Highly Magnetic Stars and Continuous Gravitational Wave Production

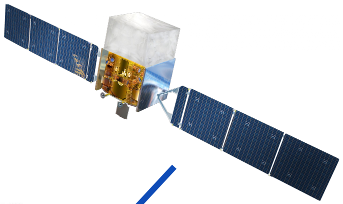
Sam Frederick

3-15-19

Ways of Observing

- Astronomy: an ***observational** science*
- **Light:** The electromagnetic spectrum

Image credit: NASA



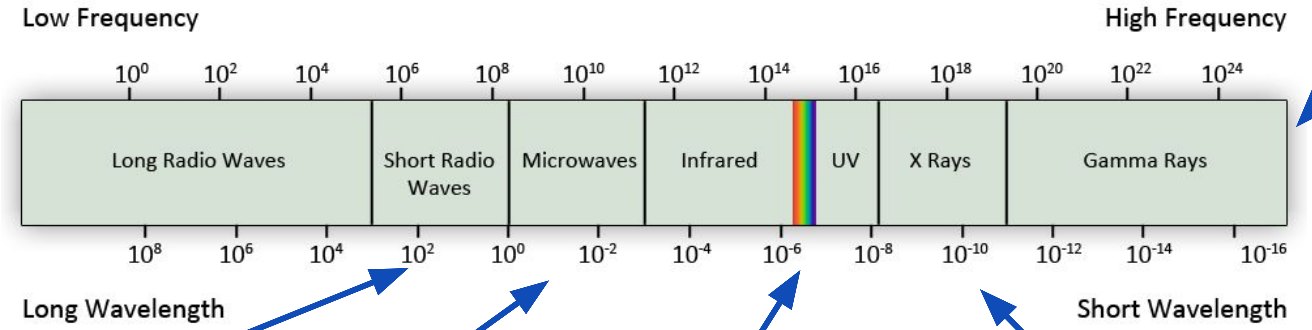


Image credit: NRAO

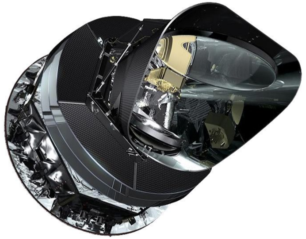


Image credit: NASA

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Ways of Observing:

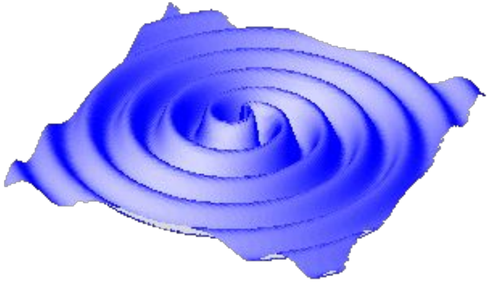


Image credit: Caltech

- **Gravitational Waves** (GWs)
- General Relativity: **high mass, high energy, large objects**
- Sources of gravitational waves:
  - **Binary "inspiral" mergers (black holes and neutron stars) Detected**
  - **Dramatic supernovae explosions**
  - **Rapidly rotating stars with rotationally asymmetric deformations**
    - Appear to "wobble" as they rotate.
    - Gravitational Waves emitted as **continuous signals** **My Research**

How LIGO detects Gravitational Waves

- Michelson Interferometer
  - Light is split, sent down two perpendicular halls, and recombined.
- Gravitational waves will alter the length of each hall.
  - Changes in length only 1/10,000 width of a proton!
- Minute changes in hall length cause *interference.*

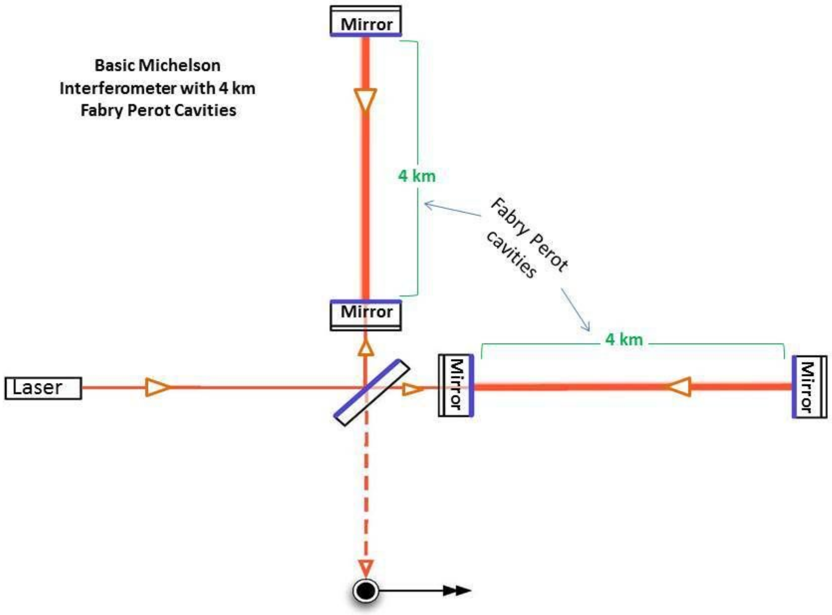
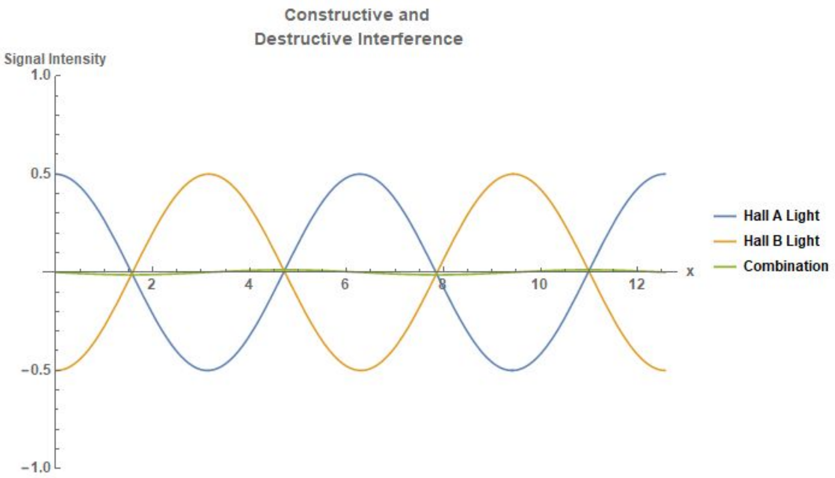
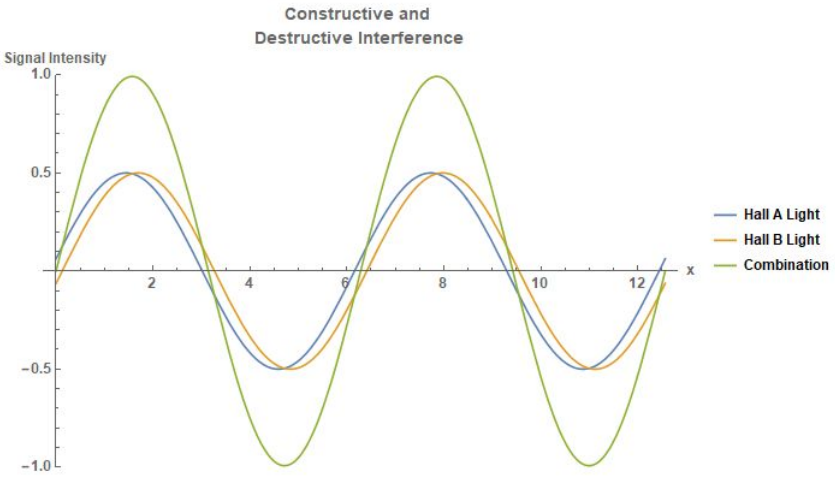


Image credit: LIGO Lab/Caltech

Interference: LIGO’s Signal

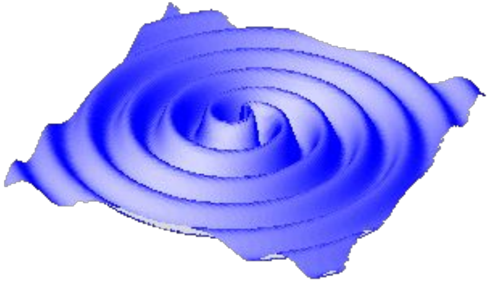




No Gravitational Wave → Destructive Interference → No Signal

Gravitational Wave → Halls Expand/Contract → Constructive Interference → Signal

Ways of Observing:



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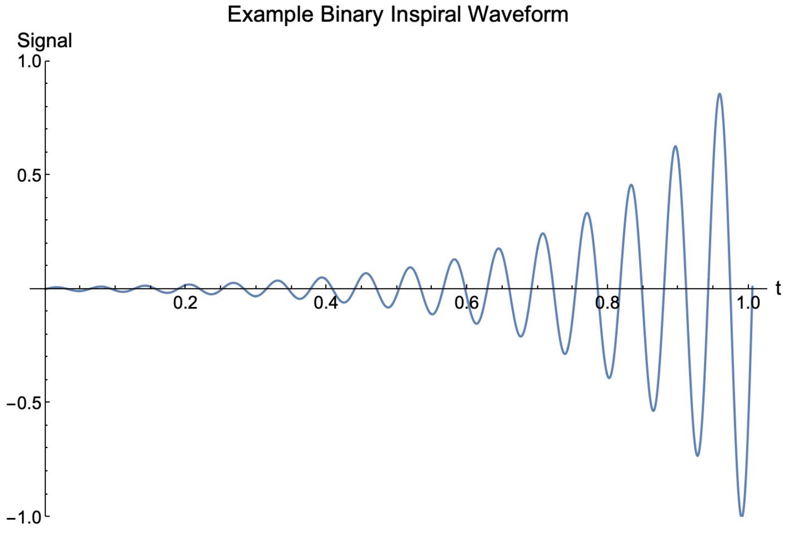
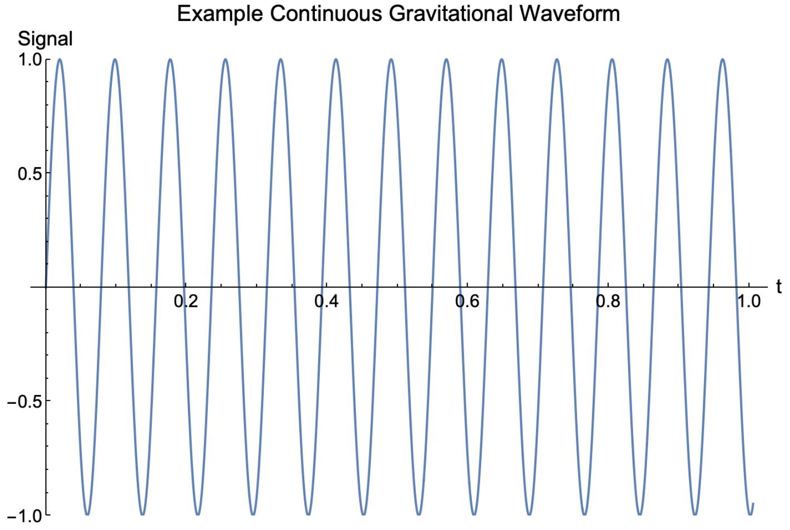
Examples of GW Detector Signals



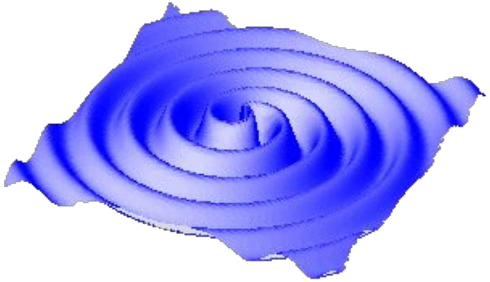
Binary Inspiral Signal



Continuous Signal

Signal strengths not to scale

Ways of Observing:



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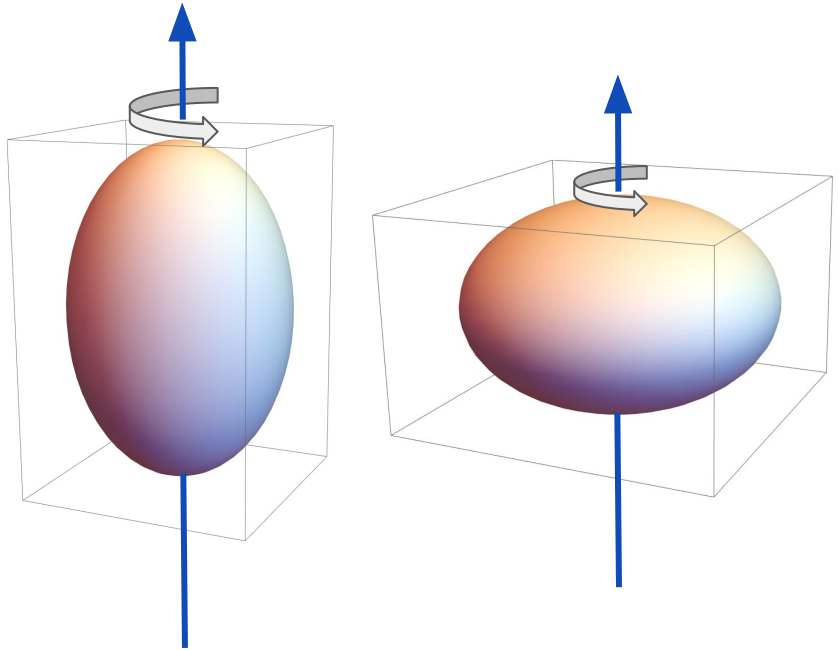
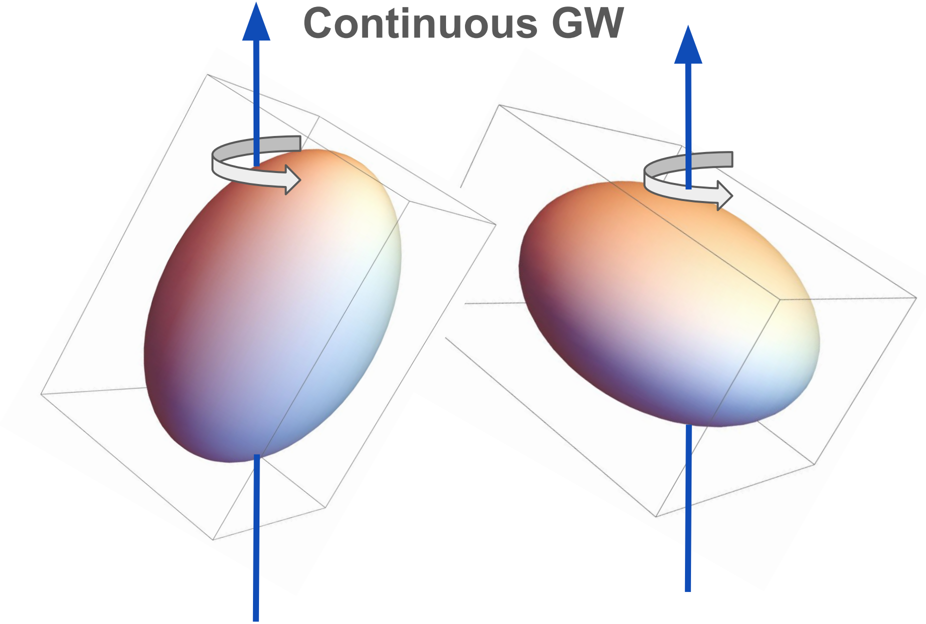
Asymmetric Rotation

Symmetric Rotators: No Continuous GW



Asymmetric Rotators: Wobble, Produce Continuous GW

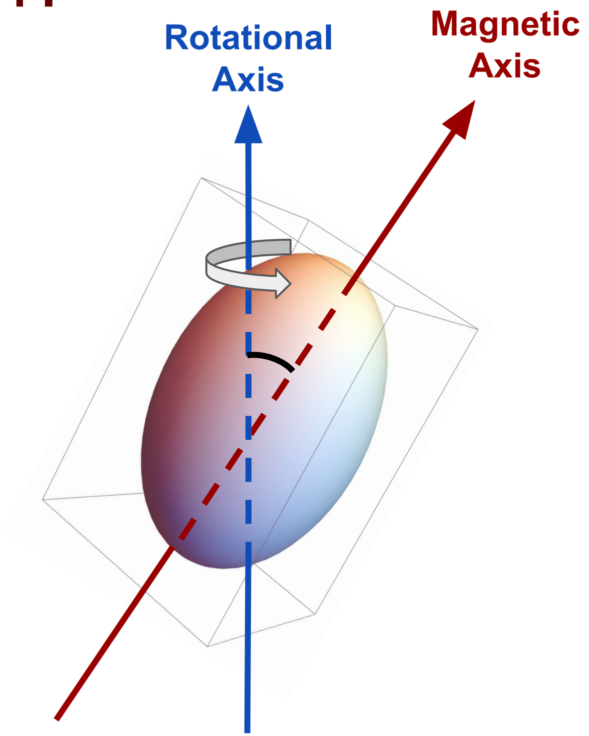


Axis of rotation in blue

Deformations not to scale

What Produces Asymmetric Rotation?

- Strong stellar magnetic fields with central axes not aligned with the rotational axis
- Production of Continuous GWs Require:
    - **Rapid Rotation**
    - **Magnetic Fields *~1 trillion - 100 trillion times stronger* than Earth's field.**
- **Magnetars provide these conditions.**



Magnetars: Background

Neutron Stars - Remnant core of massive star

- ➔ Composed almost completely of neutrons
- ➔ Core densities ~ 10^{15} g cm^{-3}

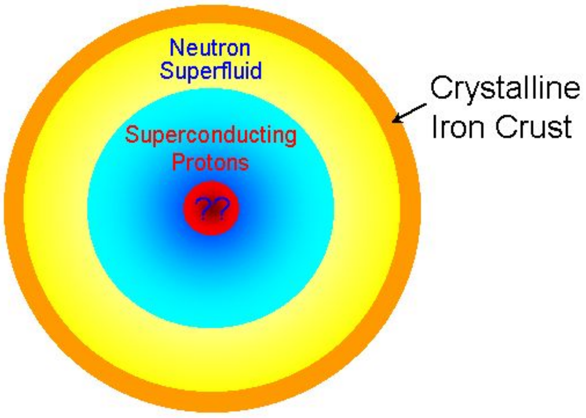


Image credit: Ohio State University

Pulsars - Rapidly rotating neutron star with a strong magnetic field

- ➔ B-field ~ 10^{12} - 10^{13} gauss
- ➔ Rotational period: ~ 0.7 s

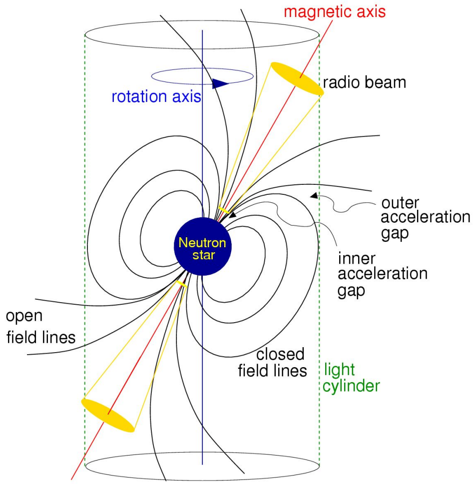


Image credit: NRAO

Magnetars - Highly magnetic pulsars

- ➔ B-field ~ 10^{15} gauss, *strongest in universe*
- ➔ Fields alter structure of star via Lorentz force.

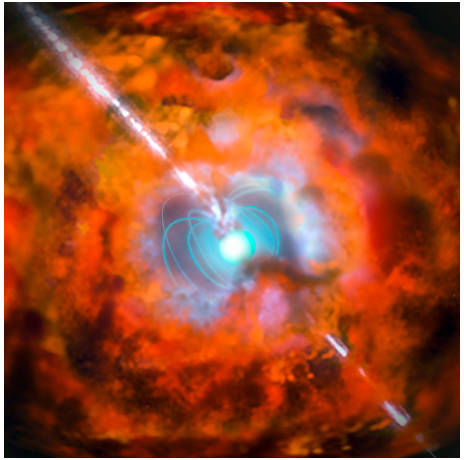


Image credit: ESO

Why Study Magnetars?

- Potential sources of gravitational waves
  - Verify existence of continuous GW sources
  - Inform, set boundaries for models of neutron star composition.
- Rapidly growing field: Rate of detection dramatically increased following launch of Swift and Fermi space telescopes.
  - First detection in 1979.

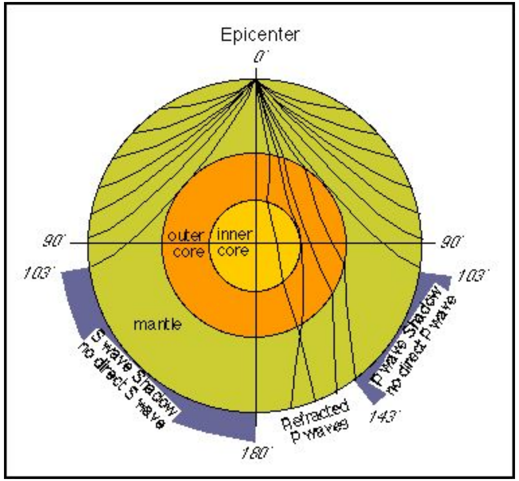


Image Credit: Columbia/Dr. Vic DiVenere

Fermi Gamma-ray Space Telescope: Launched June, 2008

NASA E/PO, Sonoma State University/Aurore Simonnet

Research Goals

- Use computational simulation to model magnetars:

1. Model stellar structure and magnetic field.

2. Evolve initial state and quantify stellar deformation due to magnetic field.

3. Compute amplitude for continuous gravitational wave

$$h \propto \frac{f^2}{r}\epsilon$$

Amplitude

Frequency of Gravitational Wave

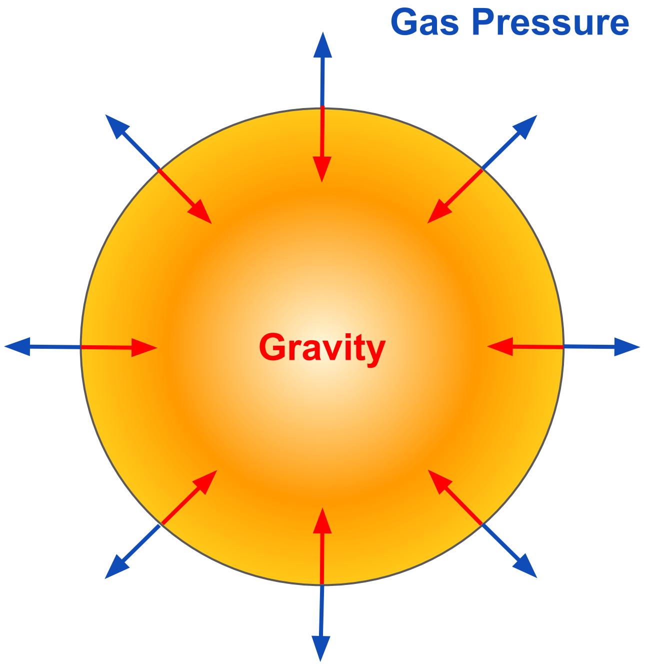
Ellipticity (Measure of deformation)

Star Distance

Stellar Model: Requirements

- **Stability - *Hydrostatic Equilibrium***
  - Balance inward force of gravity with pressure distribution.
- **Relation between pressure and density**
  - *“Polytropic Equation of State”*

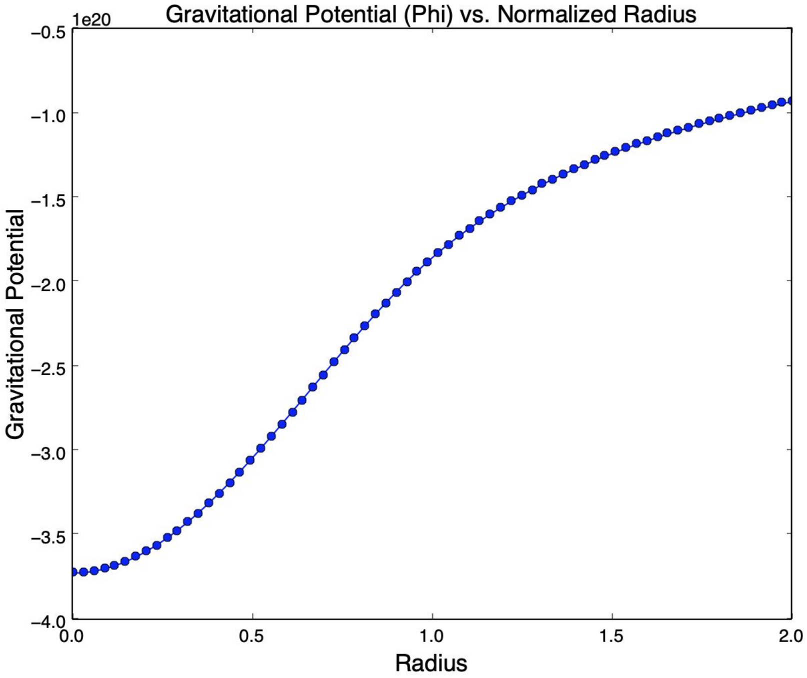
$$P(\rho) = K\rho^{\gamma}$$



Stellar Hydrostatic Equilibrium

Stellar Model: Requirements

- **Expressions for pressure and density as functions of radius**
  - Describe how structure changes throughout the star.
- **Gravitational force to balance stellar structure.**
  - **Stellar Core**
  - **Stellar Interior**
  - **Stellar Exterior**



Magnetic Field Model: Requirements

- **Require stable magnetic field model**
  - **Dynamic Stability: Field retains configuration throughout time**
  - Not all fields have stable configurations.
  - ***Unstable Poloidal Field Configuration***

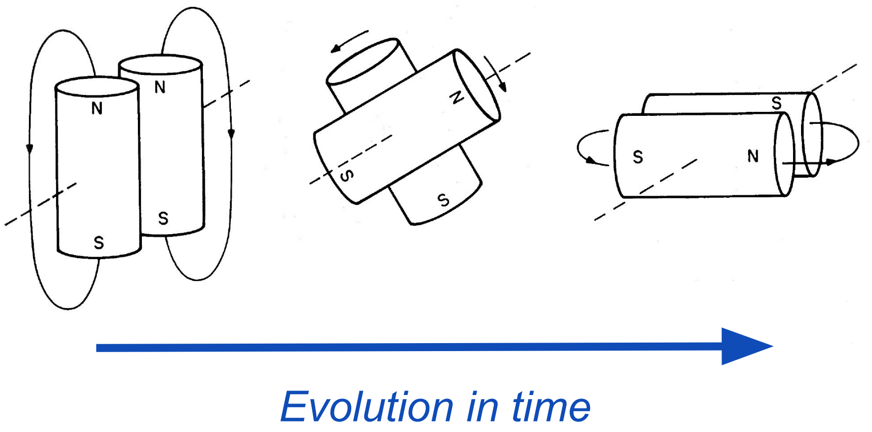


*Image Credit: E G. Flowers and M A. Ruderman. "*Evolution of pulsar magnetic fields*". In: The Astrophysical Journal 215 (June 1977), pp. 302–310.

Magnetic Field Model: Requirements

- **Stable field configuration**
  - **Poloidal Field** wrapped by **Toroidal Field**
  - Fields stabilize each other; one component affects the other.

Poloidal component stabilized by **toroidal** field

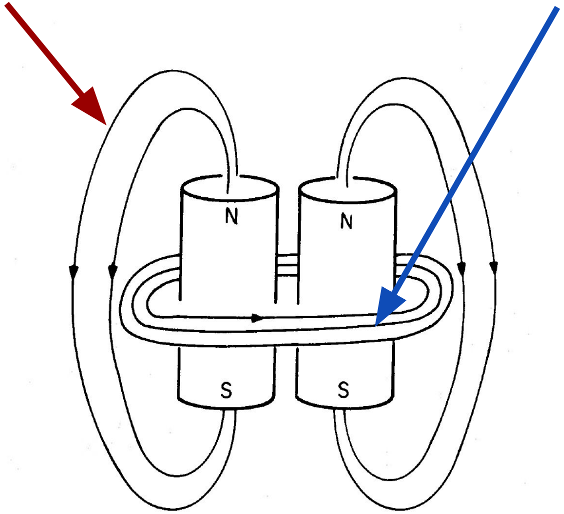
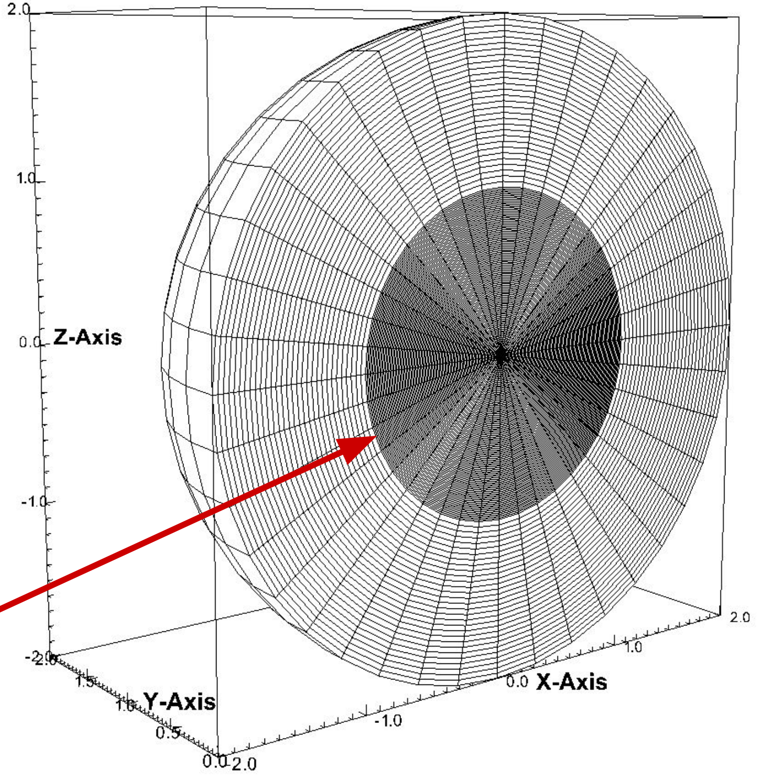


*Image Credit: E G. Flowers and M A. Ruderman. “*Evolution of pulsar magnetic fields*”. In: The Astrophysical Journal 215 (June 1977), pp. 302–310.

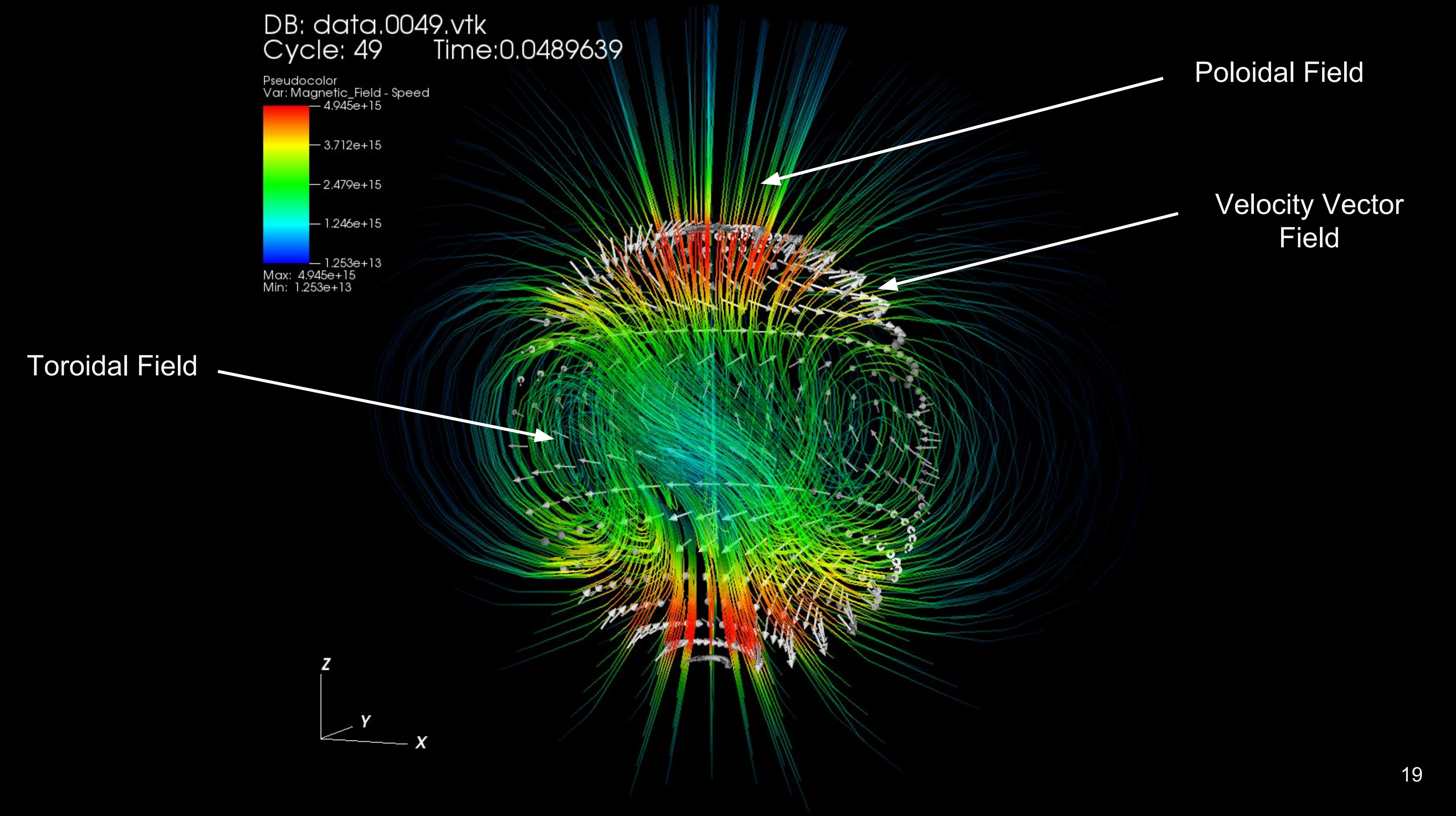
Simulation Methods

- Spherical mesh for modeling magnetars
  - Composed of hundreds of grid cells
  - Each grid cell assigned values for density, pressure, etc.
  - Higher grid resolution inside star



Stellar Radius, R = 1.0

One hemisphere of the computational domain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Cycle: 49 Time:0.0489639
Pseudocolor
Var: Magnetic_Field - Speed
4.945e+15
3.712e+15
2.479e+15
1.246e+15
1.253e+13
Max: 4.945e+15
Min: 1.253e+13
Poloidal Field
Velocity Vector Field
Toroidal Field
Z
Y
X

Concluding Remarks

- Verify model in hydrostatic equilibrium:
  - Gravitational potential balances pressure gradient.
  - Mass does is not spontaneously ejected from stellar surface.
- Confirm stability of magnetic field model:
  - Poloidal and toroidal field components self-regulate, evolve with stability under time.
- **Ongoing work:**
  - Deformation calculations
  - Gravitational Wave Amplitude Measurements

Acknowledgements

- I wish to extend appreciation and thanks to my co-mentors Dr. Michelle Kuchera and Dr. Kristen Thompson.
- Additional thanks are extended to CAAC for hosting this presentation.

“Since the light moves through them both at the speed of light, the wavelength changes are unimportant; **when they meet again, they're at the same location in spacetime, and so their wavelengths will now be identical.** What matters is that one beam of light spends longer in the detector, and so when they meet up again, they're now out-of-phase. That's where the LIGO signal comes from, and how we detect gravitational waves!”

-Dr. Ethan Siegel, Senior Contributor, Forbes