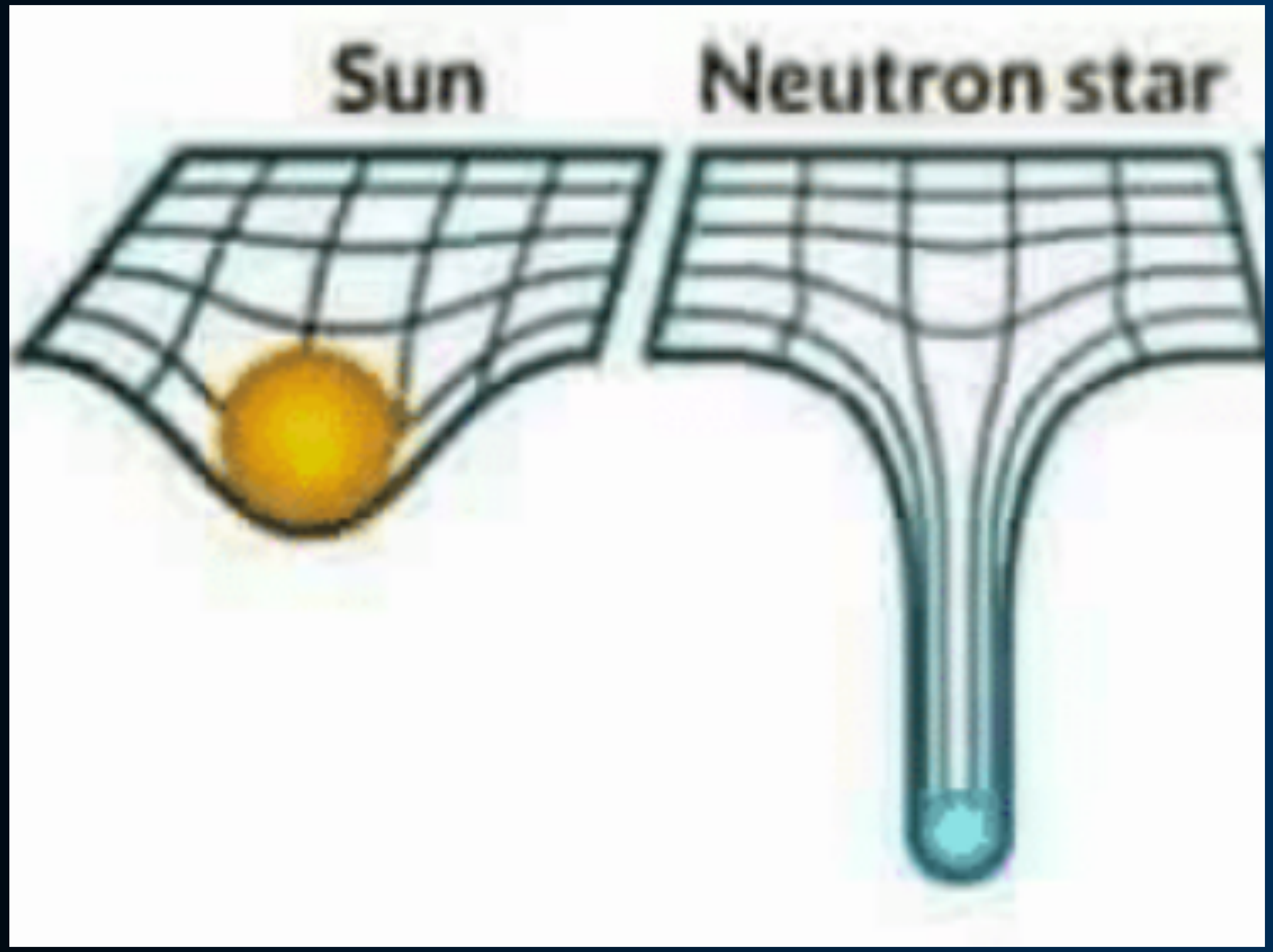
Interaction scales as v_x^{-1}

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

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

Neutron Stars: A Direct Detection Collider

- When dark matter particles hit the NS surface, they are moving relativistically



Can probe p-wave suppressed or dark matter mass splittings

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

Neutron Stars: Particle Physics Complications

- NS are supported by Fermi Degeneracy Pressure

Typical NS neutron momentum is:

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

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

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

Neutron Stars: Particle Physics Complications

- **Kinetic Energy may not be efficiently transferred in interaction.**

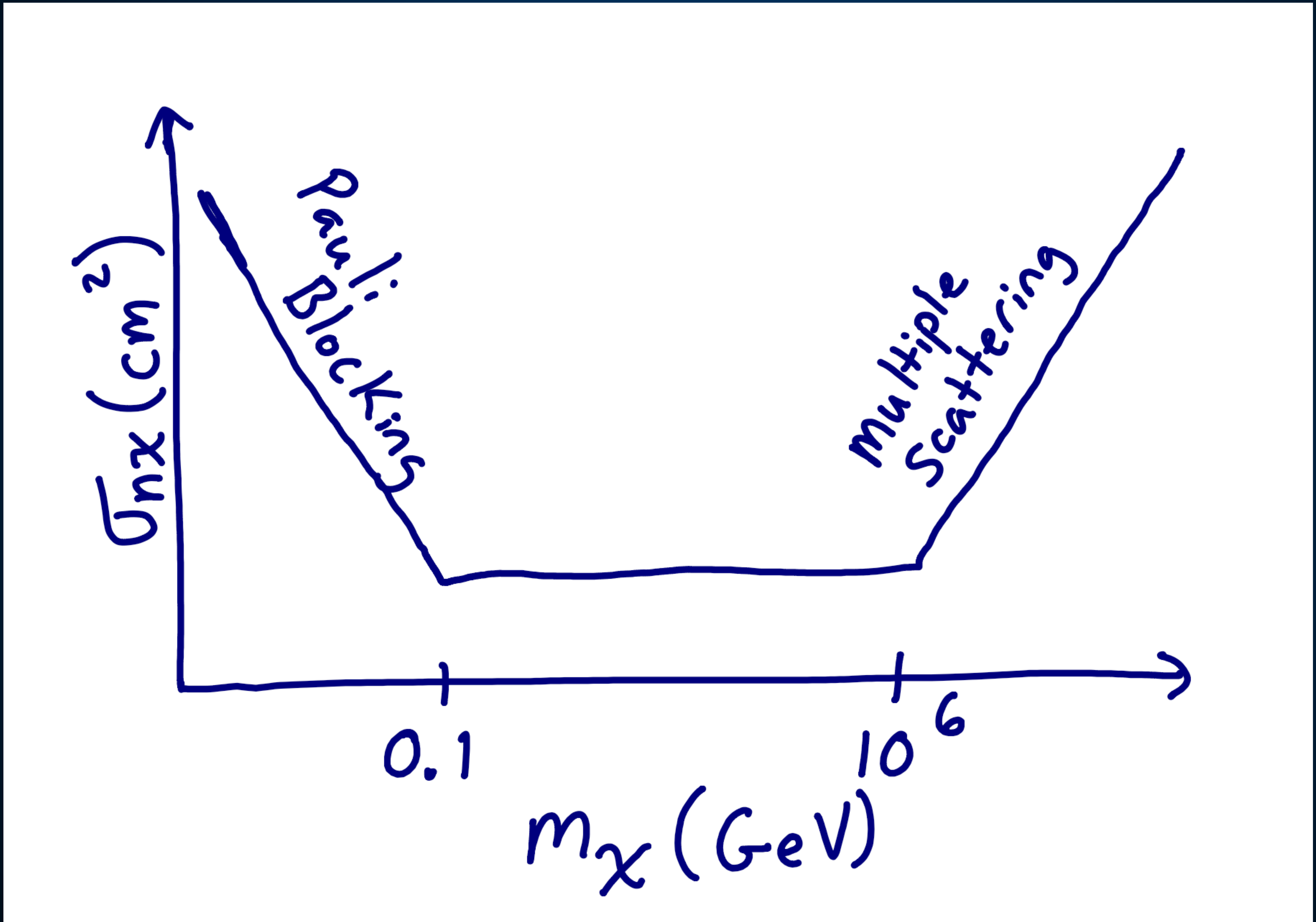
Dark Matter kinetic energy lost in a scatter with a proton is:

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

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

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

Neutron Stars: Particle Physics Complications

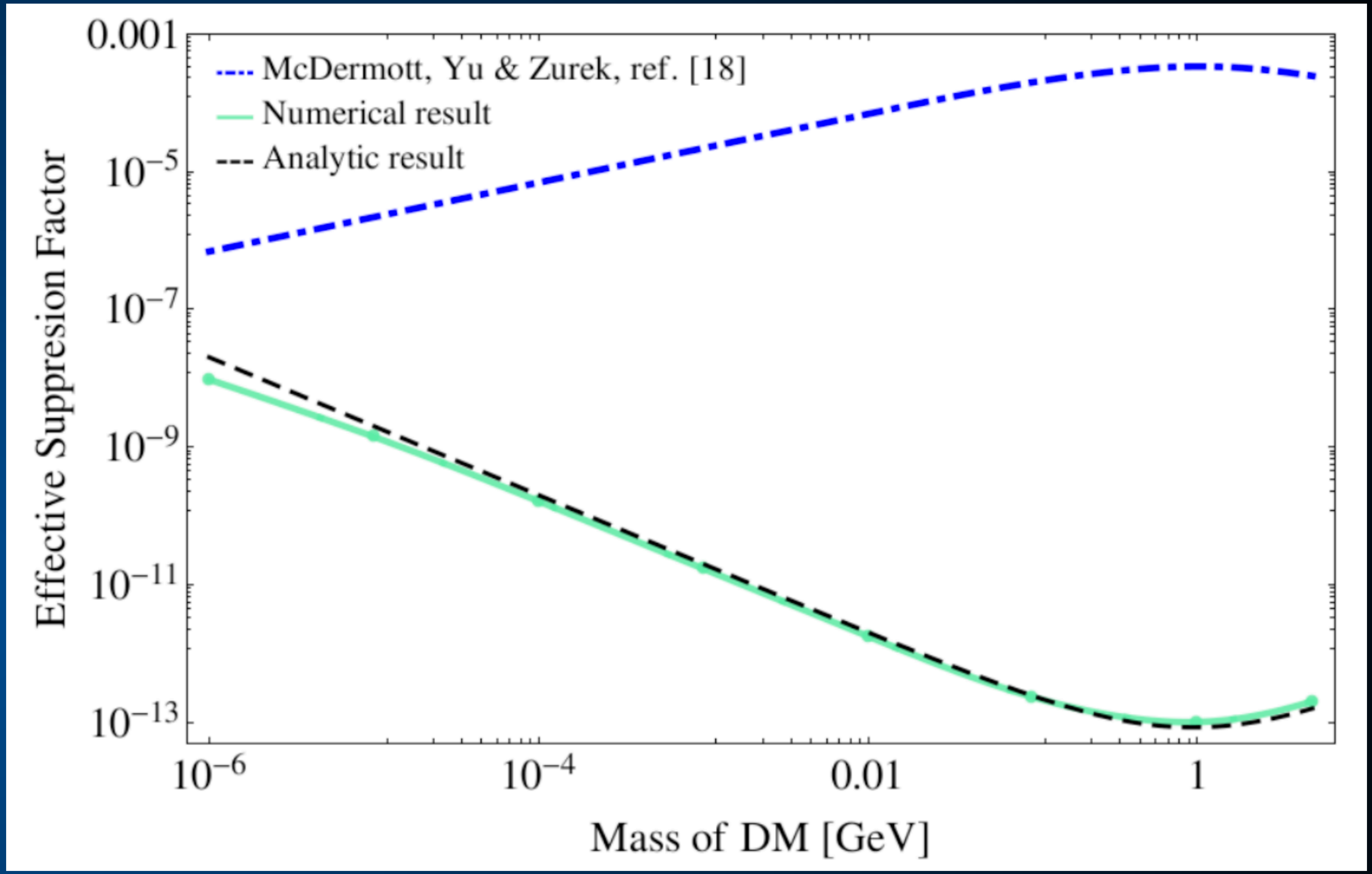


Dark Matter Thermalization

Bertoni et al. (2013; 1309.1721)

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

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



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

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

Dark Matter Collapse

- Two paths are possible:

  - If dark matter can annihilate, the large densities make annihilation inevitable.

  - If dark matter cannot annihilate, dark matter builds mass until it exceeds its own degeneracy pressure. It then collapses on a timescale:

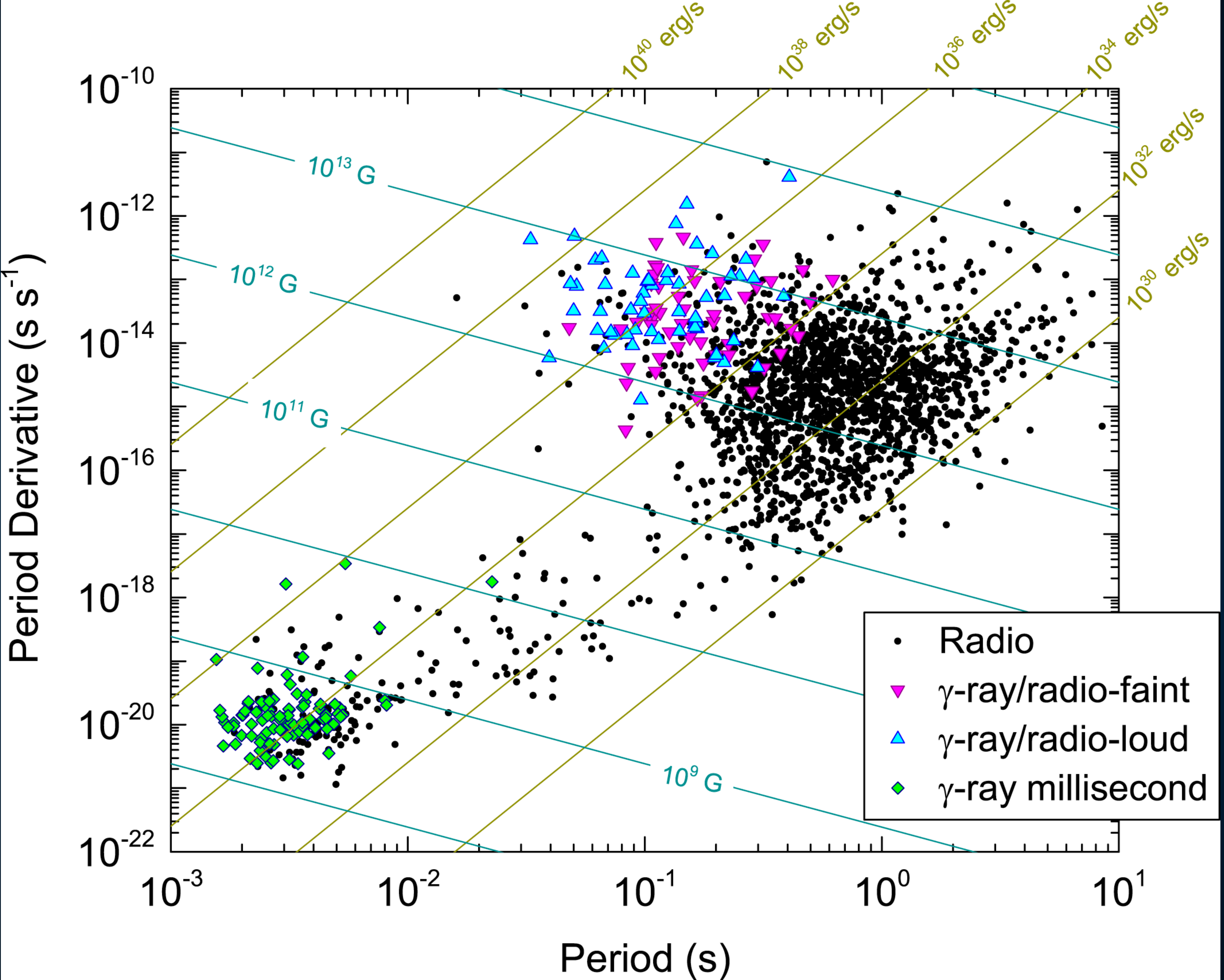
$$\tau_{\rm co} \simeq \frac{1}{n\sigma_{n\rm x}v_{\rm x}}\left(\frac{p_F}{\Delta p}\right)\left(\frac{m_{\rm x}}{2m_n}\right)$$
$$\simeq 4\times 10^5 \text{ yrs}\left(\frac{10^{-45}\text{ cm}^2}{\sigma_{\rm nx}}\right)\left(\frac{r_x}{r_0}\right),$$

Detecting DM-NS Interactions

- Requires dark matter to be non-annihilating, and additionally
  - PeV Fermionic Dark Matter

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

  - Bosonic Dark Matter
  - Attractive Self-Interacting Dark Matter


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

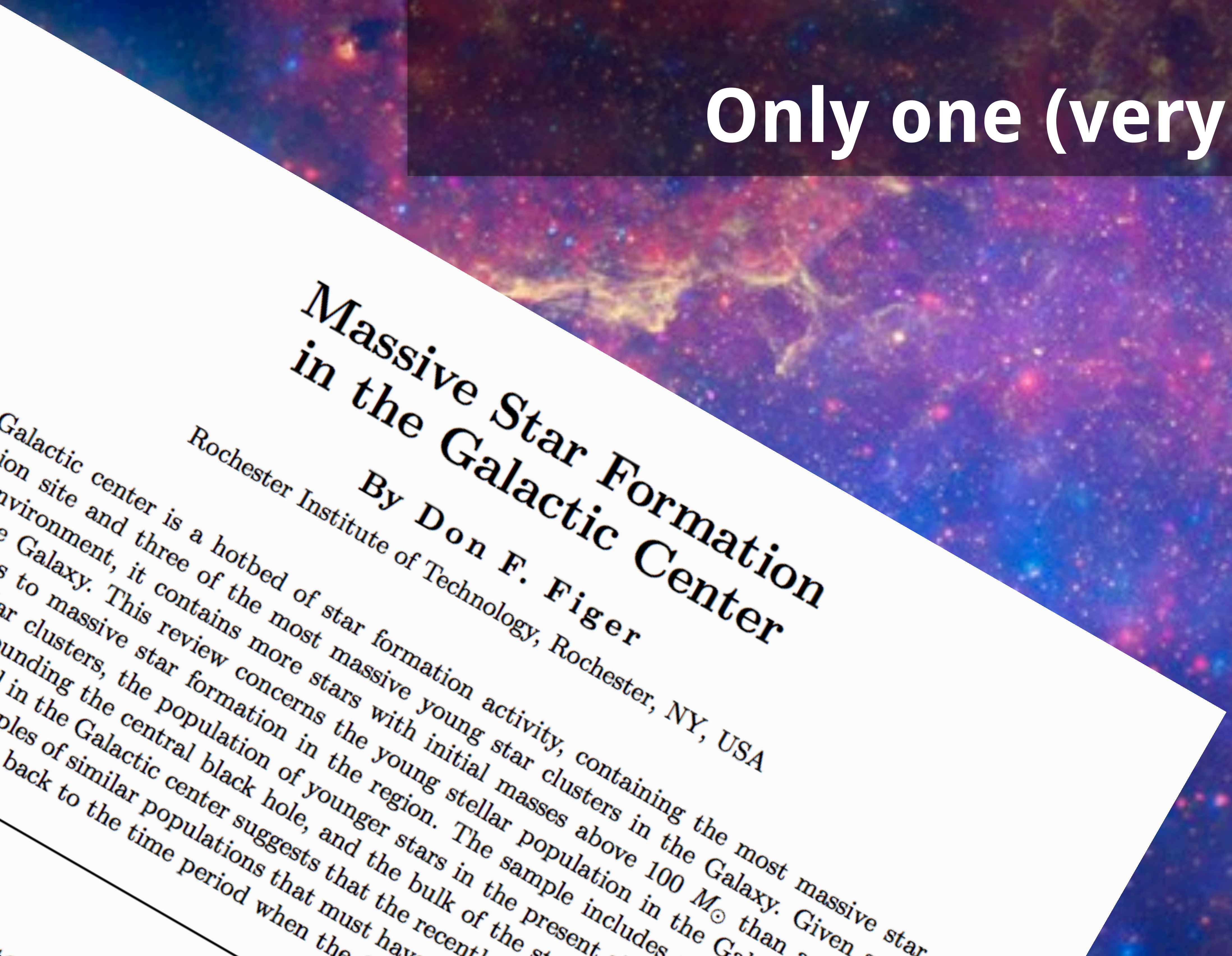
Strong Constraints on Direct Detection

McDermott et al. (1103.5472)

A Signal?

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

Only one (very young) pulsar detected



Massive Star Formation in the Galactic Center

By Don F. Figer

Rochester Institute of Technology, Rochester, NY, USA

Galactic center is a hotbed of star formation activity, containing the most massive star
ion site and three of the most massive young star clusters in the Galaxy. Given
vironment, it contains more stars with initial masses above 100 $M_\odot$ than
e Galaxy. This review concerns the young stellar population in the Ga
s to massive star formation in the region. The sample includes
ar clusters, the population of younger stars in the present
unding the central black hole, and the bulk of the
in the Galactic center suggests that the recent
ples of similar populations that must hav
back to the time period when the

THE PECULIAR PULSAR POPULATION OF THE CENTRAL PARSEC

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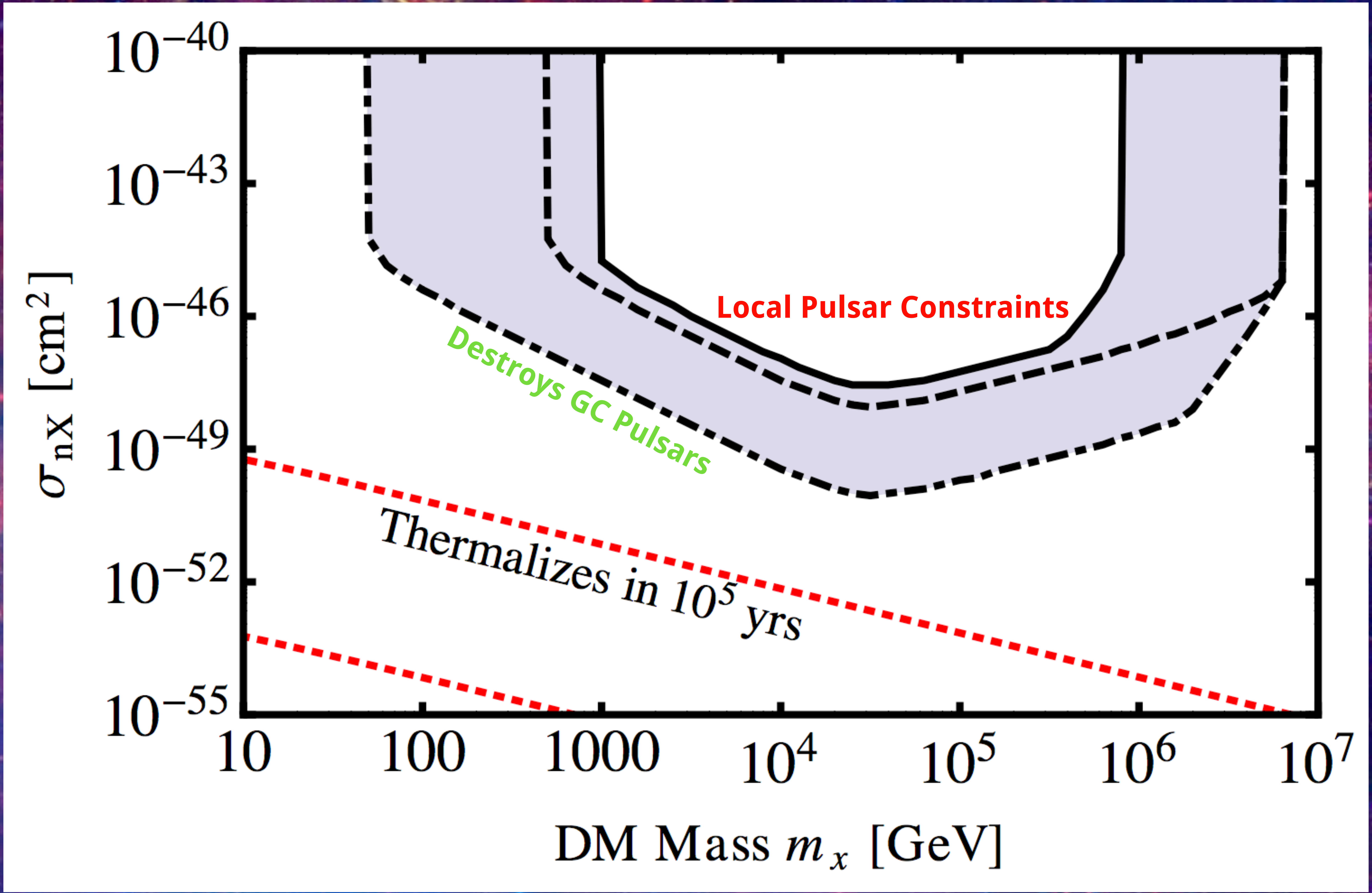
Draft version April 14, 2018

ABSTRACT

the Galactic center black hole, Sgr A*, would be potential pr
even be used to test general relativity. Despite predic
illisecond pulsars in the Galactic center, none ha
One explanation has been that hyperstrong
discovery of radio pulsations from a
the temporal scattering is mu
inary pulsar population is t
blem" in the Galactic
magnetar for
ordinar

A Signal?

Bramante & TL (1405.1031)

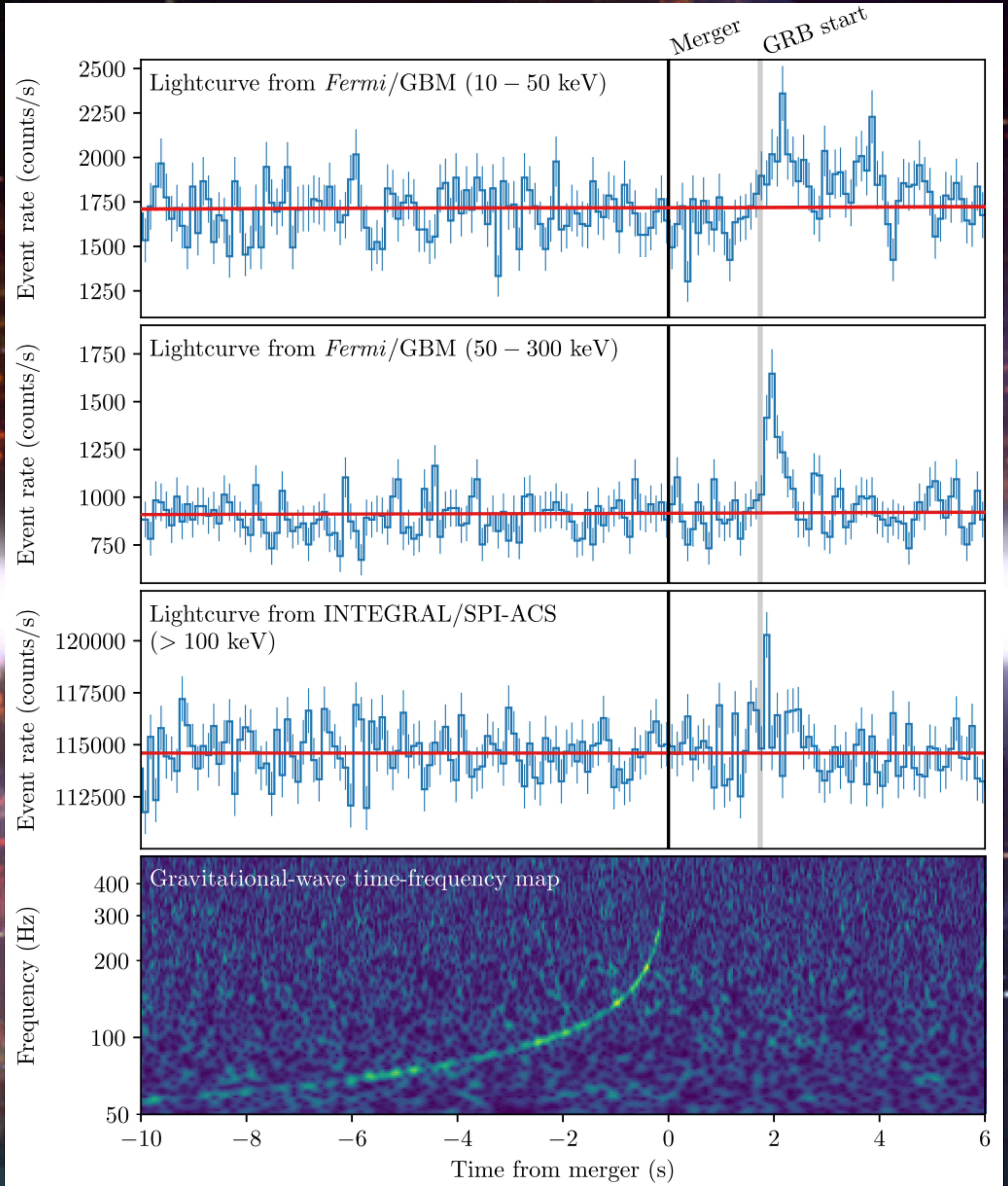


An Electromagnetic Signal?

Bramante, TL, Tsai (1706.00001)

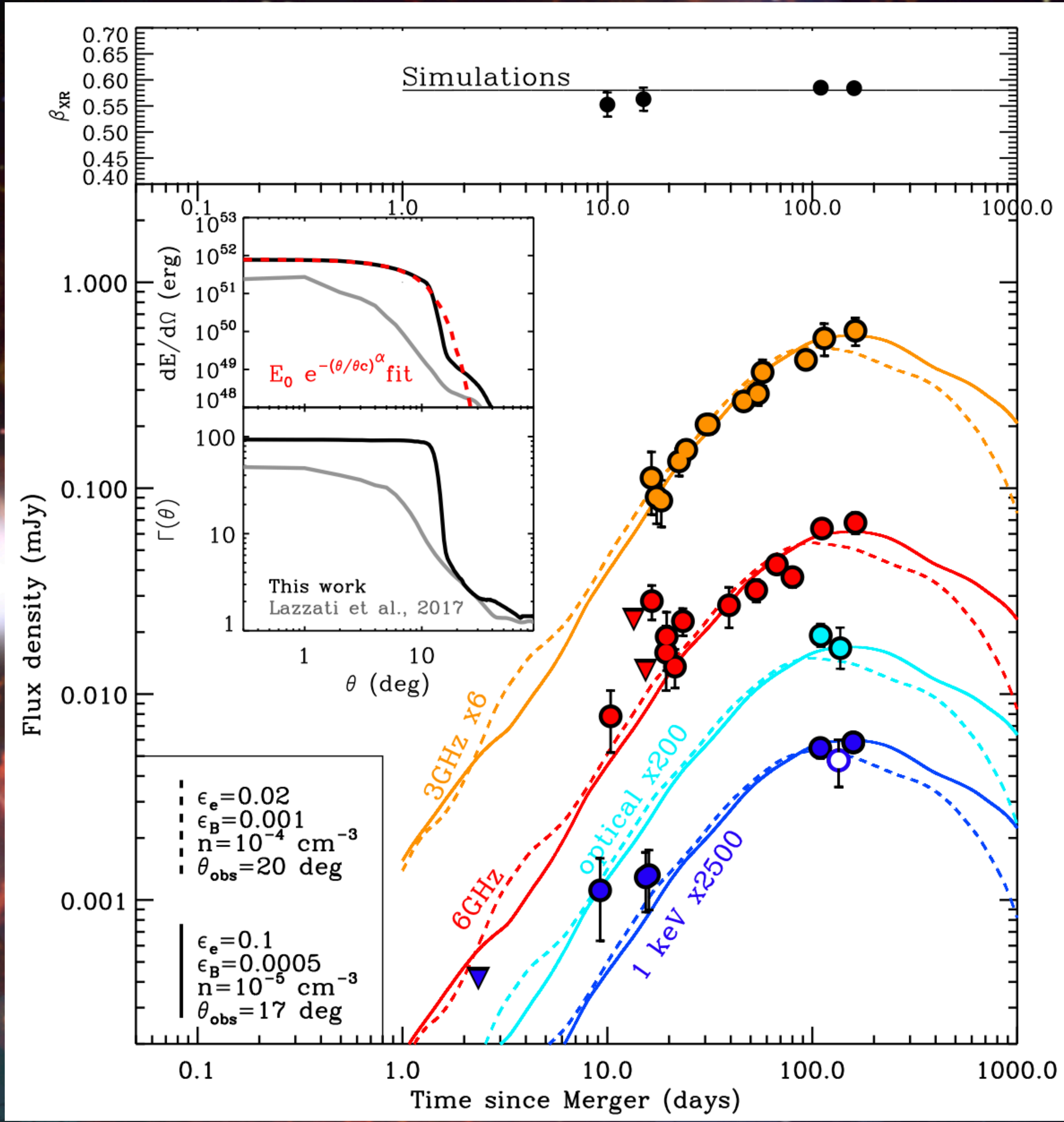
An Electromagnetic Signal?

Fermi GBM Collaboration (1710.05834)

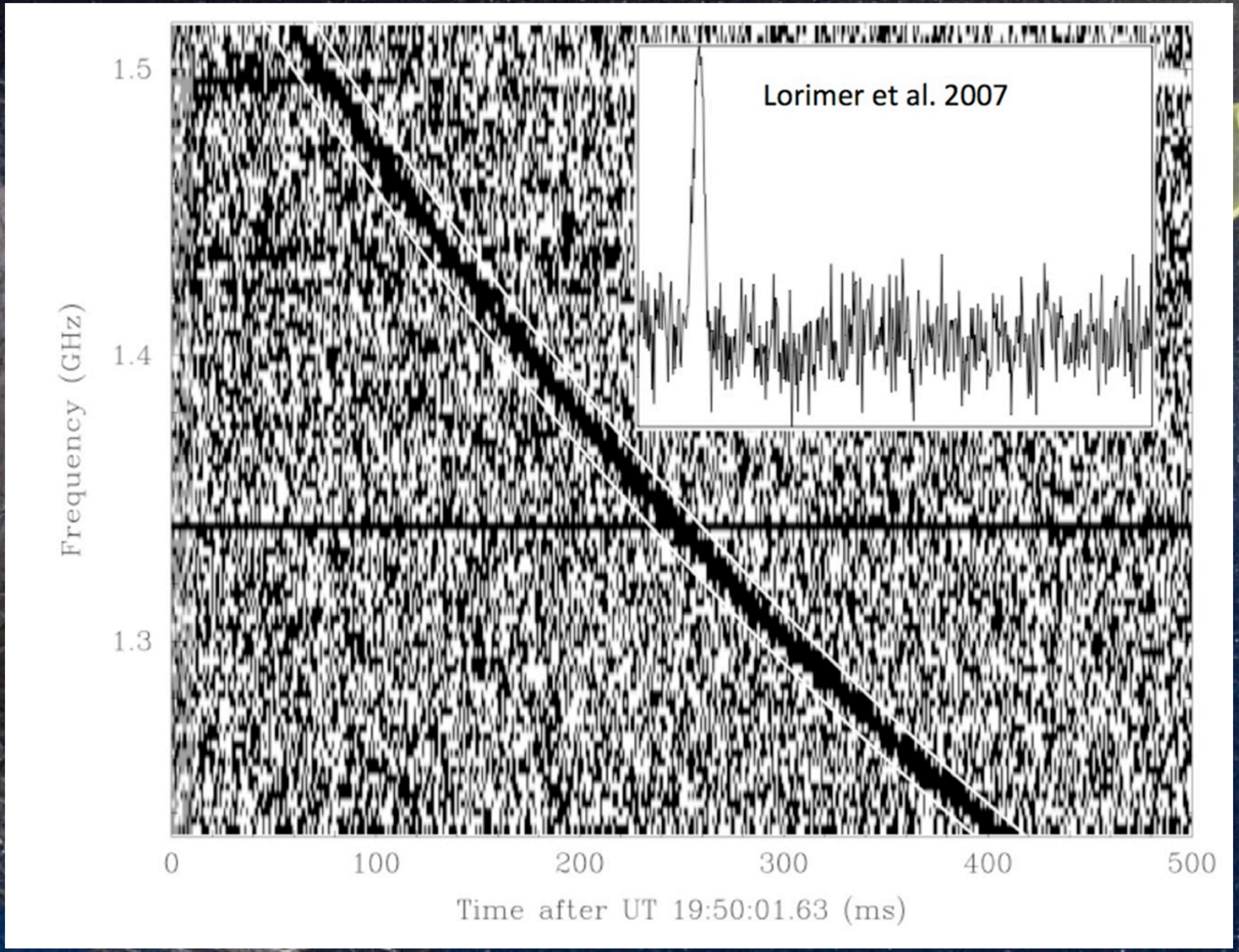


An Electromagnetic Signal?

Margutti et al. (1801.03531)



An Electromagnetic Signal?



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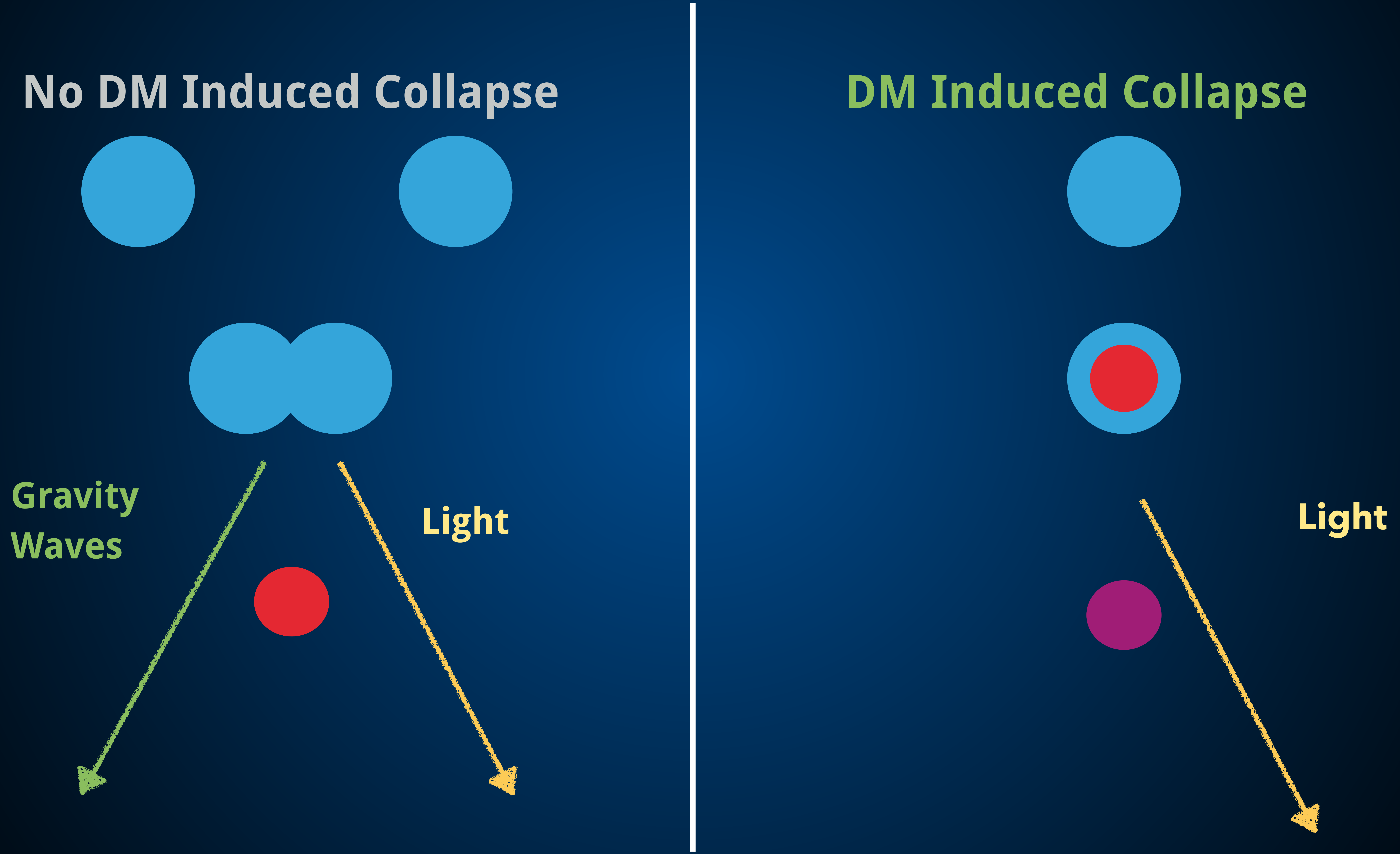

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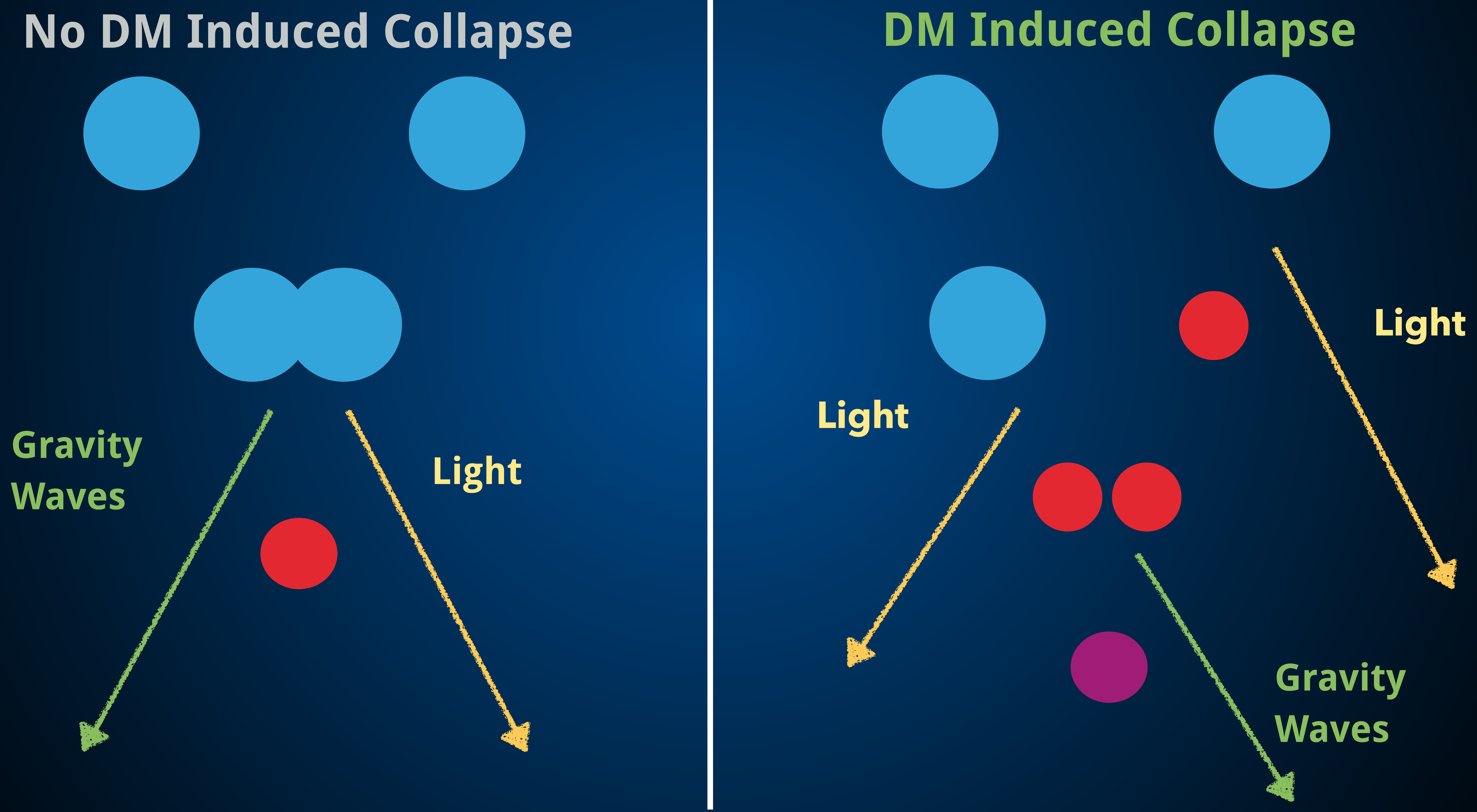

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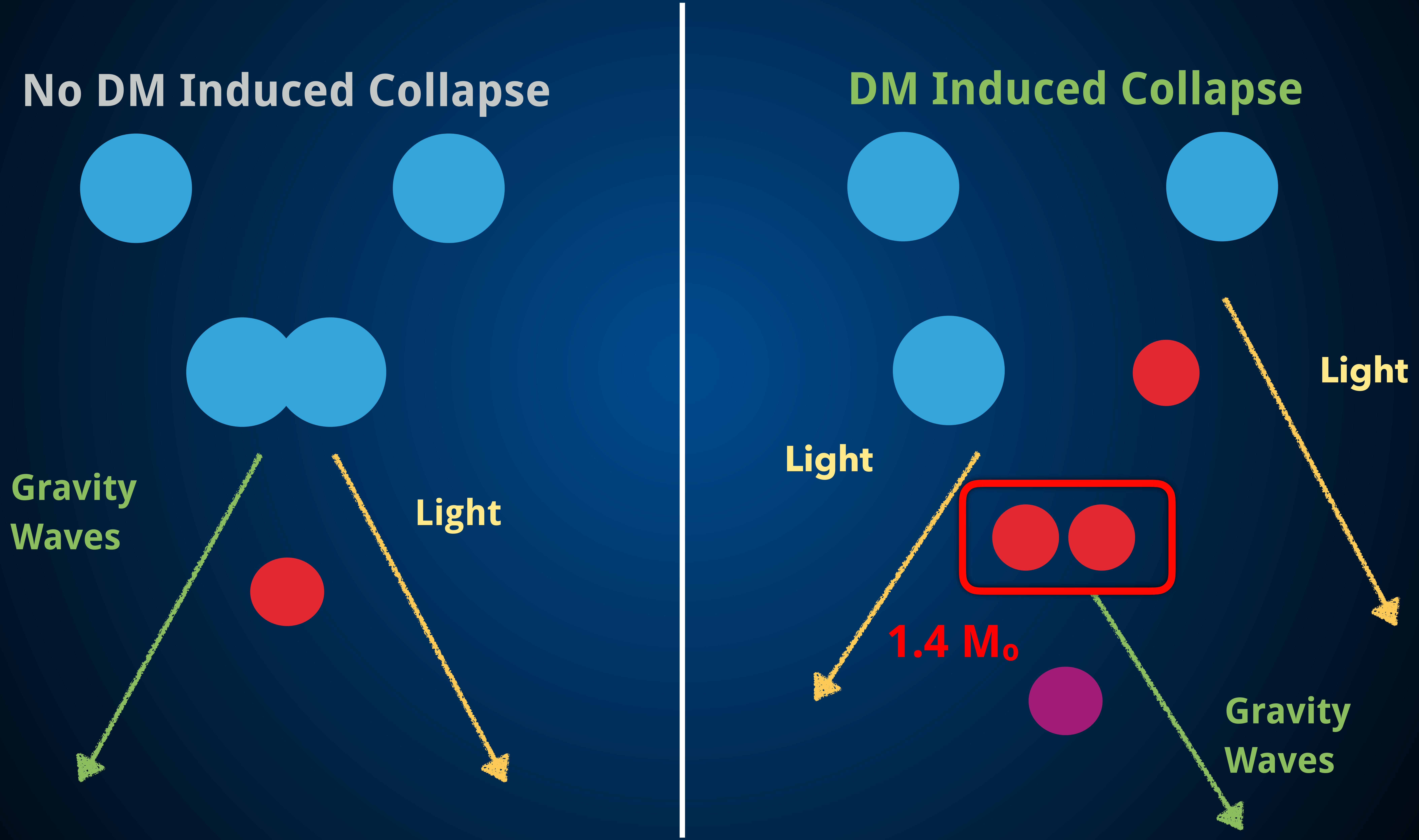
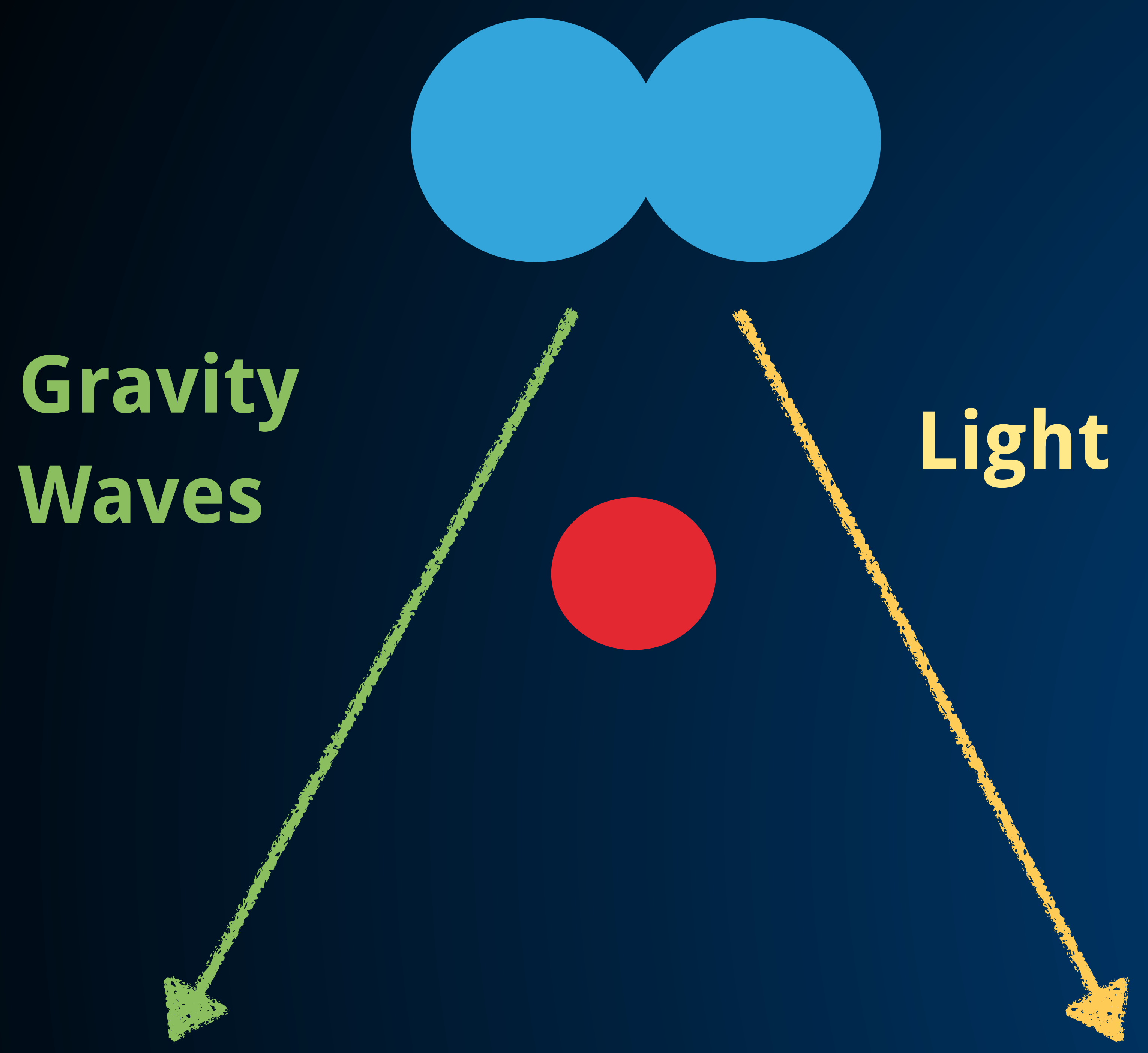
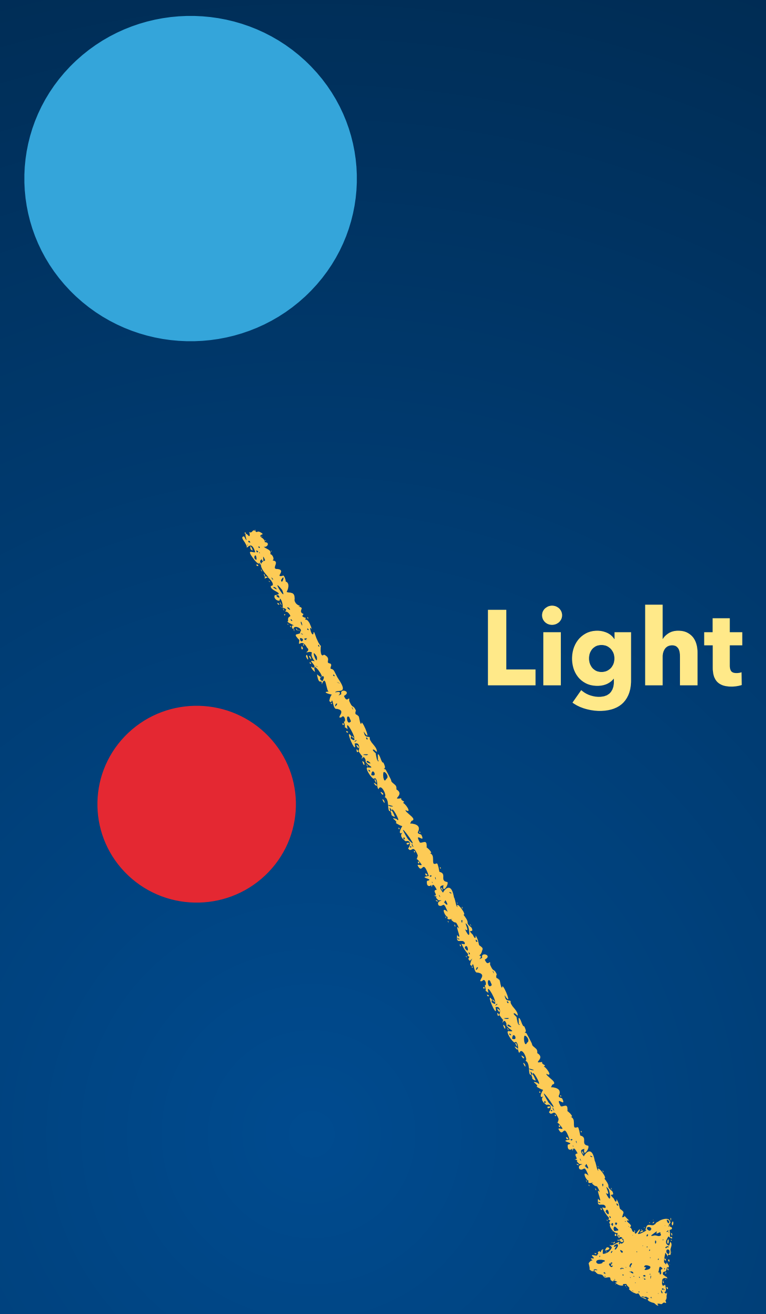




Merger Kilonovae

Electromagnetic signals and gravitational waves jointly identified.

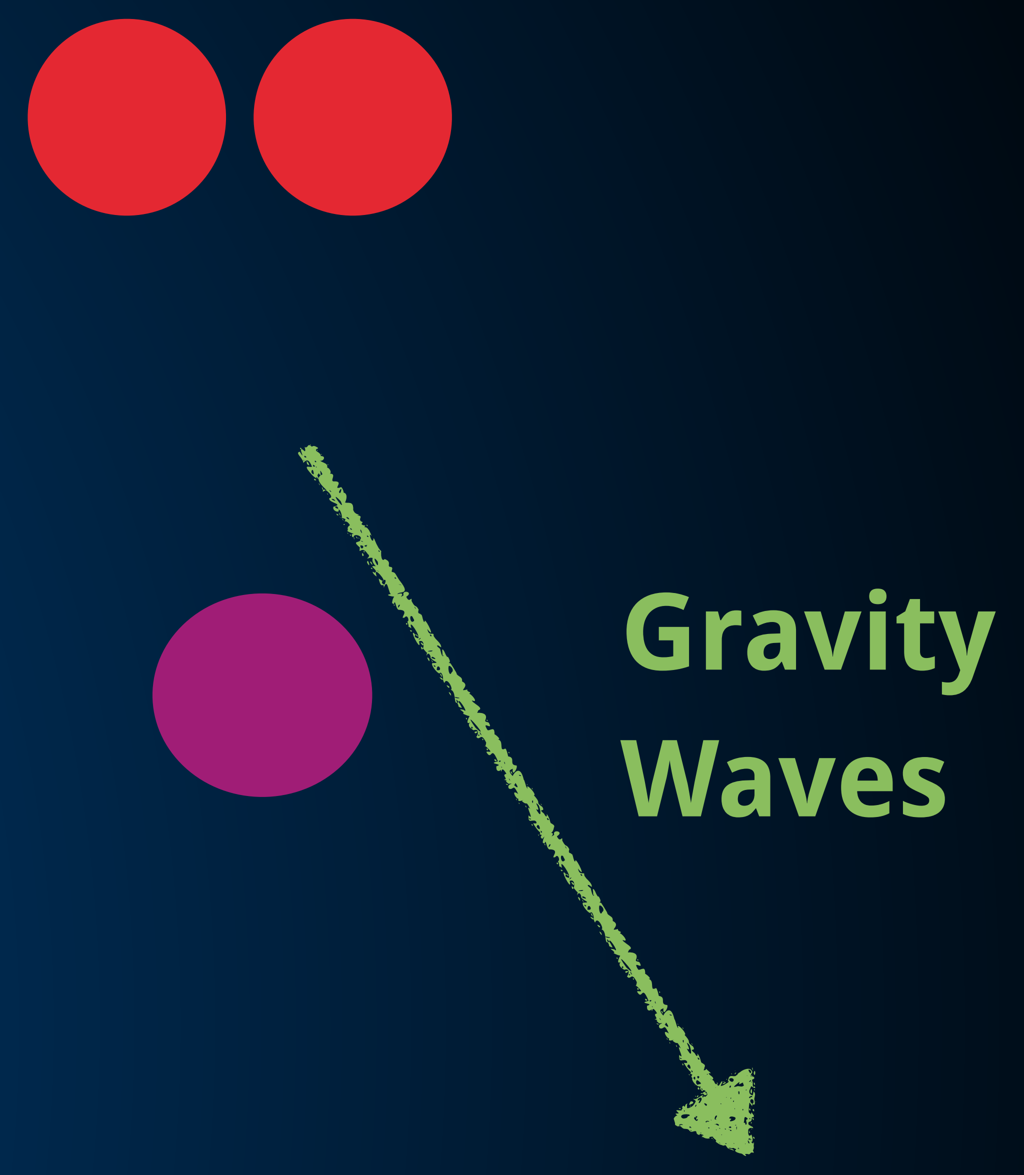
(inversely proportional to ρ_{DM})



Quiet Kilonovae

Electromagnetic signals identified without gravitational waves.

(proportional to ρ_{DM}).



Dark Mergers

Gravitational waves identified without an electromagnetic counterpart.

(proportional to ρ_{DM}).

Finding Dark Matter

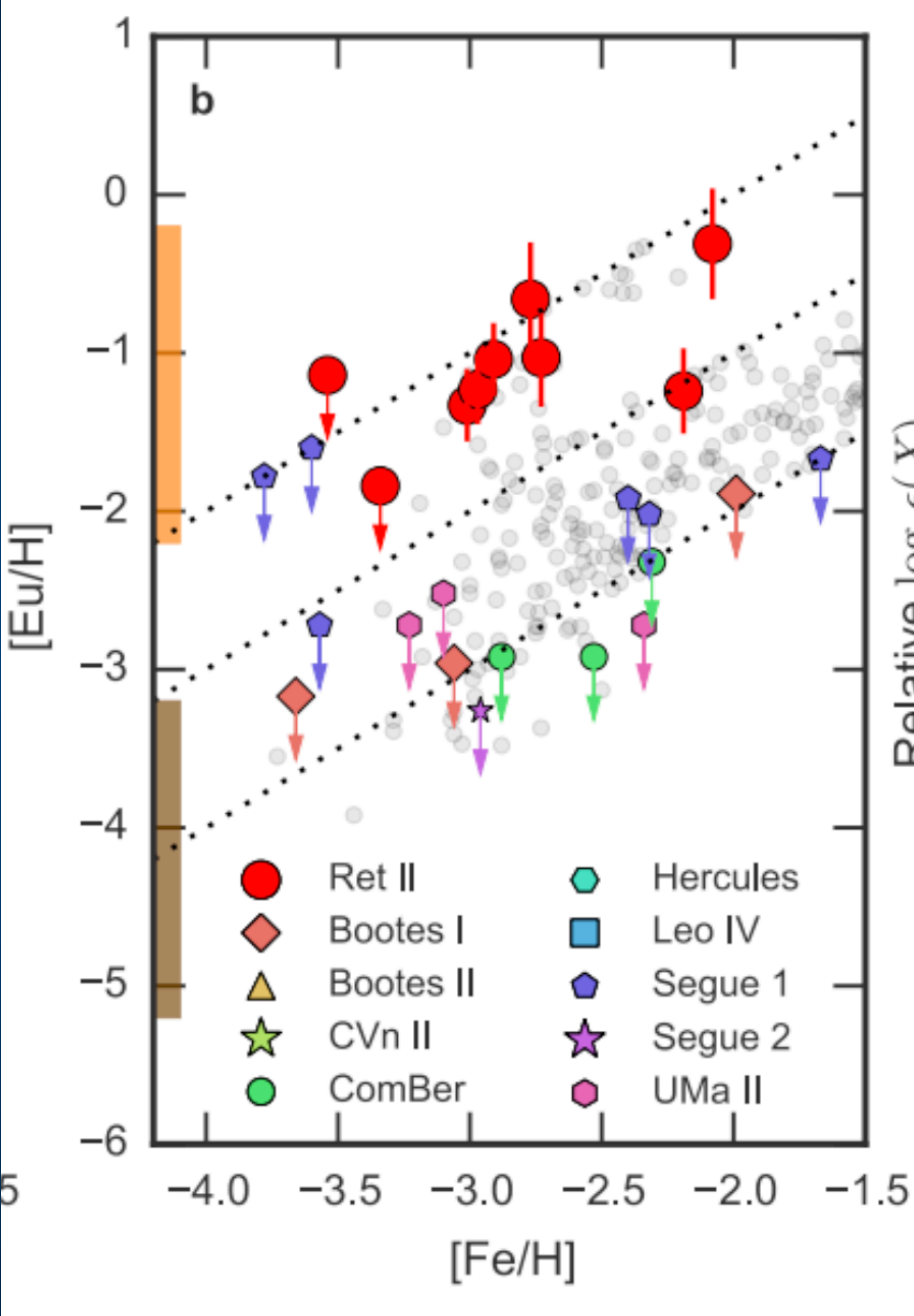
- 1.) Look in regions with where the dark matter signal should be dominant.

- 2.) Look at the distribution of events in galactic systems.

Dwarf Galaxies

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

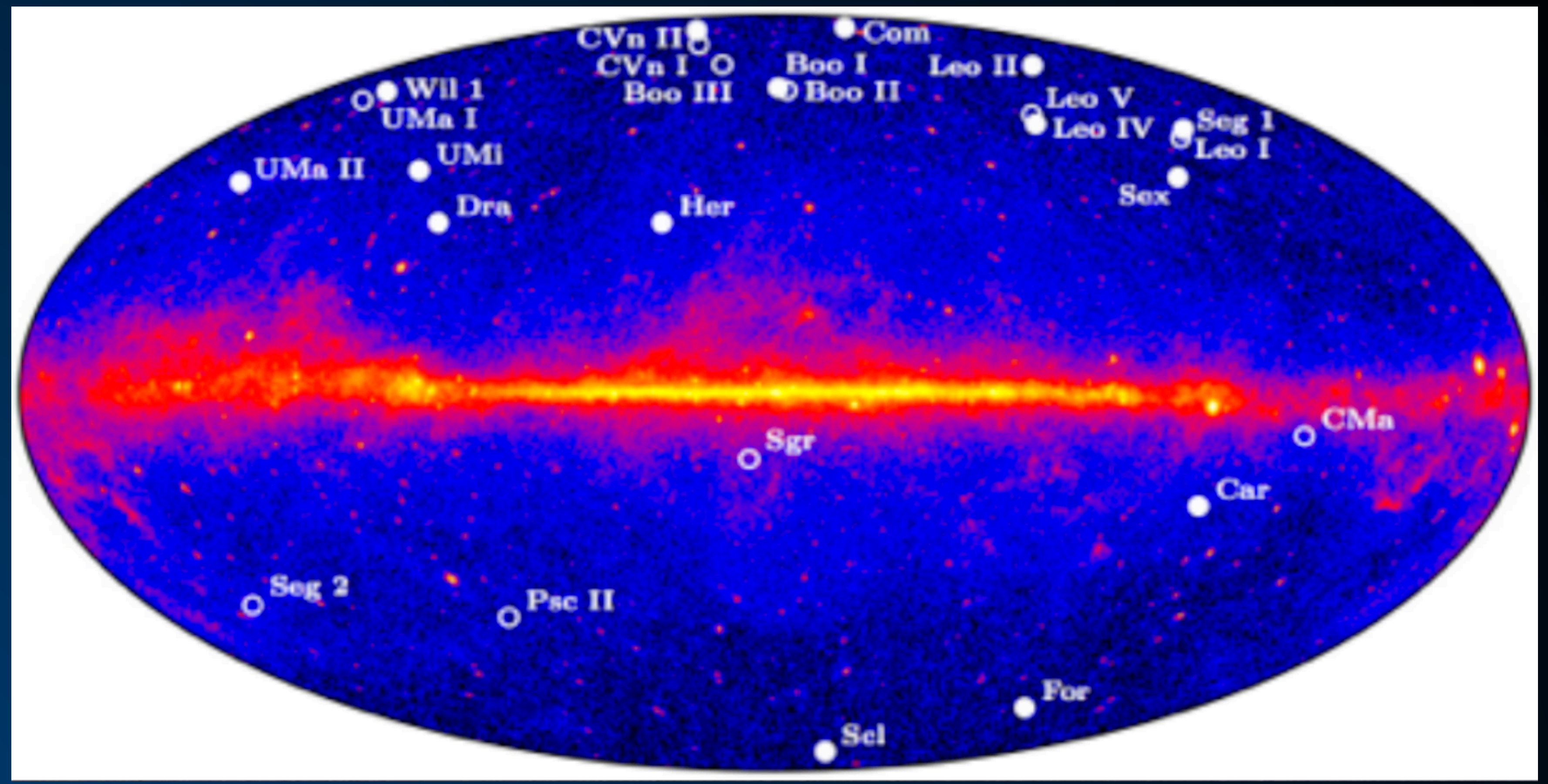
- **Reticulum II dSph**
  - **Discovered by DES in 2015**
  - **Spectroscopic follow-up determined r-process abundances.**
  - **Large r-process abundance, but low metallicity!**
  - **Rare-Formation Channel (NS mergers?)**

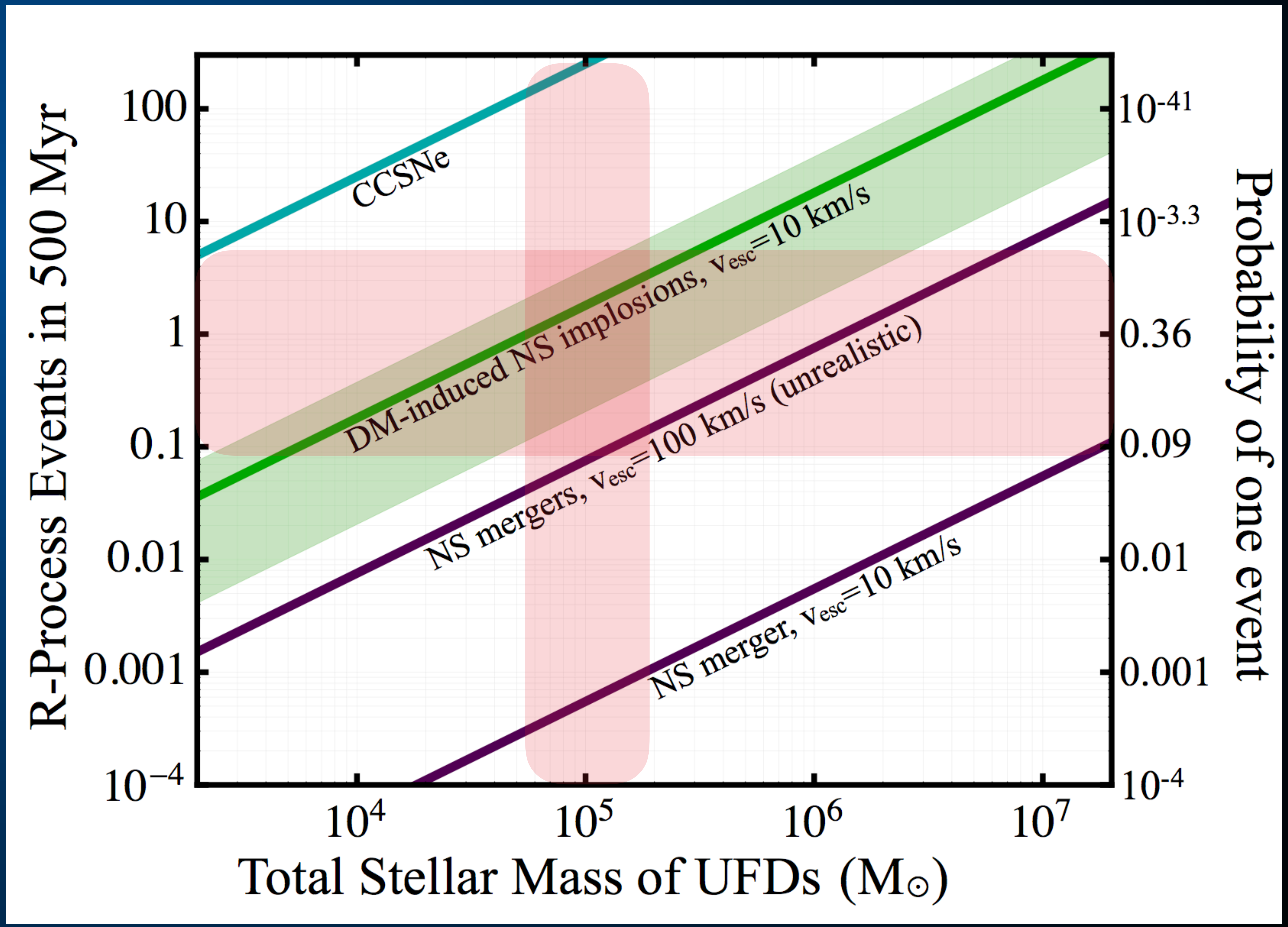


Dwarf Galaxies

- 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.

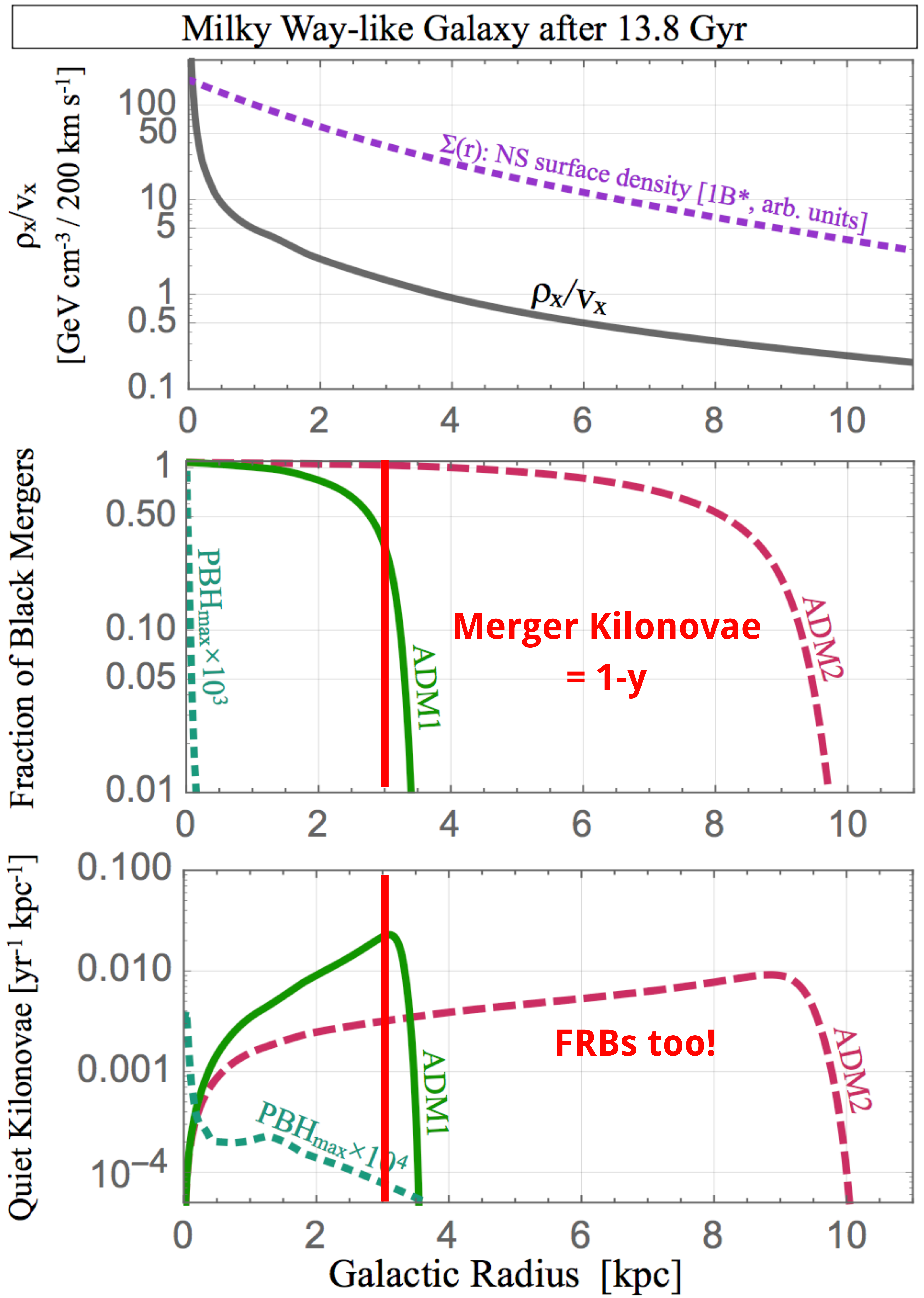




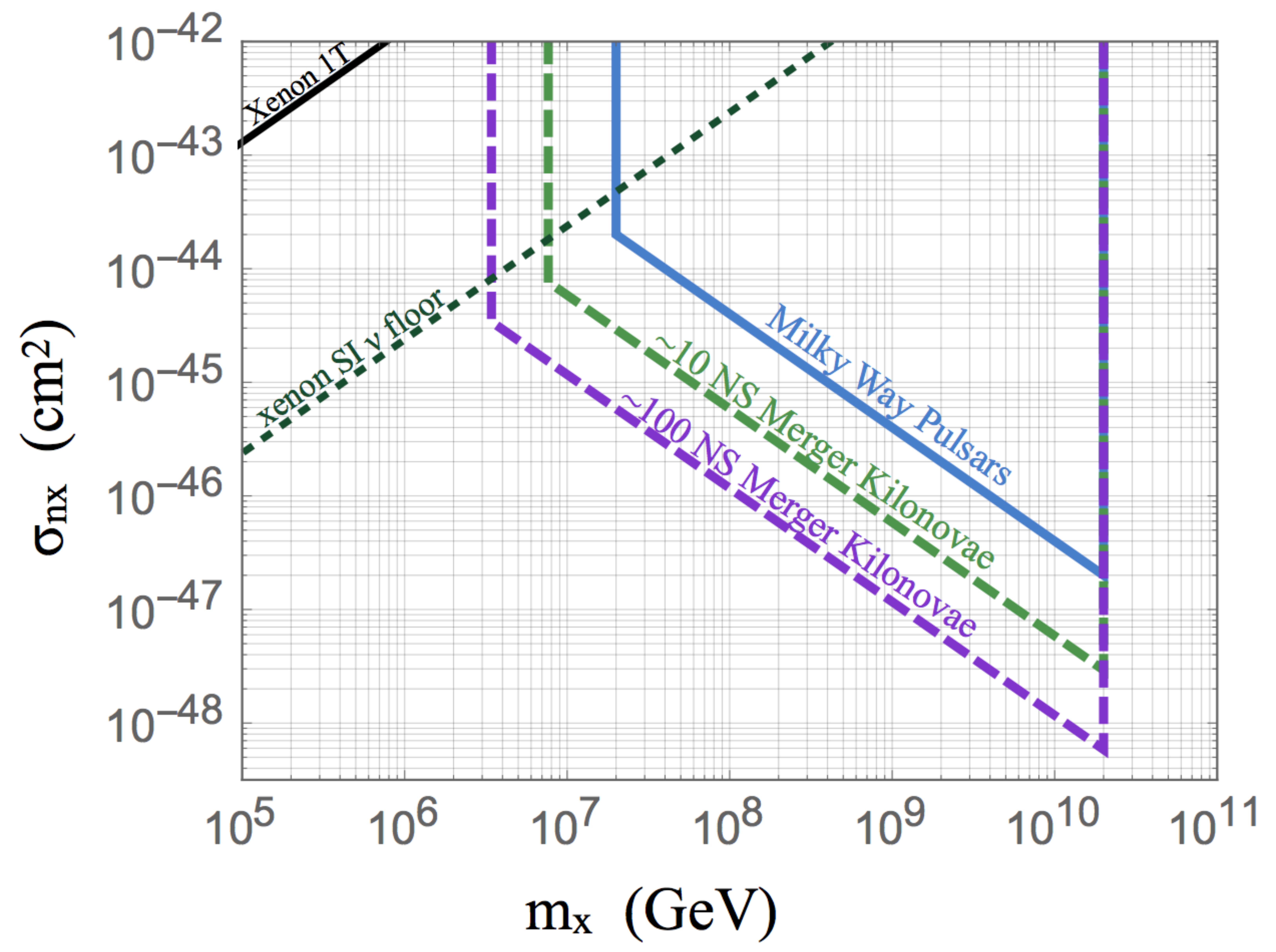
Bramante & TL (1601.06784)

Milky Way Galaxies

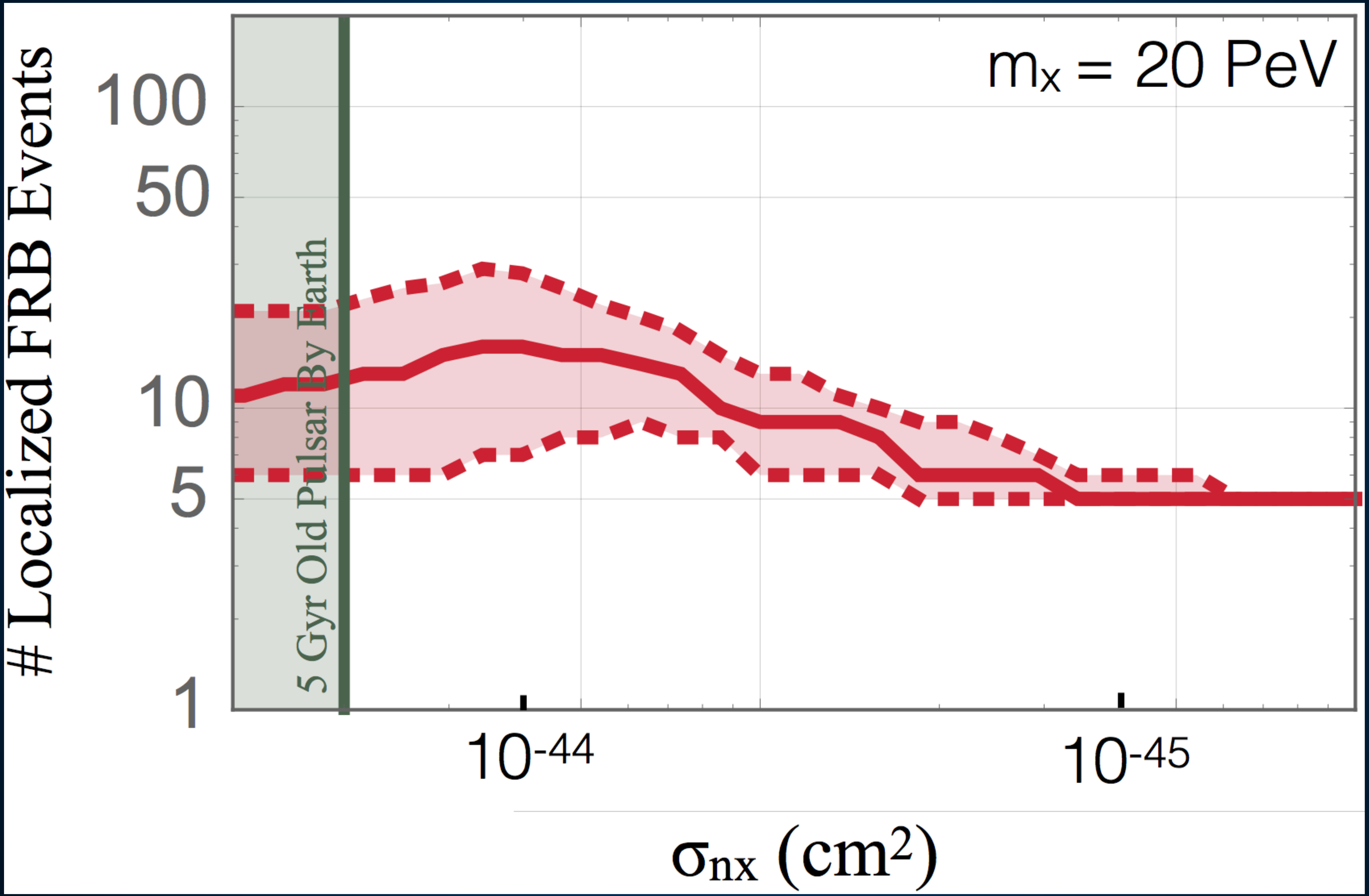
- Search for a component correlated with the dark matter density.
- Can alternatively look only at the morphology of standard merger kilonovae.
- ADM2 model already in tension with GW 170817.



Constraining Dark Matter - Merger 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.

Conclusions

- Asymmetric dark matter can produce neutron star collapse in regions with high dark matter density or low velocity dispersion.

- There are many astrophysical signals (and hints!) of such interactions.

- (Very) near-term observations can be definitive!