

TIM LINDEN

based on 1405.1031 and 1601.06784 with Joseph Bramante

DETECTING ASYMMETRIC DARK MATTER WITH NEUTRON STARS



THE OHIO STATE UNIVERSITY



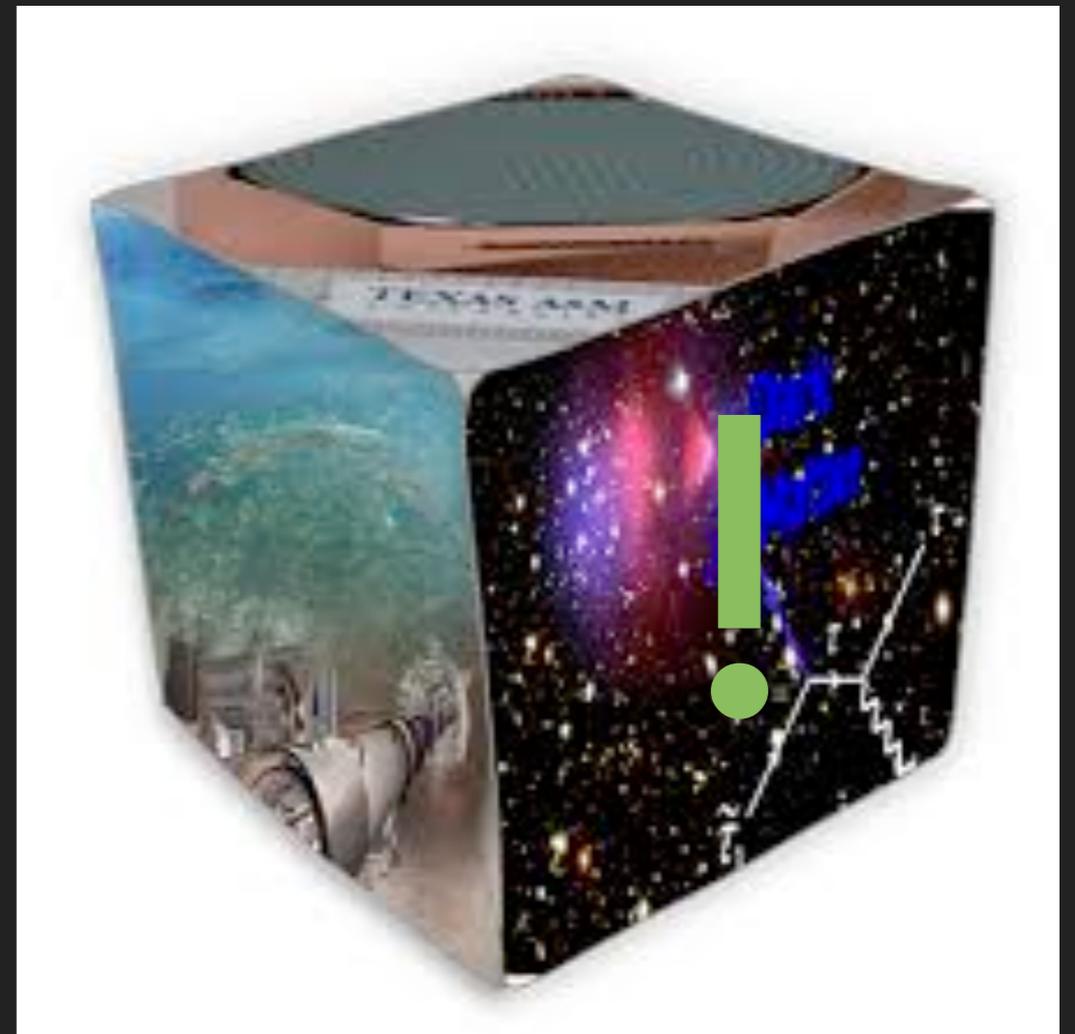
HARD TO OBSERVE DARK MATTER CANDIDATES

- ▶ Asymmetric dark matter implies no indirect detection signature.
- ▶ Additional forces needed to create the asymmetry in the dark sector may complicate the “simple thermal relic” scenario.
- ▶ But we want to know:
 - ▶ Dark Matter Particle Interactions
 - ▶ Early Universe Cosmology
 - ▶ Distribution of dark matter in the universe (indirect detection only)



EVERY NEW BEGINNING COMES FROM SOME OTHER BEGINNING'S END

- ▶ Unlike annihilating dark matter, asymmetric dark matter can acquire extremely high densities.
- ▶ Can produce detectable gravitational interactions on small scales.
- ▶ However, we do not know the dark sector forces by which these processes may occur – instead examine regions of high baryonic density.

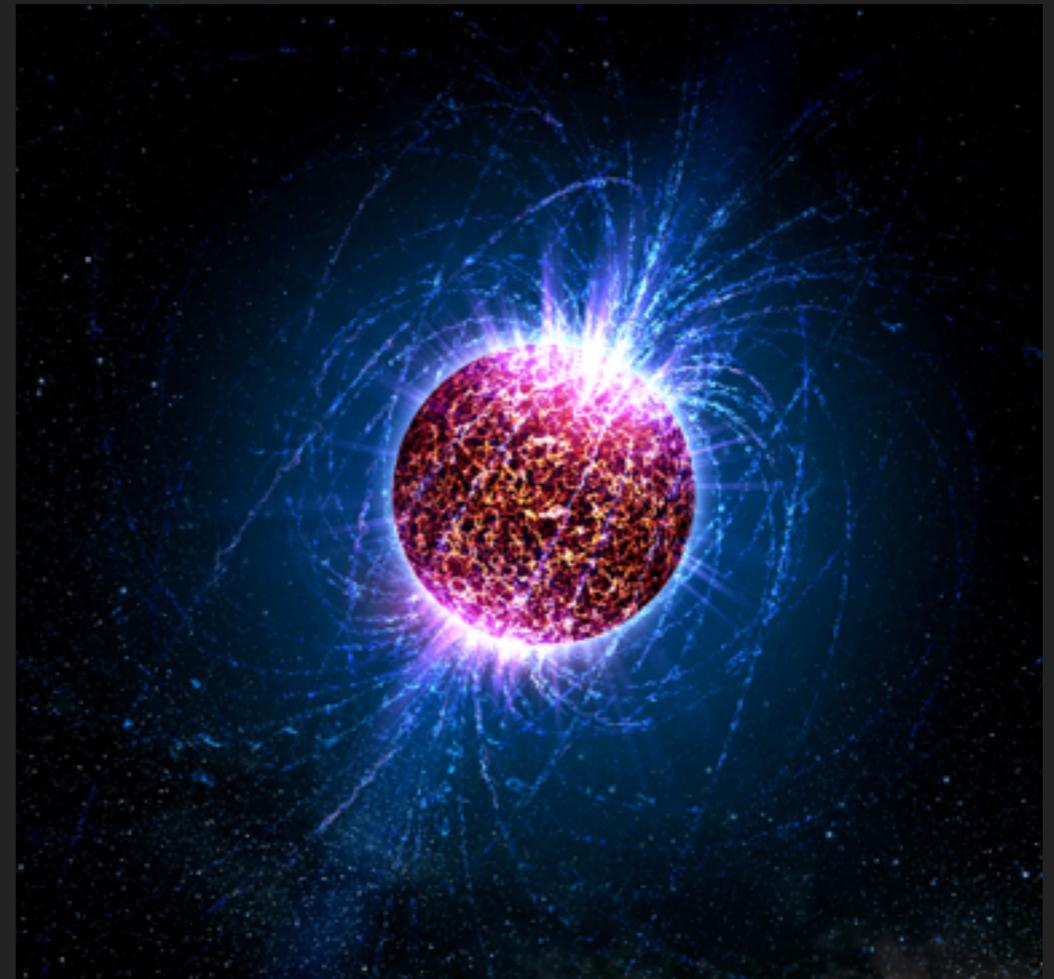


ASYMMETRIC DARK MATTER DETECTION

NEUTRON STARS AS DARK MATTER DETECTORS

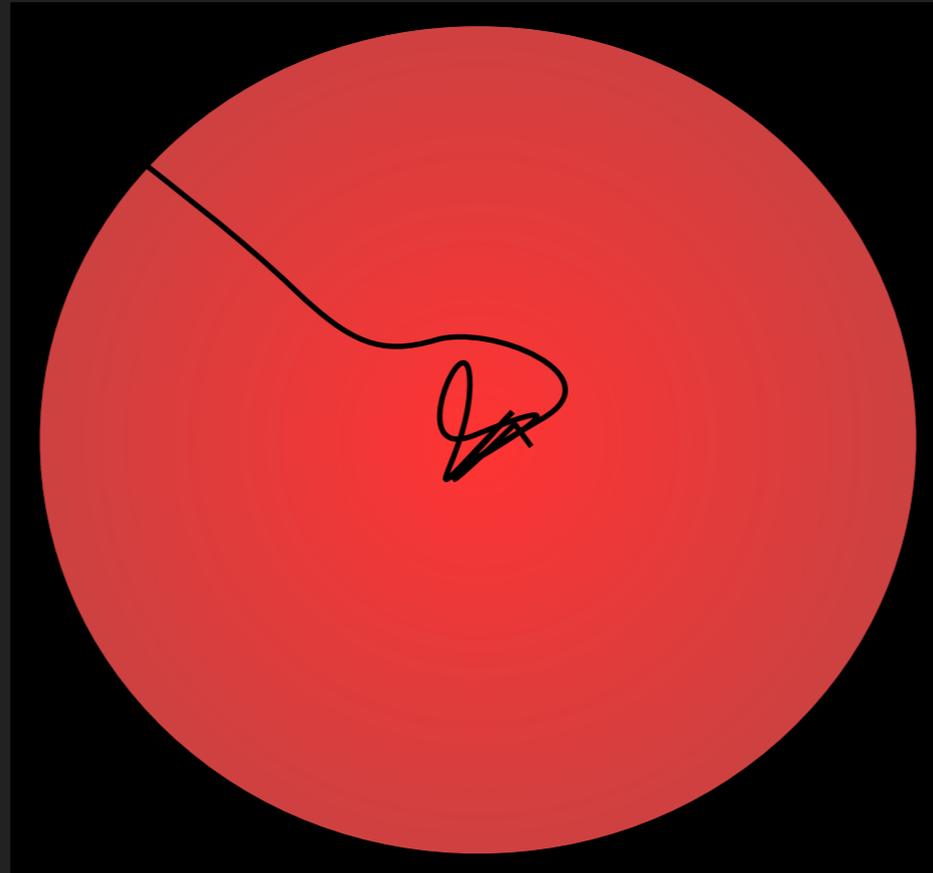


$\sim 10^4 \text{ kg yr}$



$\sim 10^{40} \text{ kg yr}$

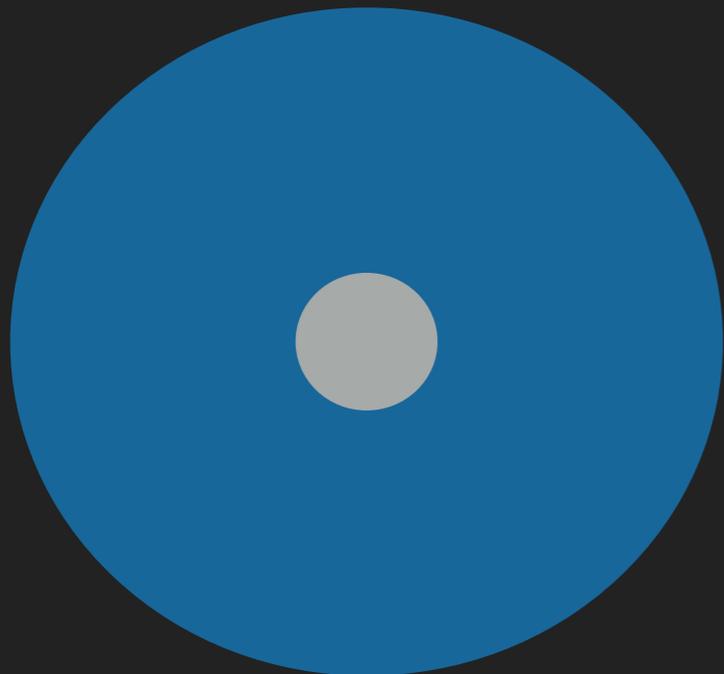
NEUTRON STARS AS DARK MATTER DETECTORS



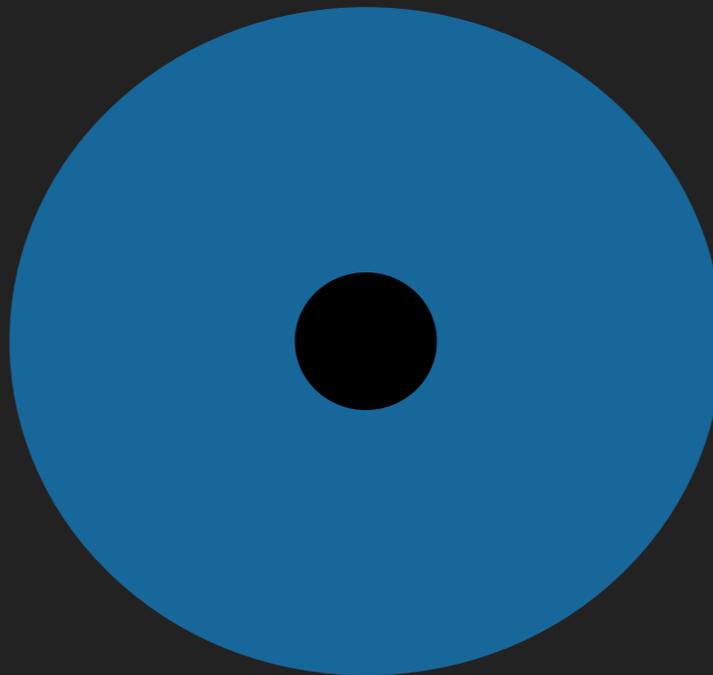
- ▶ Neutron stars provide the highest density environment where we can probe the interior physics.
- ▶ If the dark matter particle has a non-zero scattering cross-section, it scatter and become trapped in the neutron star interior.

STELLAR COLLAPSE

- ▶ If a significant dark matter mass accumulates in the neutron star center, it will thermalize, and may produce a black hole.
- ▶ The black hole will then accrete baryonic material from the neutron star.



Dark Matter Thermalizes



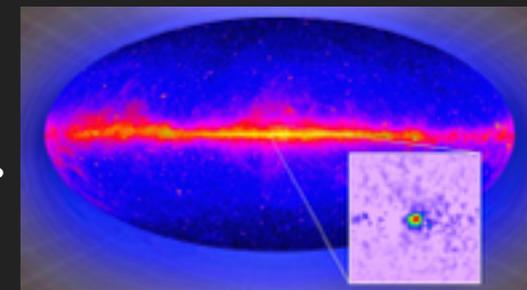
Black Hole Forms

Black Hole Accretes Neutron Star



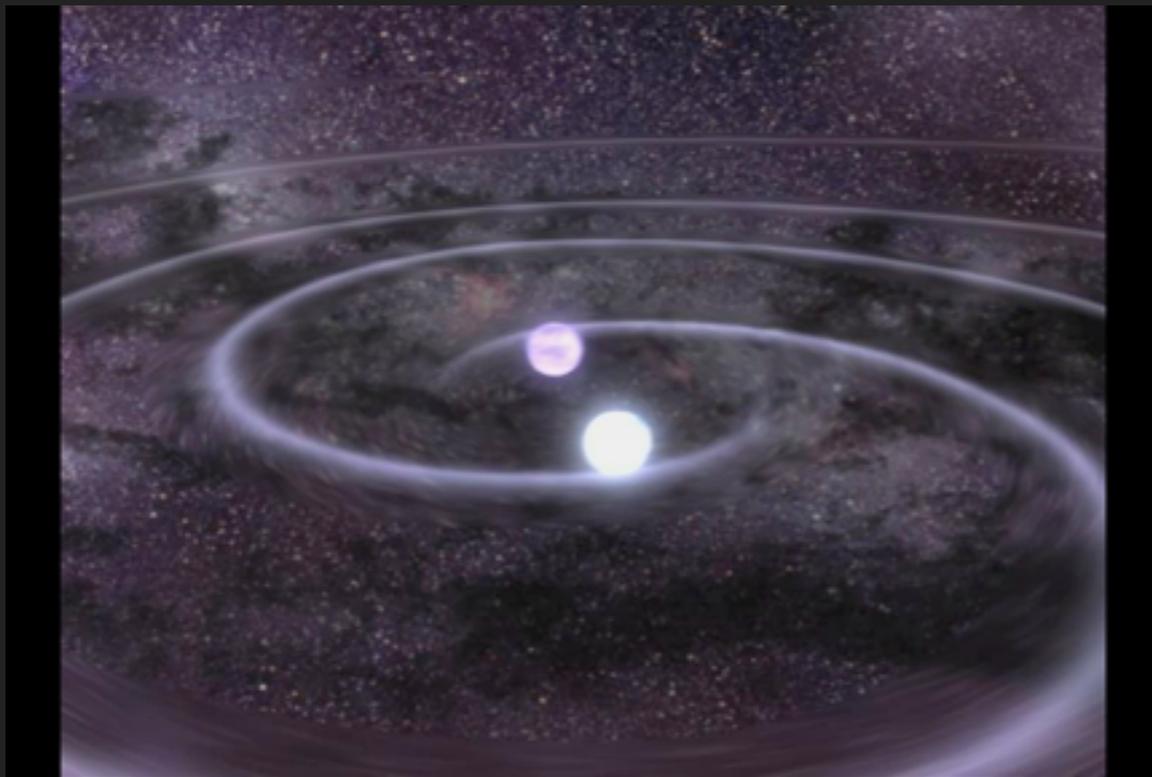
DARK MATTER PARAMETER SPACE

- ▶ The dark matter particle must have some scattering cross-section with baryons.
- ▶ The dark matter particle must be capable of obtaining extremely high central densities:
 - ▶ Fermionic GeV dark matter does not work, since Fermi degeneracy pressure stabilizes the dark matter at densities too low for collapse.
 - ▶ Bosonic dark matter without repulsive self-interactions ($m_\chi = \text{MeV} - \text{PeV}$)
 - ▶ Fermionic dark matter with an attractive scalar mediator ($m_\chi = \text{MeV} - \text{PeV}$)
 - ▶ Fermionic dark matter with ($m_\chi > \text{PeV}$)
- ▶ Only a fractional asymmetry in the dark sector is necessary.

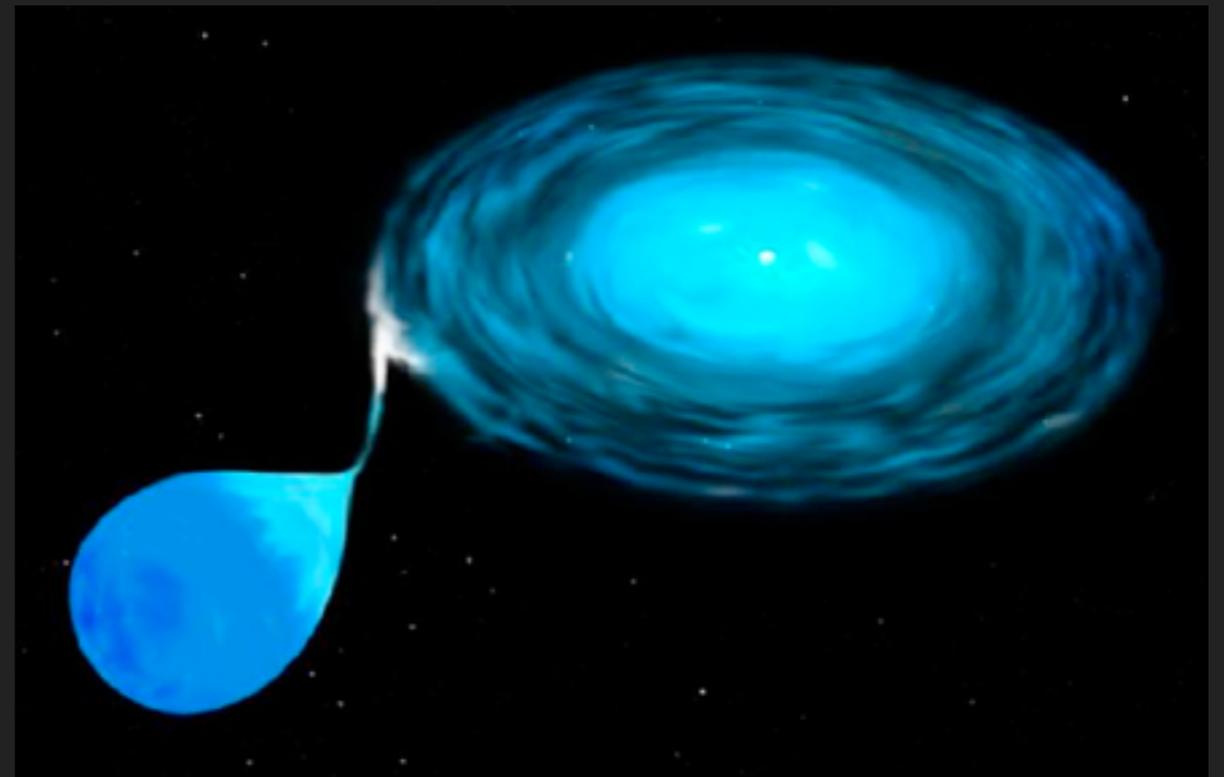


NEUTRON STAR COLLAPSE

- ▶ Neutron stars can collapse into Black Holes through astrophysical processes processes:



Double Neutron Star Merger

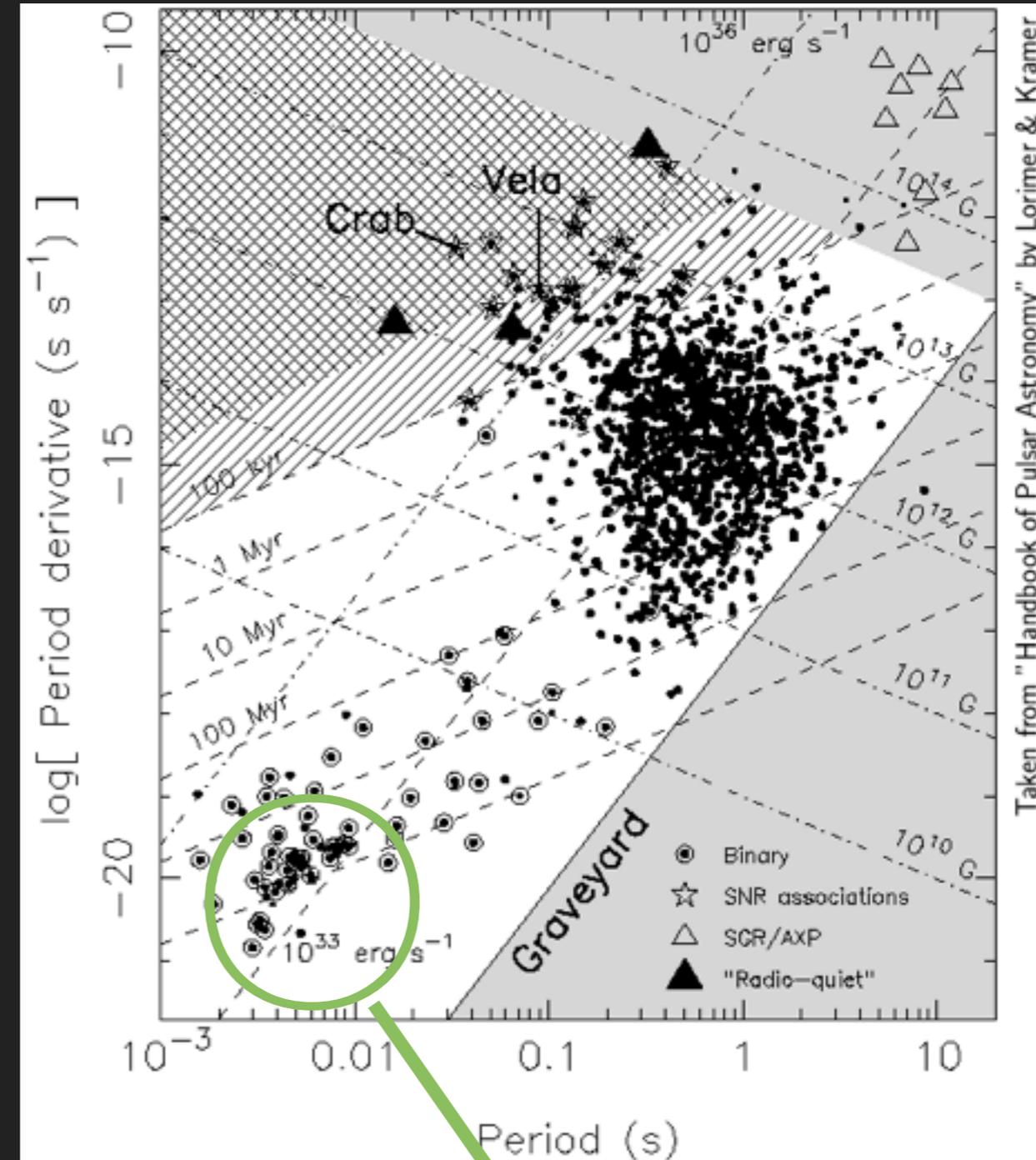


Accretion Induced Collapse

PULSARS

- ▶ A substantial fraction of neutron stars (and nearly all observable neutron stars) are pulsating radio sources.
- ▶ Regularity of the pulse period provides us substantial information about the magnetic field, energetics, and internal structure of neutron stars.
- ▶ Most importantly, the spin-down rate (roughly) indicates the pulsar age:

$$\tau = \frac{P}{(n-1)\dot{P}} = \frac{P_0}{(n-1)\dot{P}_0}$$

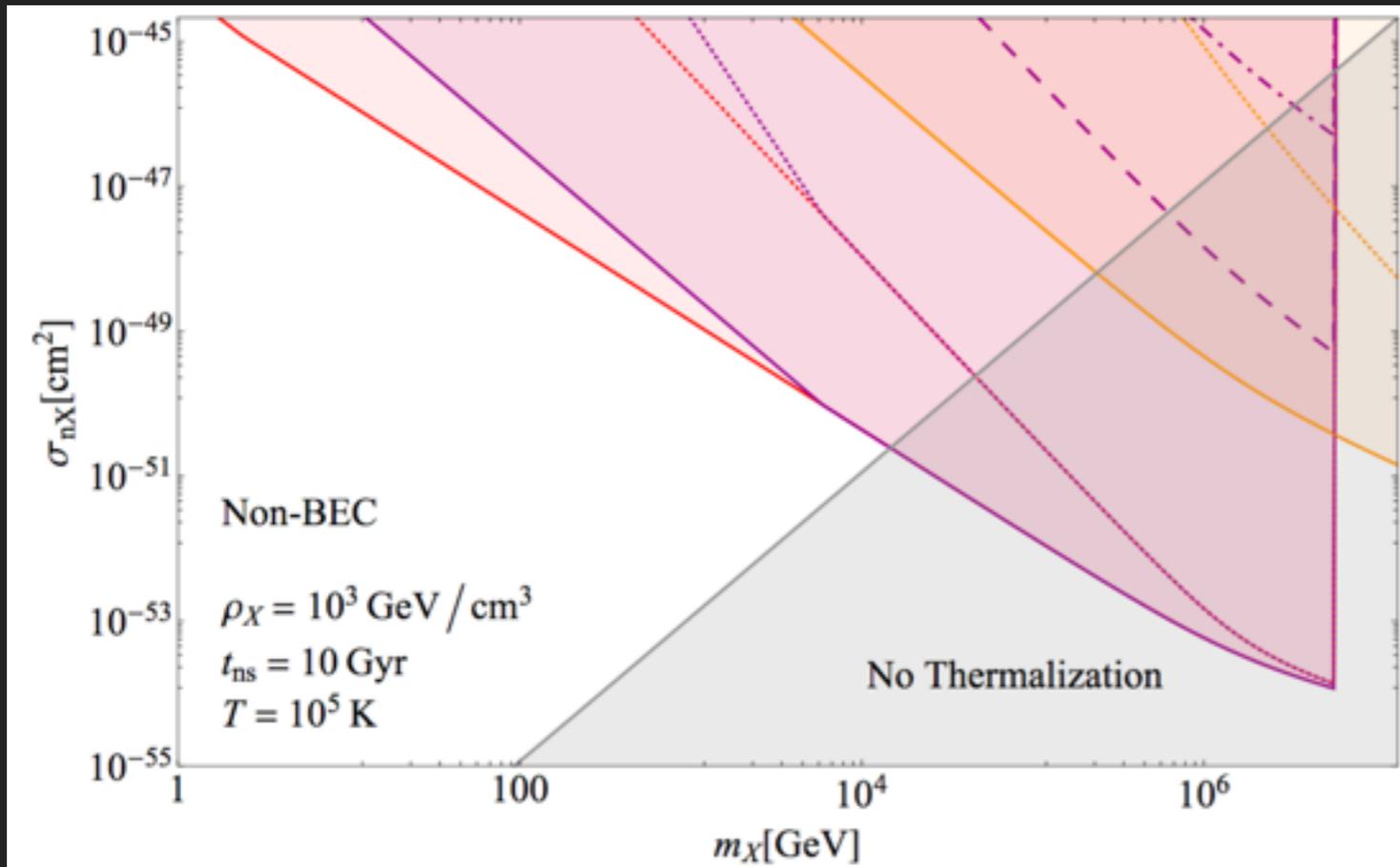


Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

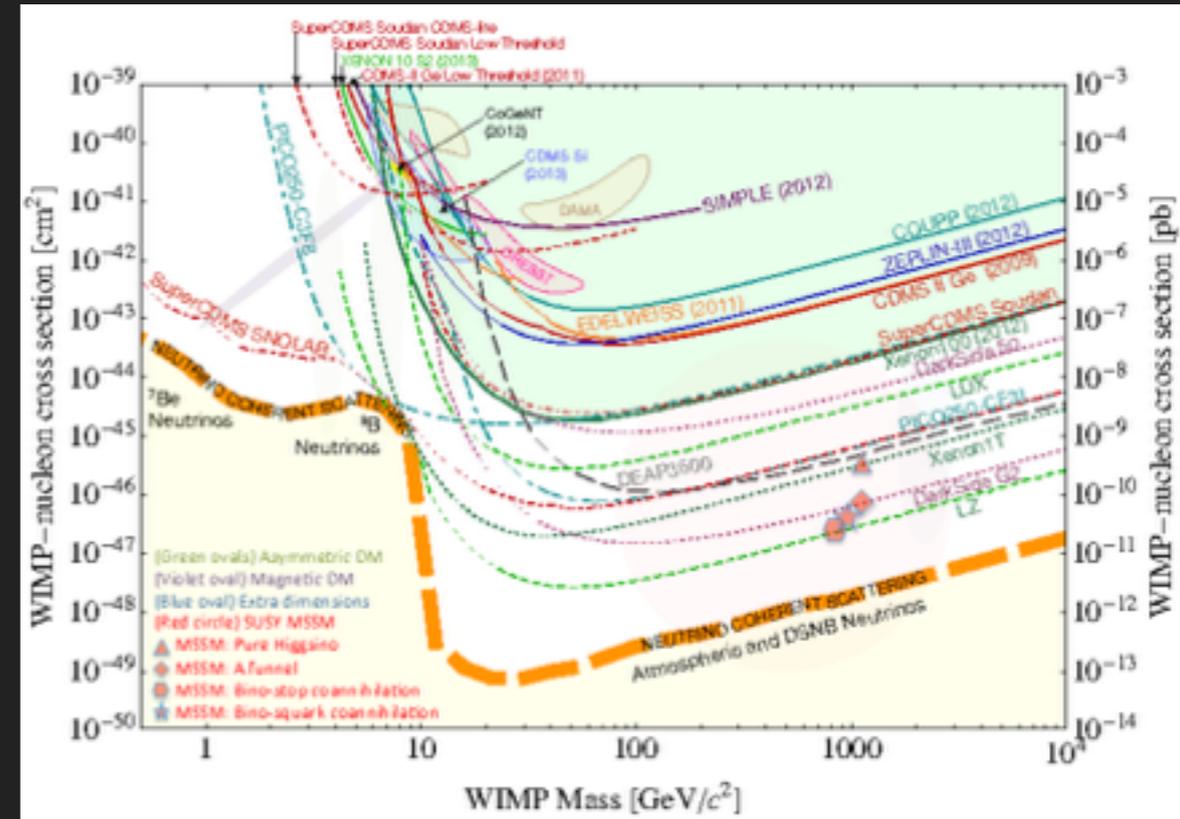
~ $\tau_H!$

NEUTRON STAR CONSTRAINTS

- ▶ More than 2000 radio pulsars have been observed in the Milky Way.



non-BEC Bosonic Dark Matter for different values of the repulsive self-interaction. (Bramante et al. 1301.0036)



- ▶ The observation of the oldest neutron stars already produces the best constraints on many dark matter models.

THIS SCENARIO CAN BE TURNED ON ITS HEAD

- ▶ Intriguingly, a “missing pulsar problem” has been observed in the central pc of the Milky Way, where the dark matter density is the highest.
- ▶ Stellar Evolution simulations expect thousands of pulsars to be observed in the central pc of the Milky Way, yet only one has been observed.
- ▶ Additionally, the observed pulsar is an extremely young magnetar.

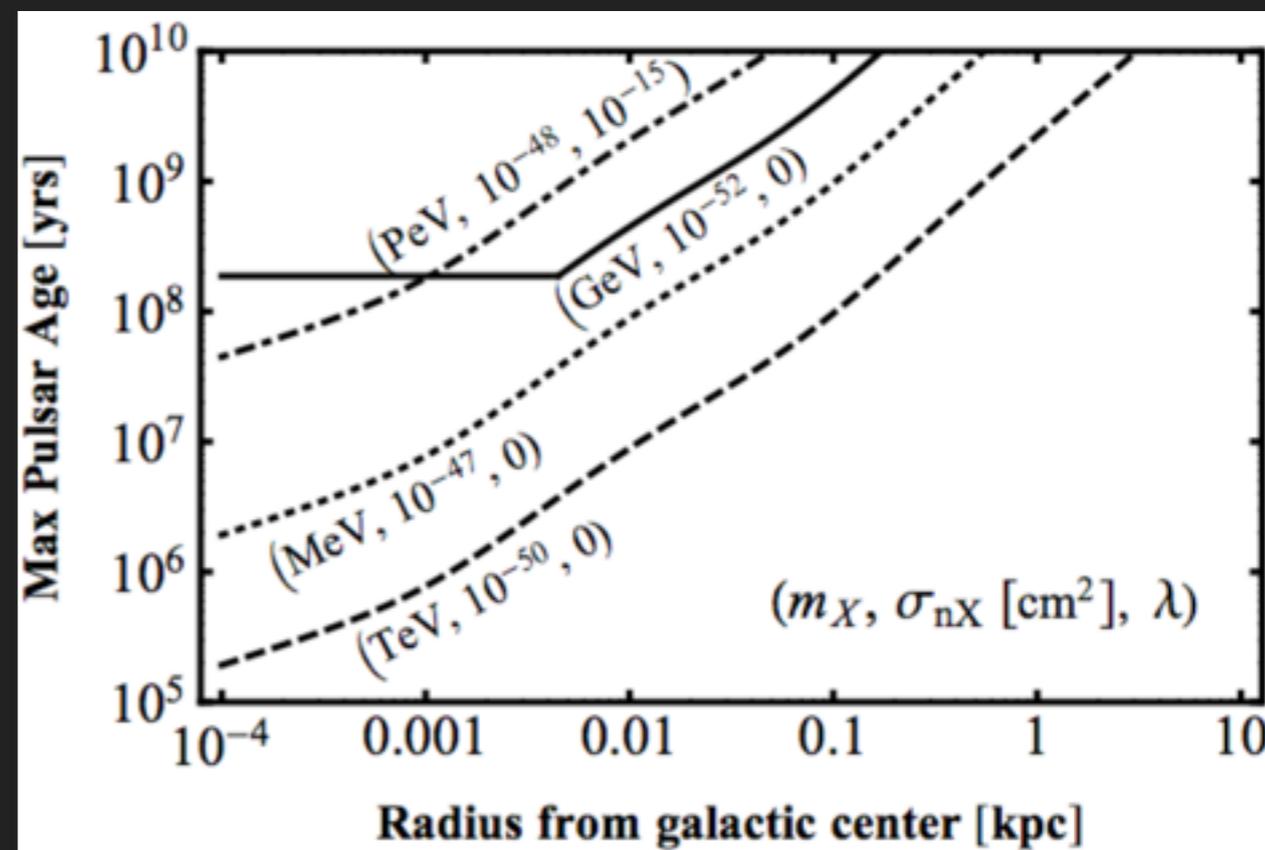
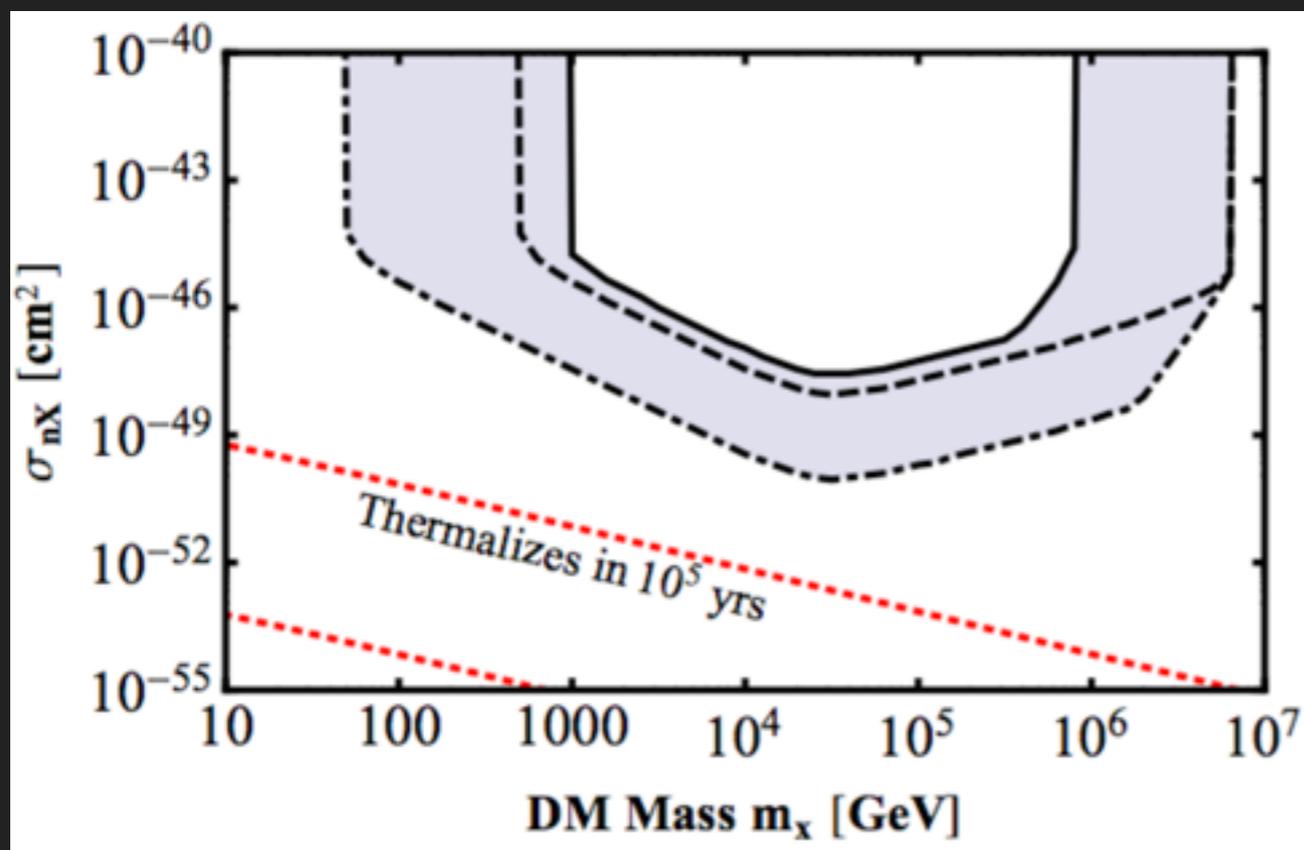
2014

THE PECULIAR PULSAR POPULATION OF THE CENTRAL PARSEC
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ABSTRACT
Pulsars orbiting the Galactic center black hole, Sgr A*, would be potential probes of both ordinary and millisecond pulsars in the Galactic center, none have been detected by deep radio surveys. One explanation has been that hyperstrong temporal scattering of radio pulsations from a high-velocity population of magnetars rather than ordinary pulsars is the cause of an intrinsic deficit in the ordinary pulsar population in the Galactic center. A “missing pulsar problem” in the Galactic center could be explained by a magnetar population rather than ordinary pulsars. The discovery of a top-heavy initial magnetar population could be used to detect bright millisecond pulsars.

THE MISSING PULSAR PROBLEM

- ▶ Since the dark matter density near the Galactic center is significantly higher than regions near the solar position (where the oldest pulsars have been found) there is a parameter space where dark matter accumulation may solve the missing pulsar problem.

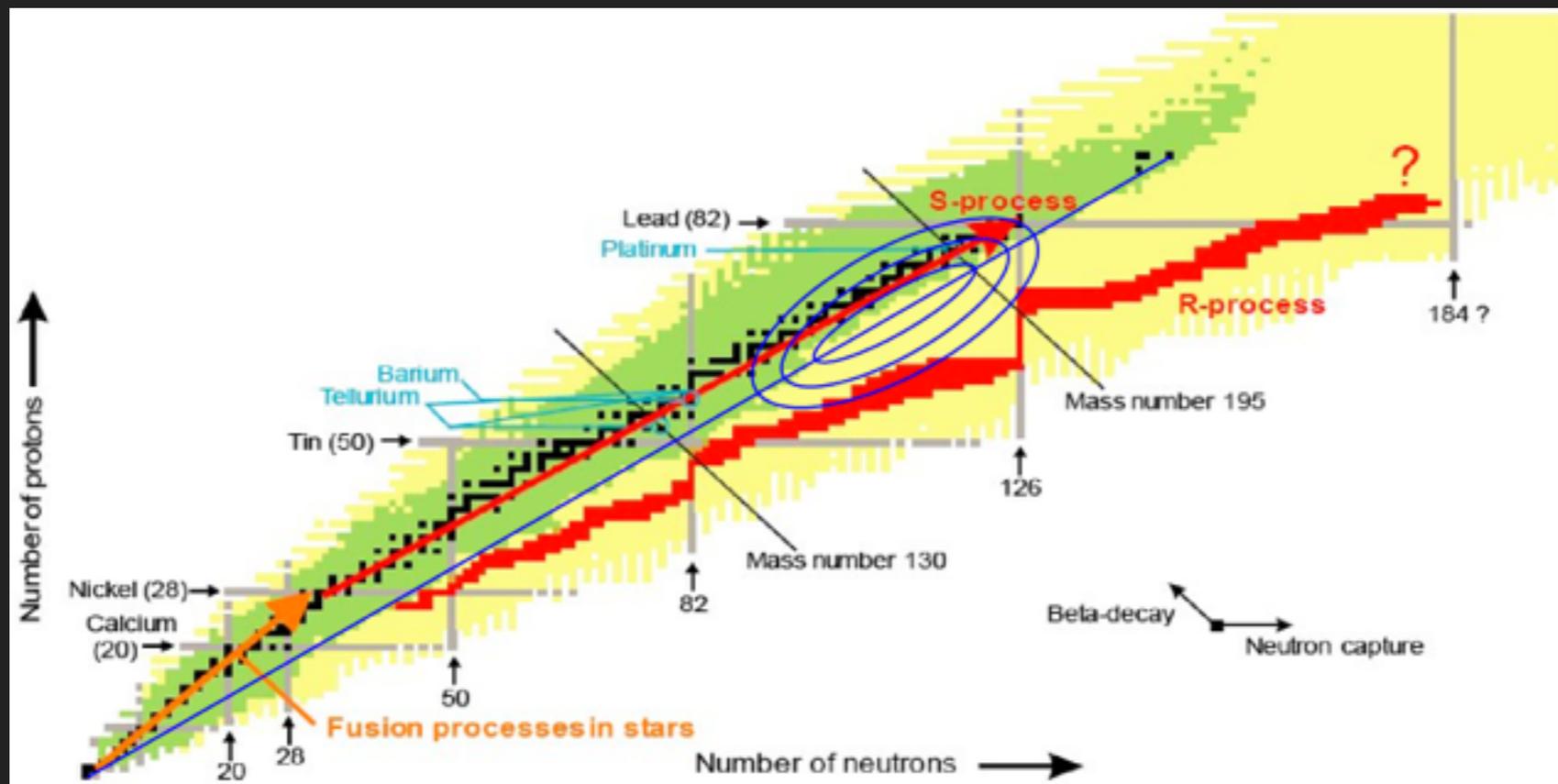
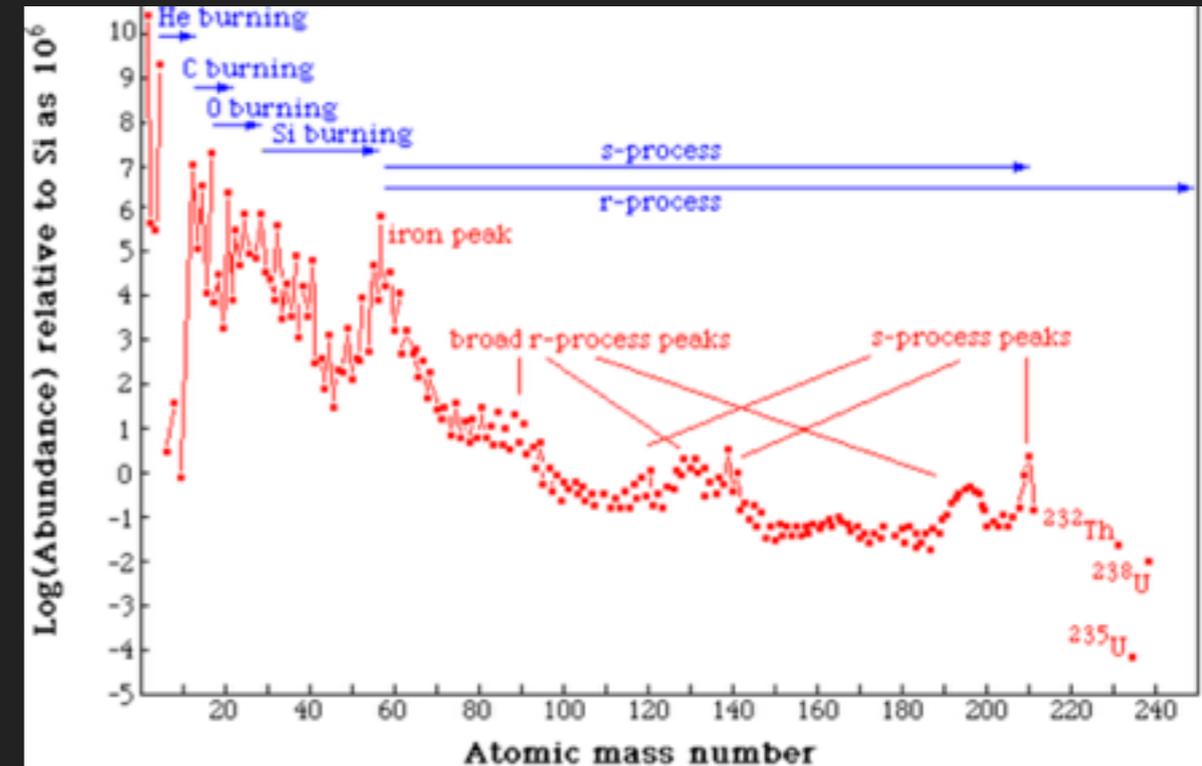


Bramante & Linden (1405.1031)

- ▶ This has a robust - (and not astrophysical!) detection signature.

R-PROCESS ENRICHMENT

- ▶ All elements heavier than Iron must be formed in neutron rich environments.
- ▶ Two leading explanations:
 - ▶ Supernovae
 - ▶ Neutron star mergers

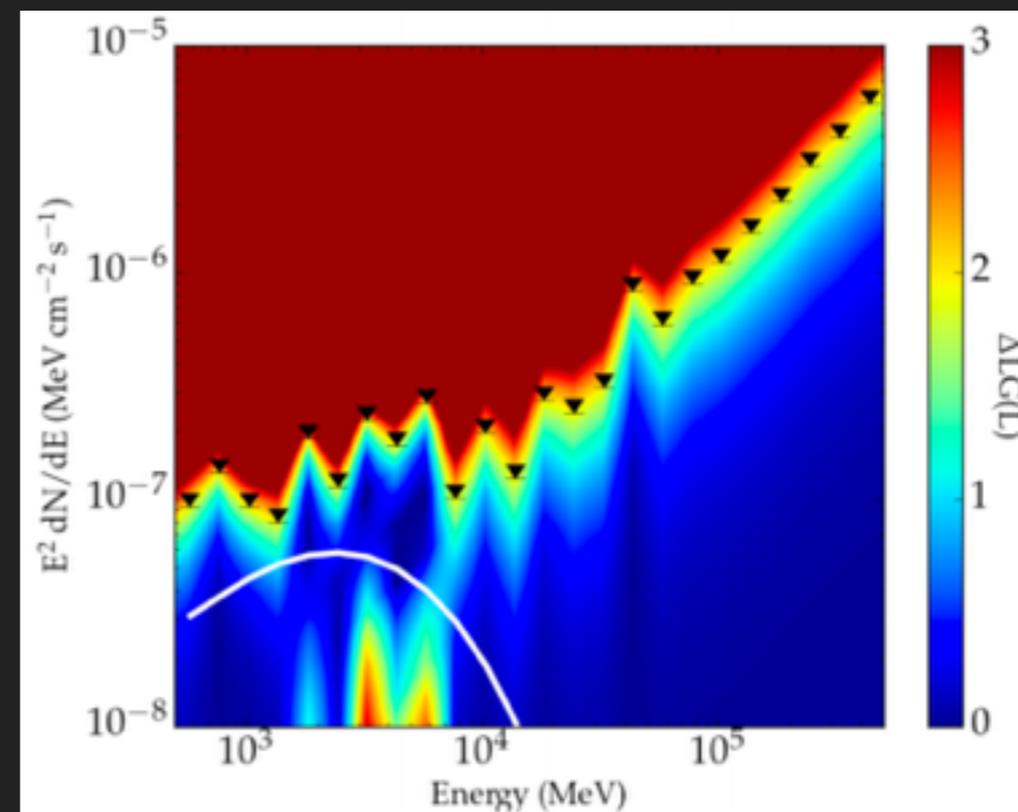
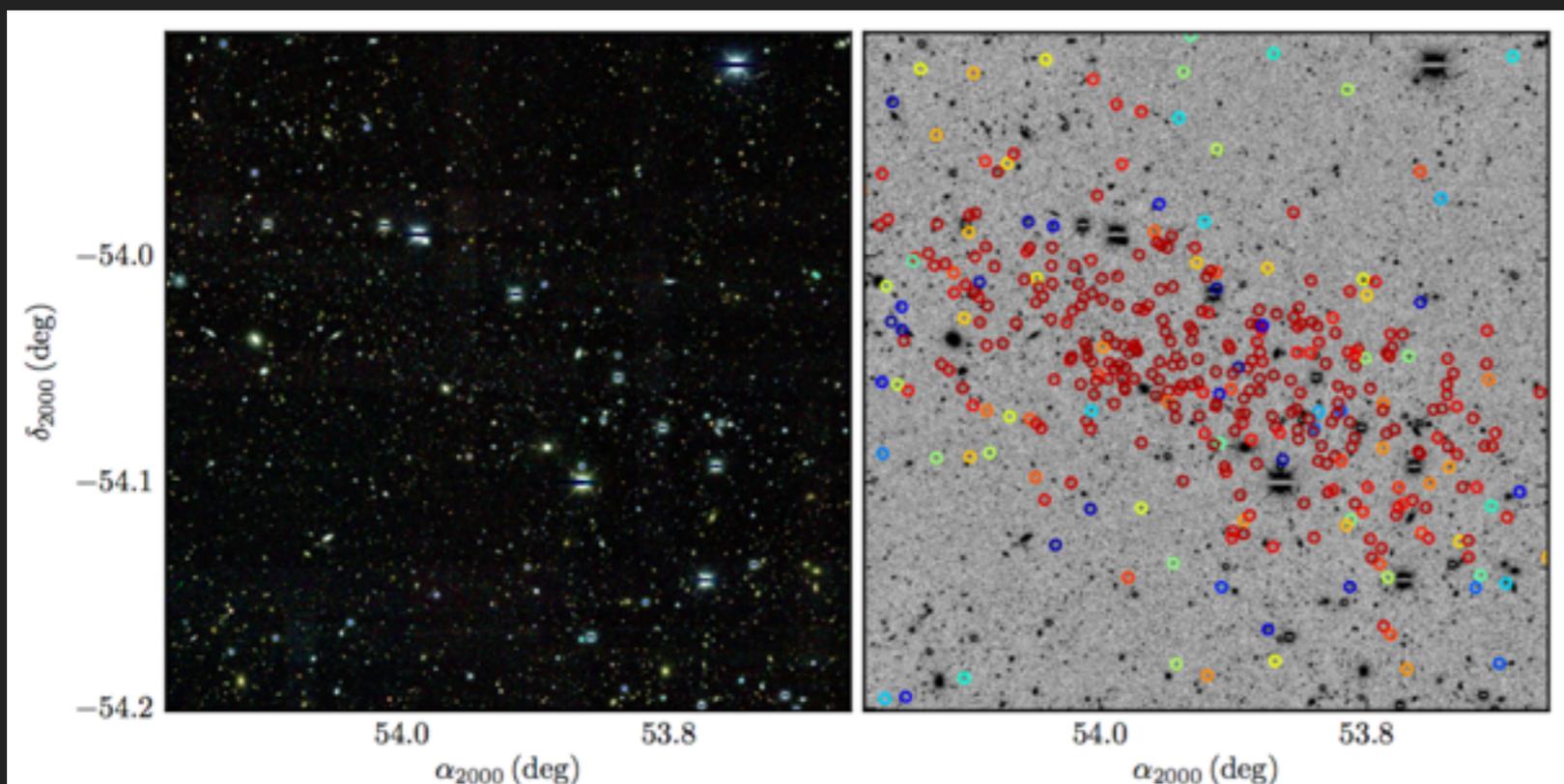


RETICULUM II

- ▶ Reticulum II dwarf galaxy discovered by DES (March 2015), at a distance of only 30 kpc from Earth.
- ▶ A 2.4σ or 2.3σ or 3.7σ or 3.2σ gamma-ray excess was quickly observed at a position consistent with this dwarf galaxy.

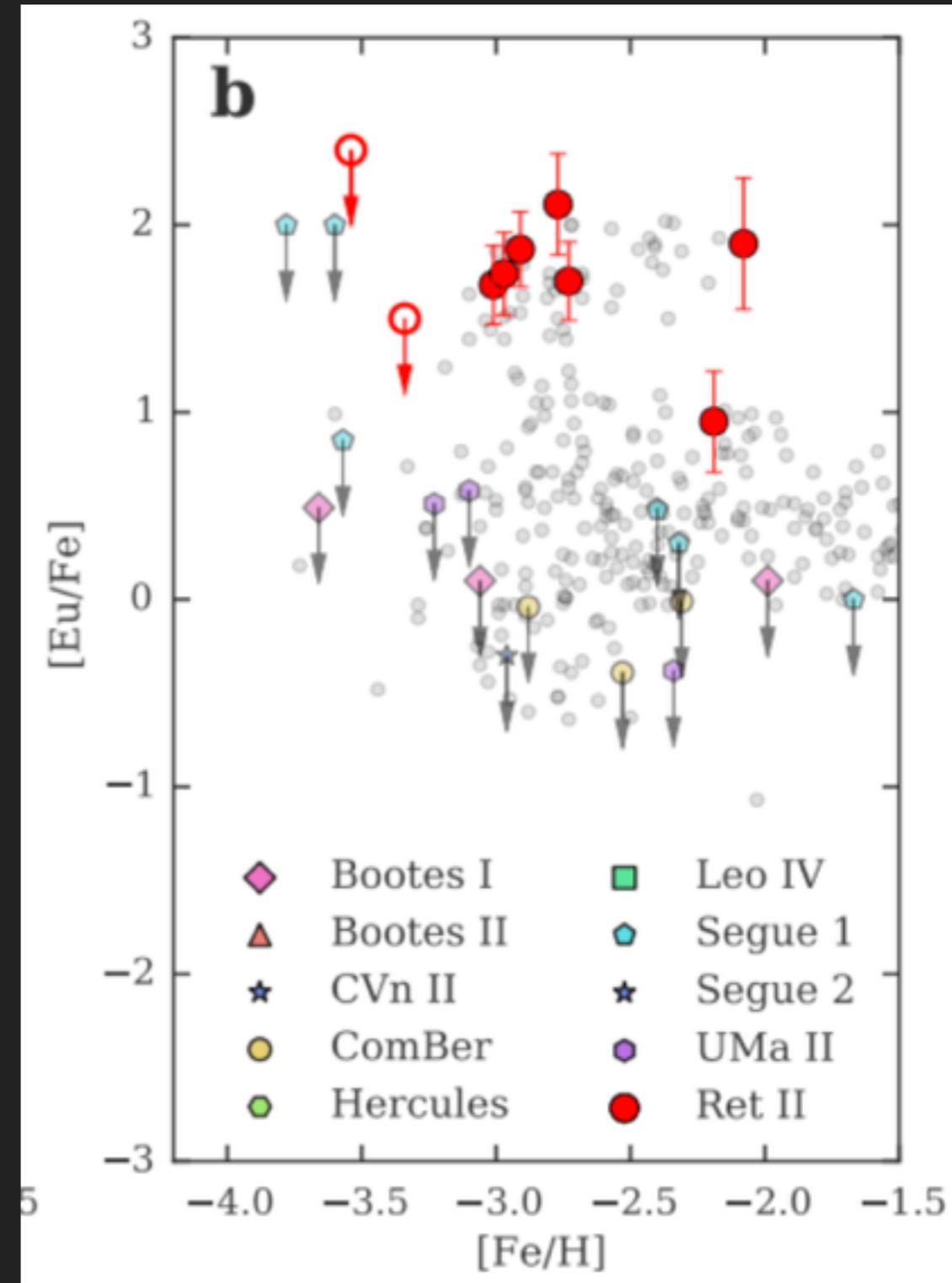
Bechtol et al. (1503.02584)

Hooper & Linden (1503.06209)



RETICULUM II

- ▶ More recently, Reticulum II has provided us with a second puzzle.
- ▶ A significant enrichment of r-process elements was observed in the vast majority of its (otherwise normal) low-metallicity stars.
- ▶ No similar enrichment has been found in any other ultra-faint dwarf spheroidal galaxy.



RETICULUM II

- ▶ This is difficult for both astrophysical interpretations of r-process production.



- ▶ Many SNe necessary to produce Reticulum II r-process abundance.
- ▶ Lack of r-process abundance in other dwarf galaxies hints towards a single rare event.
- ▶ r-process abundance should correlate with metallicity if SNe are responsible.



- ▶ NS are given large natal kicks during their formation, significantly larger than the escape velocity of dwarf galaxies.
- ▶ NS mergers take ~ 100 Myr, thus any NS-NS merger should fall far outside the dwarf galaxy.

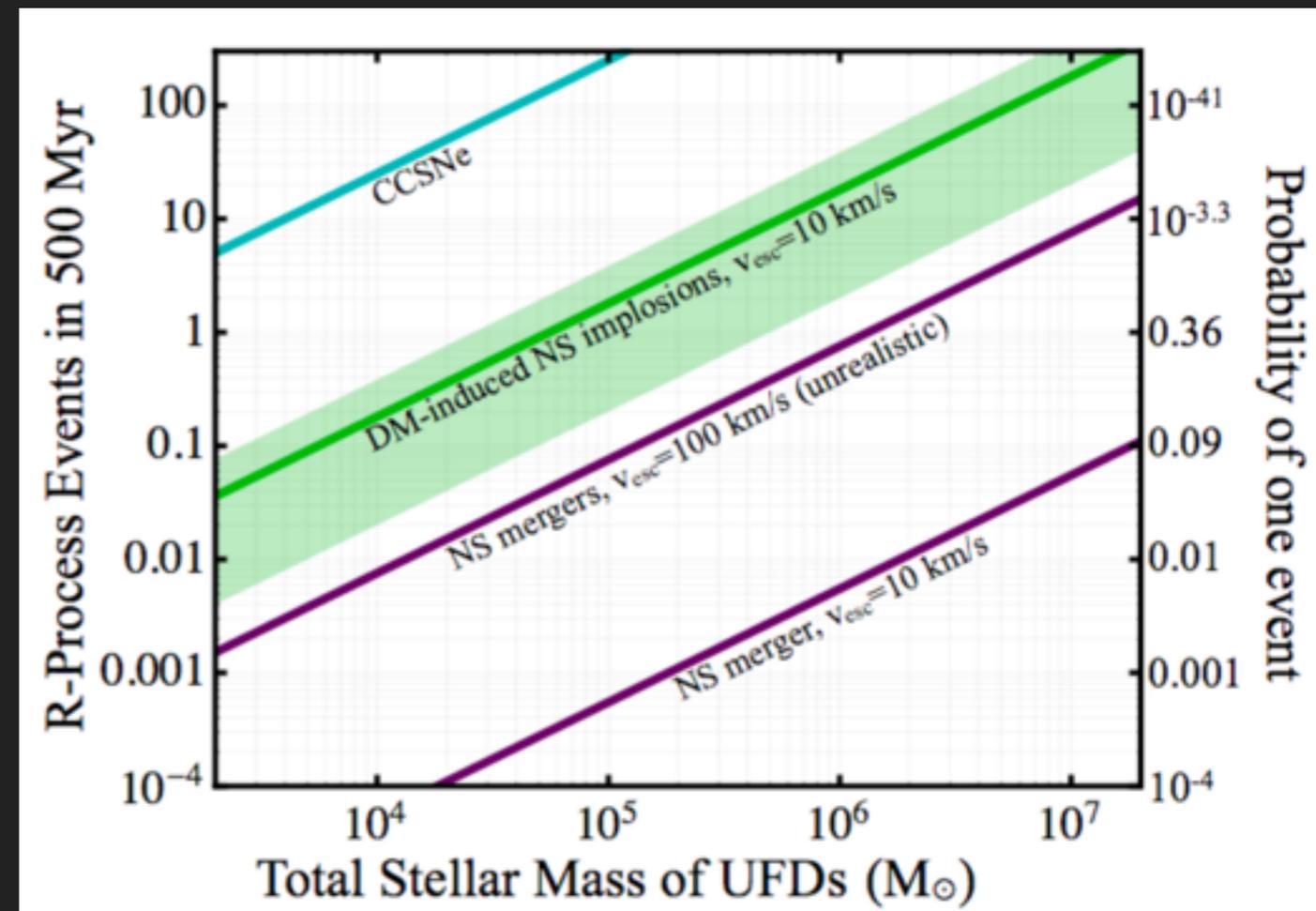
RETICULUM II

- ▶ Dwarf Galaxies have high dark matter densities!

- ▶ Dark Matter can collapse neutron stars on relevant timescales

- ▶ Simple analytic models indicate that a single neutron star collapse can also produce the neutron rich environment necessary for r-process production (detailed simulations needed)

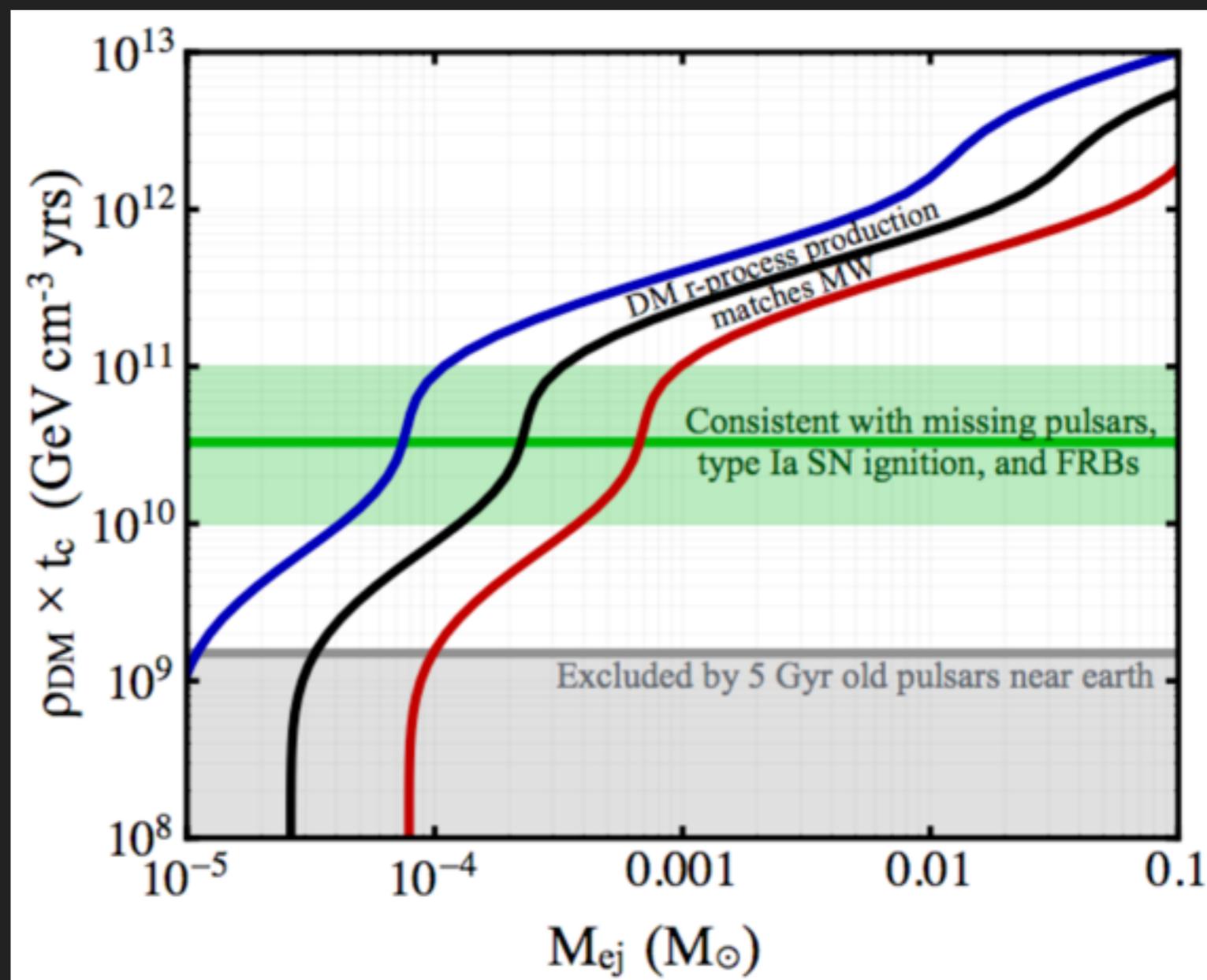
- ▶ ~1 NS collapse is expected, in line with observations.



Bramante & Linden (1601.06784)

A COMBINED DARK MATTER MODEL

- ▶ Intriguingly, the direct detection cross-sections necessary to produce r-process enrichment are compatible with those necessary to solve the missing pulsar problem.
- ▶ Additionally, these asymmetric dark matter models can also explain the ignition of Type Ia SN observations of fast radio bursts.



DIFFERENTIATING DARK MATTER FROM ASTROPHYSICS

- ▶ The maximum pulsar age should depend on the integrated dark matter density over the lifetime of the pulsar.

MeerKat/SKA

- ▶ Large variations in the r-process enrichment of ultra-faint dwarf galaxies are expected – but no large variations are expected in the r-process enrichment of Globular Clusters (which are otherwise very similar).

DES/LSST, GMT/TMT

- ▶ The observation of a single old neutron star very close to the Galactic center will rule out this parameter space.

MeerKat/SKA

CONCLUSIONS

- ▶ Asymmetric Dark Matter is a well-motivated explanation for the non-baryonic matter density of our universe.
- ▶ Neutron stars provide a sensitive observatory for asymmetric dark matter studies.
- ▶ Several astrophysical anomalies can be simultaneously solved by asymmetric dark matter models.
- ▶ These observations offer silver-bullet observations which would be difficult to mimic with astrophysical mechanisms.
- ▶ Upcoming experiments will conclusively probe this parameter space.