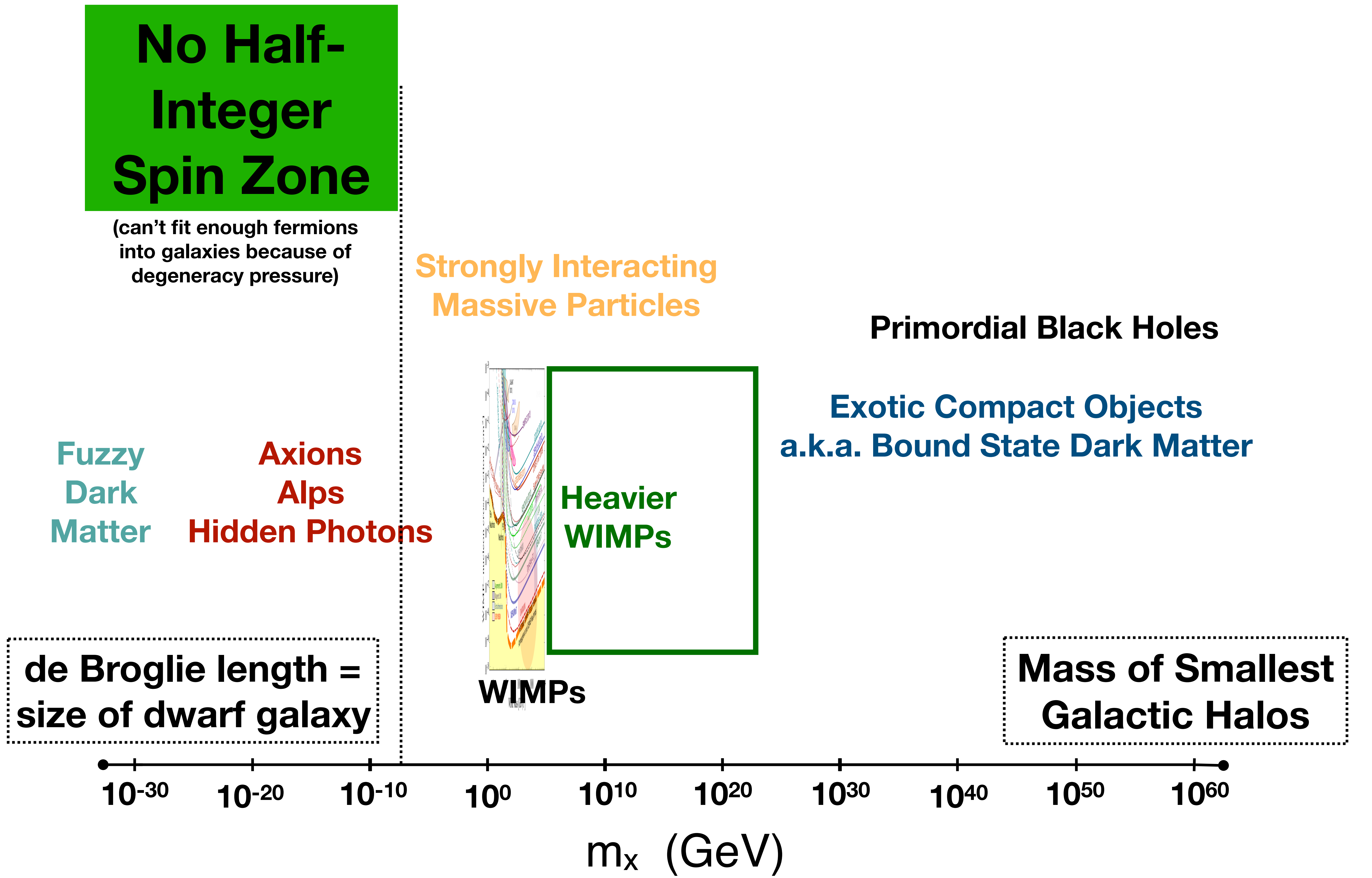
Explosive Dark Matter Production of Heavy Elements in Compact Stars

Joseph Bramante
Queen's University
McDonald Institute
Perimeter Institute

Solvay Institute Dark Side of Black Holes Workshop

Dark Matter Models (We Know Very Little)



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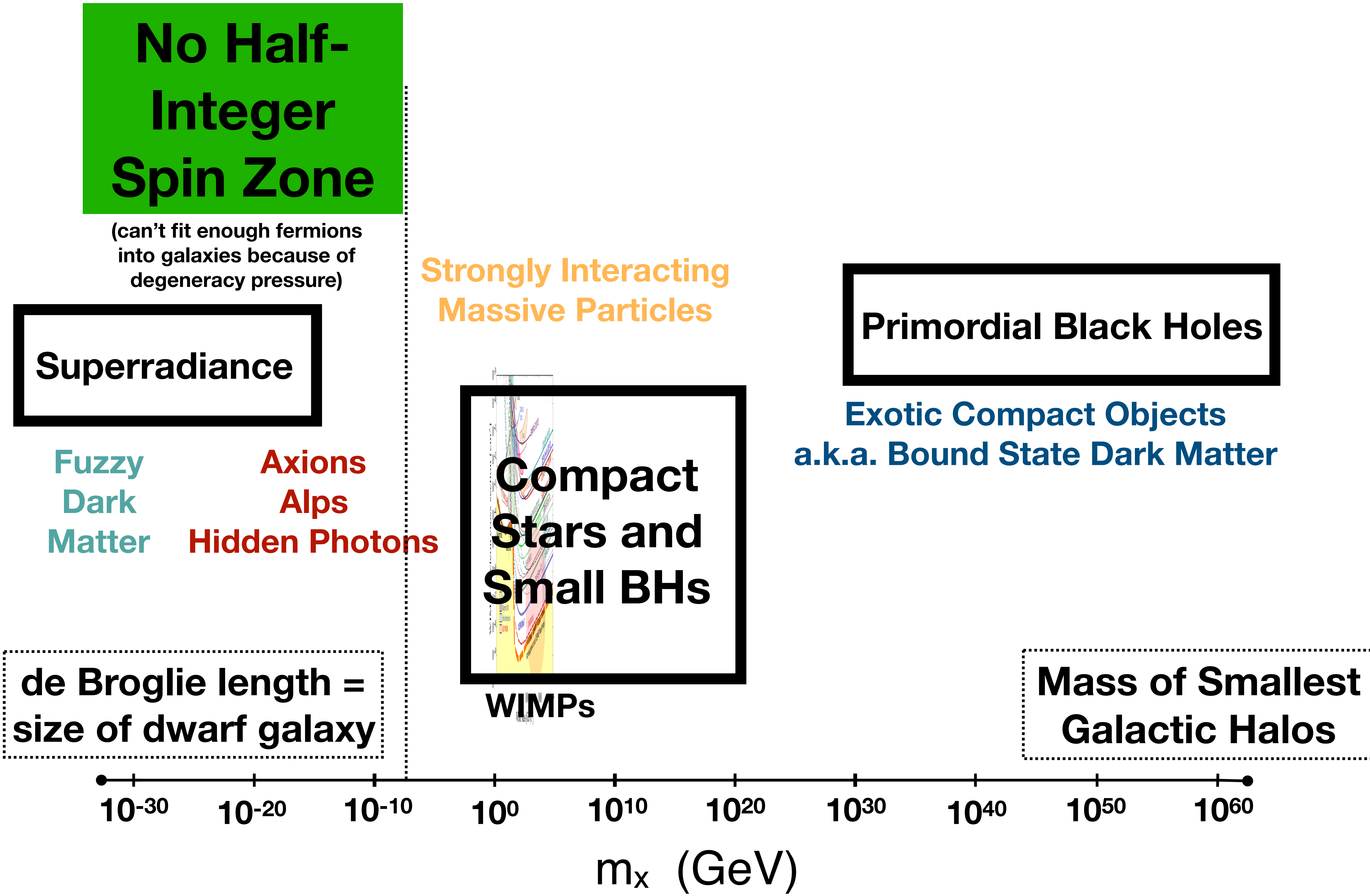
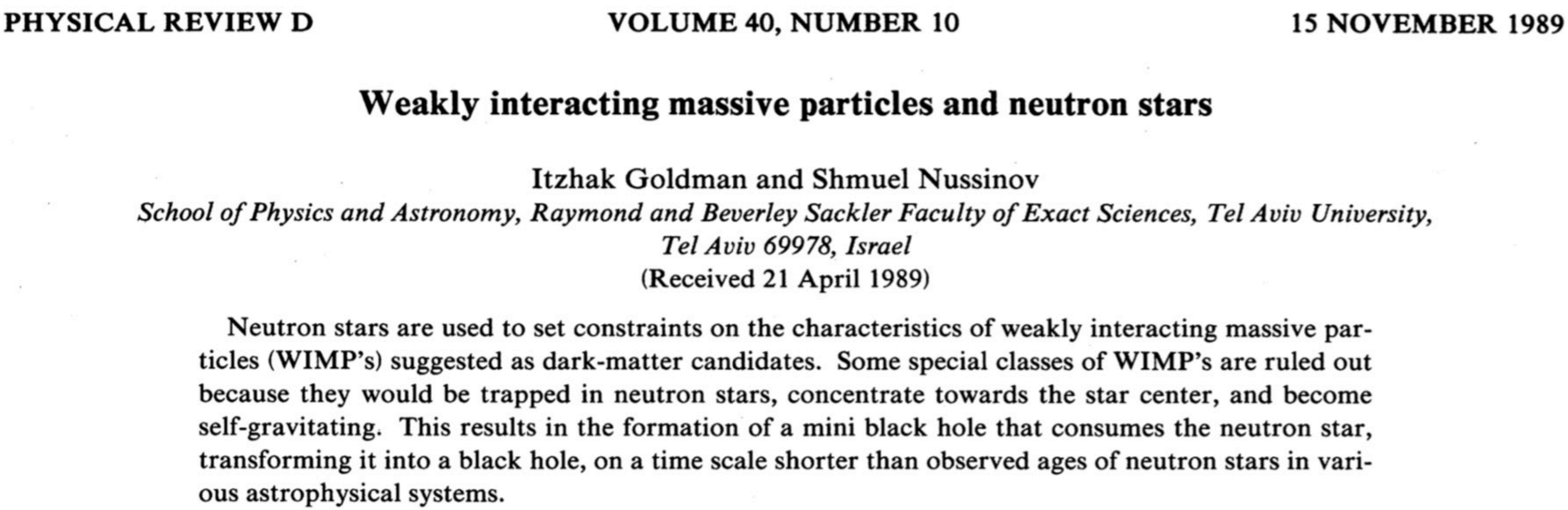


1989 ⟟ Goldman and Nussinov

Dark Matter forming Black Holes In compact stars

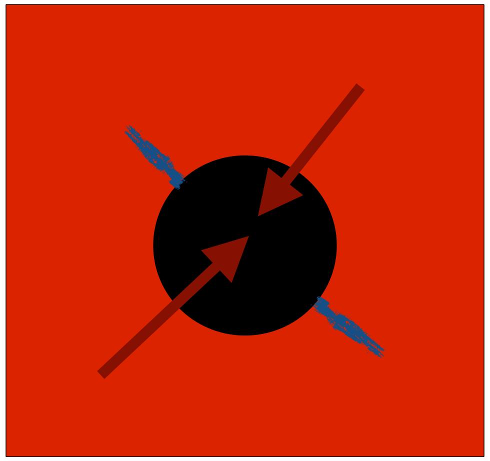


PHYSICAL REVIEW D VOLUME 40, NUMBER 10 15 NOVEMBER 1989

Weakly interacting massive particles and neutron stars

Itzhak Goldman and Shmuel Nussinov
School of Physics and Astronomy, Raymond and Beverley Sackler Faculty of Exact Sciences, Tel Aviv University, Tel Aviv 69978, Israel
(Received 21 April 1989)

Neutron stars are used to set constraints on the characteristics of weakly interacting massive particles (WIMP's) suggested as dark-matter candidates. Some special classes of WIMP's are ruled out because they would be trapped in neutron stars, concentrate towards the star center, and become self-gravitating. This results in the formation of a mini black hole that consumes the neutron star, transforming it into a black hole, on a time scale shorter than observed ages of neutron stars in various astrophysical systems.



1989 Goldman and Nussinov

Dark Matter forming Black Holes In compact stars

2010 Kouvaris, Tinyakov

2011 Kouvaris, Tinyakov — de Lavallaz, Fairbairn

McDermott, Yu, Zurek — Kouvaris

2012 Kouvaris, Tinyakov

Guver Erkoca, Reno, Sarcevic

2013 JB, Fukushima, Kumar — Bell, Melatos, Petraki — Bertoni, Nelson, Reddy

Kouvaris, Tinyakov — JB, Fukushima, Kumar, Stopnitzky

2014 JB, Linden — Fuller, Ott

Autzen, Kouvaris — Zheng, Sun, Chen

2015 JB, Elahi

JB

2016 JB, Linden

2017 JB, Unwin — JB, Delgado, Martin

JB, Linden, Tsai

2018 Kouvaris, Tinyakov, Tytgat — Garani, Genolini, Hambye

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Dark Matter forming Black Holes In Compact Stars

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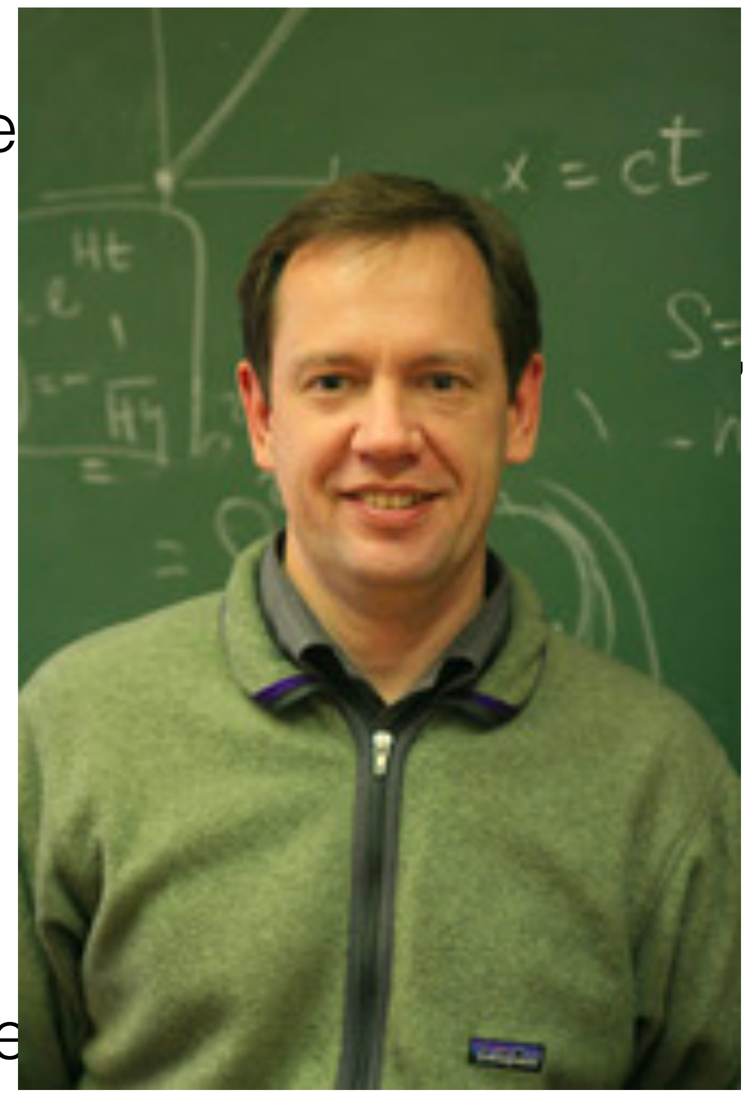

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Kouvaris, **Tinyakov**

, Sto

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JB

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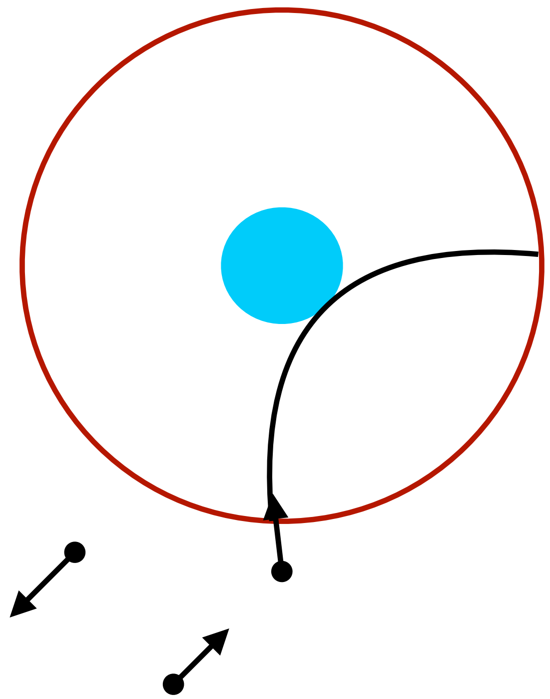
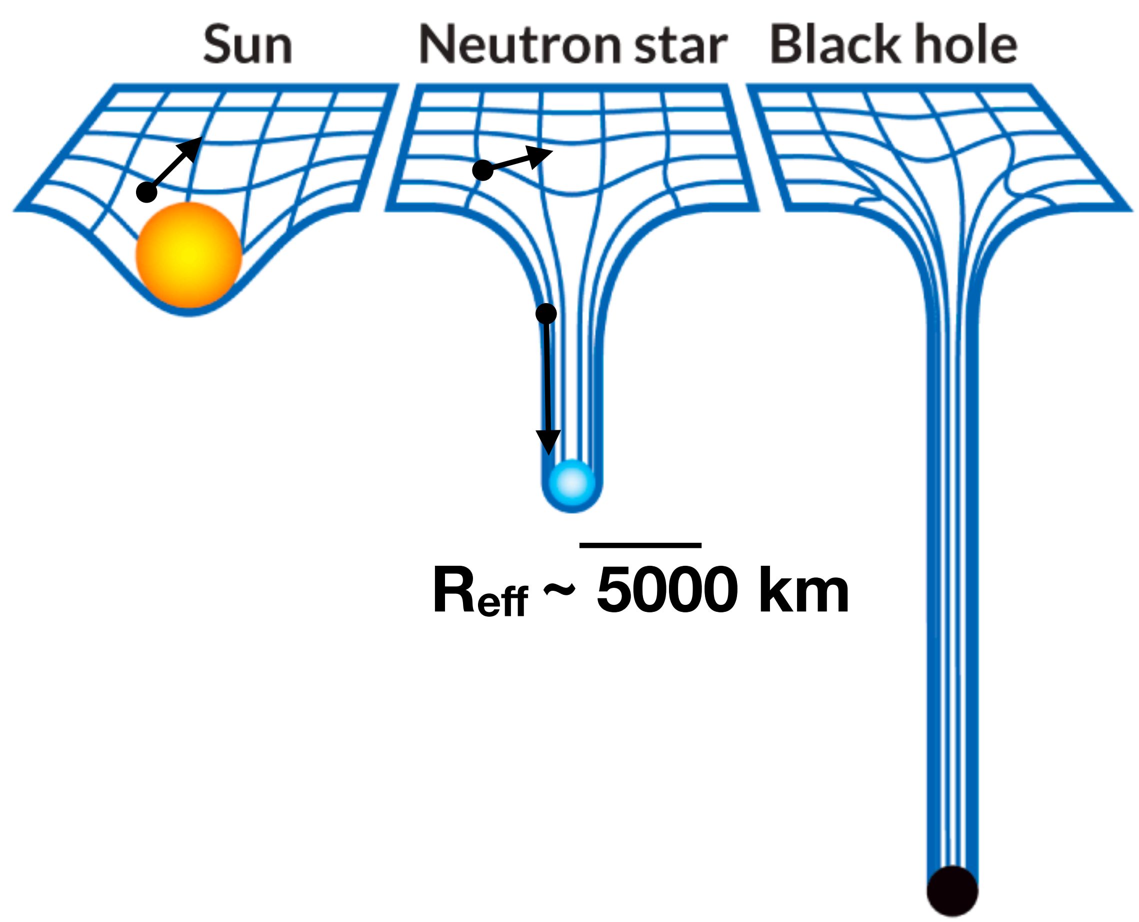
Compact Stars Collecting Dark Matter

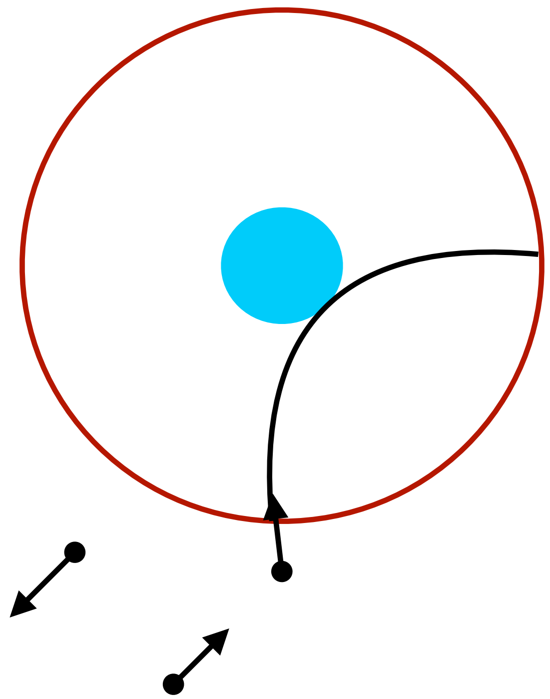


Collect dark matter over a radius

$$R_{eff} = R_s \frac{v_{esc}}{v_x}$$



Compact Stars Collecting Dark Matter



Collect dark matter over a radius

$$R_{eff} = R_s \frac{v_{esc}}{v_x}$$

Limit: saturation cross-section, total flux

$$\sigma_{sat} \sim \frac{\pi R_s^2}{N_n}$$

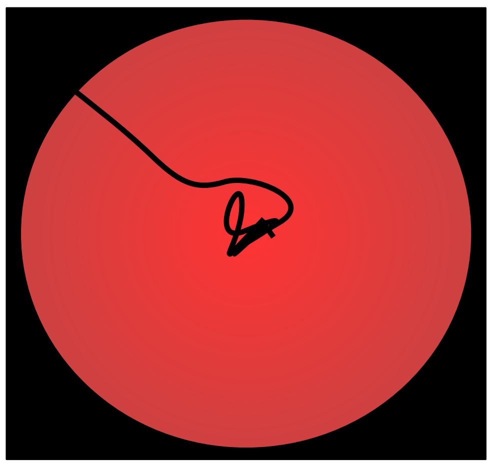
Total capture = (flux)(effective area)(fraction captured)

Neutron Star: $\sim 10^{-15} M_\odot/\mathrm{Gyr}$

White Dwarf: $\sim 10^{-12} M_\odot/\mathrm{Gyr}$

Dark Matter Imploding Neutron Stars

1. DM captured



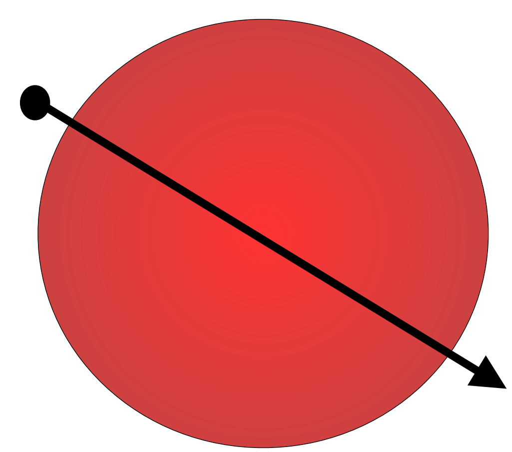
capture rate $C_X \propto \frac{\rho_x \sigma_{nx}}{v_x}$

= DM density × DM-nucleon cross section / DM velocity

→ ~10^{-14} solar masses of dark matter in 10 billion years (near solar position)

v_x velocity
ρ_x density
in MW halo

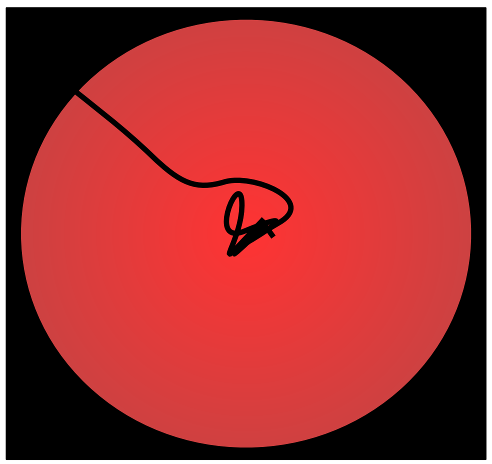
DM pulled in by neutron star grav potential



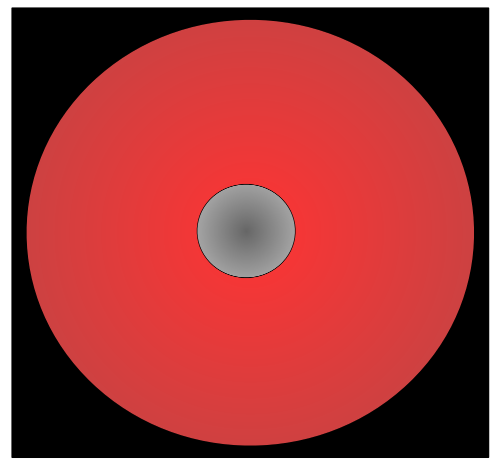
$\sigma_{\rm nx}$ **determines whether DM scatters, becomes grav bound**

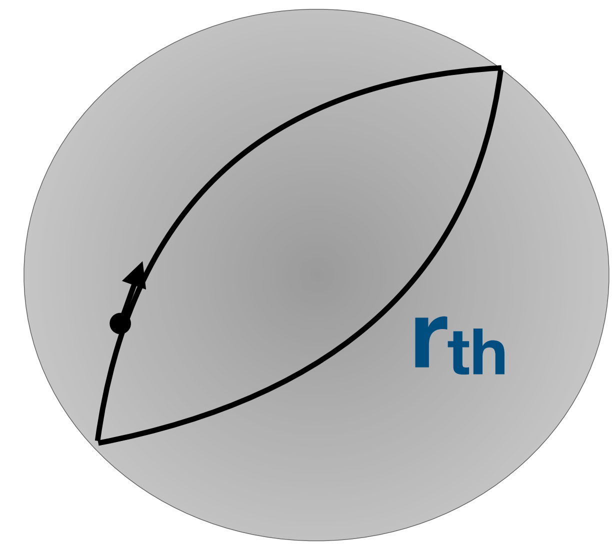
Dark Matter Imploding Neutron Stars

1. DM captured



2. DM thermalizes





Harmonic oscillator potential

$$k_B T \sim G \rho_{wd} m_x r_{th}^2$$

Thermalization radius

$$r_{th} \sim 1 \text{ millimeter} \sqrt{\frac{\text{PeV}}{m_x}} \sqrt{\frac{T_{ns}}{10^5 \text{ K}}}$$

Dark Matter Imploding Neutron Stars

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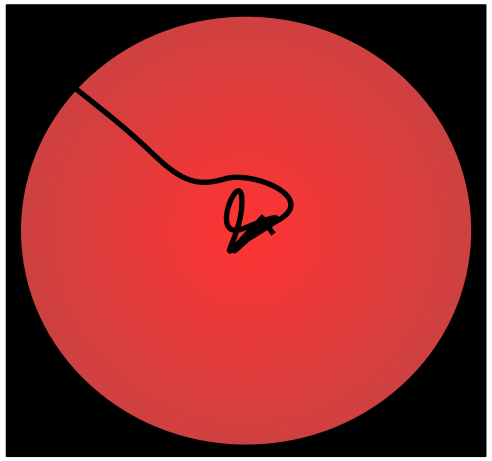

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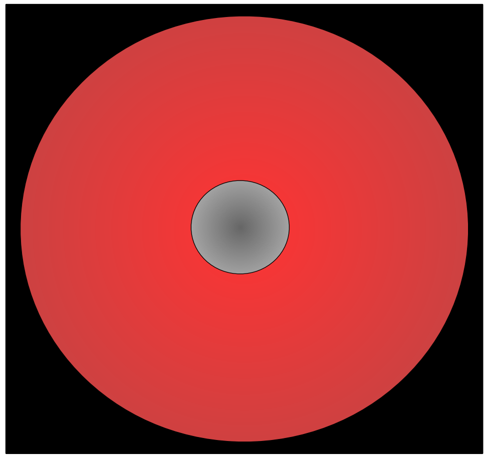
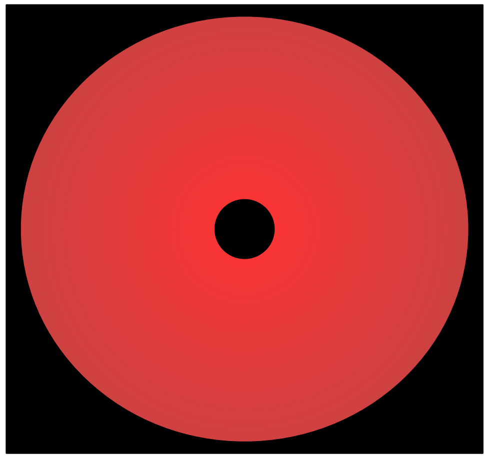


3. DM collapses



DM will collapse to a black hole if it

1. Self-gravitates $\rho_{DM} > \rho_{ns}$

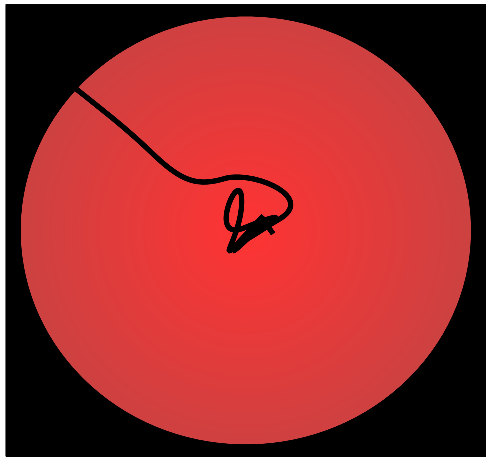
2. Exceeds its own degeneracy pressure

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

~10^{-14} solar masses for PeV mass DM

Dark Matter Imploding Neutron Stars

1. DM captured



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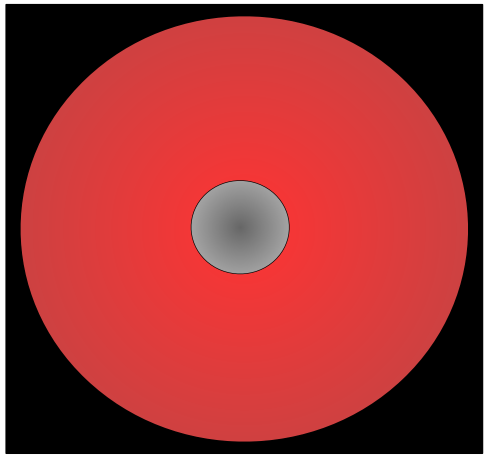

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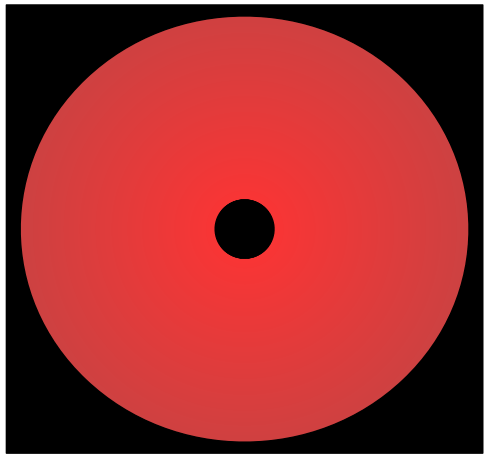
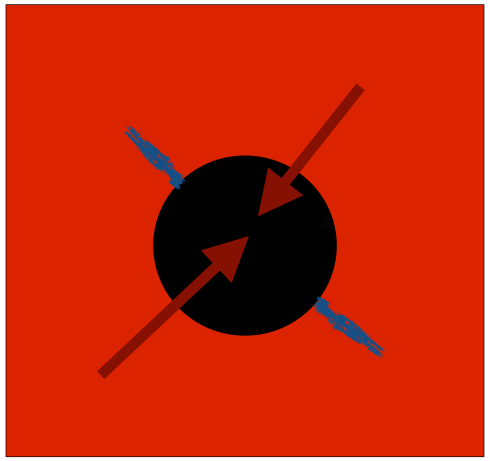


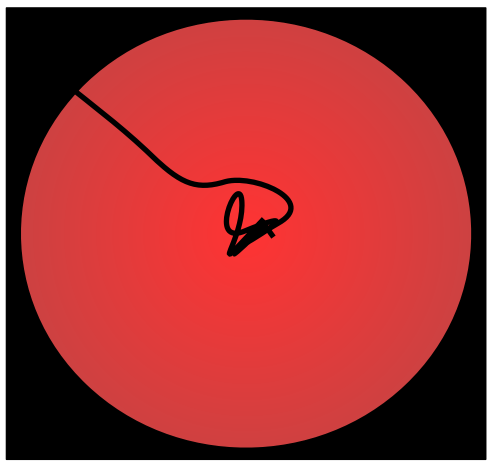
4. BH consumes neutron star



$$\frac{dM_{bh}}{dt} \approx \frac{4\pi\rho_{ns}(GM_{bh})^2}{v_s^3} - \frac{1}{15360\pi(GM_{bh})^2}$$

Dark Matter Imploding Neutron Stars

1. DM captured



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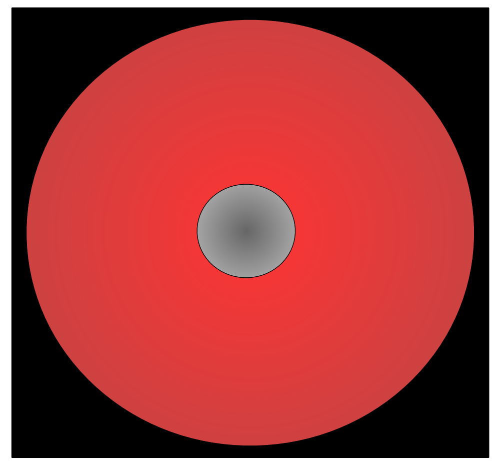

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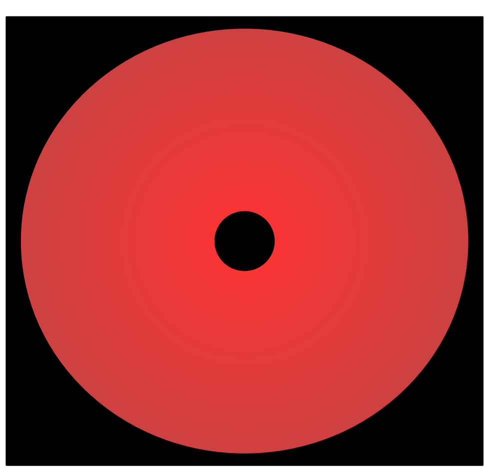

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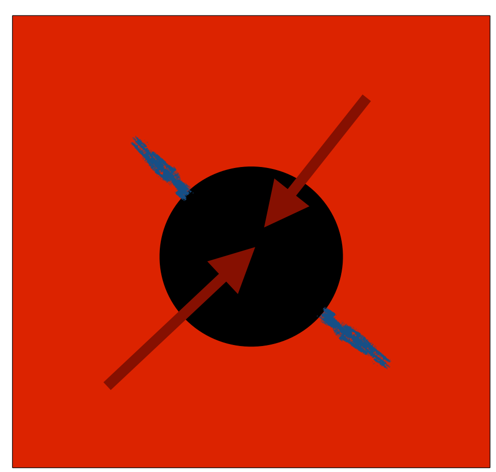
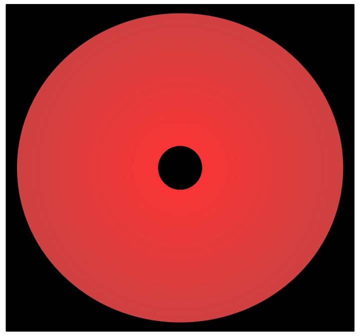


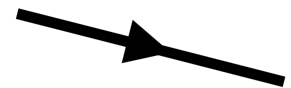
5. Form solar mass BH

$$\frac{dM_{bh}}{dt} \approx \frac{4\pi\rho_{ns}(GM_{bh})^2}{v_s^3} - \frac{1}{15360\pi(GM_{bh})^2}$$



Dark matter that implodes neutron stars

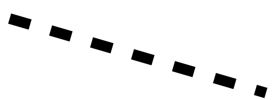
X ~GeV mass, asymmetric dark fermions — degeneracy pressure stabilizes up to a solar mass of dark matter.

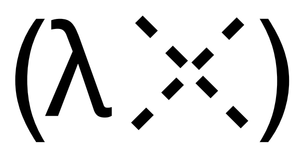


$\underline{m_X}$

✓ **KeV-PeV**

Bosonic dark matter without repulsive self interactions — requires very small effective quartic ($\lambda < 10^{-15}$).





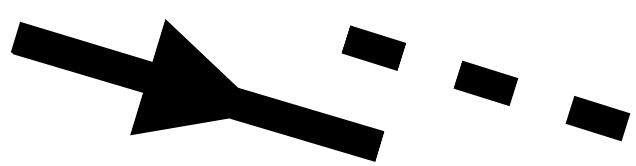
Bosonic DM Constraints
JB, Kumar, et al. 2013

✓ **PeV-EeV**

Heavy dark matter, fermionic or bosonic — fewer particles required for collapse.

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

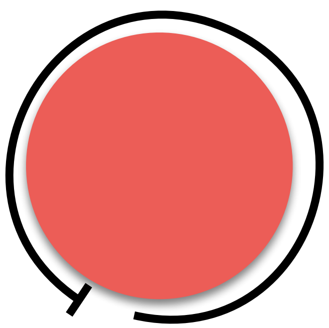
$$M_{crit}^{bos} \simeq \sqrt{\lambda} M_{pl}^3/m_X^2$$



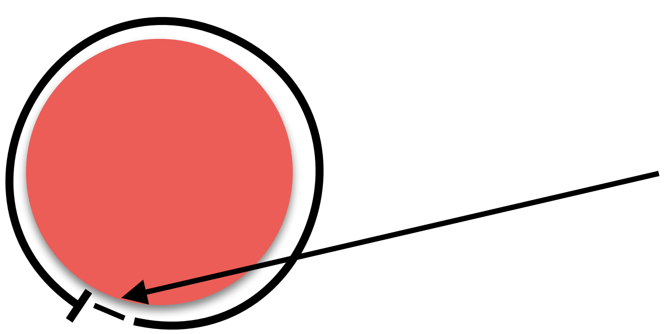
BH for~10^{-14} solar masses

Pulsars

Estimate pulsar age measuring pulse period (P)
and slowdown per pulse (Ṗ)



$$P =$$



$$\dot{P} =$$

Pulsars

Estimate pulsar age measuring pulse period (P)
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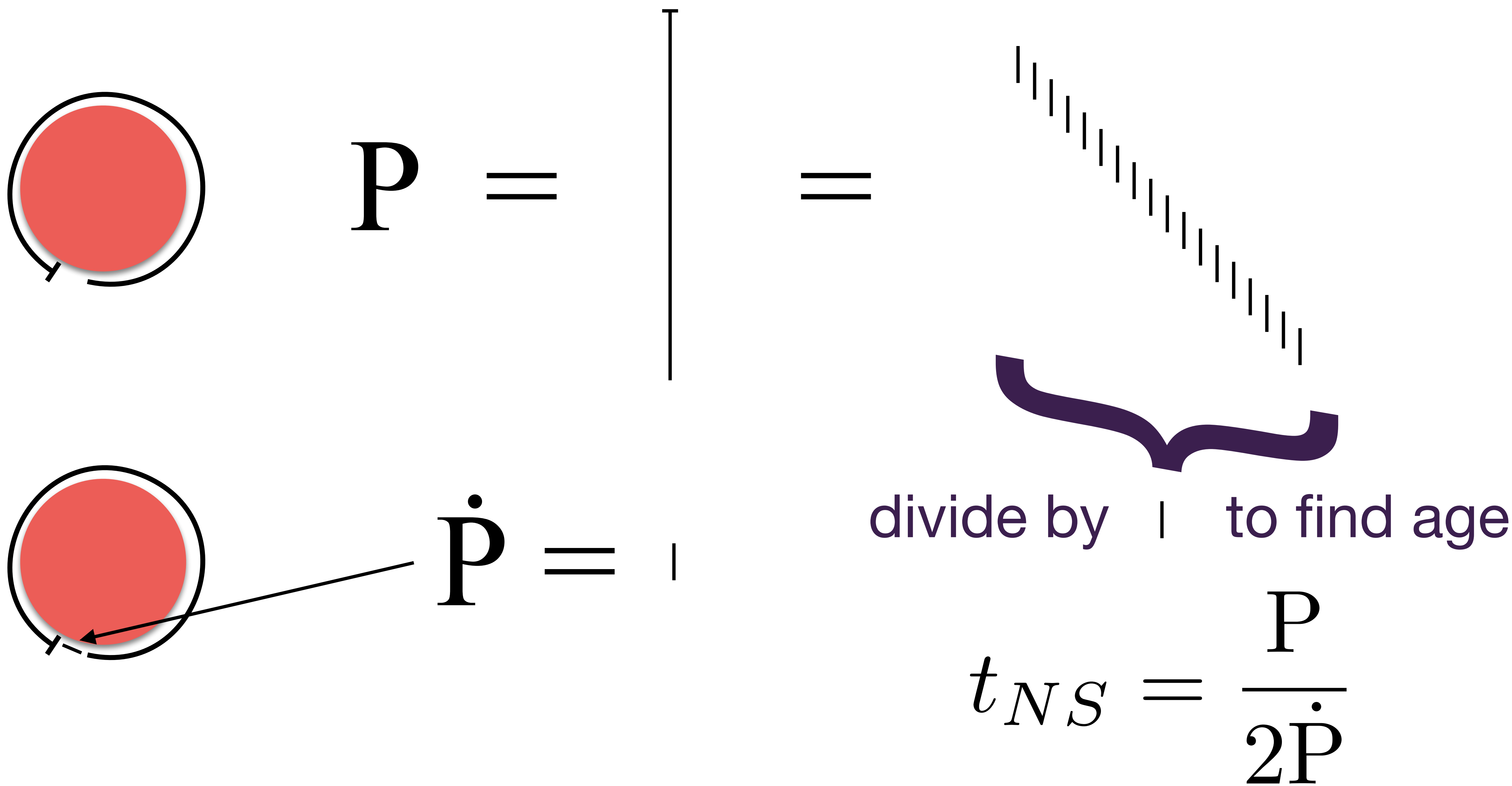
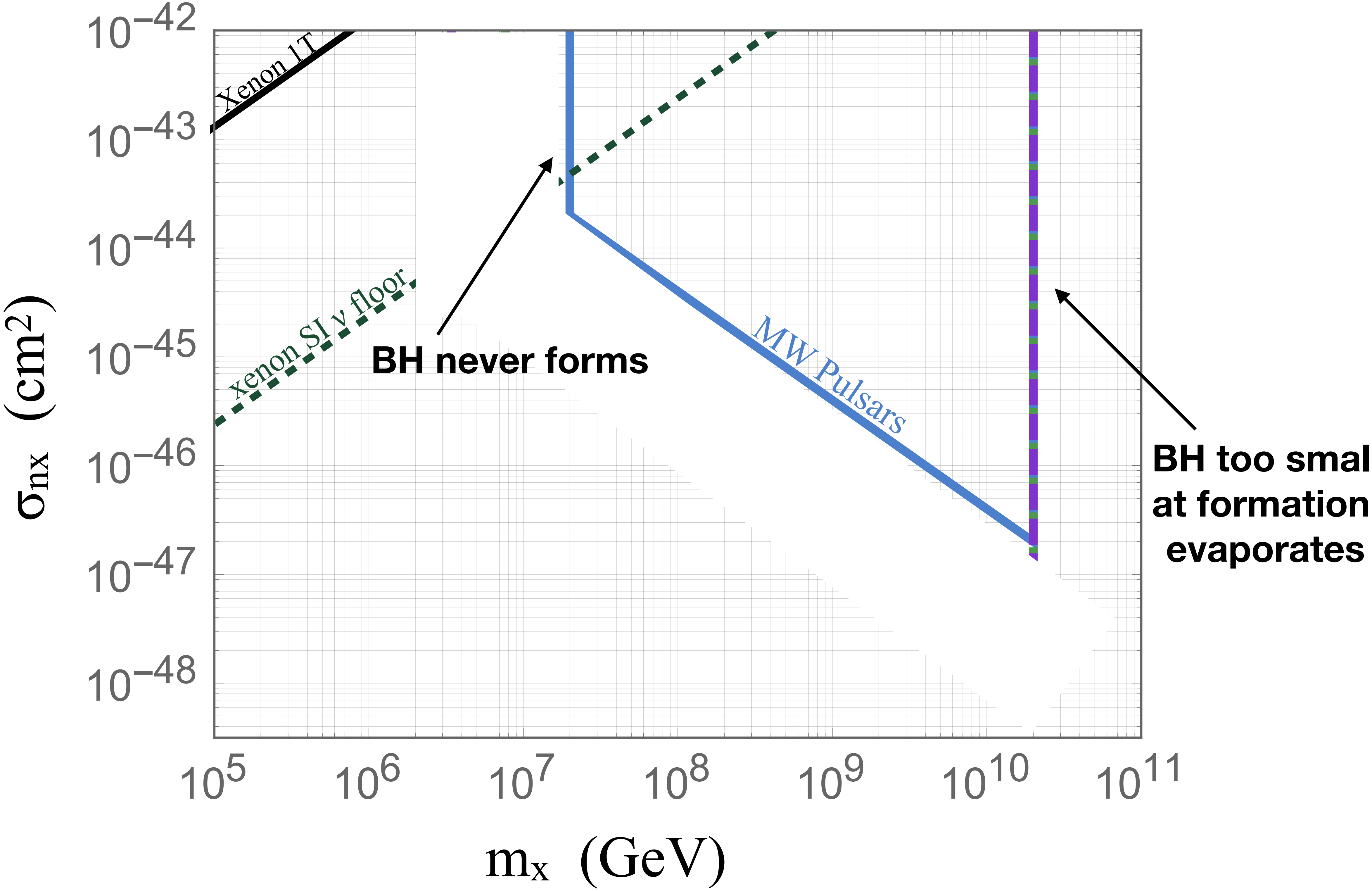
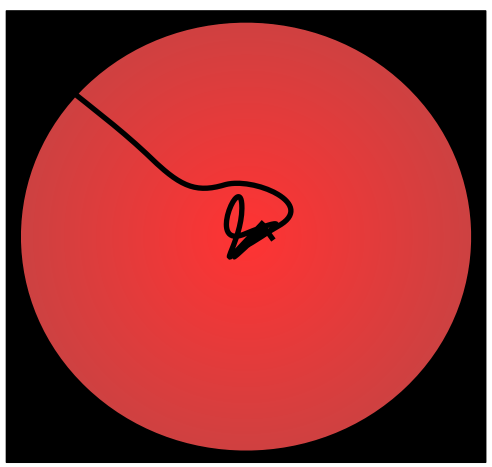


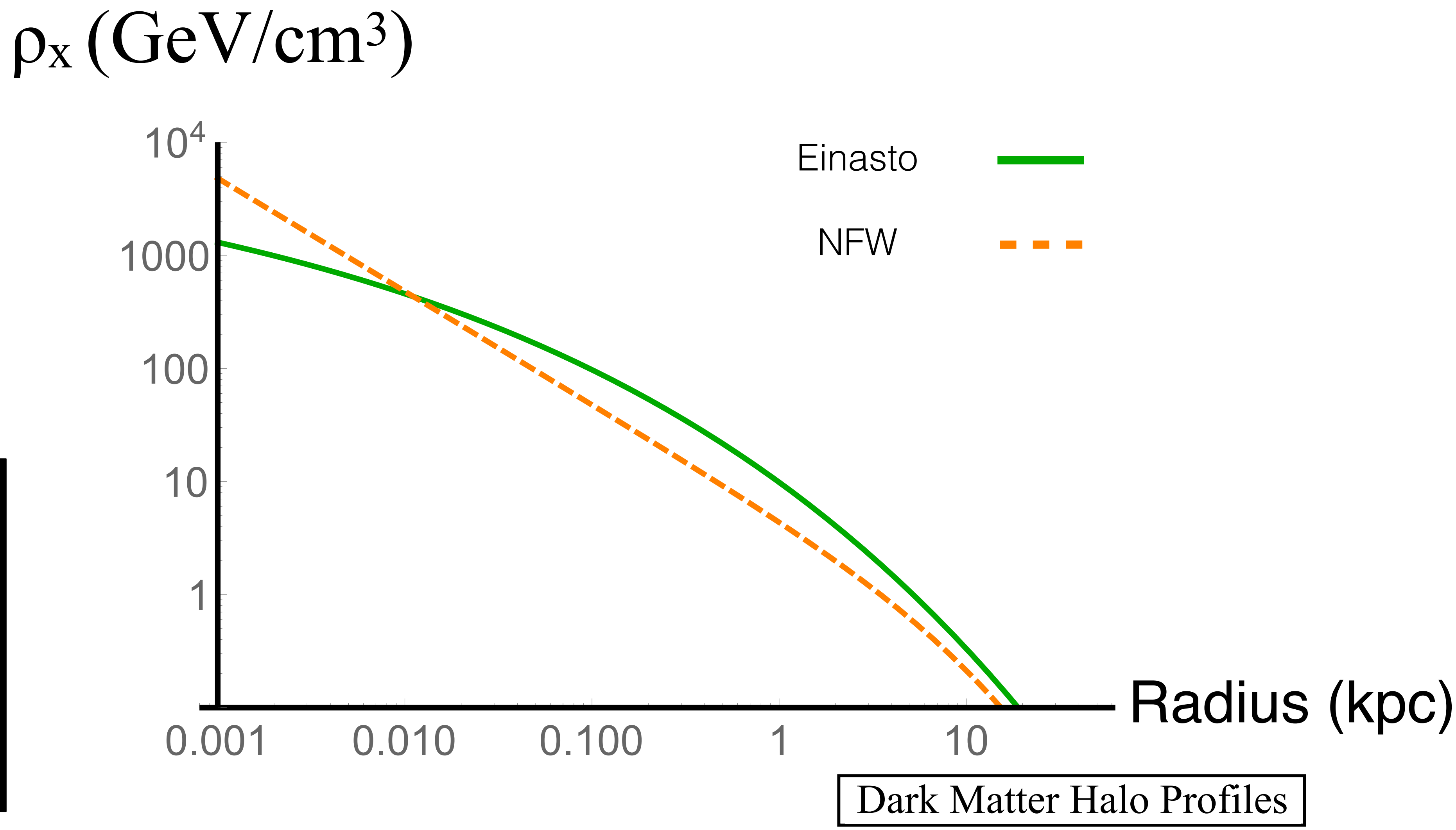
Using an old pulsar in the Milky Way the best sensitivity so far



J1738+0333, t_{NS}~5 Gyr, binary WD companion with age of− 5 Gyr JB, Elahi 2015

Dark Matter Capture in MW



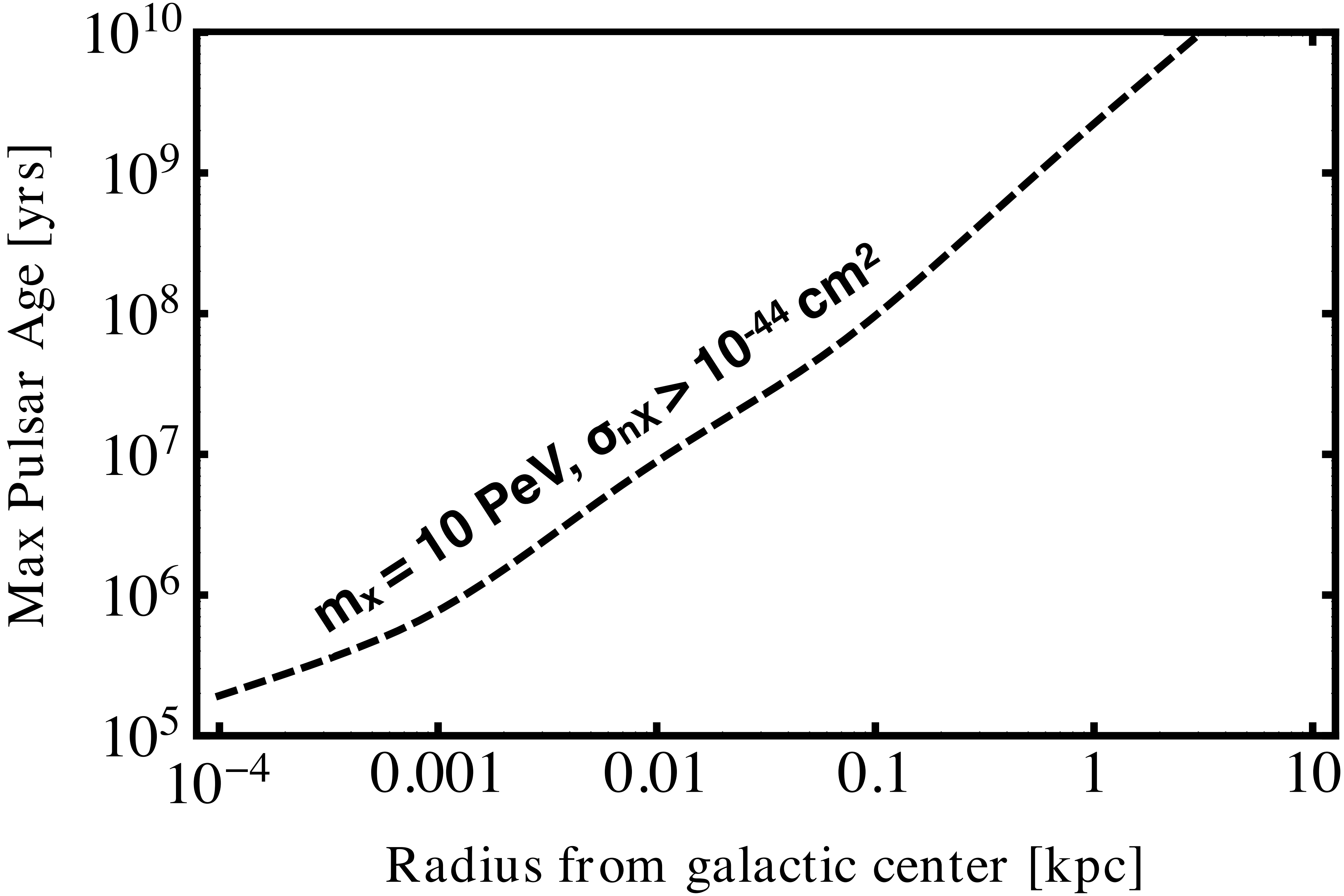


DM capture in Milky Way:

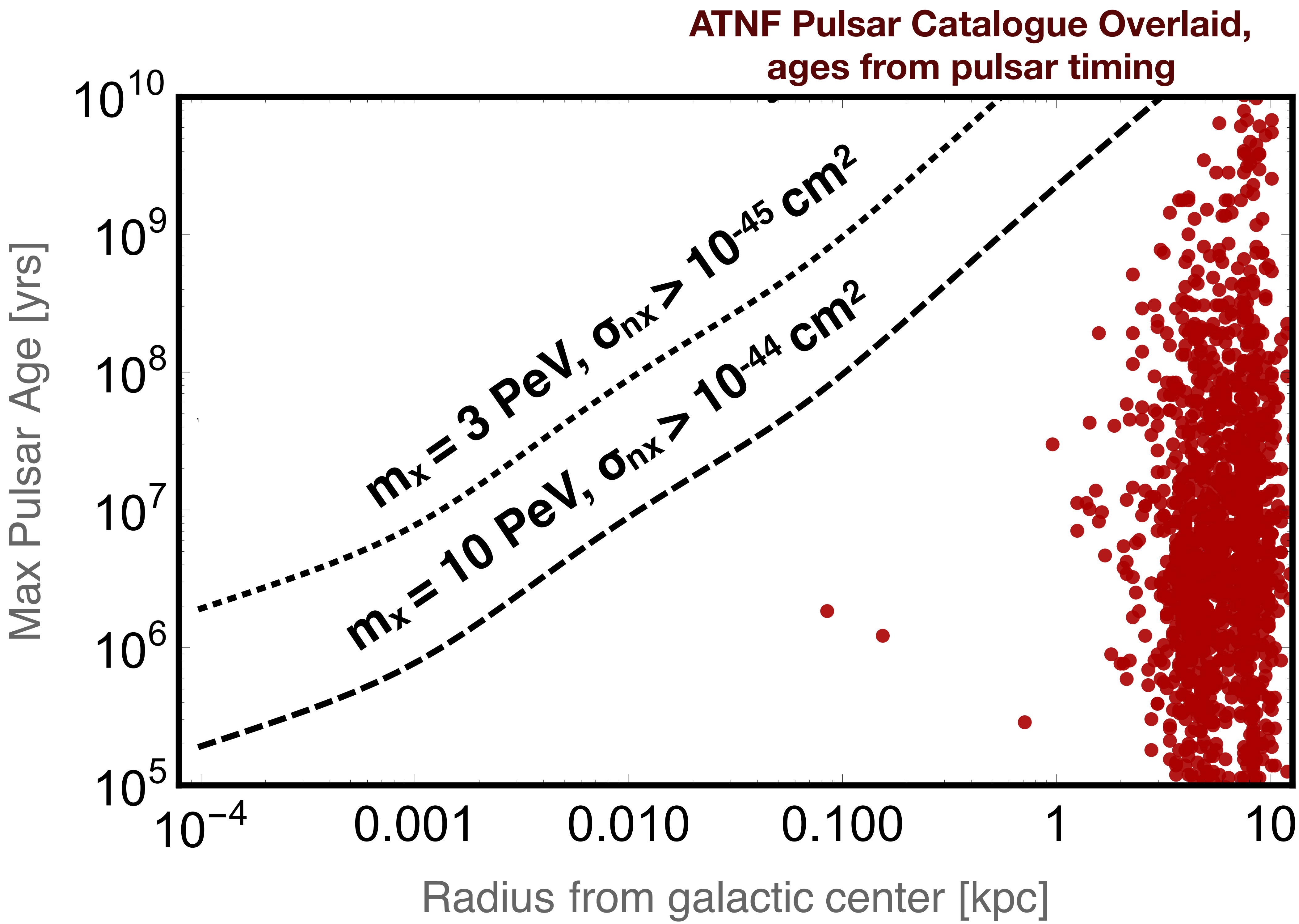
$$C_x \propto \frac{\boxed{\rho_x}}{v_x}$$

More dark matter captured in the center of galaxies
➜so pulsar implosions occur there more rapidly.

Dark Matter and Maximum Pulsar Age Curves



Dark Matter and Maximum Pulsar Age Curves



-Milky Way's 1-500 pc center surveyed in the next decade by FAST, SKA.

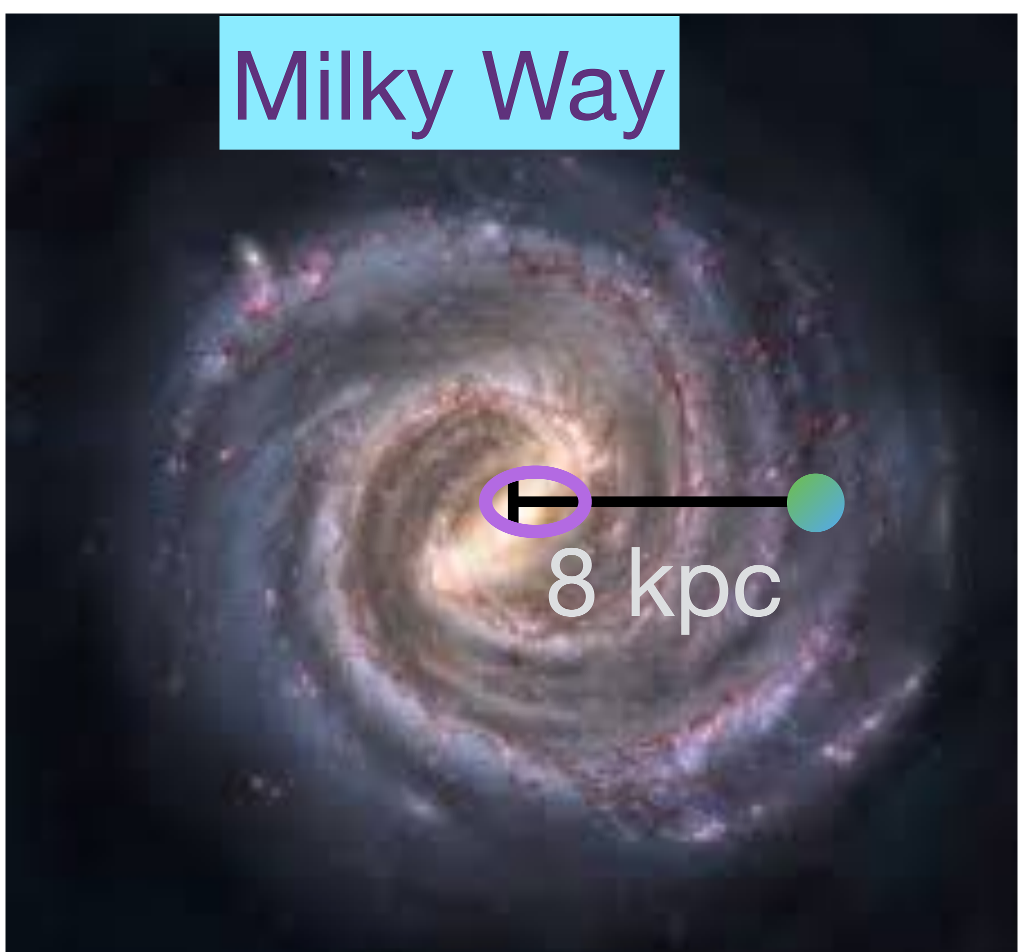
The Missing Pulsar Problem

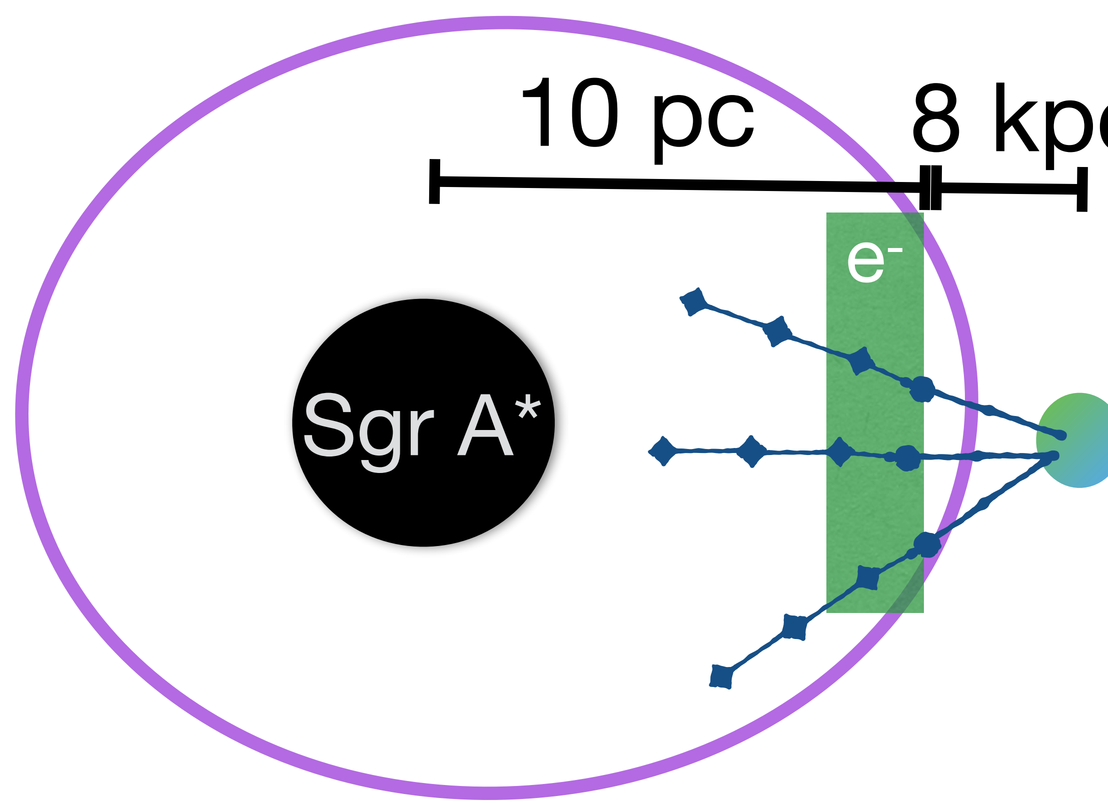
Many pulsars expected at galactic center

Up to 1000 visible pulsars expected in central parsecs

Only a few ~10^4 year old magnetars found so far

Pulses broadened by electron scattering?





Where are the galactic center pulsars?

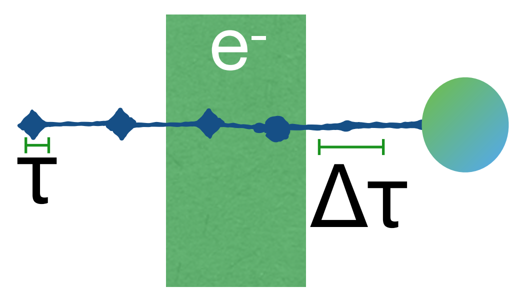
Dexter, O'Leary
1310.7022

Where are the galactic center pulsars?

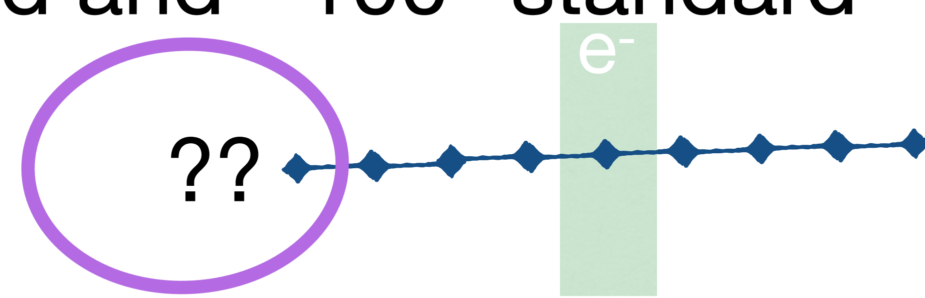
1. Temporal pulse broadening scales with the ~fourth power of observation frequency

$$\Delta\tau \sim 1\ \mathrm{s}\left(\frac{\mathrm{Ghz}}{\nu}\right)^2$$

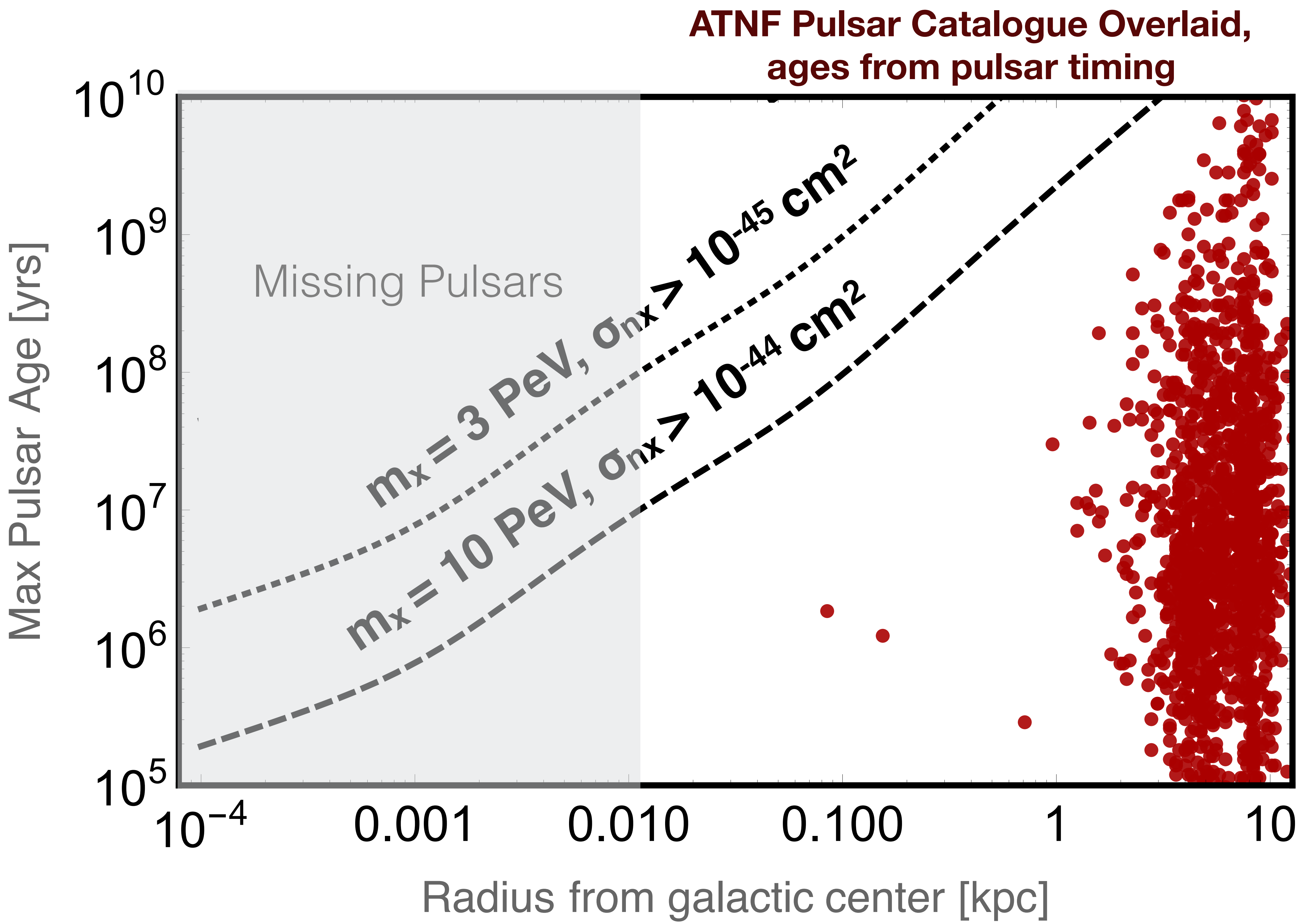
2. Magnetars (B~10^{14} Gauss) found in the central parsec, allow for exact (multi-freq.) measurements of temporal pulse broadening from the galactic center



3. Based on these measurements, we should have already seen up to ~100 millisecond period and ~100 "standard" period pulsars



Dark Matter and Maximum Pulsar Age Curves



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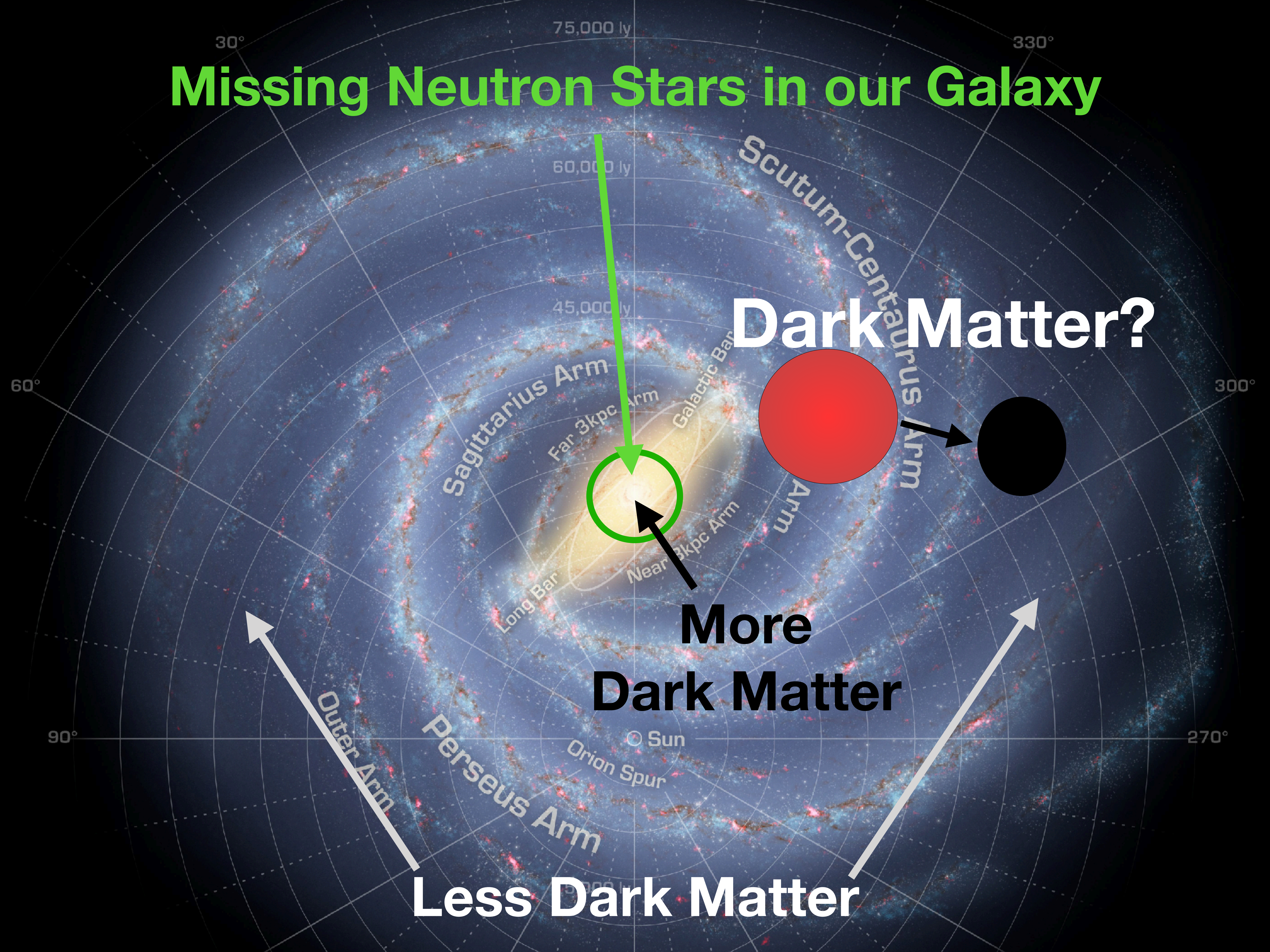
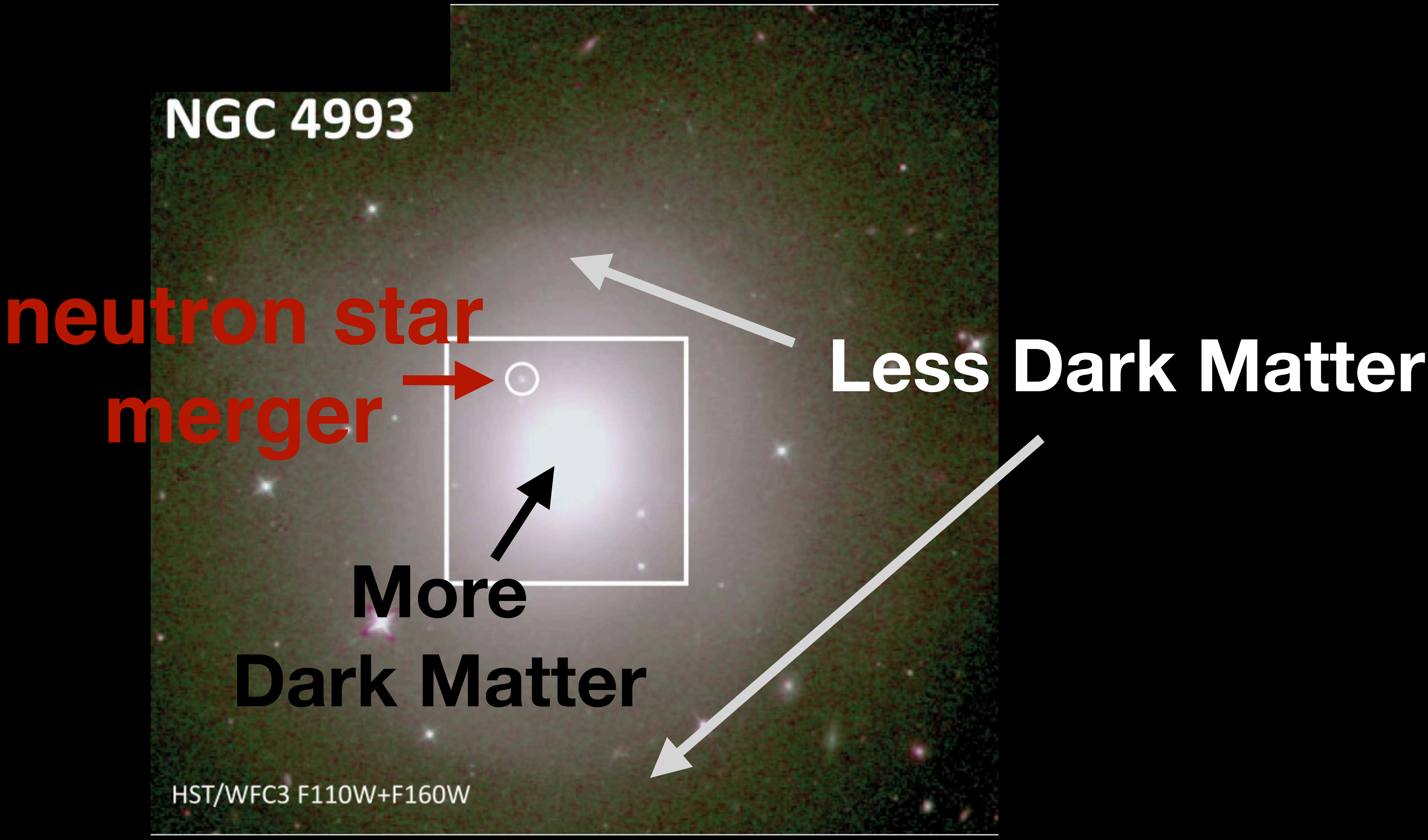
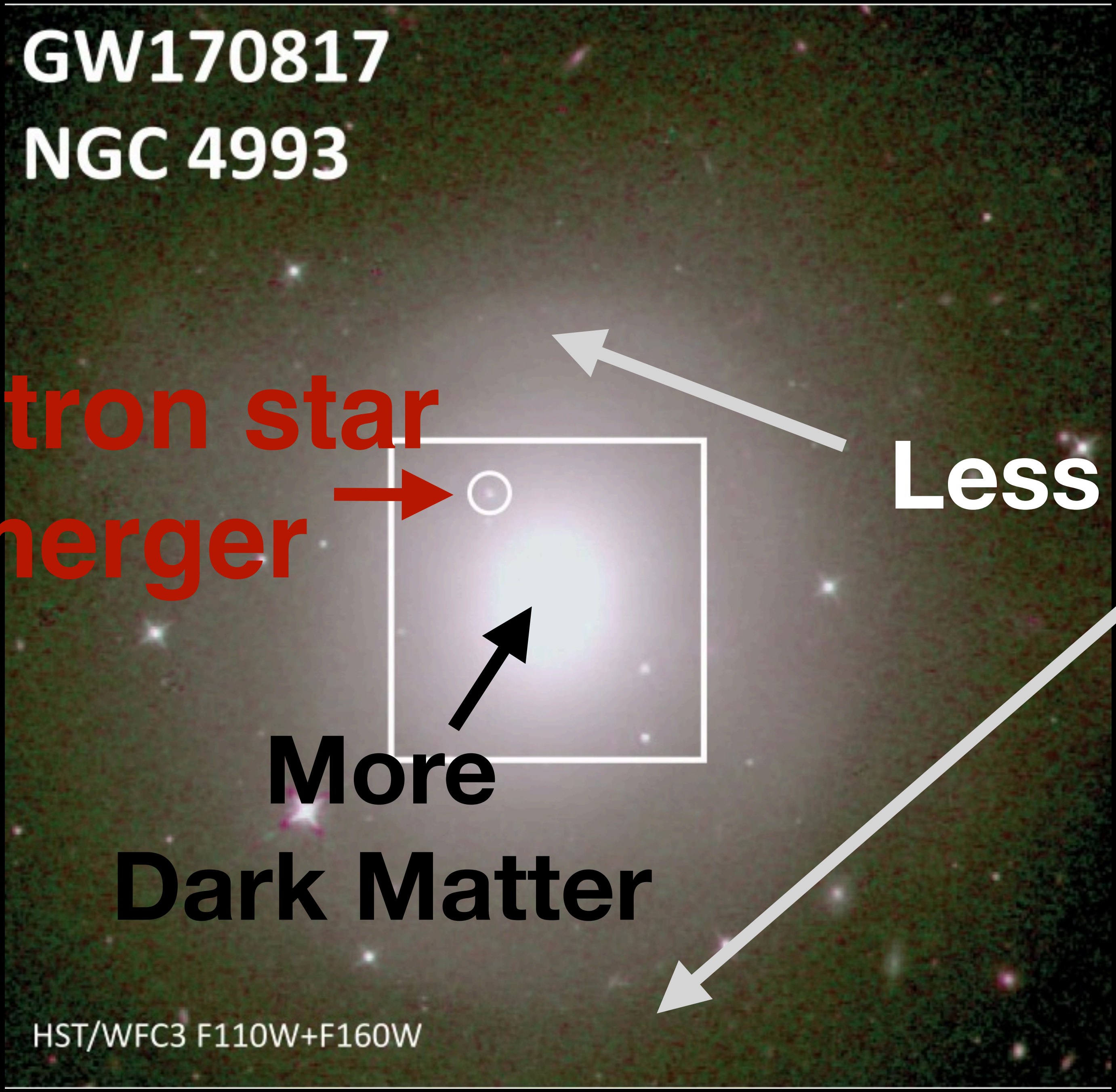

Missing Neutron Stars in our Galaxy
Dark Matter?
More
Dark Matter
Less Dark Matter
75,000 ly
60,000 ly
45,000 ly
30°
330°
60°
300°
90°
270°
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Near 3kpc Arm
Long Bar
Outer Arm
Perseus Arm
Sun
Orion Spur

Before observing a neutron star merger on August 18, 2017, we had only located neutron stars in our own galaxy.

With neutron star mergers we can hunt for dark matter in galaxies far far away.

We can now use the locations of neutron star mergers in other galaxies to hunt for neutron star imploding dark matter.



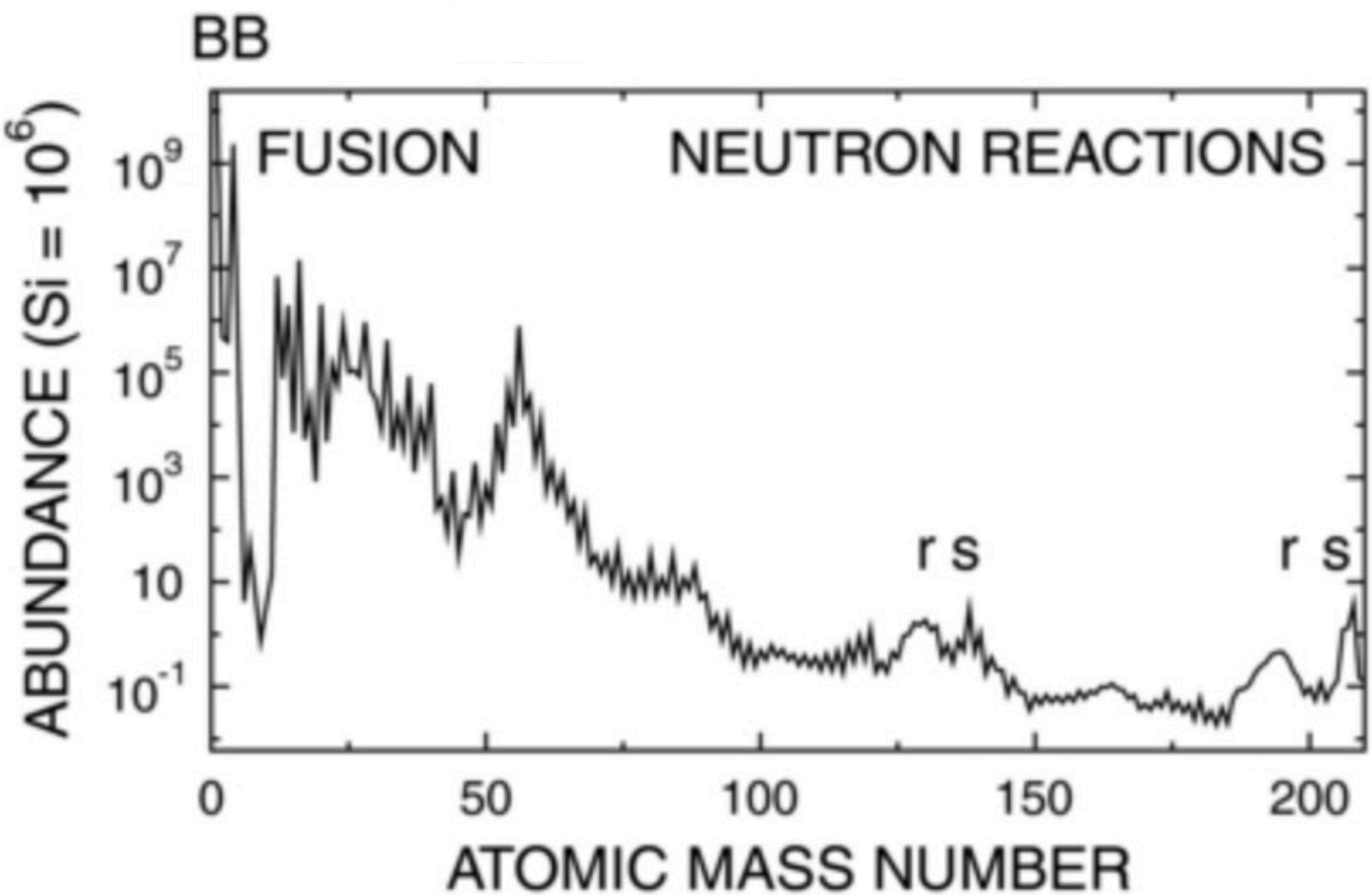


However:

-No neutron star age

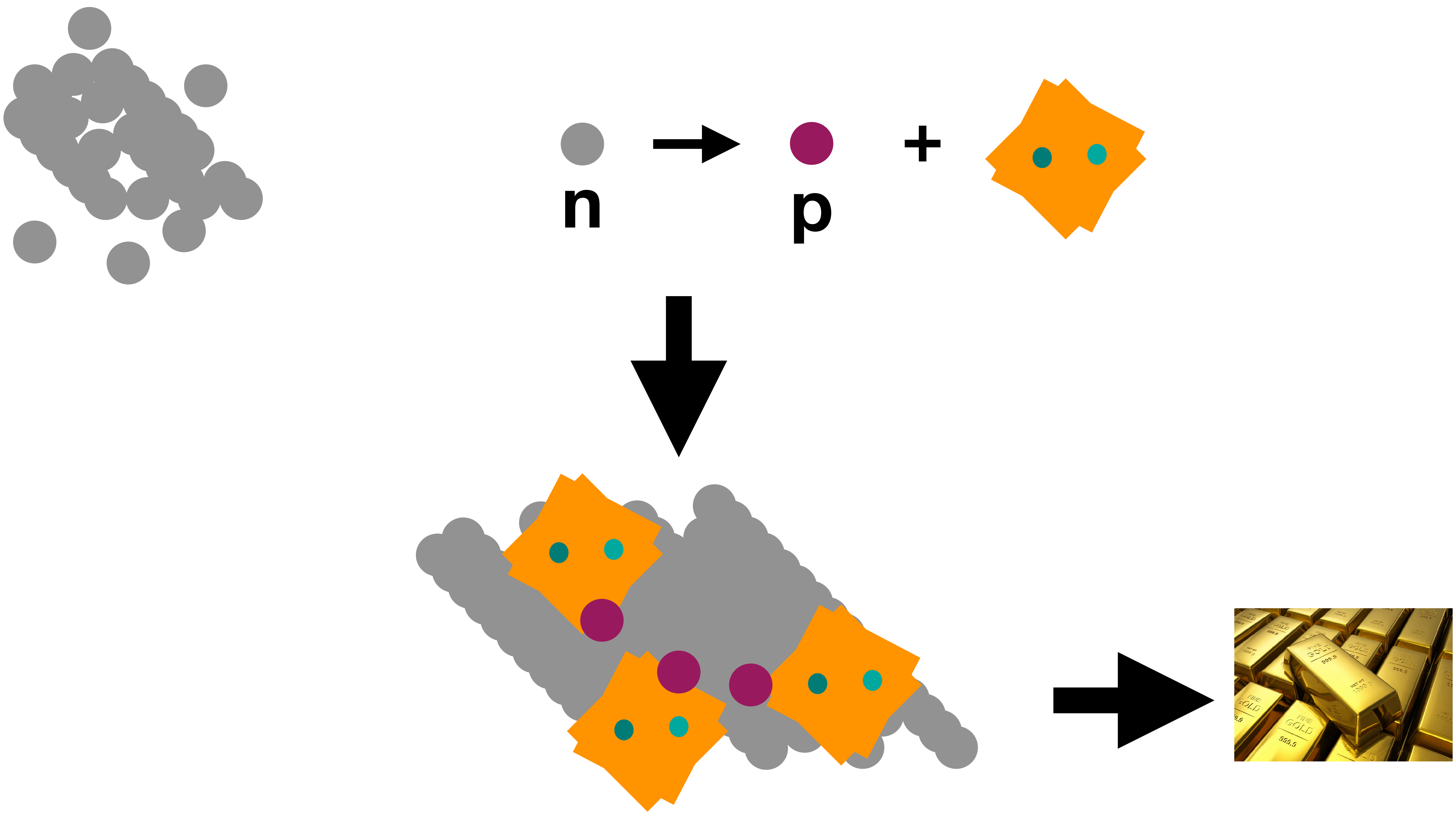
-Have to seek DM with ingenuity or statistics

R-process elements: heavy elements with peak abundances at atomic masses 80, 130, and 195, formed in a hot environment rich in free neutrons.



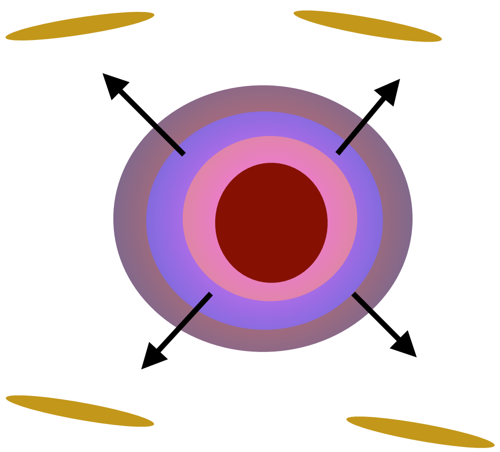
What makes gold? (elements near magic numbers)

Recipe: lots of neutrons, very hot (10^9 K)

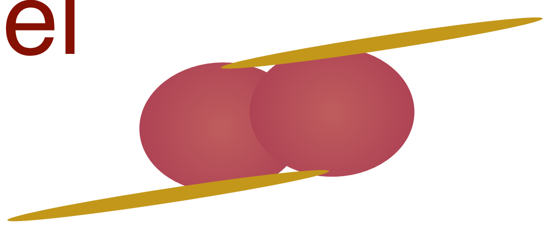


Possible r-process sites
(total 10^4 $M_\odot$ produced in Milky Way)

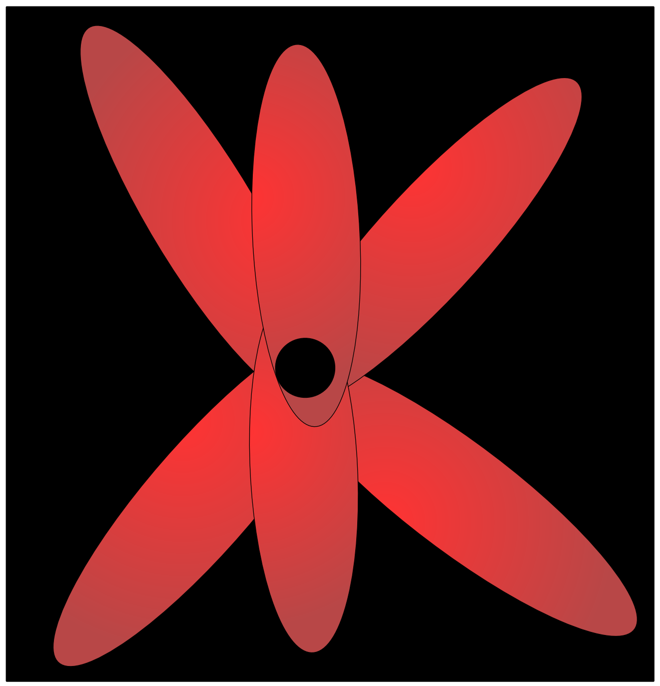
-Neutrons ejected by neutrino wind during core collapse supernovae (frequent, ~1/100 years)



-Merging neutron star binaries, tidal forces expel dense neutron star fluid (rare, ~1/10^4 years)



R-process elements from dark matter induced NS implosions



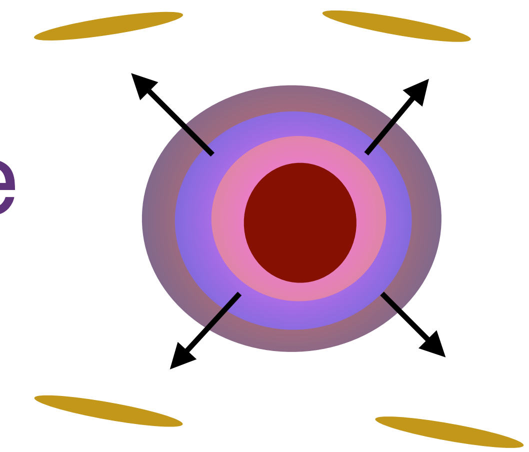
$$R_{\rm Roche} \simeq 20 \left(\frac{M_{\rm BH}}{10^{-10}\ {\rm M}_\odot} \right)^{1/3} \left(\frac{10^{14}\ {\rm g\ cm^{-3}}}{\rho_{\rm NS}} \right)^{1/3} \ {\rm m}$$

Neutron star implodes into a small black hole.
Enough potential energy to eject up to ~msol fluid.
"Tube of toothpaste" effect ejects neutron star fluid.
Same timescale as NS-NS, BH-NS mergers ~ 1 ms.

See also: forthcoming numerical GR simulations from Perimeter colleagues

JB, Linden 2016

Possible r-process sites
(total 10^4 $M_\odot$ produced in Milky Way)



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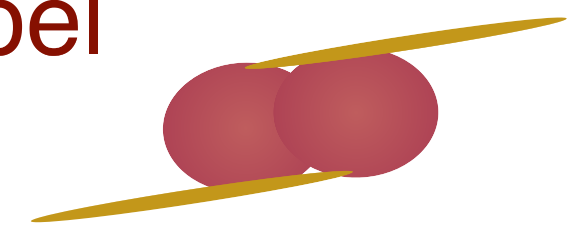
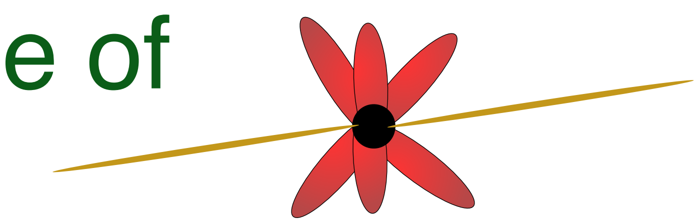


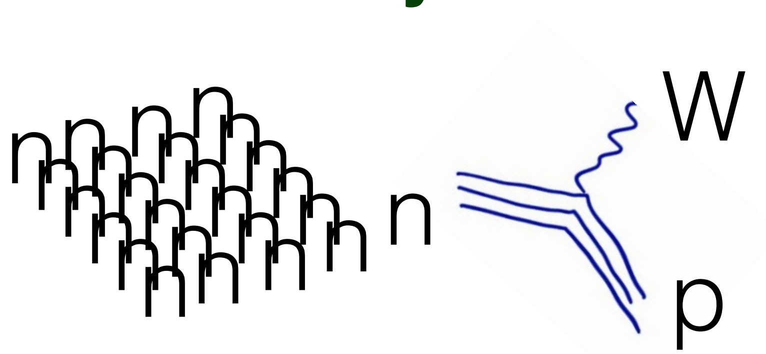
-Merging neutron star binaries, tidal forces expel dense neutron star fluid (rare, ~1/10^4 years)



-Neutron star slurped into a black hole made of dark matter at its core.

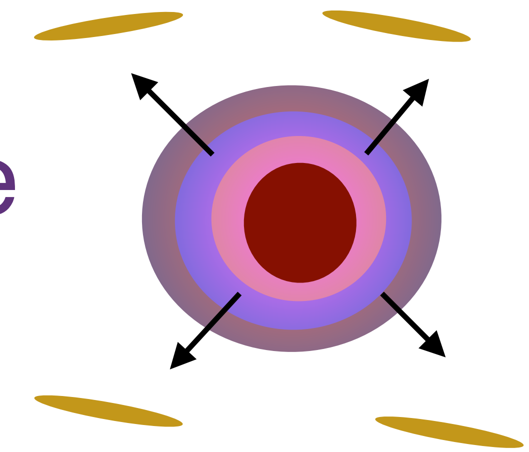
implosion tidally spurts neutron fluid

In each case, neutron rich fluid beta decays, forms heavy neutron-rich elements.

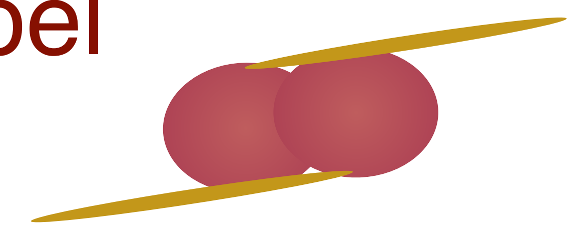


… Gold,Uranium, Europium, Barium…

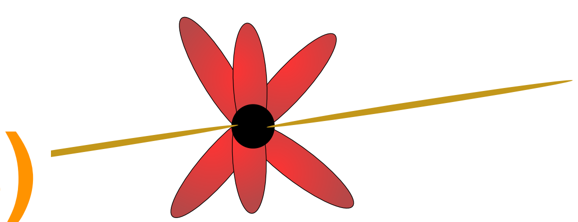
Possible r-process sites
(total 10^4 $M_\odot$ produced in Milky Way)



-Neutrons ejected by neutrino wind during core collapse supernovae (frequent, ~1/100 years)

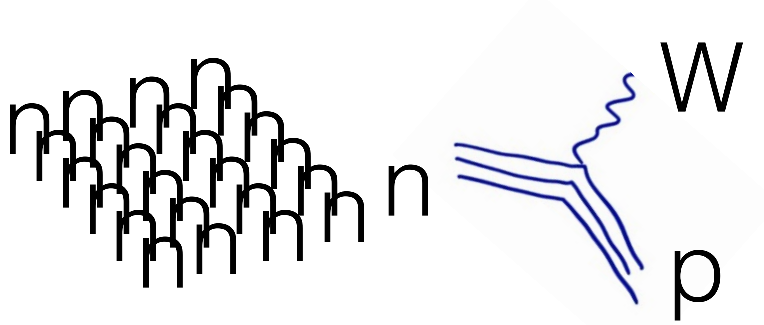


-Merging neutron star binaries, tidal forces expel dense neutron star fluid (rare, ~1/10^4 years)



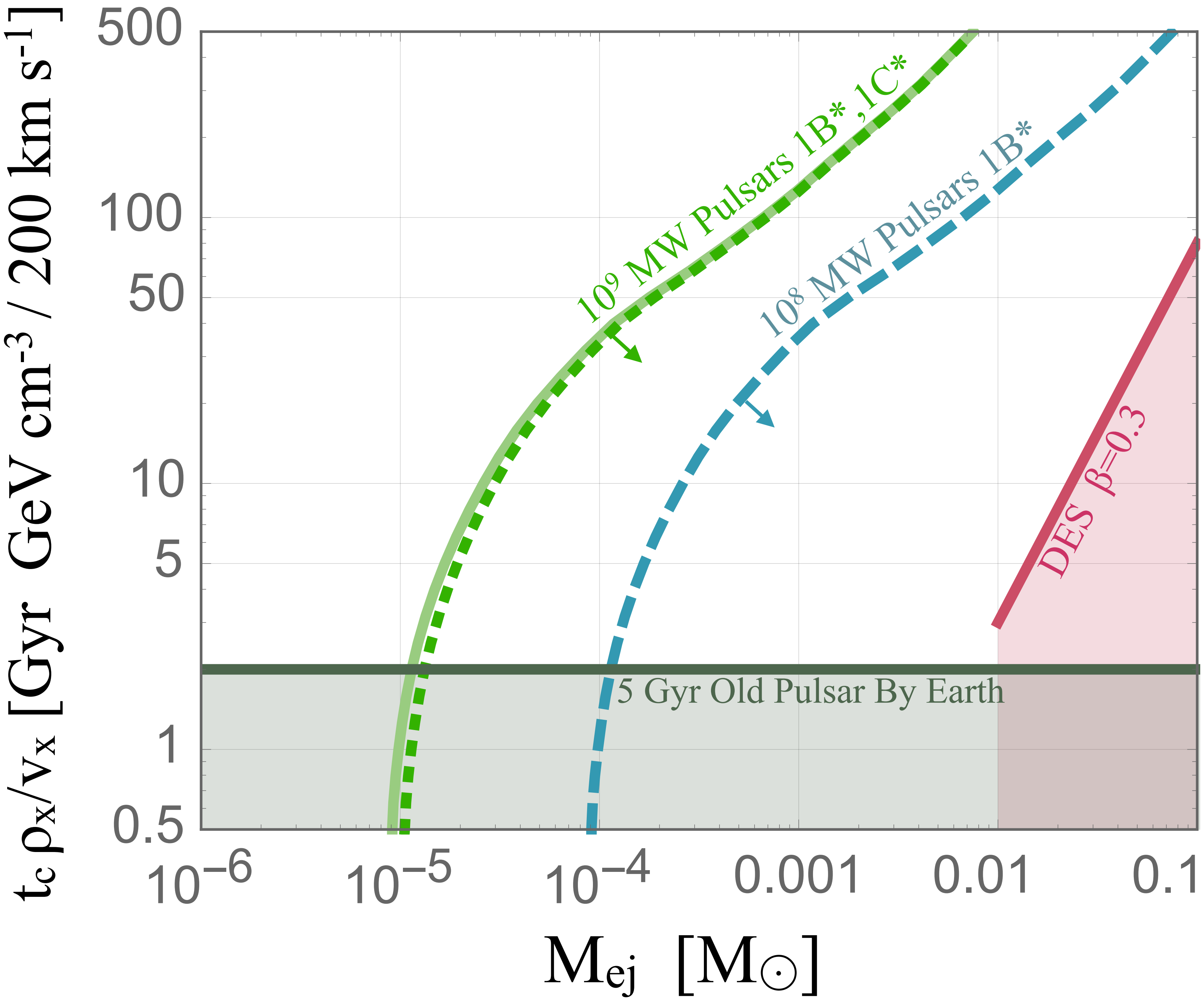
-Neutron **Self-Detecting Dark Matter**
dark mat **(Ge, Xe, Ar are r-process elements)**

In each case, neutron rich fluid beta decays, forms heavy neutron-rich elements.

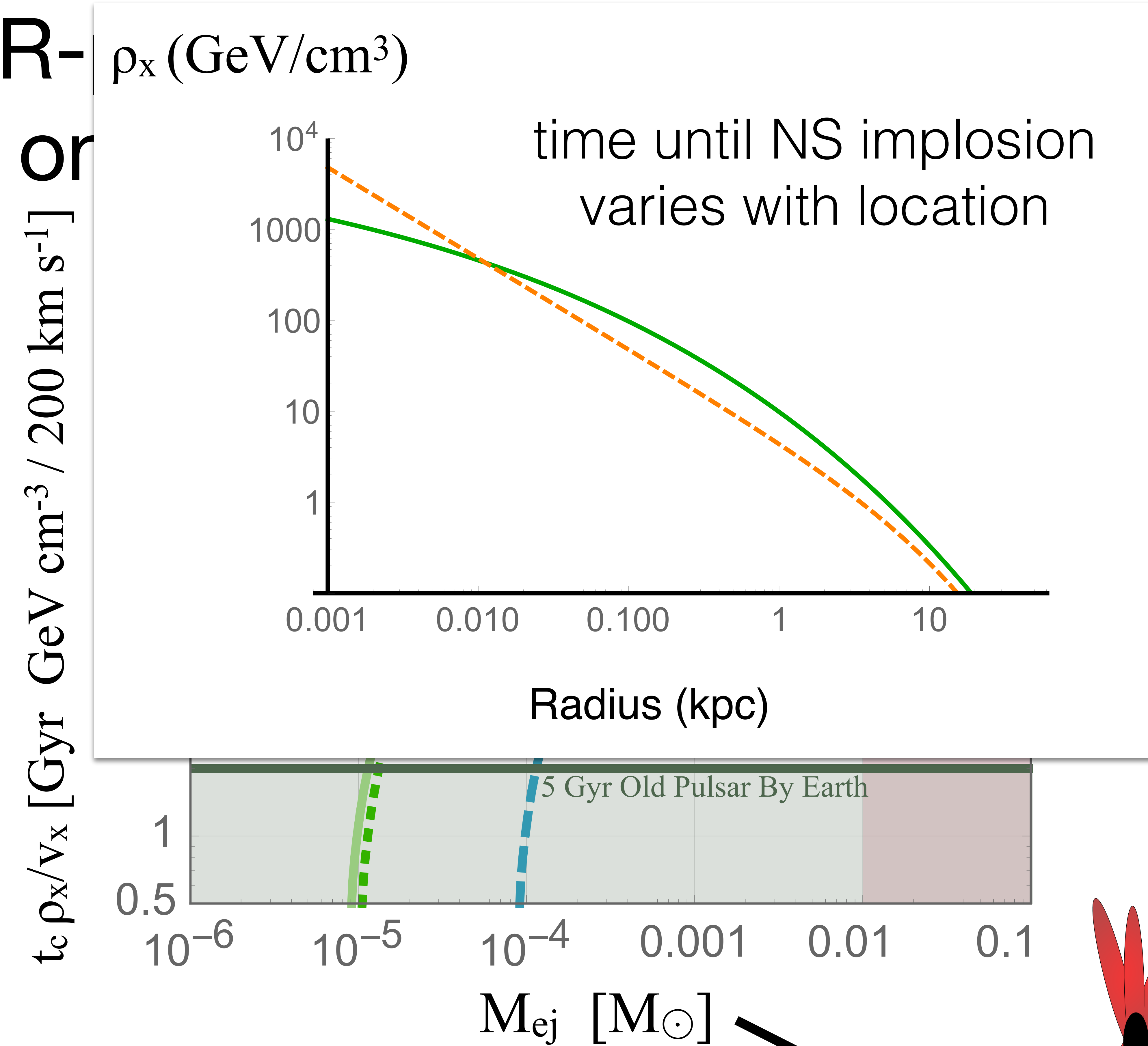


… Gold, Uranium, Europium, Barium…

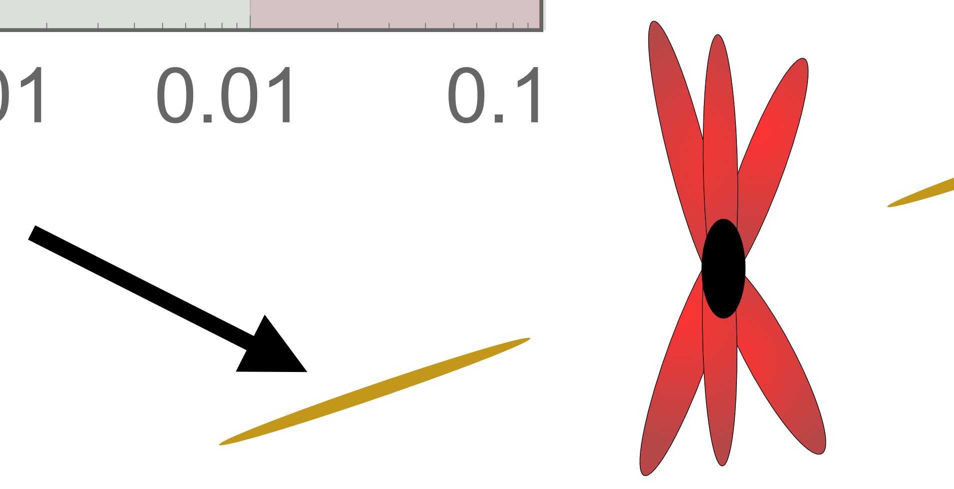
R-process and DES Bounds on NS Implosion Kilonovae



R-
or

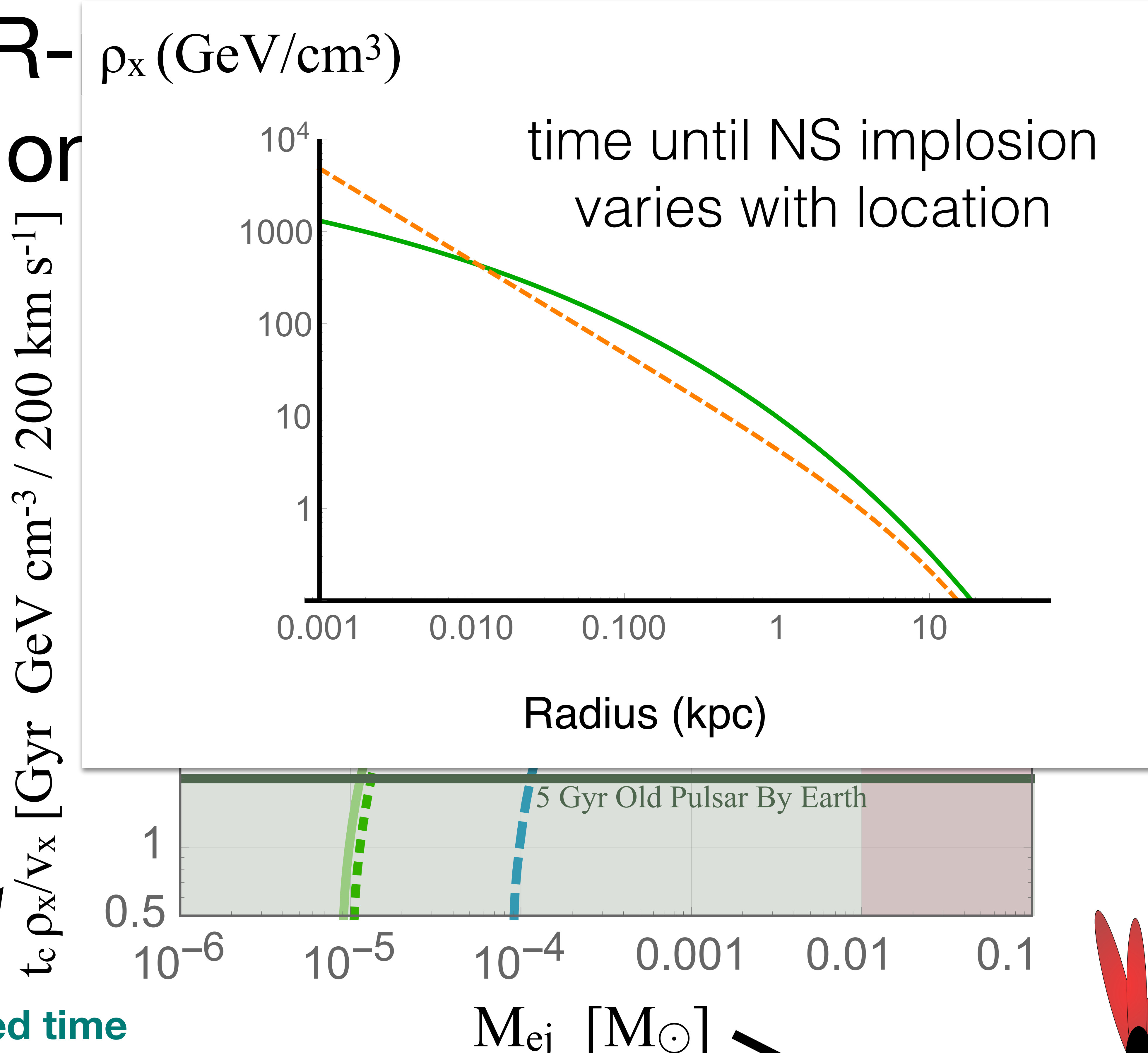


ρ_x (GeV/cm^3)
time until NS implosion
varies with location
10^4
1000
100
10
1
0.001
0.010
0.100
1
10
Radius (kpc)
$t_c\, \rho_x / v_x$ [Gyr GeV cm^{-3} / 200 km s^{-1}]
5 Gyr Old Pulsar By Earth
1
0.5
10^{-6}
10^{-5}
10^{-4}
0.001
0.01
0.1
M_{ej} [$M_\odot$]

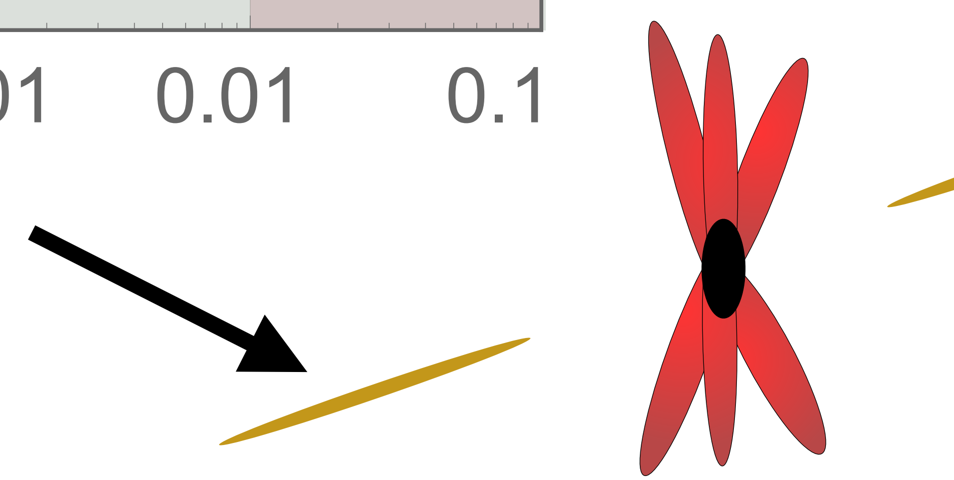


R-

or



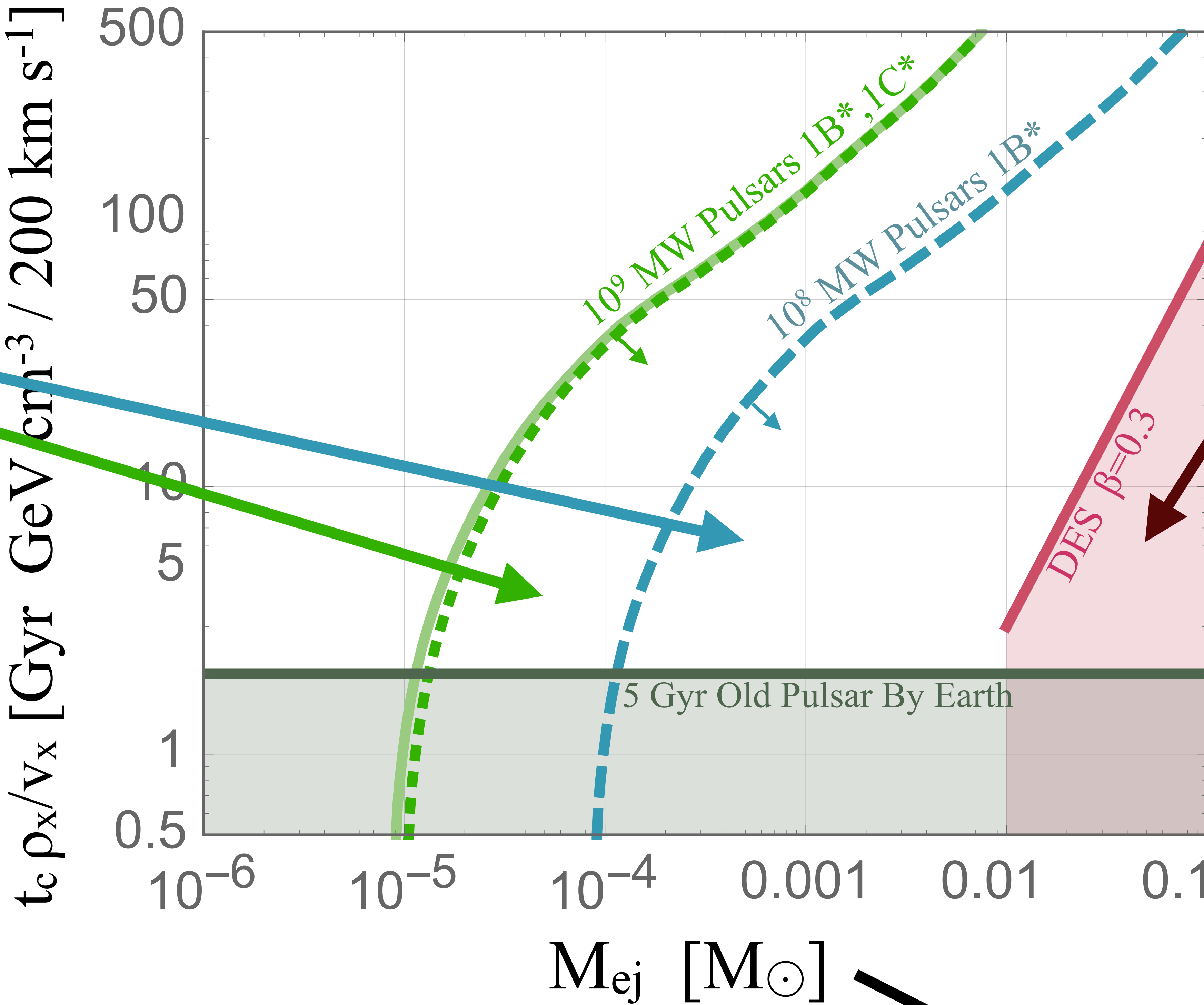
normalized time until NS implosion for GeV/cm³ (one Kouvaris)



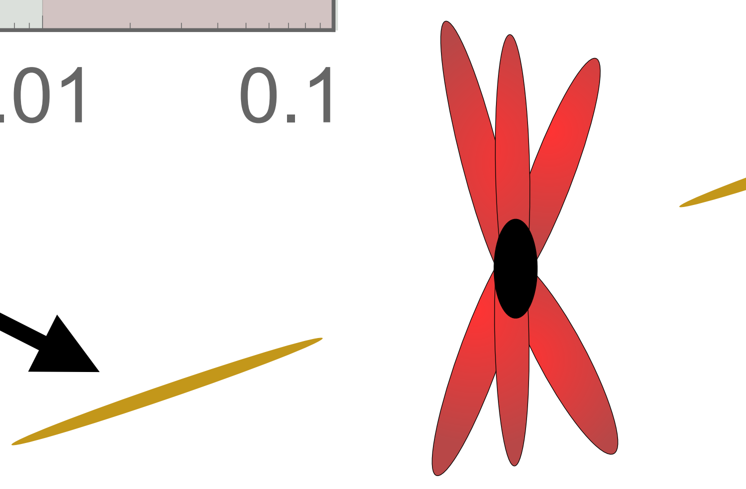
R-process and DES Bounds on NS Implosion Kilonovae

More than 10^4 r-process element production in Milky Way

(Too much gold bound!)

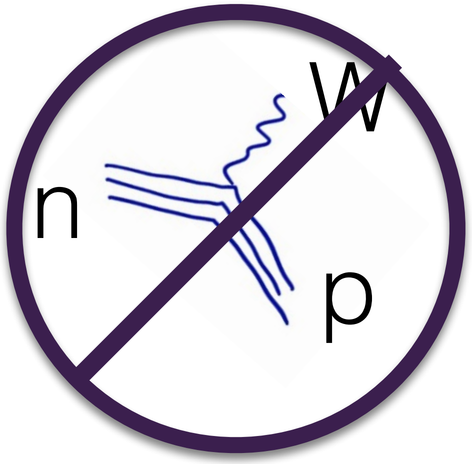


DES all-sky kilonova search



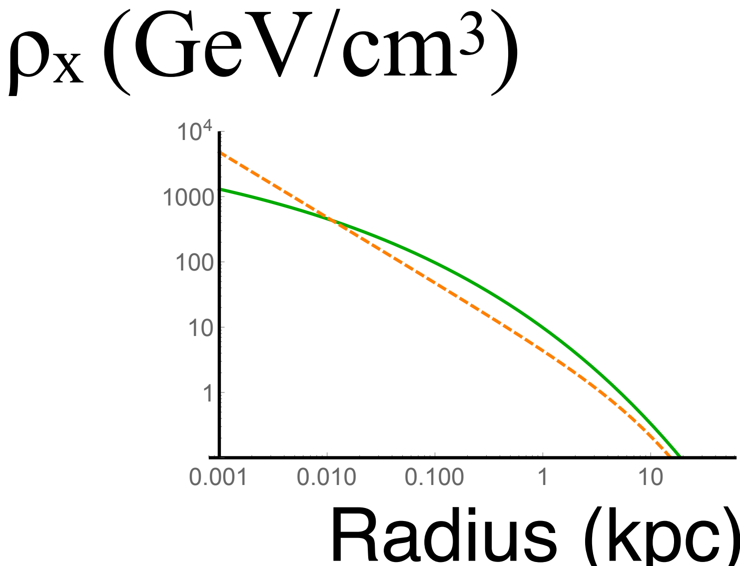
Black Mergers

JB, Linden, Tsai 2017



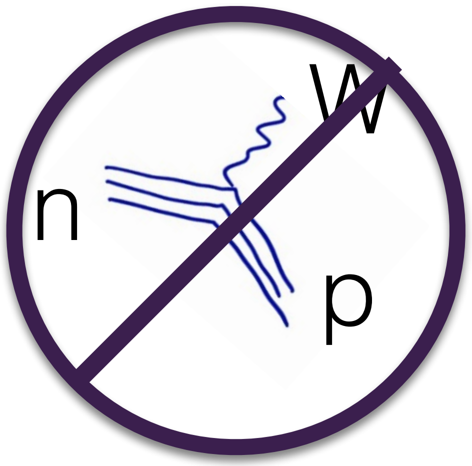
Gravity Waves
From LMBH mergers

Black merger: no kilonova accompanies collapsed NS mergers in galactic interior



Black Mergers

No Kilonova



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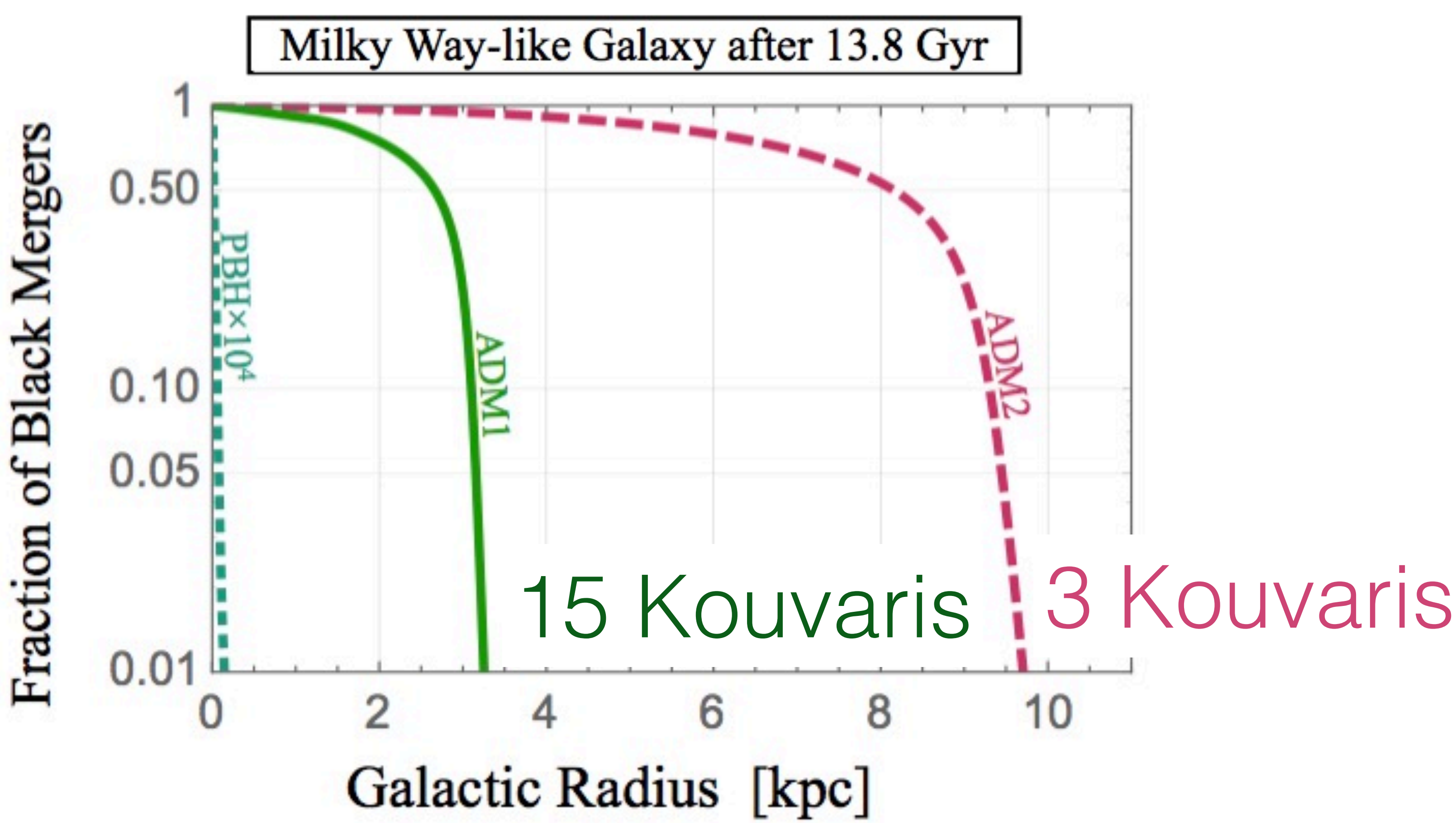
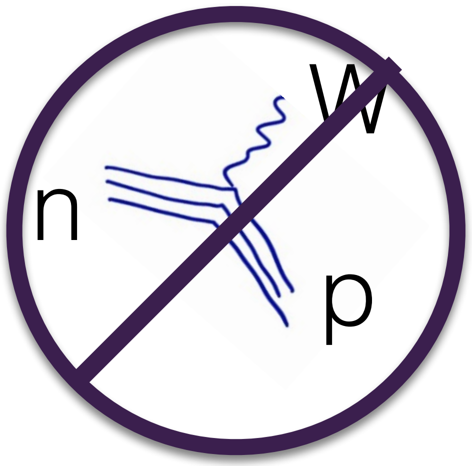
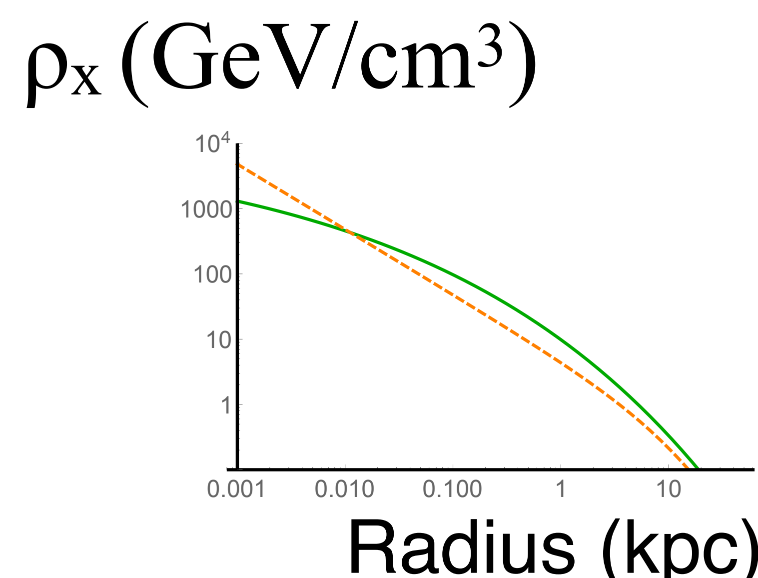


Black Mergers



Gravity Waves
From LMBH mergers

Beacom-Hopkins ’06
Star Formation
Sartore ’09 Final NS
Distribution



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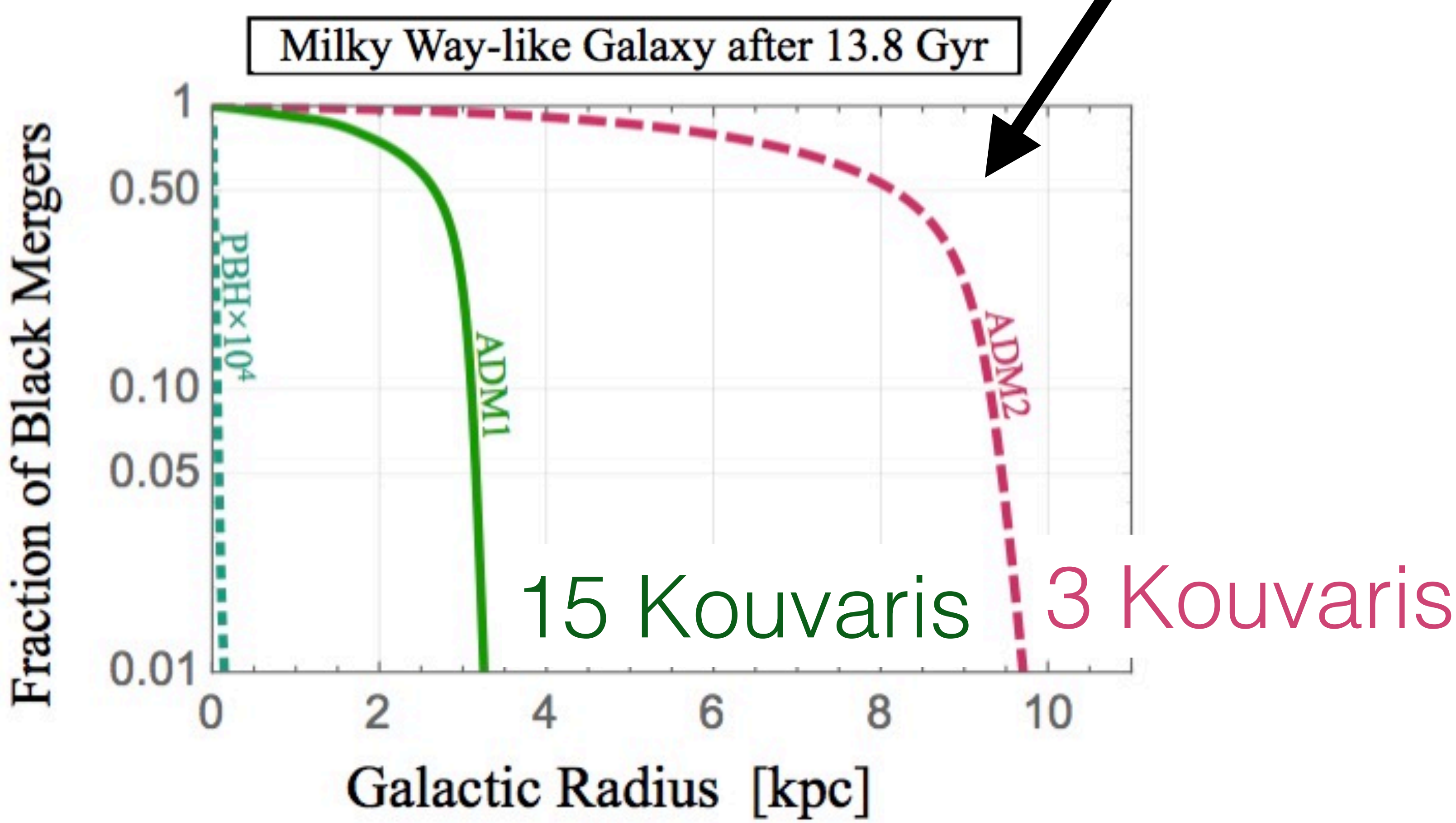
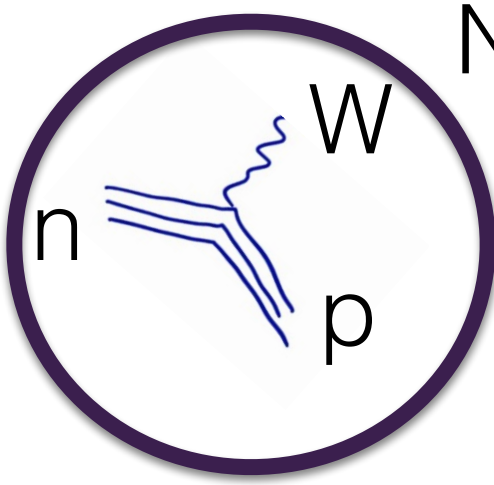
collapsed NS mergers in galactic interior

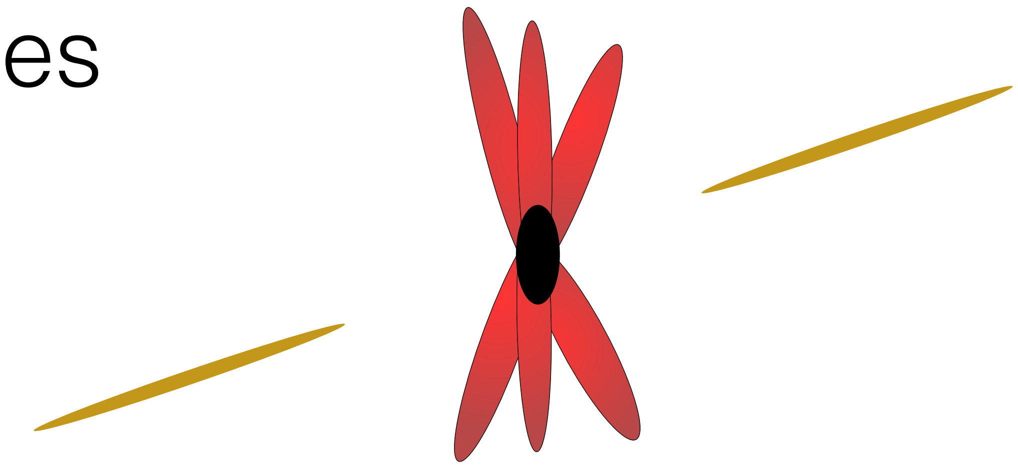


Quiet Kilonovae



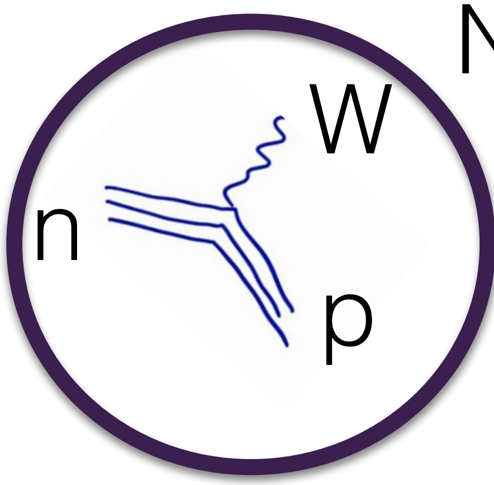
No Observable GWaves

~~Gravity Waves From NS mergers~~



Quiet Kilonovae: NS implosions create a less luminous kilonova, with no gravity wave signal

Quiet Kilonovae



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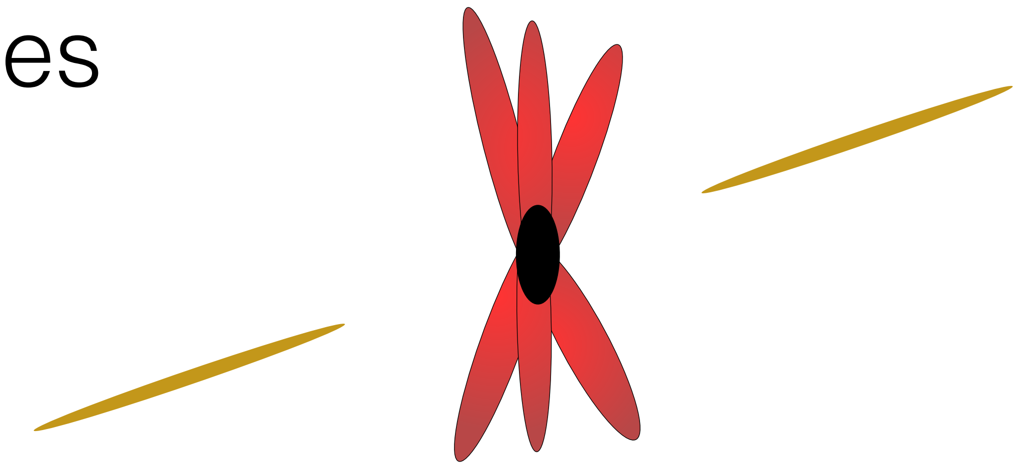

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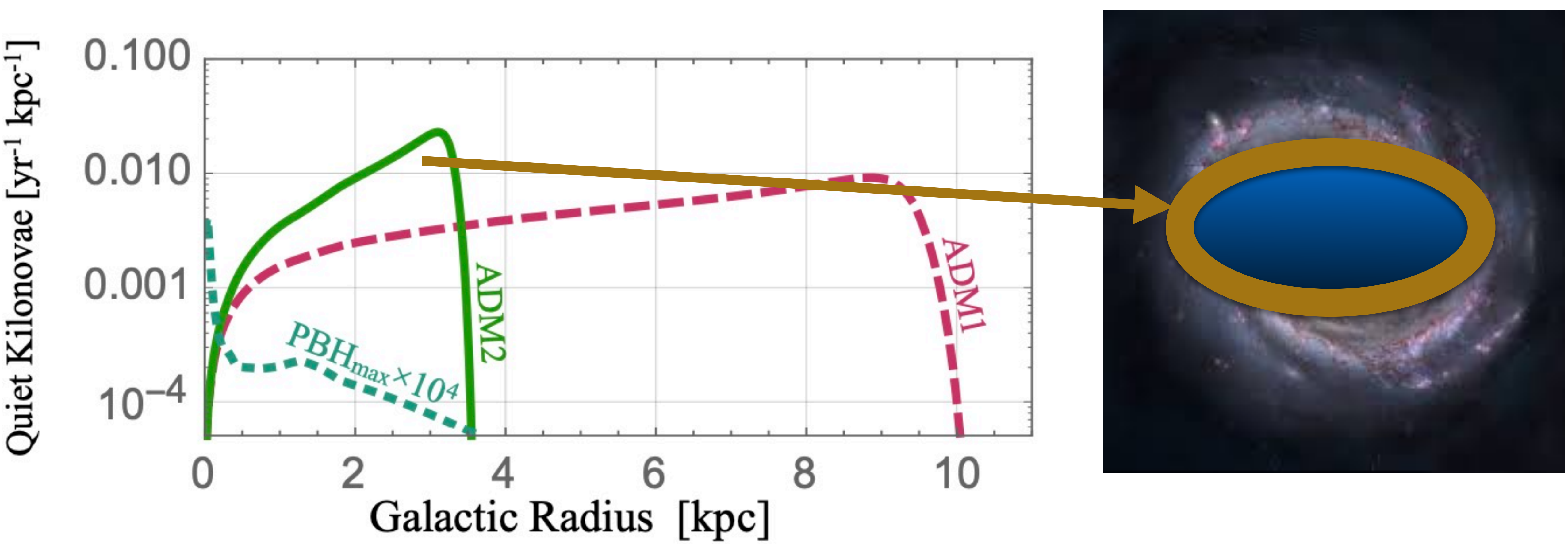
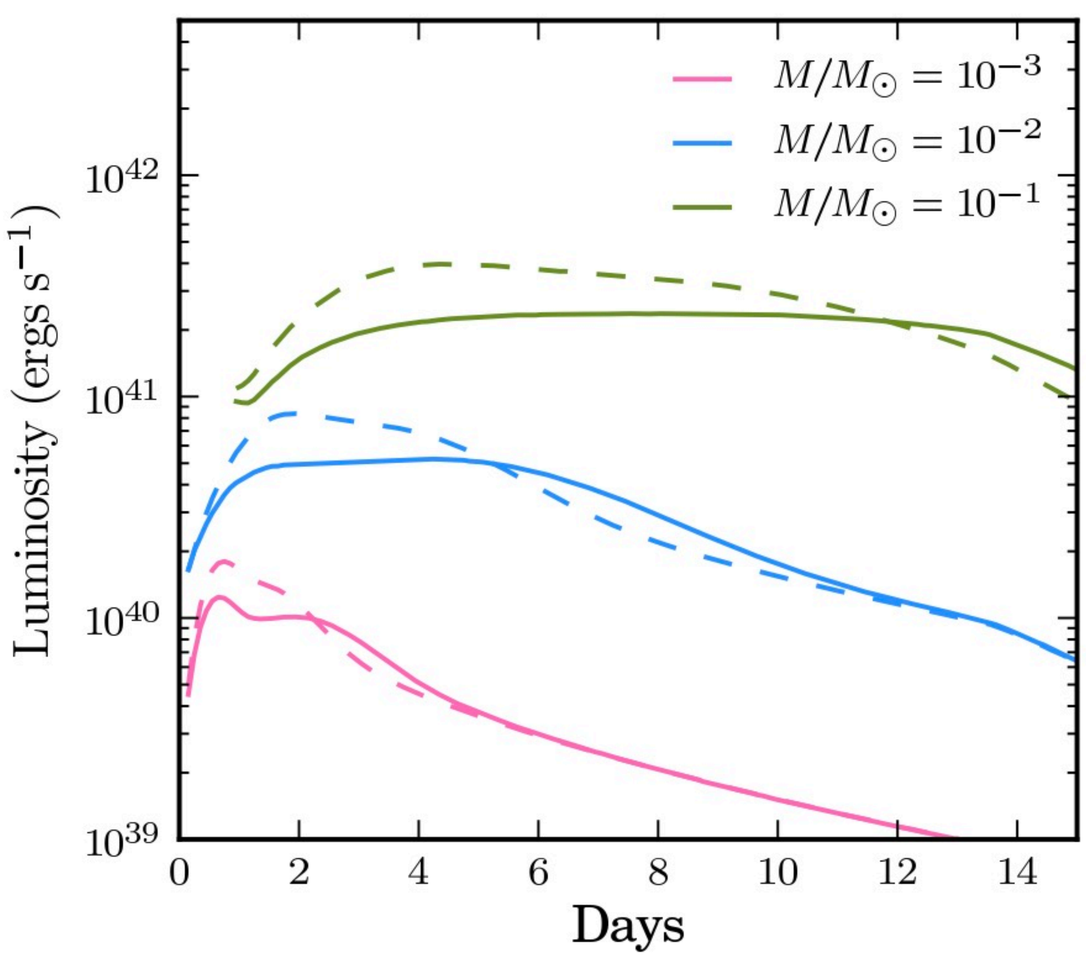
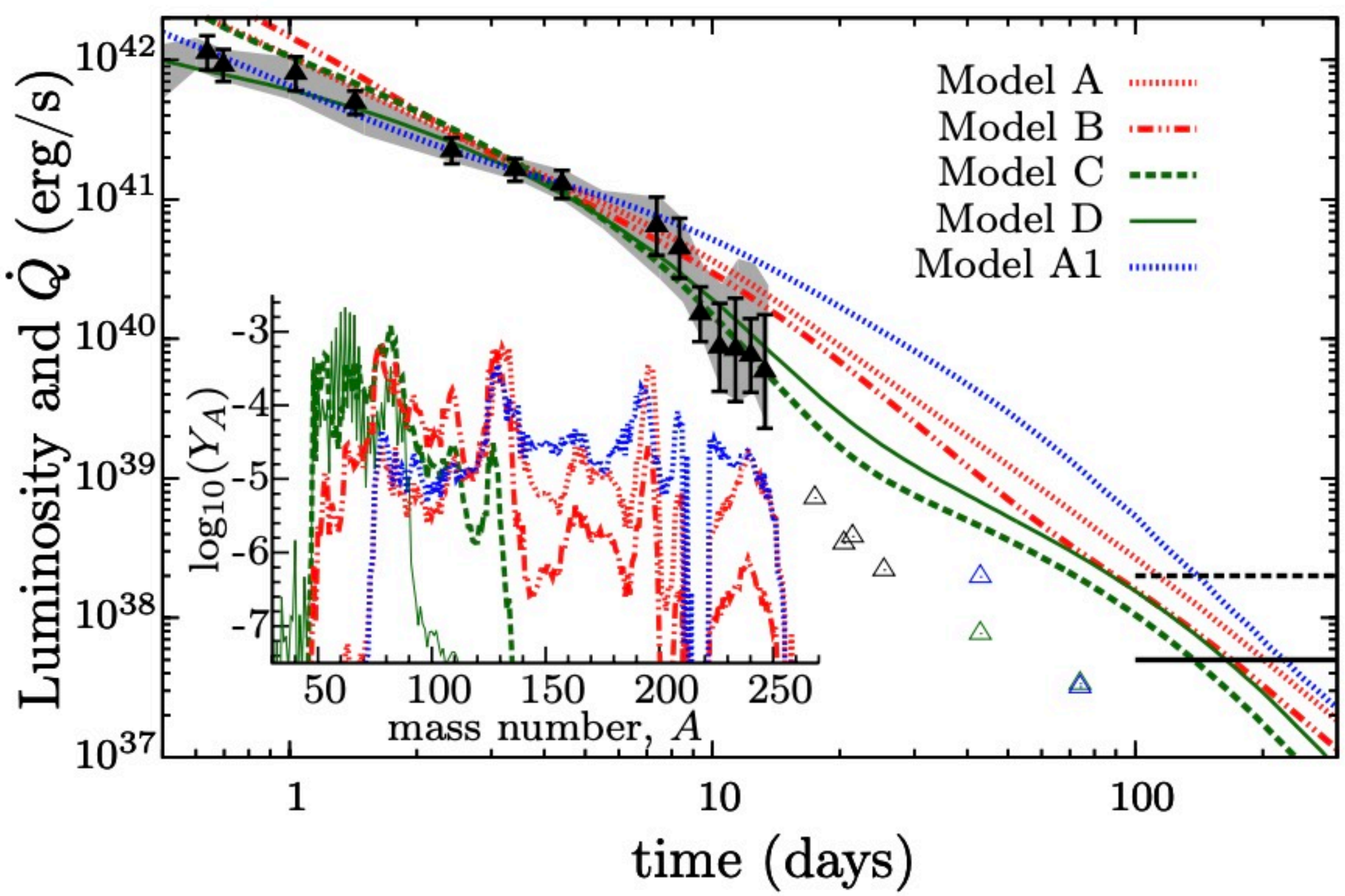


Modeled and Observed Kilonova Light Curves



Barnes, Kasen 2013



Wu, Barnes et al 2018
1808.10459

Neutron star fluid kilonovae last days and have luminosities that scale with ejected mass.

The SINS Survey — Finding Quiet Kilonovae In the Fornax Cluster

PI: Antonella Palmese **Status:** P **Affil.:** Fermilab
Center for Particle Astrophysics, MS 127, P.O. Box 500, Batavia, IL 60510 USA
Email: palmese@fnal.gov Phone: 331-707-8212 FAX: 630-840-3150

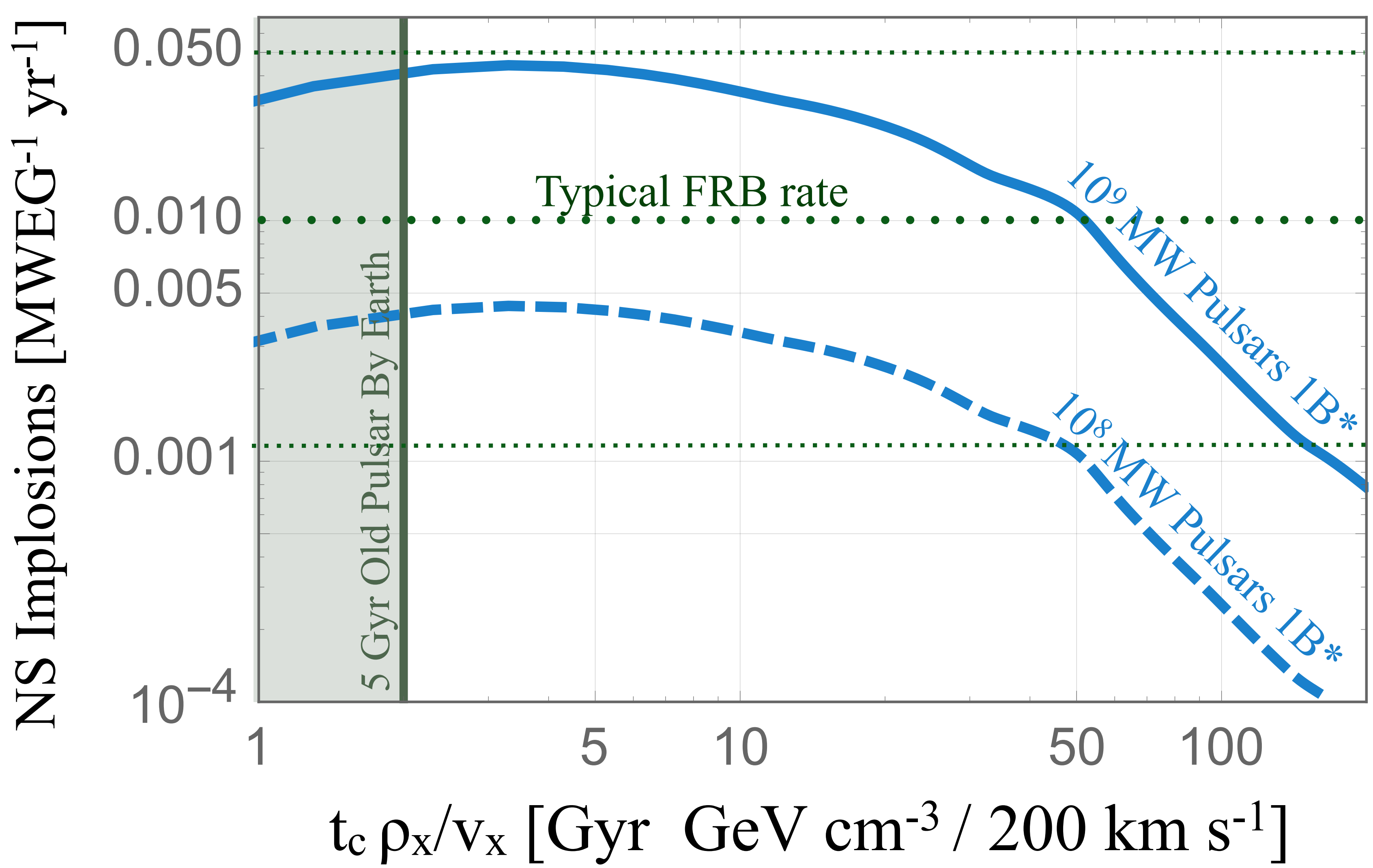
CoI: James Annis	**Status:** P	**Affil.:** Fermilab
CoI: Yu-Dai Tsai	**Status:** P	**Affil.:** Fermilab & University of Chicago
CoI: Joseph Bramante	**Status:** P	**Affil.:** Queen's University, Canada
CoI: Kenneth Herner	**Status:** P	**Affil.:** Fermilab
CoI: Zoheyr Doctor	**Status:** G	**Affil.:** University of Chicago
CoI: William Wester	**Status:** P	**Affil.:** Fermilab
CoI: Dillon Brout	**Status:** G	**Affil.:** University of Pennsylvania
CoI: Marcelle Soares-Santos	**Status:** P	**Affil.:** Brandeis University
CoI: Douglas Tucker	**Status:** P	**Affil.:** Fermilab

- 10 half nights every 3 days for 60 nights livetime
- Sensitivity to quiet kilonovae 0.2/yr per MWEG

NS Implosion Rate (could match Fast Radio Bursts)

$$R_{frb} \sim 10^{-2}\ \mathrm{MWEG}^{-1}\ \mathrm{yr}^{-1} \left(\frac{D}{2\ \mathrm{Gpc}}\right)^{-3}$$

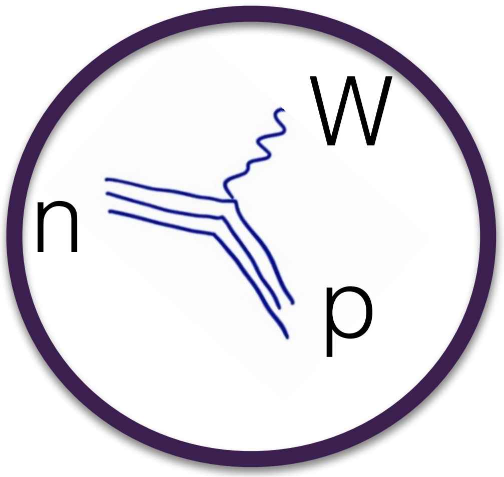
NS Implosions



-Incorporates NS dynamics, birthrates in Milky Way, capture rate for position in galaxy

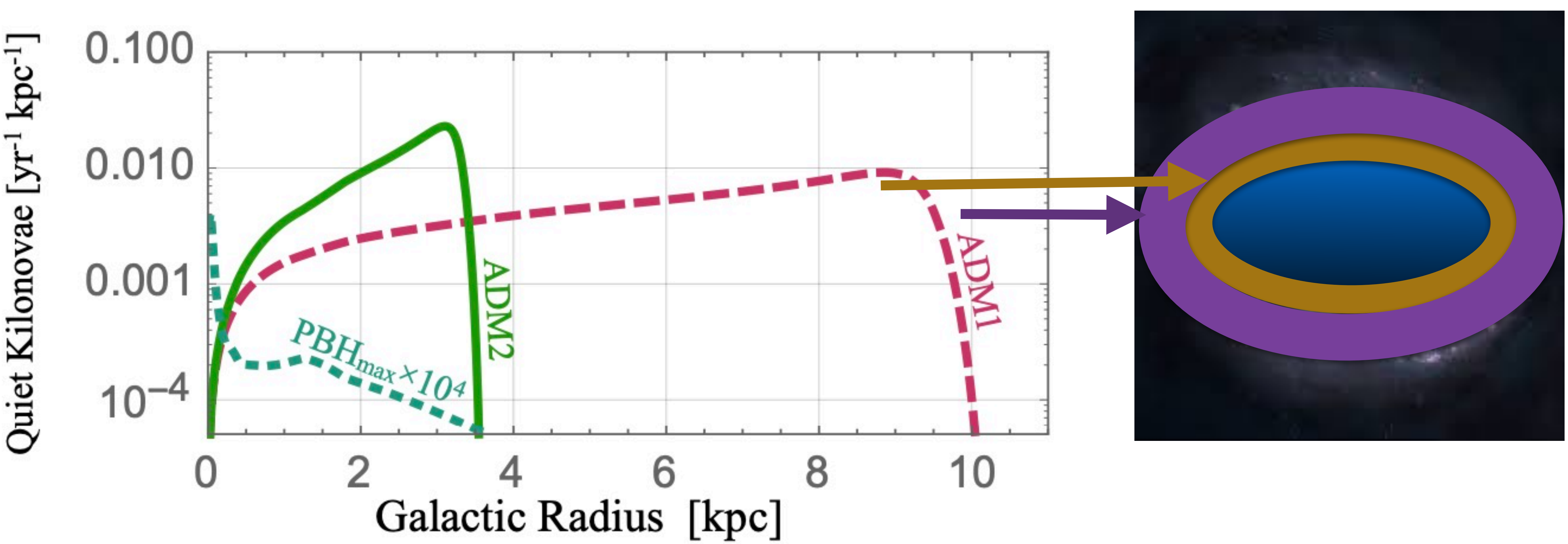
JB, Linden, Tsai 2017

R-Process Donuts



Gravity Waves
From NS mergers

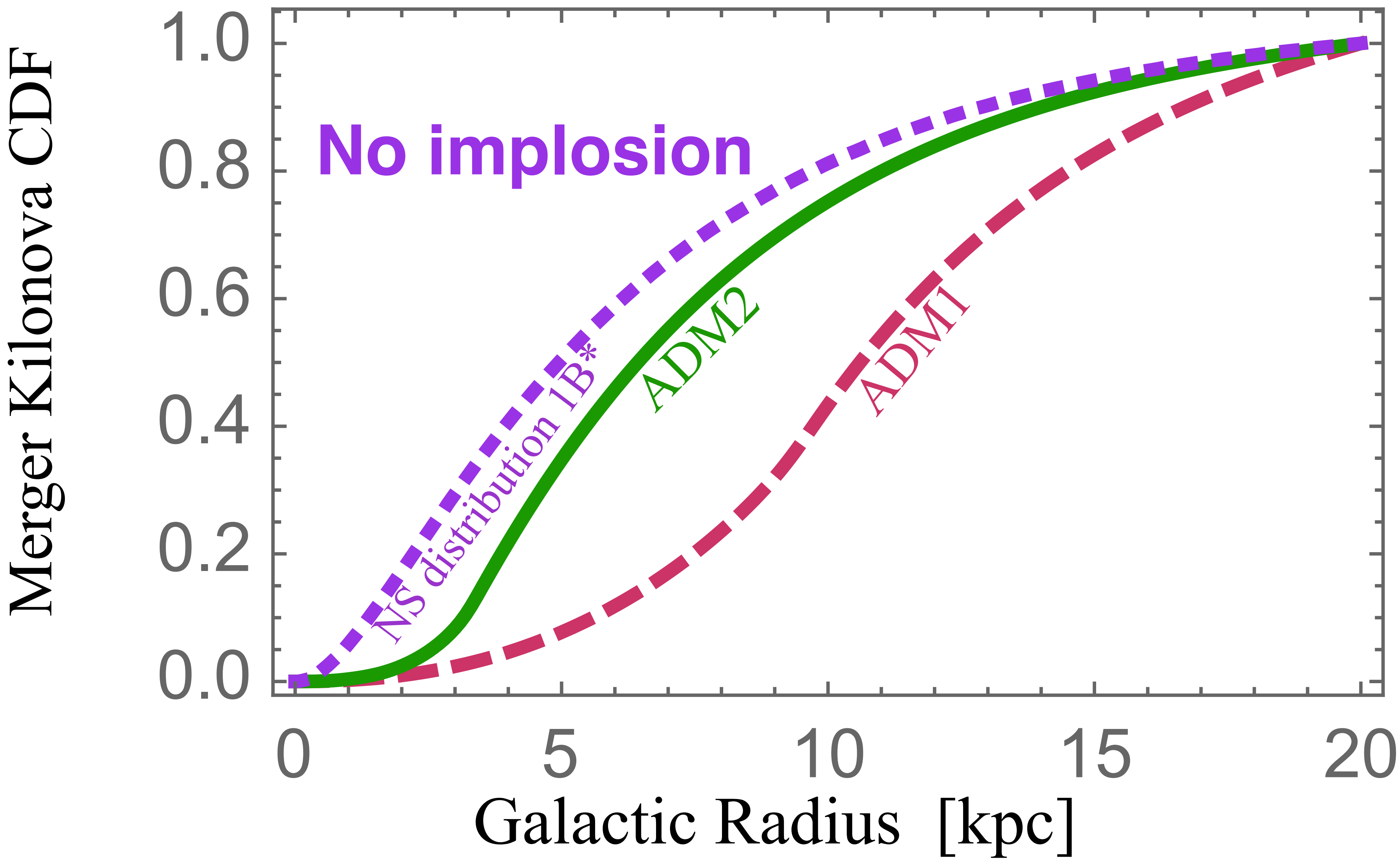
R-Process Donuts: Quiet kilonovae and standard NS merger kilonovae occur in donut shaped external regions of disc galaxies



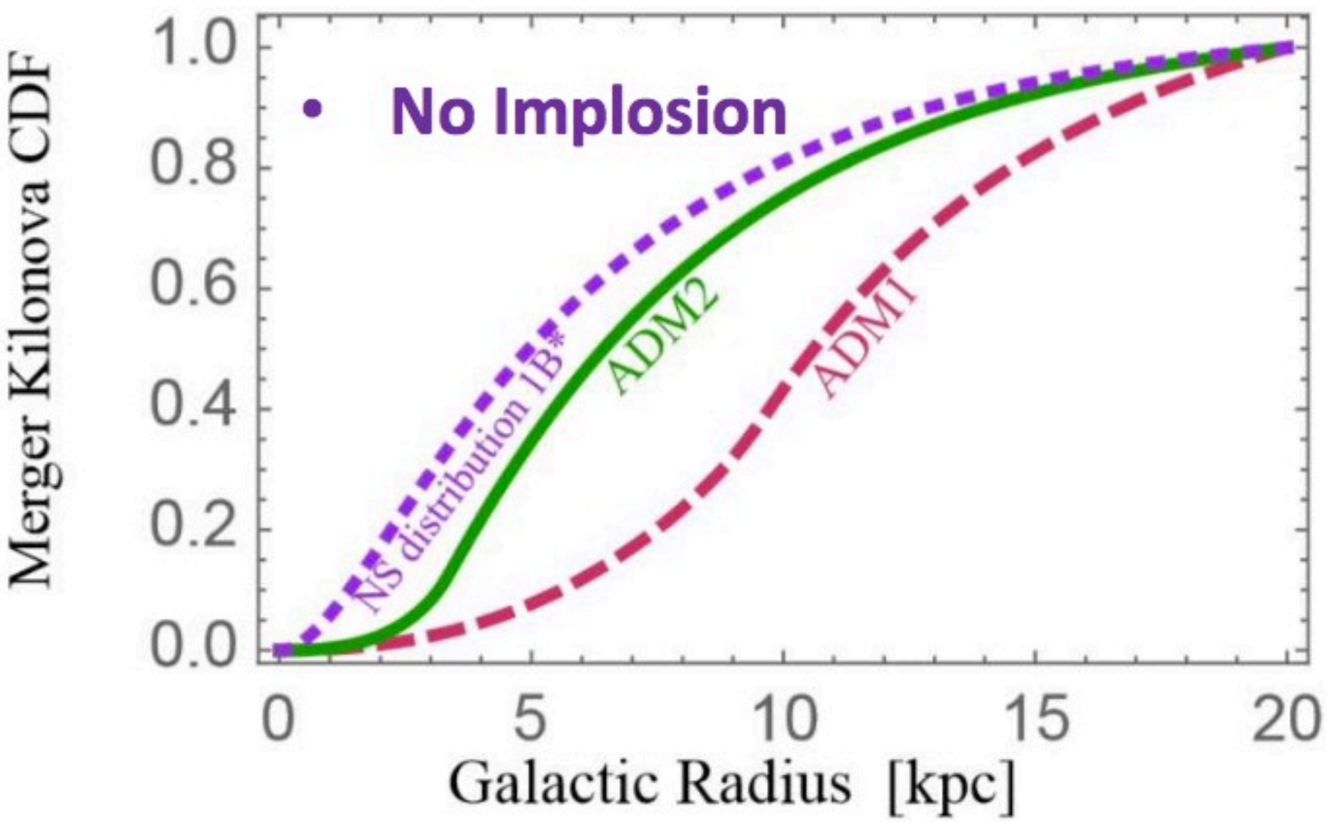
Dark Matter Alters Neutron Star Merger Locations in Galaxies

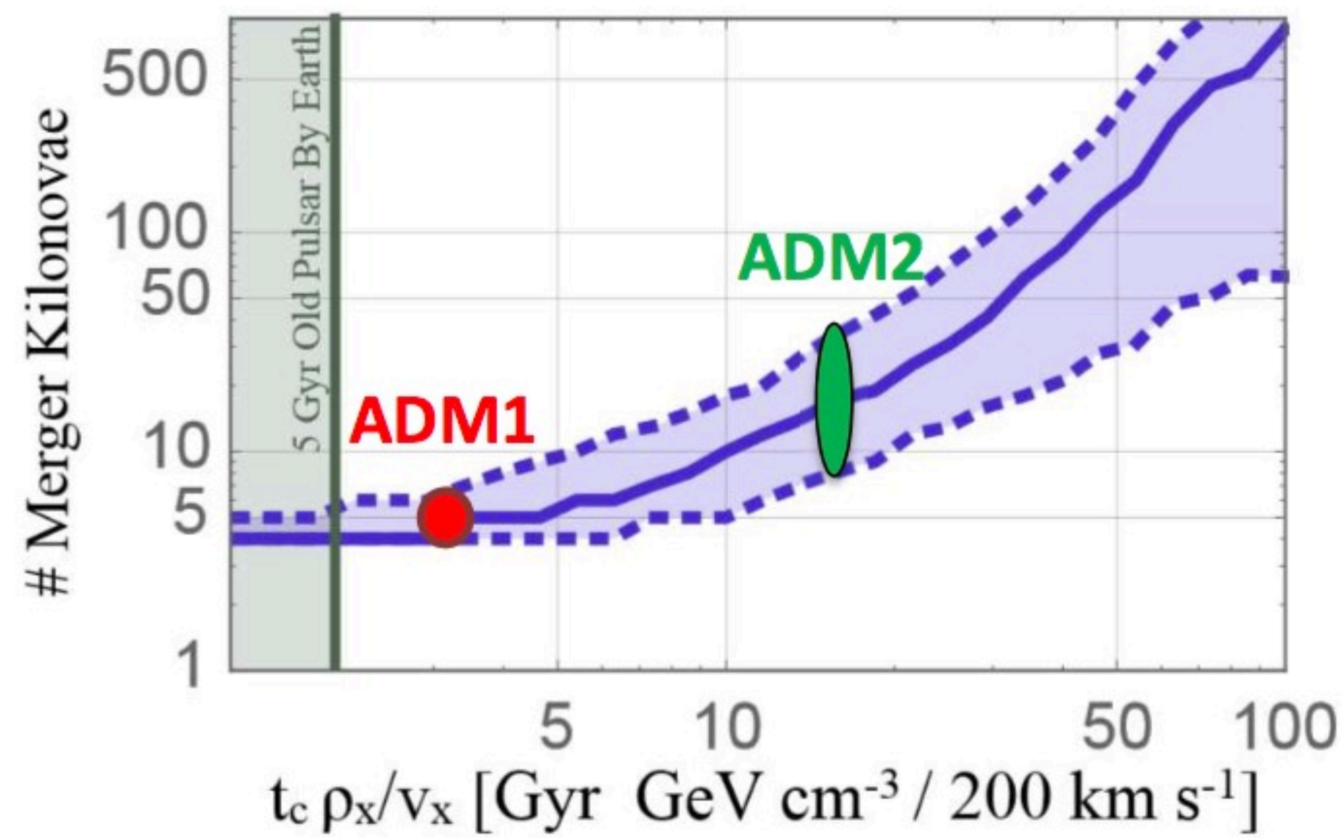
ADM1: Neutron Stars Implode 3 Gyr after birth for GeV/cm³ dark mater

ADM2: same, but 15 Gyr



Statistics of NS Mergers Located in Galaxies

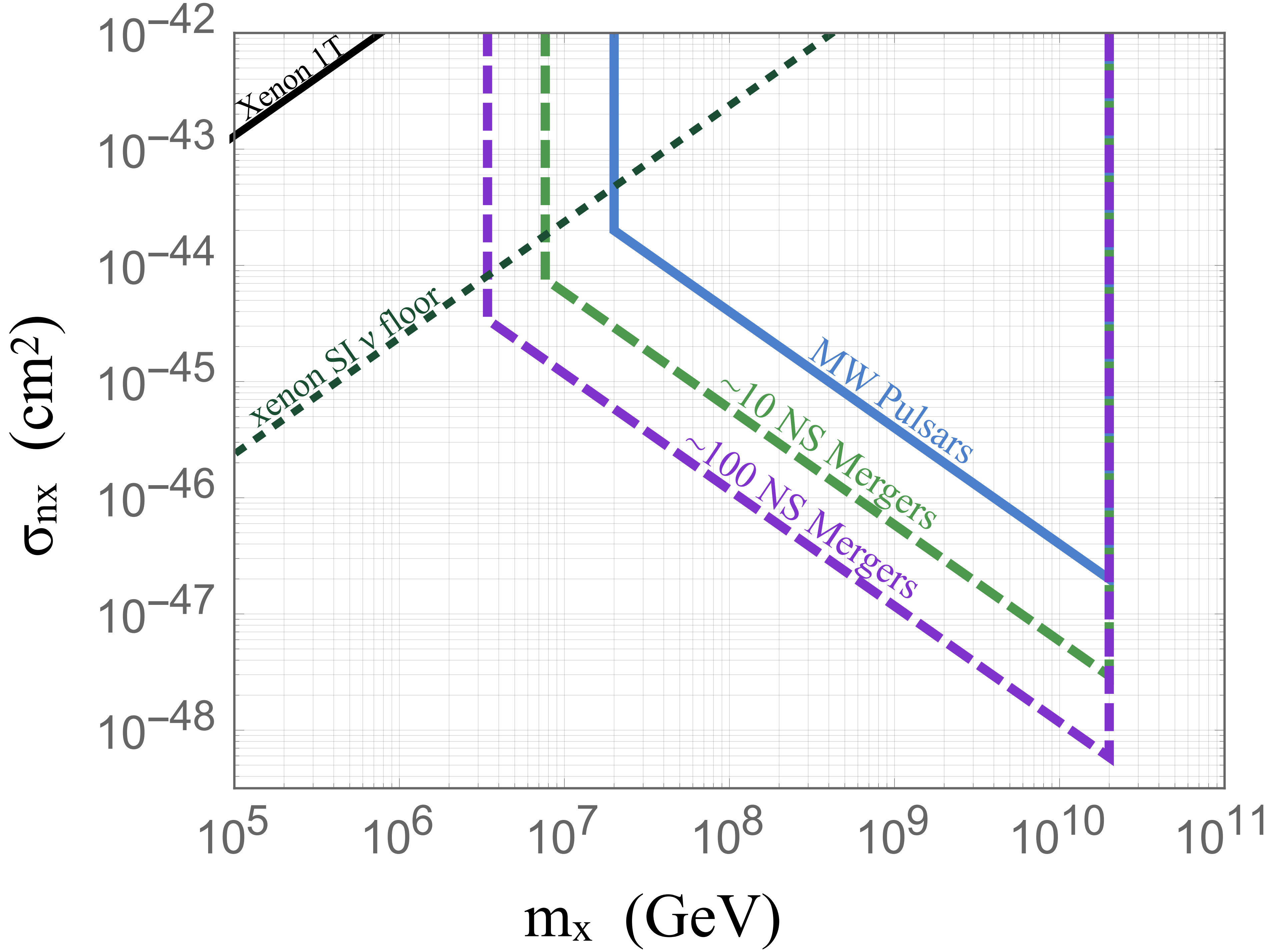




-Use large sample of Kolmogorov-Smirnov tests to determine how many NS mergers necessary to find dark matter

-Upper and lower quartile necessary to find dark matter shown in right plot

Asymmetric Dark Matter Using NS Merger Locations in Galaxies

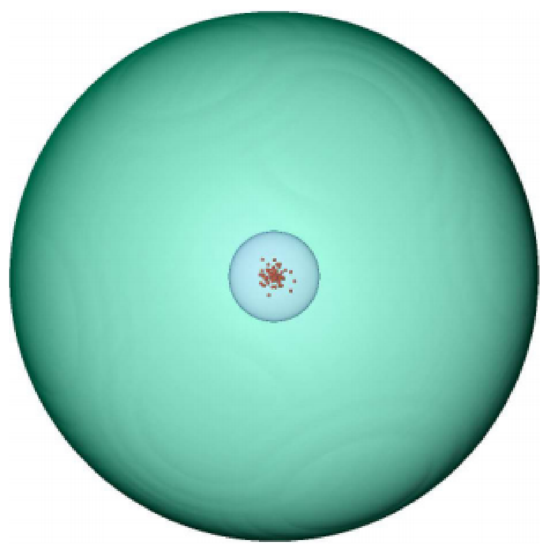


Dark Matter Ignition of Type Ia Supernovae

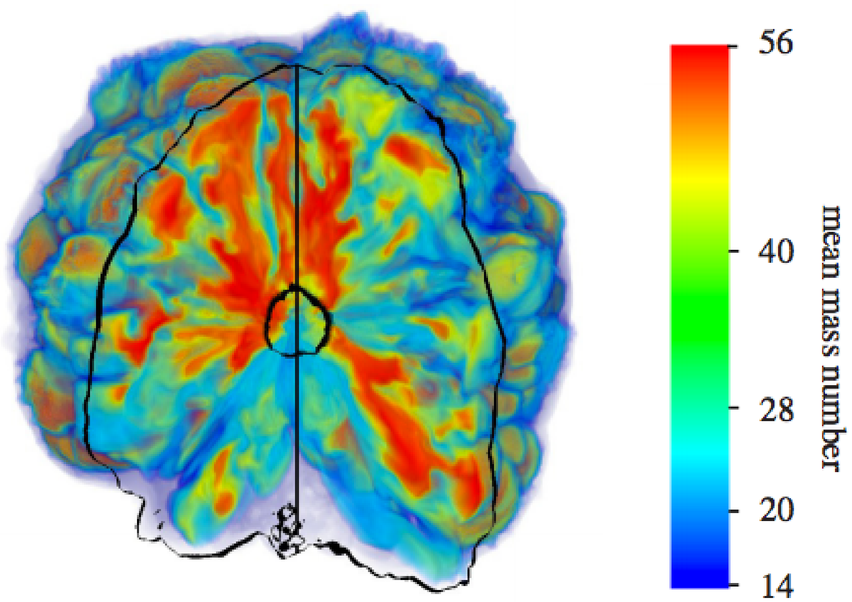
1. Heavy asymmetric dark matter can collapse inside, ignite, and explode white dwarfs.

2. There are interesting implications for the origin of Type Ia Supernovae.

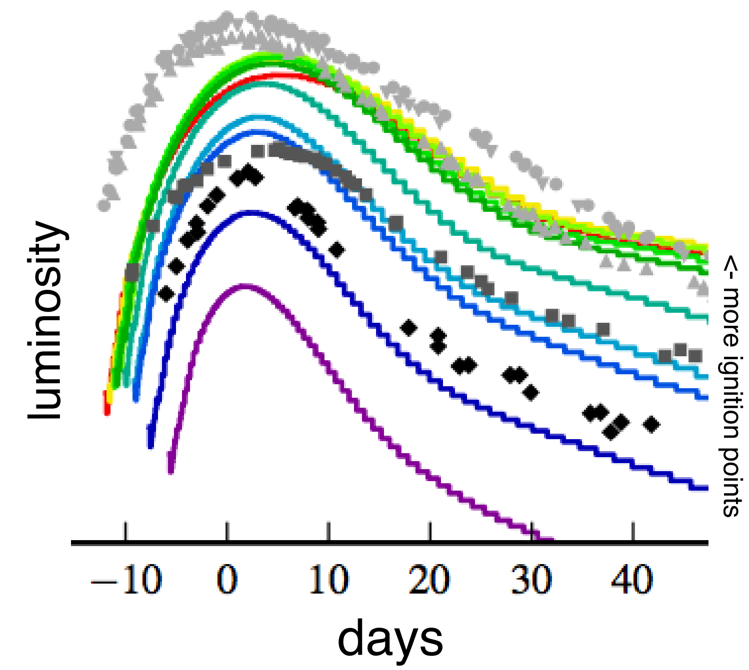
JB PRL 2015



ignition



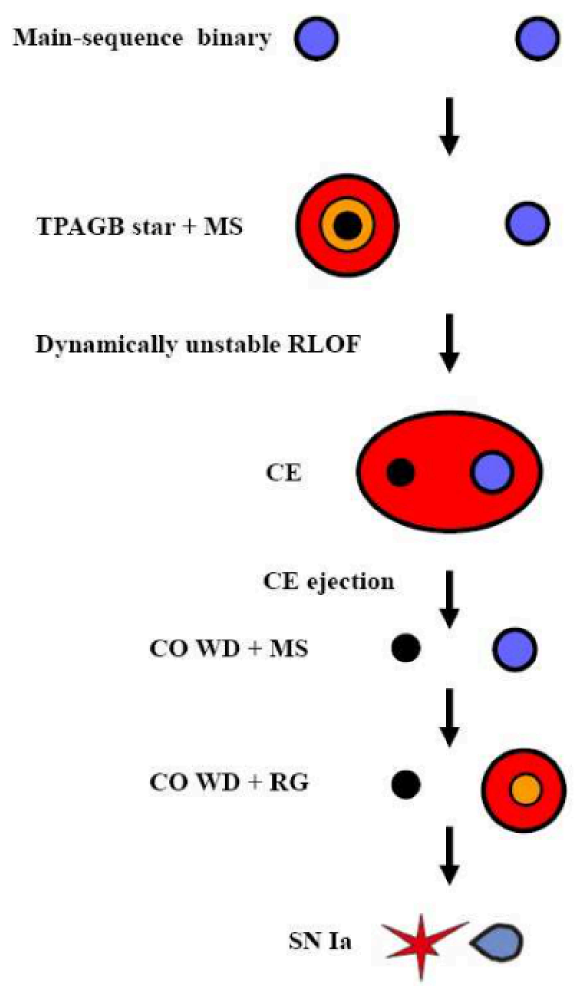
nuclei fuse (^{56}Ni)



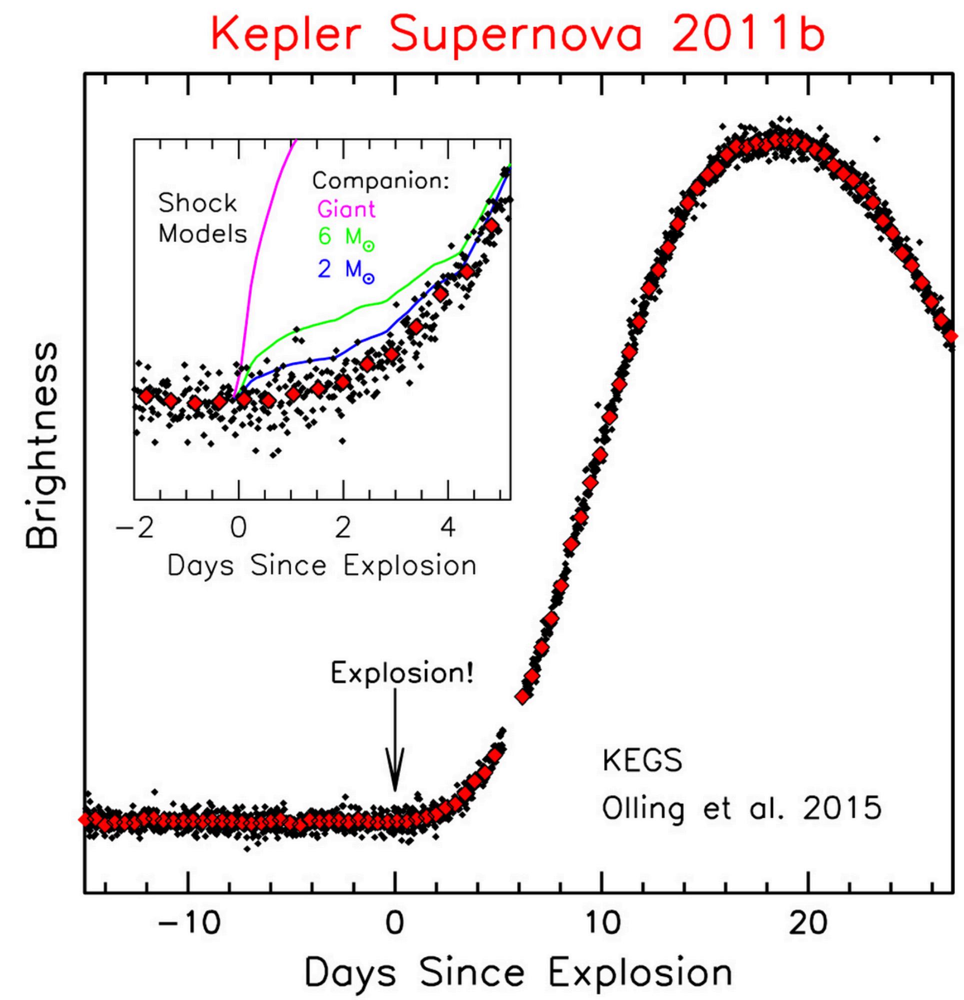
nuclei decay

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.

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



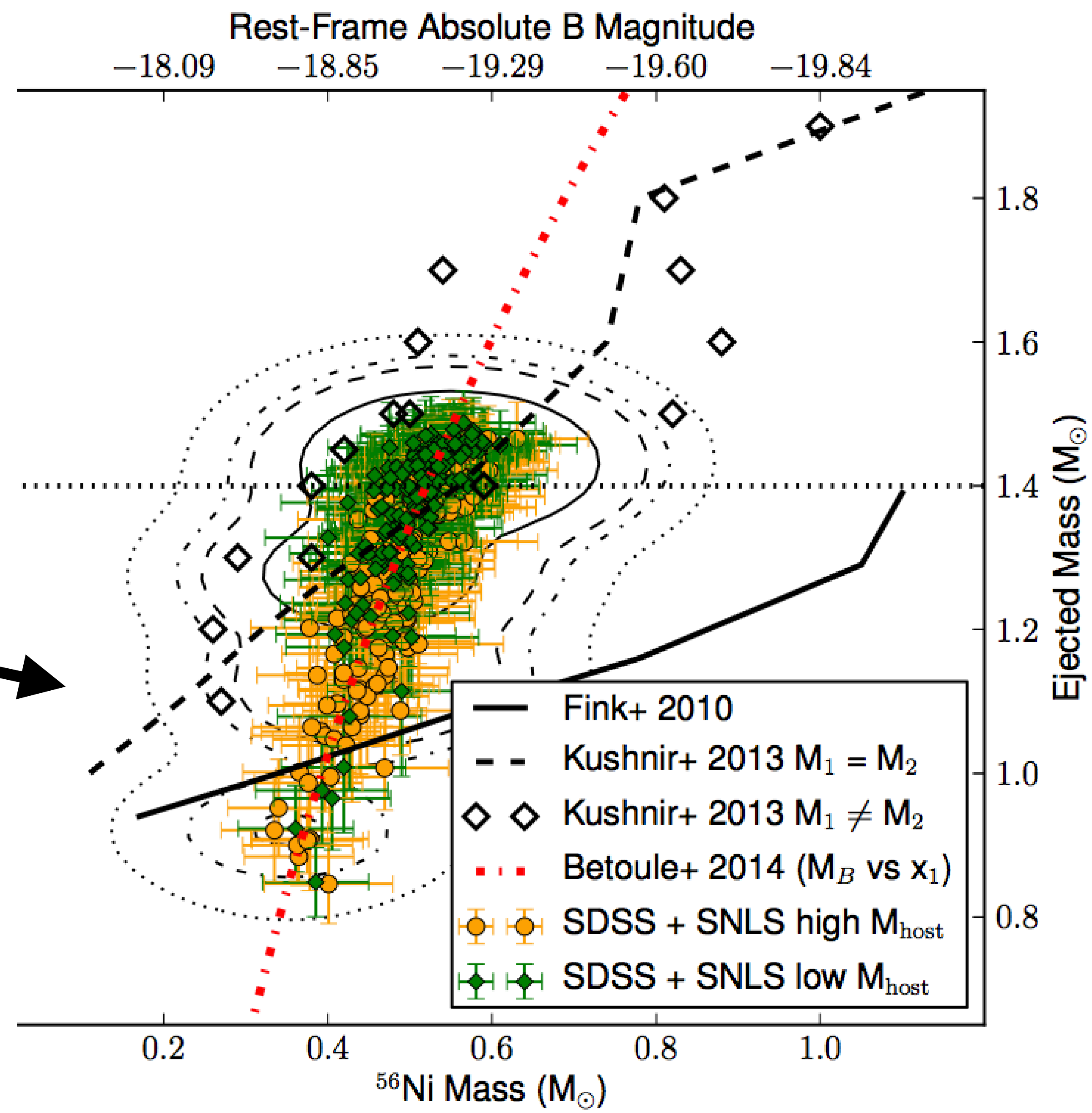
implied shocks not seen



Binary accretion ignition is now disfavored, by a lack of companion star "shocks" in SNIa light curves, along with the non-observation of H or He lines in any type Ia spectra. White dwarf mergers may work, if the merger rate can match the high rate of type Ias.

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

The existence of sub-Chandrasekhar supernovae presents a quandary that binary accretion has trouble accounting for.



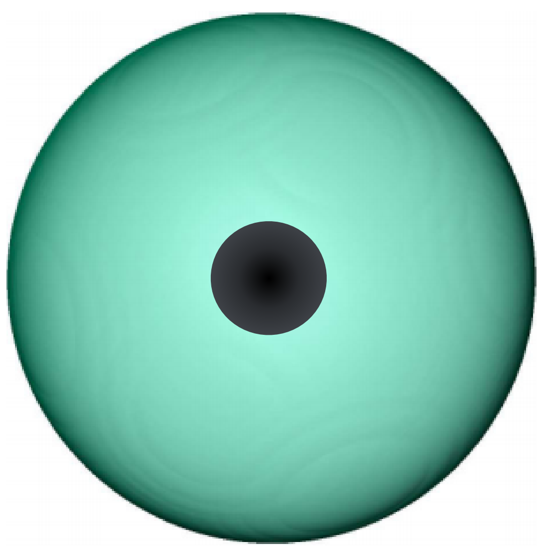
Long tail of
sub-Chandrasekhar mass SNIa

1408.6601

$$\frac{M_{\rm ej}}{M_\odot} = (1.322 \pm 0.022) + (0.185 \pm 0.018)x_1, \quad x_1 = [-3, 2]$$

Heavy Dark Matter Ignition of Type Ia Supernovae

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 collects to the point of self-gravitation within ~10^{10} years.



DM collects to the point of self-gravitation.

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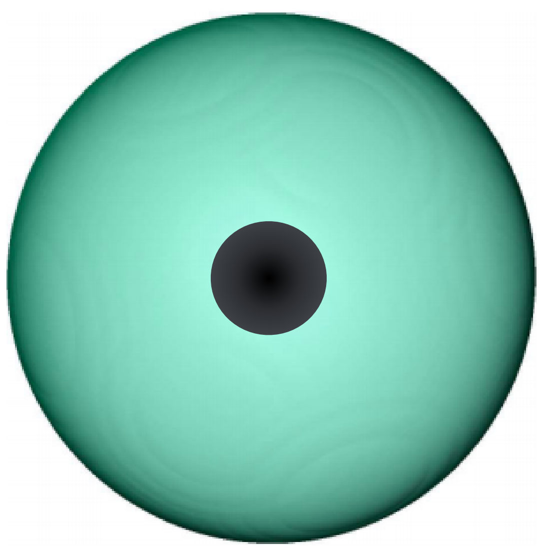

DM collects to the point of self-gravitation.

Harmonic Oscillator potential

$$k_B T \sim G \rho_{wd} m_x r_{th}^2$$

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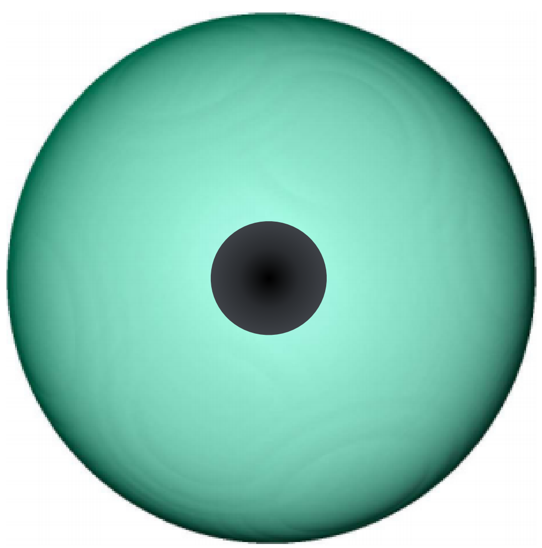

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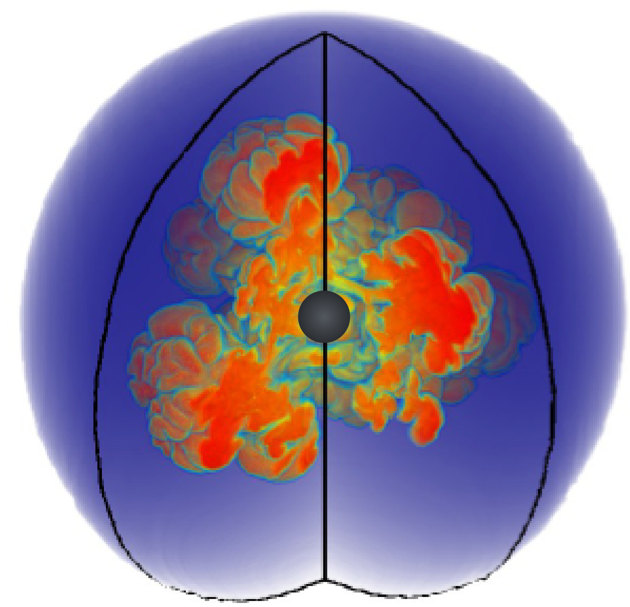
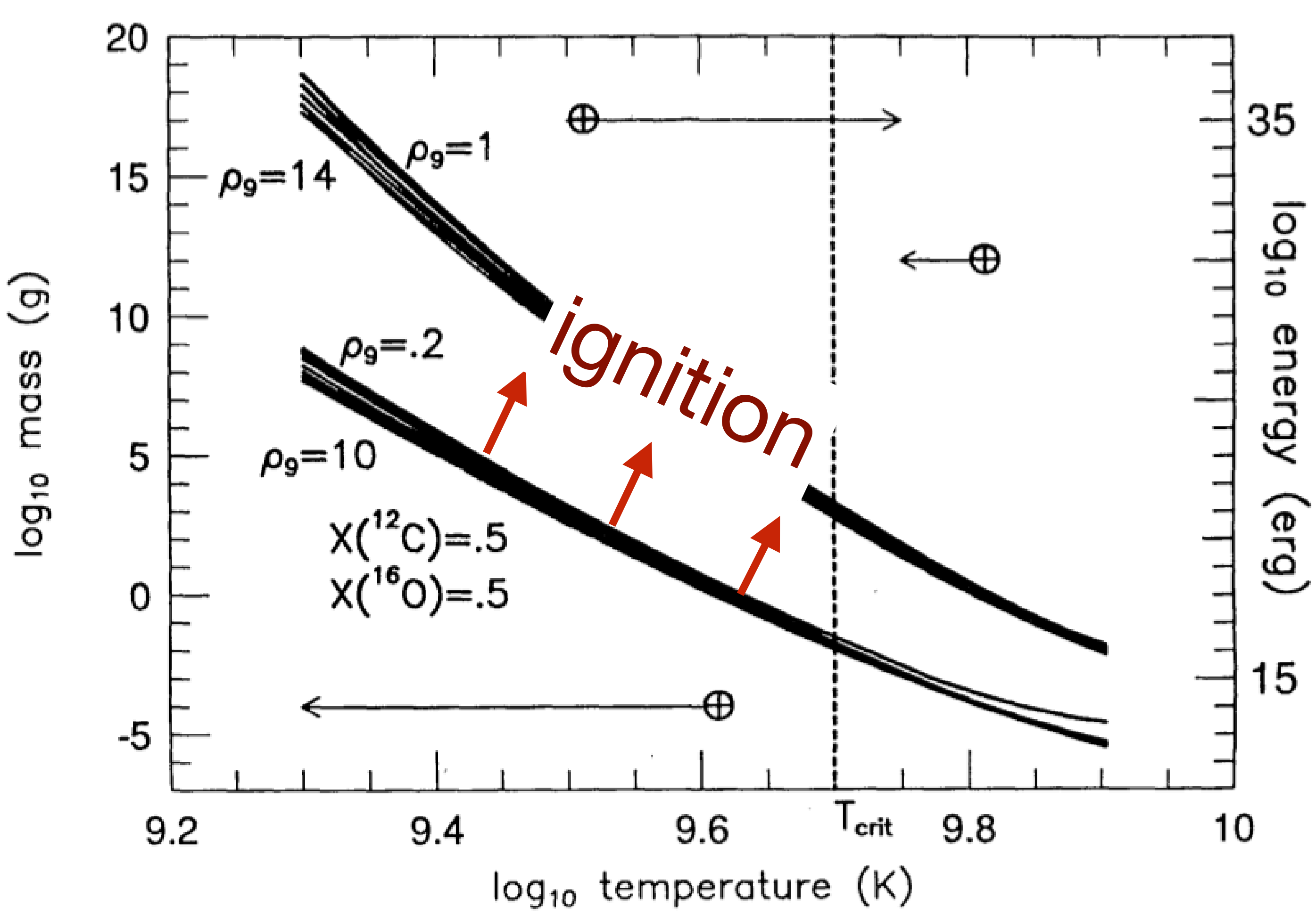


DM collapses, shedding gravitational potential energy by scattering with nuclei, igniting a supernova.

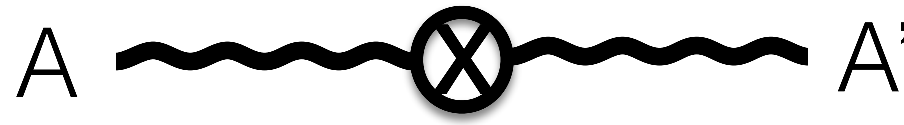
As it collapses to its minimum energy state, the dark matter will shed gravitational potential energy.



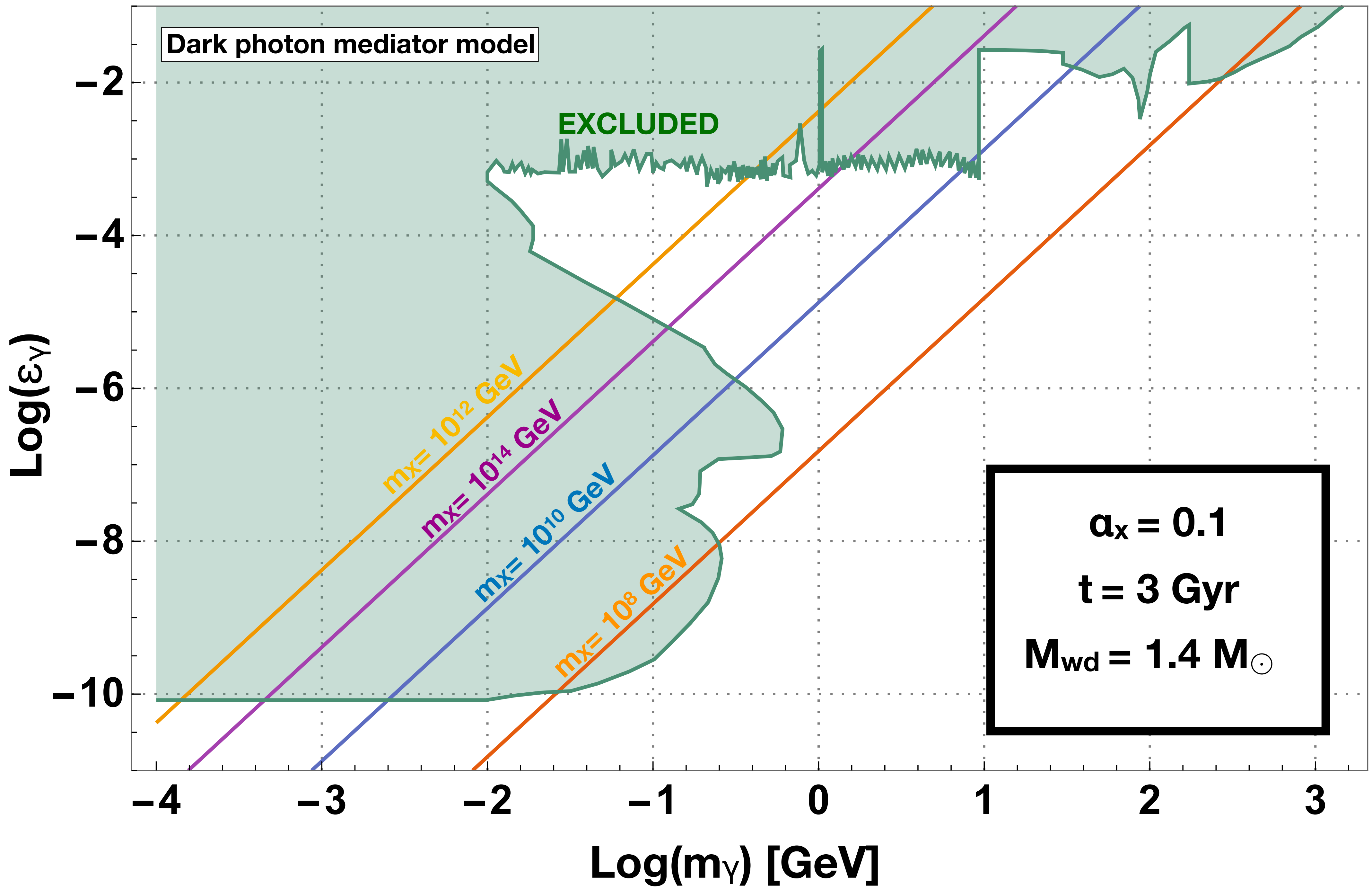
Timmes & Woosley 1992

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.

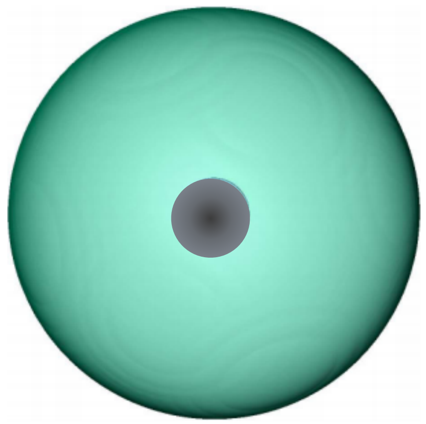
Vector Portal Model



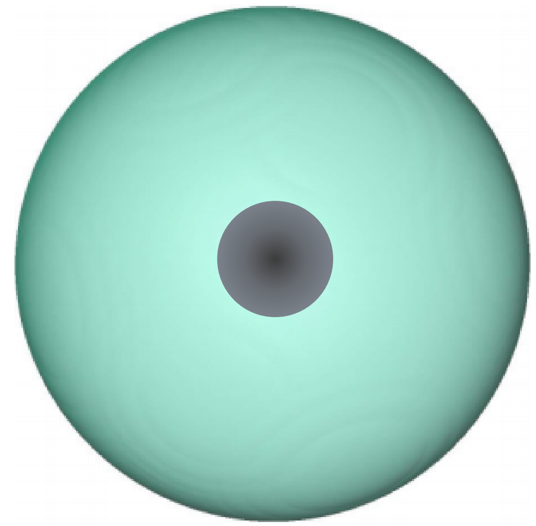
$$\mathcal{L} = \mathcal{L}_{\rm SM} + |D_\mu \Phi|^2 - V(\Phi) - \frac{1}{4} {F'}^2_{\mu\nu} + \epsilon {A'}_\mu \partial_\nu F^{\mu\nu} + \bar{X}(iD_\mu \gamma_\mu - m_X)X$$



Javier Acevedo, JB 2019



more massive WD,
DM collapses sooner

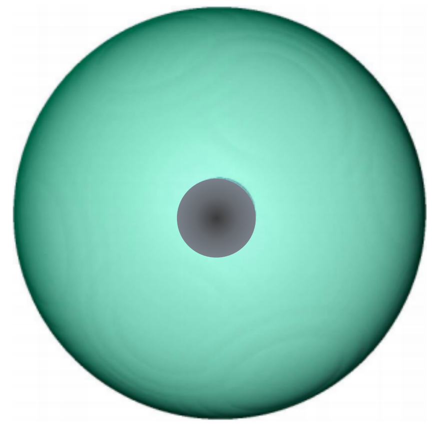


less massive WD,
DM collapses later

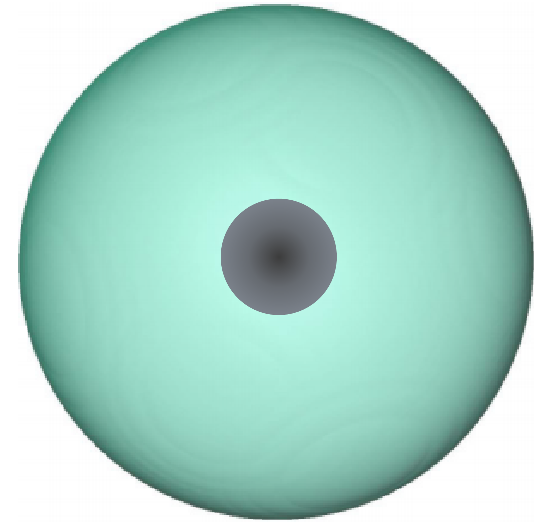
A more massive white dwarf is denser, so dark matter collects into a smaller ball, and collapses sooner.

Altogether, this shortens the time for dark matter collapse in more massive white dwarfs.

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



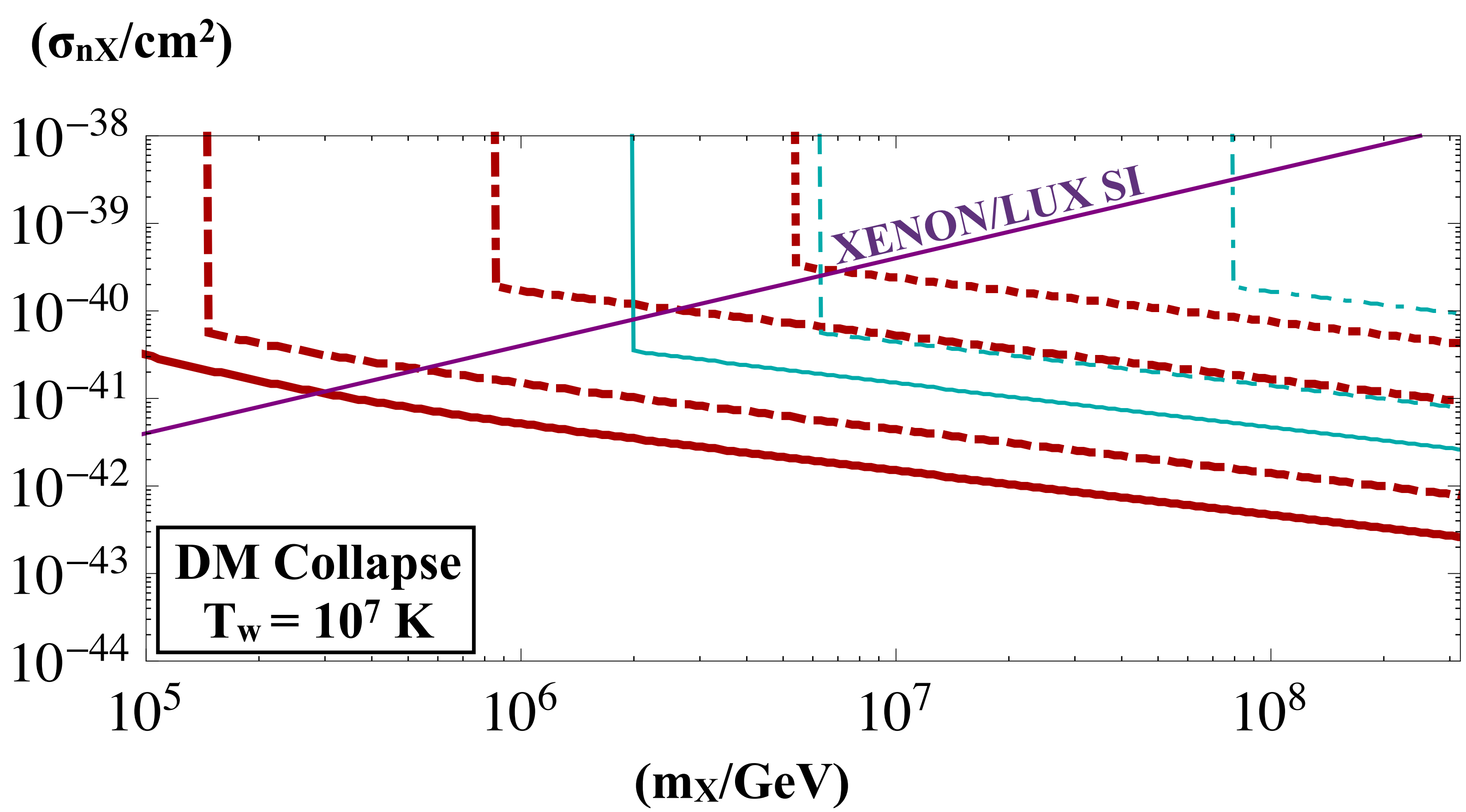
(less) DM collapses sooner



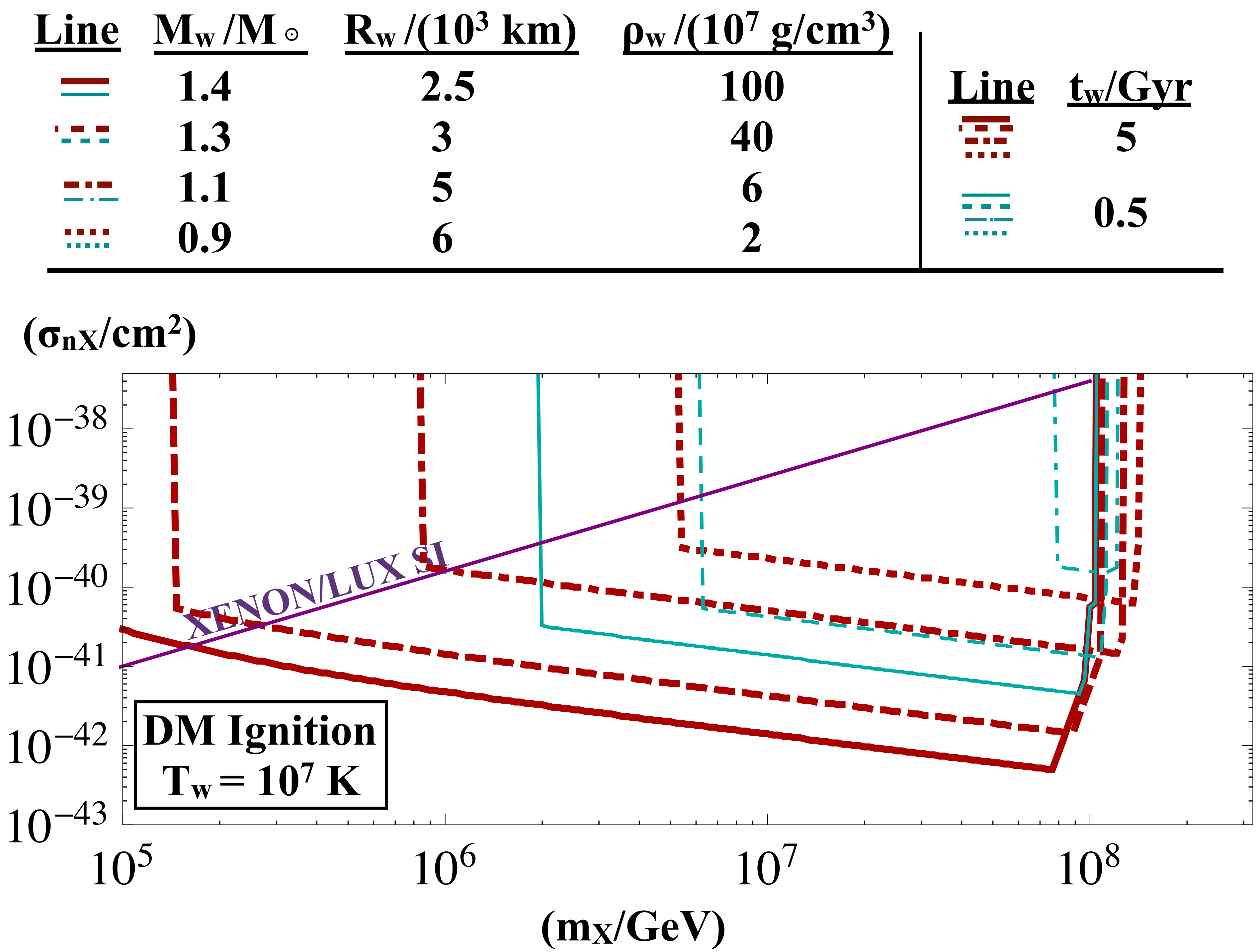
(more) DM collapses later

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

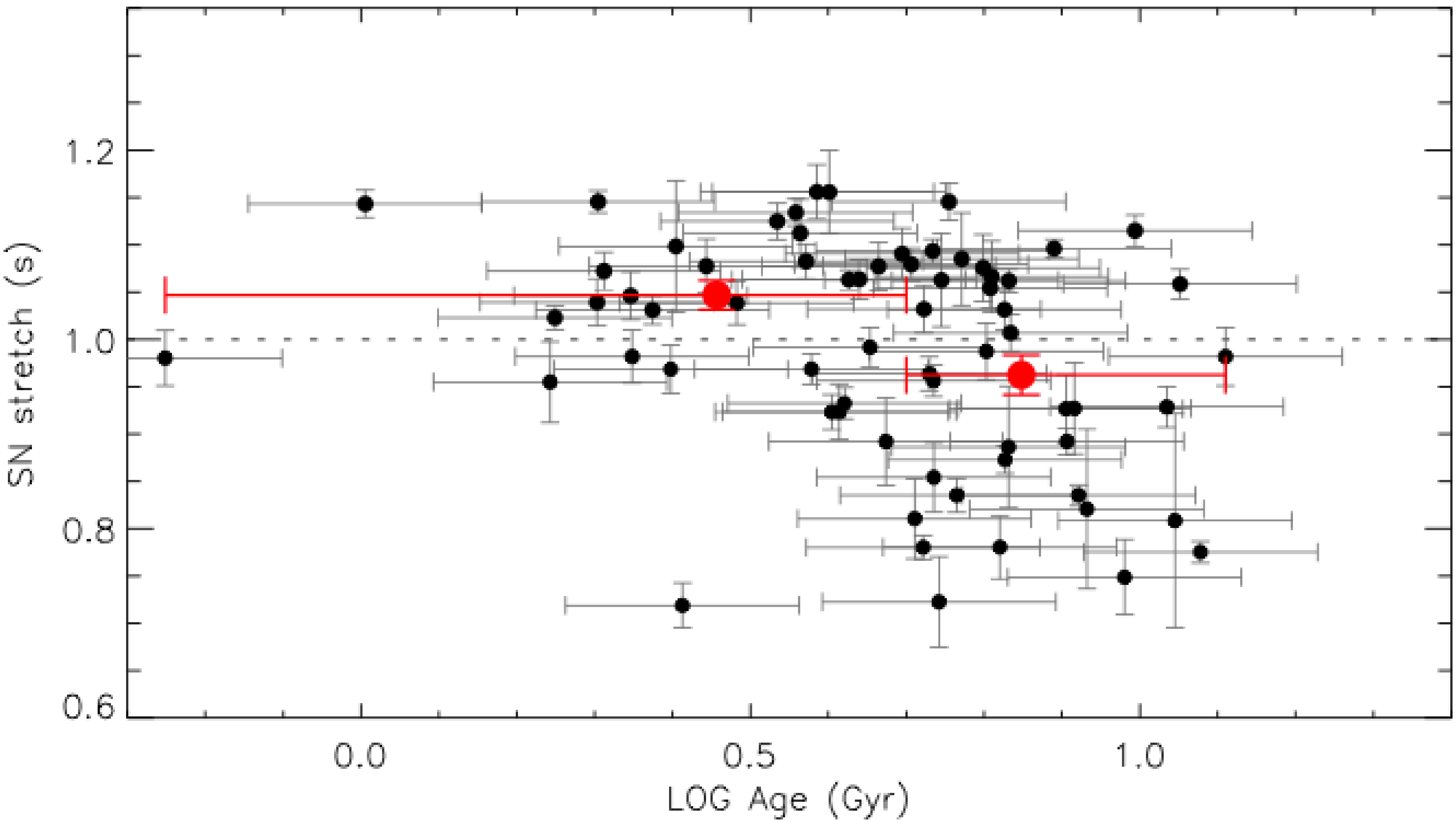
Line	t_W/Gyr
	5
	0.5



The limiting factor for heavy DM-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.

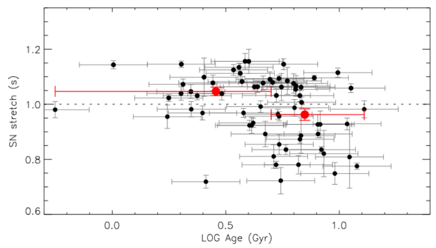


Sensitivity to high mass dark matter below current limits.

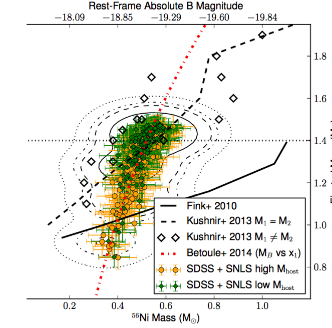


1311.6344

There is an unexplained correlation between the age of type Ia supernovae host galaxies, and the "stretch" of the type Ia lightcurve. Note that, as we saw earlier, type Ia stretch correlates with type Ia progenitor white dwarf mass.



1311.6344

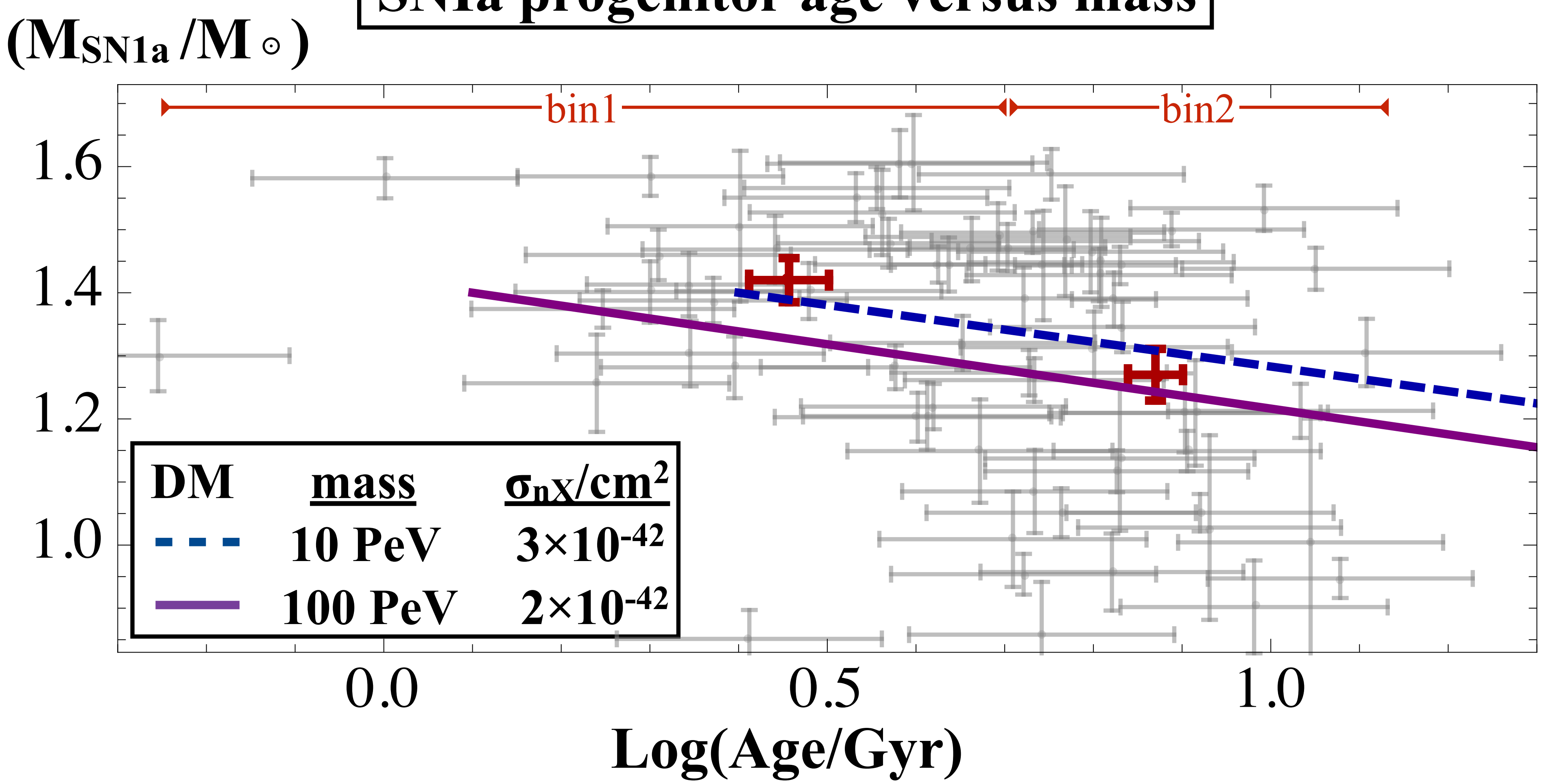


1408.6601

Data on the ages of stars adjacent to type Ia supernovae

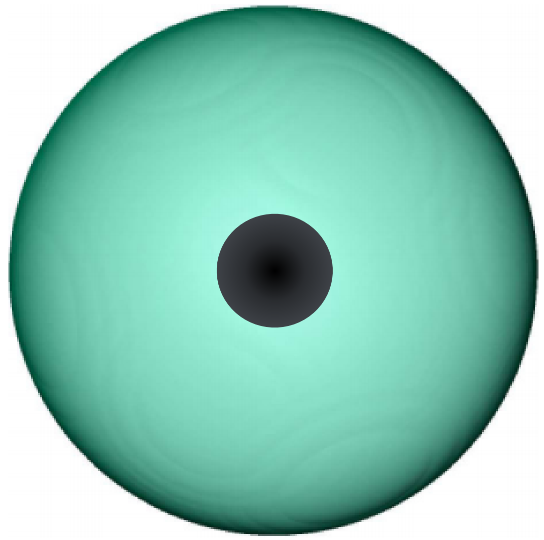
Data on the mass of type Ias inferred from luminosity

SNIa progenitor age versus mass

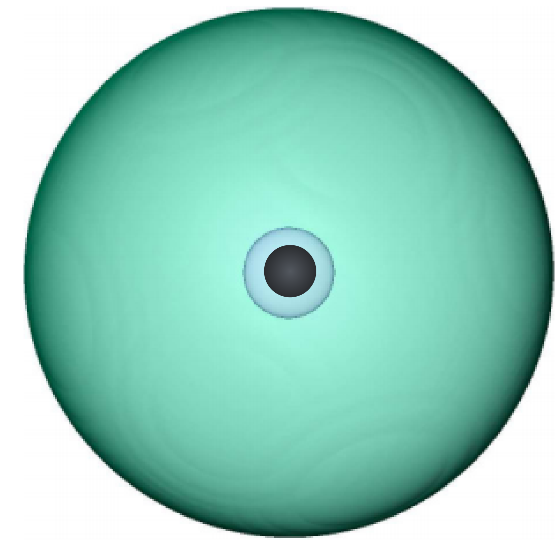


Interesting trend — more massive WDs explode sooner.

Two New Heavy Dark Matter White Dwarf Ignition Mechanisms

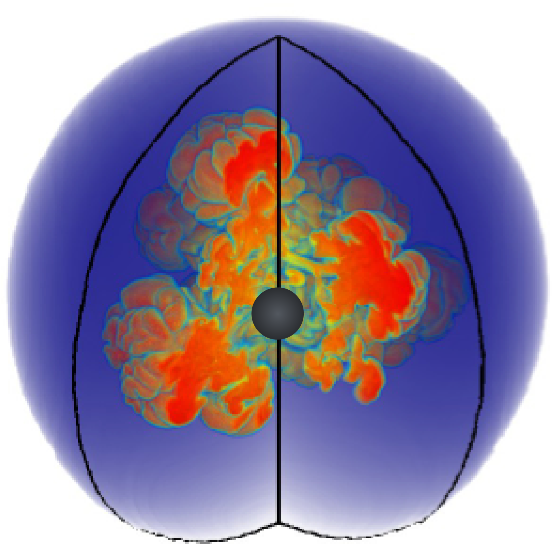


DM collects



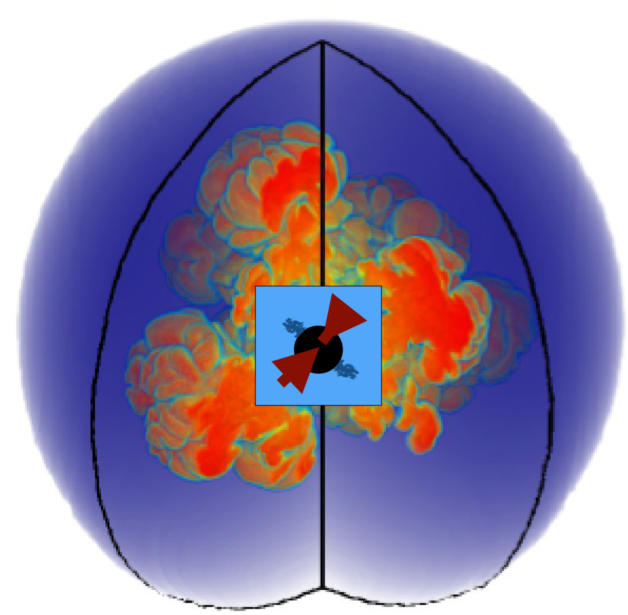
DM collapses

A. Strong Ignition

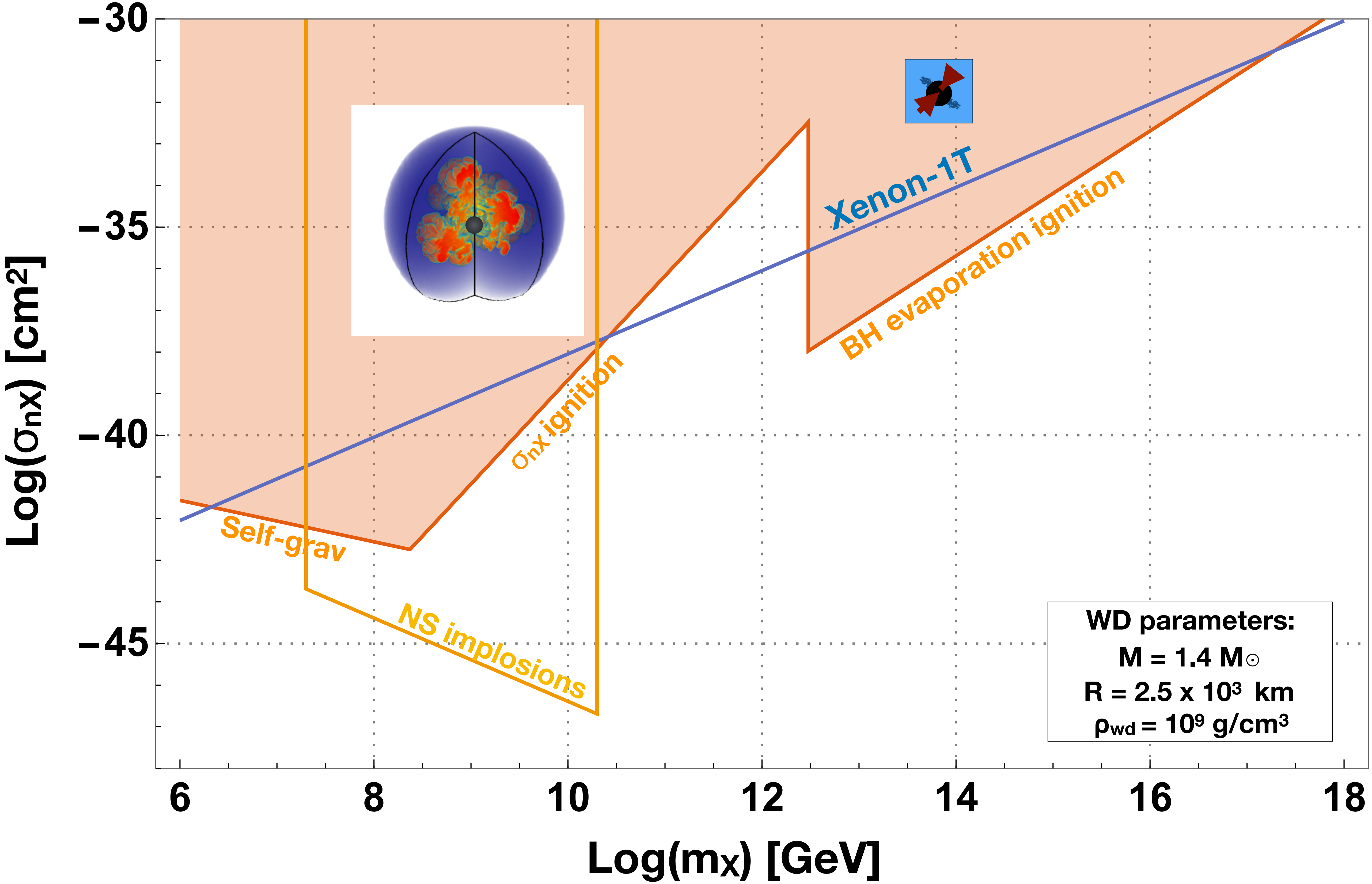


1. Higher dark matter cross-section than required for collapse causes ignition

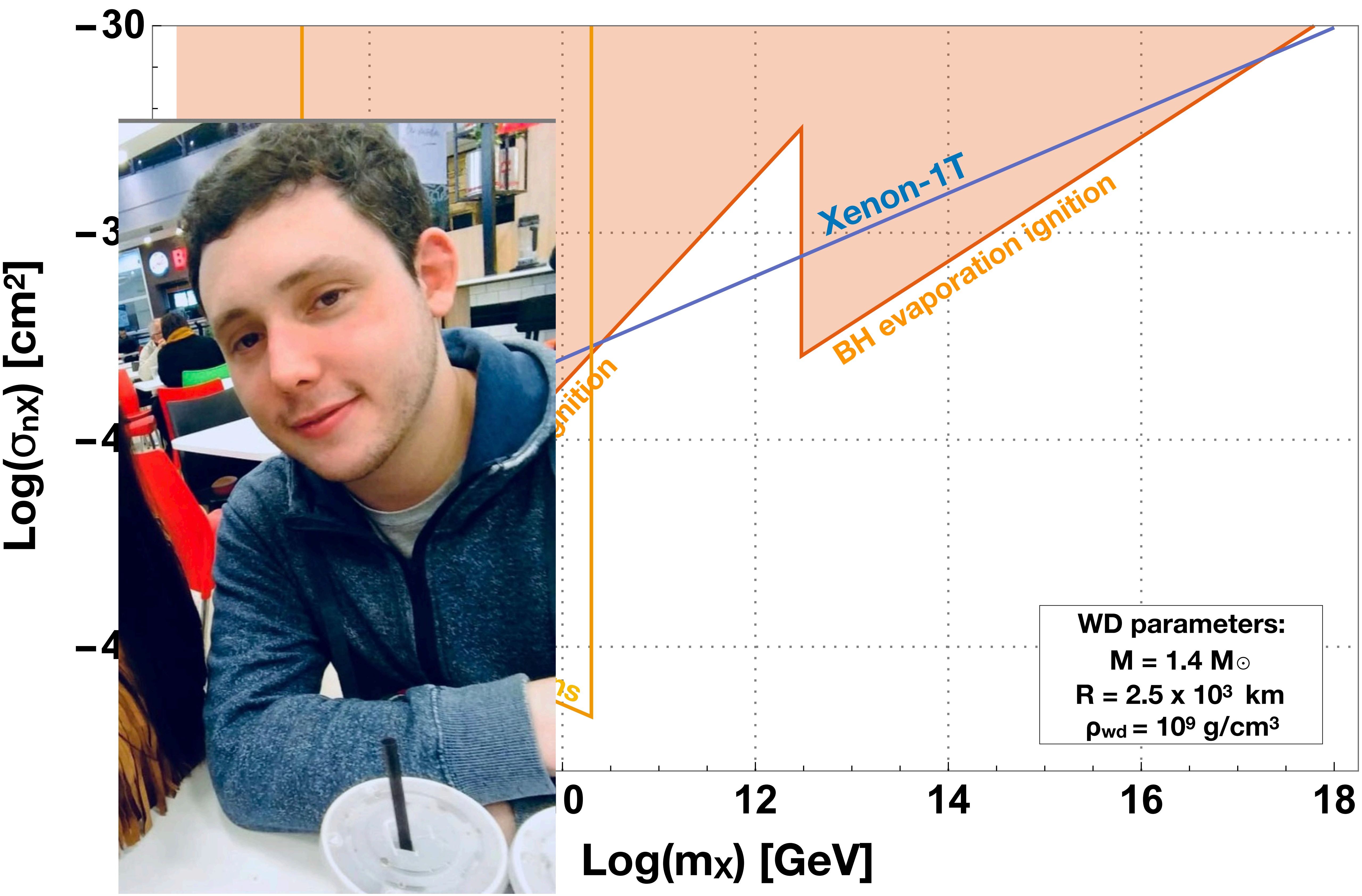
B. Hawking Ignition



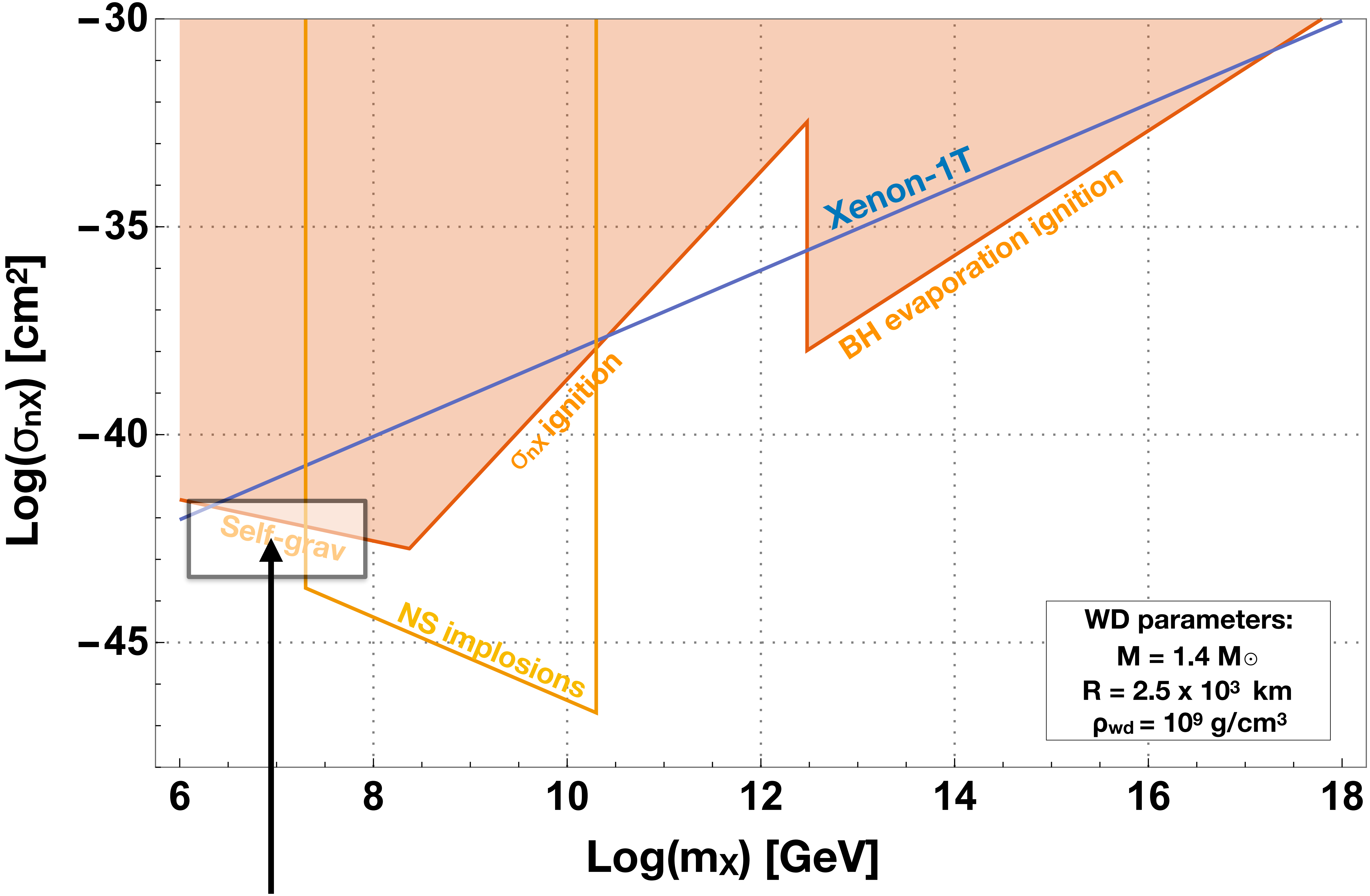
1. No ignition during collapse.
2. Small black hole forms.
3. Evaporating black hole ignites WD.



Log(σnX) [cm²]
Log(mX) [GeV]
−30
−35
−40
−45
6
8
10
12
14
16
18
Xenon-1T
BH evaporation ignition
σnX ignition
Self-grav
NS implosions
WD parameters:
M = 1.4 M⊙
R = 2.5 x 10³ km
ρwd = 10⁹ g/cm³



Javier Acevedo



Cool parameter space: implodes GC pulsars, type Ia progenitor solution, can be found at next-gen direct detection.

Thanks!