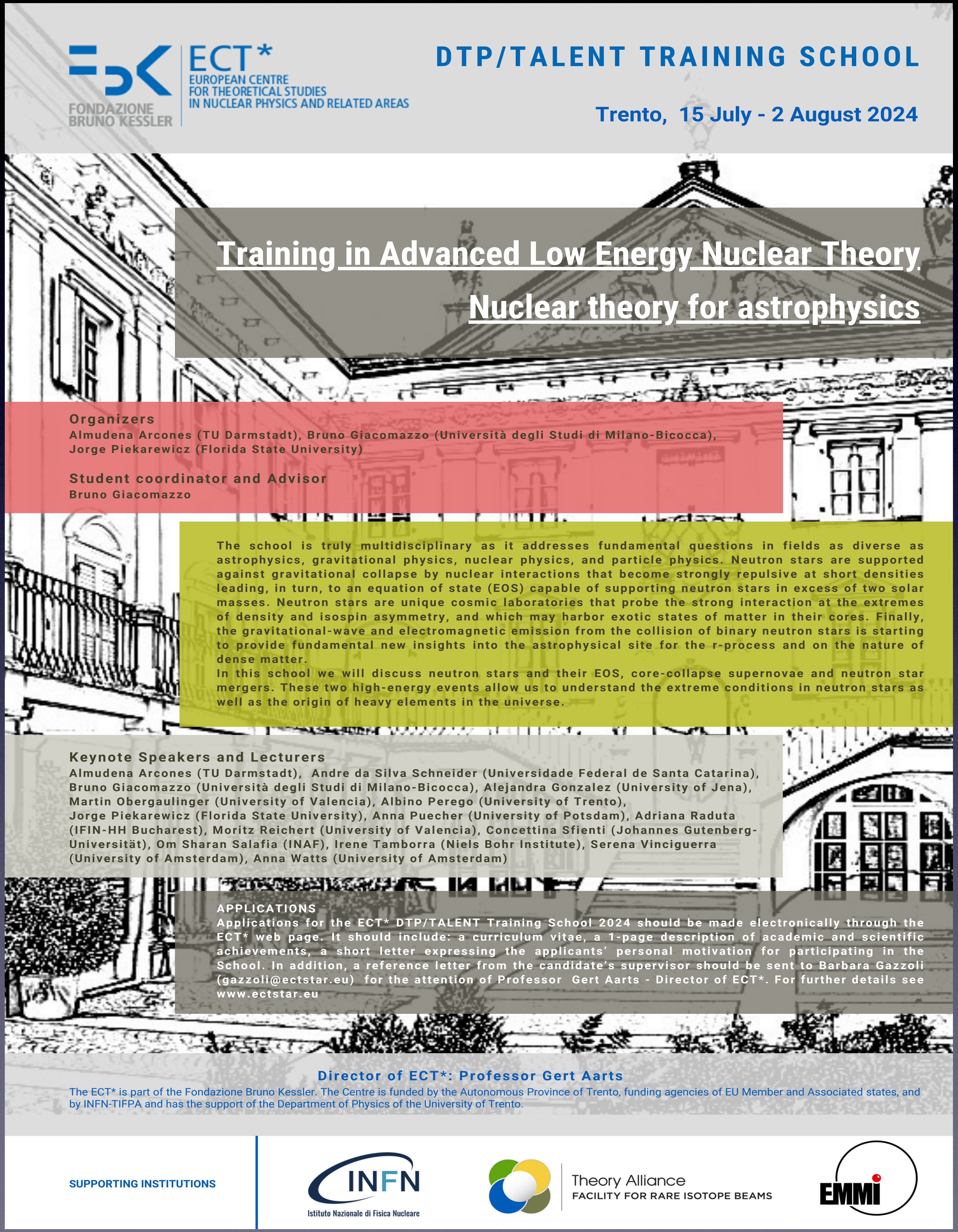
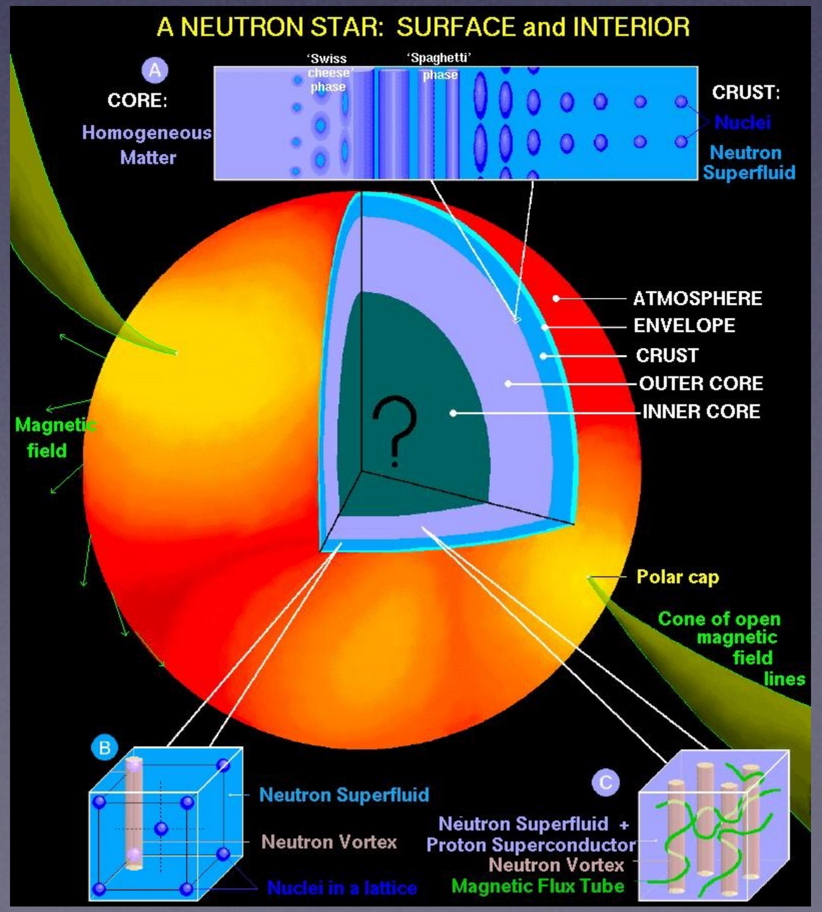
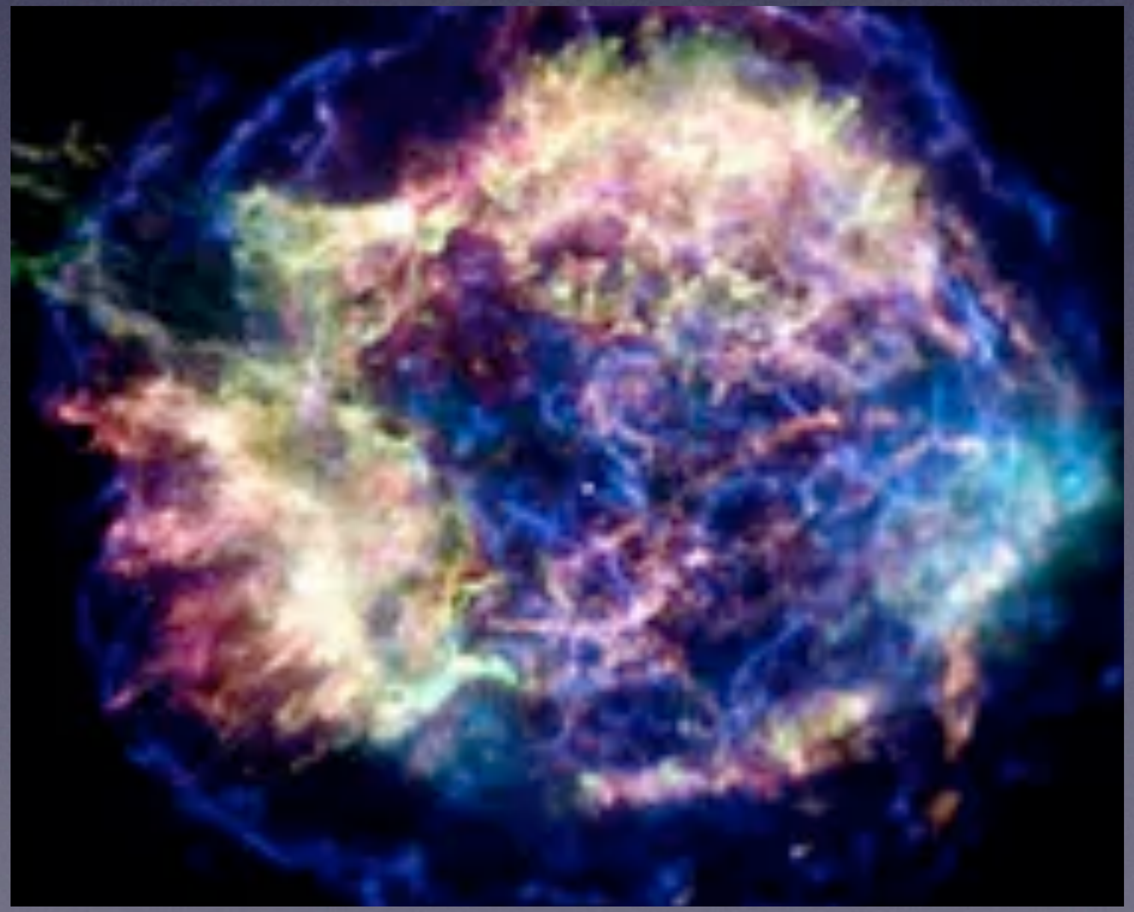
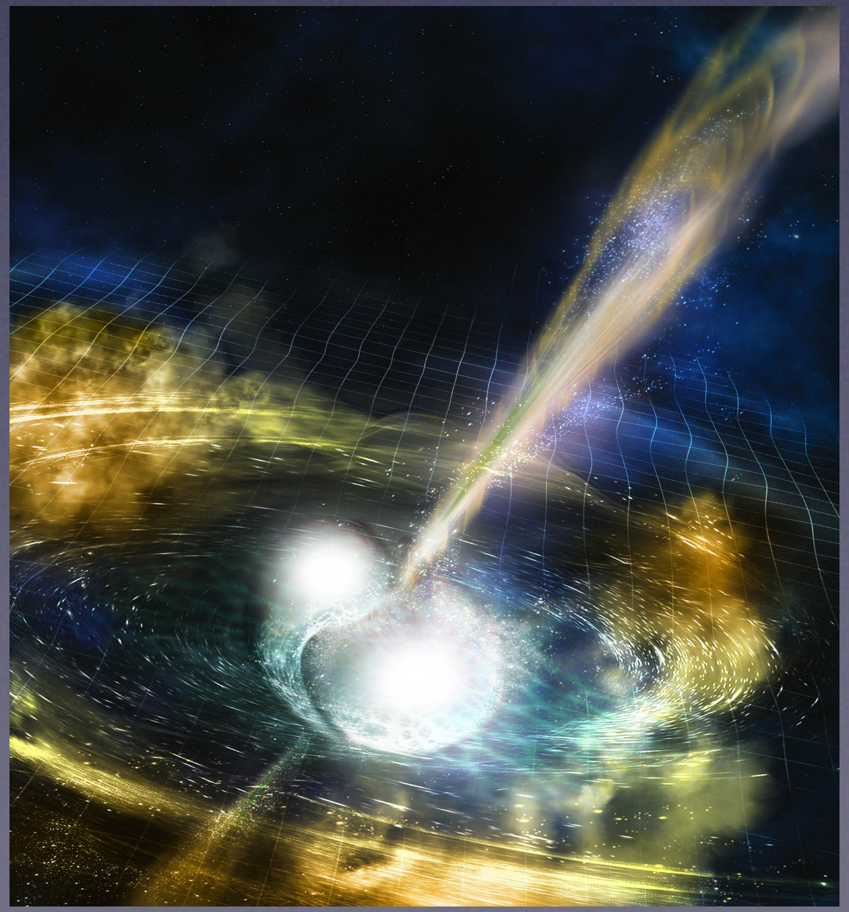
Nuclear Theory for Astrophysics



Welcome students to your new home for the next three weeks!







TALENT SCHOOL: Nuclear Theory for Astrophysics

The school is truly multidisciplinary as it addresses fundamental questions in fields as diverse as astrophysics, gravitational physics, nuclear physics, and particle physics. Neutron stars are supported against gravitational collapse by nuclear interactions that become strongly repulsive at short densities leading, in turn, to an equation of state (EOS) capable of supporting neutron stars in excess of two solar masses. Neutron stars are unique cosmic laboratories that probe the strong interaction at the extremes of density and isospin asymmetry, and which may harbor exotic states of matter in their cores. Finally, the gravitational-wave and electromagnetic emission from the collision of binary neutron stars is starting to provide fundamental new insights into the astrophysical site for the r-process and on the nature of dense matter.

In this school we will discuss neutron stars and their EOS, core-collapse supernovae and neutron star mergers. These two high-energy events allow us to understand the extreme conditions in neutron stars as well as the origin of heavy elements in the universe.

Keynote Speakers and Lecturers

Almudena Arcones (TU Darmstadt), Andre da Silva Schneider (Universidade Federal de Santa Catarina), Bruno Giacomazzo (Università degli Studi di Milano-Bicocca), Alejandra Gonzalez (University of Jena), Martin Obergaulinger (University of Valencia), Albino Perego (University of Trento), Jorge Piekarewicz (Florida State University), Anna Puecher (University of Potsdam), Adriana Raduta (IFIN-HH Bucharest), Moritz Reichert (University of Valencia), Concettina Sfienti (Johannes Gutenberg-Universität), Om Sharan Salafia (INAF), Irene Tamborra (Niels Bohr Institute), Serena Vinciguerra (University of Amsterdam), Anna Watts (University of Amsterdam)


DTP/TALENT TRAINING SCHOOL

ECT* EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

FONDAZIONE BRUNO KESSLER

Trento, 15 July - 2 August 2024

Training in Advanced Low Energy Nuclear Theory

Nuclear theory for astrophysics

Organizers
Almudena Arcones (TU Darmstadt), Bruno Giacomazzo (Università degli Studi di Milano-Bicocca), Jorge Piekarewicz (Florida State University)

Student coordinator and Advisor
Bruno Giacomazzo

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APPLICATIONS
Applications for the ECT* DTP/TALENT Training School 2024 should be made electronically through the ECT* web page. It should include: a curriculum vitae, a 1-page description of academic and scientific achievements, a short letter expressing the applicants' personal motivation for participating in the School. In addition, a reference letter from the candidate's supervisor should be sent to Barbara Gazzoli (gazzoli@ectstar.eu) for the attention of Professor Gert Aarts - Director of ECT*. For further details see www.ectstar.eu

Director of ECT*: Professor Gert Aarts

The ECT* is part of the Fondazione Bruno Kessler. The Centre is funded by the Autonomous Province of Trento, funding agencies of EU Member and Associated states, and by INFN-TIFPA and has the support of the Department of Physics of the University of Trento.

SUPPORTING INSTITUTIONS

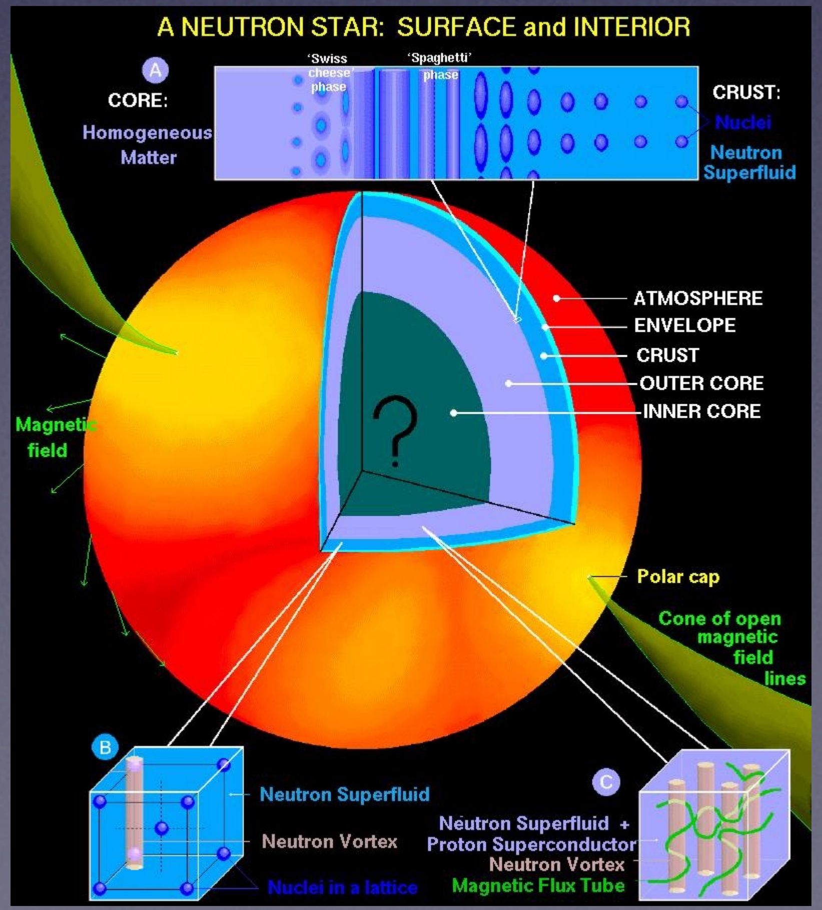
INFN Istituto Nazionale di Fisica Nucleare

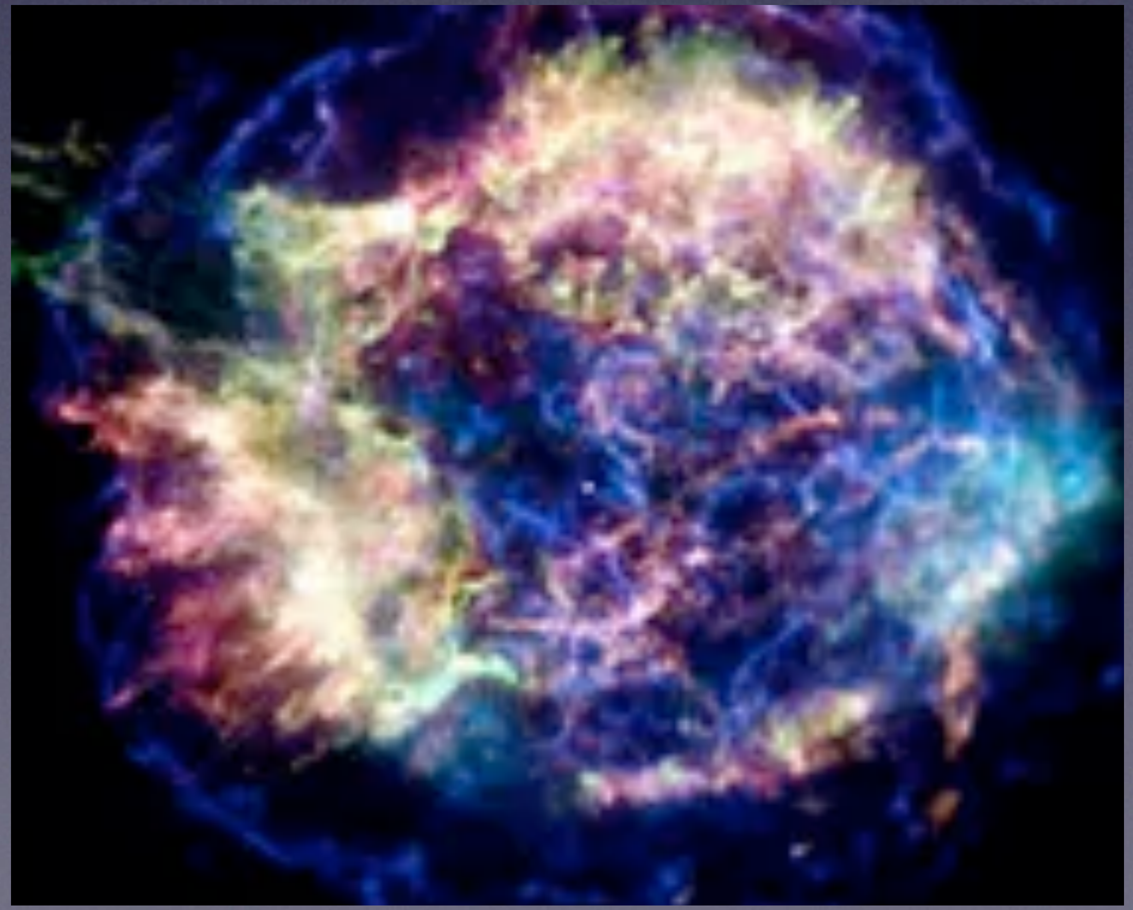
Theory Alliance FACILITY FOR RARE ISOTOPE BEAMS

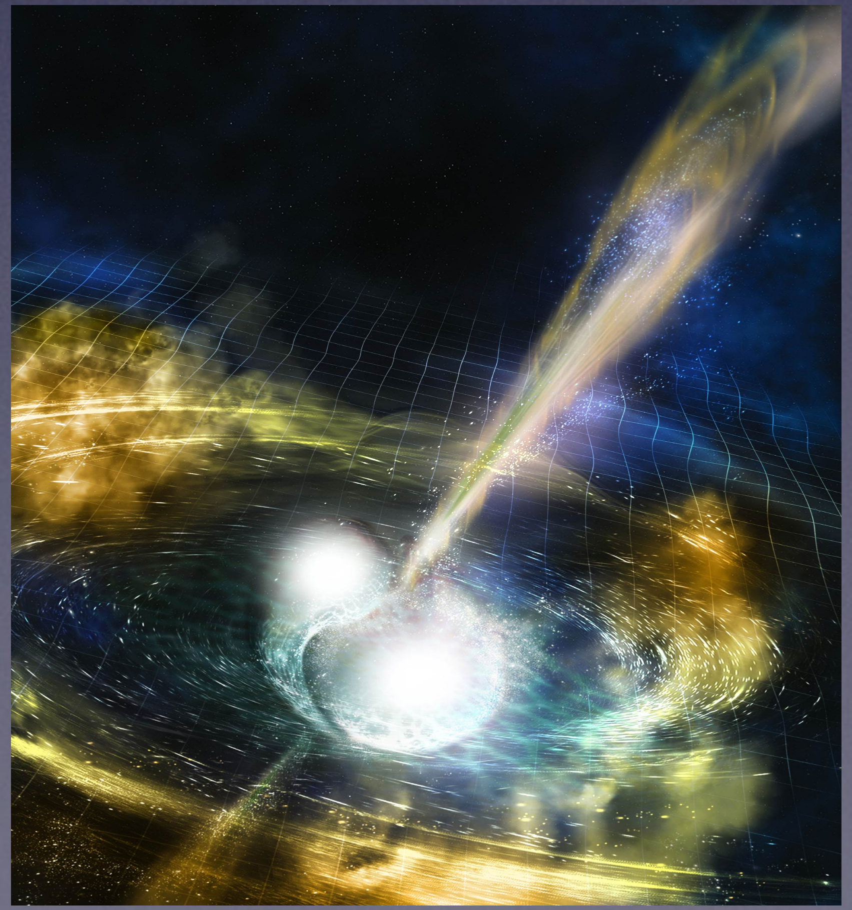
EMMI

Nuclear Theory for Astrophysics

- ***First Week: Heaven and Earth — Informing the Equation of State of NS Matter***
  (Adriana, Anna, Concettina, Serena; Jorge)
- ***Second Week: Core Collapse Supernovae***
  (Andre, Francesco, Martin, Moritz; Almudena)
- ***Third Week: Neutron Star Mergers***
  (Albino, Alejandra, Om; Bruno)

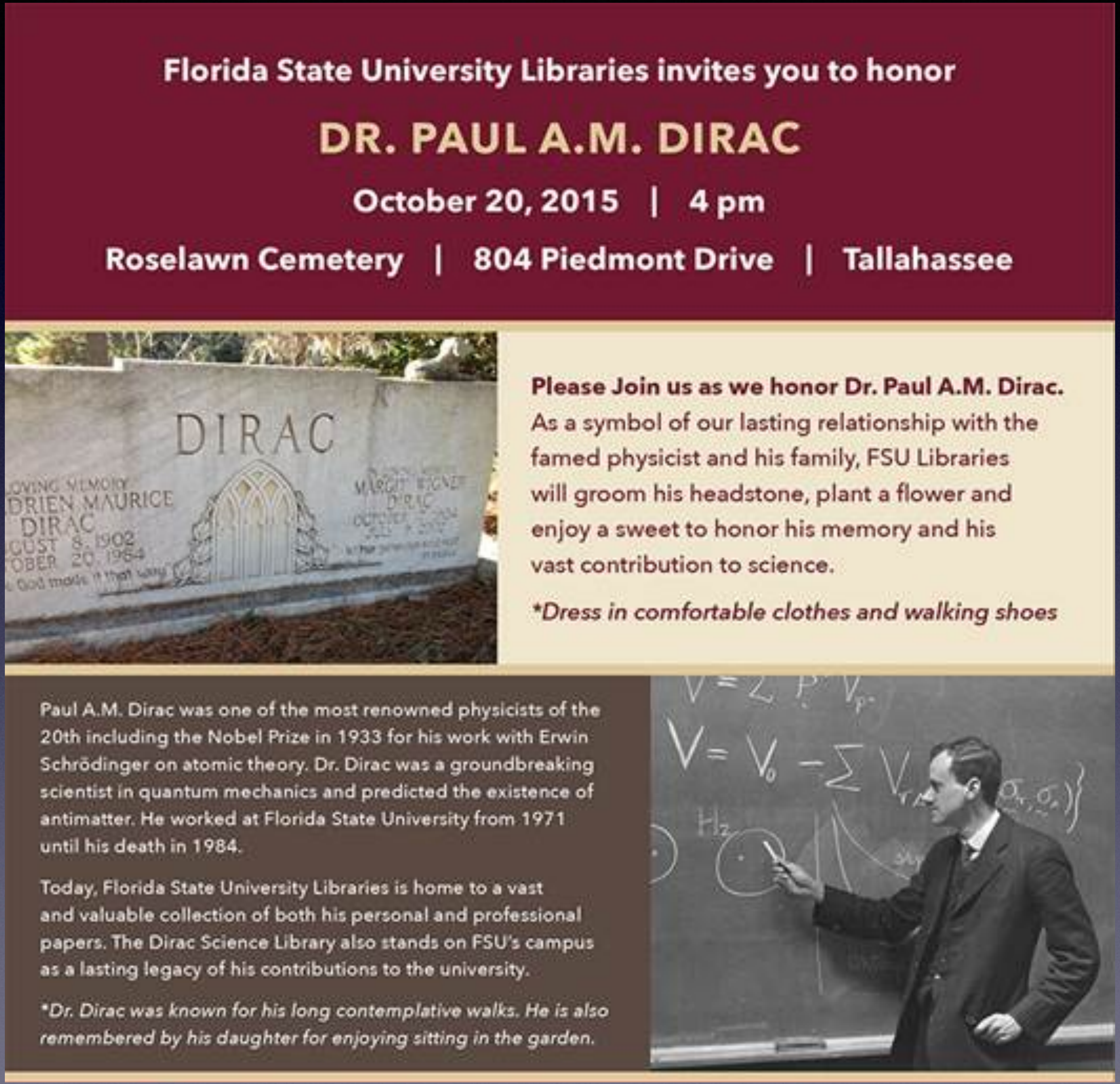


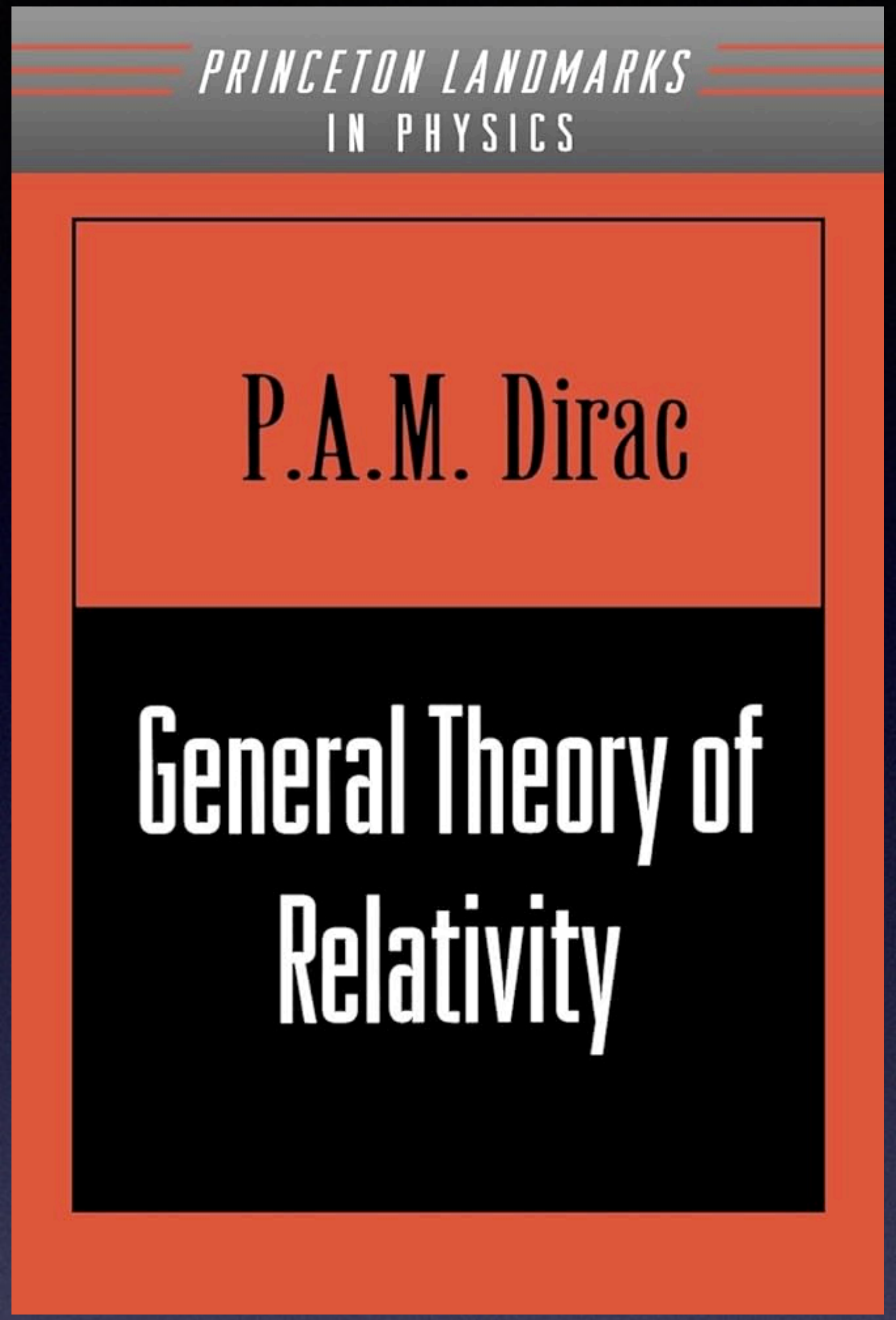




Lectures will attempt to provide an overall (personal) picture of the field

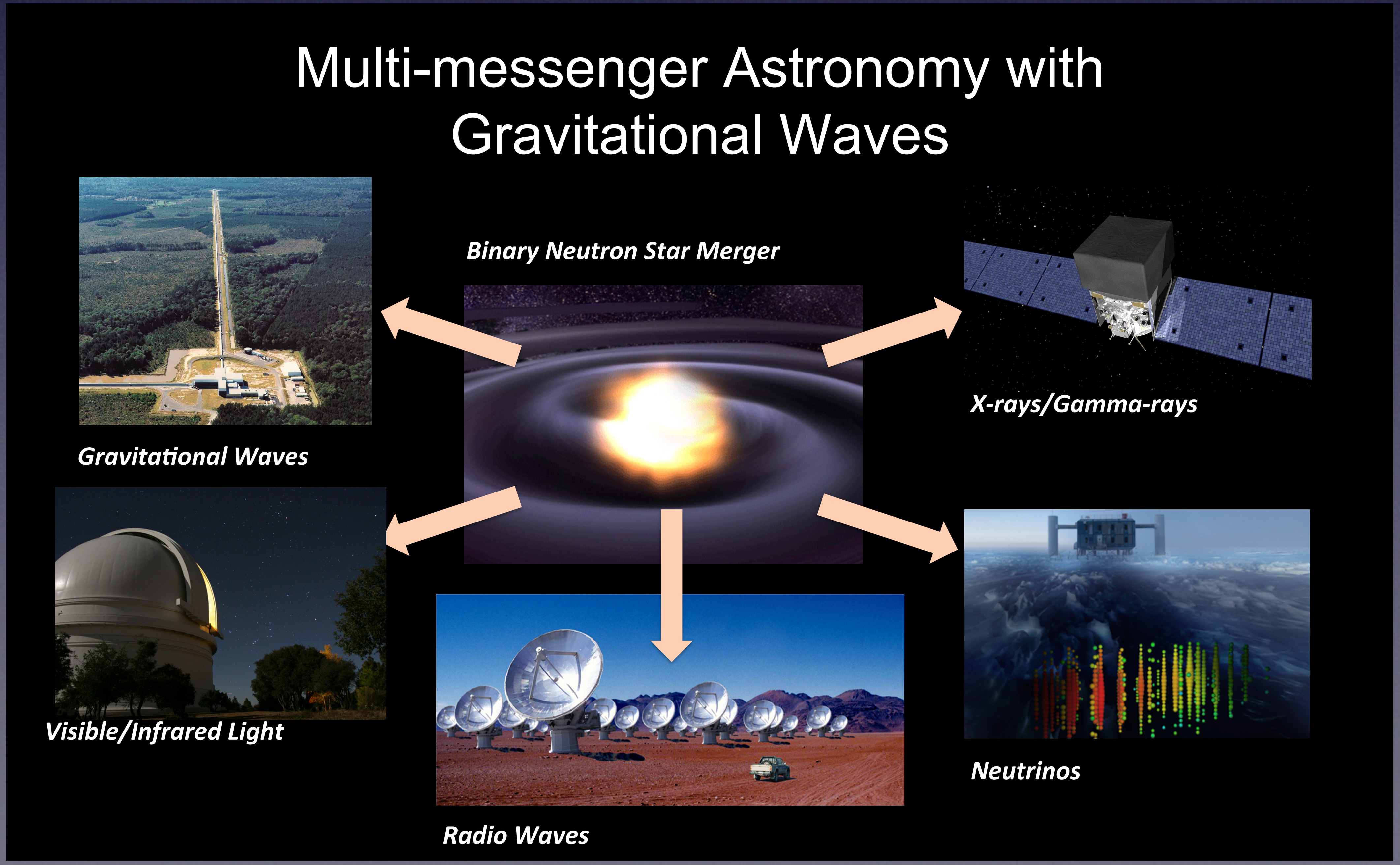
P.A.M. Dirac — Tallahassee most famous resident!





Wigner and Moshinsky

My Students and Collaborators

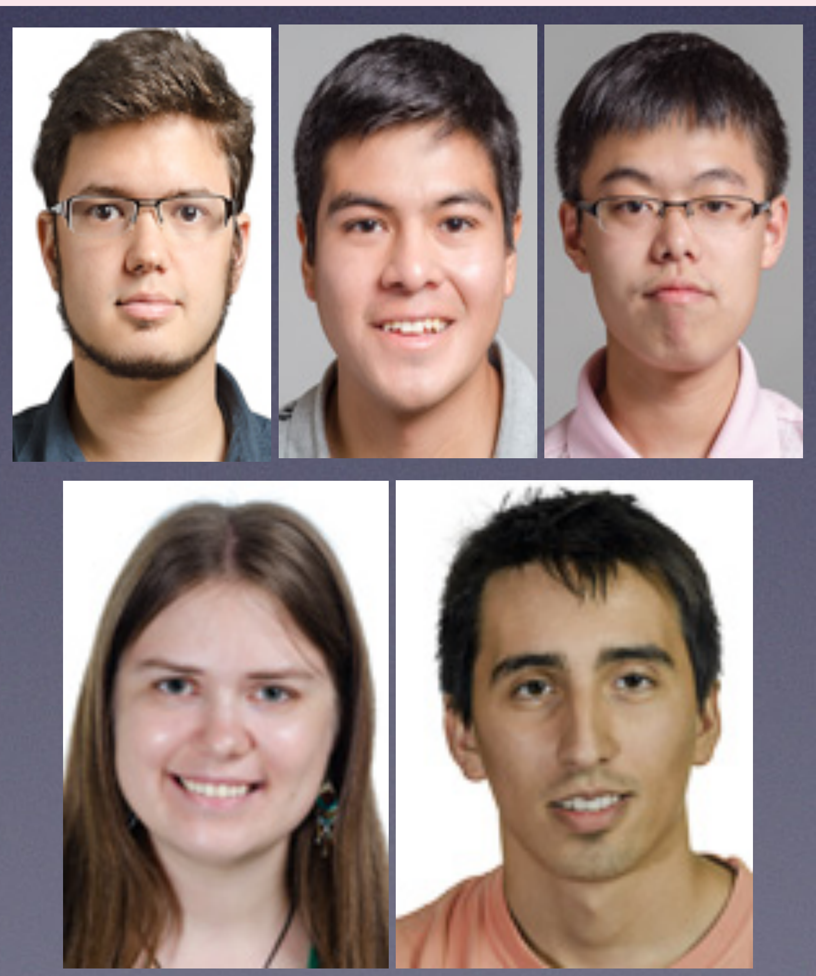


My FSU Collaborators

- Genaro Toledo-Sanchez
- Karim Hasnaoui
- Bonnie Todd-Rutel
- Brad Futch
- Jutri Taruna
- **Farrukh Fattoyev**
- **Wei-Chia Chen**
- **Raditya Utama**

My Outside Collaborators

- B. Agrawal (Saha Inst.)
- M. Centelles (U. Barcelona)
- G. Colò (U. Milano)
- C.J. Horowitz (Indiana U.)
- W. Nazarewicz (MSU)
- N. Paar (U. Zagreb)
- M.A. Pérez-Garcia (U. Salamanca)
- P.G.- Reinhard (U. Erlangen-Nürnberg)
- X. Roca-Maza (U. Milano)
- D. Vretenar (U. Zagreb)



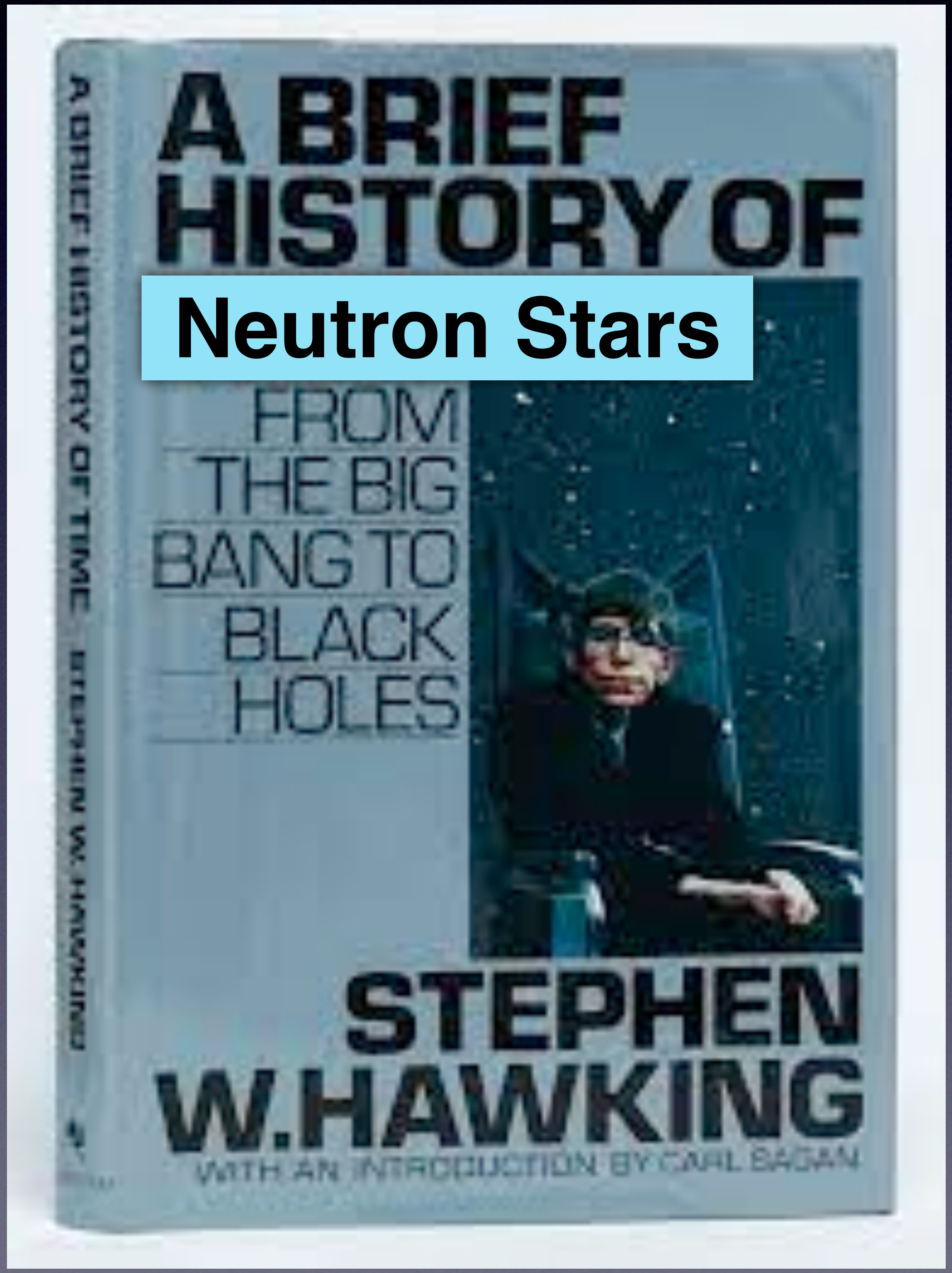
The “Old” Generation

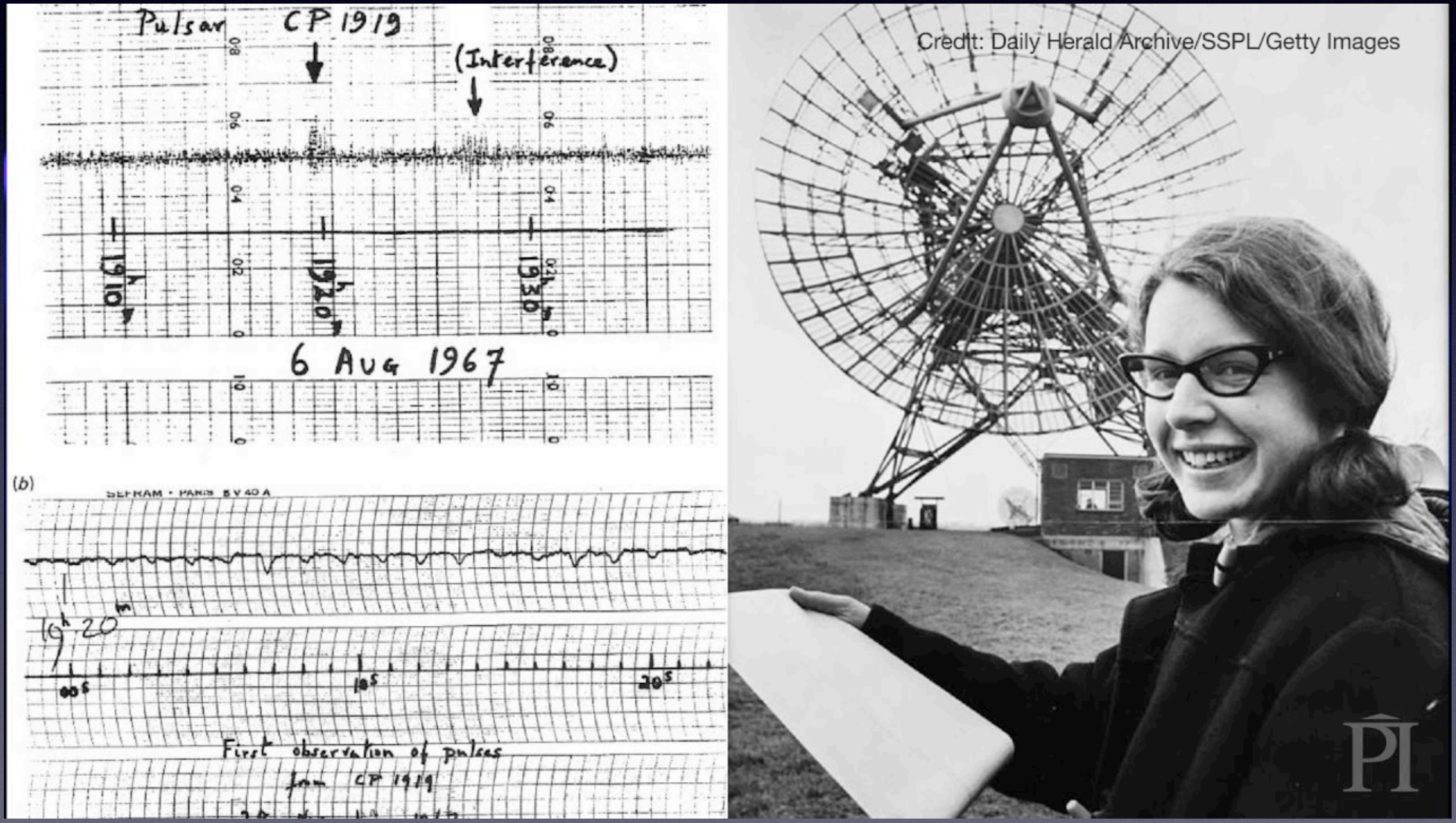
- **Pablo Giuliani**
- **Daniel Silva**
- **Junjie Yang**

The New Generation

- **Amy Anderson**
- **Marc Salinas**

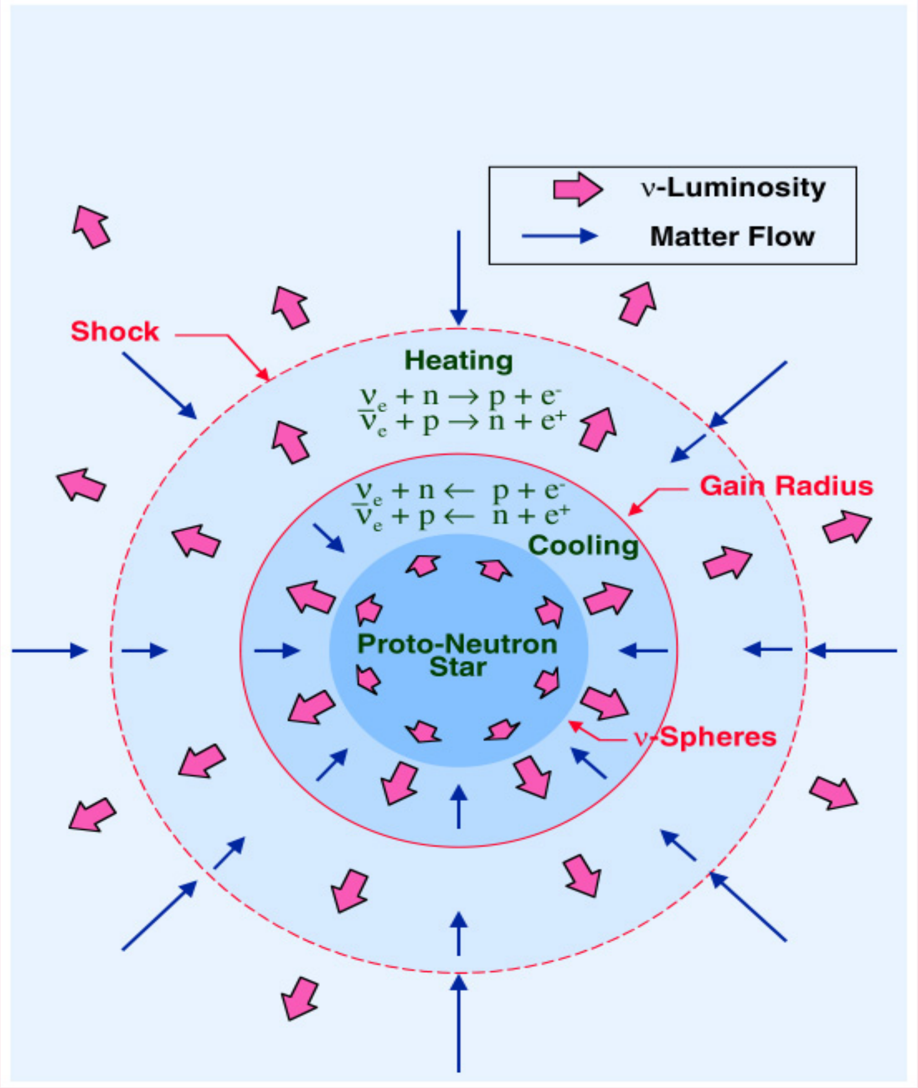
A Brief History of Neutron Stars

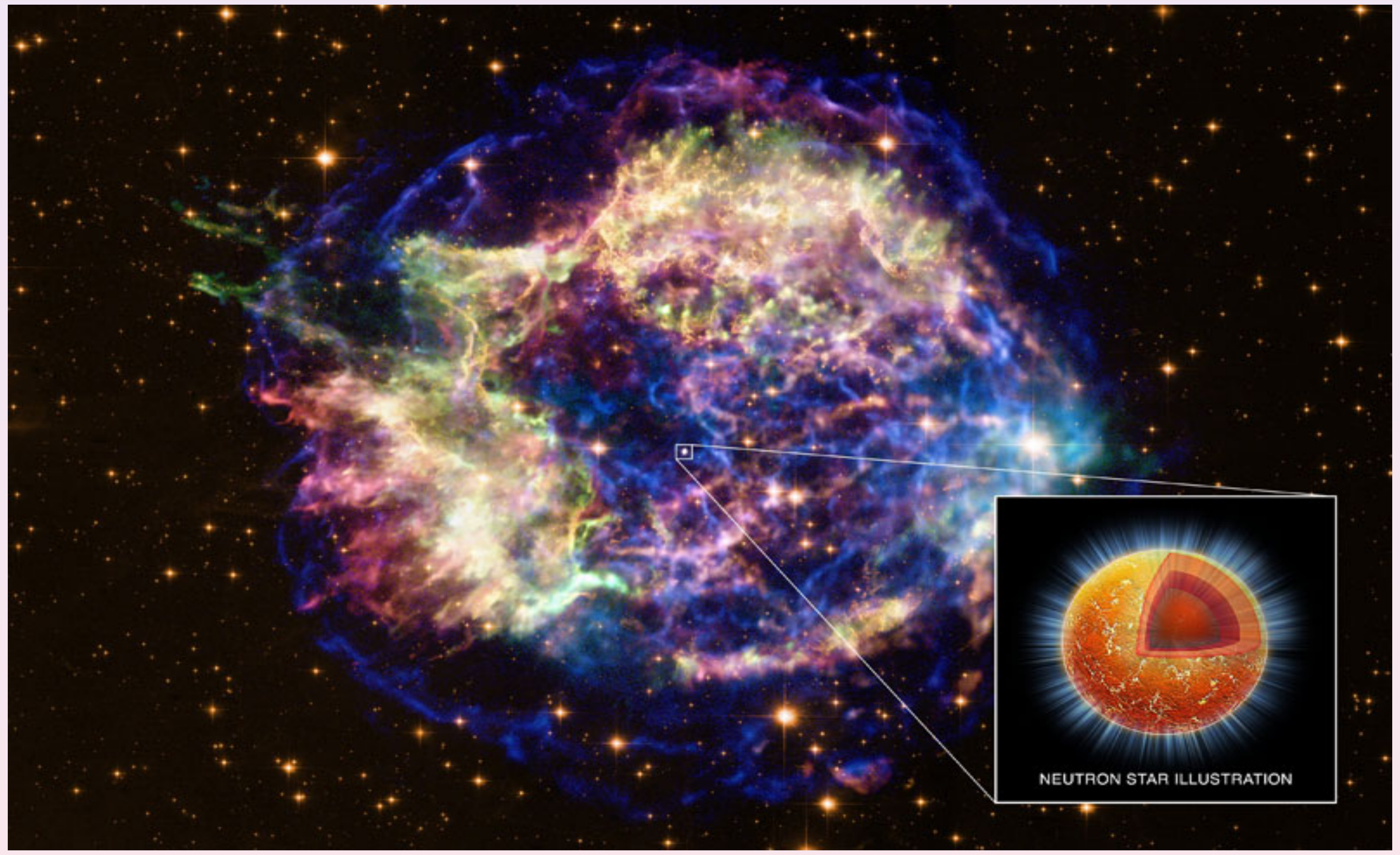




Death of a Star Birth of a Pulsar

- Big Bang creates H, He, and traces of light elements
- Massive stars create all chemical elements: from ^{6}Li to ^{56}Fe
- Once ^{56}Fe is produced the stellar core collapses
- Core overshoots and rebounds: Core-Collapse Supernova!
- 99% of the gravitational energy radiated in neutrinos
- An incredibly dense object is left behind: A neutron star or a black hole





Neutron stars are solar mass objects with 10 km radii

A very brief history of neutron stars

- Chandrasekhar predicts that WD-stars will collapse (1931)
- Chadwick discovers the neutron (1932)
- Baade-Zwicky conjecture the existence of neutron stars (1934)
- Tolman-Oppenheimer-Volkoff equation including GR (1939)

Tolman-Oppenheimer-Volkoff Limit

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

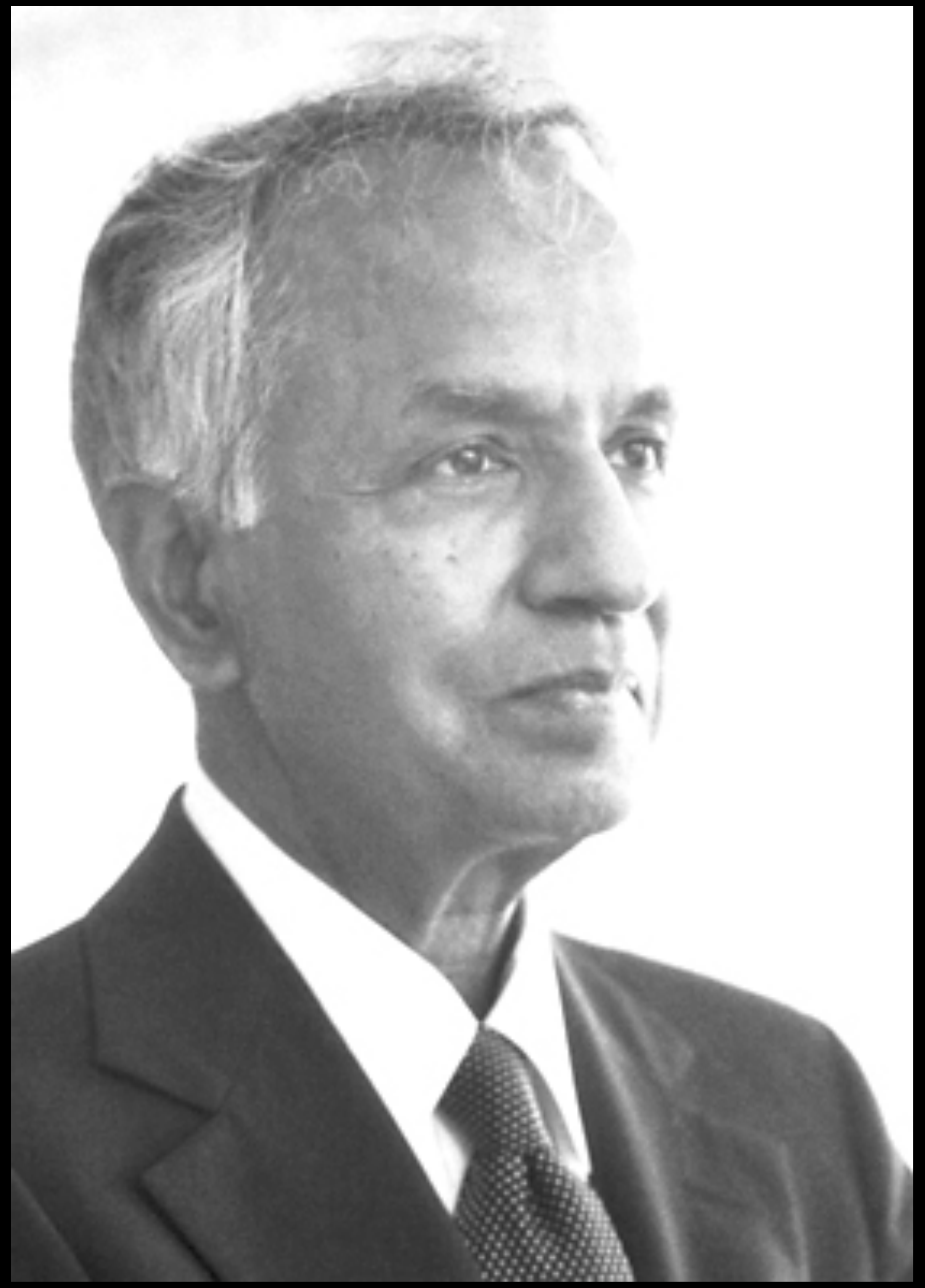
- Bell discovers pulsars accidentally as a graduate student (1967)

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.

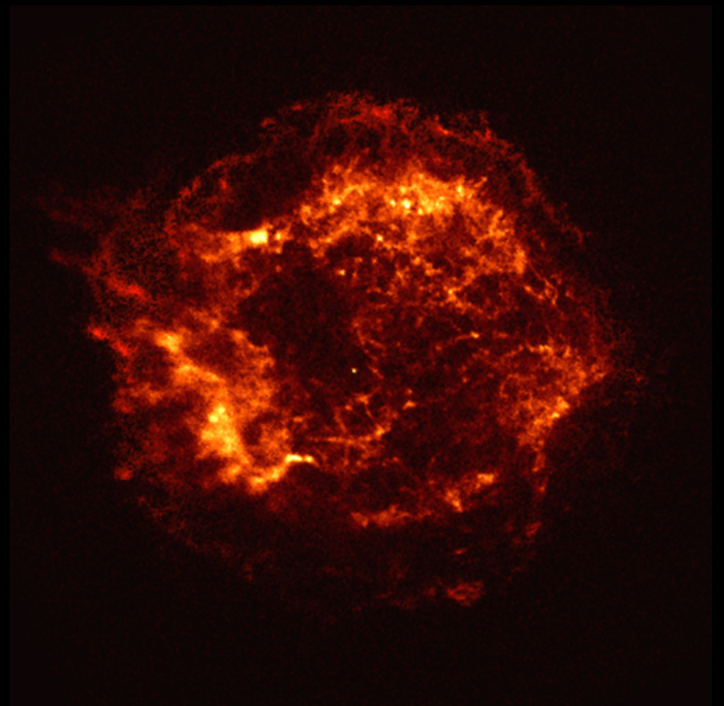
S. Chandrashekar and X-Ray Chandra

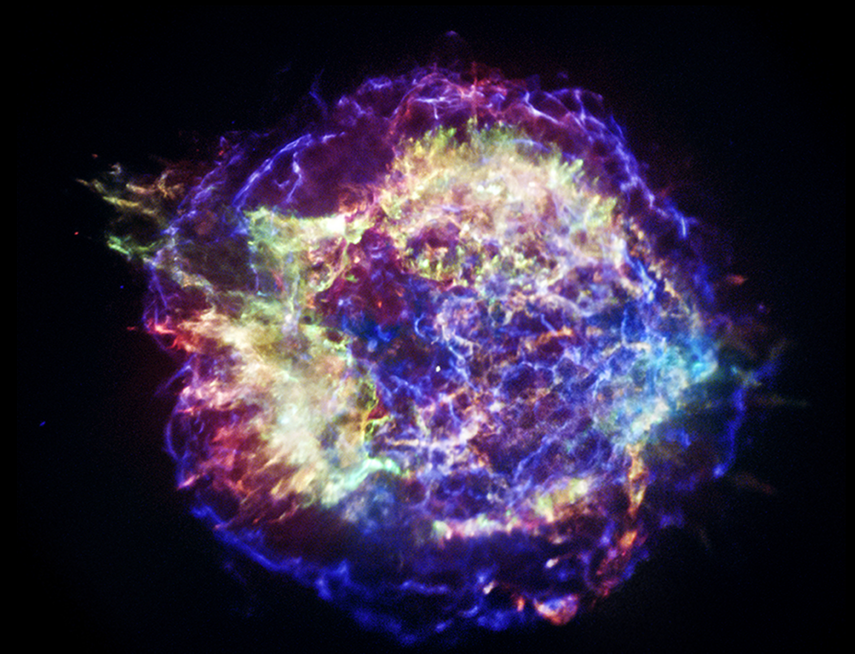
- White-dwarf stars supported by electron degeneracy pressure (Dirac and Fowler 1926)
- For WD stars in excess of 1.4 solar masses electrons become relativistic and the pressure is insufficient to support the star against gravitational collapse (1931)

$$P \sim n^{5/3} \rightarrow n^{4/3}$$



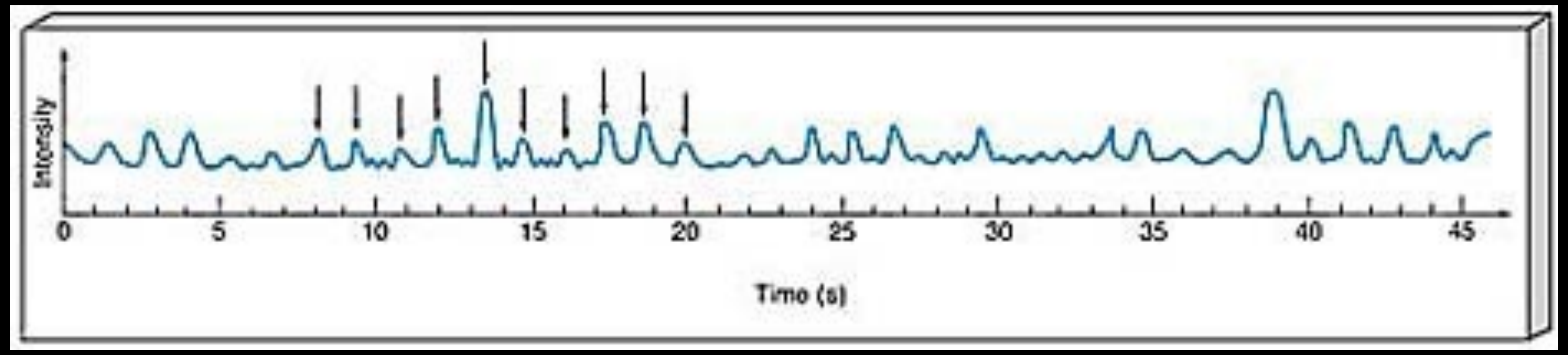
- Arthur Eddington (1919 light bending) ridiculed Chandra
- James Chadwick discovers the neutron (1932)
- Chandra awarded the Nobel Prize with W.A. Fowler (1983)
- NASA launches the *Chandra* X-ray observatory (1999)





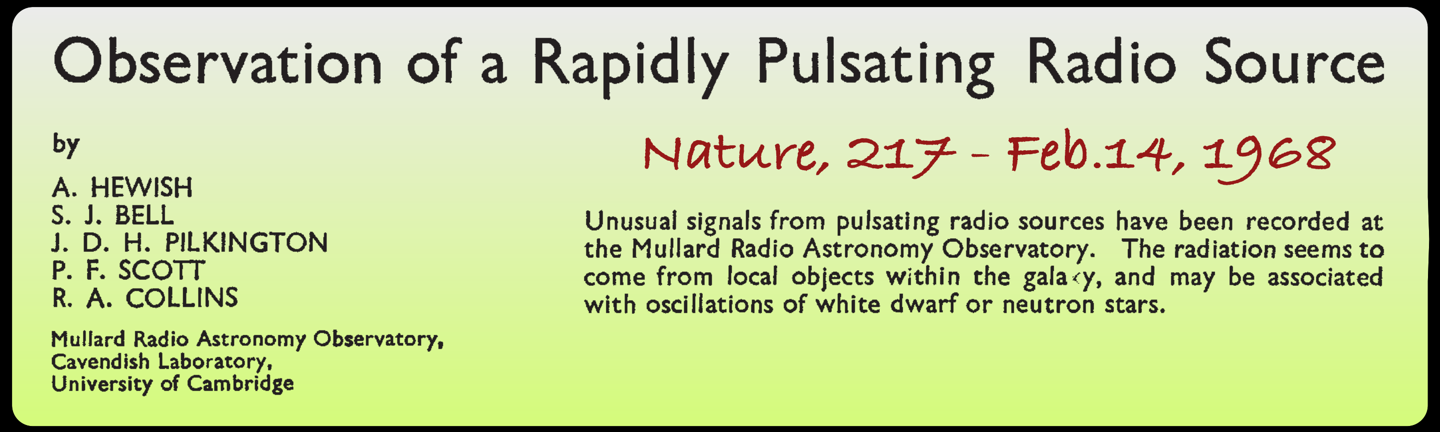
Cassiopeia A
Chandra's First Light!
August 27, 1999

Neutron Stars: Dame Jocelyn Bell Burnell



- Detected a bit of “scruff” (1967)
- Discovers amazing regularity in the signal (P=1.33730119 seconds)
- May the signal be from an alien civilization? (Little Green Man 1)
- Paper announcing first pulsar published [*Observation of a Rapidly Pulsating Radio Source* A Hewish, SJ Bell, et al., Nature 217, 709 (1968)]

- Nobel awarded to Hewish and Ryle (1974)
- “No-Bell” roundly condemned (Hoyle)



Observation of a Rapidly Pulsating Radio Source

by

A. HEWISH
S. J. BELL
J. D. H. PILKINGTON
P. F. SCOTT
R. A. COLLINS

Mullard Radio Astronomy Observatory,
Cavendish Laboratory,
University of Cambridge

Nature, 217 - Feb.14, 1968

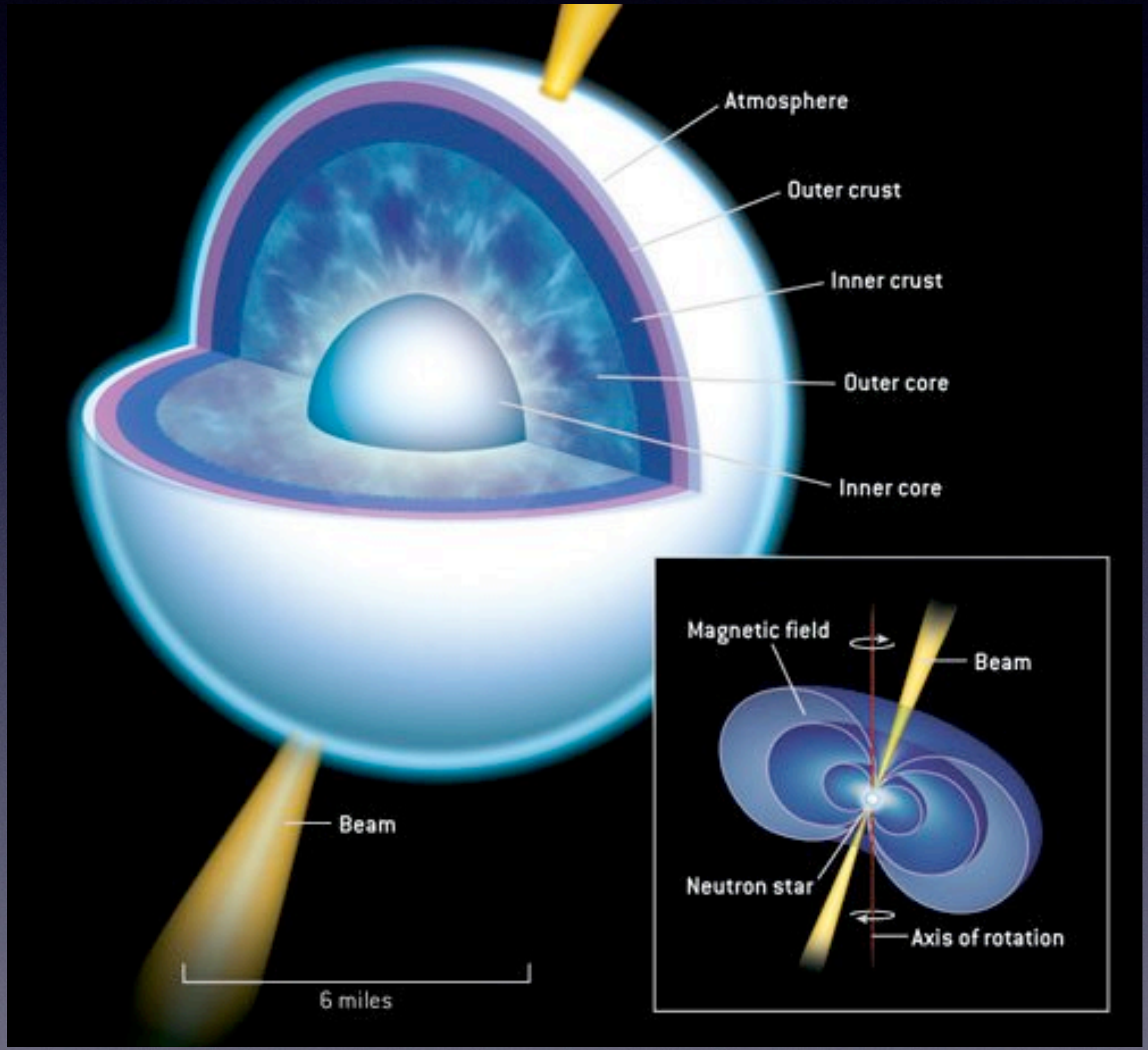
Unusual signals from pulsating radio sources have been recorded at the Mullard Radio Astronomy Observatory. The radiation seems to come from local objects within the gala‹y, and may be associated with oscillations of white dwarf or neutron stars.

“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”

Awarded Special Breakthrough Prize (2018)

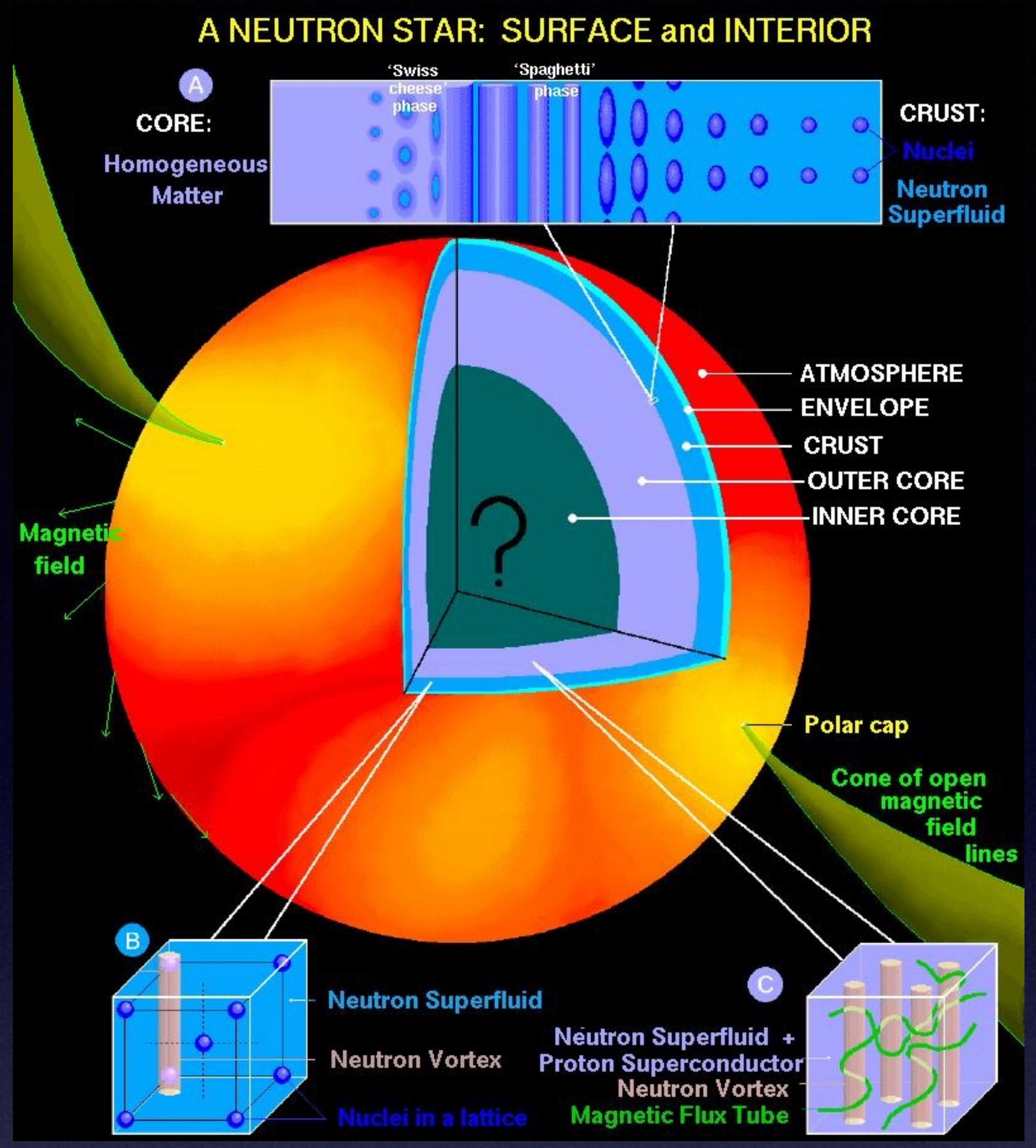
Bell donates prize ($3M) to help minority students!

A Very Brief Description of the Anatomy of a Neutron Star



Anatomy of a Neutron Star: Our Playground

- 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)

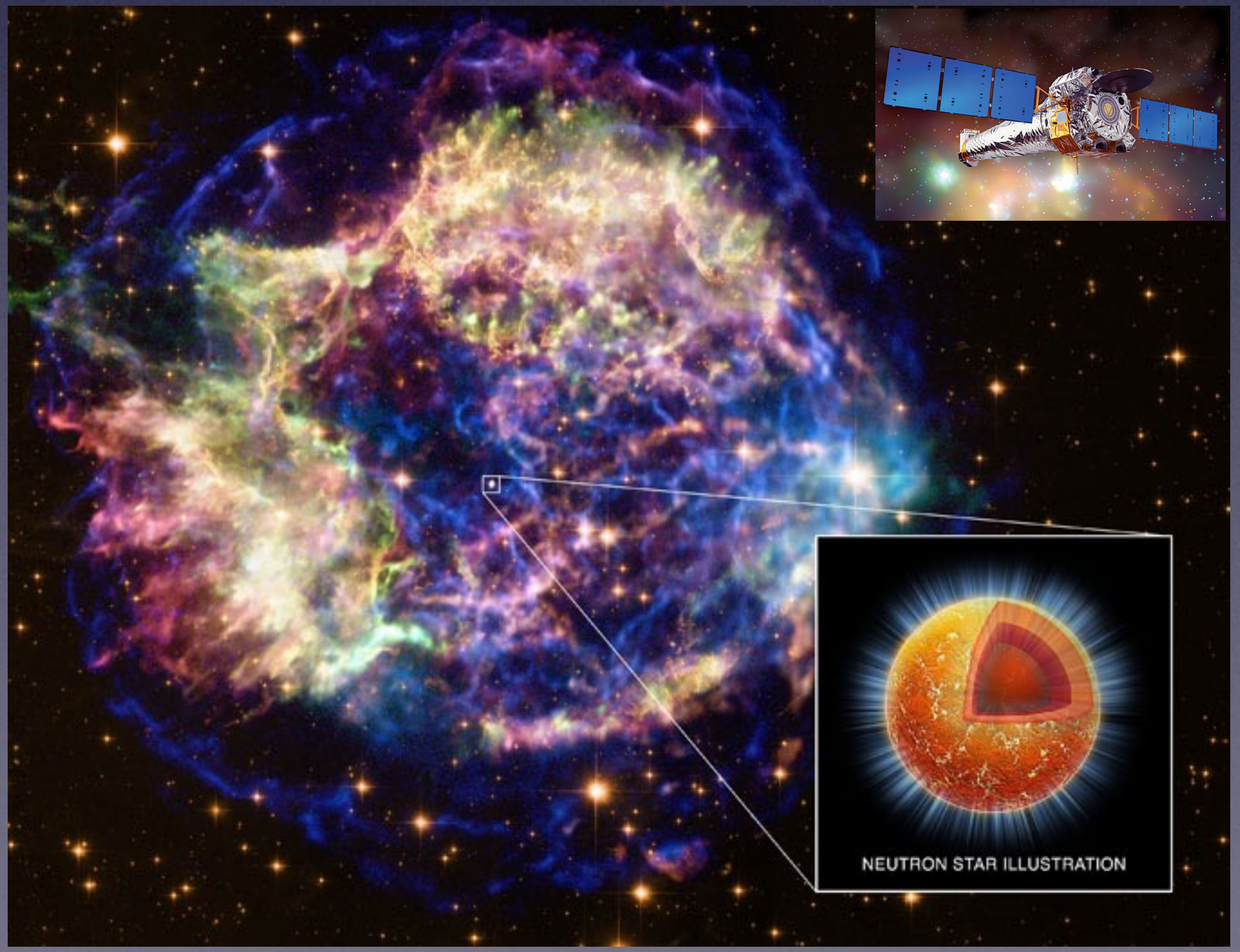


Supernova 1987a

- 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)

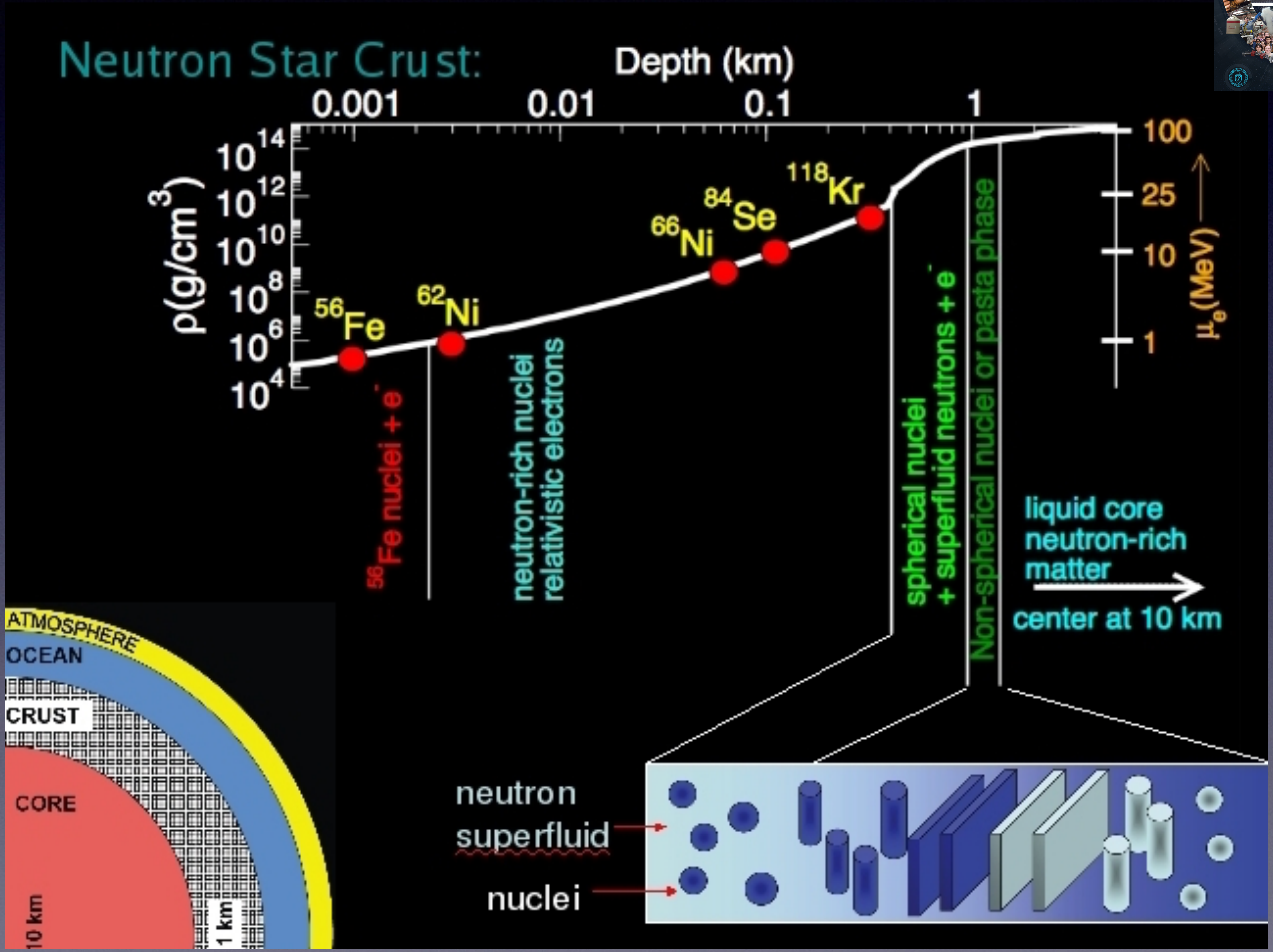
Very first light from Chandra X-ray telescope

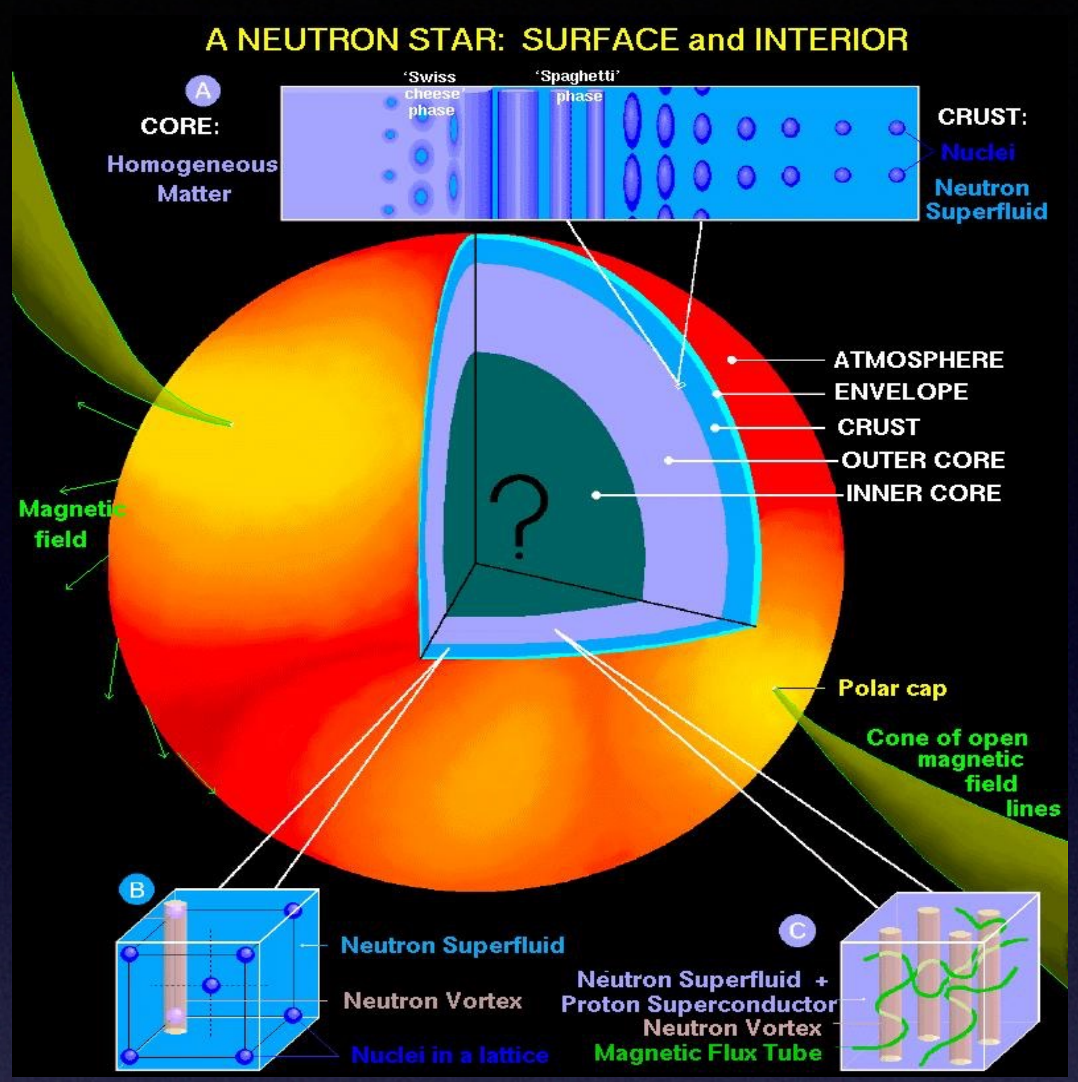


Neutron Stars: Unique Cosmic Laboratories

How Does Matter Organize Itself?

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

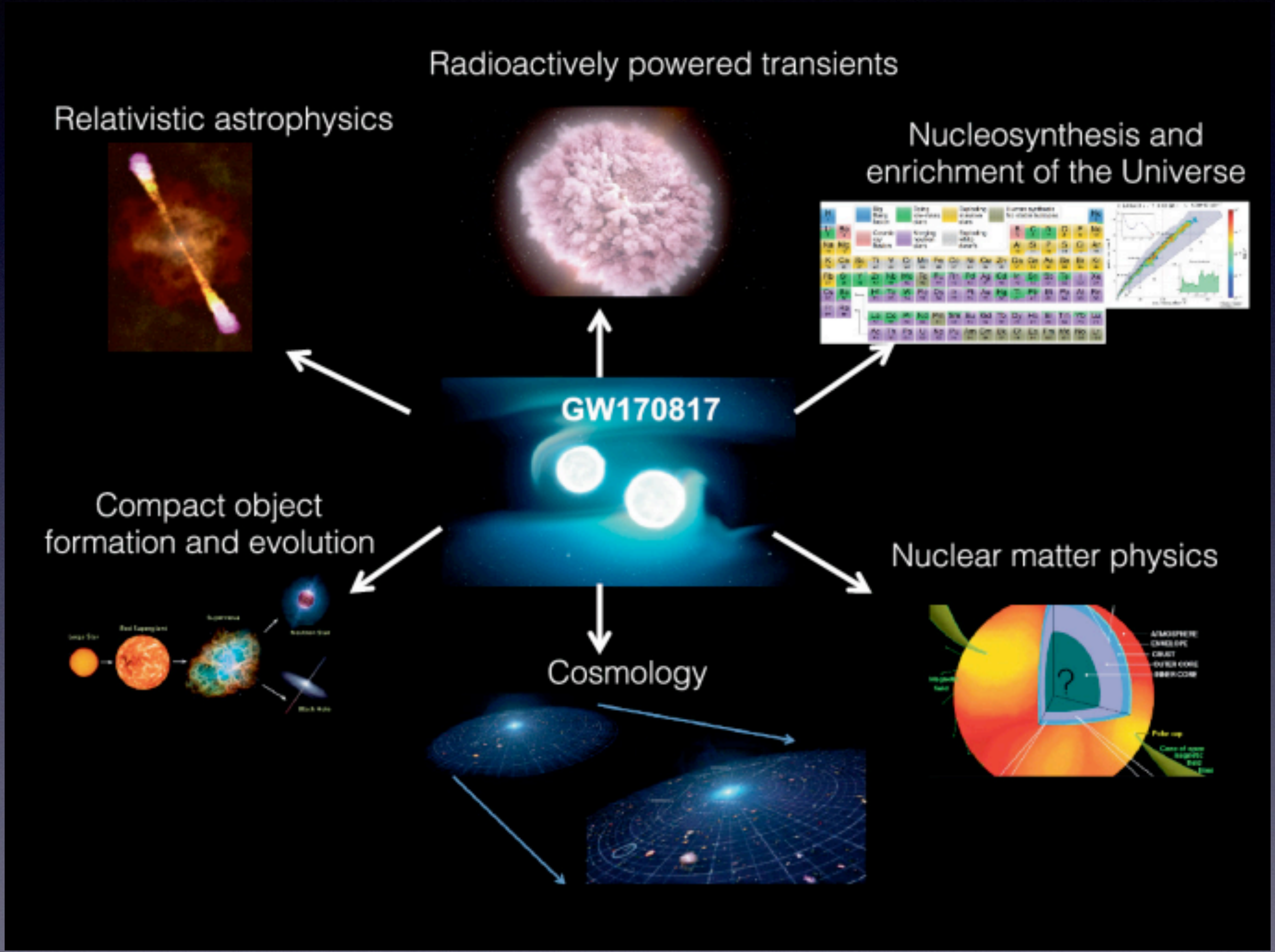


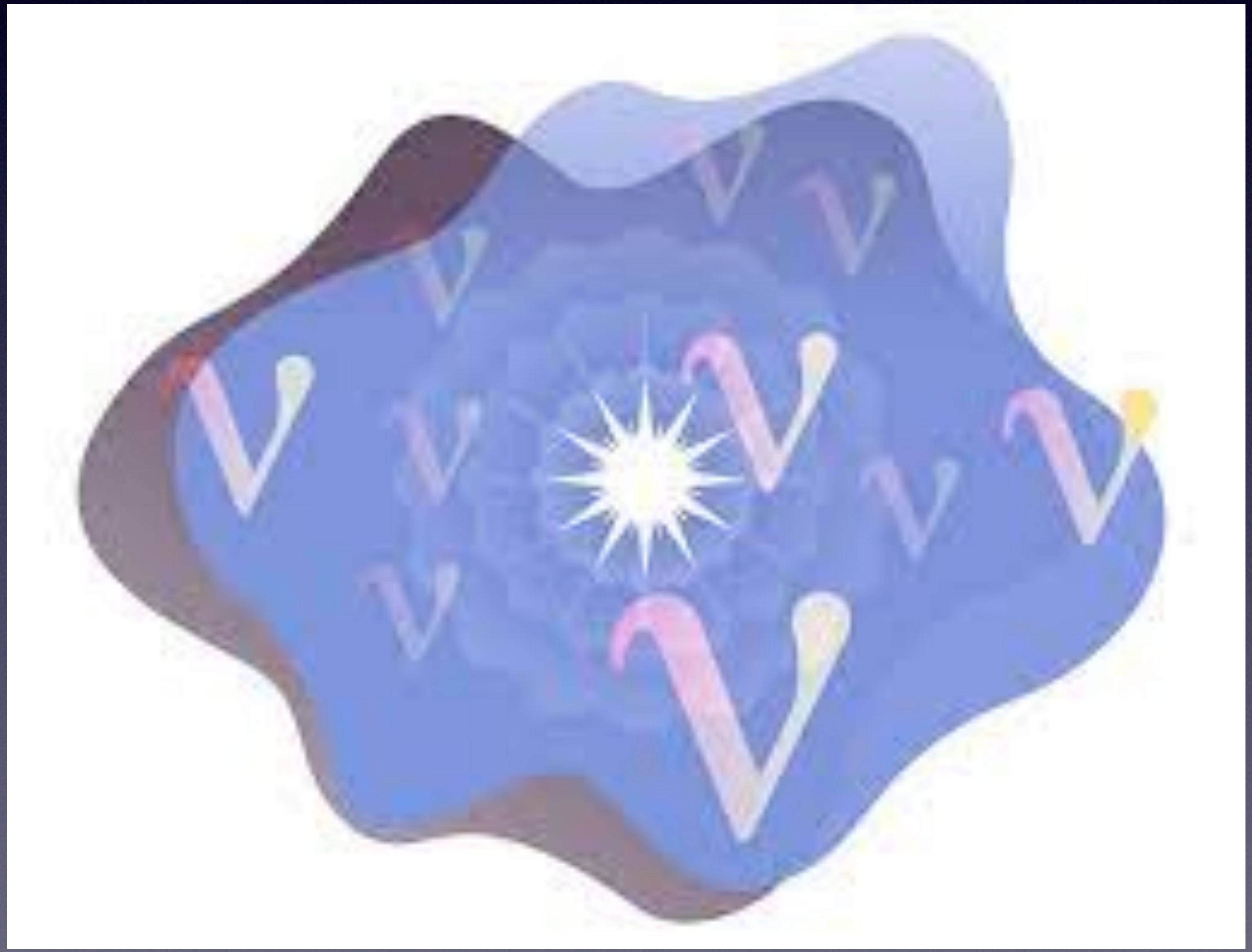


- Neutron stars probe ~10 orders of magnitude in baryon density
- Terrestrial laboratories can not recreate such exotic environment

Neutrons stars are bound by gravity and not by the strong nuclear force!

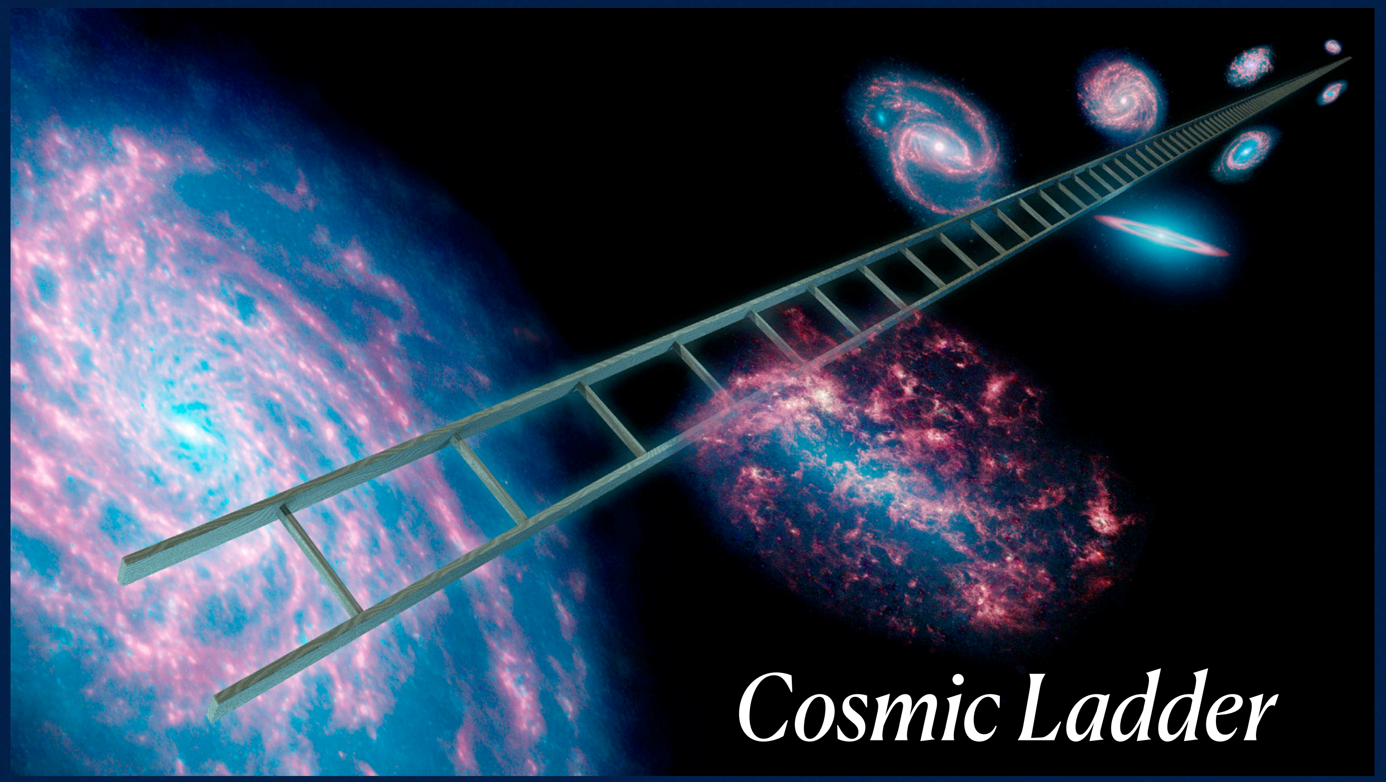
The Beginning of a New Era: Multi-messenger Astronomy

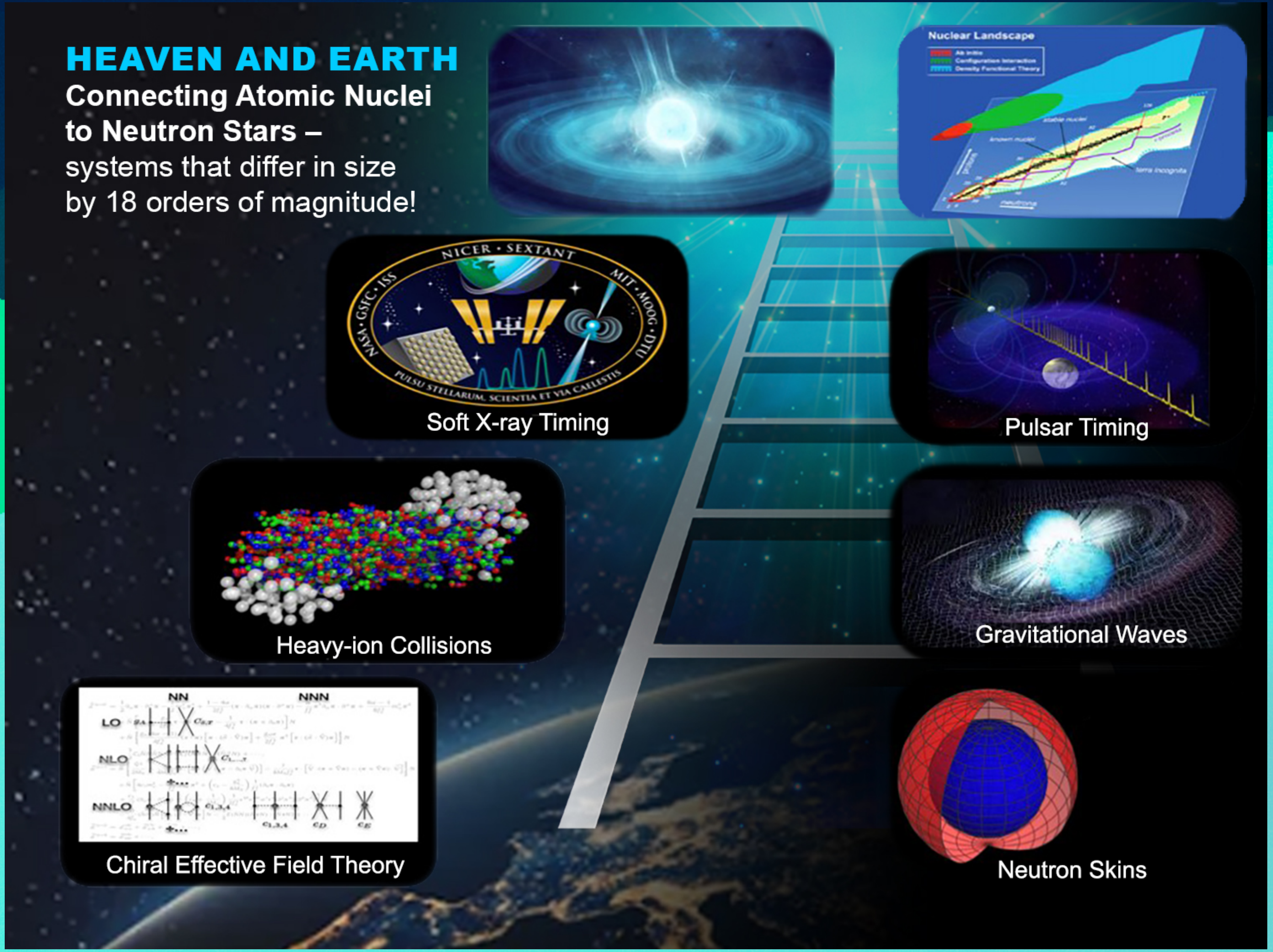




Heaven and Earth: Nuclear EOS Density Ladder

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

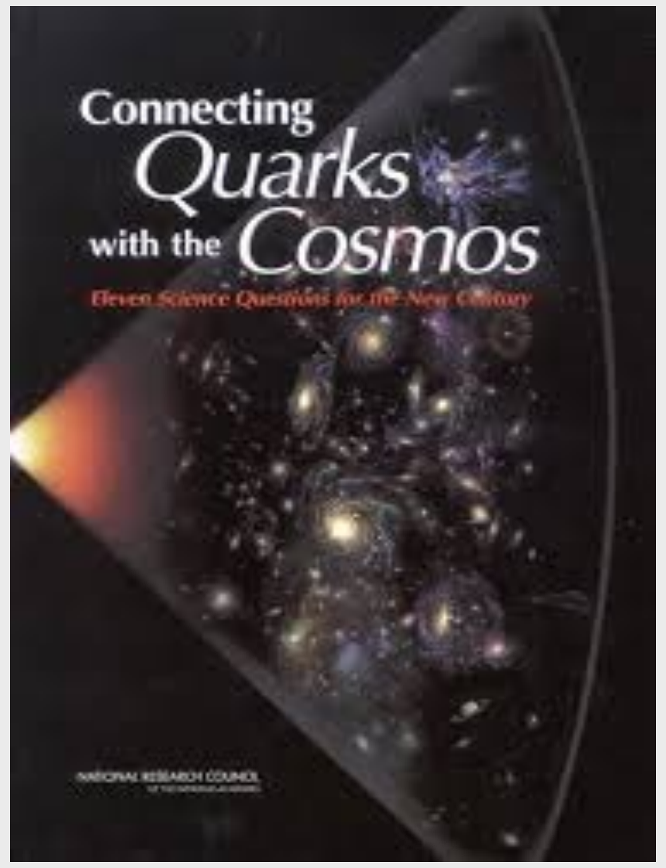




The Nuclear Physics of Neutron Stars

How were the heavy elements from iron to uranium made?

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



Neutron Stars and the Equation of State of Neutron-Star Matter

CompOSE

CompStar Online Supernovae Equations of State

The online service CompOSE provides data tables for different state of the art equations of state (EoS) ready for further usage in astrophysical applications, nuclear physics and beyond.

The cold neutron star EoS tables can be used directly within LORENE to obtain models of (rotating/magnetised) neutron stars, see the eos_compose class.

If you make use of the tables provided in CompOSE, please cite the publications describing the respective EoS models (available on the CompOSE web pages for each the model) together with a reference to the CompOSE website (https://compose.obspm.fr) and/or the original CompOSE publications :

[**TOK_2015**] S. Typel, M. Oertel, T. Klähn, Phys.Part.Nucl. 46, 633
[**OHKT_2017**] M. Oertel, M. Hempel, T. Klähn, S. Typel, Rev. Mod. Phys. 89, 015007
[**TOK_2022**] S. Typel, M. Oertel, T. Klähn et al, arxiv:2203.03209

Data tables, associated software and the manual can be freely downloaded. Log in is required if you wish to use further utilities, such as graphics and online computations. Please contact "develop.compose(at)obspm.fr" if you wish to have an account.

Monday Afternoon Session: Adriana Raduta