UNIVERSITY OF SOUTHERN DENMARK

Neutron Anomalous Decay, Dark Matter & Neutron Stars

Chris Kouvaris

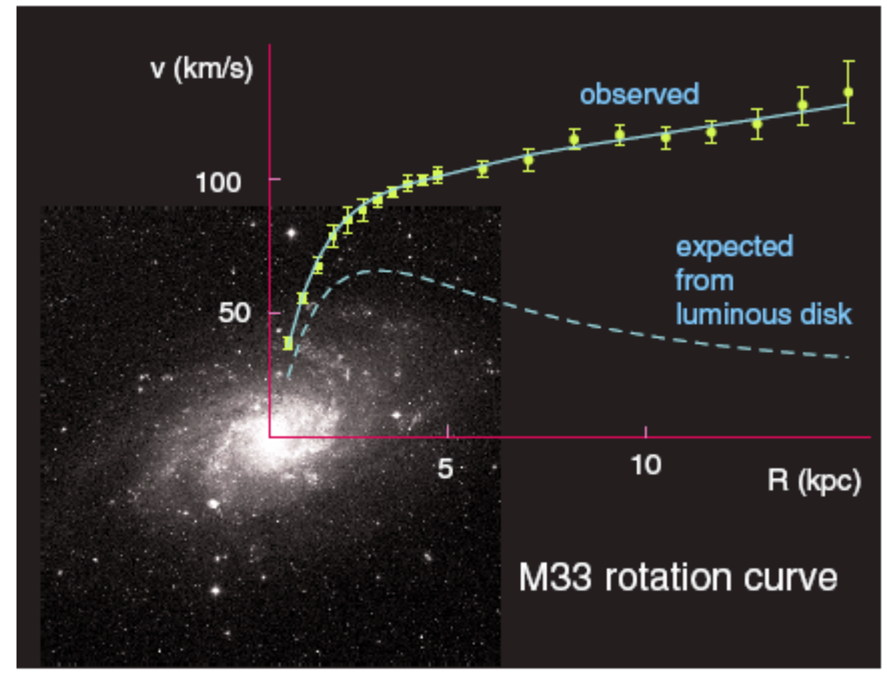
CP3 - Origins

Particle Physics & Origin of Mass

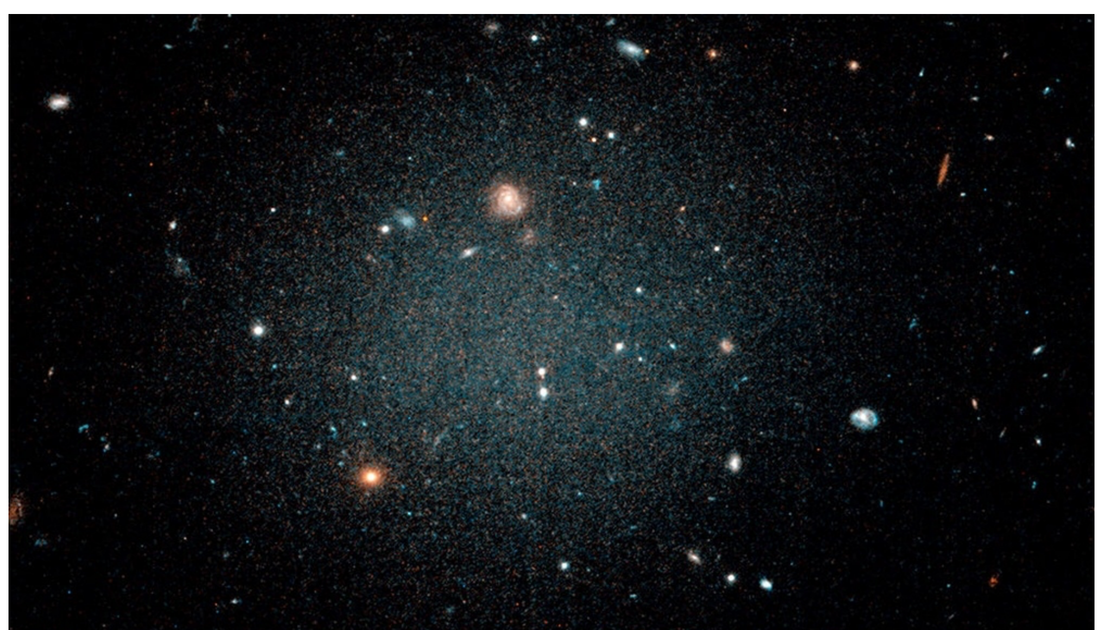
NEPLES2019, Seoul, 27 Sept. 2019

The Missing Mass of the Universe

bullet cluster

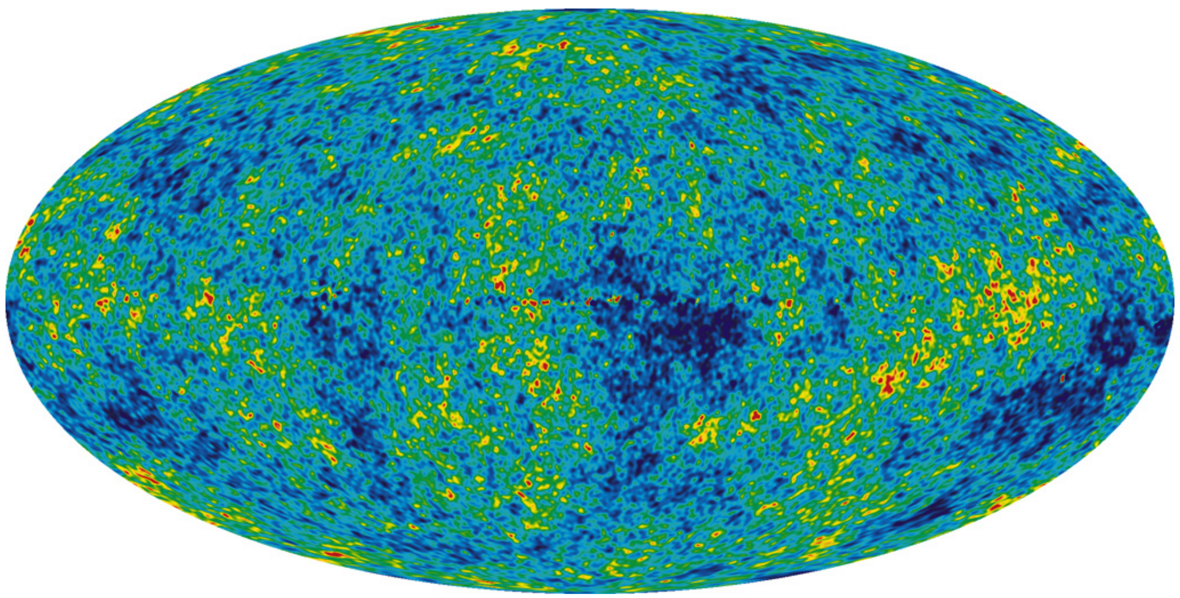


Rotation curves of galaxies

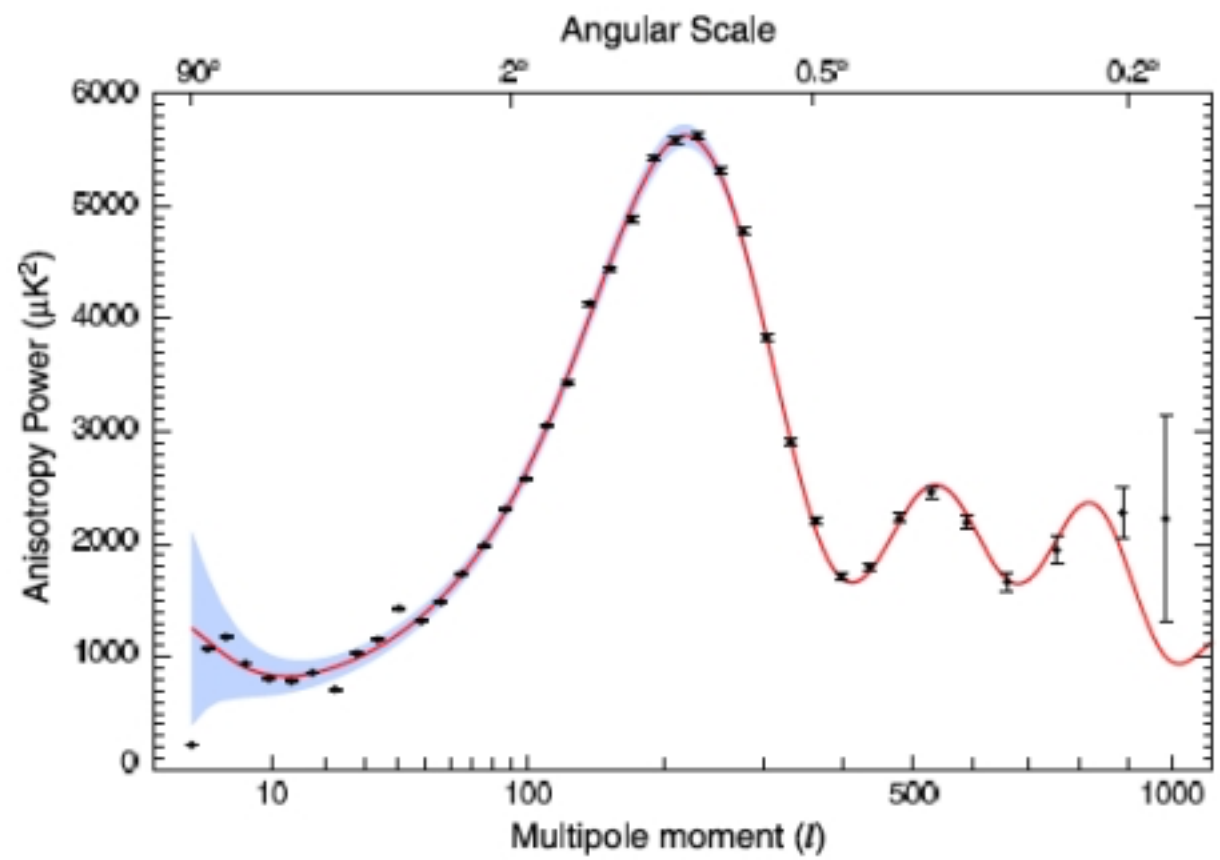


NGC1052-DF2

Dark Matter



Microwave Background Radiation



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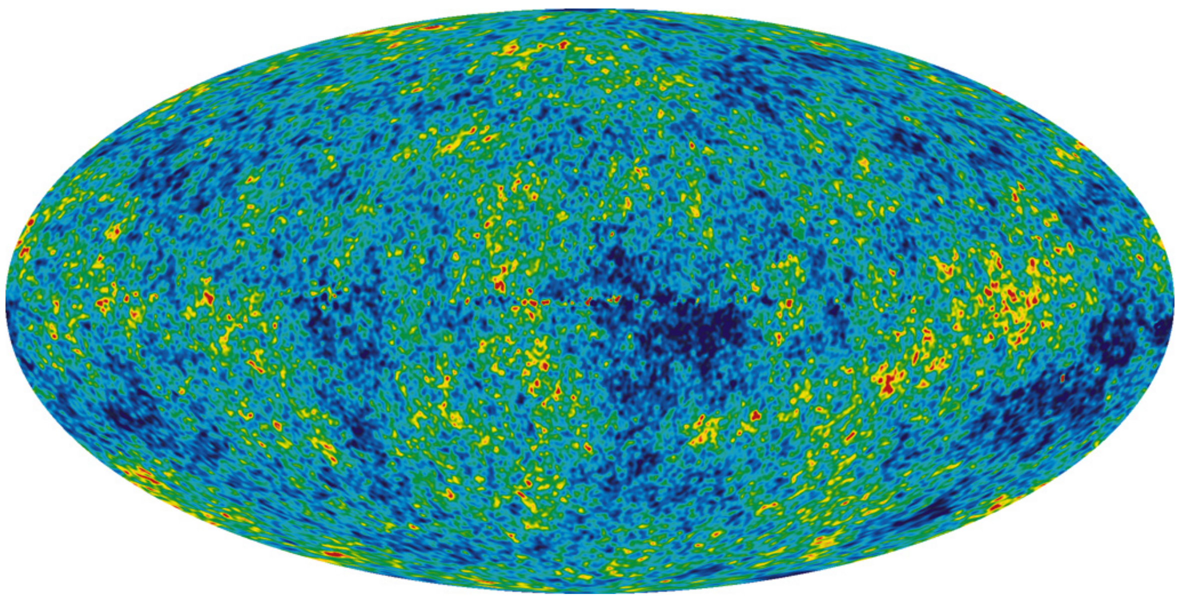

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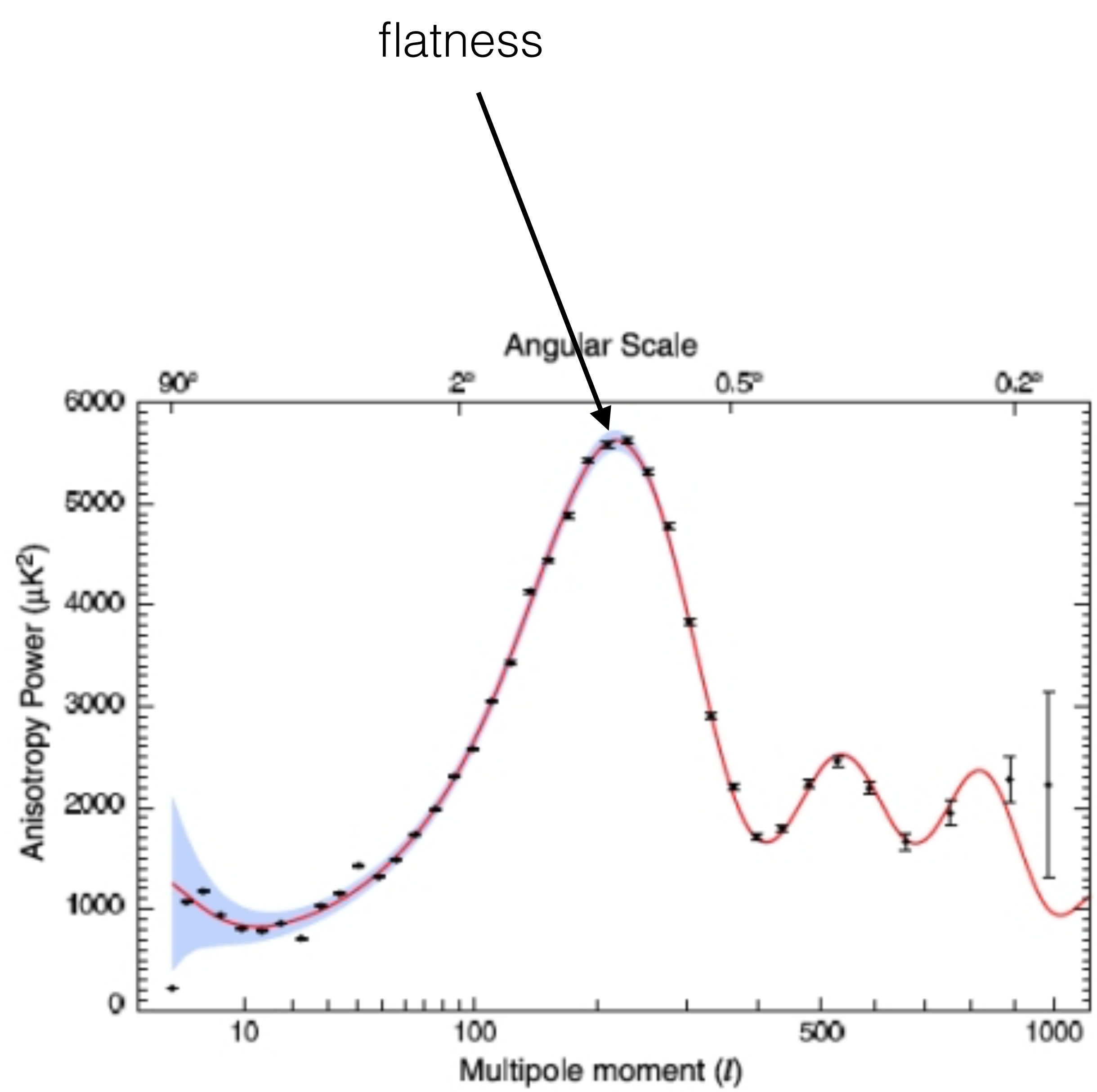

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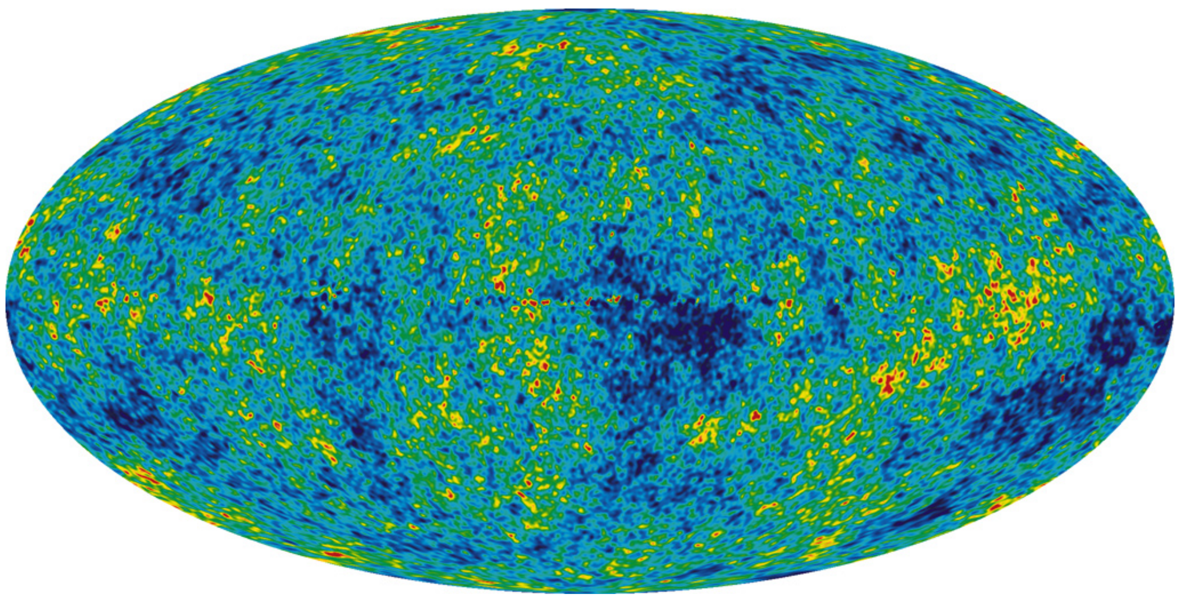

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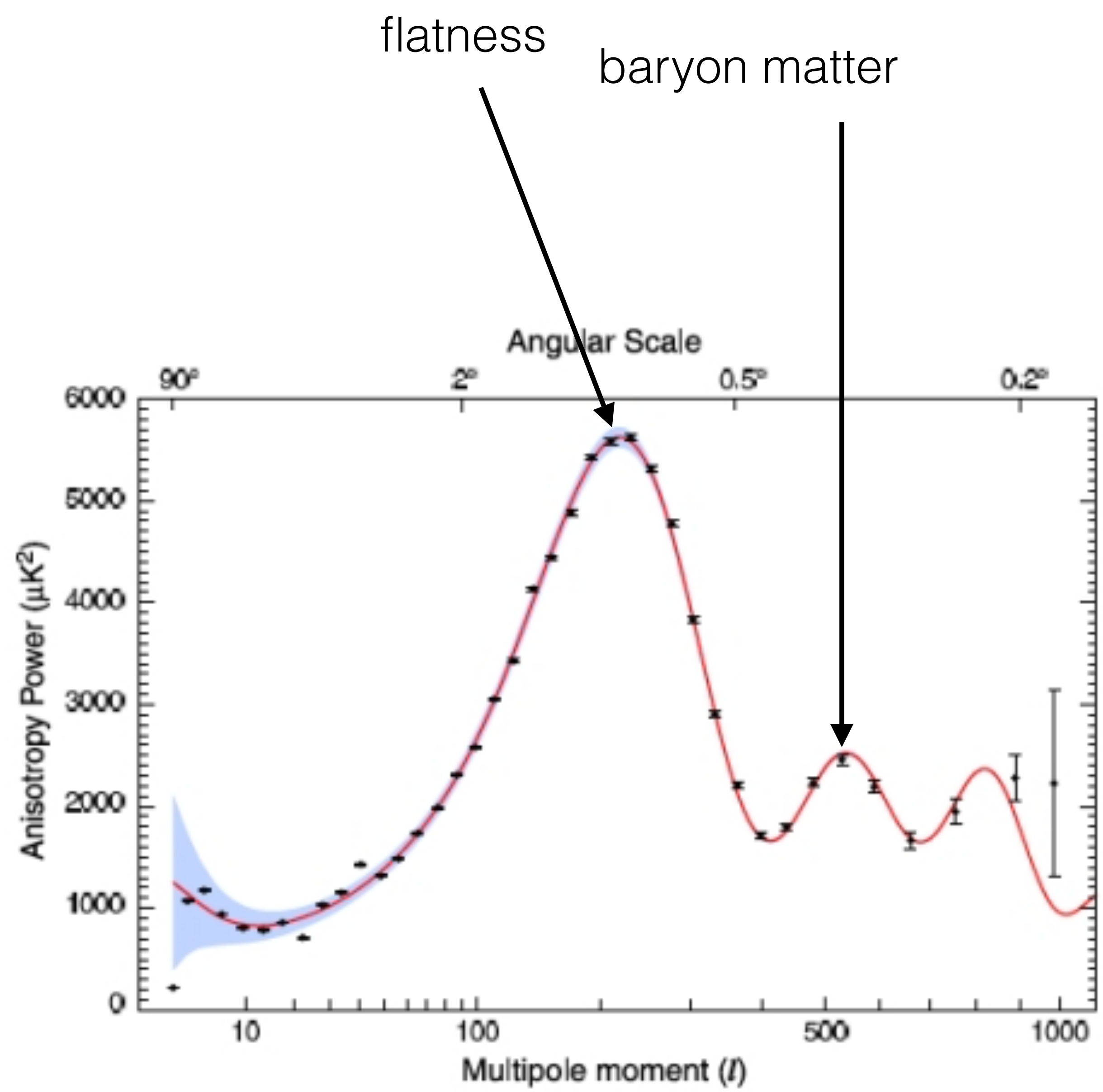

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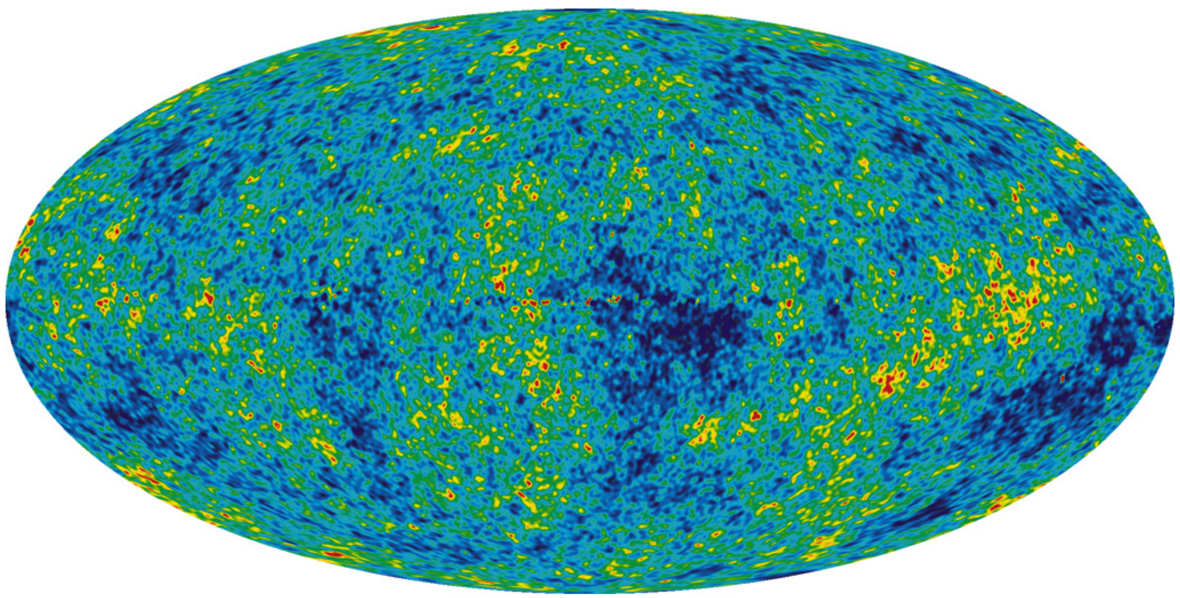

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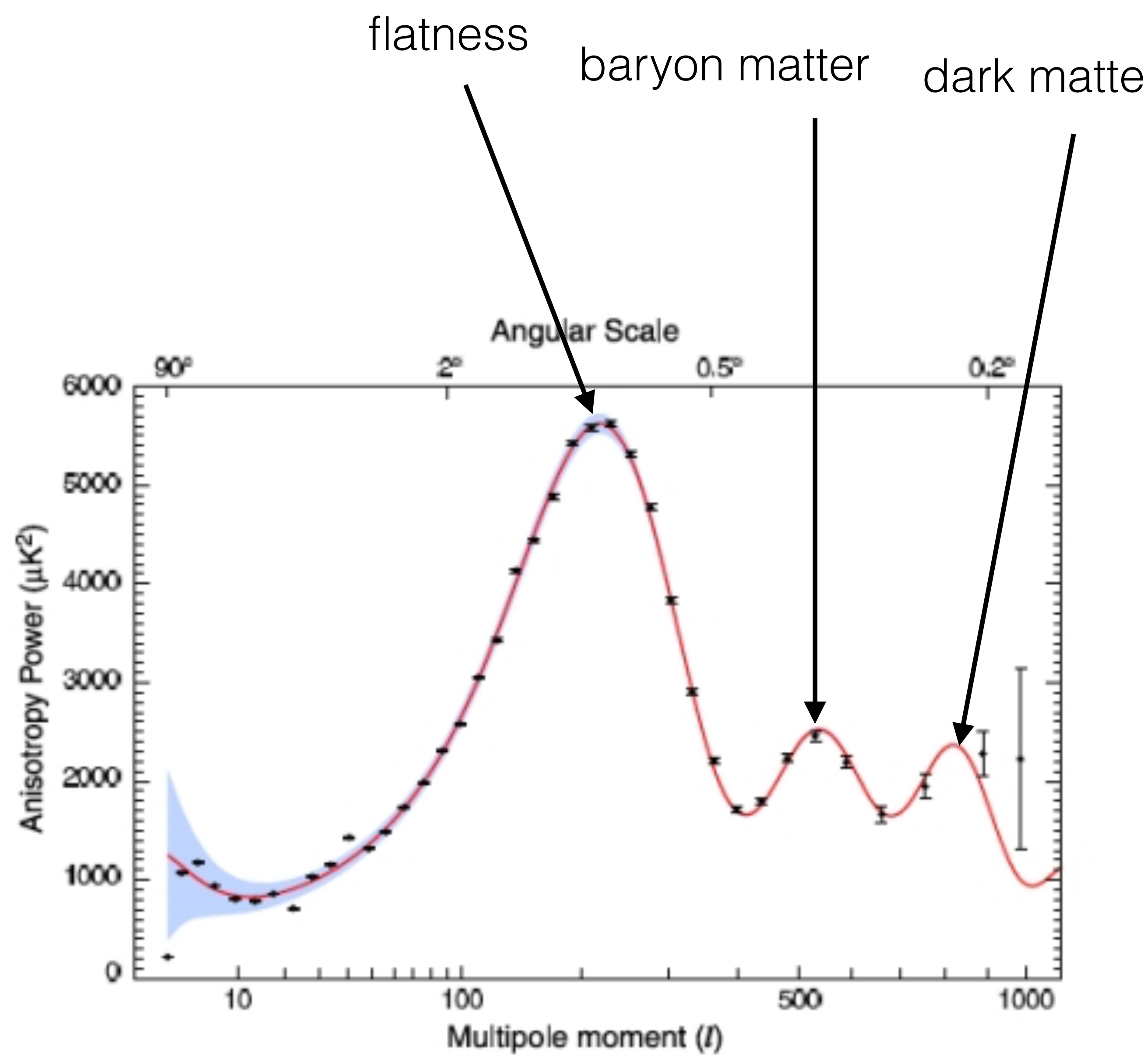

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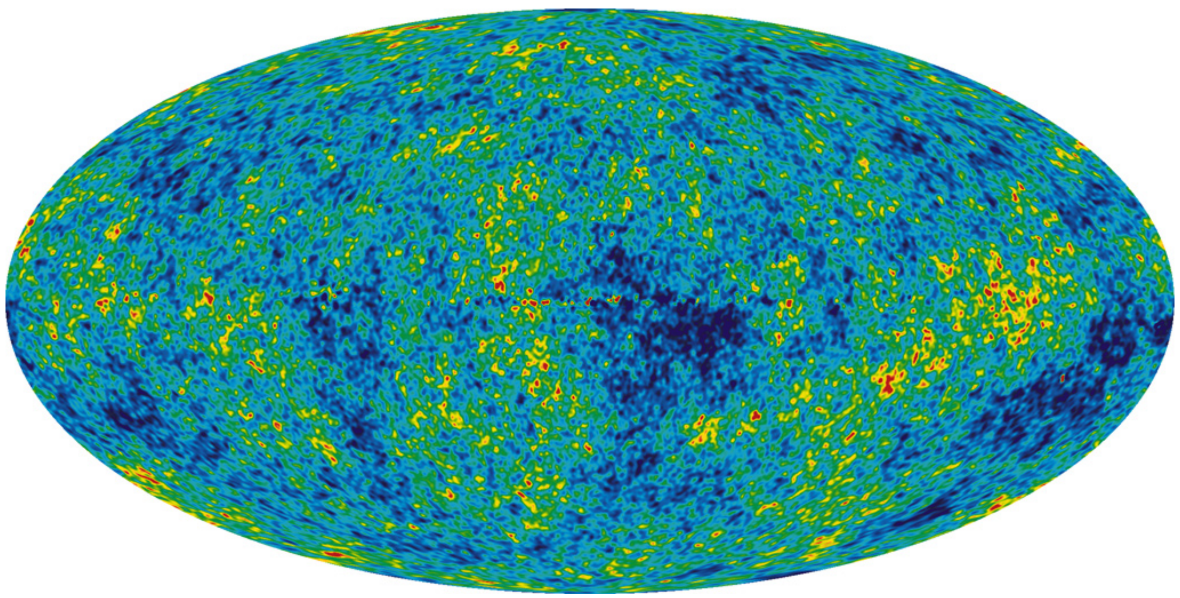

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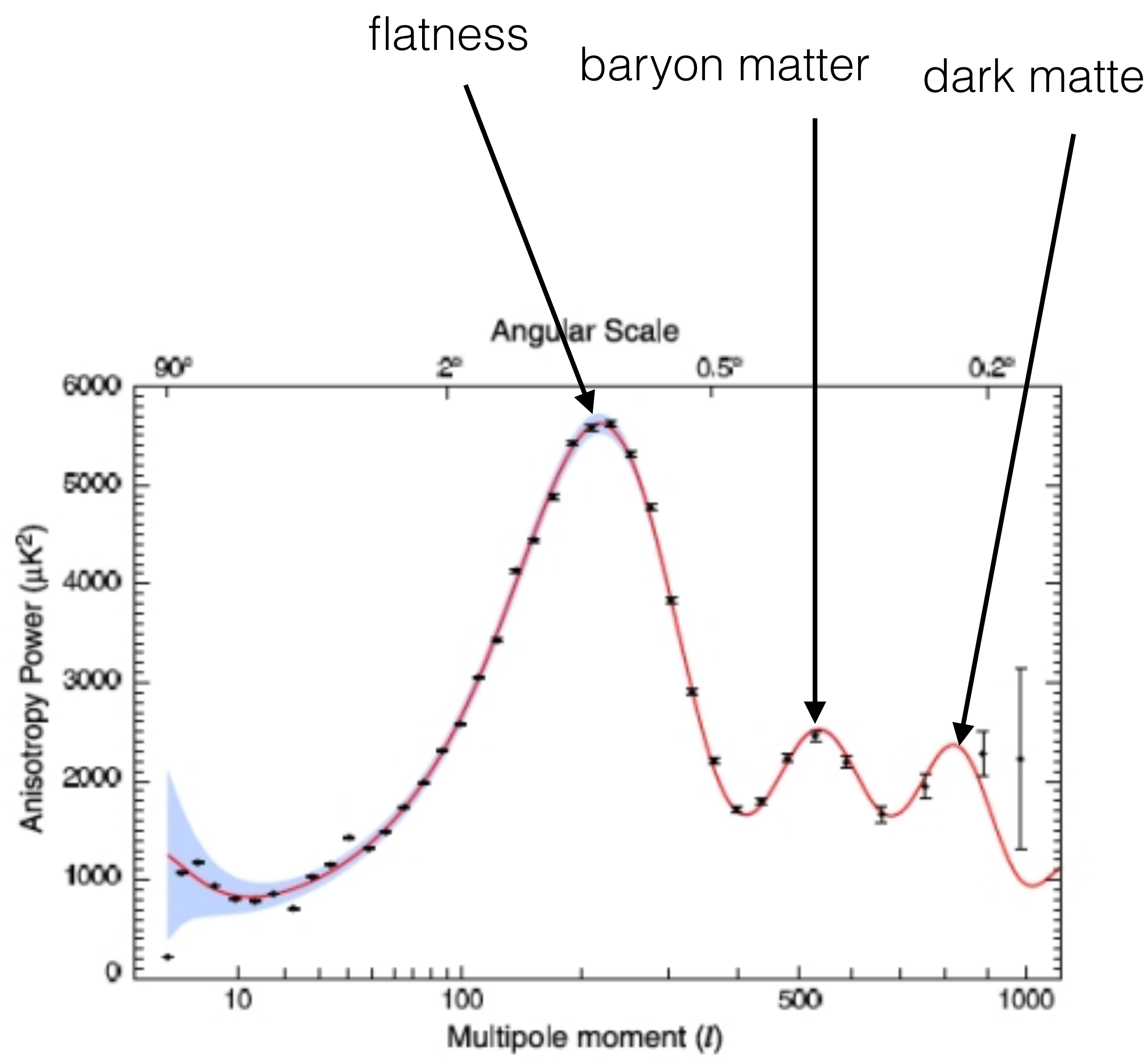

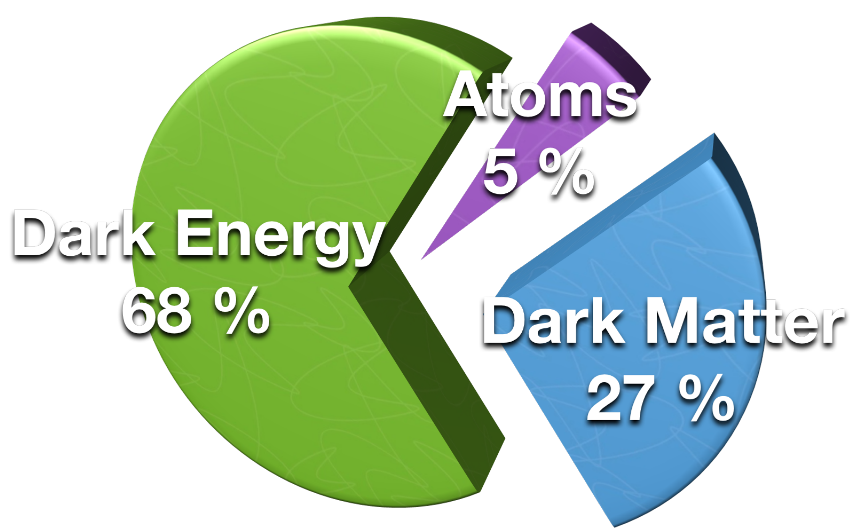

Neutron Decay Anomaly

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There is a 4σ discrepancy between bottle and beam experimental measurements of the decay width of neutron.

$$\tau_{\text{bottle}} = 879.6 \pm 0.6 \text{ s} \qquad \tau_{\text{beam}} = 888.0 \pm 2.0 \text{ s}$$

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if $m_\chi < m_p + m_e$ hydrogen atom is unstable

if $m_\chi > m_p + m_e$ $\chi \to p + e + \bar{\nu}_e$

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It could be a subdominant component of the dark sector

Neutron Stars

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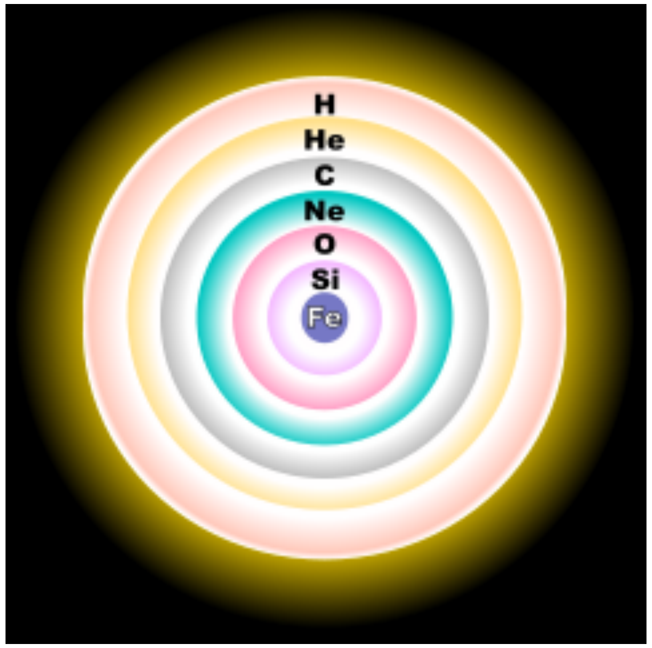
Result of Supernova II explosion of supermassive stars ~9-20 $M_{\odot}$



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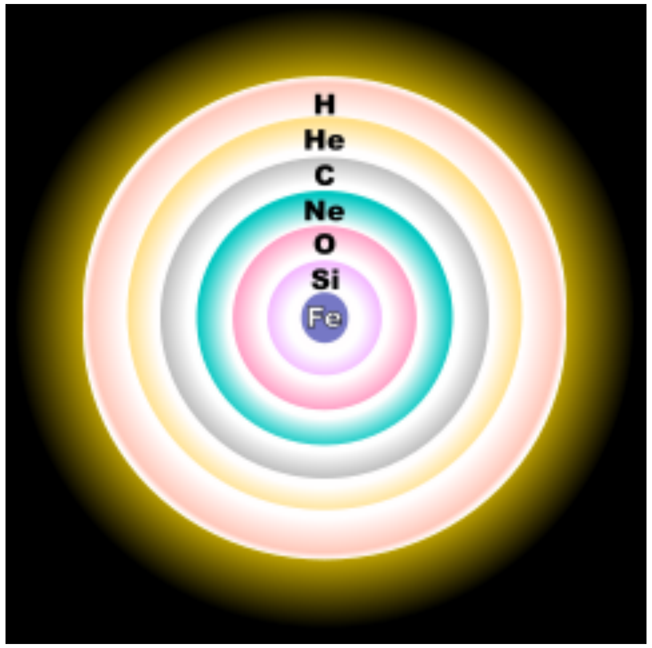

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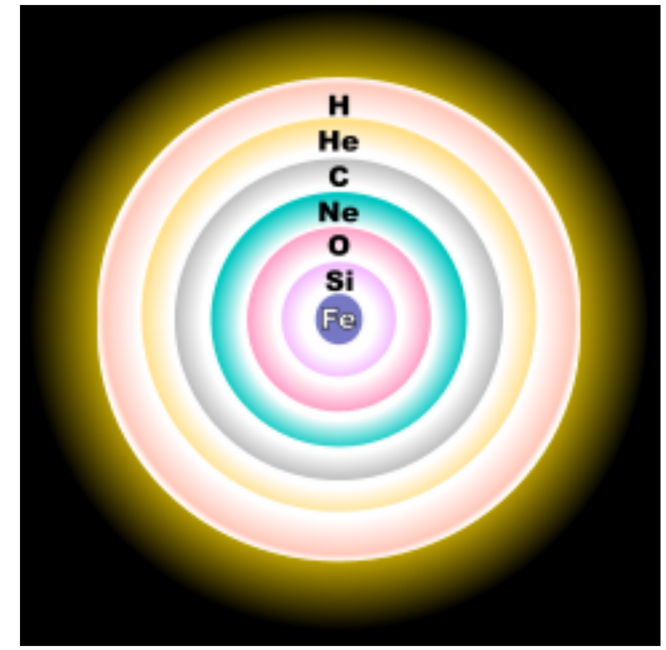

No fusion and energy production

Very compact objects:

Mass: $M \approx 1\text{-}2\ M_\odot$

Radius: $R \approx 10\text{-}12$ Km

density: 5-10 ρ_0

$n_0 = 0.16\ fm^{-3} \Rightarrow \rho_0 = 3 \cdot 10^{14}\ g/cm^3$

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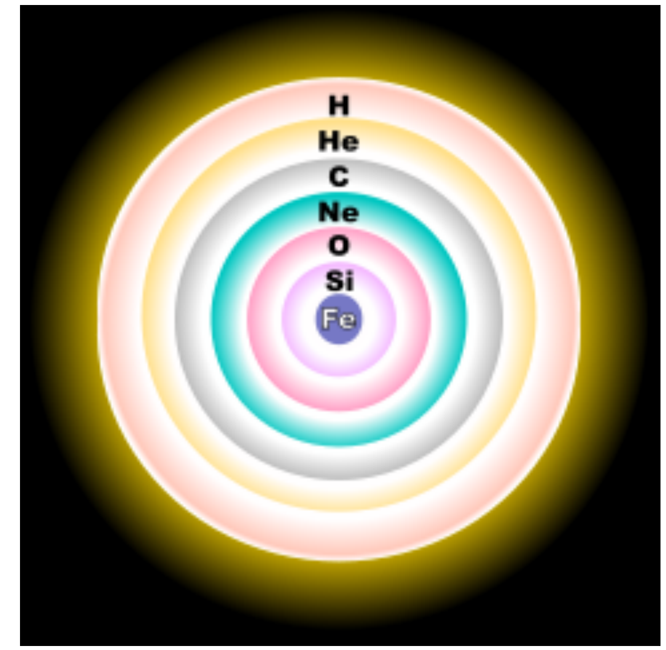

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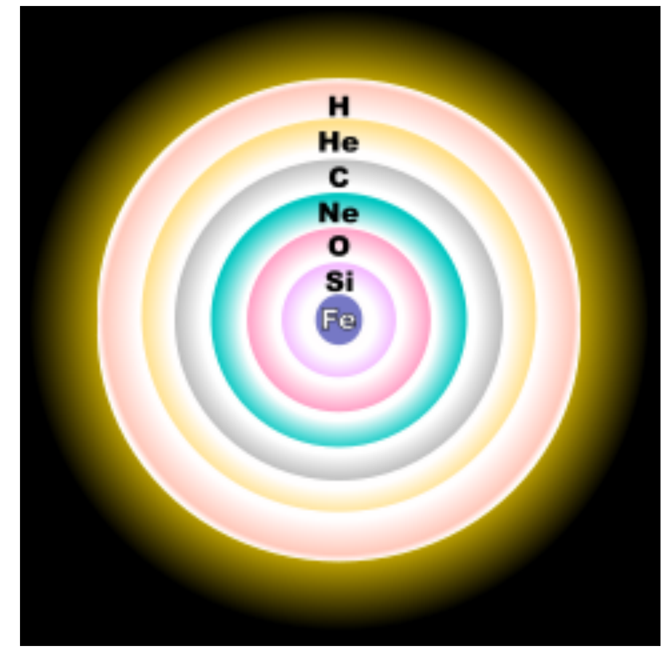

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Fast Spinning: Periods msec to sec (pulsars)

The Interior of the Neutron Stars

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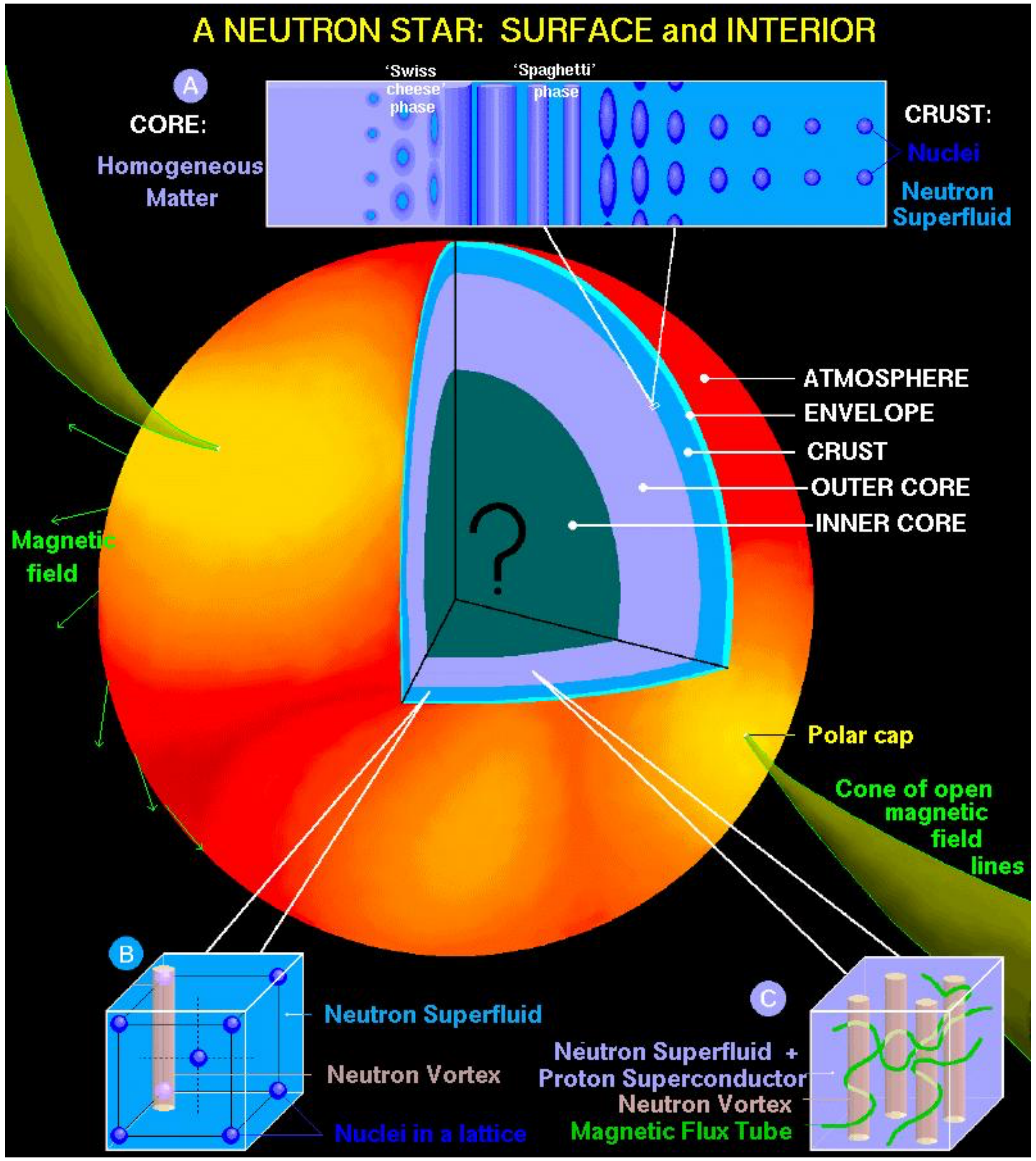
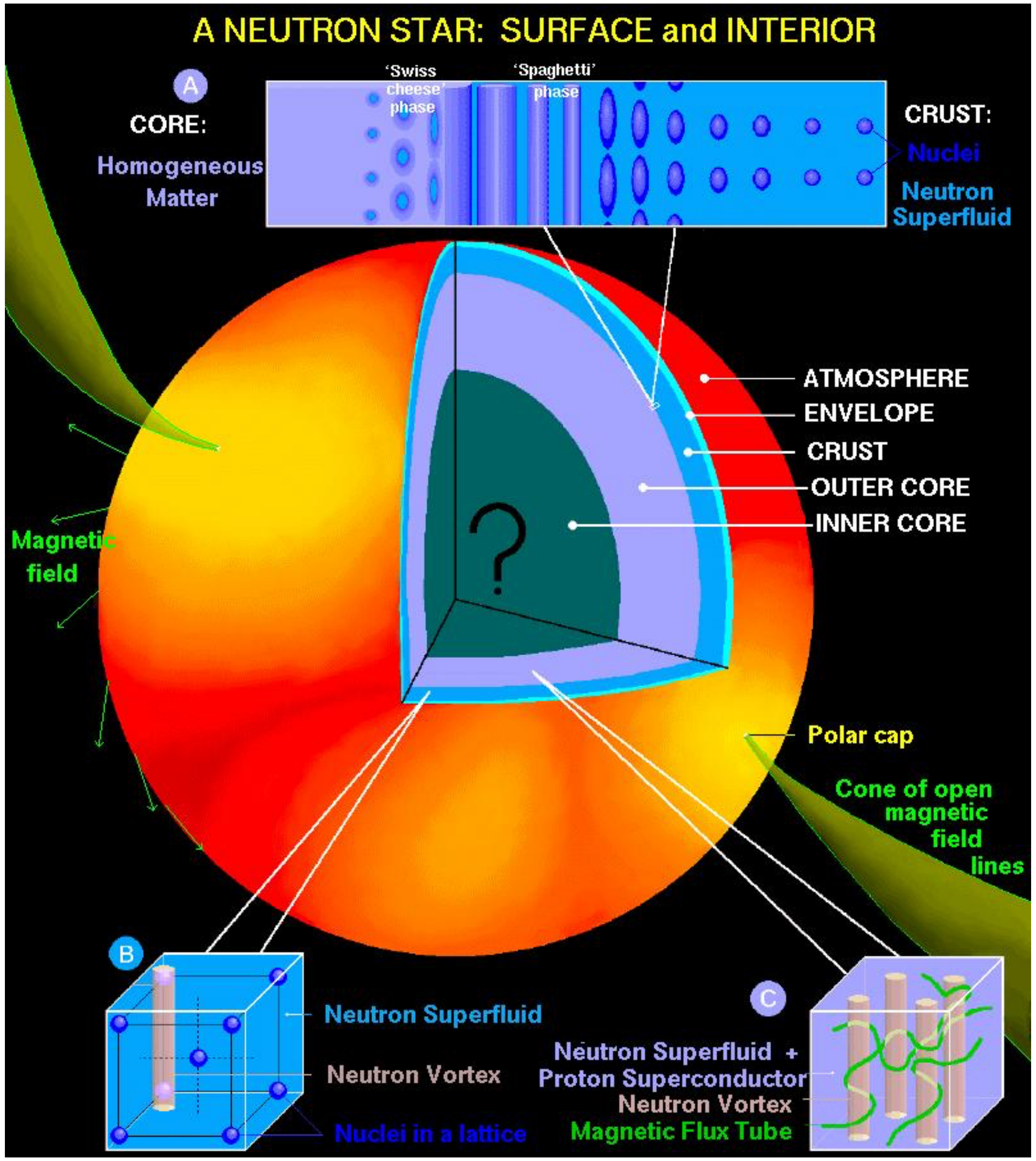


credit: http://www.astro.umd.edu/~miller/Images/NStarInt.jpeg

The Interior of the Neutron Stars

- Atmosphere

thickness: ~1 m,
density: $\rho \leq 10^4$ g/cm^3
composition: atoms, Fe…



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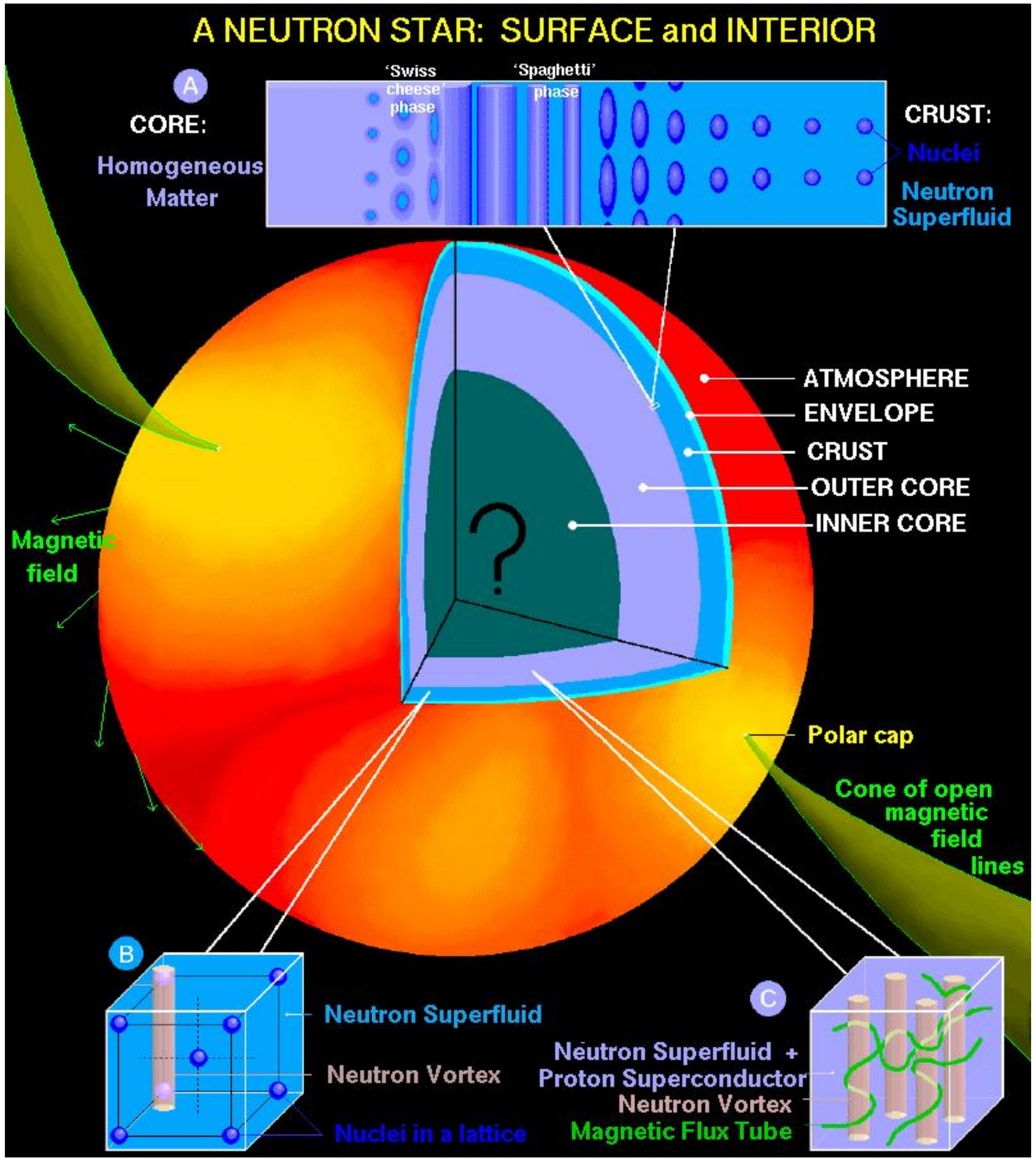
- Outer Crust/Envelope

  thickness: ~hundreds of m

  density: $\rho = 10^4 - 4 \cdot 10^{11}$ g/cm^3 (neutron drip point)

  composition: Fermi gas of electrons and lattice of neutron rich nuclei



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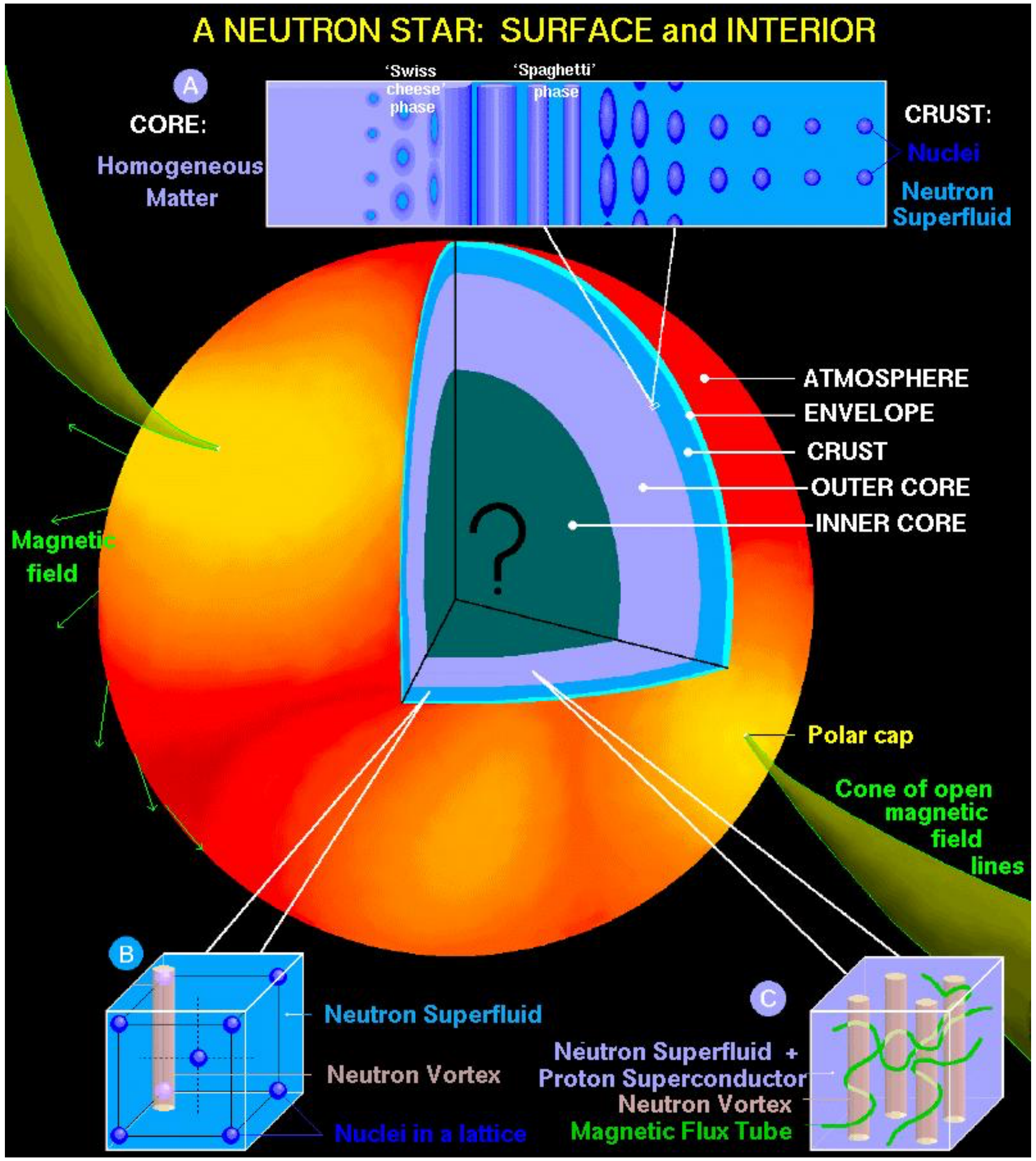
- Inner Crust

  thickness: ~1-2 km
  density: $\rho = 4 \cdot 10^{11} - 10^{14}$ g/cm^3
  composition: electron gas, neutron rich atomic nuclei and clusters and free neutrons



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 thickness: ~1-2 km
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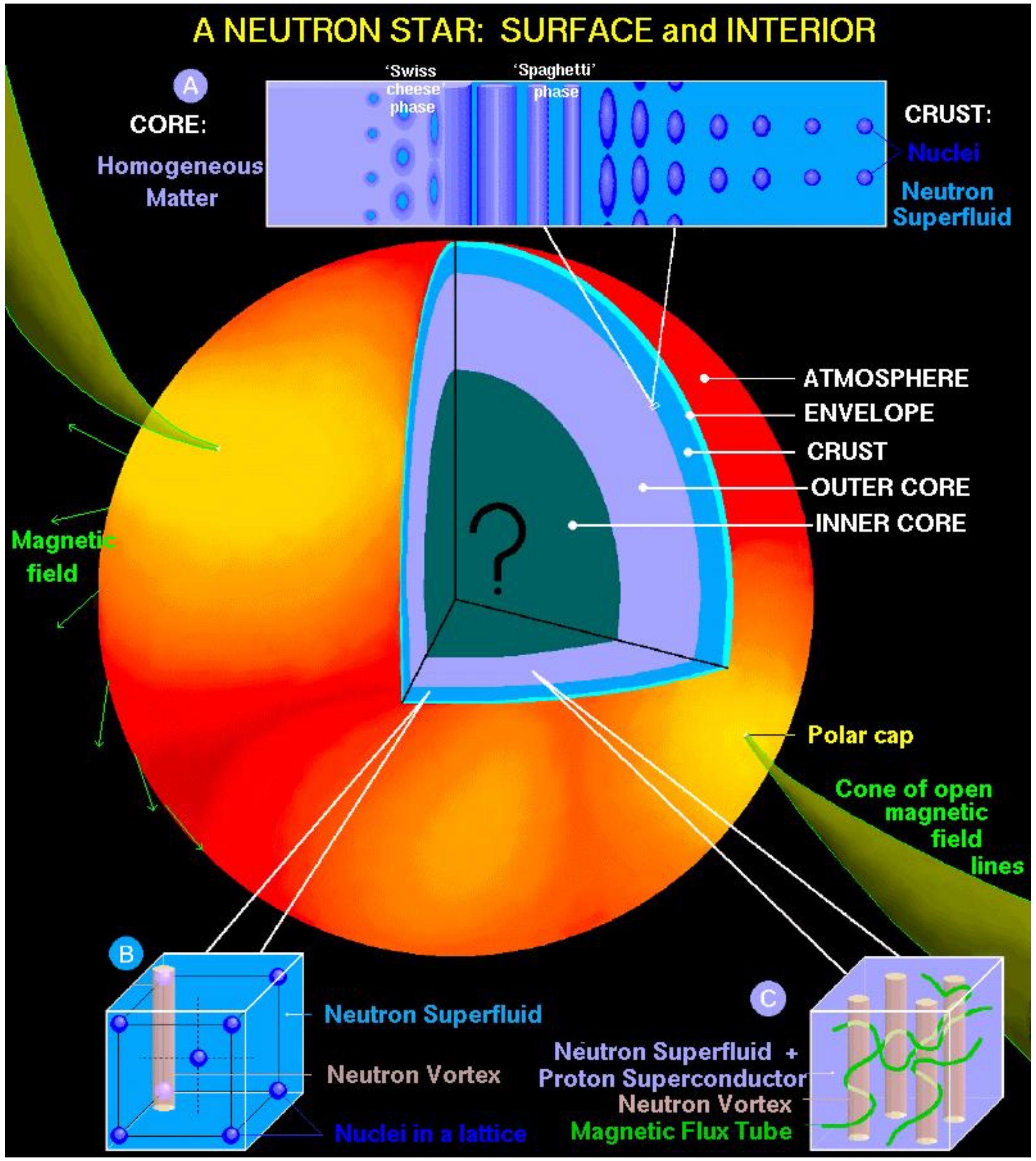
- Outer Core

 thickness: ??
 density: $\rho_0/2\text{-}2\rho_0$
 composition: free electrons, (superconducting) protons, (supefluid) neutron



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- Outer Crust/Envelope

  thickness: ~hundreds of m
  density: $\rho=10^4$-$4 \cdot 10^{11}$ g/cm^3 (neutron drip point)
  composition: Fermi gas of electrons and lattice of neutron rich nuclei

- Inner Crust

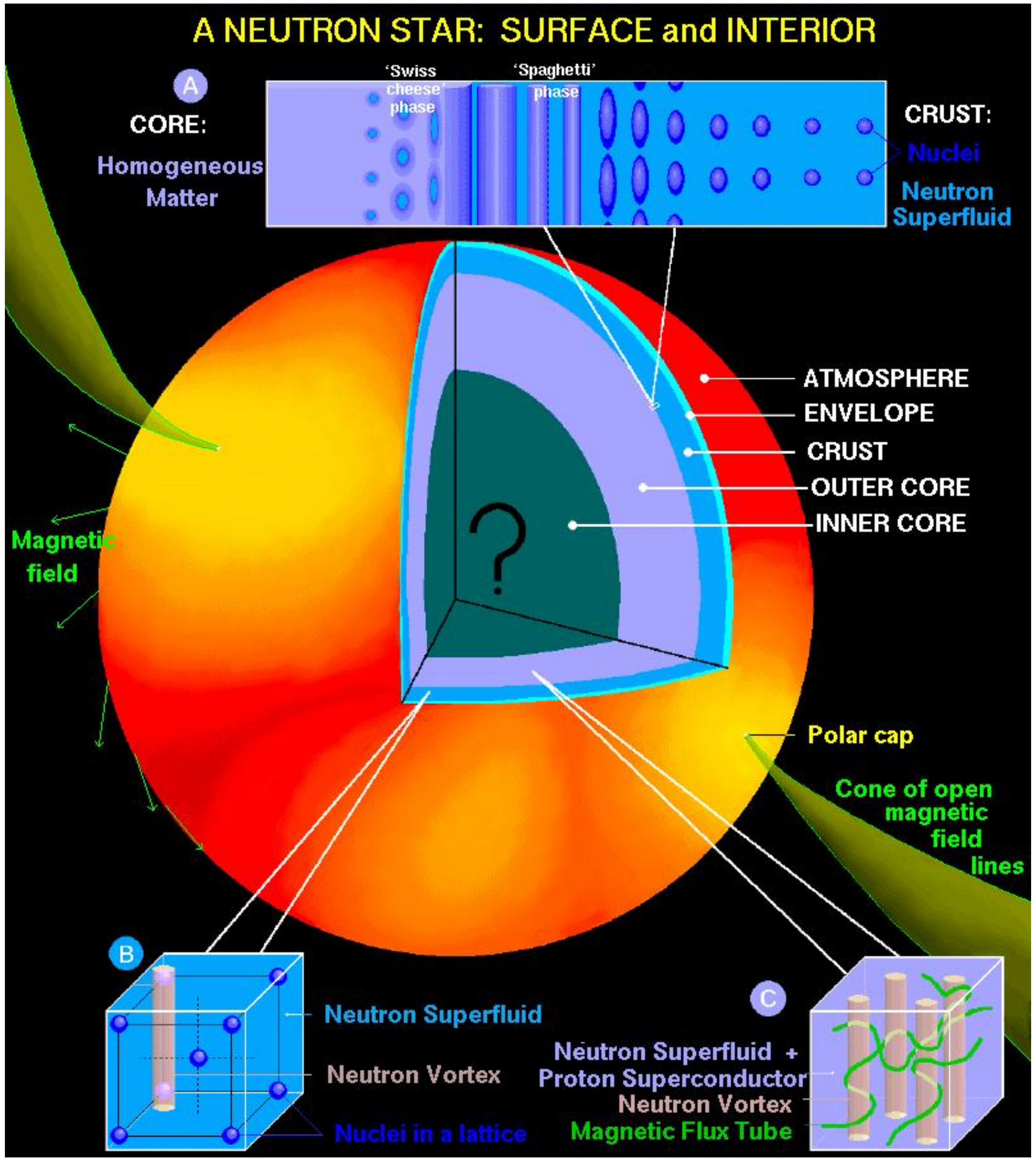
  thickness: ~1-2 km
  density: $\rho=4 \cdot 10^{11}$-10^{14} g/cm^3
  composition: electron gas, neutron rich atomic nuclei and clusters and free neutrons

- Outer Core

  thickness: ??
  density: $\rho_0/2$-$2\rho_0$
  composition: free electrons, (superconducting) protons, (supefluid) neutron

- Inner Core

  thickness: the rest
  density: 2-10 ρ_0 ??
  composition: exotic phases, quark core, color superconductive phases, meson condensation, other hadronic phases



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The Neutron Star EoS

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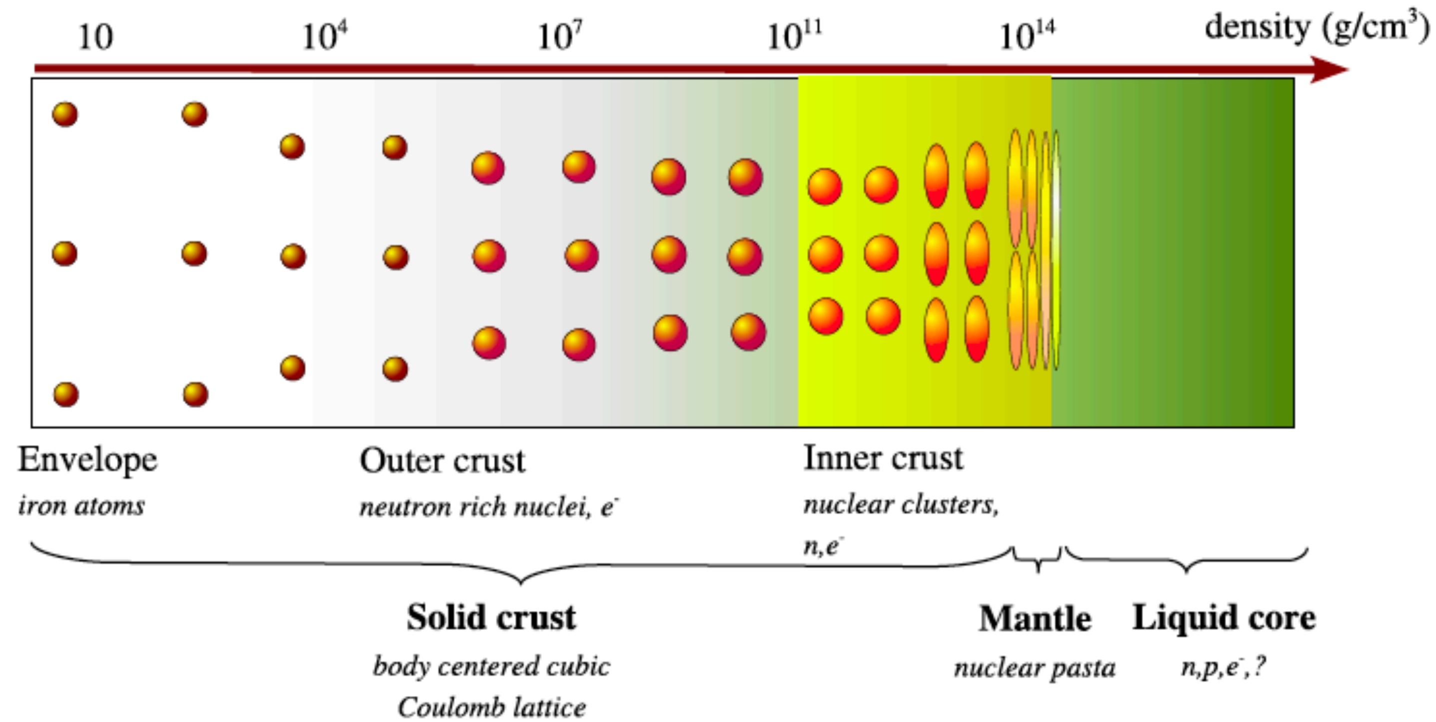

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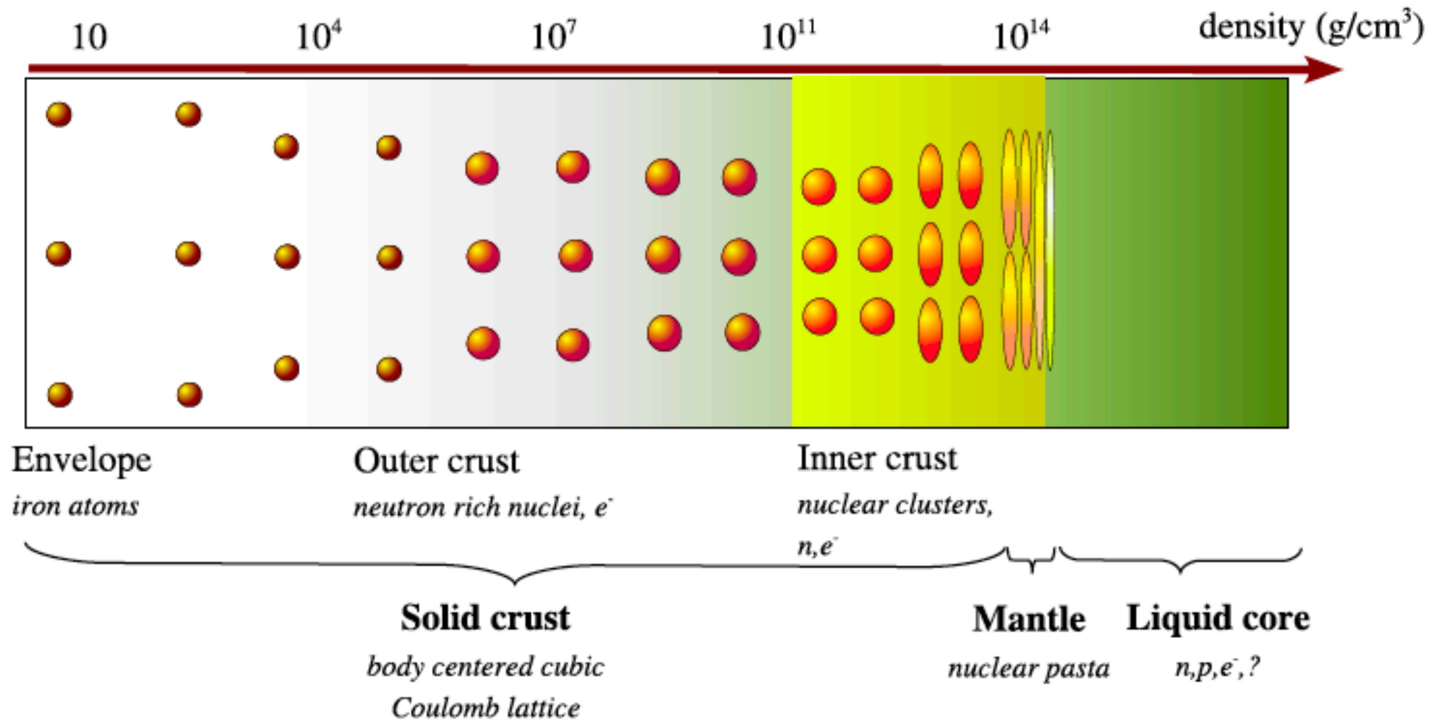

Outer Crust $\varepsilon_{\text{tot}} = n_{\text{N}} E\{A, Z\} + \varepsilon_e + \varepsilon_L$ $p_{\text{F}e} = \hbar(3\pi^2 n_e)^{1/3}$ $P = n_{\text{b}}^2 \frac{\text{d}}{\text{d}n_{\text{b}}} \left(\frac{\varepsilon_{\text{tot}}}{n_{\text{b}}} \right)$

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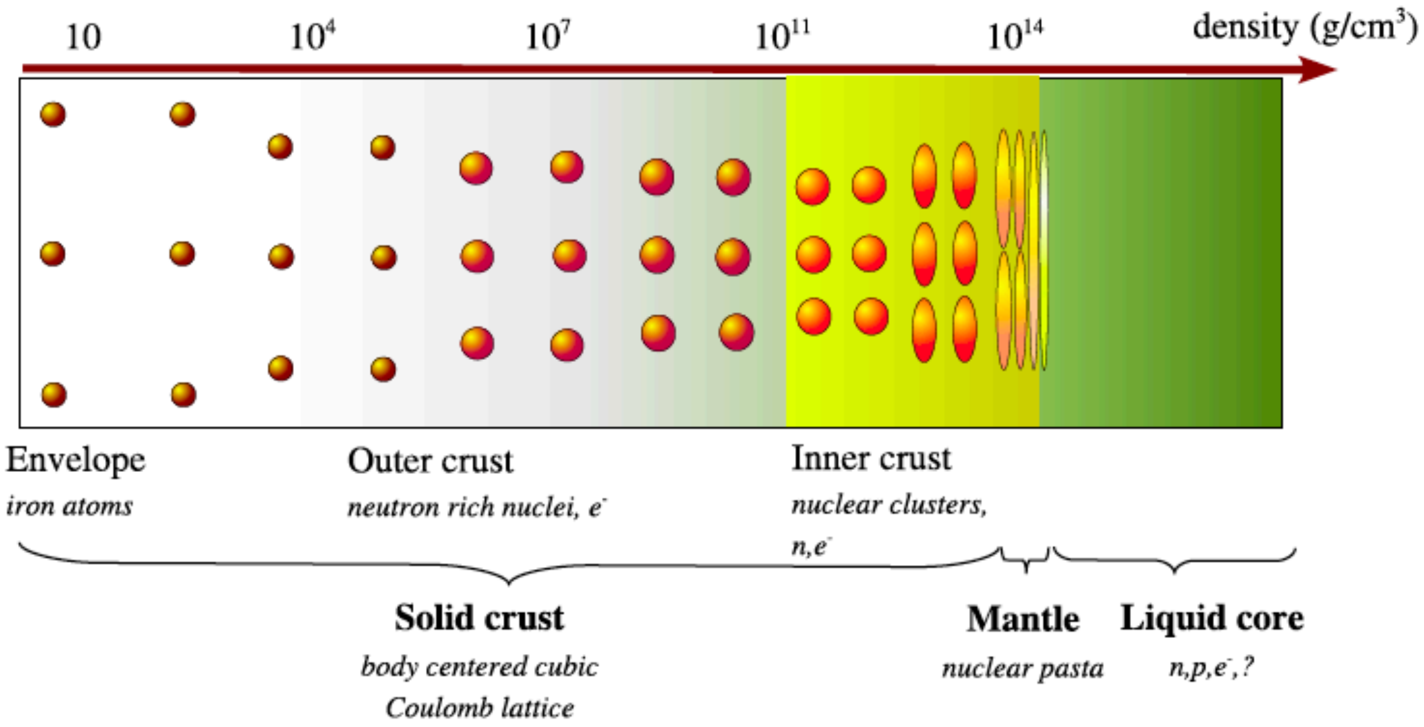

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Neutron drip point $\mu'_n \equiv \mu_n - m_n c^2 = \left(\frac{\partial E\{A,Z\}}{\partial N}\right)_Z - m_n c^2$

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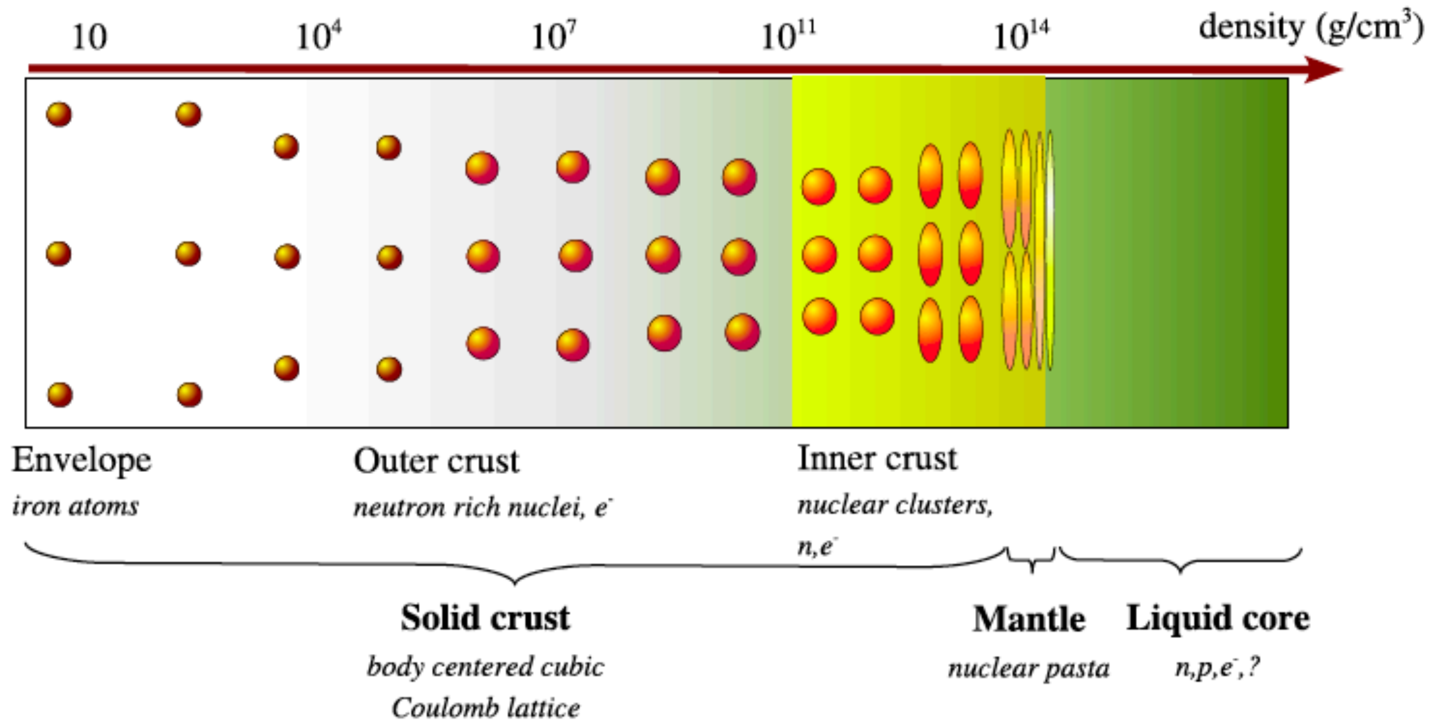

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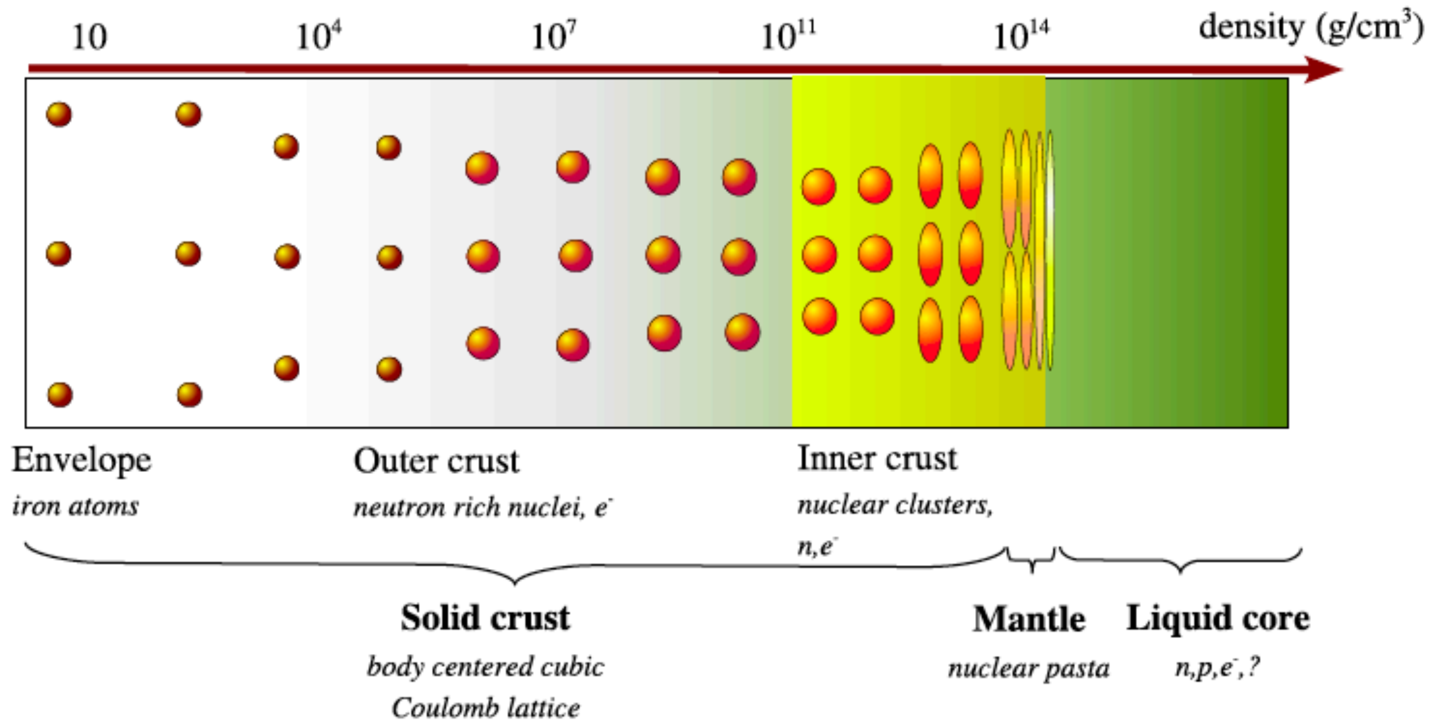

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Inner Crust $\varepsilon_{\rm tot} = n_{\rm N} E\{A,Z\} + \varepsilon_e + \varepsilon_L + \varepsilon_n$ pasta phases

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Outer Core: weak equilibration

$$n \to p + e^- + \bar{\nu_e}$$
$$p + e^- \to n + \nu_e$$

direct Urca process

The Neutron Star EoS

Outer Core: weak equilibration

$$n + n \rightarrow p + e^- + \bar{\nu_e} + n$$
$$n + p + e^- \rightarrow n + \nu_e + n$$

modified Urca process

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neutron decay inside neutron star

$$n \rightarrow \chi + \phi$$

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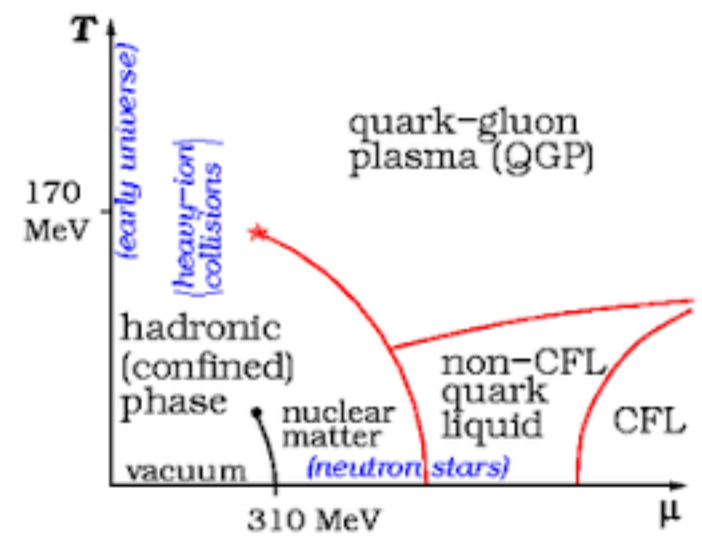
Inner Core: potential exotic quark phases



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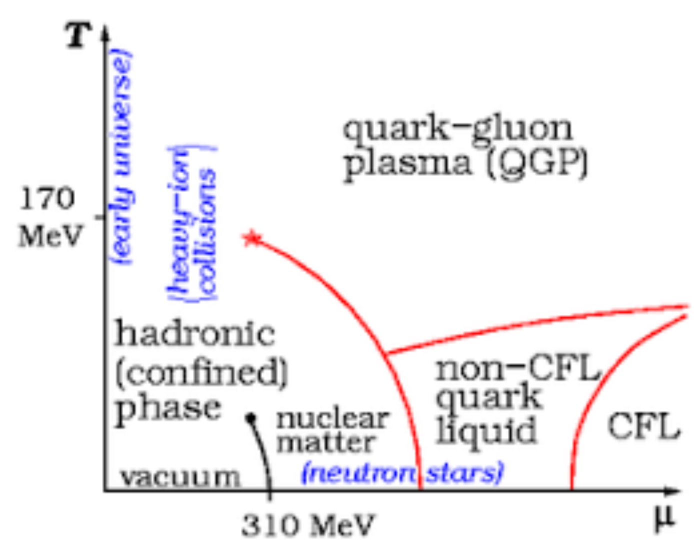

EoS are constrained by mass-radius relations, GW
EoS+ Tolman Oppenheimer Volkoff

$$\frac{dP}{dr} = -\frac{GM\rho}{r^2} \frac{\left[1 + \frac{P}{\rho}\right]\left[1 + \frac{4\pi r^3 P}{M}\right]}{\left[1 - \frac{2GM}{r}\right]}$$

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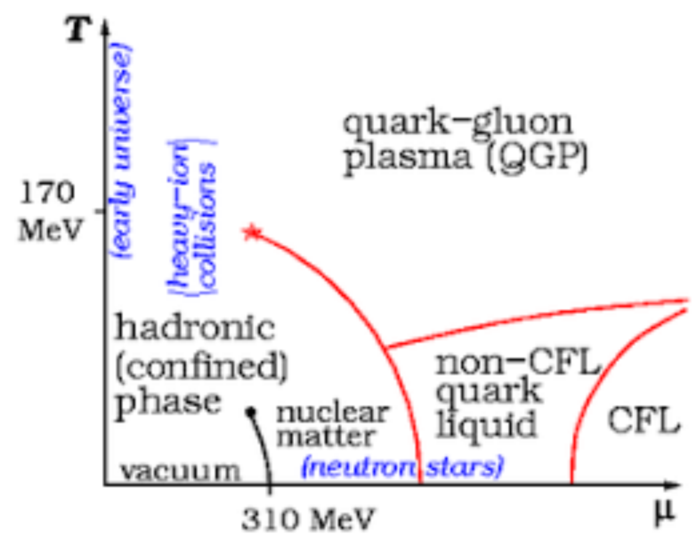

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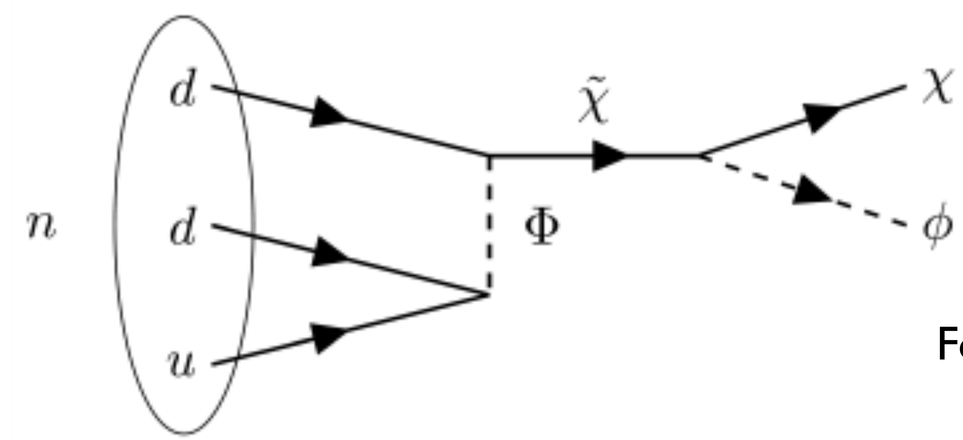
Neutron Anomalous Decay

$$\mathcal{L} = \lambda_q \, \epsilon^{ijk} \, \overline{u^c_{L}}_i \, d_{Rj} \Phi_k + \lambda_\chi \Phi^{*i} \bar{\tilde{\chi}} \, d_{Ri} + \lambda_\phi \, \bar{\tilde{\chi}} \, \chi \, \phi$$



Fornal Grinstein '18

Energy density

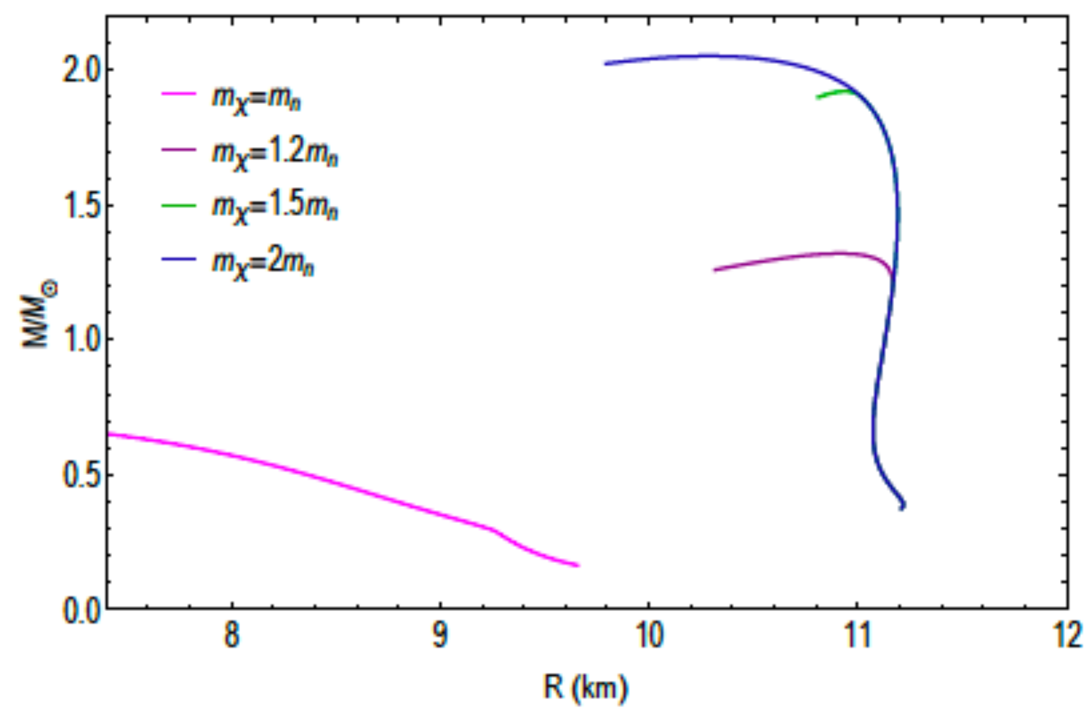
$$\varepsilon(n_n, n_\chi) = \varepsilon_{\rm nuc}(n_n) + \varepsilon_\chi(n_\chi)$$

chemical equilibrium

$$\Delta E \equiv \frac{\partial \varepsilon(n_{\rm F} - n_\chi, n_\chi)}{\partial n_\chi} = \mu_\chi(n_\chi) - \mu_{\rm nuc}(n_n)$$

Neutron Anomalous Decay & Neutron Stars

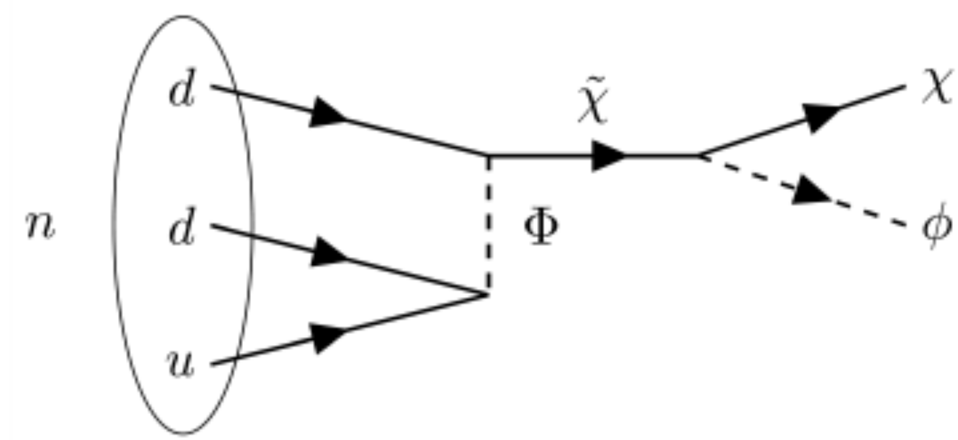
Using typical EoS for nuclear matter and the TOV equation, one can get the mass-radius relation of a NS with chemical equilibrium between DM and neutrons



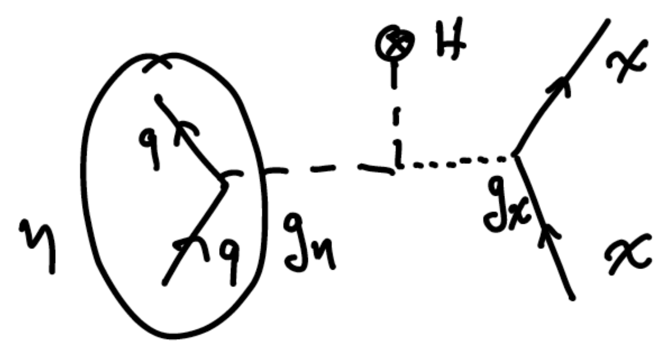
Baym, Beck, Geltenbort, Shelton ‘18

Baryon-DM Interactions via the Higgs Portal

$$\mathcal{L} = \lambda_q \, \epsilon^{ijk} \, \overline{u^c_{L i}} \, d_{Rj} \Phi_k + \lambda_\chi \Phi^{*i} \bar{\tilde{\chi}} \, d_{Ri} + \lambda_\phi \, \bar{\tilde{\chi}} \, \chi \, \phi \, + \mu H^\dagger H \phi + g_\chi \bar{\chi} \chi \, \phi + \text{h.c.}$$



The Higgs portal induces neutron-DM interactions



$$g_n = \frac{\mu \sigma_{\pi n}}{m_h^2} \qquad \sigma_{\pi n} \;=\; \textstyle\sum_q \langle n | m_q \bar{q} q | n \rangle \approx 370 \text{ MeV}$$

Baryon-DM Interactions via the Higgs Portal

Energy density

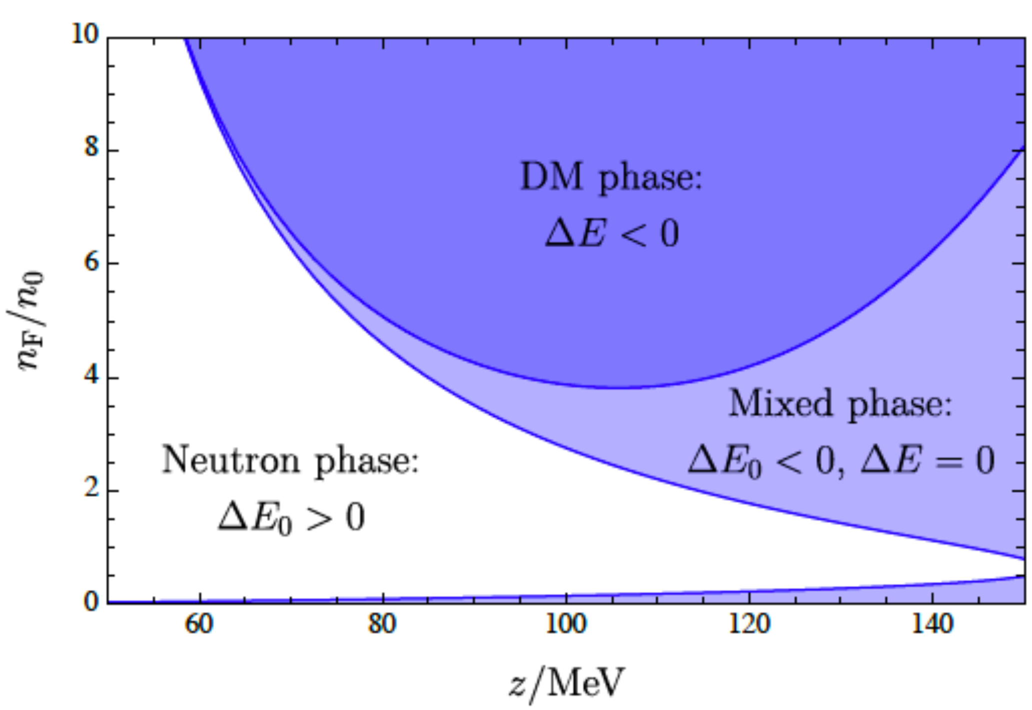
$$\varepsilon(n_n, n_\chi) = \varepsilon_{\rm nuc}(n_n) + \varepsilon_\chi(n_\chi) + \frac{n_\chi n_n}{z^2}$$

$$z \equiv m_\phi / \sqrt{|g_\chi g_n|}$$

$$V_Y = \frac{g_\chi g_n}{4\pi} \frac{e^{-m_\phi r}}{r} \qquad \varepsilon_Y = \frac{g_\chi g_n}{4\pi} n_\chi n_n \int_0^R \frac{e^{-m_\phi r}}{r} 4\pi r^2 dr \simeq \frac{g_\chi g_n n_\chi n_n}{m_\phi^2} = \frac{n_\chi n_n}{z^2}$$

chemical equilibrium

$$\Delta E \equiv \frac{\partial \varepsilon(n_{\rm F} - n_\chi, n_\chi)}{\partial n_\chi} = \mu_\chi(n_\chi) - \mu_{\rm nuc}(n_n) + \frac{n_{\rm F} - 2n_\chi}{z^2}$$



$g_\chi \lesssim 4 \times 10^{-4}$ DM Self-Interactions constraints

$g_n \sim -10^{-14}$ Constraints from rapid cooling of stars

$m_\phi \sim 0.1\ {\rm eV}$

Grinstein Nielsen CK PRL '19

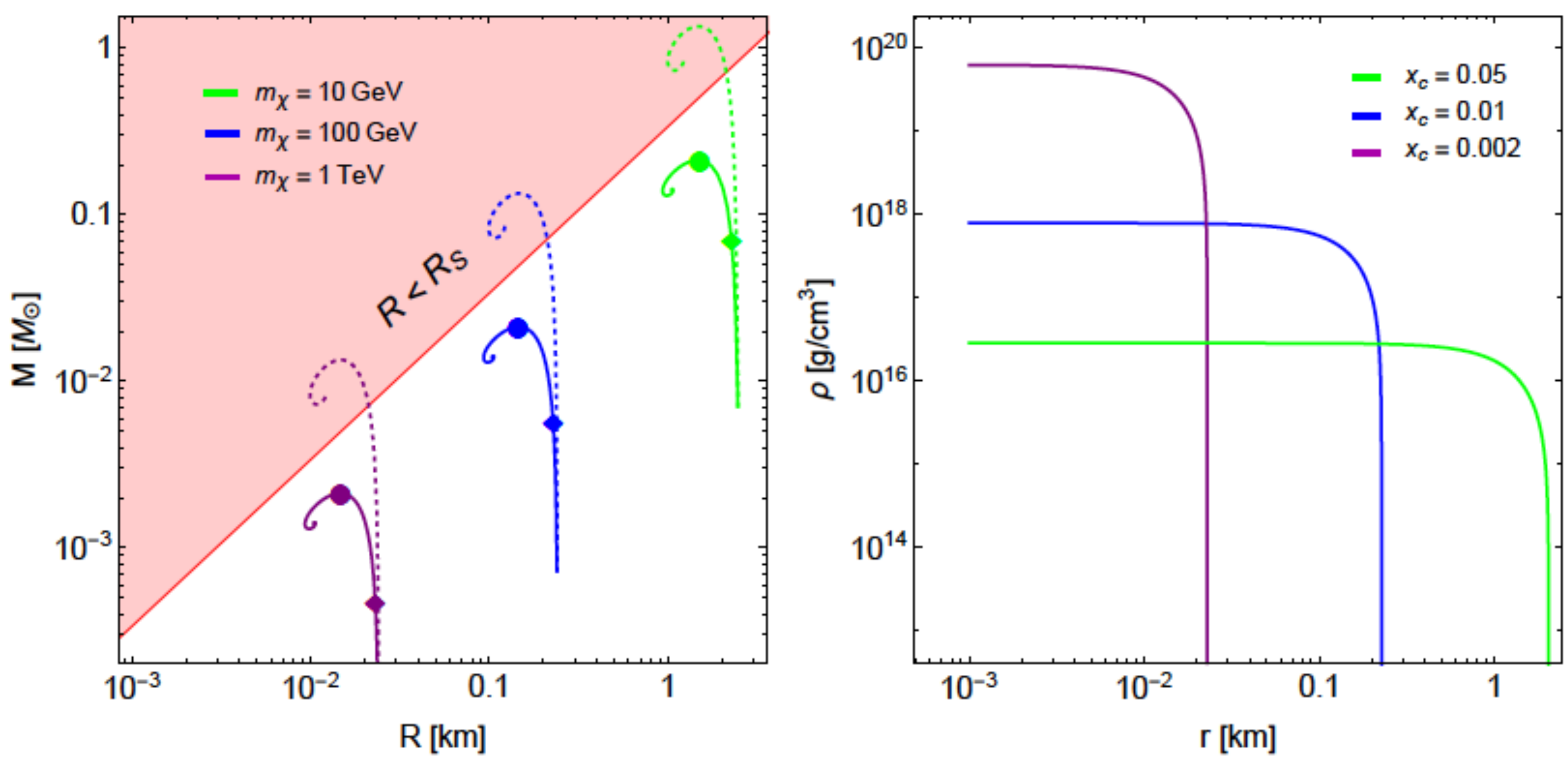
Asymmetric Fermionic Dark Stars

Tolman-Oppenheimer-Volkoff with Yukawa self-interactions

$$P = \frac{g_s}{2} m_\chi^4 \psi(x) \pm \frac{\alpha g_s^2}{18\pi^3} \frac{m_\chi^6}{\mu^2} x^6,$$

$$\rho = \frac{g_s}{2} m_\chi^4 \xi(x) \pm \frac{\alpha g_s^2}{18\pi^3} \frac{m_\chi^6}{\mu^2} x^6.$$

$$\frac{dP}{dr} = -\frac{GM\rho}{r^2} \frac{\left[1 + \frac{P}{\rho}\right]\left[1 + \frac{4\pi r^3 P}{M}\right]}{\left[1 - \frac{2GM}{r}\right]}$$

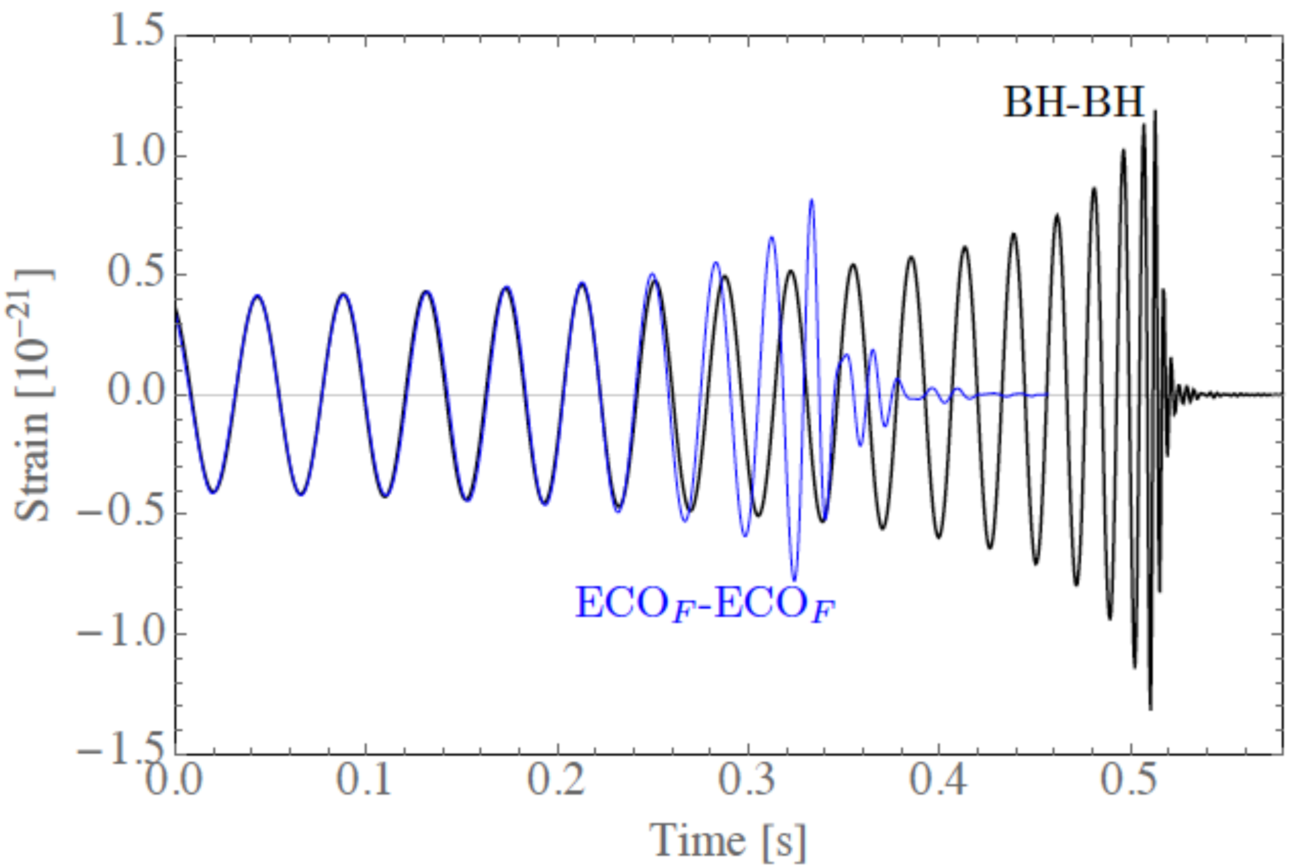


(a) $M(R)$ for repulsive interactions

(b) $\rho(r)$ for repulsive interactions

CK, Nielsen '15

Gravitational Waves from Dark Stars



Giudice, McCullough, Urbano '16

Observation

- Gravitational Waves:
- DS+DS->DS or BH
- DS+NS-> DS*
- DS+BH->BH
- Spinning DS

Tidal Deformations of Dark Stars

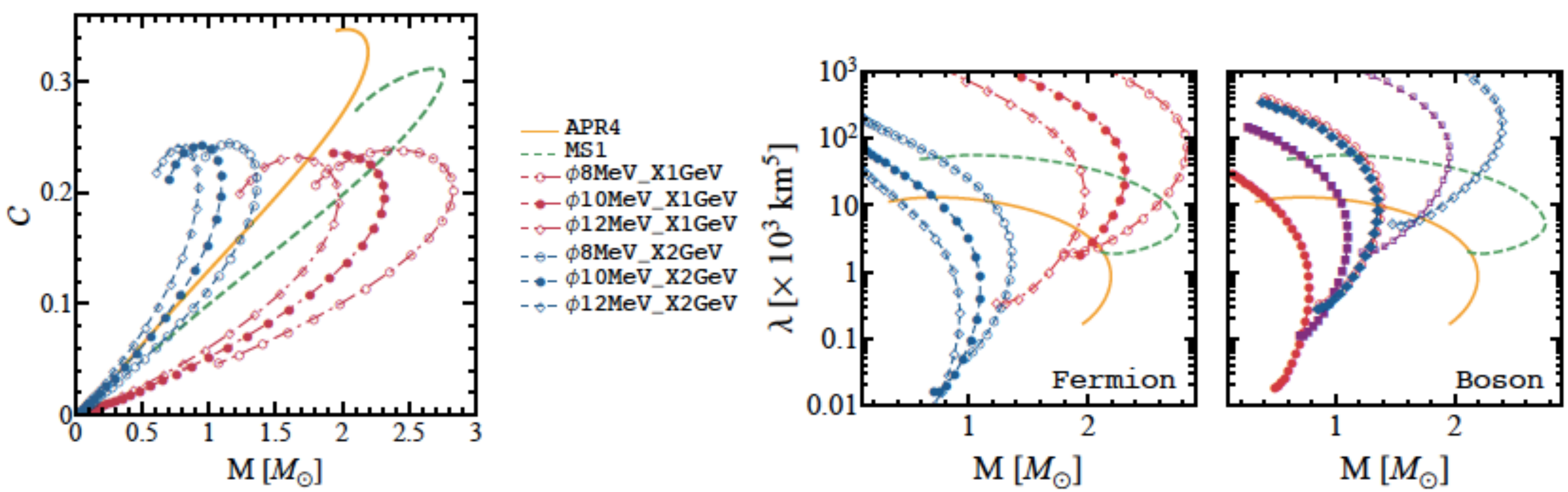
How stars deform in the presence of an external gravitational field?

$$V = -(1/2)\varepsilon_{ij} x^i x^j$$

$$Q_{ij} = -\lambda \varepsilon_{ij}$$

$$\lambda = \frac{2}{3} k_2 R^5$$

Love number



Maselli, Pnigouras,Nielsen,
CK, Kokkotas, 17

Conclusions

Neutron Decay Anomaly

- if this persists, deviation from SM
- strong constraints from NS
- most likely a subdominant component of DM

Asymmetric Dark Stars

- can be probed by gravitational waves
- New Dark Stars distinguishable from NS and BH binaries
- Interesting new binary mergers