Fermionic Dark Matter and Electron-Capture Supernovae

Pathways to Low-Mass Neutron Stars

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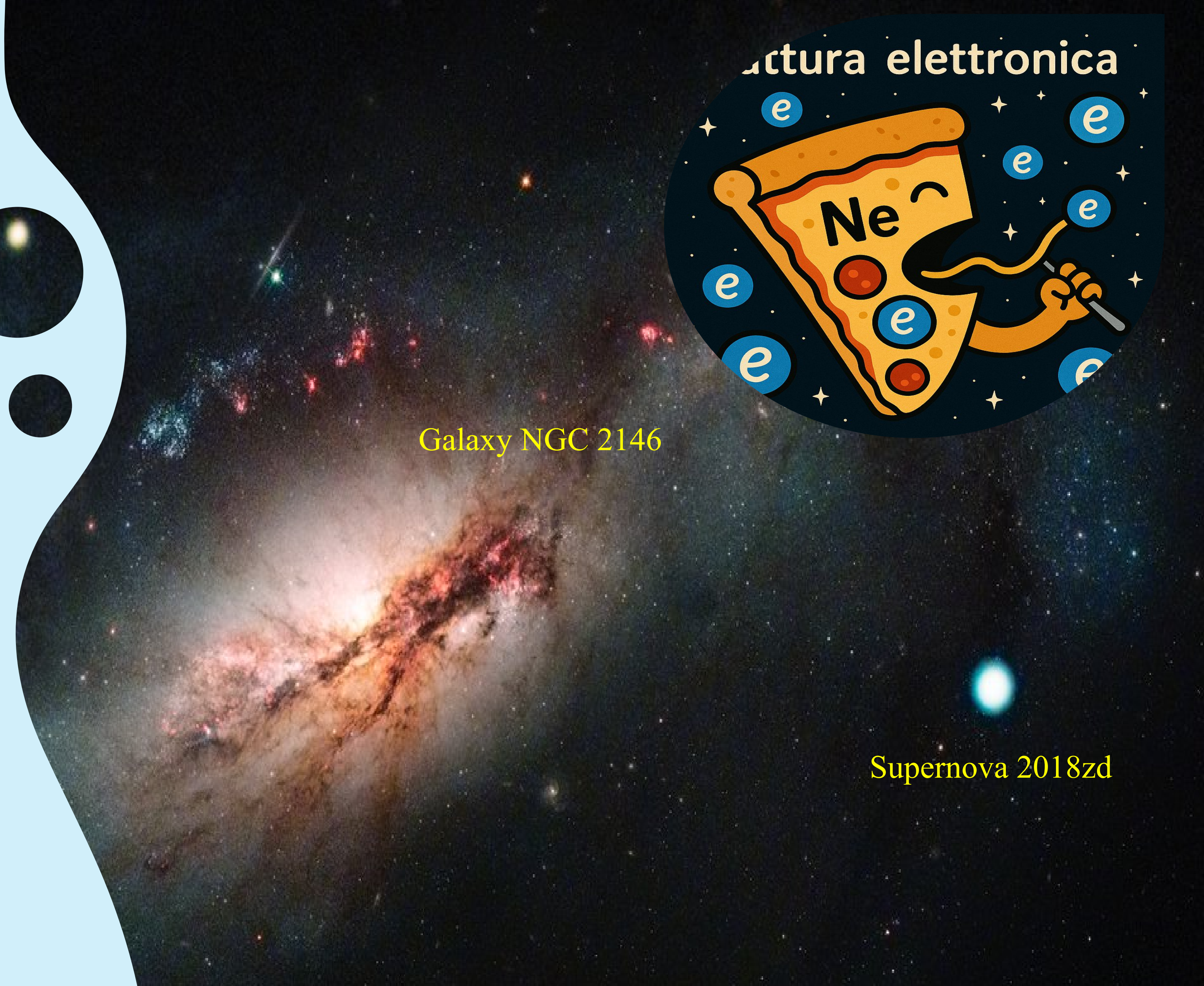
SEMINARIO SCIENTIFICO, INFN Pisa



Las Cumbres Observatory and Hubble Space Telescope color composite of the electron-capture supernova 2018zd (the large white dot on the right) and the host starburst galaxy NGC 2146 (toward the left). Credit: NASA/STScI/J. DePasquale; LCO

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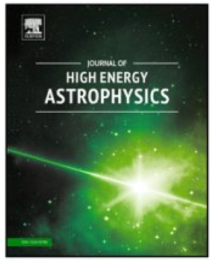

Triggering electron capture supernovae: Dark matter effects in degenerate white-dwarf-like cores of super-asymptotic giant branch stars

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OCTOBER 22, 2025 FEATURE The GIST

Exploring how dark matter alters electron-capture supernovae and the birth of neutron stars

by Ingrid Fadelli, Phys.org

edited by Sadie Harley, reviewed by Robert Egan Editors' notes

Outline

Introduction

- Nuclear Matter
- Neutron Star Anatomy
- Equation of State: Uncertainties and Implications

Electron capture supernovae (ECSNe): Discovery and Implication

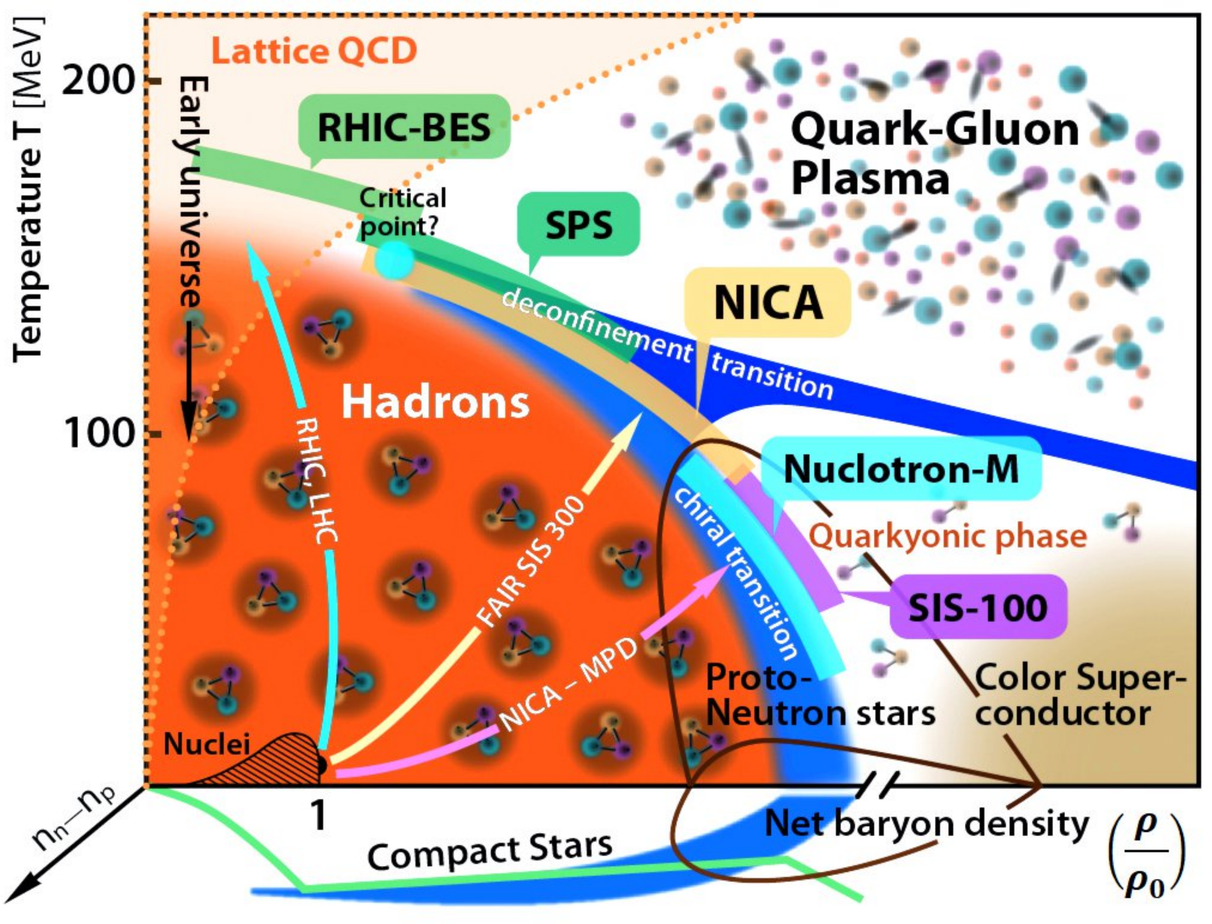
EoS for Dark Matter, Neutron star and White dwarf

Dark matter effect on Neutron star formed from ECSN

Implication and Future Prospective

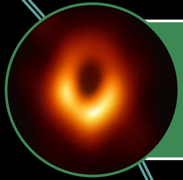
Nuclear Matter: Nuclei and Neutron Star

Nuclear Matter Phase Diagram

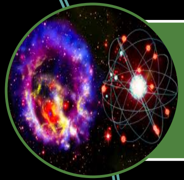


Universe 4, 52, 2018

Neutron Star: A Physics Goldmine

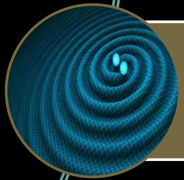


Astrophysics: What is the minimum mass of a black hole?

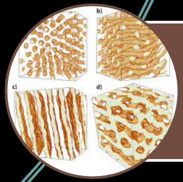


Nuclear Physics: What are the limits of nuclear existence and the EOS of nuclear matter?

Particle Physics: Dense quark matter and quark-gluon plasma?

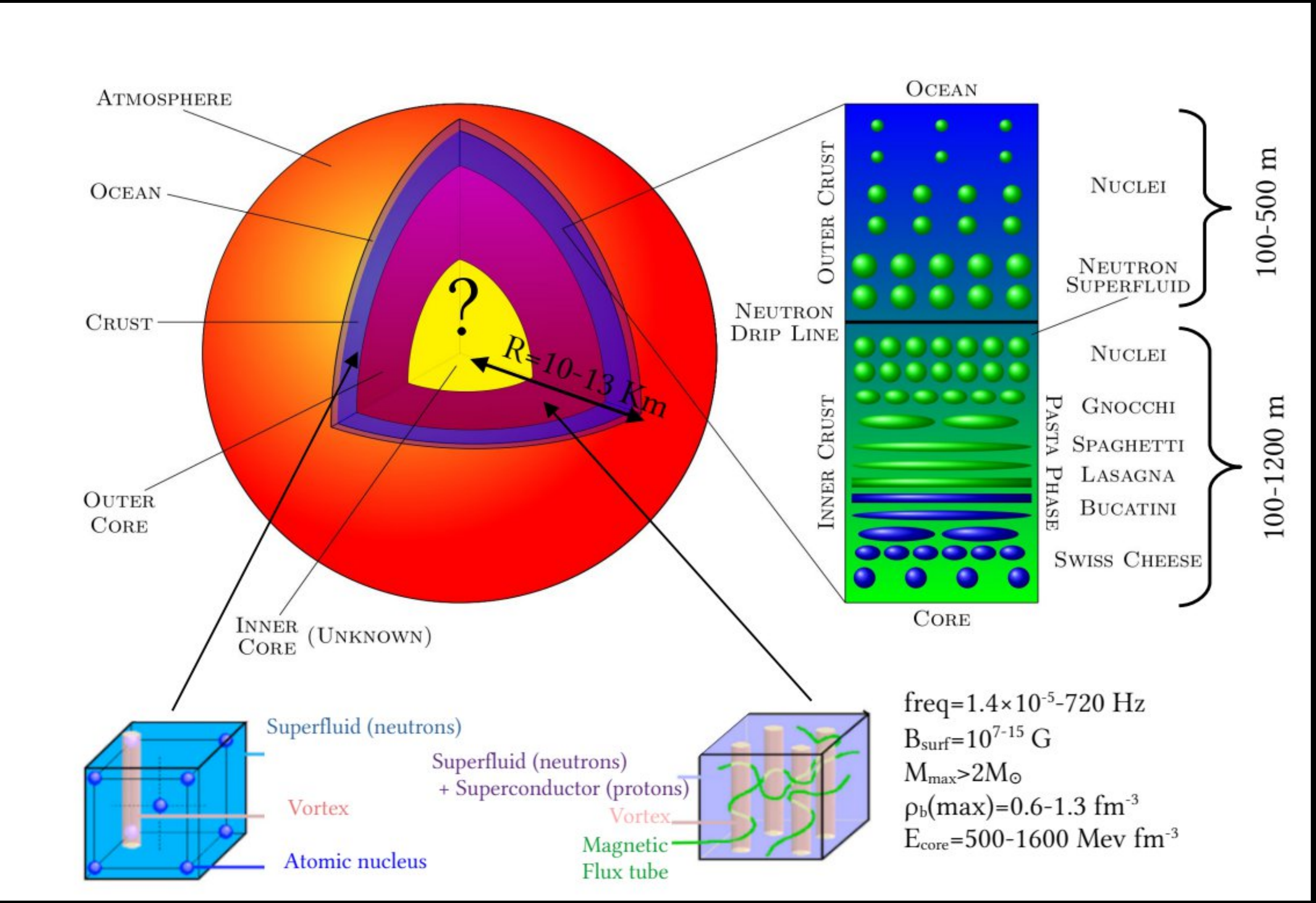


General Relativity: Rapidly rotating neutrons stars as a source of gravitational waves?



Condensed-Matter Physics: Signatures for the liquid to crystalline state transition?

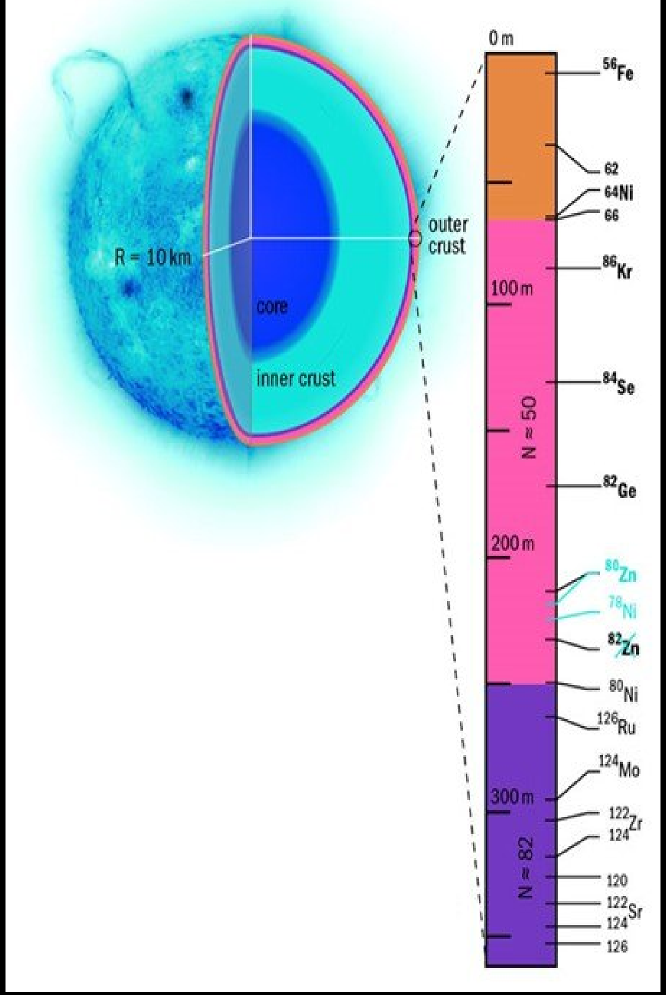
Anatomy of Neutron Star

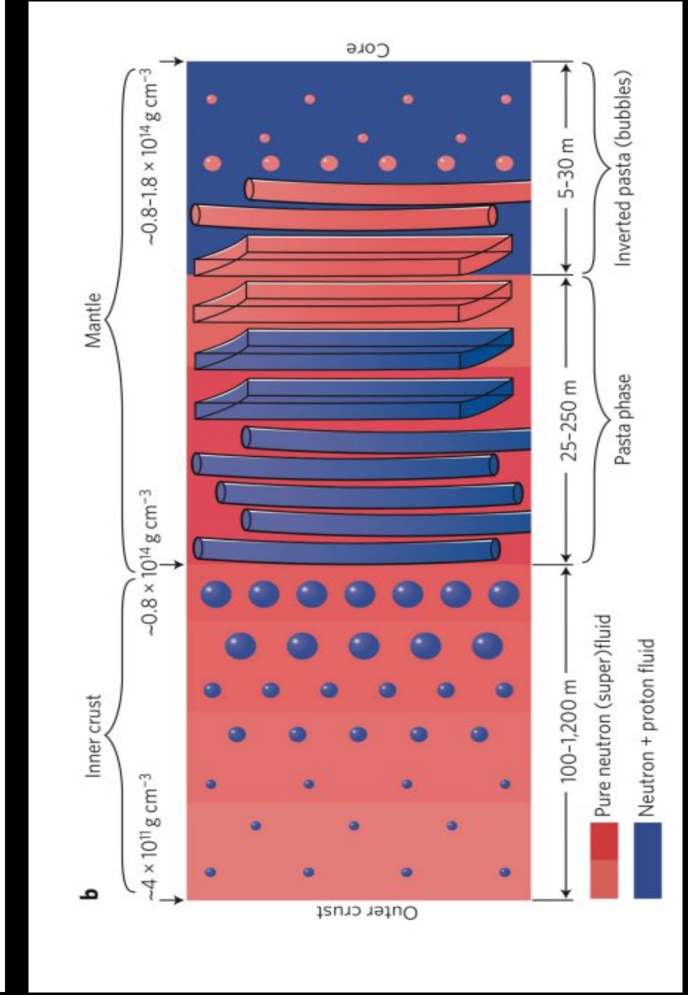


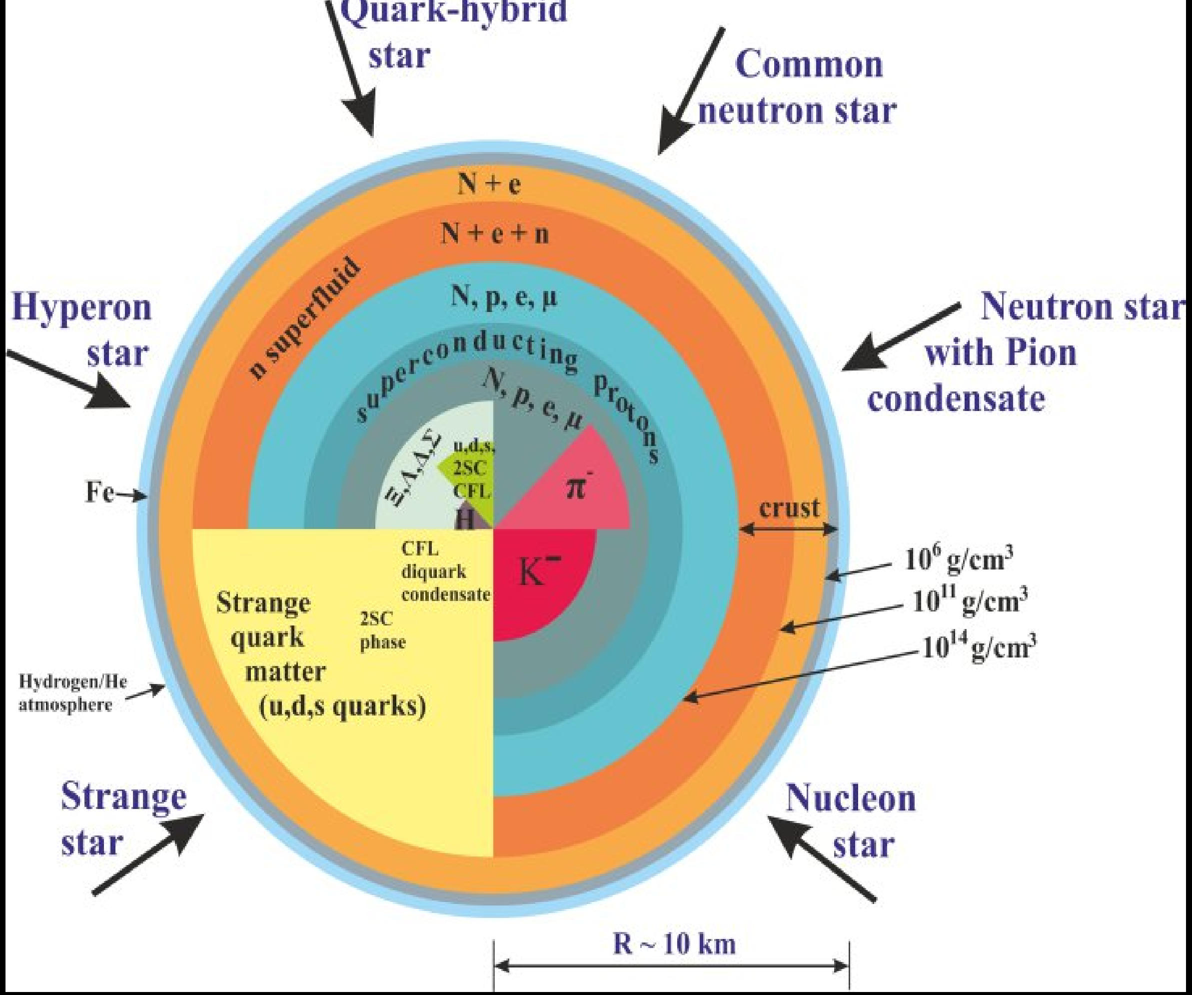
From Crust to Core

- **Outer Crust:** $10^{-10}\rho_0 < \rho < 10^{-3}\rho_0$
  "Coulomb Crystal" of progressively more neutron-rich nuclei.
- **Inner Crust** $10^{-3}\rho_0 < \rho < 10^{-1}\rho_0$
  "Nuclear Pasta" xotic shapes immersed in a neutron vapor.
- **Outer/Inner Core** $10^{-1}\rho_0 < \rho < 10\rho_0$
  "Fermi Liquid" of uniform neutron-rich atter ("Exotic Phases?").

Annual Review of Nuclear and Particle Science 56, 327–374 (2006)







Outer Crust

A solid Coulomb lattice of fully ionized atomic nuclei submerged in electron gas.

Inner Crust

Neutrons *"drip out of nuclei"*

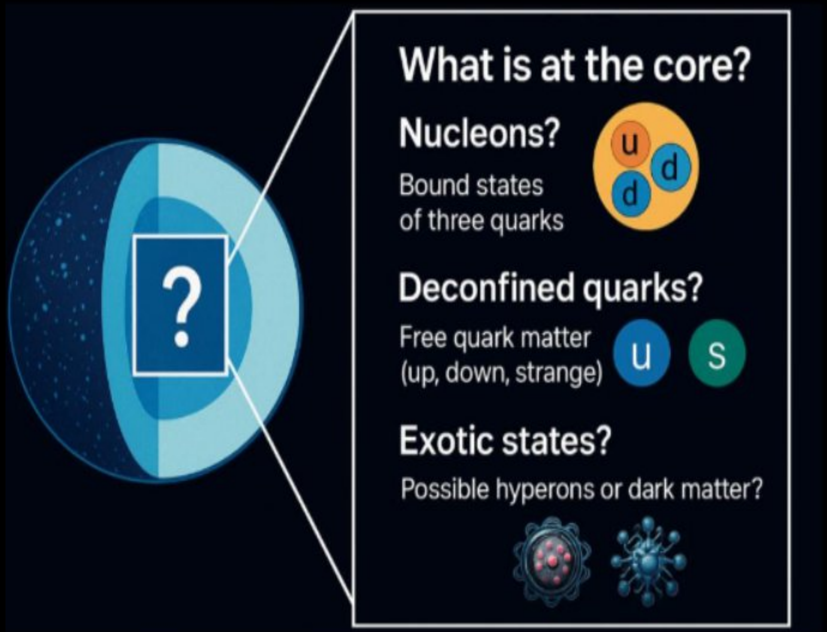
Core

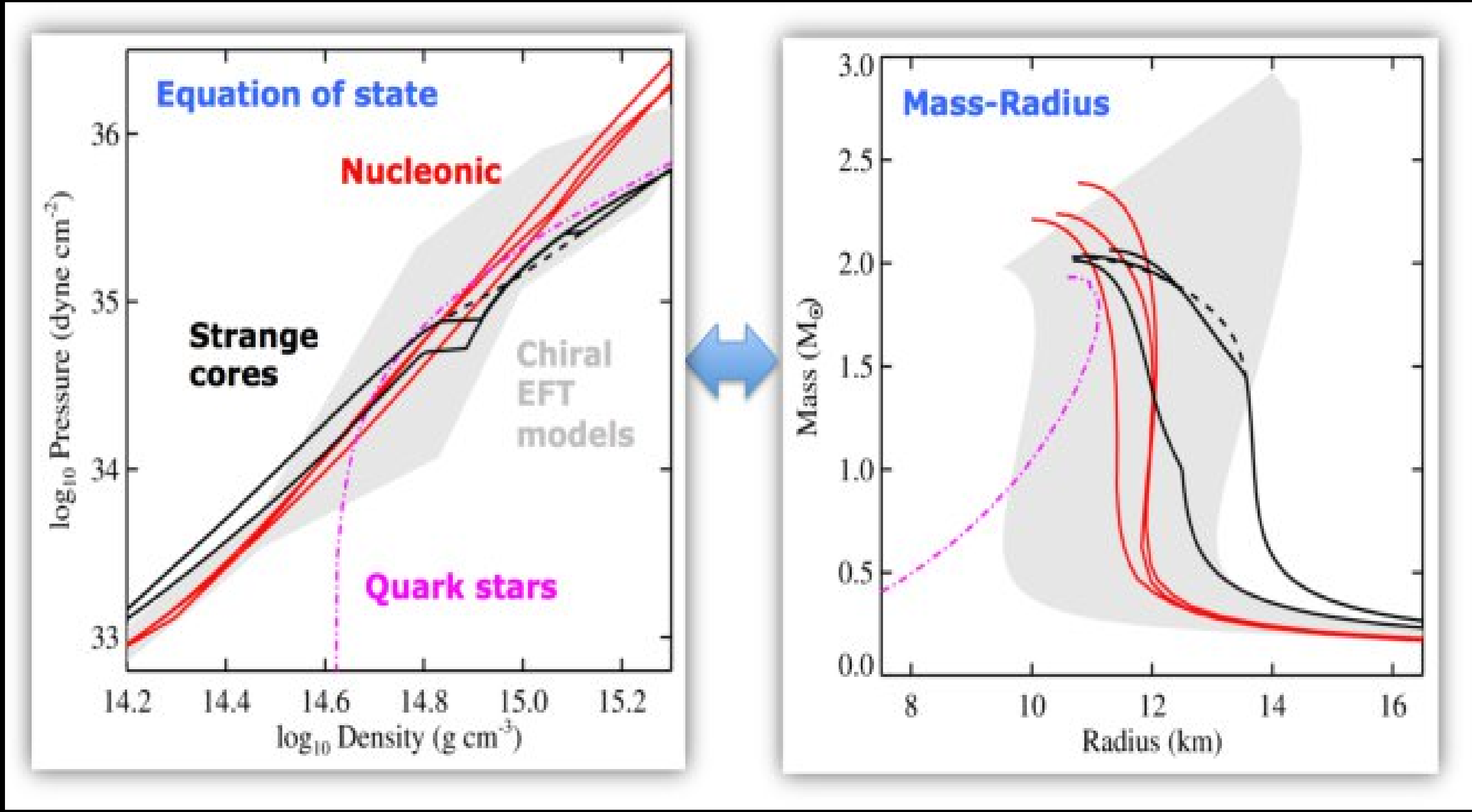
Uniform neutron-rich matter in chemical equilibrium.

Baryon density

EoS and Mass-Radius of star

arXiv.1501.00042

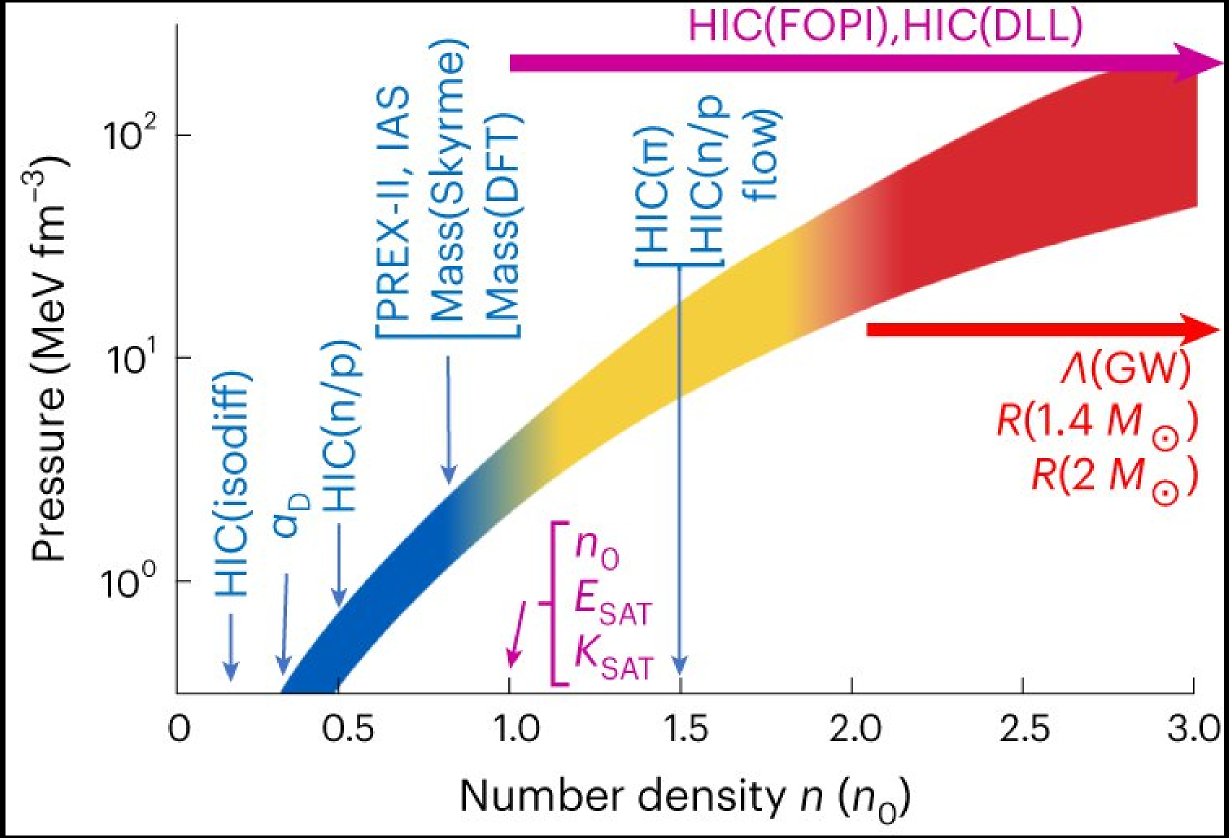




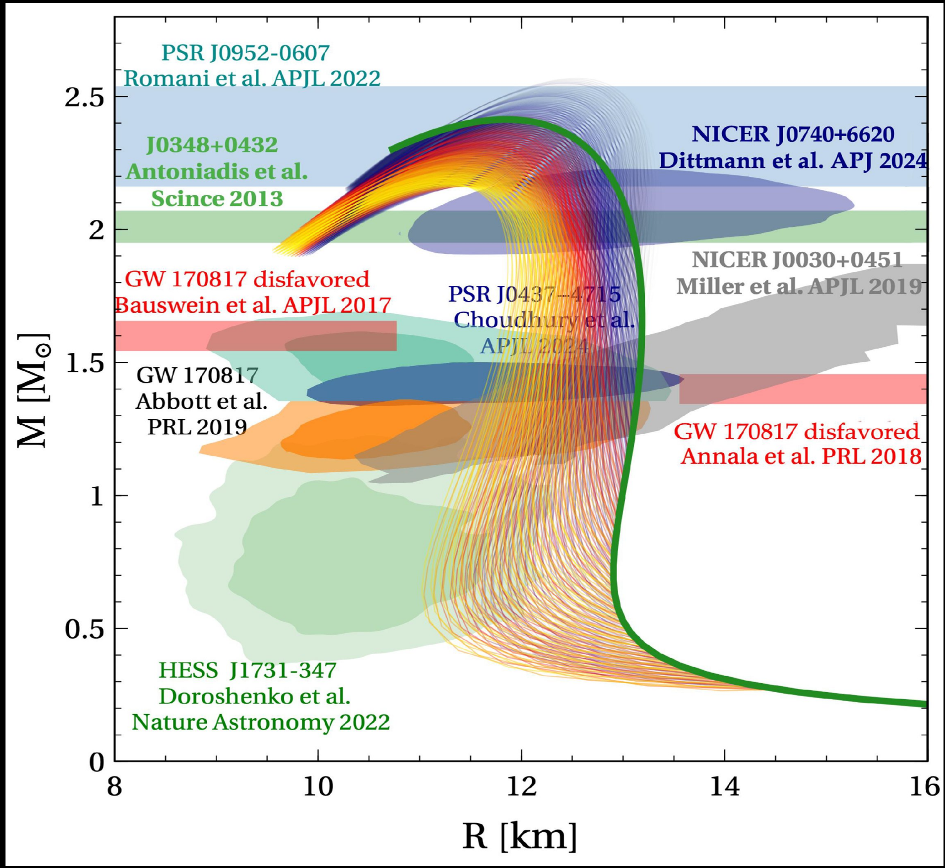
EoS must span 10-11 orders of magnitude in baryon density.

EoS needs joint analyses of nuclear theory, nuclear experiment and astrophysical observations

Constraints on the Ns EoS



Nature Astronomy **volume 8**, pages 328–336 (2024)



Universe **2025**, *11*(5), 141

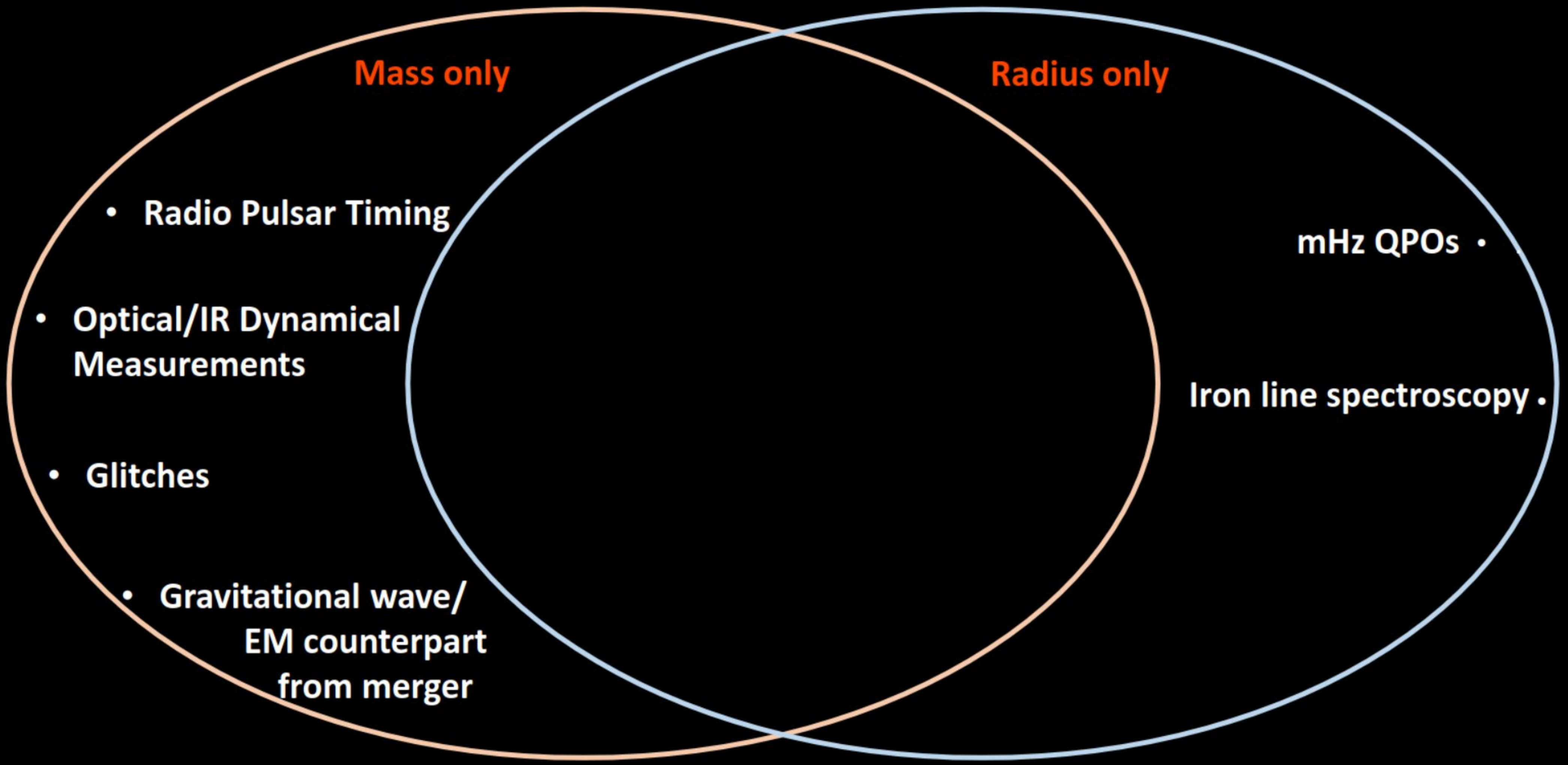
- A given NS EoS should at least satisfy 2M⊙ mass star.
- Ns mass and radius provide most significant information on the EoS.

Techniques to constrain the mass and/or Radius

Mass only

- Radio Pulsar Timing
- Optical/IR Dynamical Measurements
- Glitches
- Gravitational wave/ EM counterpart from merger

Techniques to constrain the mass and/or Radius



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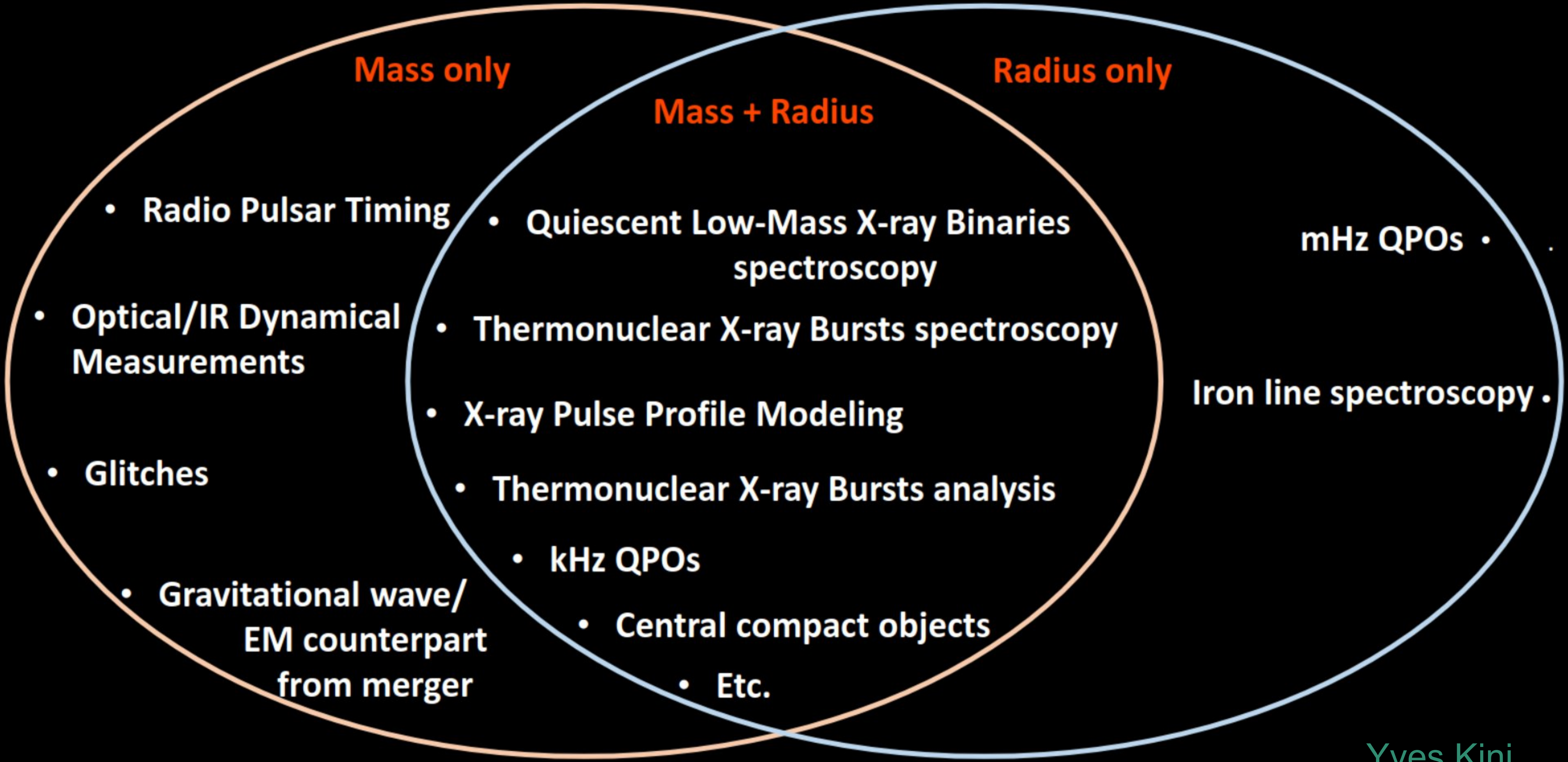
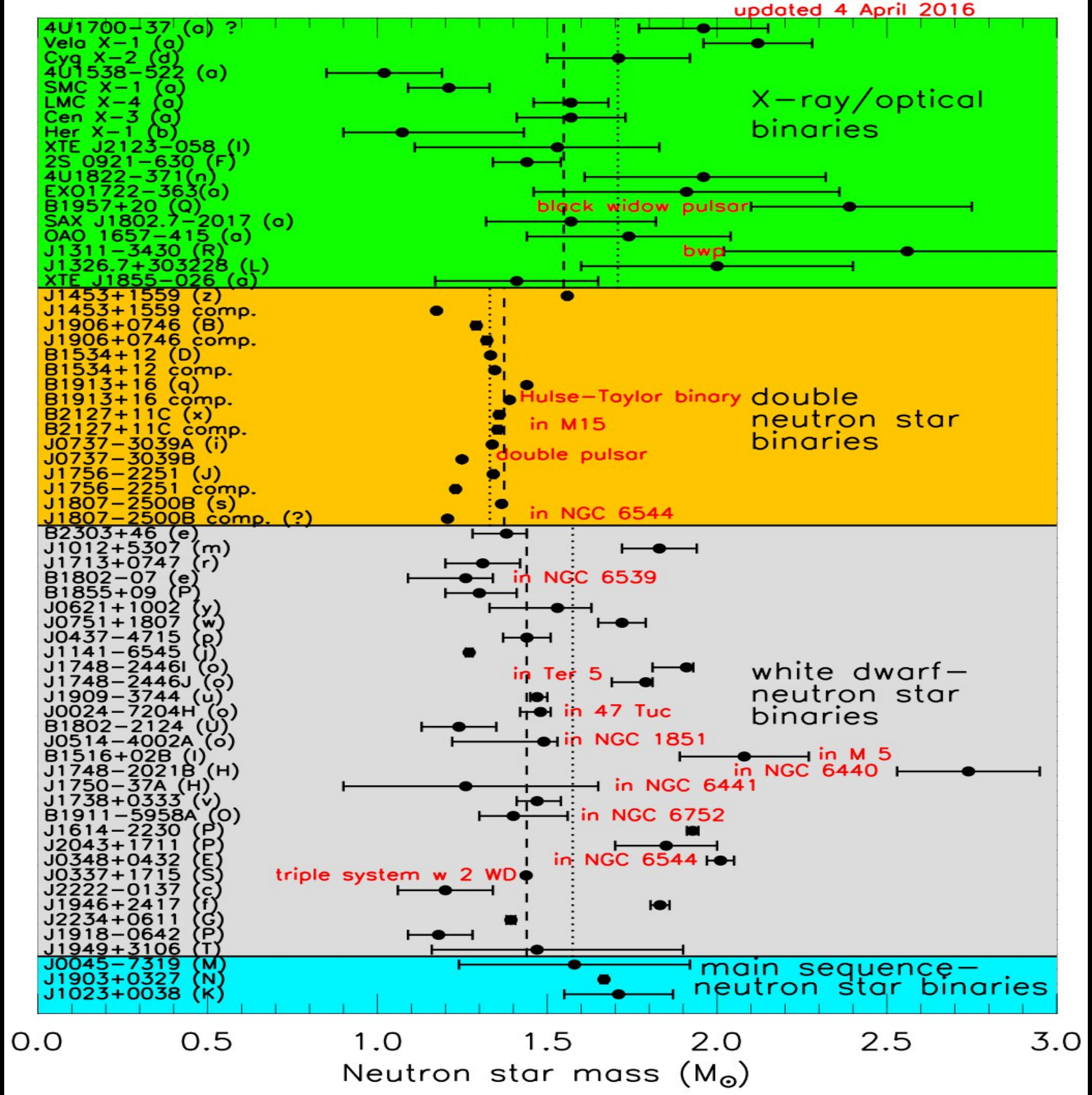


Yves Kini



DNSs are no more compatible with 1.4 M anymore.

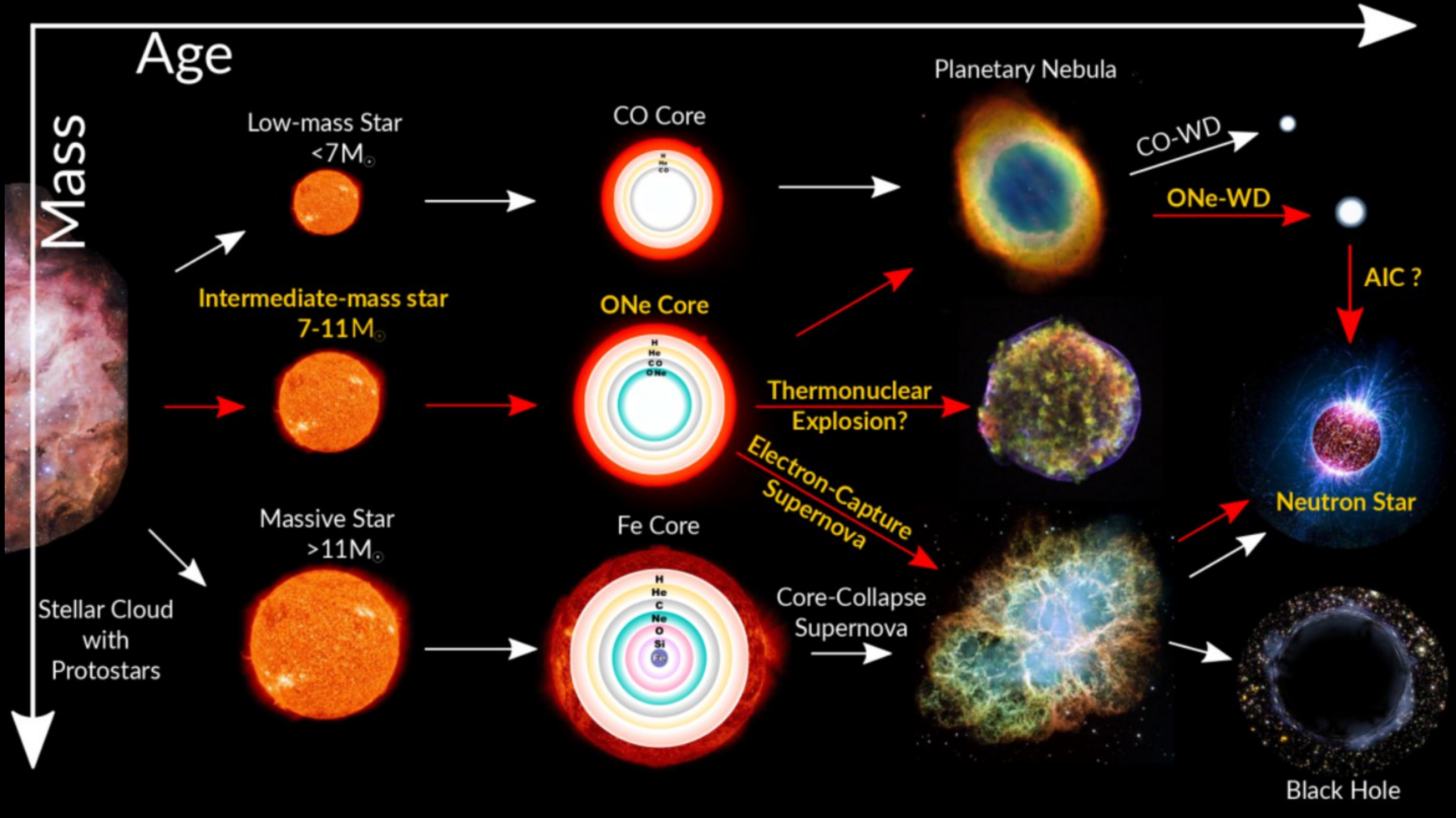
Some Notable Cases < 1.25 M⊙

- 4U 1538--52 (0.87 ± 0.07 M⊙)
- SMC X-1 (1.04 ± 0.09 M⊙
- Her X-1 (1.07 ± 0.36 M⊙)
- PSR J0453+1559 (1.174 ± 0.004 M⊙),
- PSR J1756--2251 (1.230 ± 0.007 M⊙)
- PSR J0737--3039B (1.249 ± 0.0007 M⊙)
- PSR J1946+2052 ~ 1.2 M⊙

What is the origin of such low mass NSs?

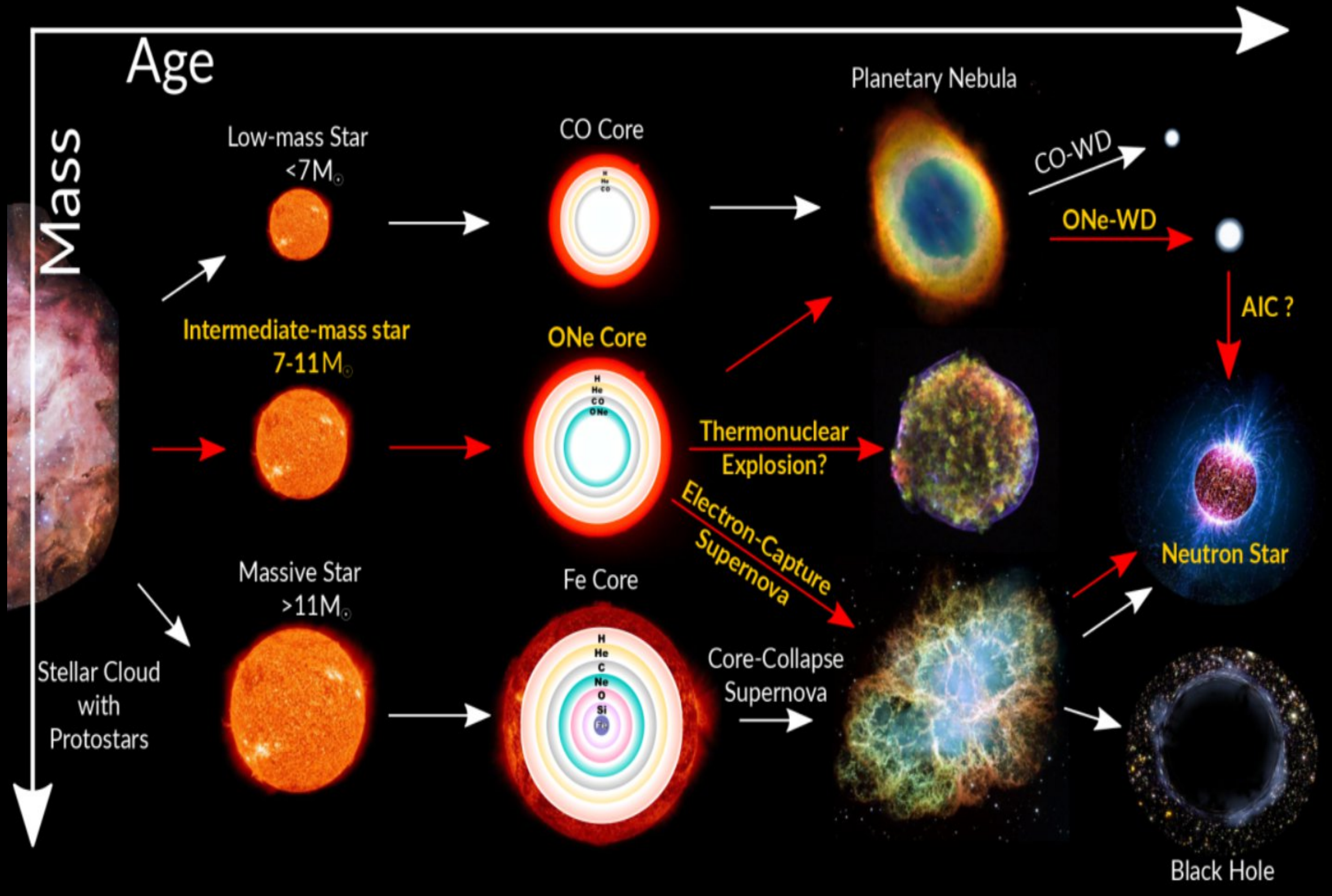
https://stellarcollapse.org/index.php/nsmasses.html

Stellar Evolution: lifetime and death depends on mass



Credit: Gabriel Martínez Pinedo

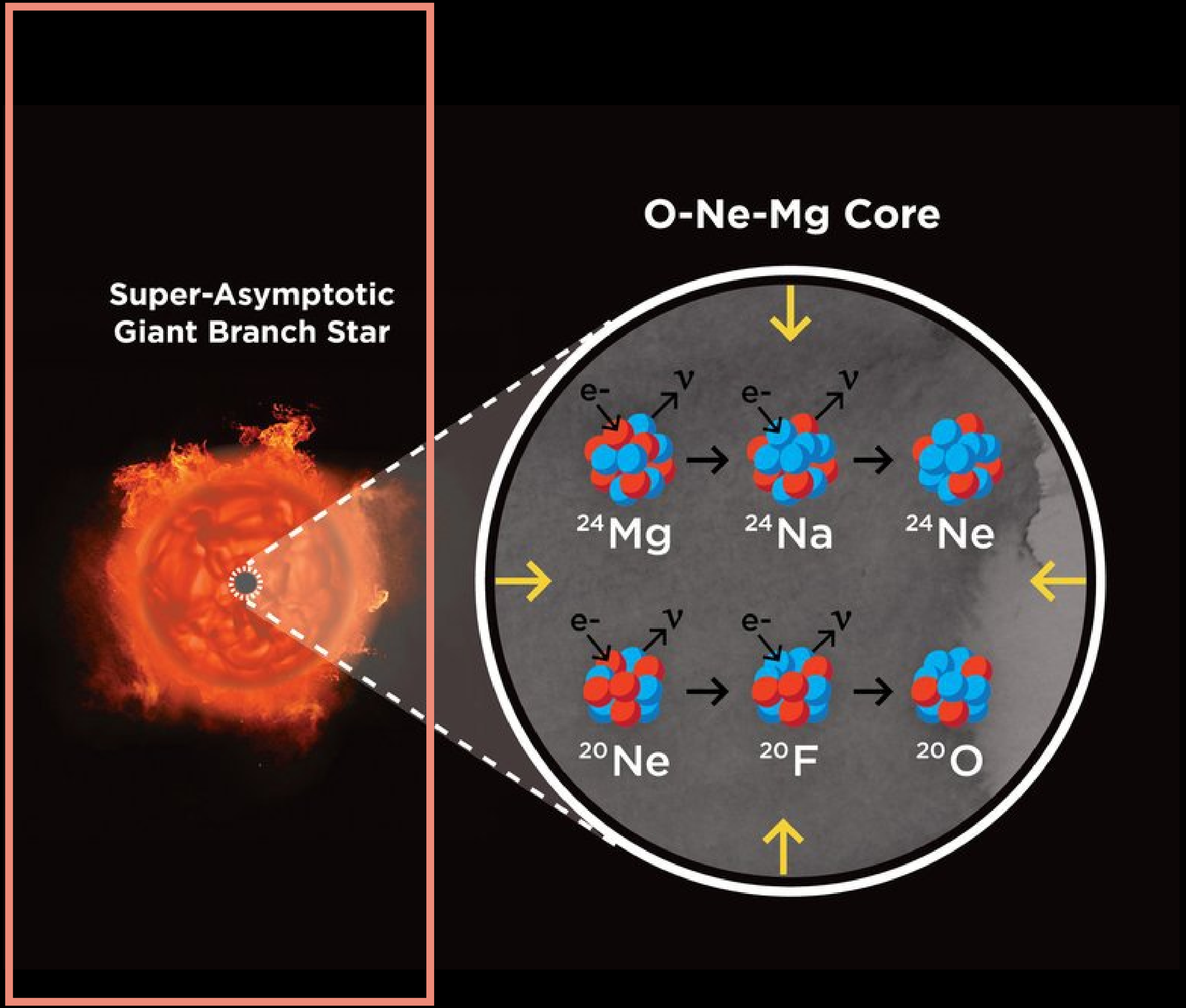
Stellar Evolution: lifetime and death depends on mass



- Nomoto and others developed detailed models of electron-capture supernovae, exploring how O–Ne–Mg cores collapse differently from iron-core supernovae.
- For decades, these events remained only theoretical since no unambiguous observational signature was found.
- Only recently, discoveries such as SN 2018zd provided the first clear evidence of an ECSN, confirming the long-standing predictions.

Credit: Gabriel Martínez Pinedo

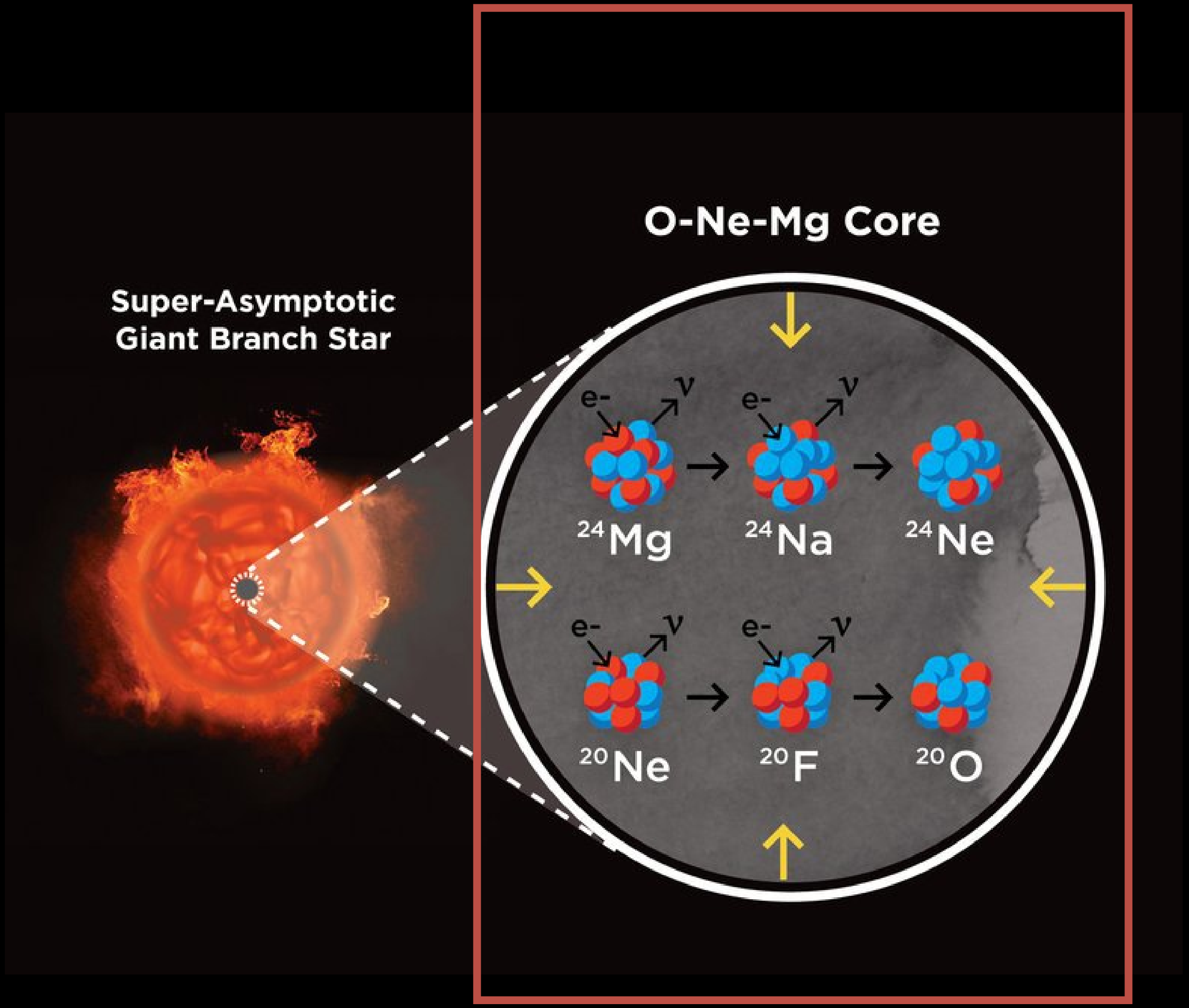
Electron Capture Supernovae



Artist impressions of a super-asymptotic giant branch star (left) and its core (right) made up of oxygen (O), neon (Ne), and magnesium (Mg). Credit: S. Wilkinson; Las Cumbres Observatory

- A super-asymptotic giant branch star is the end state of stars in a mass range of around 8-10 solar masses, whose core is pressure supported by electrons (e-)

Electron Capture Supernovae



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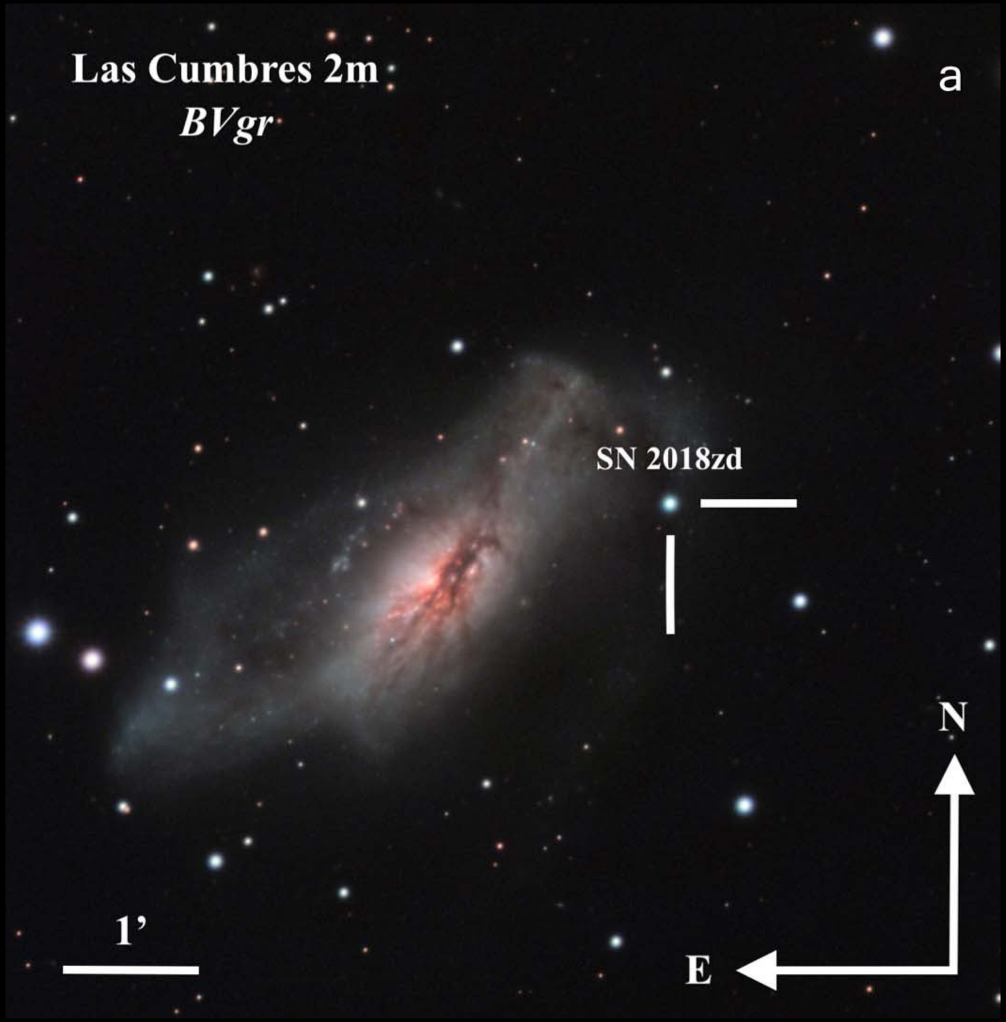
- A super-asymptotic giant branch star is the end state of stars in a mass range of around 8-10 solar masses, whose core is pressure supported by electrons (e-)
- When the core becomes dense enough, neon and magnesium start to eat up electrons (so called electron-capture reactions), reducing the core pressure and inducing a core-collapse supernova

First evidence of ECSN-supernova 2018zd



- SN 2018zd, the first strong electron-capture supernova candidate, was discovered on **March 2, 2018** by Japanese amateur astronomer **Koichi Itagaki** using a **0.35-m telescope** at his Yamagata observatory while comparing fresh CCD images of **NGC 2146** with earlier references.

Hiramatsu, D., *et al.* The electron-capture origin of supernova 2018zd. *Nat Astron* **5**, 903–910 (2021)

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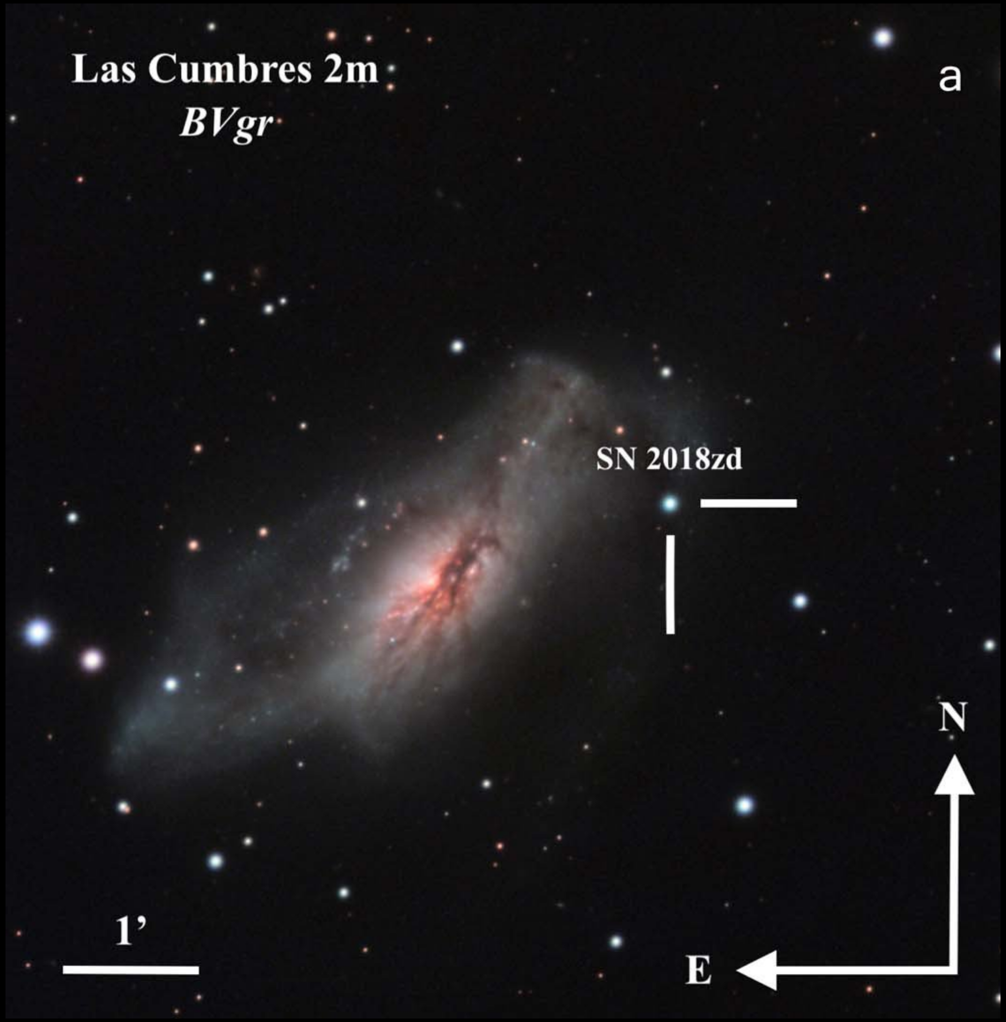

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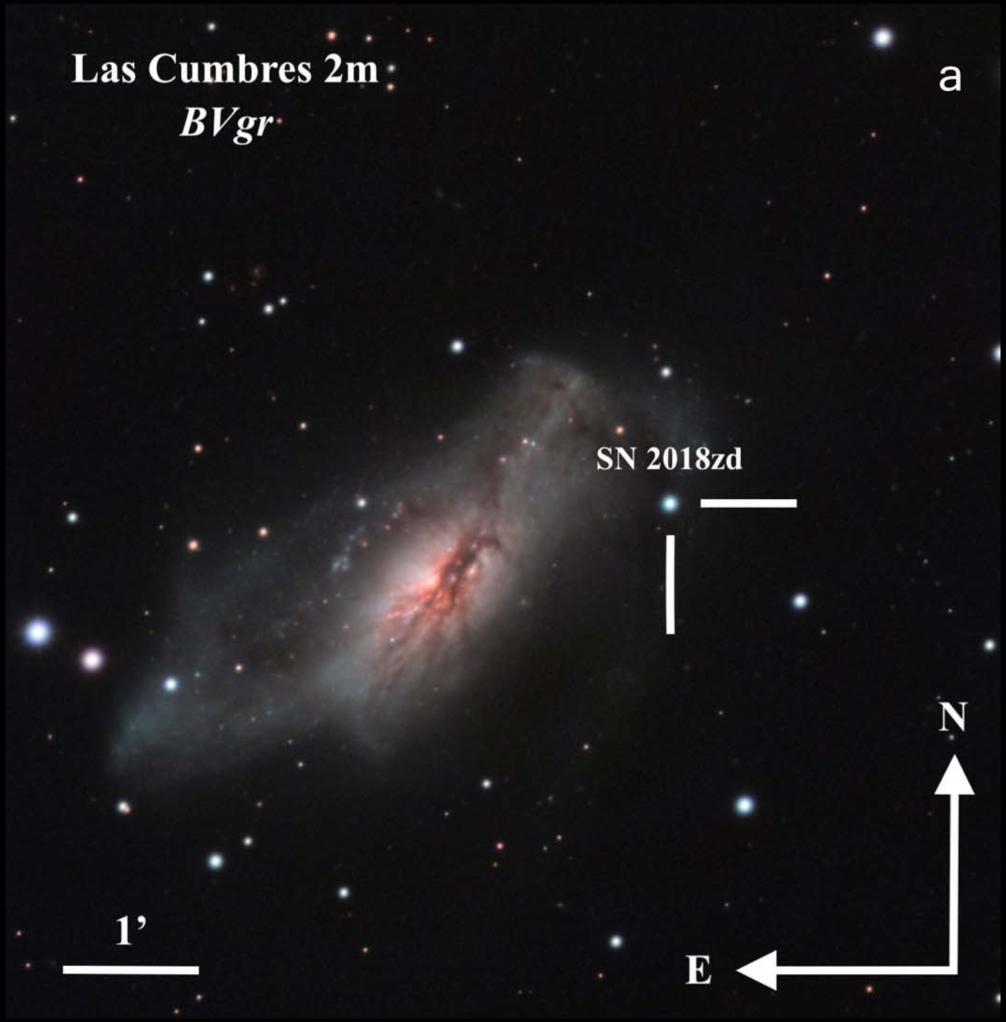
Koichi Itagaki's homespun observatory in Yamagata is one of three he maintains across Japan in hopes of spotting supernovae before anyone else. Credit: Science.

First evidence of ECSN-supernova 2018zd



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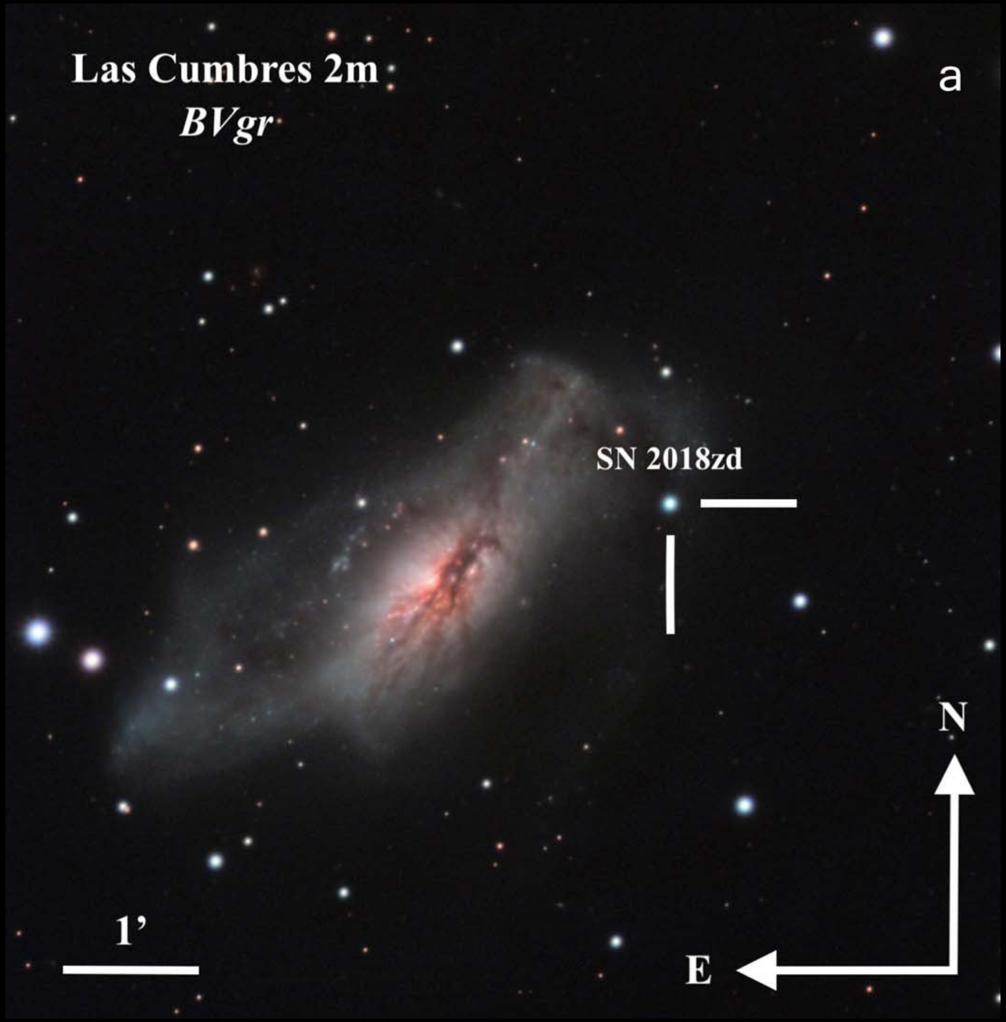

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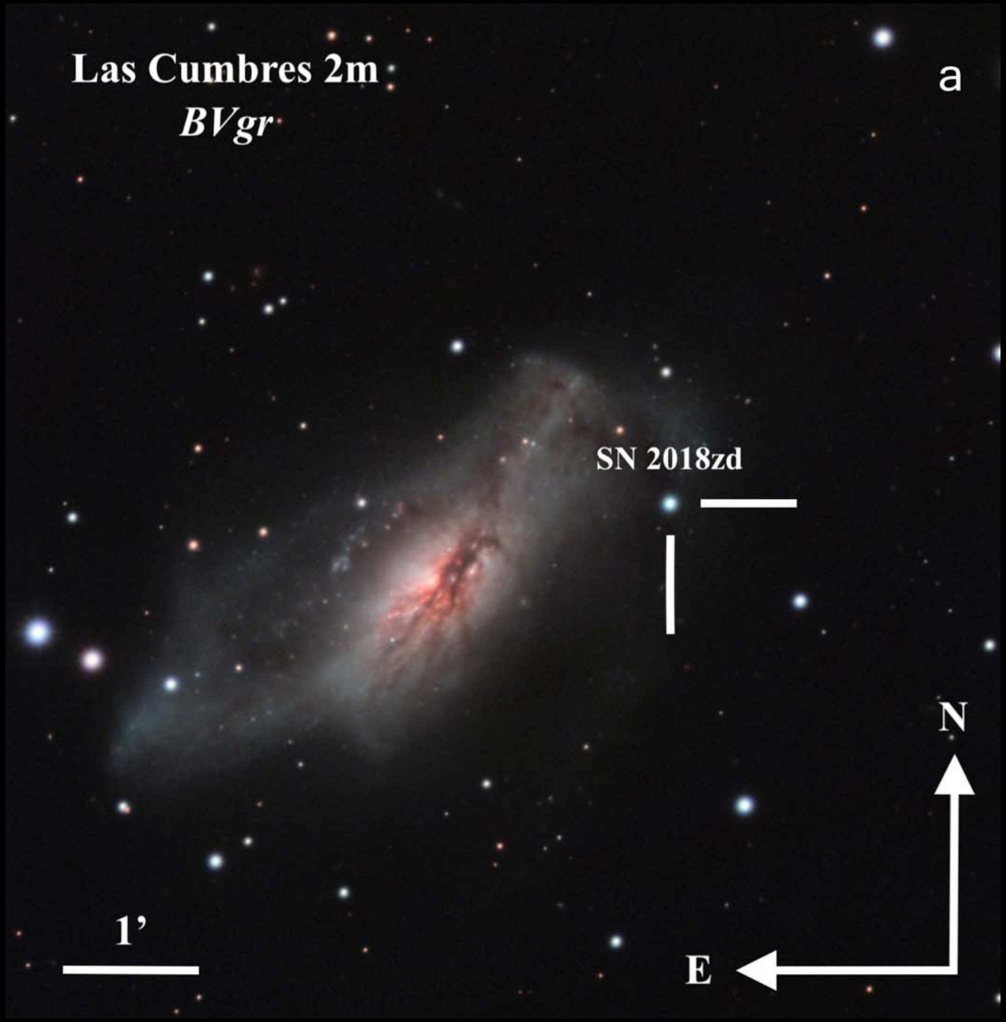

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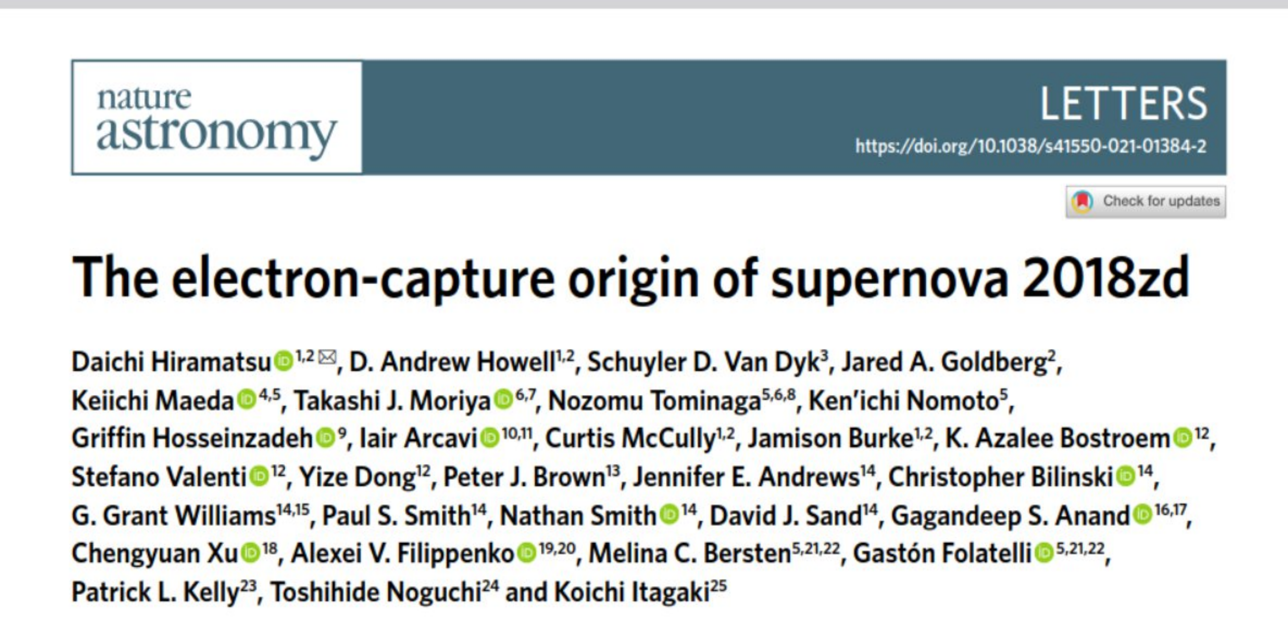
nature astronomy
LETTERS
https://doi.org/10.1038/s41550-021-01384-2
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The electron-capture origin of supernova 2018zd

Daichi Hiramatsu[1,2] ✉, D. Andrew Howell[1,2], Schuyler D. Van Dyk[3], Jared A. Goldberg[2], Keiichi Maeda[4,5], Takashi J. Moriya[6,7], Nozomu Tominaga[5,6,8], Ken'ichi Nomoto[5], Griffin Hosseinzadeh[9], Iair Arcavi[10,11], Curtis McCully[1,2], Jamison Burke[1,2], K. Azalee Bostroem[12], Stefano Valenti[12], Yize Dong[12], Peter J. Brown[13], Jennifer E. Andrews[14], Christopher Bilinski[14], G. Grant Williams[14,15], Paul S. Smith[14], Nathan Smith[14], David J. Sand[14], Gagandeep S. Anand[16,17], Chengyuan Xu[18], Alexei V. Filippenko[19,20], Melina C. Bersten[5,21,22], Gastón Folatelli[5,21,22], Patrick L. Kelly[23], Toshihide Noguchi[24] and Koichi Itagaki[25]

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What it means for **the Crab Nebula**

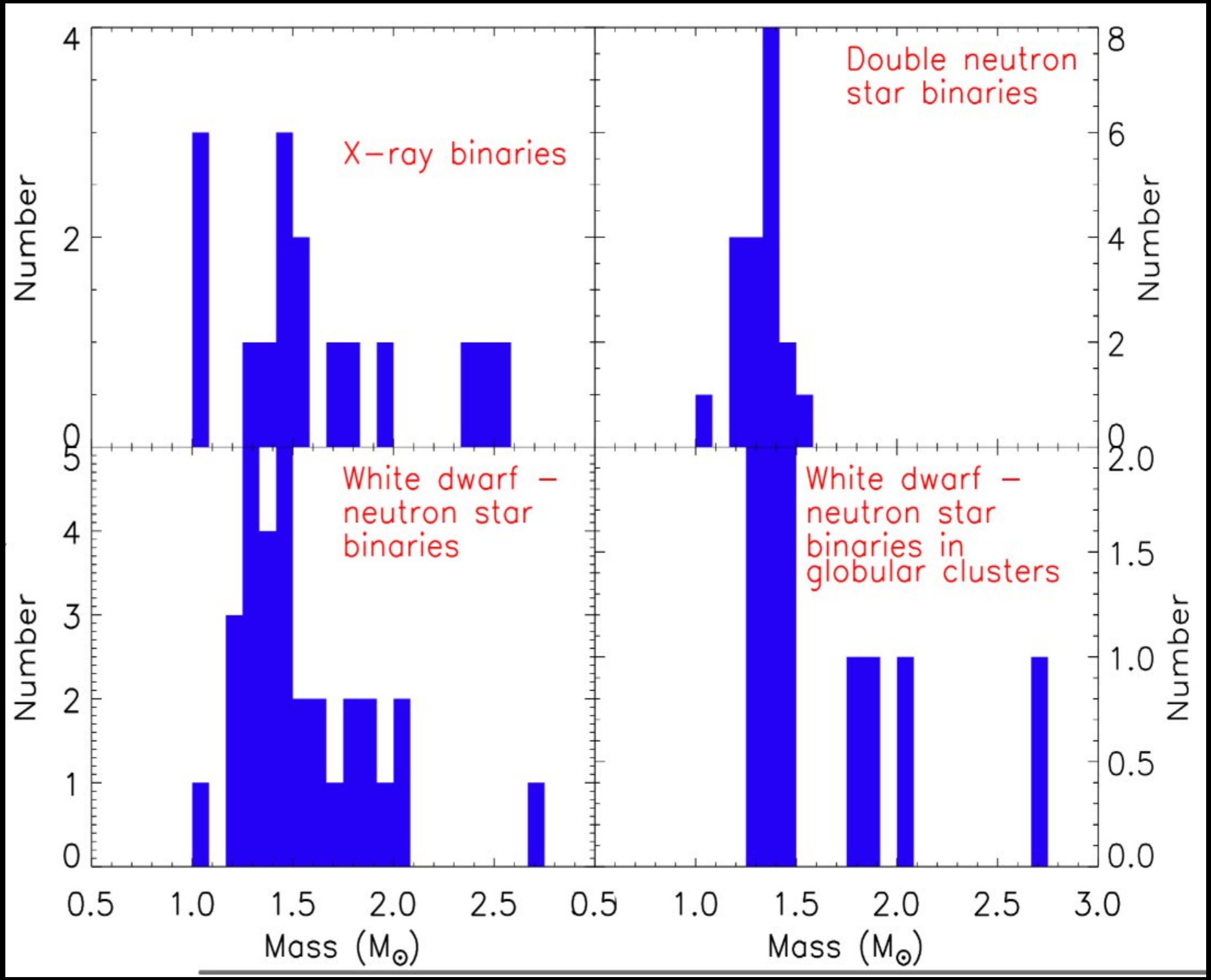
Credit: NASA, ESA, NRAO/AUI/NSF and G. Dubner (University of Buenos Aires)

- In 1054 A.D., a supernova called SN 1054 occurred in the Milky Way. According to Chinese and Japanese records, it was so bright that it could be seen in the daytime for 23 days and at night for nearly two years.
- The resulting remnant – the Crab Nebula – has been studied in great detail. It was previously the best candidate for an electron-capture supernova, but this was uncertain partly because the explosion happened nearly 1,000 years ago. The new result increases the confidence that the historic SN 1054 was an electron-capture supernova.
- Interaction between the ejecta and pre-supernova mass loss explains the brightness, supporting the Crab's origin as an electron-capture supernova.

However

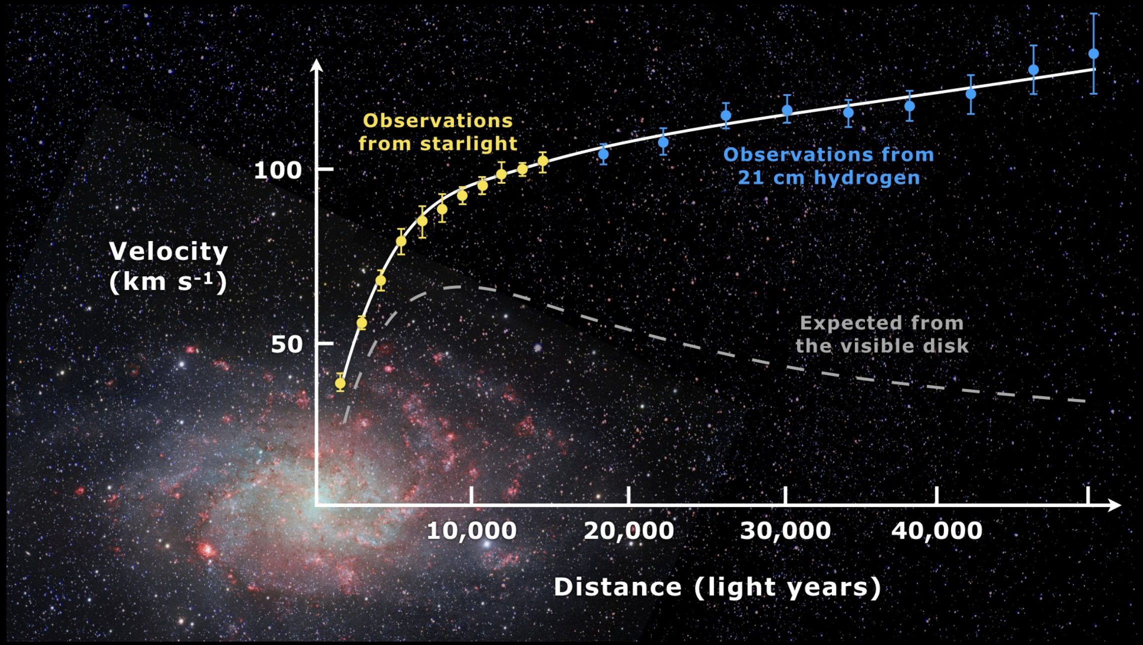
- **O–Ne White Dwarfs:** Theory predicts electron-capture supernovae (ECSN) from O–Ne WDs with a progenitor WD mass ≈ **1.35 M☉**, collapsing to a neutron star of ≈ **1.25 M☉** (after neutrino losses).
- **Expected Mass Floor:** This sets a "canonical minimum" NS mass around **1.25 M☉**.
- **Observed Outliers:** Yet, some pulsars are significantly lighter:

- **Possible Explanations:???**



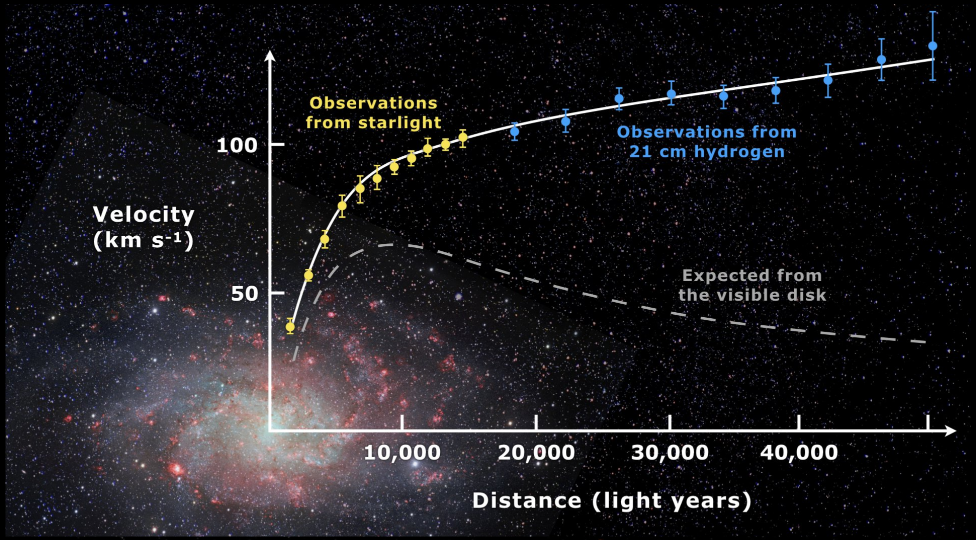
https://stellarcollapse.org

DARK Matter



Observations
from starlight
Observations from
21 cm hydrogen
100
50
Velocity
(km s-1)
Expected from
the visible disk
10,000
20,000
30,000
40,000
Distance (light years)

DARK Matter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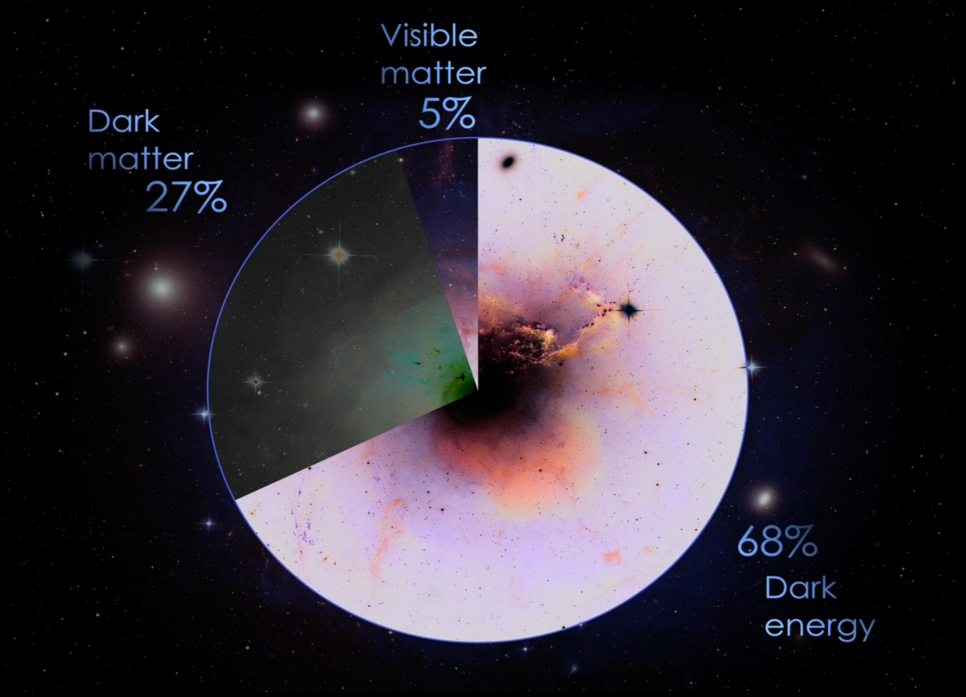
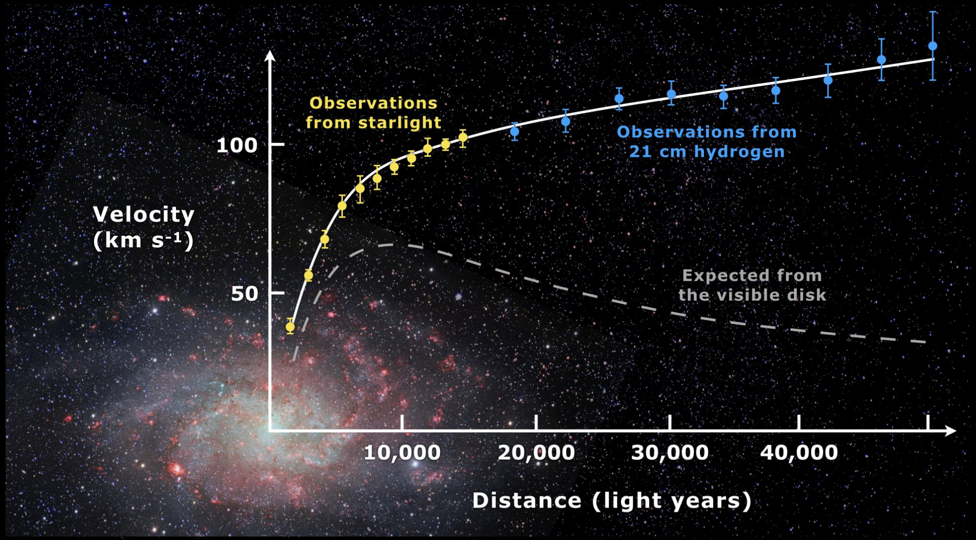
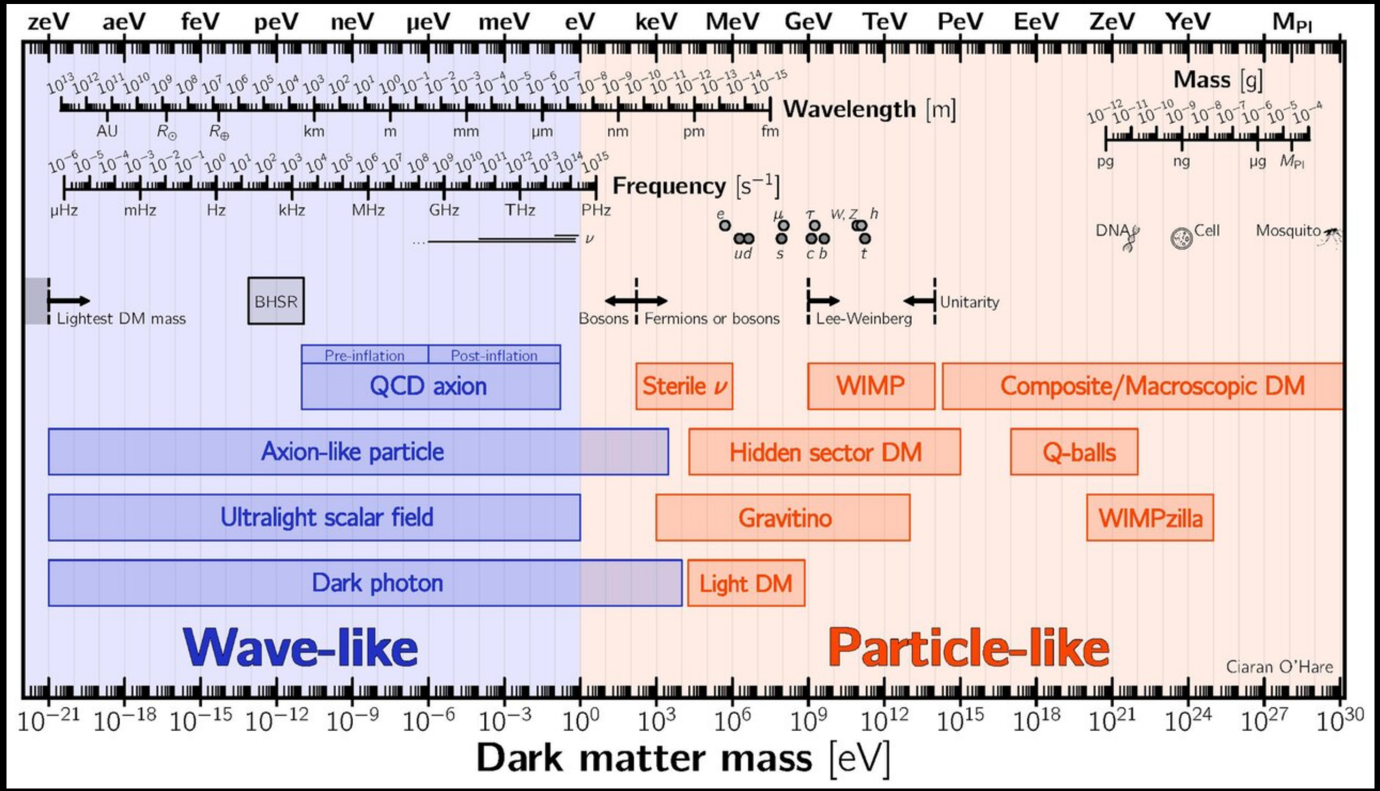
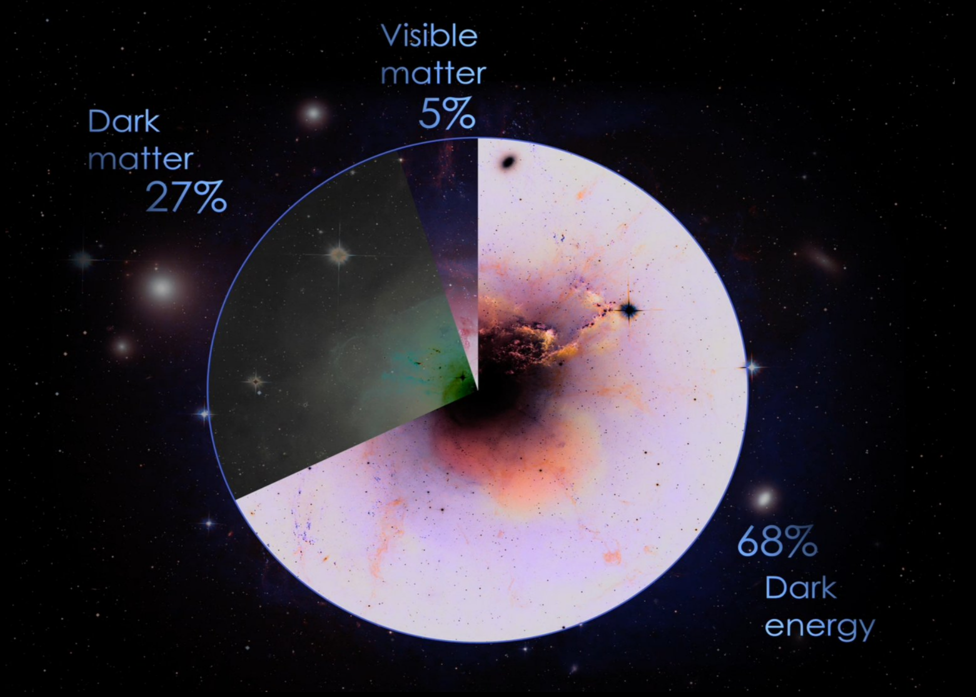

Visible
matter
5%
Dark
matter
27%
68%
Dark
energy

DARK Matter







Neutron stars and white dwarfs act as natural dark-matter detectors: capture, heating, cooling, and structural shifts let us infer DM particle properties indirectly.

Credit: NASA

Motivation

- What the Mass of the NS from the ECSN without DM? Can DM explain the low mass NSs?
- We map the Ne WD at the EC threshold with the final Remnant NS in the presence of DM. No dynamical simulation.
- Assume no accretion or loss and therefore, conserving Baryon number and Dark Matter number.

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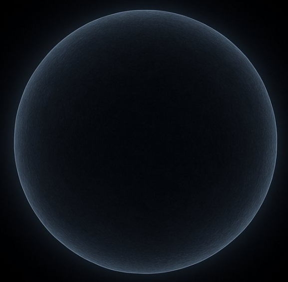
$\Delta N_B = \Delta N_\chi = 0$



Final Remnant NS

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Ne WD at the Electron capture threshold

Final Remnant NS

What we need? 1- WD EOS, 2- NS EOS (composition dependent), 3- DM model

White Dwarf Matter

In this work, we consider the case of unmagnetized and zero temperature (T = 0) stellar matter, corresponding to white dwarfs where the temperature is lower then the crystallization temperature.

The total energy density of this system can be written as

$$\varepsilon = n_X M_N(A,Z) + \varepsilon_e + \varepsilon_L$$

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Energy density contribution due to ions (i.e. nuclei, since we consider fully ionized atoms) and n_X is the number density of ions which is related to the number density of electrons n_e by the charge neutrality condition.

Chamel and Fantina, 2015

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$$\varepsilon_e = \frac{m_e c^2}{8\pi^2 \lambda_e^3}\left[x_e\left(1+2x_e^2\right)\sqrt{1+x_e^2} - \ln\left(x_e + \sqrt{1+x_e^2}\right)\right]$$ is the energy density of electrons.

Chamel and Fantina, 2015

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$\varepsilon_L = Ce^2 n_e^{4/3} f(Z)$ is the Coulomb lattice energy, considering point like ions. C is the lattice constant.

Chamel and Fantina, 2015

Electron capture instability

- Inside the WD, at sufficiently high mass-densities, electron capture by a nucleus ${}^{A}_{Z}X$ can become energetically favorable,

$$ {}^{A}_{Z}X + e^- \rightarrow {}^{A}_{Z-1}Y + \nu_e . $$

- Within the star, the pressure $P(r)$ must vary continuously.The Gibbs free energy per nucleon is given by:

$$ g = \frac{\varepsilon + P}{n} $$

- The pressure (P^*) at which the onset of electron capture, takes place can then be determined by the condition that the Gibbs free energy per baryon remains unchanged before and after the electron capture reaction

$$ g\left(A,Z,P^*\right) = g\left(A,Z-\Delta Z,P^*\right) $$

Chamel and Fantina, 2015

NS and DM Model

- To model the ordinary matter (OM) fluid of a DM admixed neutron star (DANS) we use a new microscopic EOS using the Brueckner-Hartree-Fock (BHF) quantum many-body approach. (Bombaci, I., Logoteta, D., 2018).

- For DM, we consider non-self-annihilating ideal fermionic DM.

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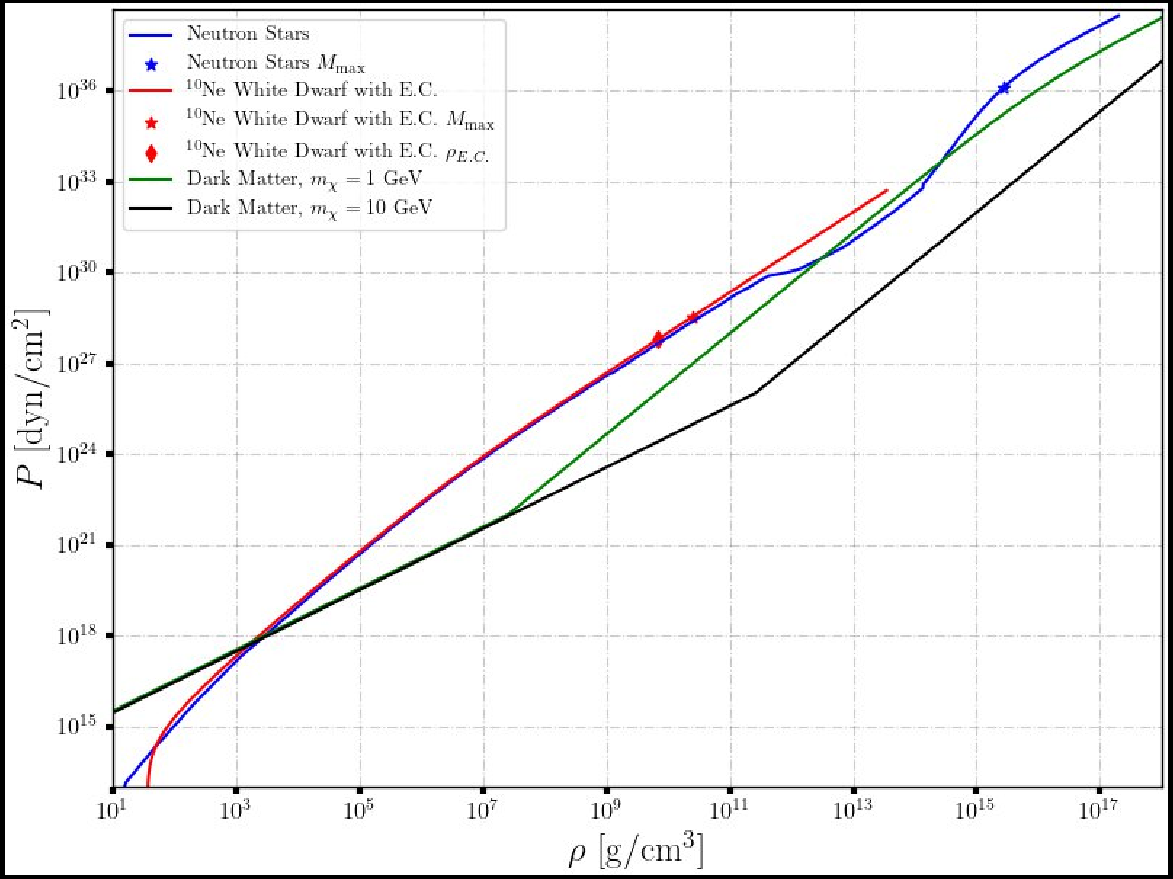

Kaplan et al., 2009; Zurek, 2014, Logoteta et al., 2021

Structure equations for DM admixed compact stars

Since the non-gravitational interaction between DM and ordinary matter is negligible compared to interaction which determine ordinary matter EOSs , it is possible to write TOV equation as

$$\frac{dP_j}{dr} = -G\frac{m_{tot}(r)\,\varepsilon_j(r)}{c^2 r^2}\left(1+\frac{P_j(r)}{\varepsilon_j(r)}\right)\left(1+\frac{4\pi r^3 P_{tot}(r)}{c^2 m_{tot}(r)}\right)\left(1-\frac{2Gm_{tot}(r)}{c^2 r}\right)^{-1}$$

and

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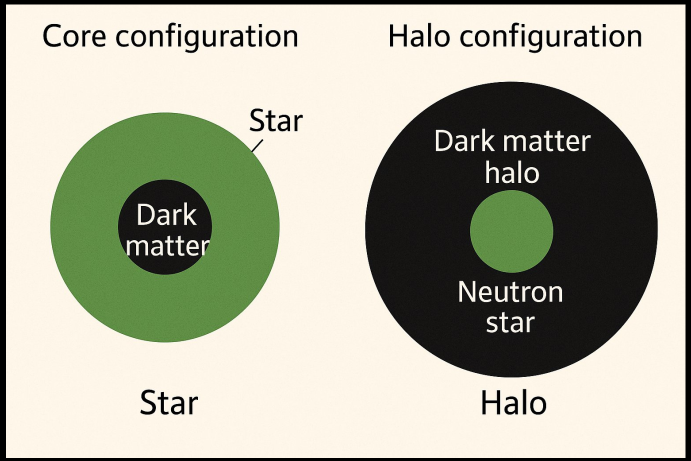

Where,

- $m_{tot}(r) = m_{OM}(r) + m_{DM}(r)$
- $P_{tot}(r) = P_{OM}(r) + P_{DM}(r)$
- With boundary conditions $m_j(0) = 0, \quad \varepsilon_j(0) = \varepsilon_{c,j}$
- The total gravitation mass is then given by $M_j \equiv m_j(R_j) = \frac{4\pi}{c^2}\int_0^{R_j} r^2 \varepsilon_j(r)\,dr$
- With $M_{tot} = M_{OM} + M_{DM}$

In our scenario we assume that during the collapse of the DAWD-like core into the remnant DANS both the total baryon number and the total DM particle number are conserved. In other words, we assume that no accretion or ejection of either ordinary matter and DM components occurs during the stellar transition.

DM Number fraction

$$y_\chi = \frac{N_D}{N_B + N_D}$$

Where,

$$N_B = \int_0^{R_{OM}} n_B(r)\, dV$$

$$N_D = \int_0^{R_{DM}} n_D(r)\, dV$$

And $dV = \left(1 - \frac{2Gm_{tot}(r)}{c^2 r}\right)^{-1/2} 4\pi r^2 dr$

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DM Mass fraction

The baryonic and dark mass of the DM admixed compact star (DACS) (DAWD or DANS) then follows as

$$M_B = m_n N_B \text{ And } M_D = m_\chi N_D$$

The mass fraction, generally used in literature as

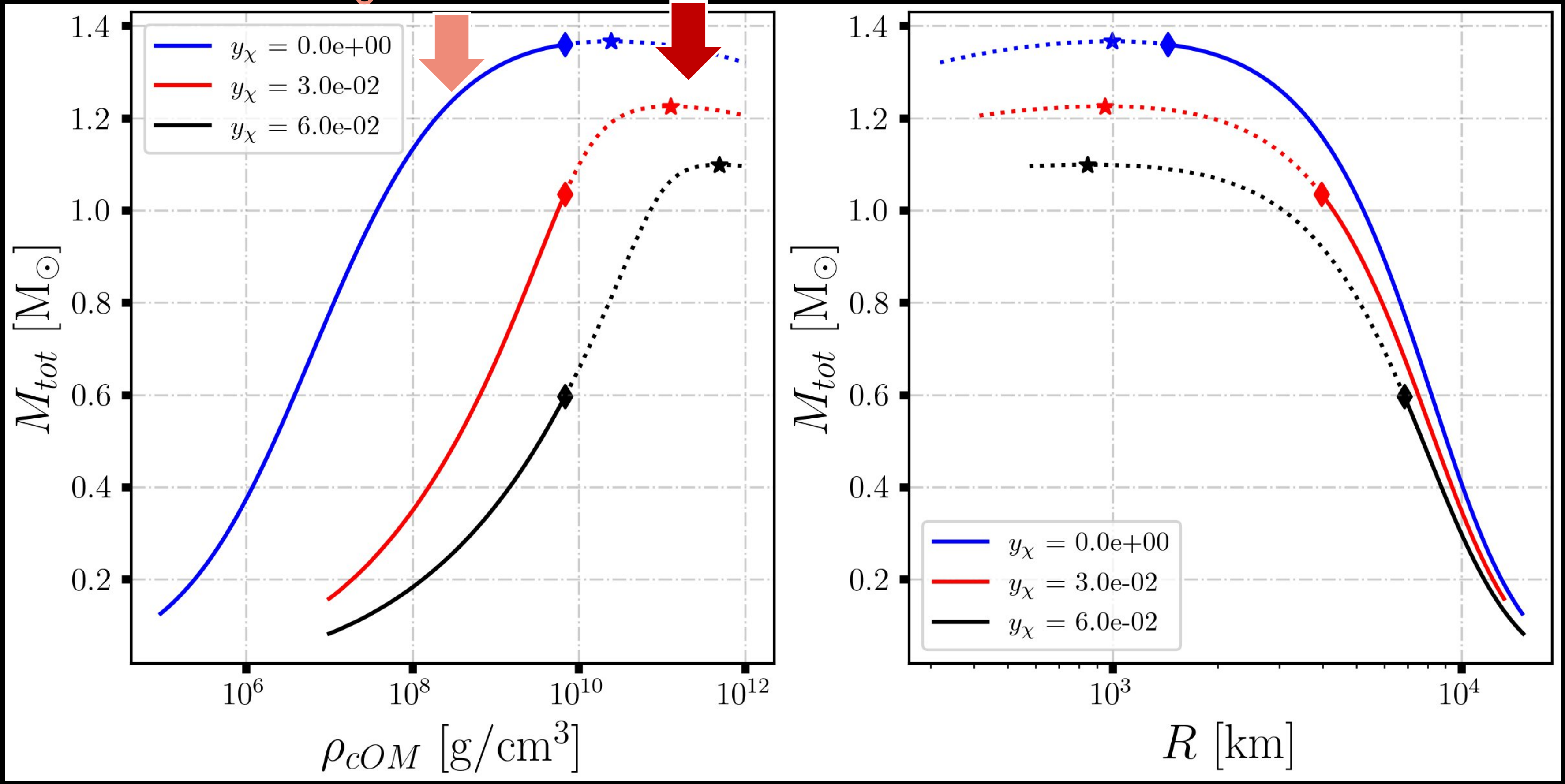
$$f_\chi = \frac{M_{DM}}{M_{OM}+M_{DM}}$$

within our scenario will not be constant during the stellar process which forms the remnant DANS of an ECSN.

Effect of DM on degenerate white dwarfs

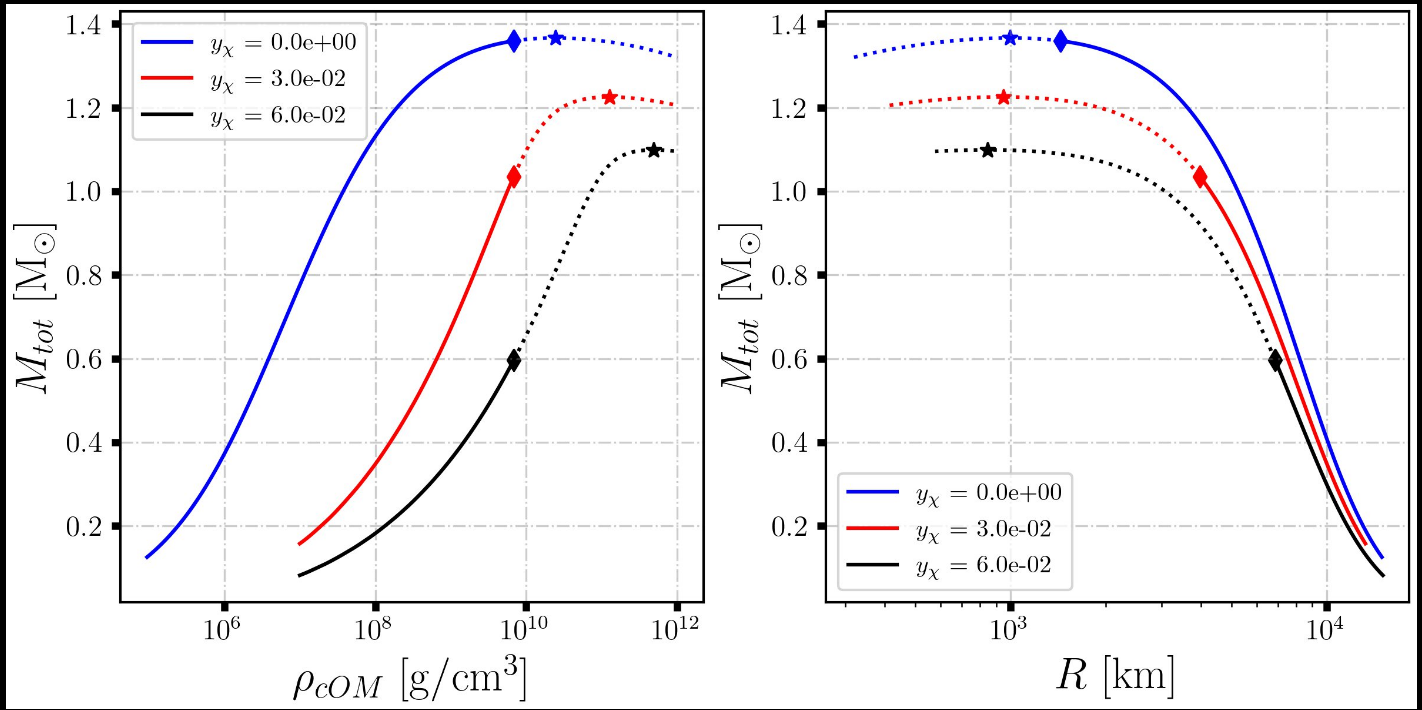
Stable against EC Unstable.

m_χ=1 GeV



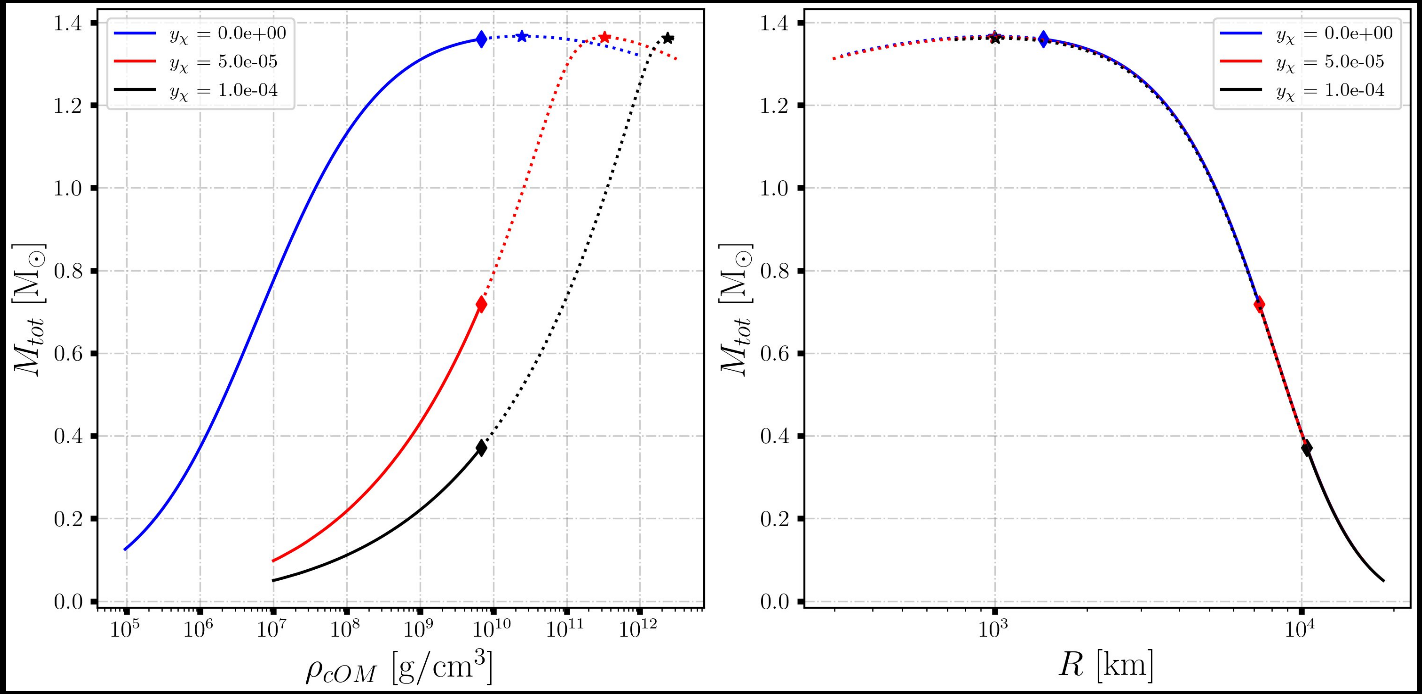
In the case of electron capture on 20Ne, $20\mathrm{Ne} + e^- \rightarrow 20\mathrm{F} + \nu_e$ $\rho*$ (20 Ne) = 6.82 × 10^9 g/cm3

Consequently, $20\mathrm{F} + e^- \rightarrow O_{20} + \nu_e$ having $\rho*$ (20 F) = 1.40 × 10^9 g/cm3, undergoes further EC



m_χ=1 GeV

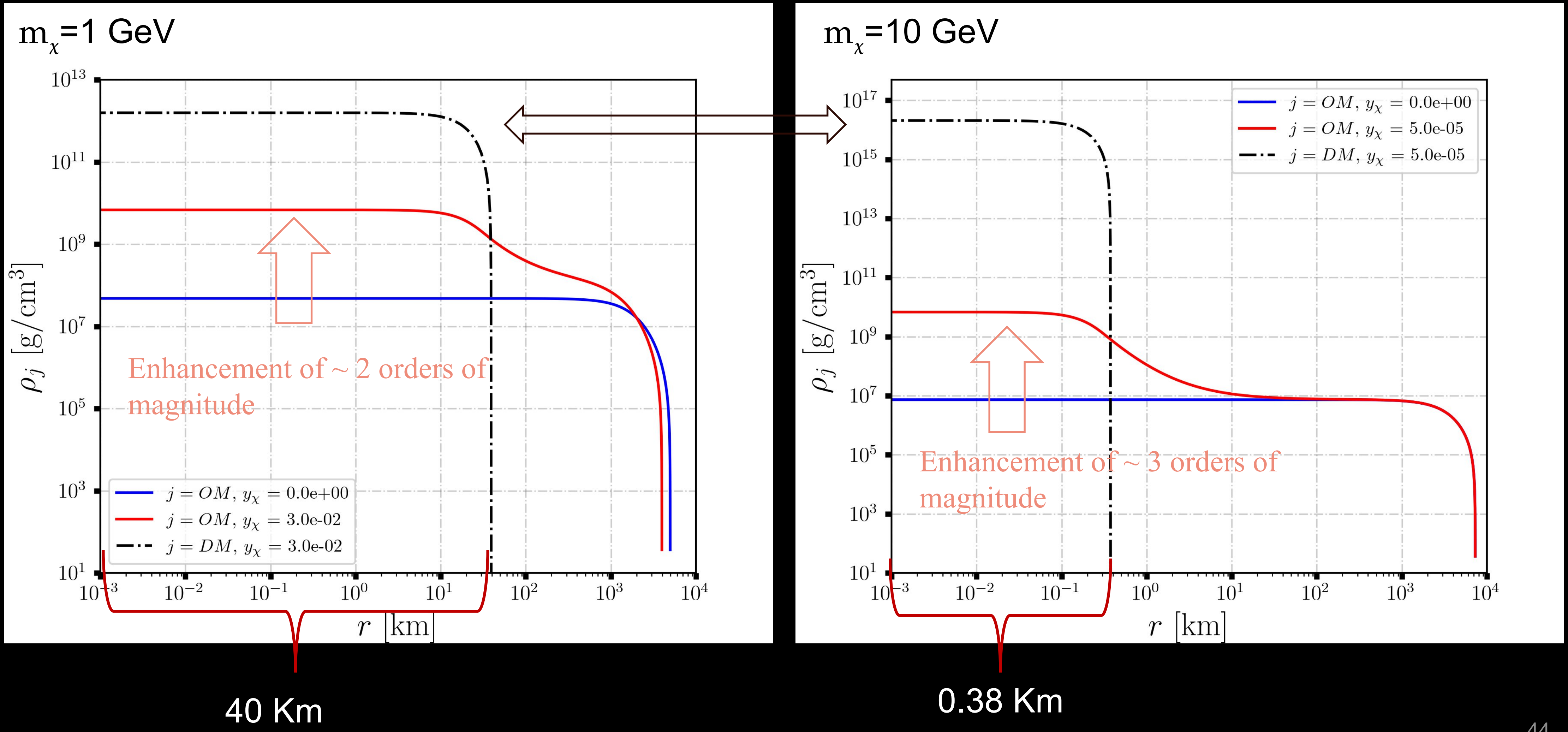
Presence of DM in white dwarfs leads to a reduction in the Chandrasekhar mass, to a decrease in the corresponding ordinary matter radius , and an increase in the ordinary matter central density.



m_χ=10 GeV

Even a tiny addition of DM leads to significant changes in the mass–central-density

Radial mass-density profiles at the same total gravitational mass



To Quantify

y_χ	M_{ch} [$M_\odot$]	R_{ch}[km]	$\rho_{c_{OM}}$ [g/cm^3]	ρ^* [g/cm^3]	M^* [$M_\odot$]	R^*[km]
No DM						
0	1.366	998.92	2.4201×10^{10}	6.82×10^9	1.359	1440.7
$m_\chi = 1$ GeV						
3×10^{-2}	1.225	956.05	1.2328×10^{11}	6.82×10^9	1.0353	3970.2
6×10^{-2}	1.028	837.10	4.9770×10^{11}	6.82×10^9	0.5964	6865.6
$m_\chi = 10$ GeV						
5×10^{-5}	1.3634	1035.8	3.1257×10^{11}	6.82×10^9	0.7184	7272.6
1×10^{-4}	1.3616	1005.13	2.3919×10^{12}	6.82×10^9	0.3707	10400.0

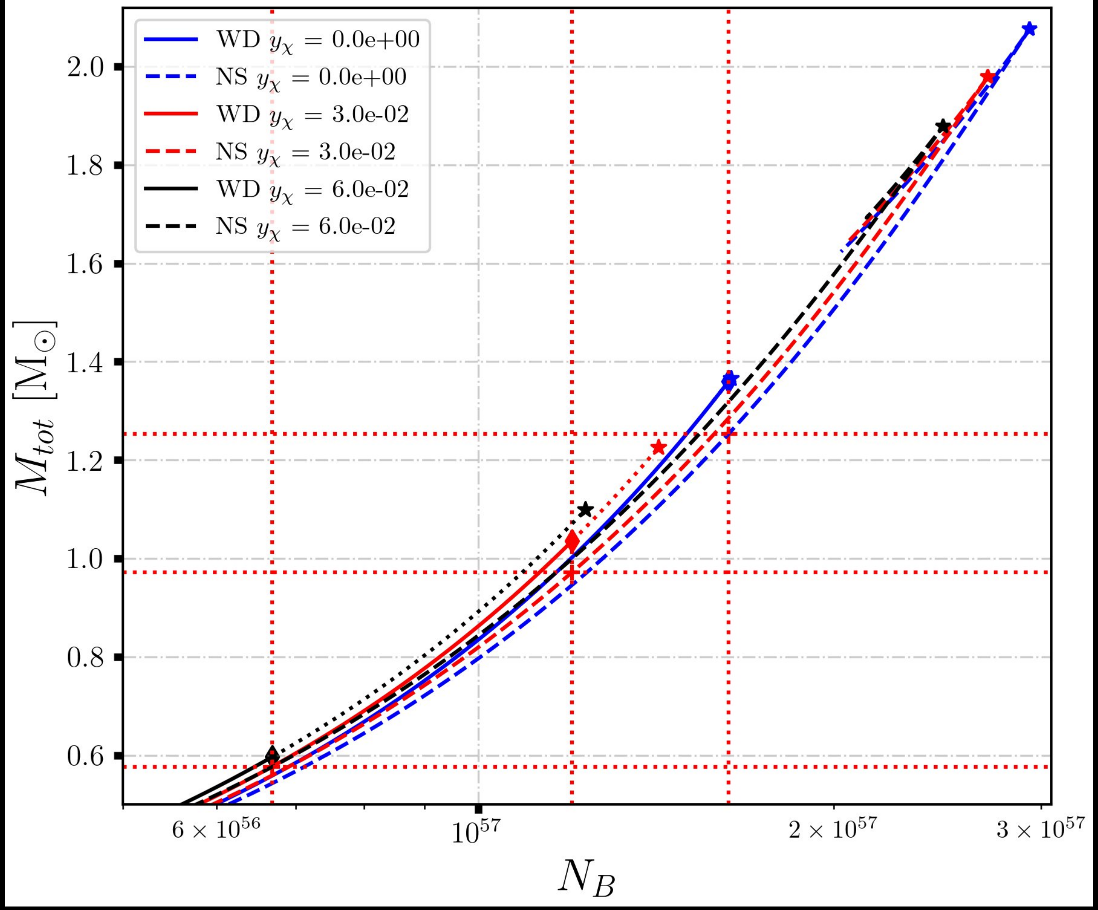
Increases with DM mass and fraction

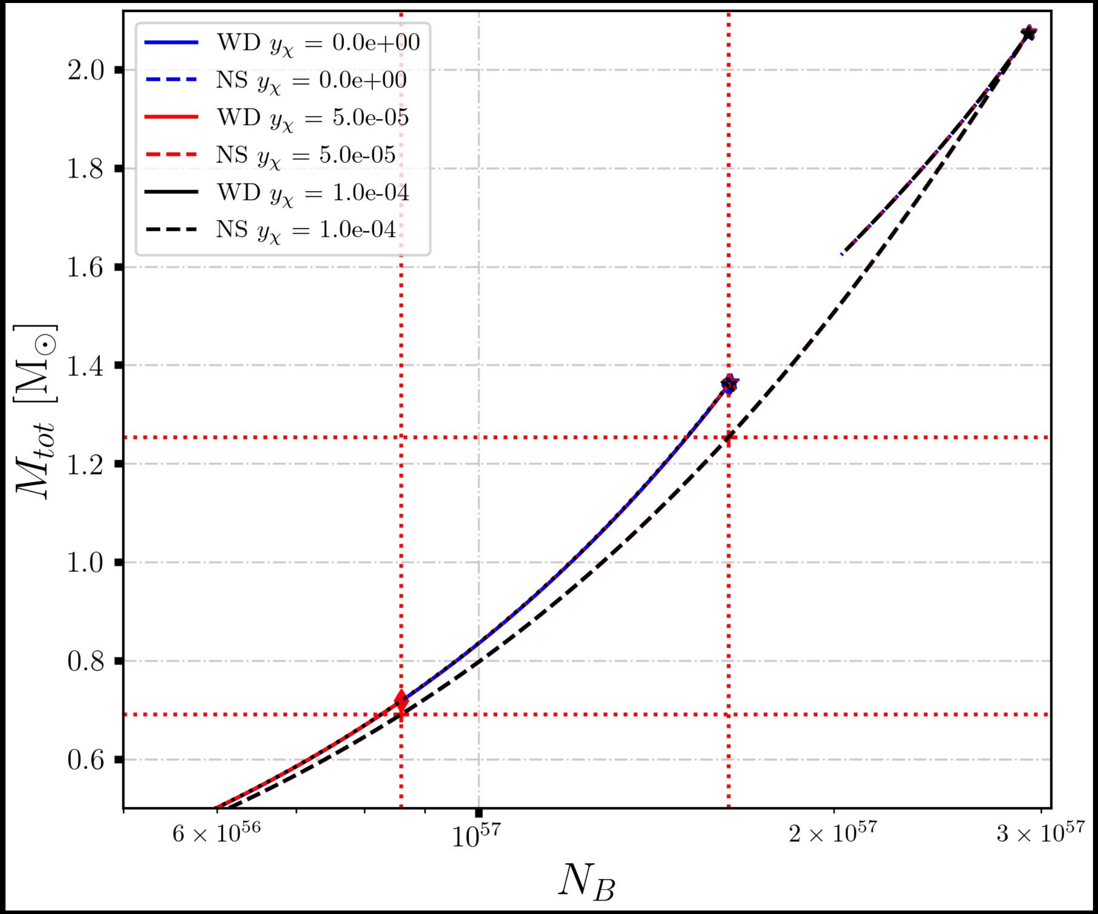
Decreases with DM mass and fraction

The EC threshold density remain same, due to no interaction of NM and OM. However, the gravitational interaction between OM and DM, leads to a redistribution of OM within the WD due to the influence of the DM. As a result, the EC process that triggers the ECSN is initiated at a lower critical stellar mass compared to white dwarfs without DM.

WD to NS transition: Conserving Baryon number and Dark matter number

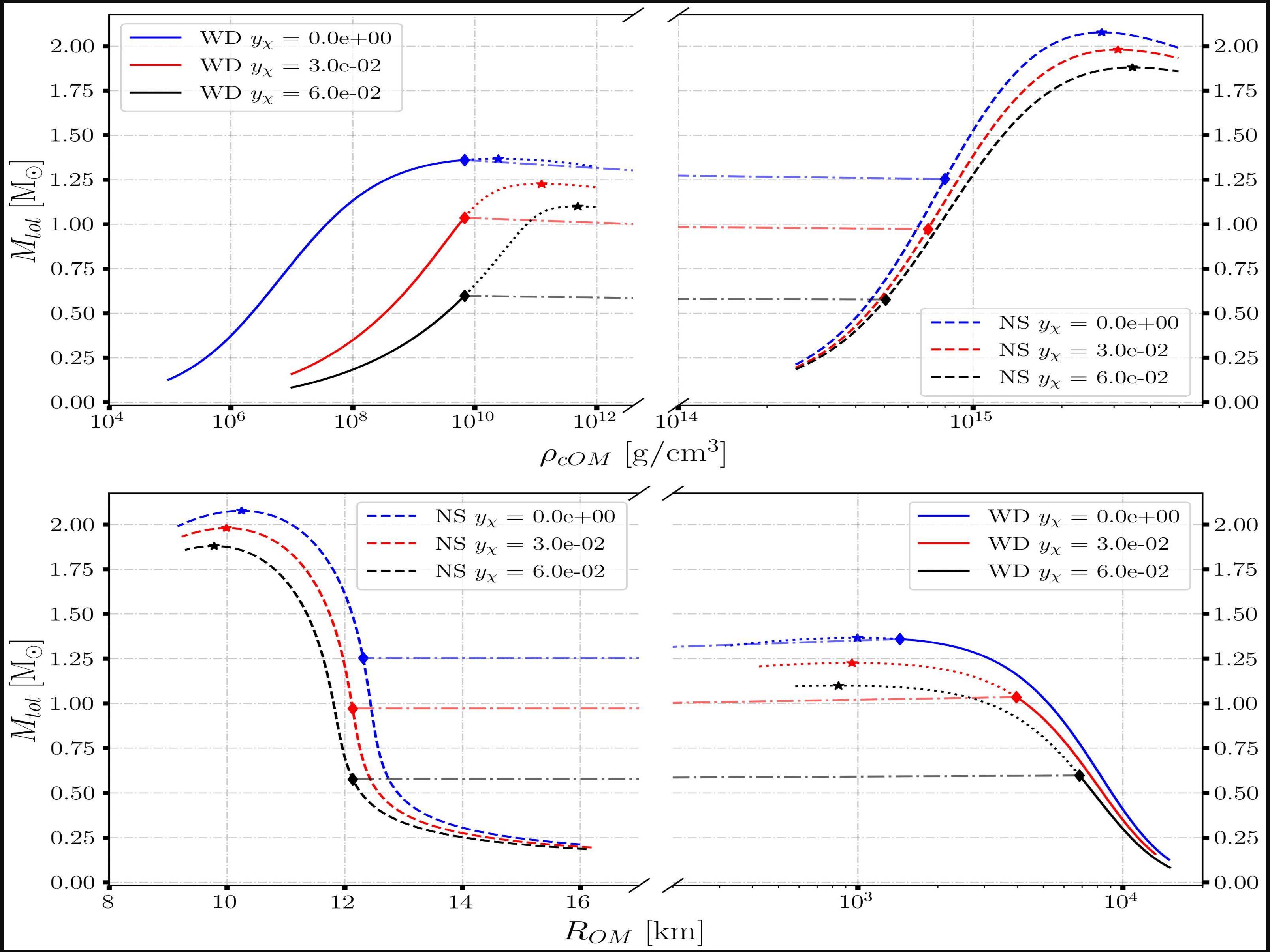
Bombaci and Datta, 2000





WD → NS

m_χ=1 GeV



WD to NS transition in the presence of DM

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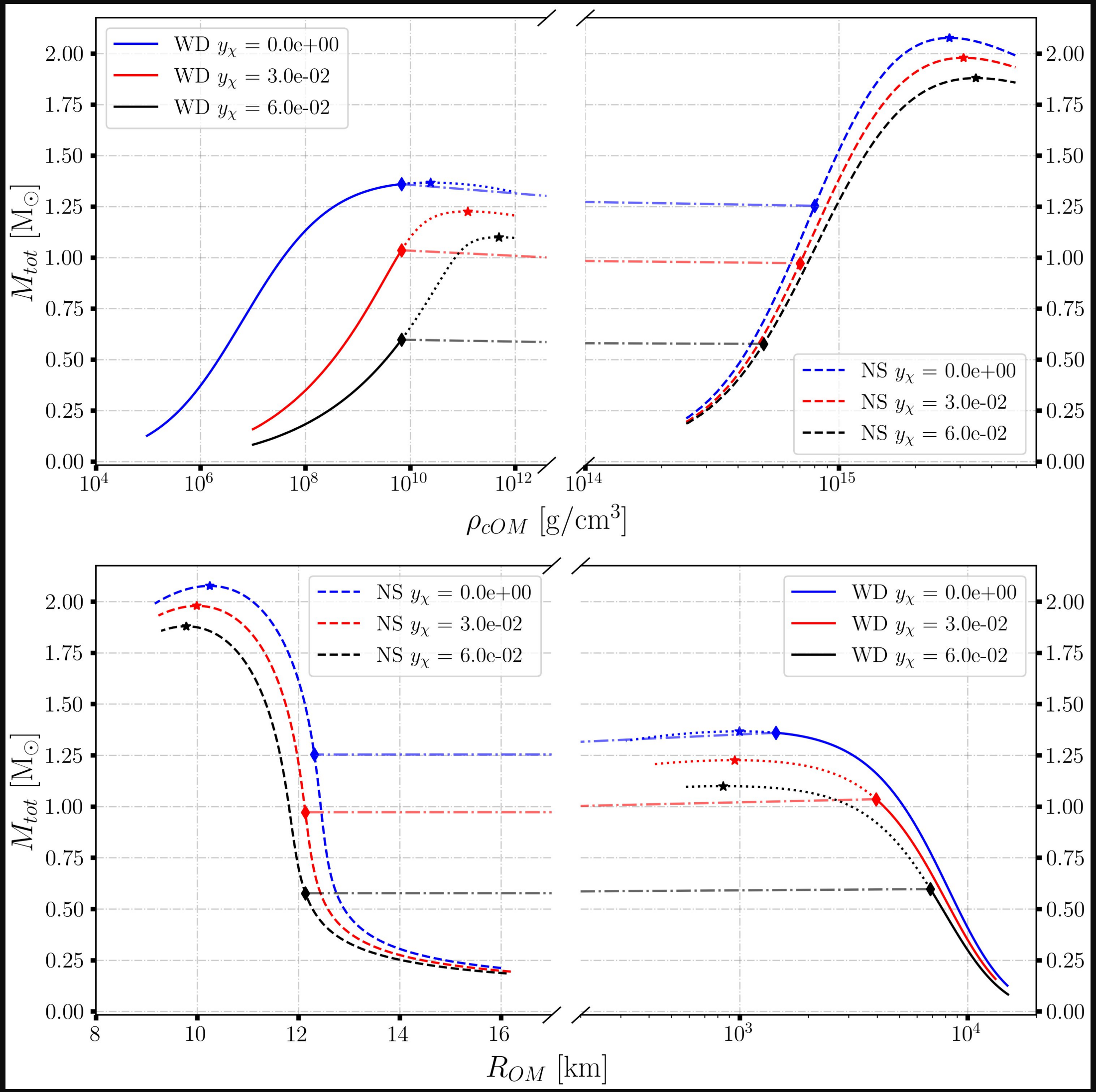
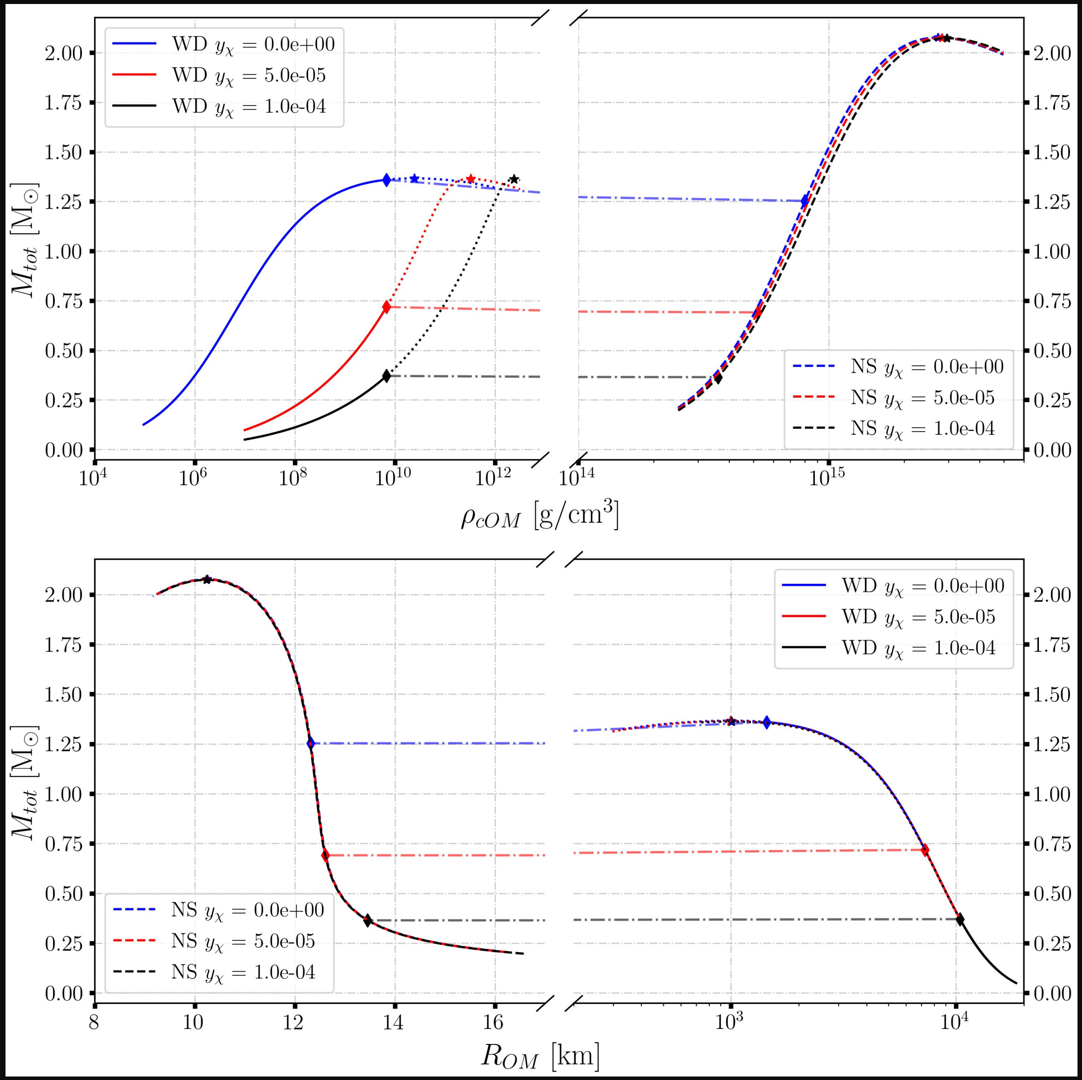


m$_\chi$=1 GeV



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WD → NS

y_χ	M^*_{OM} $[M_\odot]$	R^*_{OM} [km]	M^*_{DM} $[M_\odot]$	R^*_{DM} [km]	M^* $[M_\odot]$	M^{NS}_{OM} $[M_\odot]$	R^{NS}_{OM} [km]	M^{NS}_{DM} $[M_\odot]$	R^{NS}_{DM} [km]	M^{NS}_{tot} $[M_\odot]$	E^{conv} [$\times 10^{53}$ erg]
No DM											
0	1.359	1440.7			1.359	1.253	12.317			1.253	1.903
$m_\chi = 1$ GeV											
3×10^{-2}	1.0020	3970.193	0.0333	40.7306	1.0353	0.9385	12.1383	0.0329	5.7617	0.971	1.144
6×10^{-2}	0.5582	6865.600	0.0382	38.6725	0.5964	0.5379	12.1418	0.0378	6.6232	0.576	0.357
$m_\chi = 10$ GeV											
5×10^{-5}	0.7180	7272.626	3.854×10^{-4}	0.3883	0.7184	0.6905	12.612	3.853×10^{-4}	0.3617	0.692	0.472
1×10^{-4}	0.3703	10399.74	3.975×10^{-4}	0.3837	0.3707	0.3643	13.453	3.970×10^{-4}	0.3666	0.365	0.102

WD → NS

With No DM, ECSN can not describe PSR J0453+1559 with 1.17 M

y_χ	M^*_{OM} [$M_\odot$]	R^*_{OM} [km]	M^*_{DM} [$M_\odot$]	R^*_{DM} [km]	M^* [$M_\odot$]	M^{NS}_{OM} [$M_\odot$]	R^{NS}_{OM} [km]	M^{NS}_{DM} [$M_\odot$]	R^{NS}_{DM} [km]	M^{NS}_{tot} [$M_\odot$]	E^{conv} [$\times 10^{53}$ erg]
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No change in DM mass during the transition

WD → NS

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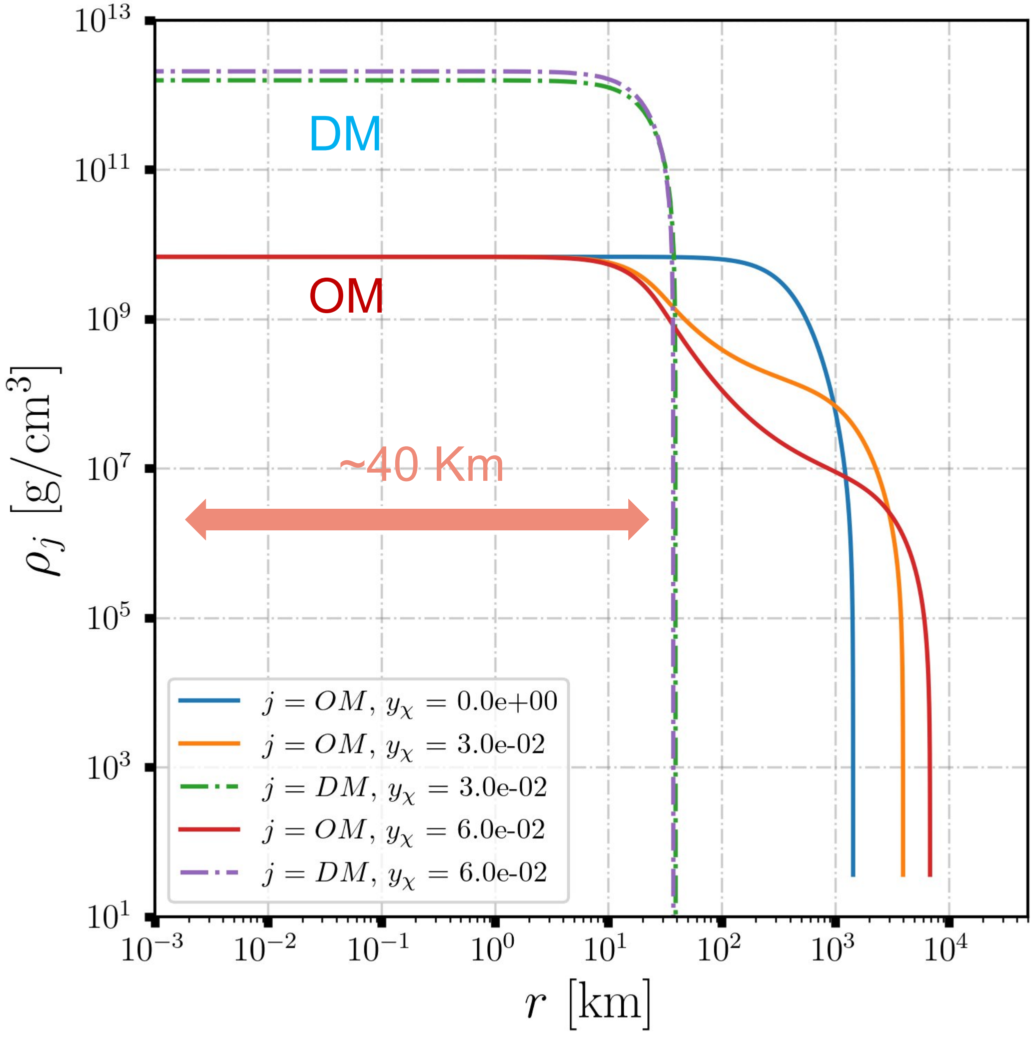
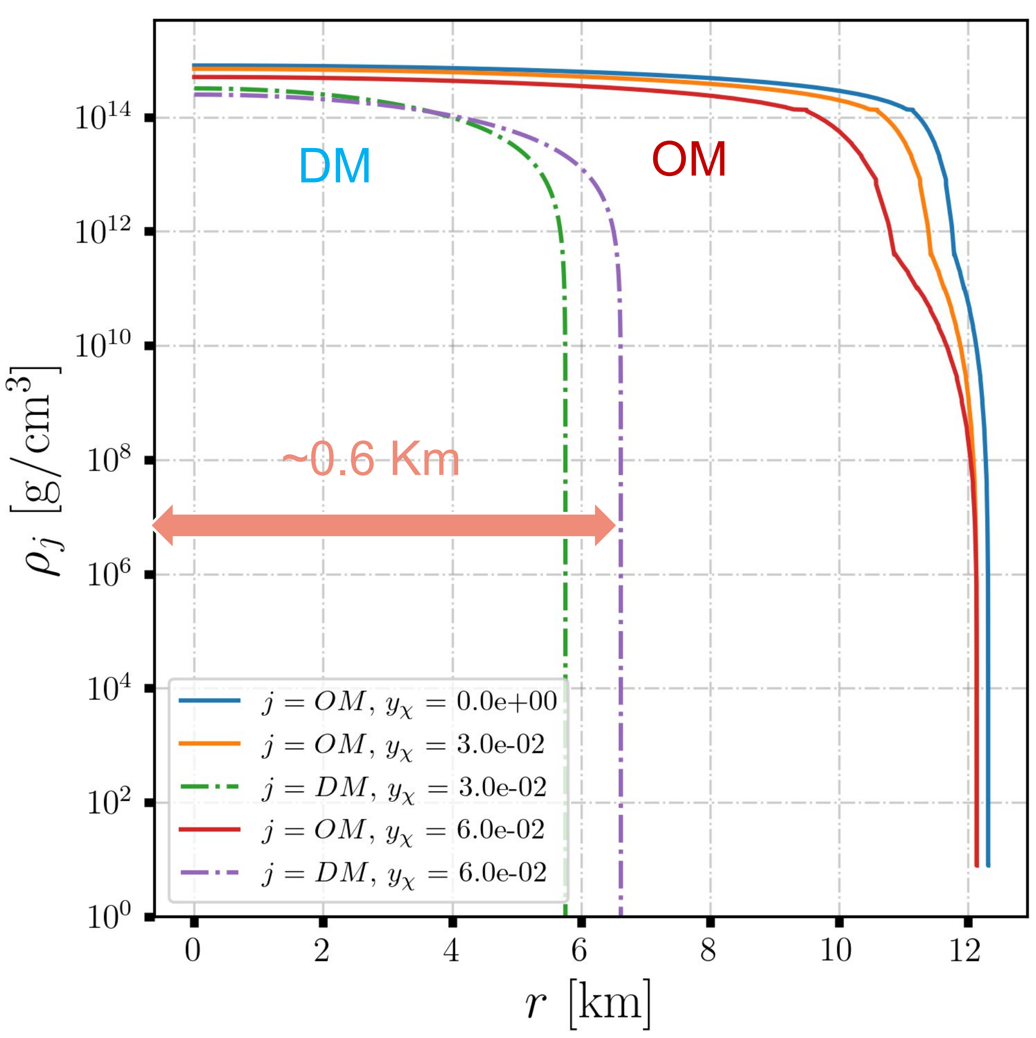
DM can reduce the NS mass considerably from ECSN.

DM can results in further reduction in the energy released

Mass-density profiles for WD and NS

m_χ=1 GeV





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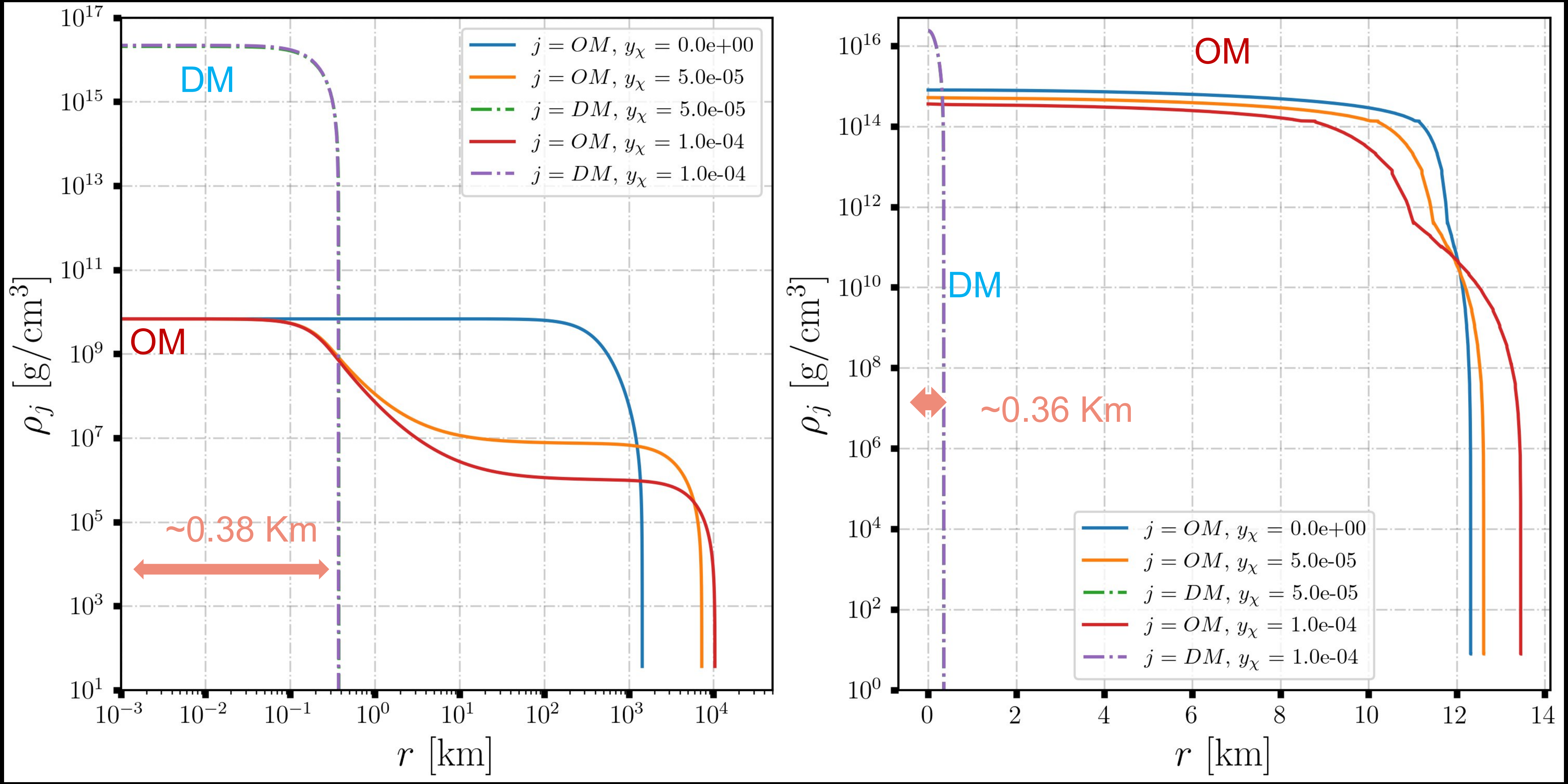

Conclusion

- Recent observations have established electron-capture supernovae as a real, distinct pathway to neutron-star formation, validating decades of theoretical work on collapsing O–Ne–Mg cores.

- Incorporating dark matter in the progenitor/core raises or lowers the electron-capture threshold and, at fixed baryon number, predicts systematically lower gravitational NS masses; this is directly testable with the emerging population of low NS mass systems

- A synthesis of EC-WD microphysics with multimessenger data (NICER radii, GW tidal deformabilities, precision pulsar timing) provides a coherent inference framework that can tightens constraints on the cold dense-matter EOS and crust properties.

Future Implications and Prospective

- Can we identify candidate neutron stars that may have formed through electron-capture supernovae using our current understanding of nuclear theory and observational constraints?

- For such neutron stars, what can we infer about their internal structure, including possible signatures of dark-matter admixture or deviations from standard nuclear microphysics?

- Given a confirmed ECSN candidate, to what extent can we constrain the mass and fractional abundance of the dark-matter component responsible for modifying the collapse threshold?

THANK YOU

Collaborators

Prof. Ignazio Bombaci (INFN Pisa & UNIPI)

&

Domenico Scordino (Former UNIPI student)