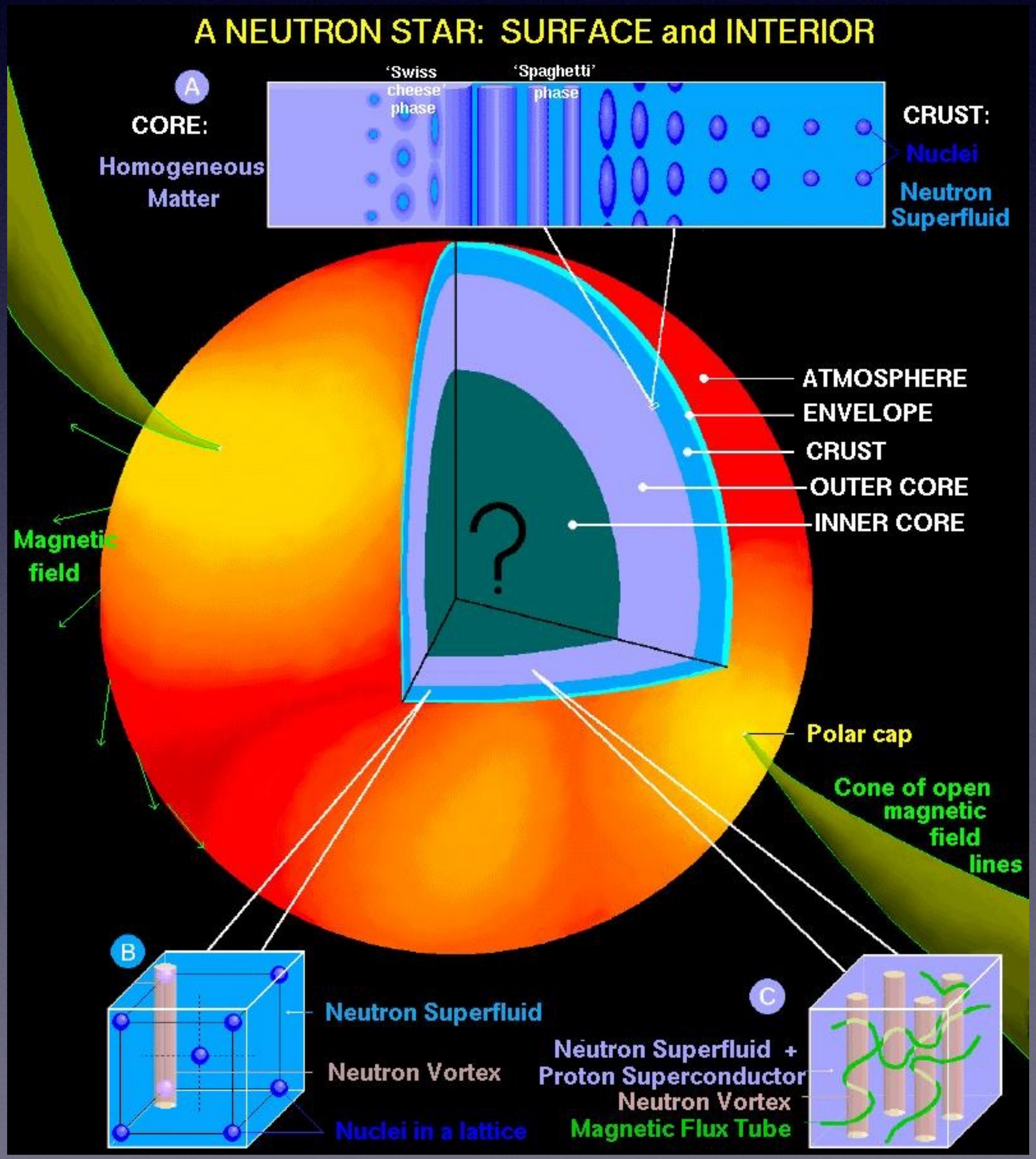
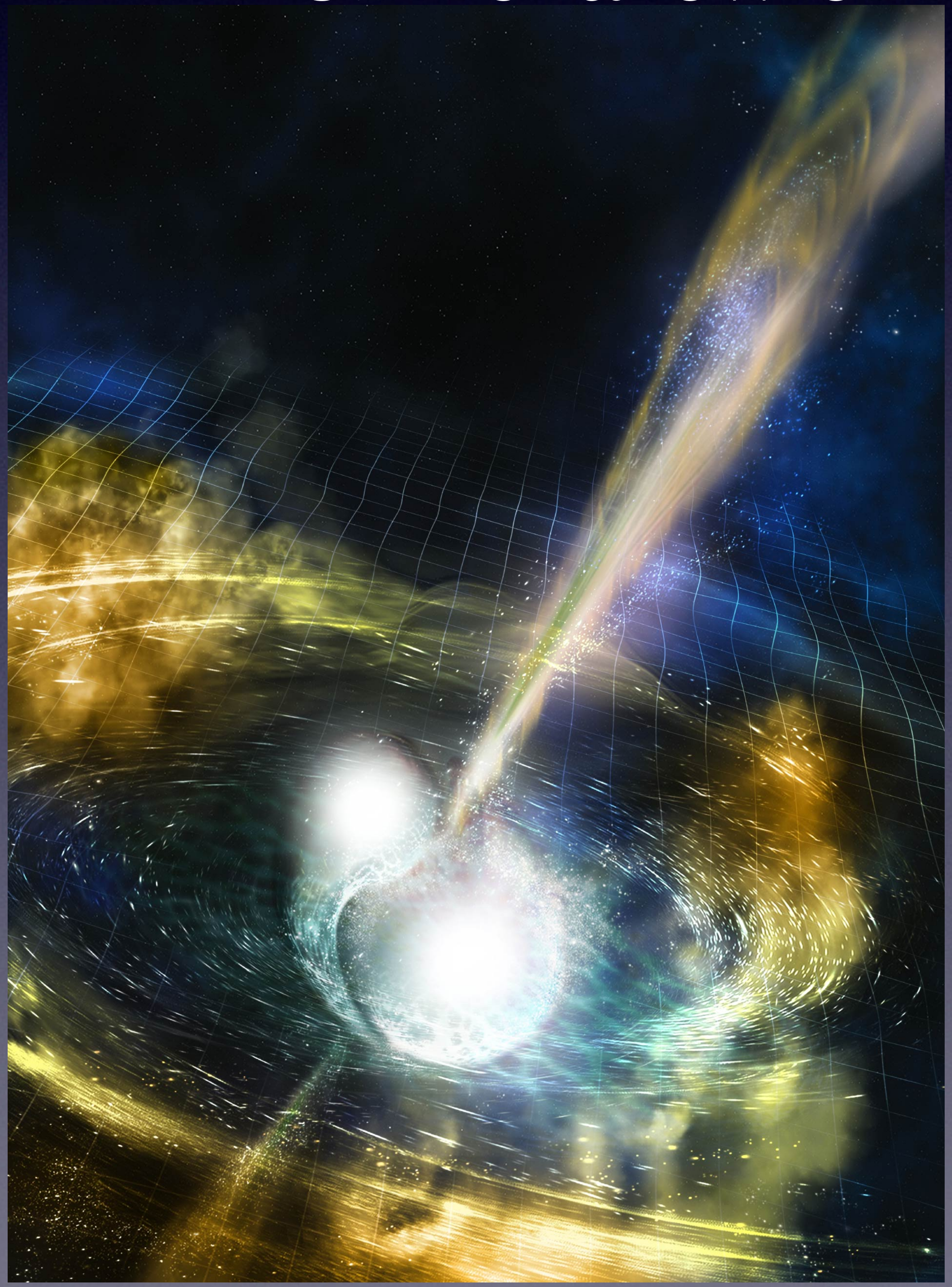
U.S. DEPARTMENT OF ENERGY | Office of Science

Heaven and Earth: Nuclear Astrophysics in the Multimessenger Era

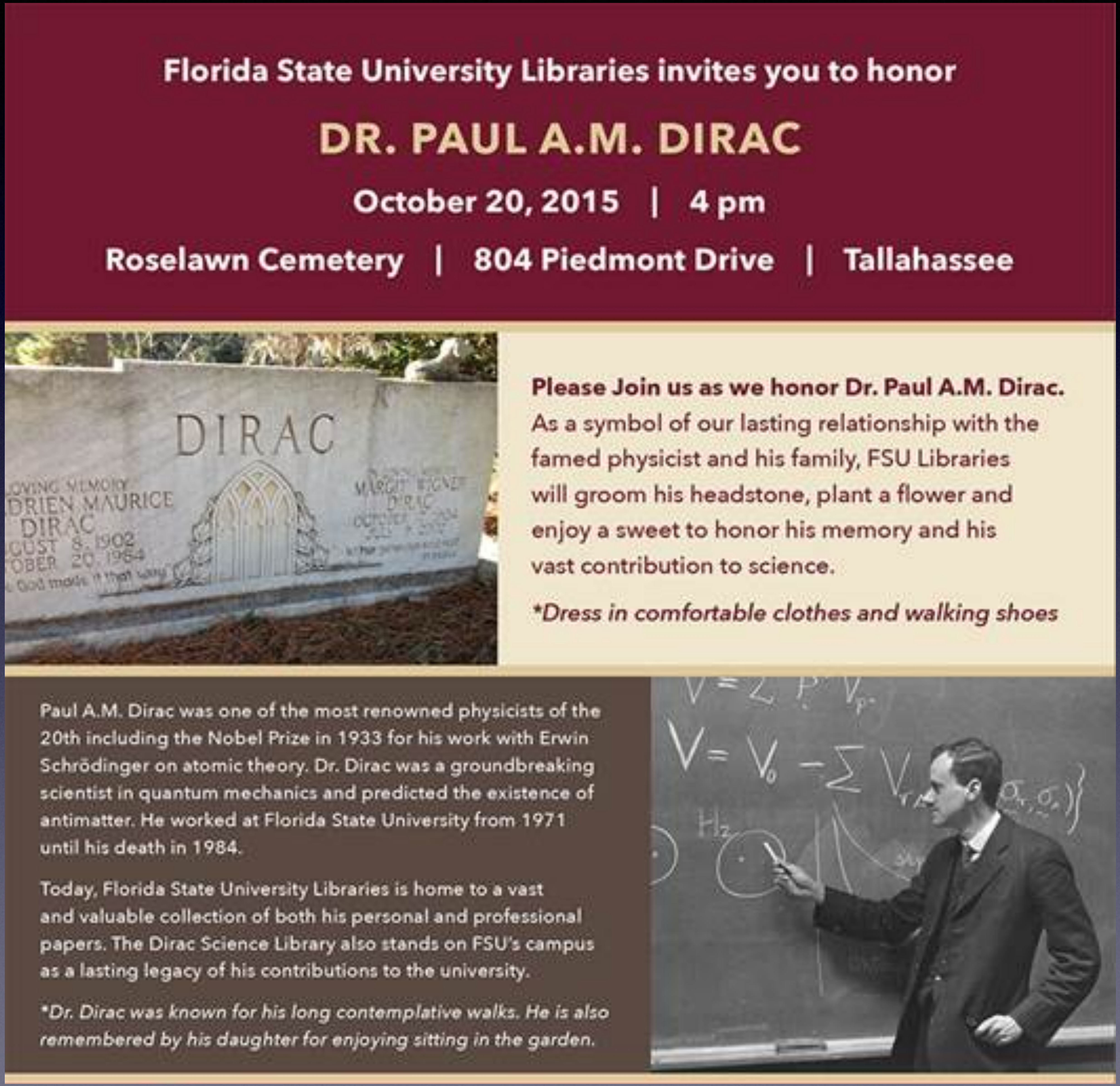
UC RIVERSIDE | 2023 National Nuclear Physics Summer School

J. Piekarewicz





P.A.M Dirac: From Cambridge to Tallahassee



Florida State University Libraries invites you to honor

DR. PAUL A.M. DIRAC

October 20, 2015 | 4 pm

Roselawn Cemetery | 804 Piedmont Drive | Tallahassee

Please Join us as we honor Dr. Paul A.M. Dirac.
As a symbol of our lasting relationship with the famed physicist and his family, FSU Libraries will groom his headstone, plant a flower and enjoy a sweet to honor his memory and his vast contribution to science.

**Dress in comfortable clothes and walking shoes*

Paul A.M. Dirac was one of the most renowned physicists of the 20th including the Nobel Prize in 1933 for his work with Erwin Schrödinger on atomic theory. Dr. Dirac was a groundbreaking scientist in quantum mechanics and predicted the existence of antimatter. He worked at Florida State University from 1971 until his death in 1984.

Today, Florida State University Libraries is home to a vast and valuable collection of both his personal and professional papers. The Dirac Science Library also stands on FSU's campus as a lasting legacy of his contributions to the university.

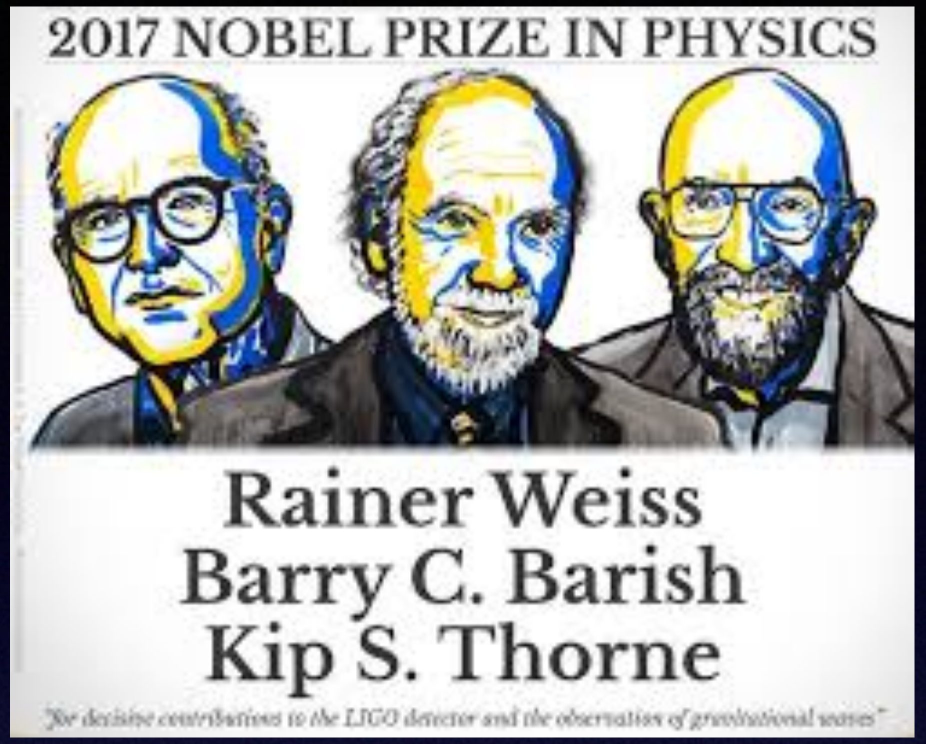
**Dr. Dirac was known for his long contemplative walks. He is also remembered by his daughter for enjoying sitting in the garden.*

Wigner and Moshinsky

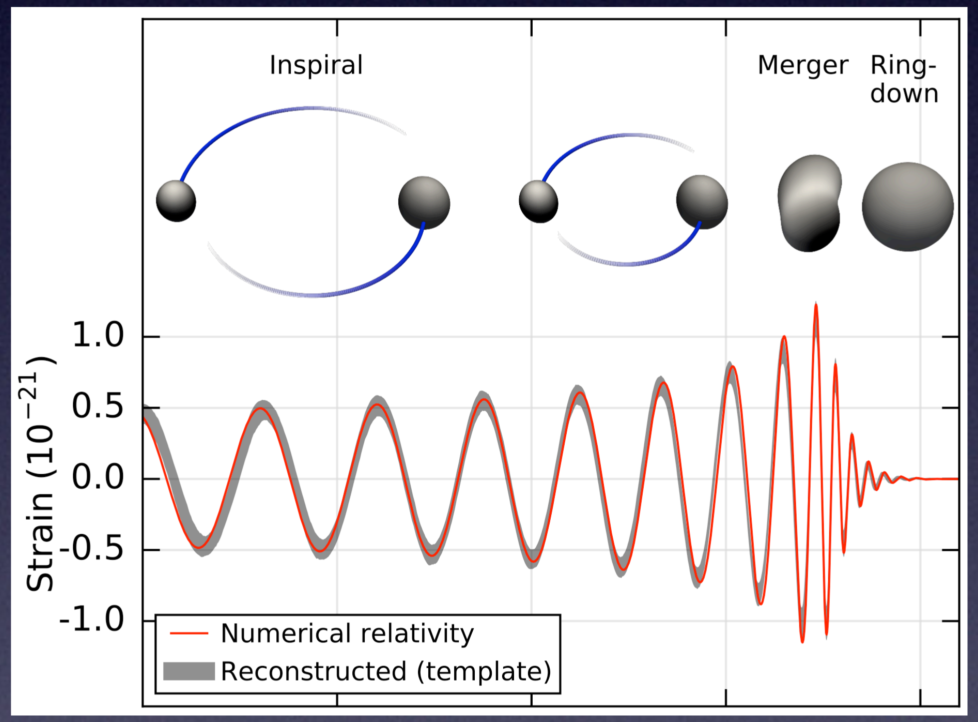
Lectures will attempt to provide an overall personal picture of the emergent field of multi-messenger astronomy from a nuclear physics perspective

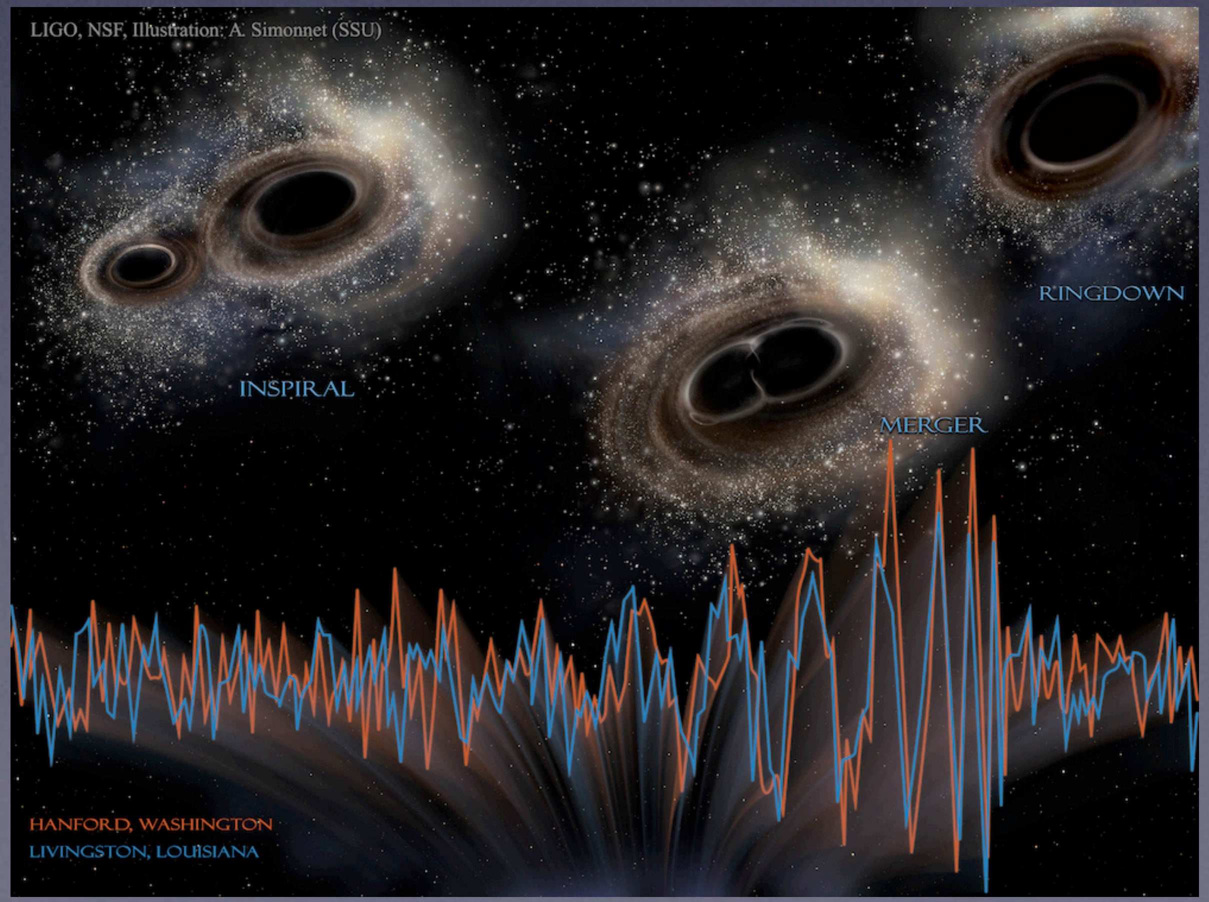
Please ask questions!

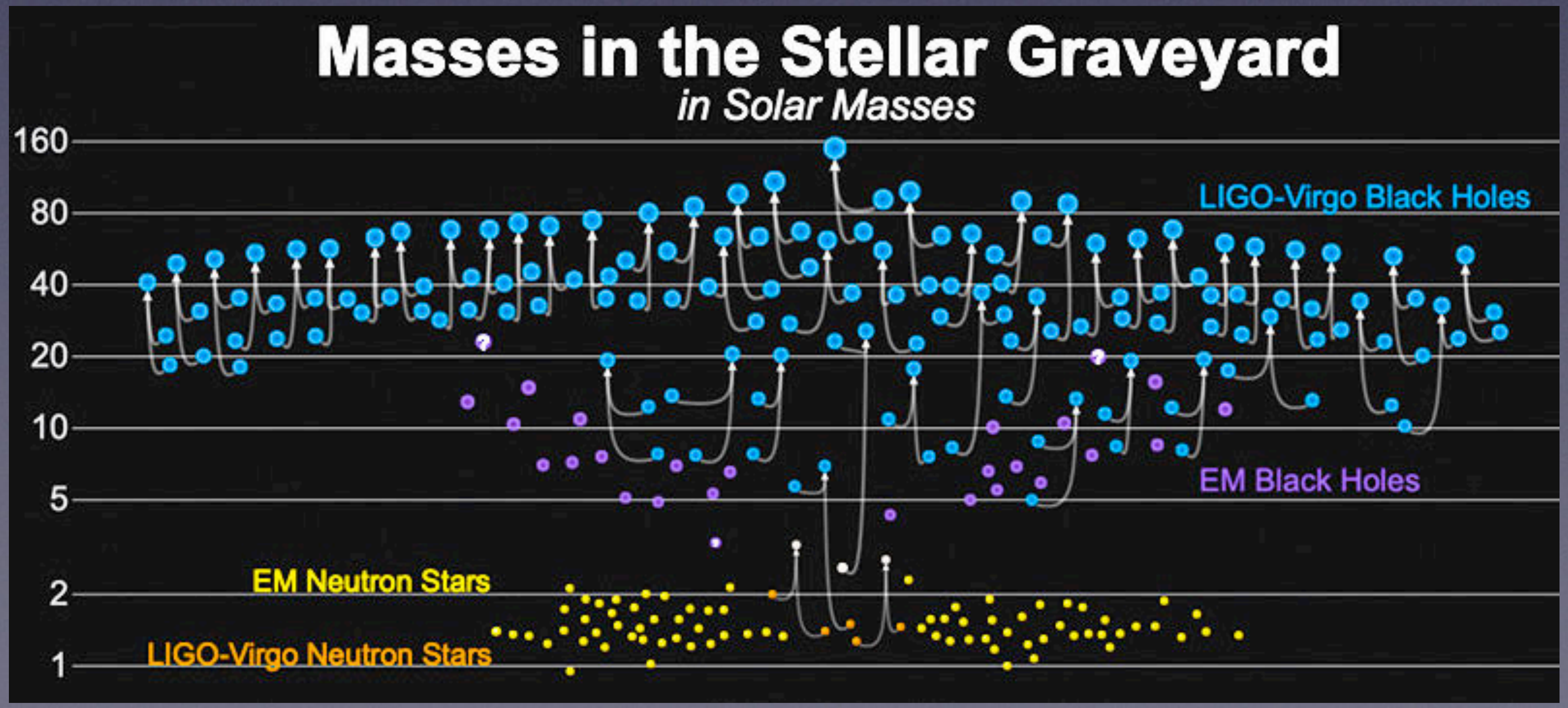
"We have detected gravitational waves; we did it"
David Reitze, February 11, 2016



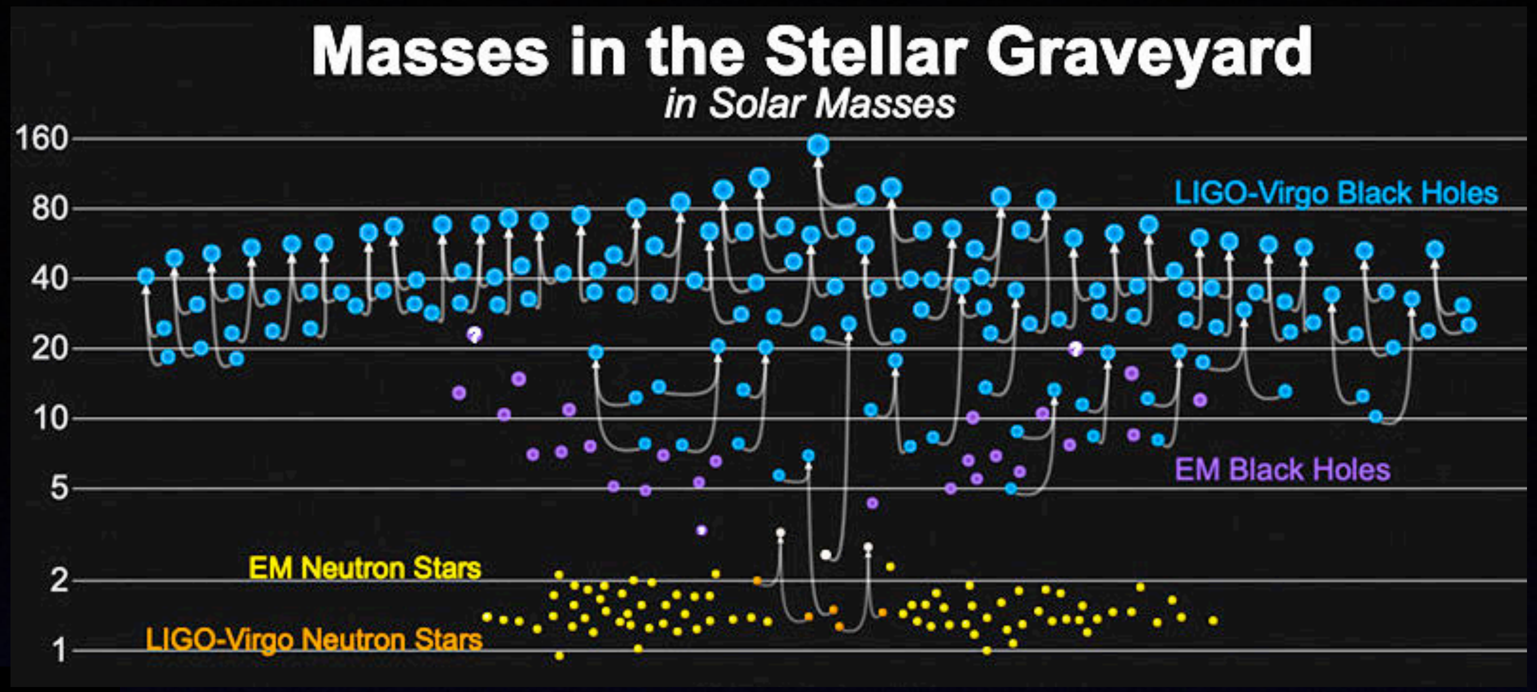
- The dawn of a new era: GW Astronomy
  - Initial black hole masses are 36 and 29 solar masses
  - Final black hole mass is 62 solar masses;
    3 solar masses radiated in Gravitational Waves!

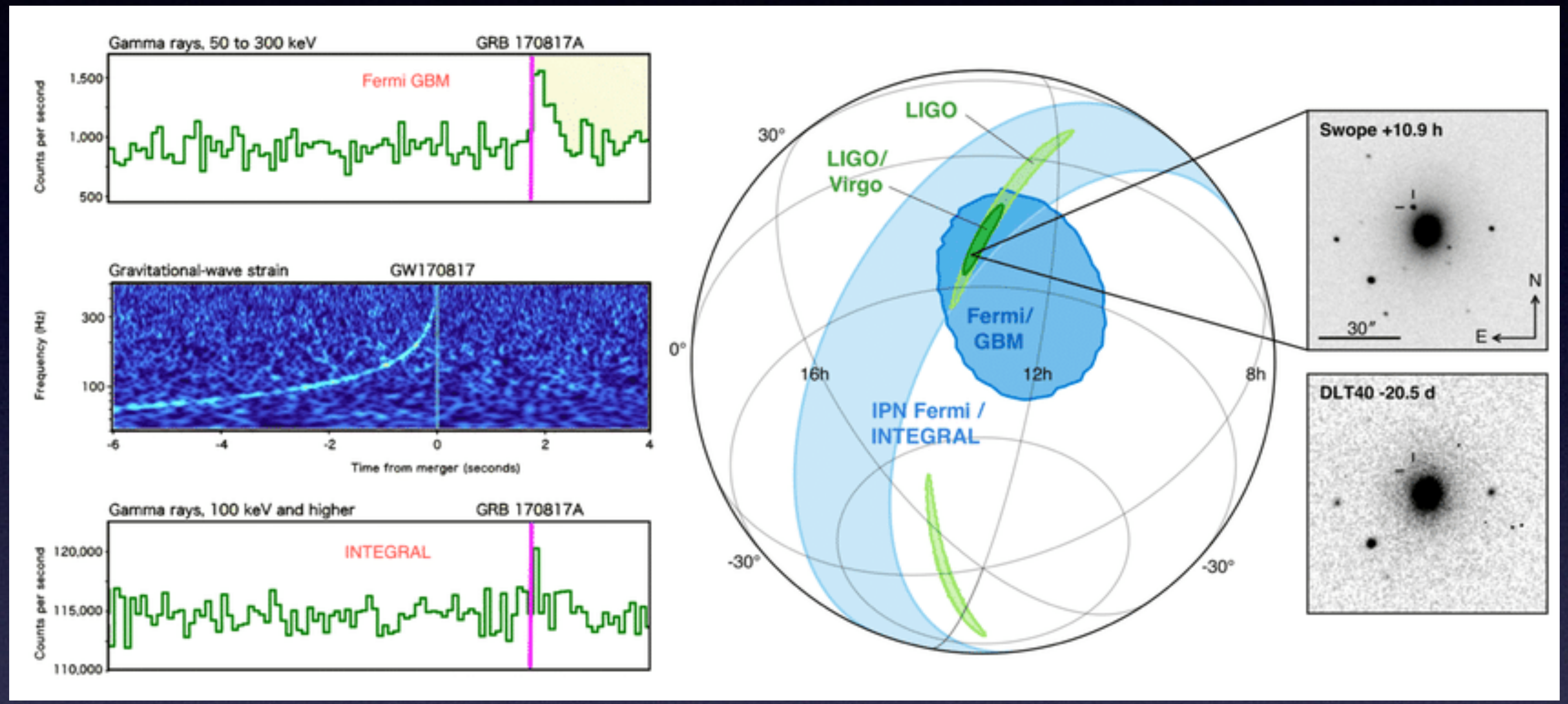




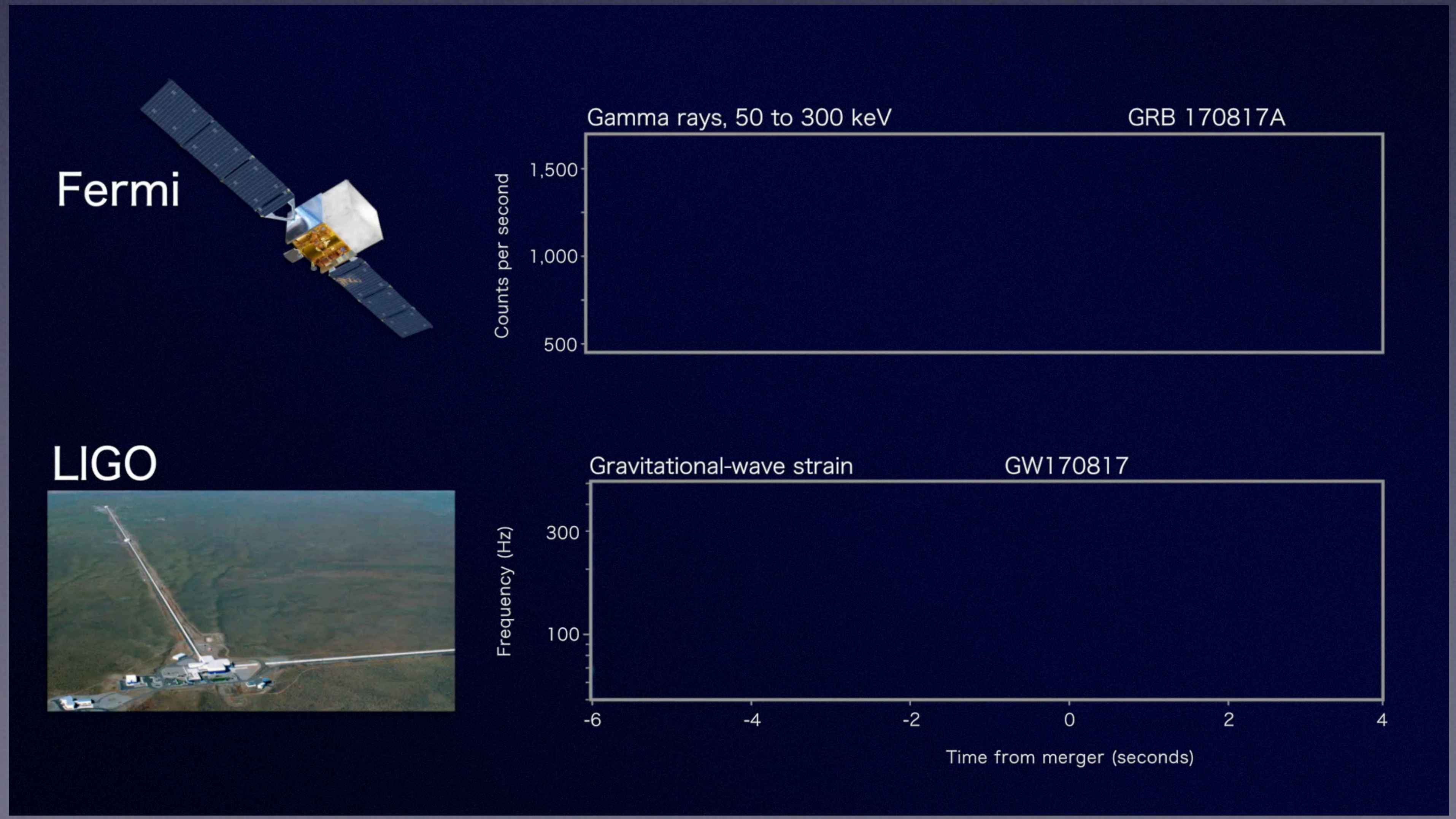


GW170817: The Beginning of the Multimessenger Era





GW170817



Jocelyn Bell: As a graduate student discovers neutron stars

- Bell discovers pulsars as a graduate student in (1967)
- Discovers by accident an amazingly regular signal
- First thought that signal came from an alien civilization

Nobel Prize awarded to her mentor (1974)
Awarded Special Breakthrough Prize (2018)
Bell donates prize ($3M) to help minority students!

Listen to the sounds of the Vela pulsar,
which was produced after the explosion
of a massive star about 10,000 years ago.
The star spins on its axis 11 times per second.

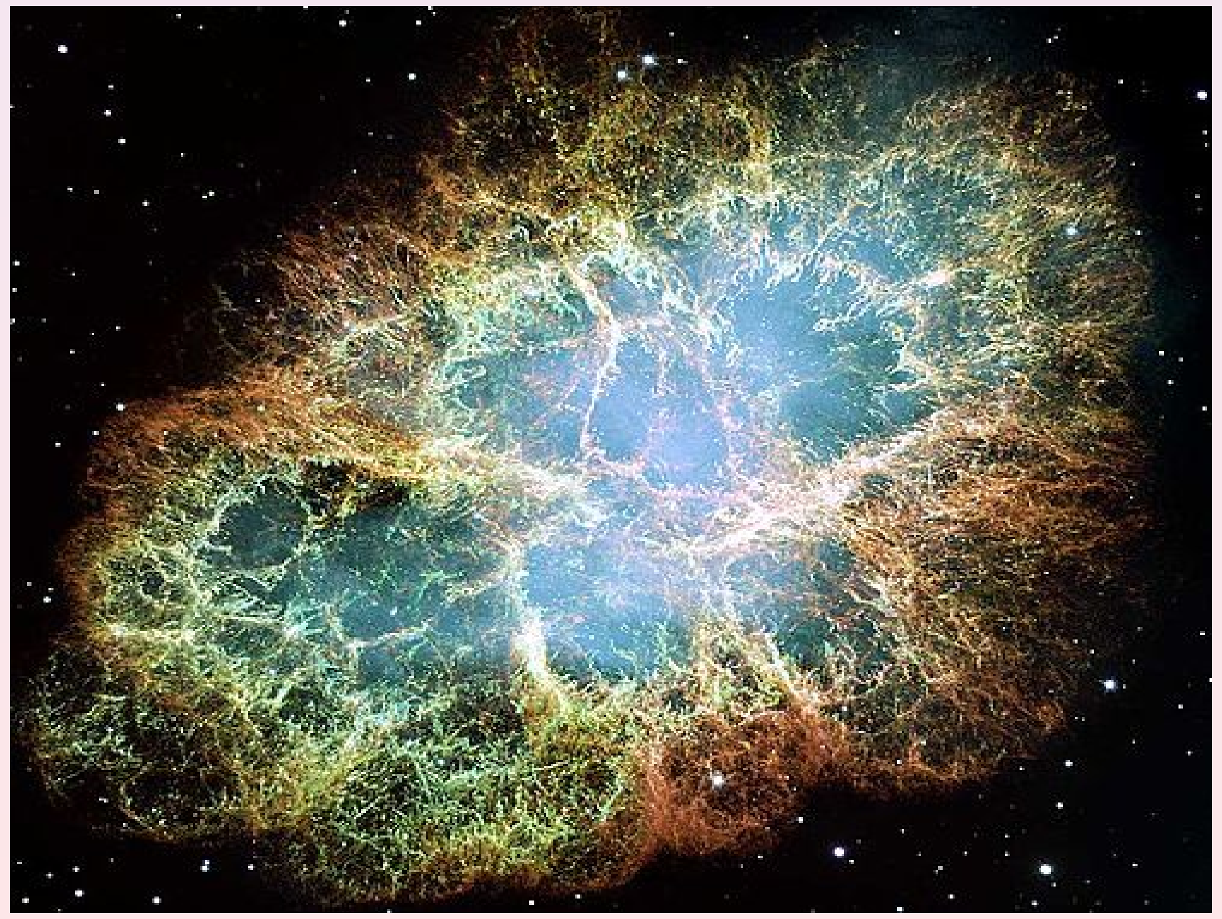
"I believe it would demean Nobel Prizes if they were awarded to research students, except in very exceptional cases and I do not believe this is one of them"

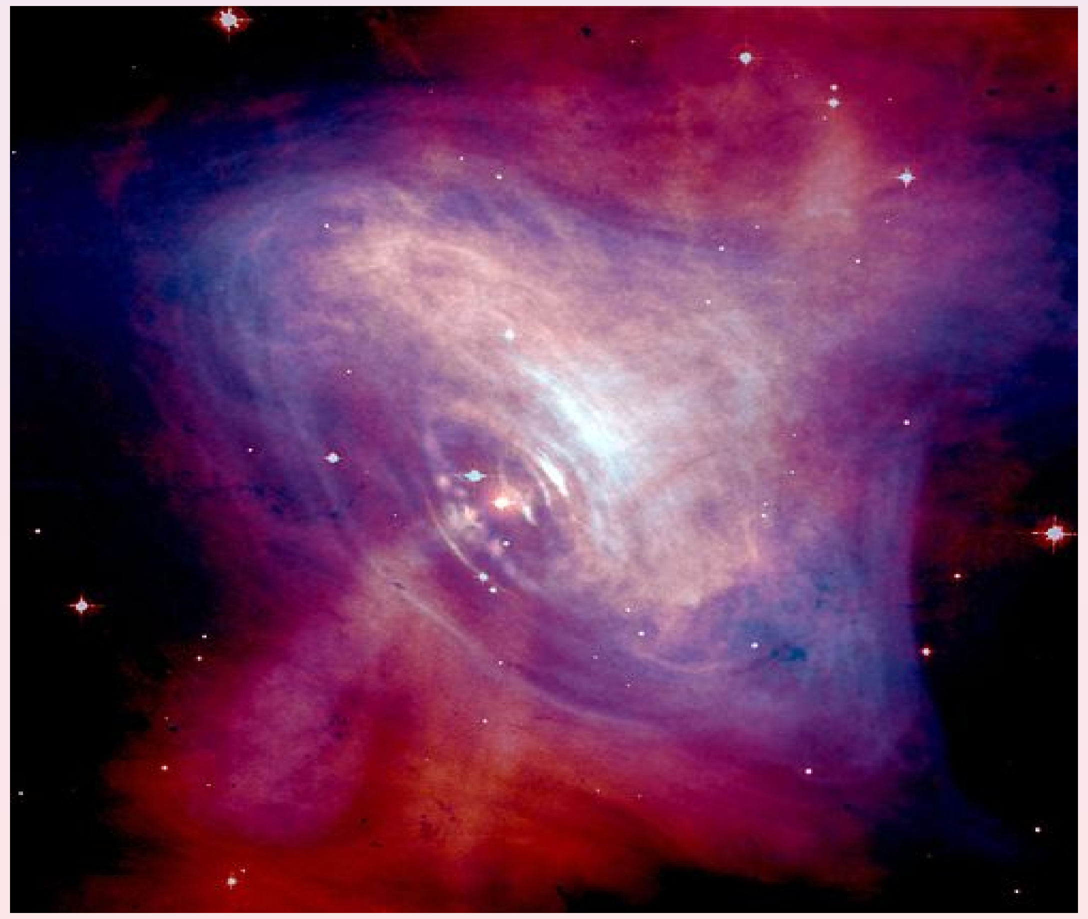
Biography of a Neutron Star: The Crab Pulsar

- SN 1054 first observed as a new *"star"* in the sky on July 4, 1054
- Event recorded in multiple Chinese and Japanese documents
- Event also recorded by Anasazi residents of Chaco Canyon, NM
- Crab nebula and pulsar became the SN remnants

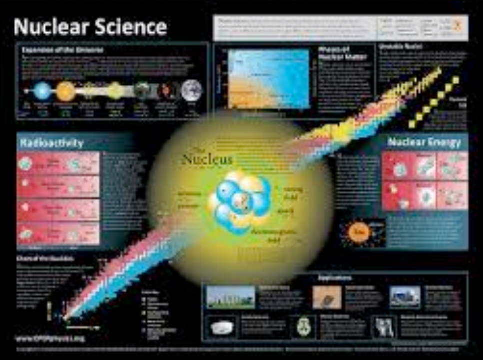
Name: PSR B0531+21
POB: Taurus
Mass: 1.4 $M_{\odot}$
Radius: 10 km
Period: 33 ms

Distance: 6,500 ly
Temperature: 10^6 K
Density: 10^{14} g/cm^3
Pressure: 10^{29} atm
Magnetic Field: 10^{12} G

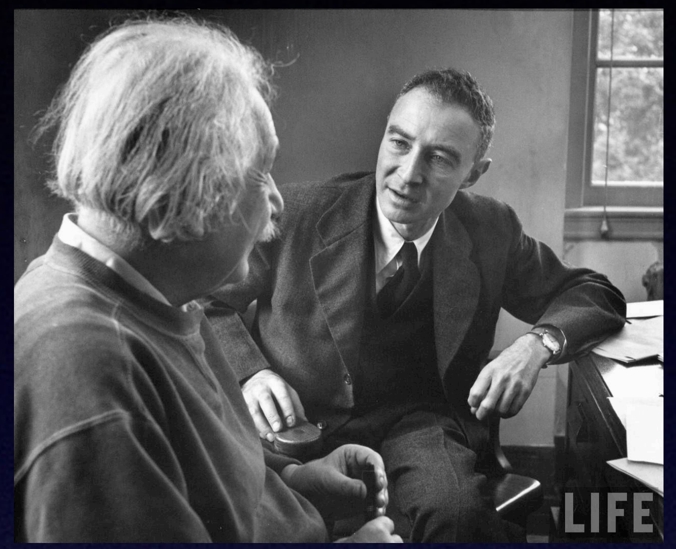


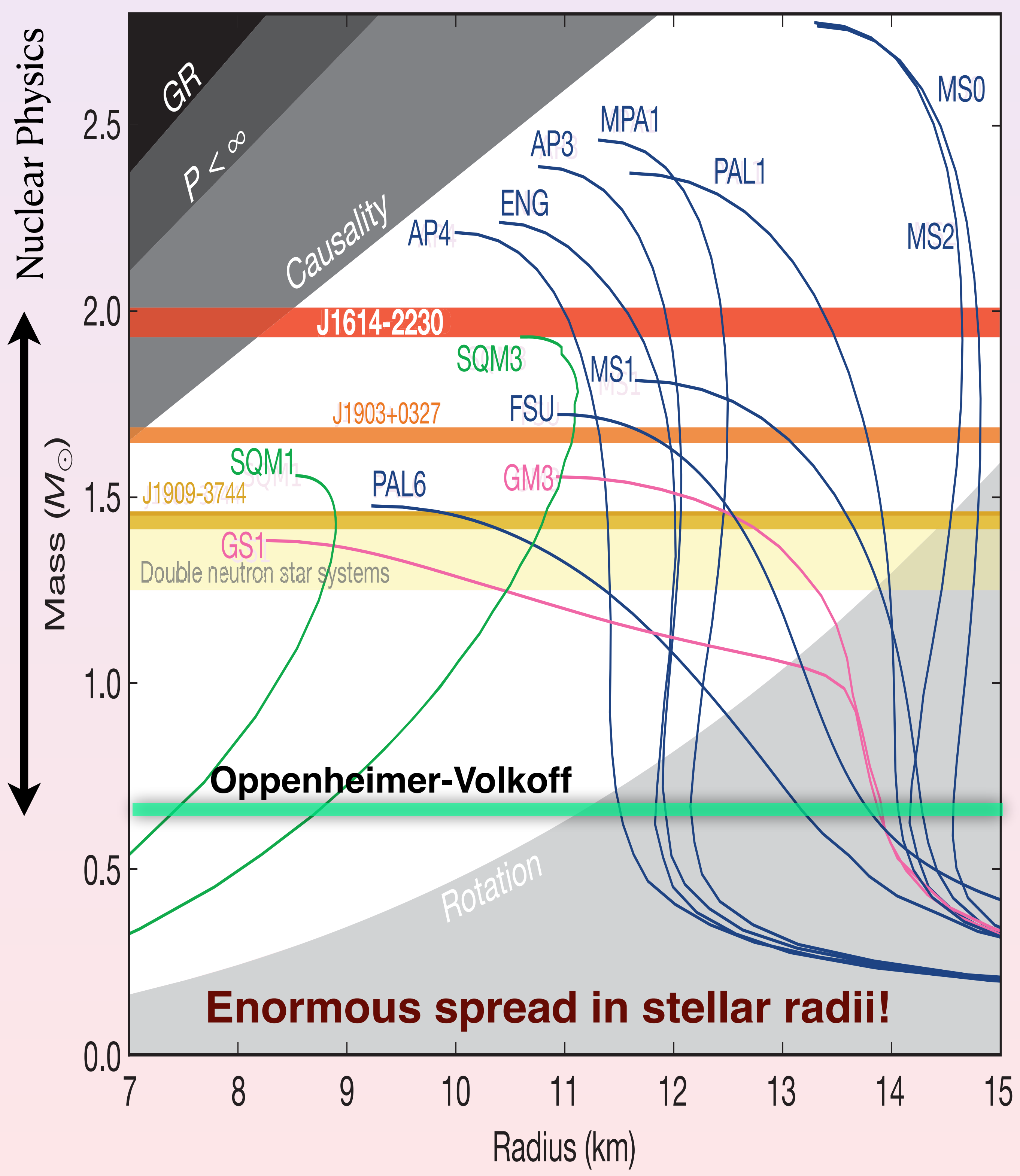


Neutron Stars: The Role of Nuclear Science



- Neutron stars are the remnants of massive stellar explosions (CCSN)
  Bound by gravity — NOT by the strong force!
  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!





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

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

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

Nuclear Physics Critical

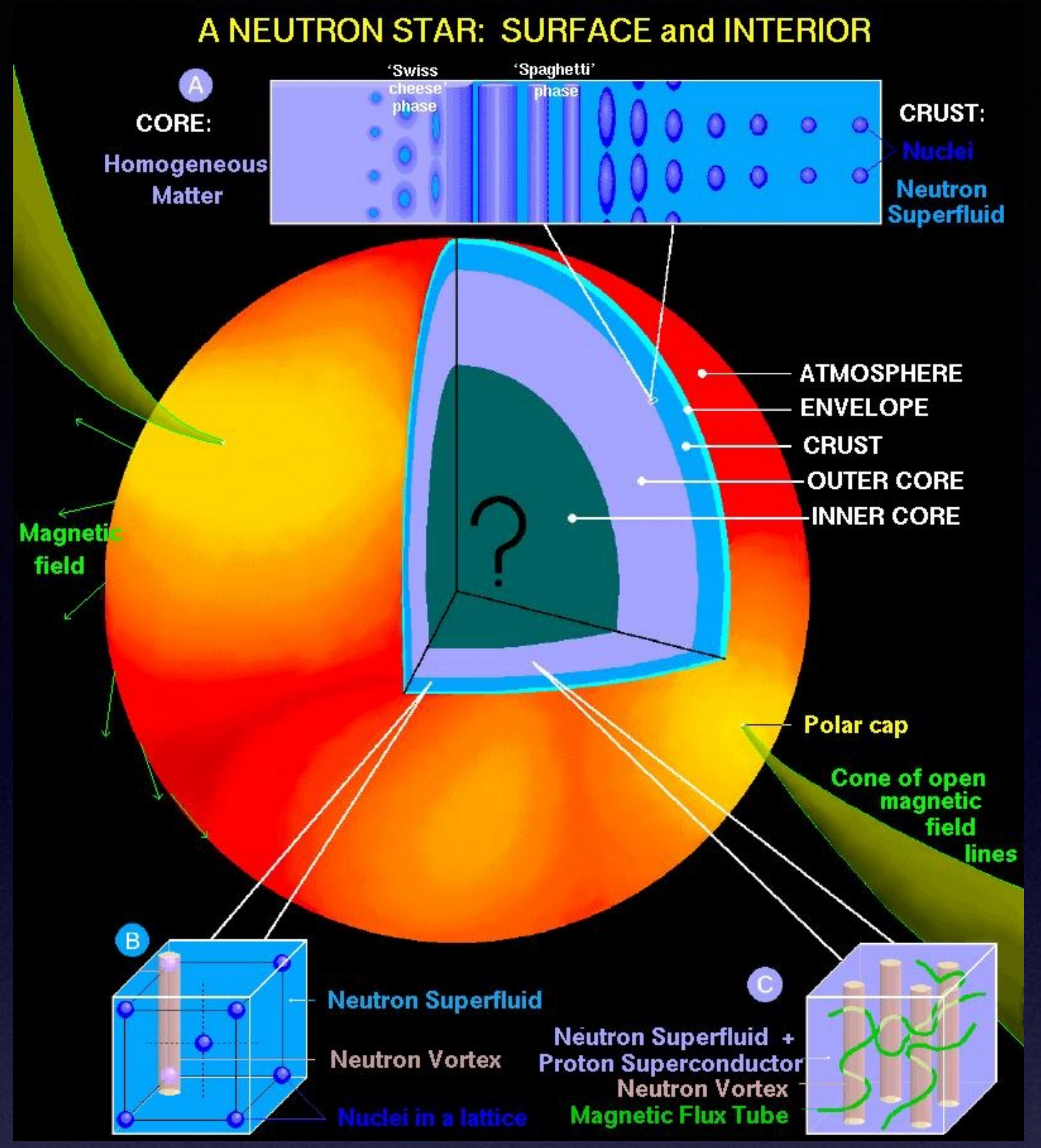
Micro-macro connection

Status before GW170817

Many nuclear models that account for the properties of finite nuclei yield enormous variations in the prediction of neutron-star radii and maximum mass

Only observational constraint in the form of two neutron stars with a mass in the vicinity of $2M_{sun}$

Anatomy of a Neutron Star:Our Sandbox



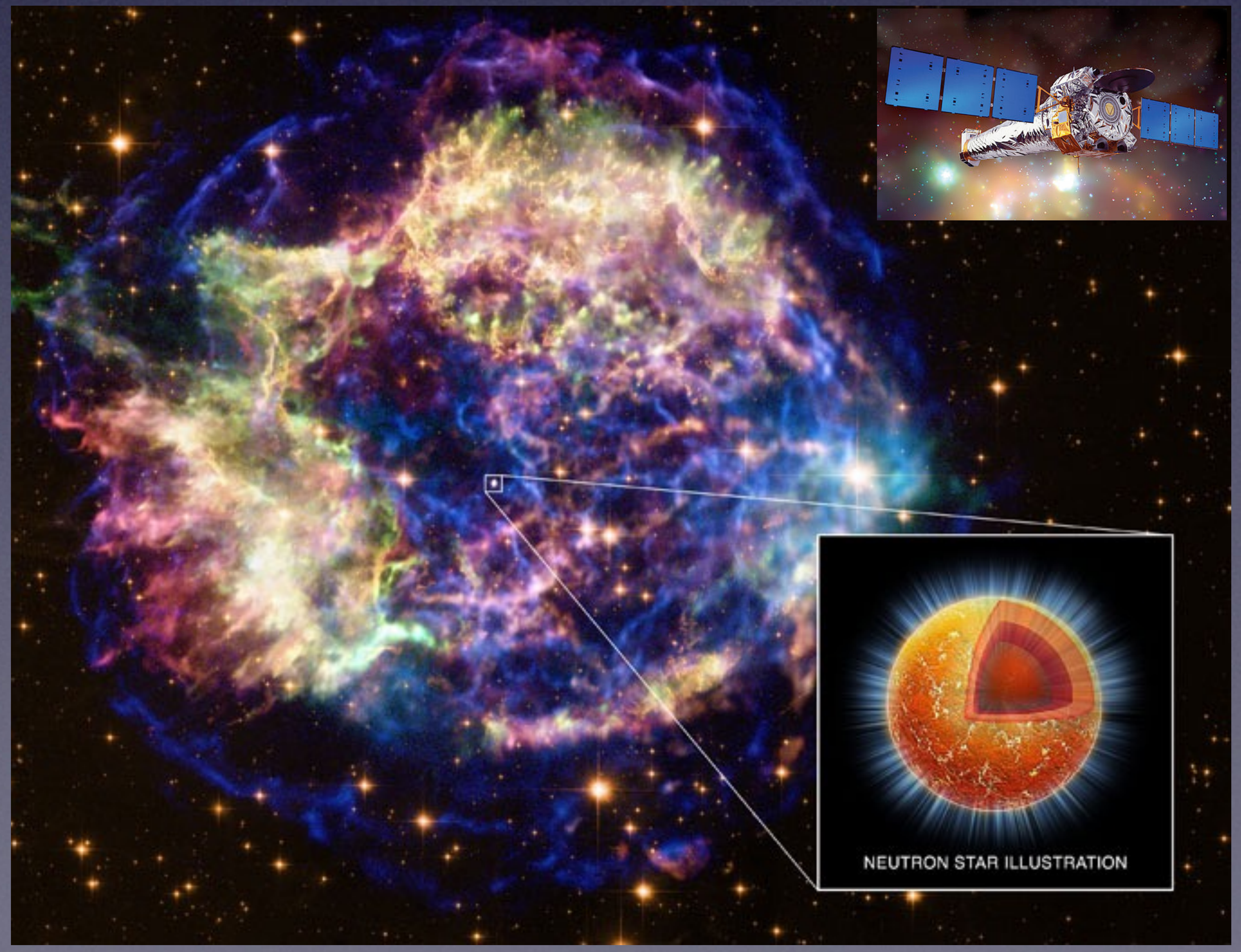
- Atmosphere (10 cm): Shapes Thermal Radiation ($L=4\pi\sigma R^2T^4$)
- Envelope (100 m): Huge Temperature Gradient (10^8K $\leftrightarrow$ 10^6K)
- Outer Crust (400 m): Coulomb Crystal (Exotic neutron-rich nuclei)
- Inner Crust (1 km): Coulomb Frustration ("Nuclear Pasta")
- Outer Core (10 km): Uniform Neutron-Rich Matter (n,p,e,μ)
- Inner Core (?): Exotic Matter (Hyperons, condensates, quark matter)

Supernova 1987a

- 12 anti-neutrinos from Kamiokande
- 8 anti-neutrinos from IMB
- 5 anti-neutrinos from Baksan
- (Arrival a few hours before the EM radiation)

Cassiopeia A (circa 1690)

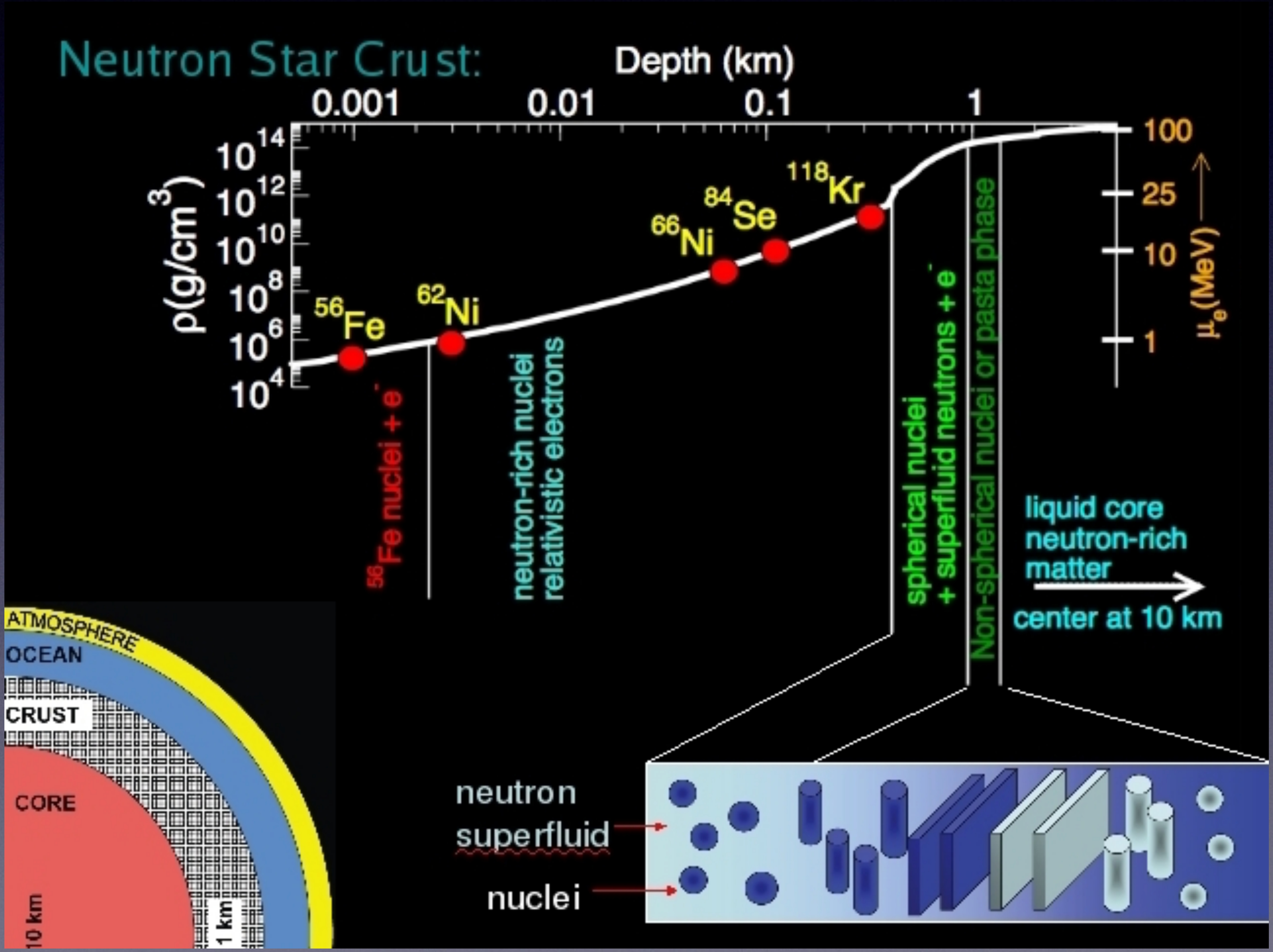
Very first light from Chandra X-ray telescope

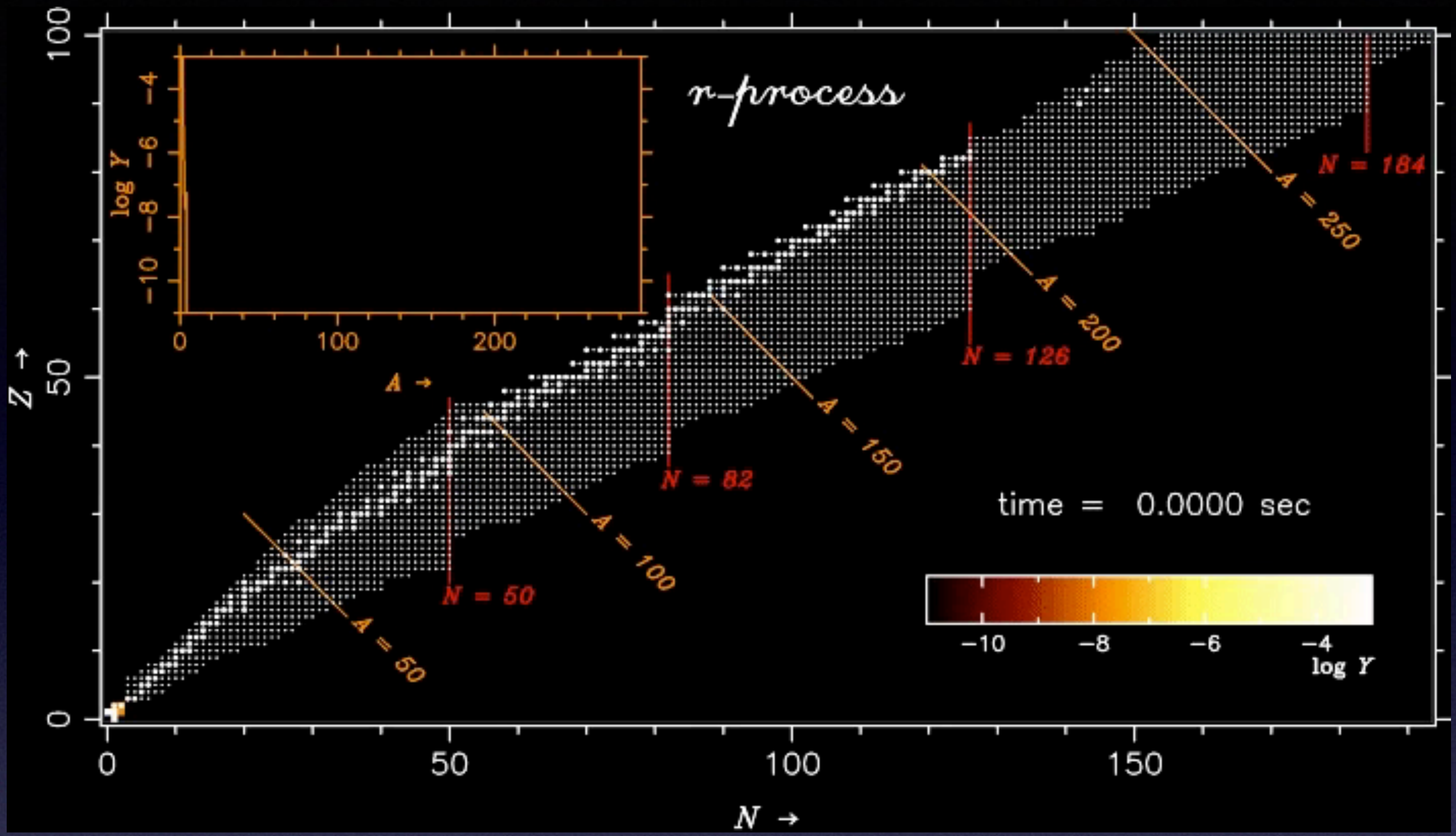


Neutron Stars: Unique Cosmic Laboratories

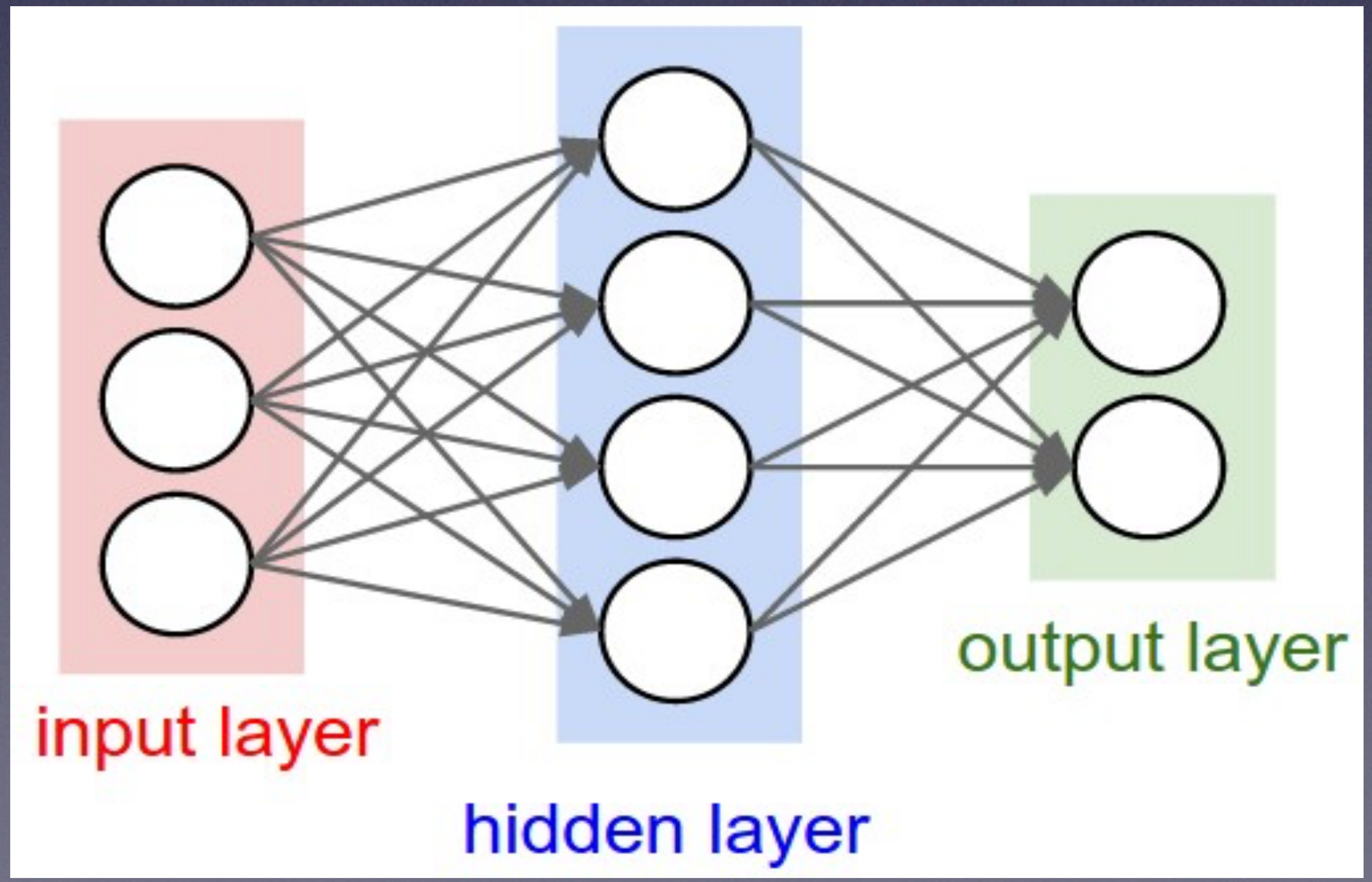
How Does Matter Organize Itself?

What is the ground state of matter at a given density?





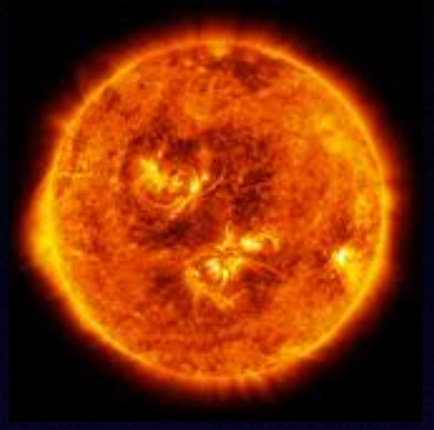
Experiment, Theory, and AI/ML



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

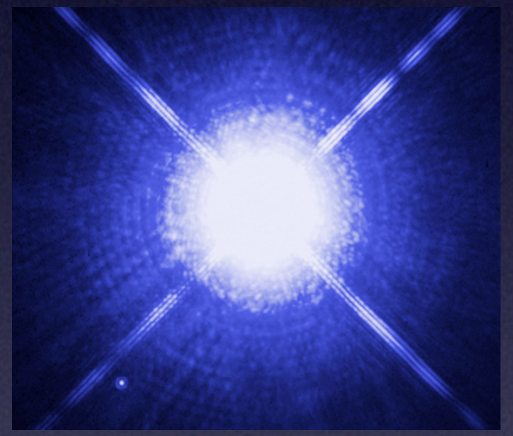
Equation of state: textbook examples

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



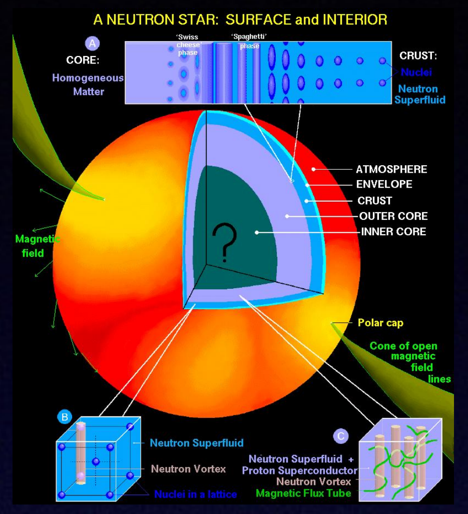
$$P(n,T) = nk_{\mathrm{B}}T \leftrightarrow P(\mathcal{E}) = \frac{2}{3}\mathcal{E}$$

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

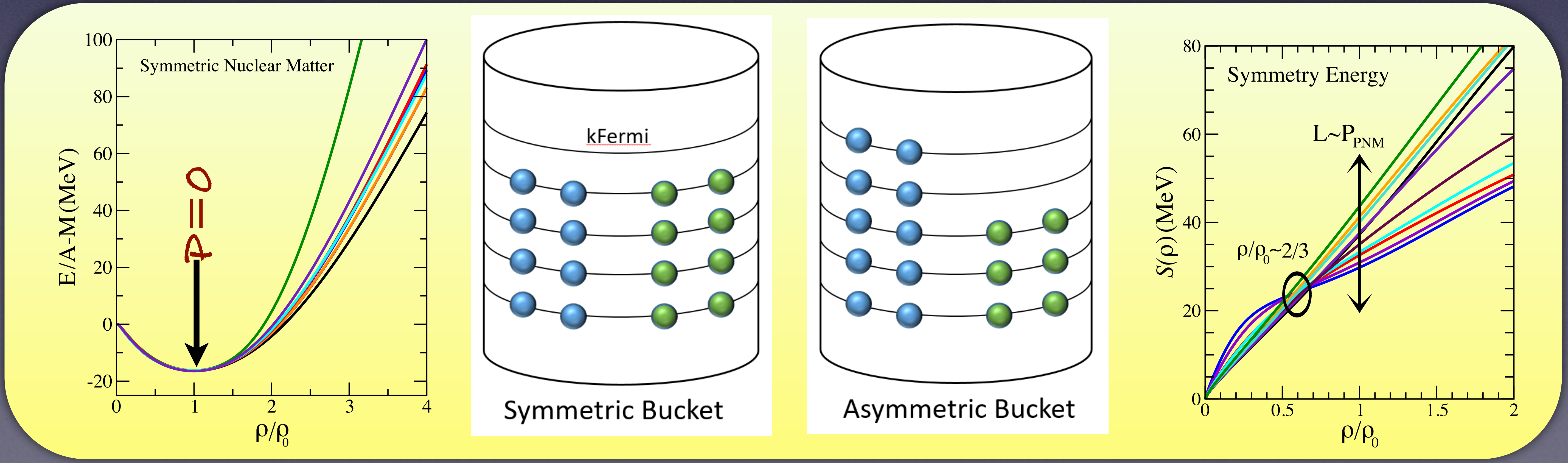


$$P(n,T\!=\!0) \approx n^{4/3} \leftrightarrow P(\mathcal{E}) = \frac{1}{3}\mathcal{E}$$

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



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

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

"Stiff" ⟶ L large

"Soft" ⟶ L small

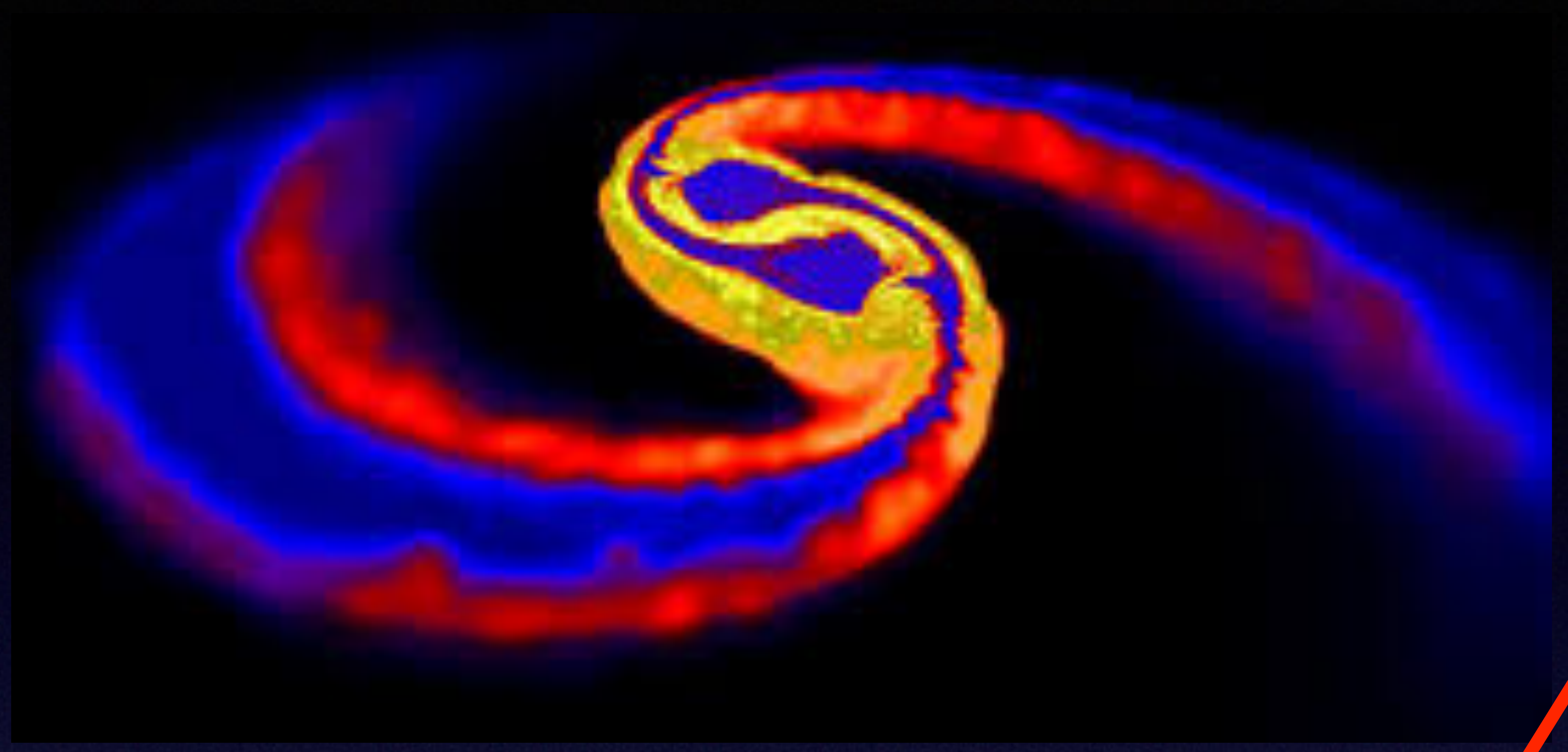
Tidal Polarizability and Neutron-Star Radii (2017)

Electric Polarizability:

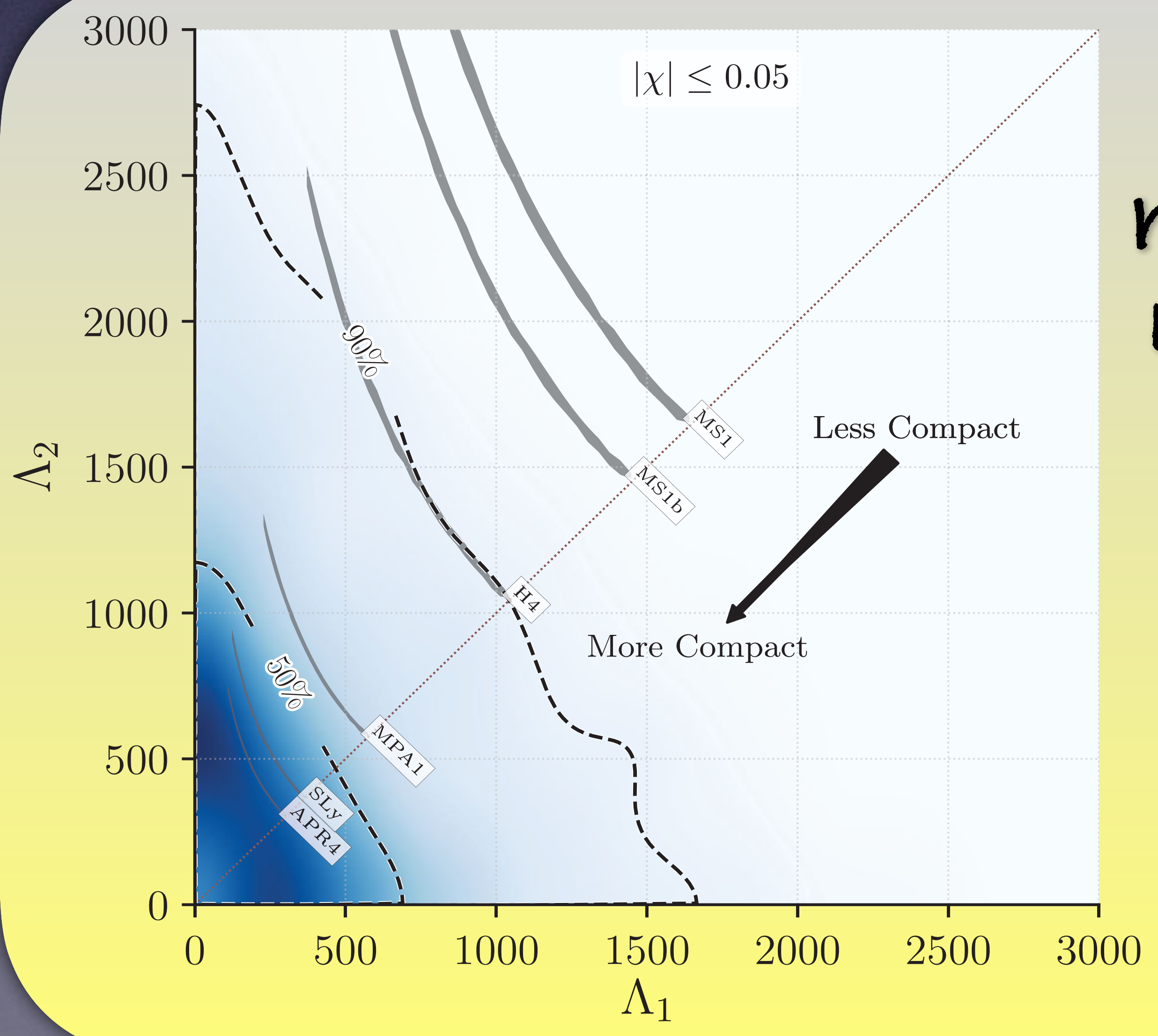
- Electric field induced a polarization of charge
- A time dependent electric dipole emits electromagnetic waves: $P_i = \chi E_i$

Tidal Polarizability (Deformability):

- Tidal field induces a polarization of mass
- A time dependent mass quadrupole emits gravitational waves: $Q_{ij} = \Lambda \mathcal{E}_{ij}$



$$\Lambda = k_2 \left(\frac{c^2 R}{2GM}\right)^5 = k_2 \left(\frac{R}{R_s}\right)^5$$



GW170817 rules out very large neutron star radii!

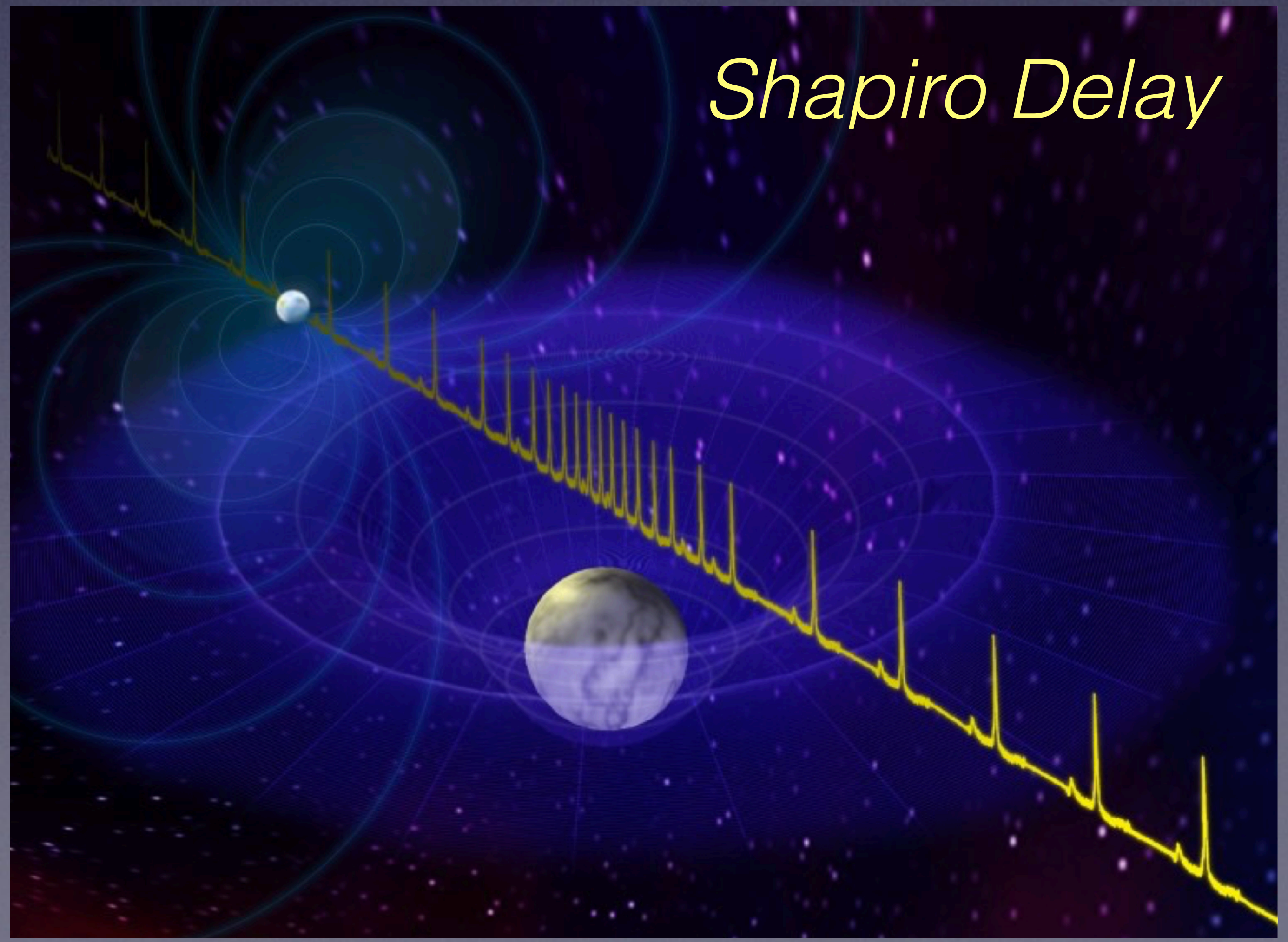
Neutron Stars must be compact

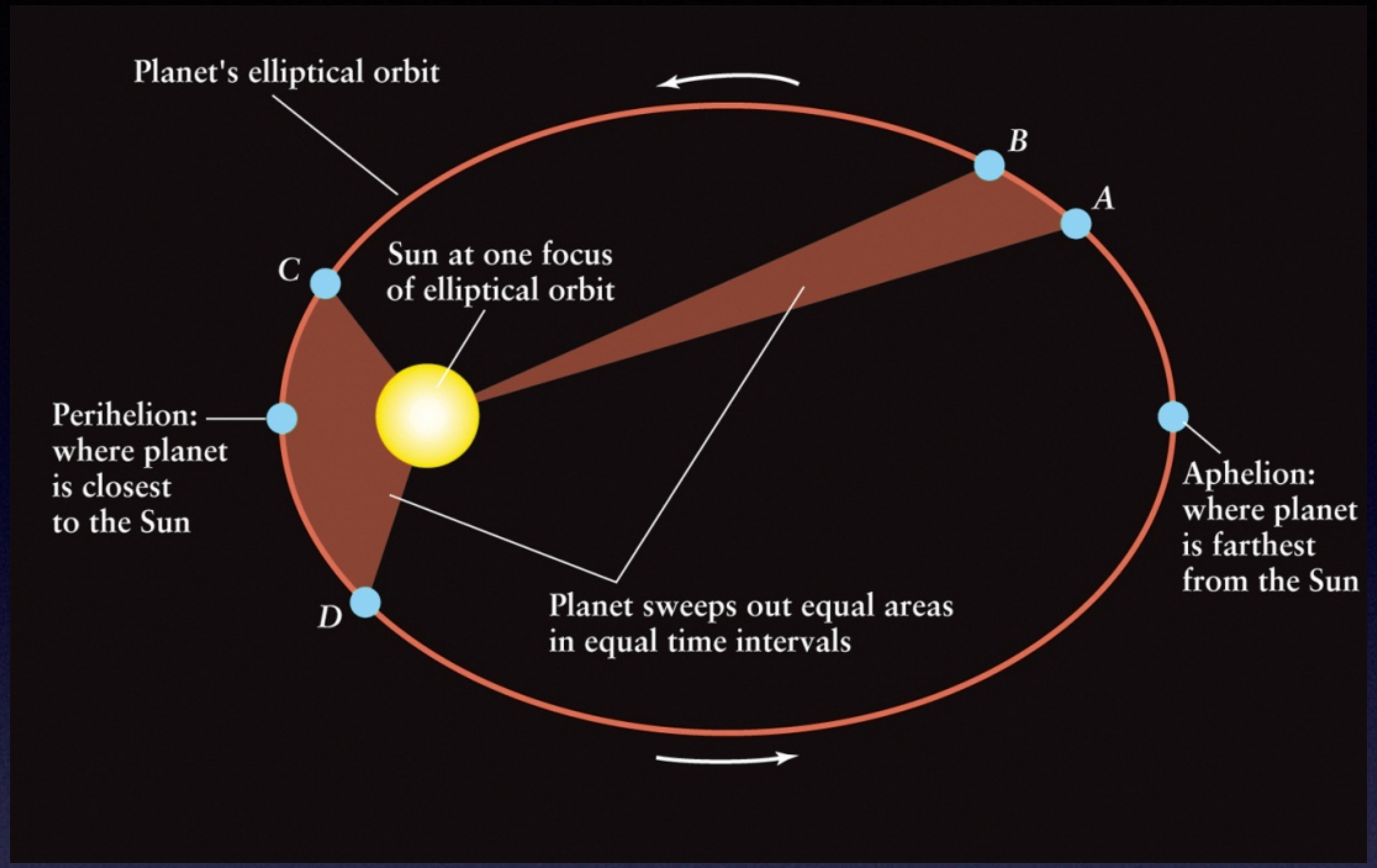
$$\Lambda_{1.4} = 390^{+190}_{-120}\ (90\%)$$

(Latest LIGO/Virgo analysis)

The tidal polarizability measures the "fluffiness" (or stiffness) of a neutron star against deformation. Very sensitive to stellar radius!

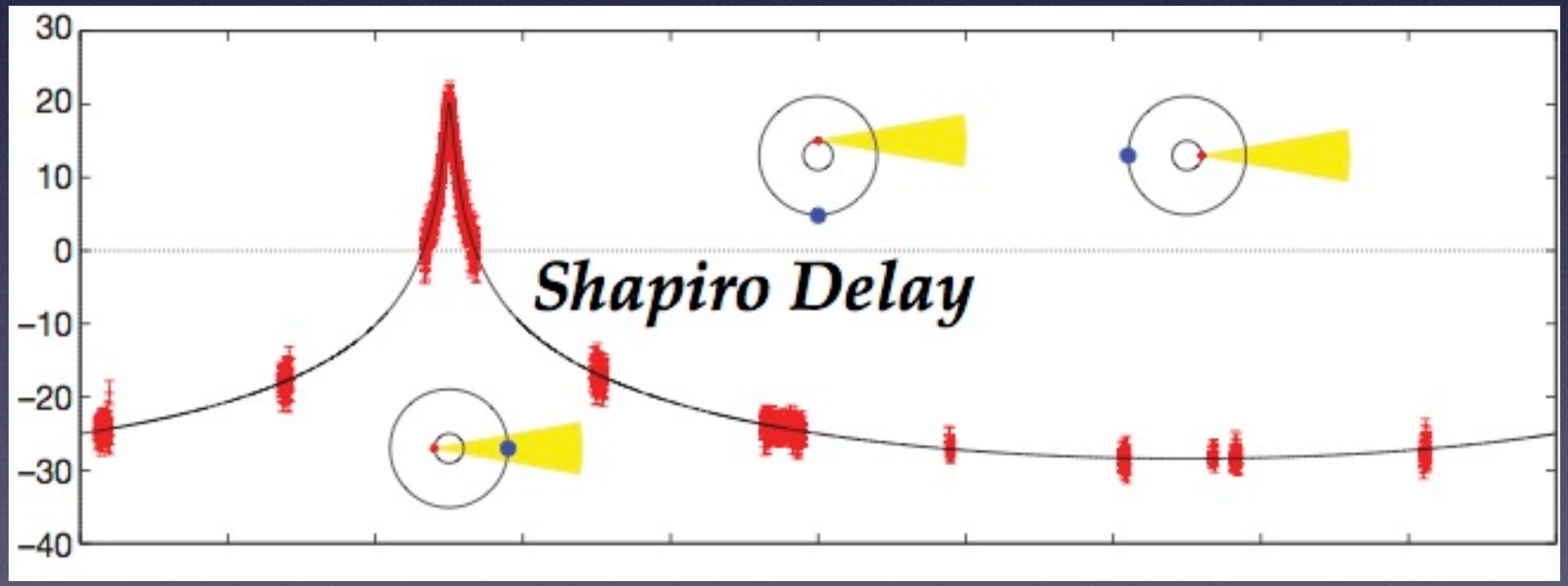
Measuring Heavy Neutron Stars (2019)
Shapiro Delay: General Relativity to the Rescue





Newtonian Gravity sensitive to the total mass of the binary
Kepler's Third Law

$$G(M_{\rm ns}+M_{\rm wd}) = 4\pi^2\frac{a^3}{P^2}$$



Shapiro delay — a purely General Relativistic effect can break the degeneracy

$$\delta t = \frac{GM_{\rm wd}}{c^3}\ln\left(\frac{4r_1r_2}{d^2}\right) \approx 10\mu s$$

Cromartie/Fonseca et al. (2020)

$$M = 2.08 \pm 0.07 M_\odot$$

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

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

$$M = 2.08 \pm 0.07\, M_\odot$$

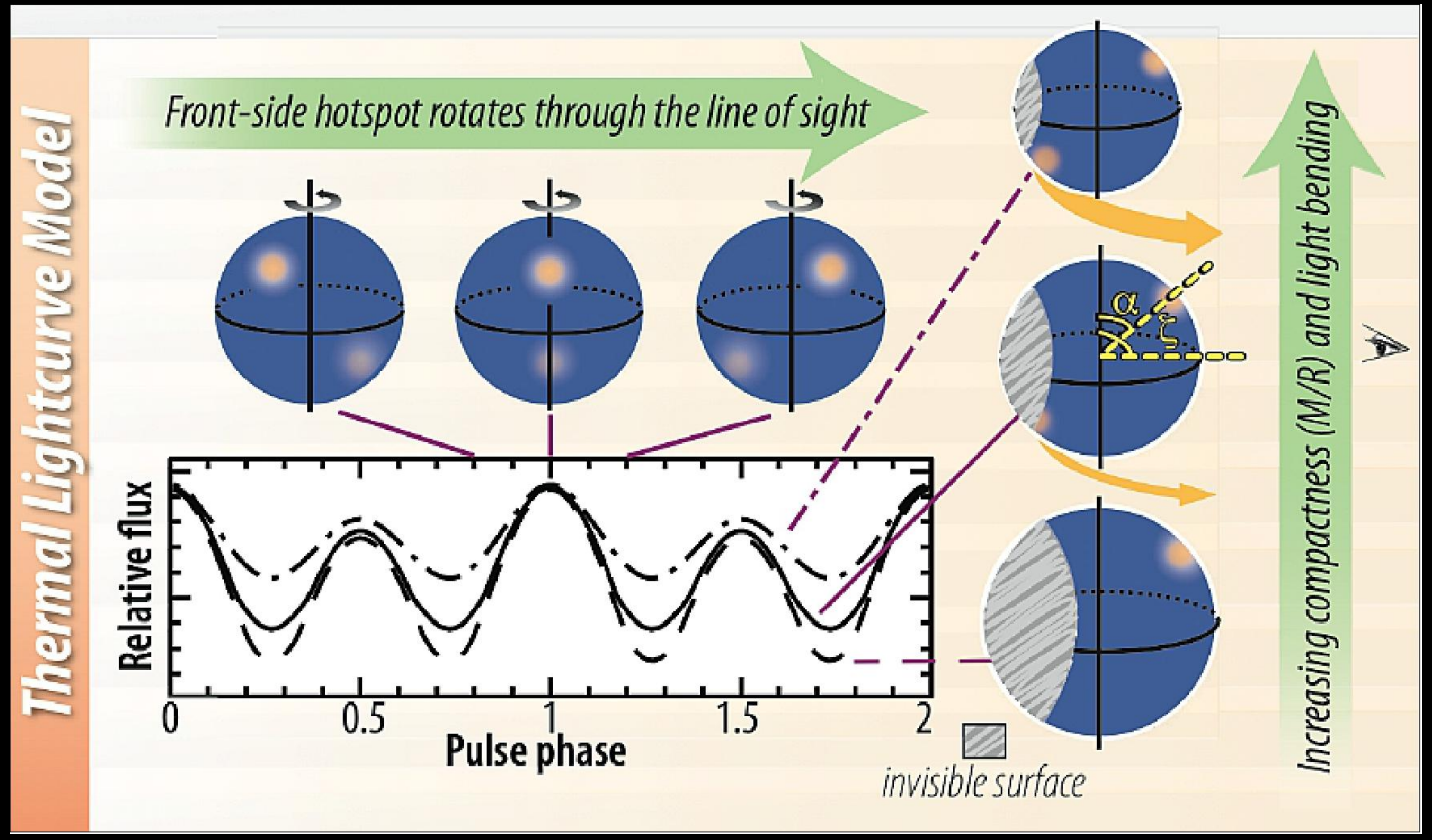
Shapiro delay: Cromartie *et al.* (2020)

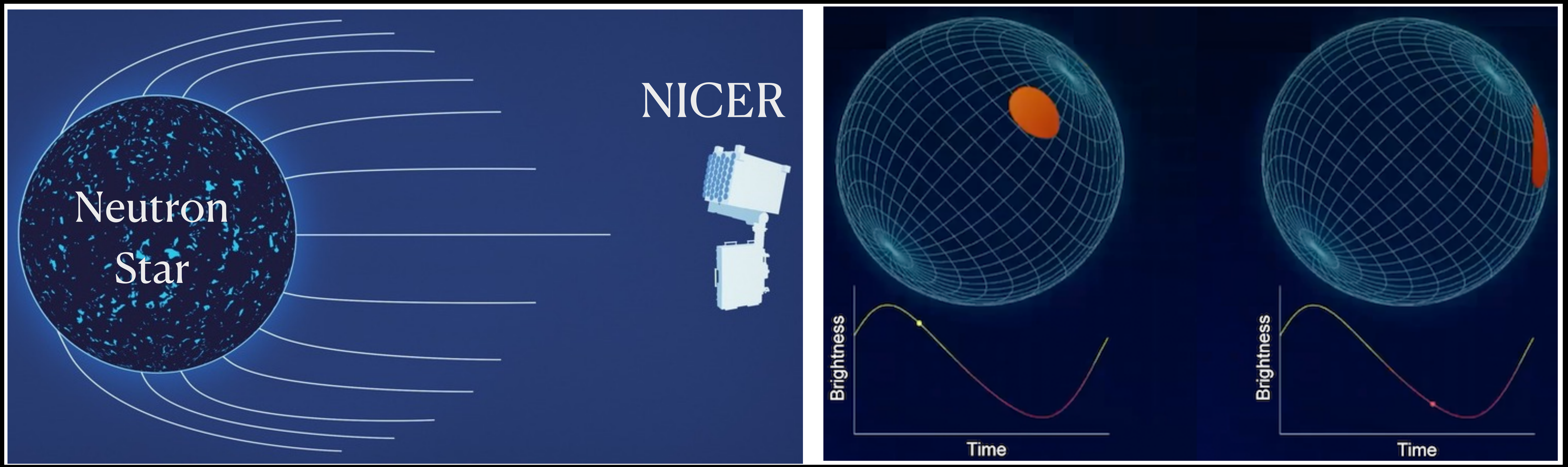
$$R_{2.0} = 12.39^{+1.30}_{-0.98}\ \mathrm{km}$$

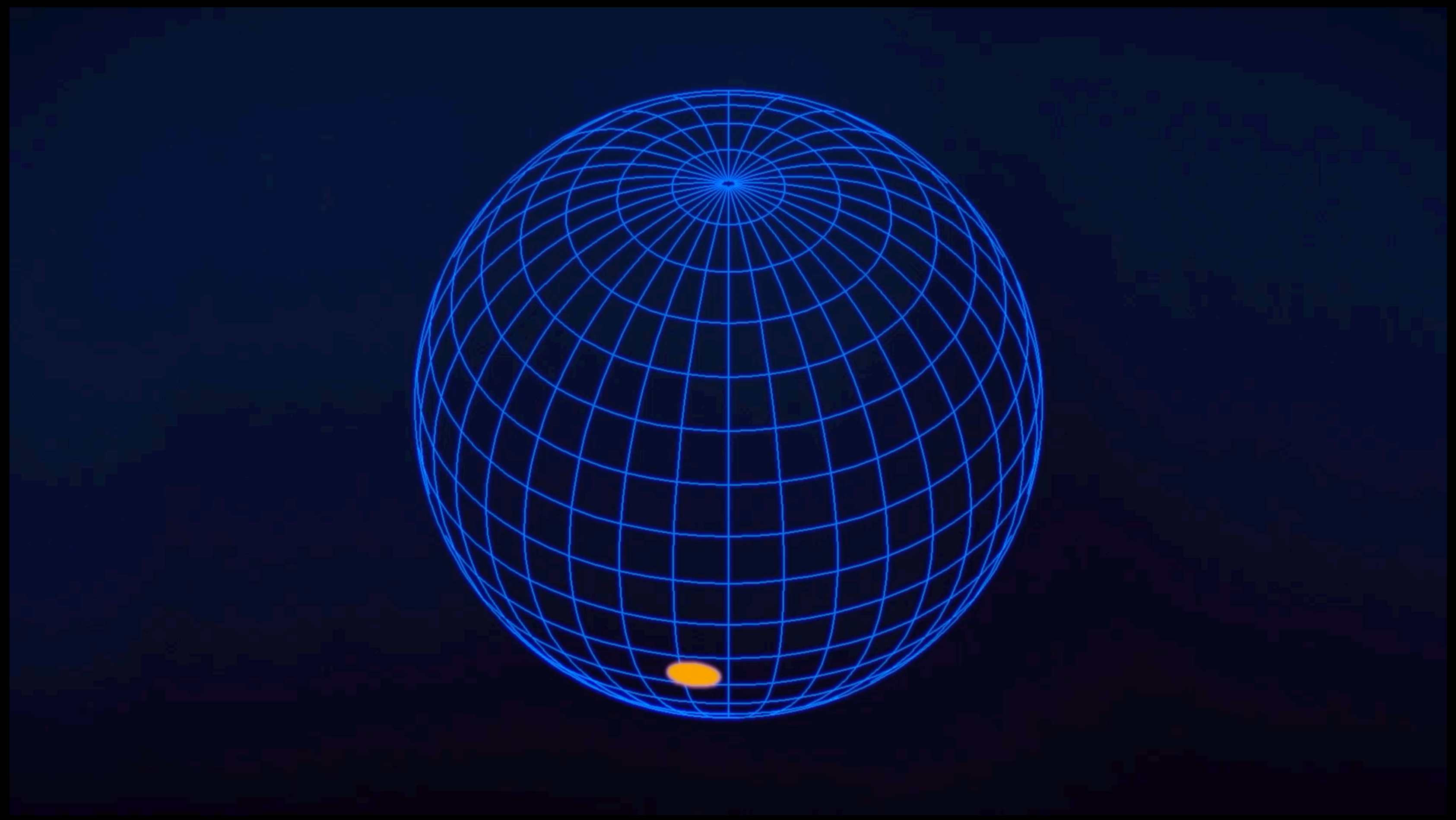
Riley *et al.* (2021)

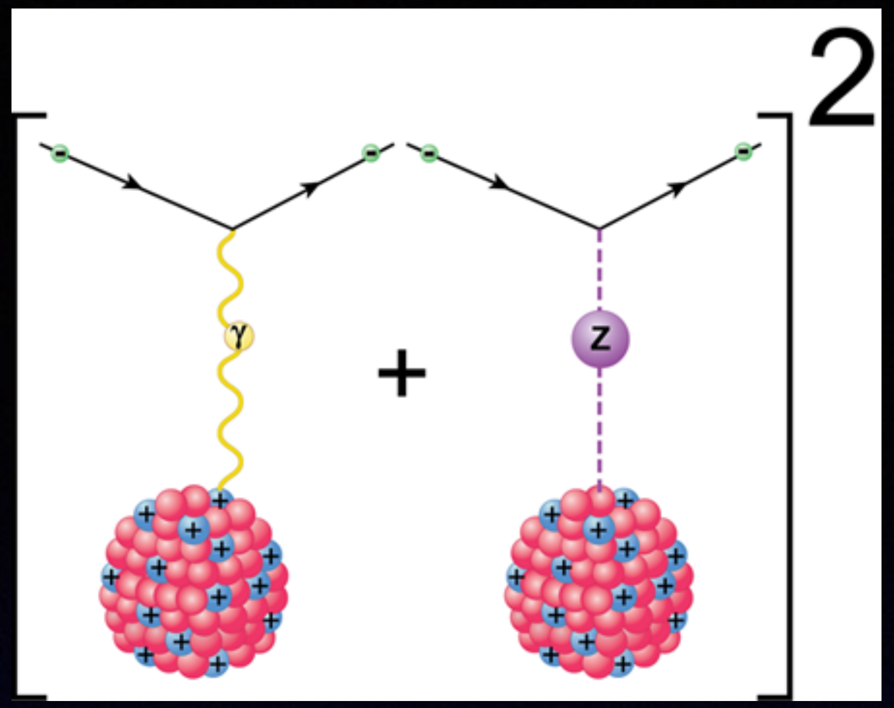
$$R_{2.0} = 13.7^{+2.6}_{-1.5}\ \mathrm{km}$$

Miller *et al.* (2021)









Parity Violating e-Nucleus Scattering

Searching fo our most accurate picture of the nuclear weak-charge distribution!

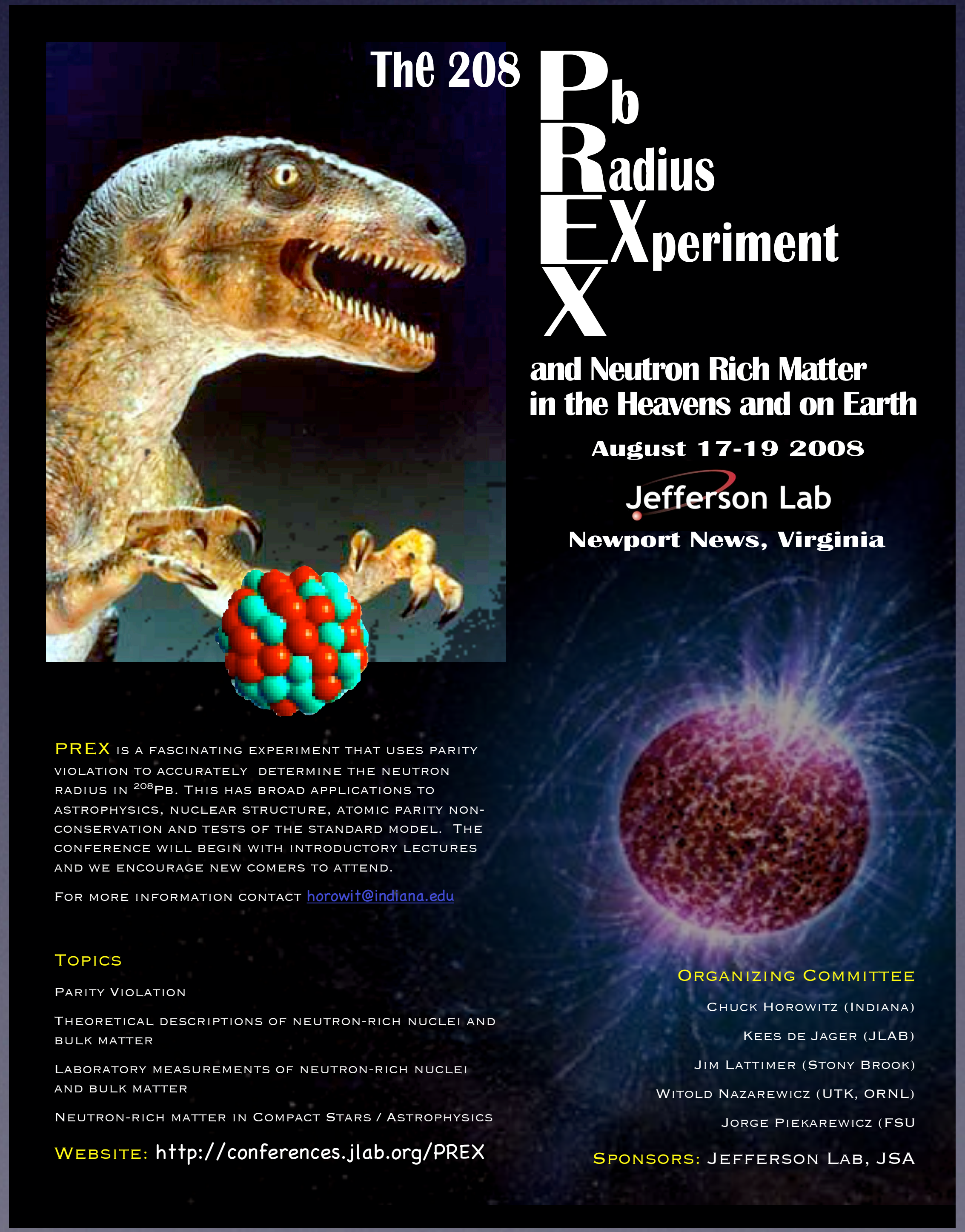
1979 Nobel Prize
EW unification

- Charge (proton) density known with enormous precision
  - Probed via parity-conserving elastic e-scattering
- Weak-charge (neutron) density known very poorly known
  - Probed via parity-violating asymmetry in elastic e-scattering
  - Z_0 couples preferentially to neutrons in the target

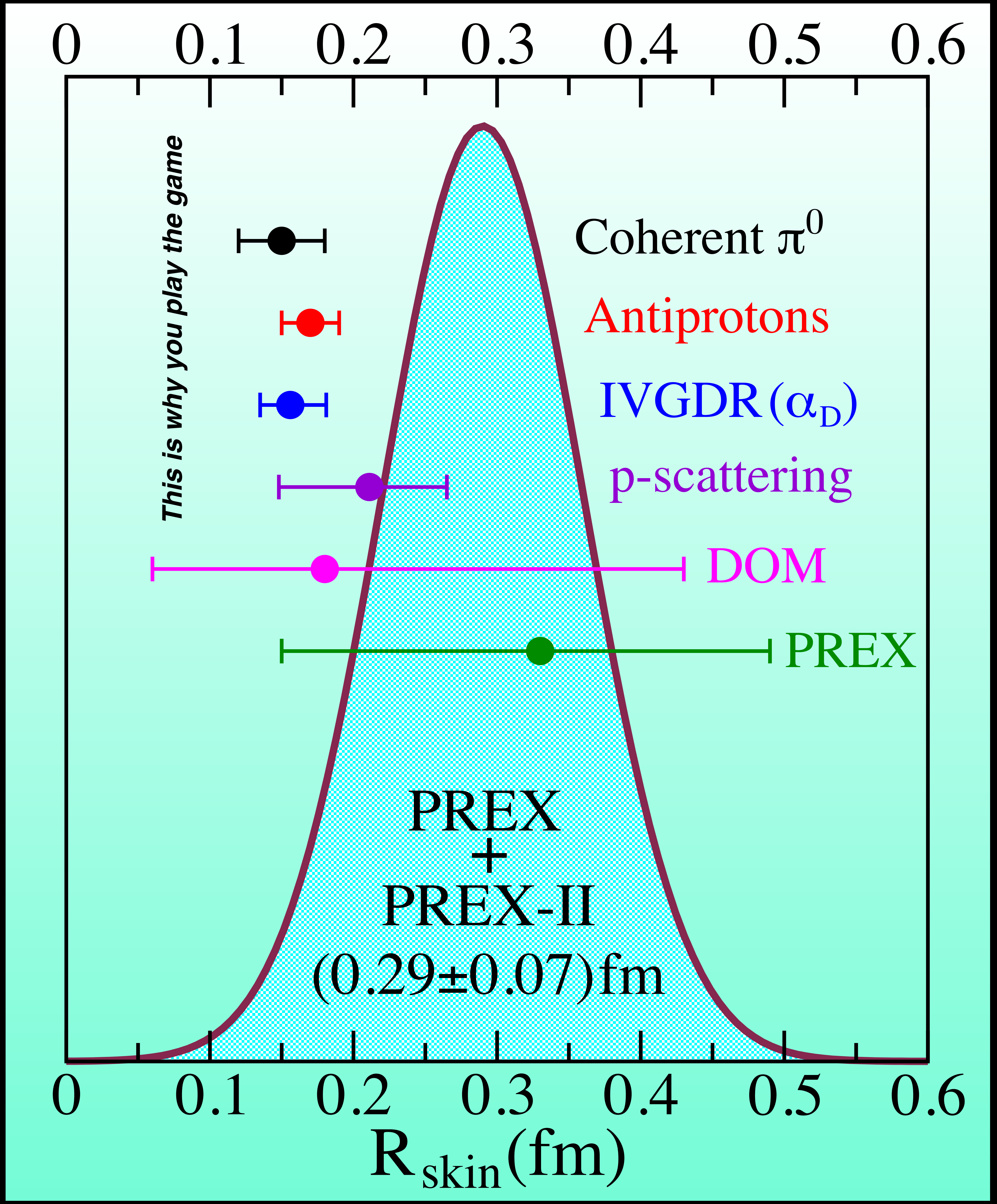
$$A_{\mathrm{PV}} \equiv \left[\frac{\left(\frac{d\sigma}{d\Omega}\right)_R - \left(\frac{d\sigma}{d\Omega}\right)_L}{\left(\frac{d\sigma}{d\Omega}\right)_R + \left(\frac{d\sigma}{d\Omega}\right)_L}\right] = \left(\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\right)\frac{F_{wk}(Q^2)}{F_{ch}(Q^2)} \simeq 10^{-6}$$

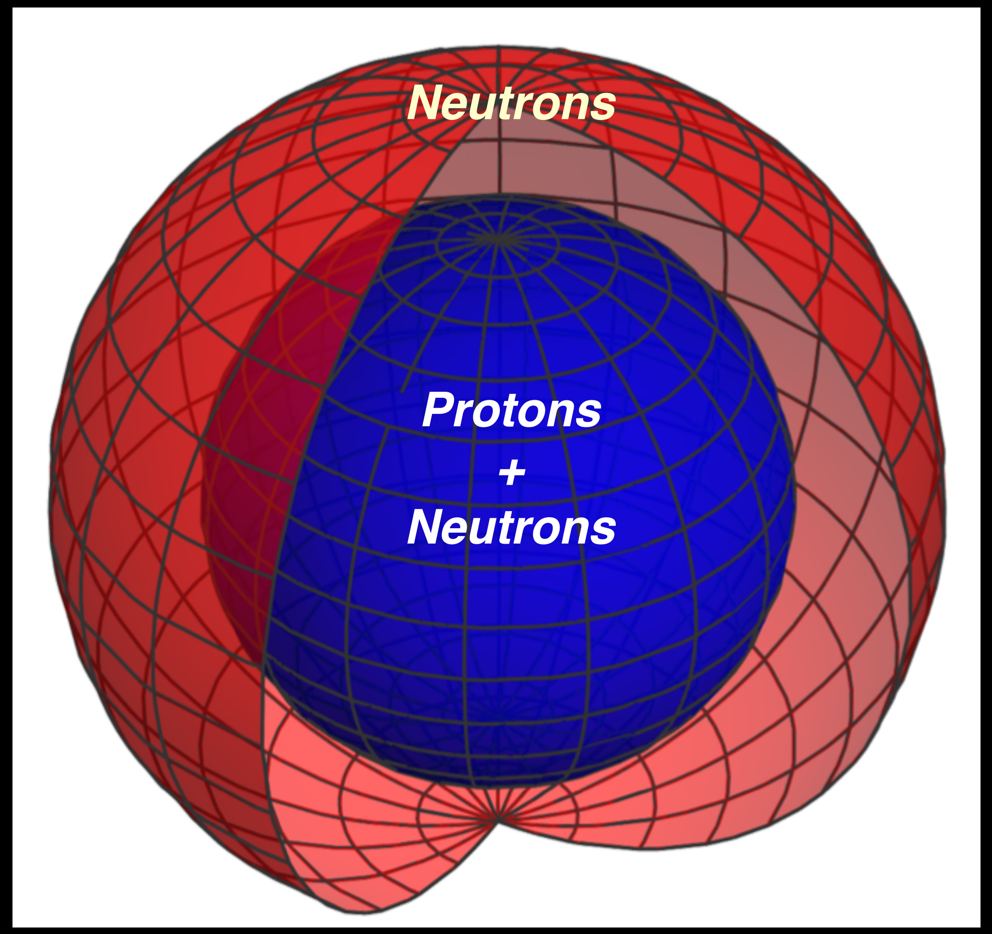
	up-quark	down-quark	proton	neutron
γ-coupling	$+2/3$	$-1/3$	$+1$	0
Z_0-coupling	$\approx +1/3$	$\approx -2/3$	≈ 0	-1

$$g_{\mathrm{v}} = 2t_z - 4Q\sin^2\theta_{\mathrm{W}} \approx 2t_z - Q$$



The neutron skin thickness of ^{208}Pb (Z=82, N=126)





Heroic effort from our experimental colleagues