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**Magnetized dense nuclear matter...
far far out there**



Presenter: Dr Jacobus Diener **Date:** Apr 16th, 2024
Department of Physics and Astronomy, BIUST **Venue:** ANSTT5

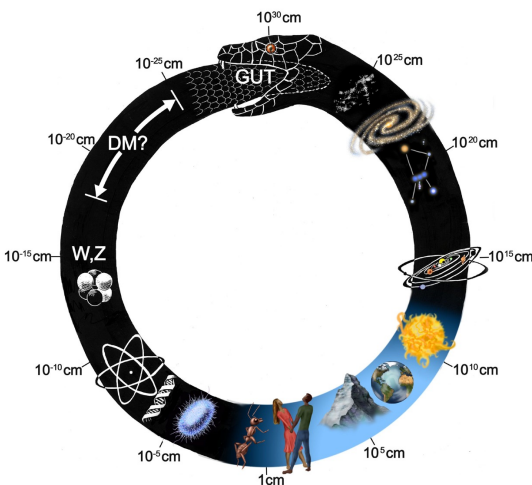
www.biust.ac.bw
BIUST | *Driving Change*

f i s

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Sheldon Glashow's Ouroboros

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Ouroboros



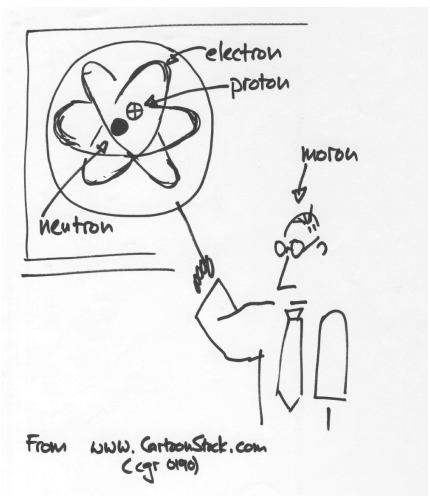
By Microsoft Designer; ouroboros, neutron star, nuclei, connection




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Neutron stars

Where nuclear physics meets unclear physics

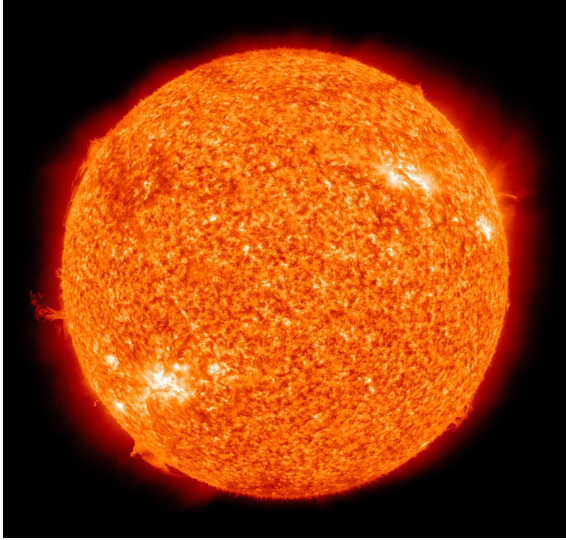


From [www. CartoonStock.com](http://www.CartoonStock.com)
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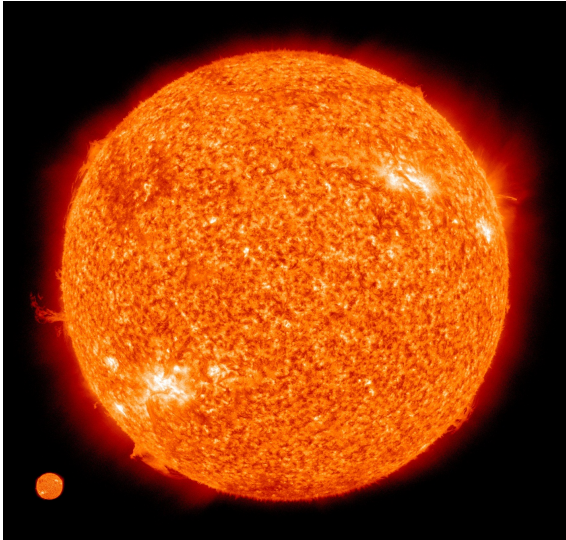
The sun



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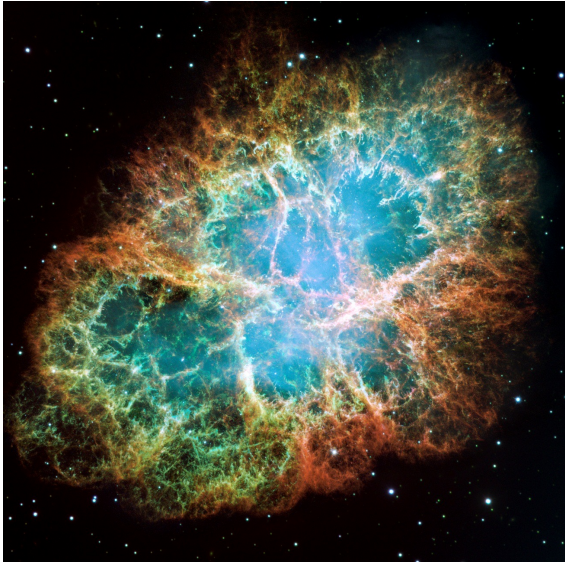
A sun



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Crab Nebula




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The image shows the Crab Nebula, a complex of glowing filaments of gas and dust. The central region is a bright, blue-white ring, while the outer filaments are a mix of green, yellow, and orange. The background is dark with scattered stars.

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Crab pulsar

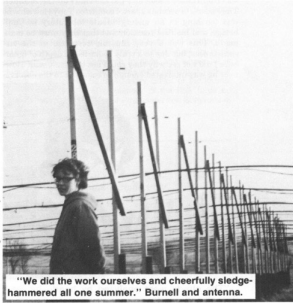
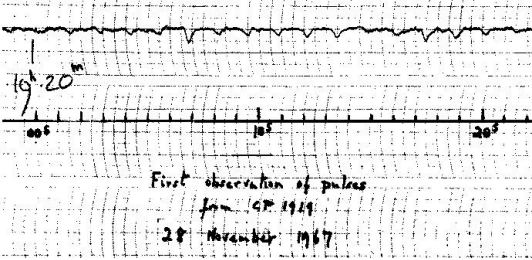



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The image shows the Crab pulsar, a rapidly rotating neutron star. It is surrounded by a complex, multi-colored nebula of gas and dust, with swirling patterns of purple, blue, and red. The pulsar itself is a small, bright white spot in the center.

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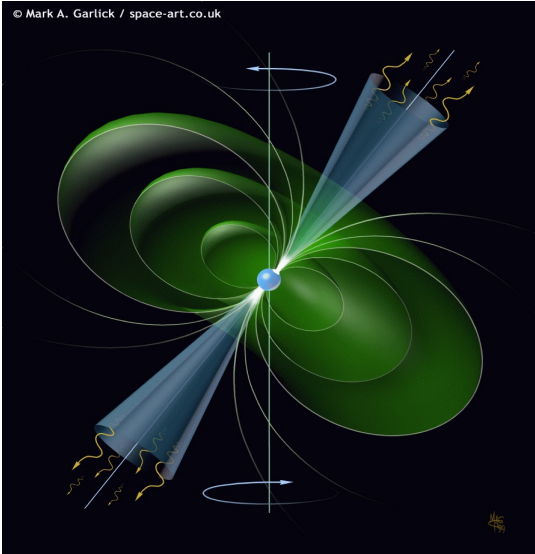

Little Green Men in 1967?



Speaker icon

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Pulsars in general




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In comparison...

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Our sun's mass is 2×10^{30} kg = 333 000x

Radius of the sun is ~700 000 km

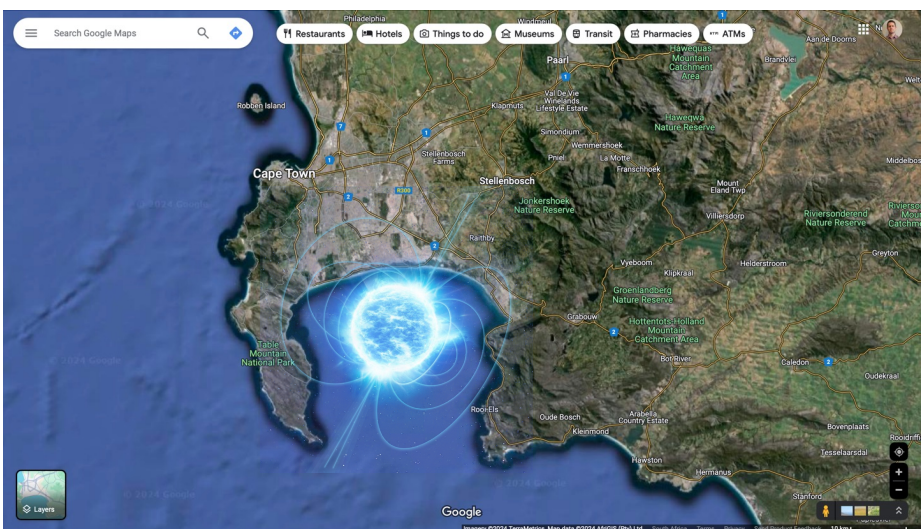
= 

Pulsars have mass similar to the sun, but radii of ~10 km!

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Size comparison

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Credits: Google and ESA

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Neutron star matter

1 heaped tablespoon

= 500 0

4128 0012 3456 7890

L WALKER

Member since 10

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Compact objects

Stellar evolution

low- and medium-mass stars (including the Sun)

main sequence → red giant → "planetary" nebula → white dwarf

nebula → high-mass stars

main sequence → red supergiant → supernova

high-mass star → neutron star

very high-mass star → black hole


not to scale

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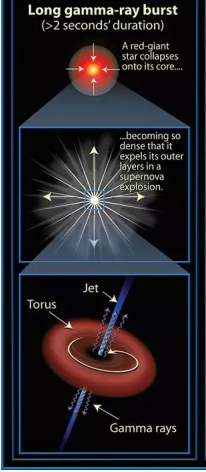
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Gamma-Ray Bursts



Gamma-Ray Bursts (GRBs): The Long and Short of It

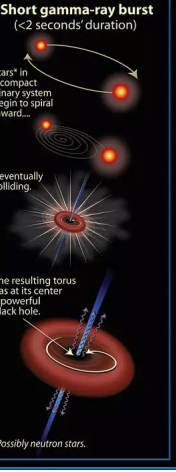
Long gamma-ray burst
(>2 seconds' duration)



A red-giant star collapses onto its core... becoming so dense that it expels its outer layers in a supernova explosion.

Torus Jet
Gamma rays

Short gamma-ray burst
(<2 seconds' duration)




Stars in a compact binary system begin to spiral inward... eventually colliding.

The resulting torus has at its center a powerful black hole.

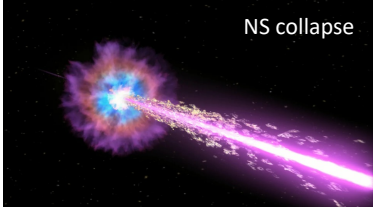
*Possibly neutron stars.

NS merger



Credit: University of Warwick/Mark Garlick, from [here](#)

NS collapse




Credit: NASA/Swift/Cruz deWilde

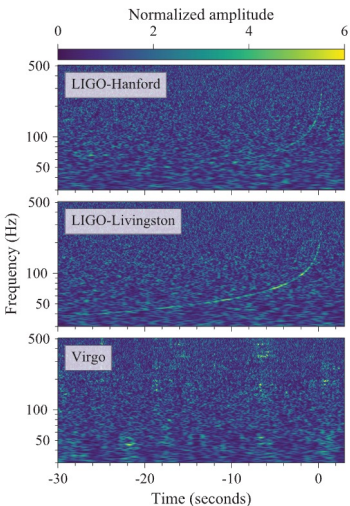
Credit: <https://www.mpe.mpg.de/1048427/CompactObjects>

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GW170817



- Observed 7 August 2017 by LIGO and Virgo GW detectors
- Inspiralling neutron stars
- Follow-up observations in
 - Gamma-ray
 - X-ray
 - UV
 - Optical
 - IR
 - Radio



By LIGO Scientific Collaboration and Virgo Collaboration

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GW170817

Observation are used to

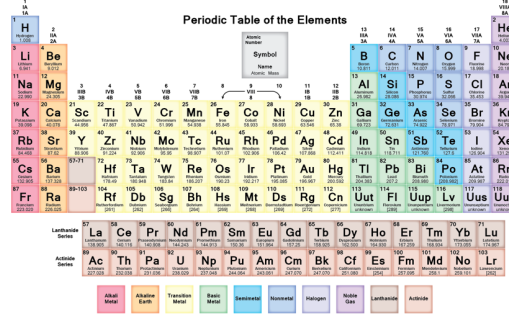
- Constraint EoS of dense nuclear matter
 - Tidal deformation \propto induced mass quadrupole.
- Measure Hubble constant
 - Standard siren vs standard candle
- Compare heavy-ion collisions measurements and data
 - Hot nuclear matter and afterglow
- Nucleosynthesis
 - Spectral analysis

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Confirmation of r -process site

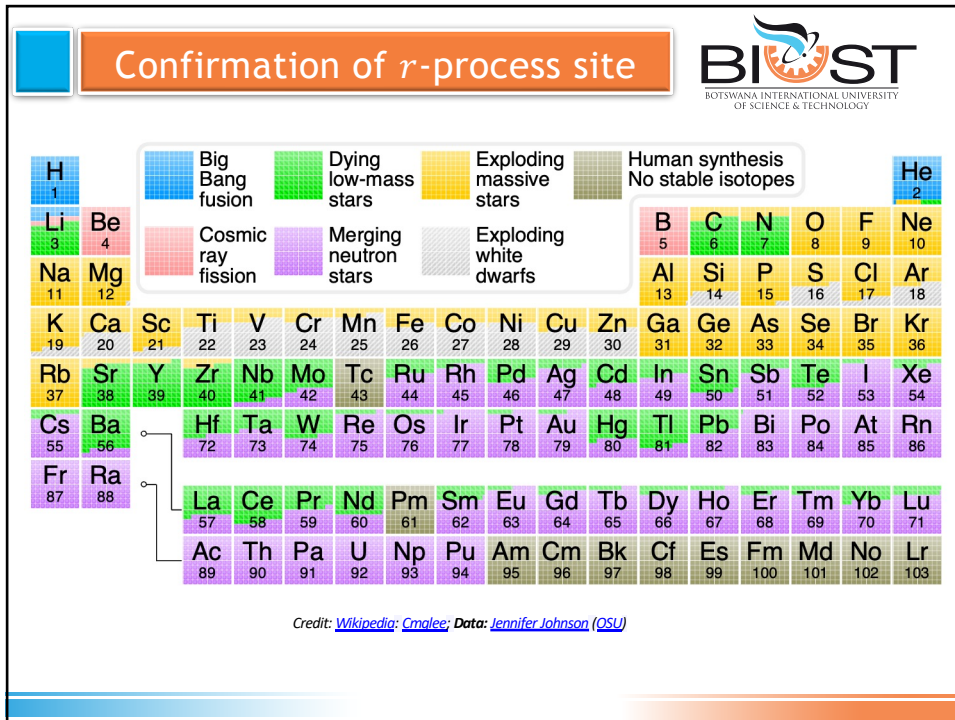
- r -process: rapid neutron capture to form heavy elements
- Uncertainty of the astrophysical site
 - (Core-collapse) SN
 - NS mergers

Periodic Table of the Elements

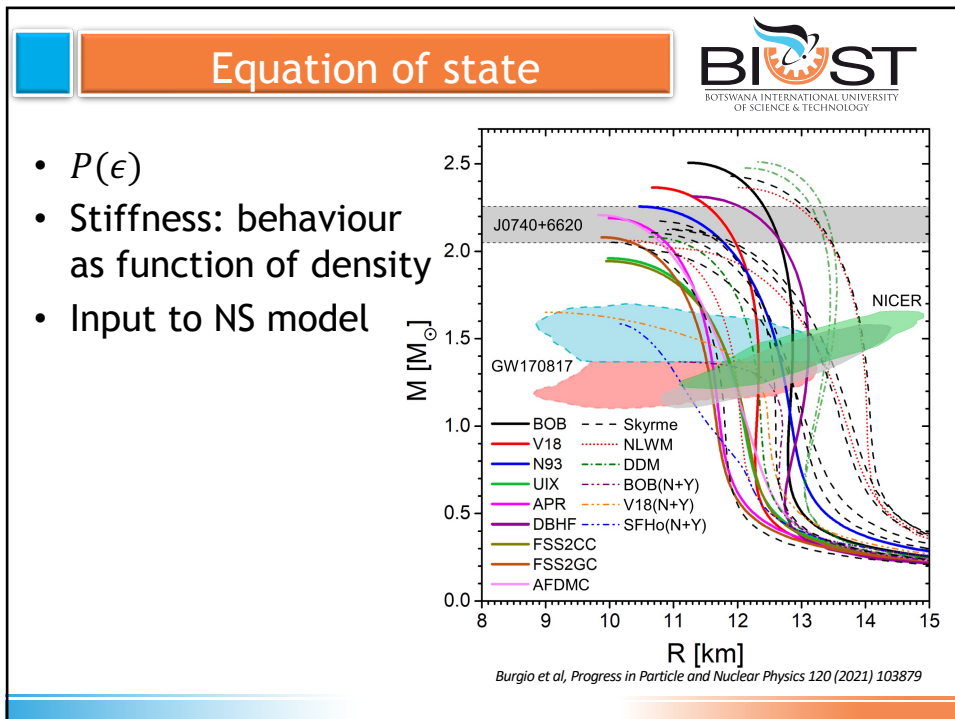


The periodic table shows elements from Hydrogen (H) to Oganesson (Og). It is color-coded by groups: Alkali Metals (pink), Alkaline Earths (orange), Transition Metals (yellow), Main Group (green), Lanthanides (light blue), Actinides (dark blue), Noble Gases (purple), and Halogens (light purple).

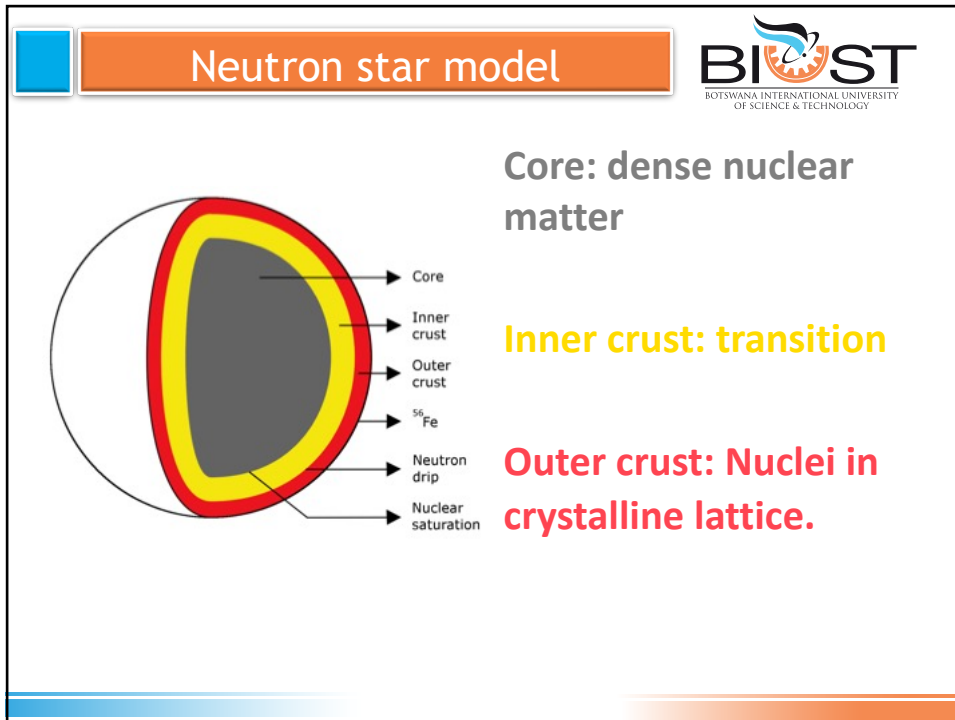
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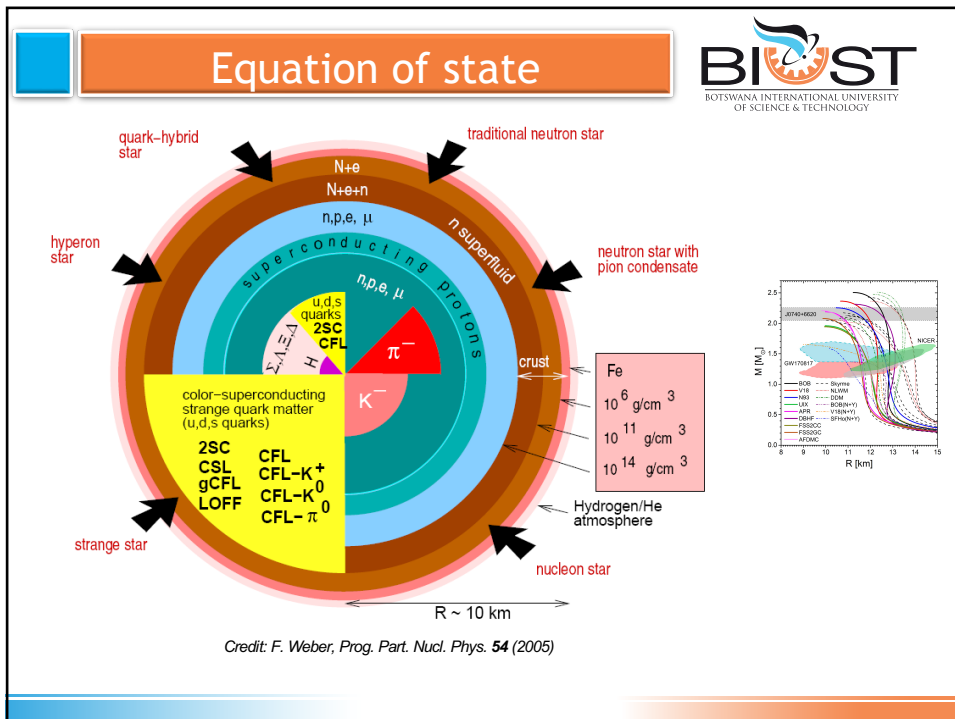
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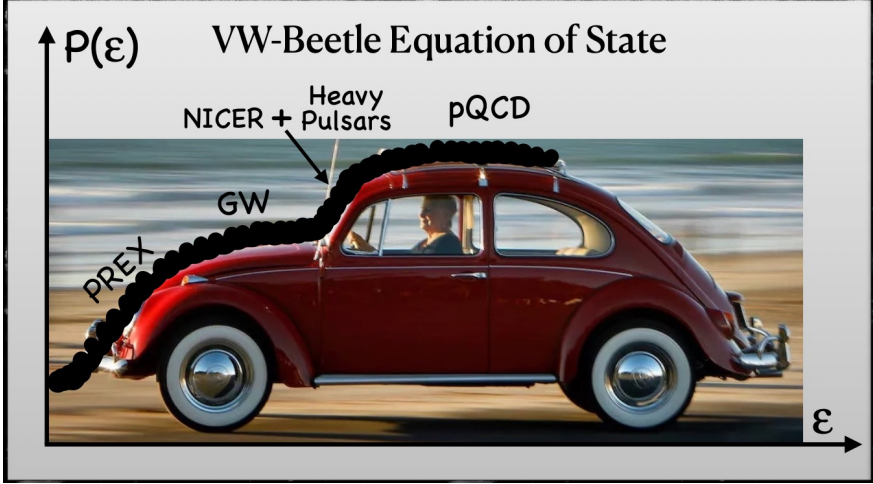


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Nuclear equation of state




VW-Beetle Equation of State



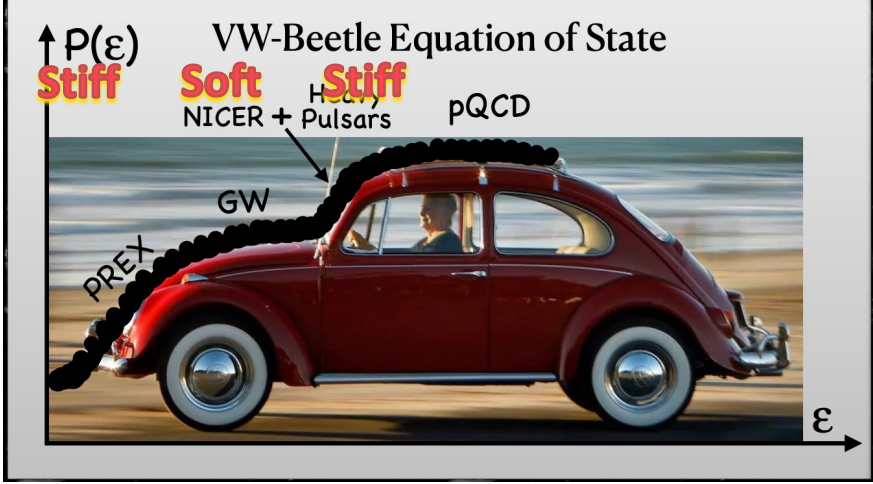
Credit: J Piekarewicz, [arXiv:2403.16154v1](https://arxiv.org/abs/2403.16154v1)

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Nuclear equation of state




VW-Beetle Equation of State

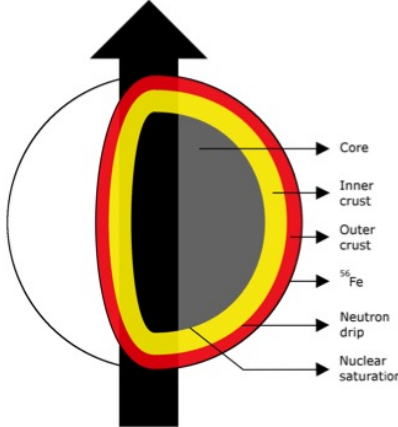


Credit: J Piekarewicz, [arXiv:2403.16154v1](https://arxiv.org/abs/2403.16154v1)

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Magnetised neutron star model






Magnetic field

- External
 - “Outside” of modelled NS part
- Internal
 - Generated by or
 - Fossilized

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Magnetised neutron star model



- Magnetic field, B , not generally included
 - Coupling strengths are small $\mu_N \propto \frac{1}{m} \ll m$
- BUT
 - m is rest mass, not effective mass
 - To be compared to *product* of dipole moment and magnetic field: $g_N B$
- Density dependence of m and g_N not known.

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Magnetised matter

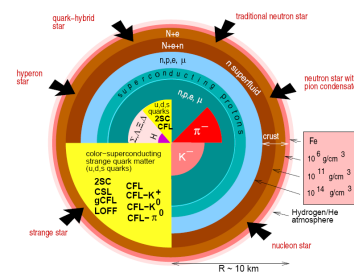
Fundamentally different from unmagnetised systems

1. Neutral particles's spin is explicitly included
2. Charged particles lose fermion characteristics in directions parallel to B
3. Pressure in magnetised matter is not isotropic

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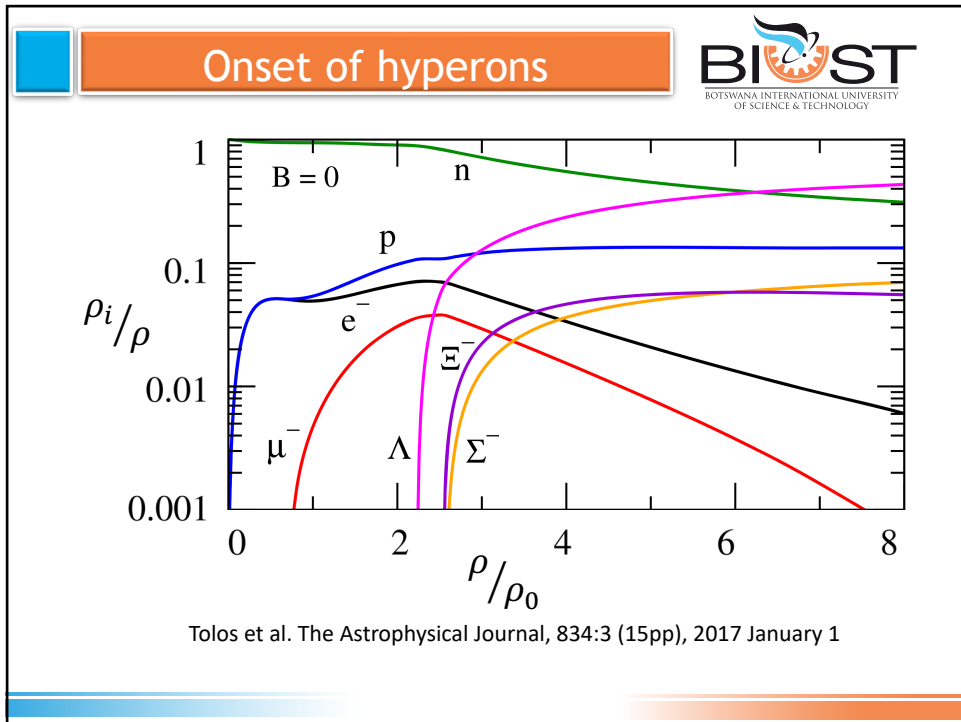
Magnetised matter

- Magnetised n, p, e and μ matter
- Magnetised hyperon matter
 - Heavy baryons
 - Λ, Ξ, Σ

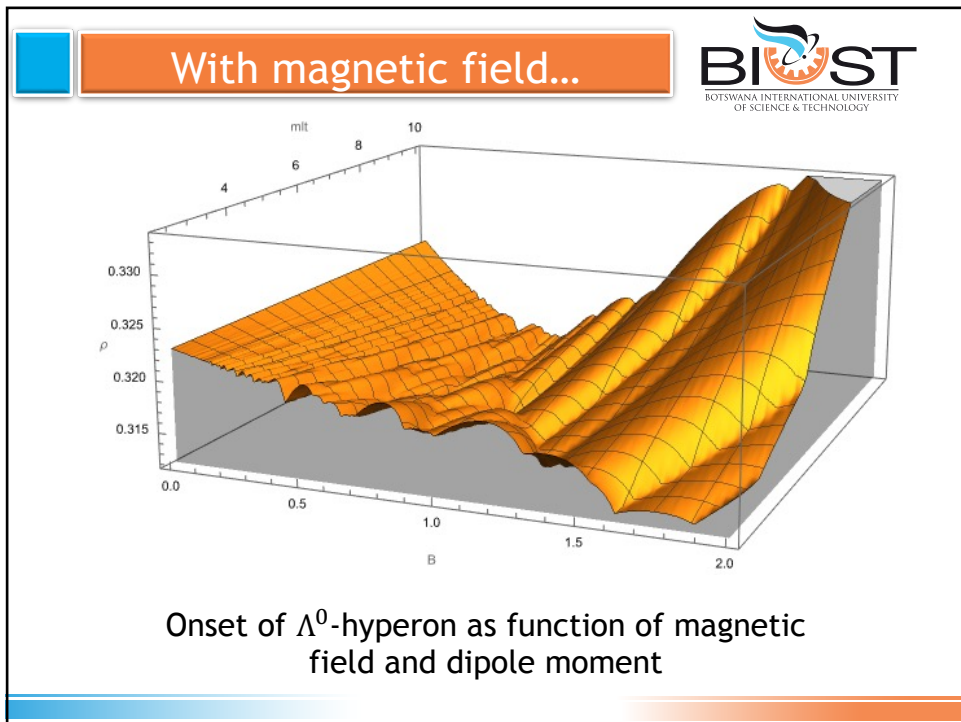


Credit: F. Weber, *Prog. Part. Nucl. Phys.* **54** (2005)

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Magnetars




- ***Highly*** magnetized neutron stars
- Fast Radio bursts
 - Extra-galactic,
 - High energy,
 - Lasting for milliseconds to seconds, as
 - Repeating and non-repeating sources.




Thetakeiv on gifer.com

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Magnetars




- ***Highly*** magnetized neutron stars
- Fast Radio bursts
 - Extra-galactic,
 - High energy,
 - Lasting for milliseconds to seconds, as
 - Repeating and non-repeating sources.
 - Lasting for milliseconds to seconds.
 - When detected on earth the signal is 1000 fainter than a cell phone on the moon.




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Telescope for B??





- The Hydrogen Intensity and Real-time Analysis eXperiment (HIRAX)
 - radio telescope array,
 - frequency range of 400 to 800 MHz,
 - SKA technology demonstrator, but also
 - Cutting-edge science instrument in own right.





PARTNERS


































































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HIRAX outriggers




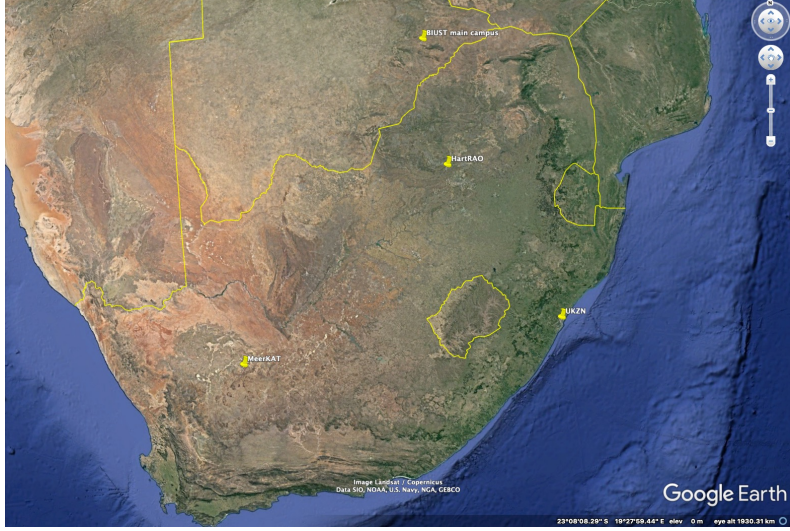
To learn more about FRB we need to follow-up

- Location of source
- Better Angular resolution
- Distributed telescopes

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HIRAX outriggers





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BIUST campus




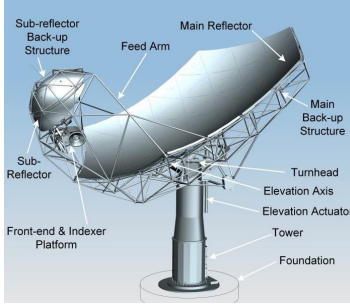
- Low frequency interferometer on campus
 - Funding committed
 - MoA to signed before mid-2024

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BIUST campus




- Low frequency interferometer on campus
 - Funding committed
 - MoA to signed before mid-2024
- SKA-mid dish as well
 - Breaking ground by Oct 2024





<https://www.skao.int/en/explore/telescopes/ska-mid>

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Conclusions





- EoS of dense matter still unknown.
 - Many specialized investigations
 - Data not limited to initial intention.
- Nuclear and neutron physics still very relevant.
 - Nuclei and nuclear matter fundamental d.o.f. for significant density range.

P. Hadrálek & J. C. Casado / ESO

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