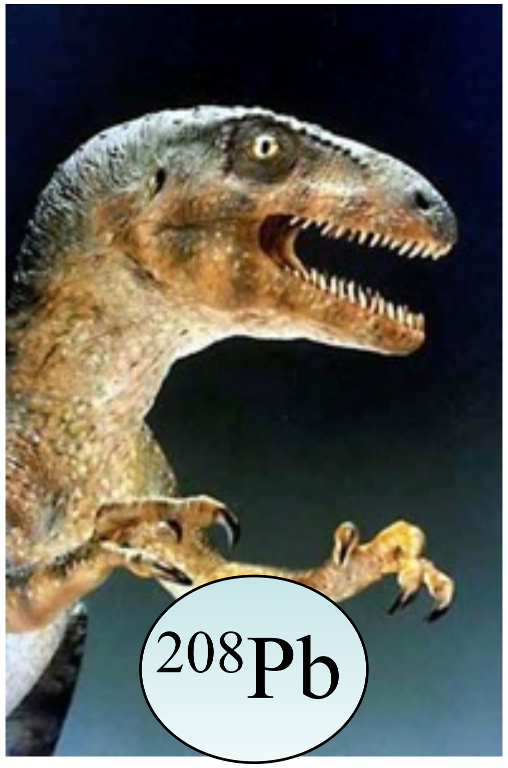
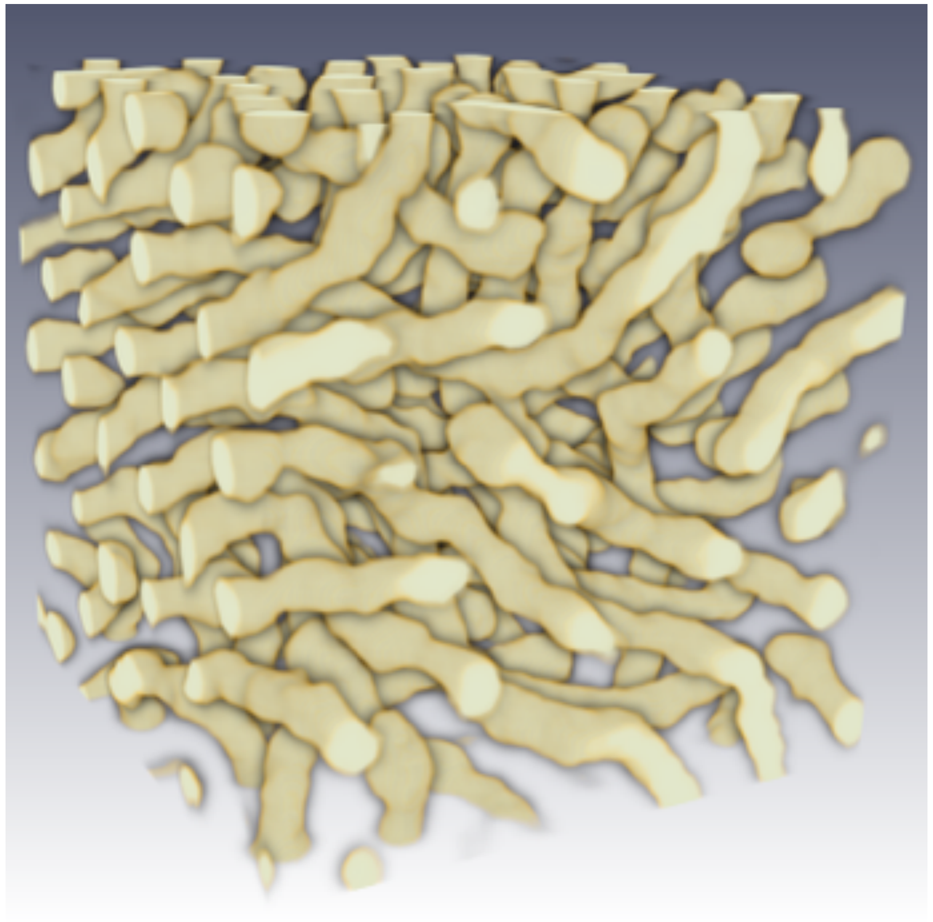
Neutron rich matter for relativistic astrophysics



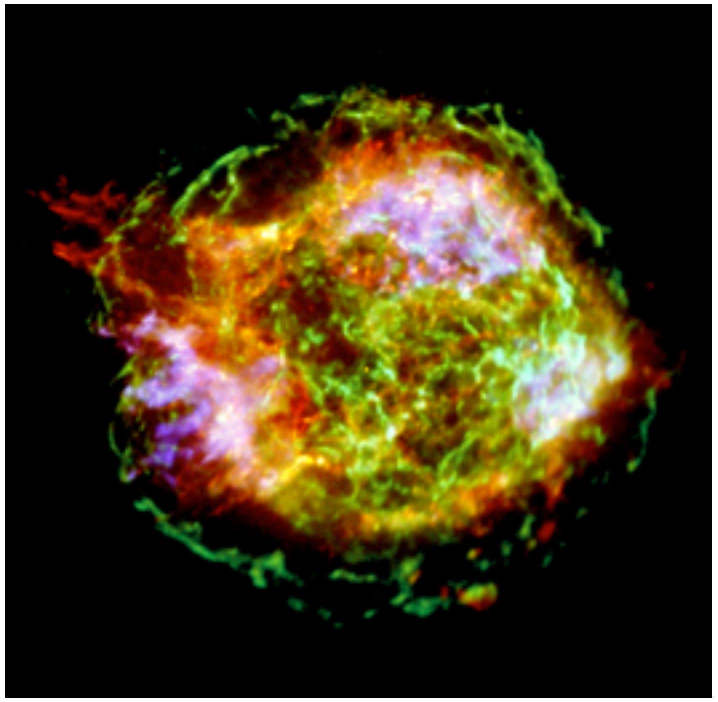


C. J. Horowitz, Indiana University

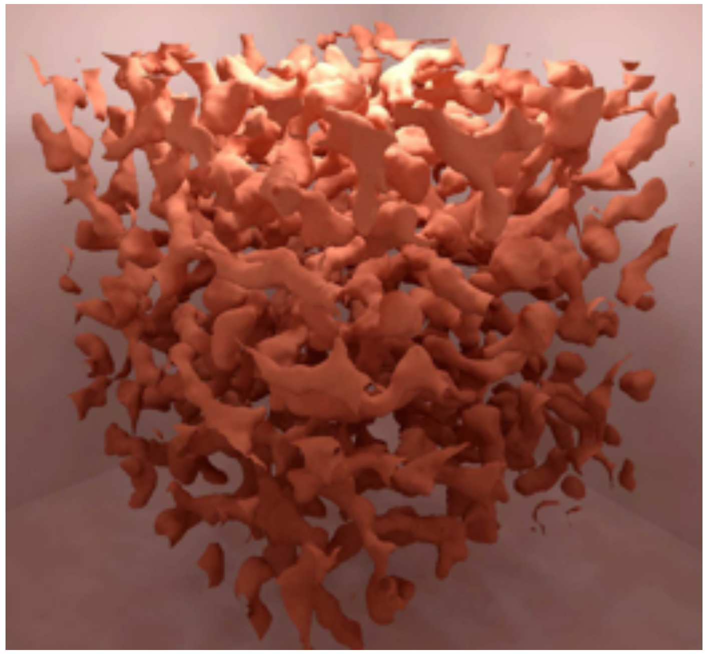
“Texas in Texas”: 50 years of Relativistic Astrophysics, Dallas, Dec. 2013

Neutron Rich Matter

- Compress almost anything to 10^{11}+ g/cm^3 and electrons react with protons to make neutron rich matter. This material is at the heart of many fundamental questions in nuclear physics and astrophysics.
  - What are the high density phases of QCD?
  - Where did chemical elements come from?
  - What is the structure of many compact and energetic objects in the heavens, and what determines their electromagnetic, neutrino, and gravitational-wave radiations?
- Interested in neutron rich matter over a tremendous range of density and temperature were it can be a *gas, liquid, solid, plasma, liquid crystal (nuclear pasta), superconductor ($T_c=10^{10}$ K!), superfluid, color superconductor...*



Supernova remanent
Cassiopea A in X-rays



MD simulation of Nuclear
Pasta with 100,000 nucleons

Probing n rich matter for relativistic astrophysics

- Neutron rich matter provides the source of the field equations.

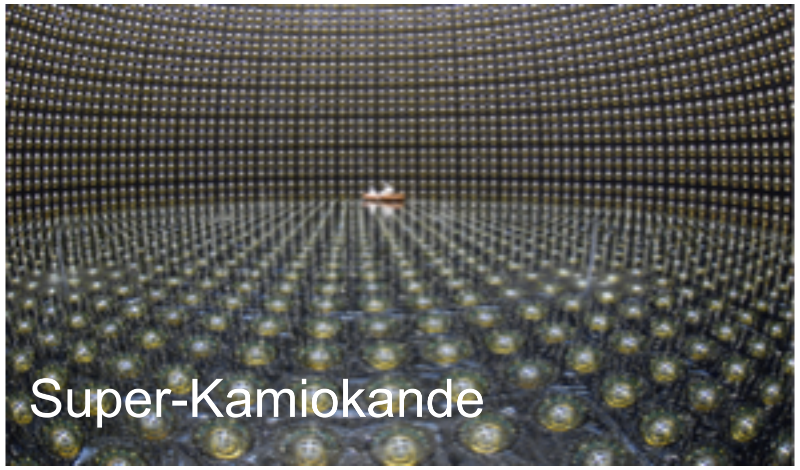
$$G_{\mu\nu} + g_{\mu\nu}\Lambda = 8\pi T_{\mu\nu}$$

Left hand side is sterile, vacuous, while RHS contains all of the “meat and potatoes”. Matter can be probed with:

- **Laboratory Experiment:** neutron skin thickness of ^{208}Pb via parity violating electron scattering.
- **X-ray observation** of neutron star radii.
- **Supernova neutrinos,** n rich matter and nucleosynthesis.
- **Gravitational wave observation** of solid neutron rich matter.

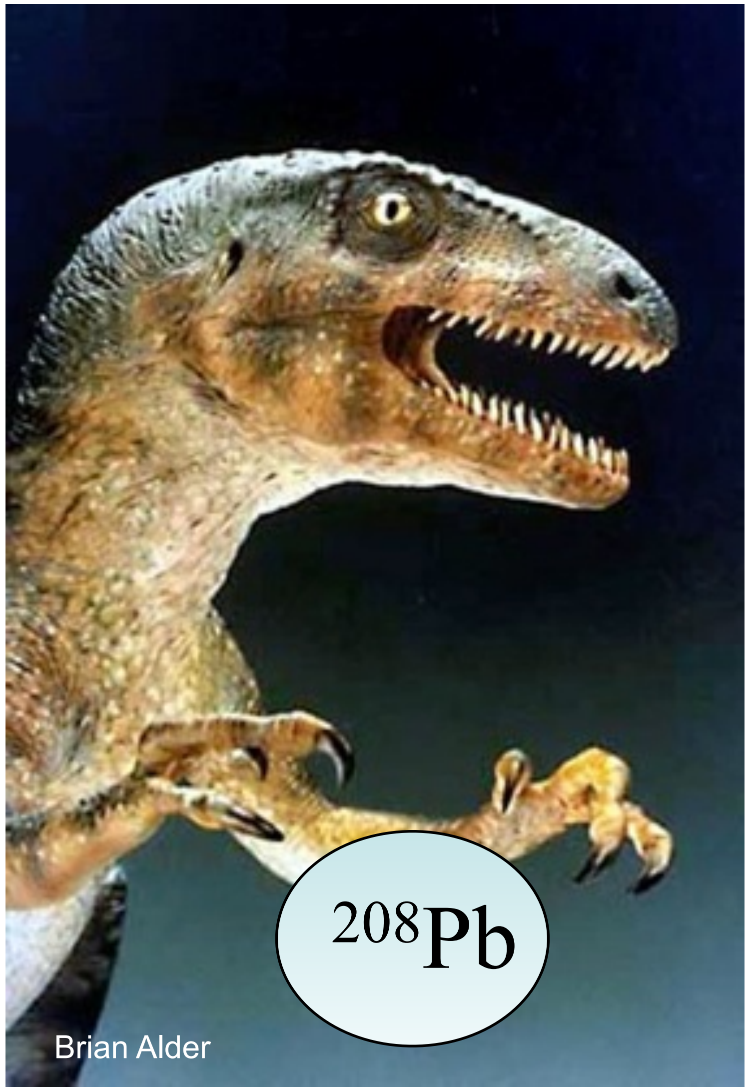

JLAB


Chandra


Super-Kamiokande


VIRGO

Laboratory probe of neutron rich matter



PREX uses parity violating electron scattering to accurately measure the neutron radius of ^{208}Pb.

This has important implications for neutron rich matter and astrophysics.

Parity Violation Isolates Neutrons

- In Standard Model Z^0 boson couples to the weak charge.
- Proton weak charge is small:

$$Q_W^p = 1 - 4\sin^2\Theta_W \approx 0.05$$

- Neutron weak charge is big:

$$Q_W^n = -1$$

- Weak interactions, at low Q^2, probe neutrons.
- Parity violating asymmetry A_{pv} is cross section difference for positive and negative helicity electrons

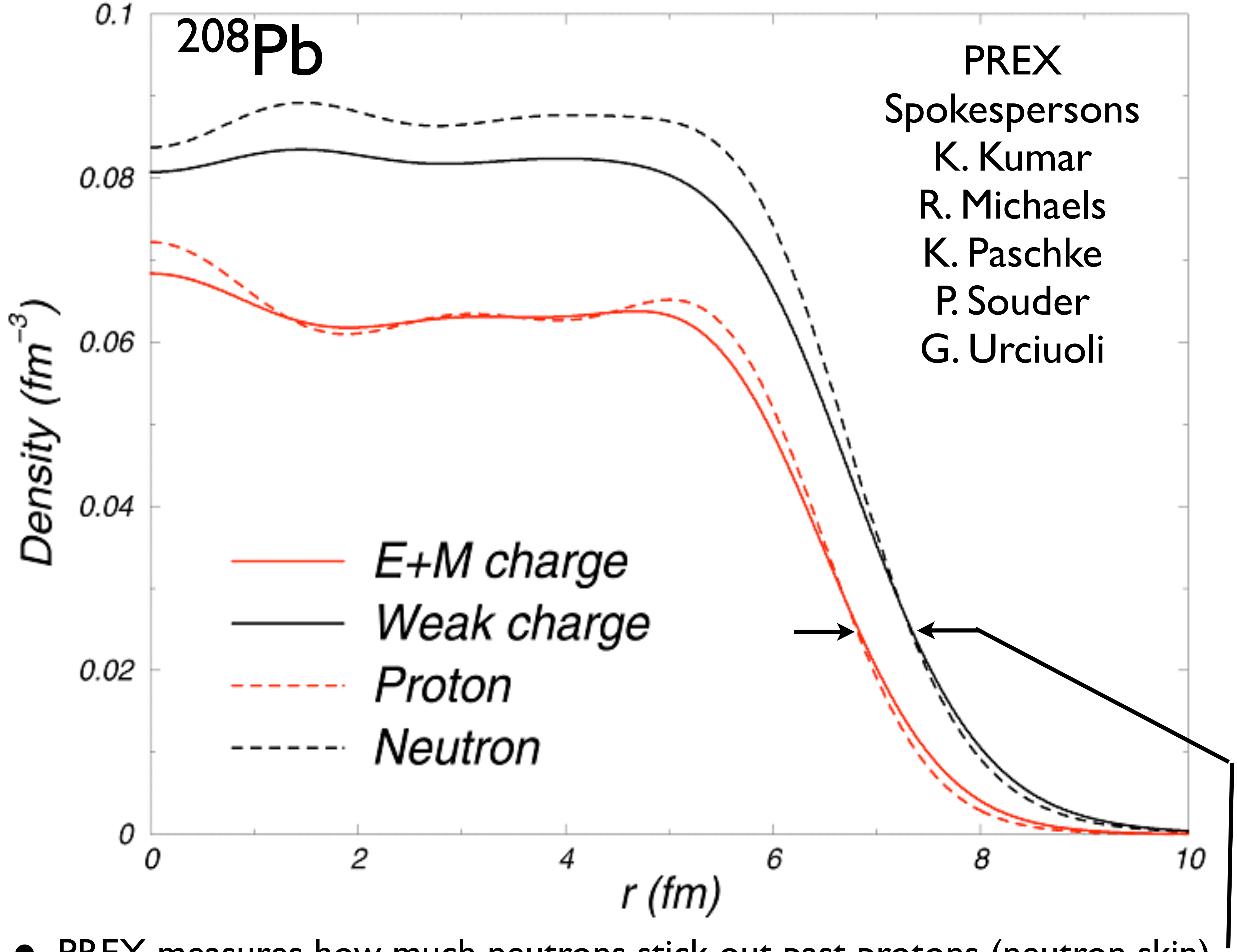
$$A_{pv} = \frac{d\sigma/d\Omega_+ - d\sigma/d\Omega_-}{d\sigma/d\Omega_+ + d\sigma/d\Omega_-}$$

- A_{pv} from interference of photon and Z^0 exchange. In Born approximation

$$A_{pv} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \frac{F_W(Q^2)}{F_{\text{ch}}(Q^2)}$$

$$F_W(Q^2) = \int d^3r \frac{\sin(Qr)}{Qr} \rho_W(r)$$

- Model independently map out distribution of weak charge in a nucleus.
- **Electroweak reaction free from most strong interaction uncertainties.**
  - Donnelly, Dubach, Sick first suggested PV to measure neutrons.

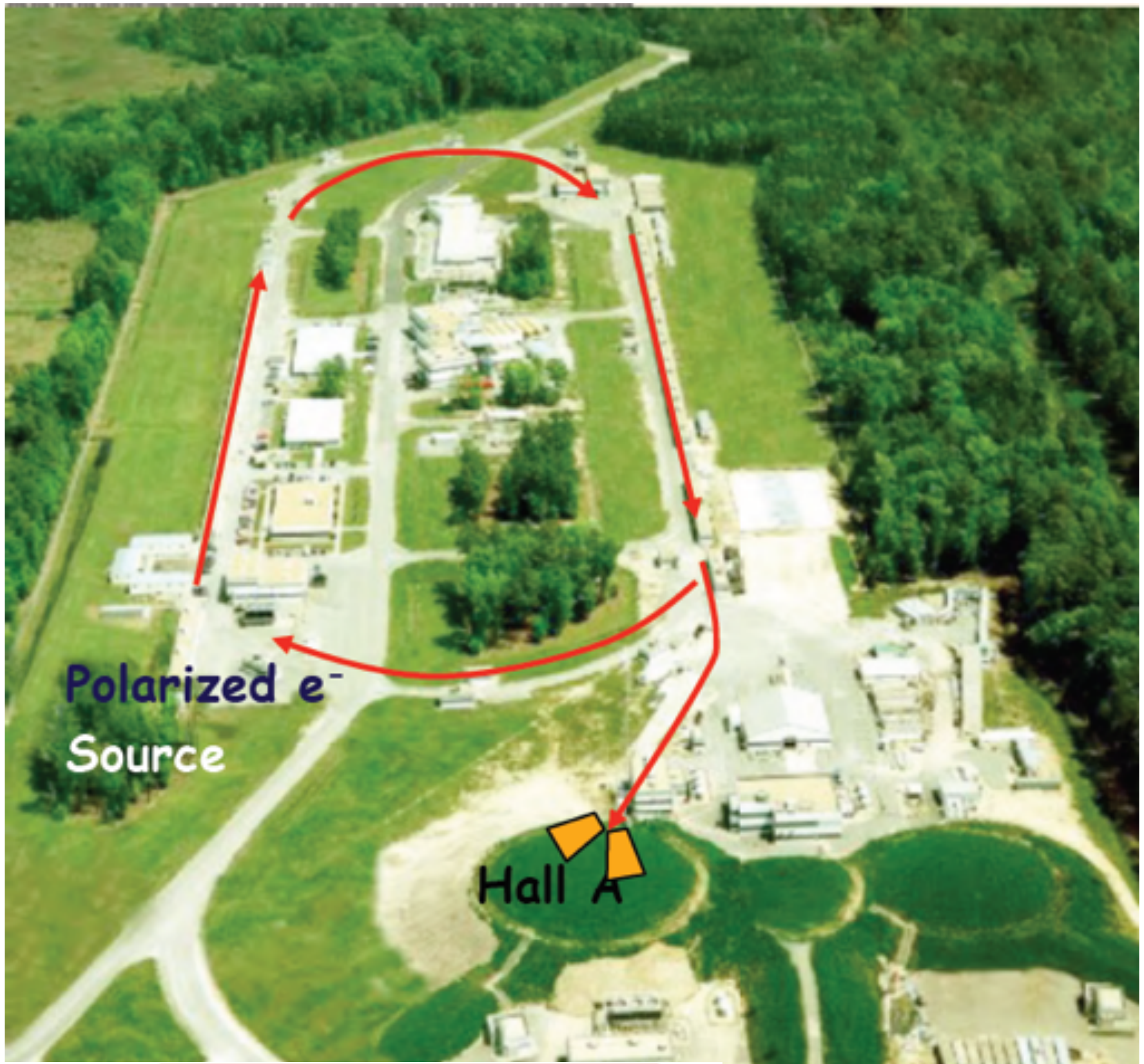


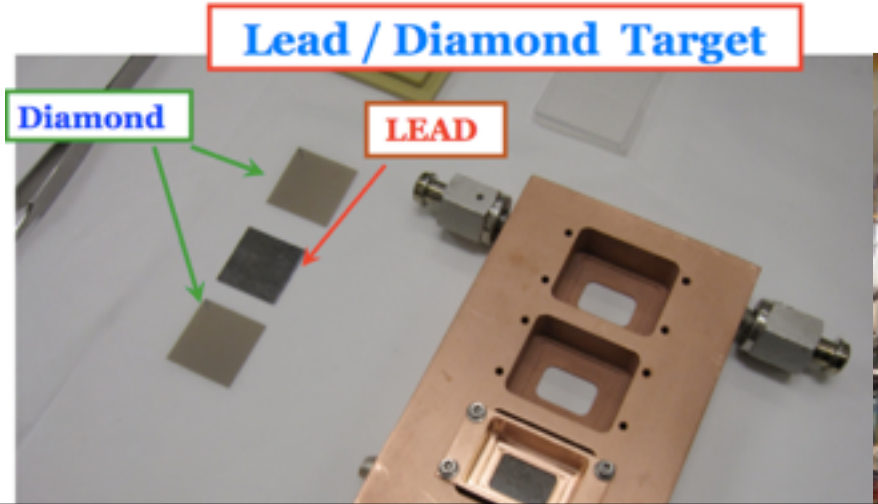
PREX
Spokespersons
K. Kumar
R. Michaels
K. Paschke
P. Souder
G. Urciuoli

- PREX measures how much neutrons stick out past protons (neutron skin).

First PREX result and future plans

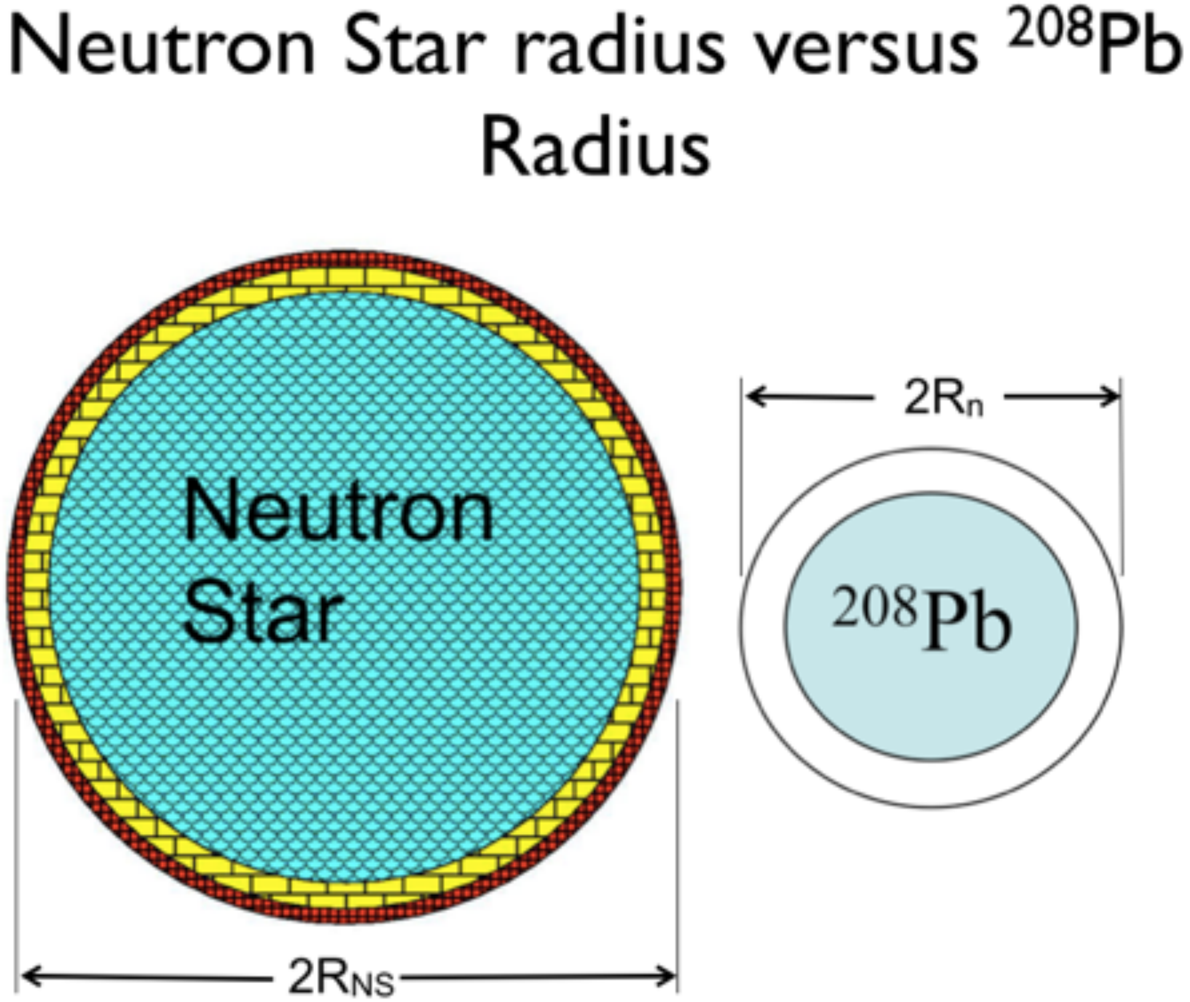
- At Jefferson Laboratory, 1.05 GeV electrons elastically scattered from thick ^{208}Pb foil. PRL **108**, 112502, PRC **85**, 032501
- A_{PV}=0.66 ±0.06(stat) ±0.014(sym) ppm
- Neutron skin thickness: R_n-R_p=$0.33^{+0.16}_{-0.18}$ fm
- Experiment achieved systematic error goals.
- Future plans: **PREX-II** (approved 25 days) Run ^{208}Pb again to accumulate more statistics. Goal: R_n to ±0.06 fm.
- **CREX**: Approved follow on for ^{48}Ca with goal: R_n to ±0.02 fm.





Density Dependence of EOS

- Pressure of neutron matter pushes neutrons out against surface tension ==> R_n-R_p of ^{208}Pb determines P at low densities of about $2/3\rho_0$ (average of surface and interior ρ).
- Radius of (~$1.4M_{sun}$) NS depends on P at medium densities of ρ_0 and above.
- Maximum mass of NS depends on P at high densities.


Neutron Star radius versus ^{208}Pb Radius

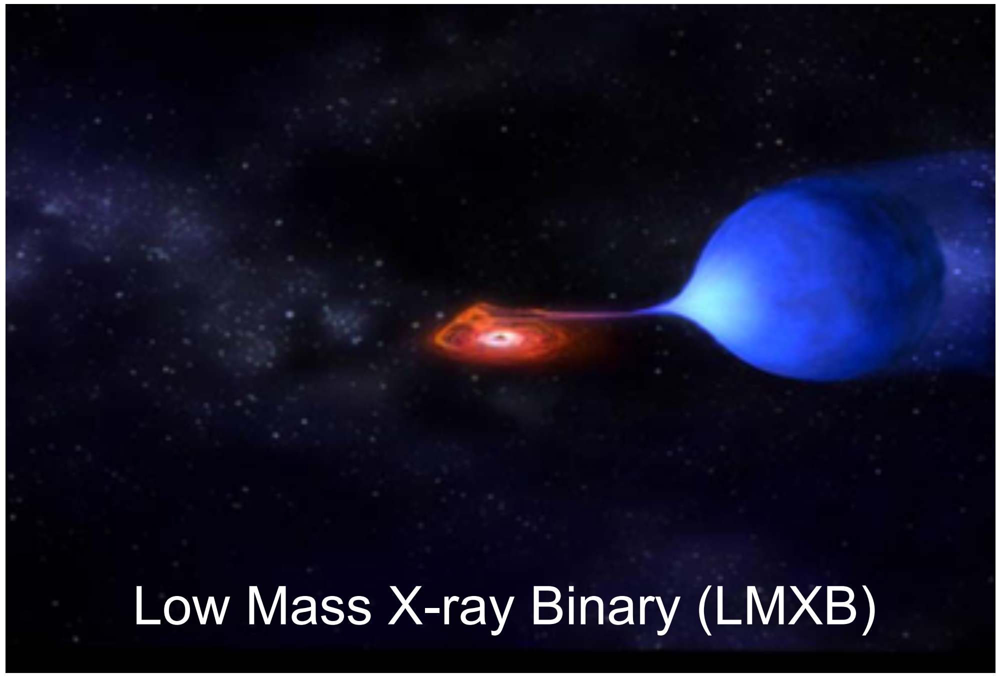
- These three measurements constrain density dependence of EOS and possible pressure changes from phase transitions.

X-ray observations of NS radii, masses

- Deduce surface area from luminosity, temperature from X-ray spectrum.

$$L_\gamma = 4\pi R^2 \sigma_{\rm SB}\, T^4$$

- Complications:
  - Non-blackbody corrections from atmosphere models can depend on composition and B field.
  - Need accurate distance to star.
  - Curvature of space: measure combination of radius and mass.
- NS in globular clusters: expect simple nonmagnetic hydrogen atmospheres and know distance.



Low Mass X-ray Binary (LMXB)

- X-ray bursts: NS accretes material from companion that ignites a runaway thermonuclear burst.
- Eddington luminosity: when radiation pressure balances gravity --> gives both M and R.

Quiescent NS in Globular Clusters: Guillot et al., arXiv:1302.0023

- Considers five LMXB in M13, M28, NGC6304, NGC6397, Omega Cen.
- Simple assumptions:
  - Nonmagnetic hydrogen atmospheres: no evidence for B field, heavier elements should rapidly sink, one companion star observed to have H envelope.
  - Spherically symmetric: no observed pulsations.
  - All observed stars have approximately the same radius (independent of mass): consistent with most EOS, greatly improves statistics.
  - Distance to stars known: Globular cluster distances good but perhaps not perfect, *Gaia should give ~ perfect distances soon.*
  - Interstellar absorption from X-ray data.
- Result $R = 9.1^{+1.3}_{-1.5}$ km (90%-confidence).

Globular Cluster Omega Centauri

NASA / JPL-Caltech / M. Boyer (Univ. of Minnesota)

Spitzer Space Telescope

IRAC • MIPS

ssc2008-07a

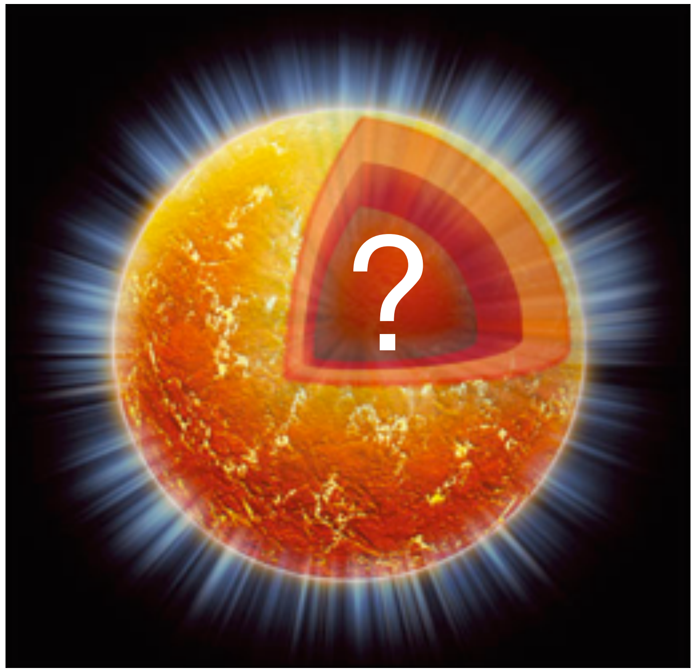
NS Radius Score Card

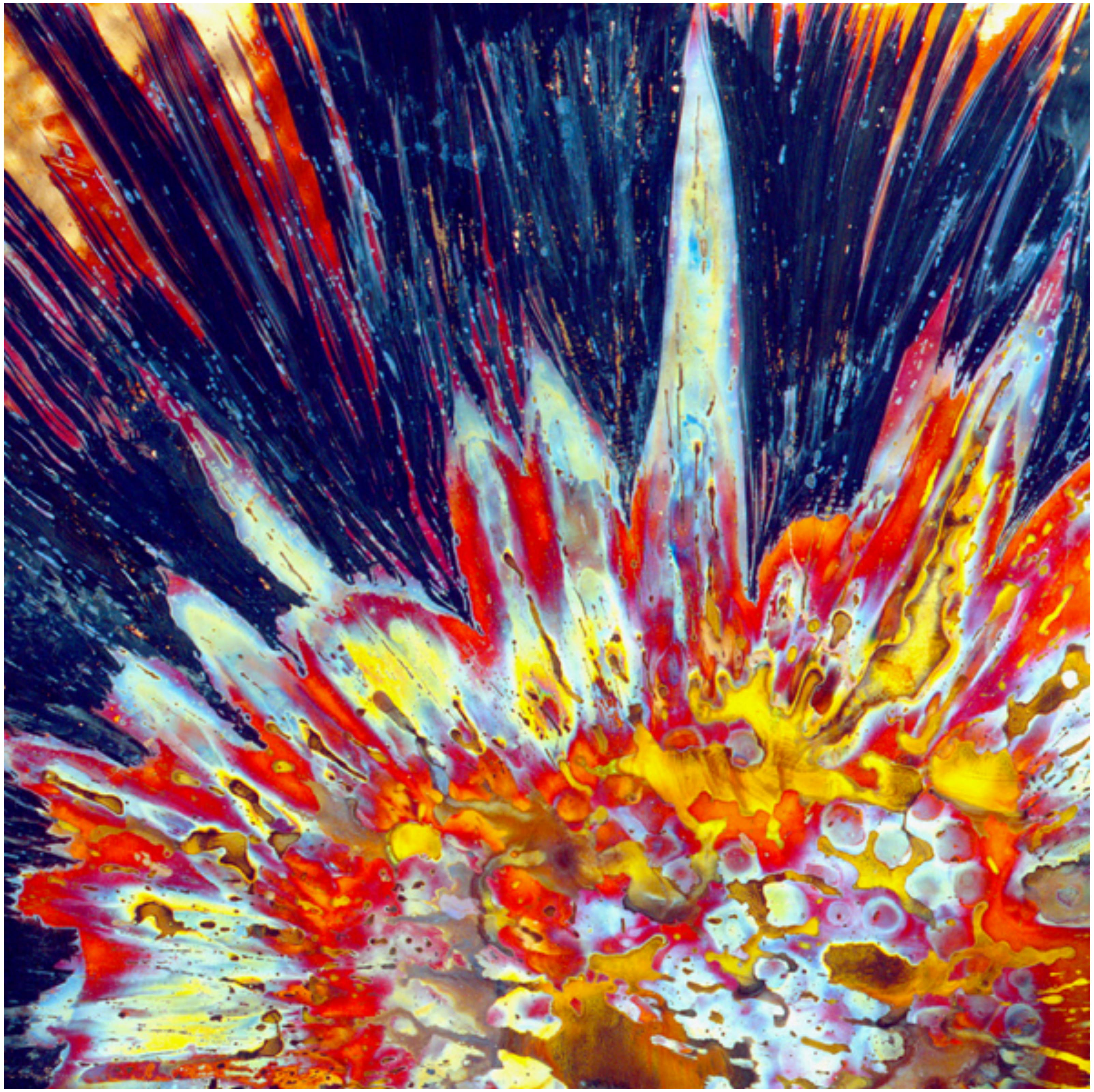
Group	Systems	Radius	
Ozel et al	X-ray bursts	~10 km	Burst systems complicated?
Guillot et al	Quiescent LMXB	~10 km	
Steiner et al	Quiescent LMXB (X-ray bursts?)	~12 km	Assumes nuclear physics known.
Poutanen et al	Super Bursts	~14 km	Sophisticated atmospheres

- Expect neutron skin in ^{208}Pb to be thin, medium (0.15 - 0.20 fm), or thick for R=10, 12, 14 km. PREX result —> $R_n\text{-}R_p=0.33^{+0.16}_{-0.18}$ fm weakly favors R=12+km, but stat error is large.
- If R=10 km (for $1.4M_{sun}$) than EOS is soft at ~$2\rho_0$ and rapidly stiffens at higher densities to support $2M_{sun}$. Can explore this transition with HI collisions.
- New X-ray missions NICER and LOFT —> R by studying pulse profiles.
- **Neutron star radii are very important observables for the properties of dense matter and for our understanding of cold dense QCD.**

What are neutron stars made of?

- They are made of **strongly interacting stuff.** The strong interactions produce high pressures that support $2M_{sun}$ NS.
- Mass and radius measurements alone, determine the pressure, but do not directly determine the composition.
- Could be strongly interacting quarks or strongly interacting nucleons (hadrons) but not nearly free quarks.
- Example: what is the role of hyperons (baryons with strange quarks)?
  - Hyperon-nucleon two-body forces are attractive to fit energies of hyper-nuclei. These attractive 2-body forces suggest hyperons should significantly reduce the pressure, in apparent conflict with observations of $2M_{sun}$ stars.
  - Solution likely involves repulsive three-body forces that increase pressure. Do these 3-body forces prevent the appearance of hyperons or just increase the pressure of matter with hyperons?
- **Observations of NS cooling** provide additional information on composition because NS cool by neutrino emission from their dense interiors. [See talk by S. Reddy]

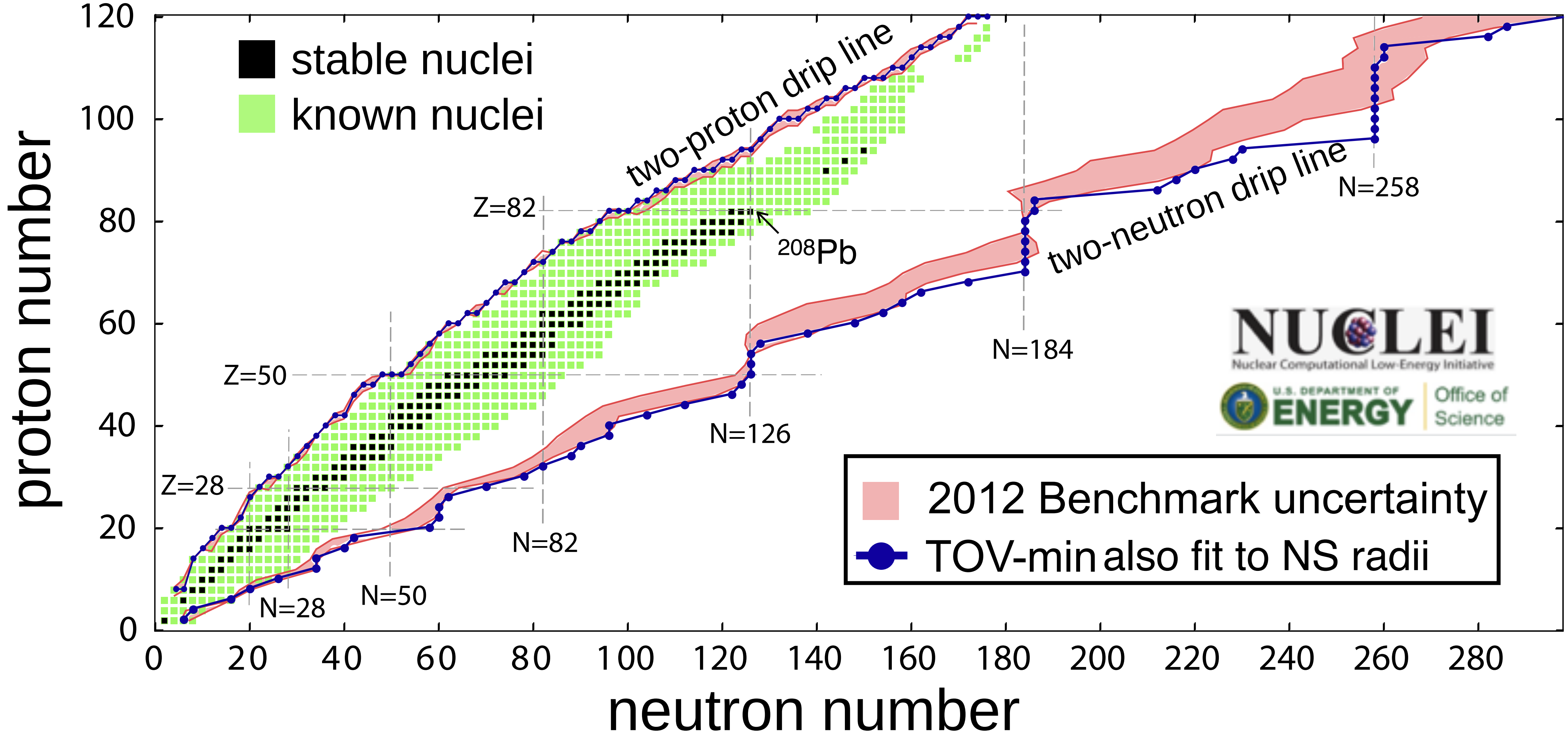




Nucleosynthesis and neutron rich matter

Radioactive stamp collecting

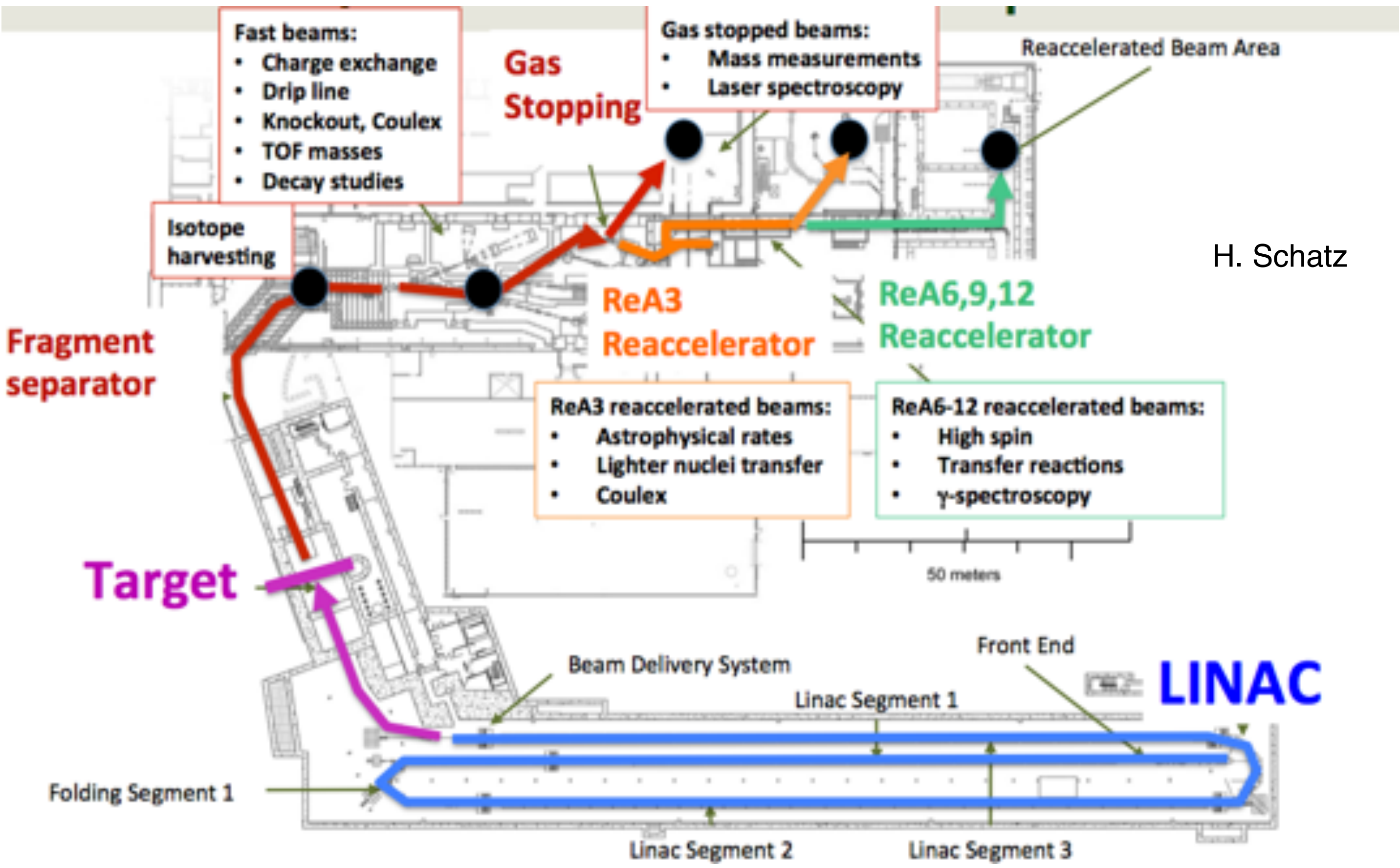
- *“All science is either physics or stamp collecting”* — E. Rutherford. With the naming of element 104 Rutherfordium, he finally got his stamp!
- How many stamps are there? Erler et al [Nature **486**(2012)509] estimate about 7000 particle stable nuclei with Z<120.



- Neutron drip line where neutrons become unbound. Estimate from 4 state of the art energy functionals (red bands) fit to properties of known nuclei.
- TOV-min is energy functional fit to both nuclei and NS: R=12.5km, M_{max}=2.2M_{sun}.

Facility for Rare Isotope Beams

- Powerful “stamp collector” being built at Michigan State. Finished by 2020.
- Intense primary (Uranium) beam fragments and radioactive nuclei of interested separated and used for experiments before they decay.
- FRIB can make a significant fraction of possible isotopes. Green region in lower right figure

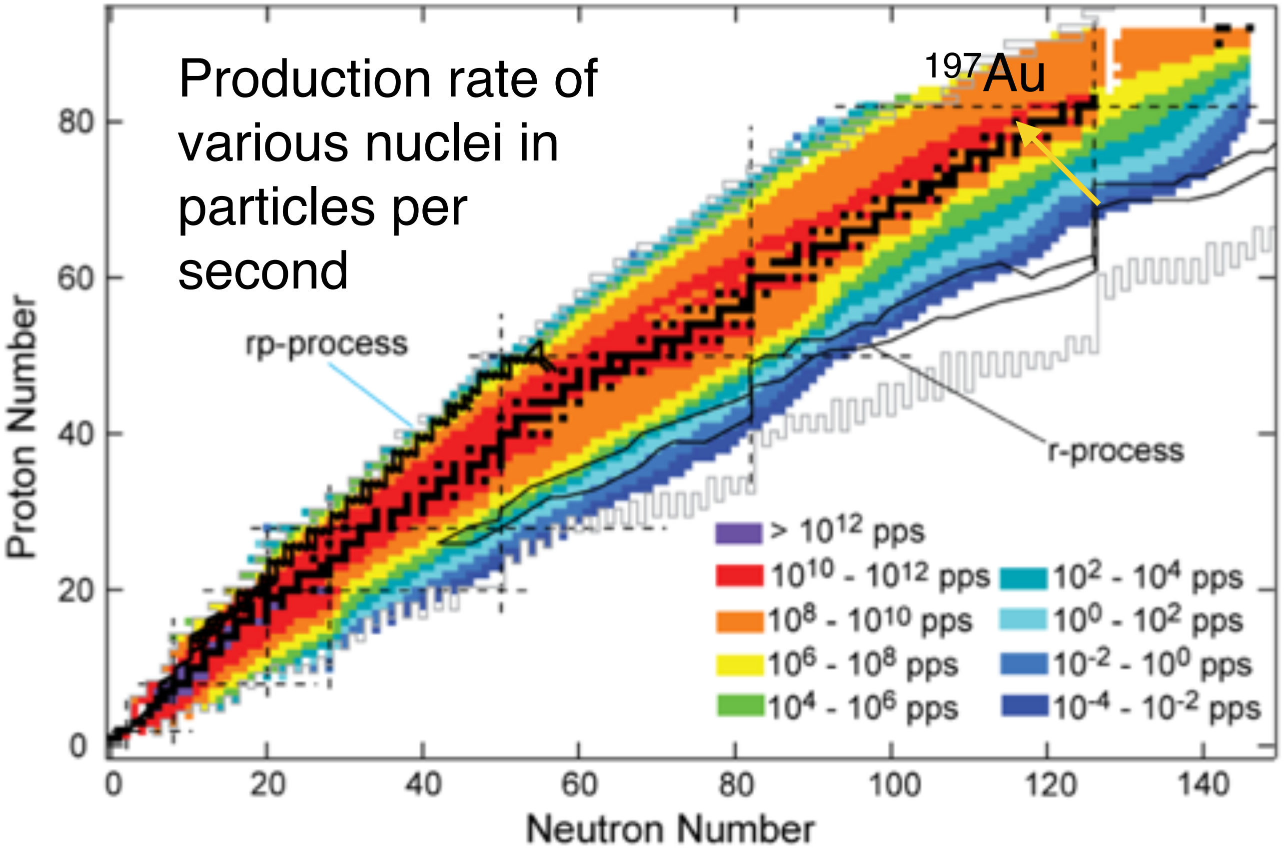

Fast beams:
- Charge exchange
- Drip line
- Knockout, Coulex
- TOF masses
- Decay studies

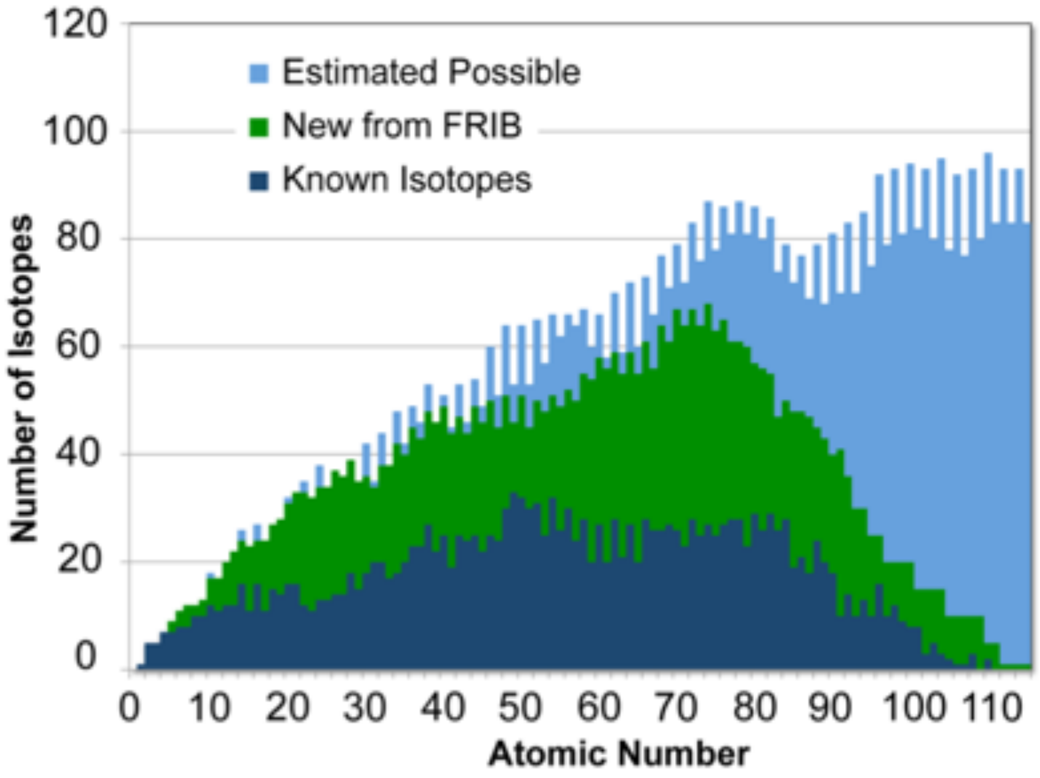
Gas stopped beams:
- Mass measurements
- Laser spectroscopy

ReA3 reaccelerated beams:
- Astrophysical rates
- Lighter nuclei transfer
- Coulex

ReA6-12 reaccelerated beams:
- High spin
- Transfer reactions
- γ-spectroscopy

H. Schatz

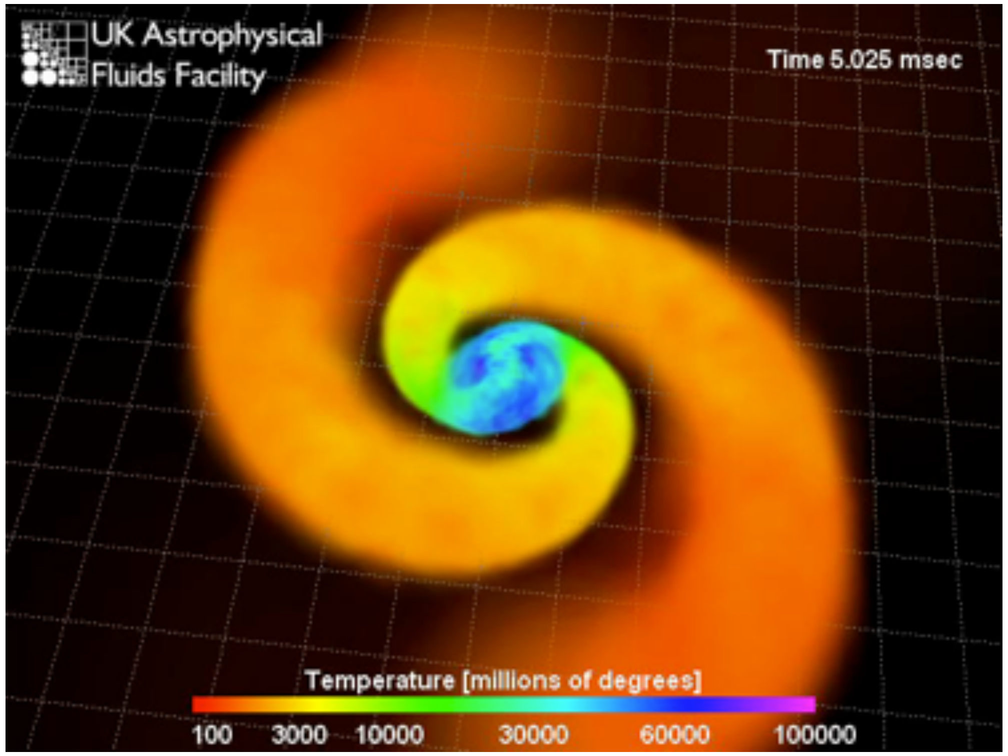

Production rate of various nuclei in particles per second



B. Sherrill

r-process: NS mergers vs SN

- Half of heavy elements (including gold) made in r-process where seed nuclei rapidly capture many neutrons.
- What makes all of the neutrons?
  - **Neutrinos:** ratio of n/p in supernova ν driven wind set by rates of ν capture.
  - **Gravity:** compresses matter until electron capture drives it n rich. Tidal forces during NS mergers can eject n-rich material.
- Follow fluid element in tidal tail as it decompresses (next pages).
- Matter ejecta so n rich that it undergoes robust r-process!



- r-process yield depends on:
  - How much material is ejected per merger? Simulations that better resolve low densities.
  - What is merger rate? Advanced LIGO will soon directly observe rate.

Simulation by Stephan Rosswog, University of Leicester. Visualization by Richard West, UKAFF.

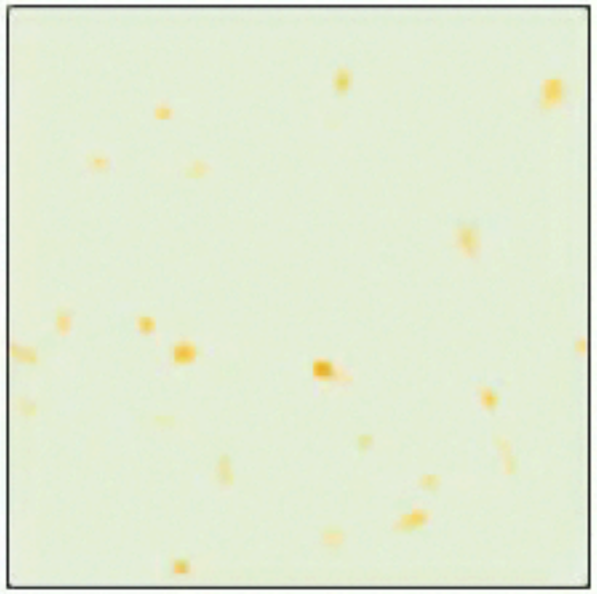
Nuclear Pasta Formation

- During a NS merger tidal excitation decreases density: uniform nuclear matter -> nuclear pasta -> nuclei + n -> r-process.
- Nuclear matter, at somewhat below ρ_0, forms complex shapes because of competition between short range nuclear attraction and long range Coulomb repulsion —> "Coulomb frustration".
- Semiclassical model for n,p interaction: $v(r)=a\, e^{-r^2/\Lambda} + b_{ij}\, e^{-r^2/2\Lambda} + e_i e_j\, e^{-r/\lambda}/r$
- Parameters of short range interaction fit to binding E and saturation density of nuclear matter.
- Simple model allows MD simulations with 300,000+ nucleons, for long times 10^7 + fm/c.

Simulation of pasta formation. ArXiv:1307.1678

51200
nucleons,
$Y_P=0.4$,
$T=1$ MeV,
$\lambda=10$ fm,
$\xi=2\times10^{-8}$
c/fm,
$L_0=80$ fm

$L=(1+\xi t)L_0$



$n=0.1200\mathrm{fm}^{-3}$

Few thousand core weeks of CPU time

Andre Schneider

Neutrinos as messengers of neutron rich matter


Searching for El Dorado with supernova neutrinos in Super-Kamiokande

- Supernova neutrinos carry unique flavor information closely related to nucleosynthesis.
- Help determine what chemical elements core collapse supernovae make and if they are the site of the r-process

SN neutrinos and r-process nucleosynthesis

- Important alternative site for the r-process is the neutrino driven wind in core collapse supernovae.

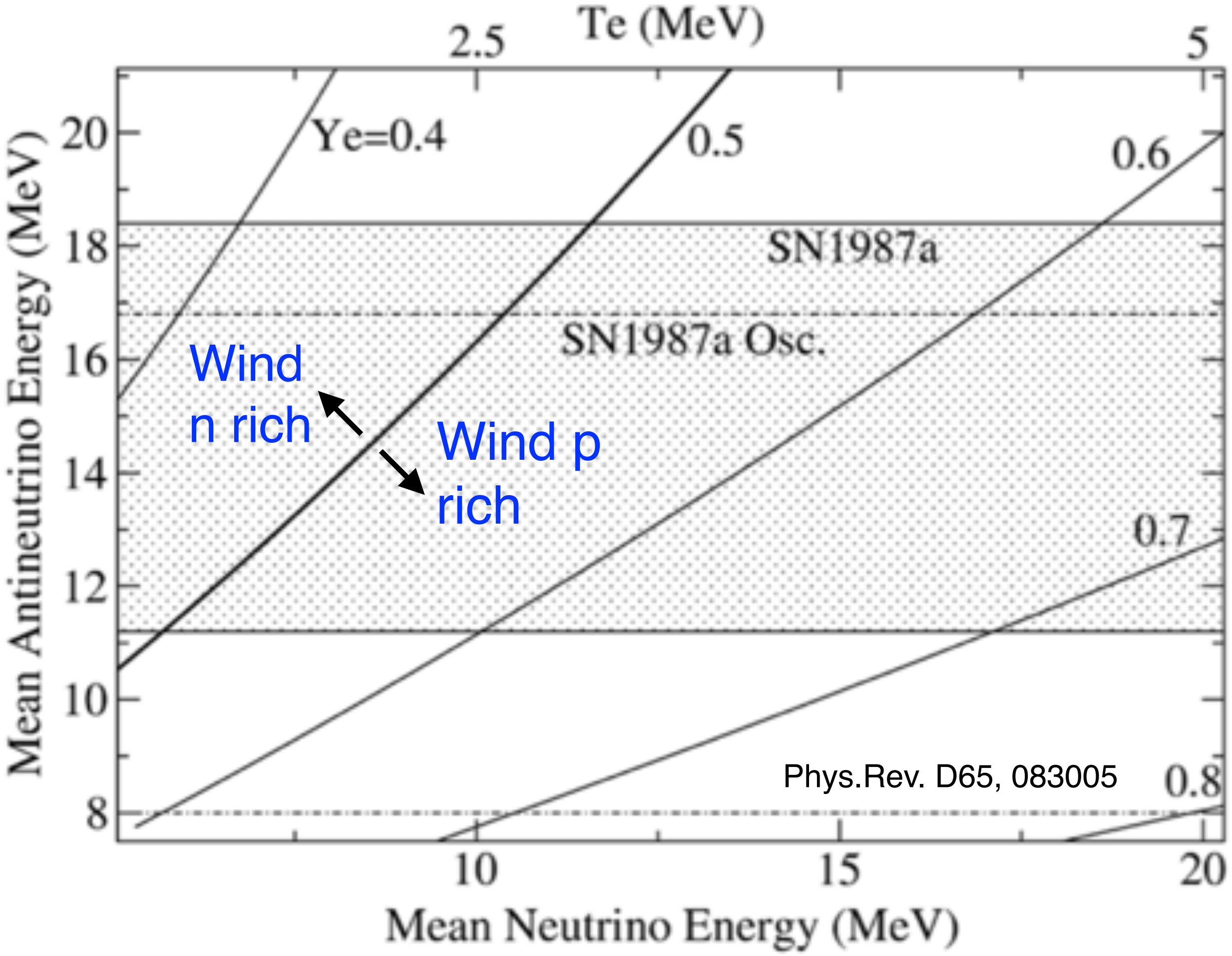
- Ratio of neutrons to protons in wind set by capture rates that depend on neutrino and anti-neutrino energies.

$$\nu_e + n \rightarrow p + e \qquad \bar{\nu}_e + p \rightarrow n + e^+$$

$$\Delta E = \langle E(\bar{\nu}_e)\rangle - \langle E(\nu_e)\rangle$$

- Measure ΔE, difference in energy for **antineutrinos** and **neutrinos**. If ΔE is large, wind will be neutron rich. If ΔE is small, wind will be proton rich and likely a problem for r-process.

- Composition (Y_e) of wind depends on anti-neutrino energy (Y-axis) [results from ~20 SN1987A events shown] and energy of neutrinos (X-axis). Energy of neutrinos, not yet measured, depends on properties of n rich gas (nu-sphere). [G. Shen]

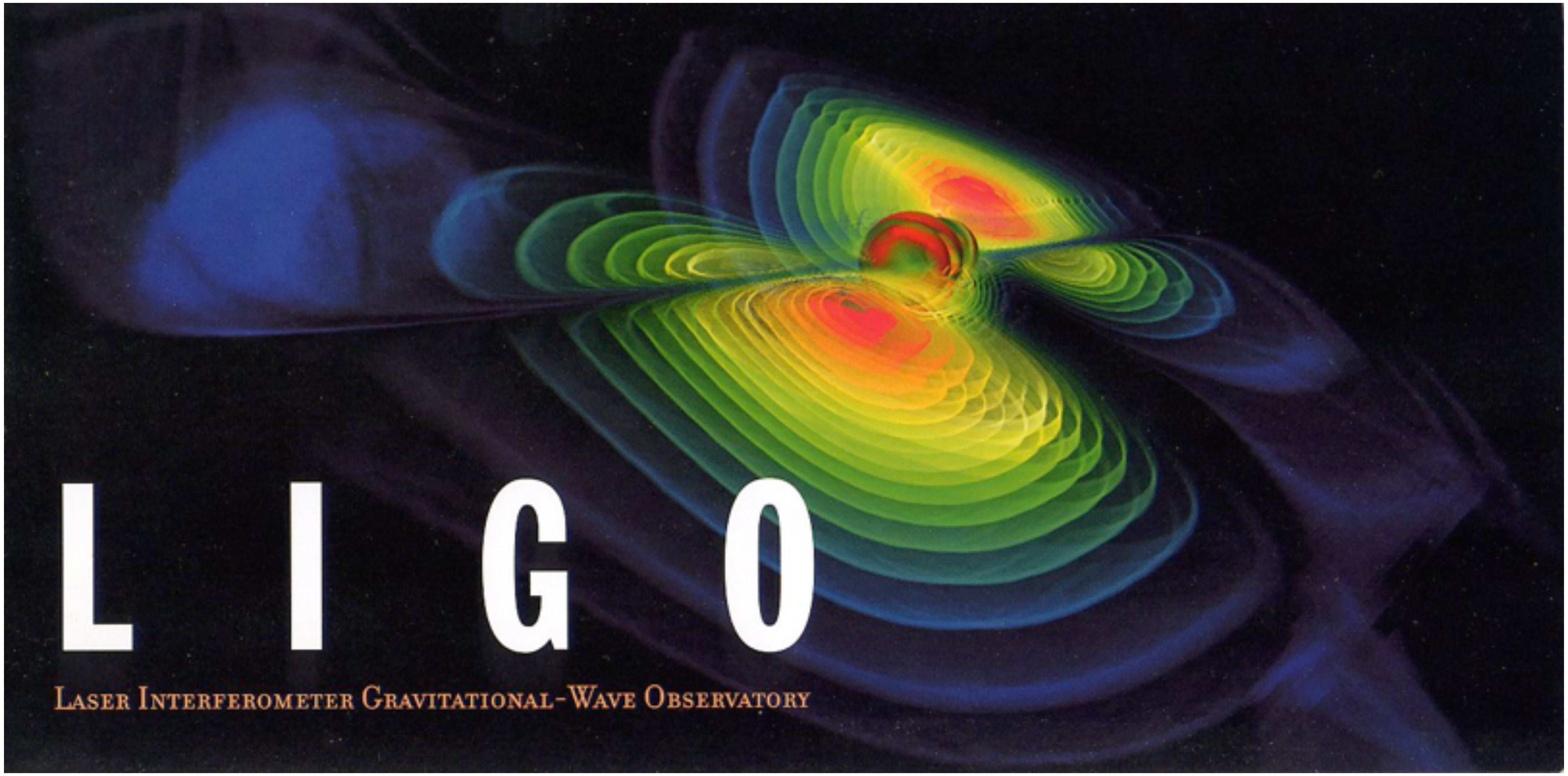


Phys.Rev. D65, 083005

Need good neutrino energy measurements for next galactic SN (liquid argon?) in addition to anti-neutrino measurements from Superkamiokande and other present detectors .

Present SN simulations find too few neutrons for (main or 3rd peak: Au, actinides) r-process.

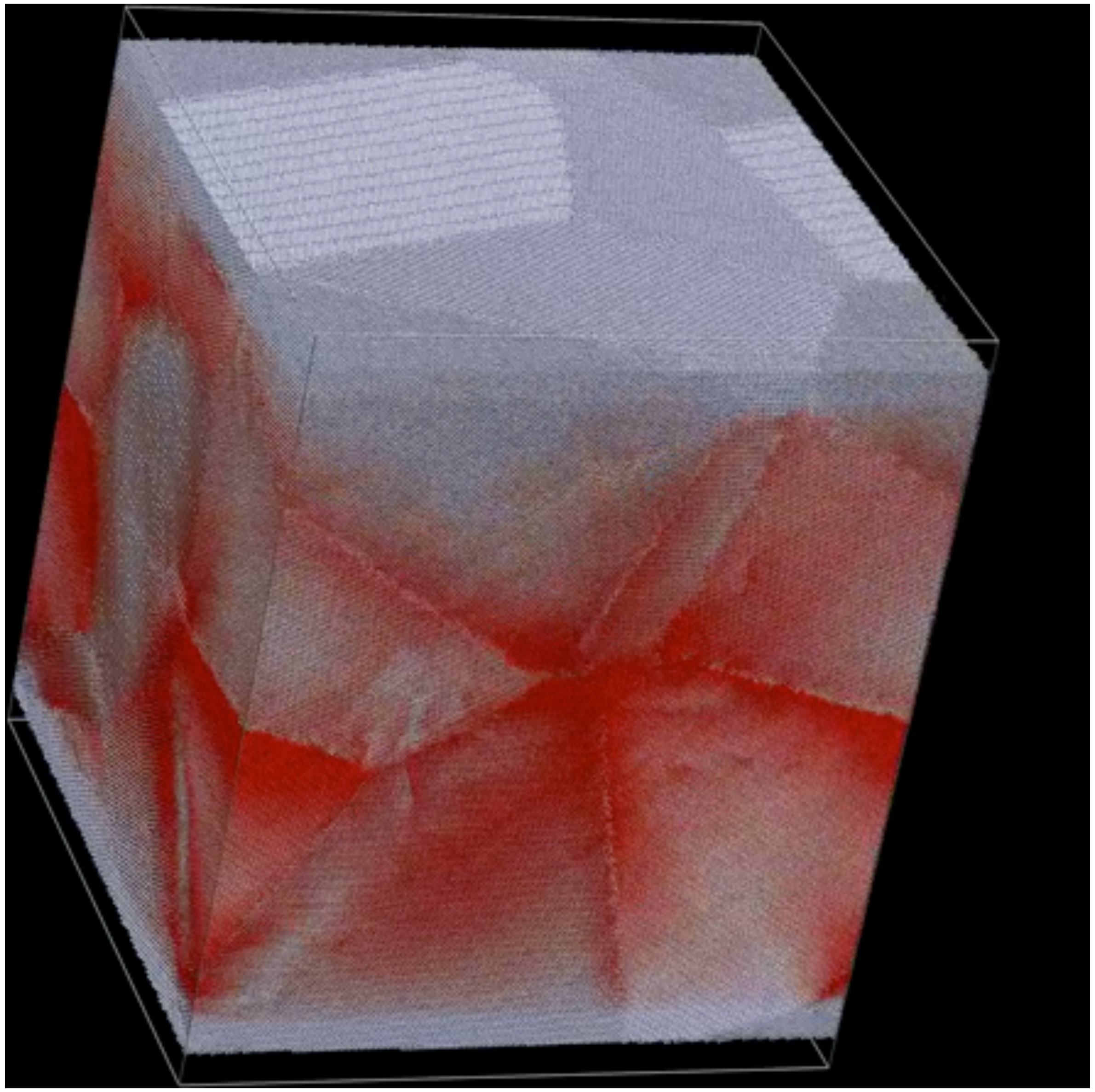
Gravitational wave messengers



Are uniquely sensitive to the **shapes** of astronomical objects

Astro-material Science

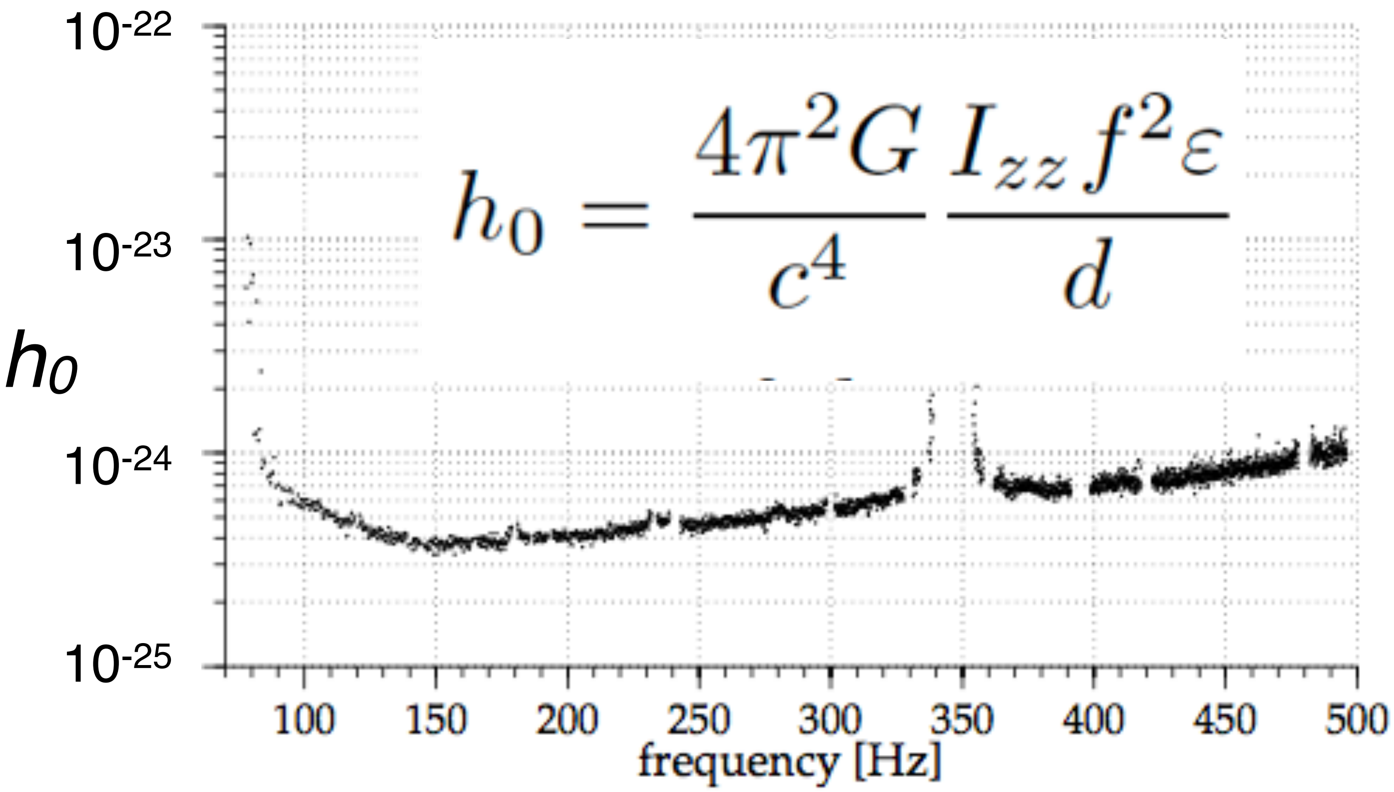
- Solids keep their shapes. GW can probe for exotic astrophysical solids.
- To generate GW put a mass on a stick and shake. Need both a large mass and a ***strong stick***.
- Not just how strong is a given material, but ***what is the strongest possible stick***?
- A mountain on a rapidly rotating NS efficiently radiates GW.
- Maximum size of a mountain depends on strength of neutron star (NS) crust.
- We find NS crust is strongest material known: 10^{10} times stronger than steel. It can support few cm tall mountains!
- Our strong crust can support ellipticities $\epsilon=(I_1-I_2)/I_3$ up to about 10^{-5}.



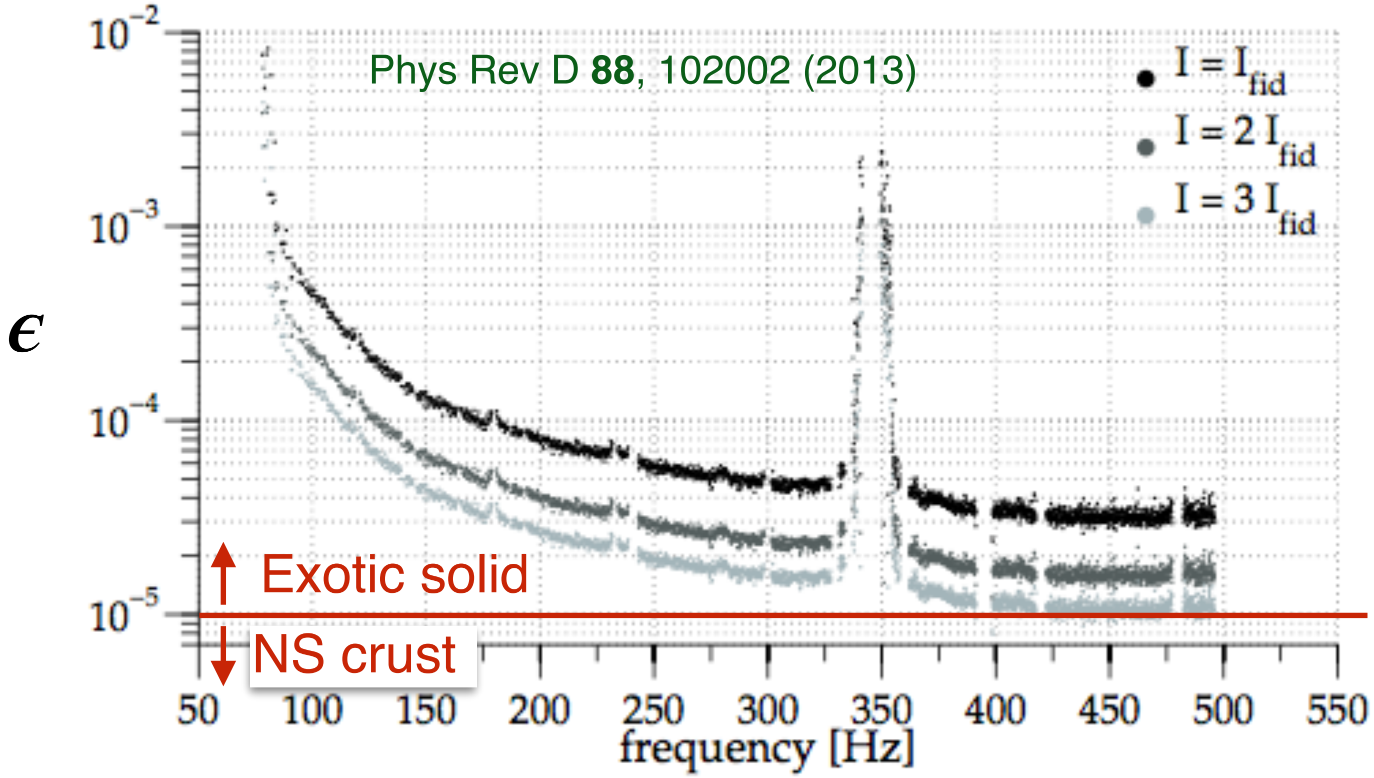
MD simulation of crust breaking with 13 million ions including the effects of defects, impurities, and grain boundaries... Red indicates deformation. CJH, K. Kadau, Phys Rev Let. **102**,191102 (2009)

Continuous GW from Galactic Center

- Search for GW, from isolated neutron stars near the galactic center, using LIGO S5 data.
- Sensitive to strain $h_0 < 10^{-24}$.
- At distance d=8.3 kpc corresponds to ellipticity ϵ of 10^{-5} to 10^{-4}.
- Near but slightly above maximum for NS crust.
- High density solid phase (if it exists) likely supports larger ϵ.
- Example: color superconducting phase with strange quarks paired to up or down quarks of different Fermi momenta by forming a nonuniform crystal lattice.
- Advanced LIGO will improve by x10 and be sensitive to maximally deformed conventional NS crust.



$$h_0 = \frac{4\pi^2 G}{c^4} \frac{I_{zz} f^2 \varepsilon}{d}$$

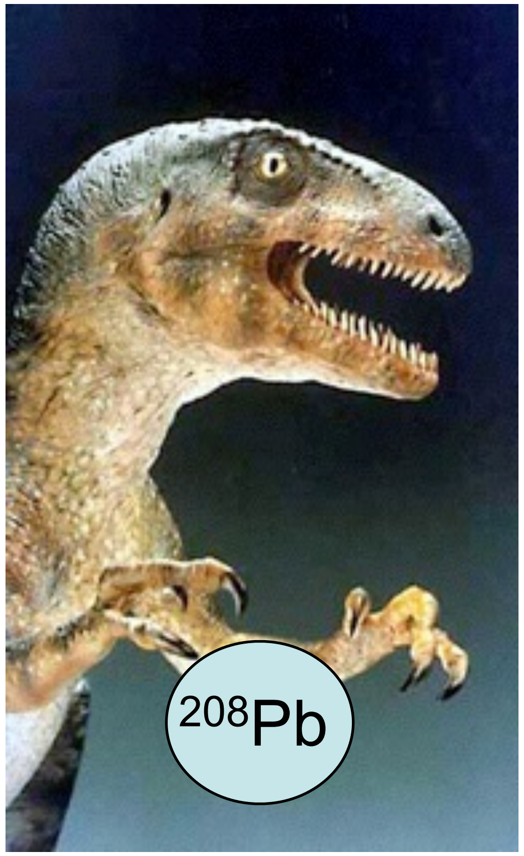


Phys Rev D **88**, 102002 (2013)

↑ Exotic solid

↓ NS crust

Neutron Rich Matter



- PREX uses parity violating electron scattering to measure the neutron radius of ^{208}Pb —> determines pressure of n rich matter.
- X-ray observations of NS radii probe *liquid* n rich matter.
- Energies of supernova neutrinos, important for nucleosynthesis, depend on properties of *gaseous* n rich matter.
- Gravitational waves can probe *solid* n rich matter.

- Collaborators: D. Berry, M. Gorchtein, K. Kadau, R. Michaels, J. Piekarewicz, G. Shen... Students: C. Briggs, J. Hughto, A. Schneider.
- Supported in part by DOE grants DE-FG02-87ER40365 (Indiana U.) and DE-SC0008808 (NUCLEI SciDAC).