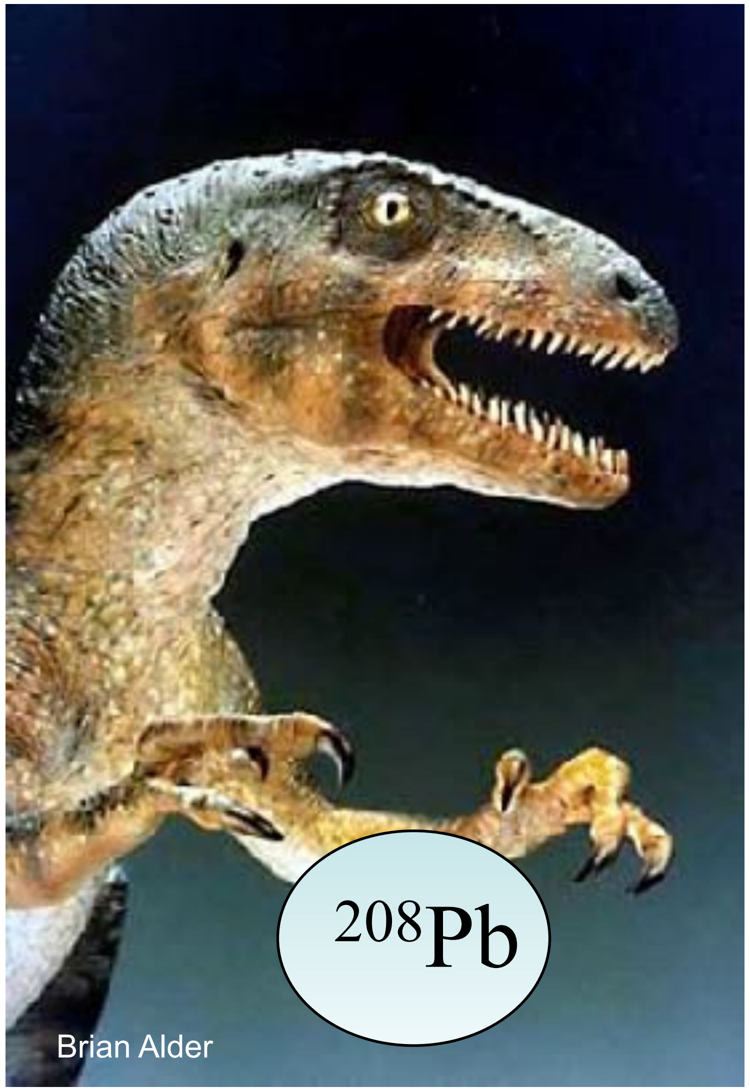
EOS and neutrinos

Chuck Horowitz, Indiana University
Electromagnetic Signatures of r-process Nucleosynthesis in Neutron Star Binary Mergers, INT, Aug. 2017

Laboratory probes 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

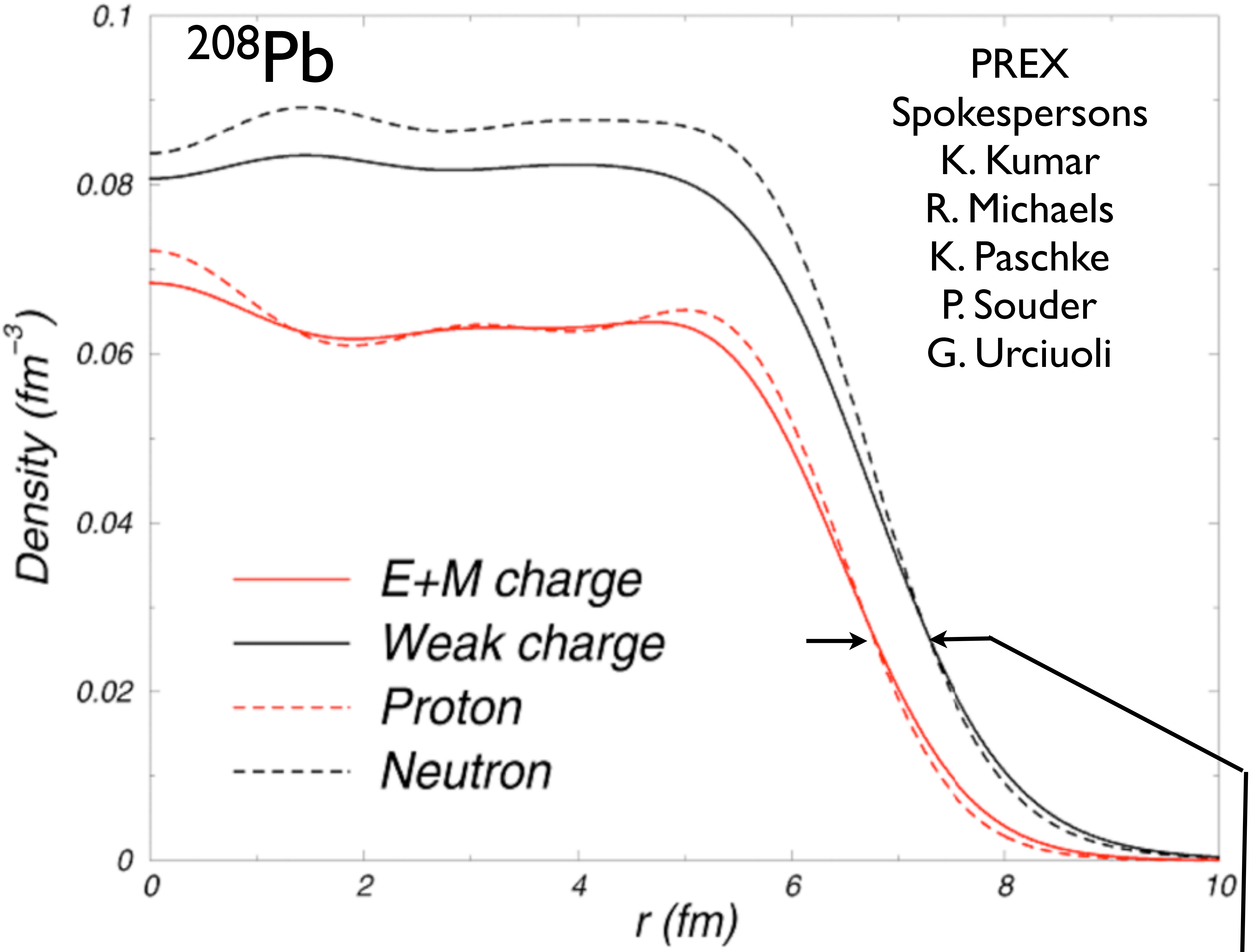
$$A_{pv} = \frac{d\sigma/d\Omega_+ - d\sigma/d\Omega_-}{d\sigma/d\Omega_+ + d\sigma/d\Omega_-}$$

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

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

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

- Model independently map out distribution of weak charge in a nucleus.
- **Electroweak reaction free from most strong interaction uncertainties.**

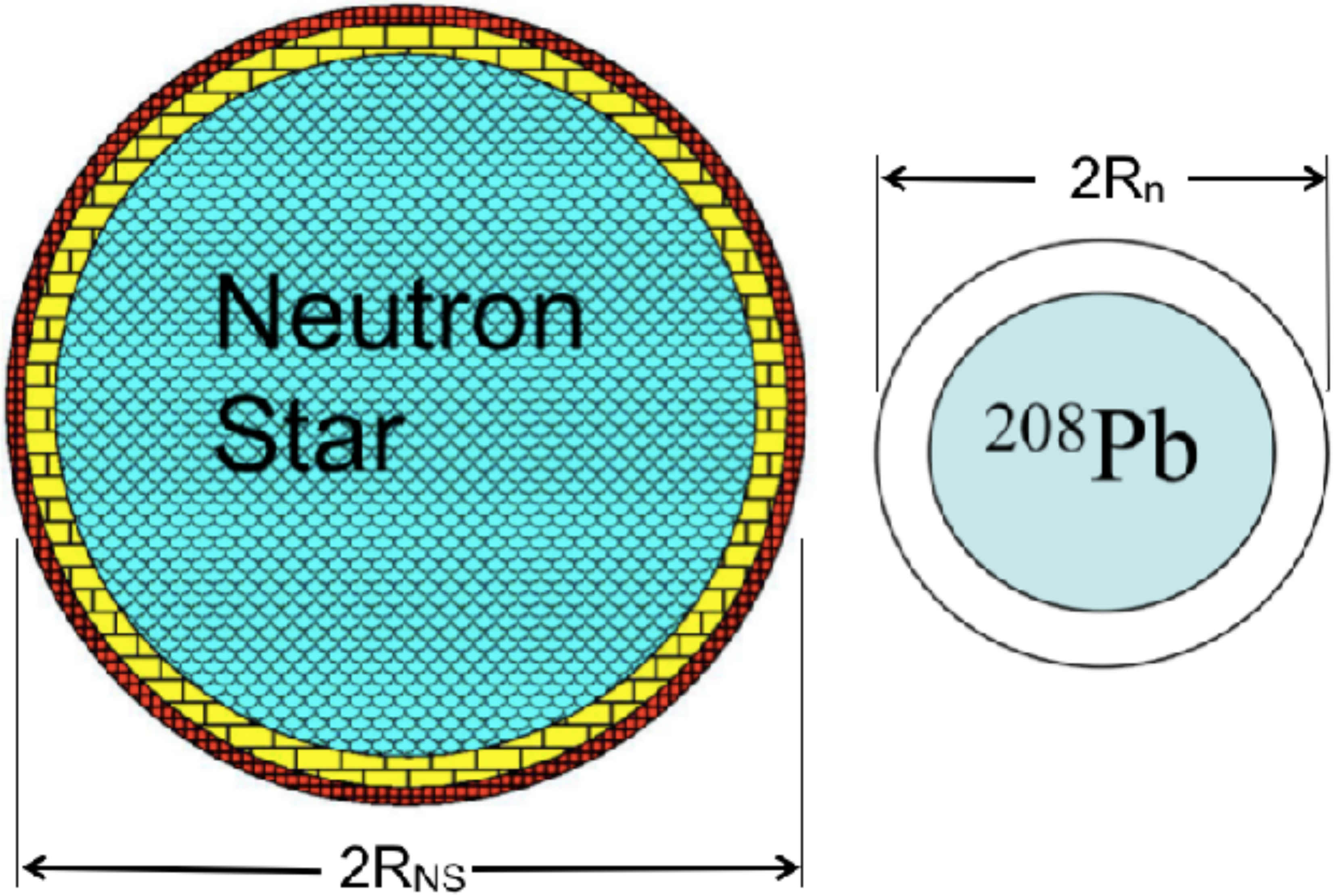


PREX
Spokespersons
K. Kumar
R. Michaels
K. Paschke
P. Souder
G. Urciuoli

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

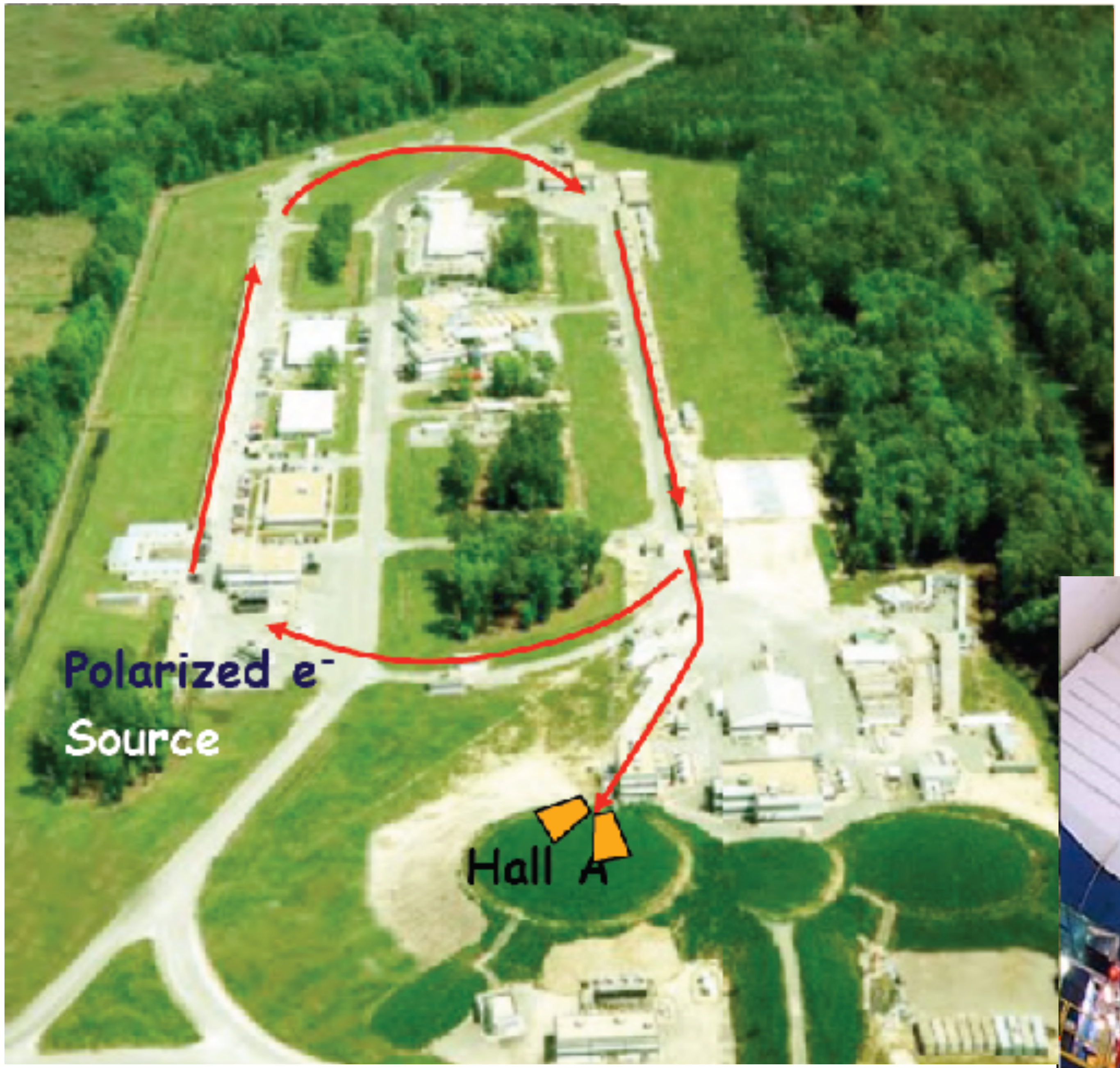
Radii of ^{208}Pb and Neutron Stars

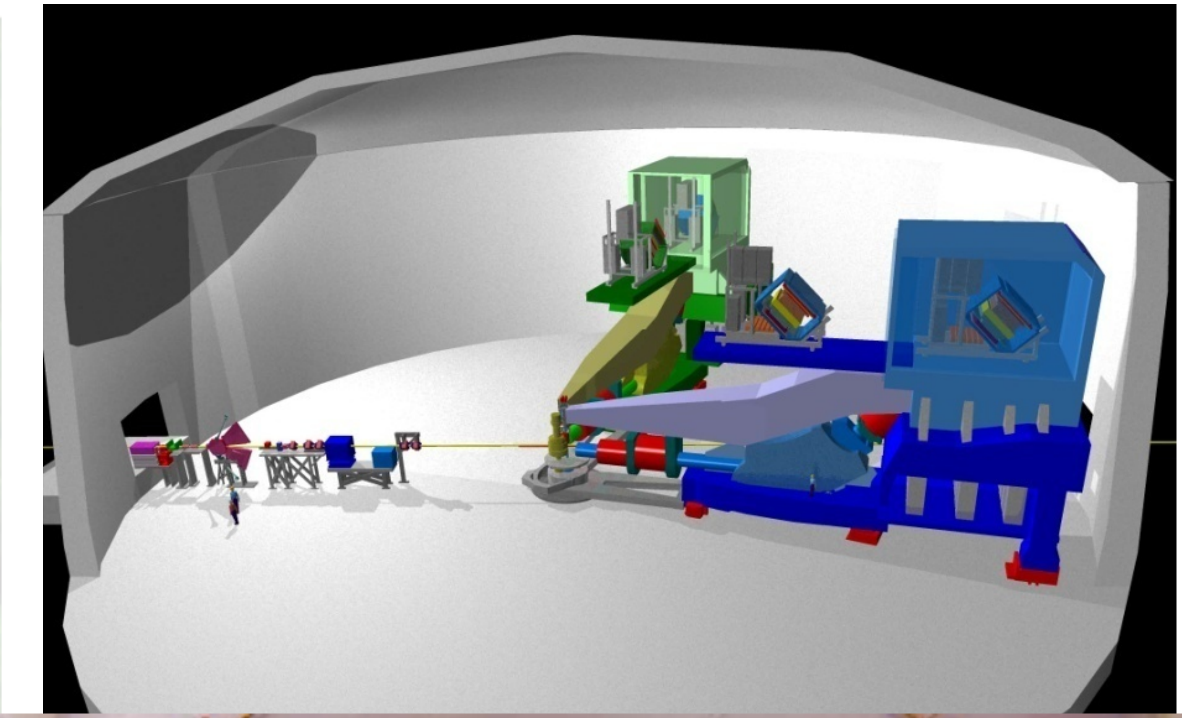
- Pressure of neutron matter pushes neutrons out against surface tension ==> R_n-R_p of ^{208}Pb correlated with P of neutron matter.
- Radius of a neutron star also depends on P of neutron matter.
- Measurement of R_n (^{208}Pb) in laboratory has important implications for the structure of neutron stars.

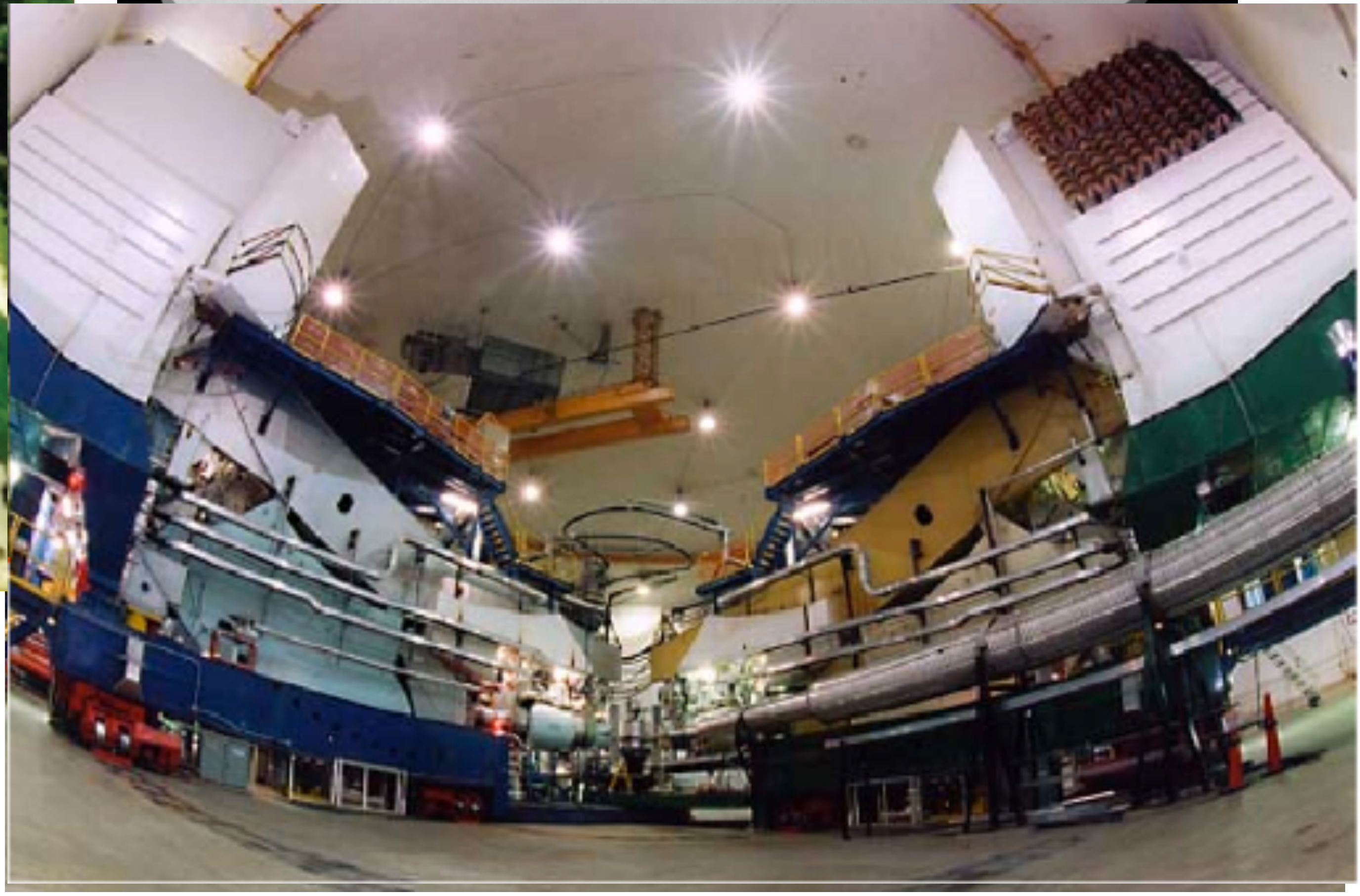


Neutron star is 18 orders of magnitude larger than Pb nucleus but has same neutrons, strong interactions, and equation of state.

Hall A at Jefferson Lab







R. Michaels, JLAB

Parity violating neutron radius experiments

- **PREX**: ran in 2010. 1.05 GeV electrons elastically scattering at ~5 deg. from ^{208}Pb

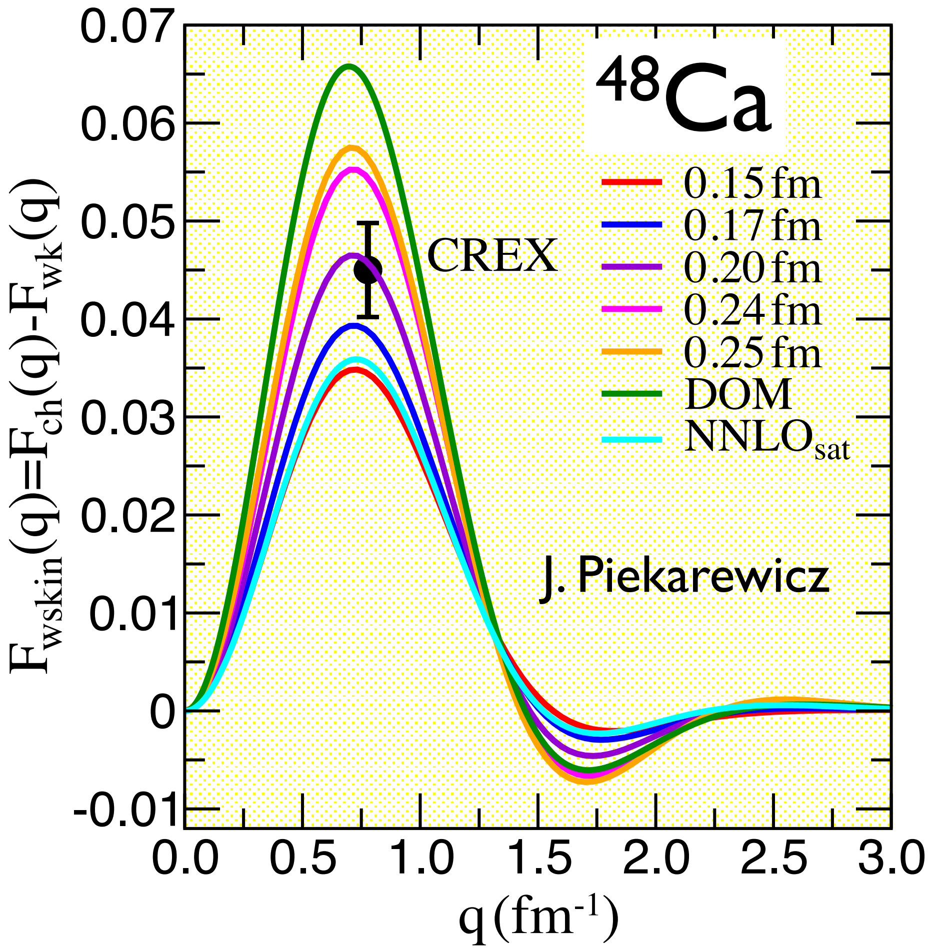
  A_{PV} = 0.657 ± 0.060(stat) ± 0.014(sym) ppm

- From A_{pv} I inferred neutron skin: $R_n - R_p = 0.33^{+0.16}_{-0.18}$ fm.

- Next runs (hope for 2018)

- **PREX-II**: ^{208}Pb with more statistics. Goal: R_n to ±0.06 fm.

- **CREX**: Measure R_n of ^{48}Ca to ±0.02 fm. Microscopic calculations feasible for light n rich ^{48}Ca to relate R_n to *three neutron forces*.



- Microscopic coupled cluster calculations for ^{48}Ca make sharp prediction R_n-R_p=0.135±0.015 fm using chiral interaction NNLO$_{sat}$ [Nature Physics **12** (2016) 186].

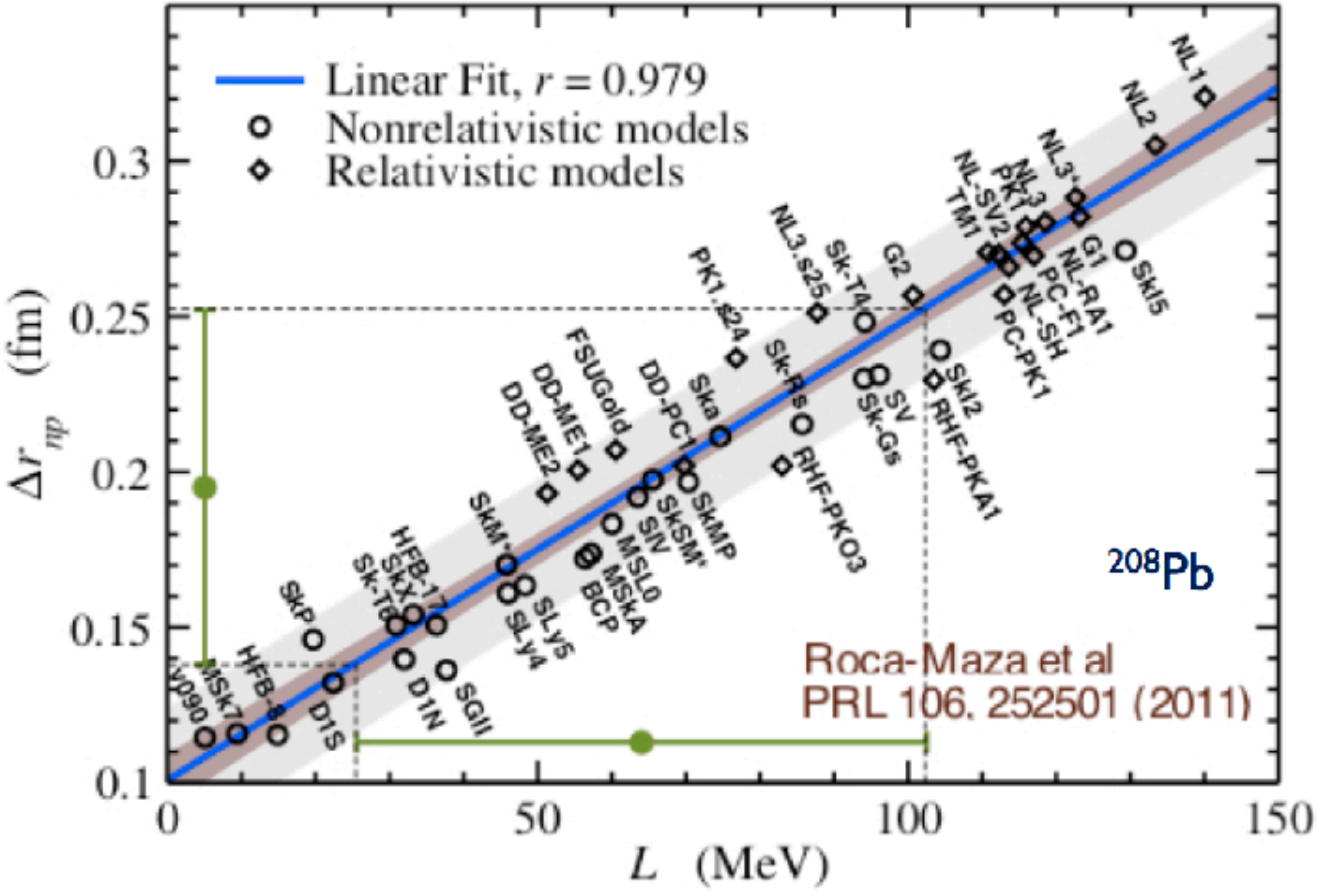
- Many DFT calc. have larger skins, and dispersive optical model (DOM) gives R_n-R_p=0.25±0.02 fm.

Symmetry Energy

- Describes how much energy of nuclear matter rises as one goes away from N=Z.
- $S(n)=S_0 + dS/dn\ (n-n_0)+\ldots$
- $L=n_0(dS/dn)/3$ —> pressure of n matter at n_0.
- ^{208}Pb has 44 extra n. Place them in center costs S(n0), place them in surface and only costs S(low density).
- Large L pushes neutrons out against surface tension and gives thick n skin.

L vs. r_n

Mean-Field predictions show a clear correlation between neutron skin of a heavy nucleus and the density slope of the symmetry energy.



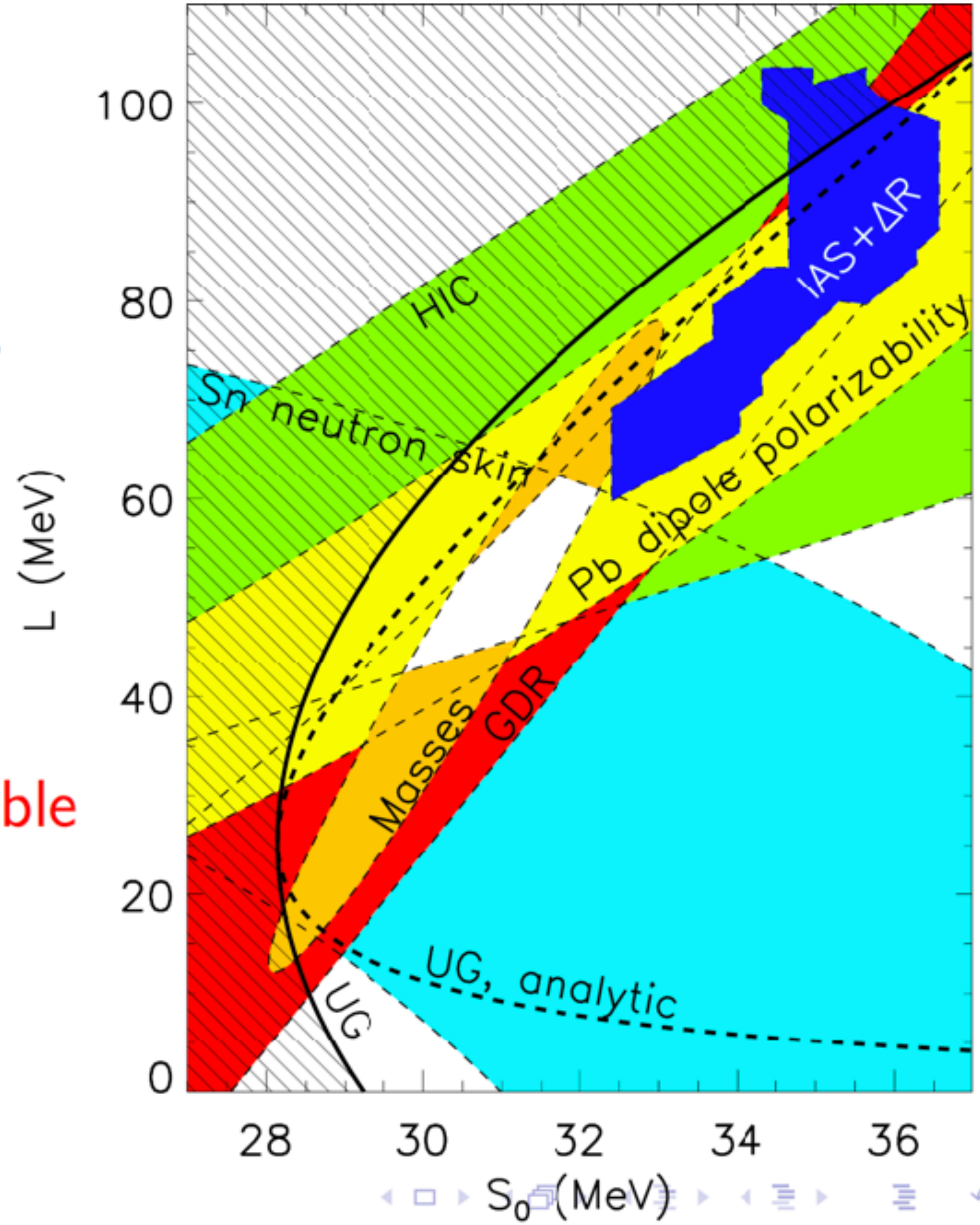
r_n calibrates the **Equation of State of** neutron rich matter

Isovector Skins and Isobaric Analog States from Danielewicz et al. (2017)

Other experimental constraints from Lattimer & Lim (2013)

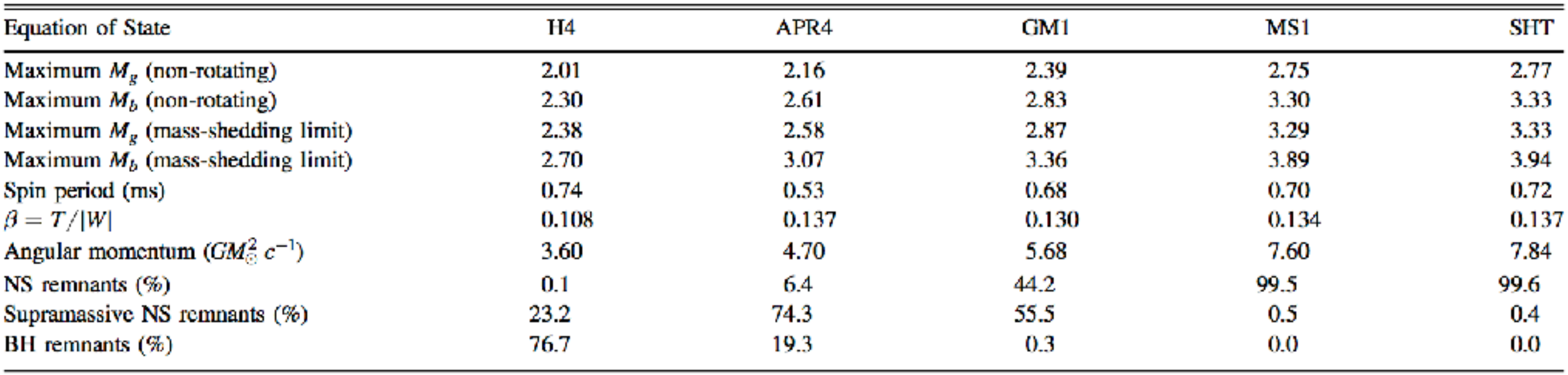
Unitary gas constraints from
Kolomeitsev et al. (2016)

Experimental and neutron matter constraints are compatible with unitary gas bounds.

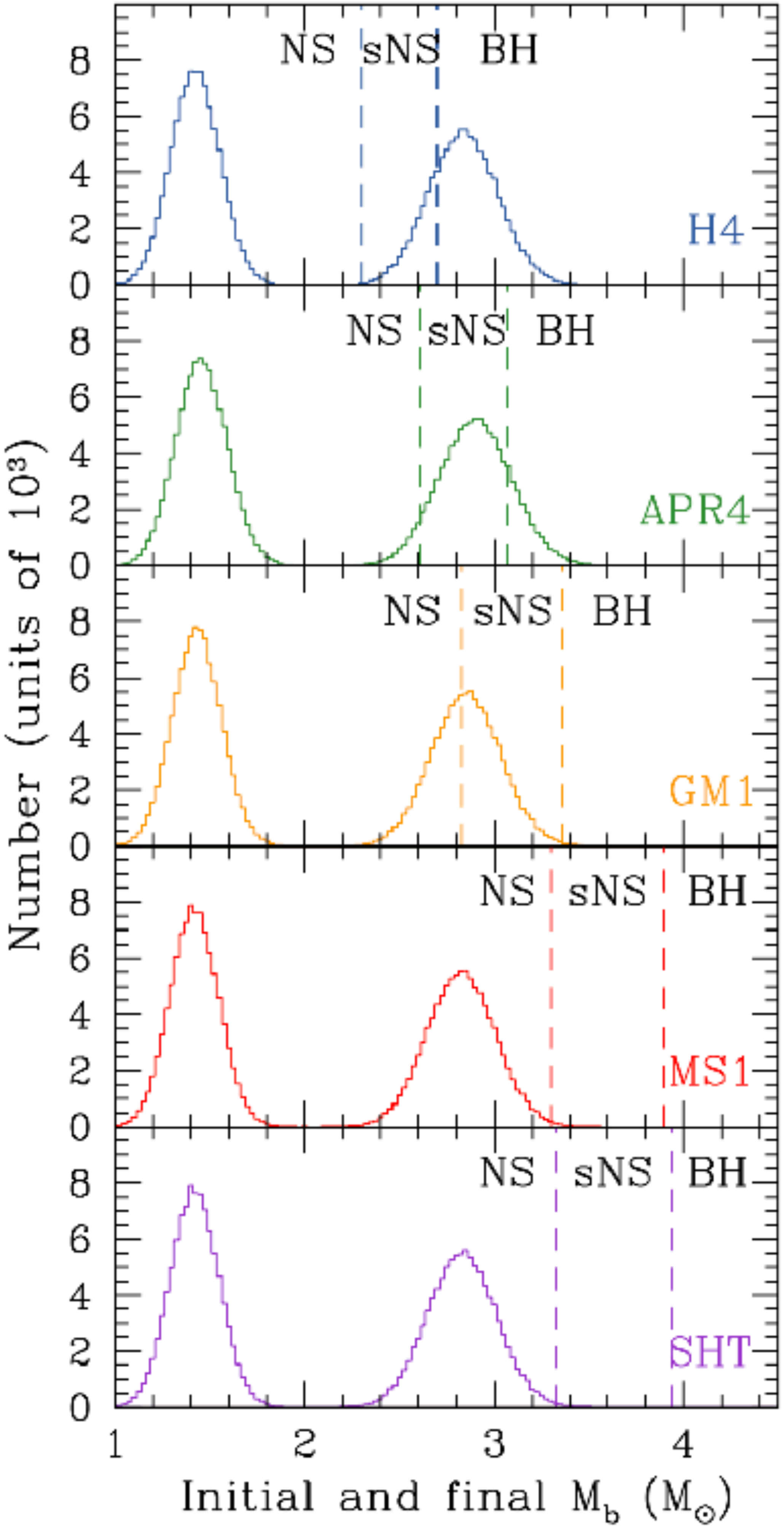


The Fate of Neutron Star Binary Mergers

Anthony L. Piro , Bruno Giacomazzo, and Rosalba Perna, ApJ 844:L19



Equation of State	H4	APR4	GM1	MS1	SHT
Maximum M_g (non-rotating)	2.01	2.16	2.39	2.75	2.77
Maximum M_b (non-rotating)	2.30	2.61	2.83	3.30	3.33
Maximum M_g (mass-shedding limit)	2.38	2.58	2.87	3.29	3.33
Maximum M_b (mass-shedding limit)	2.70	3.07	3.36	3.89	3.94
Spin period (ms)	0.74	0.53	0.68	0.70	0.72
$\beta = T/\lvert W\rvert$	0.108	0.137	0.130	0.134	0.137
Angular momentum ($GM_\odot^2\, c^{-1}$)	3.60	4.70	5.68	7.60	7.84
NS remnants (%)	0.1	6.4	44.2	99.5	99.6
Supramassive NS remnants (%)	23.2	74.3	55.5	0.5	0.4
BH remnants (%)	76.7	19.3	0.3	0.0	0.0


NS
sNS
BH
H4
APR4
GM1
MS1
SHT
0
2
4
6
8
1
2
3
4
Number (units of 10^3)
Initial and final M_b ($M_\odot$)

NICER

Neutron star Interior Composition ExploreR

Keith Gendreau, NASA GSFC
Principal Investigator

NASA

GSFC

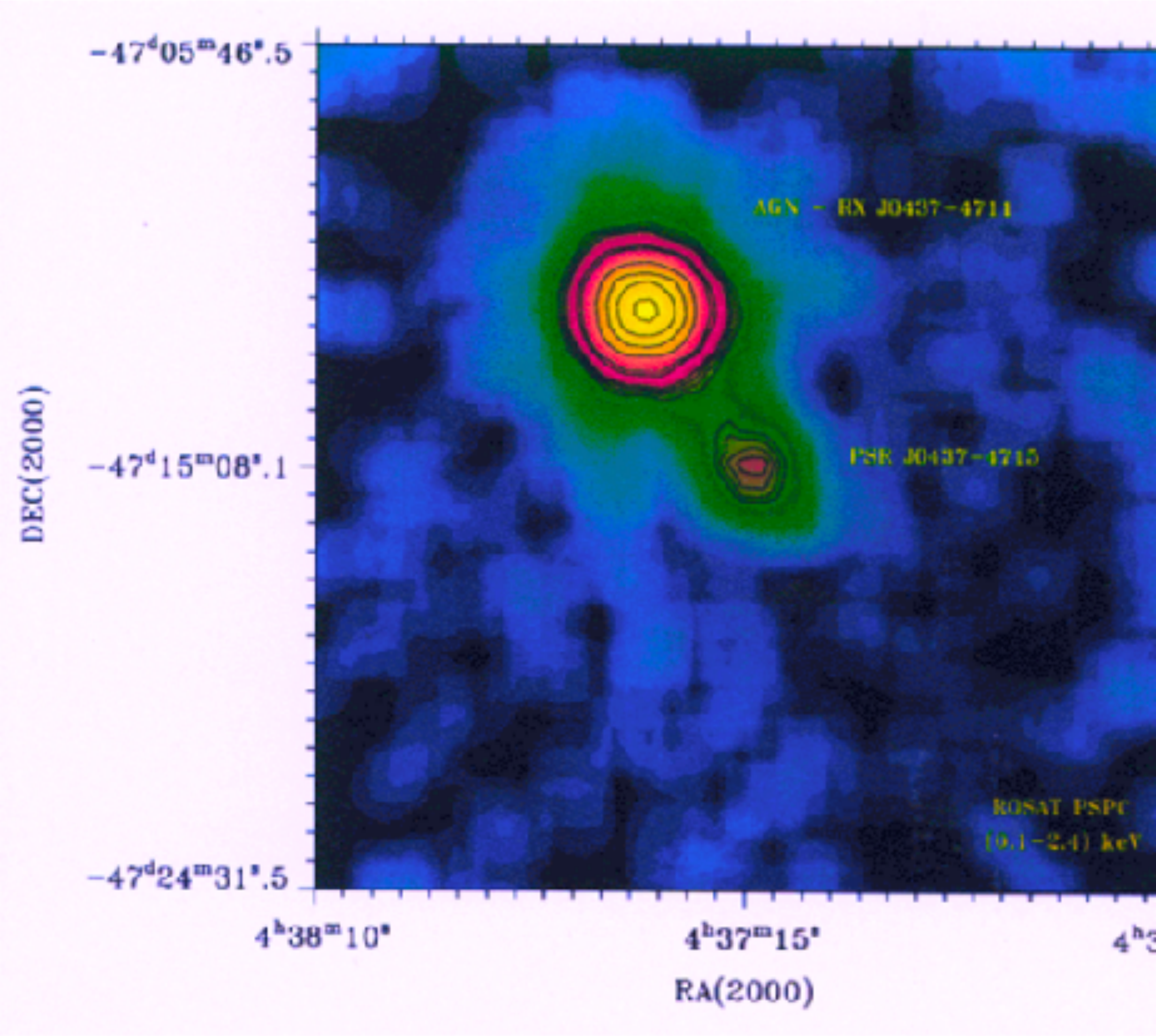
MIT KAVLI
INSTITUTE

Electroweak Radius Experiments

Experiment	Nucleus	Accuracy
PRAD	p	<1%
CREX	^{48}Ca	0.6%
PREX II	^{208}Pb	1%
NICER	PSR J0437	5%

PSR J0437

- Is closest and brightest millisecond pulsar
- Rotation period: 5.75 ms
- Distance to earth 156.3 parsec (509.8 light years)
- Mass 1.44 M_{sun} (in orbit with white dwarf)

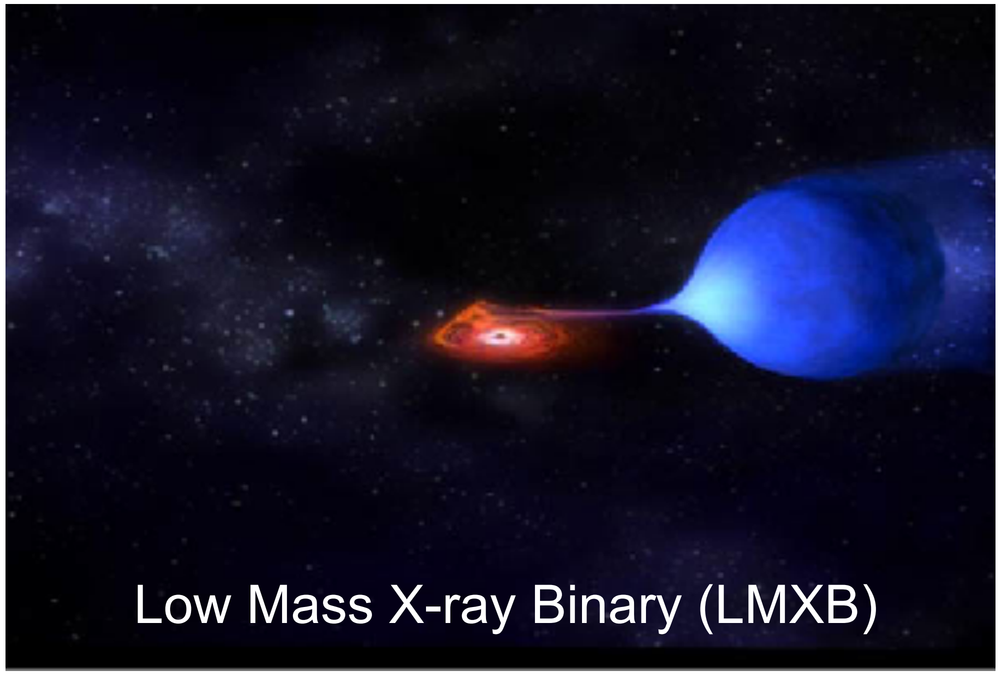


X-ray observations of NS radii

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

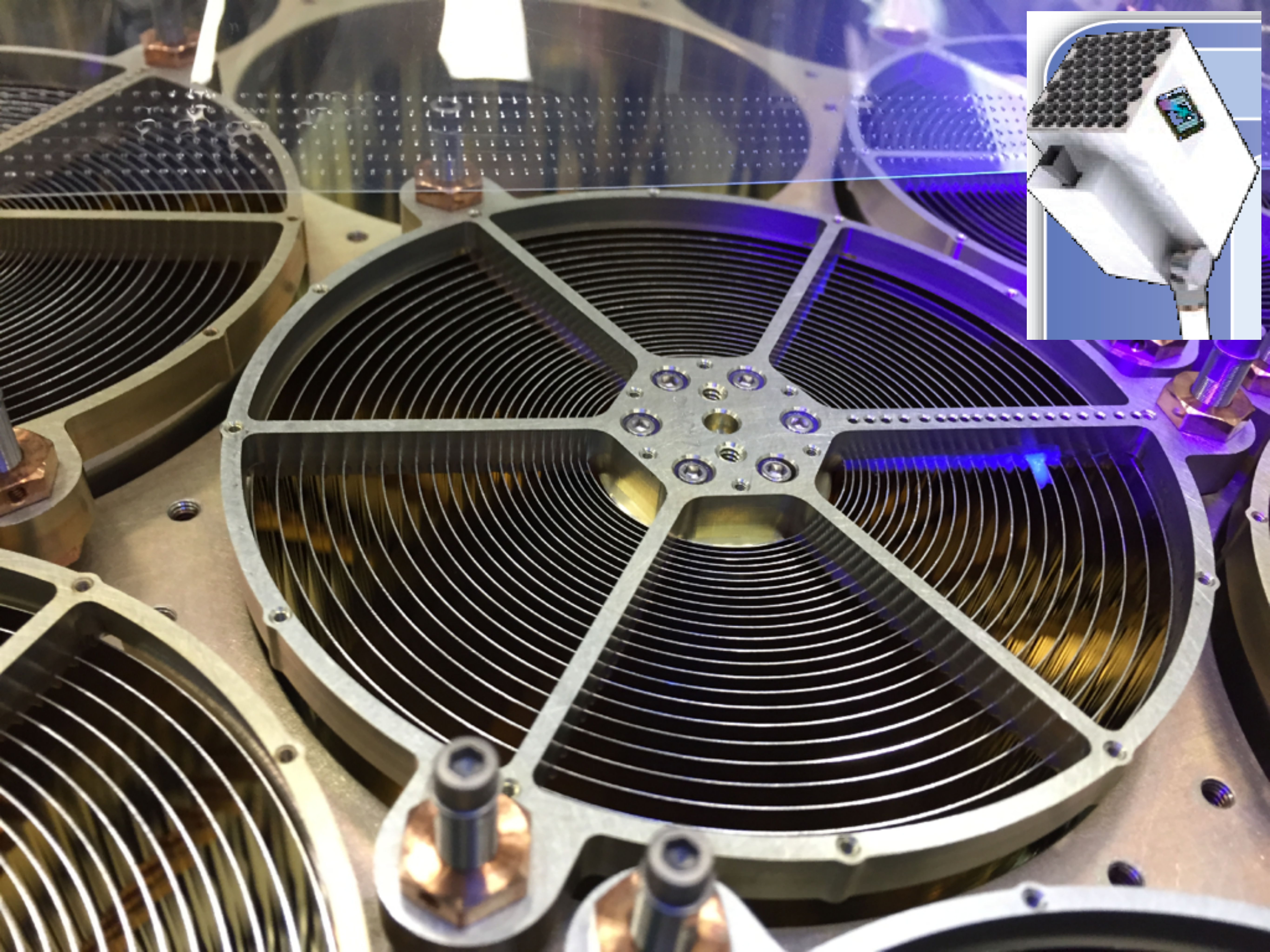
$$L_\gamma = 4\pi R^2 \sigma_{SB}\, T^4$$

- Complications:
  - Need distance (parallax for nearby isolated NS...)
  - Non-blackbody corrections from atmosphere models can depend on composition and B field.
  - Curvature of space: measure combination of radius and mass.
  - Hot spots and nonuniform temperatures.
- NS in globular clusters: expect simple nonmagnetic hydrogen atmospheres and know distance.



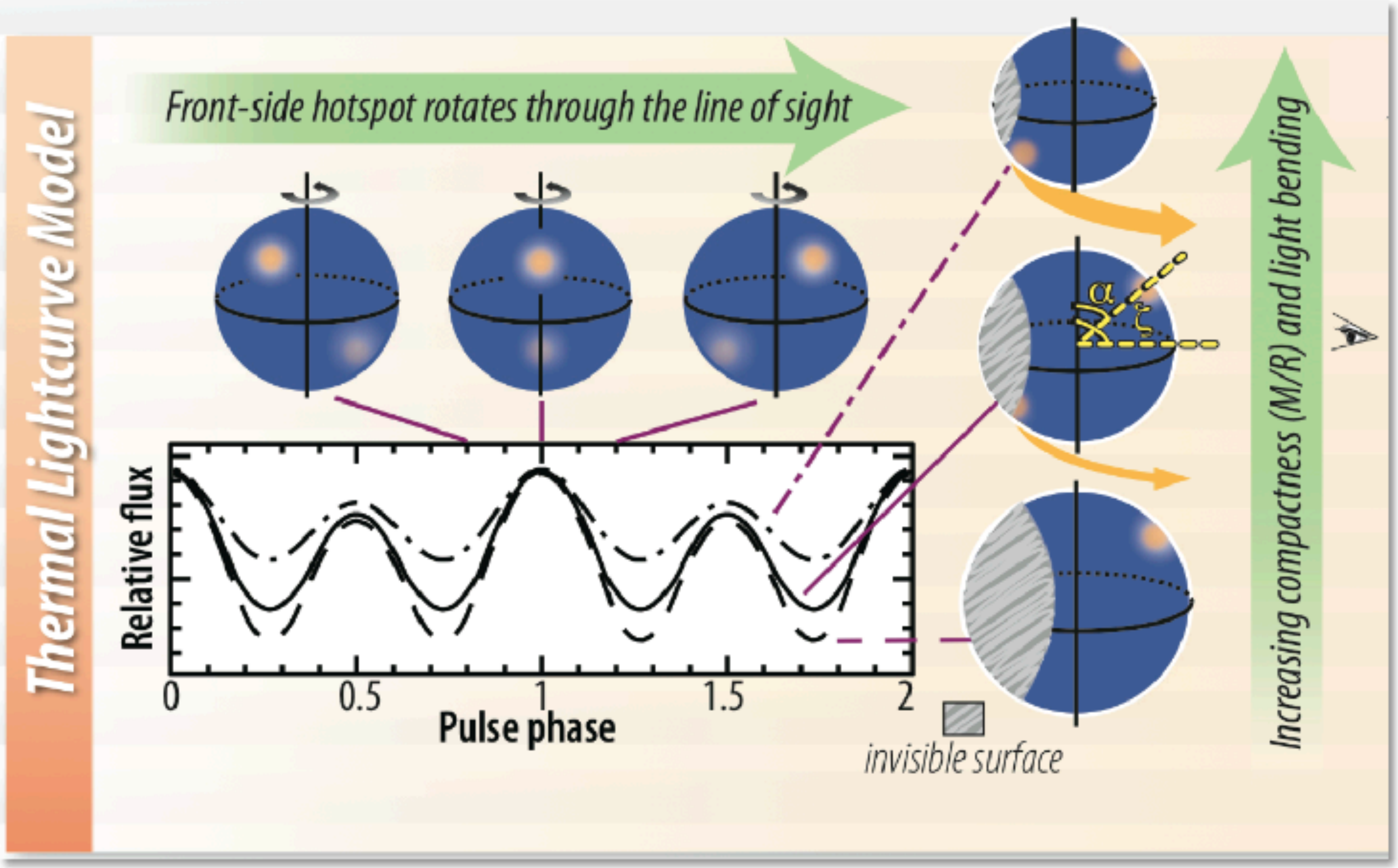
Low Mass X-ray Binary (LMXB)

- 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!
- However important uncertainties may remain in extracted radii. Suleimanov and Poutanen use more sophisticated atmosphere models and find larger radii.



Science Measurements

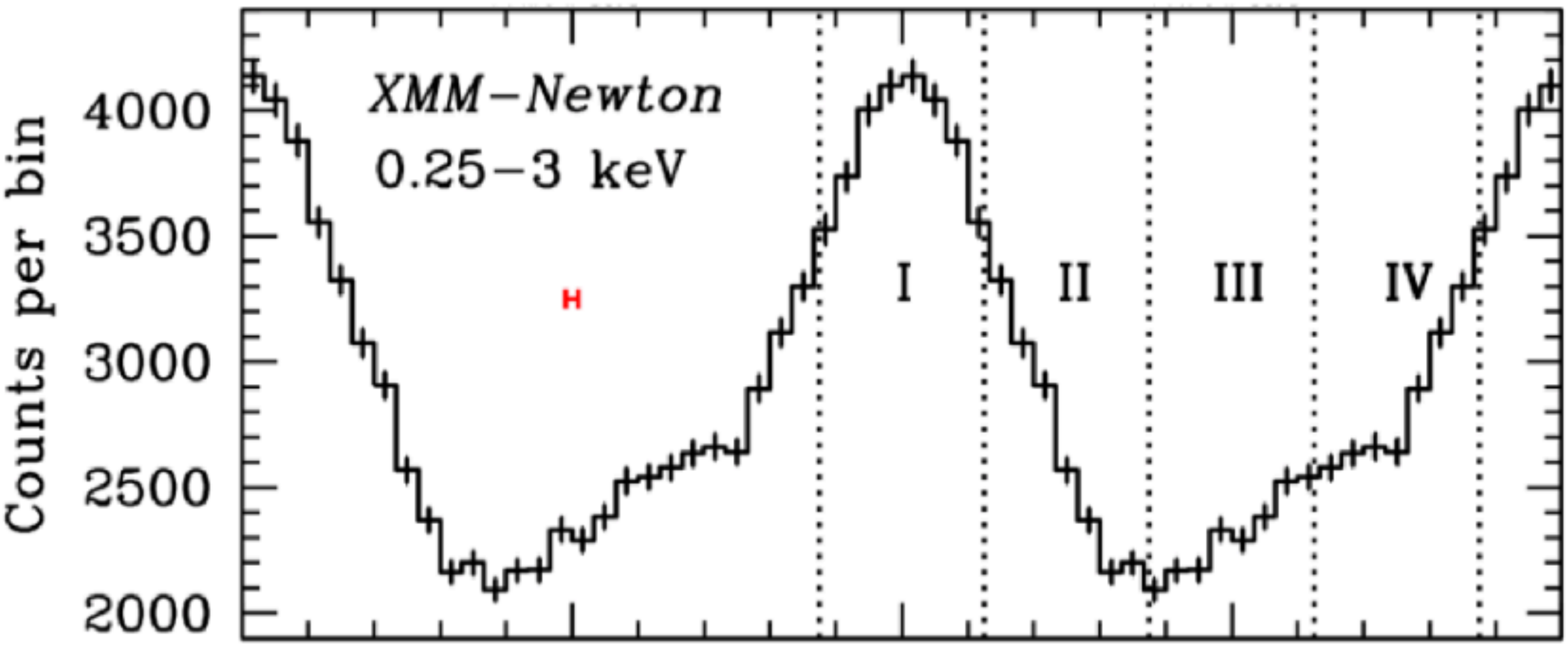
Reveal stellar structure through lightcurve modeling, long-term timing, and pulsation searches



Lightcurve modeling constrains the compactness (*M*/*R*) and viewing geometry of a non-accreting millisecond pulsar through the depth of modulation and harmonic content of emission from rotating hot-spots, thanks to gravitational light-bending…

Example: X-ray pulse waveform of J0437–4715

Produced by thermal emission from its heated polar caps



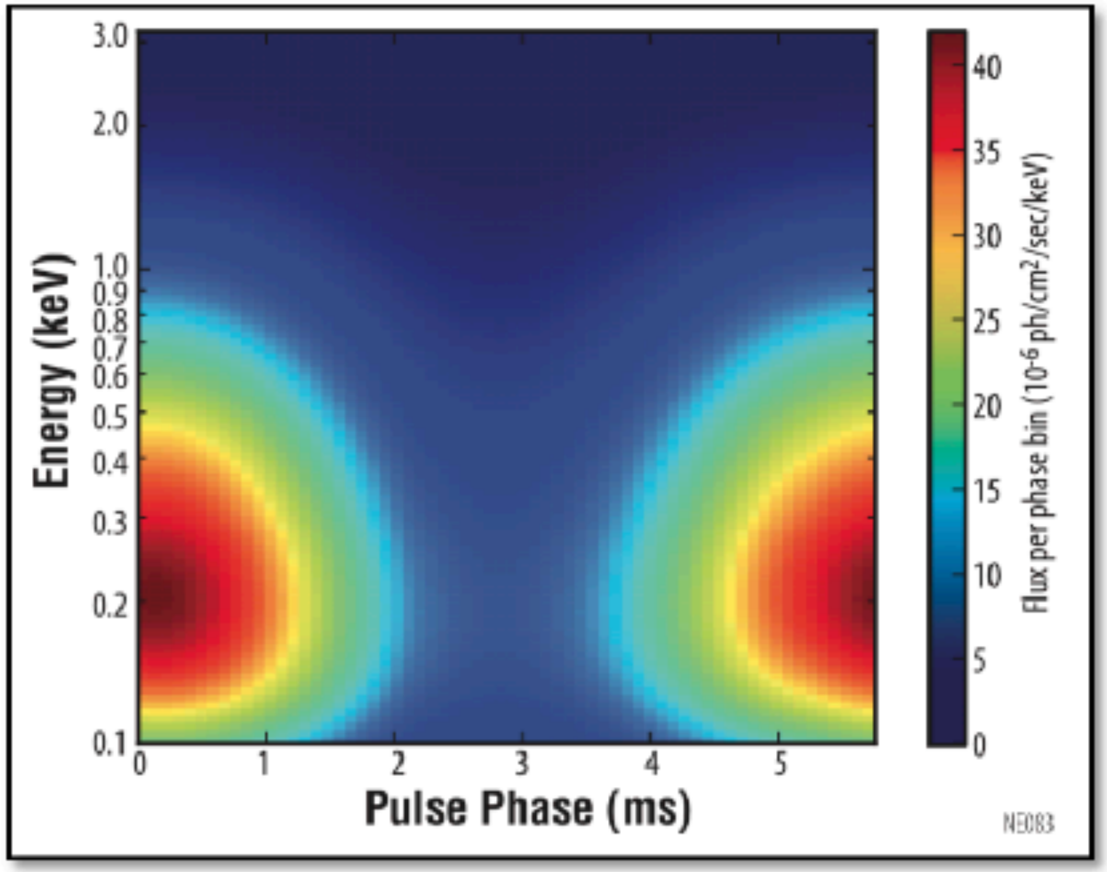
Pulse waveform observed using the XMM-Newton EPIC pn detector

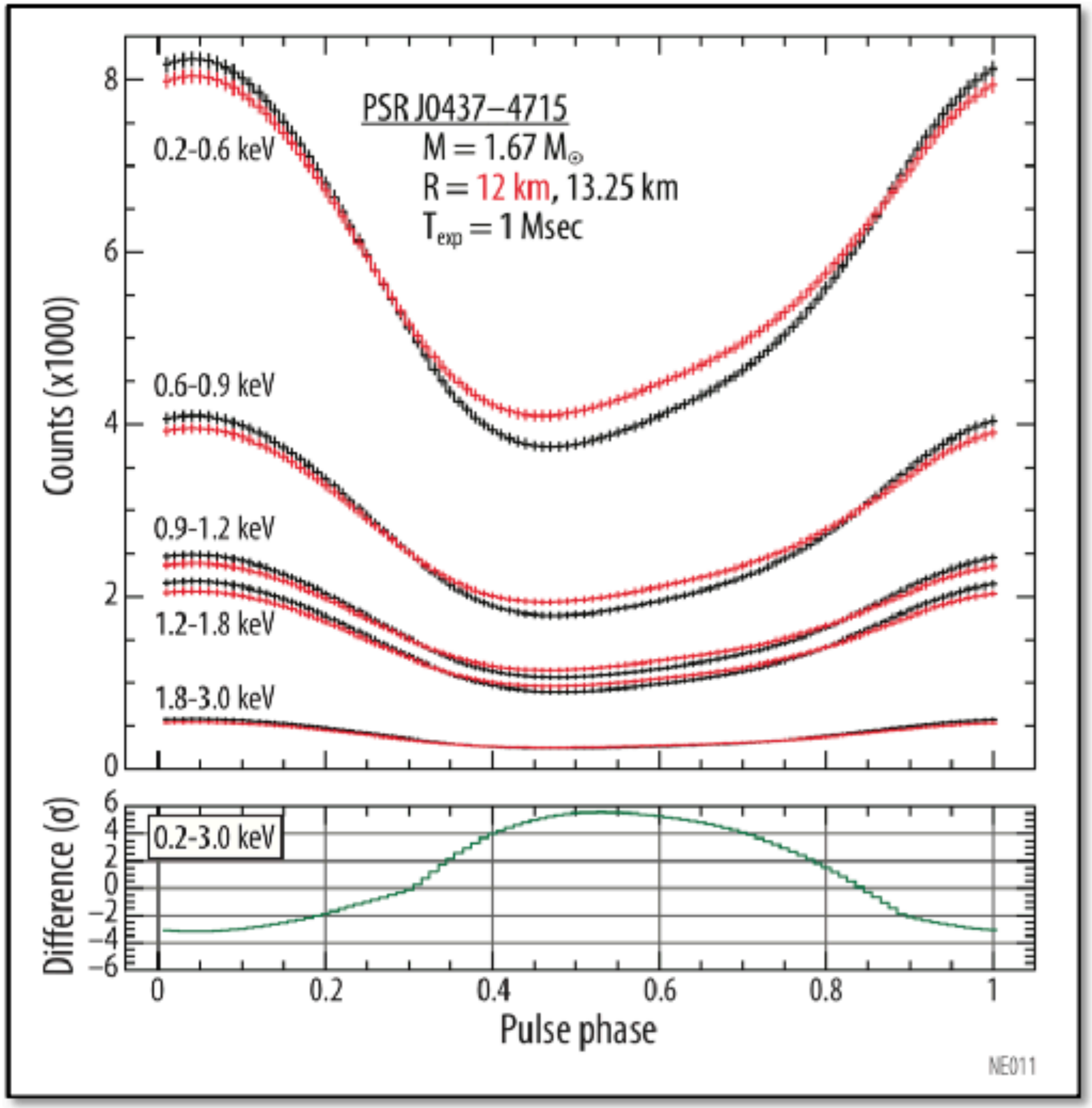
The red horizontal error bar shows the 70 μs absolute timing uncertainty

The vertical dotted lines show phase intervals used for spectroscopy

Original slide from Fred Lamb

Science Measurements (cont.)





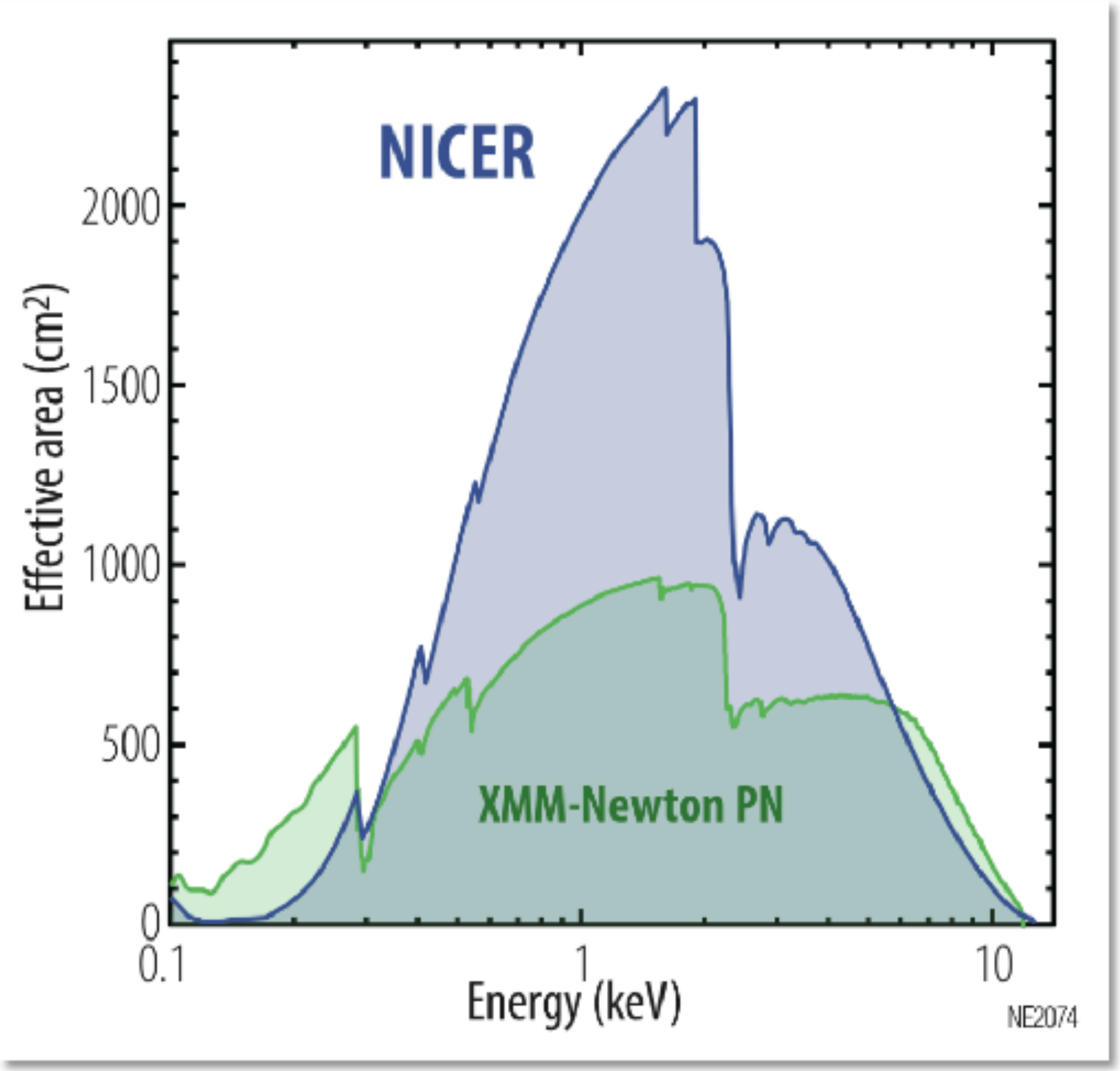
… while phase-resolved spectroscopy promises a direct constraint of radius *R*.

Instrument Performance

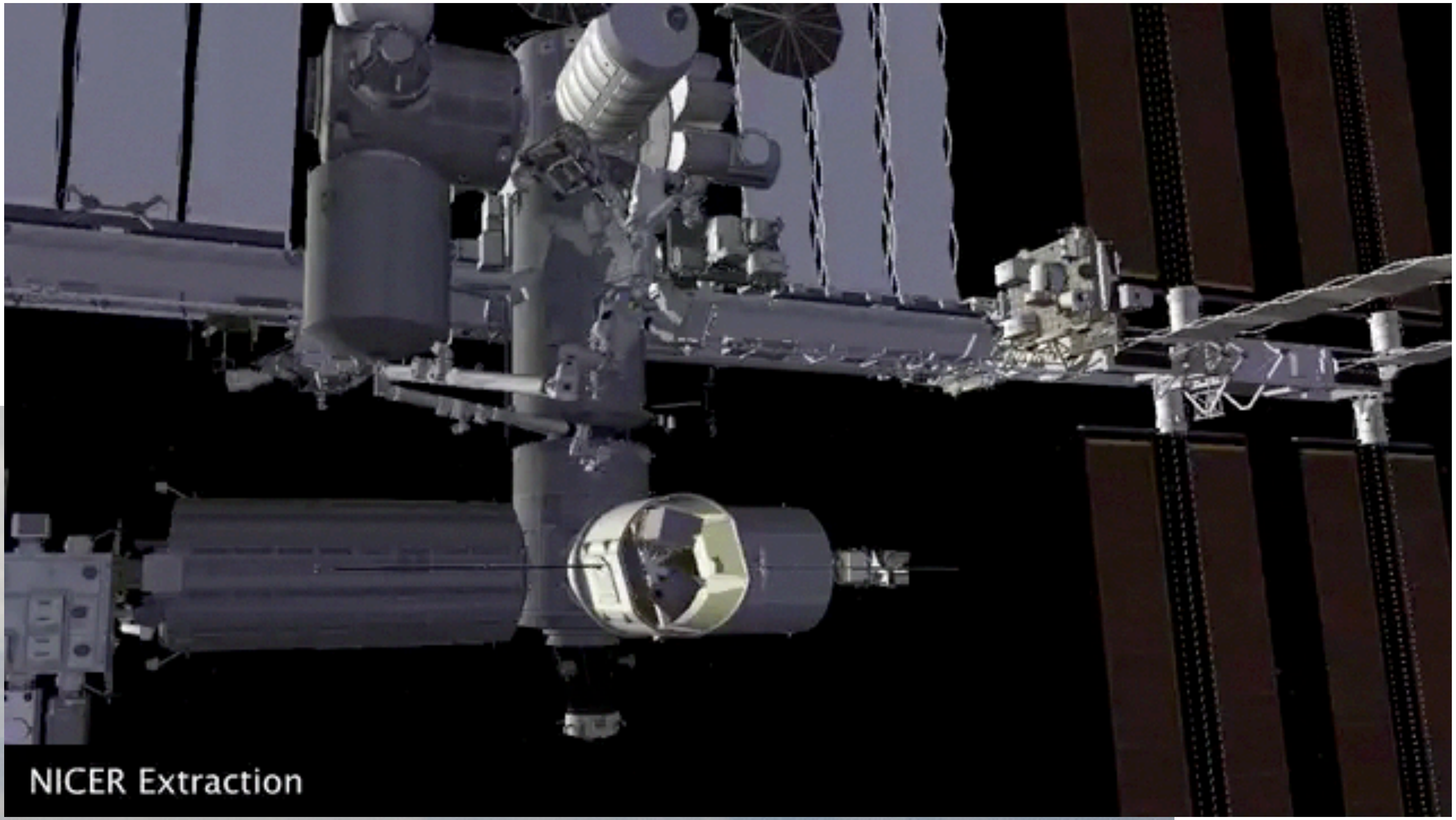
NICER

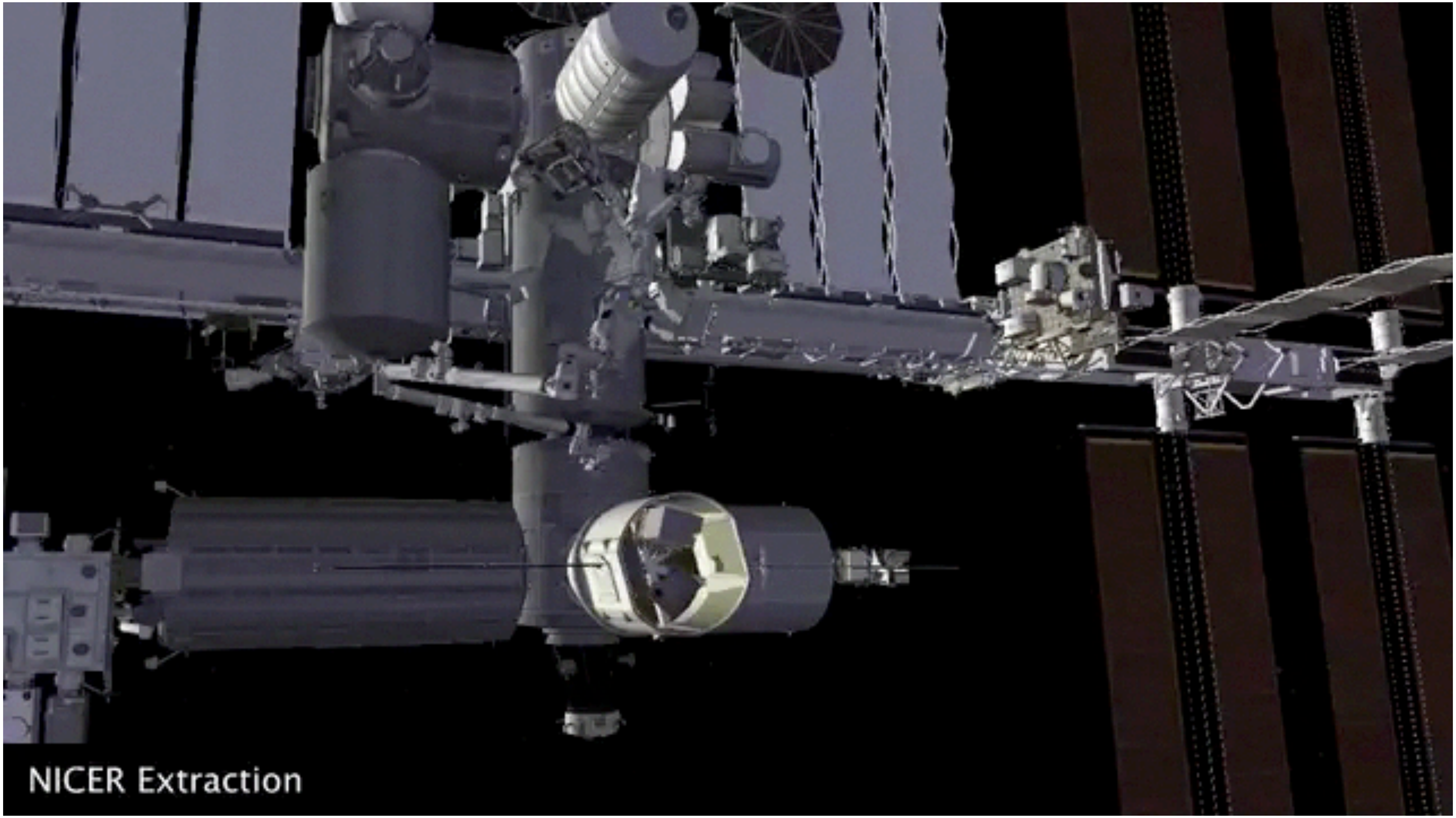
High-throughput, low-background soft X-ray timing and spectroscopy

- ***Bandpass:*** 0.2–12 keV
- ***Effective area:***
  > 2000 cm² @ 1.5 keV,
  600 cm² @ 6 keV
  2x XMM-Newton for soft X-ray timing
- ***Energy resolution:***
  85 eV @ 1 keV,
  137 eV @ 6 keV
  Similar to XMM and Chandra
- ***Time-tagging resolution:***
  < 300 nsec (absolute)
  ~25x better than RXTE
  ~100–1000x better than XMM
- ***Spatial resolution:*** 5 arcmin diam.
  non-imaging FOV
- ***Background:*** Dominated by diffuse
  cosmic XRB (soft)
- ***Sensitivity:*** 3 x 10^{-14} ergs s^{-1} cm^{-2}
  (0.5–10 keV, 5σ in 10 ksec)
  ~30x better than RXTE,
  ~4x better than XMM

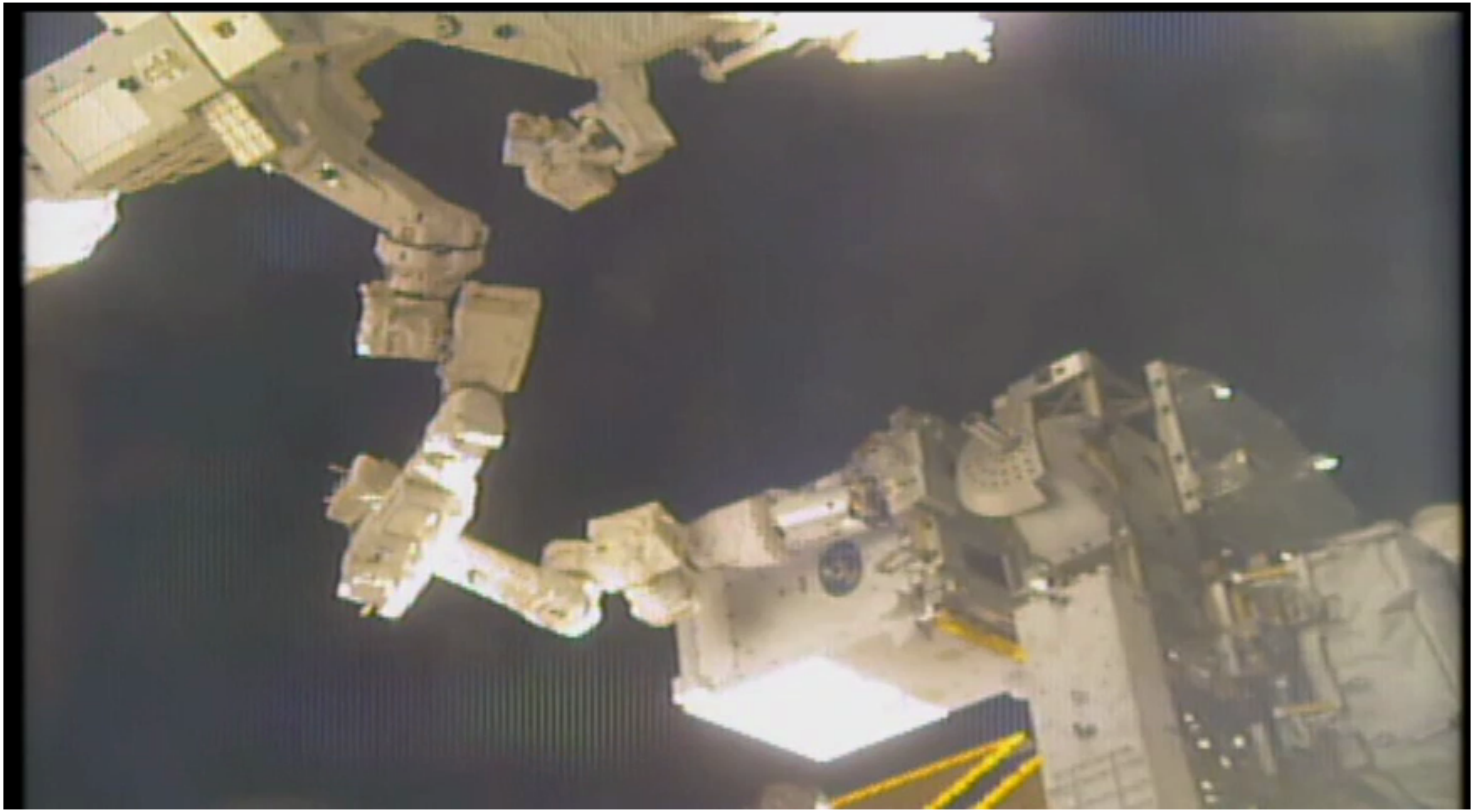


NICER launched June 3 and was installed June 13-14, 2017





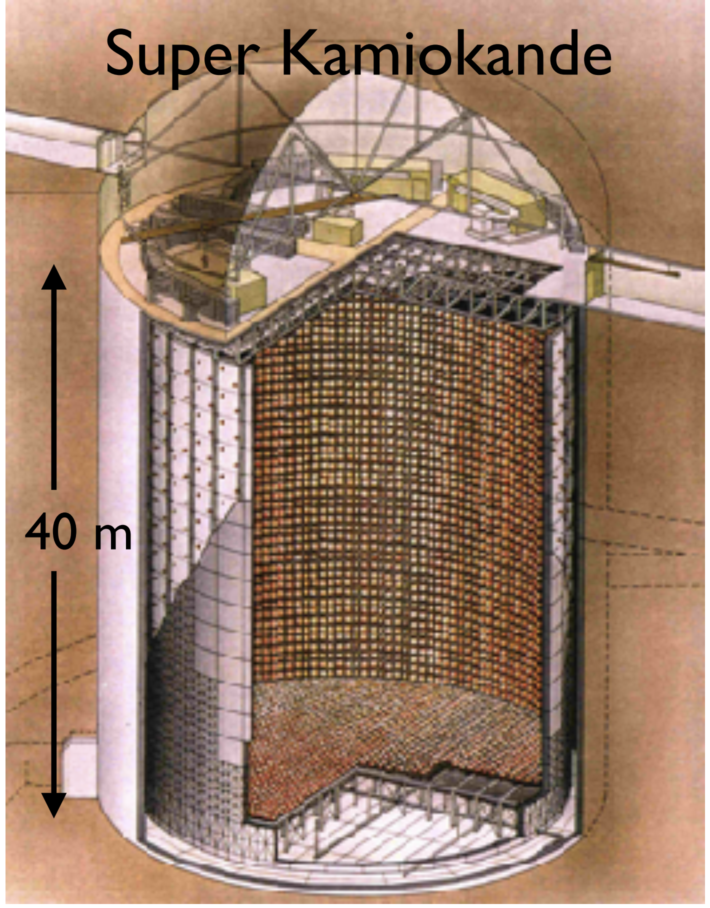
NICER Extraction



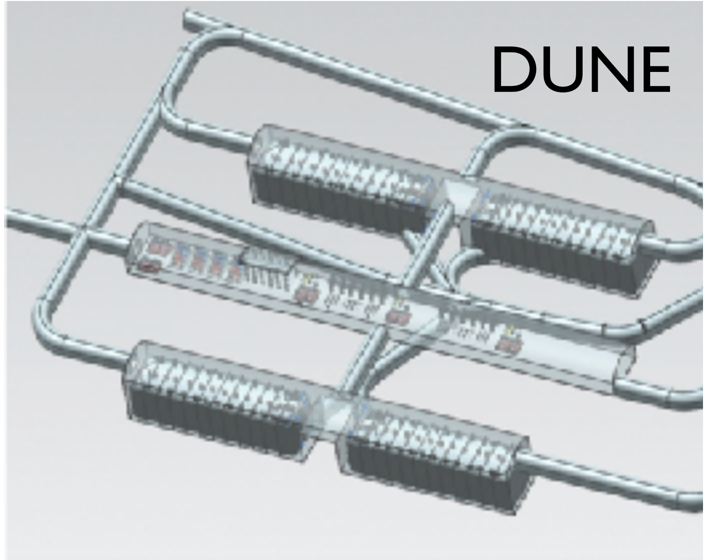
- First NICER results in ~ one year. It would be great to have PREX II, CREX results shortly thereafter! (Run in late 2018??)

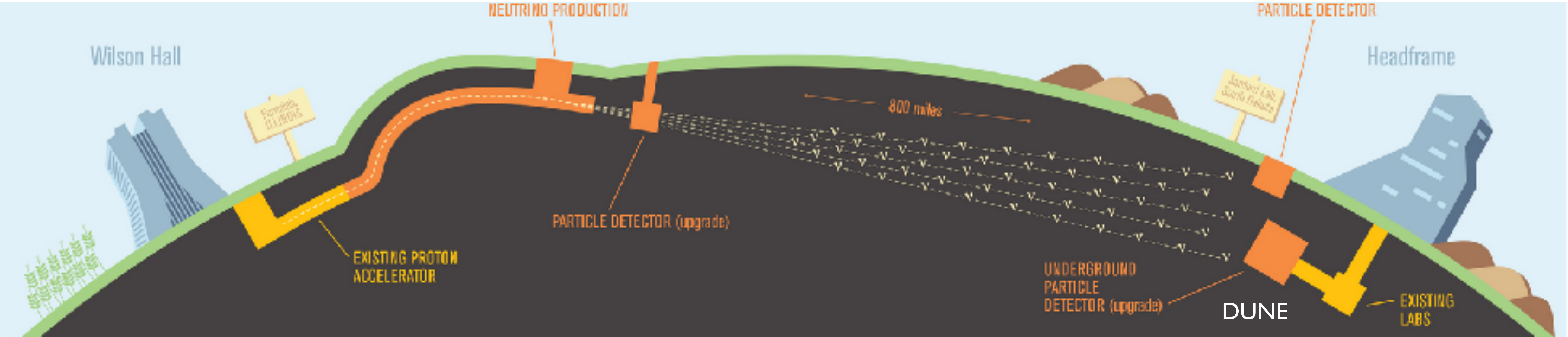
Neutrinos

Detecting Supernova Neutrinos



- SN radiate the gravitational binding energy of a neutron star, 0.2 $M_{sun}c^2$, as 10^{58} neutrinos in ~10 s
- Historic detection of ~20 neutrinos from SN1987A
- Expect several thousand events from next galactic SN in Super Kamiokande: 32 kilotons of H_2O + phototubes. **Good antineutrino detector.**
- Deep Underground Neutrino Experiment (DUNE) in South Dakota plans 40 kilotons of liquid Ar to study oscillations of Fermilab neutrinos. **Good neutrino detector.**
- Hyper Kamiokande is possible very large version of SuperK. Expect 100,000 events. Good for late times.





SN neutrinos and r-process nucleosynthesis

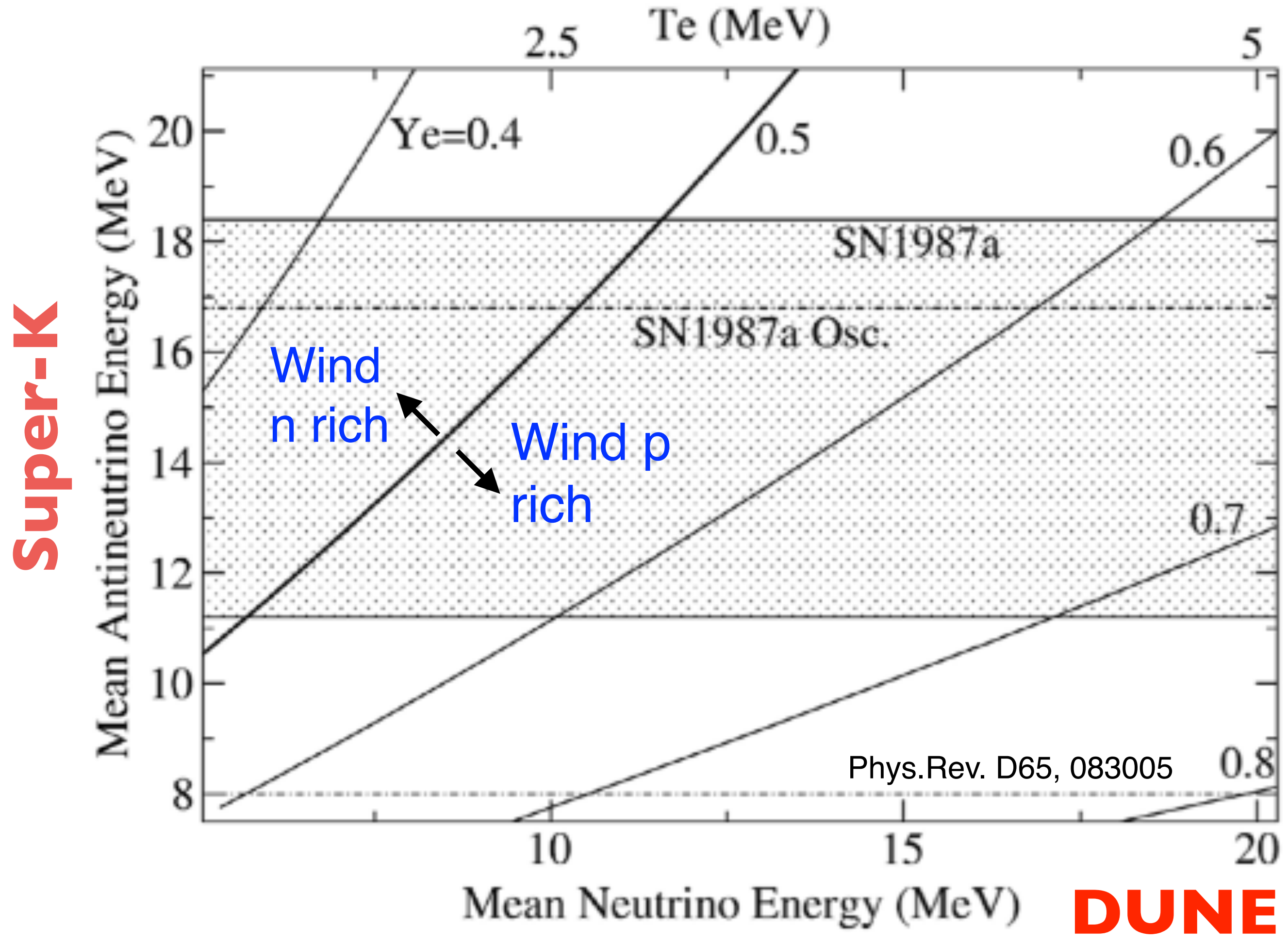
- Possible site of r-process (makes Au, Pt, U,…) is the neutrino driven wind in SN.

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

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

- 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

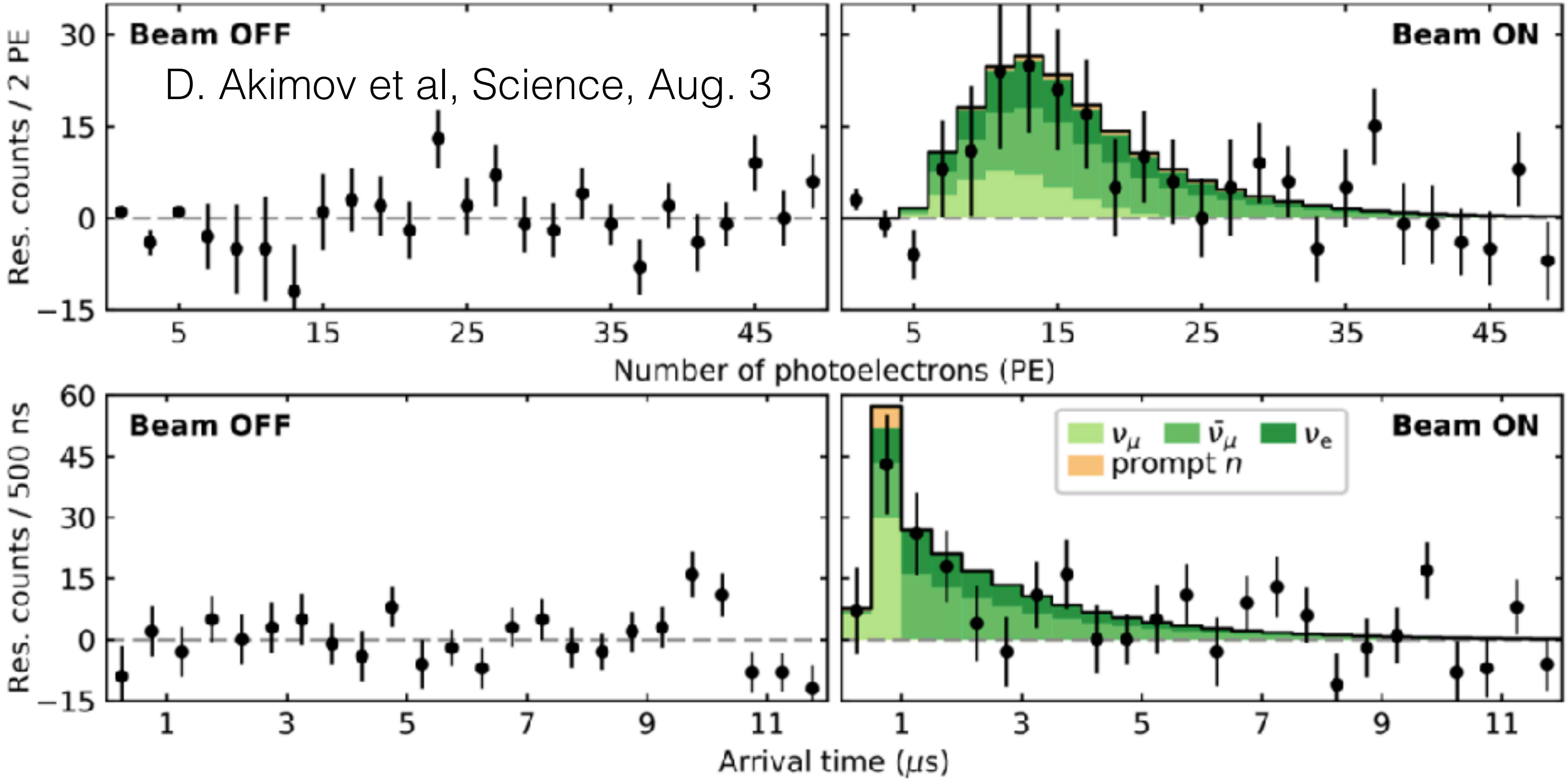
Need to calibrate DUNE by measuring charged current Ar cross section. Can do at SNS.

SN simulations find too few neutrons for (main or 3rd peak: Au, actinides) r-process. Not r-process site??

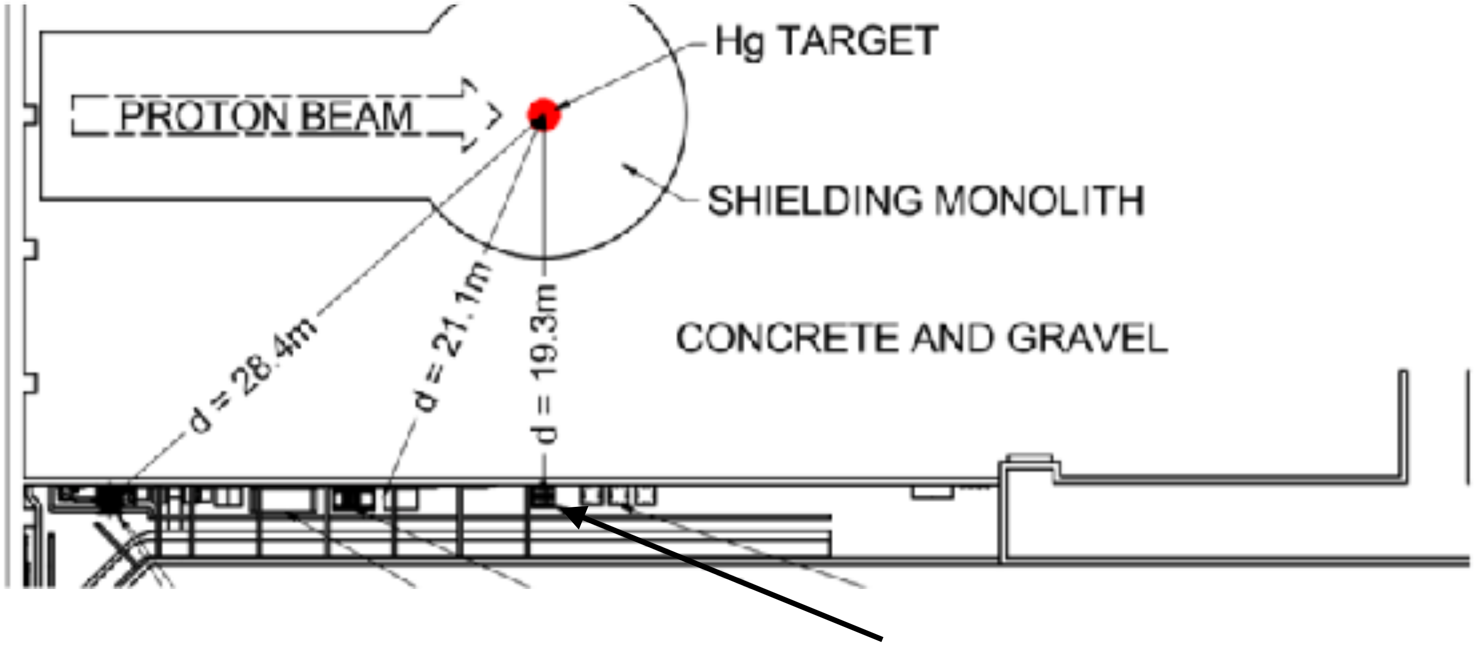
Instead site may be neutron star mergers. LIGO is measuring rate.

Neutral current detection via coherent nu-nucleus elastic scattering

- Important to have a good SN nu_x detector (neutral current) in addition to existing anti-nu_e (H_2O, liquid scint.) and nu_e (liquid Ar DUNE) detectors.
- One possibility is neutrino-nucleus elastic scattering in large dark matter detectors.
- Large coherent cross section ~ N^2, sensitive to all six nu flavors, all detector mass contributes (not just small H fraction) —> very large yields:
- 10s of events per TON for SN at 10 kpc compared to 100s of events per kiloton for conventional detector.



D. Akimov et al, Science, Aug. 3



15 kg CsI detector

Observation of nu-nucleus elastic scattering using pion decay at rest neutrinos at SNS

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

Six flavor neutrino transport

- **Three flavor transport**: nu_e, anti-nu_e and nu_x
- **Four flavor**: nu_e, anti-nu_e, nu_x, anti-nu_x where weak magnetism splits nu_x and anti-nu_x.
- **Six flavor**: nu_e, nu_mu, nu_tau and anti-nus. Real muons, from large electron chemical potential or high temperatures, split nu_mu from nu_tau. [1706.04630]
- Six flavor transport will give most accurate predictions for neutrino spectra, signals in neutrino detectors and for neutrino oscillations.

Thermal Pions

- Hot SN and NS merger matter may contain not only muons but also thermal pions.

- Large electron chemical potential favors pi-

- Important uncertainties in strength of pion - nucleon or nuclear matter interactions. These could dramatically change number of pions.

SN Quantum Numbers

	Precollapse	SN	Neutron Star
# nu radiated		**10^{58}**	
Baryon #	10^{57}	10^{57}	**10^{57}**
Electron #	10^{57}	—>	**10^{56}**
Muon #	0	—>	**10^{55}**
Tau #	0	**10^{54}**	0
Strangeness	0	—>	?

- **Deleptonization**: During SN electron # of 10^{57} is radiated.
- **Muonization**: During SN muon # of **minus** 10^{55} is radiated.
- **Tau #**: Produce equal numbers of nu-tau, anti-nu-tau. However anti-nu_tau leave faster because of weak magnetism leaving star nu-tau rich [PLB **443** (1998) 58].

ν interactions in SN matter

ν_e + n —> p + e (Charged current capture rxn)
ν + N —> ***ν*** + N (Neutral current elastic scattering, important opacity source for mu and tau ***ν***)

- Neutrino-nucleon neutral current cross section in SN is modified by axial or spin response S_A, and vector response S_V, of the medium.

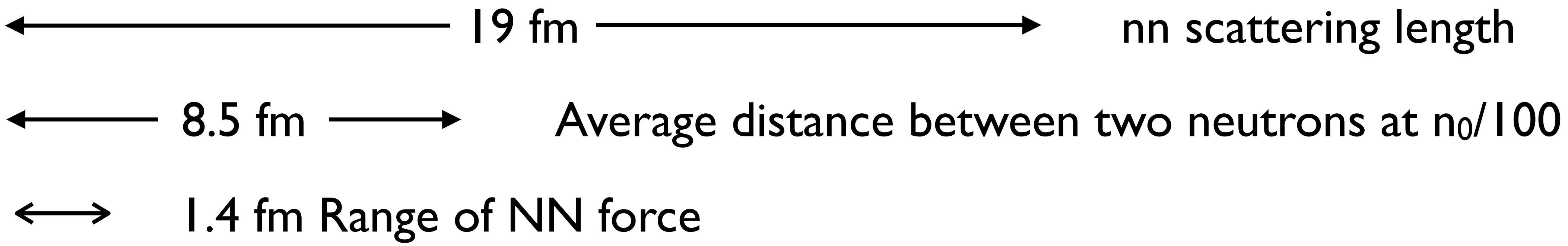
$$\frac{1}{V}\frac{d\sigma}{d\Omega} = \frac{G_F^2 E_\nu^2}{16\pi^2}\Big(g_a^2(3-\cos\theta)(n_n+n_p)S_A + (1+\cos\theta)n_n S_V\Big)$$

- Responses S_A, S_V —> 1 in free space. Normally S_A dominates because of $3g_a^2$ factor.

Neutrinosphere as unitary gas

- Much of the action in SN at *low densities* near neutrinosphere at $n \sim n_0/100$ (nuclear density n_0).

- Average distance between two neutrons near neutrinosphere is less than NN scattering length.



19 fm nn scattering length

8.5 fm Average distance between two neutrons at $n_0/100$

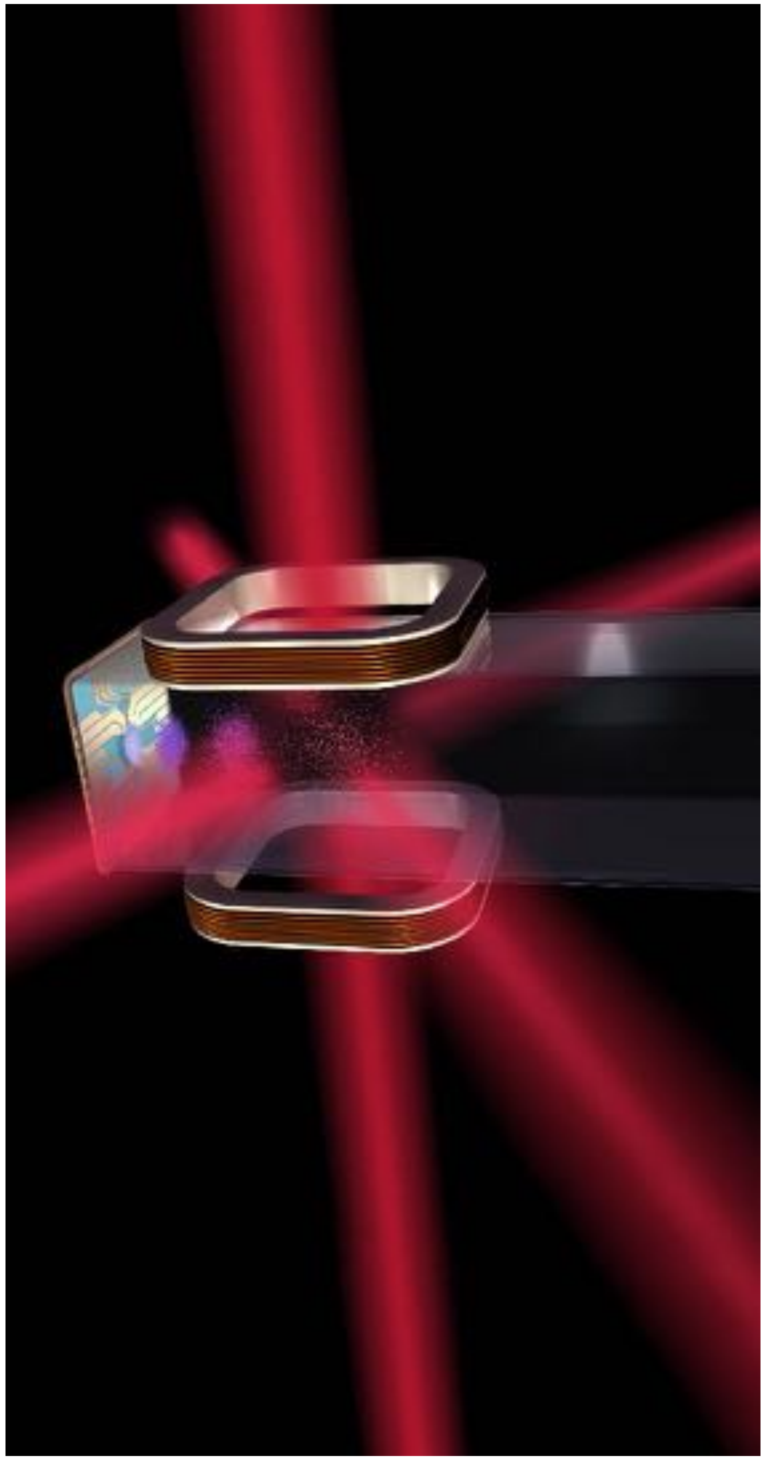
1.4 fm Range of NN force

- Because of the long scattering length one can have important correlations even at low densities.

- Two neutrons are correlated into spin zero $^1S_0$ state that reduces spin response $S_A<1$.

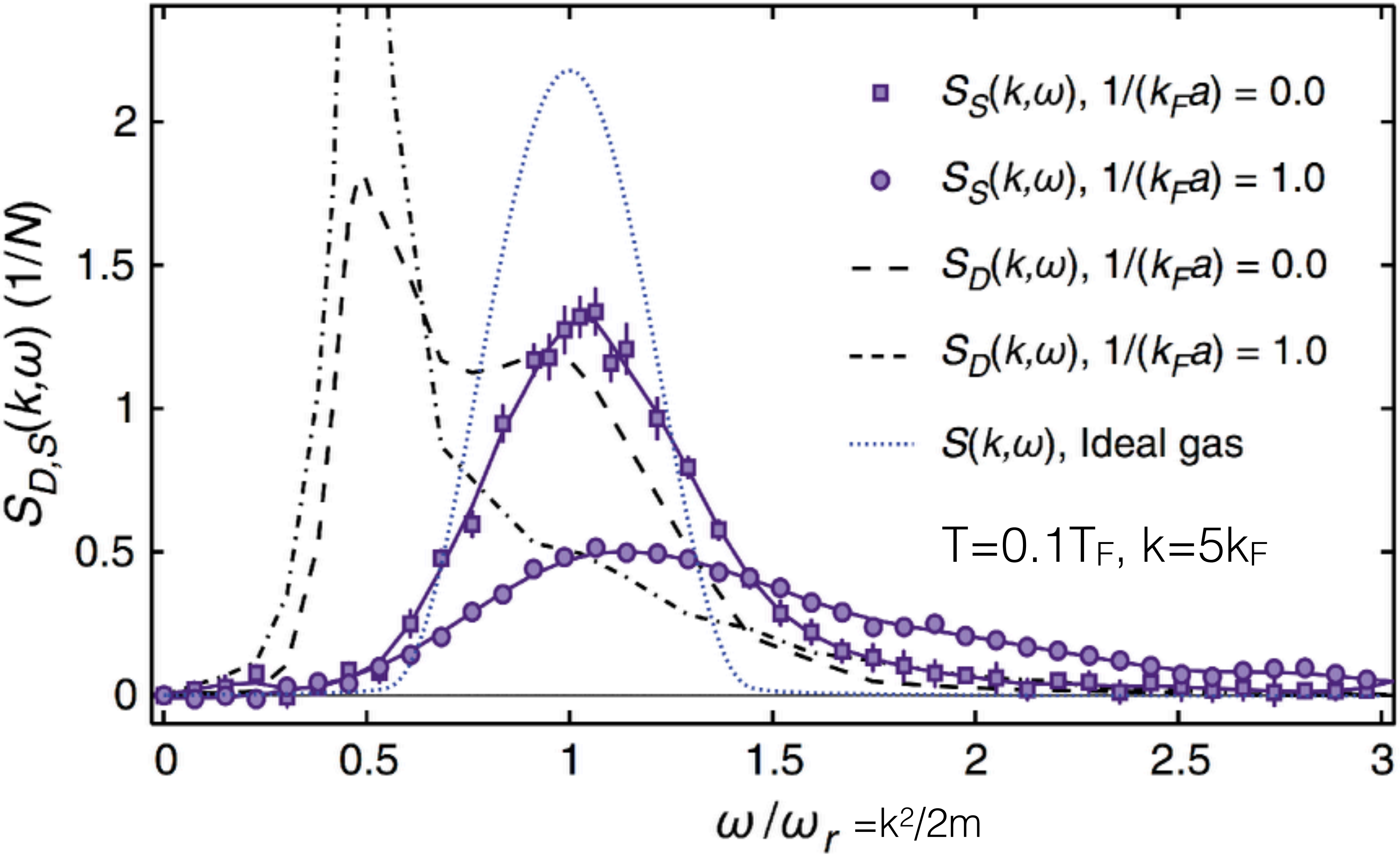
Can the spin response of a unitary gas help a supernova explode?

- Well posed question.
- Helpful to think of neutrinos interacting with a unitary gas as a special model system for nuclear matter. Many theoretical and **experimental results** for cold atoms near unitarity.
- Spin response reduces neutral current scattering opacity.
- Effect may be important even at low ~10^{12} g/cm^3 densities because of the large scattering length.
- Probably helps 2D (and 3D?) simulations explode perhaps somewhat earlier???



Dynamic Spin Response of a Strongly Interacting Fermi Gas

[S. Hoinka, PRL **109**, 050403]



$T=0.1T_F$, $k=5k_F$

$=k^2/2m$

Static structure factors: $S_V(q) = \int dw S_D(q,w)$, $S_A(q) = \int dw S_S(q,w)$

Virial Expansion for Unitary Gas

- In high T and or low density limit, expand P in powers of fugacity z=Exp[chemical pot/T]

$$P = \frac{2T}{\lambda^3} \sum_{n=1}^{4} b_n z^n \qquad\qquad n = \frac{z}{T}\frac{dP}{dz}$$

- Long wavelength response:

$$S_V(q \to 0) = T/(\partial P/\partial n)_T = z(\partial n/\partial z)/n,$$

$$S_V(q \to 0) = \frac{1 + 4zb_2 + 9z^2 b_3 + 16z^3 b_4}{1 + 2zb_2 + 3z^2 b_3 + 4z^3 b_4}$$

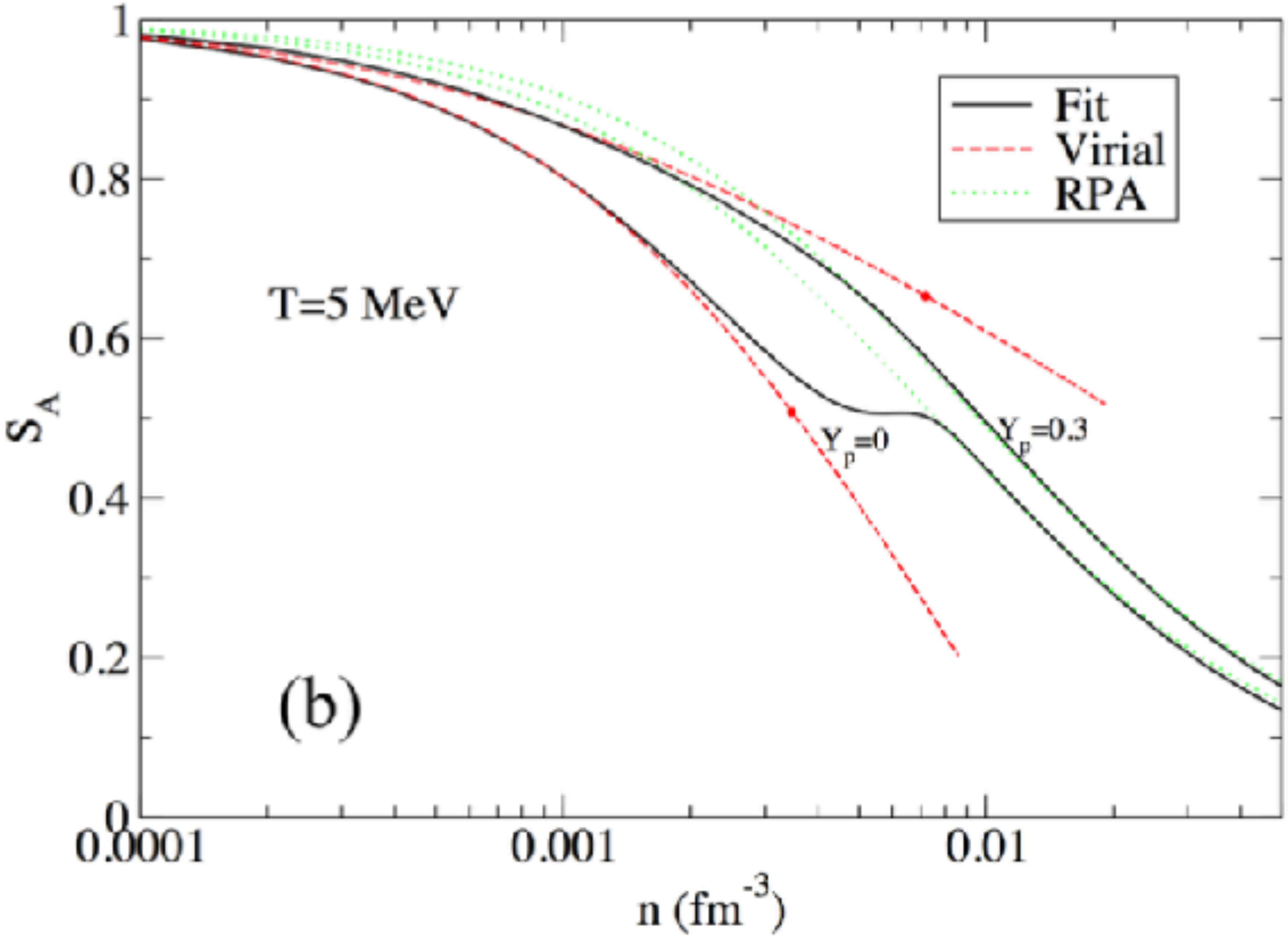
- Axial response: $S_A(q \to 0) = \frac{2z}{n} \frac{\partial}{\partial(z_1 - z_2)} (n_1 - n_2)\big|_{z_1 = z_2}$

Axial Response in Virial Expansion

- At low densities n and or high temperatures T one can expand equation of state in powers of the fugacity $z=e^{\mu/T}$ with μ the chemical potential.

- Generalize to partially spin polarized gas to determine long wavelength limit of axial response:
  $S_A \sim 1 + \lambda^3 n\, b_a$
  with b_a 2nd viral coefficient for spin polarization gas.

- b_a is about -0.64 from observed nucleon-nucleon elastic scattering phase shifts.



In Phys. Rev. C **95** (2017) 025801 we provide a simple fit $S_A^f(n,T,Y_p)$, valid for all densities, that reproduces viral result at low densities and a common Random Phase Approximation model at high densities. Fit can easily be used in SN simulation.

Unitary gas virial coefficients

- Second order b_2 from integral over two particle scattering phase shifts. b_2 known for Unitary, neutron and nuclear matter.

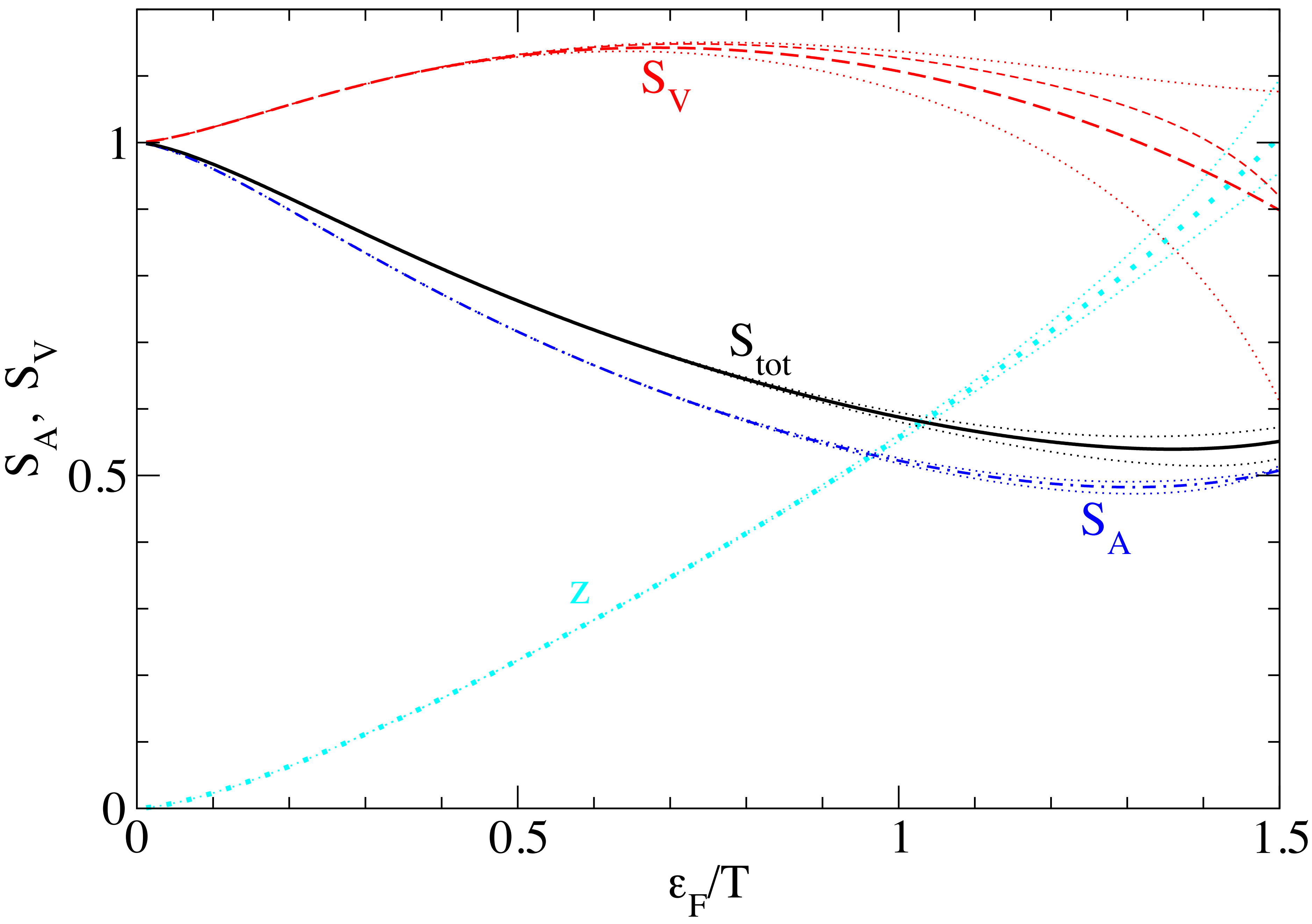
- Third order b_3 from partition function for three interacting particles in a harmonic trap. Then take limit trap frequency —> 0.

- 4th order b_4 from Path Integral Monte Carlo simulations.

- b_3, b_4 only known for unitary gas.

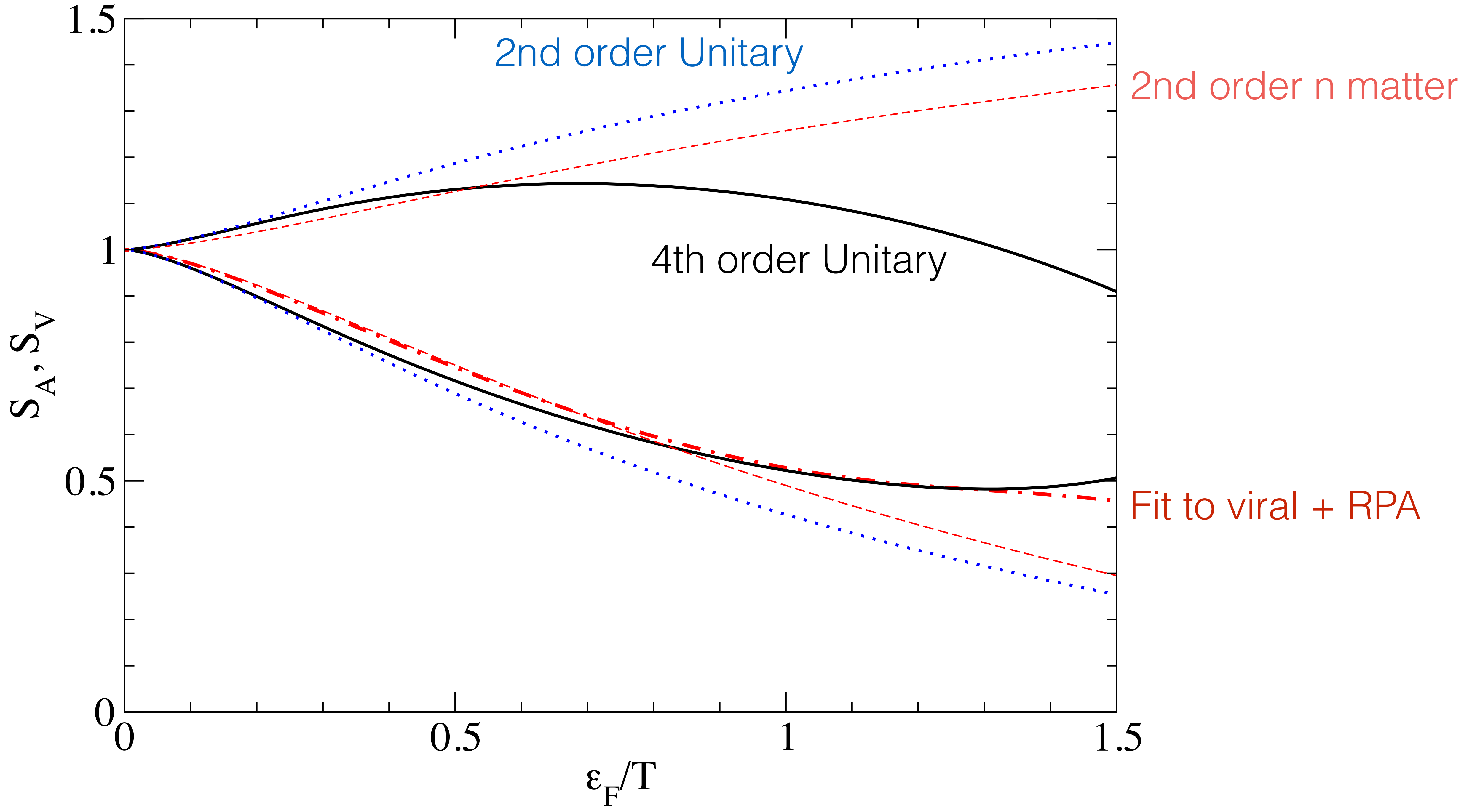
- For Unitary gas, b_n independent of T. Responses only function of Fermi energy/ temperature.

4th order Unitary results

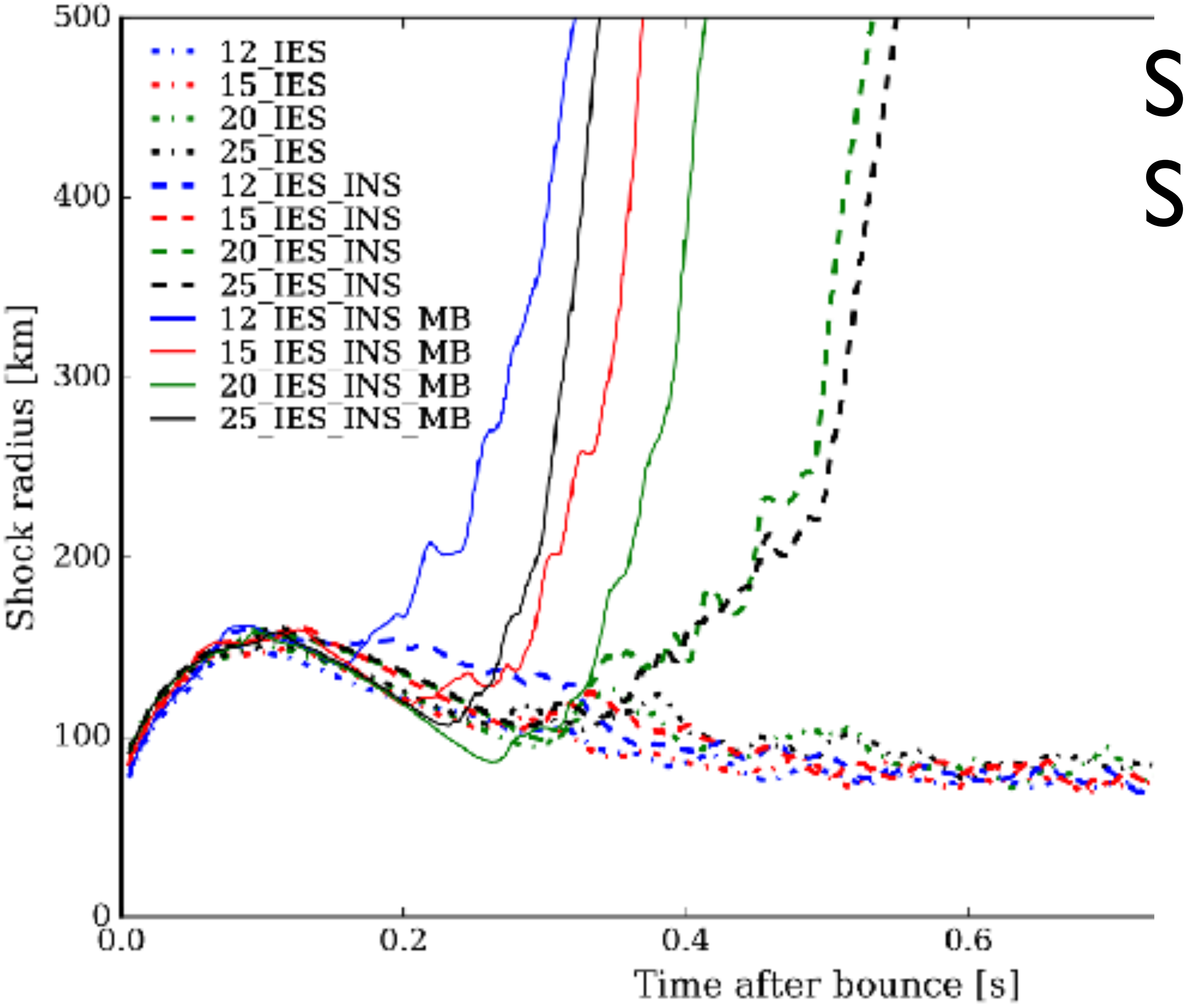


Unitary gas response

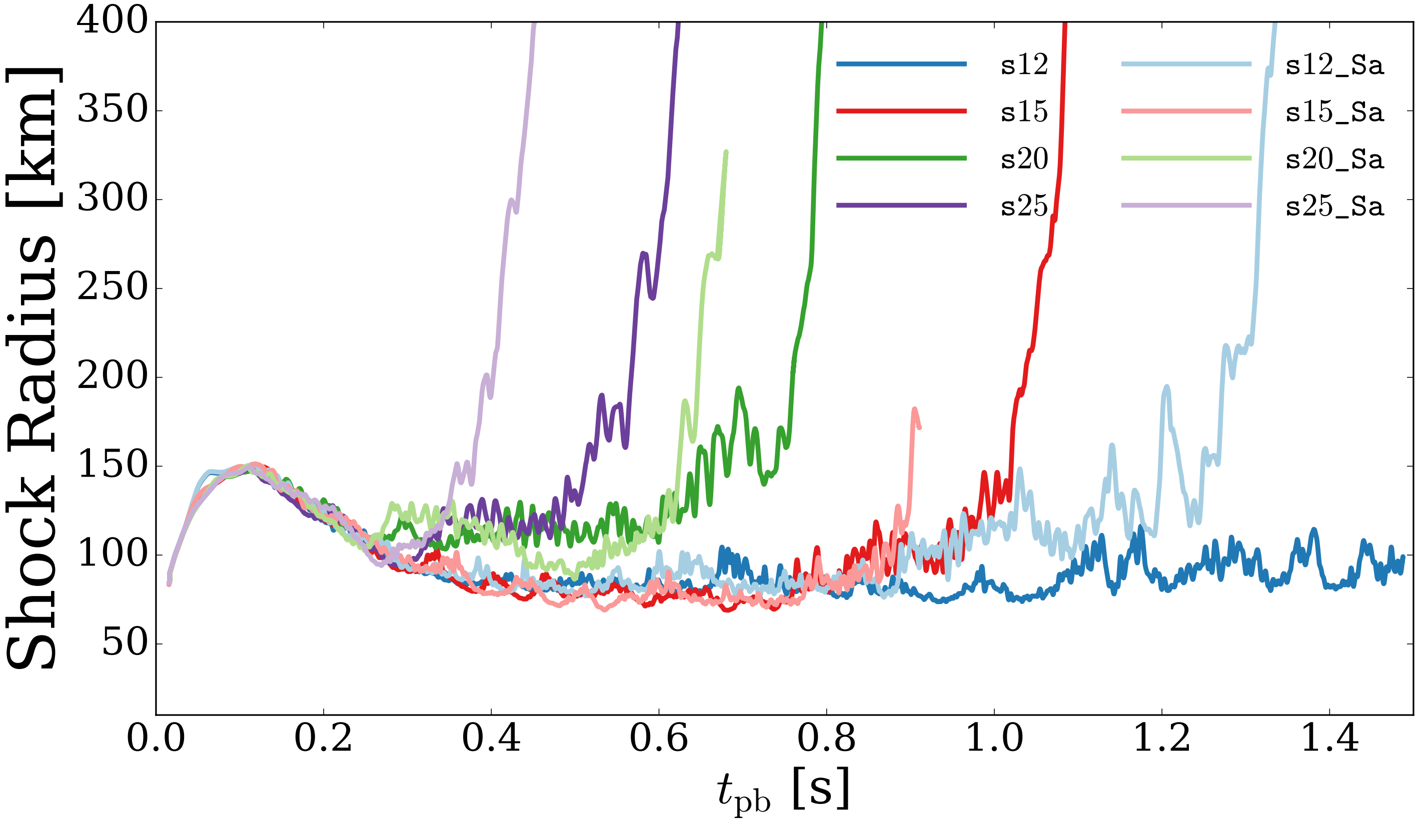
arXIv:1708.01788



Shock radius vs time for 2D SN simulations



All 2-D SN simulations by Burrows [arXiv:1611.05859] with correlations (S_A<1) explode (solid lines) while 12 and 15 M_{sun} stars fail to explode, and 20, 25 M_{sun} explode later, without correlations (S_A=1).



Preliminary 2D SN simulations by Evan O'Connor for 12 to 25 M_{sun} stars explode earlier (lighter color) if correlations (S_A<1) included.

Sensitivity of SN dynamics motivates better treatments of neutrino interactions in SN matter.

EOS and Neutrinos

- Axial response of supernova matter: Liliana Caballero, Z. Lin, Evan O’Connor, Achim Schwenk
- PREX, CREX: Krishna Kumar, R. Michaels, P. Souder…

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