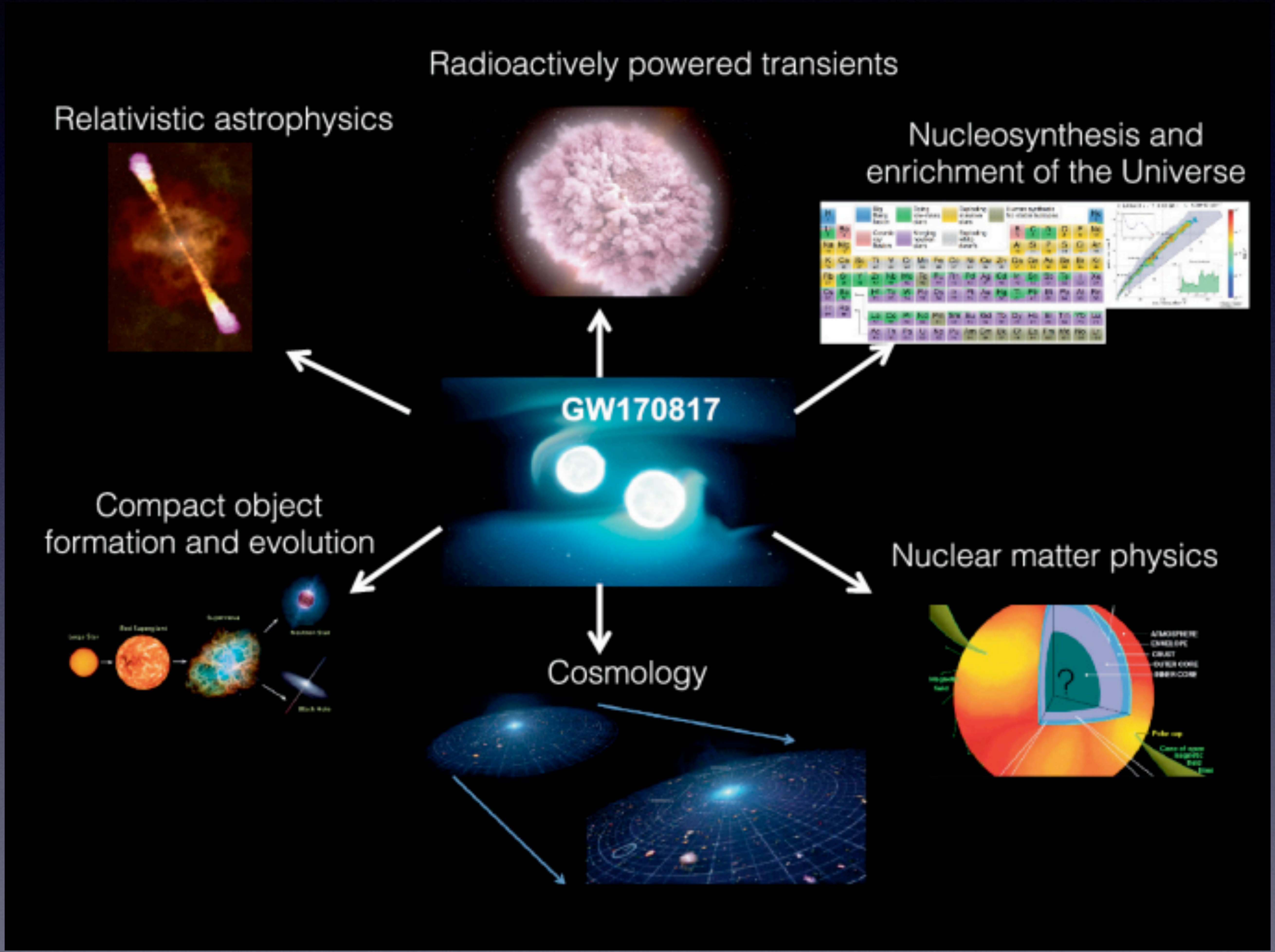
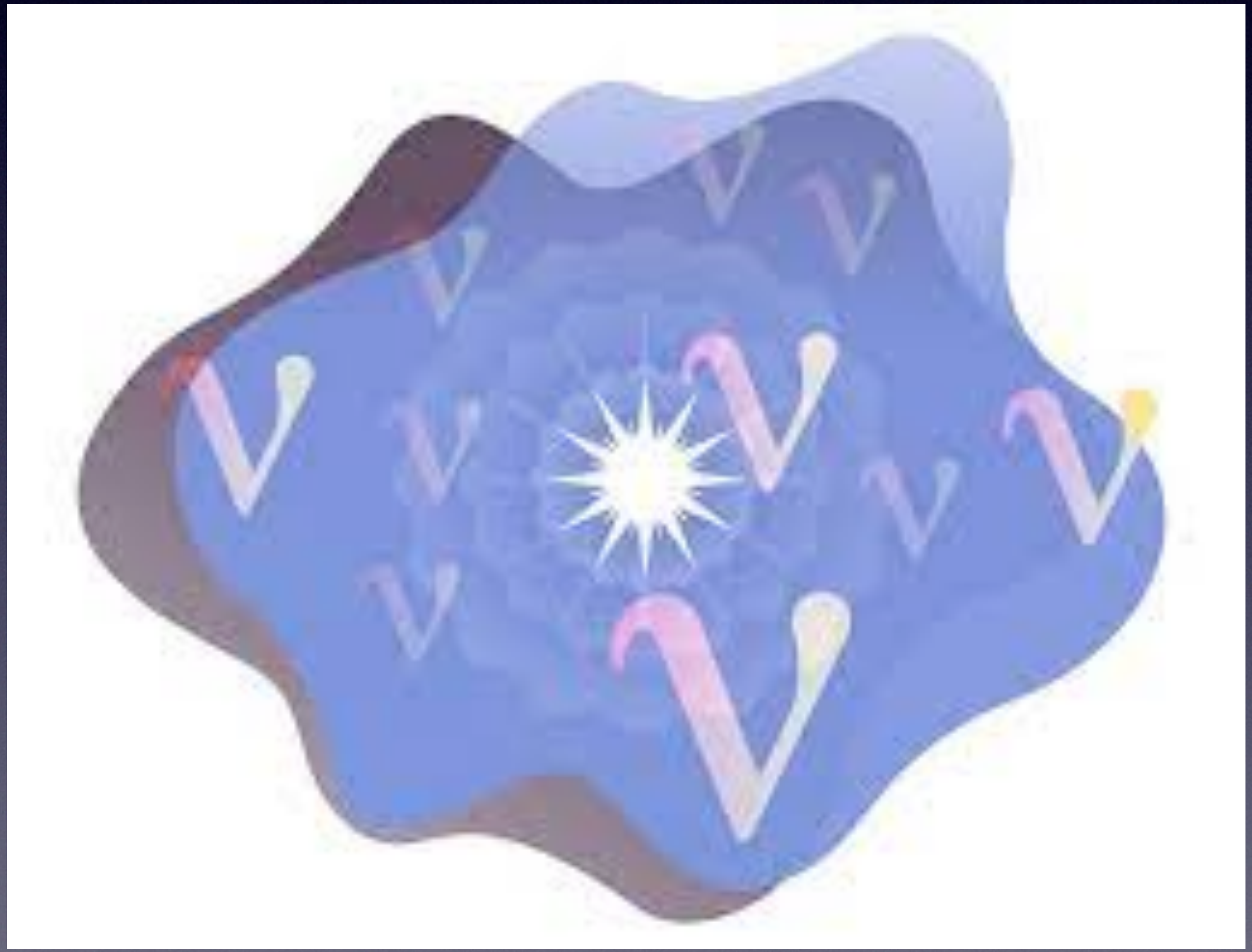
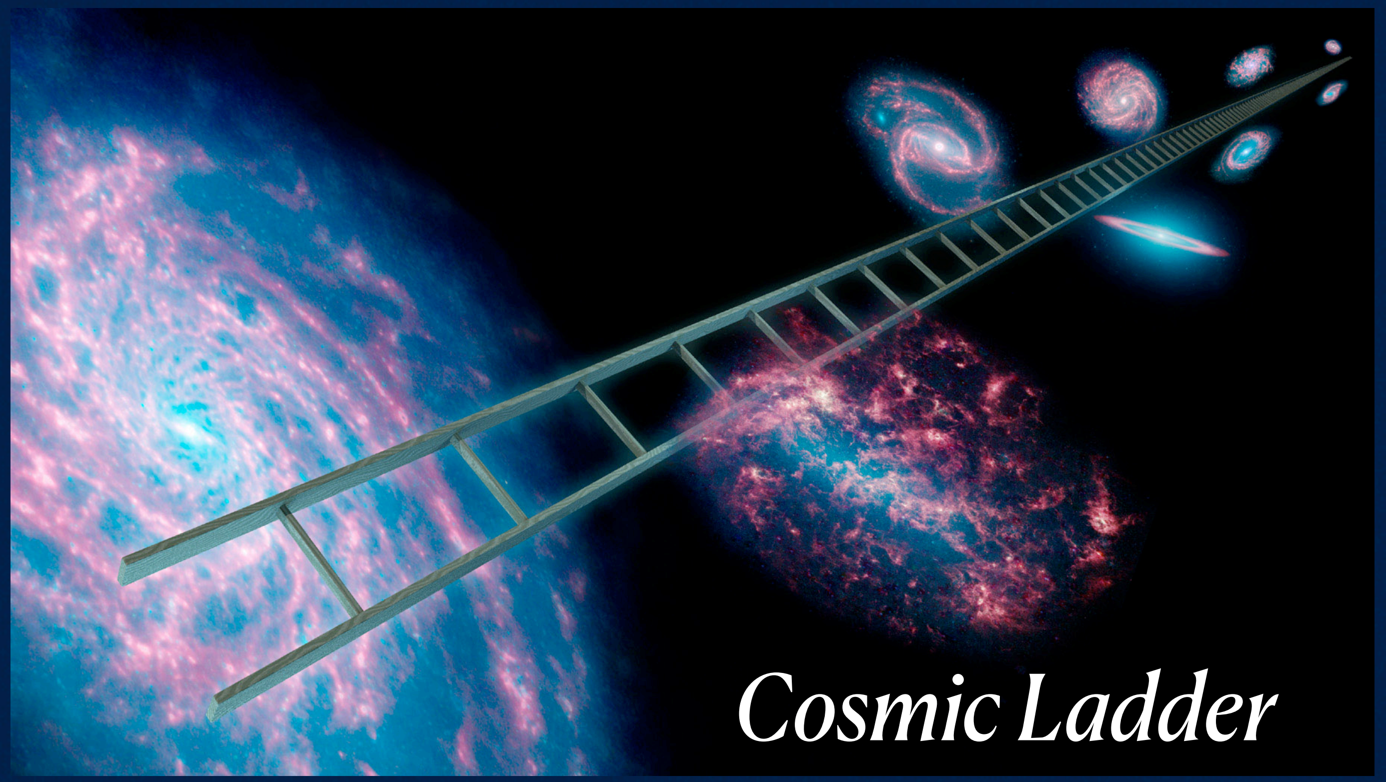
The Beginning of a New Era:
Multi-messenger Astronomy

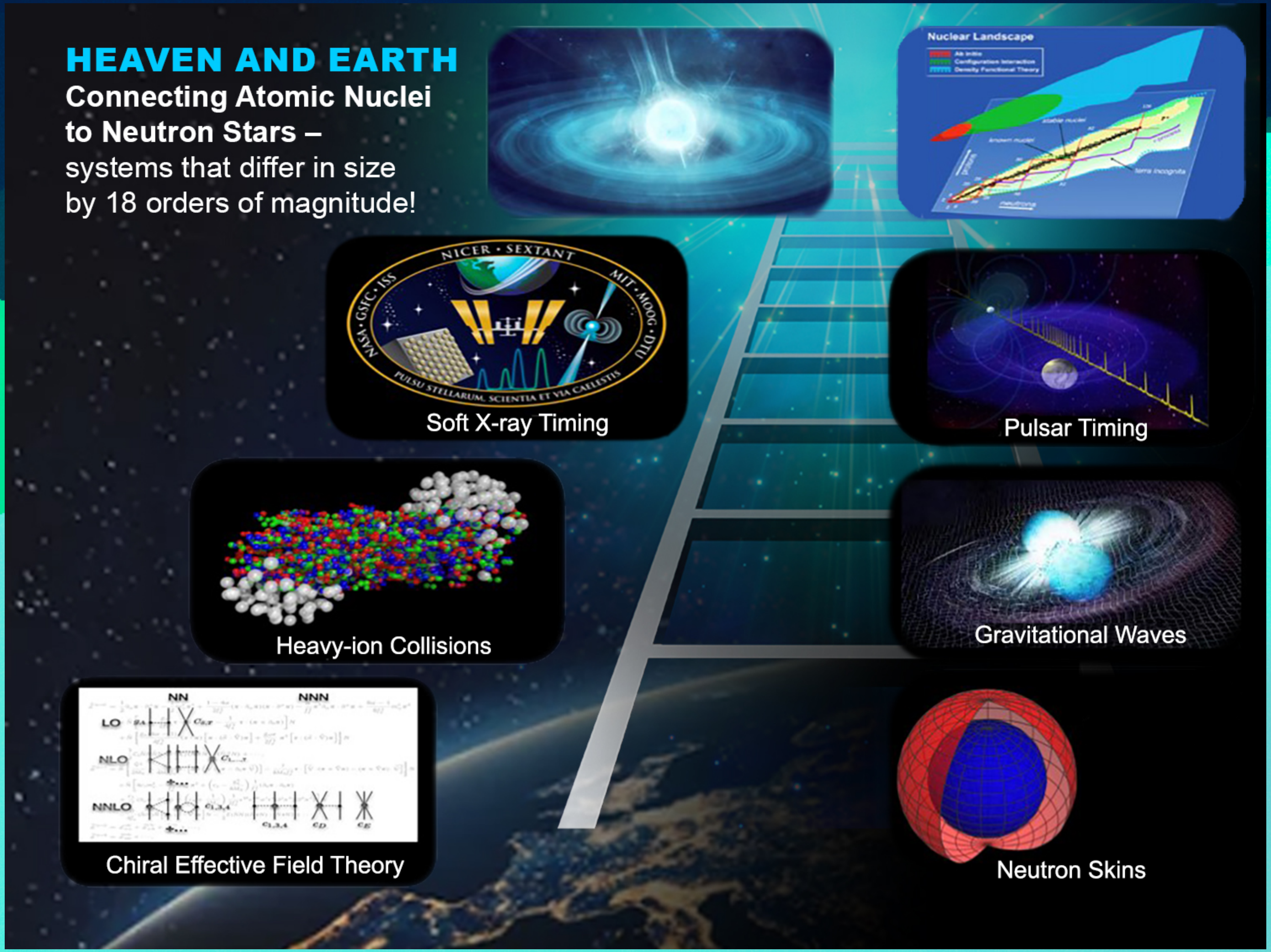




Heaven and Earth: Nuclear EOS Density Ladder

No single method can constrain the EOS over the entire density domain. Instead, each rung on the ladder provides information that can be used to determine the **EOS** at neighboring rungs

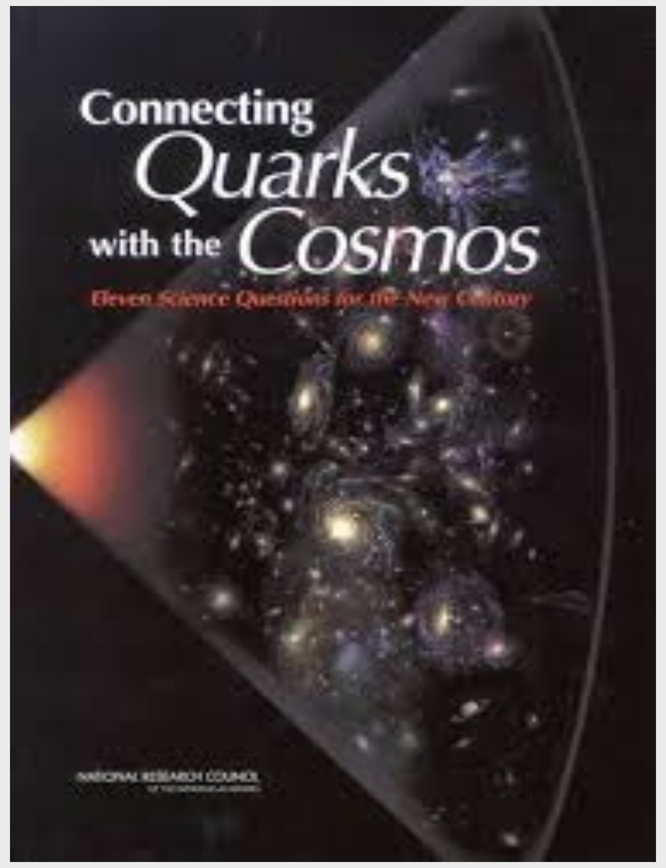




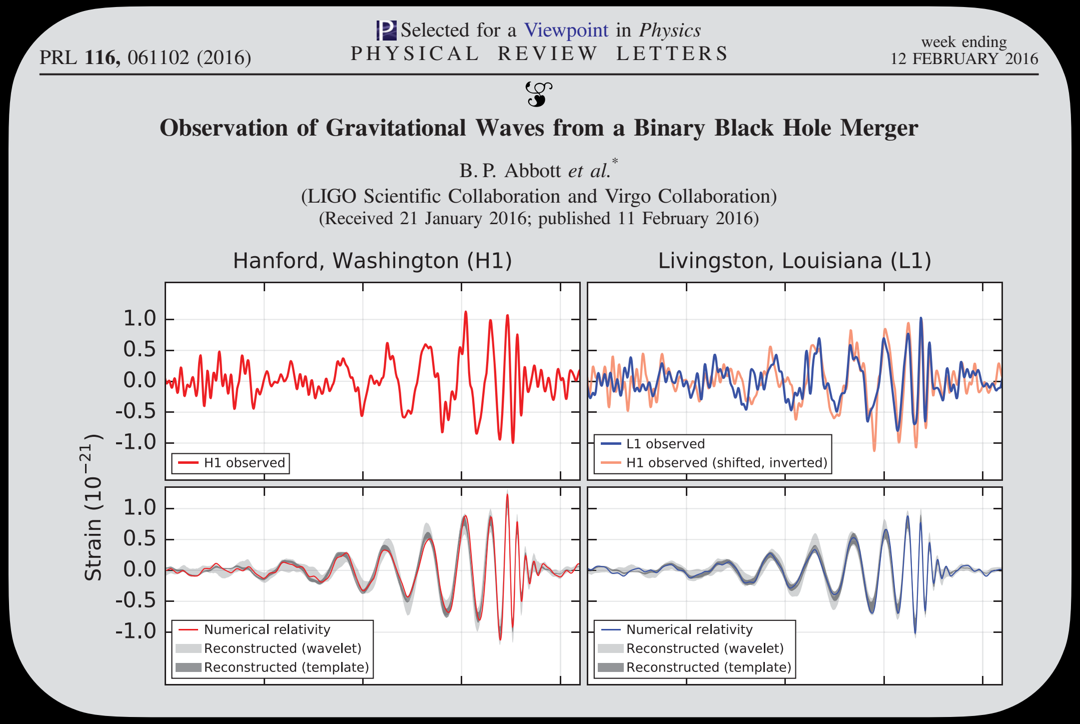
The Nuclear Physics of Neutron Stars

How were the heavy elements from iron to uranium made?

Are there new states of matter at ultrahigh temperatures and densities?

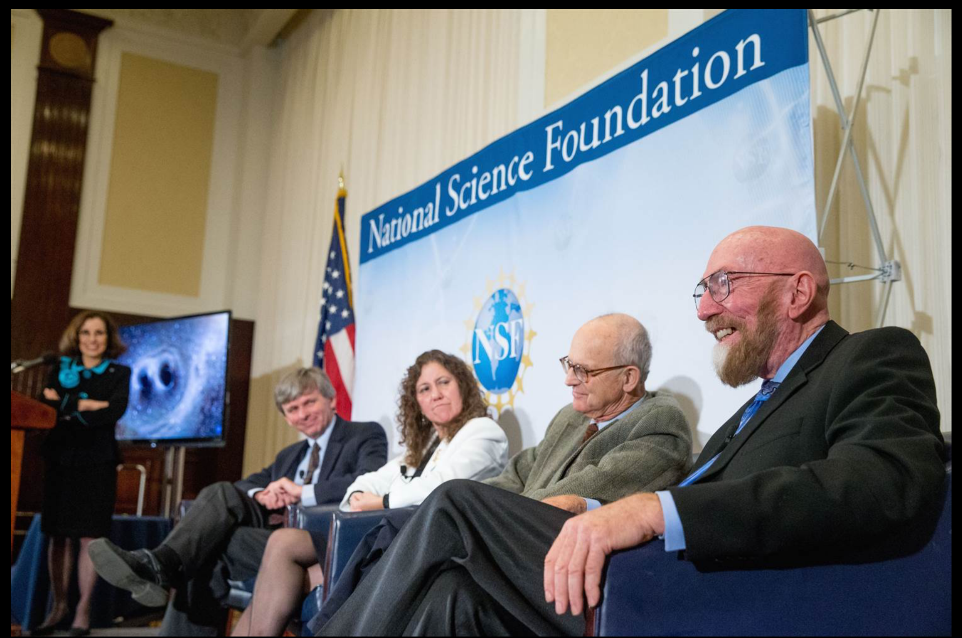


GW150914: The Dawn of Gravitational Wave Astronomy


Selected for a Viewpoint in *Physics*
PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

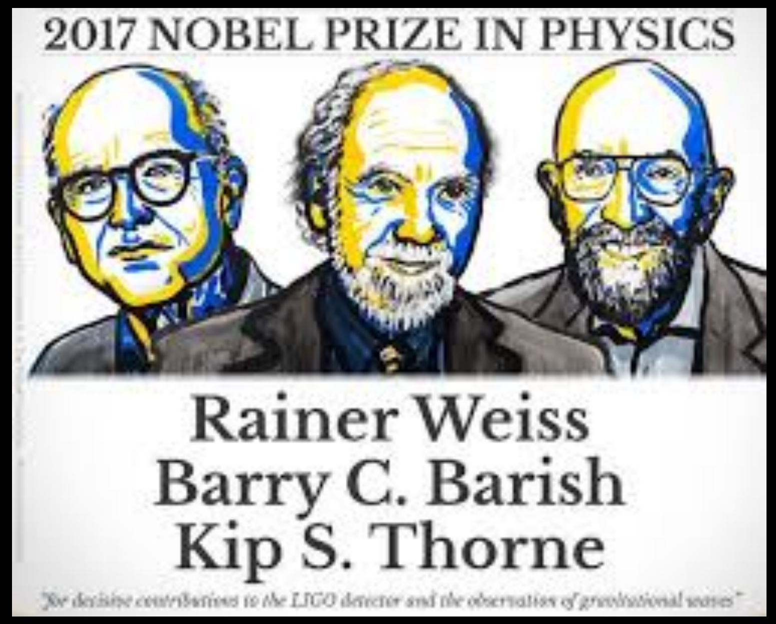
Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

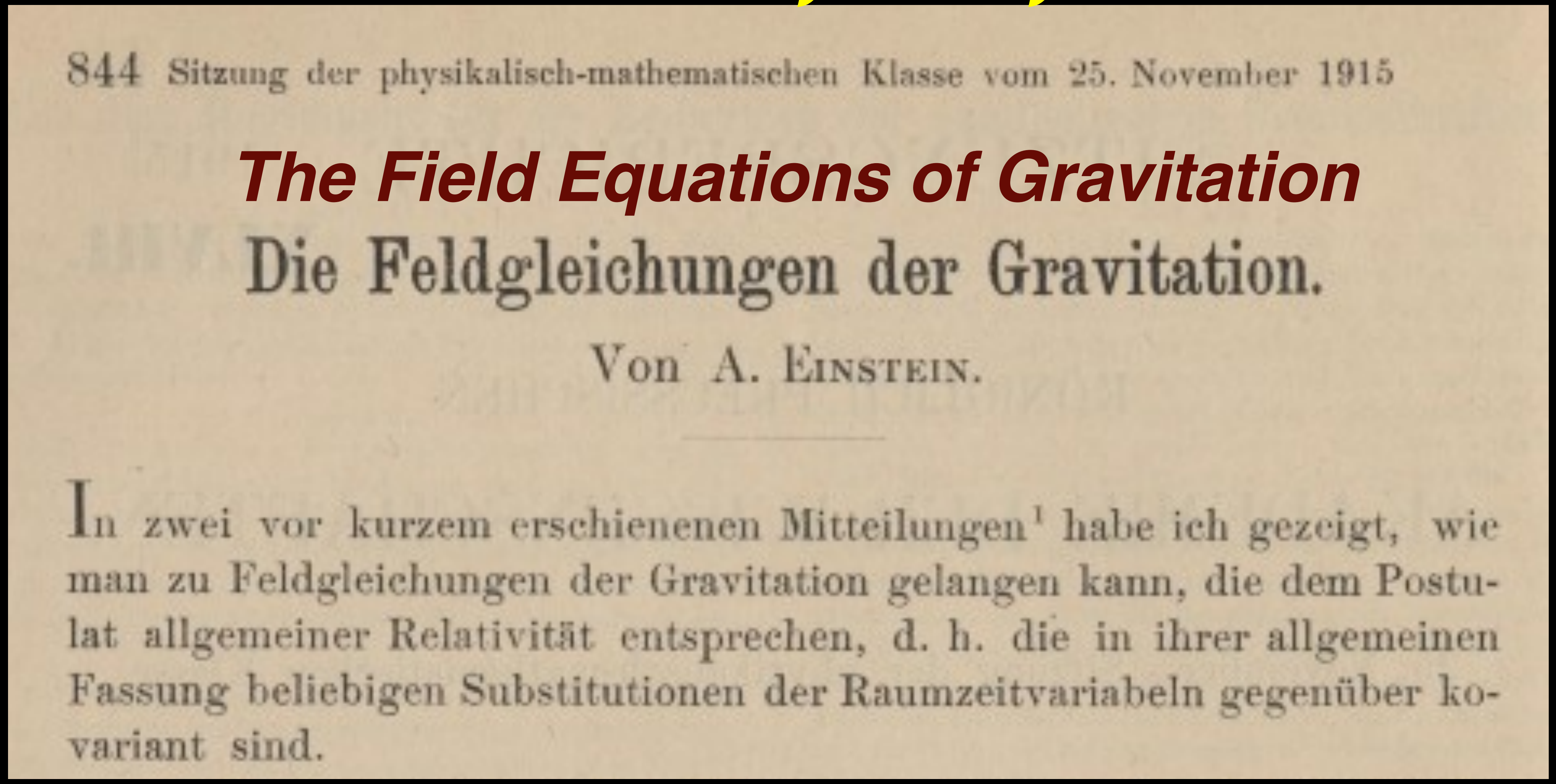


We have detected gravitational waves; we did it

Initial black hole masses: 36 and 29 solar masses
Final black hole mass: 62 solar masses
3 solar masses radiated in Gravitational Waves!



It took exactly 100 years!

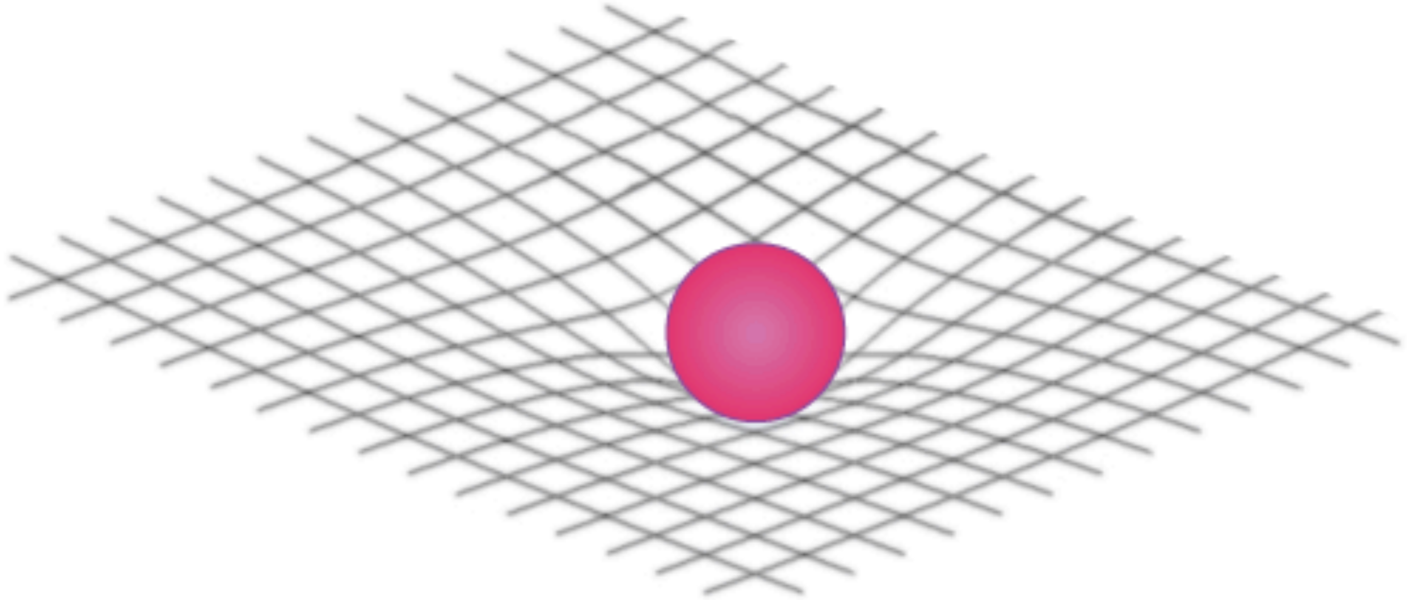

844 Sitzung der physikalisch-mathematischen Klasse vom 25. November 1915

The Field Equations of Gravitation

Die Feldgleichungen der Gravitation.

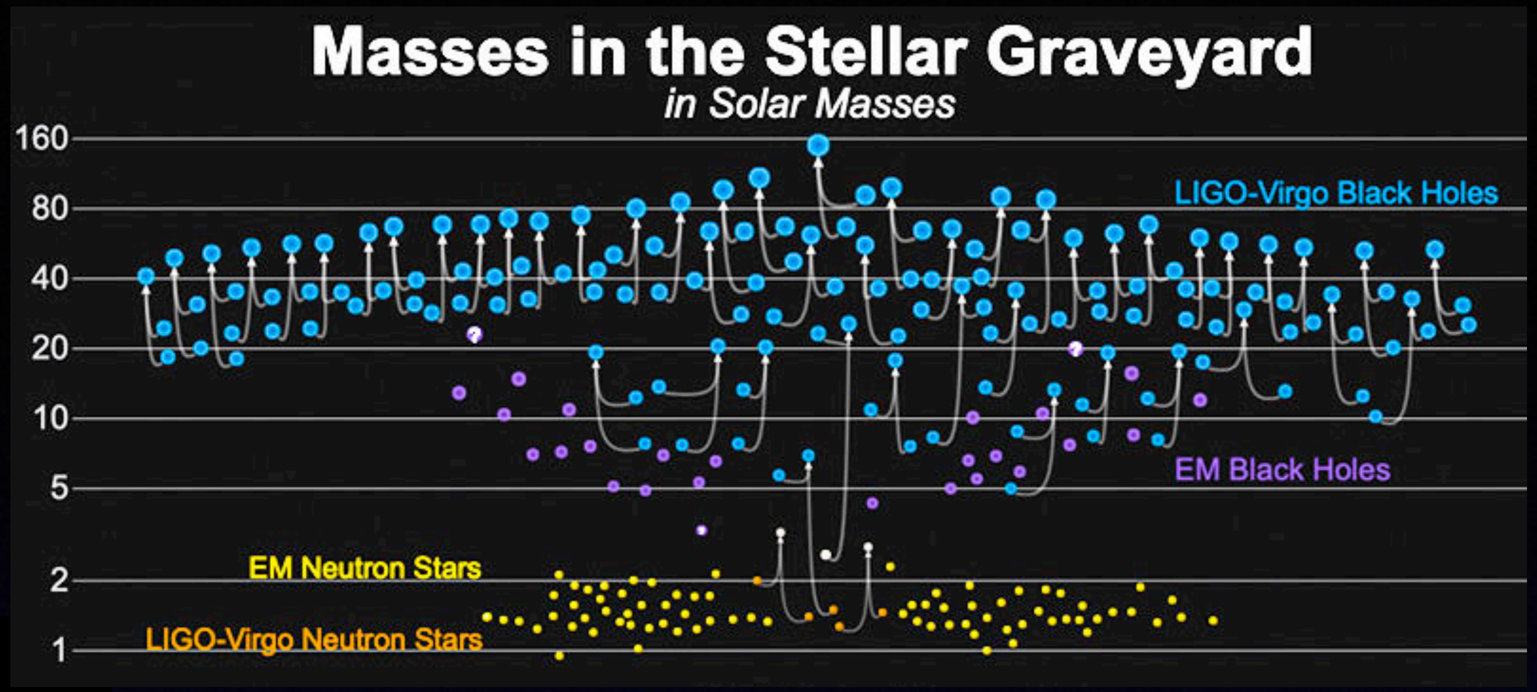
Von A. Einstein.

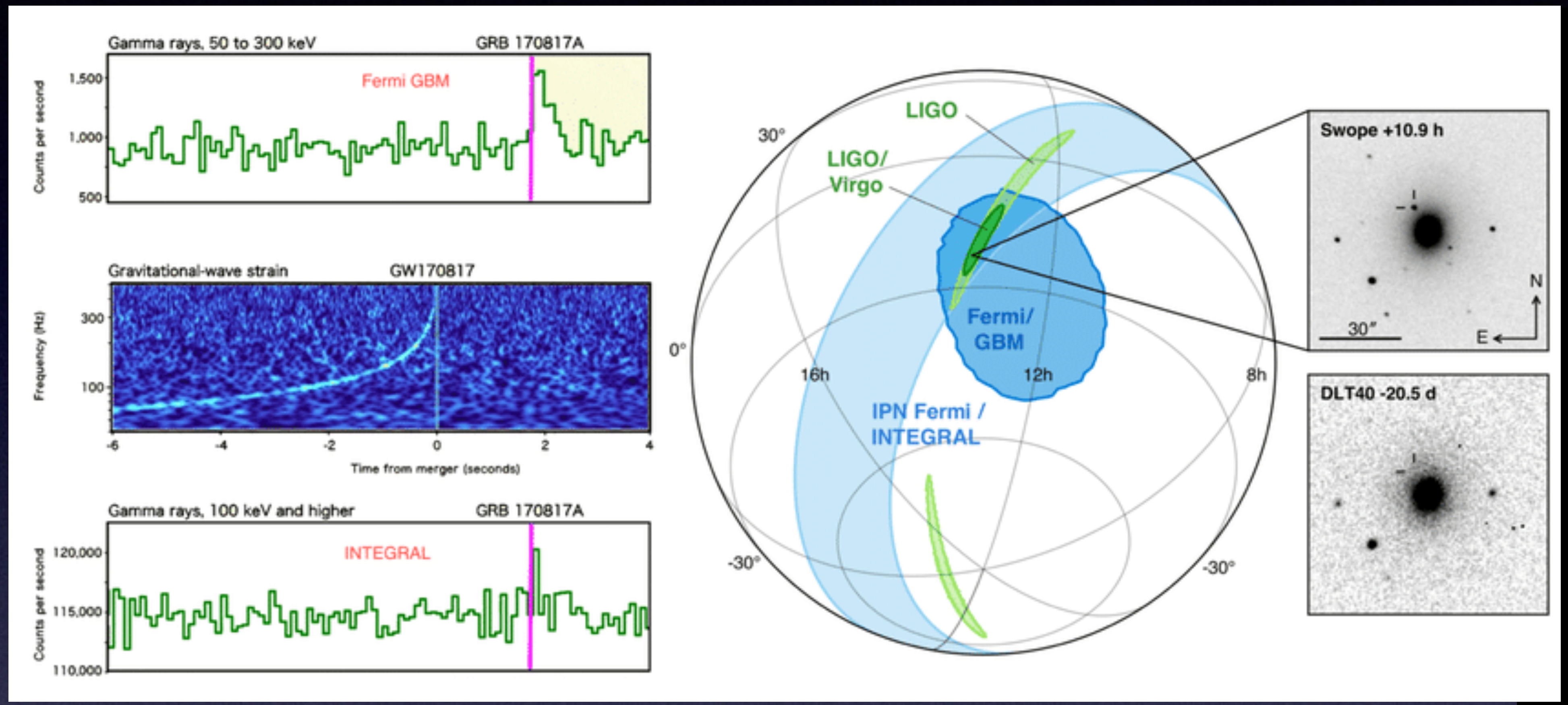
In zwei vor kurzem erschienenen Mitteilungen[1] habe ich gezeigt, wie man zu Feldgleichungen der Gravitation gelangen kann, die dem Postulat allgemeiner Relativität entsprechen, d. h. die in ihrer allgemeinen Fassung beliebigen Substitutionen der Raumzeitvariabeln gegenüber kovariant sind.



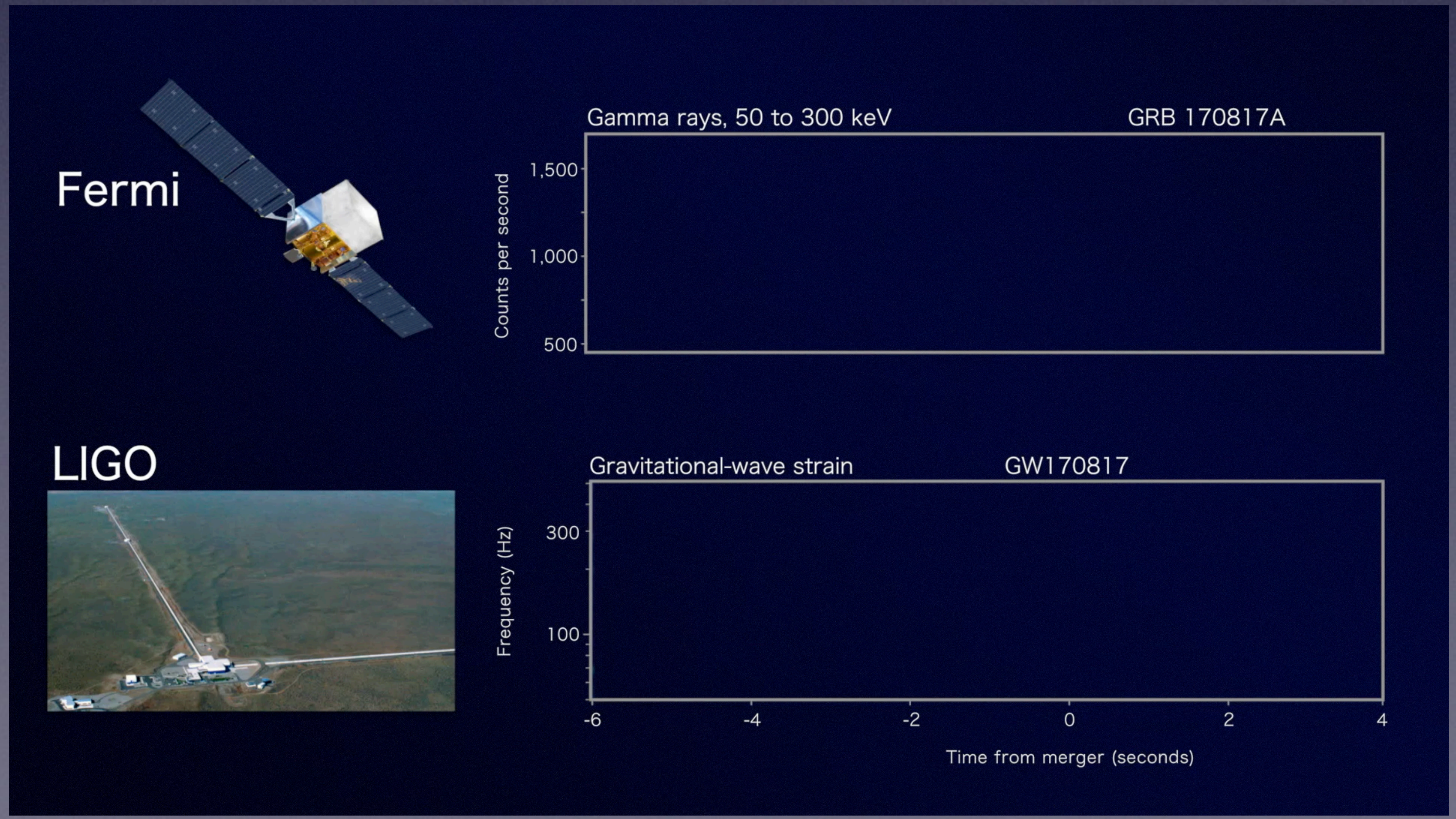
$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

GW170817: The Beginning of the Multi-messenger Era

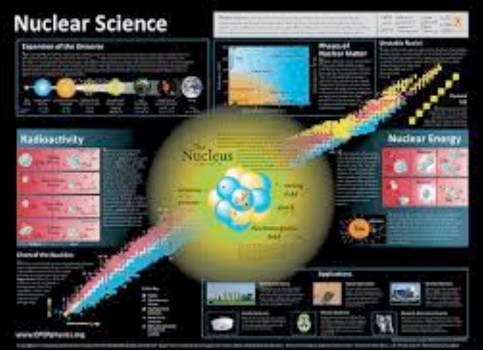




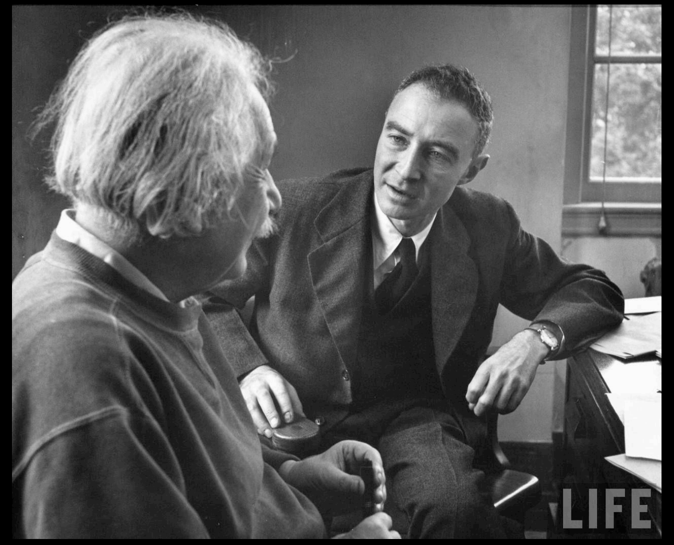
GW170817



Neutron Stars: The Role of Nuclear Science

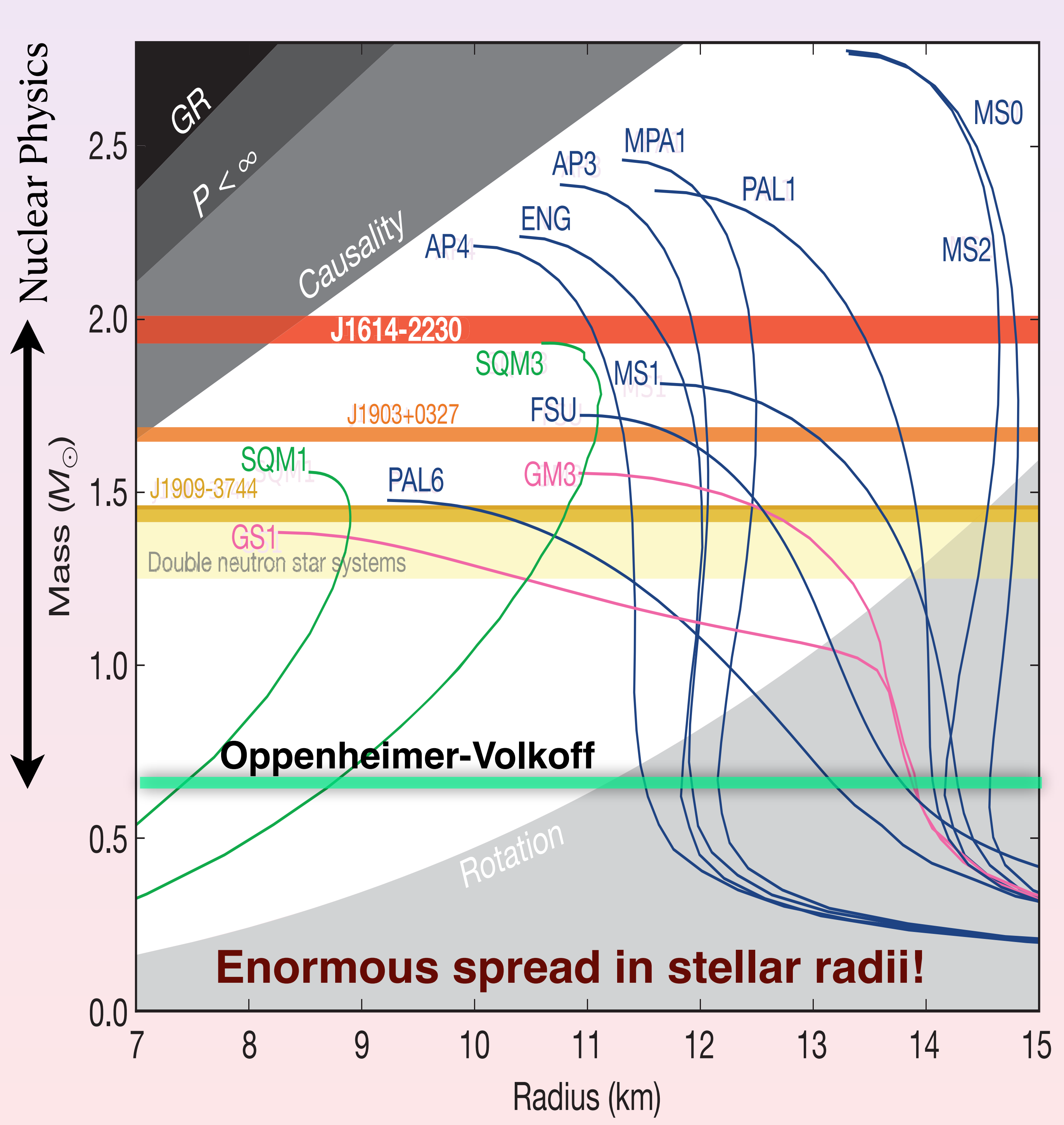


- Neutron stars are the remnants of massive stellar explosions (CCSN)
  Satisfy the TOV equations: Transition from Newtonian Gravity to Einstein Gravity



- Only Physics that the TOV equation is sensitive to: Equation of State
- Increase from 0.7 to 2 Msun transfers ownership to Nuclear Physics!

Nuclear interaction is responsible for describing finite nuclei and neutron stars!



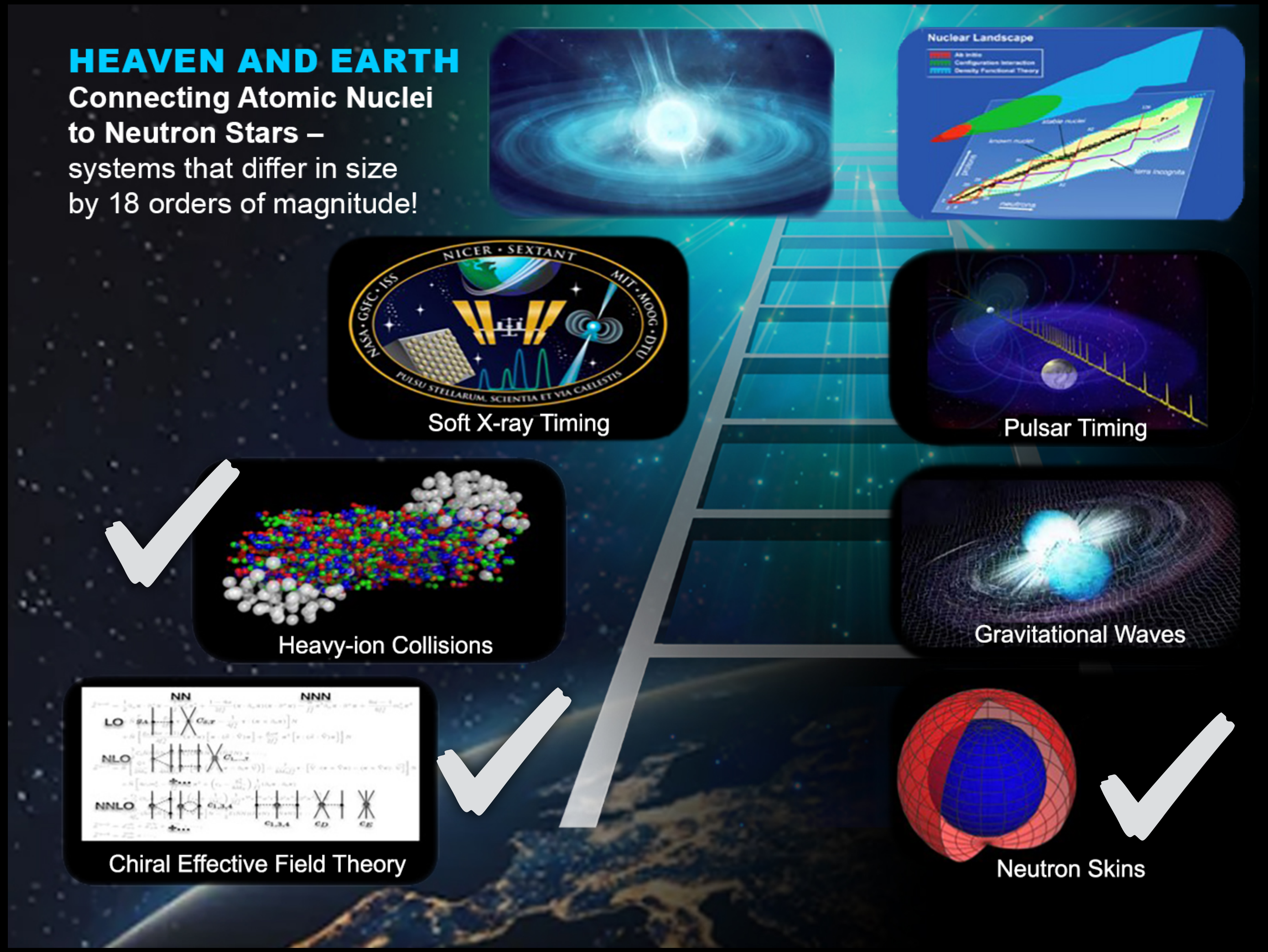
$$\frac{dM}{dr} = 4\pi r^2 \mathcal{E}(r)$$

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

Need an EOS: $P = P(\mathcal{E})$ relation

Nuclear Physics Critical

Micro-macro connection



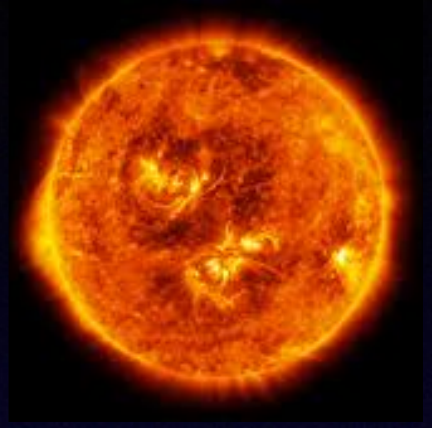
Nuclear Physics and Neutron Stars

EOS-101: The Equation of State of Neutron-Rich Matter

Equation of state: textbook examples

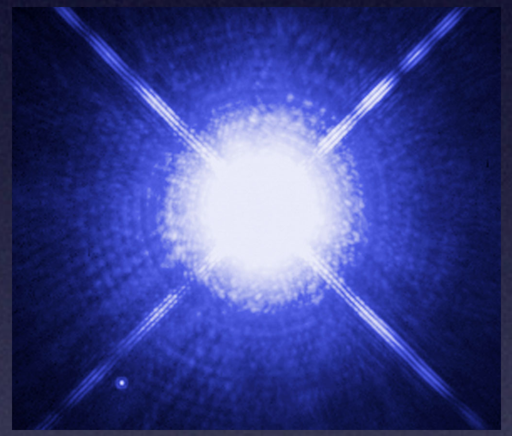
- Non-interacting classical gas
  high temperature, low density limit

$$P(n,T) = nk_{\rm B}T \leftrightarrow P(\mathcal{E}) = \frac{2}{3}\mathcal{E}$$

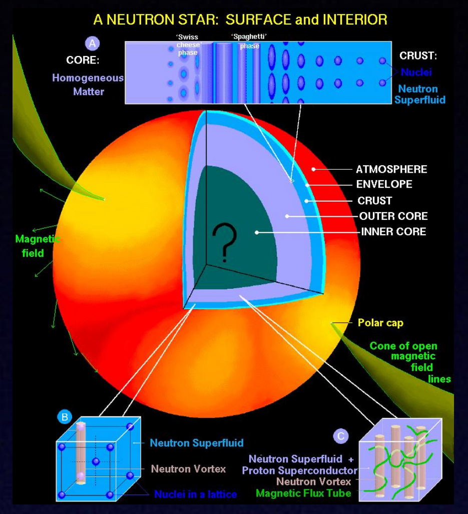


- Non-interacting (UR) quantum gas
  high density, low temperature limit

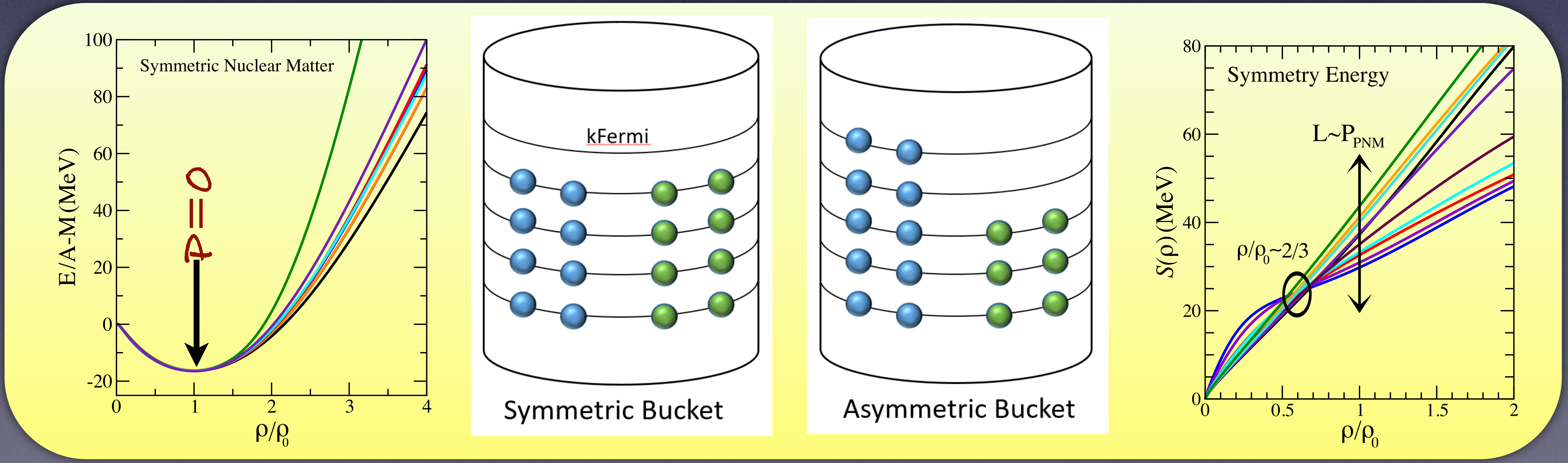
$$P(n,T\!=\!0) \approx n^{4/3} \leftrightarrow P(\mathcal{E}) = \frac{1}{3}\mathcal{E}$$



Equation of state of neutron-rich matter: NON-textbook example



- Strongly-interacting quantum fluid
  high density, low temperature limit
- Two "quantum liquids" in μ-equilibrium
- Charge-neutral system (neutralizing leptons)
- Density dependence and isospin asymmetry of the EOS poorly constrained



$$S(\rho_0) \approx \Big(E_{\rm PNM} - E_{\rm SNM}\Big)(\rho_0) = J$$

$$P_{\rm PNM} \approx \frac{1}{3}L\rho_0 \ \text{(Pressure of PNM)}$$

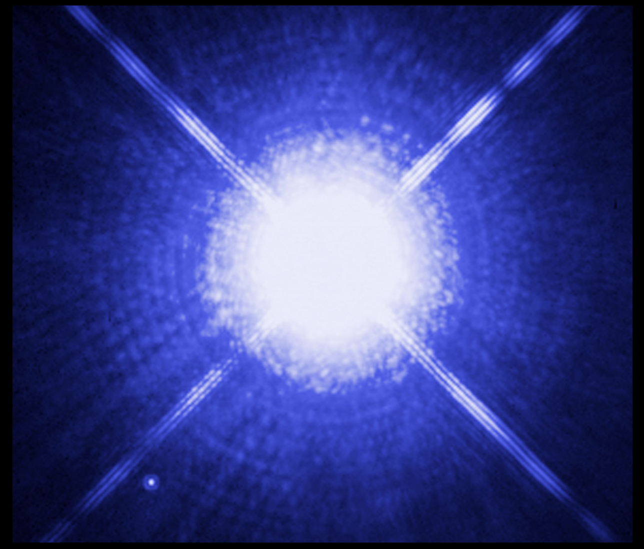
"Stiff" ⟶ L large

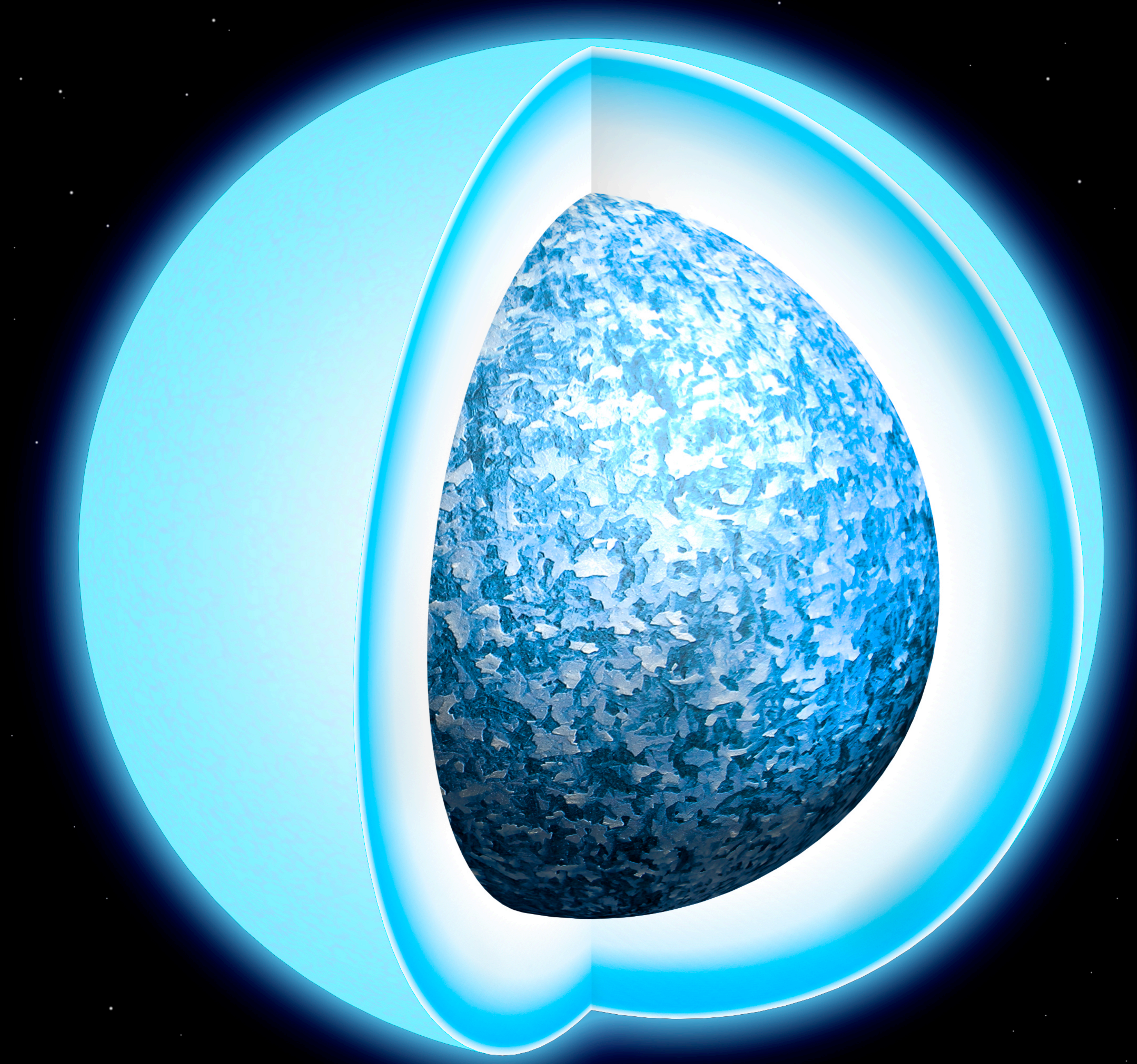
"Soft" ⟶ L small

Gravity vs Degeneracy Pressure

A few last words on white-dwarf stars

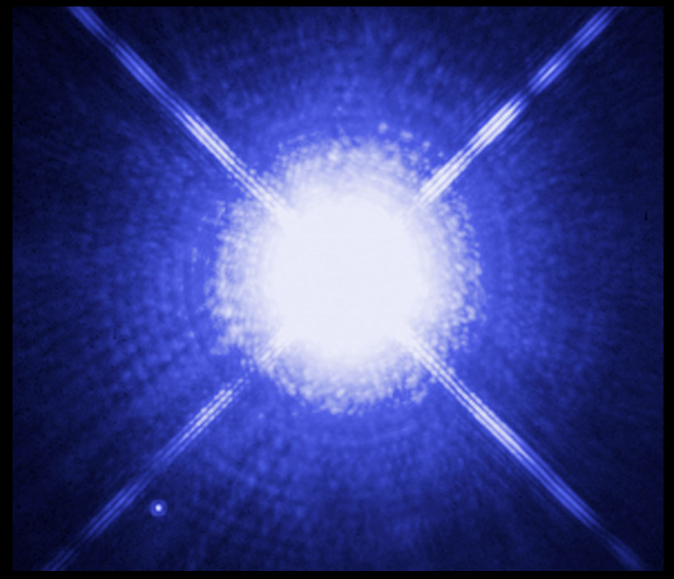
Sirius A and B





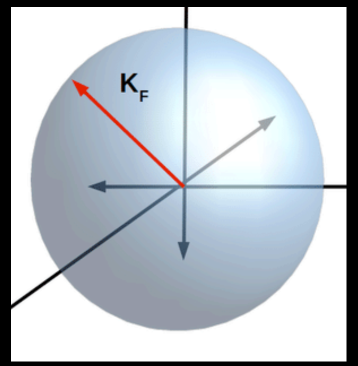
Why are not all death stars black holes?
What supports death stars
against gravitational collapse?

The Fate of our Sun: Quantum Mechanics and Special Relativity



Our Sun now ... and in 5 billion years!

A Relativistic Fermi Gas



$$\left[\frac{N}{V} \equiv n = \frac{k_{\mathrm{F}}^3}{3\pi^2} \quad (p_{\mathrm{F}} = \hbar p_{\mathrm{F}})\right]$$

$$\mathcal{E}(n) = \mathcal{E}_0\left[x_{\mathrm{F}} y_{\mathrm{F}}(x_{\mathrm{F}}^2 + y_{\mathrm{F}}^2) - \ln(x_{\mathrm{F}} + y_{\mathrm{F}})\right]$$

NR: $\frac{3}{5} n\varepsilon_{\mathrm{F}} \propto n^{5/3}$

UR: $\frac{3}{4} n p_{\mathrm{F}} c \propto n^{4/3}$

$$P(n) = \mathcal{E}_0\left[\frac{2}{3} x_{\mathrm{F}}^3 y_{\mathrm{F}} - x_{\mathrm{F}} y_{\mathrm{F}} + \ln(x_{\mathrm{F}} + y_{\mathrm{F}})\right]$$

$$x_{\mathrm{F}} = \frac{p_{\mathrm{F}} c}{mc^2}; \quad y_{\mathrm{F}} = \frac{\varepsilon_{\mathrm{F}}}{mc^2} = \sqrt{1 + x_{\mathrm{F}}^2}; \quad \mathcal{E}_0 = \frac{1}{8\pi^2} \frac{(mc^2)^4}{(\hbar c)^3}$$

White-dwarf Stars: The fate of our Sun

- Supported against GW collapse by electron degeneracy pressure … a QM effect due to the Pauli exclusion principle
- For low mass stars electrons are non-relativistic and pressure scales as $n^{5/3}$

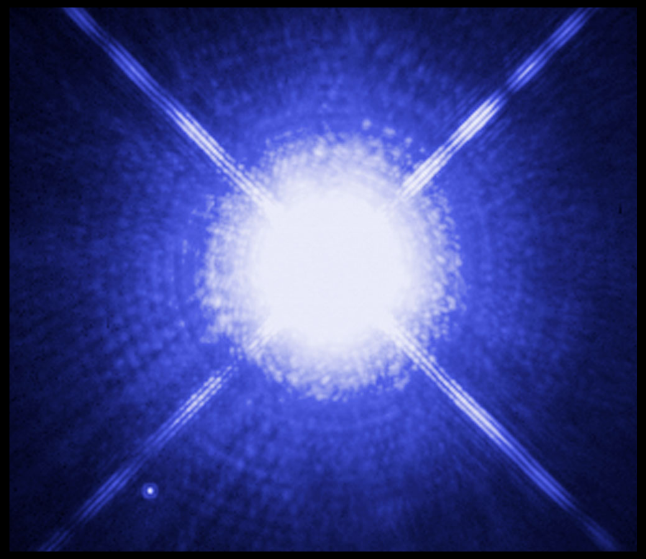
$$\varepsilon(p) = \sqrt{(pc)^2 + (mc^2)^2} \rightarrow \frac{p^2}{2m} + \text{constant}$$

- For high mass stars electrons are relativistic and pressure scales only as $n^{4/3}$ … star loses pressure support

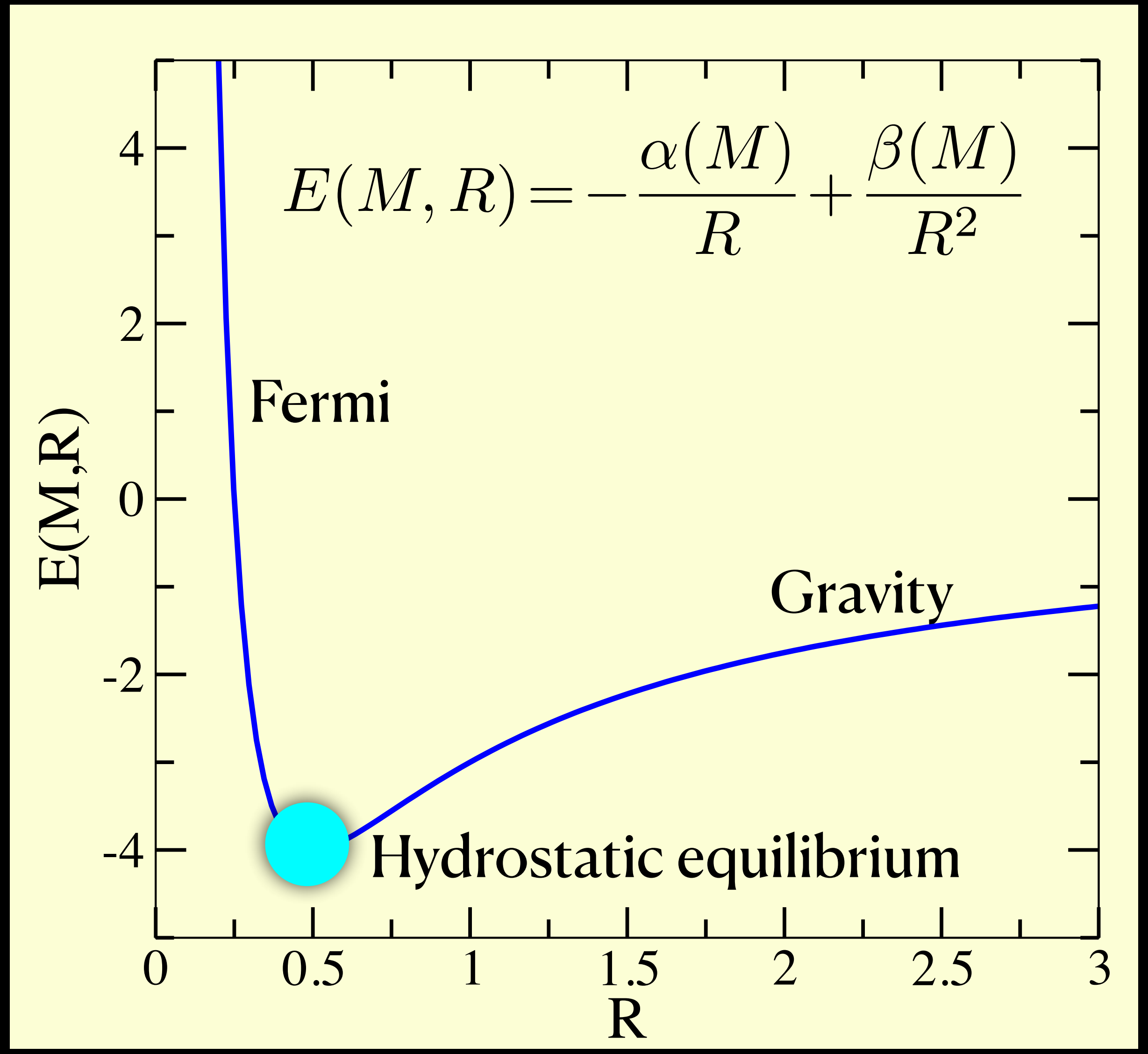
$$\varepsilon(p) = \sqrt{(pc)^2 + (mc^2)^2} \rightarrow pc$$

- White dwarf collapses when $M_\star \geq M_{\mathrm{ch}} = 1.4\, M_\odot$

Quantum mechanics delays the collapse of WD stars — but special relativity ultimately seals its fate!



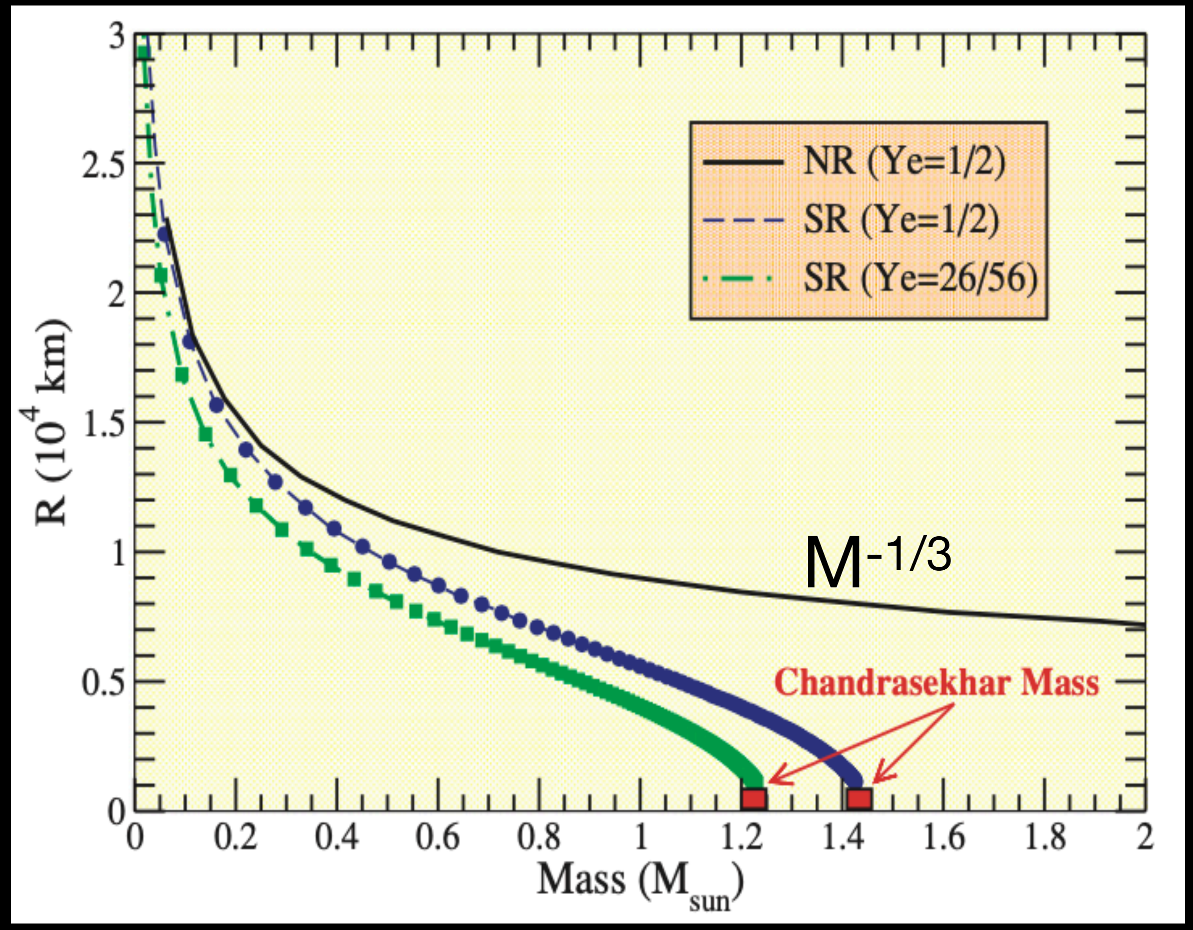
A Toy Model for Newtonian Stars
(A star of uniform density)



Gravitational Energy: $$\frac{E_G(M,R)}{Mc^2} = -\frac{3}{10}\left(\frac{M}{R}\right)$$

NR free Fermi Gas: $$\frac{E_{FG}^{(NR)}(M,R)}{Mc^2} = 1 + K_{NR}\left(\frac{M^{2/3}}{R^2}\right)$$

Equilibrium configuration: $$R(M) = (0.71\times 10^4\ \mathrm{km})\left(\frac{M}{M_\odot}\right)^{-1/3}$$

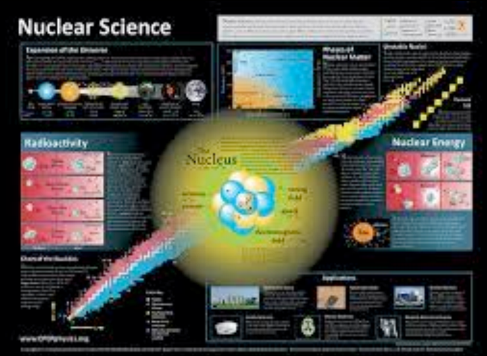


UR free Fermi Gas: $$\frac{E_{FG}^{(UR)}(M,R)}{Mc^2} = K_{UR}\left(\frac{M^{1/3}}{R}\right)$$

Chandrasekhar Mass: $$M_{\mathrm{ch}} = (6.86\ M_\odot)Y_e^2 \xrightarrow{Y_e=1/2} 1.72\ M_\odot$$

Ultimately, special relativity leads to the collapse of WDs

Neutron Stars: The Role of Nuclear Science



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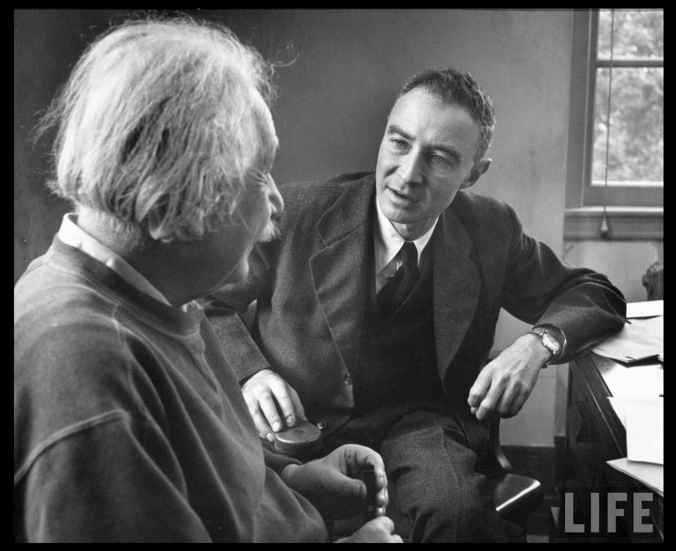

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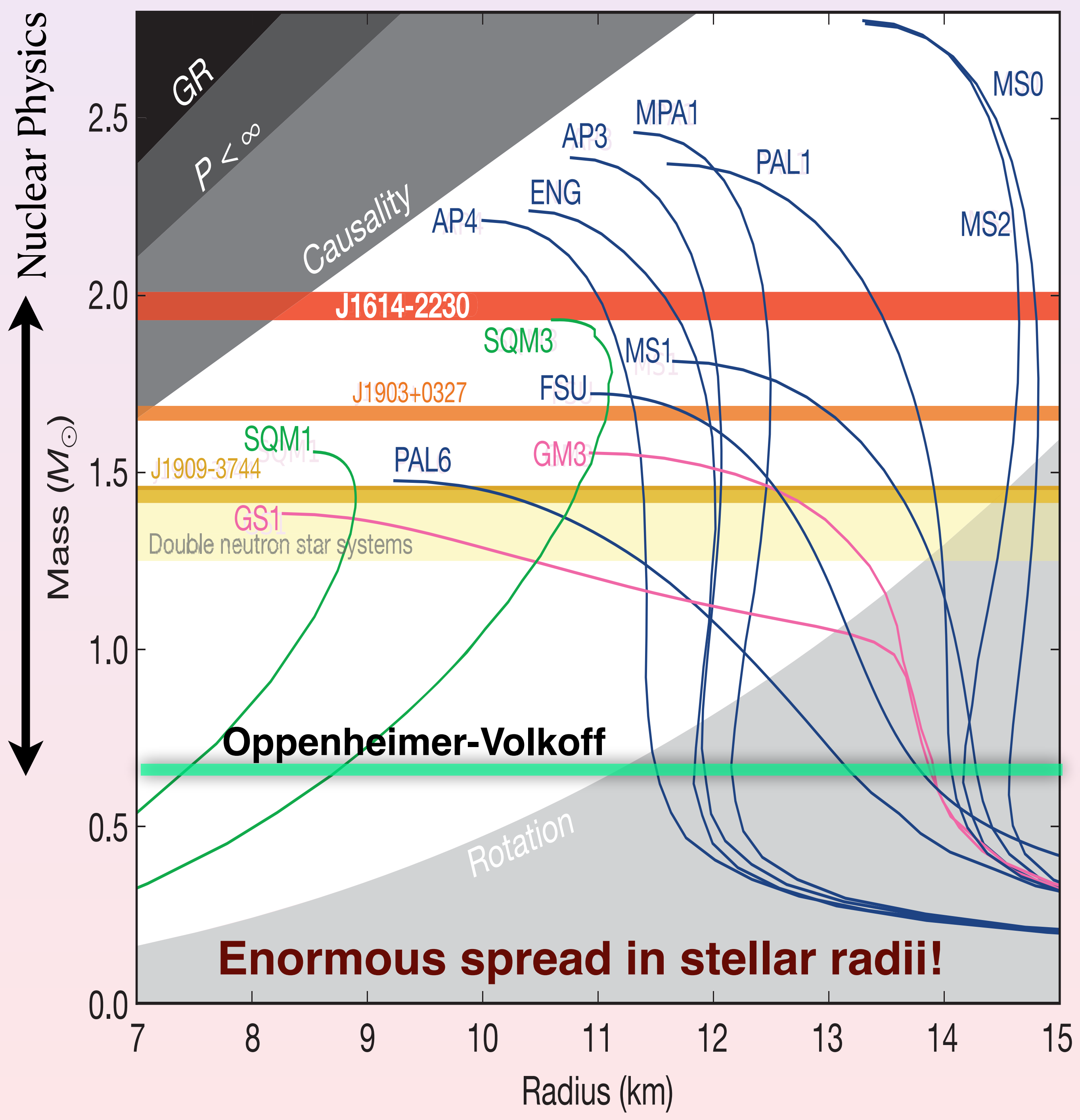

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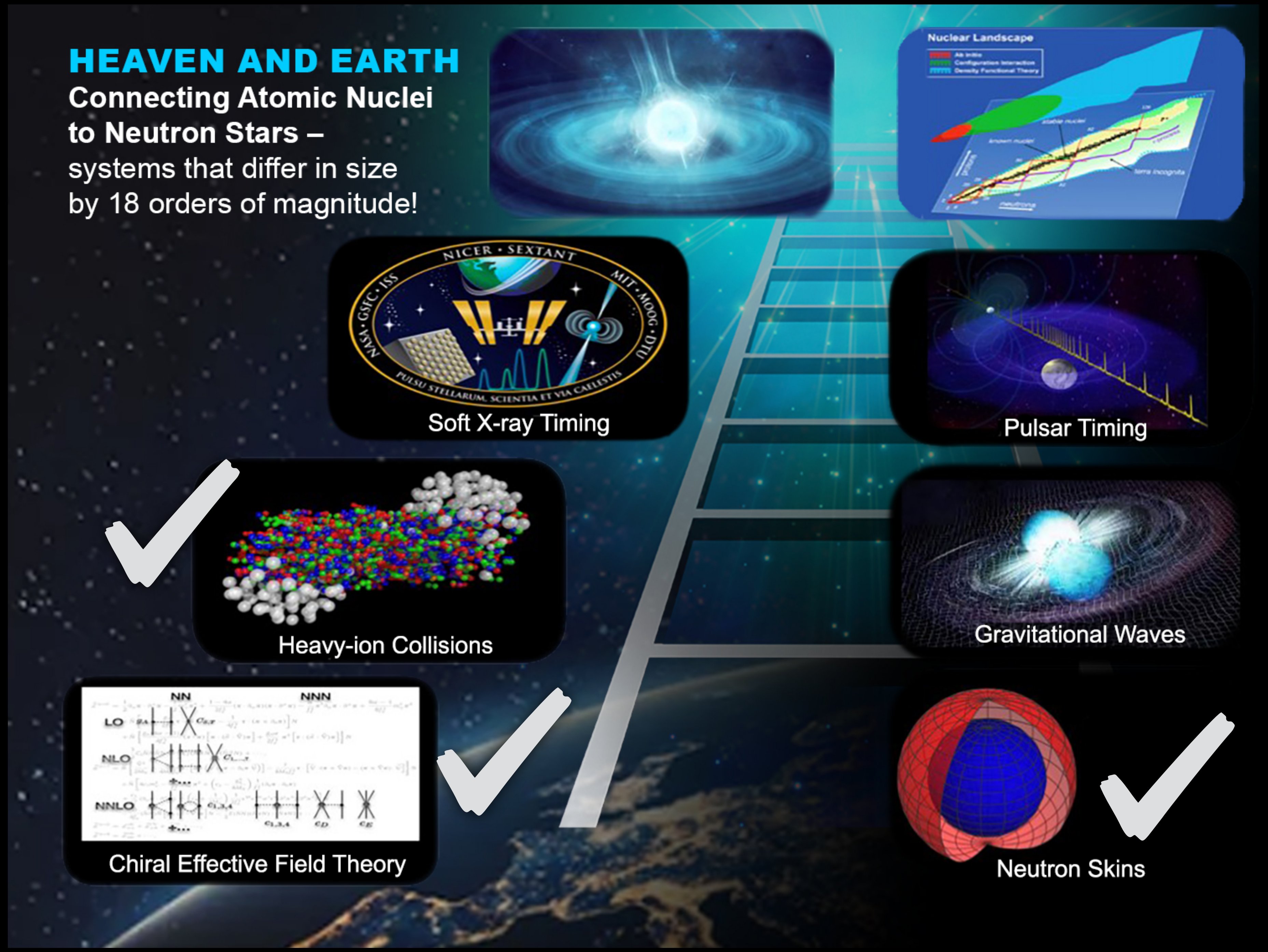

Nuclear Physics and Neutron Stars

Neutron-star Interior Composition Explorer (NICER)
Simultaneous Mass and Radius Measurements (2019-2021)

NICER was launched from Kennedy's Space Center on June 3, 2017 aboard SpaceX Falcon 9 Rocket and docked at the International Space Station two days later.

NICER measures the compactness of the Neutron Star by looking at back of the star!

Pulse Profile: The stellar compactness controls the light profile from the hot spot

$$\xi = \frac{2GM}{c^2 R} = \frac{R_S}{R}$$

$M = 2.08 \pm 0.07\,\mathrm{M}_\odot$

Shapiro delay: Cromartie *et al.* (2020)

$R_{2.0} = 12.39^{+1.30}_{-0.98}\ \mathrm{km}$

Riley *et al.* (2021)

$R_{2.0} = 13.7^{+2.6}_{-1.5}\ \mathrm{km}$

Miller *et al.* (2021)

Stiff EOS! Large L!

Micro-Macro