Heavy asymmetric dark matter igniting type Ia supernovae and collapsing galactic center pulsars

Joseph Bramante
University of Notre Dame

Cosmo Cruise 2015

based on JB 1505.07464

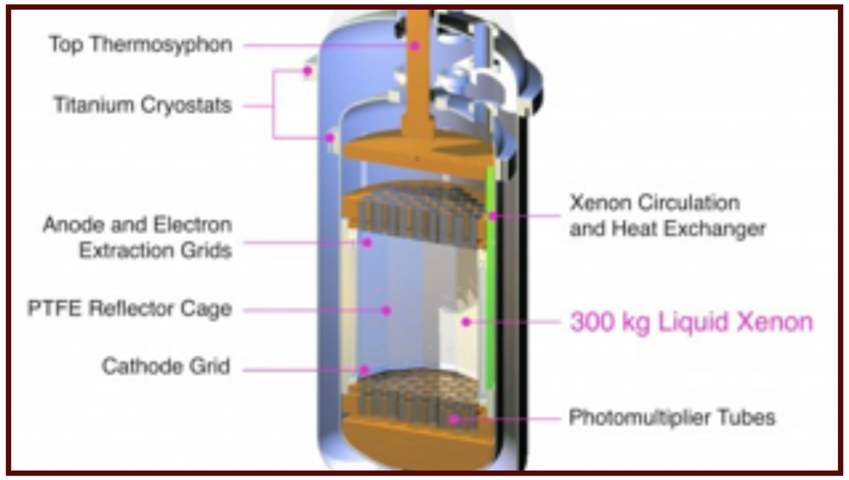
see also:
JB Linden 1405.1031, JB Elahi 1504.04019

Special thanks to preliminary collaborators:
Matthew McCullough (CERN) and Robert Lasenby (Oxford)

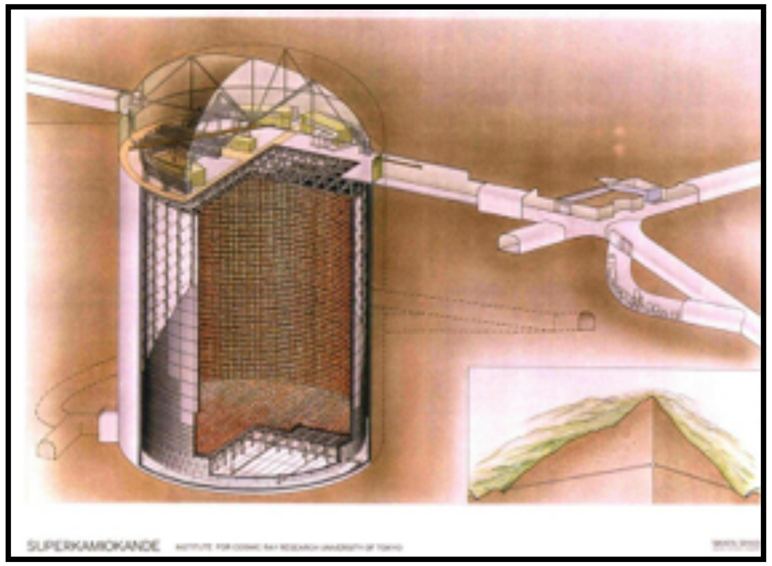
Thanks to Peter Garnavich (professor at Notre Dame who studies type Ia supernovae).

Be sure to check out related work by
Graham, Rajendran, Varela: 1505.04444

Dark matter in stars: If DM has nontrivial interactions with visible matter, it will have some impact on stellar evolution.



10 ton years

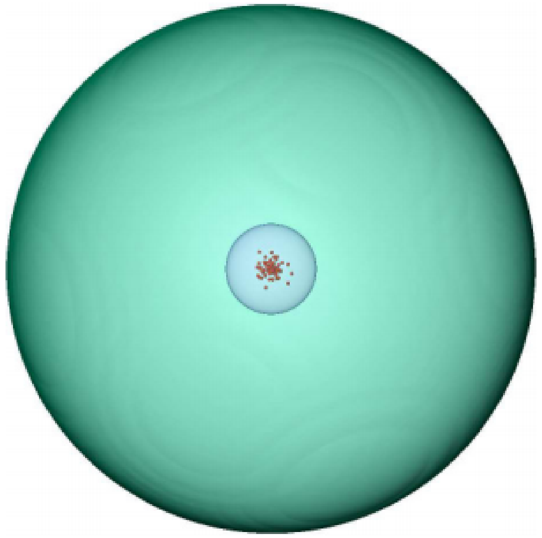


10^6 ton years

10^{36} ton years

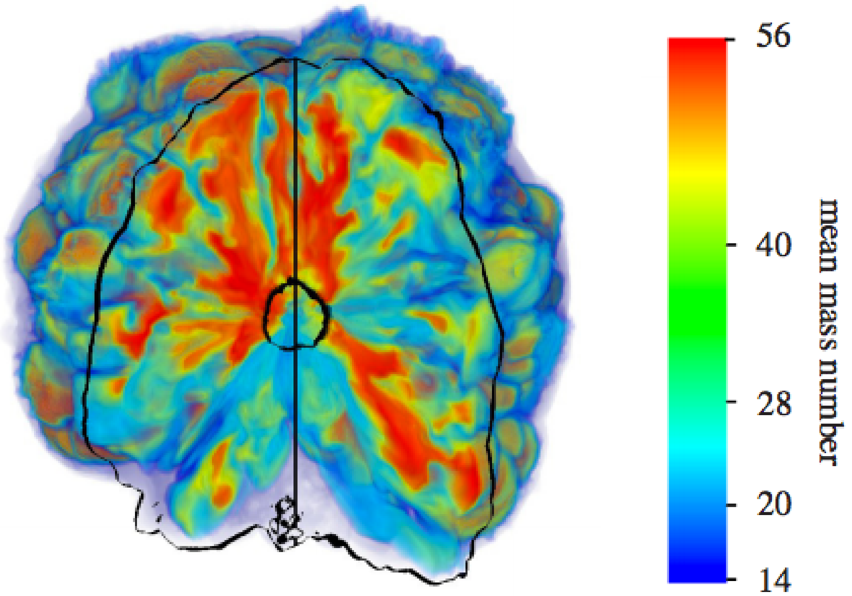
If it scatters in a terrestrial detector, it has scattered $\sim 10^{30}$ times more in a star.

Type Ia supernovae erupt when a portion of white dwarf becomes heated, igniting a thermonuclear flame-front that sweeps through the star, followed by an explosion.*

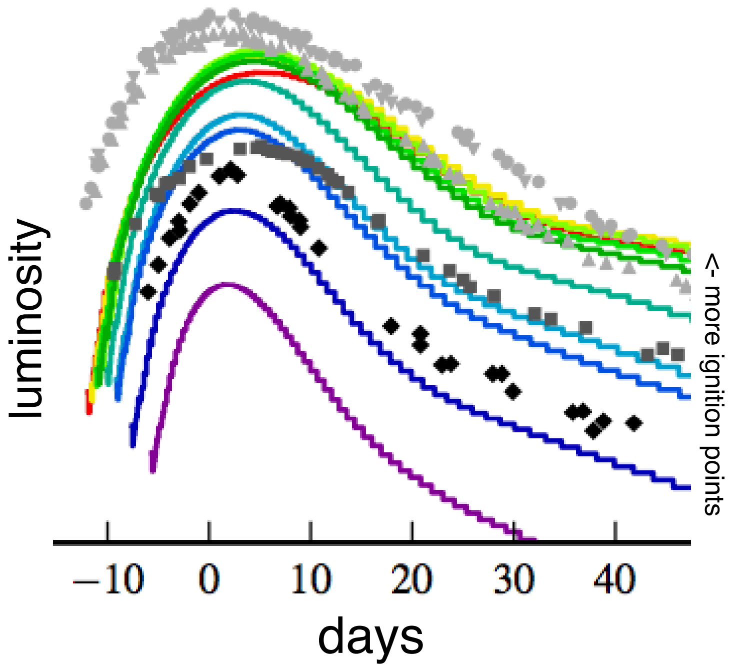


Ignition region inside WD

ignition



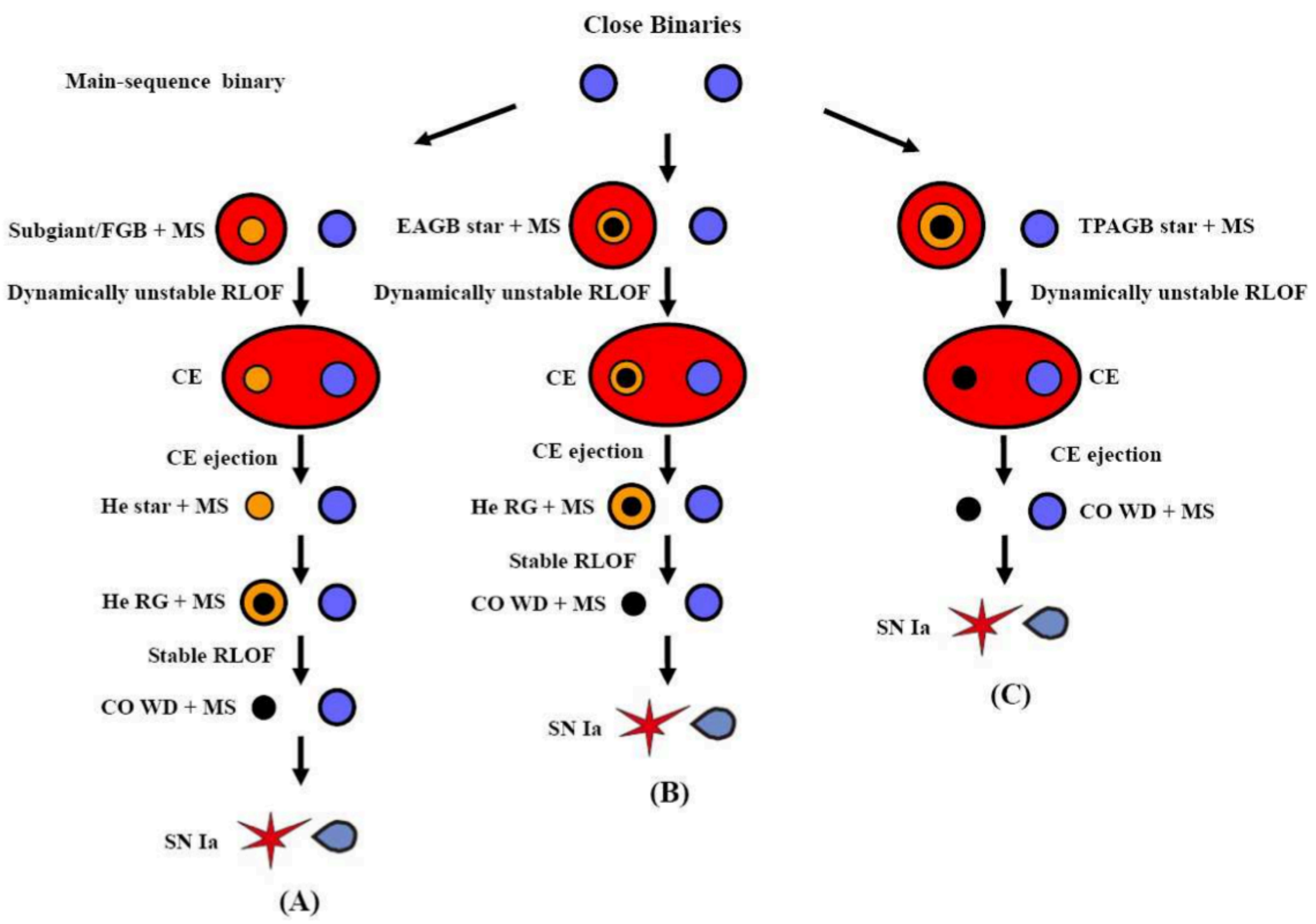
nuclei fuse (^{56}Ni)

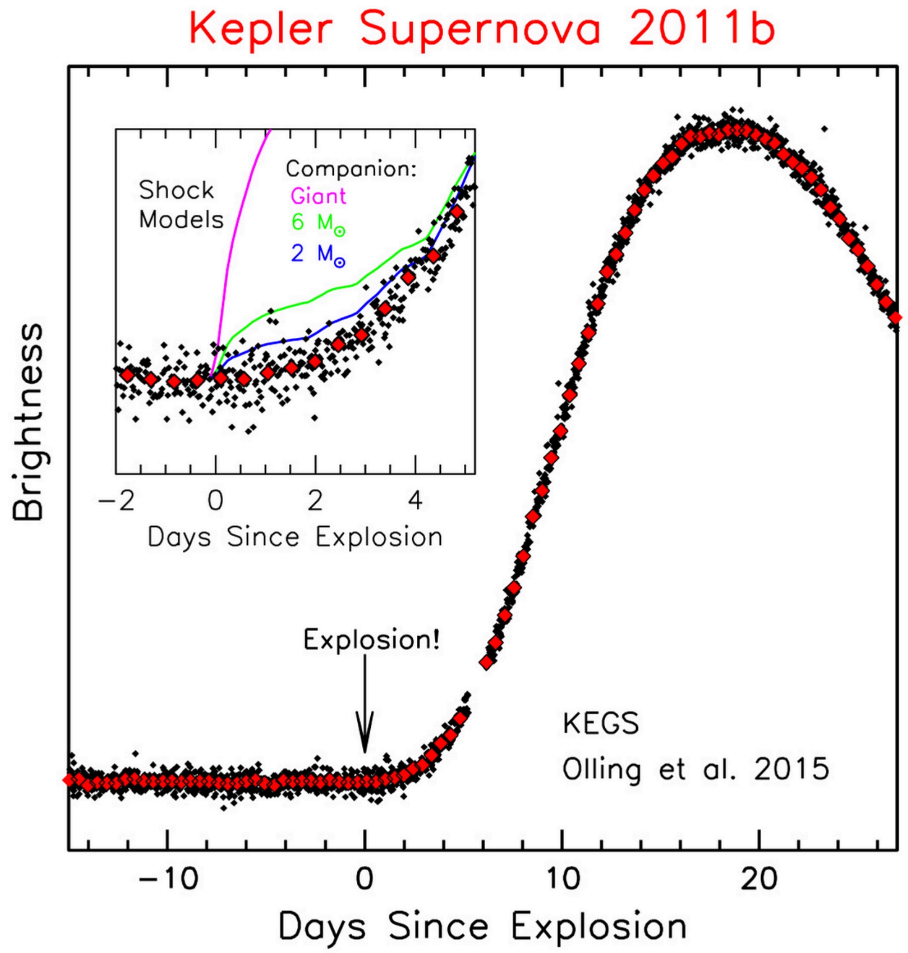


nuclei decay

*The veracity of the final two statements, along with the location and number of ignition spots, flame propagation, and "deflagration vs. detonation" are all topics of active research: see e.g. 1308.3257 (figures), 1308.4833, 1309.4042.

It is not clear what ignites type Ia supernovae. Candidates include binary accretion to criticality (Chandrasekhar mass), and white dwarfs merging.

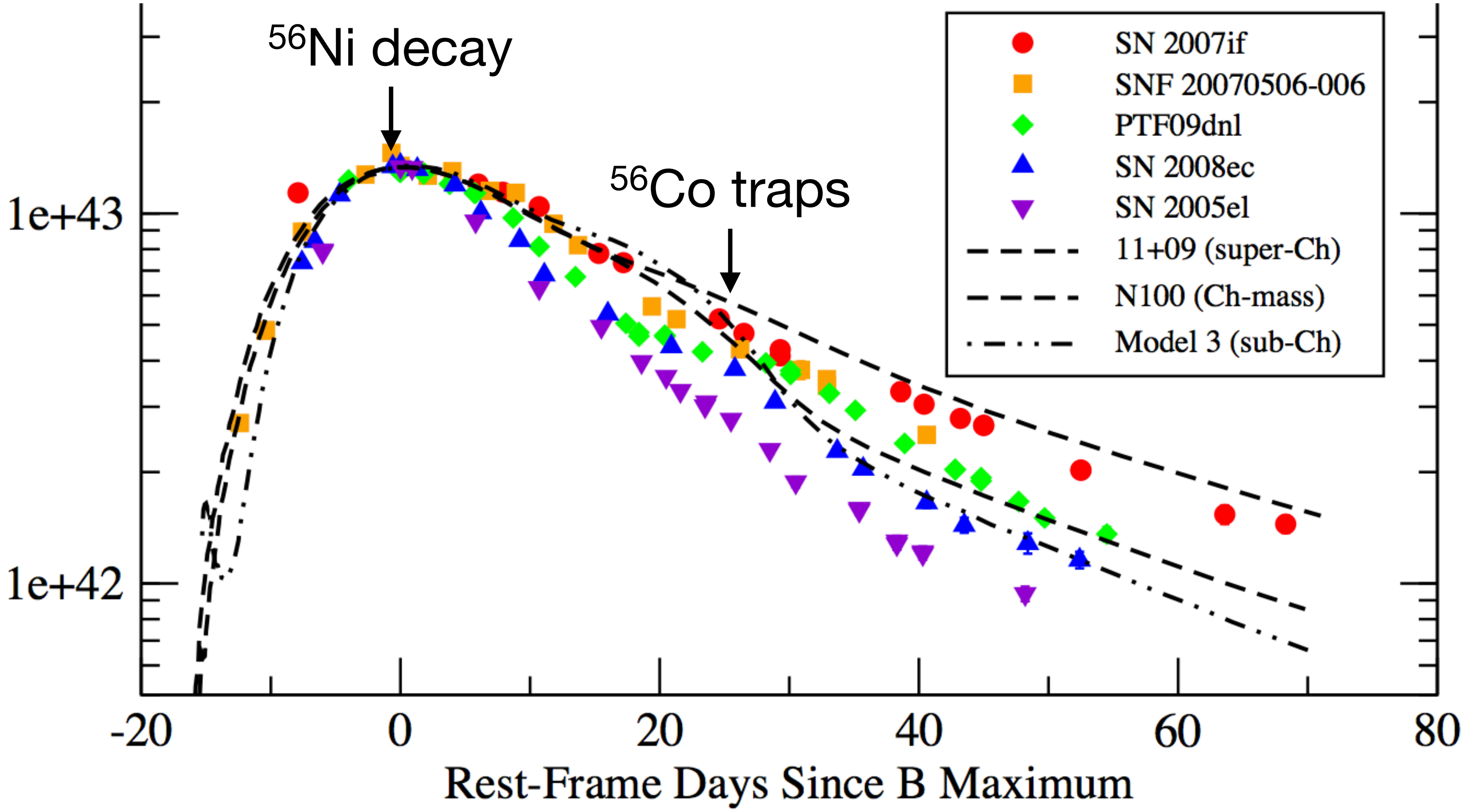




Binary ignition is now somewhat disfavored, by a lack of companion star "shocks" in SNIa light curves, and observations of sub-Chandrasekhar mass type Ia supernovae. White dwarf mergers may not match the high rate of type Ia supernovae.

Maoz et al. 1312.0628 (Review), Olling et al. Nature 2015

Recent observations indicate that half of type Ia supernovae originate from a sub-Chandrasekhar (< 1.4 solar mass) white dwarf. This implies that "sub-critical" white dwarfs are igniting.

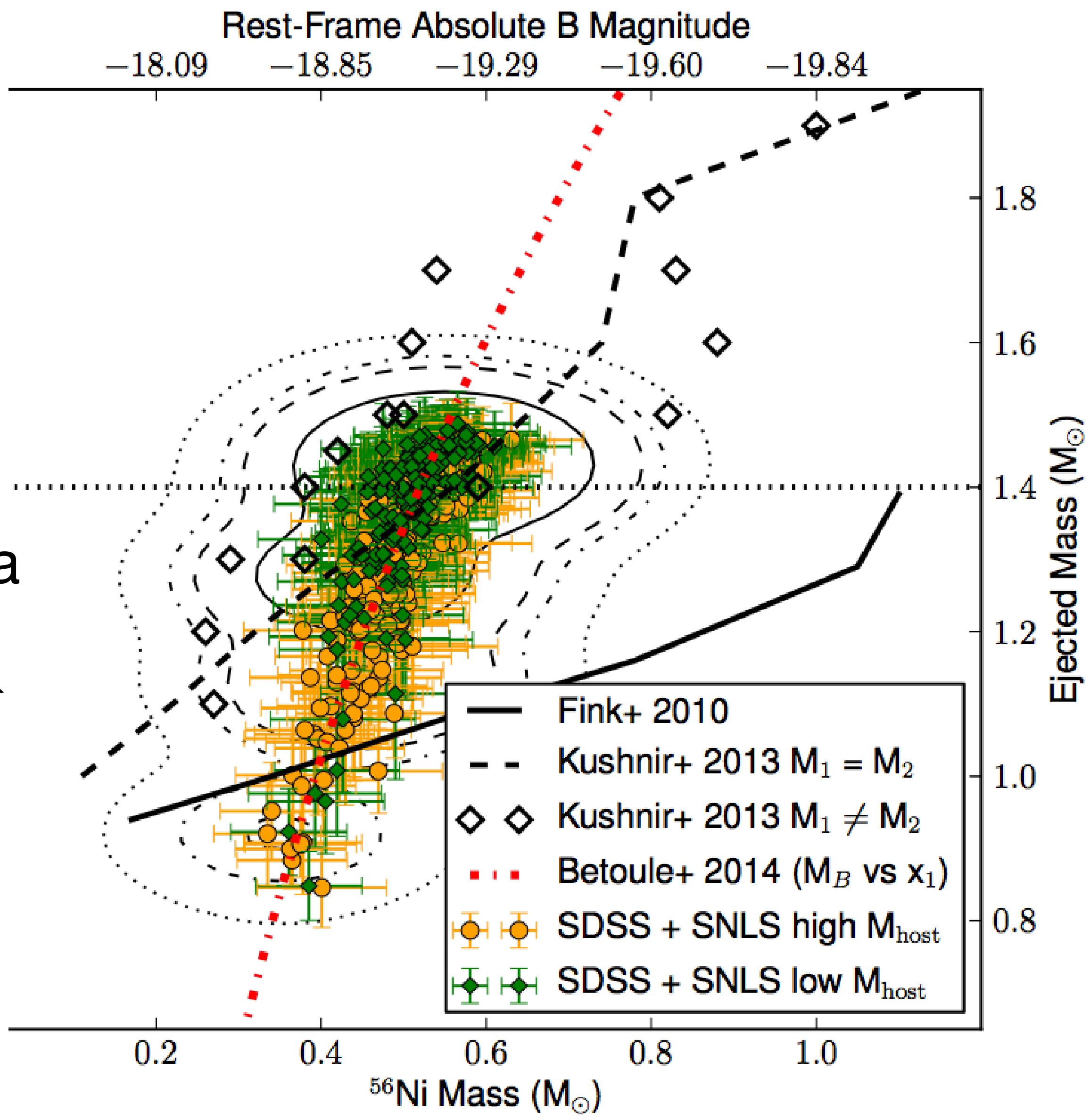


1402.6842

By measuring the maximum luminosity (dominated by ^{56}Ni→^{56}Co decay) and the luminosity tail (shaped by ^{56}Co decay and bulk optical trapping), the masses of type Ia progenitors can be inferred.

Strizinger et al. 2006, Scalzo et al. 1402.6842, Scalzo Ruiter Sim 1408.6601

The existence of sub-Chandrasekhar supernovae presents a quandary that binary accretion has trouble accounting for (He, H fusion shells not seen in any spectra).



Long tail of sub-Chand. SNIa

1408.6601

0.1-100 PeV asymmetric dark matter (either bosonic or fermionic), could be an explanation for sub-Chandrasekhar SNIa.

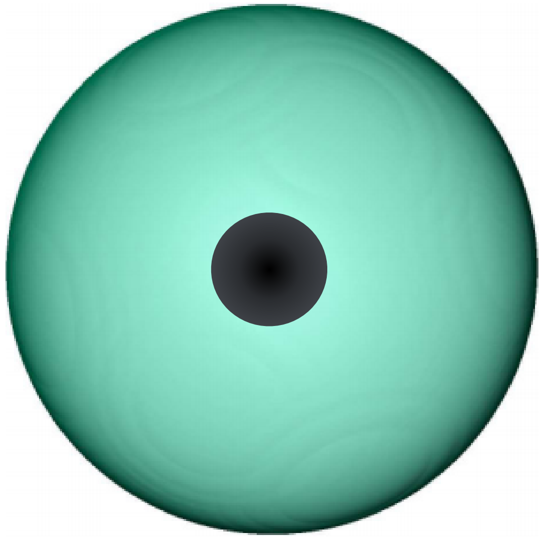
Asymmetric dark matter models suppose that dark matter in galactic halos, like ordinary matter in galactic halos, is composed of particles and not antiparticles of some symmetry.

$$\enclose{circle}{\phi}\,\phi^* \quad \text{or} \quad \enclose{circle}{\psi}\,\bar{\psi}$$

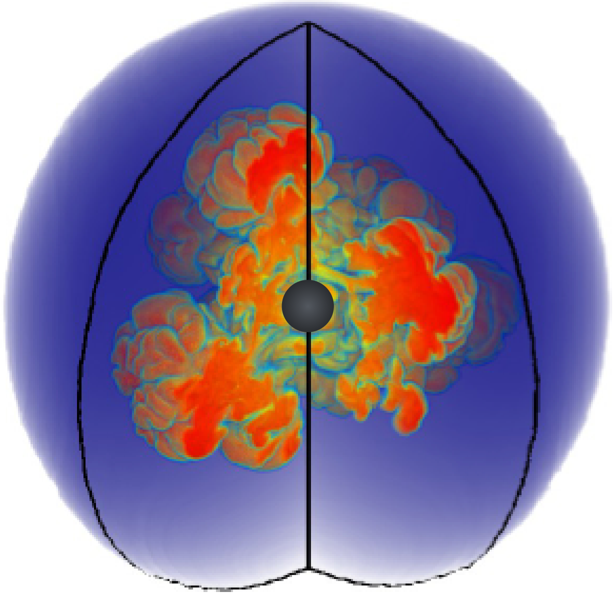
This dark asymmetry could arise in conjunction with the baryon/lepton asymmetries.

For our purposes, the dark matter’s asymmetry allows DM to efficiently collect and collapse in stars without annihilating to lighter particles (annihilation forbidden by the dark asymmetry).

In order to ignite a carbon-oxygen white dwarf, the dark matter must be **heavy** so that it thermalizes inside a *small* volume within the white dwarf, and reaches the point of self-gravitation within ~10^9 years.

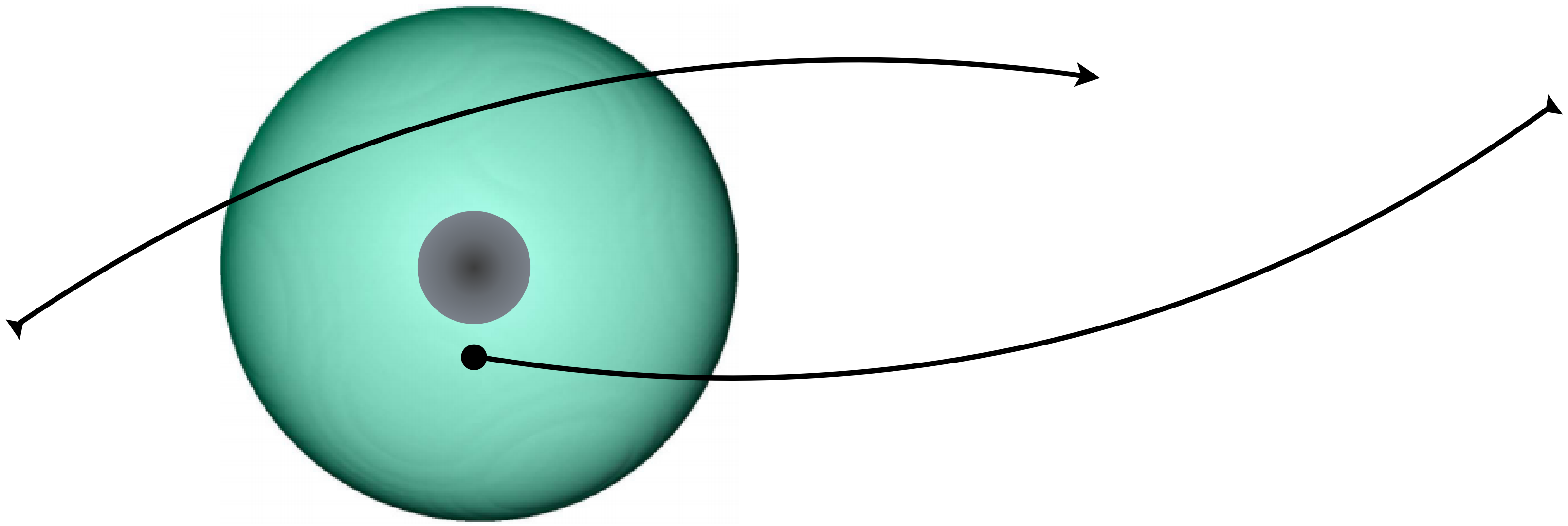


DM collects to the point of self-gravitation.



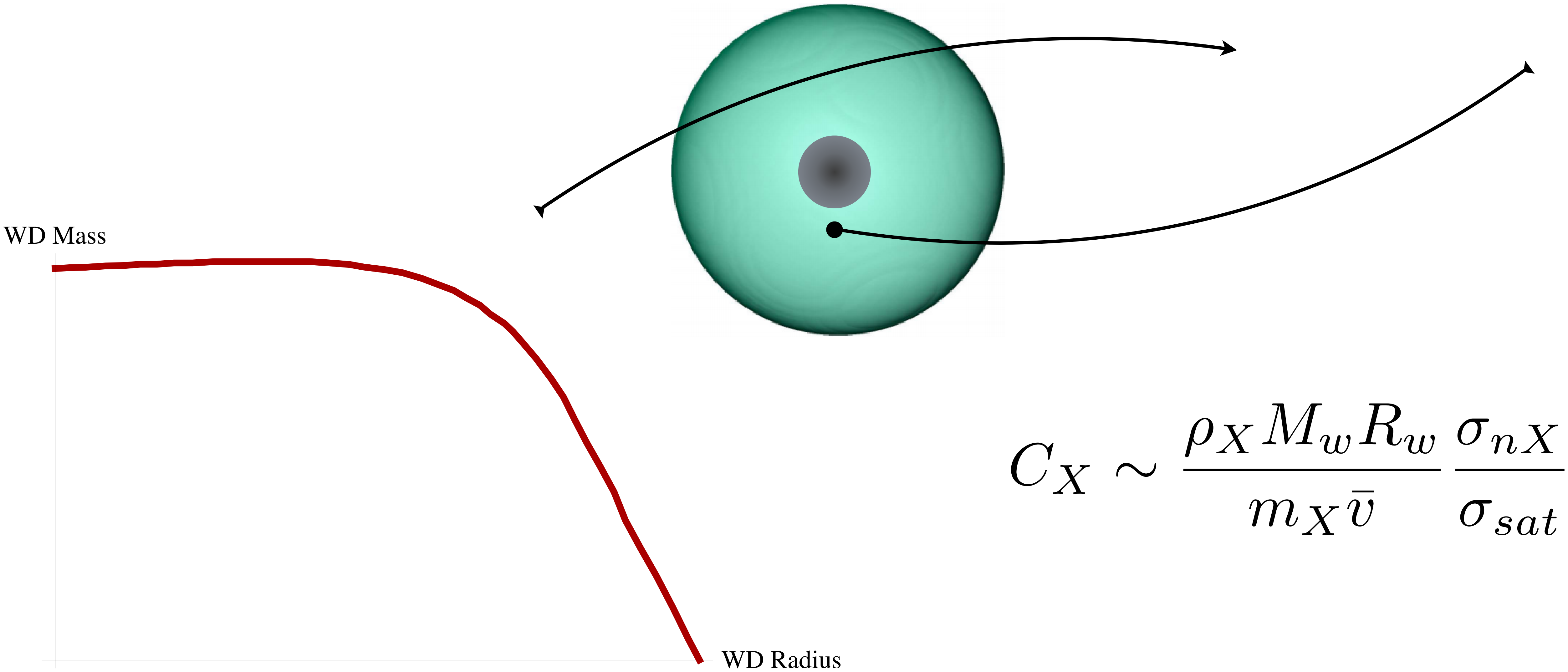
DM collapses, shedding gravitational potential energy, igniting a SNIa.

Dark matter collection in white dwarfs increases with white dwarf mass and DM-nucleon cross-section.



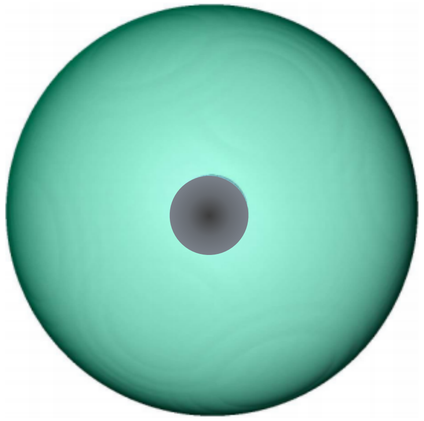
$$C_X \sim \frac{\rho_X M_w R_w}{m_X \bar{v}} \frac{\sigma_{nX}}{\sigma_{sat}}$$

Dark matter collection in white dwarfs increases with white dwarf mass and DM-nucleon cross-section.

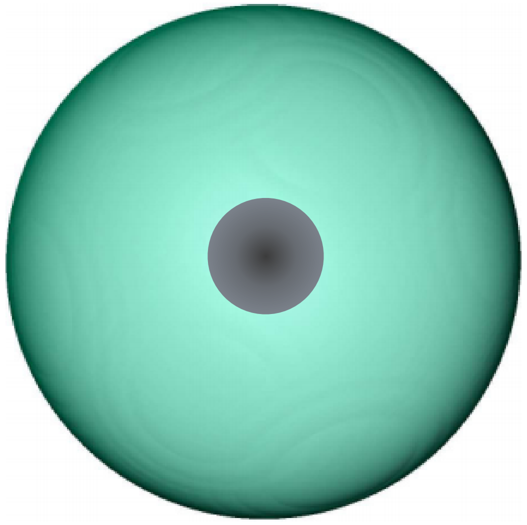


$$C_X \sim \frac{\rho_X M_w R_w}{m_X \bar{v}} \frac{\sigma_{nX}}{\sigma_{sat}}$$

As the white dwarf mass increases above 0.8 solar masses, relativistic, degenerate electrons must move faster to stabilize the WD, and the white dwarf's radius decreases non-linearly.



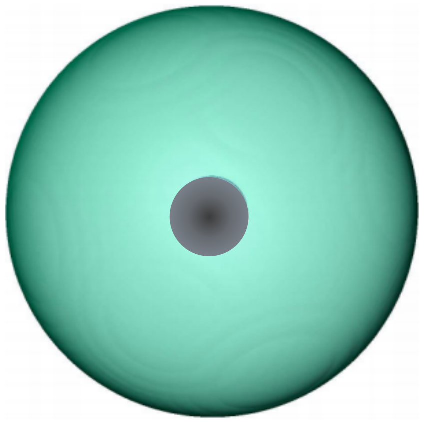
collapses sooner



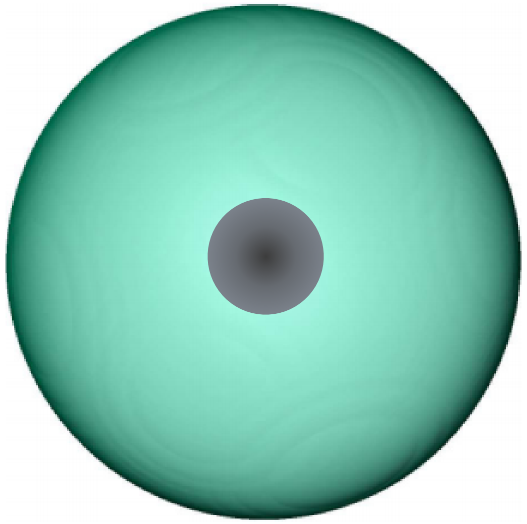
collapses later

$$N_{sg} \sim \frac{T_w^{3/2}}{m_X^{5/2}\,\rho_w^{1/2}}$$

So more massive white dwarfs not only collect dark matter faster, but because the more massive white dwarf is denser, dark matter collects into a smaller ball, and collapses sooner. Altogether, this shortens the time for dark matter collapse in more massive white dwarfs.



collapses sooner

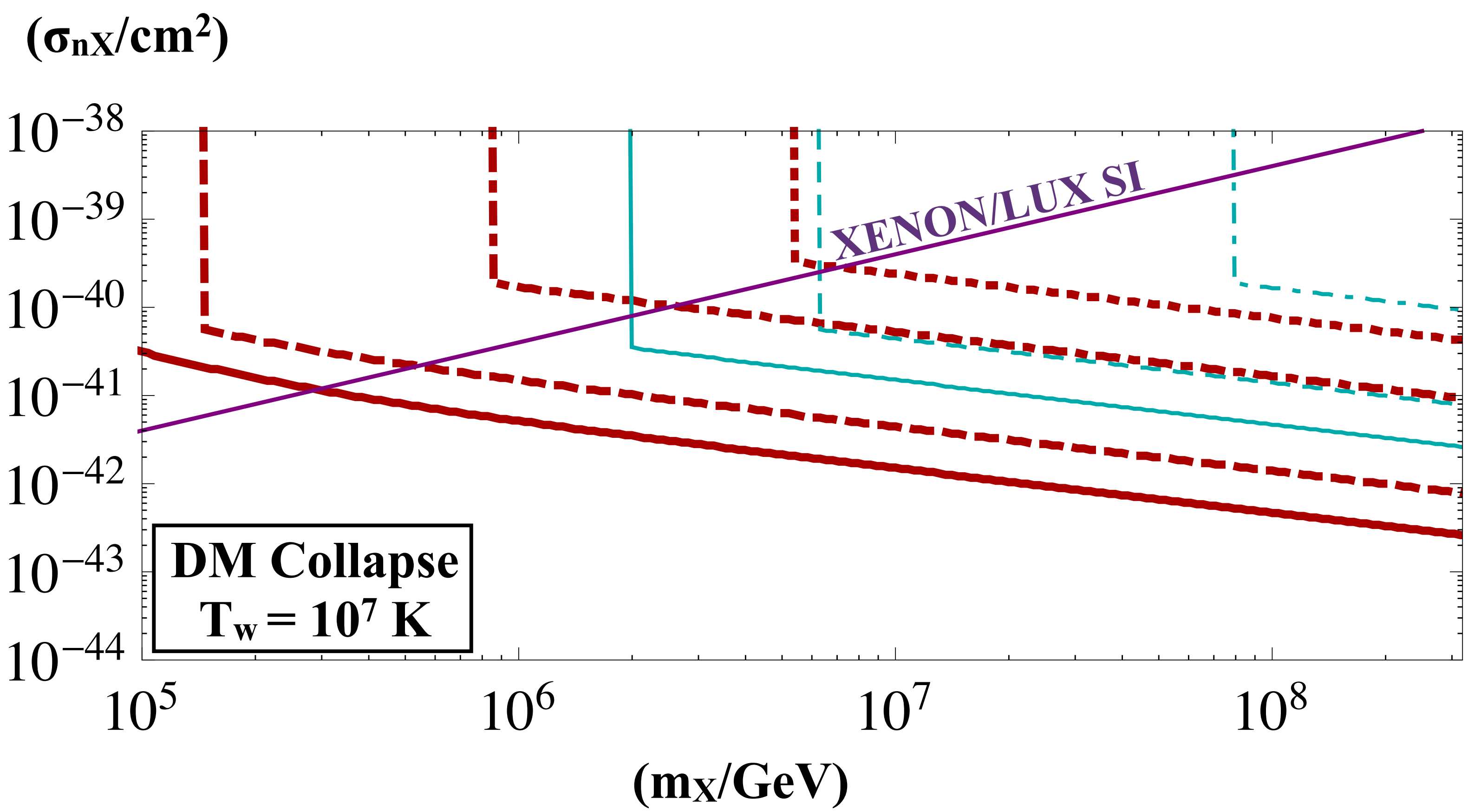


collapses later

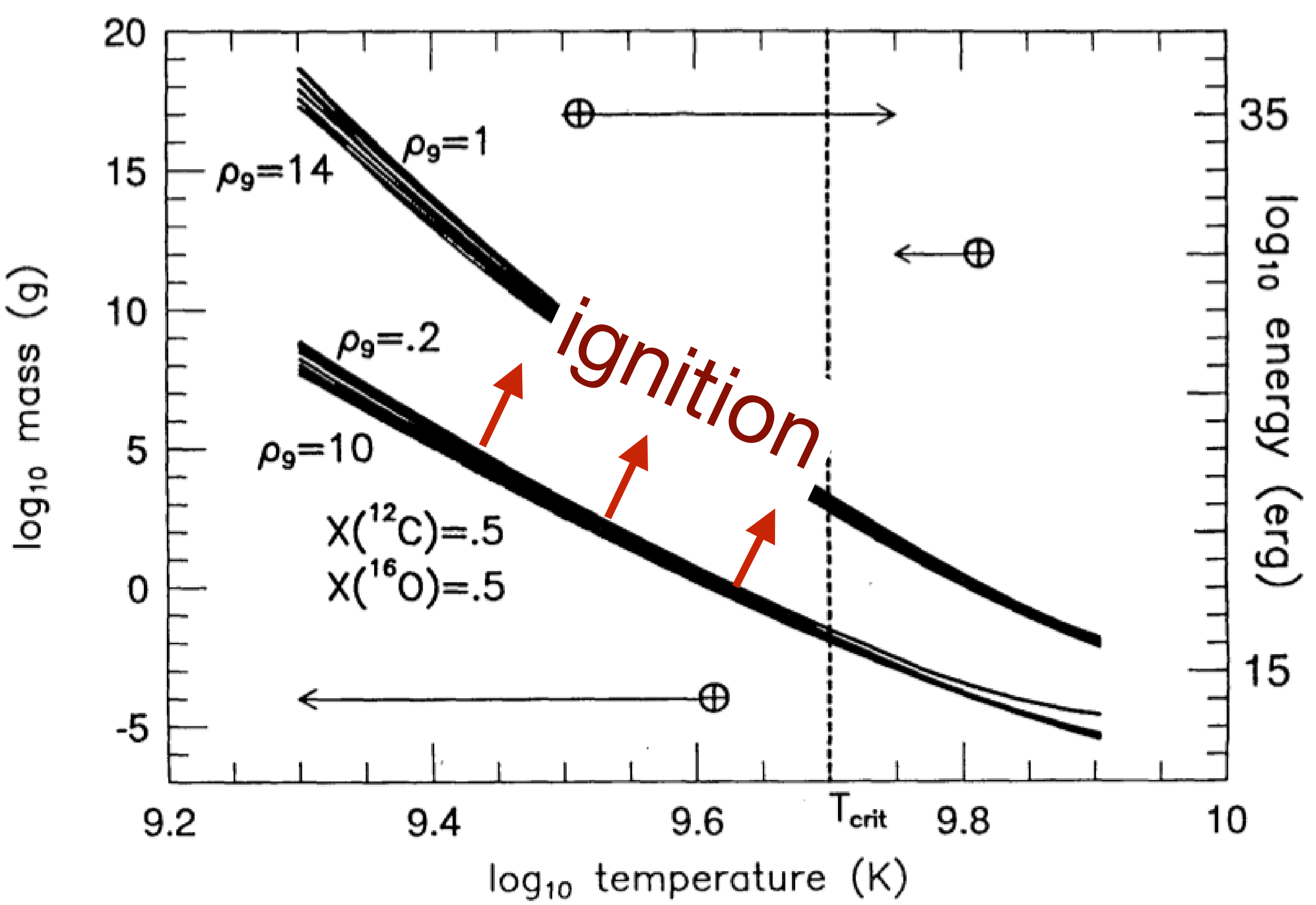
$$N_{sg} \sim \frac{T_w^{3/2}}{m_X^{5/2}\,\rho_w^{1/2}}$$

Line	$M_w/M_\odot$	$R_w/(10^3$ km)	$\rho_w/(10^7$ g/cm^3)
—	1.4	2.5	100
- -	1.3	3	40
-·-	1.1	5	6
⋯	0.9	6	2

Line	t_w/Gyr
— - - ⋯	5
— -·- ⋯	0.5



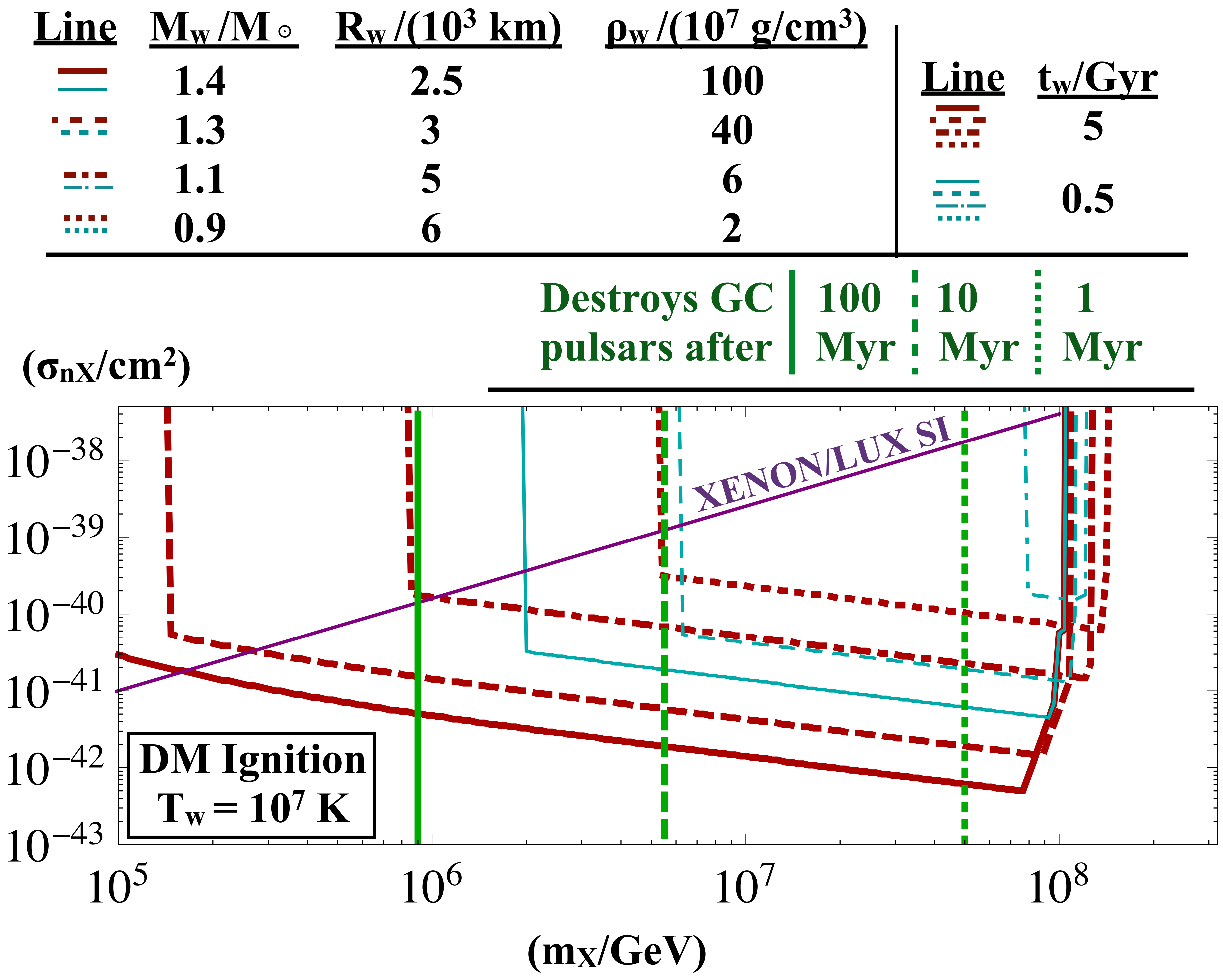
As it collapses to its minimum energy state (a tiny quantum-pressure-stabilized ball of DM), the dark matter will shed gravitational potential energy.



Timmes & Woosley 1992

For ignition to occur, at a given temperature, the speed of nuclear burning across a fixed region must exceed the white dwarf’s electron conduction diffusion rate.

The limiting factor for heavy ADM-induced-ignition of white dwarfs is the mass of the DM particle. Heavier DM collapses after fewer particles have collected, and fewer collapsing particles transfer less heat.



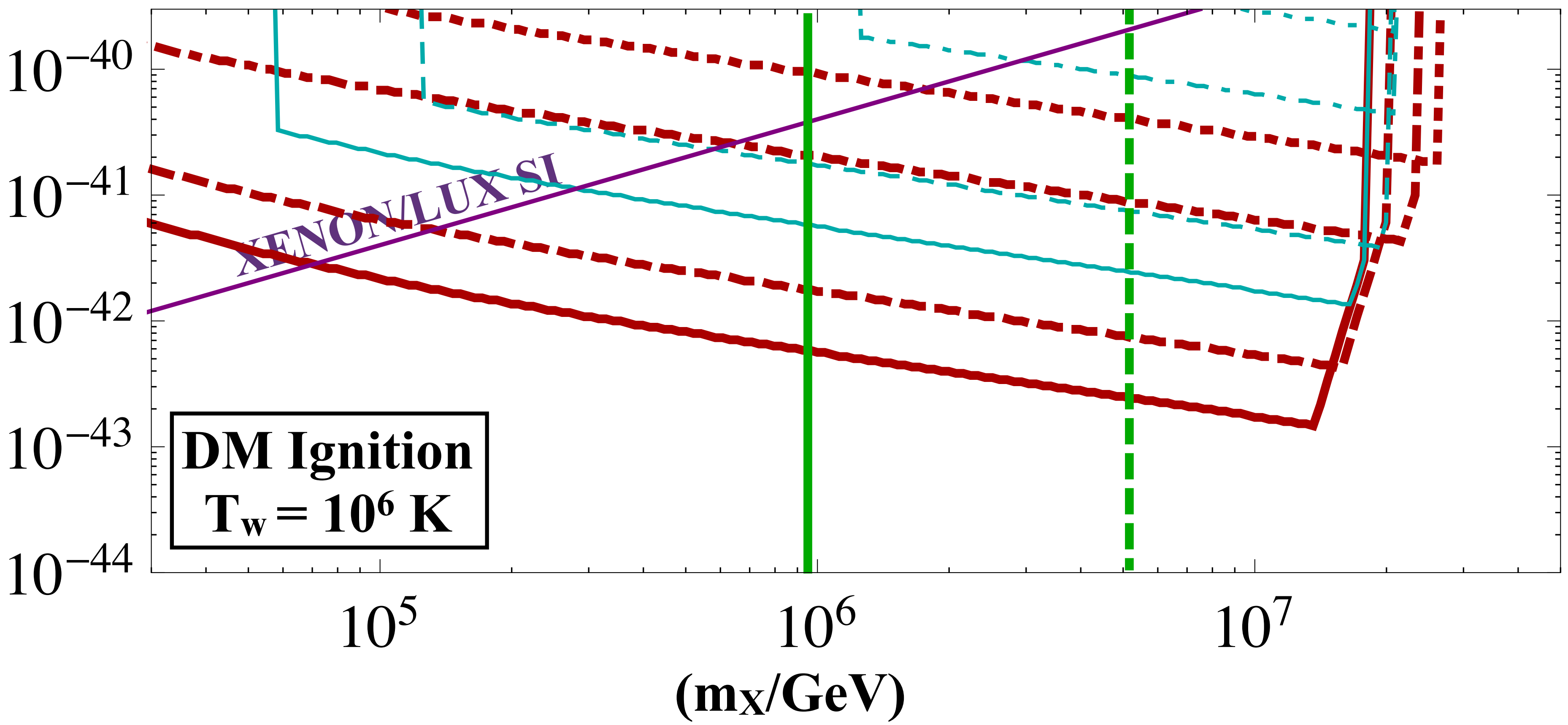
$$N_{sg} \sim \frac{T_w^{3/2}}{m_X^{5/2}\,\rho_w^{1/2}}$$

If the WD is cooler, fewer DM particles are required for collapse.

Line	$M_w/M_\odot$	$R_w/(10^3$ km)	$\rho_w/(10^7$ g/cm^3)
━	1.4	2.5	100
- -	1.3	3	40
-·-	1.1	5	6
⋯	0.9	6	2

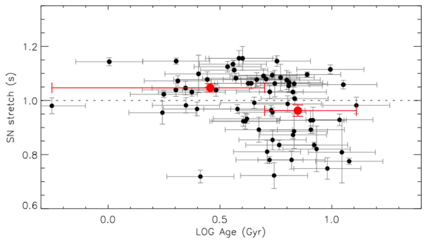
Line	t_w/Gyr
━ - - -·- ⋯	5
━ - - -·- ⋯	0.5

Destroys GC pulsars after	┃ 100 Myr	┇ 10 Myr	⋮ 1 Myr



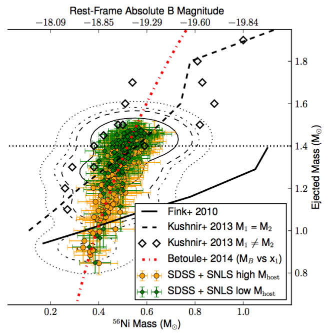
$$N_{sg} \sim \frac{T_w^{3/2}}{m_X^{5/2}\,\rho_w^{1/2}}$$

ADM in SNIa data



1311.6344

Data on the ages of stars adjacent to type Ia supernovae



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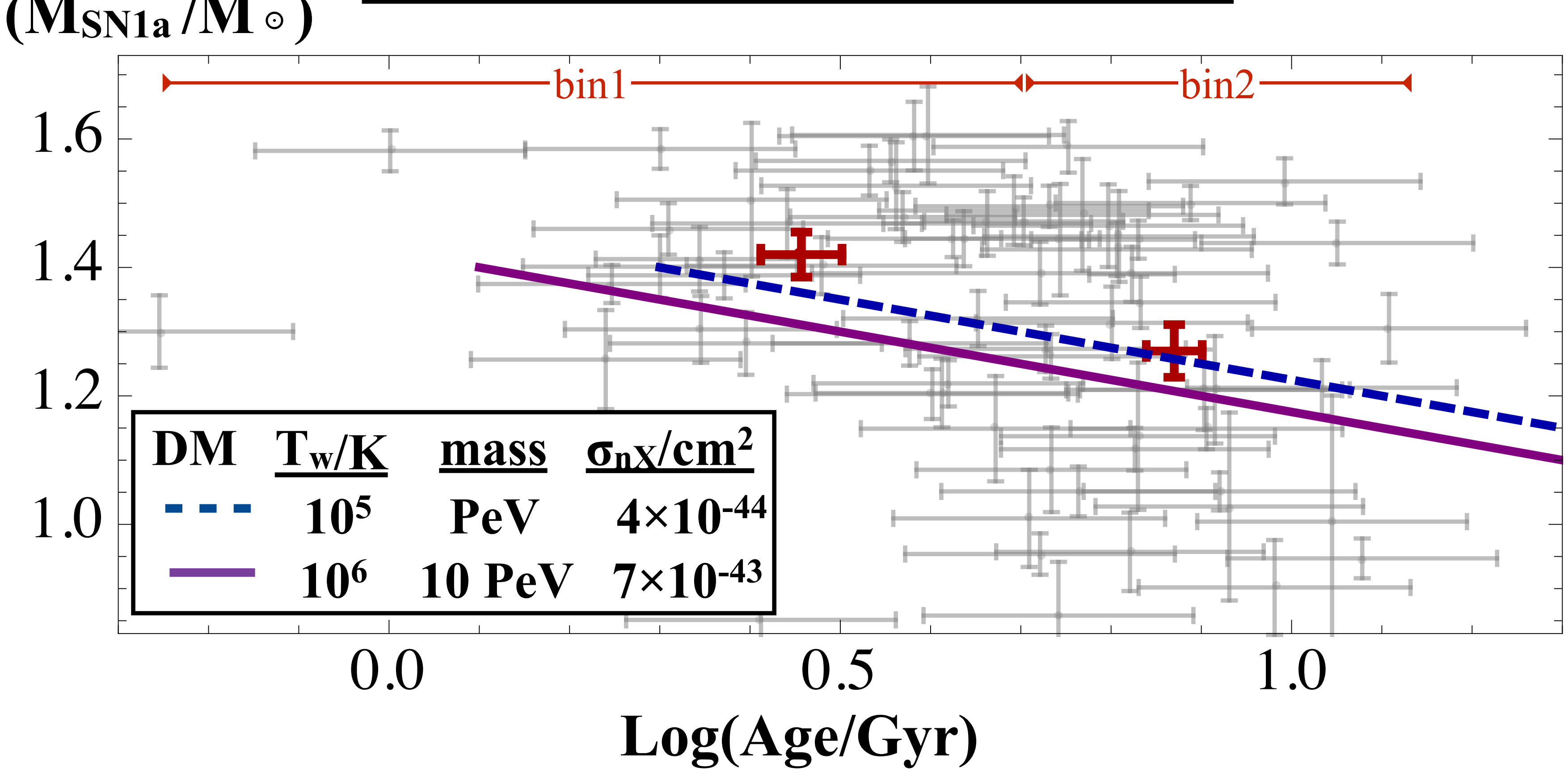
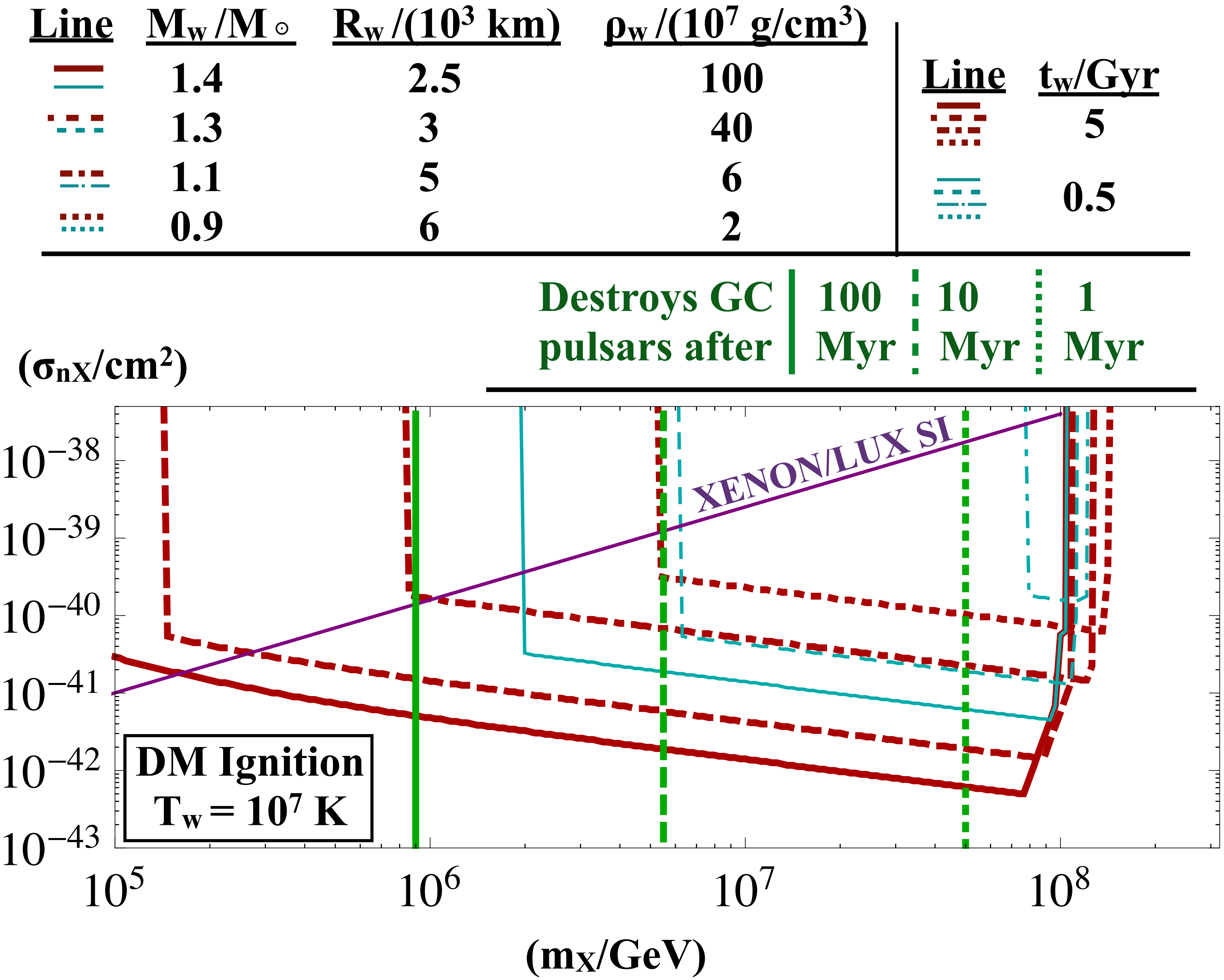
Data on the mass of type Ias inferred from luminosity

Search for DM ignition of SNIa

SNIa progenitor age versus mass



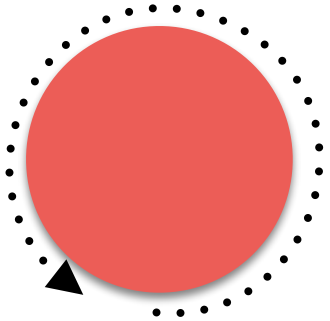
Transition to missing pulsar problem



To explain the importance of the green lines, we need to know a few things about pulsars…

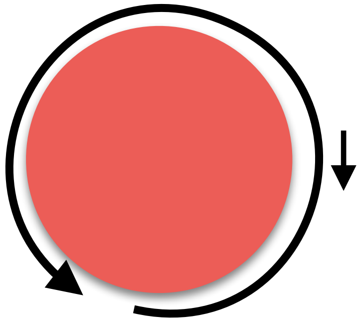
A pulsar is a spinning neutron star, observed as a regularly radiating revolving magnetic dipole. It is very near collapsing (escape velocity of 0.7 c).

We can tell roughly how old it is by measuring its radio pulses.

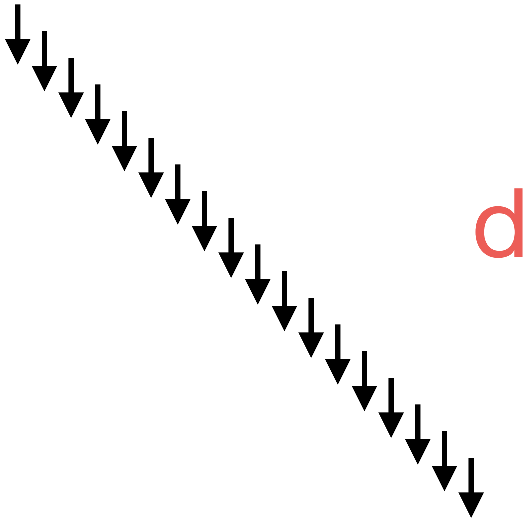


$$\mathrm{P}$$

$$t_{NS} = \frac{\mathrm{P}}{2\dot{\mathrm{P}}}$$

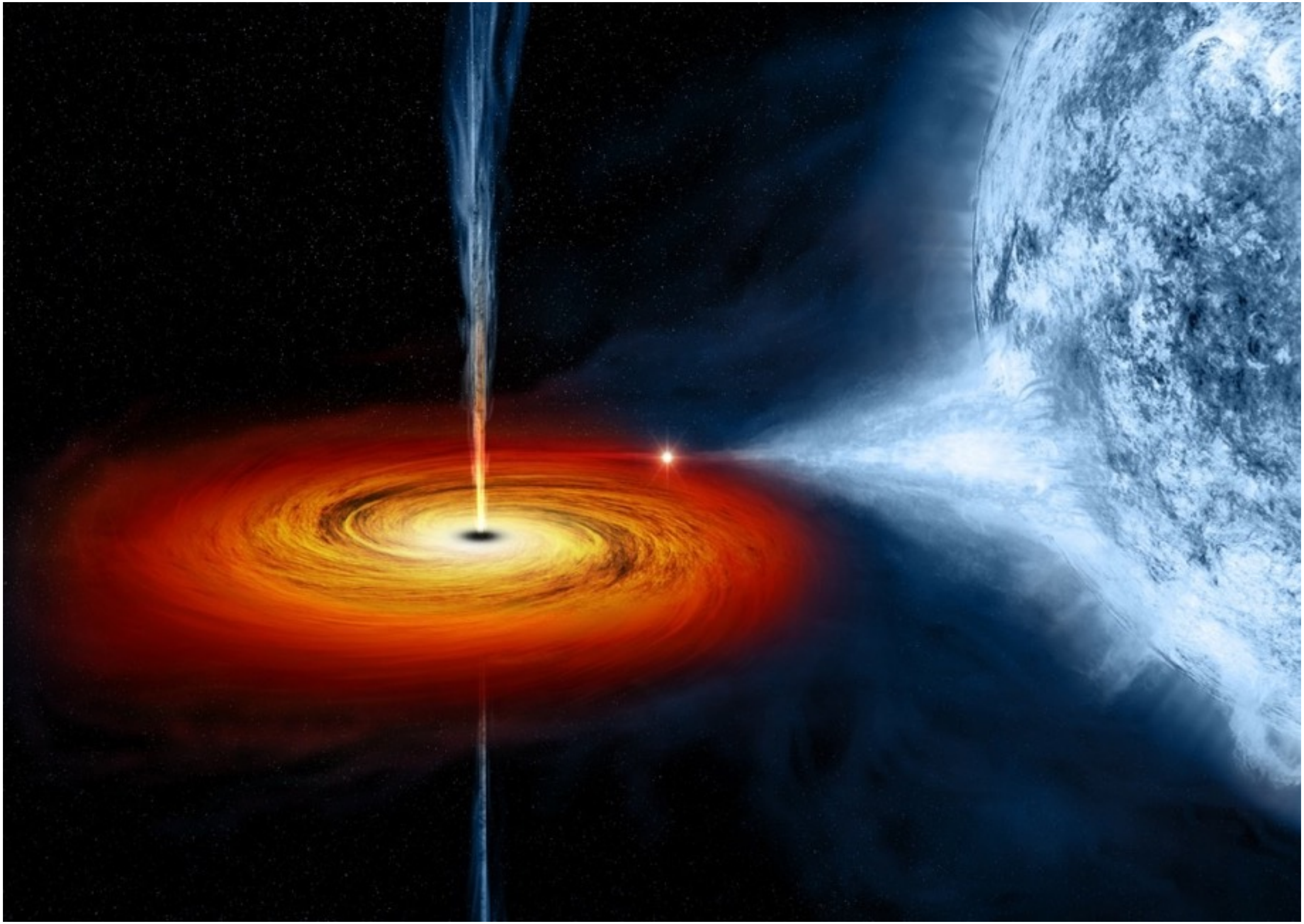


$$\dot{\mathrm{P}}$$



divided by ↓

(Older) Millisecond pulsars form from x-ray binaries



The missing pulsar problem

Prior to the detection of a very luminous magnetar one tenth of a parsec away from the ($10^8 \odot$ mass) black hole at the galactic center, it was assumed that pulsars had not been detected there, because a charged screen of material at the galactic center was broadening pulse signals. Pulsars are expected because of a large population of high mass progenitor stars and X-ray binary systems.

The missing pulsar problem

However, measurements of radio pulses from the newly discovered galactic center magnetar indicate a much cleaner path for radio pulses than was supposed. In addition, measurements of the radio pulses’ angular broadening match those of SgA*. This suggests that the scattering screen is homogeneous.

The missing pulsar problem

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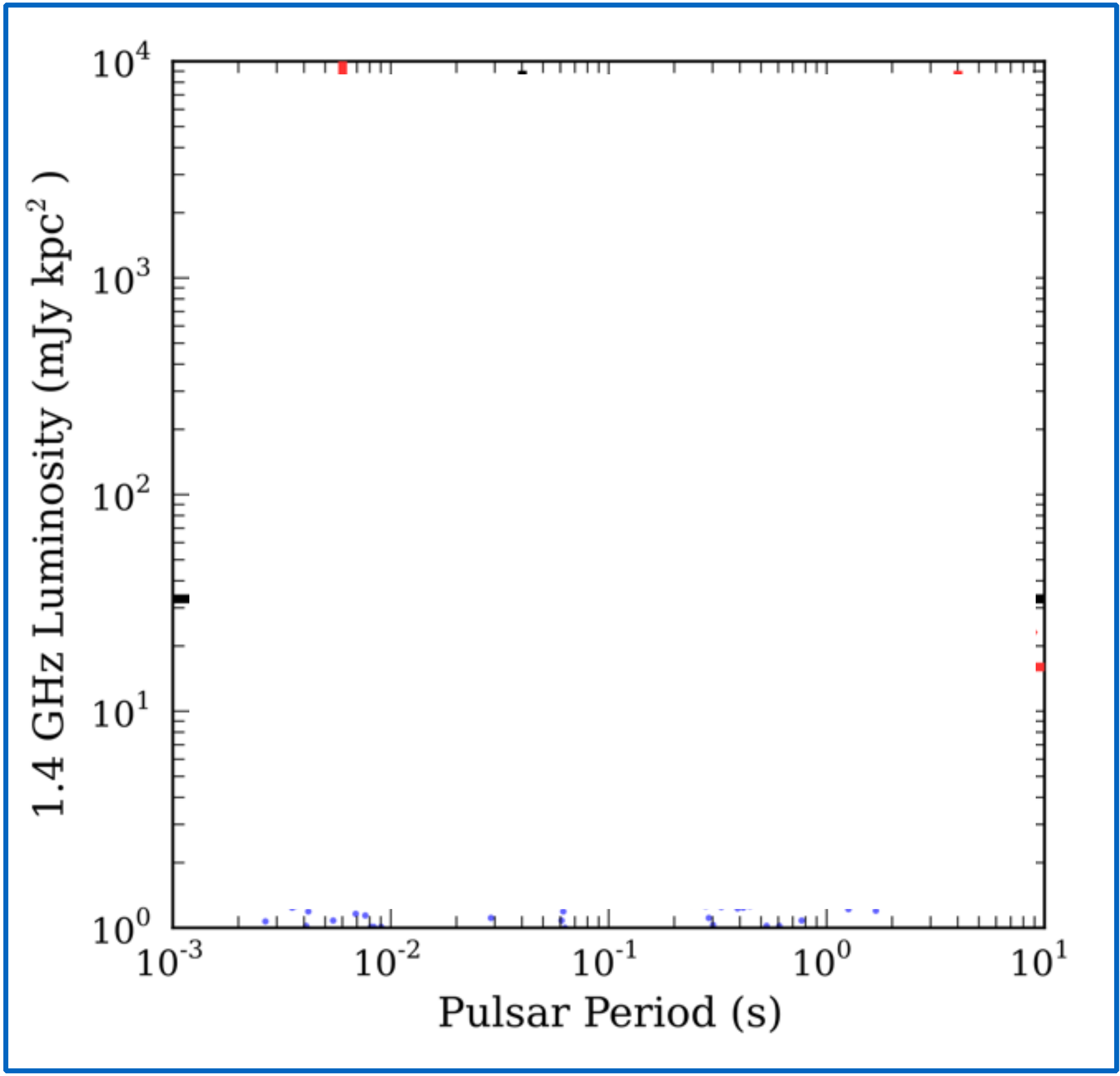
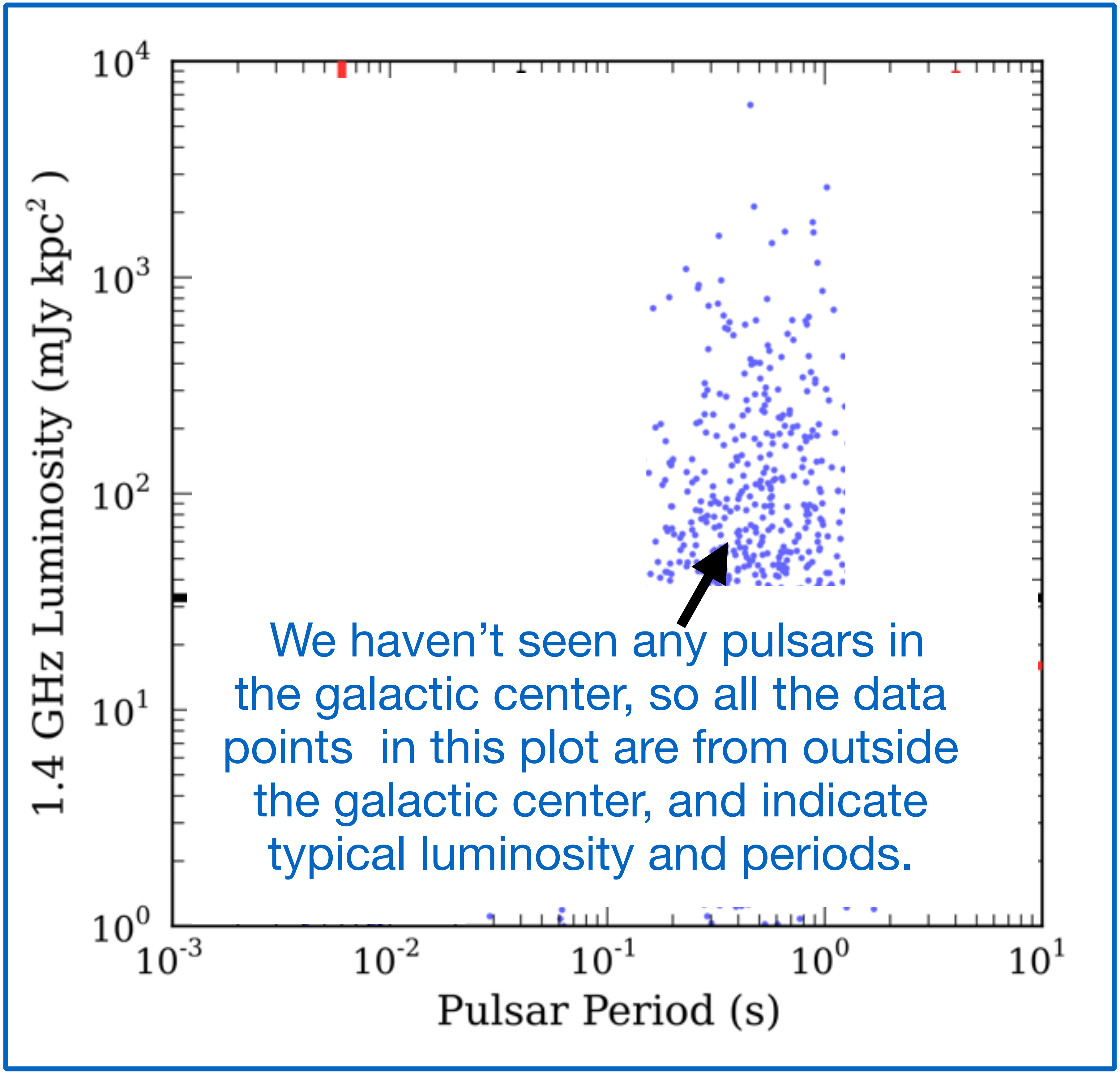
This creates two missing pulsar problems. Both young and old millisecond pulsars seem to be absent. There are 50-500 missing millisecond pulsars.

The missing pulsar problem

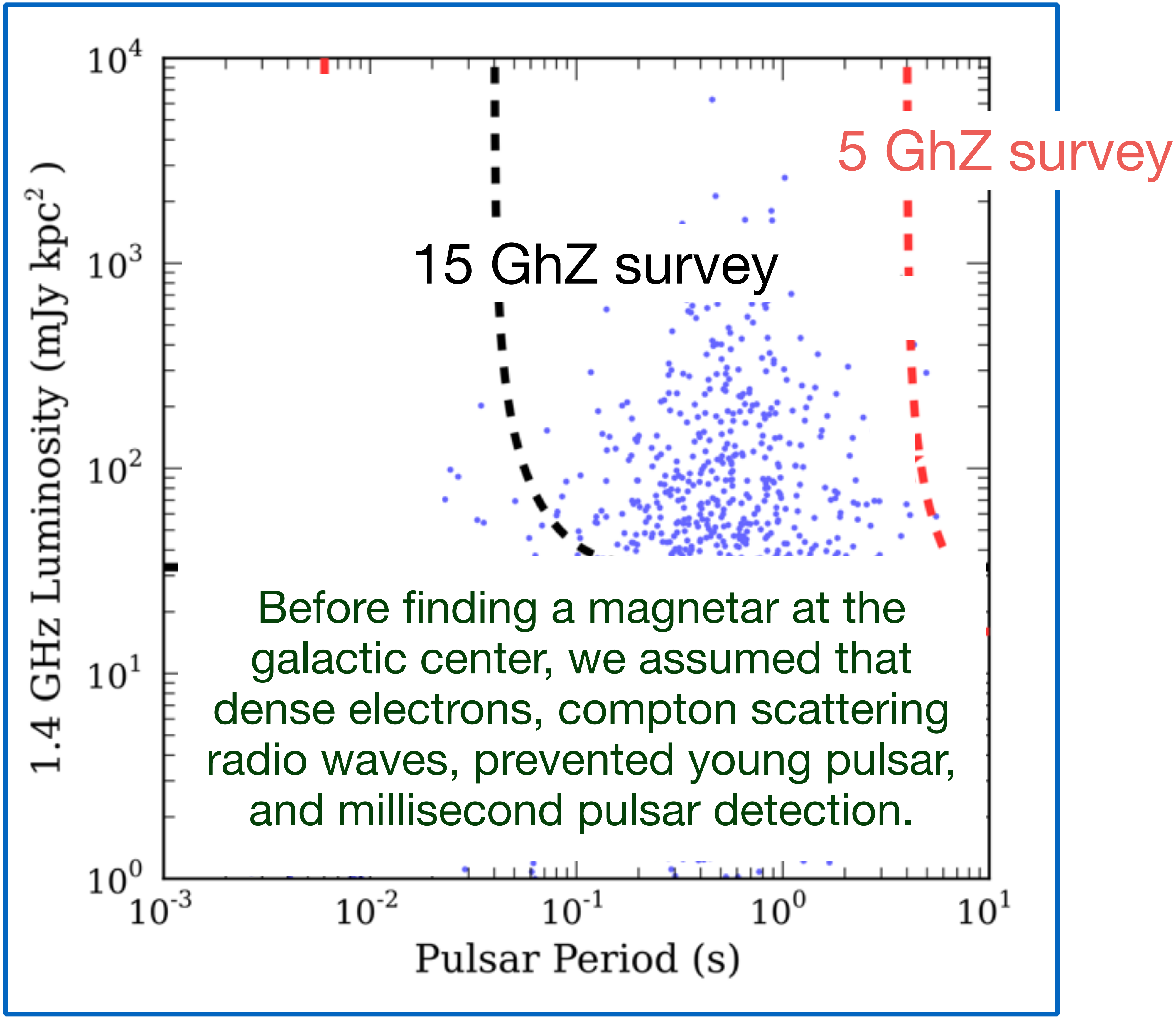


Dexter, O’Leary
1310.7022

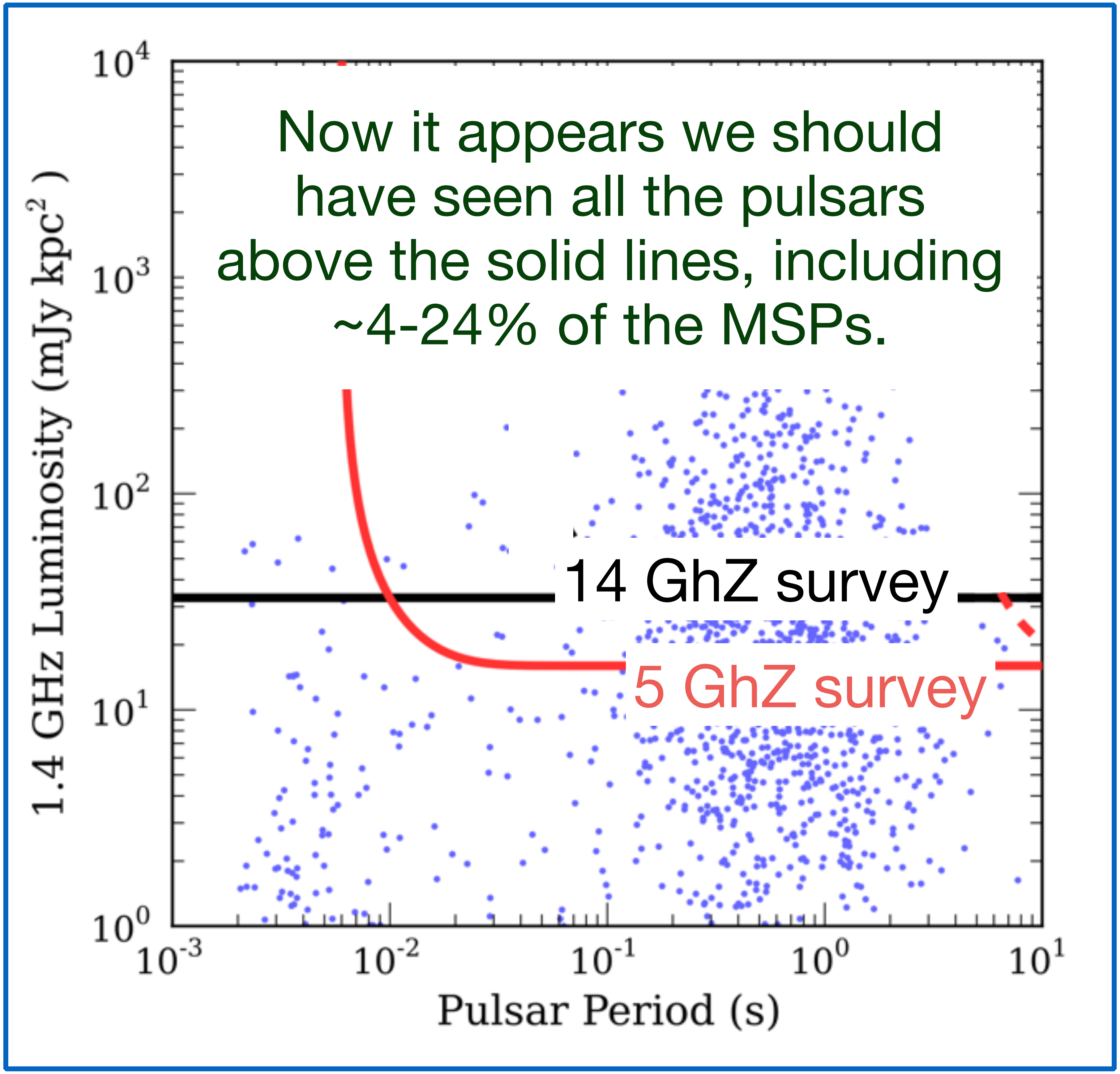


We haven’t seen any pulsars in the galactic center, so all the data points in this plot are from outside the galactic center, and indicate typical luminosity and periods.

Survey sensitivity before magnetar

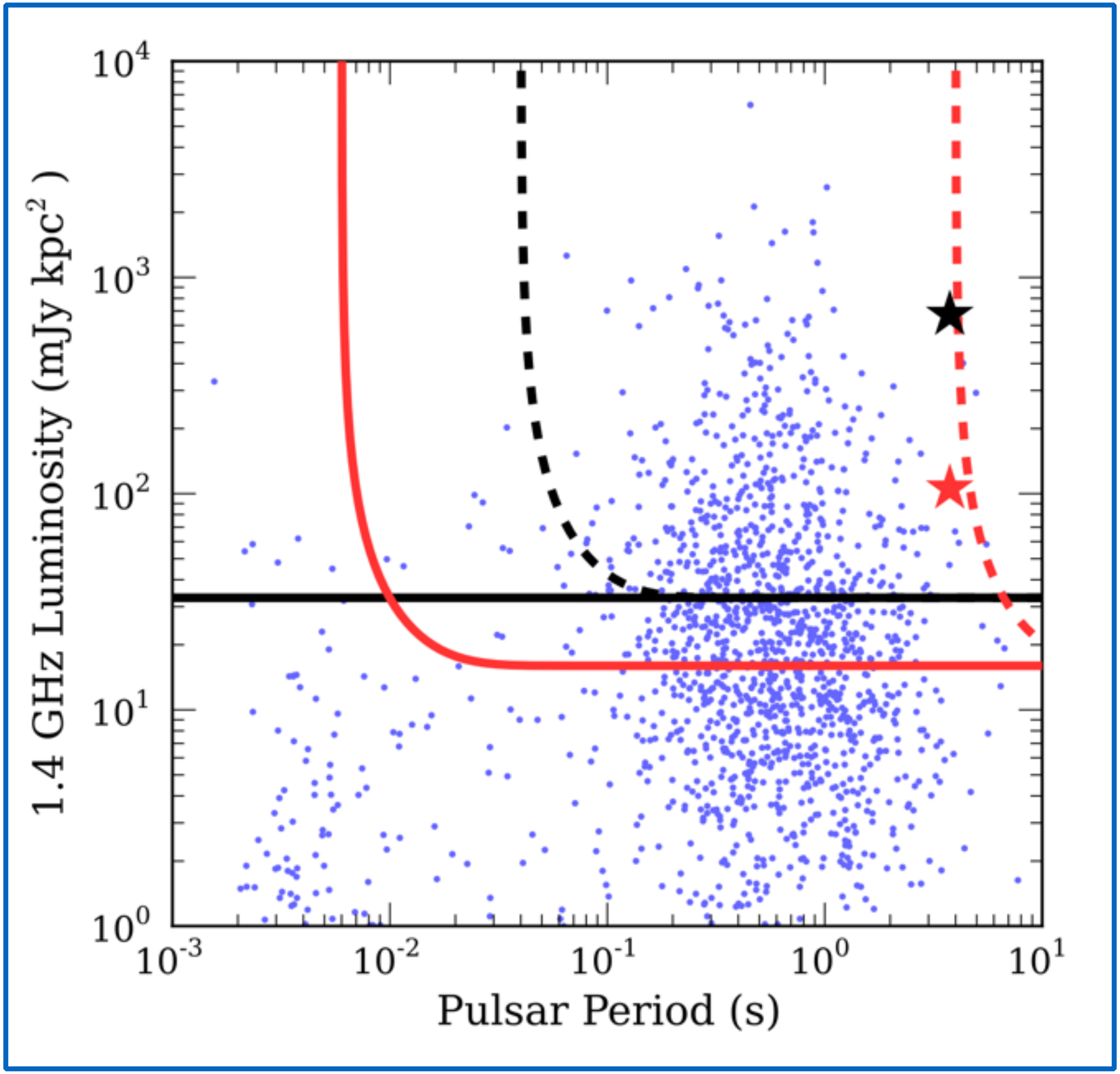


Before finding a magnetar at the galactic center, we assumed that dense electrons, compton scattering radio waves, prevented young pulsar, and millisecond pulsar detection.



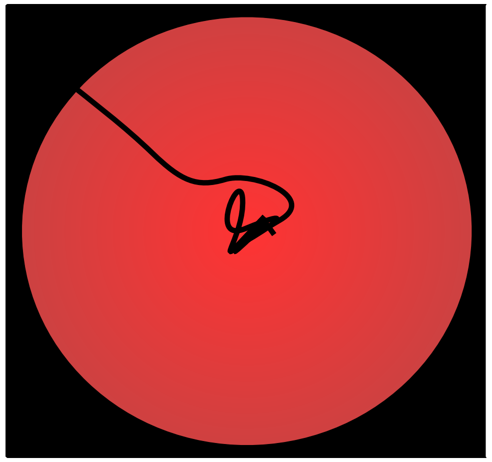
Now it appears we should have seen all the pulsars above the solid lines, including ~4-24% of the MSPs.

Where are the galactic center pulsars?

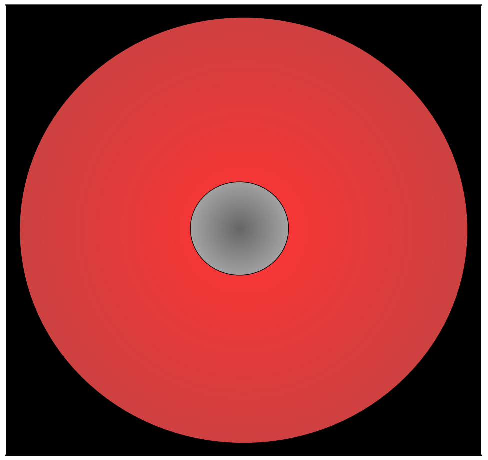


Asymmetric Dark Matter Imploding Pulsars

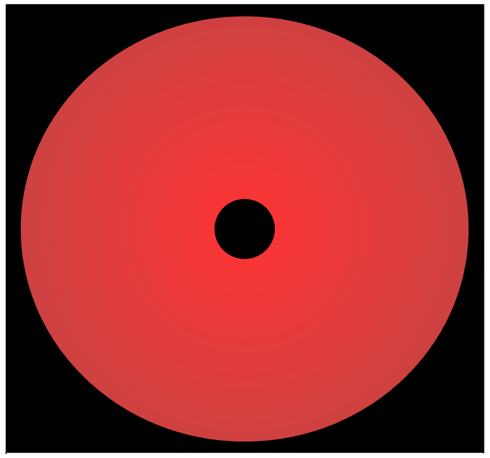
1. DM captured



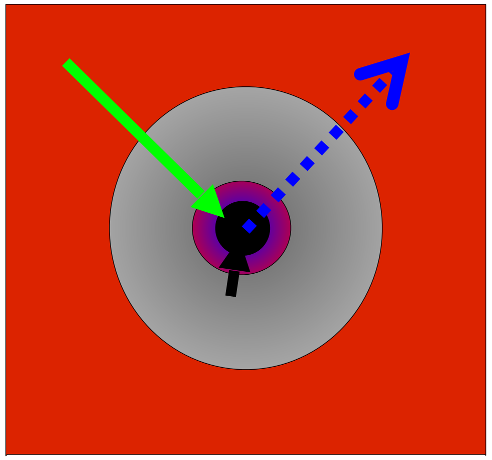
2. DM thermalizes



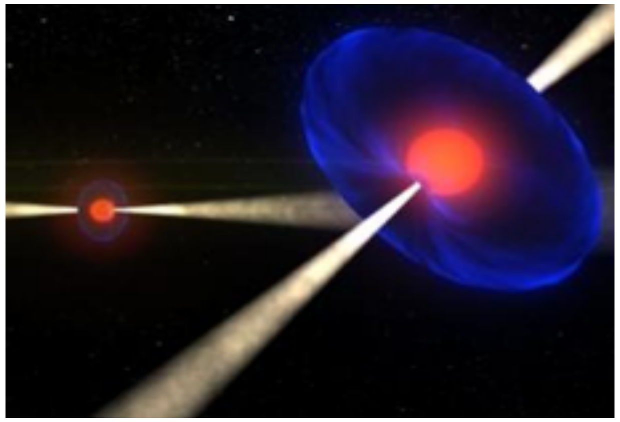
3. DM collapses



4. BH accretes, radiates

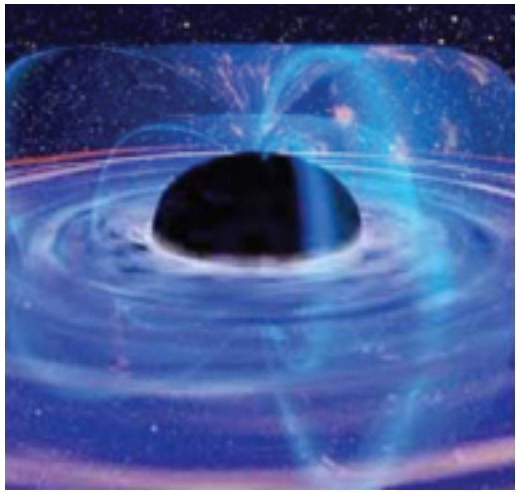


5a. if it shrinks, (Hawking)



no collapse

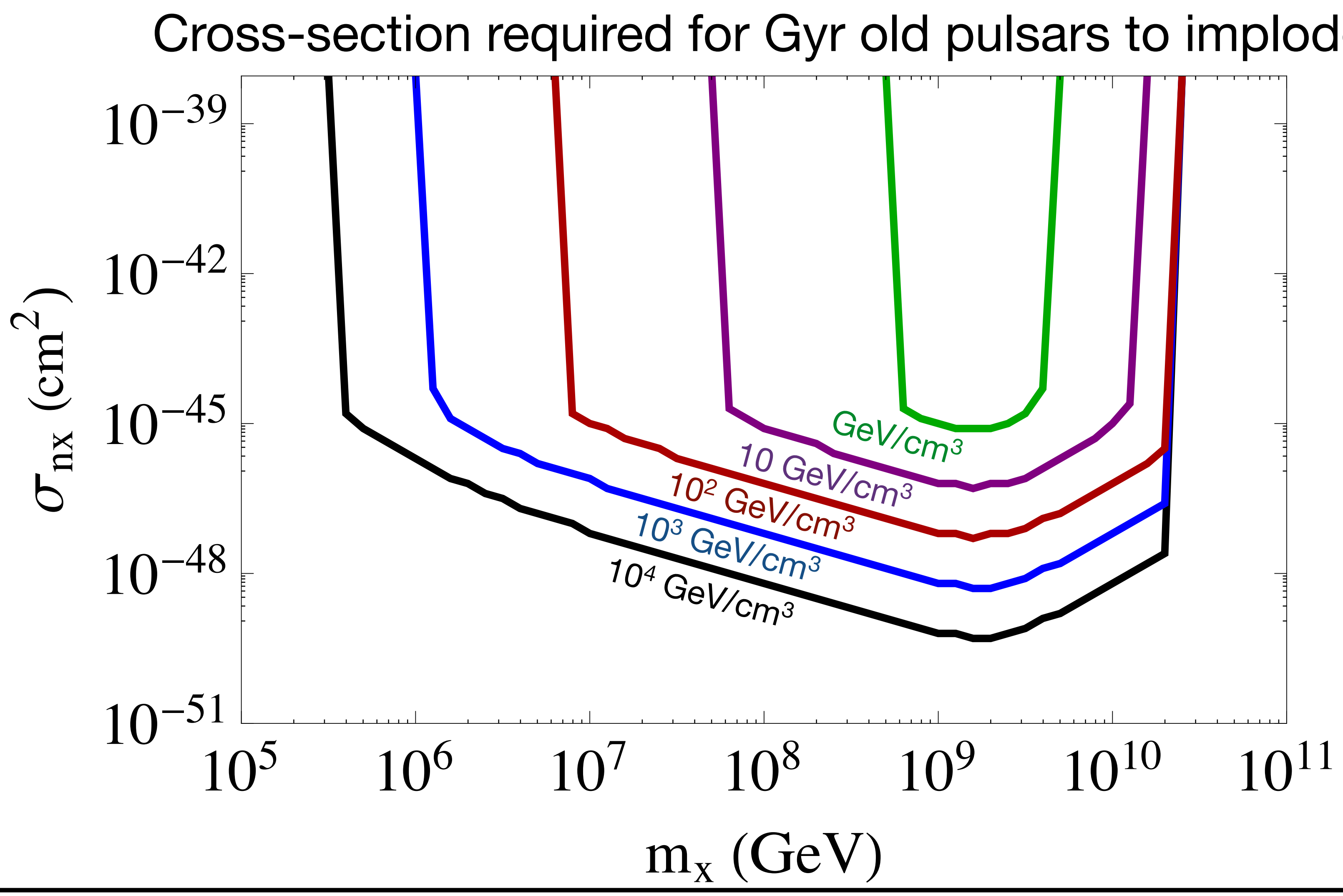
5b. if it grows rapidly,



collapse

See also work by Linden, Elahi, JB, Fuller, Ott, recently, and Nussinov, Goldman, Bertone, **Fairbairn**, Kouvaris, Tinyakov, McDermott, Yu, Zurek, Baldes, Bell, Petraki …

For scattering cross-sections exceeding 10^{-45} cm^2, dark matter saturates the neutron star's geometric cross-section (the total mass of captured DM remains constant).

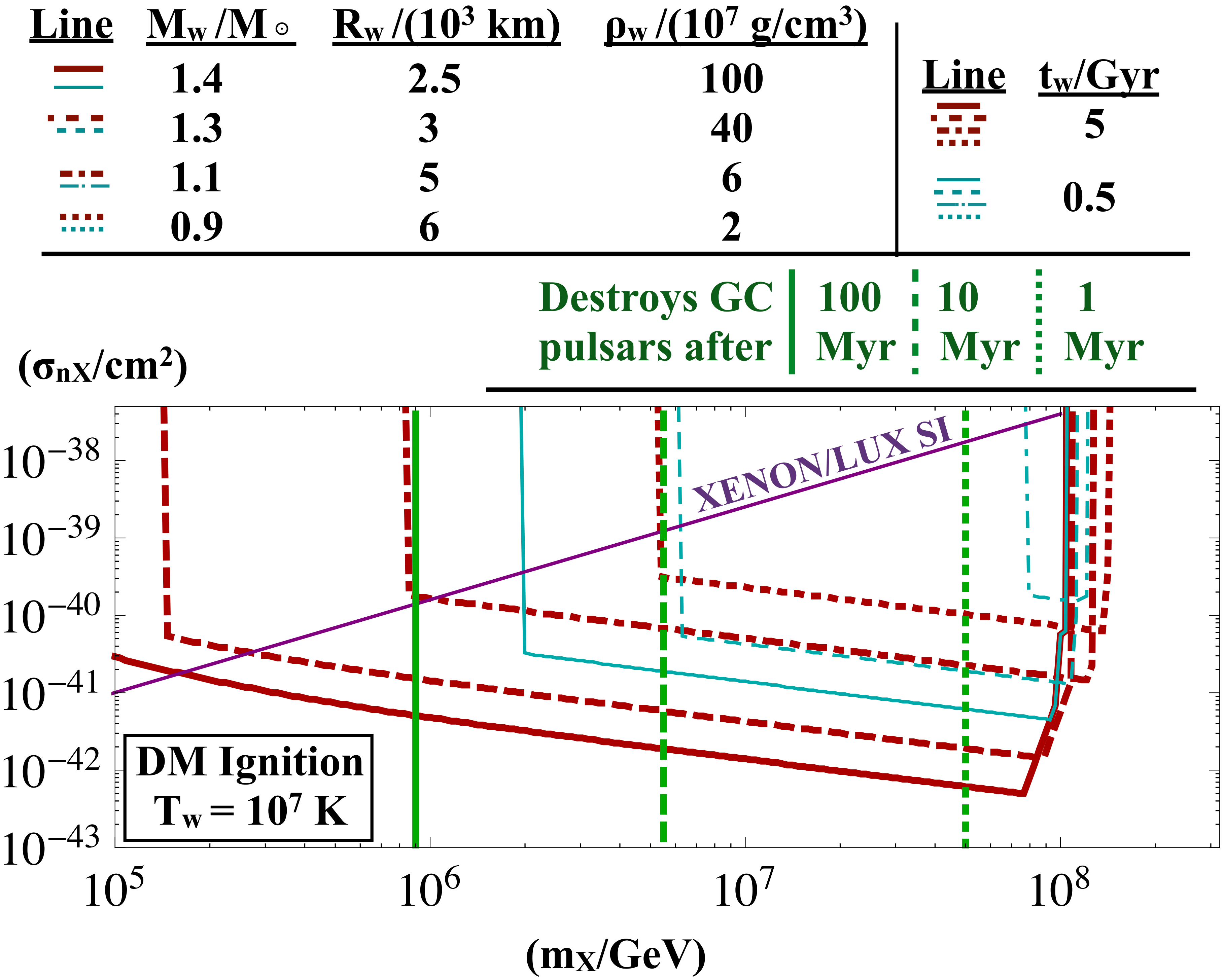


$$M_{crit}^{ferm} \sim M_{pl}^3/m_X^2$$

Critical number to form a black hole:

$$M_{crit}^{bos} \simeq \sqrt{\lambda} M_{pl}^3/m_X^2$$

PeV mass asymmetric dark matter can explain (or be constrained by) type Ia supernovae, missing pulsars, frbs.



Summary

- ★ 0.1-100 PeV mass asymmetric dark matter, either bosonic or fermionic, ignites type Ia supernovae and implodes old pulsars in dense DM baths.
- ★ Evidence does not yet rule out either phenomenon.
- ★ More swiftly exploding SNIa at the center of galaxies, and pulsar age curves tracking DM halo density at the galactic center are interesting signals to look for.

[A] Free-fall time.

$$t_{ff} \sim \sqrt{3\pi/(32G\rho_X)} \simeq 0.5 \text{ s } (\rho_{w7})^{-1/2} \left(\frac{r}{r_{th}}\right)^{3/2}$$

[B] DM self-scatter time.

$$t_{XX} \sim (n_X \sigma_{XX} v_X)^{-1} \simeq 10^{11} \text{ s } \left(\frac{m_X}{\text{PeV}}\right)^{3/2} (\rho_{w7})^{-1} \left(\frac{T_w}{10^5 \text{ K}}\right)^{-1/2} \left(\frac{\sigma_{XX}}{10^{-40} \text{ cm}^2}\right)^{-1} \left(\frac{r}{r_{th}}\right)^{7/2}$$

[C] DM-nucleon scatter time.

$$t_{nX} \sim (n_N \sigma_{aX} v_X)^{-1} \simeq 10^4 \text{ s } \left(\frac{\mathrm{m_X}}{\text{PeV}}\right)^{1/2} (\rho_{\mathrm{w7}})^{-1} \left(\frac{\mathrm{T_w}}{10^5 \text{ K}}\right)^{-1/2} \left(\frac{\sigma_{\mathrm{nX}}}{10^{-40} \text{ cm}^2}\right)^{-1} \left(\frac{\mathrm{r}}{\mathrm{r_{th}}}\right)^{1/2}$$

Once [A] > [B], thermalized collapse.

[A] Heat imparted by DM to WD during thermalized collapse.

$$\dot{Q}_{he} = N_{sg}\epsilon/t_{sta} \simeq 10^{28}\ \mathrm{GeV/s}\left(\frac{m_X}{\mathrm{PeV}}\right)^{-23/8}(\rho_{w7})^{1/8}\left(\frac{T_w}{10^5\ \mathrm{K}}\right)^{21/8}\left(\frac{\sigma_{nX}}{10^{-40}\ \mathrm{cm}^2}\right)\left(\frac{\sigma_{XX}}{10^{-40}\ \mathrm{cm}^2}\right)^{-3/4}$$

[B] Diffusion rate in the WD.

$$\dot{Q}_{dif} \simeq 4\pi^2 r_{he} T_{he}^3 (T_{he} - T_w)/15\kappa_c\rho_w$$

If [A] > [B], ignition!

The full capture equation.

$$C_X = \frac{\sqrt{24\pi} G \rho_X M_w R_w}{m_X \bar{v}} \mathrm{Min}\left(1, \frac{\sigma_{aX}}{\sigma_{sat}}\right) \left[1 - \frac{1 - e^{-B^2}}{B^2}\right]$$

$$B^2 = \frac{6 m_X v_{esc}^2}{m_N \bar{v}^2 (m_X/m_N - 1)^2}$$

$$\sigma_{sat} \sim R_w^2 / N_N$$