Neutron Stars as physics laboratories

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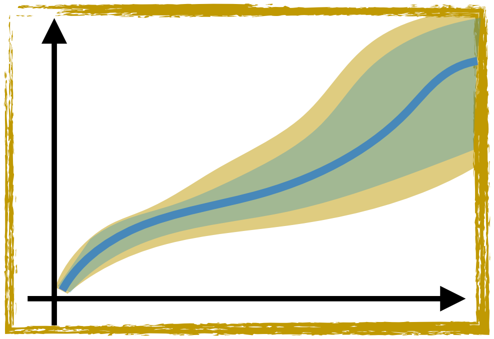
Online/In Person

Departament de Física Quàntica i Astrofísica

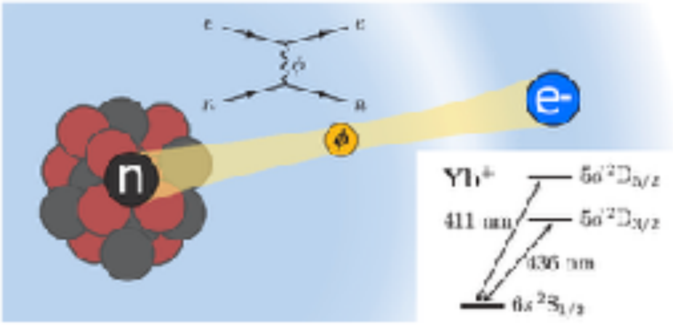
@HadNucAtUB

Neutron Stars as physics laboratories

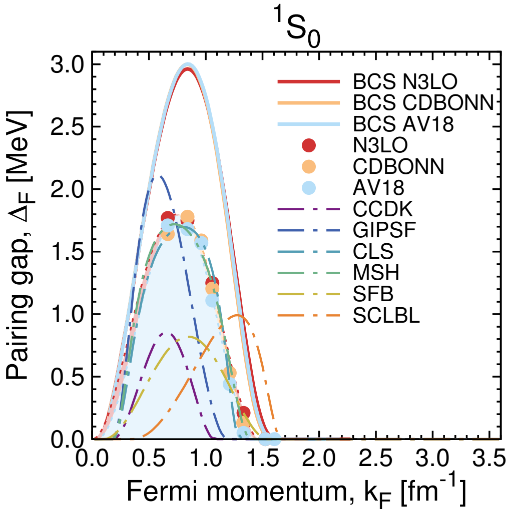
1) Neutron stars in 2022



2) Dark matter



3) Superfluid critical temperature



Death of stars

Mass

>100 $M_\odot$

50-100 $M_\odot$

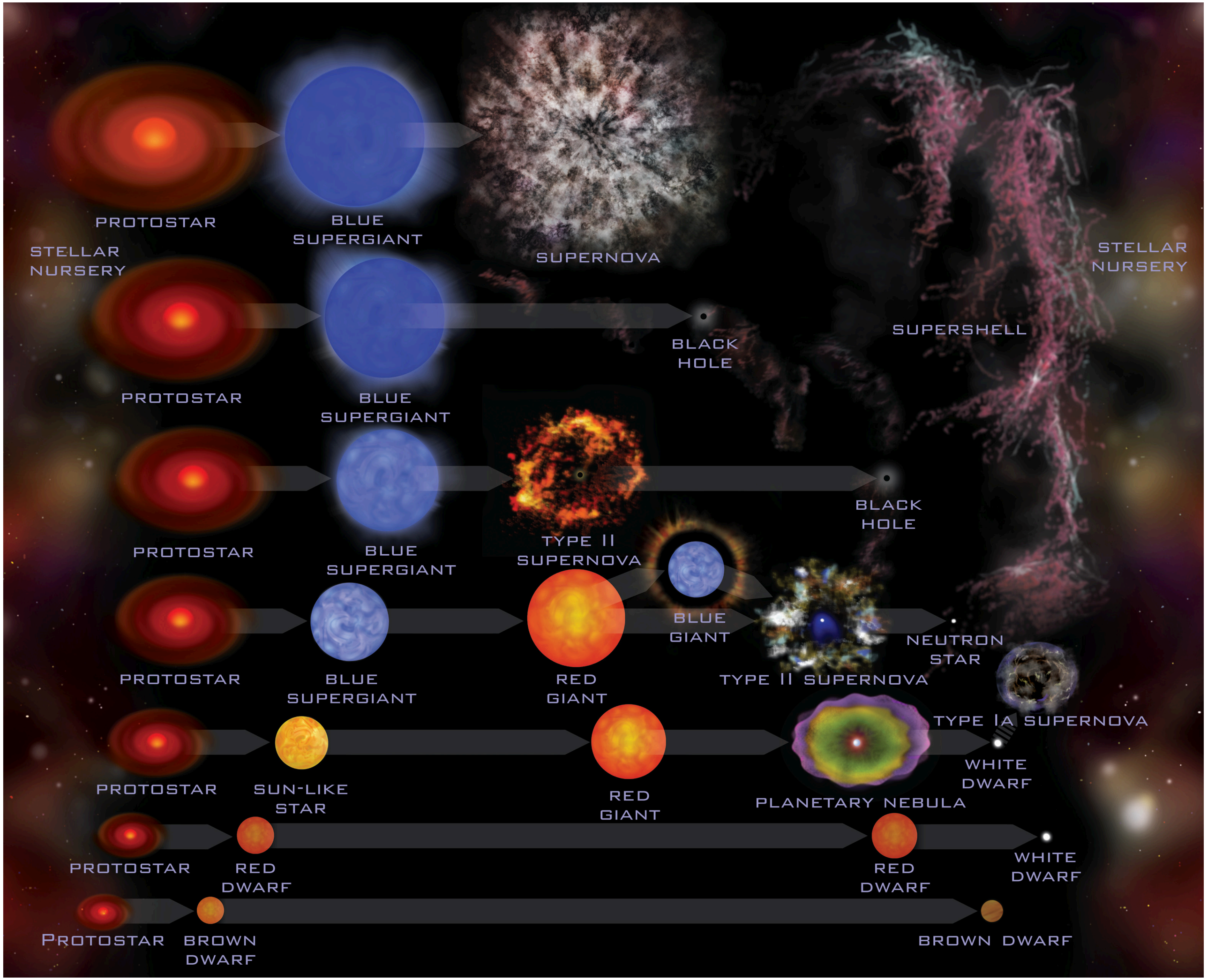
25-50 $M_\odot$

8-25 $M_\odot$

0.4-8 $M_\odot$

0.08-0.4 $M_\odot$

< 0.08 $M_\odot$



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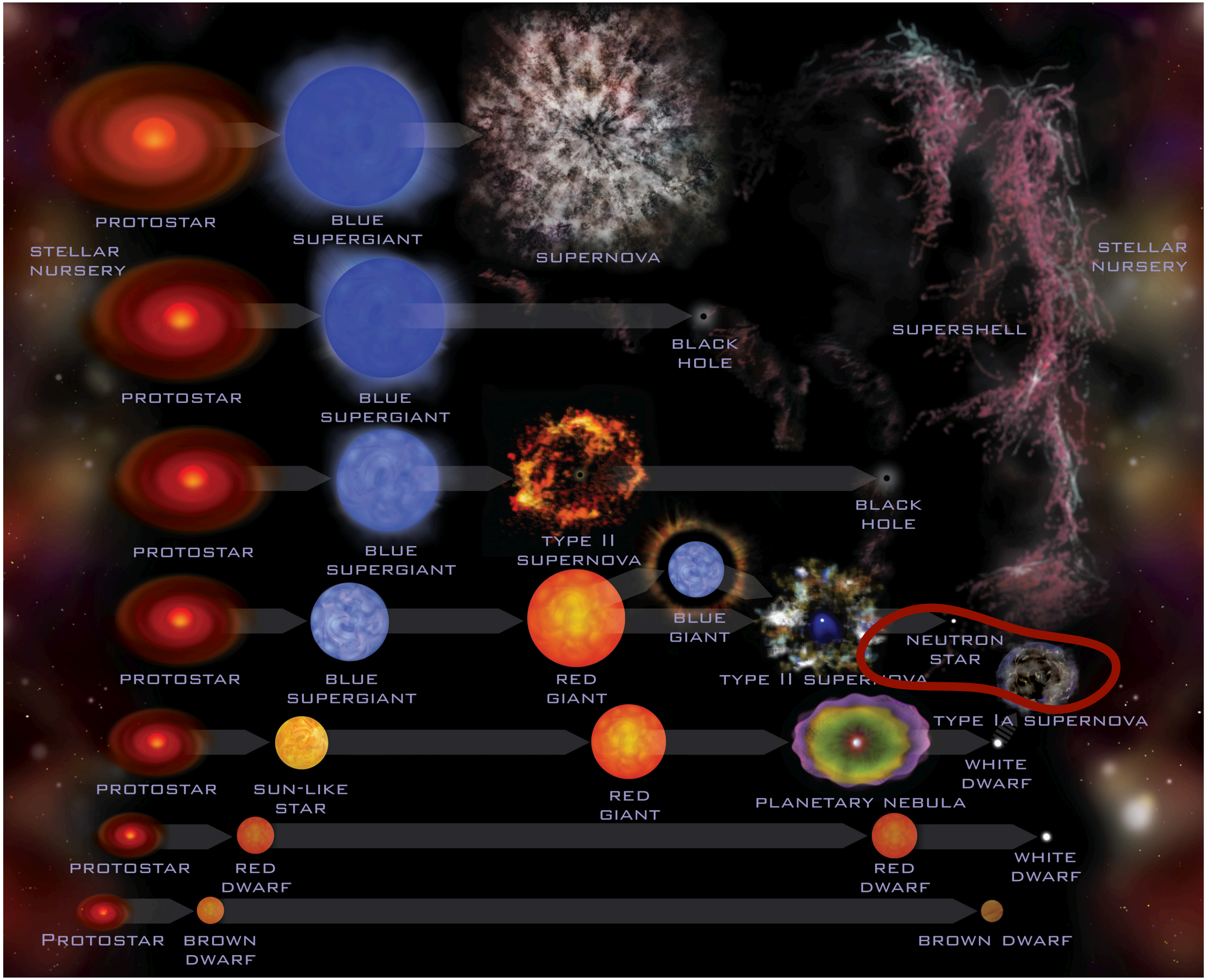
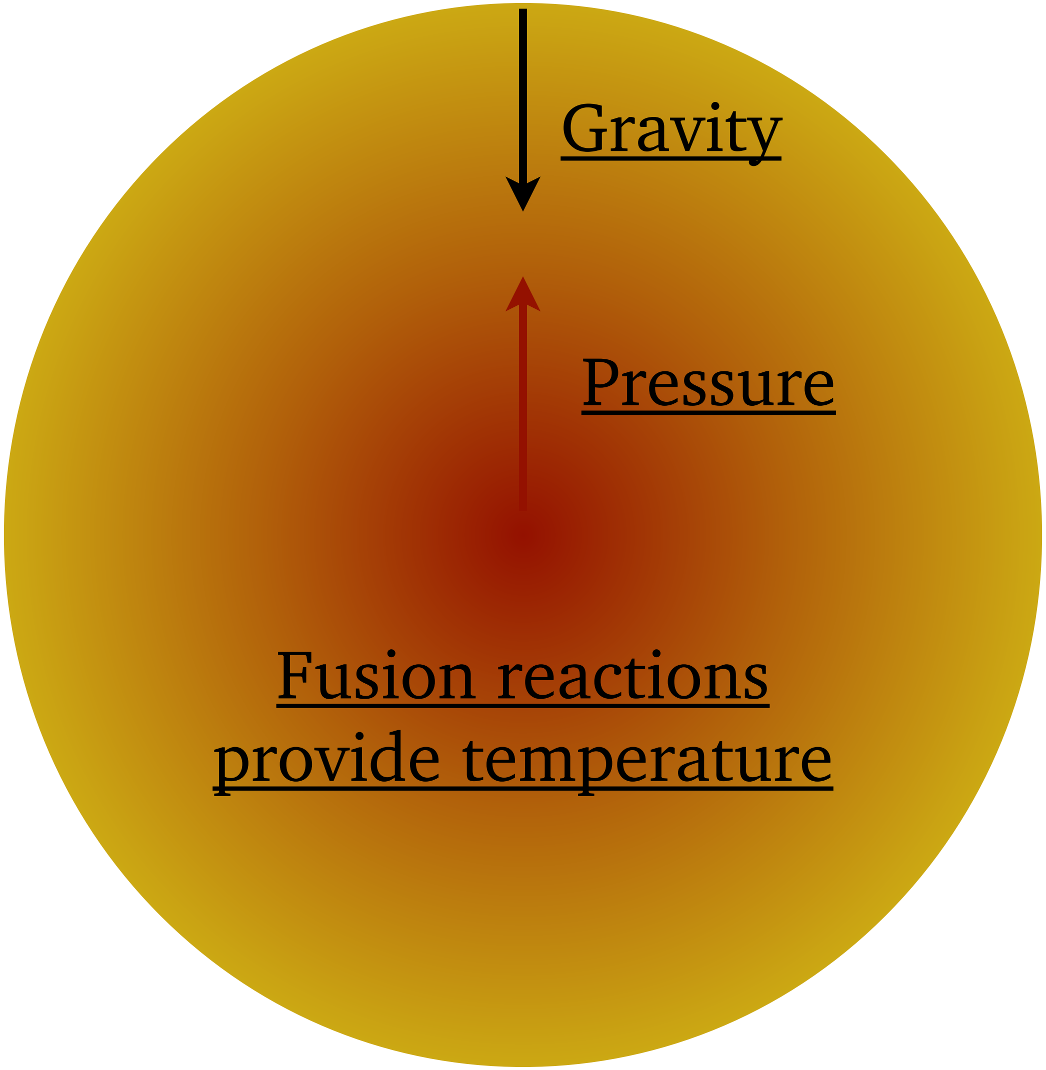
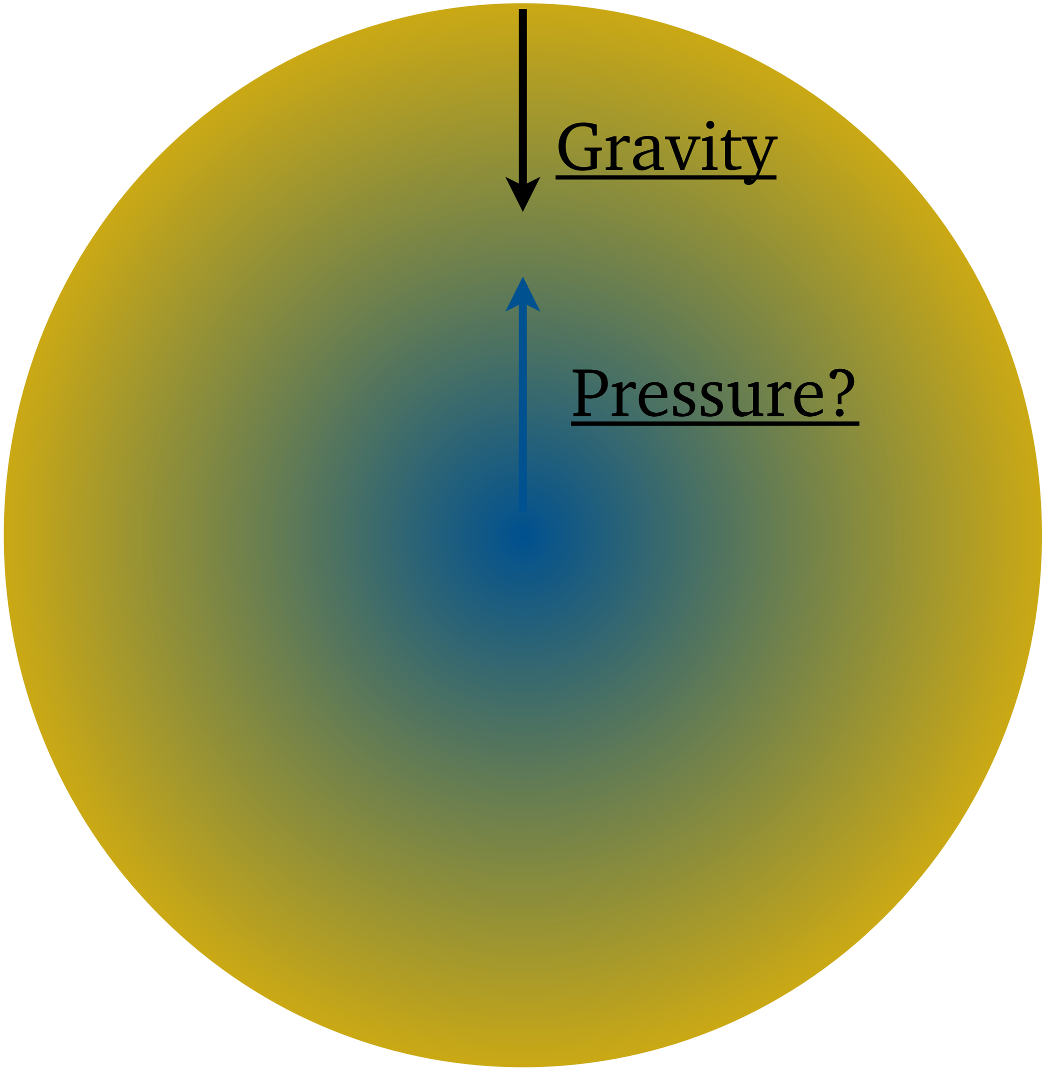
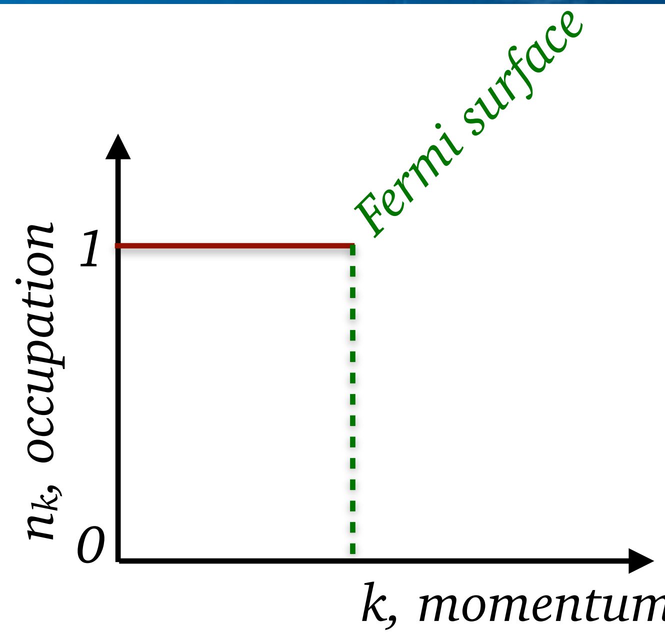




Temperature provides pressure!

Degenerate matter & pressure





Degeneracy pressure

$$p \approx \rho^{\Gamma}$$

Pauli principle & neutron interactions provide pressure without T

Mass

$$M \approx 1.5 M_{\odot} = 3 \times 10^{33} \ \ \text{g}$$

Radius

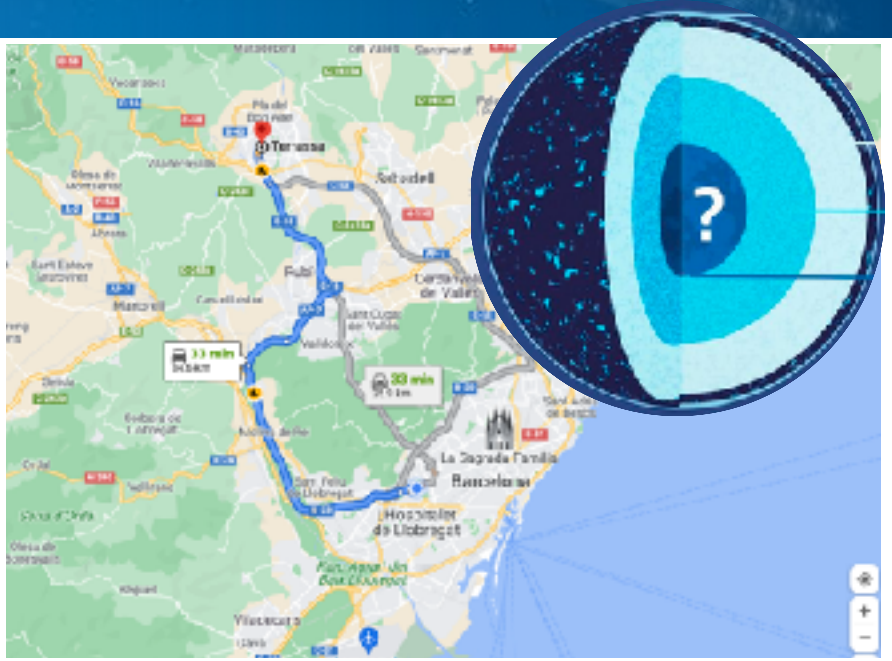
$$R \approx 10 \ \ \text{km}$$

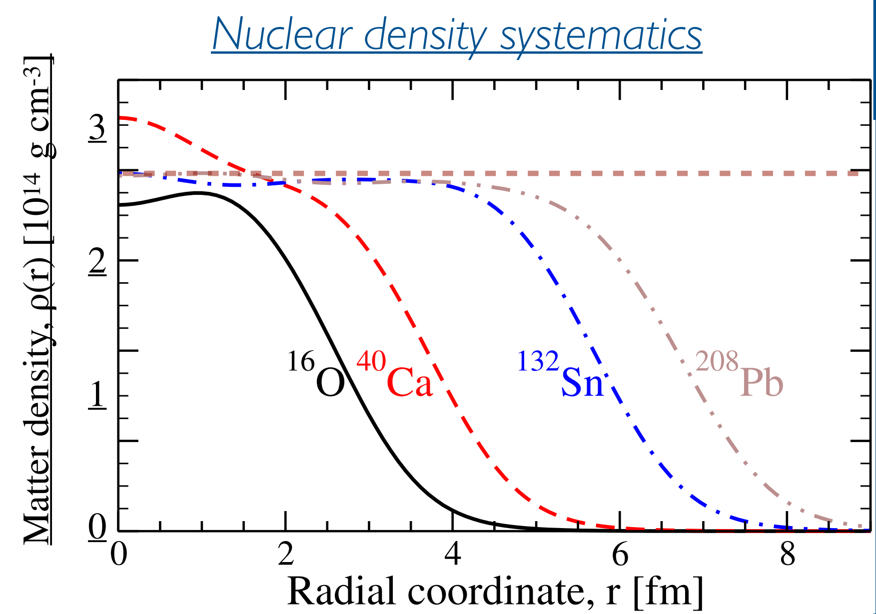
Mass density

$$\rho = \frac{M}{V} \approx 7 \times 10^{14} \ \ \text{g} \ \ \text{cm}^{-3}$$

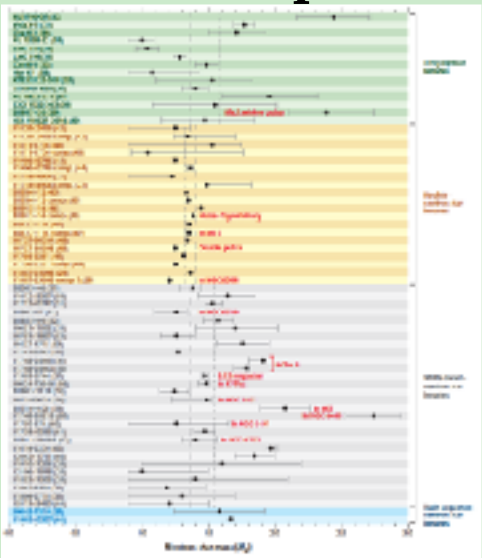
Nuclear saturation density

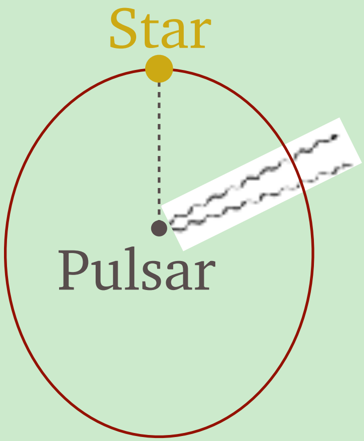
$$\rho_0 = 0.16 \ \ \text{fm}^{-3}$$
$$\approx 3 \times 10^{14} \ \ \text{g} \ \ \text{cm}^{-3}$$



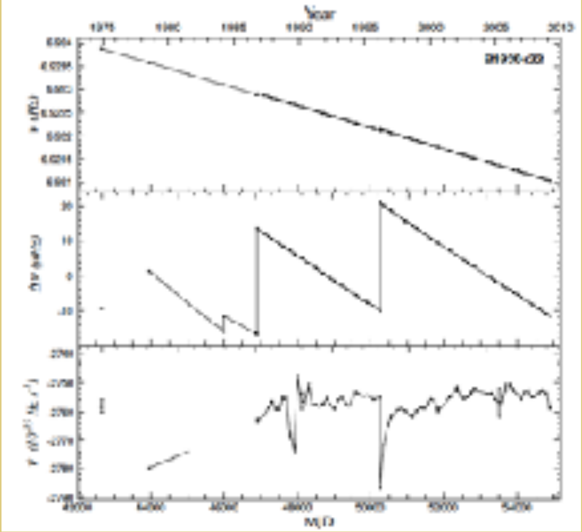


Radio pulsar binaries



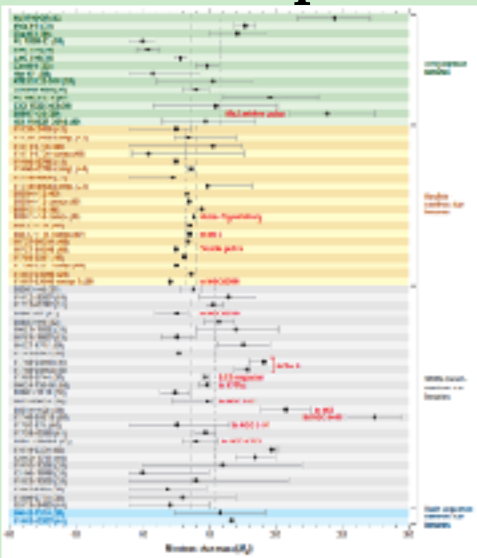


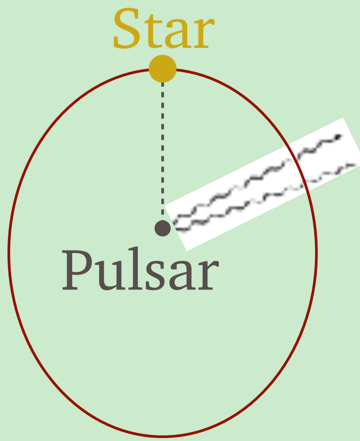
Pulsars in isolation



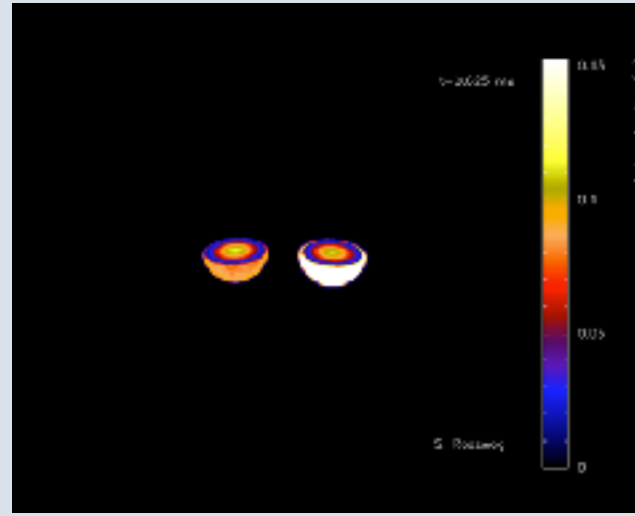
Multimessenger observations

Radio pulsar binaries





Gravitational wave binaries



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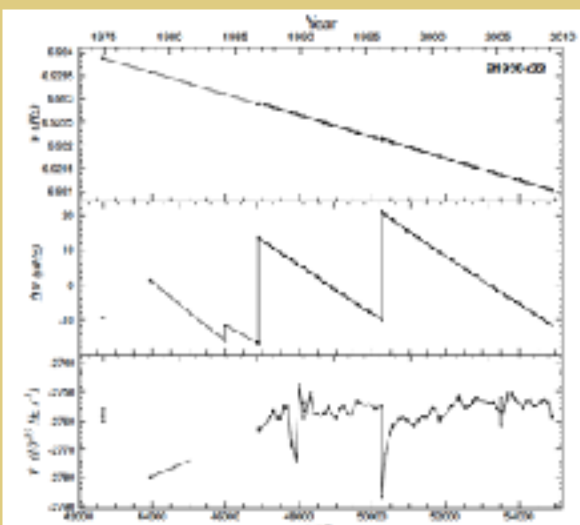
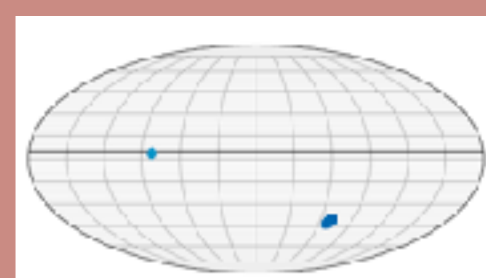
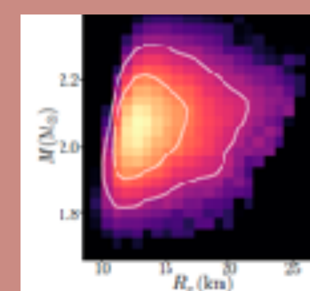


X-rays from accreting NS





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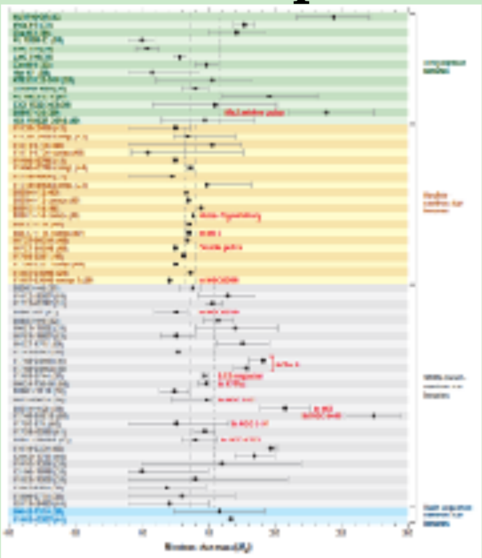

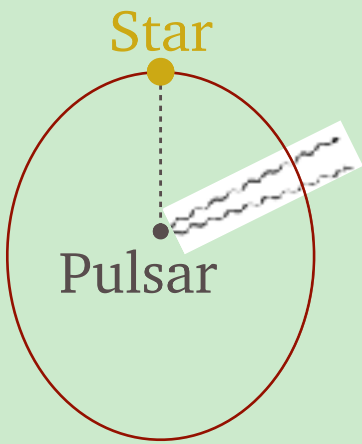

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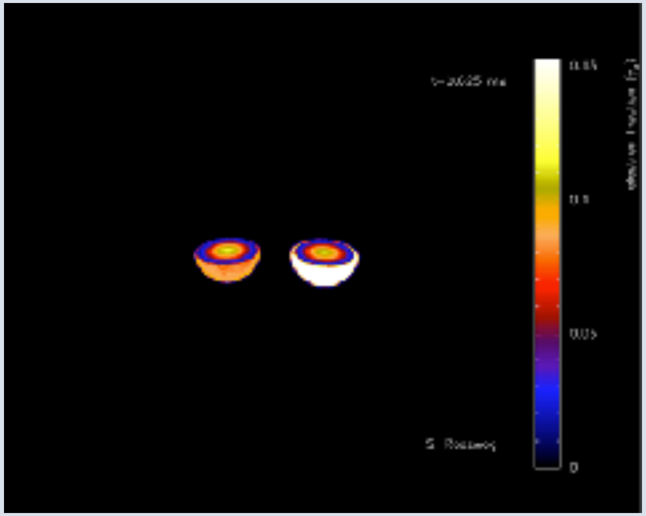

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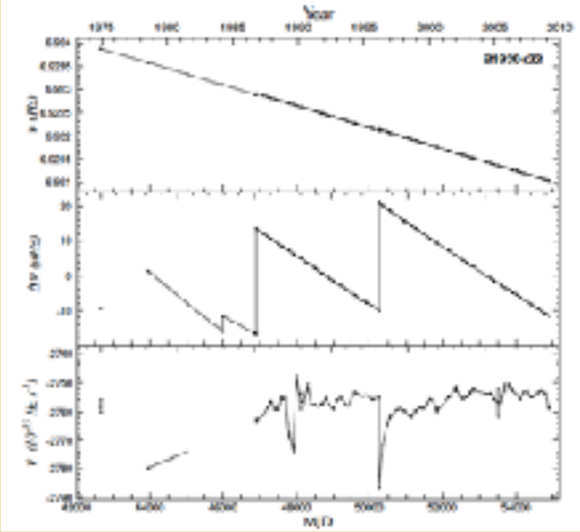

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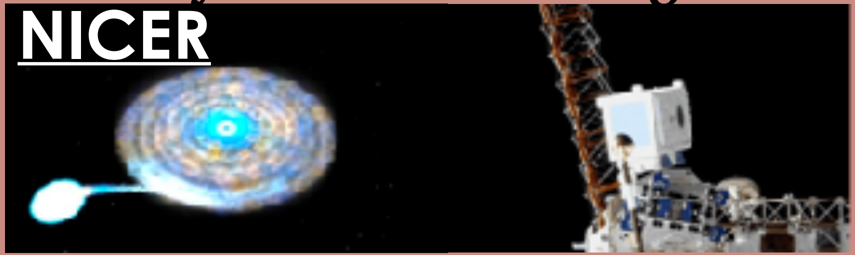
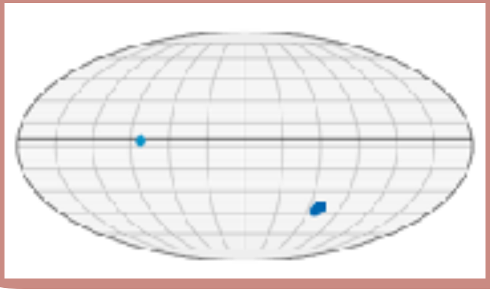
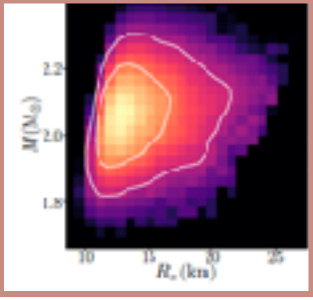






From EoS to M-R

Tolman-Oppenheimer-Volkov equations

$$\frac{dp}{dr} = -\frac{G}{c^2}\frac{(m + 4\pi p r^3)(\epsilon + p)}{r(r - 2Gm/c^2)}$$

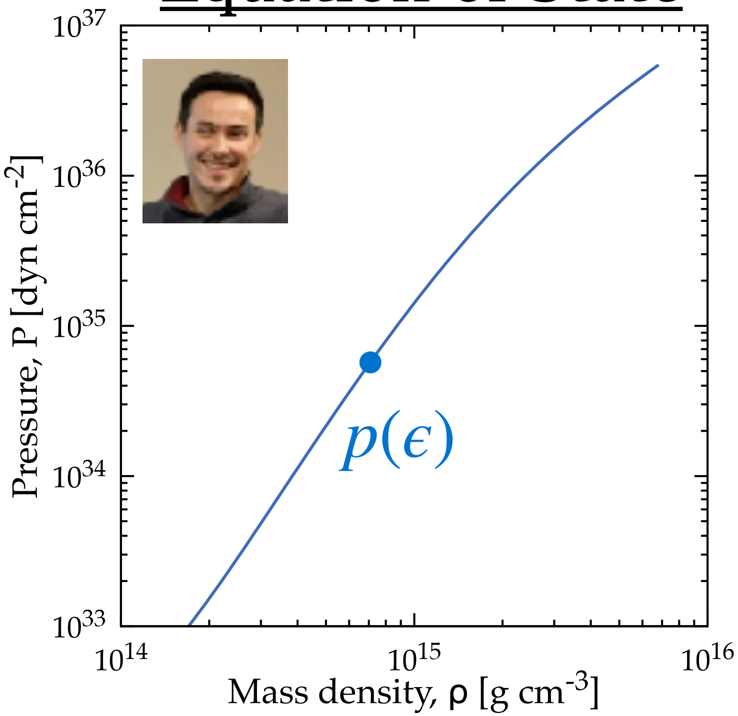
$$\frac{dm}{dr} = \frac{4\pi}{c^2}\epsilon r^2$$

+

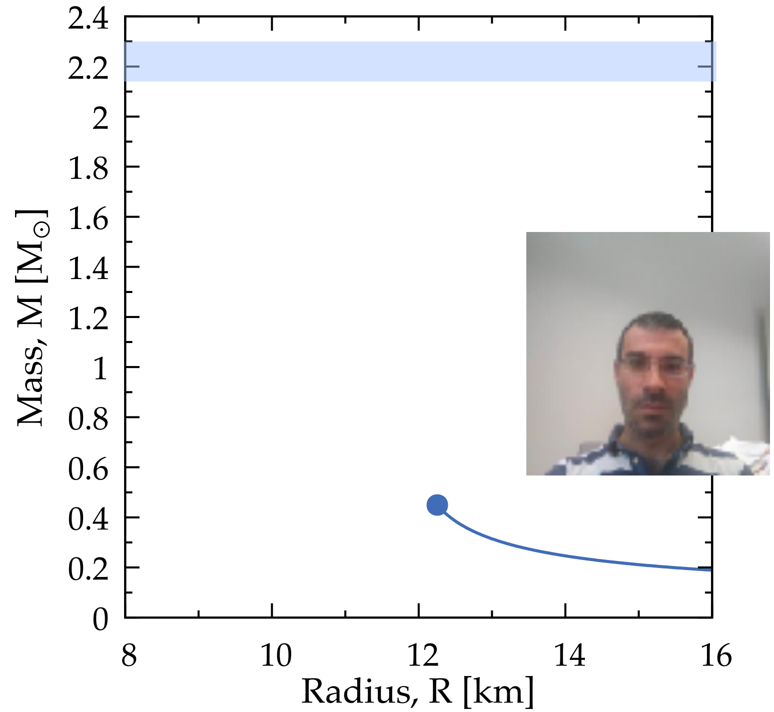
EoS

$$p \equiv p(\epsilon)$$

Equation of State



Mass-Radius



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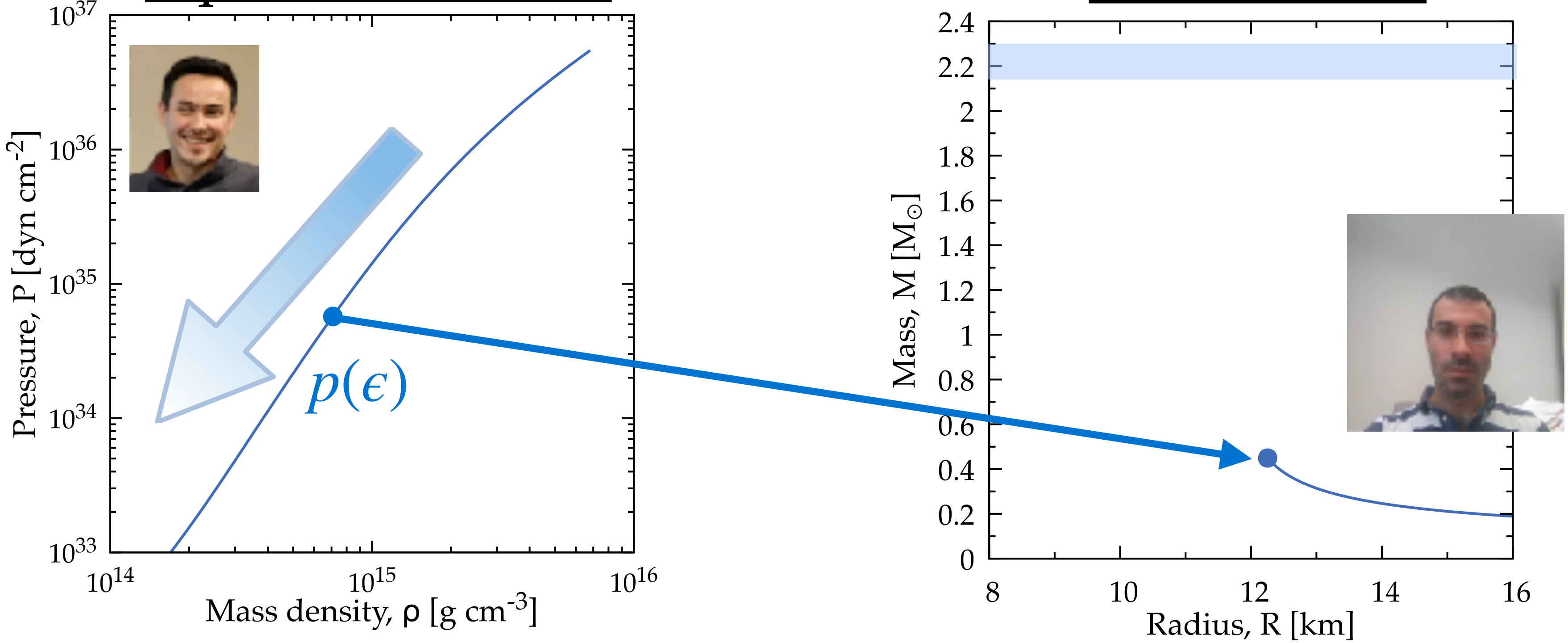
Equation of State | Mass-Radius



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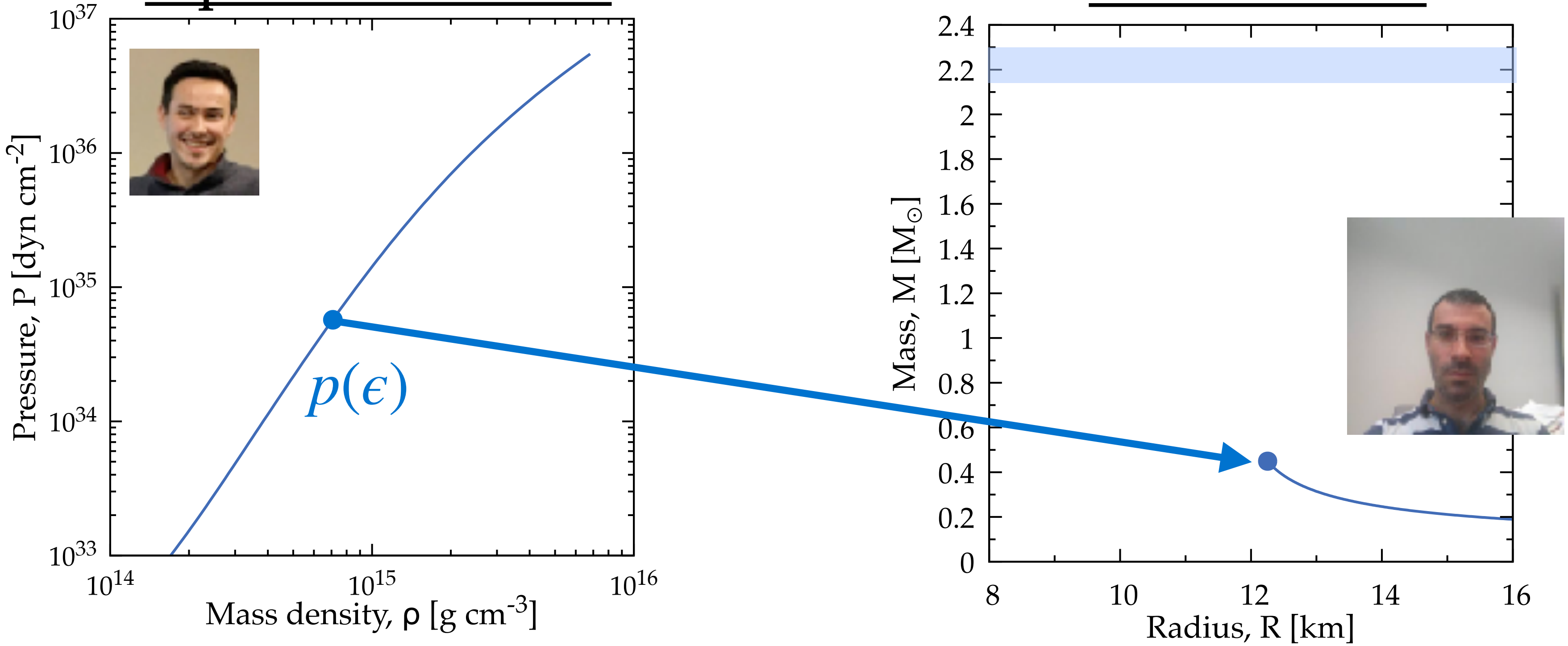
__Equation of State__ __Mass-Radius__



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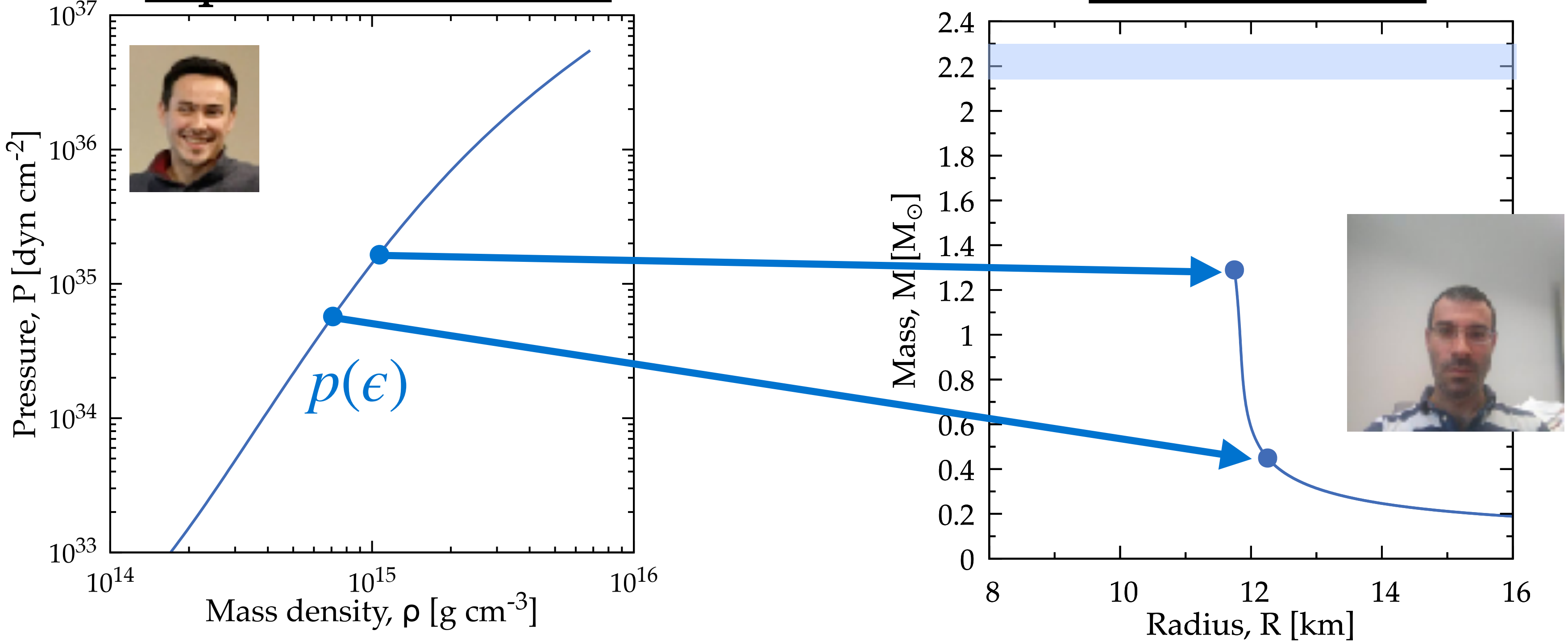
Equation of State — Mass-Radius



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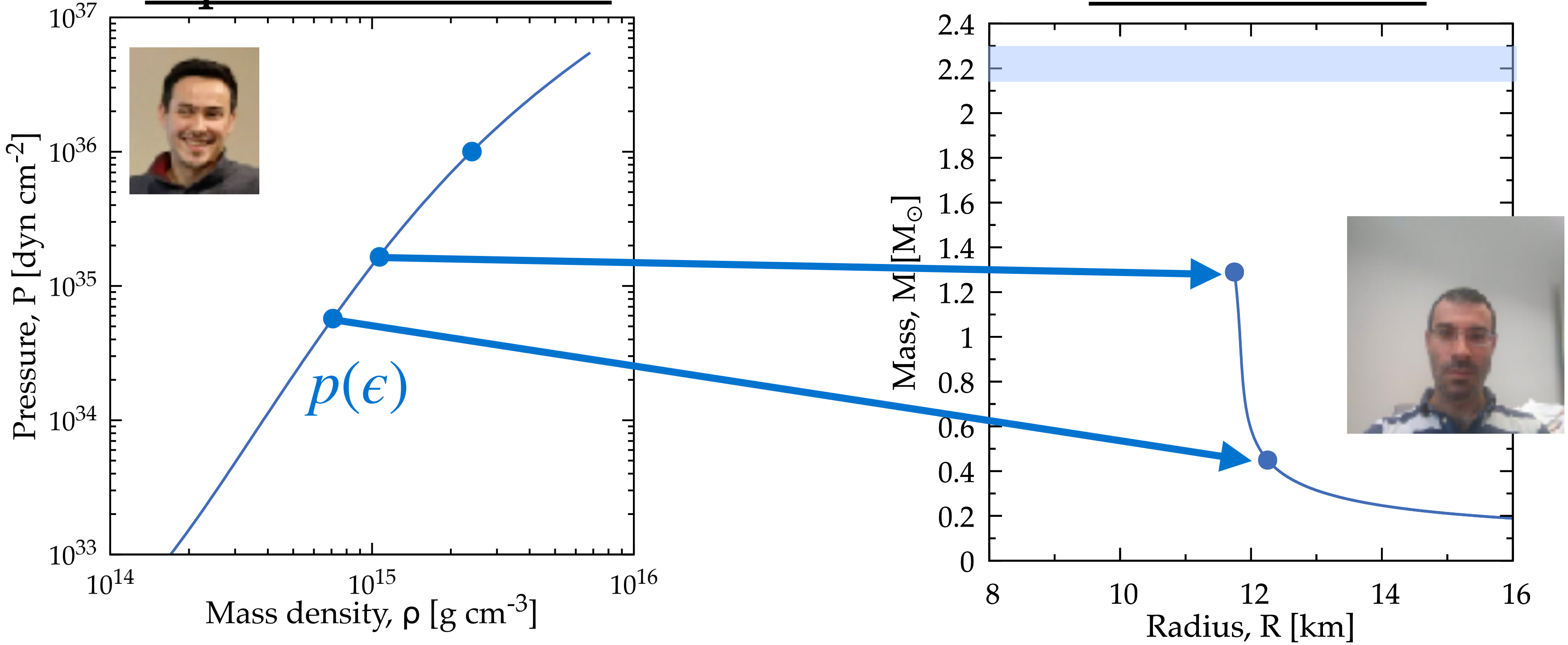
Equation of State | **Mass-Radius**



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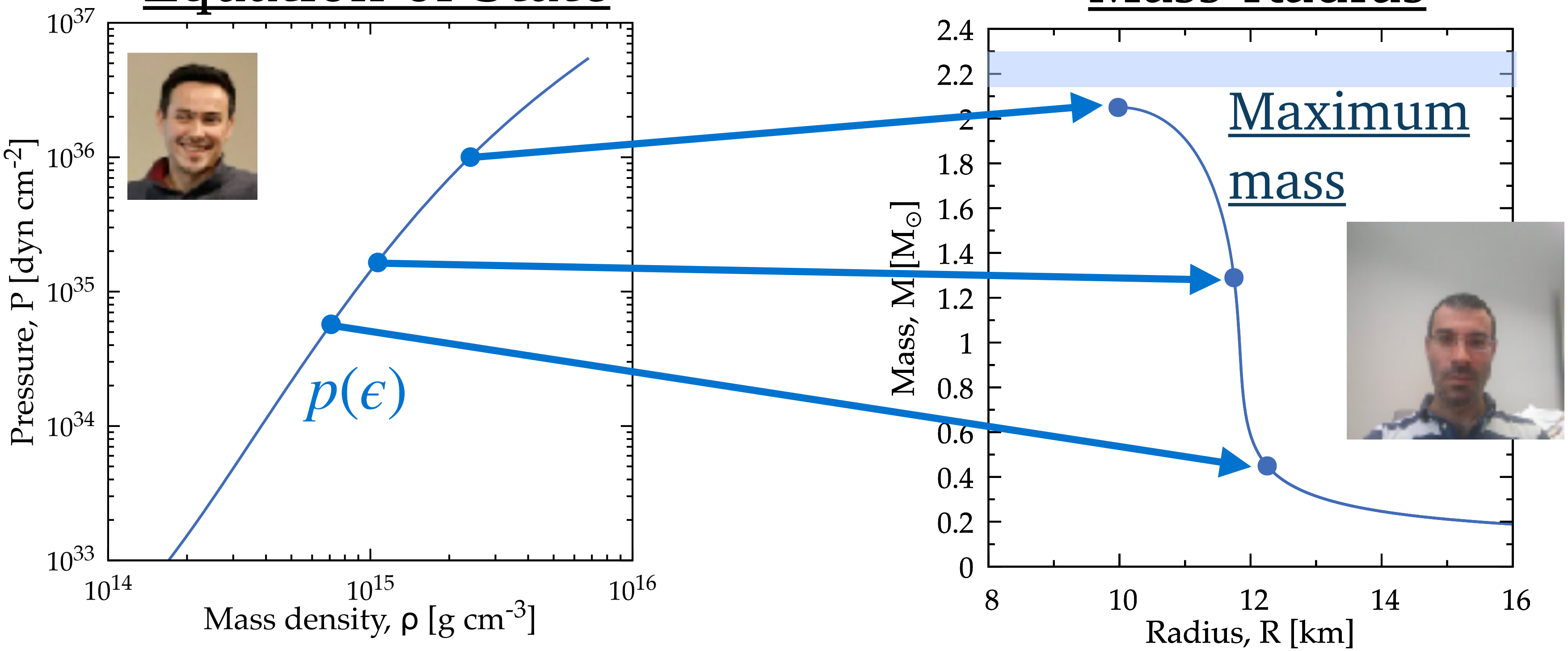
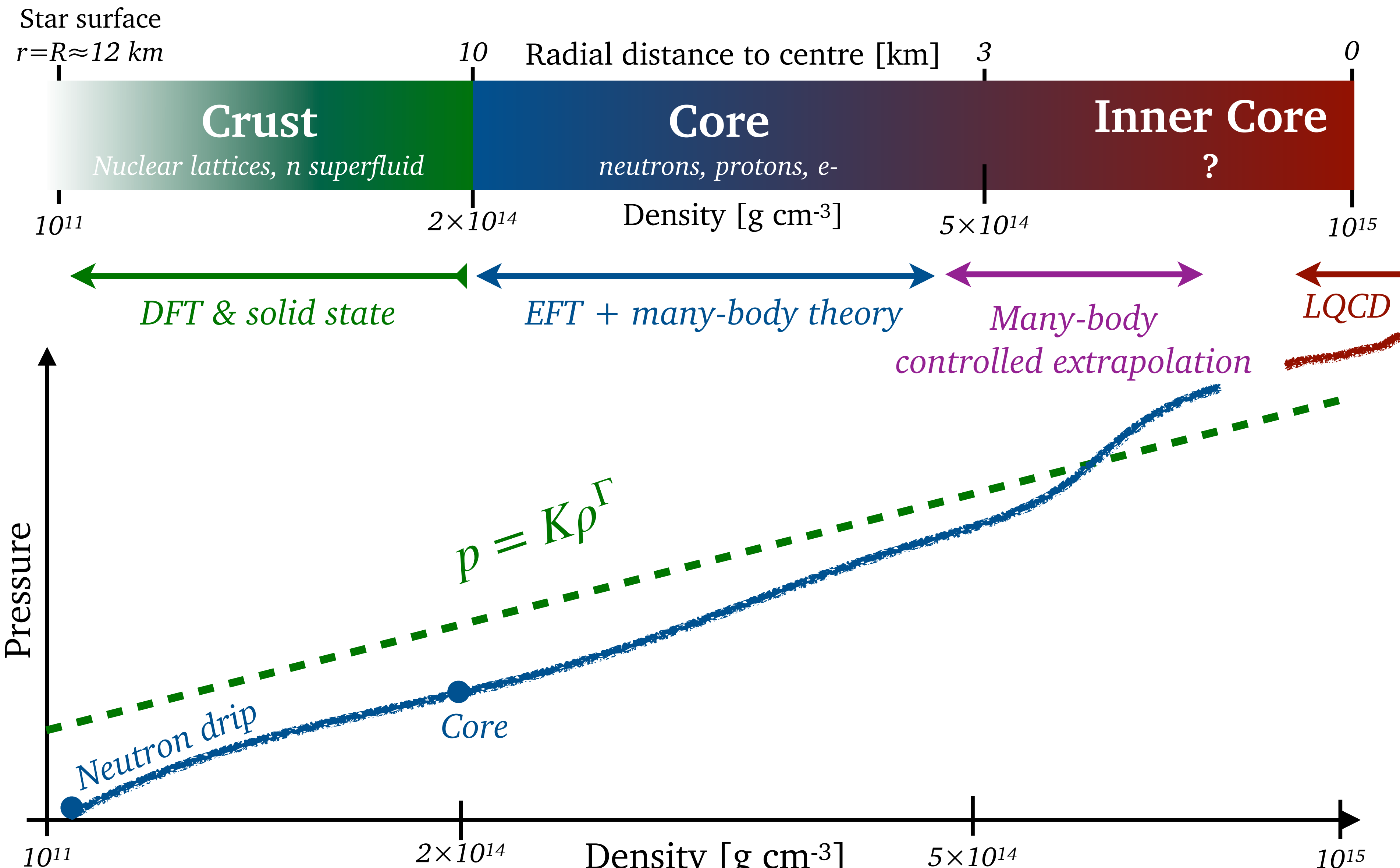
Equation of State

Mass-Radius



Nuclear astrophysics models



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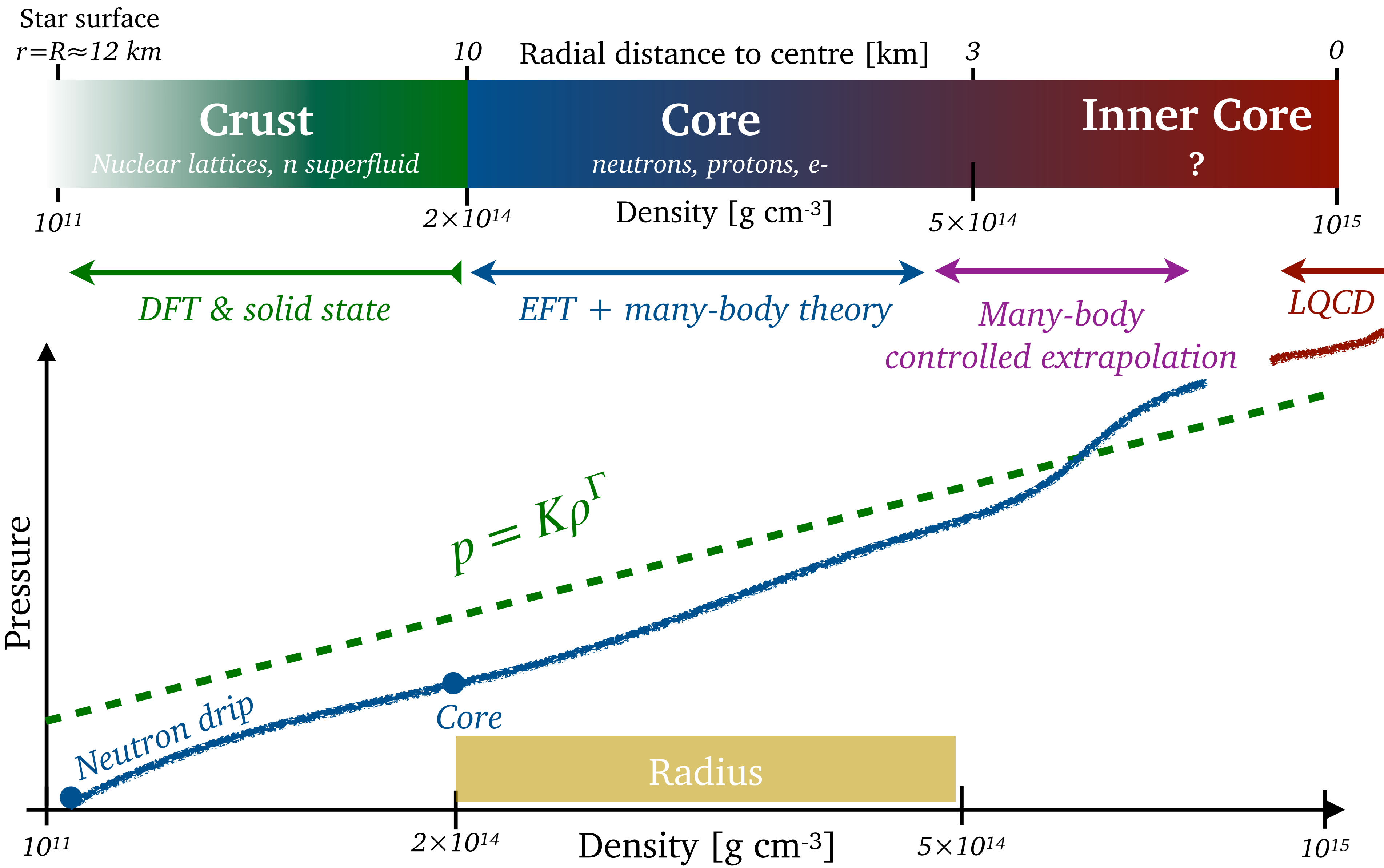

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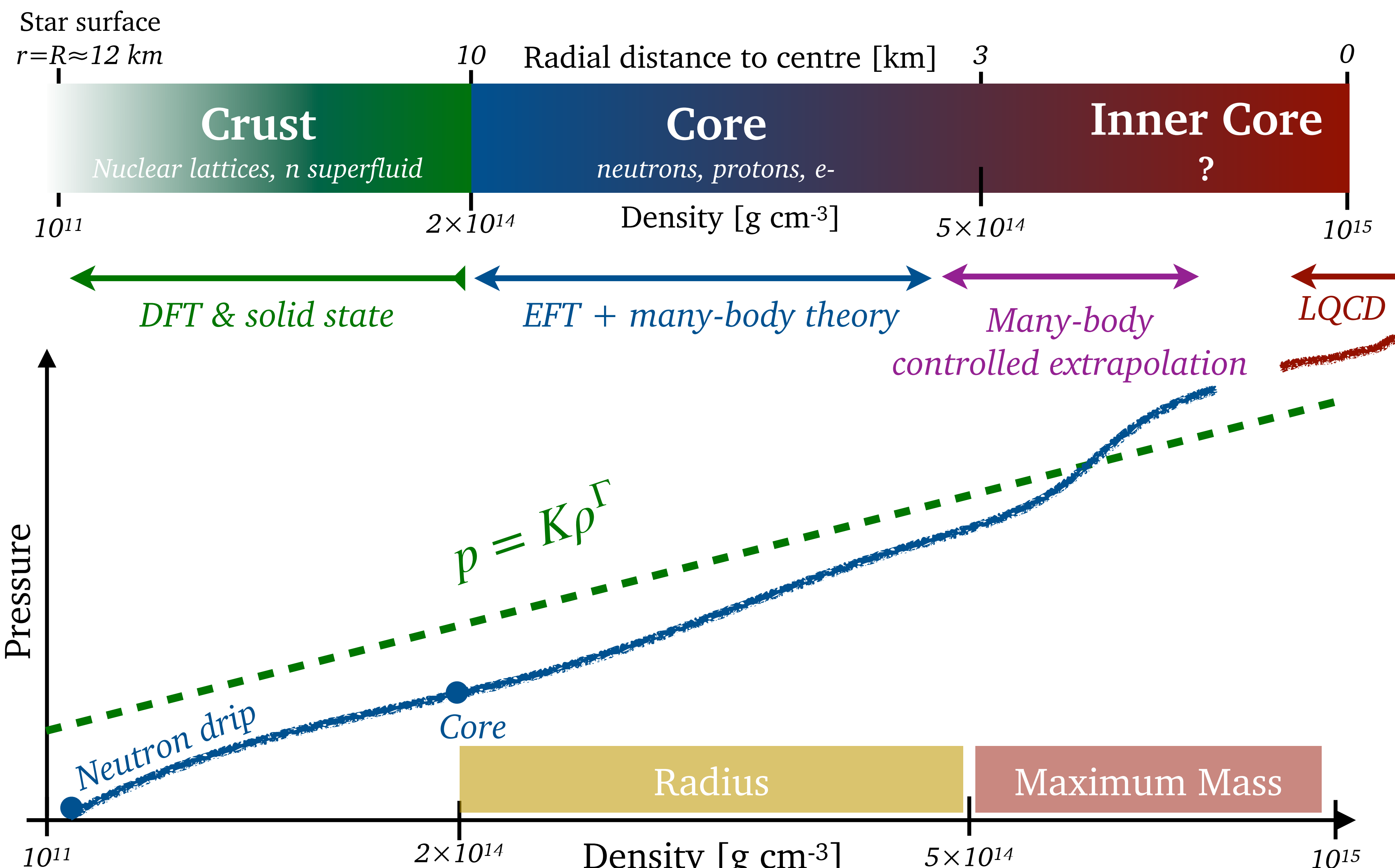
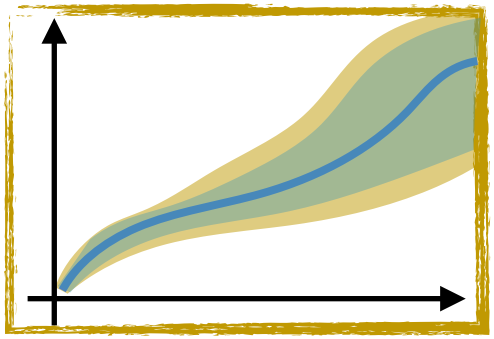
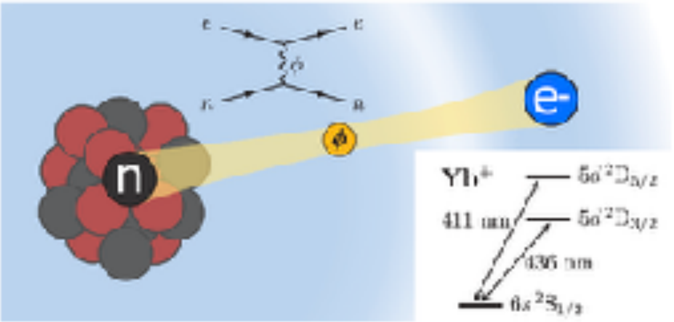
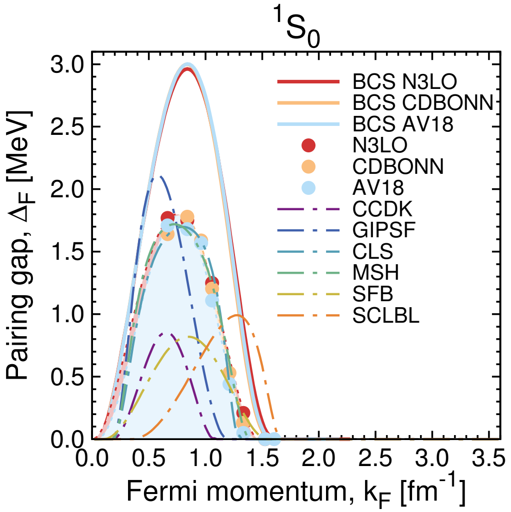




1) Neutron stars in 2022

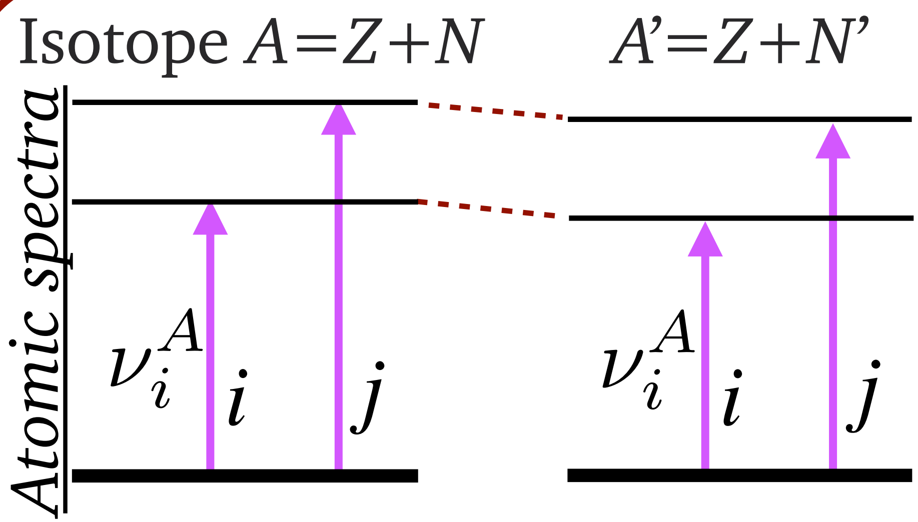


2) Dark matter



3) Superfluid critical temperature

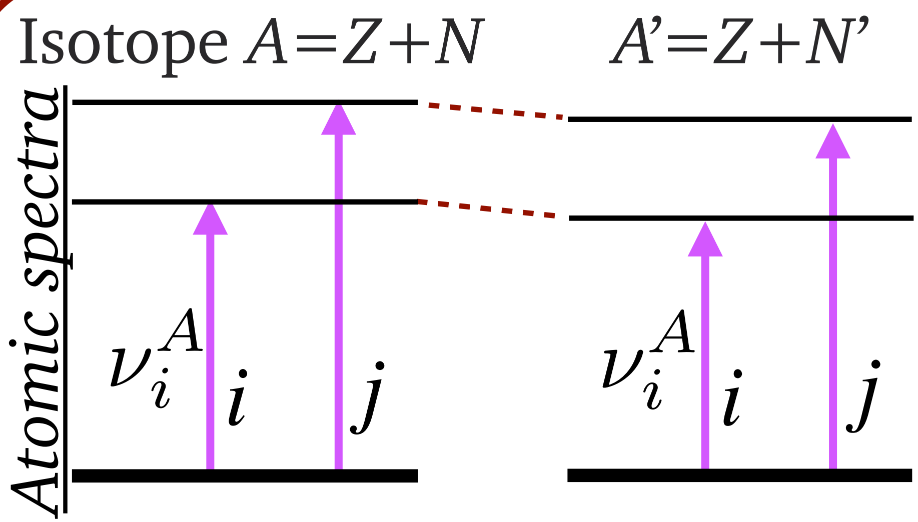
Exotic neutron-electron coupling



Isotope shift linear relation

$$\delta\nu_i^{A,A'} = M_i \frac{A' - A}{AA'} + F_i \delta\langle r^2\rangle^{A,A'}$$

Exotic neutron-electron coupling



Isotope shift linear relation

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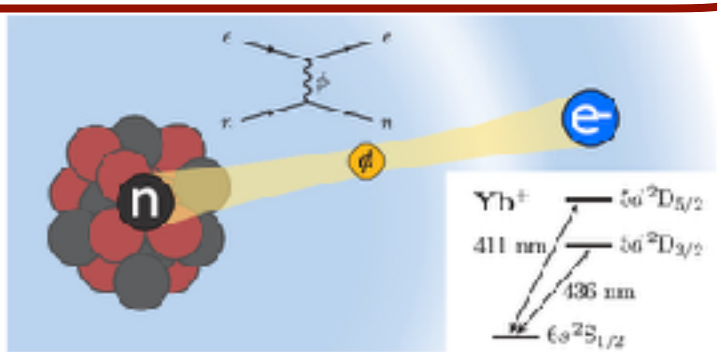
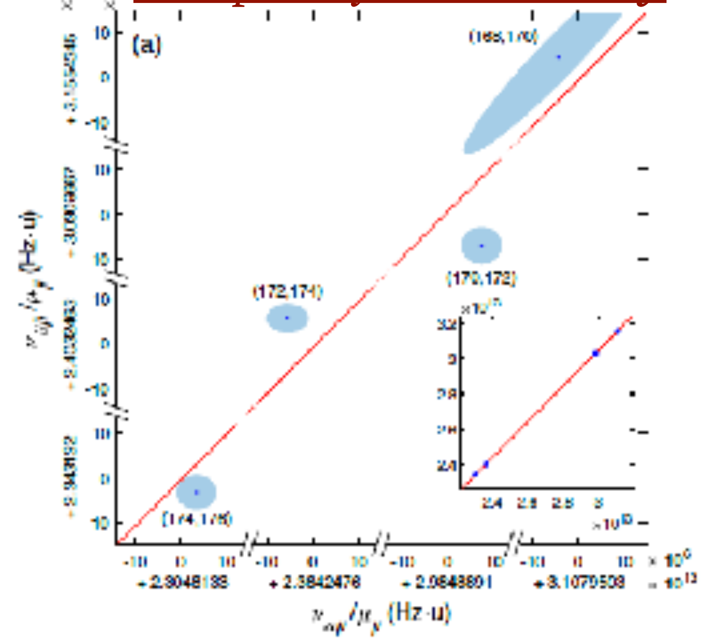
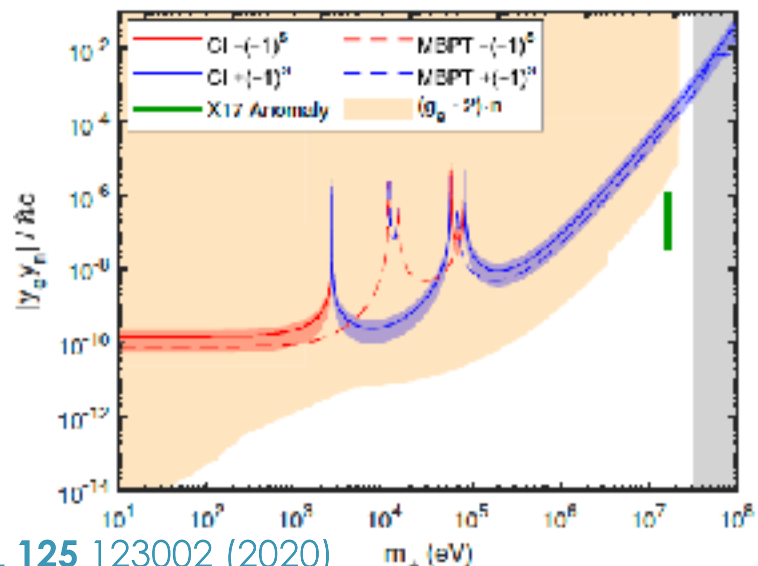


Isotope shift nonlinearity



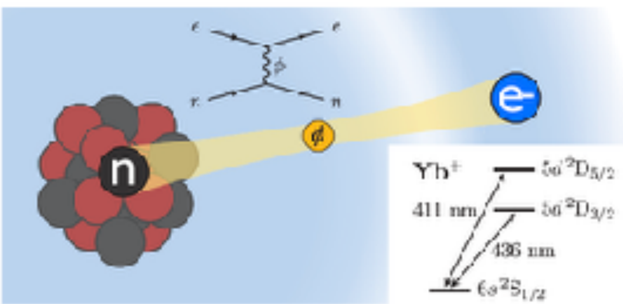


Counts, Berengut el al PRL **125** 123002 (2020)

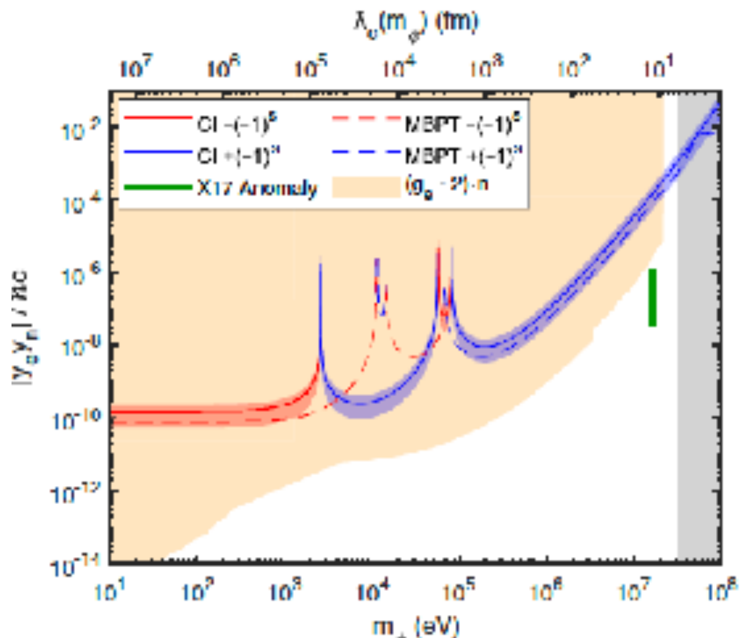
From atoms to neutron stars

$$V_\phi(r) = \frac{(-)^{s+1} y_e y_n}{4\pi} \frac{e^{-m_\phi r}}{r}$$

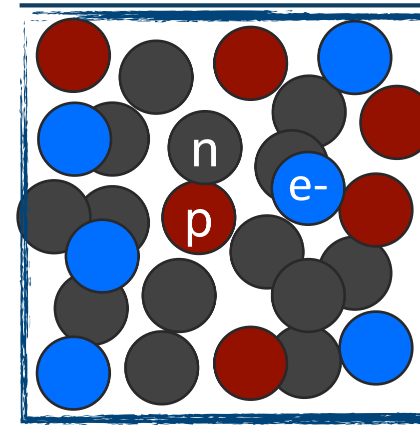
Atoms



$$\langle r \rangle \approx a_0 = 1\ \text{Å}$$
$$\approx 10^5\ \text{fm}$$



Neutron stars



$$\langle r \rangle \approx n^{-1/3} \approx 1\ \text{fm}$$

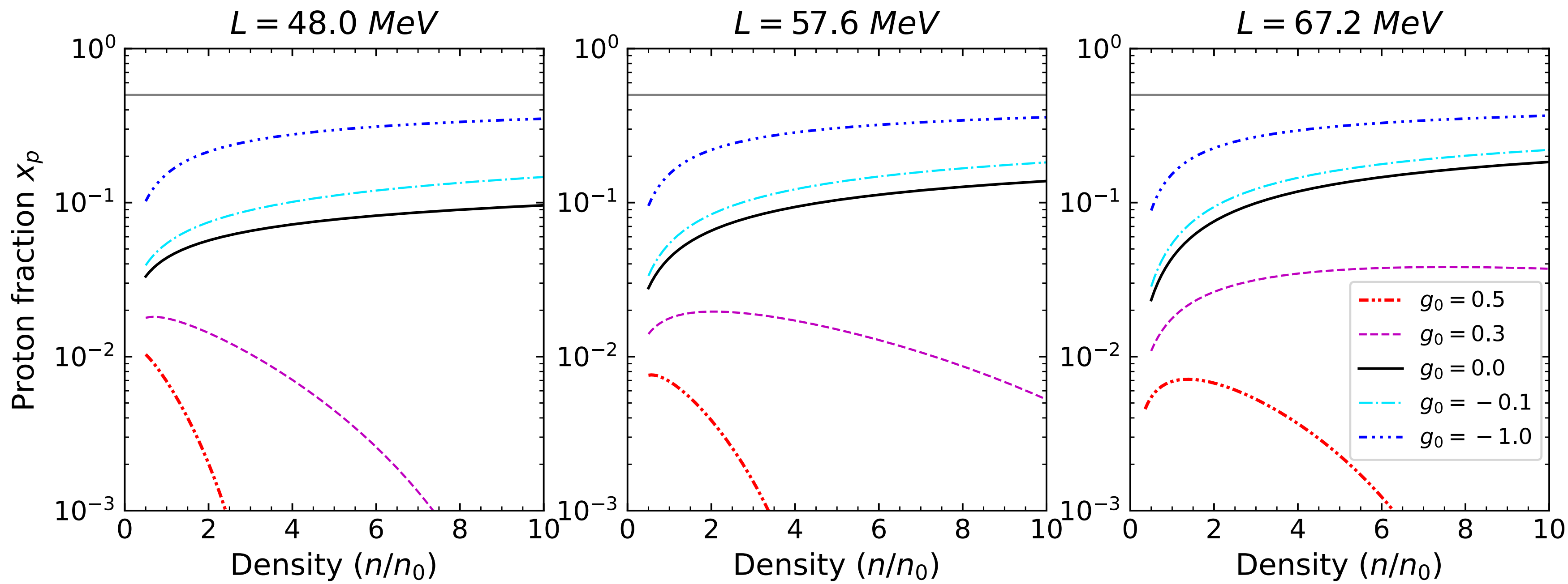
Star surface
r=R≈12 km

Radial distance to centre [km]: *10*, *3*, *0*

Crust	Core	Inner Core
Nuclear lattices, n superfluid	*neutrons, protons, e-*	?

Density [g cm^{-3}]: 10^{11}, 2×10^{14}, 5×10^{14}, $10^{1…}$

What about neutron stars?

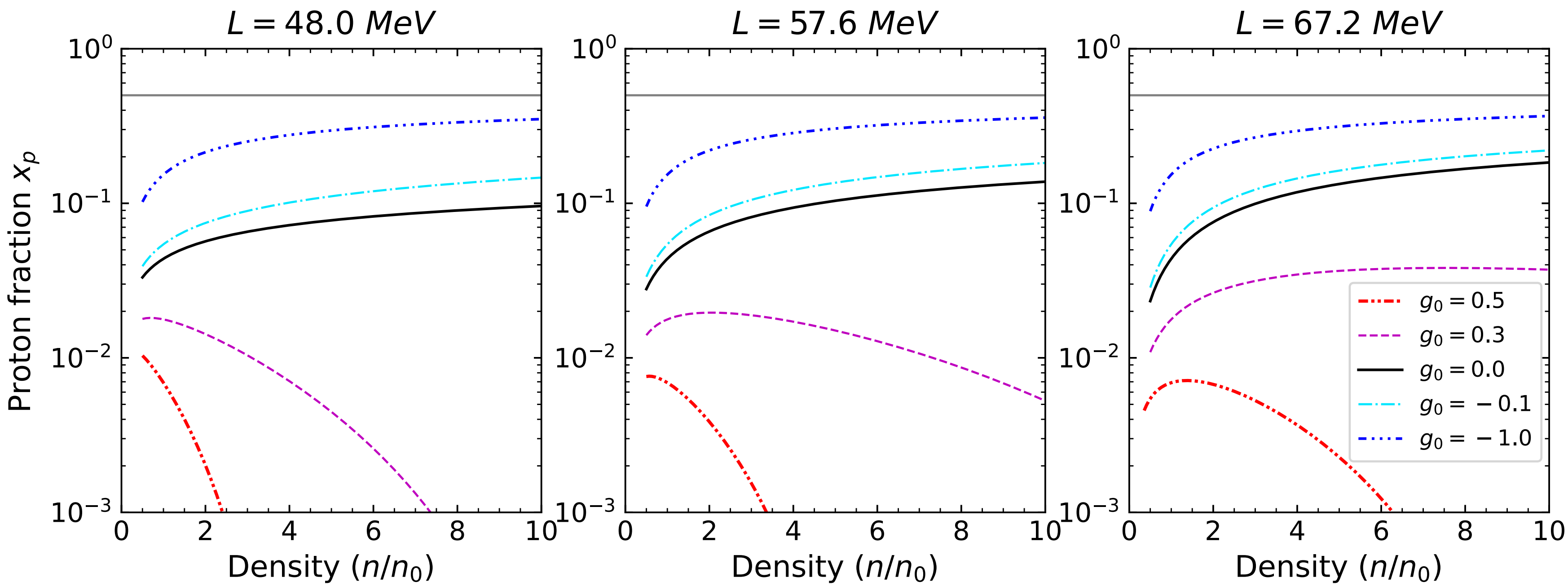


Tort & Rios, in prep
Tort, TFG

β-equilibrium

$$n \rightarrow p + e^- + \bar{\nu}_e$$
$$p + e^- \rightarrow n + \nu_e$$
$$\Rightarrow \mu_n = \mu_p + \mu_e$$

What about neutron stars?

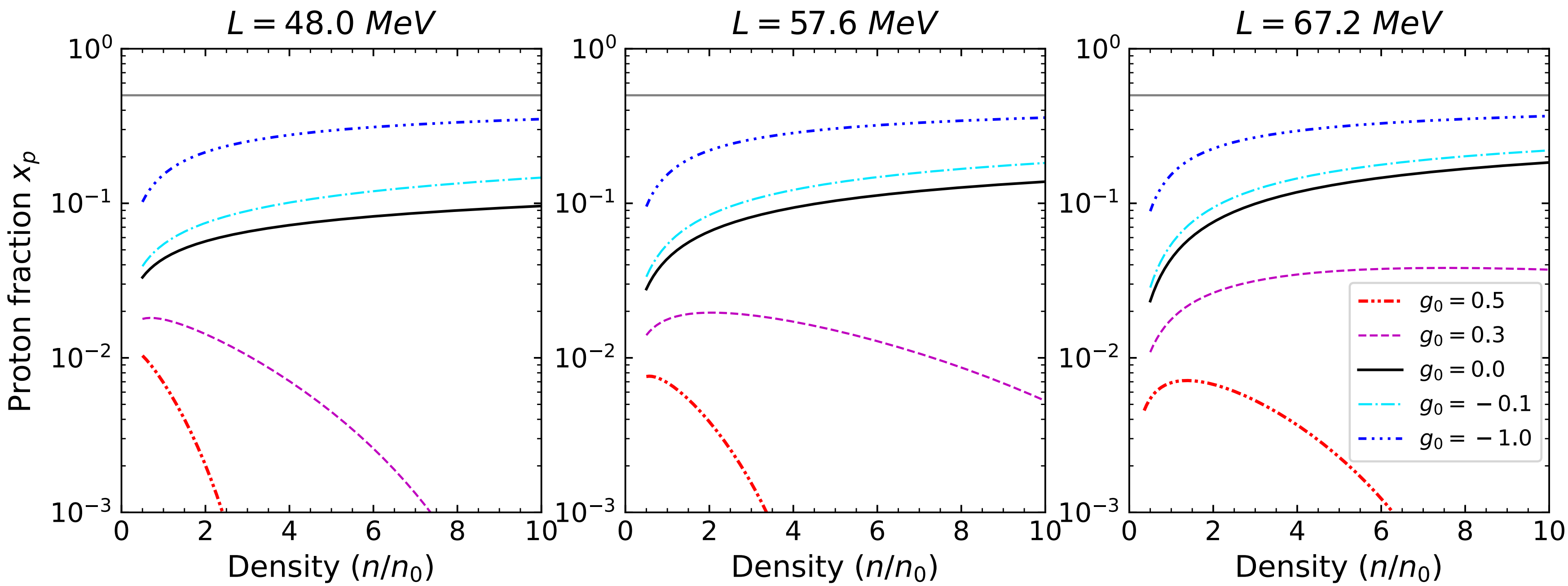


Tort & Rios, in prep
Tort, TFG

β-equilibrium

$$\left.\begin{aligned} n &\to p + e^- + \bar{\nu}_e \\ p + e^- &\to n + \nu_e \end{aligned}\right\} \Longrightarrow \quad \mu_n + \boxed{\mu_{n,\phi}} = \mu_p + \mu_e + \boxed{\mu_{e,\phi}}$$

What about neutron stars?



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β-equilibrium

$$\left.\begin{array}{l} n \rightarrow p + e^- + \bar{\nu}_e \\ p + e^- \rightarrow n + \nu_e \end{array}\right\} \Longrightarrow \mu_n + \boxed{\mu_{n,\phi}} = \mu_p + \mu_e + \boxed{\mu_{e,\phi}}$$

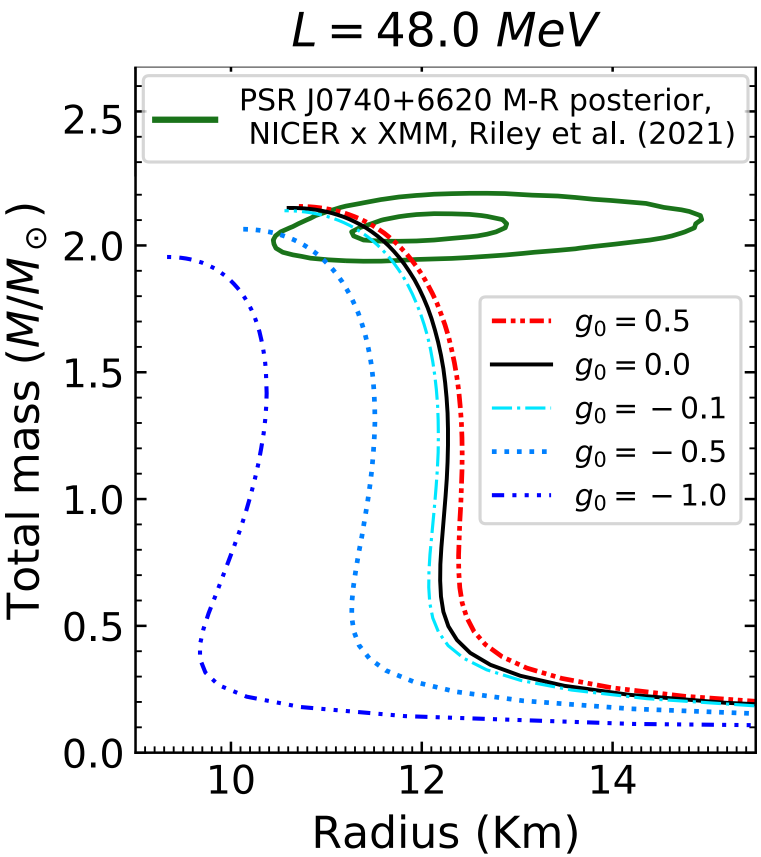
Symmetry energy

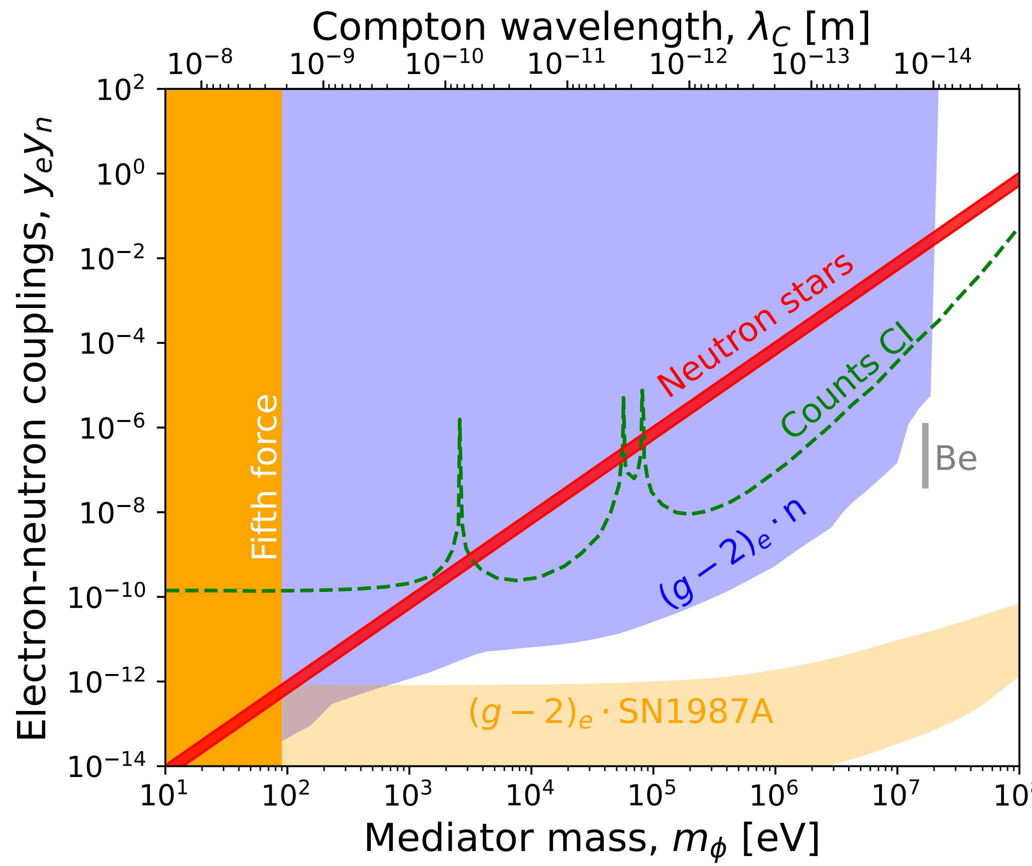
$$S_g(n) = S(n) - \frac{n}{4}\frac{(-)^{s+1} y_e y_n}{m_\phi^2} = S(n) - g_0 \frac{n}{n_0} S(n_0)$$

Dimensionless coupling

$$\boxed{g_0 = (-)^{s+1} \frac{n_0}{S(n_0)} \frac{y_e y_n}{4 m_\phi^2}}$$

Couplings and bounds





Tort & Rios, in prep
Tort, TFG

- **No bounds** for + coupling
- **Bounds** for - coupling

Neutron Stars as physics laboratories

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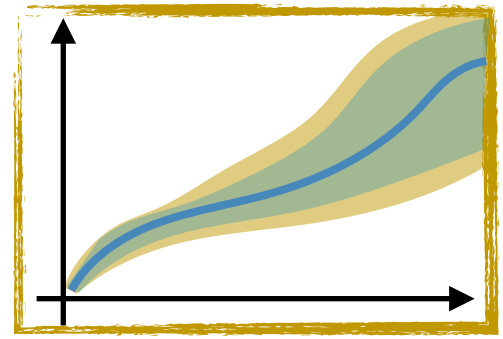

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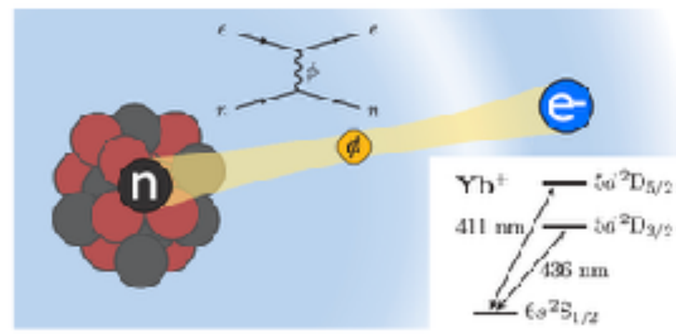

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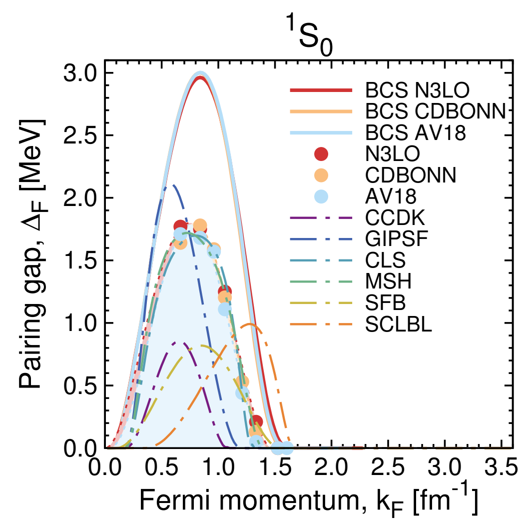
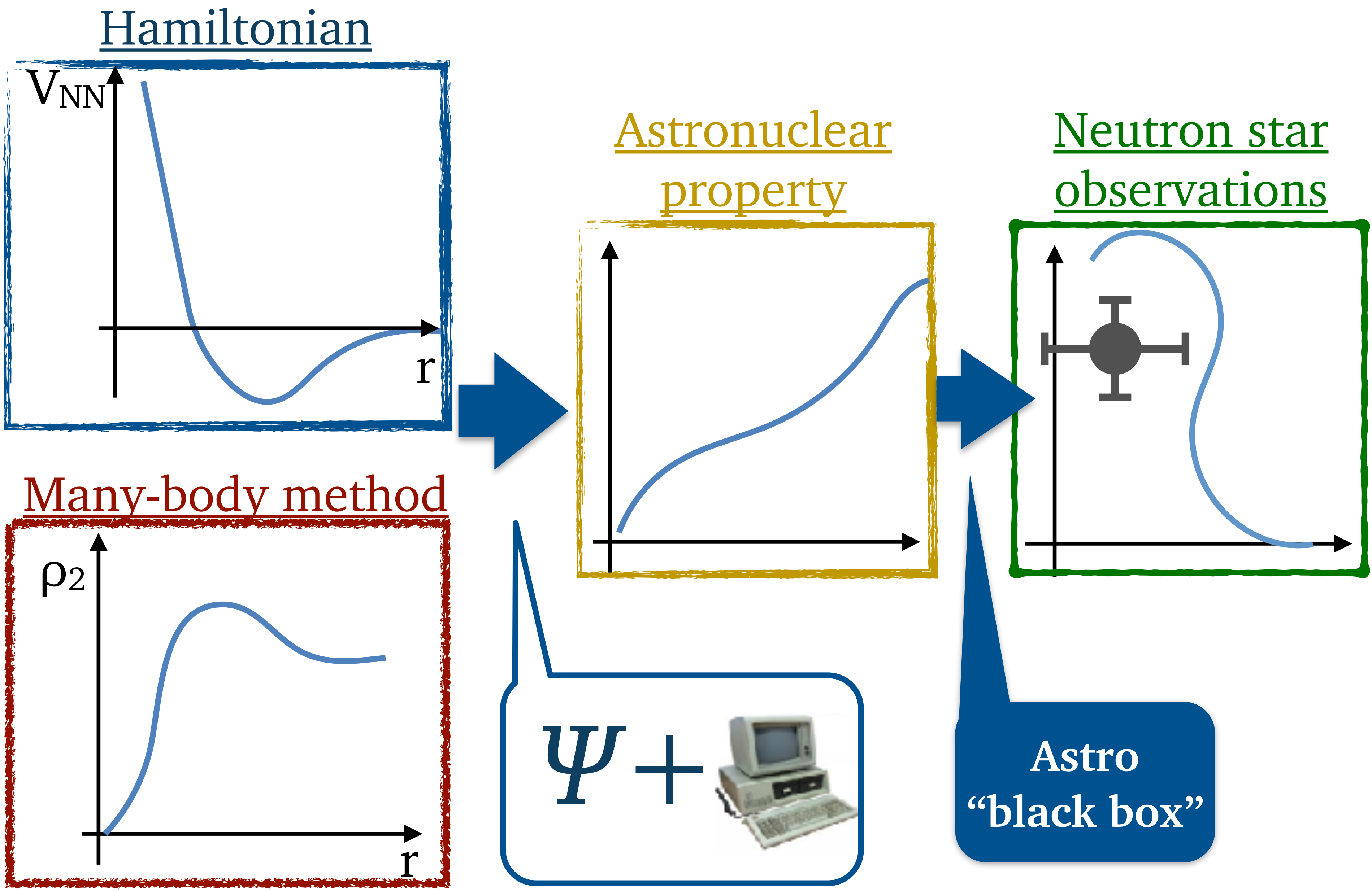
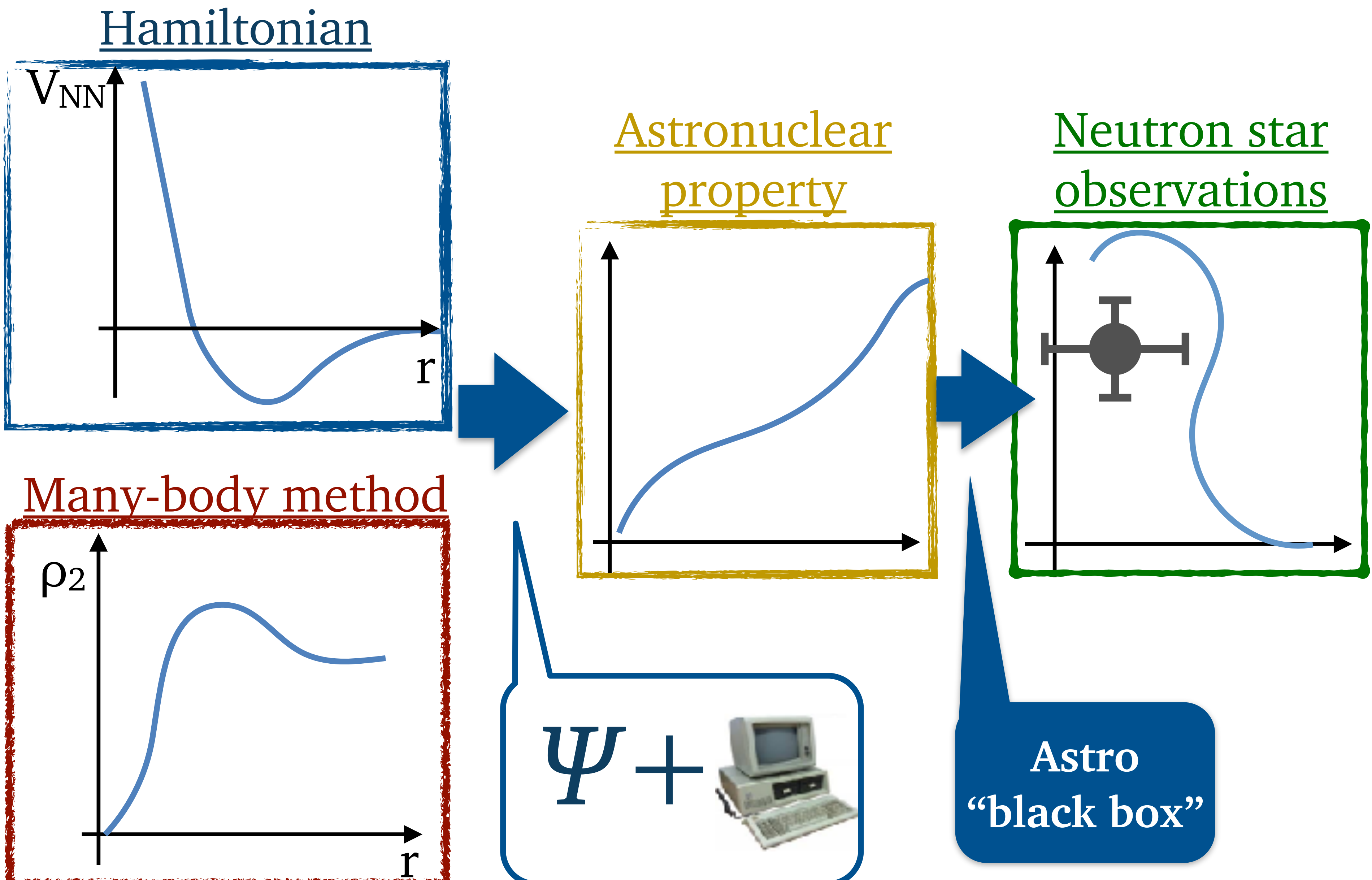


Nuclear predictions 19xx style

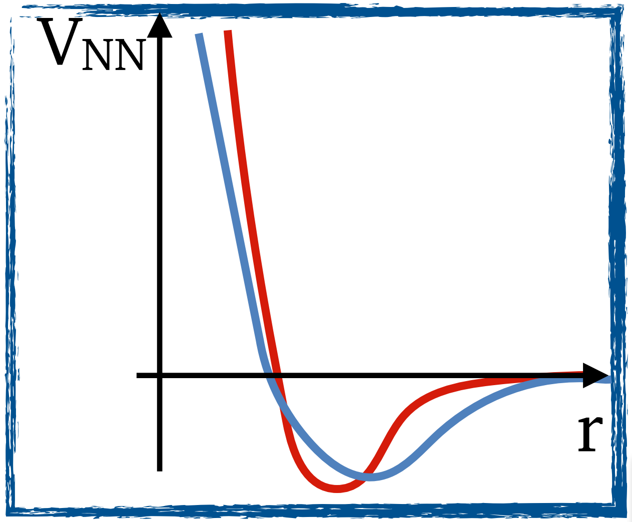


Nuclear predictions 19xx style

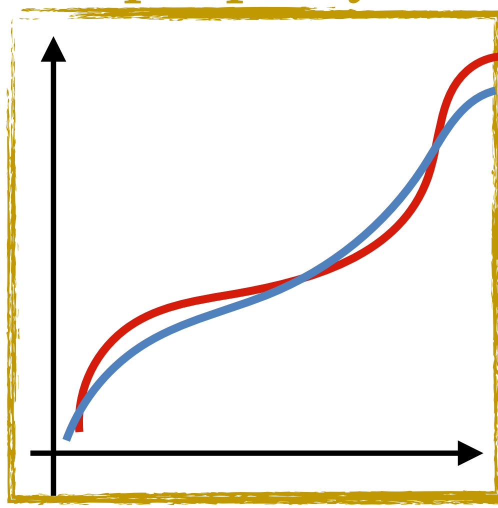


Nuclear predictions 19xx style

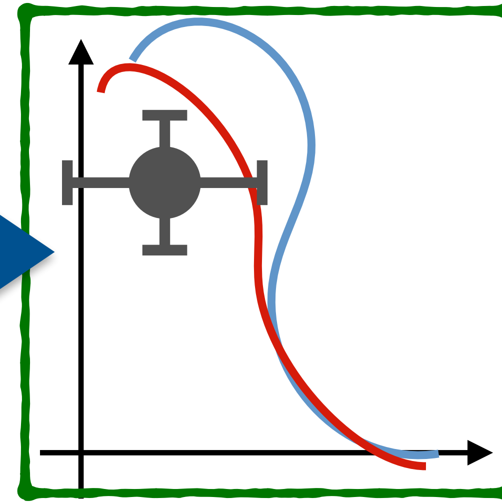
Hamiltonian



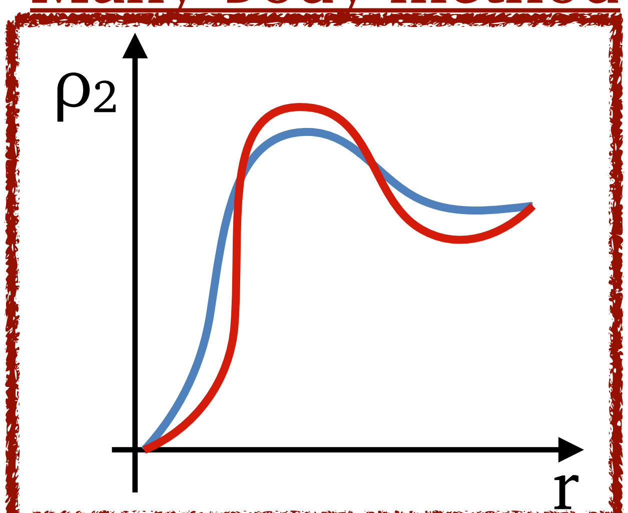
Astronuclear property

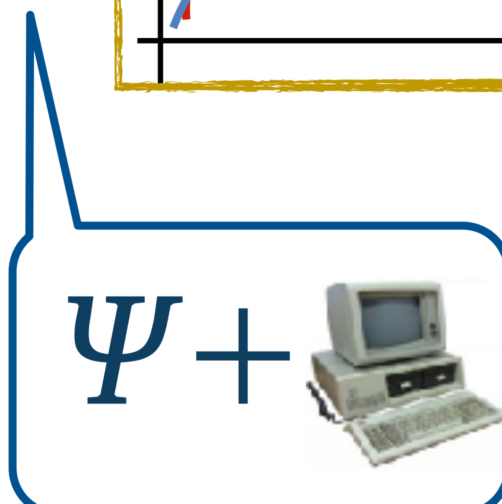


Neutron star observations



Many-body method

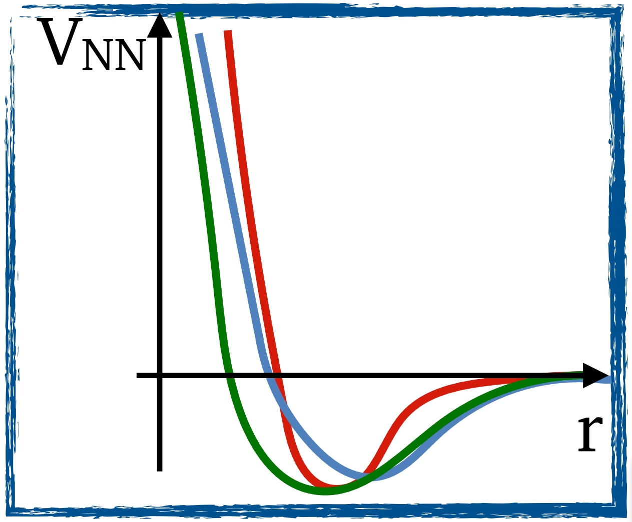




Astro “black box”

Nuclear predictions 19xx style

Hamiltonian



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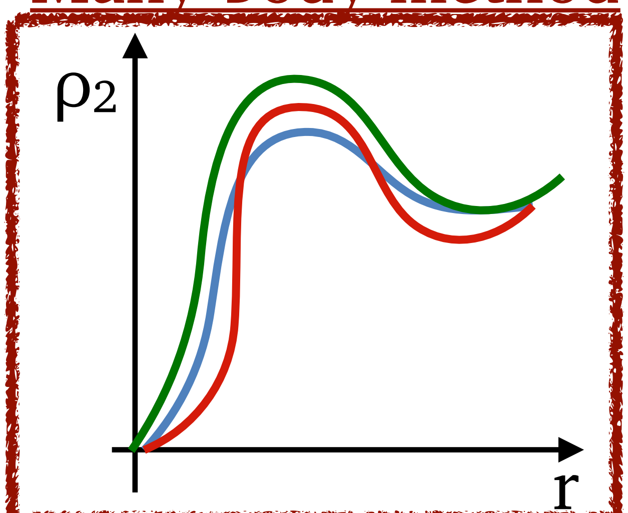
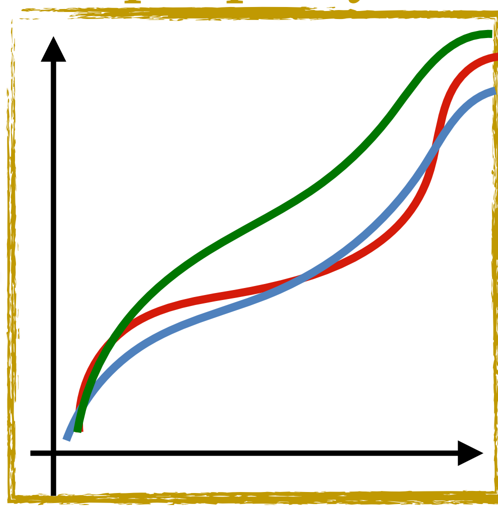
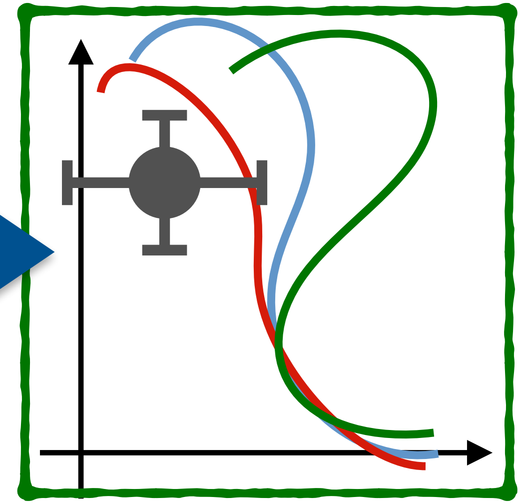
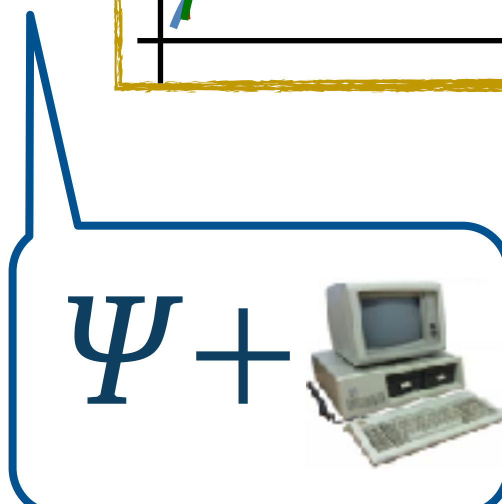


Astronuclear property



Neutron star observations

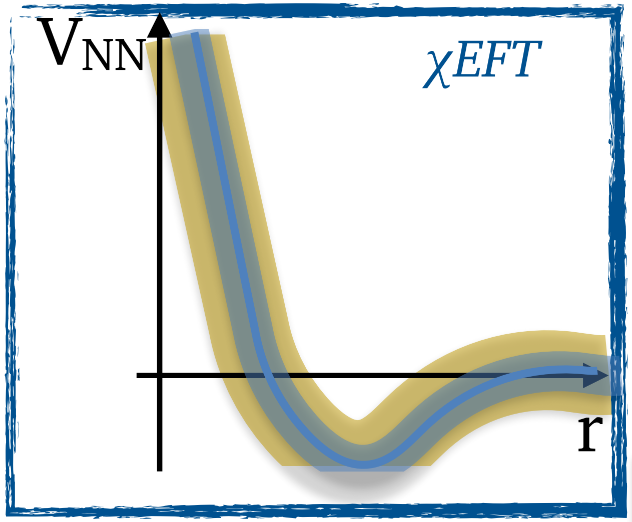




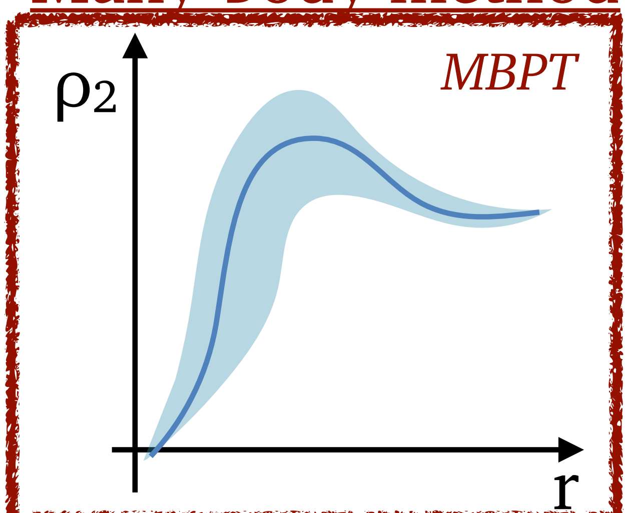
Astro “black box”

Nuclear error quantification

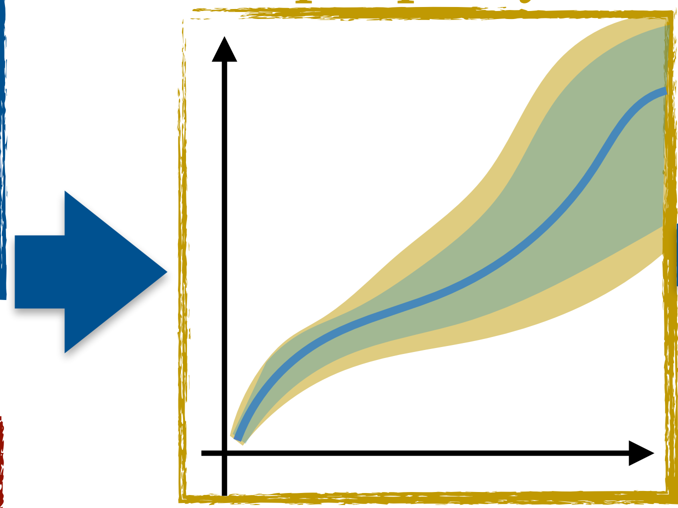
Hamiltonian



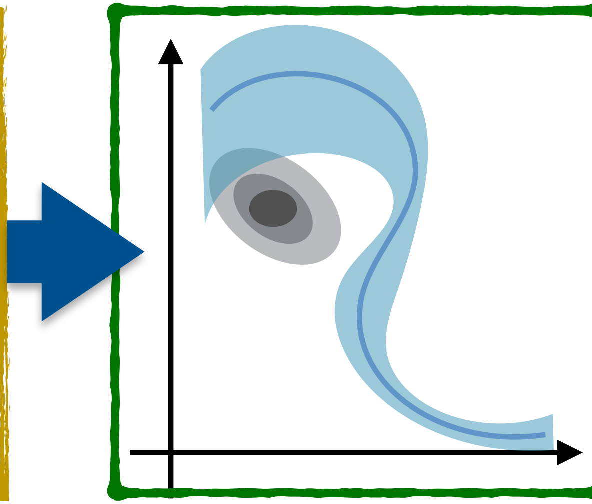
Many-body method



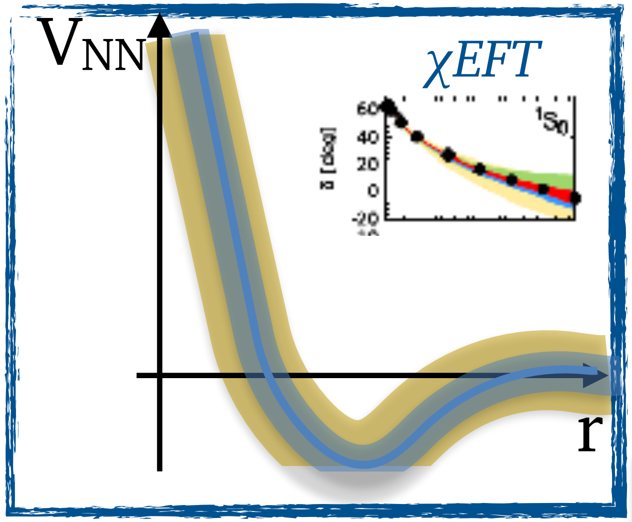
Astronuclear property



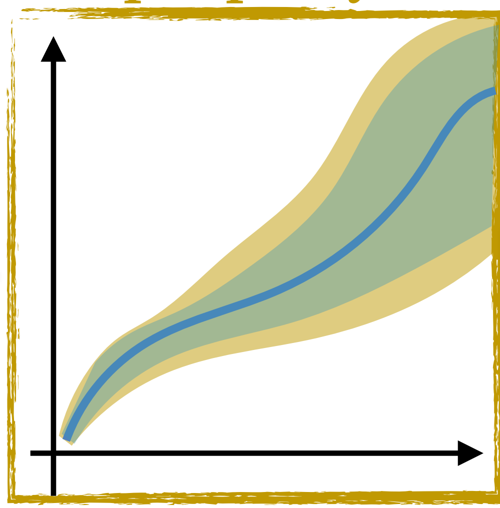
Neutron star observations



Hamiltonian

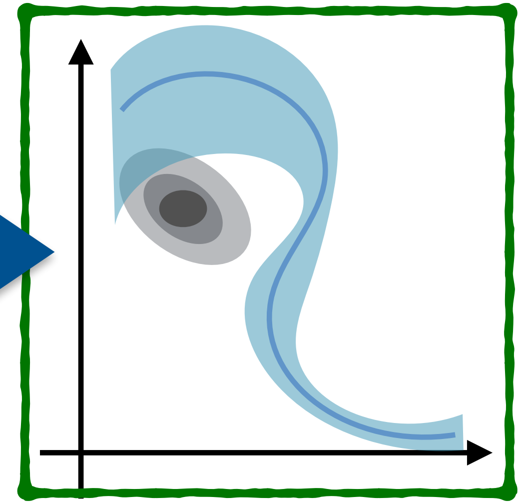


Astronuclear property

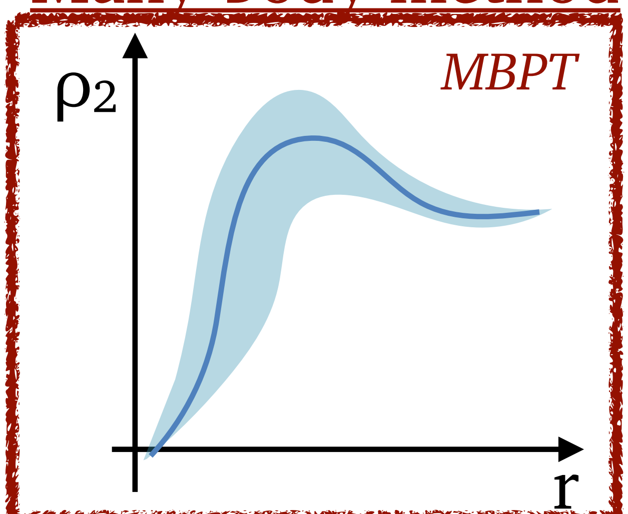


?

Neutron star observations

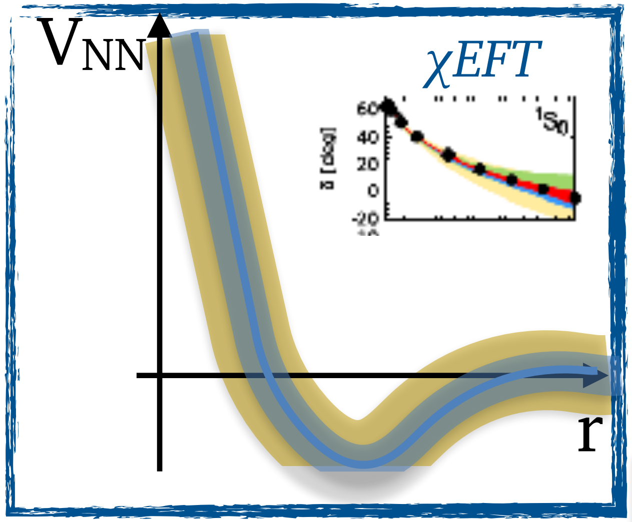


Many-body method

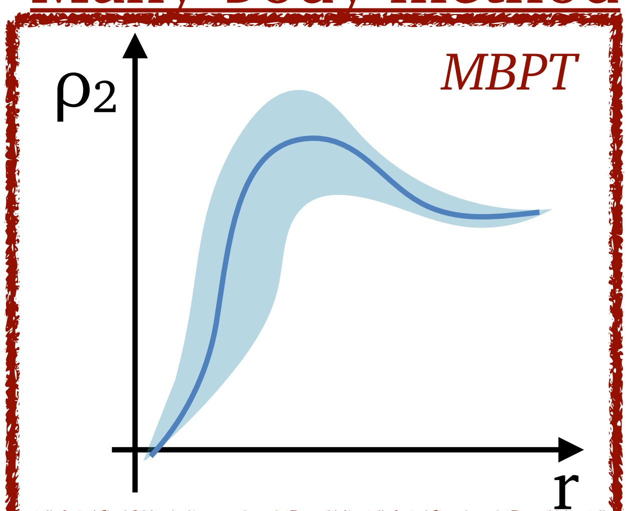


Nuclear error quantification

Hamiltonian

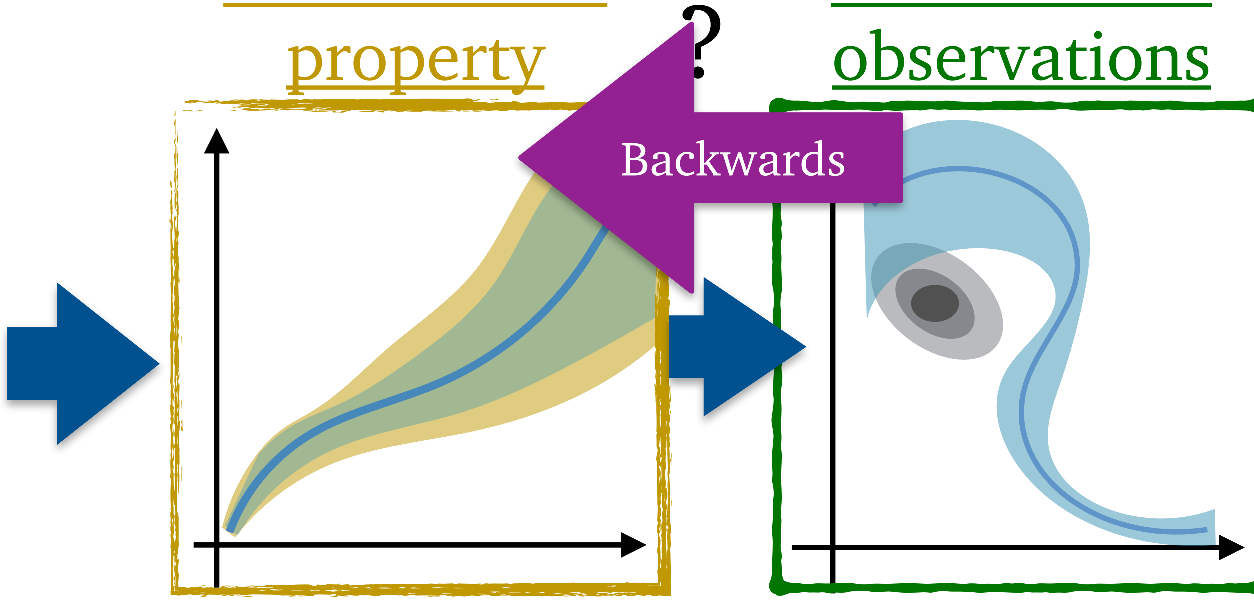


Many-body method

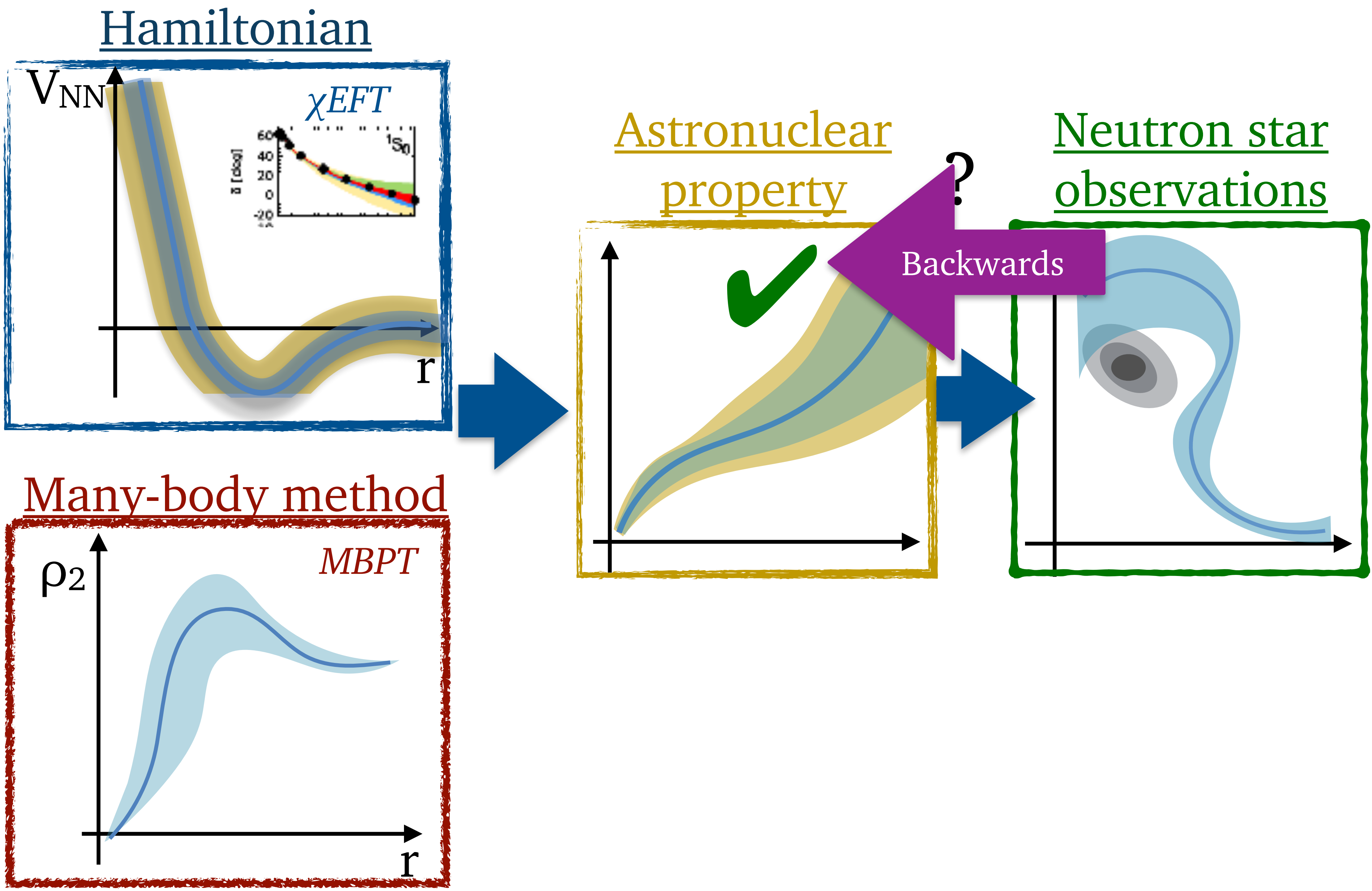


Astronuclear property

Neutron star observations



Nuclear error quantification



From M-R to EoS

Backwards

Tolman-Oppenheimer-Volkov equations

$$\frac{dp}{dr} = -\frac{G}{c^2}\frac{(m + 4\pi p r^3)(\epsilon + p)}{r(r - 2Gm/c^2)}$$

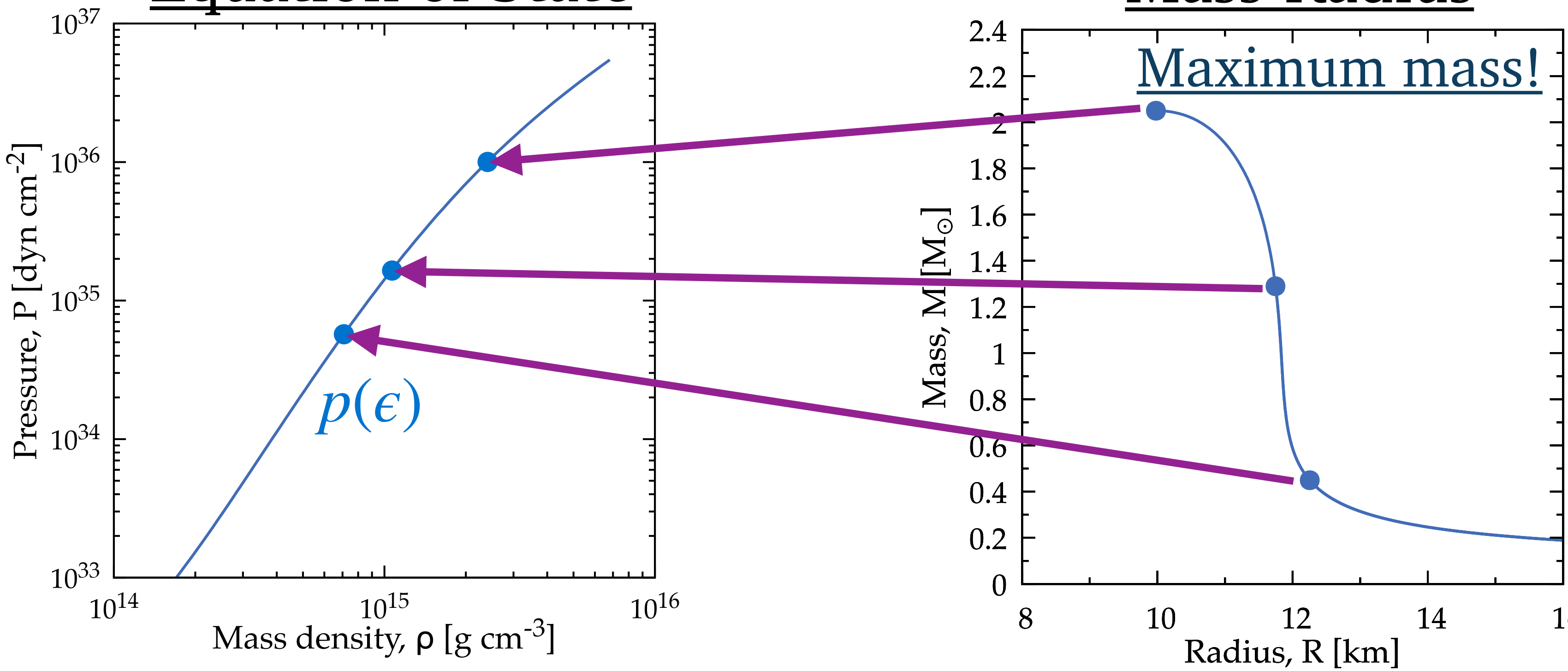
$$\frac{dm}{dr} = \frac{4\pi}{c^2}\epsilon r^2$$

+

EoS

$$p \equiv p(\epsilon)$$

Equation of State | Mass-Radius



From M-R to EoS

Backwards

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+

EoS

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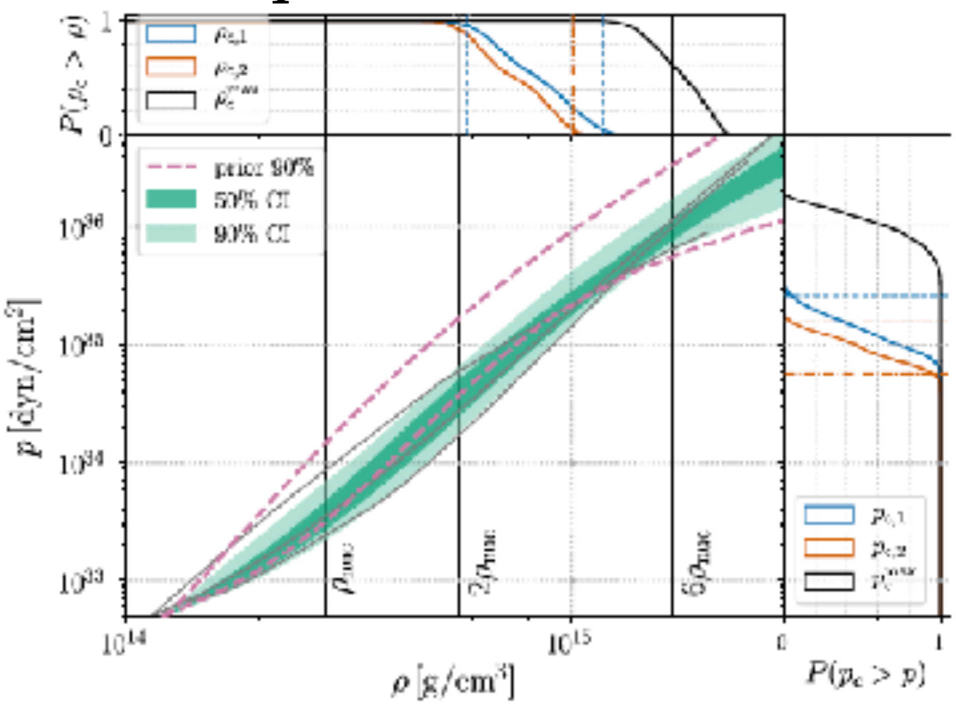
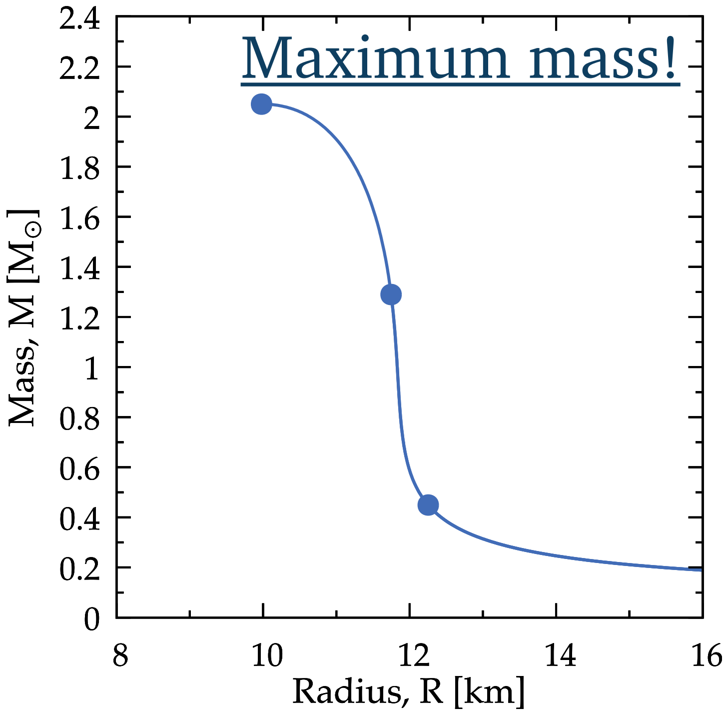
LIGO/VIRGO PRL 121 161101 (2018)

Equation of State

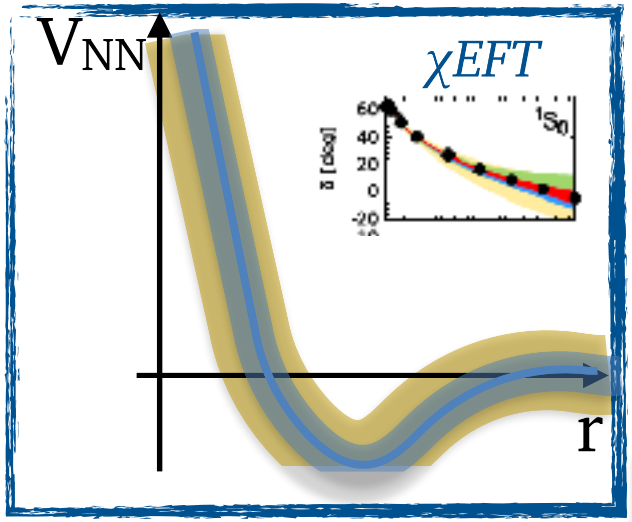


Mass-Radius

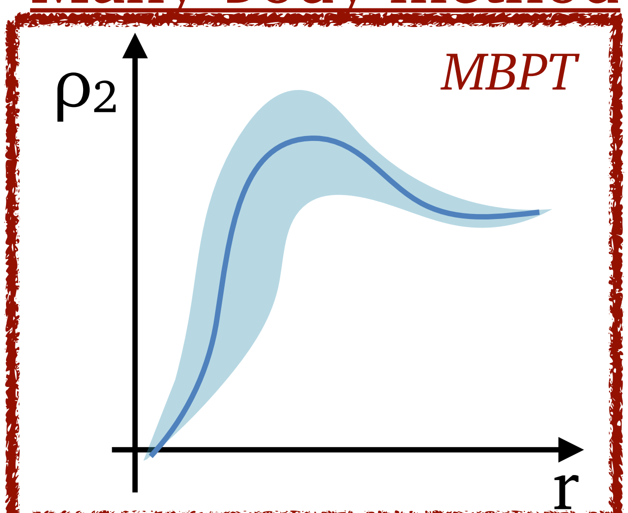


Nuclear error quantification

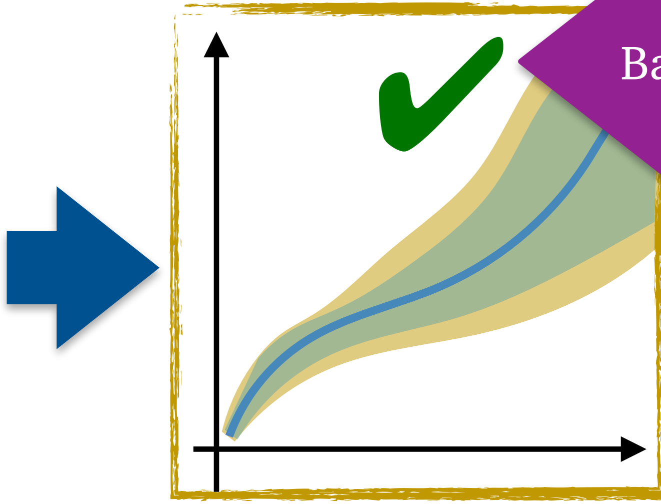
Hamiltonian



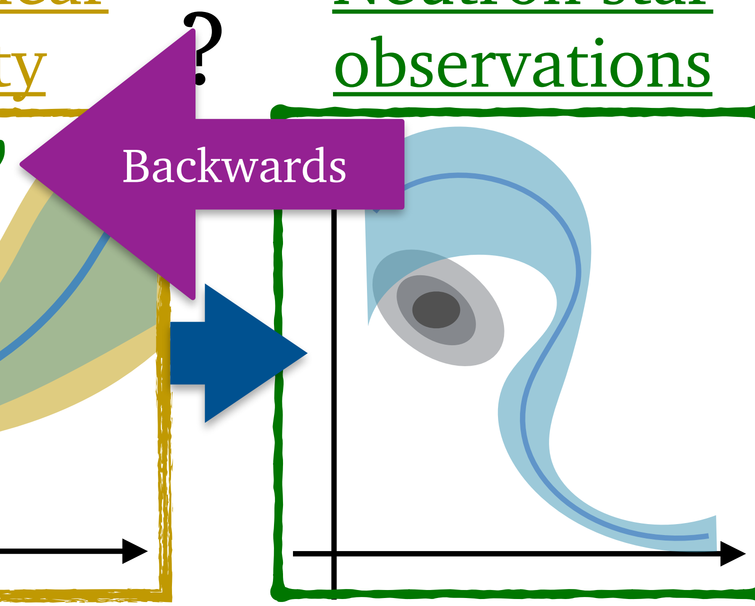
Many-body method



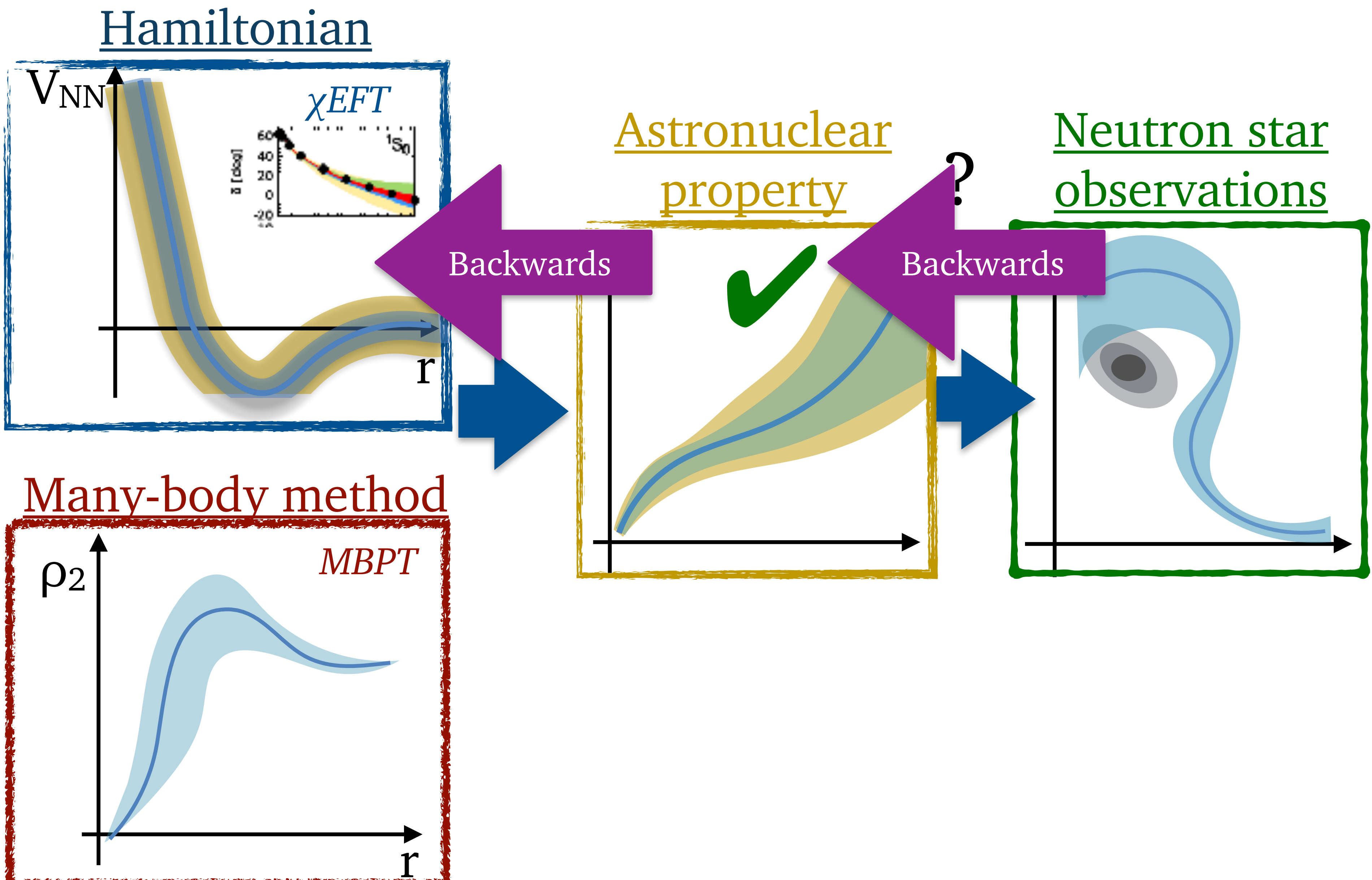
Astronuclear property



Neutron star observations

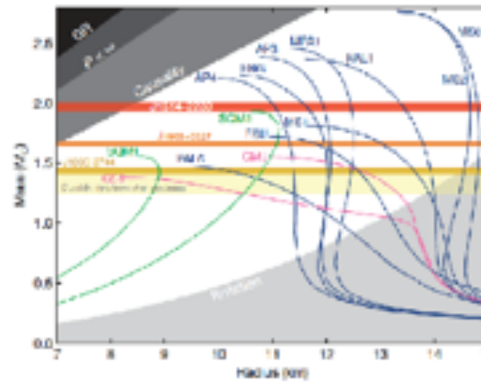


Nuclear error quantification

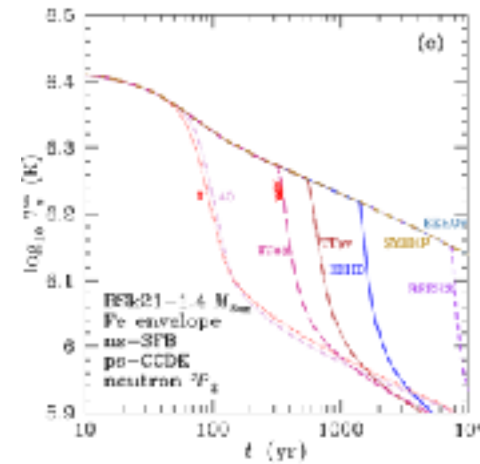


Neutron star modelling

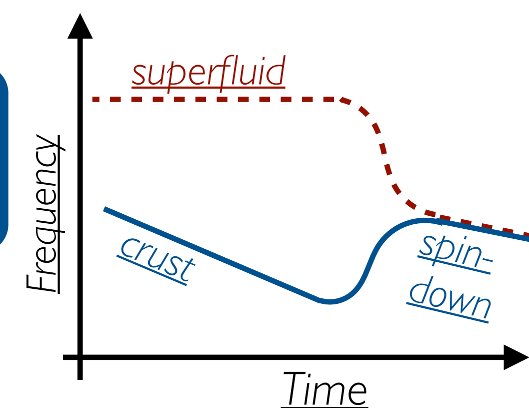
Input #1
EoS
→
Observable #1
Mass-Radius relation



Input #2
Pairing gap
→
Observable #2
Cooling curve



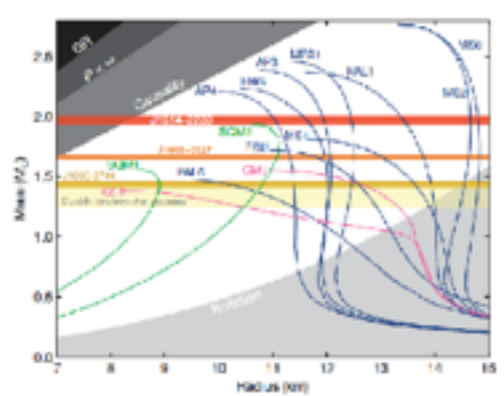
Input #3
Crust-core
→
Observable #3
Glitching



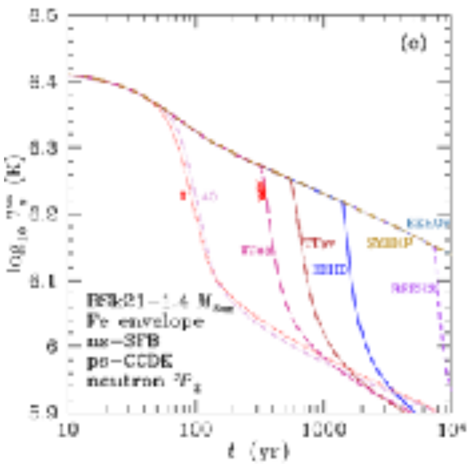
Neutron star modelling

Input
Consistent many-body theory

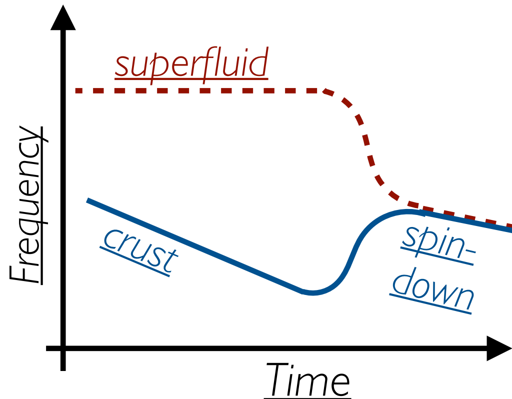
Observable #1
Mass-Radius relation



Observable #2
Cooling curve



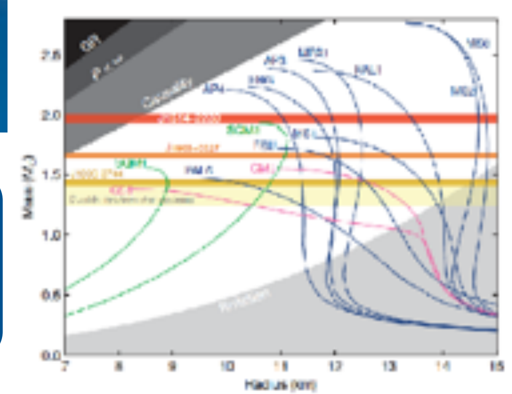
Observable #3
Glitching



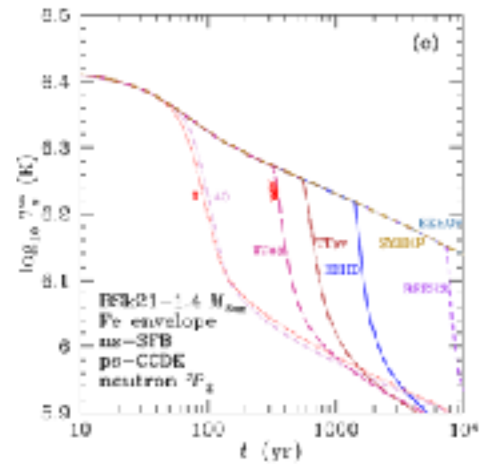
Neutron star modelling

Input
Consistent many-body theory

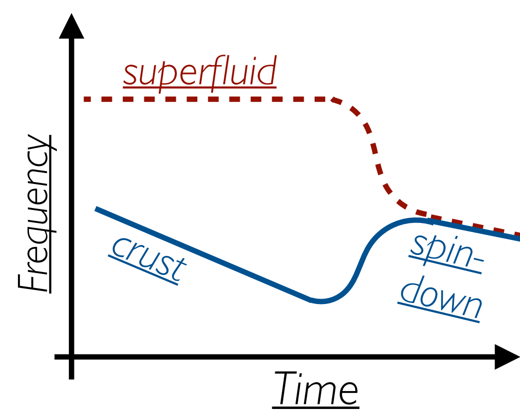
Observable #1
Mass-Radius relation
"Normal"



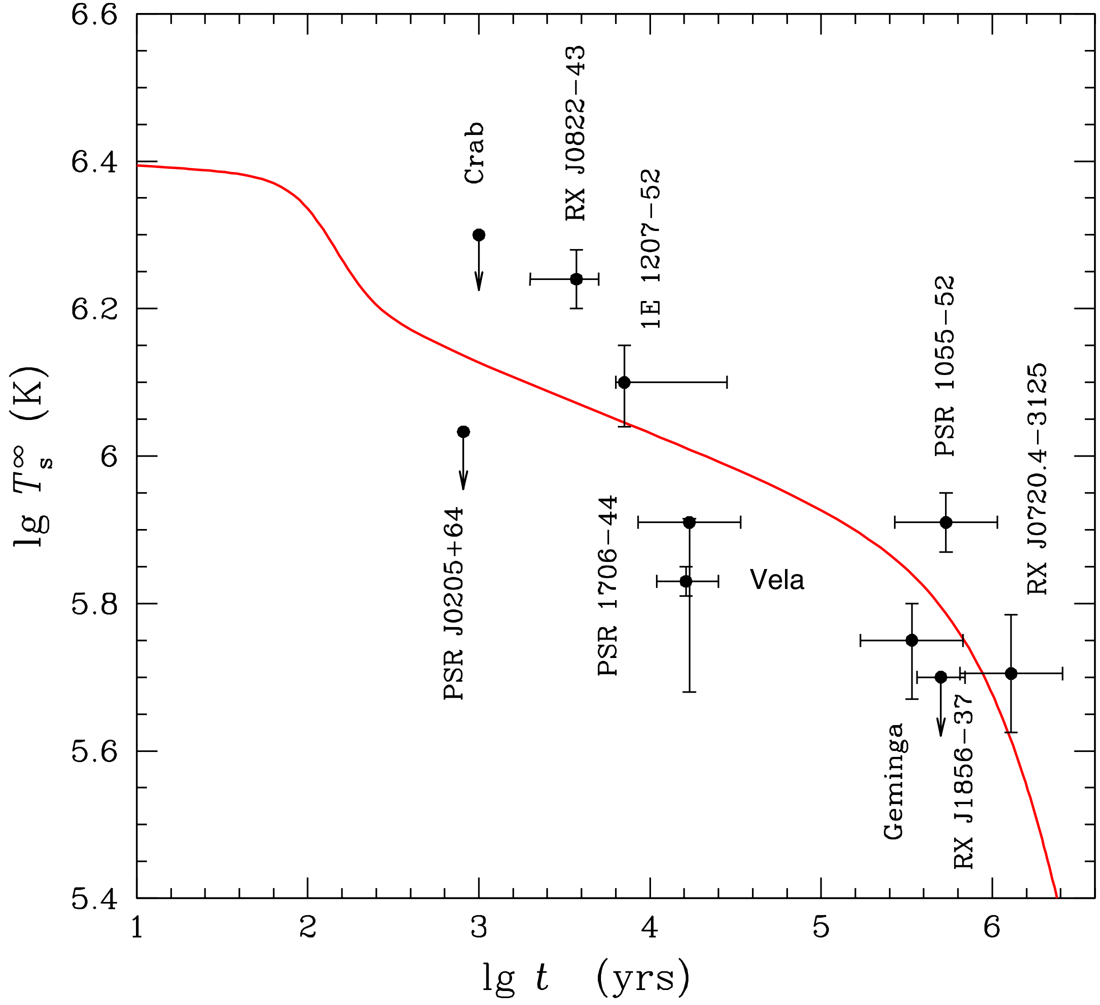
Observable #2
Cooling curve
"Superfluid"



Observable #3
Glitching
"Superfluid"



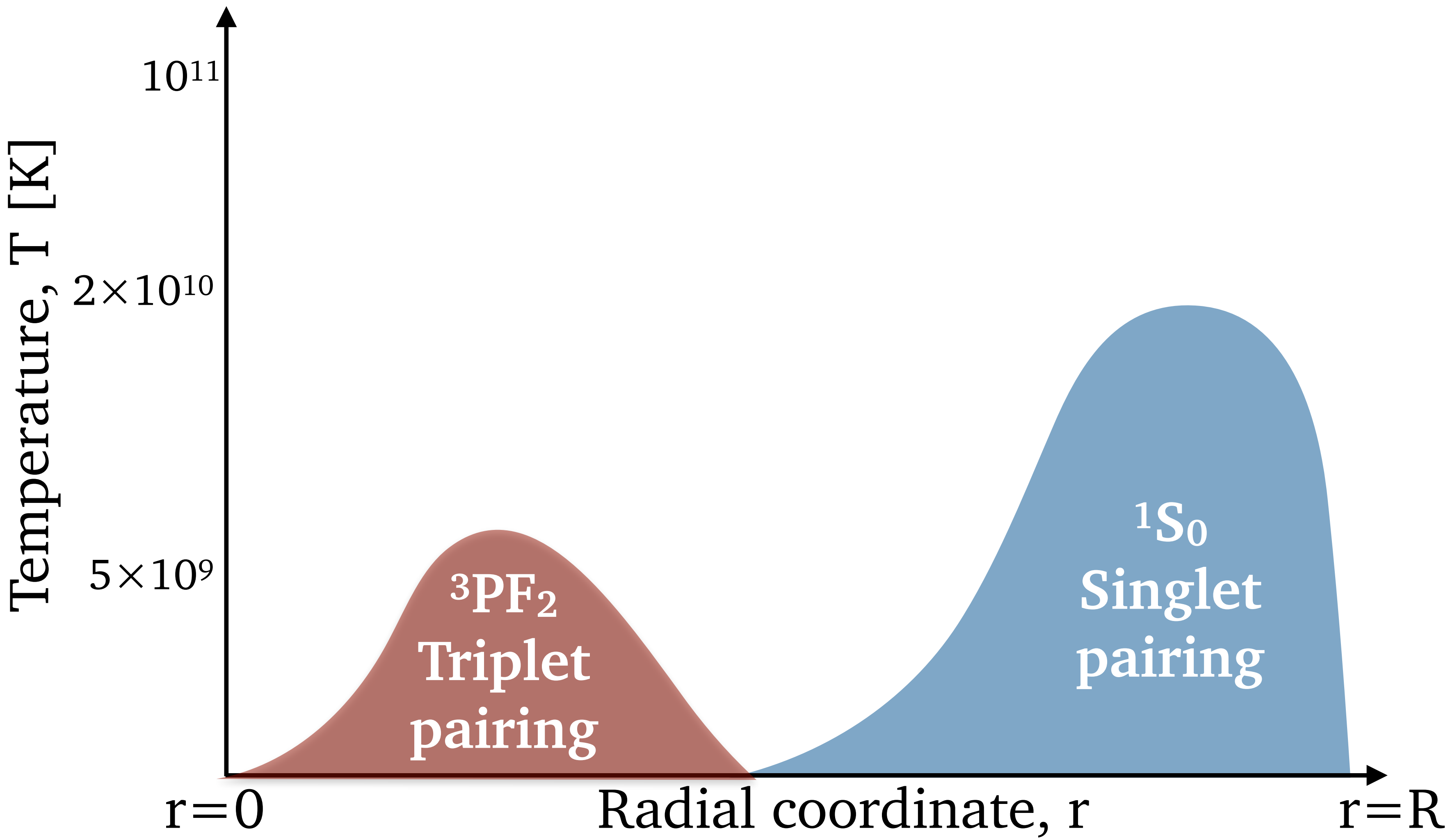
Cooling curve of neutron stars



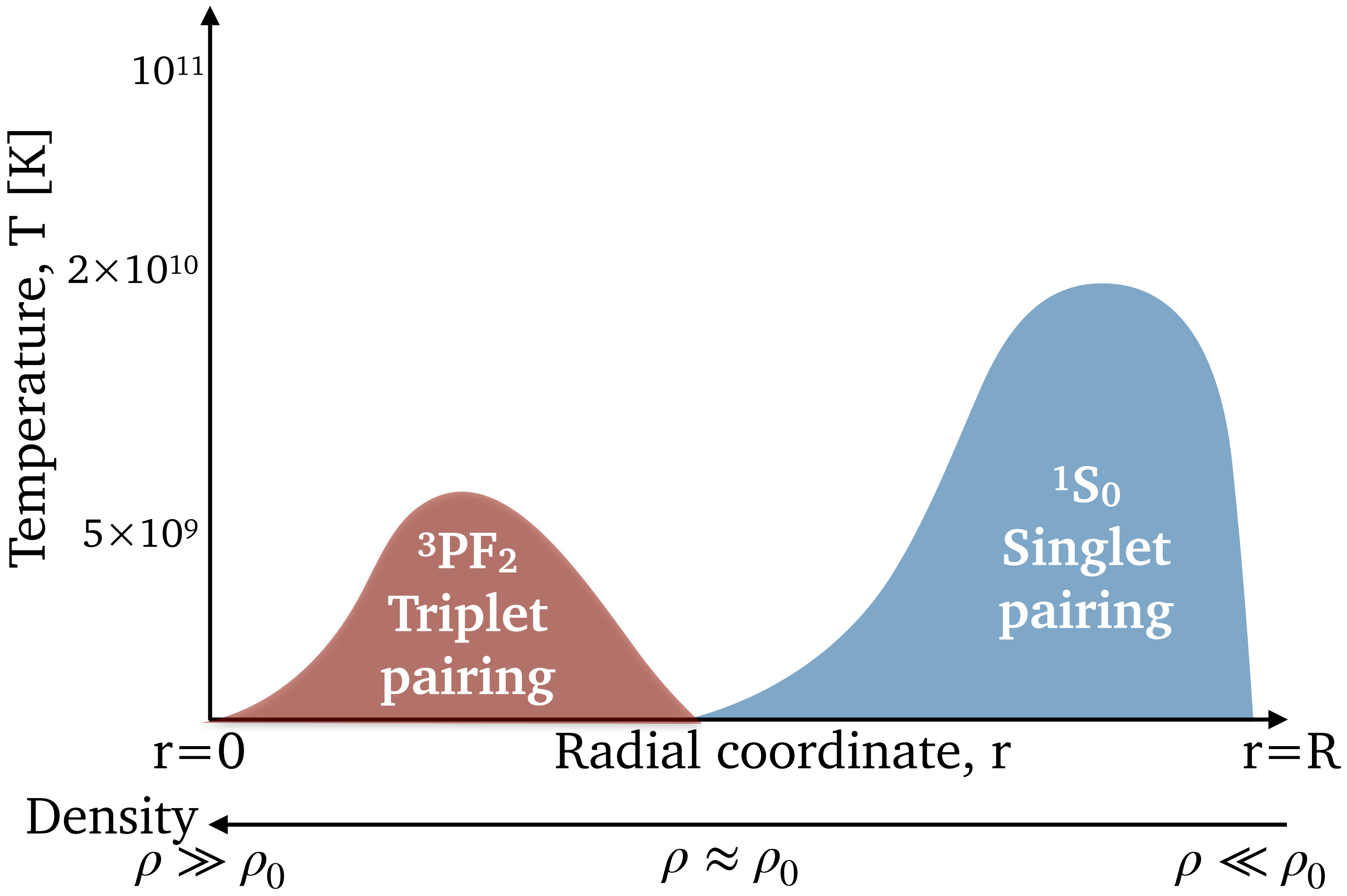
- Observational data available for a handful of NS
- Sensitive to **interior** physics (mostly **pairing**)

Yakovlev & Pethick, ARAA **42** 169 (2004)

Pairing gaps & cooling



Pairing gaps & cooling



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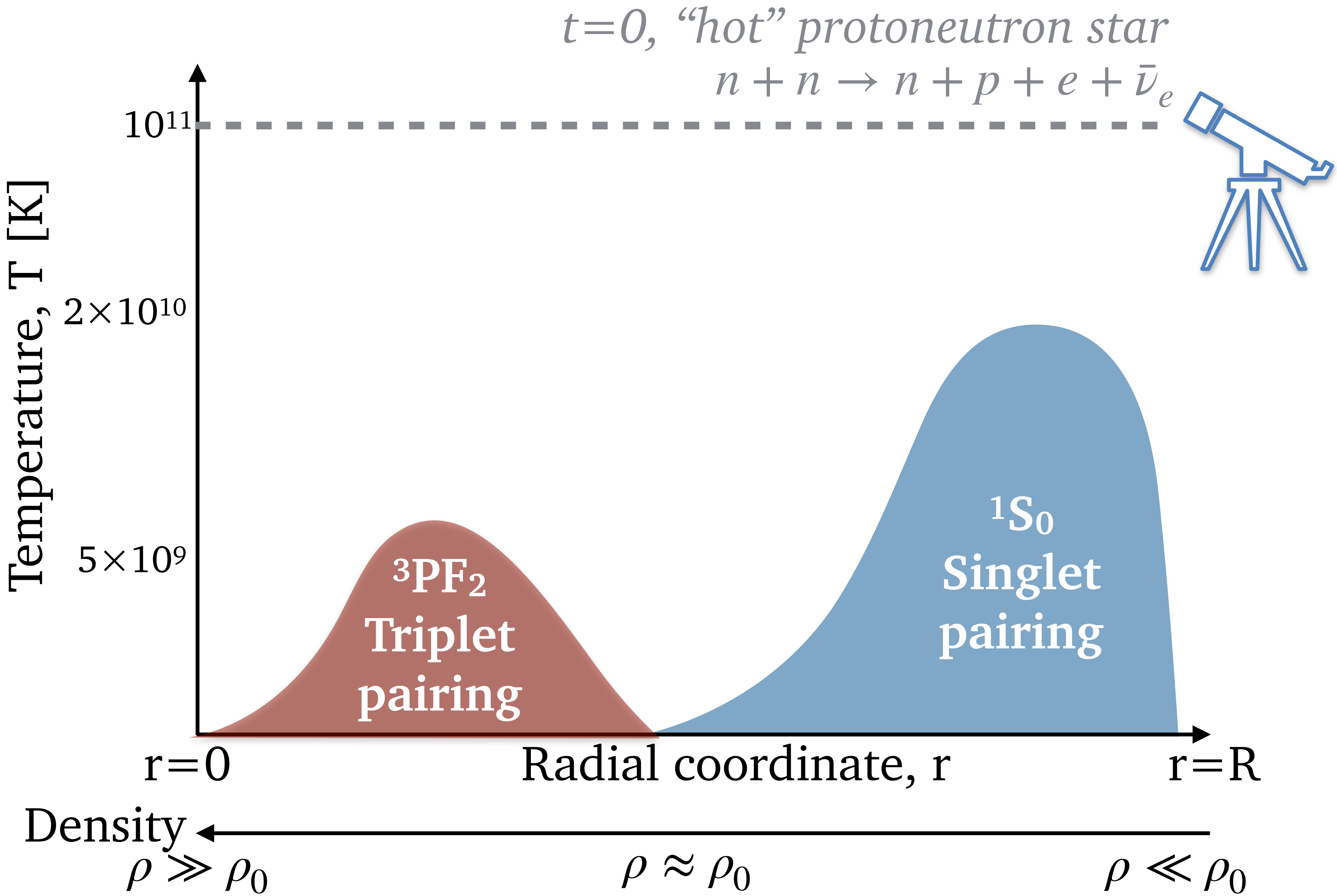

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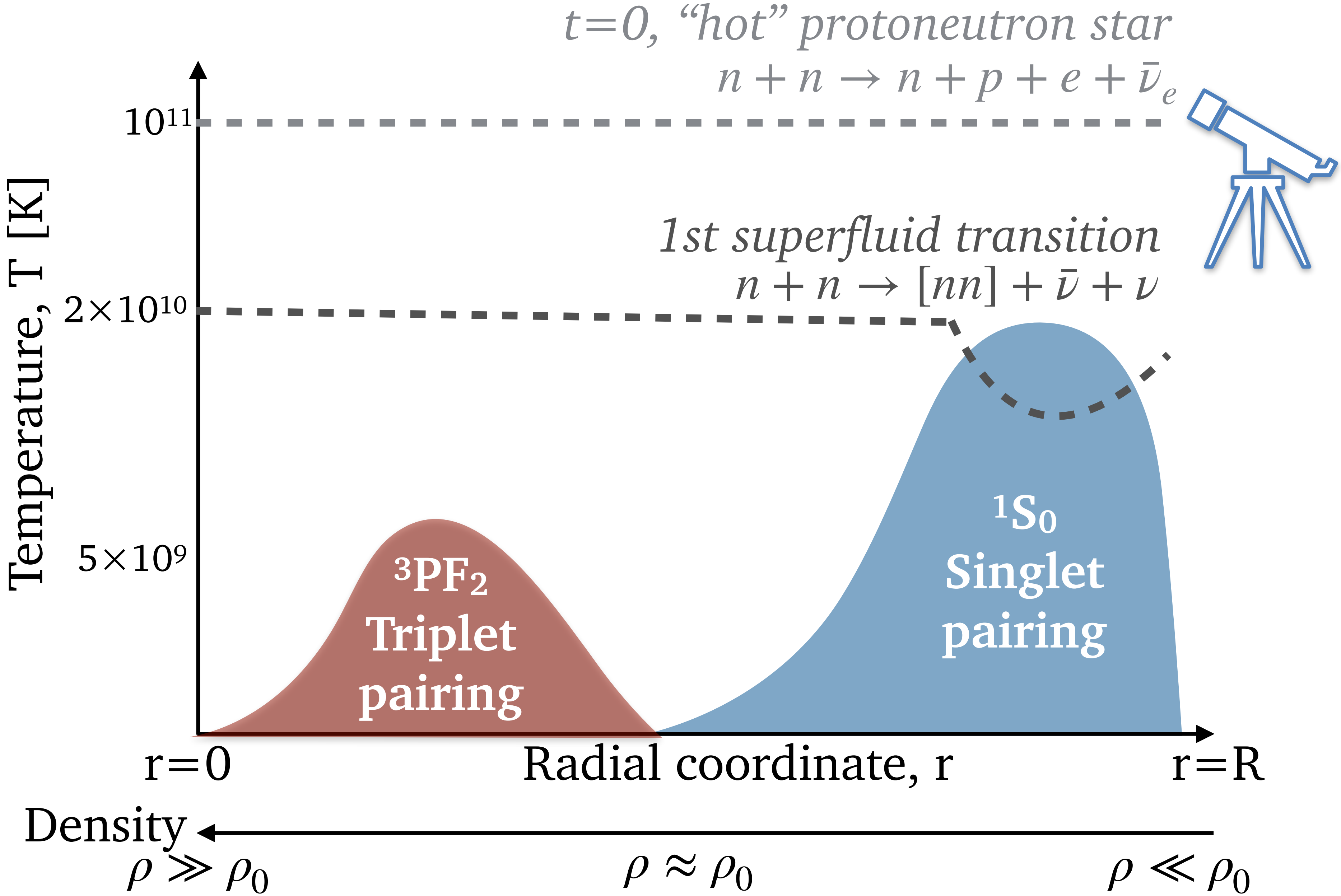

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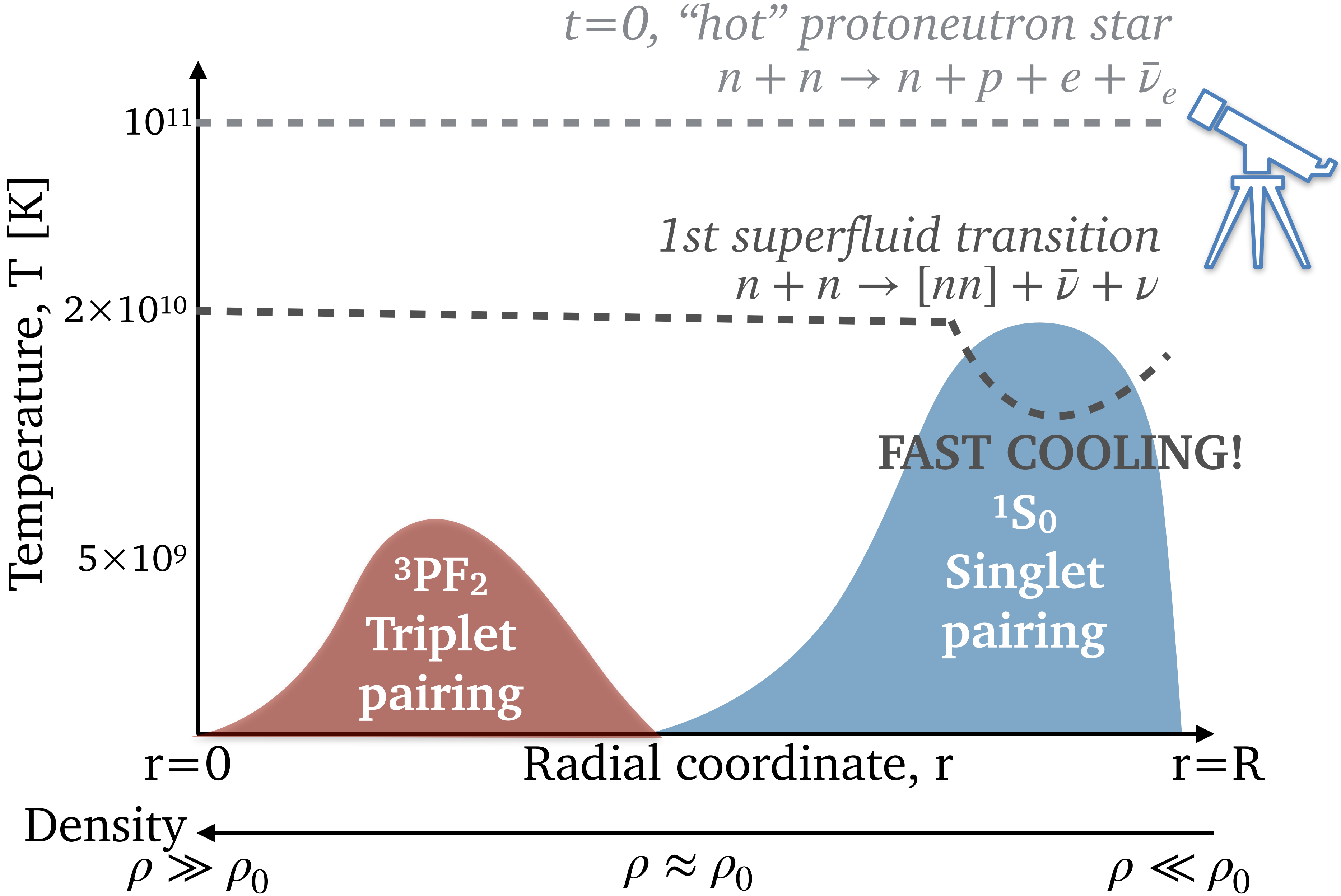
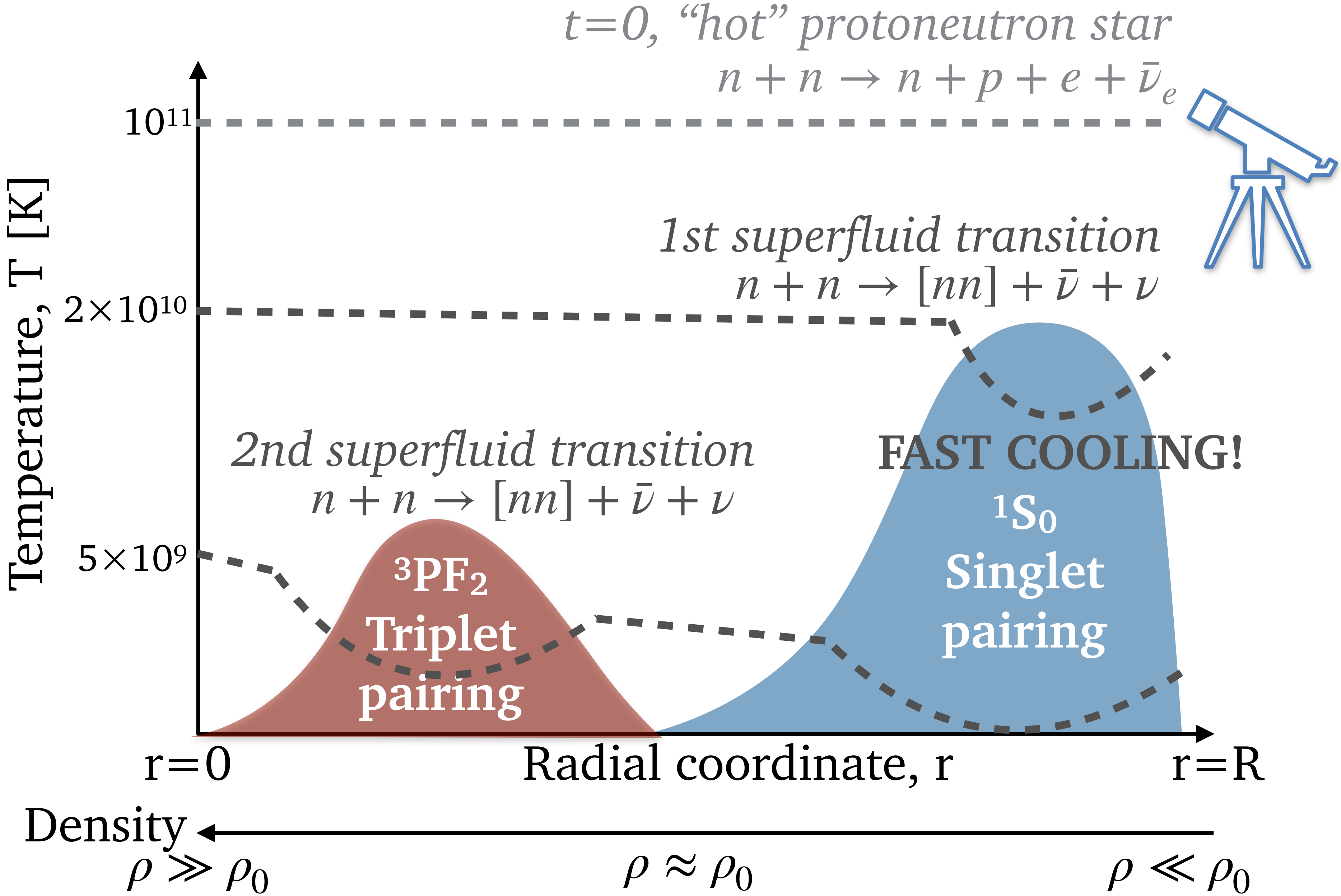
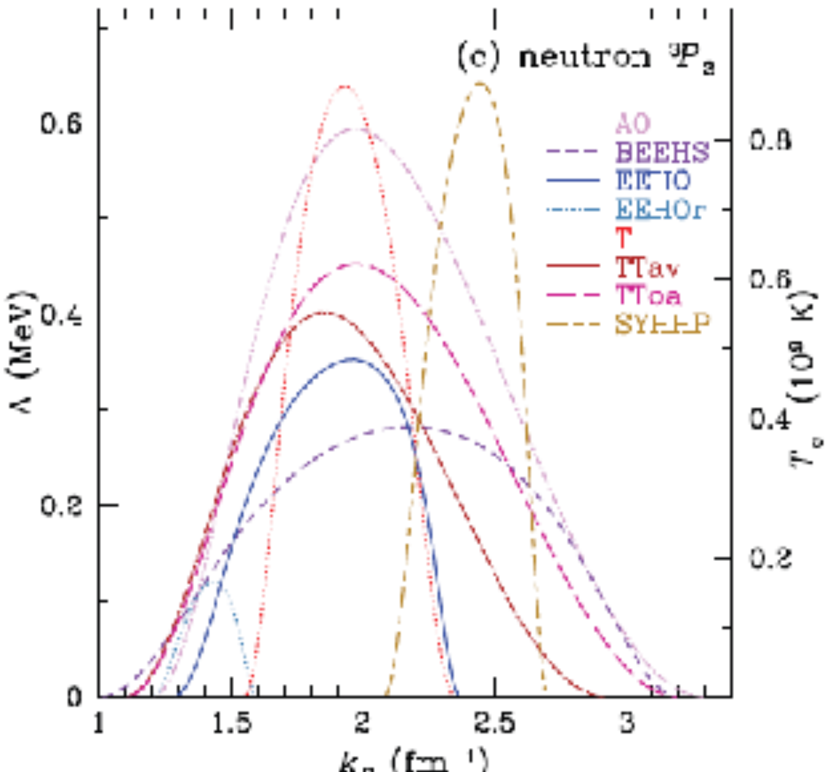
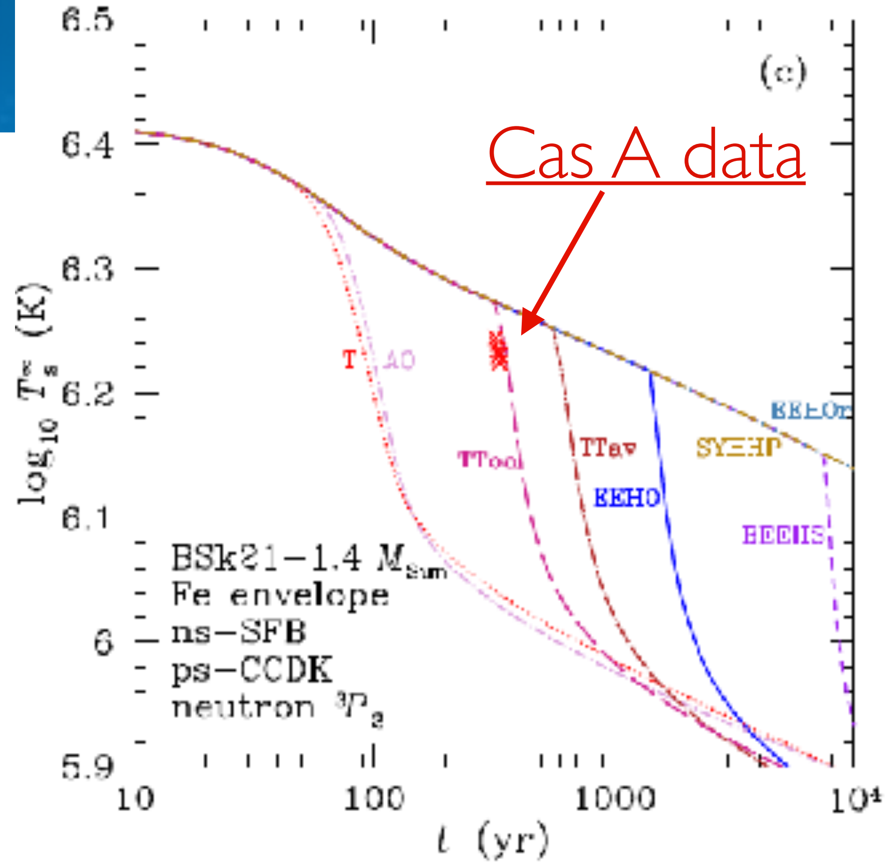


Pairing gaps & cooling



Cooling of CasA





[Ho, *et al.*, PRC **91** 015806 (2015)](#)

[Page, *et al.*, *PRL* **106** 081101 (2011)](#)

Ingredients

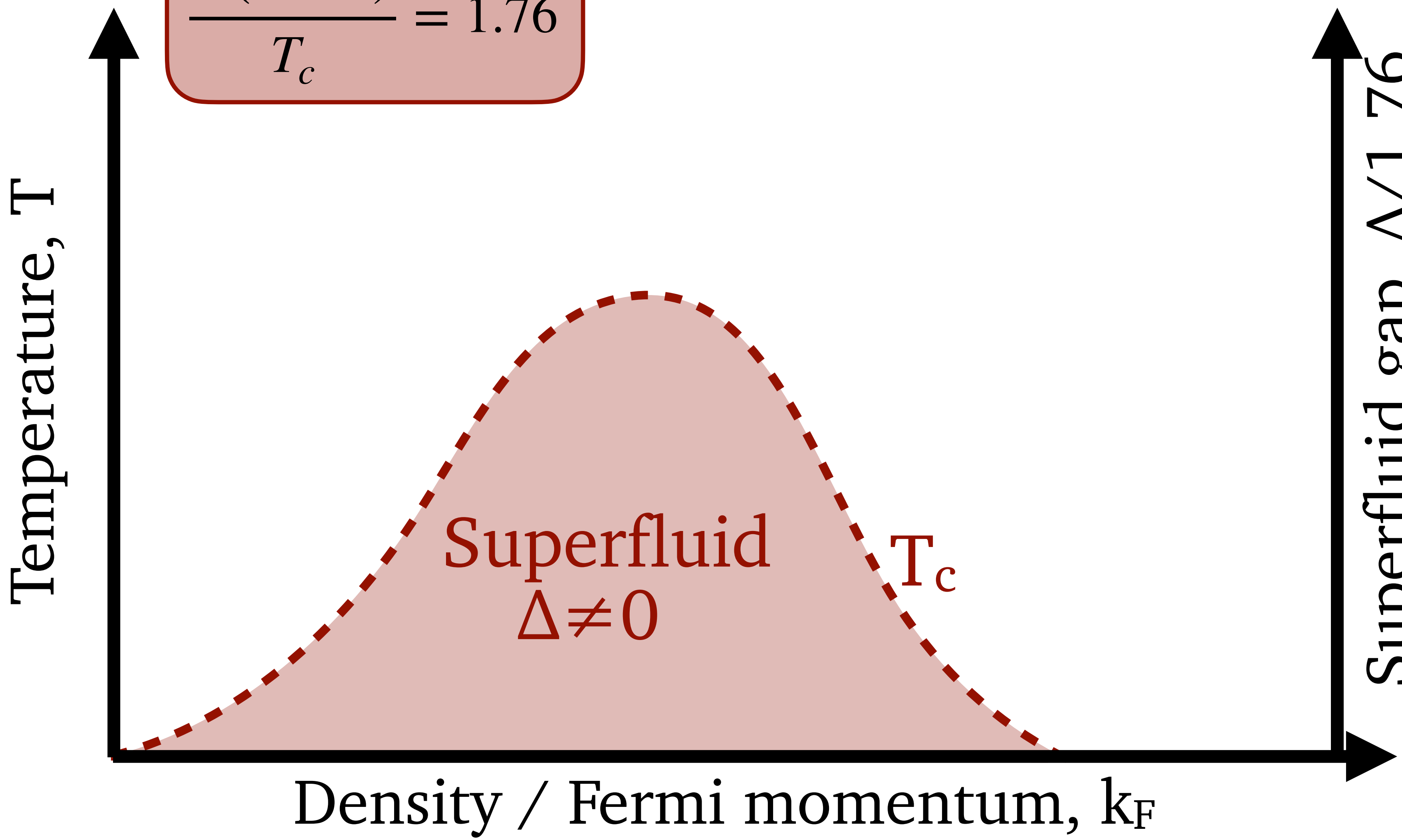
(a) Mass of pulsar
(b) EoS (determines radius)
(c) Internal composition
(d) **Pairing gaps** ($^1S_0$ & $^3PF_2$ channels)
(e) Atmosphere composition

Name	Process	Emissivity (erg cm^{-3} s^{-1})
Modified Urca (neutron branch)	$n+n \to n+p+e^- + \bar{\nu}_e$ $n+p+e^- \to n+n+\nu_e$	$\sim 2\times10^{21}\, R T_9^8$
Modified Urca (proton branch)	$p+n \to p+p+e^- + \bar{\nu}_e$ $p+p+e^- \to p+n+\nu_e$	$\sim 10^{21}\, R T_9^8$
Bremsstrahlungs	$n+n \to n+n+\nu+\bar{\nu}$ $n+p \to n+p+\nu+\bar{\nu}$ $p+p \to p+p+\nu+\bar{\nu}$	$\sim 10^{19}\, R T_9^8$
Cooper pair	$n+n \to [nn]+\nu+\bar{\nu}$ $p+p \to [pp]+\nu+\bar{\nu}$	$\sim 5\times10^{21}\, R T_9^7$ $\sim 5\times10^{19}\, R T_9^7$
Direct Urca (nucleons)	$n \to p+e^- + \bar{\nu}_e$ $p+e^- \to n+\nu_e$	$\sim 10^{27}\, R T_9^6$

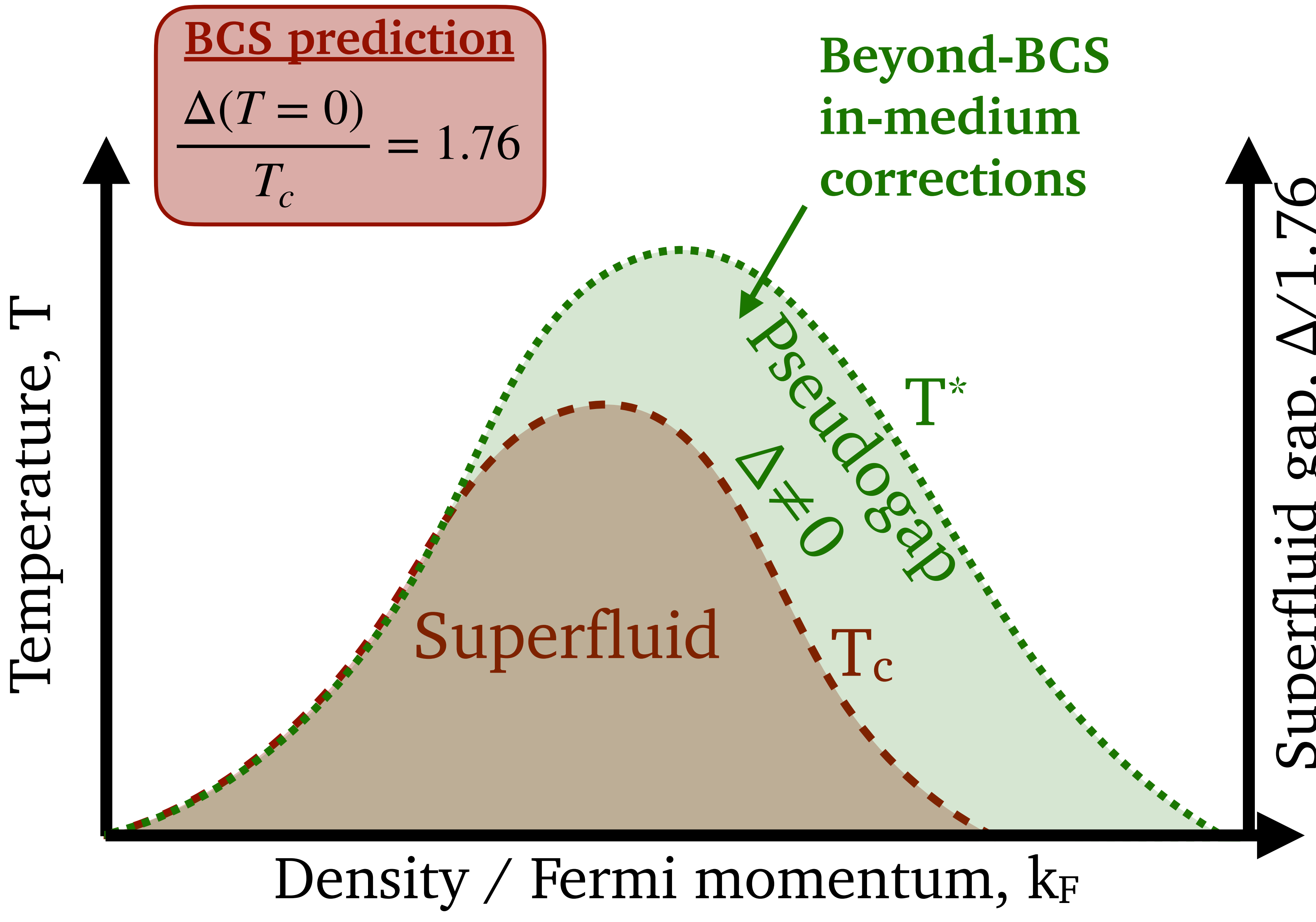
Gaps and critical temperatures

BCS prediction

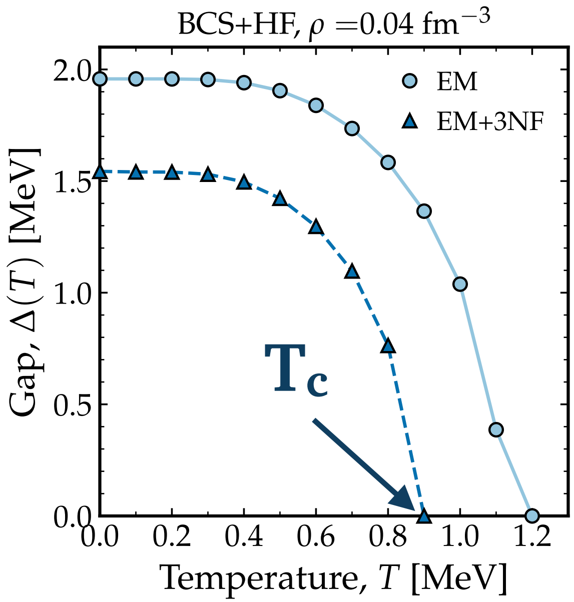
$$\frac{\Delta(T=0)}{T_c} = 1.76$$

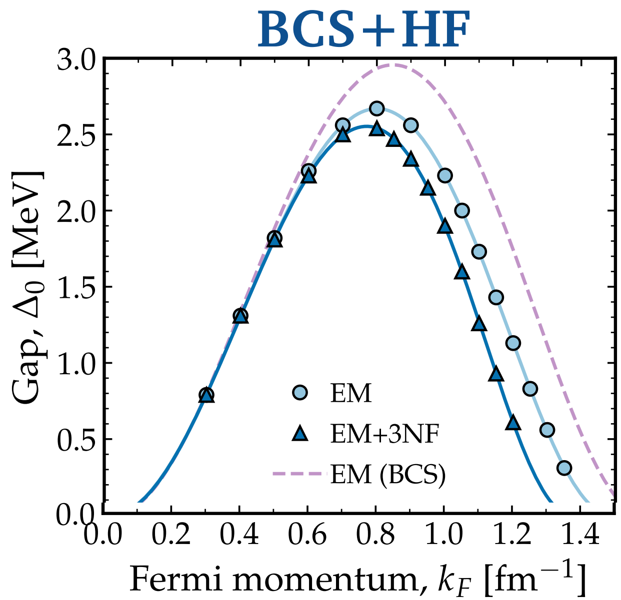


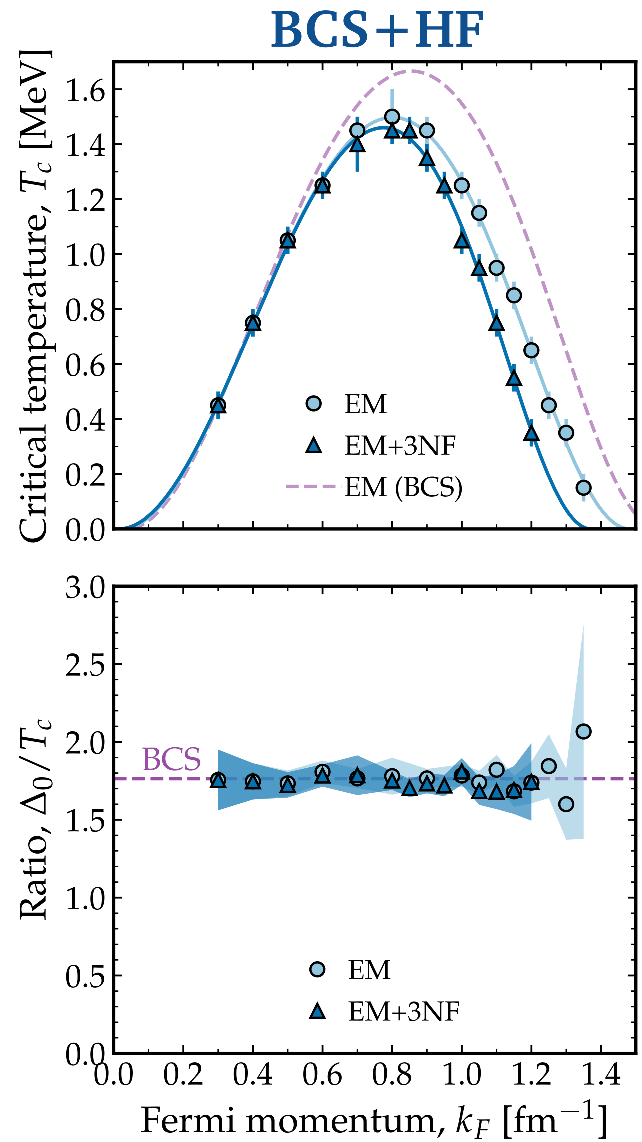
Gaps and critical temperatures



BCS+HF predictions







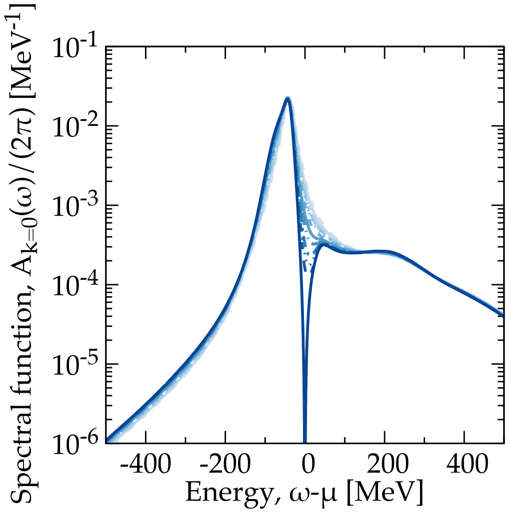
BCS+HF equation

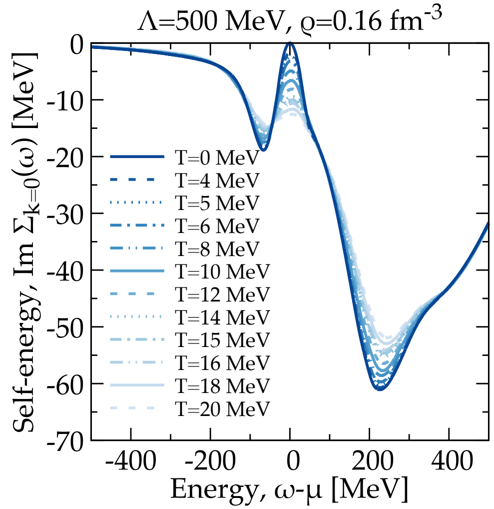
$$\Delta_k^L = -\sum_{L'} \int_{k'} \frac{\langle k | V_{nn}^{LL'} | k' \rangle}{2\sqrt{\chi_{k'}^2 + |\Delta_{k'}|^2}} \Delta_{k'}^{L'}$$

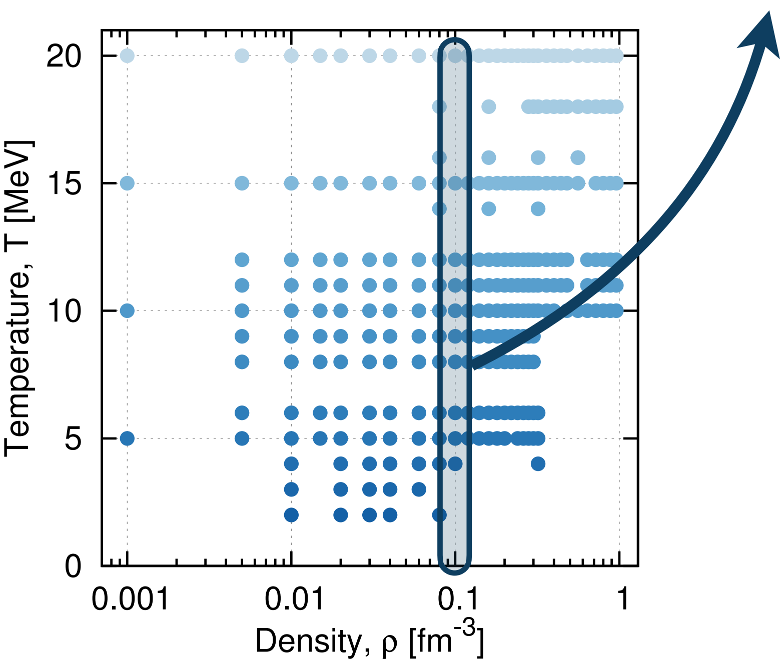
$$\chi_k = \varepsilon_k - \mu \quad + \quad \varepsilon_k = \frac{k^2}{2m} + U(k) - \mu$$

Drissi & Rios, in preparation

Beyond-BCS predictions



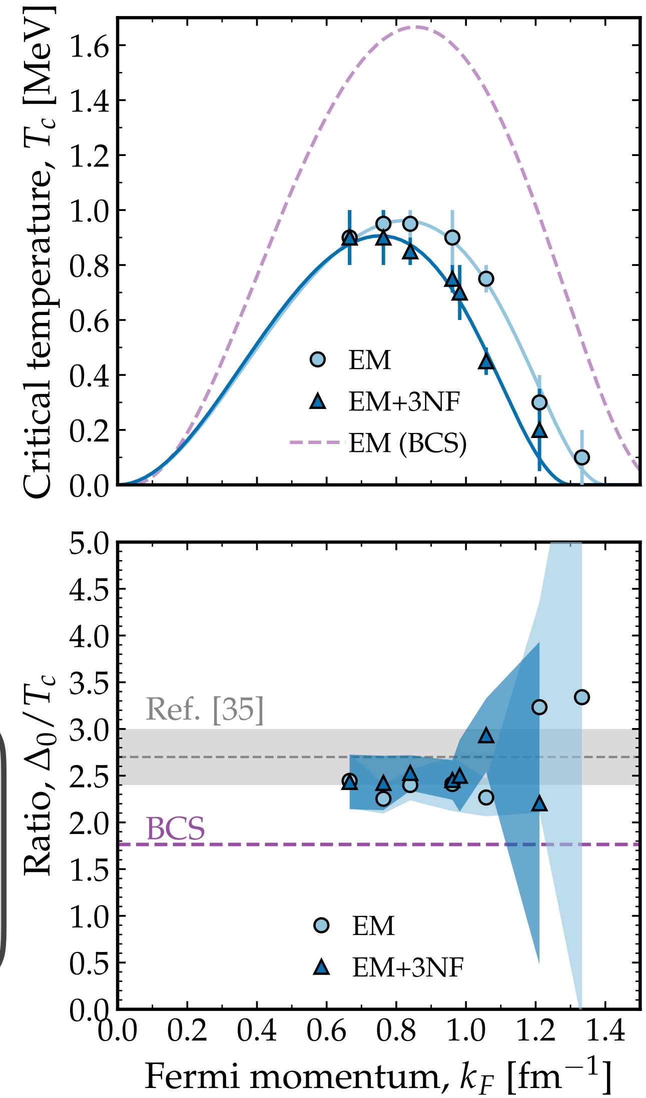




Unitary gas

$$\frac{\Delta(T=0)}{T_c} \approx 2.6$$

SCGF+SRC



Drissi & Rios, in preparation

Beyond-BCS predictions

Unitary gas

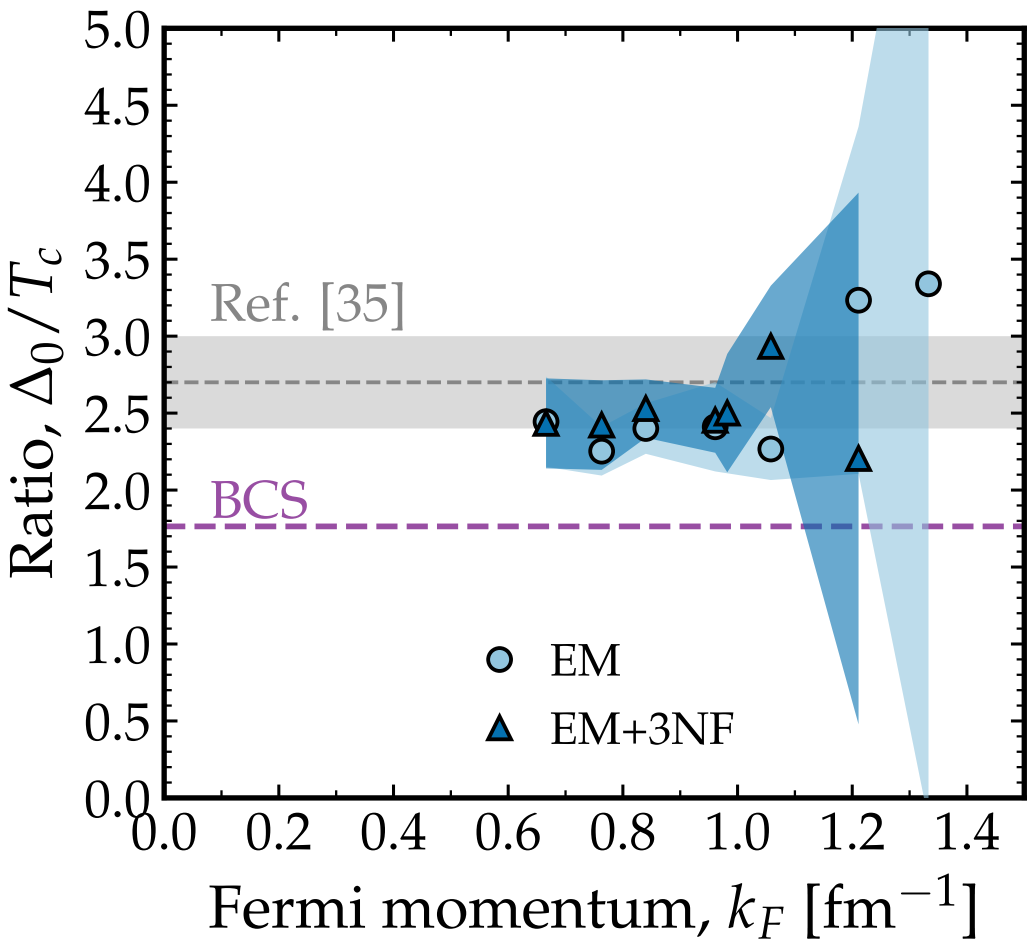
$$\frac{\Delta(T=0)}{T_c} \approx 2.6$$

SCGF+SRC

$$\frac{\Delta(T=0)}{T_c} \approx 2.4$$

BCS prediction

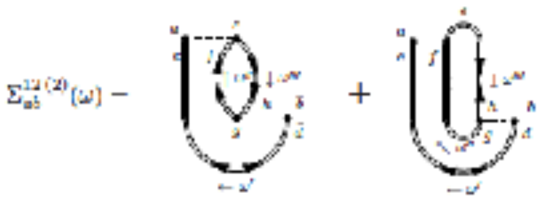
$$\frac{\Delta(T=0)}{T_c} = 1.76$$



Drissi & Rios, in preparation

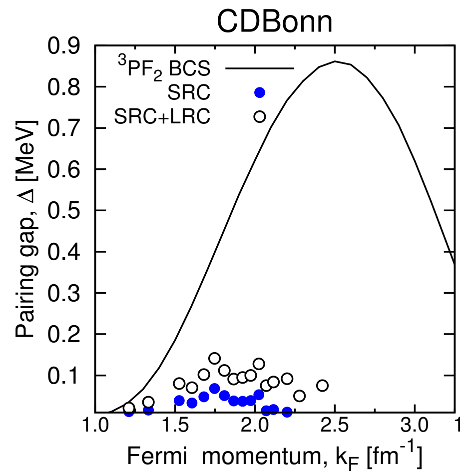
- **Numerically** demanding ✘
- Can't **systematize** long-range correlations ✘

How to go beyond BCS?



Normal state ⟷ Superfluid $\Delta(k_F)$

+



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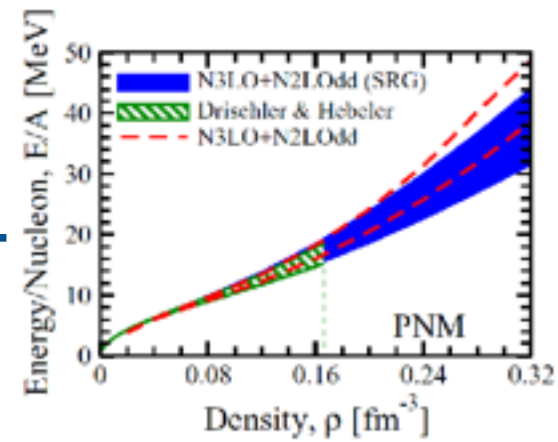
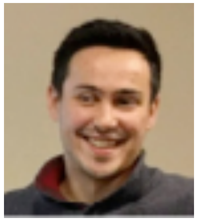


◉ Nambu-covariant Green's Functions

- Symmetry breaking ✔
- Finite temperature ✔
- Systematic expansion w diagrams ✔
- 3 nucleon forces ✔



M. Drissi

Drissi, Rios & Barbieri, arxiv:2107.09759 + arXiv:2107.09763

Nambu-Covariant Perturbation Theory

Nambu fields

[Anderson, 1958] [Nambu, 1960]

- $\mathscr{B}$ and $\bar{\mathscr{B}}$ ≡ orthonormal bases $|b\rangle \to |\bar{b}\rangle$
- Let $\bar{\cdot}$ be the involution ($\bar{1} = 2, \bar{2} = 1$)
- Define $\mu \equiv (b, g)$ and $\bar{\mu} \equiv (\bar{b}, \bar{g})$ where $g \in \{1,2\}$
- Then Nambu fields are defined as

$$\mathrm{A}^{\mu} \equiv \mathrm{A}^{(b,g)} \equiv \begin{pmatrix} a_b \\ a^{\dagger}_{\bar{b}} \end{pmatrix}_g$$

$$\mathrm{A}^{\dagger}_{\mu} \equiv \mathrm{A}^{\dagger}_{(b,g)} \equiv \begin{pmatrix} a^{\dagger}_b & a_{\bar{b}} \end{pmatrix}_g$$

- Canonical anticommutation relation

$$\{\mathrm{A}^{\mu}, \mathrm{A}^{\nu}\} = \delta_{\mu\bar{\nu}} \;,\; \{\mathrm{A}^{\dagger}_{\mu}, \mathrm{A}^{\dagger}_{\nu}\} = \delta_{\mu\bar{\nu}} \;,\; \{\mathrm{A}^{\mu}, \mathrm{A}^{\dagger}_{\nu}\} = \delta_{\mu\nu}$$

Operators

- Operators as polynomial of Nambu fields

$$O \equiv \sum_{\mu_1\dots\mu_{2k}} o^{\mu_1\dots\mu_k}{}_{\mu_{k+1}\dots\mu_{2k}} \mathrm{A}^{\dagger}_{\mu_1}\dots\mathrm{A}^{\dagger}_{\mu_k}\mathrm{A}^{\mu_{k+1}}\dots\mathrm{A}^{\mu_{2k}}$$

$$O \equiv \sum_{\mu_1\dots\mu_{2k}} o_{\mu_1\dots\mu_{2k}} \mathrm{A}^{\mu_1}\dots\mathrm{A}^{\mu_{2k}}$$

$$O \equiv \sum_{\mu_1\dots\mu_{2k}} o^{\mu_1\dots\mu_{2k}} \mathrm{A}^{\dagger}_{\mu_1}\dots\mathrm{A}^{\dagger}_{\mu_{2k}}$$

Tensor definitions

- Let $\mathscr{W}$ a unitary Bogoliubov transformation

$$\mathrm{B}^{\mu} = \sum_{\nu} (\mathscr{W}^{\dagger})^{\mu}{}_{\nu} \mathrm{A}^{\nu}$$

$$\mathrm{B}^{\dagger}_{\mu} = \sum_{\nu} \mathscr{W}^{\nu}{}_{\mu} \mathrm{A}^{\dagger}_{\nu}$$

- Definition: *(p,q)*-tensor is multi-dim array s.t.

$$t'^{\mu_1\dots\mu_p}{}_{\nu_1\dots\nu_q} \equiv \sum_{\kappa_1\dots\kappa_p} \sum_{\lambda_1\dots\lambda_q} (\mathscr{W}^{\dagger})^{\mu_1}{}_{\kappa_1}\dots(\mathscr{W}^{\dagger})^{\mu_p}{}_{\kappa_p} \; t^{\kappa_1\dots\kappa_p}{}_{\lambda_1\dots\lambda_q} (\mathscr{W})^{\lambda_1}{}_{\nu_1}\dots(\mathscr{W})^{\lambda_q}{}_{\nu_q}$$

- *p contravariant* & *q covariant* indices

Metric tensor

- Definition: (0,2)-, (1,1)-, (2,0)-tensors

$$\left.\begin{aligned} g_{\mu\nu} &\equiv \delta_{\mu\bar{\nu}} \\ g^{\mu}{}_{\nu} &\equiv \delta_{\mu\nu} \\ g^{\mu\nu} &\equiv \delta_{\mu\bar{\nu}} \end{aligned}\right\} + \text{transform like a tensor}$$

- Raising/lowering indices of a tensor:

$$o_{\mu_1\dots\mu_{2k}} = \sum_{\alpha_1\dots\alpha_k} g_{\mu_1\alpha_1}\dots g_{\mu_k\alpha_k} \, o^{\alpha_1\dots\alpha_k}{}_{\mu_{k+1}\dots\mu_{2k}}$$

Perturbative expansion

Hamiltonian partitioning

$$\Omega = \Omega_0 + \Omega_1$$

$$\Omega_0 = \frac{1}{2}\sum_{\mu\nu} U_{\mu\nu} A^\mu A^\nu$$

$$\Omega_1 = \sum_{k=1}^{n} \frac{1}{(2k)!} \sum_{\mu_1\ldots\mu_{2k}} v^{(k)}_{\mu_1\ldots\mu_{2k}} A^{\mu_1}\ldots A^{\mu_{2k}}$$

Covariant **k-body** vertices

Green's functions

- Contravariant **k-body** Green's function

$$(-1)^k \, \mathcal{G}^{\mu_1\ldots\mu_{2k}}(\tau_1,\ldots,\tau_{2k}) \equiv \left\langle \mathrm{T}\left[A^{\mu_1}(\tau_1) \; \ldots \; A^{\mu_{2k}}(\tau_{2k})\right]\right\rangle$$

with $\langle\, . \,\rangle = \mathrm{Tr}\left(. \,\rho\right)$ and $\rho \equiv \dfrac{e^{-\beta\Omega}}{\mathrm{Tr}\left(e^{-\beta\Omega}\right)}$

- Unperturbed case: $\Omega \longleftrightarrow \Omega_0$

Expansion

- Interaction picture expression

$$(-1)^k \, \mathcal{G}^{\mu_1\ldots\mu_{2k}}(\tau_1,\ldots,\tau_{2k}) = \frac{\left\langle \mathrm{T}\left[e^{-\int_0^\beta \mathrm{d}s\, \Omega_1(s)} \, A^{\mu_1}(\tau_1) \; \ldots \; A^{\mu_{2k}}(\tau_{2k})\right]\right\rangle_0}{\left\langle \mathrm{T} e^{-\int_0^\tau \mathrm{d}s\, \Omega_1(s)}\right\rangle_0}$$

- Perturbative expansions

$$\left\langle \mathrm{T}\left[e^{-\int_0^\beta \mathrm{d}s\, \Omega_1(s)} \, A^{\mu_1}(\tau_1) \; \ldots \; A^{\mu_{2k}}(\tau_{2k})\right]\right\rangle_0 =$$

$$\sum_{n=0}^{+\infty} \frac{(-1)^n}{n!} \int_0^\beta \mathrm{d}\tau_1' \ldots \int_0^\beta \mathrm{d}\tau_n' \left\langle \mathrm{T}\left[\Omega_1(\tau_1')\ldots\Omega_1(\tau_n') \, A^{\mu_1}(\tau_1) \; \ldots \; A^{\mu_{2k}}(\tau_{2k})\right]\right\rangle_0$$

- Statistical Wick theorem + Linked-cluster theorem

$\Rightarrow$ Feynman diagrammatics *almost* as usual

- We provide a set of **Feynman rules**
- Also rules to evaluate **Matsubara sums**
- **Simpler** expressions than in other approaches (Gorkov Green's functions or BMPT

Drissi, Rios & Barbieri, Paper I, arxiv:2107xx

Perturbative expansion

Expansion

- Interaction picture expression

$$(-1)^k \; \mathscr{G}^{\mu_1\dots\mu_{2k}}(\tau_1,\dots,\tau_{2k}) = \frac{\left\langle \mathrm{T}\left[e^{-\int_0^\beta \mathrm{d}s\; \Omega_1(s)}\; \mathrm{A}^{\mu_1}(\tau_1)\;\dots\;\mathrm{A}^{\mu_{2k}}(\tau_{2k})\right]\right\rangle_0}{\left\langle \mathrm{T} e^{-\int_0^\tau \mathrm{d}s\; \Omega_1(s)}\right\rangle_0}$$

- Perturbative expansions

$$\left\langle \mathrm{T}\left[e^{-\int_0^\beta \mathrm{d}s\; \Omega_1(s)}\; \mathrm{A}^{\mu_1}(\tau_1)\;\dots\;\mathrm{A}^{\mu_{2k}}(\tau_{2k})\right]\right\rangle_0 =$$

$$\sum_{n=0}^{+\infty}\frac{(-1)^n}{n!}\int_0^\beta \mathrm{d}\tau_1'\dots\int_0^\beta \mathrm{d}\tau_n' \left\langle \mathrm{T}\left[\Omega_1(\tau_1')\dots\Omega_1(\tau_n')\; \mathrm{A}^{\mu_1}(\tau_1)\;\dots\;\mathrm{A}^{\mu_{2k}}(\tau_{2k})\right]\right\rangle_0$$

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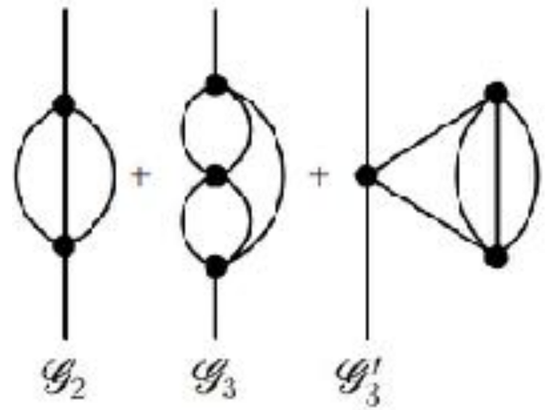
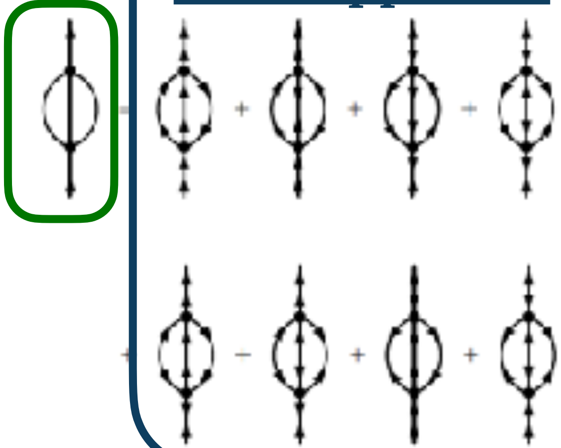
HFB partitioning 3rd order



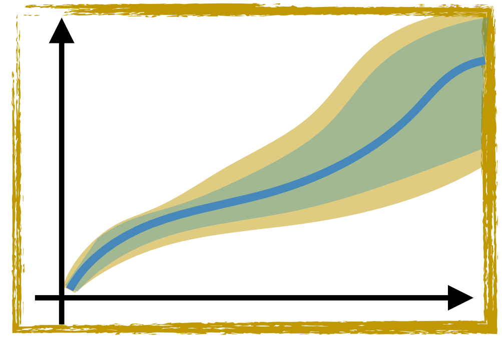
Components of "old" approach



Drissi, Rios & Barbieri, arxiv:2107.09759 + arXiv:2107.09763

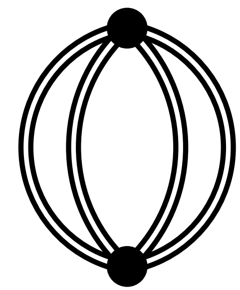
Conclusions

1) **Normal core physics** predictions



- EoS & thermodynamics

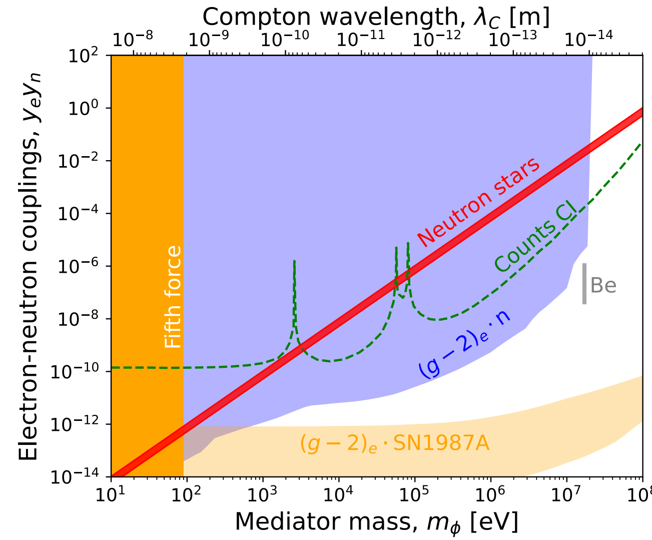
2) **Superfluidity extensions**



- Error quantification work in progress

3) **New physics in dense matter**

- Bounds from NS structure



Next:

Numerical implementations

Uncertainties in predictions

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TRIUMF

(@TRIUMF from 10/2021)

Thank you!

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