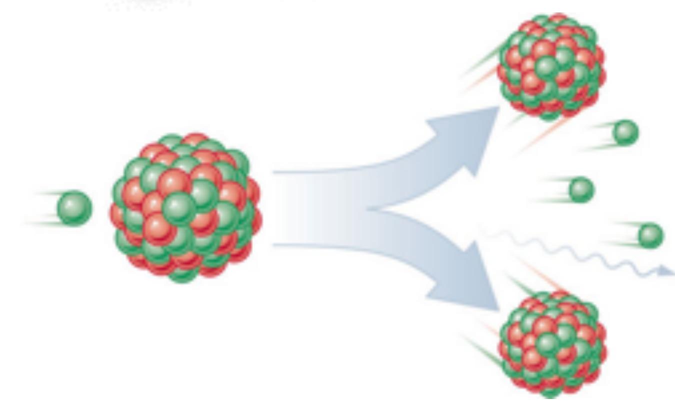
Nuclear Theory for Astrophysics

prospects and challenges
in the multi-messenger era

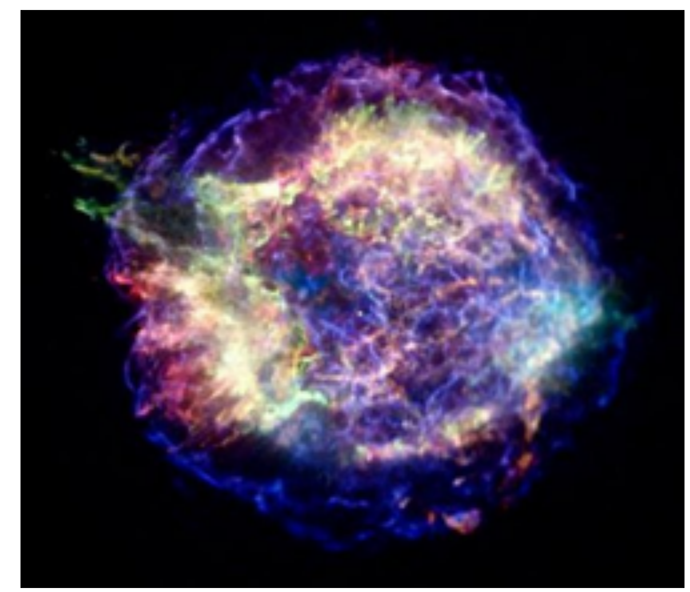
- Big Questions
- Recent Progress & Prospects
- Needs

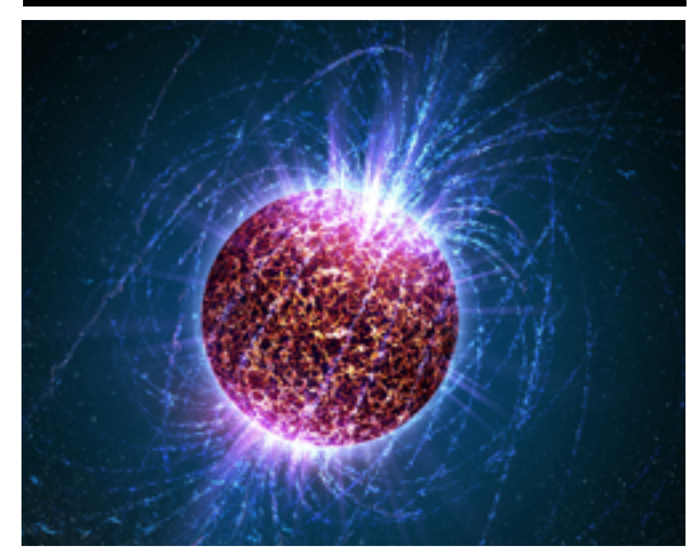
Low Energy Town Meeting, Texas, August 21-23, 2014

Big Questions



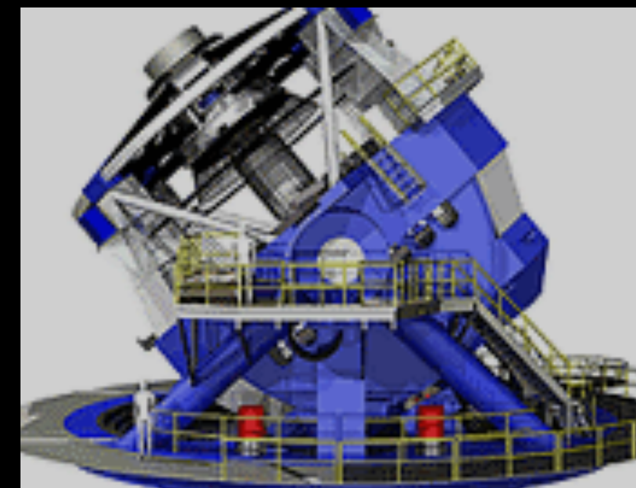
1. Where and how are the heavy elements synthesized ?
2. How do massive stars evolve and explode ?
3. What are the nuclear and neutrino processes that shape cosmic explosions and nucleosynthesis ?
4. What are the phases and properties of matter encountered in neutron stars, supernova and binary neutron star mergers ?
5. Can we interpret multi-messenger signals with advanced modeling and simulations to extract fundamental nuclear physics ?



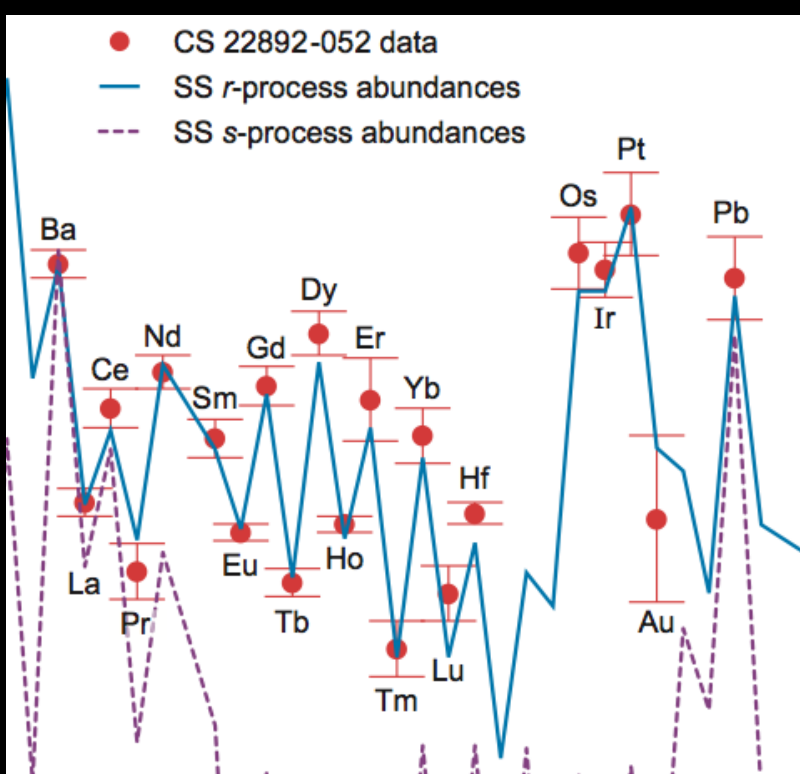


Nuclear Astrophysics in the Multi-Messenger Era

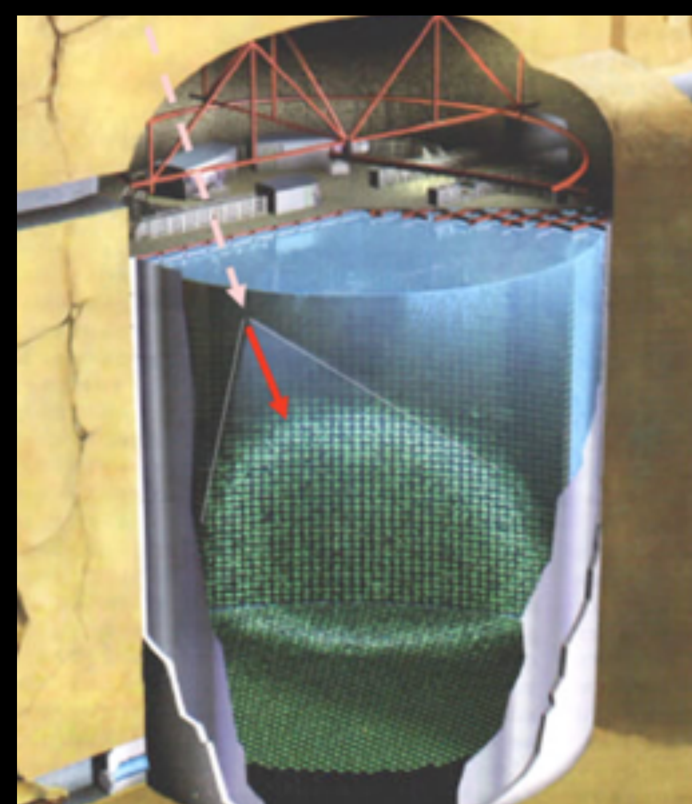





Photons



Abundances

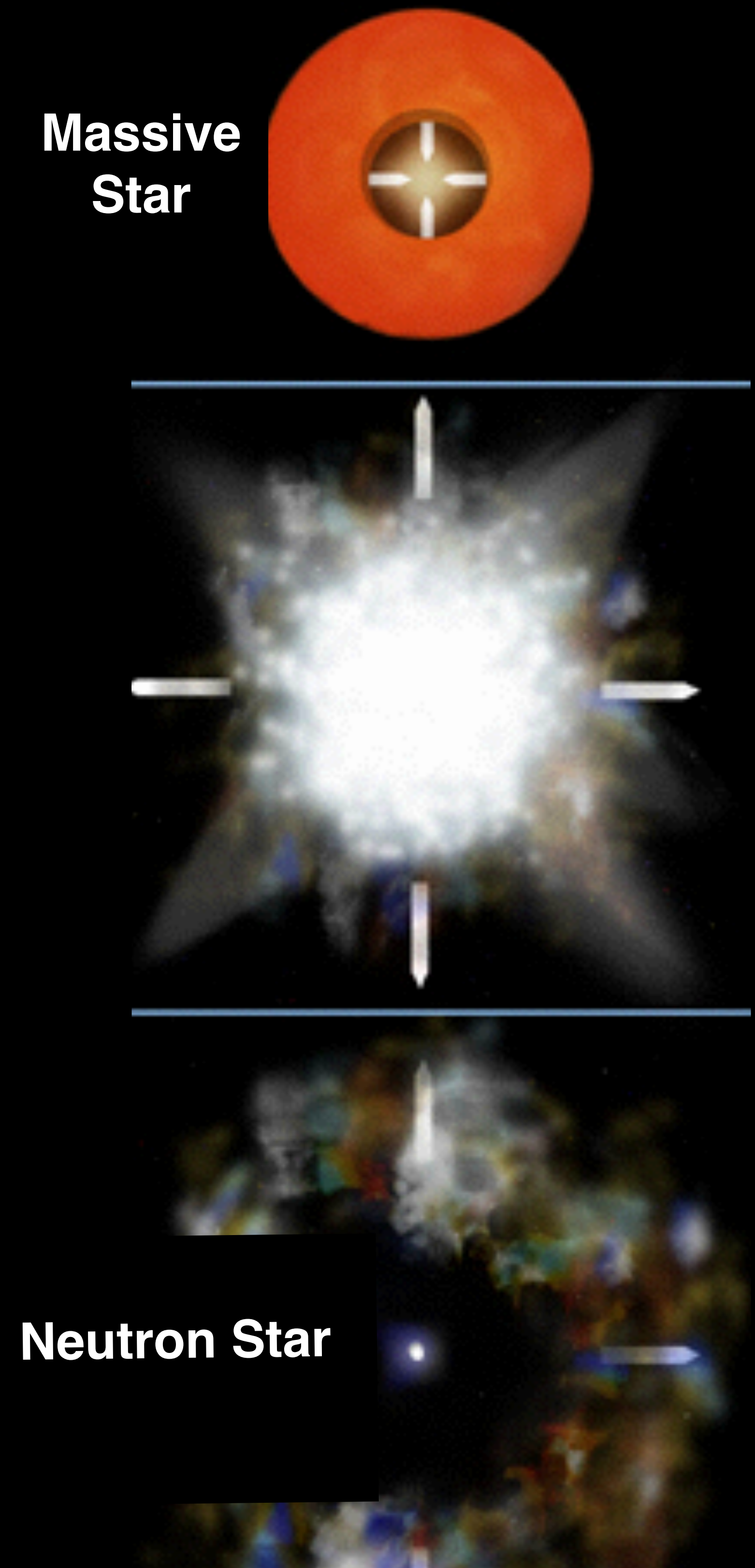


Neutrinos

Gravitational Waves

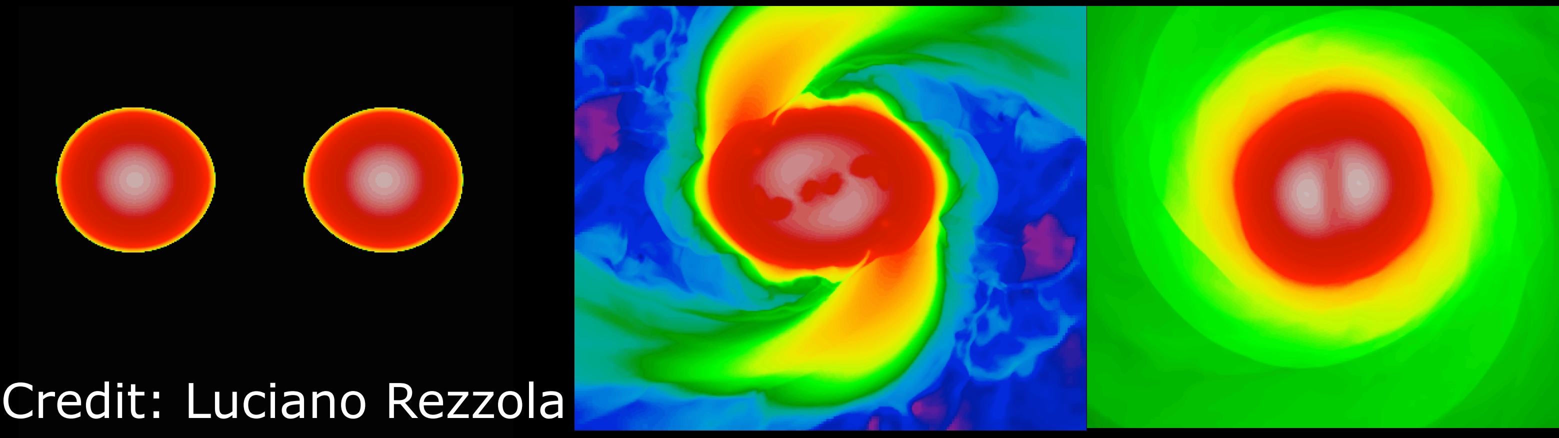
Sources

Supernova



Credit: NASA/CXC/S Lee

Binary Neutron Star Mergers

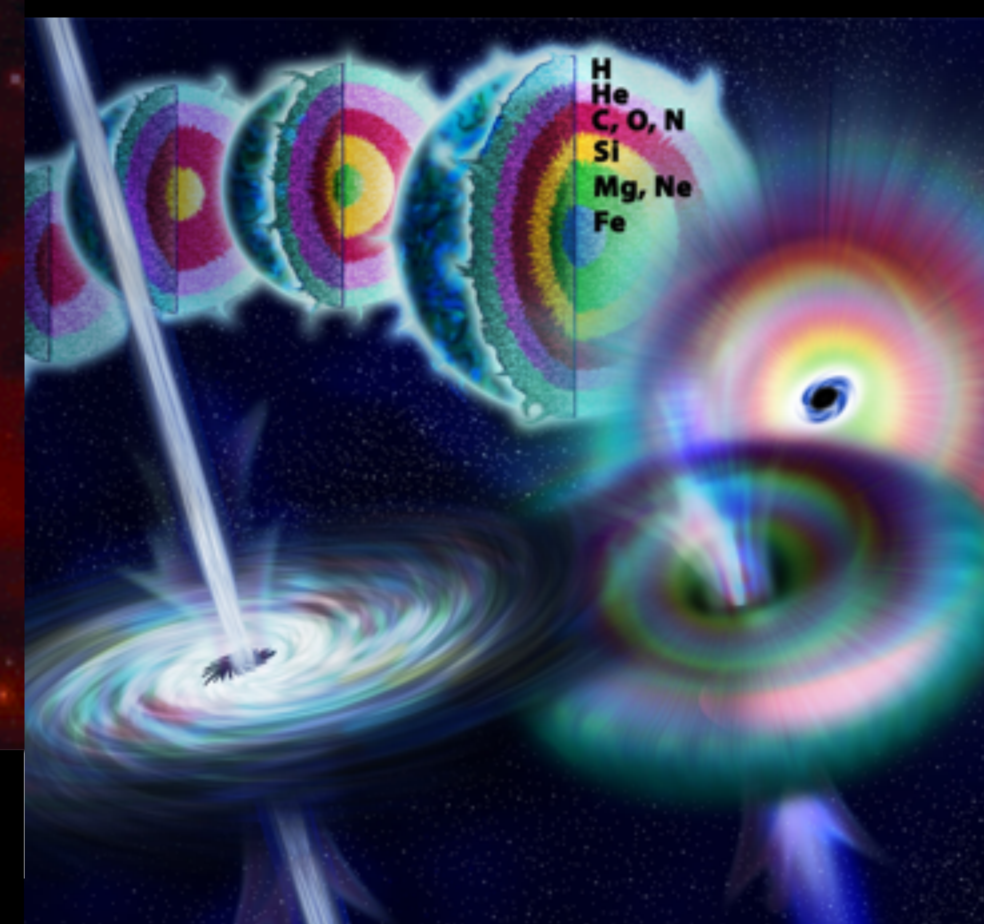


Credit: Luciano Rezzola

X-ray Bursts

Credit: David Hardy & PPARC

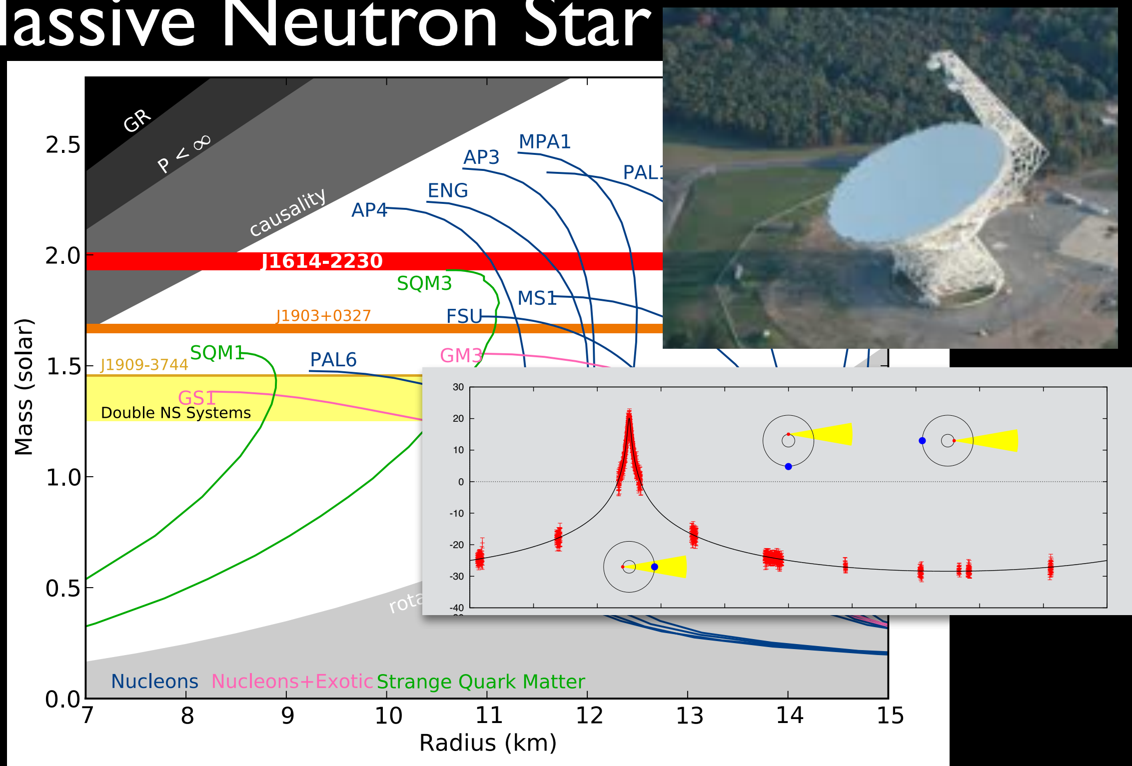
Hypernova



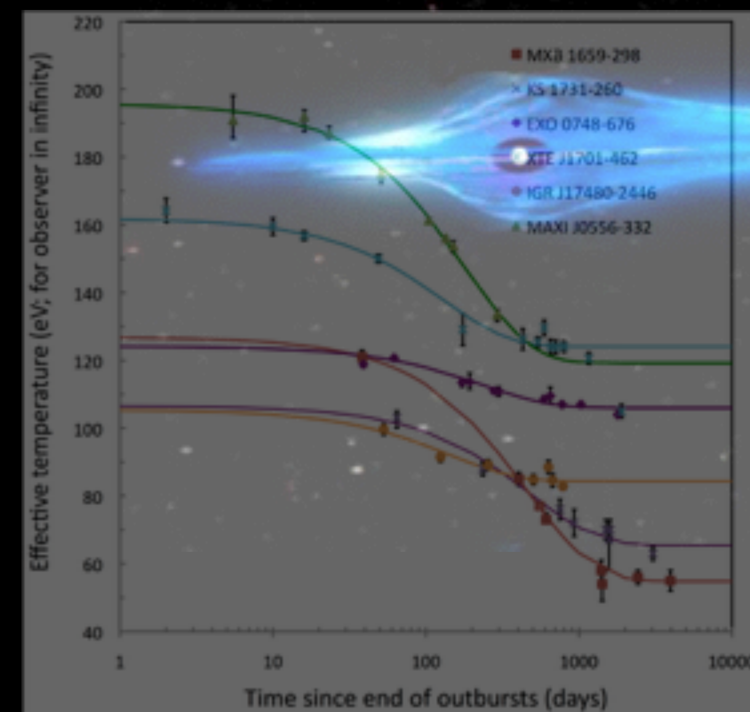
Credit: Nicolle Rager Fuller/NSF

Driven by Observations

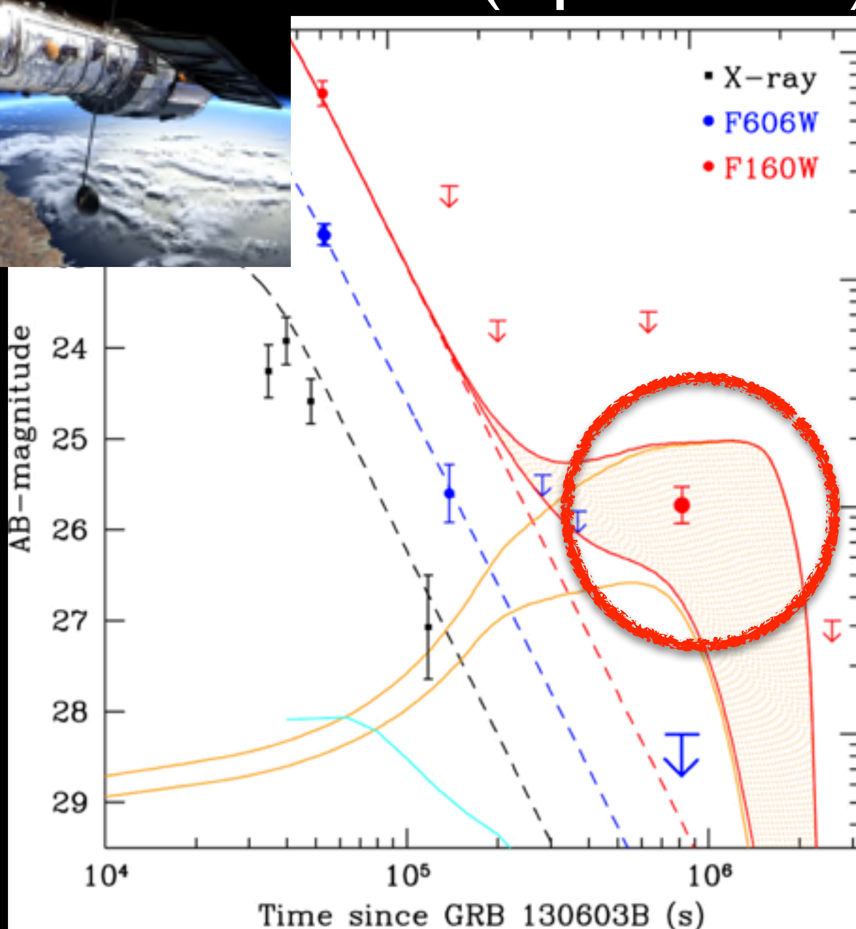
Massive Neutron Star

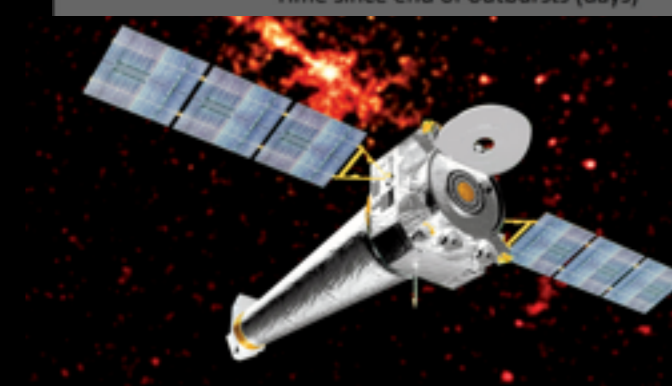


Thermal Relaxation in Accreting Neutron Stars

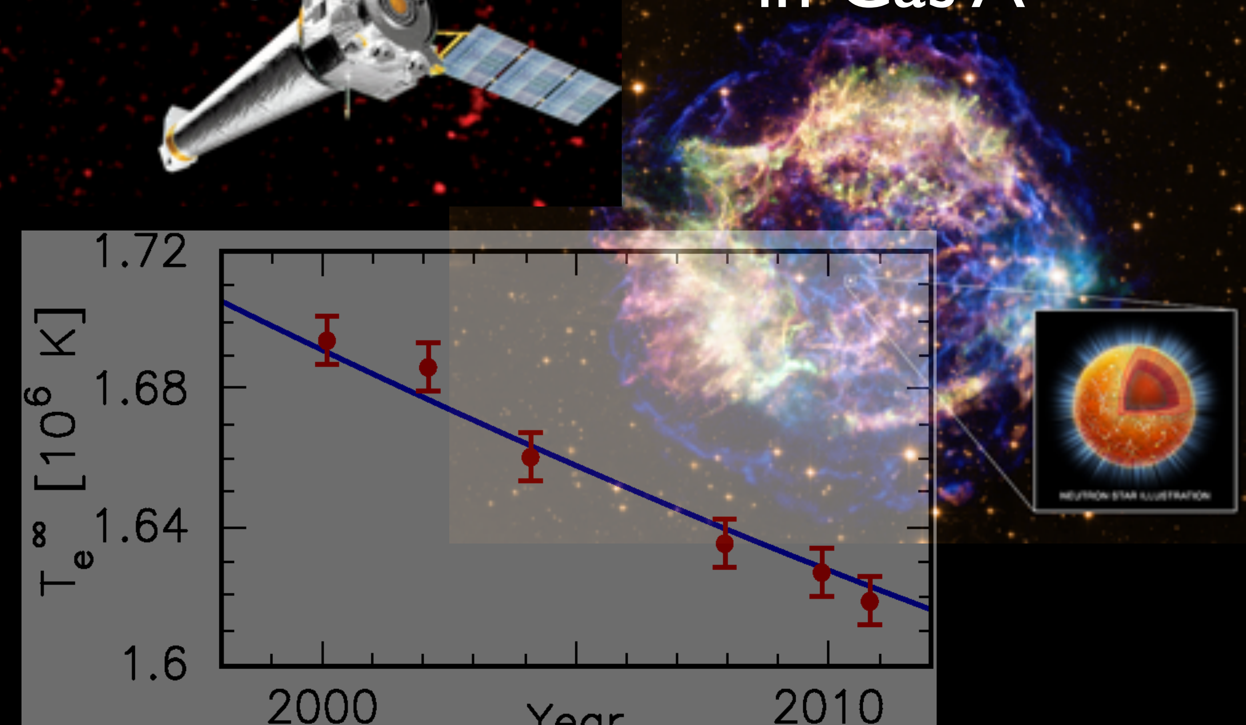


Kilo Nova (r-process ?)

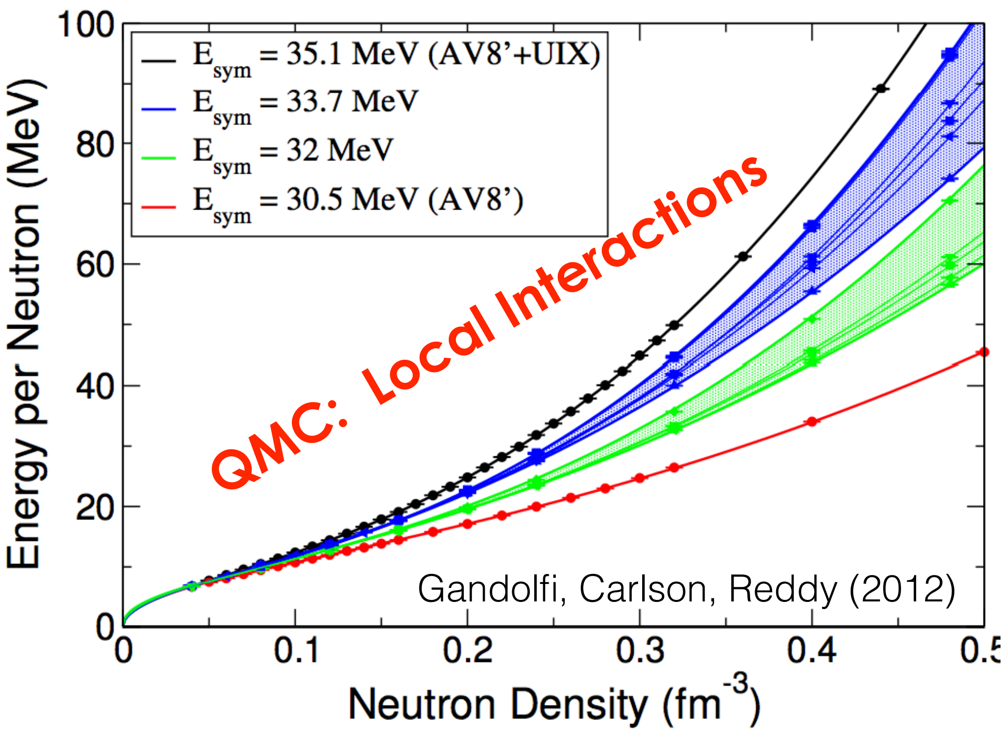


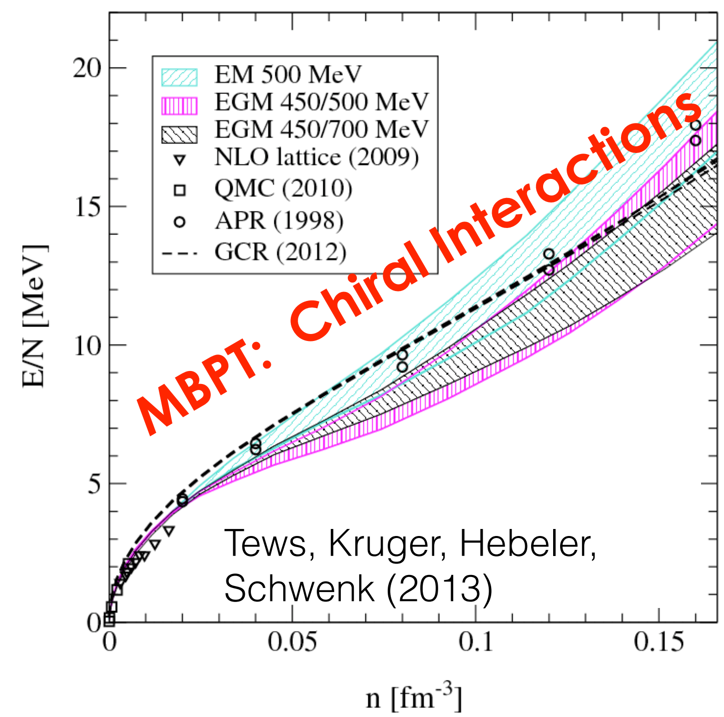


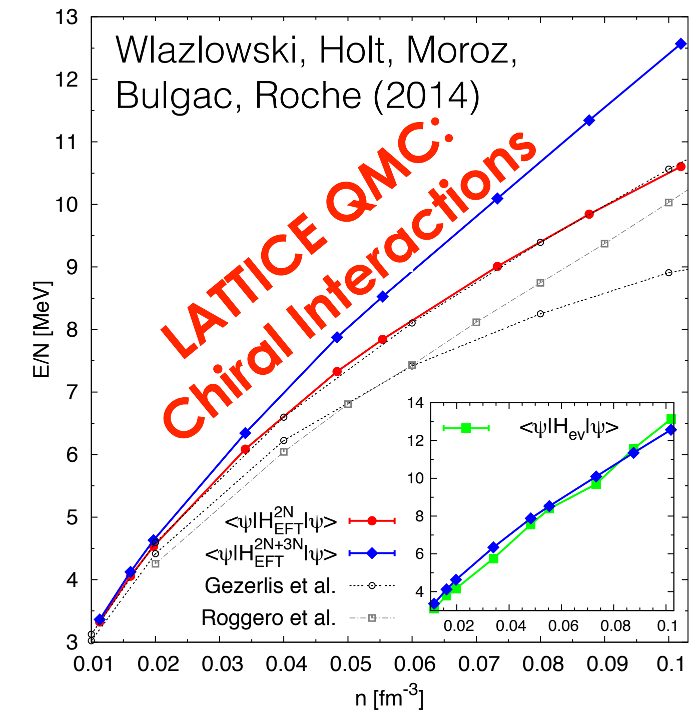
Rapid Cooling in Cas A



Nailing the Neutron Matter EoS at Saturation Density.

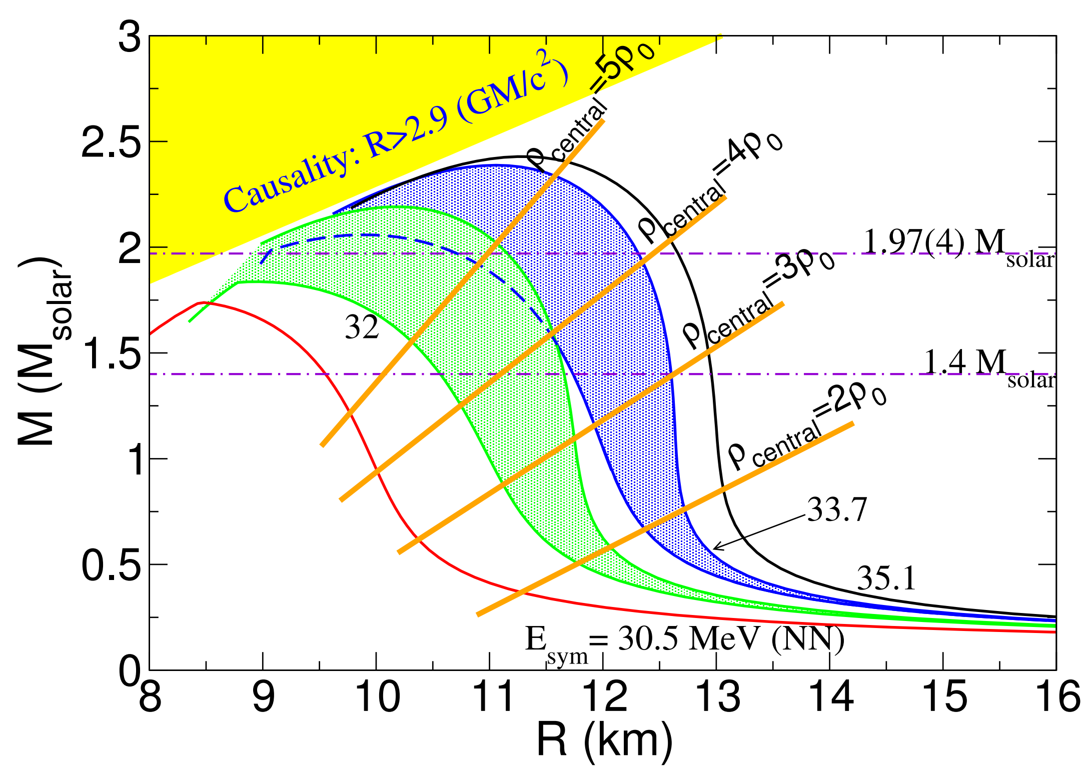


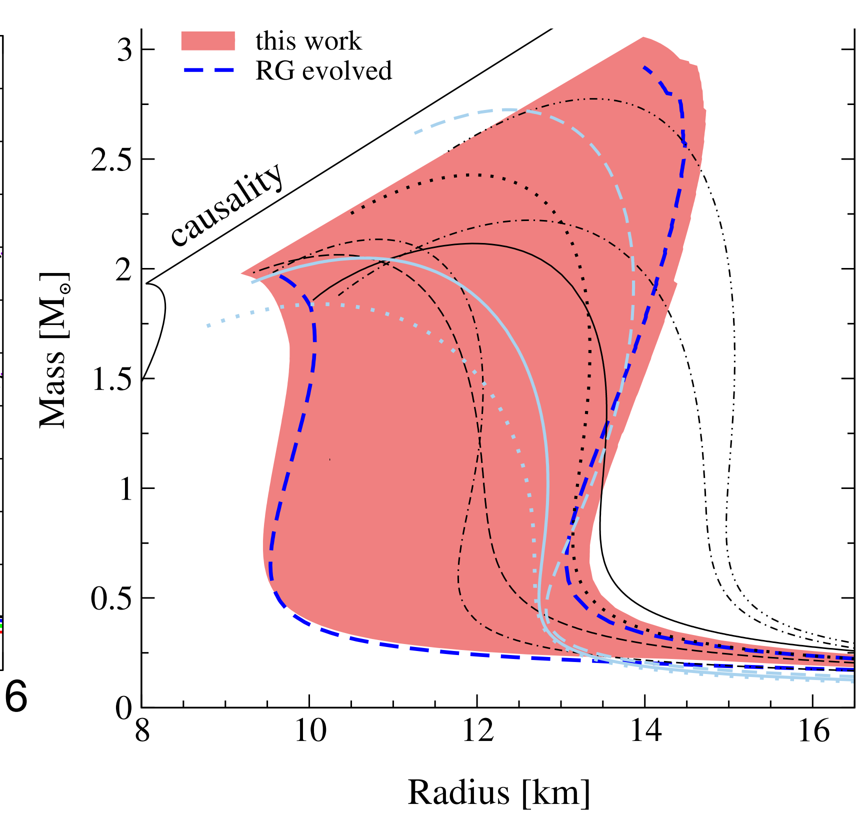




First steps towards quantifying uncertainties due to the interaction and many-body theory.

With implications for neutron star mass and radius.





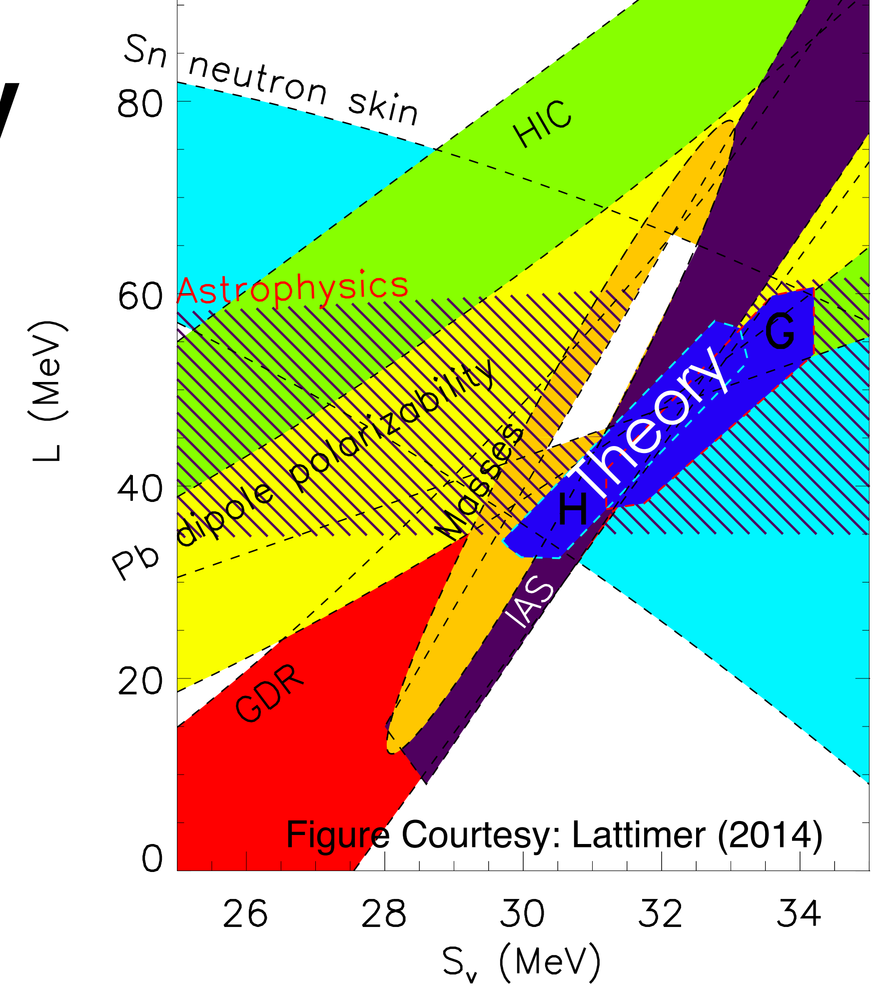
Neutron Matter & Symmetry Energy

EoS of neutron matter and its relation to the properties of nuclei.

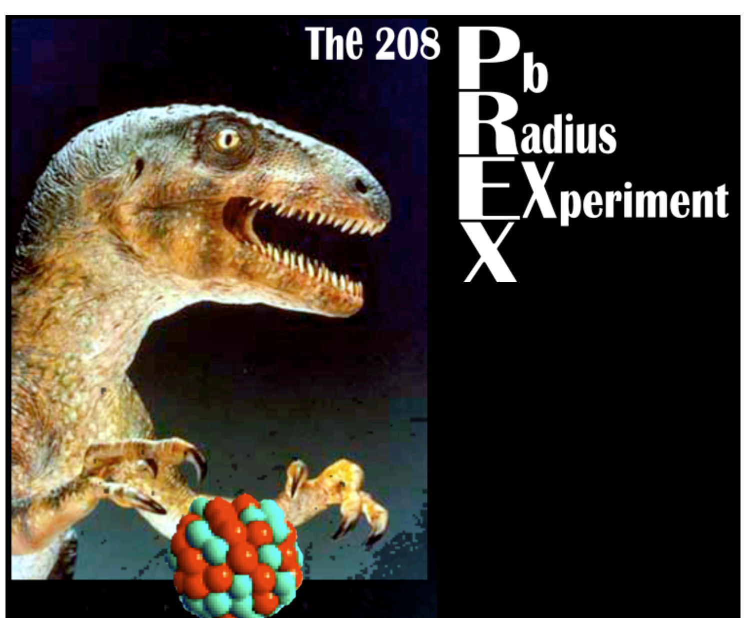
$$S(\rho) = E(\rho, x=0) - E(\rho, x=1/2)$$

$$E(\rho,x) = E(\rho,1/2)+(1-2x)^2 S_2(\rho)+..$$

$$S_2(\rho) = \mathbf{S_v} + \frac{\mathbf{L}}{3}\frac{\rho-\rho_s}{\rho_s} + \ldots$$



- Nuclear measurements (neutron skin, isospin diffusion, dipole polarizability) correlate S & L.
- Neutron star radius is sensitive to L.
- Theory can help combine and understand the systematics

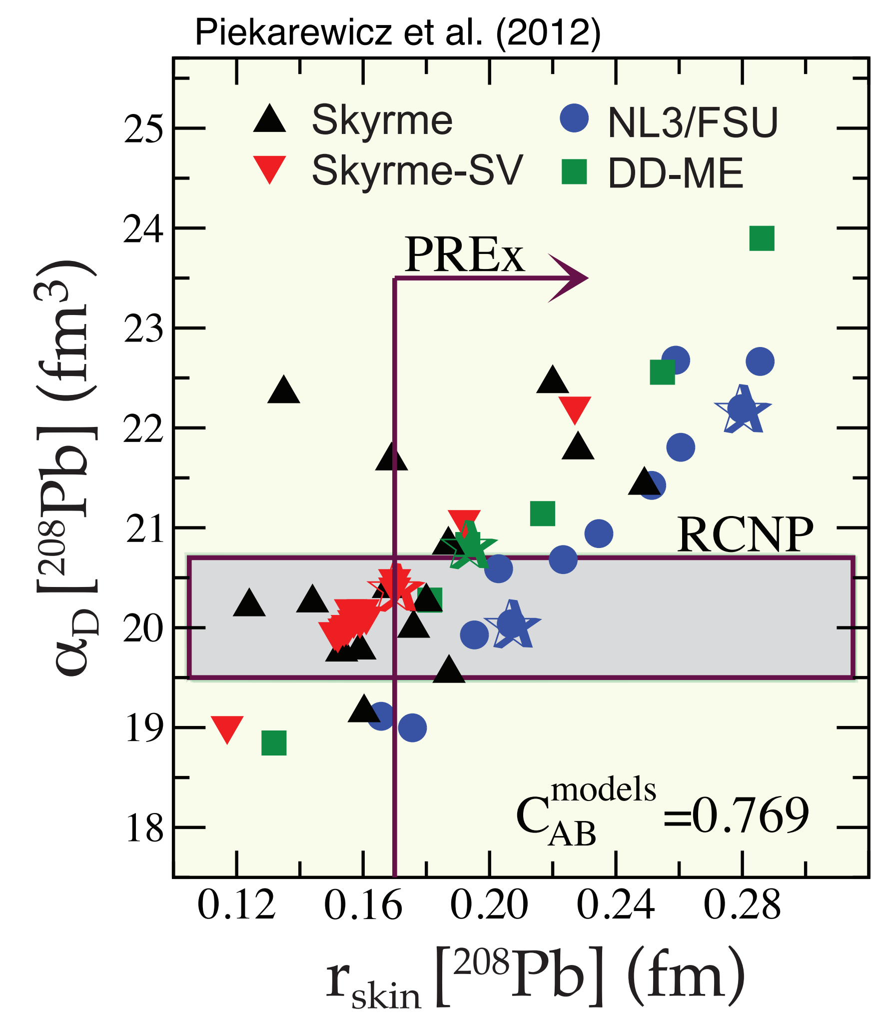


^{208}Pb r_{skin}

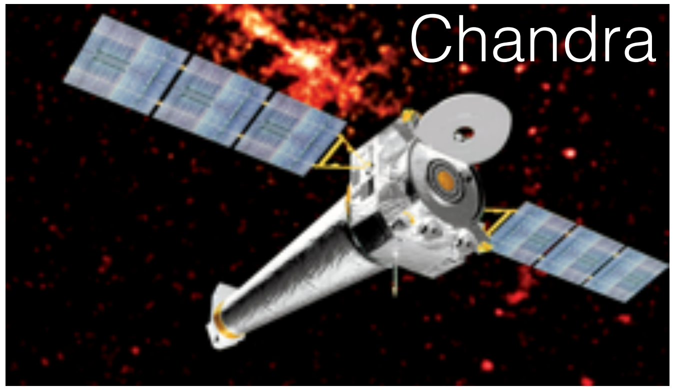
PREX: $0.34^{+0.15}_{-0.17}\, fm$

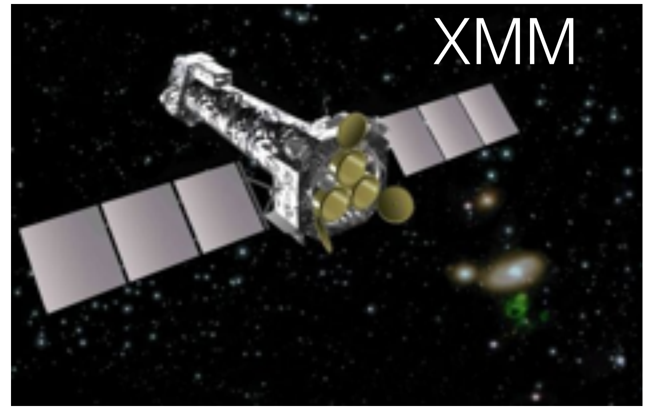
αD (Tamii et al.) $0.156^{+0.025}_{-0.021}\, fm$

Theory: $0.168 \pm 0.022\, fm$



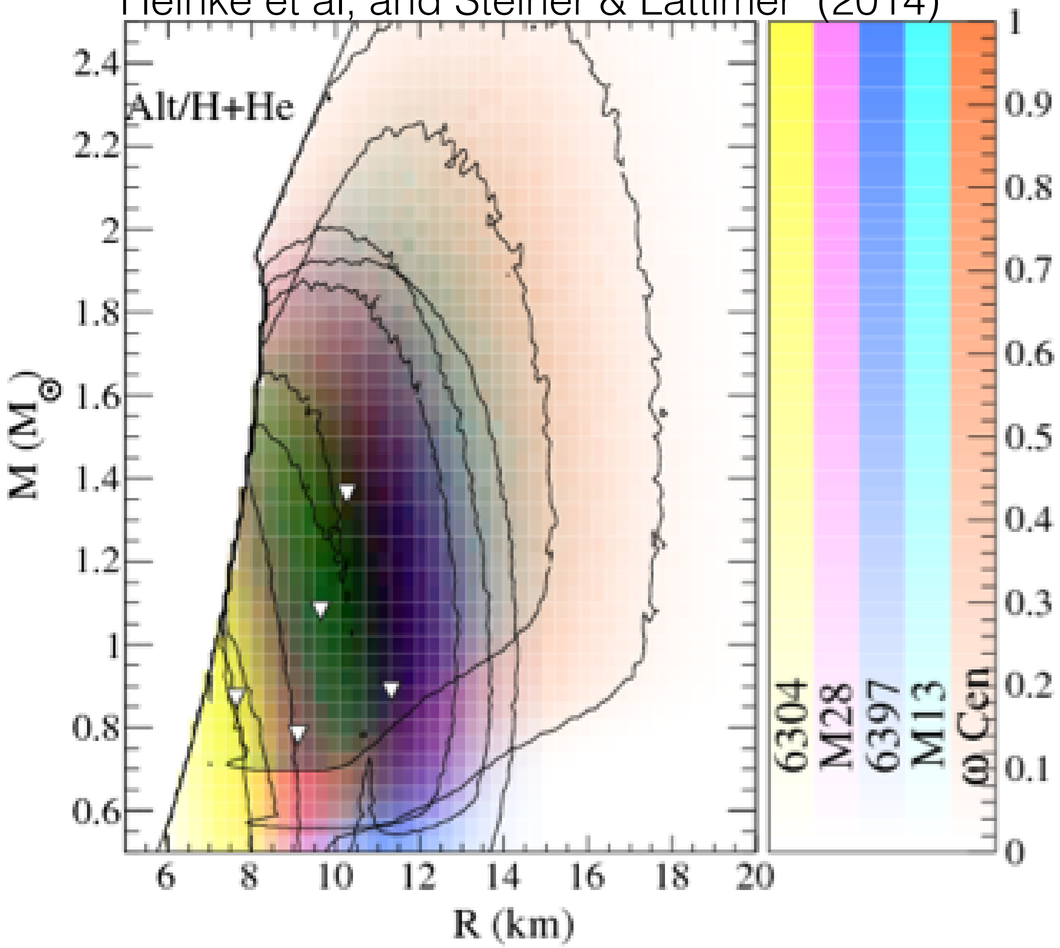
Radii from Astronomy, Astrophysics and Nuclear Physics

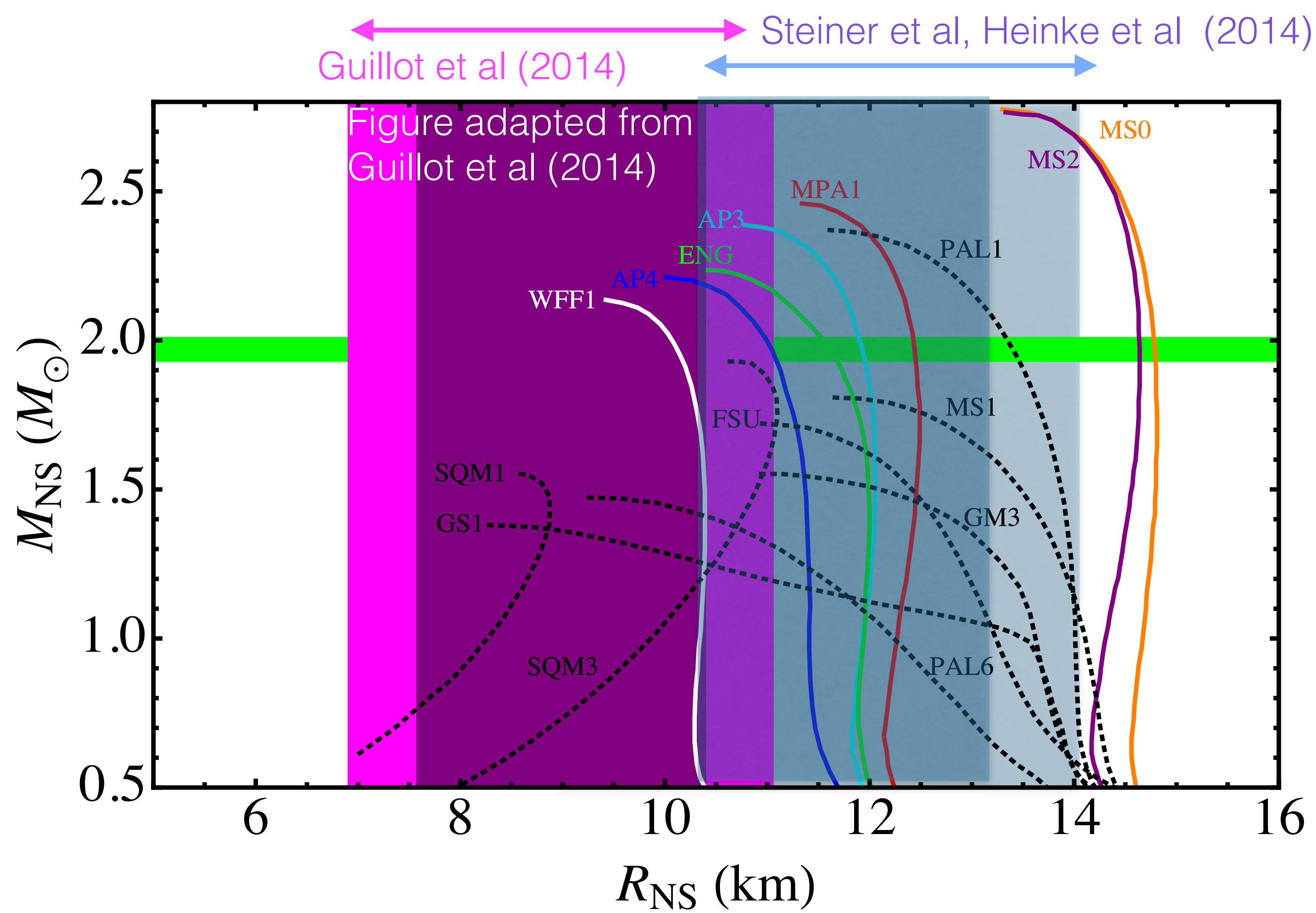




- Extracting radii from observations is challenging due to large systematic errors.
- Astrophysical modeling, and input from nuclear theory can help disentangle and reduce systematics.

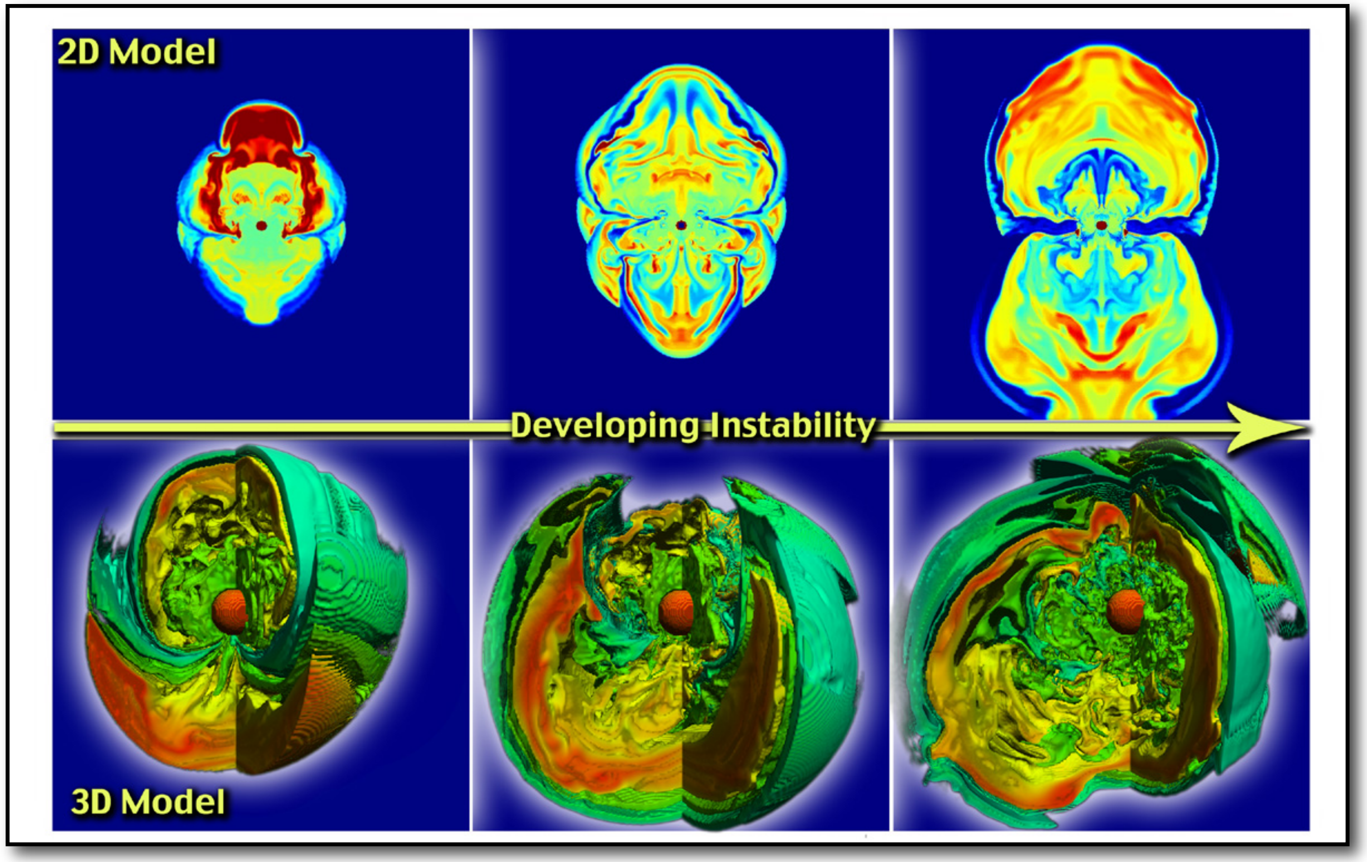
Heinke et al, and Steiner & Lattimer (2014)

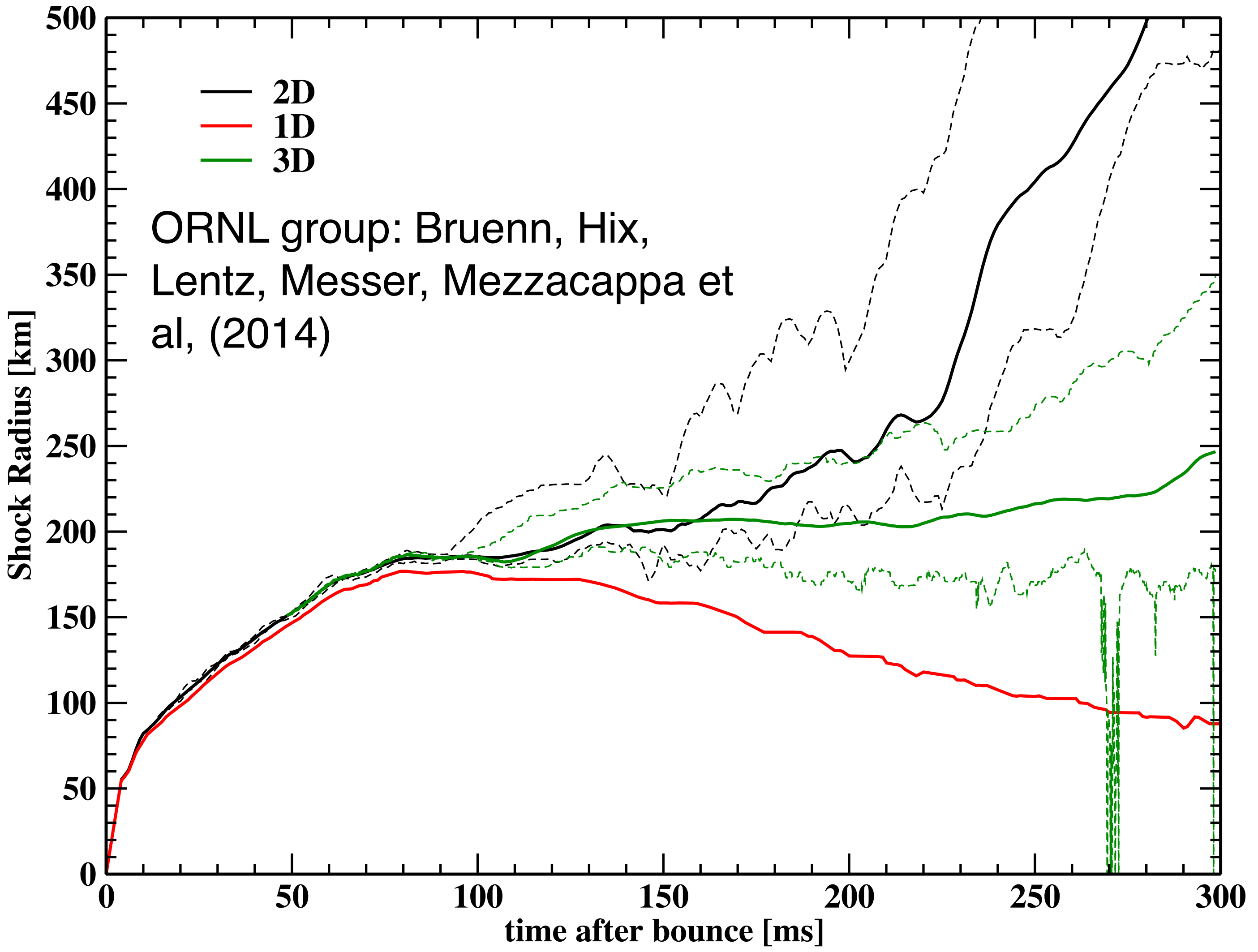




Core Collapse Supernova

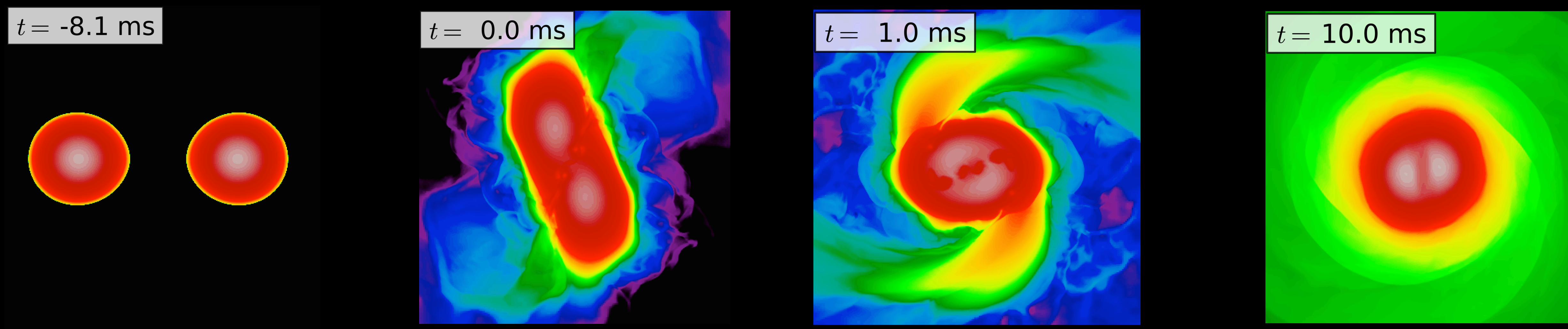
- Mature 2D models predict explosions, first 3D models being studied.
- Significant advances in instabilities during the past decade.
- Detailed predictions for explosion energy, neutrinos and gravitational waves.
- Advanced simulations in 1& 2 D with resolution to unravel role of nuclear EoS and neutrino physics.





Neutron Star Merger Dynamics

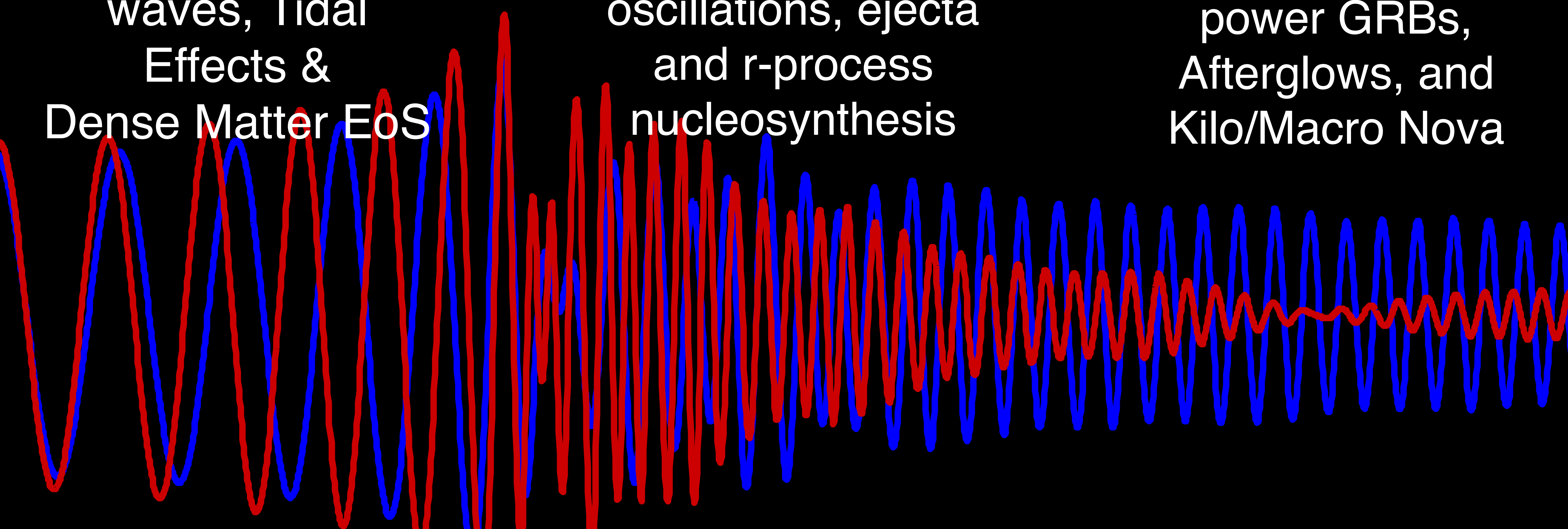
(General) Relativistic (Very) Heavy-Ion Collisions at ~ 100 MeV/nucleon



Inspiral:
Gravitational waves, Tidal Effects & Dense Matter EoS

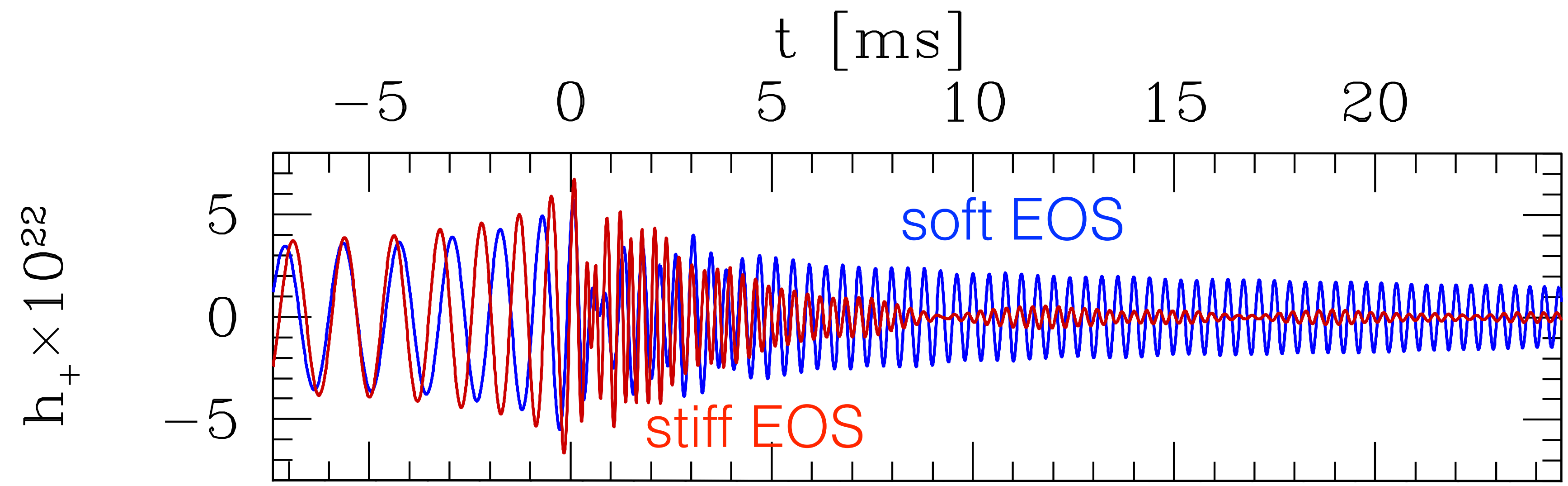
Merger:
Disruption, NS oscillations, ejecta and r-process nucleosynthesis

Post Merger:
Ambient conditions power GRBs, Afterglows, and Kilo/Macro Nova



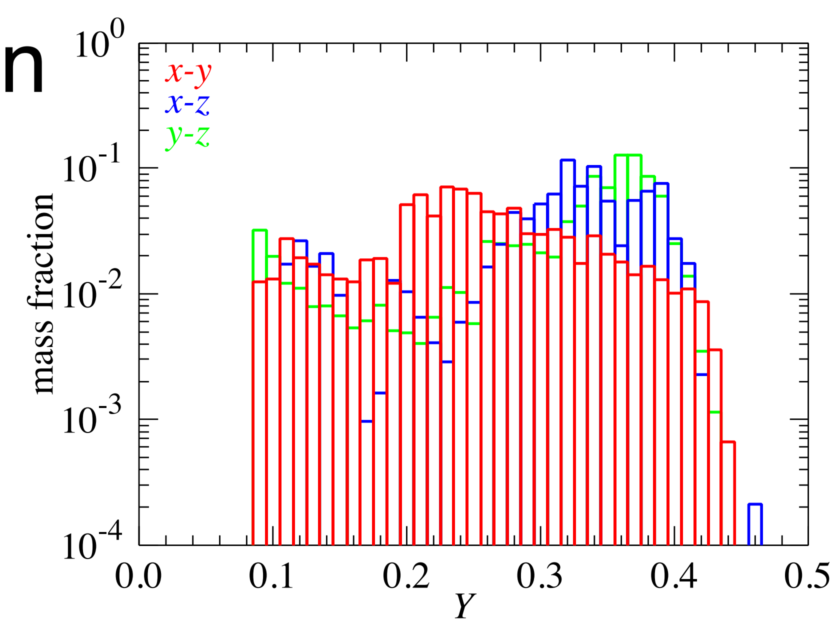
Gravitational Waves

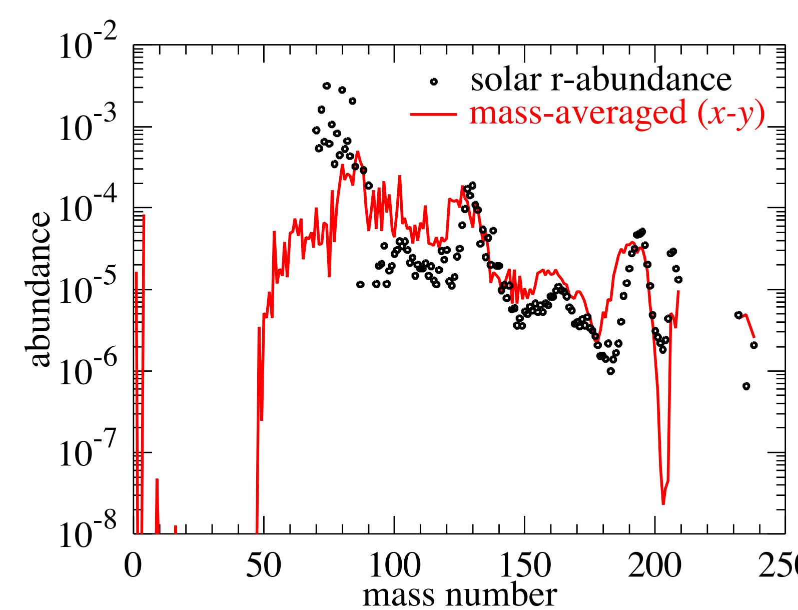
Range ~200-300 Mpc
Rate ~ 1-100 /yr, Data: 2016-2017
Could have far reaching implications for nuclear physics !



Nuclear physics has an impact on:

- Tidal effects on the inspiral wave form.
- Post merger oscillations.
- Amount and composition of matter ejected.
- Nucleosynthesis.
- Lifetime of the hyper massive neutron star.





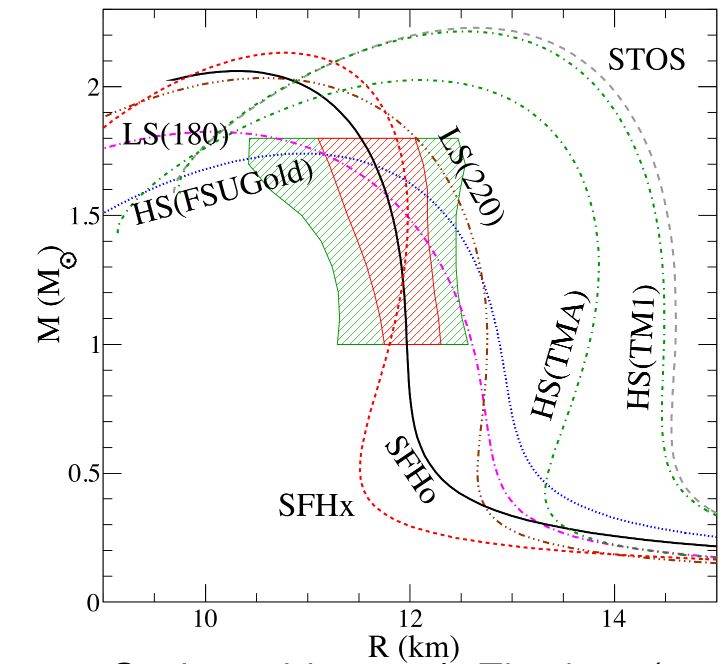
Wanajo, Sekiguchi, et al. 2014

EoS for Supernova & Mergers Simulations

New class of nuclear EoSs developed for simulations. Constrained by

- L & S measurements
- Neutron star radii
- Ab initio neutron matter calculations
- Virial expansion of low density hot matter
- Low energy heavy-ion reactions

Include a range of behavior of the symmetry energy.



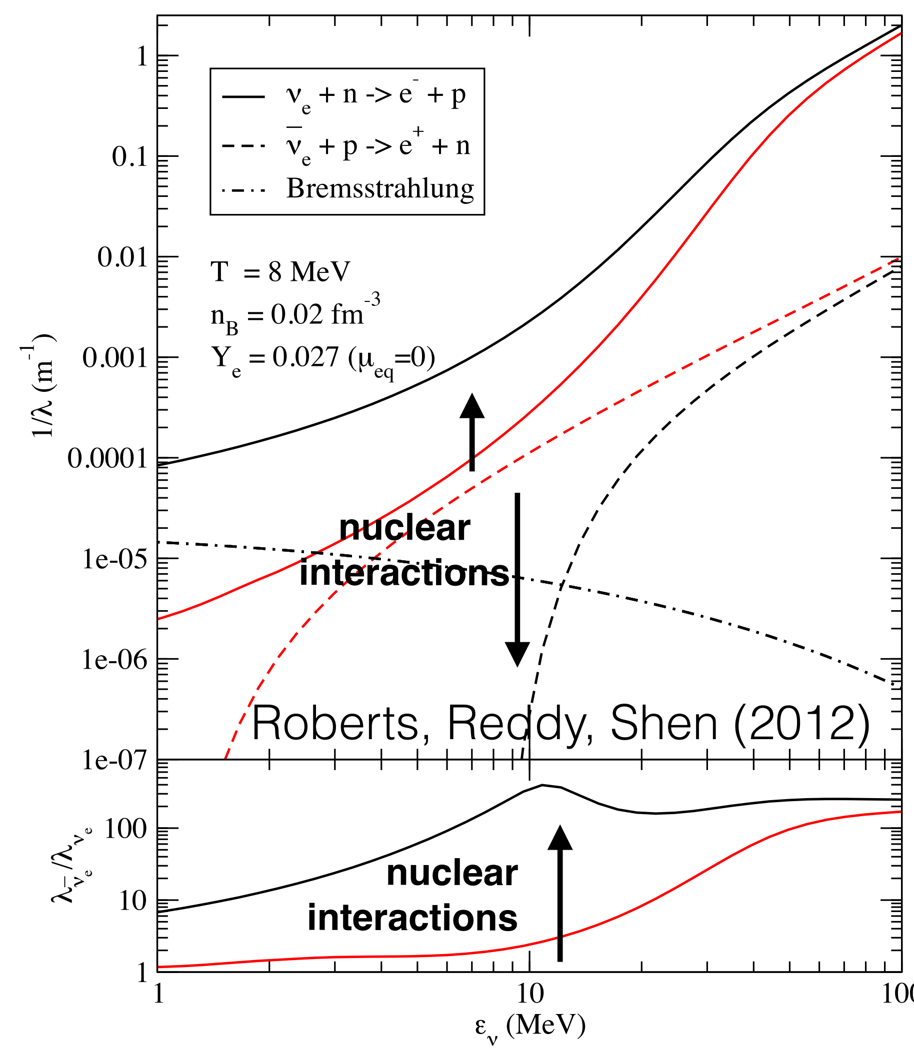
Steiner, Hempel, Fischer (2014)

Weak Interactions in Hot & Dense Matter

Nuclear many-body effects modify weak rates in dense matter.

In the neutrino-sphere, the nuclear symmetry energy plays a crucial role:

- Directly influences the relative difference between electron and anti-electron neutrino spectra.
- Indirectly impacts the ambient conditions for r-process nucleosynthesis.



Warm matter at sub-nuclear density

Relevant & Tractable

- Directly influences supernova and merger dynamics.
- Neutrino decoupling region (neutrino-sphere).
- Nuclear interactions well understand.
- At high temperature virial expansion exists.

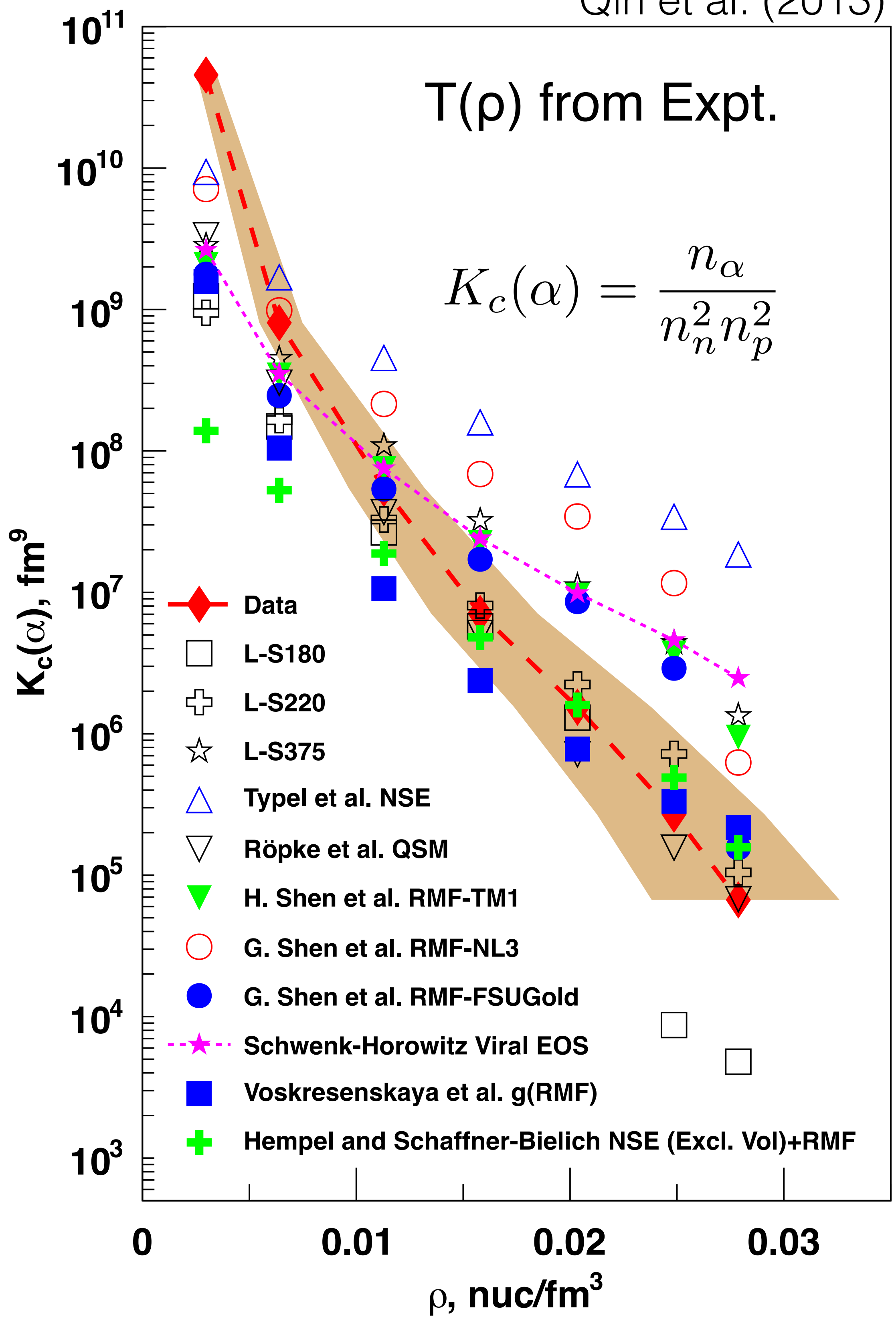
Key Issues:

What is the symmetry energy ?

How do clusters dissolve ?

What is the response (to neutrinos)?

Qin et al. (2013)

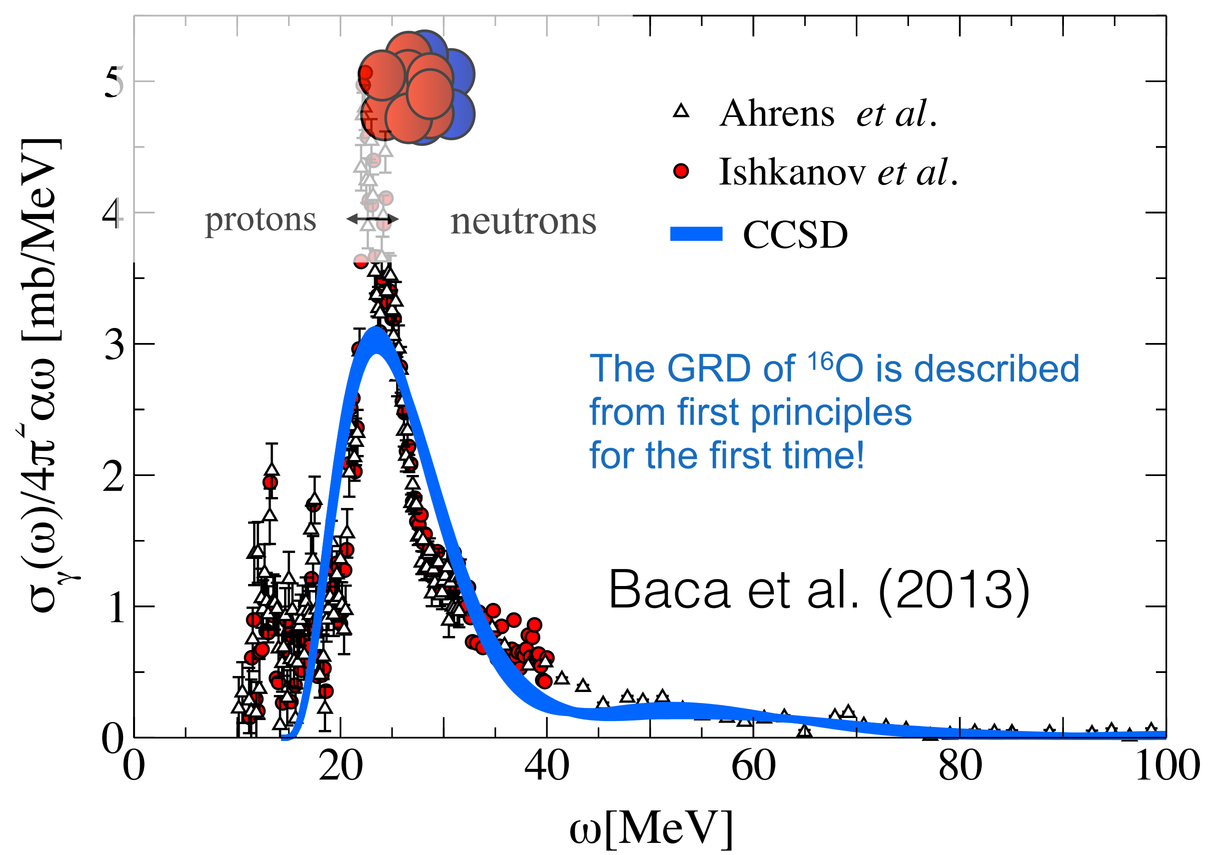


Low energy heavy-ion experiments can provide guidance.

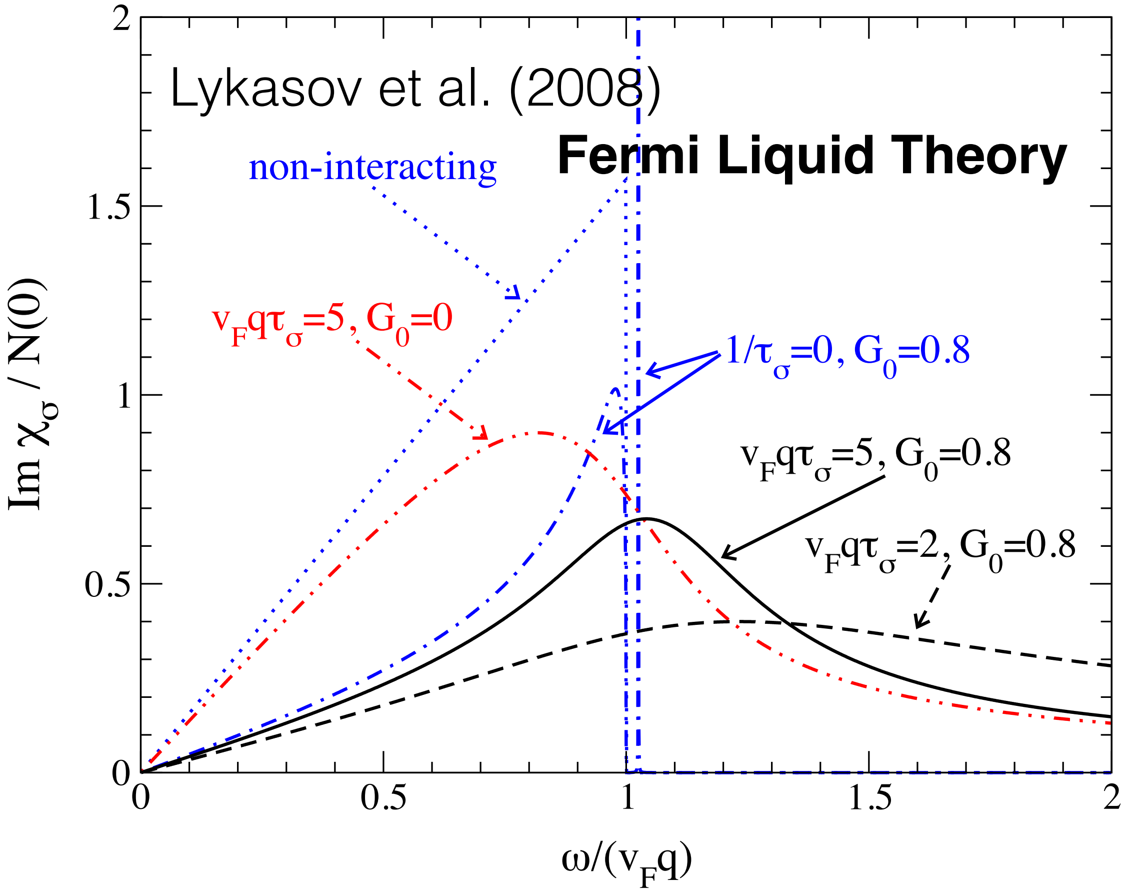
Towards a Quantitive Theory of Response of Nuclei and Nuclear Matter

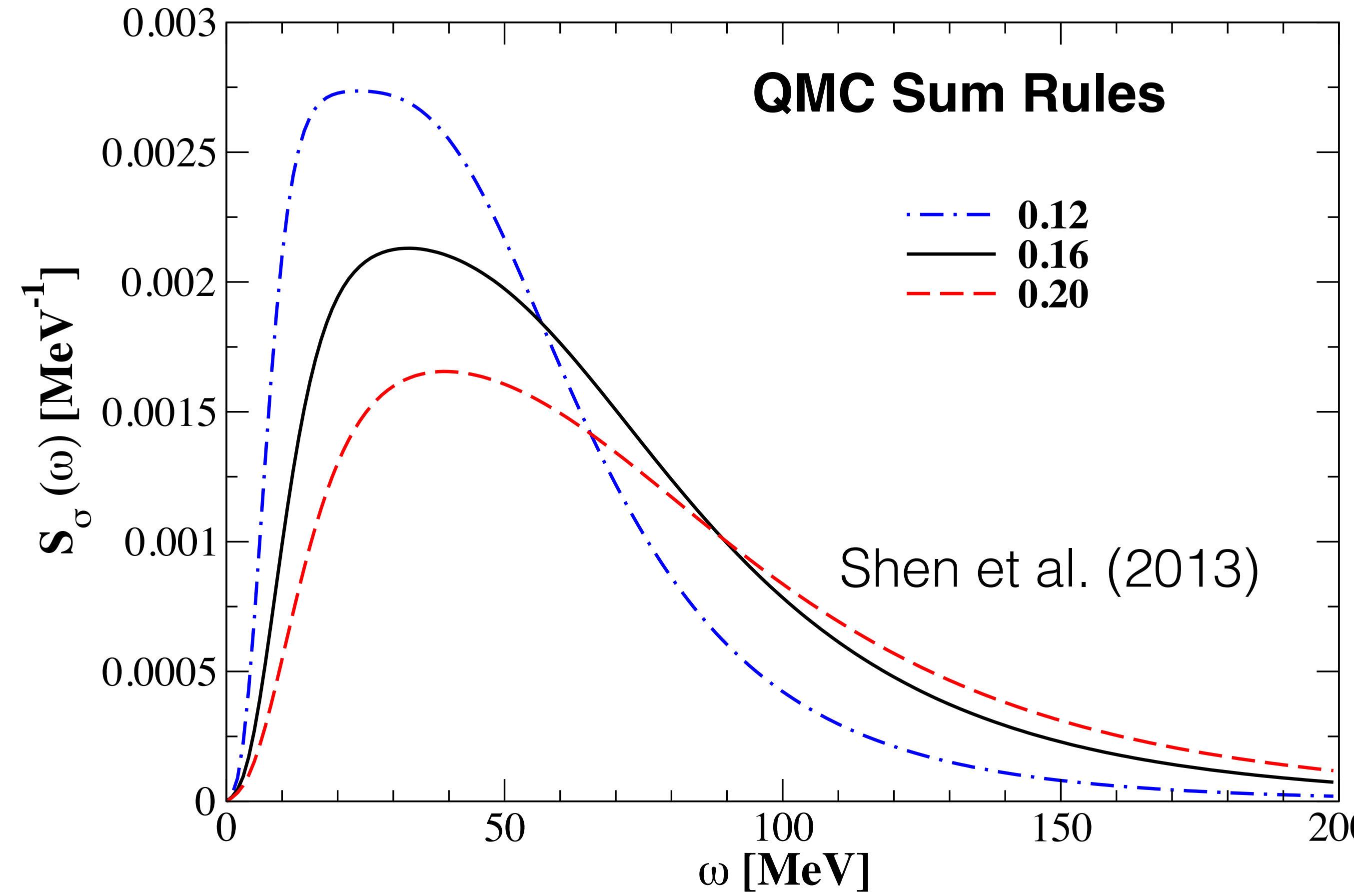
- Collective & Multi-pair excitations.
- Exact QMC techniques for Euclidean Response and sum-rules.
- EFT and two-body currents
- Response of hot and dense nuclear matter.

Giant Dipole Resonance



Spin Response of Neutron Matter



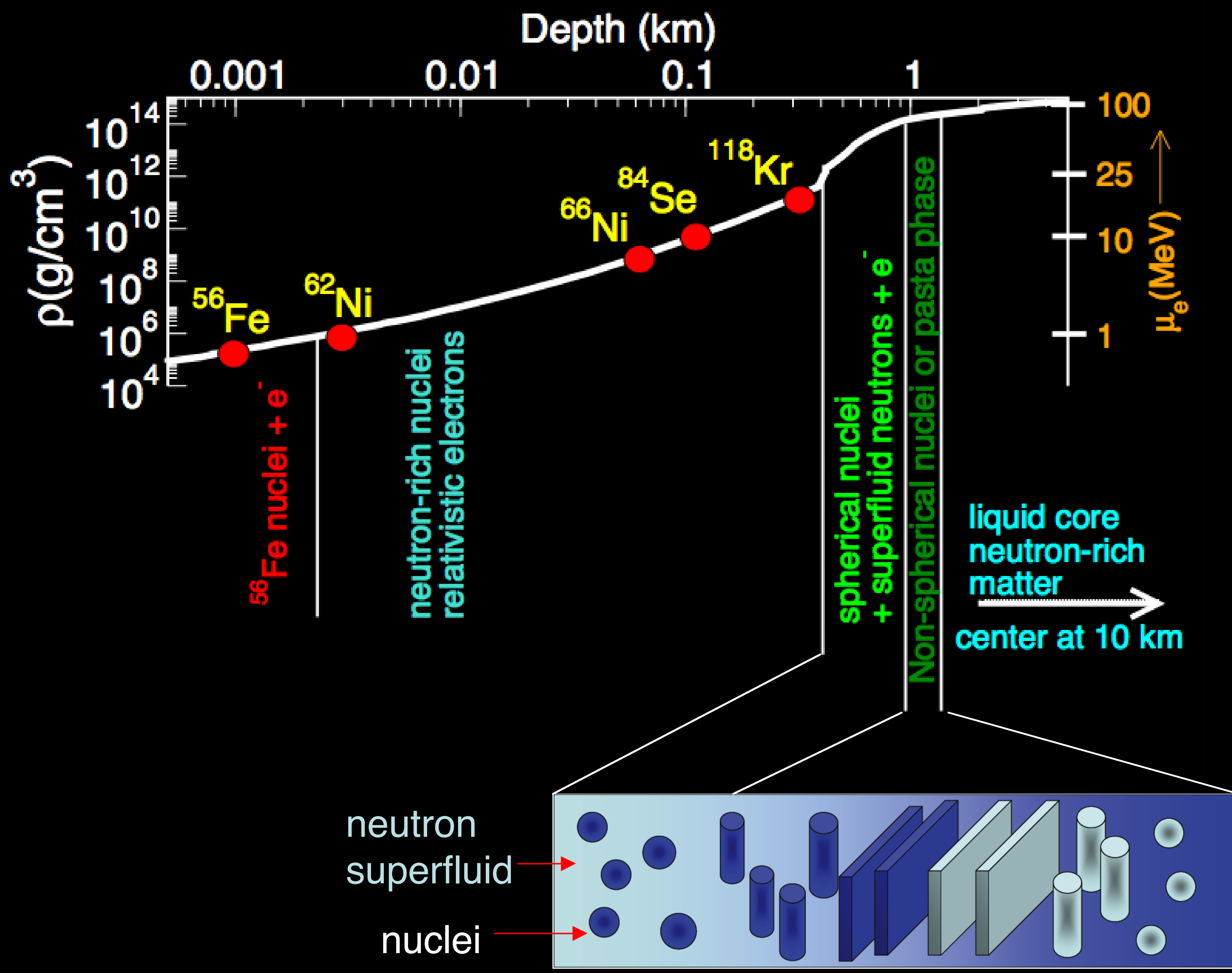


Dynamics & the Neutron Star Crust

Key to understanding a host of time dependent phenomena:
Glitches, Superbursts, Transient Cooling, Magnetic Field Decay, Giant Flares.

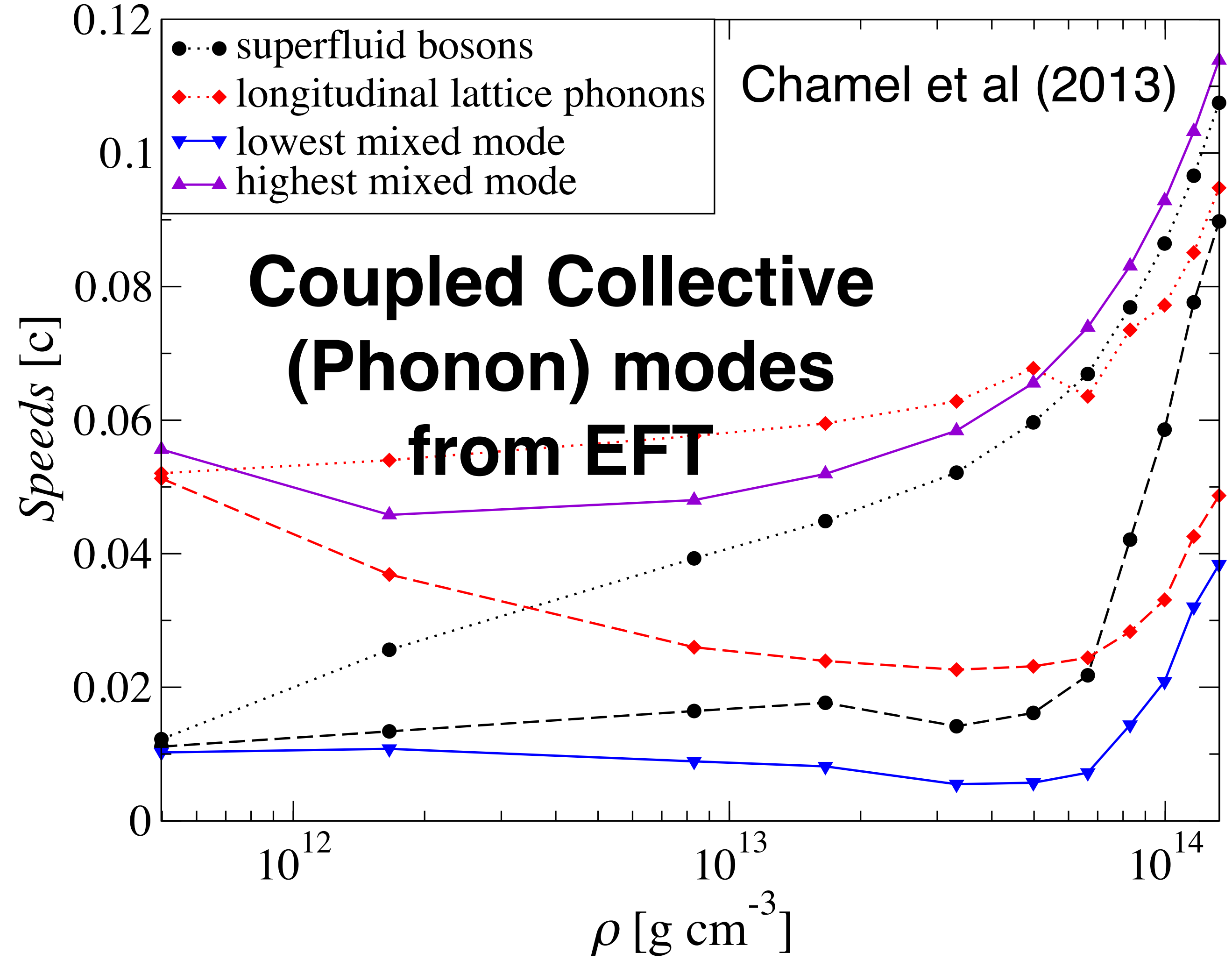
Recent theoretical work sheds light on:

- **Transport properties** (thermal and electrical conductivity, viscosity)
- **Nuclear and neutrino reactions**
- **Superfluid properties and vortex dynamics**



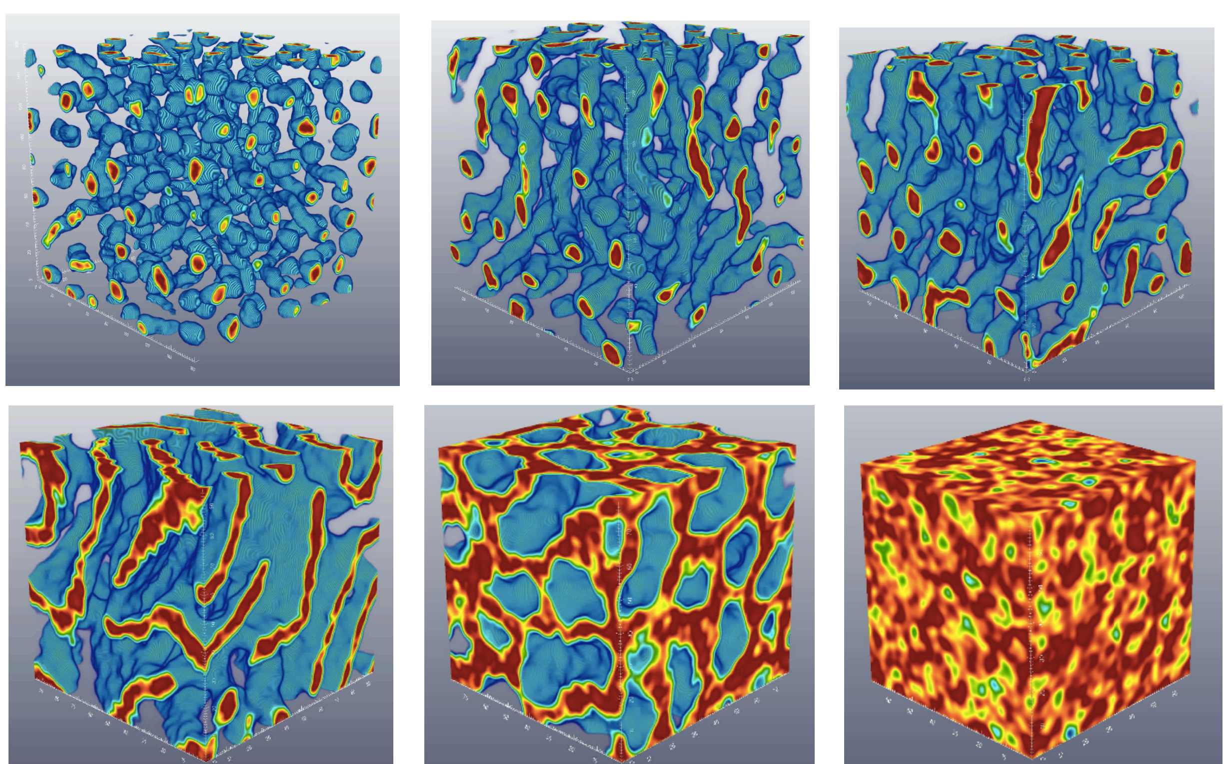
A Microscopic Basis for Crust Models

- **Large scale Hartree-Fock (HF) and Time-Dependent HF**
- **Molecular Dynamics at high temperatures.**
- **Vortex pinning and dynamics.**
- **Low energy effective field Theory.**



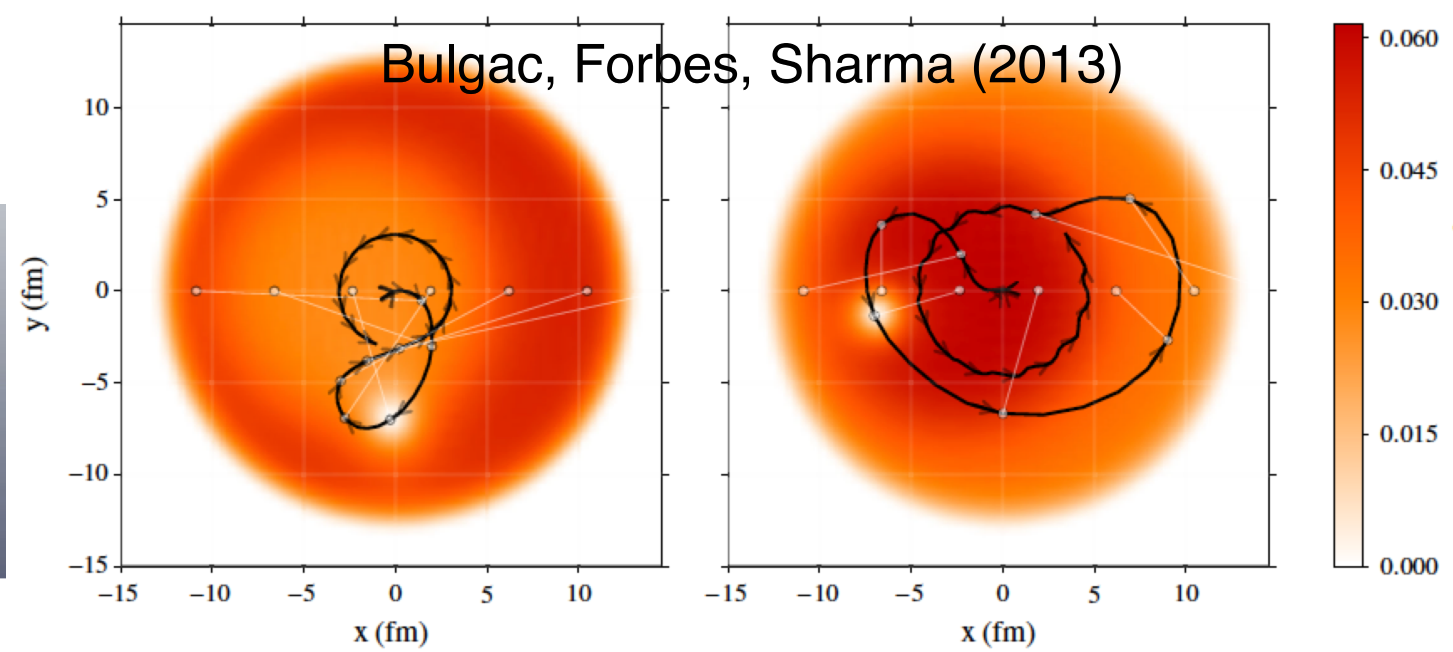
Coupled Collective (Phonon) modes from EFT

Schneider, Horowitz, Berry (2013)



Molecular Dynamics of Pasta

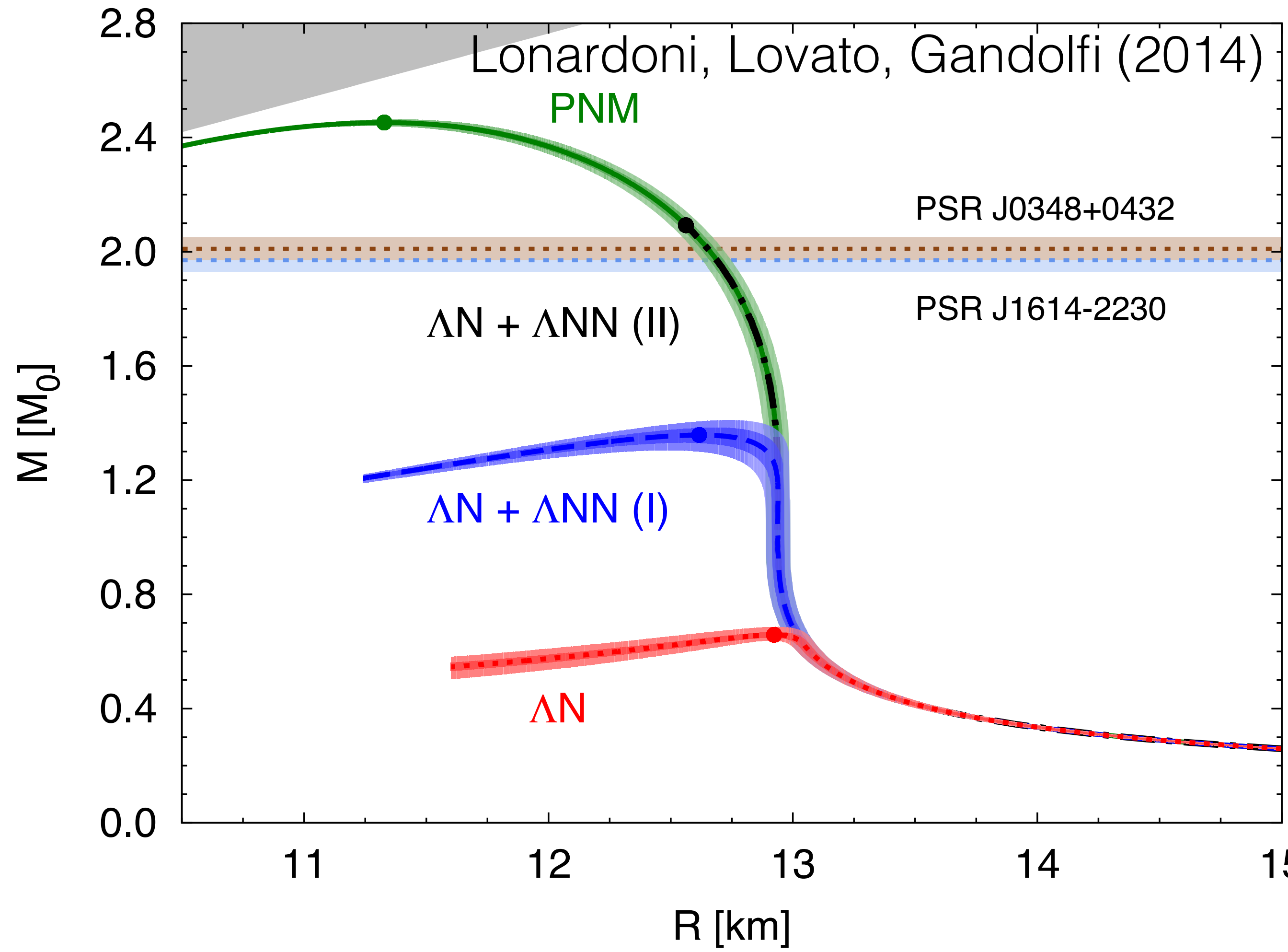
Direct simulations of vortex motion



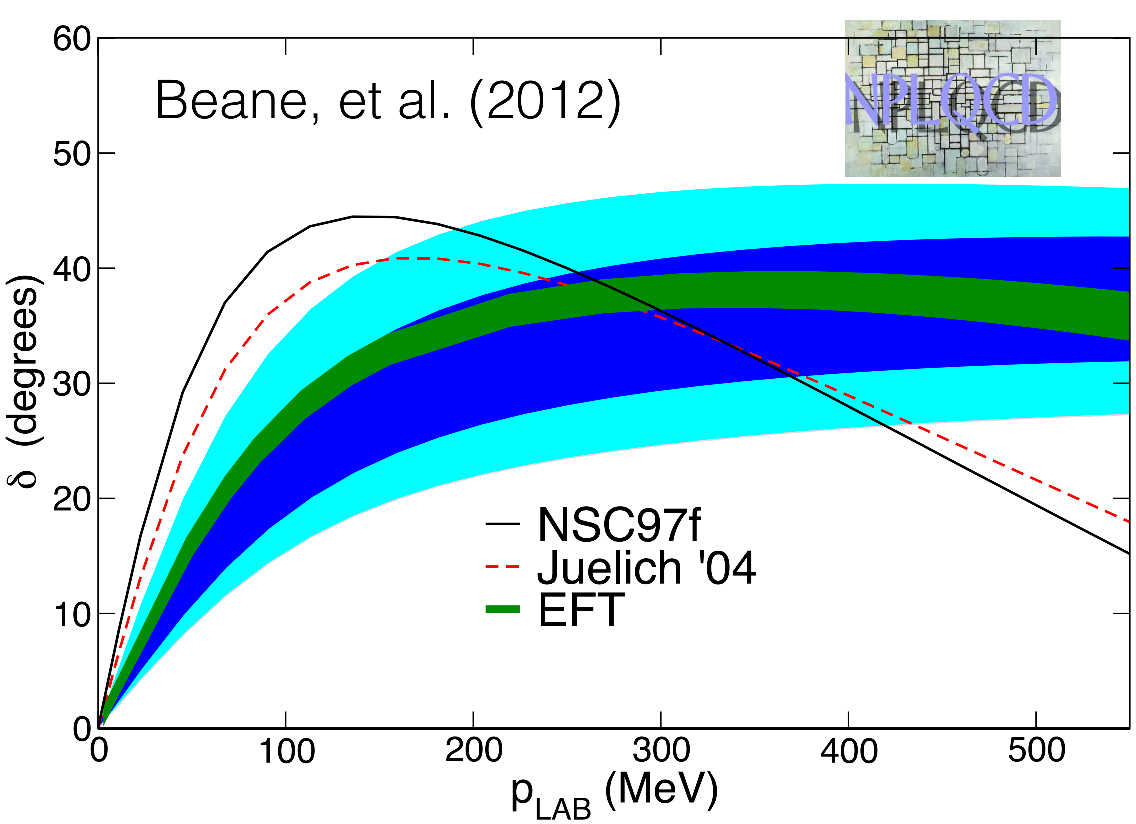
Matter at Supra-nuclear Density

The 2 solar mass neutron star poses serious challenges:

Softening phase transitions are ruled out. But,
How are hyperons suppressed ?
When does the nucleon picture break down ?
What can we learn from heavy-ions experiments ?



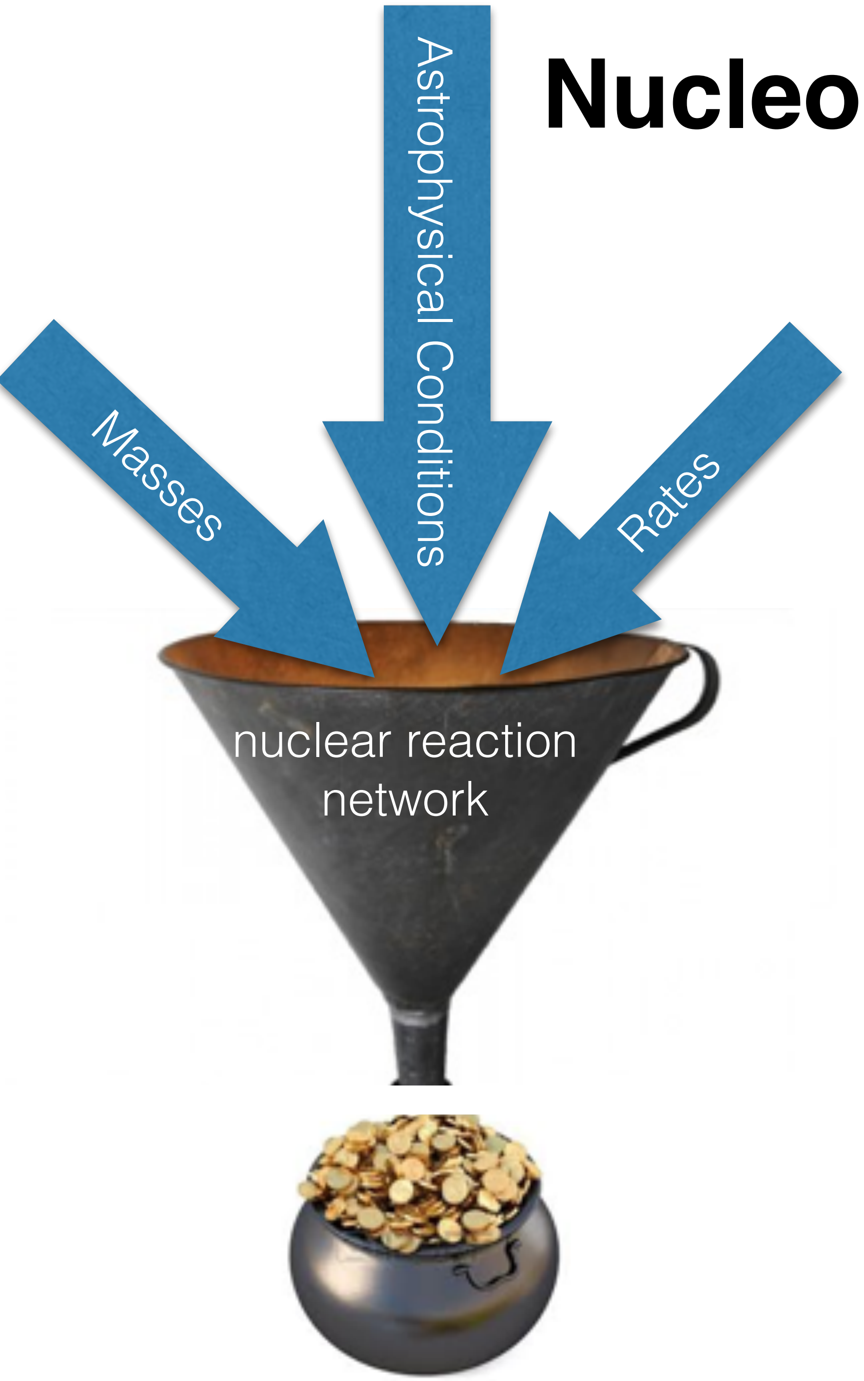
$^1S_0\ n\Sigma^-$ phase shift from LQCD



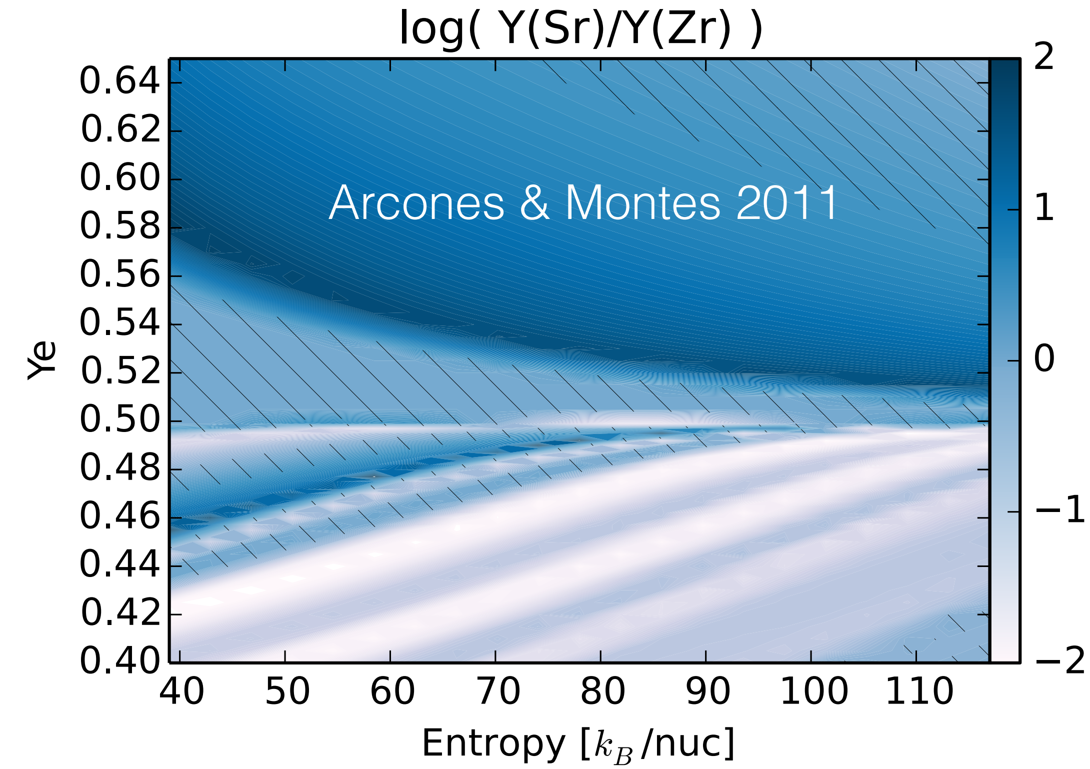
Path Forward:

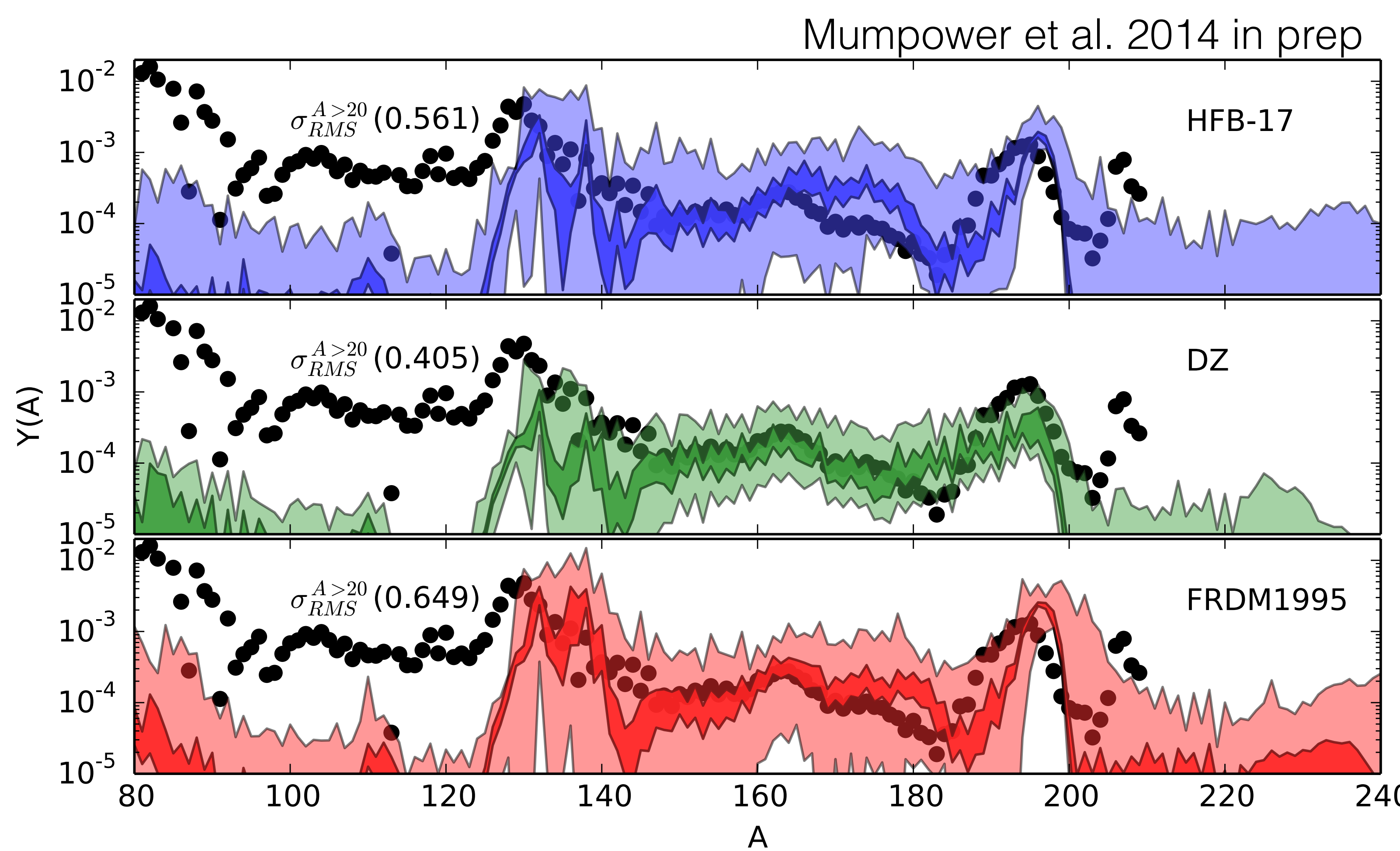
- EFT with Delta's & QMC
- Hyper-nuclear phenomenology
- Lattice QCD input
- Heavy-ion phenomenology and transport theory.

Nucleosynthesis & Nuclear Physics Input



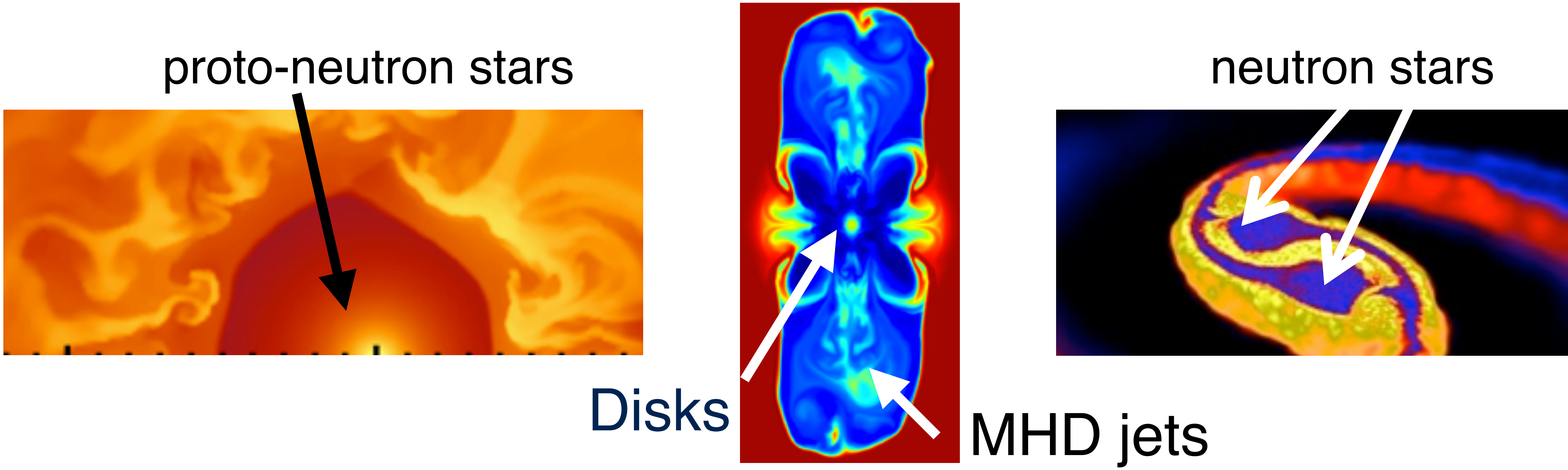
Specific abundance ratios can constrain astrophysical conditions if we can understand nuclear uncertainties and systematics.



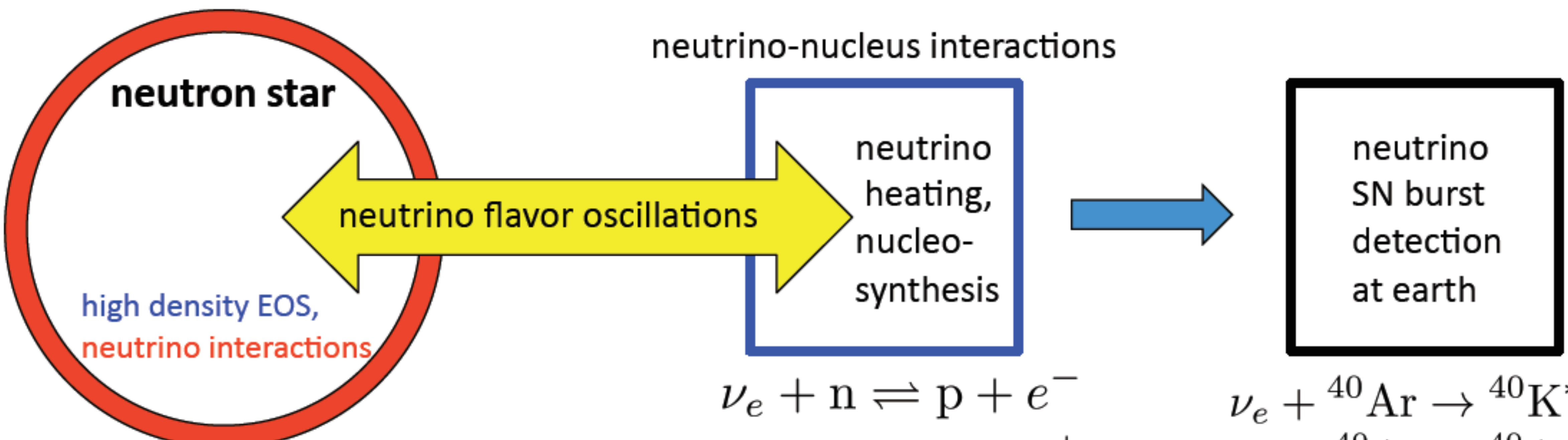


- Efforts underway to disentangle diversity of astrophysical conditions and uncertainties in input nuclear physics.
- Uncertainty quantification and Bayesian analysis poised to play a big role.

Nucleosynthesis & Neutrinos



Neutrino oscillations play an important role (sets Y_e):

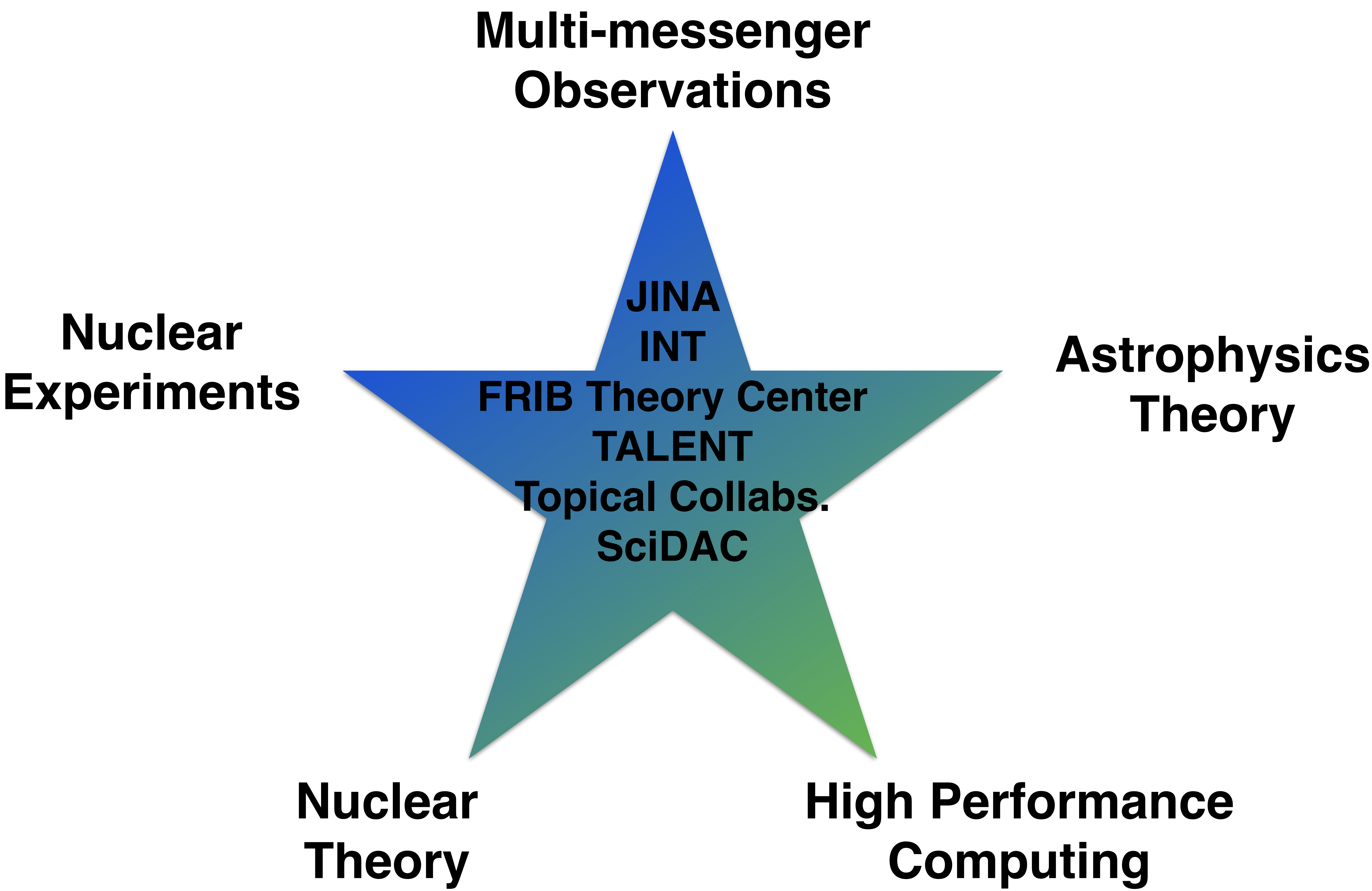


$$\nu_e + \mathrm{n} \rightleftharpoons \mathrm{p} + e^-$$
$$\bar{\nu}_e + \mathrm{p} \rightleftharpoons \mathrm{n} + e^+$$

$$\nu_e + {}^{40}\mathrm{Ar} \to {}^{40}\mathrm{K}^* + e^-$$
$$\nu_x + {}^{40}\mathrm{Ar} \to {}^{40}\mathrm{Ar}^* + \nu_x$$

Figure Credit: G. Fuller

Creating and Sustaining the Community



Needs

Students:
Strengthen university efforts
Training, education & networking

Postdocs:
National fellowships
Connect laboratory & university efforts

Junior Faculty & Staff:
Create positions

Connections:
astrophysics, particle physics, condensed matter physics, cosmology and applications

Computing :
Access & people support

Outlook

These are exciting times for nuclear astrophysics.

The next decade holds more promise.

Theory & computing are poised to play a big role.

Building the community at this stage is critical