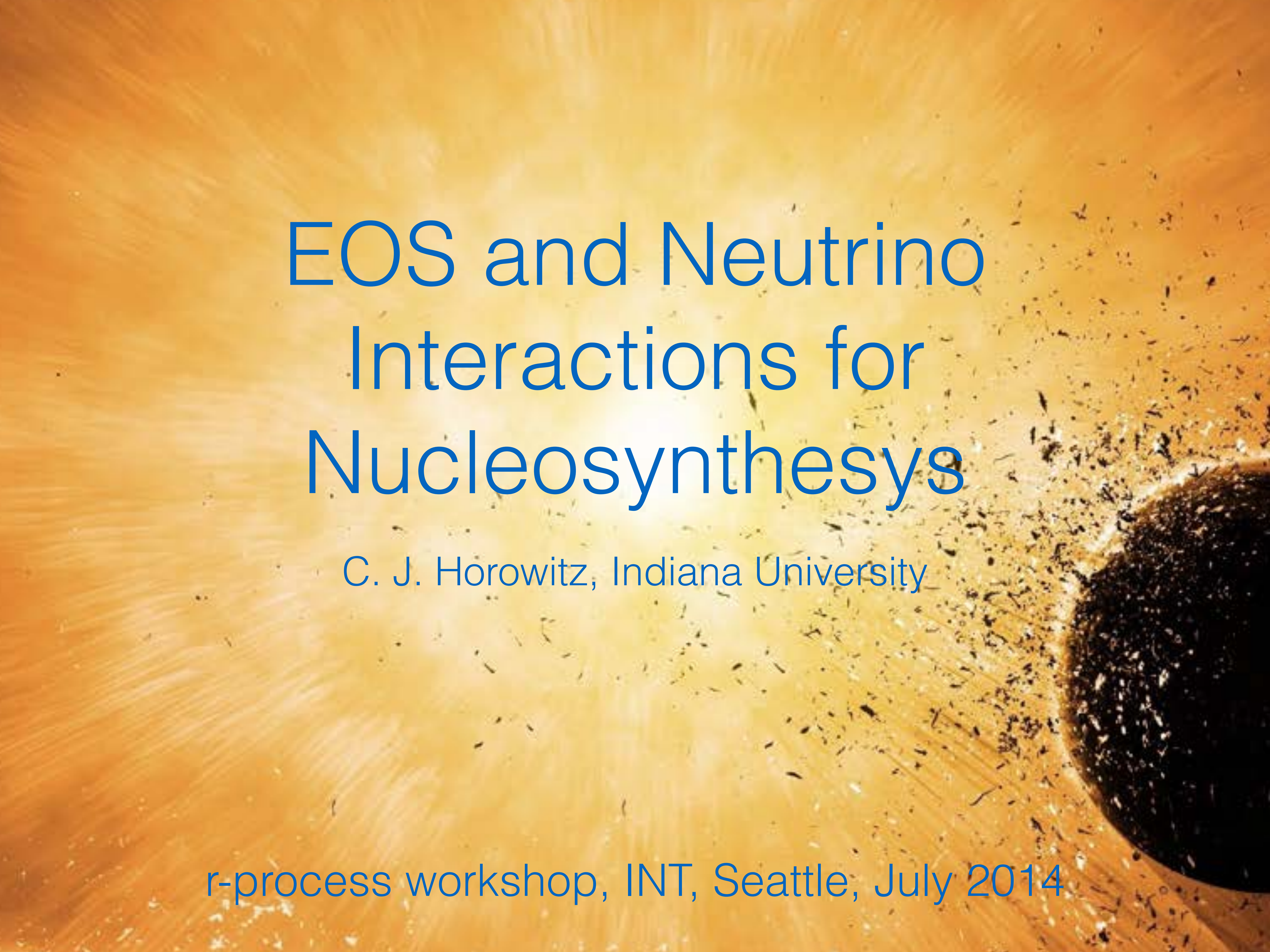


EOS and Neutrino Interactions for Nucleosynthesys

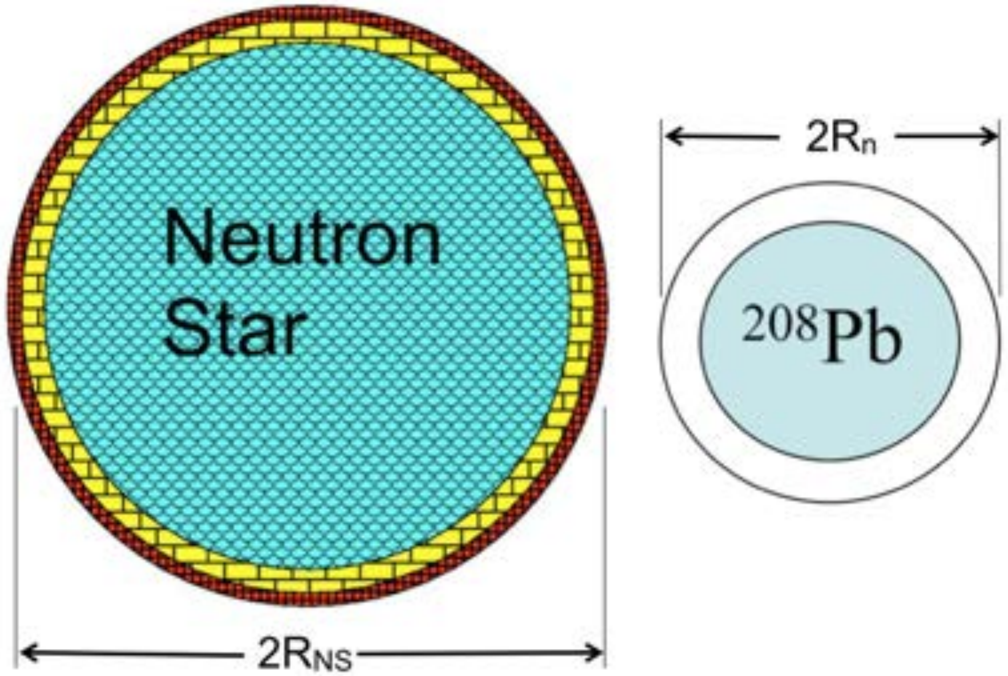
C. J. Horowitz, Indiana University

r-process workshop, INT, Seattle, July 2014

EOS

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 ($\sim 1.4M_{sun}$) NS depends on P at medium densities of $\sim 2\rho_0$.
- 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.

PREX uses Parity Violation to measure R$_n$(^{208}Pb)

- 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

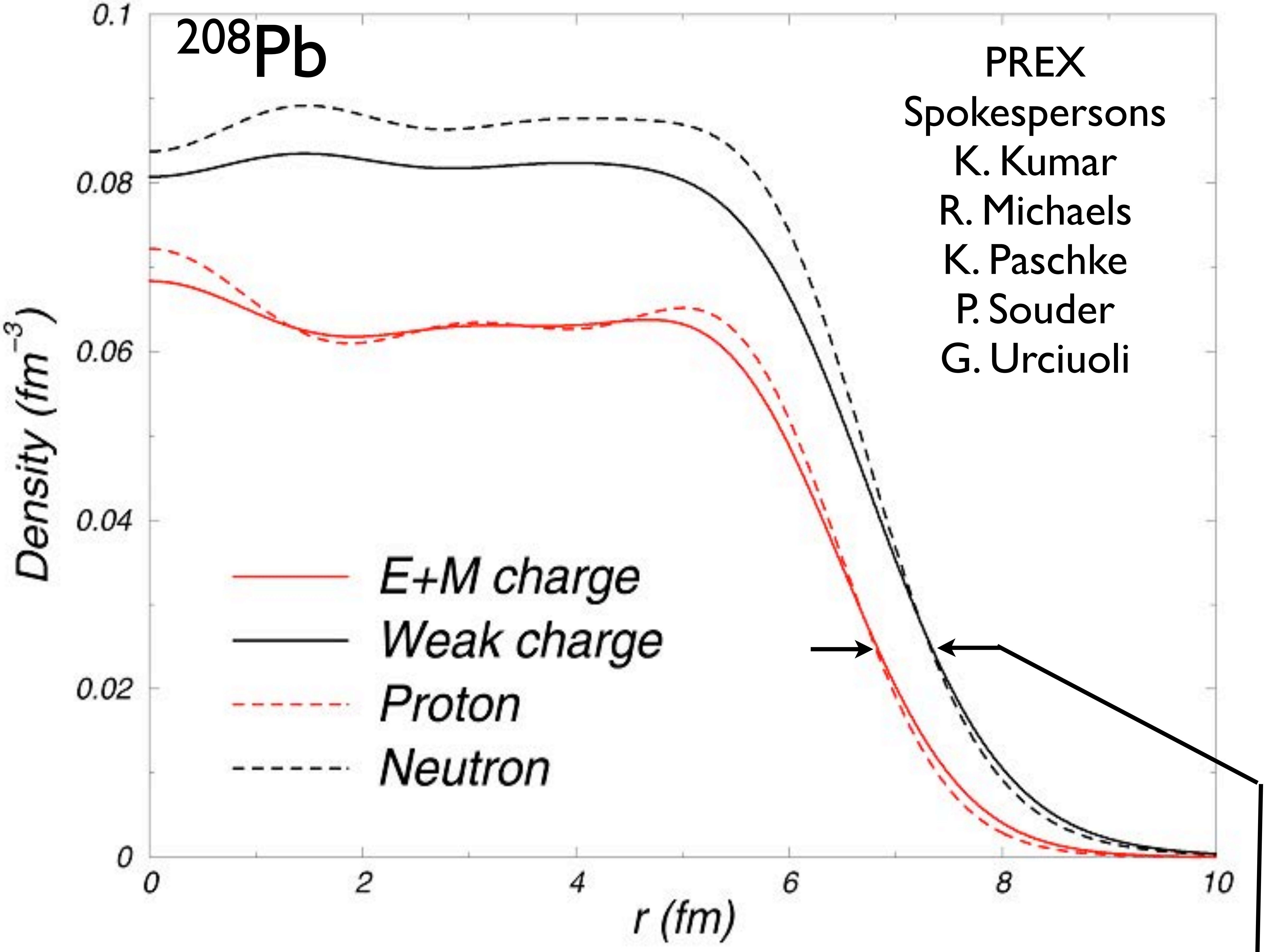
$$A_{pv} = \frac{d\sigma/d\Omega_+ - d\sigma/d\Omega_-}{d\sigma/d\Omega_+ + d\sigma/d\Omega_-}$$

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

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

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

- 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.

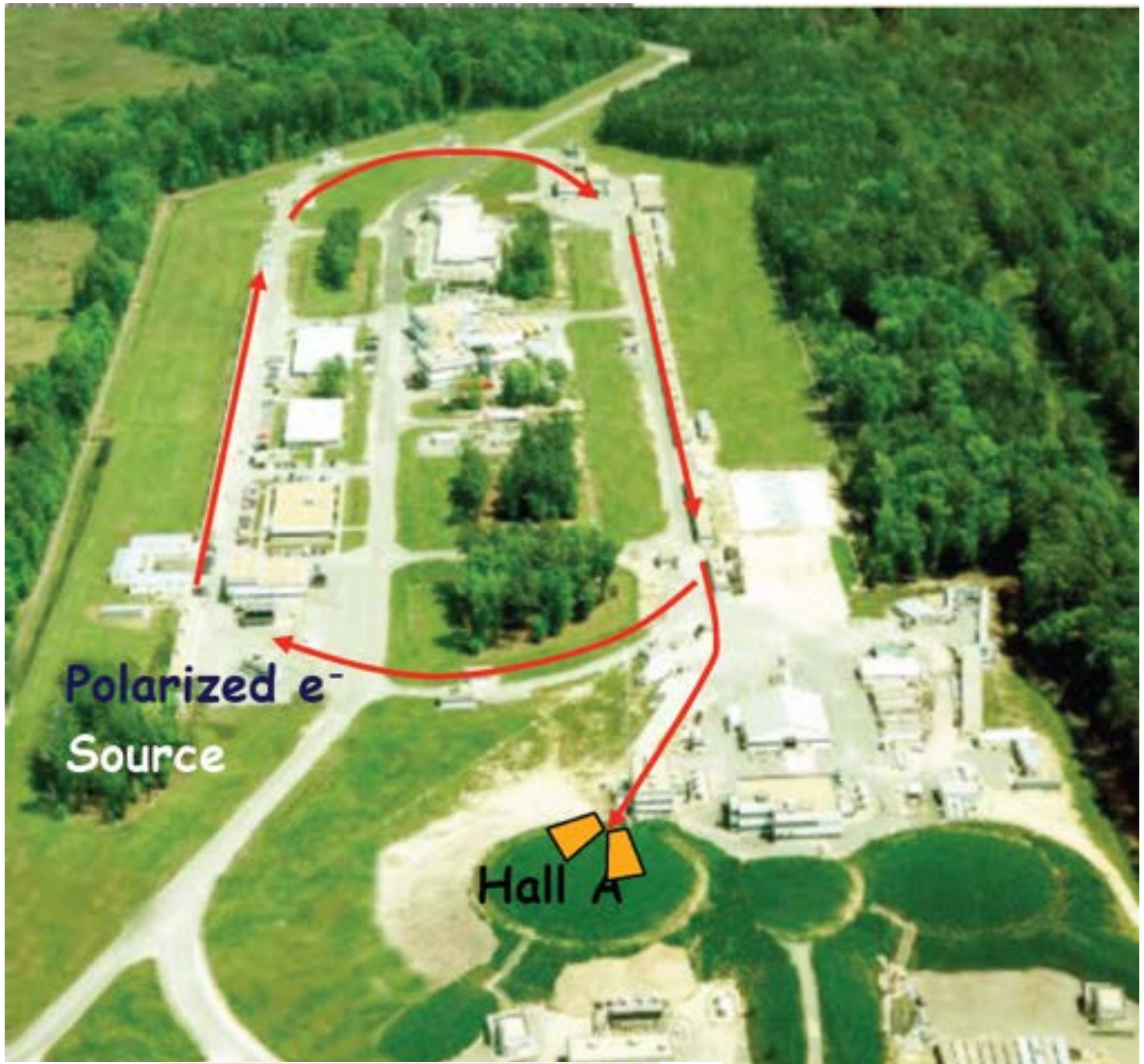


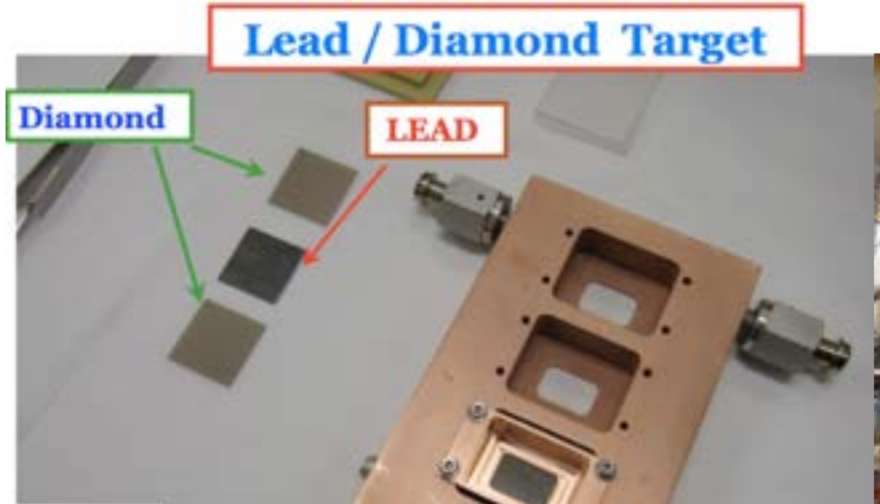
PREX
Spokespersons
K. Kumar
R. Michaels
K. Paschke
P. Souder
G. Urciuoli

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

First PREX result and future plans

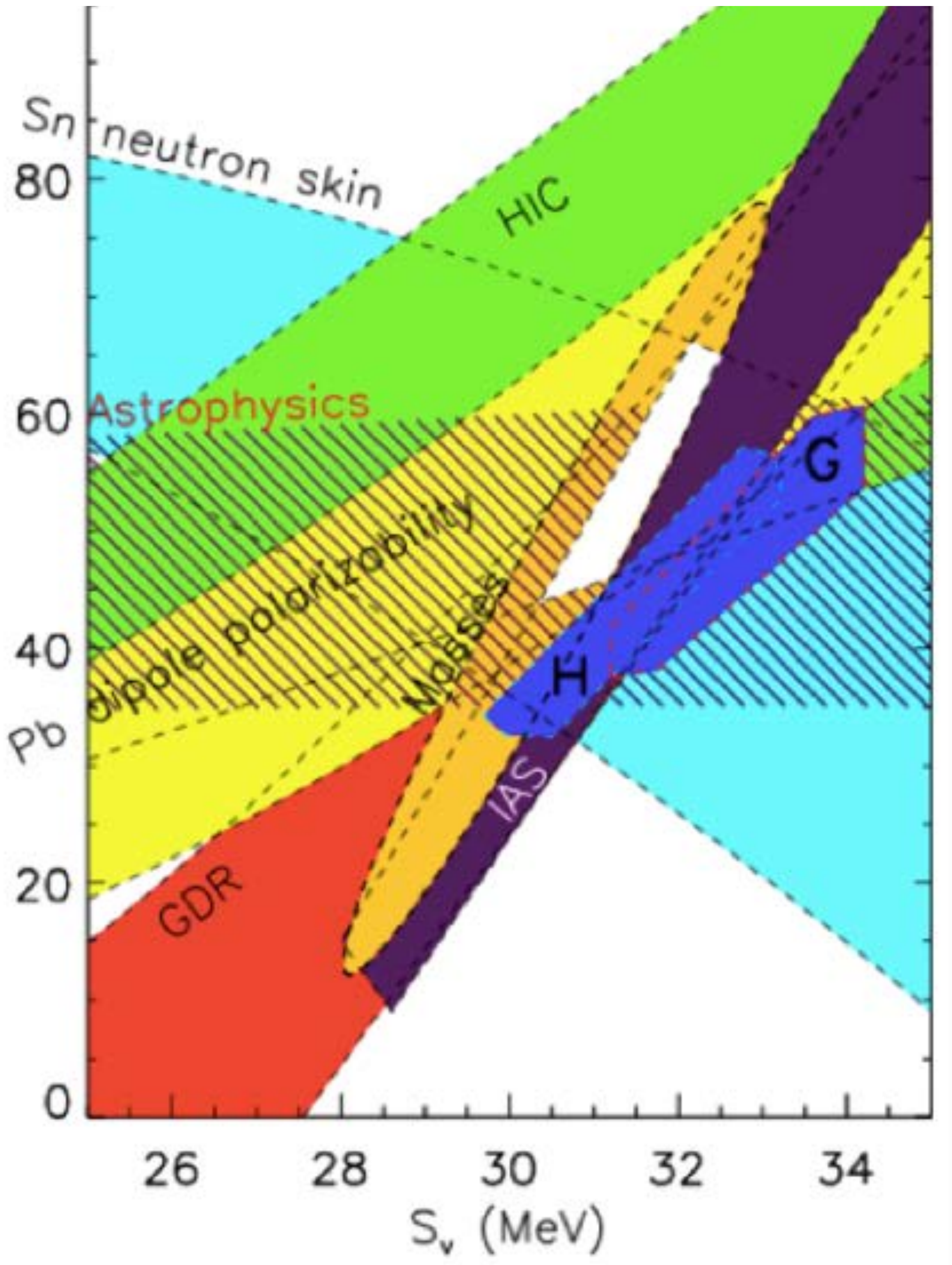
- At Jefferson Laboratory, 1.05 GeV electrons elastically scattered from thick ^{208}Pb foil. PRL **108**, 112502, PRC **85**, 032501
- A_{PV}=0.66 ±0.06(stat) ±0.014(sym) ppm
- Neutron skin thickness: $R_n - R_p = 0.33^{+0.16}_{-0.18}$ fm
- Experiment achieved systematic error goals.
- Future plans: **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.





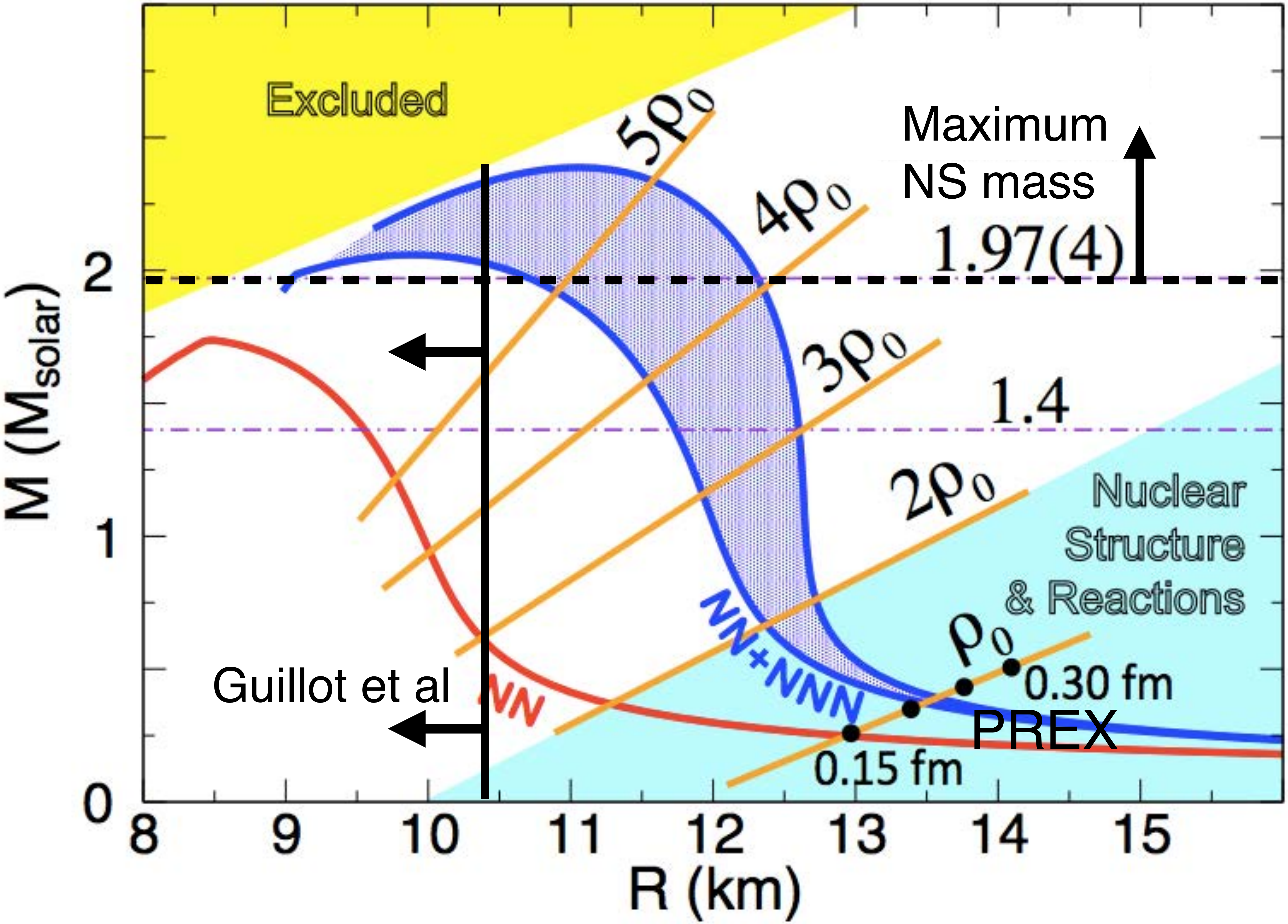
Model dependent determinations of neutron skins

- Neutron skin thickness closely related to L (density dependance of symmetry energy).
- Light blue region in Lattimer et al from Japanese *model dependent* analysis of proton elastic scattering from Sn isotopes. Very old relativistic impulse approximation amplitudes from me were fudged so that ^{58}Ni had zero skin. Then amplitudes were used to describe Sn scattering. This is *definitely model dependent!*
- *Danielewicz also has very precise Isobaric Analog State result that assumes same Sn skin analysis!*



Steiner and Lattimer

Gandolfi et al. PRC85, 032801 (2012)



Fate of NS merger central object

- Prompt collapse to black hole, delayed collapse, or absolutely stable.

- Is very important EOS observable!

- Observation of black hole formation (with some knowledge of total system mass) sets UPPER limit on maximum NS mass, and rules out all very stiff EOSs.

SN neutrinos and r-process nucleosynthesis

- Half of heavy elements (including gold) are believed made in the rapid neutron capture process. Seed nuclei captures many n and decay. **What makes all the neutrons?**
- **Neutrinos:** Important possible 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 / anti-neutrino energies.

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

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

- Measure ΔE, difference in average 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.

Searching for El Dorado with supernova neutrinos

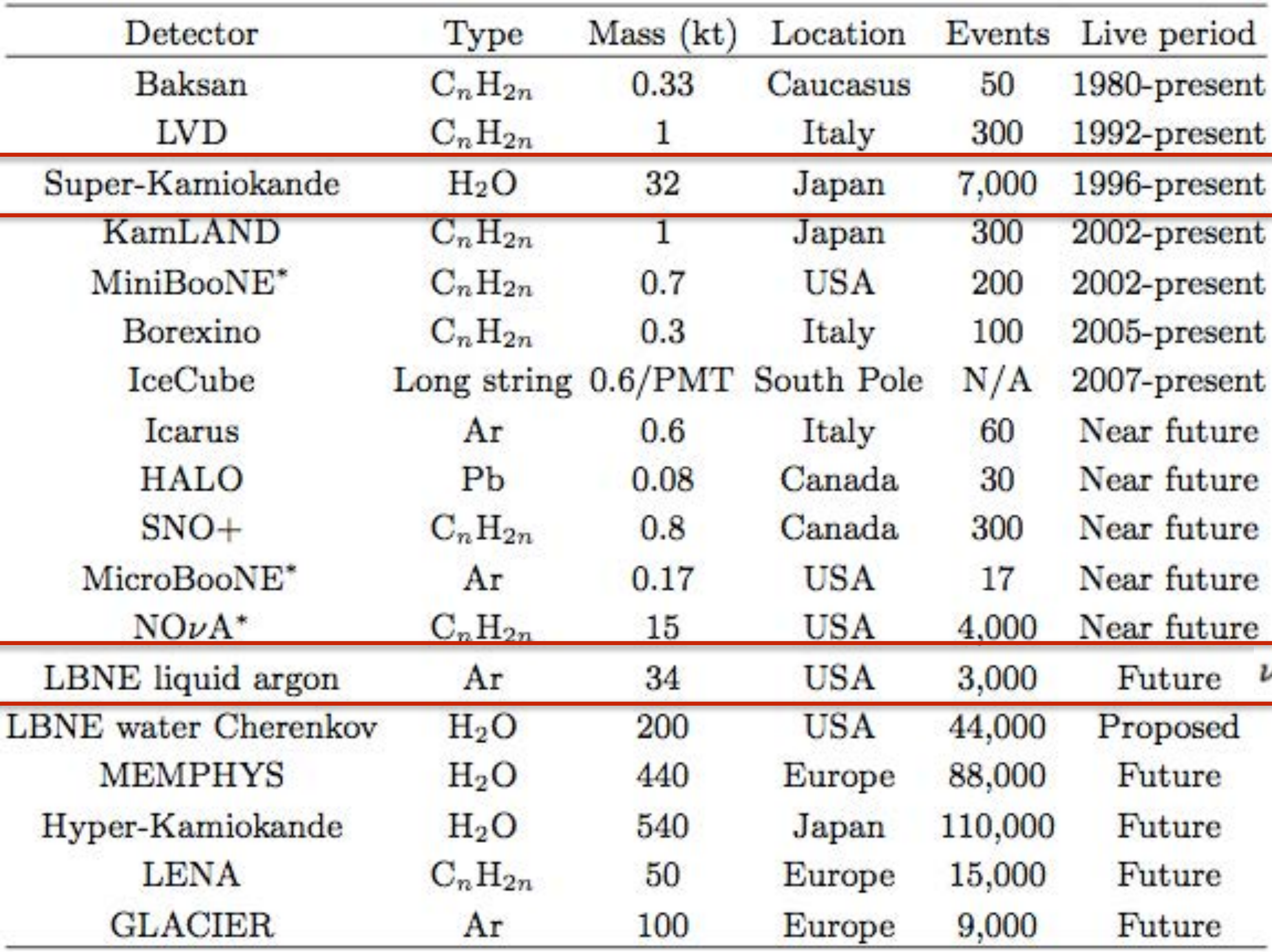
Important to measure energy of both anti-nu (SK) and neutrinos (liquid argon?).

ΔE depends on some nuclear physics including symmetry E at low densities.

However, present SN simulations find too few neutrons.

Supernova Neutrino Detectors

- **Are crucial to our whole field!**



Detector	Type	Mass (kt)	Location	Events	Live period
Baksan	C_nH_{2n}	0.33	Caucasus	50	1980-present
LVD	C_nH_{2n}	1	Italy	300	1992-present
Super-Kamiokande	H_2O	32	Japan	7,000	1996-present
KamLAND	C_nH_{2n}	1	Japan	300	2002-present
MiniBooNE*	C_nH_{2n}	0.7	USA	200	2002-present
Borexino	C_nH_{2n}	0.3	Italy	100	2005-present
IceCube	Long string	0.6/PMT	South Pole	N/A	2007-present
Icarus	Ar	0.6	Italy	60	Near future
HALO	Pb	0.08	Canada	30	Near future
SNO+	C_nH_{2n}	0.8	Canada	300	Near future
MicroBooNE*	Ar	0.17	USA	17	Near future
NOνA*	C_nH_{2n}	15	USA	4,000	Near future
LBNE liquid argon	Ar	34	USA	3,000	Future
LBNE water Cherenkov	H_2O	200	USA	44,000	Proposed
MEMPHYS	H_2O	440	Europe	88,000	Future
Hyper-Kamiokande	H_2O	540	Japan	110,000	Future
LENA	C_nH_{2n}	50	Europe	15,000	Future
GLACIER	Ar	100	Europe	9,000	Future

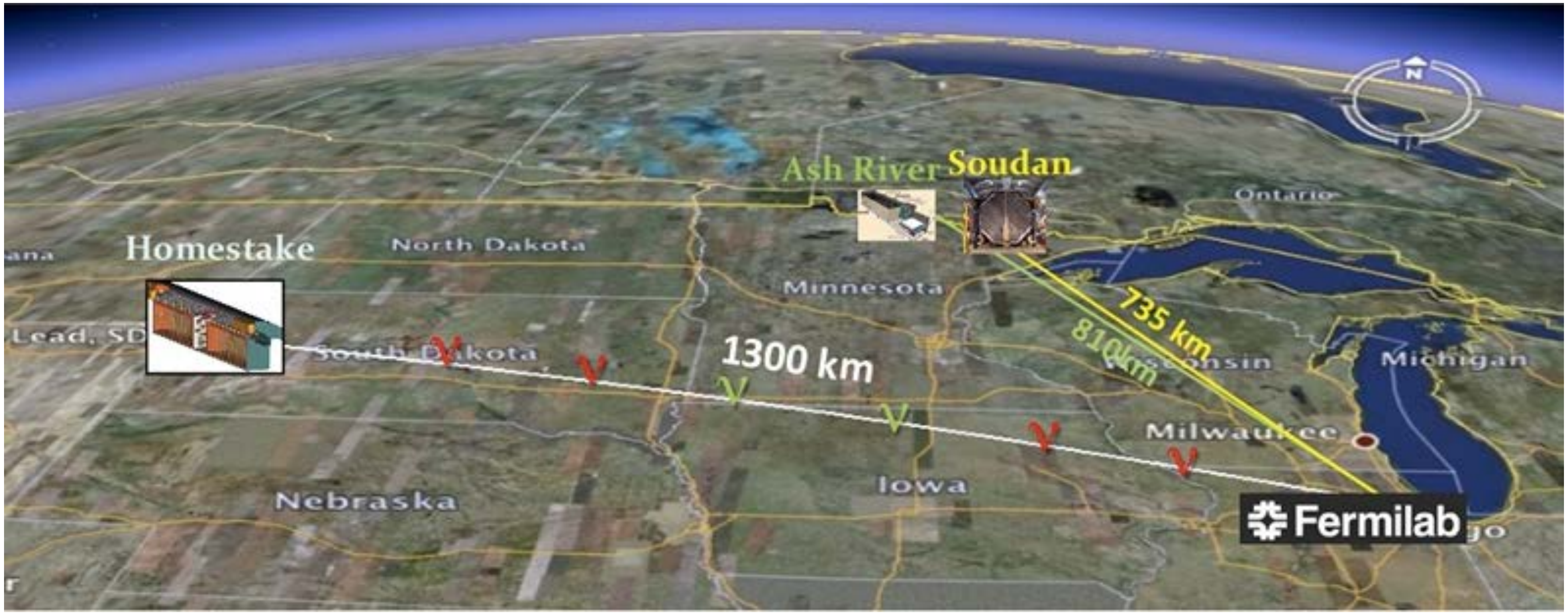
$\bar{\nu}_e + p \rightarrow e^+ + n$

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

Supernova neutrino detectors. Events from a SN at 10kpc (considerable model variation). — Kate Scholberg

Important to measure spectrum of all three components: electron neutrinos, electron antineutrinos, and nu-x. Can measure nu-x in elastic scattering detector.

Long Baseline Neutrino Experiment



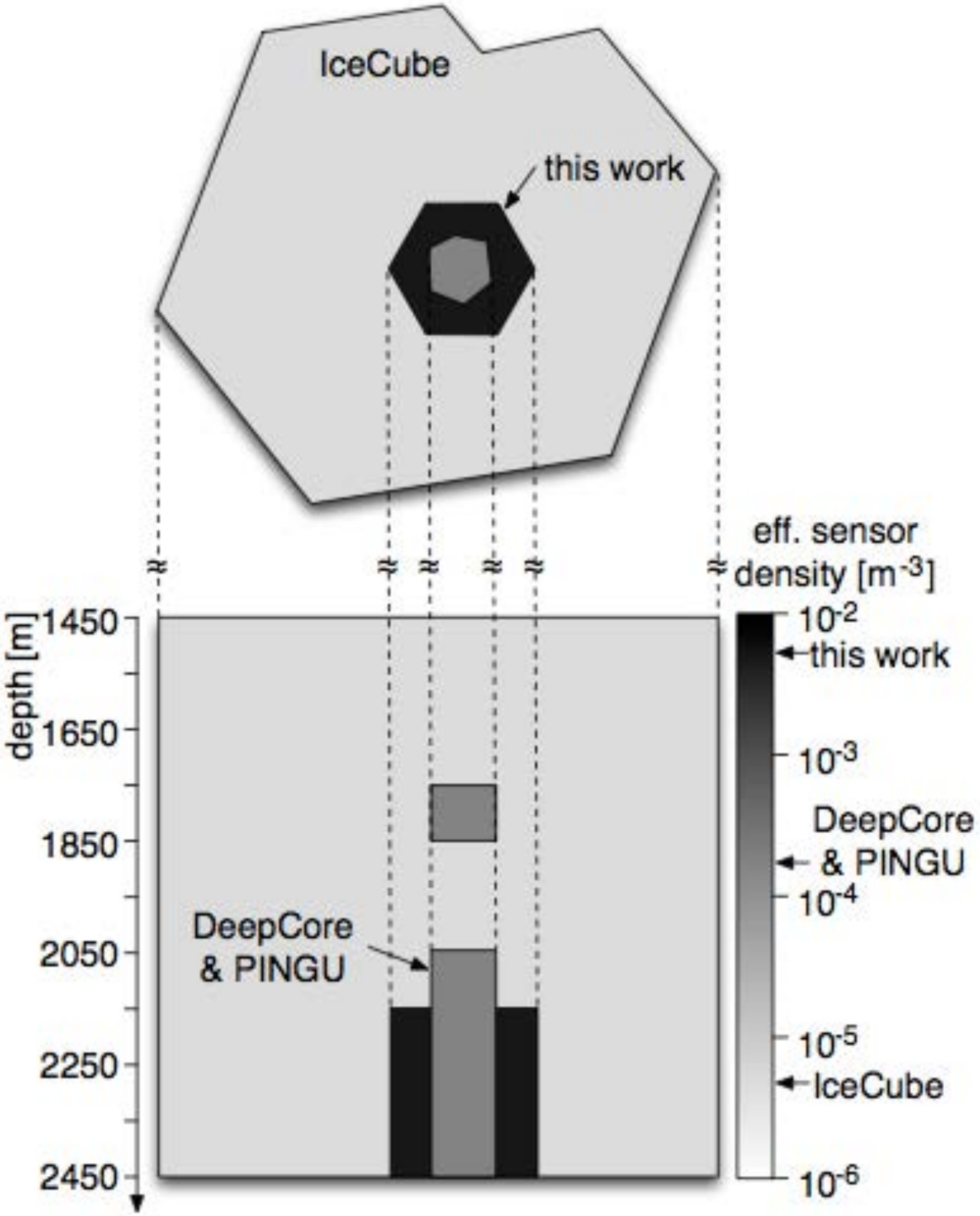
- Send neutrino and antineutrino beams from Fermilab (near Chicago) 1300 km to a large (34 kt) liquid Ar detector in the Homestake gold mine in South Dakota. Main goal: observe CP violation in neutrino oscillations.

- Powerful supernova detector that should be able to measure electron neutrino energies very well.

- Combine anti-nu E from Super K with nu E from LBNE to predict composition of neutrino driven wind and likely strongly disfavor r-process in wind.

Detecting extra-galactic supernova neutrinos in the Antarctic ice (10 Megaton detector)

- Preliminary idea to instrument inner region of IceCube to obtain 10 MeV threshold and 10 Mt effective volume.
- Issues with cost, photodetectors, and noise.
- See SN to 10 Mpc with rate of 1 to 4 per year.
- Boser et al, arXiv:1304.2553
- Coincident with GW signal.
- What do you learn from handful of events?
- What else can this detector do?



SN neutrinos and r-process nucleosynthesis

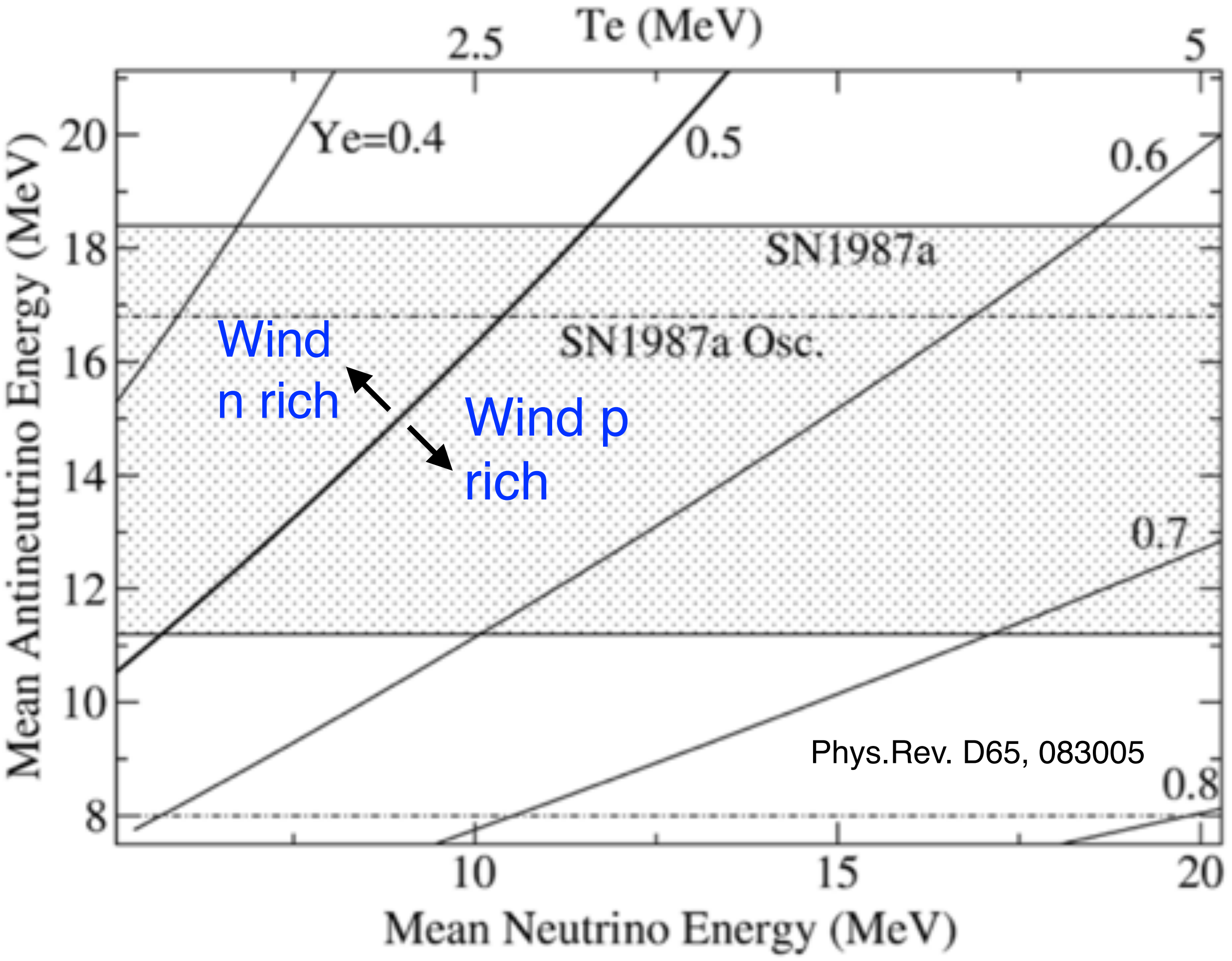
- Ratio of neutrons to protons in wind set by capture rates that depend on neutrino and anti-neutrino energies.

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

- Weak magnetism important

- Measure difference in average energy of **antineutrinos** and **neutrinos**. If large, wind will be neutron rich. If it 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).



Phys.Rev. D65, 083005

LBNE measures X axis and Super-K measures Y axis.

Present SN simulations find too few neutrons for (main or 3rd peak) r-process. Suggests this is not r-process site. However composition still determines what SN wind makes!

Neutrinosphere Problem

- Build detailed neutrino atmosphere model with quantifiable uncertainties to predict ν_e, anti-ν_e, and ν_x spectra for:
    - SN ν detectors
    - Input to ν oscillation calculations
    - Electron fraction Y_e of ν driven wind and nucleosynthesis
- Focus on $\Delta E = \langle E(\text{anti-}\nu_e)\rangle - \langle E(\nu_e)\rangle$

“Femtonovae”

- Core collapse SN dominated by neutrinos. Much of the “action” occurs near the neutrinosphere (surface of last scattering) at temperatures of ~5 MeV, densities of 1/1000 to 1/10 ρ_0, and neutron rich compositions.

- A “Femtonova” is a very small new star. Suggested name for HI collisions applied to astrophysics, and in particular to recreate neutrinosphere conditions.

- **Study in the laboratory the equation of state, symmetry energy, composition, and neutrino response … of neutrinosphere material.**
  - Recreating ~5 MeV temperature is straight forward.
  - Recreating low densities occurs as system expands but it may be difficult to measure the density.
  - Recreating the very neutron rich conditions is harder. Perform HI collisions with proton rich and then neutron rich radioactive beams and extrapolate to very neutron rich conditions.

Chemical Freeze Out

- HI collisions create warm source regions that then expand with time.
- Nucleons in source regions interact to form light clusters D, ^{3}H, ^{3}He, ^{4}He.
- Source expands to such low densities that clusters stop interacting and the chemical composition freezes out.
- One can then measure this final composition which should correspond to the composition of equilibrium nuclear matter at the freeze out temperature and density.
- Several ways to measure freeze out temperatures (often near 5 MeV). For example looking at ratio of yields. $T_{HHe}=14.3/ \ln[1.59 (Y_D Y_{4He}/Y_{3H} Y_{3He})]$
- Measuring freeze out densities are more difficult. Example, can get source sizes from two-particle correlation functions.

Virial expansion for Neutrinosphere EOS

- Start with pure neutron matter, then include clusters.
- Assume: system in gas phase and has not undergone a phase transition with increasing density or decreasing T and that the fugacity $z=e^{\mu/T}$ with μ the chemical pot is small.
- Expand pressure in powers of z :

  $$P=2T/\lambda^3[z+b_2z^2+b_3z^3+\ldots],$$

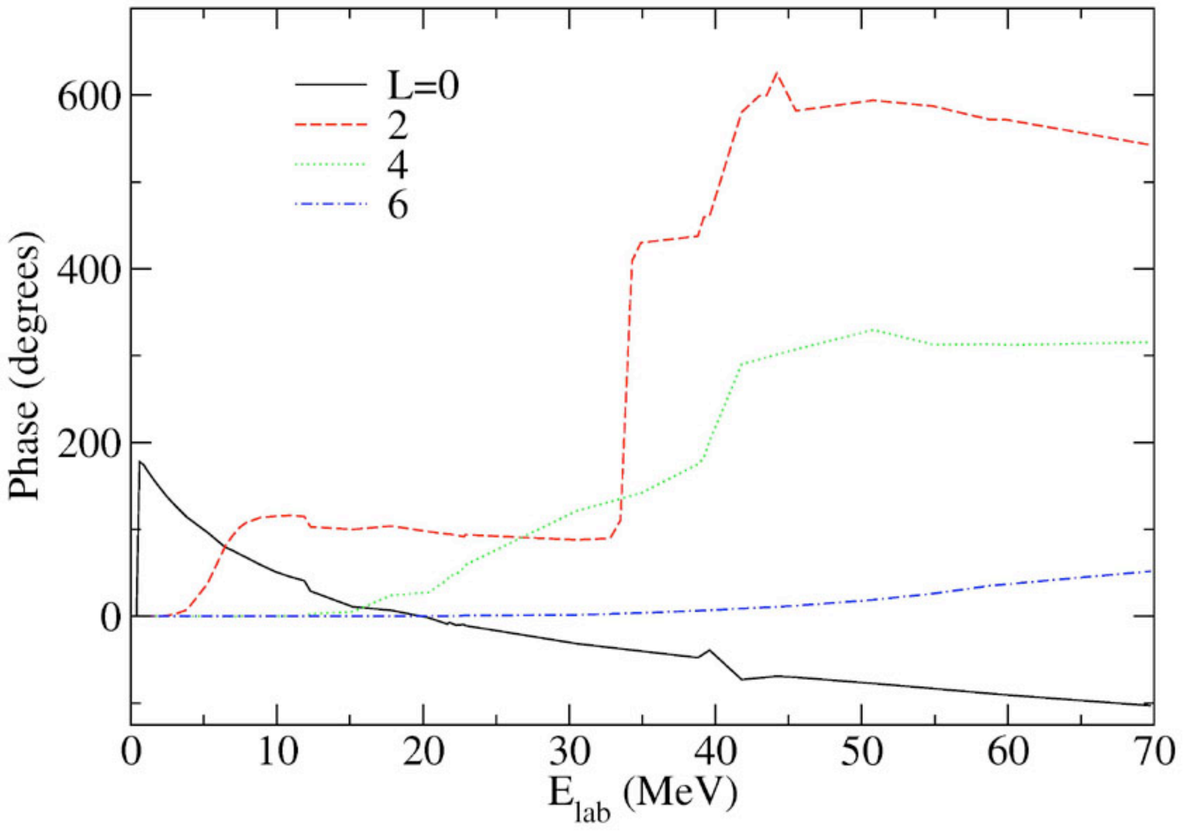
  Here λ=thermal wavelength=$(2/mT)^{1/2}$
- 2nd virial coef. $b_2(T)$ from 2 particle partition function which depends on density of states determined from phase shifts:

$$b_2 = 2^{1/2}\sum_B e^{E_B/T} + \frac{2^{1/2}}{\pi}\int_0^\infty dk\, e^{-E_k/2T}\sum_l (2l+1)d\delta_l(k)/dk \pm 2^{-5/2}$$

Nuclear Matter: *n*, *p*, α system

$$\frac{P}{T} = \frac{2}{\lambda^3}[z_p + z_n + (z_n^2 + z_p^2) b_n + 2 z_n z_p (b_{nuc} - b_n)] + \frac{1}{\lambda_\alpha^3}[z_\alpha + z_\alpha^2 b_\alpha + z_\alpha (z_p + z_n) b_{\alpha n}]$$

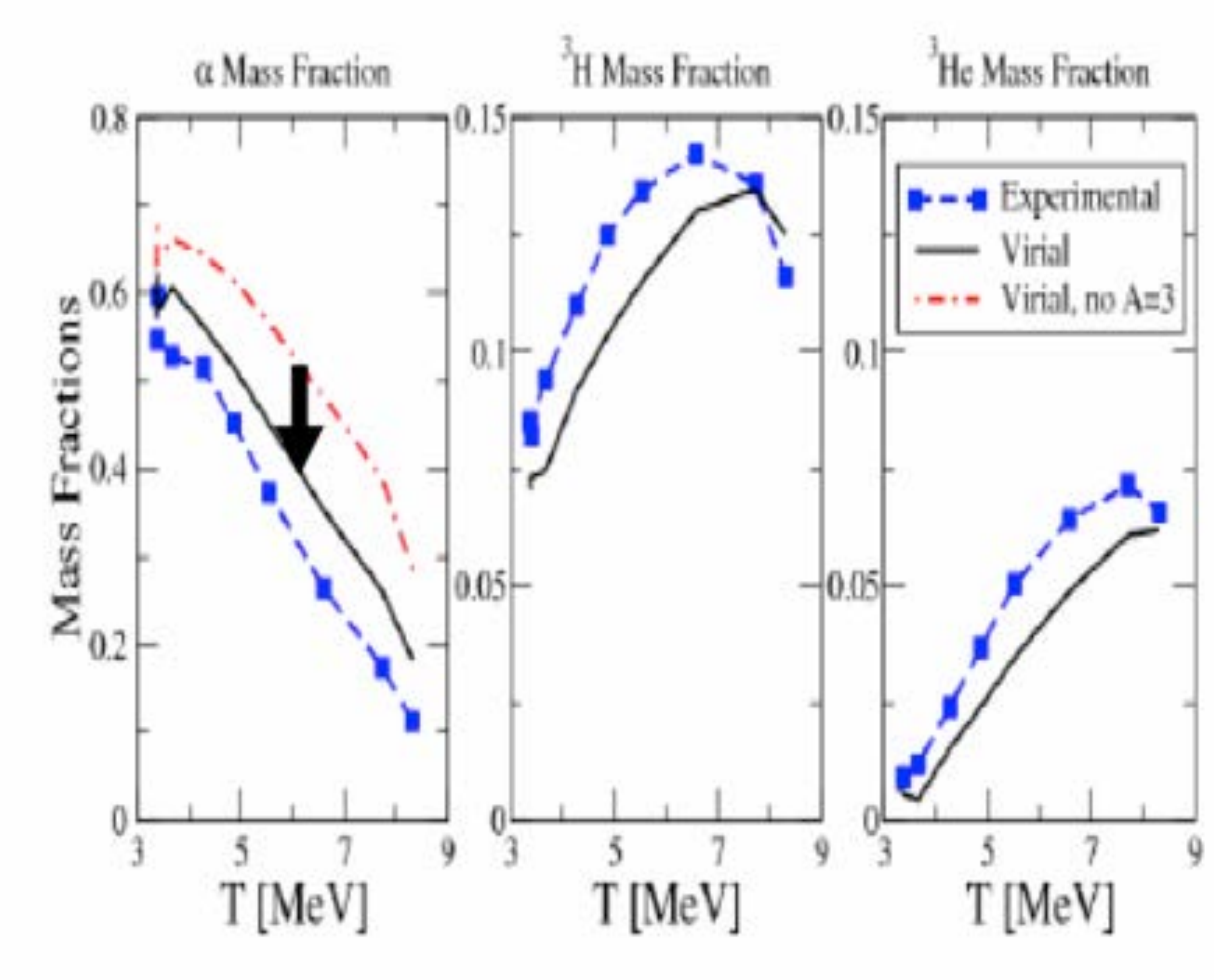
- Need four virial coefficients:
  - b_n for neutron matter,
  - b_{nuc} for symmetric nuclear matter,
  - b_α for alpha system,
  - $b_{\alpha n}$ for interaction between an α and N.
- Virials from NN, Nα and $\alpha\alpha$ elastic scattering phase shifts.

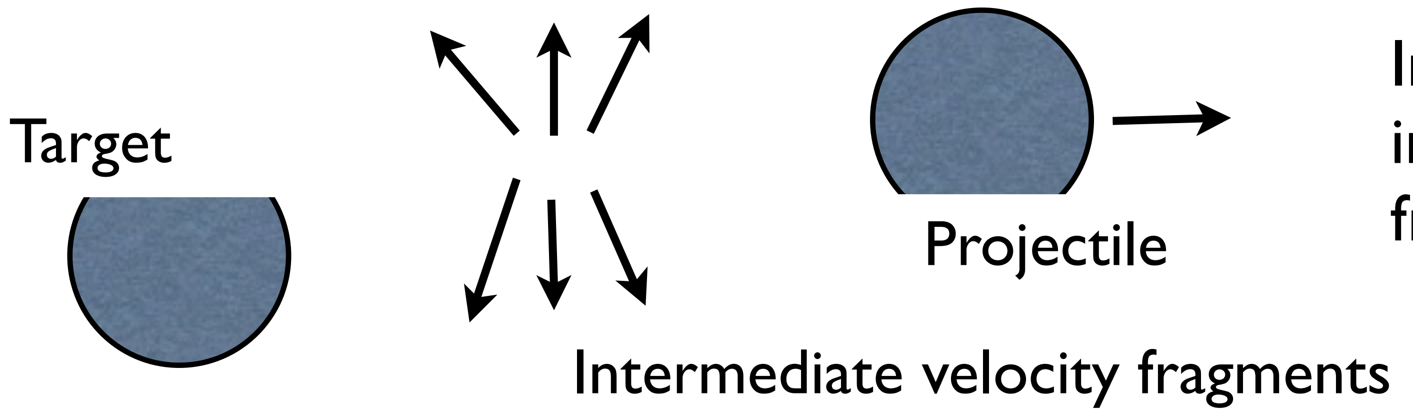


$\alpha-\alpha$ Elastic Phase Shifts

Recreating Neutrinosphere on Earth

- Can study neutrinosphere like conditions with heavy ion collisions in lab.
- Composition of intermediate velocity fragments in 35 MeV/n ^{64}Zn on ^{92}Mo and ^{197}Au: Data (blue squares) Kowalski et al, PRC **75**, 014601(2007). Virial EOS black





In a peripheral HI collision, intermediate velocity fragments from warm low density region.

Symmetry Energy shift

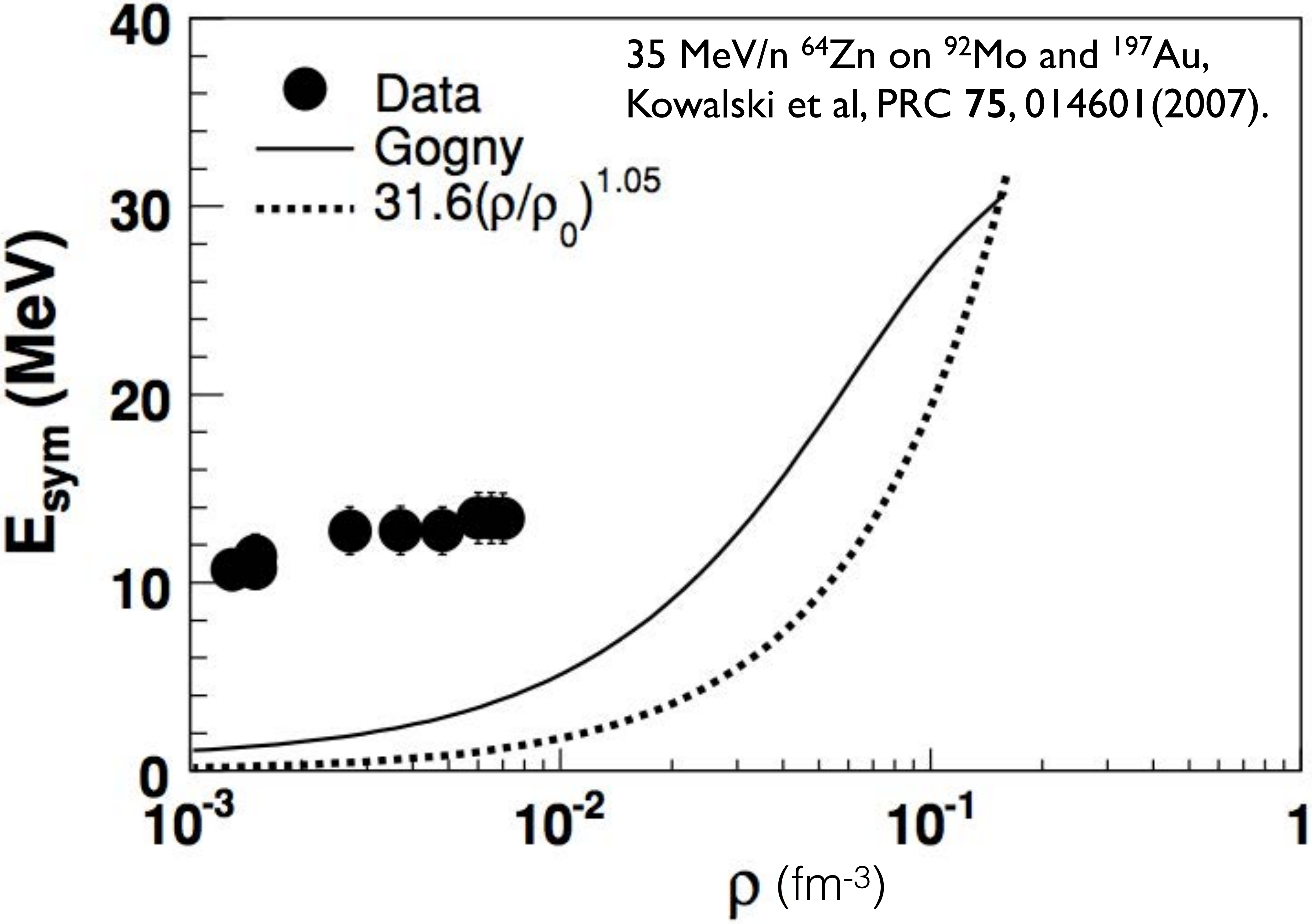
- Proton in n rich matter more bound than neutron because of symmetry energy.
- Symmetry energy at low density can be calculated exactly with virial expansion (with A. Schwenk). Find it is much larger than in some mean field models because of cluster formation.
- Neutrino absorption cross section increased by energy shift which increases energy and phase space of outgoing electron-> lowers E(nu).
- Consider $\boldsymbol{\nu}_e$ + n -> p + e

$$\Delta U = U_n - U_p = \lambda^3 T(n_n - n_p)(b_{pn} - \hat{b}_n)$$

$$\frac{\sigma_{\nu_e}(\Delta U)}{\sigma_{\nu_e}(0)} = \frac{(E_\nu + \Delta U)^2[1 - f(E_\nu + \Delta U)]}{E_\nu^2[1 - f(E_\nu)]} .$$

- Effect opposite for anti-neutrino absorption and reduces cross section increasing E(anti-nu).
- Increases ΔE and makes wind somewhat more neutron rich. Probably not enough for r-process ?? But symmetry energy is relevant.

Idea due to L. Roberts, my work with G. Shen, C. Ott, E. O’Connor



35 MeV/n ^{64}Zn on ^{92}Mo and ^{197}Au, Kowalski et al, PRC **75**, 014601(2007).

Symmetry energy from isoscaling analysis of ratio of yields of light clusters with different N/Z values. The temperature varies from about 4 MeV (lowest density) to 10 MeV (highest density)

EOS and Neutrino Interactions for Nucleosynthesys

- Combine information from Super-K for anti-$\boldsymbol{\nu}_{\mathrm{e}}$ and LBNE for $\boldsymbol{\nu}_{\mathrm{e}}$ from a galactic supernova, allows one to infer the composition of nu driven wind providing more accurate nucleosynthesis predictions.

- Should make detailed neutrino atmosphere model to predict $\boldsymbol{\nu}_{\mathrm{e}}$, anti-$\boldsymbol{\nu}_{\mathrm{e}}$, and $\boldsymbol{\nu}_{\mathrm{x}}$ spectra for: SN $\boldsymbol{\nu}$ detection, $\boldsymbol{\nu}$-osc calculations, $\boldsymbol{\nu}$-wind Y_e and nucleosyntheses.

- **Femtonovae: Can recreate neutrinosphere conditions in lab with HI collisions and measure EOS, composition, symmetry E, nu-response to benchmark nu-atmosphere model.**

- Both HI collisions and Virial EOS find large Symmetry E (or self E) shift that will increase $\boldsymbol{\nu}_{\mathrm{e}}$ and reduce anti-$\boldsymbol{\nu}_{\mathrm{e}}$ charged current cross sections.

- Collaborators: G. Shen, E. O'Connor, C. Ott, A. Schwenk, Z. Lin… Supported in part by DOE grants DE-FG02-87ER40365 (Indiana U.) and DE-SC0008808 (NUCLEI SciDAC).