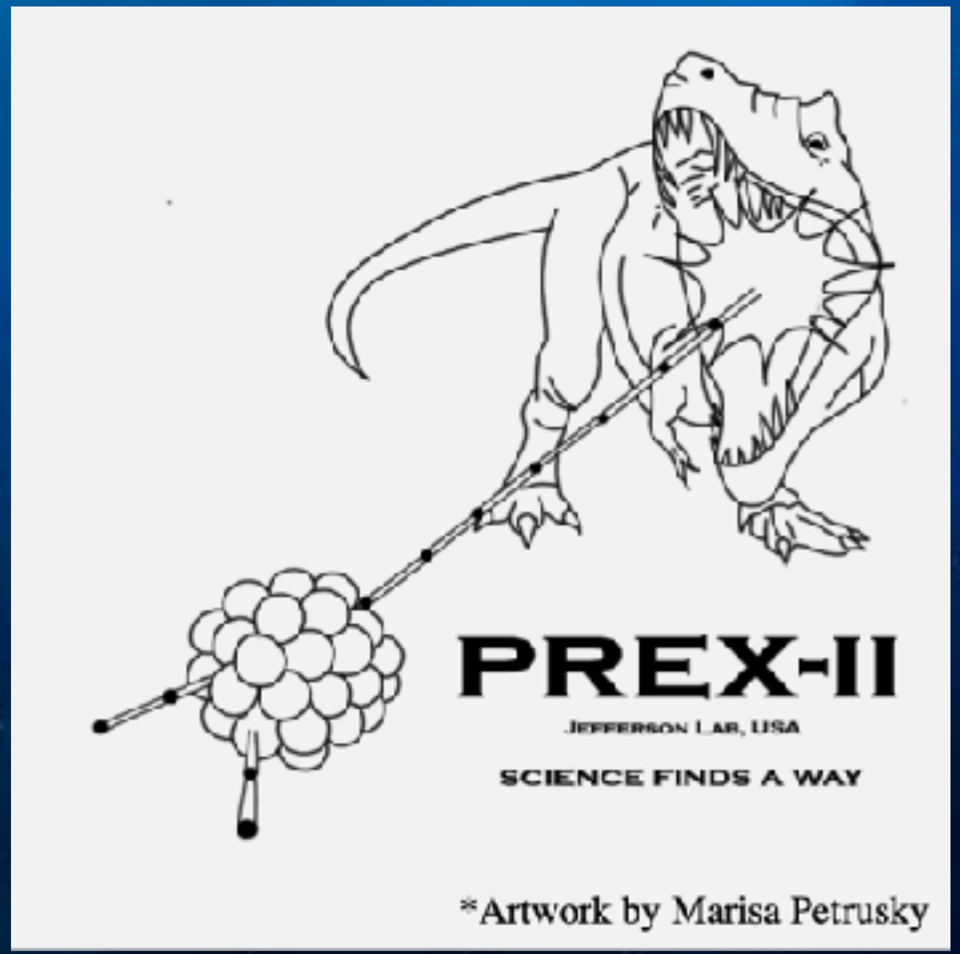
PREX / CREX Neutron Density Experiments

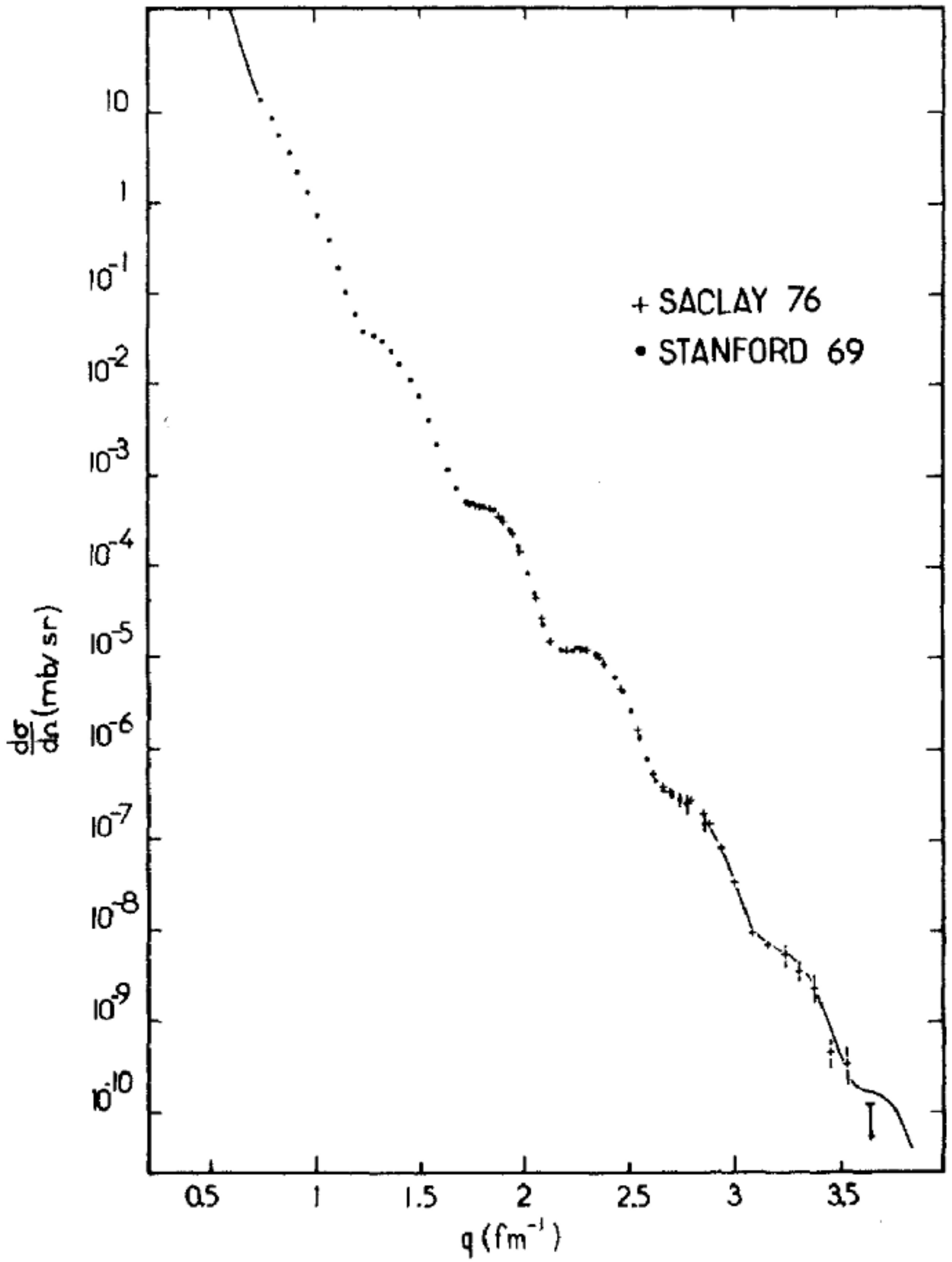


Chuck Horowitz, Indiana U.

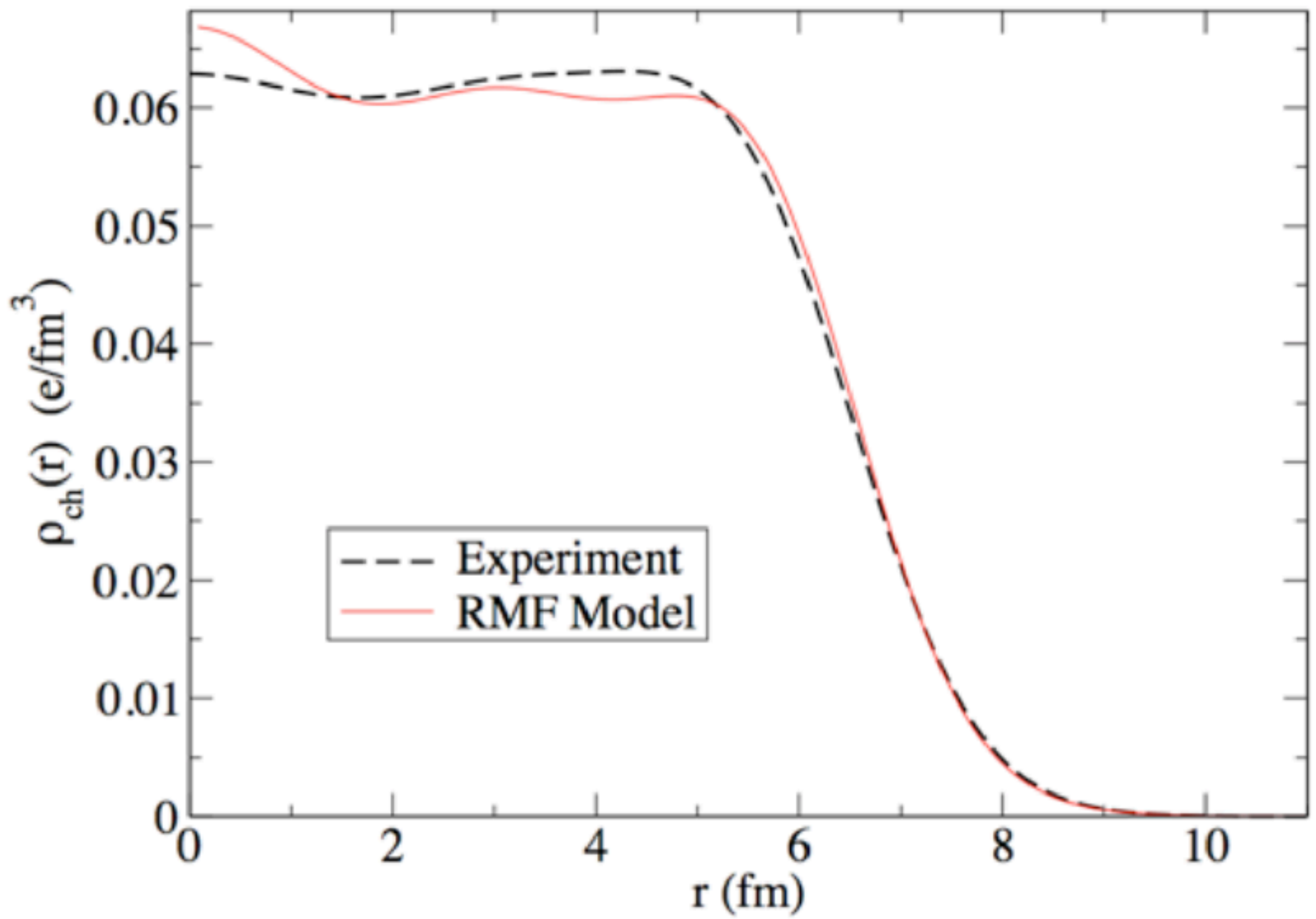
NuSym2022, Catania 2022

Neutron Densities

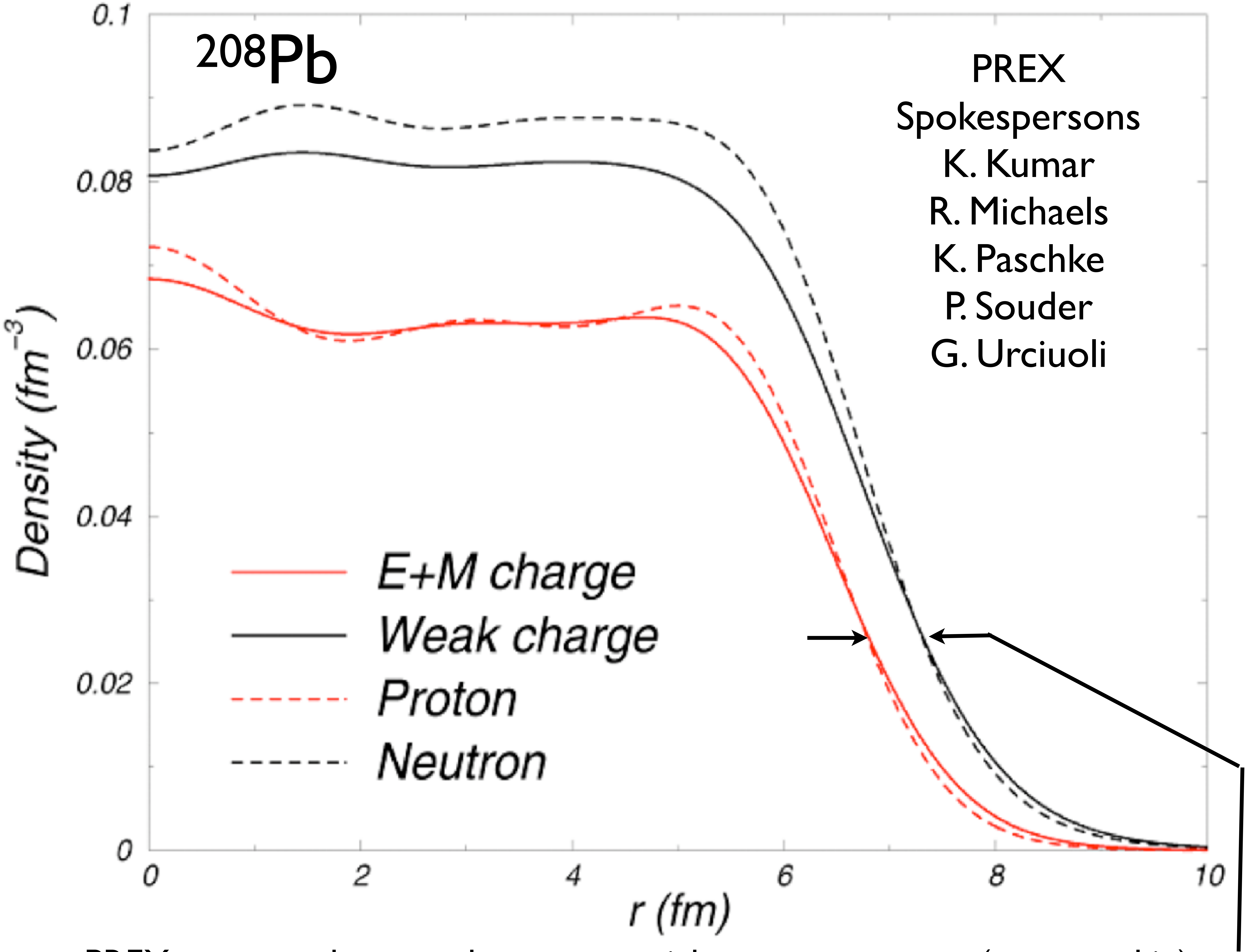
Charge Density of ^{208}Pb, accurately measured in elastic electron scattering.



Cross section measured over 12 orders of magnitude.



These elastic charge densities ***are*** our picture of the atomic nucleus!



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

PREX uses Parity V. to Isolate 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

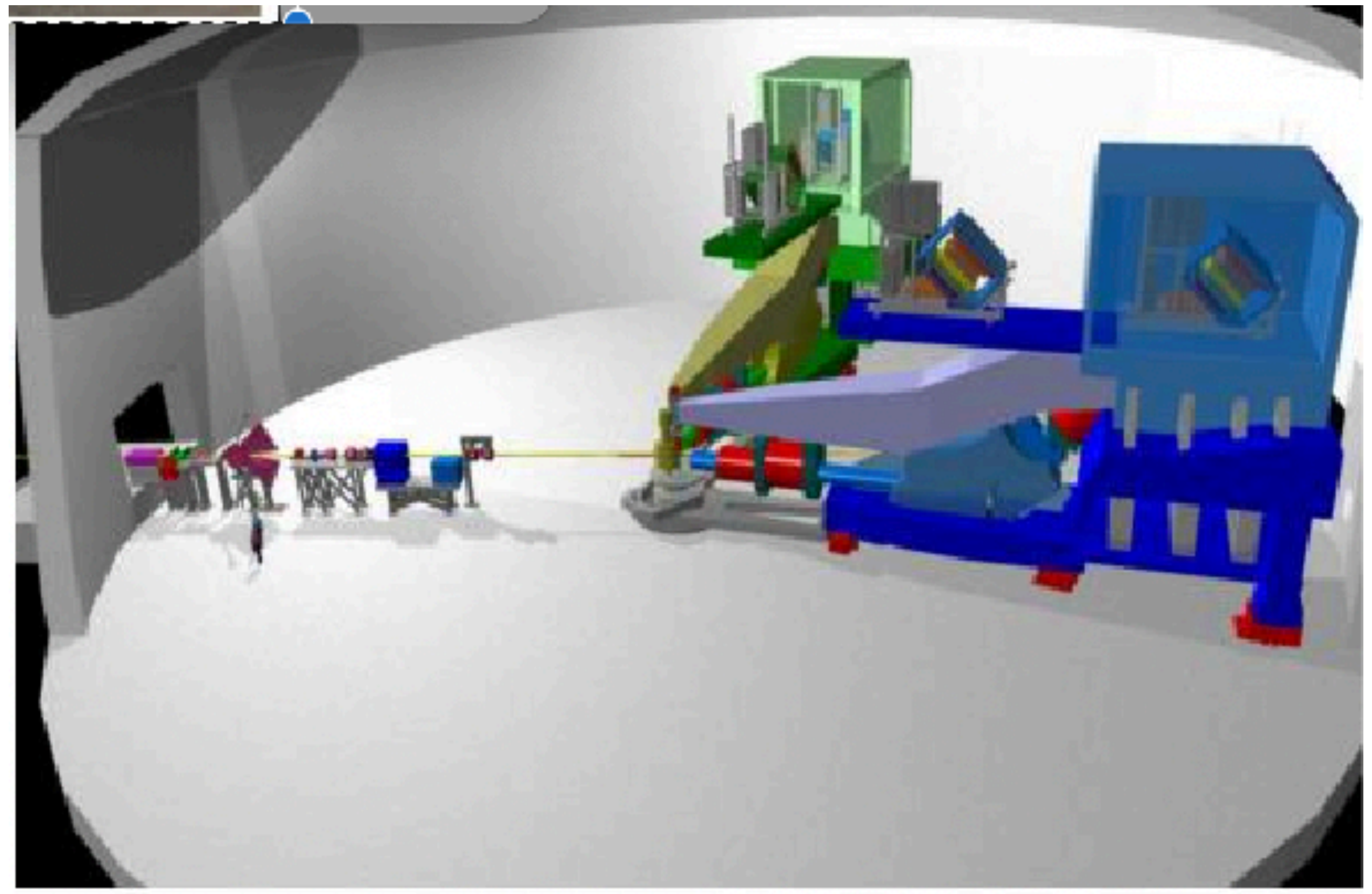
- A_{pv} from interference of photon and Z^0 exchange.
- Determines weak form factor

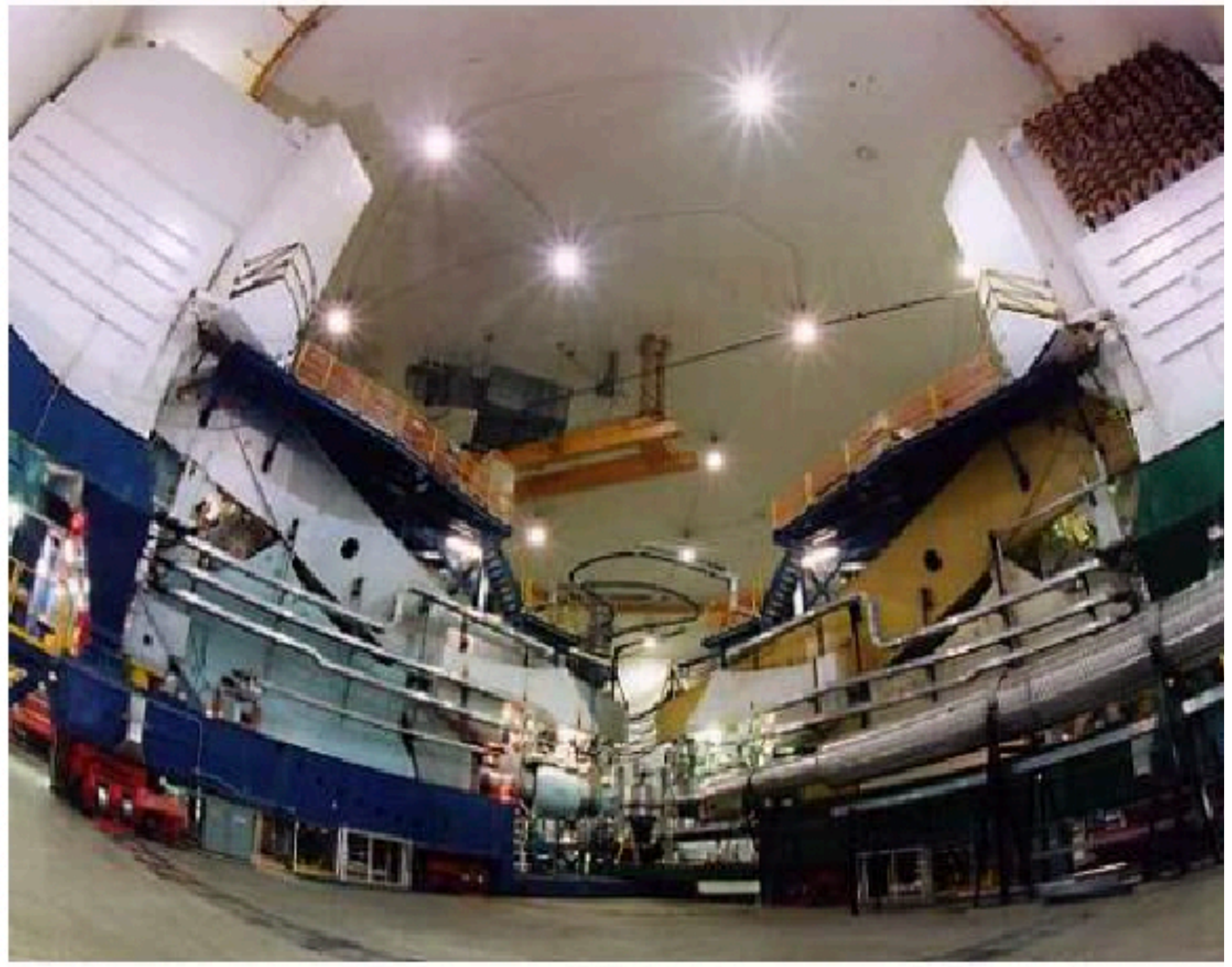
$$F_W(q) = \frac{1}{Q_W}\int d^3r j_0(qr)\rho_W(r)$$

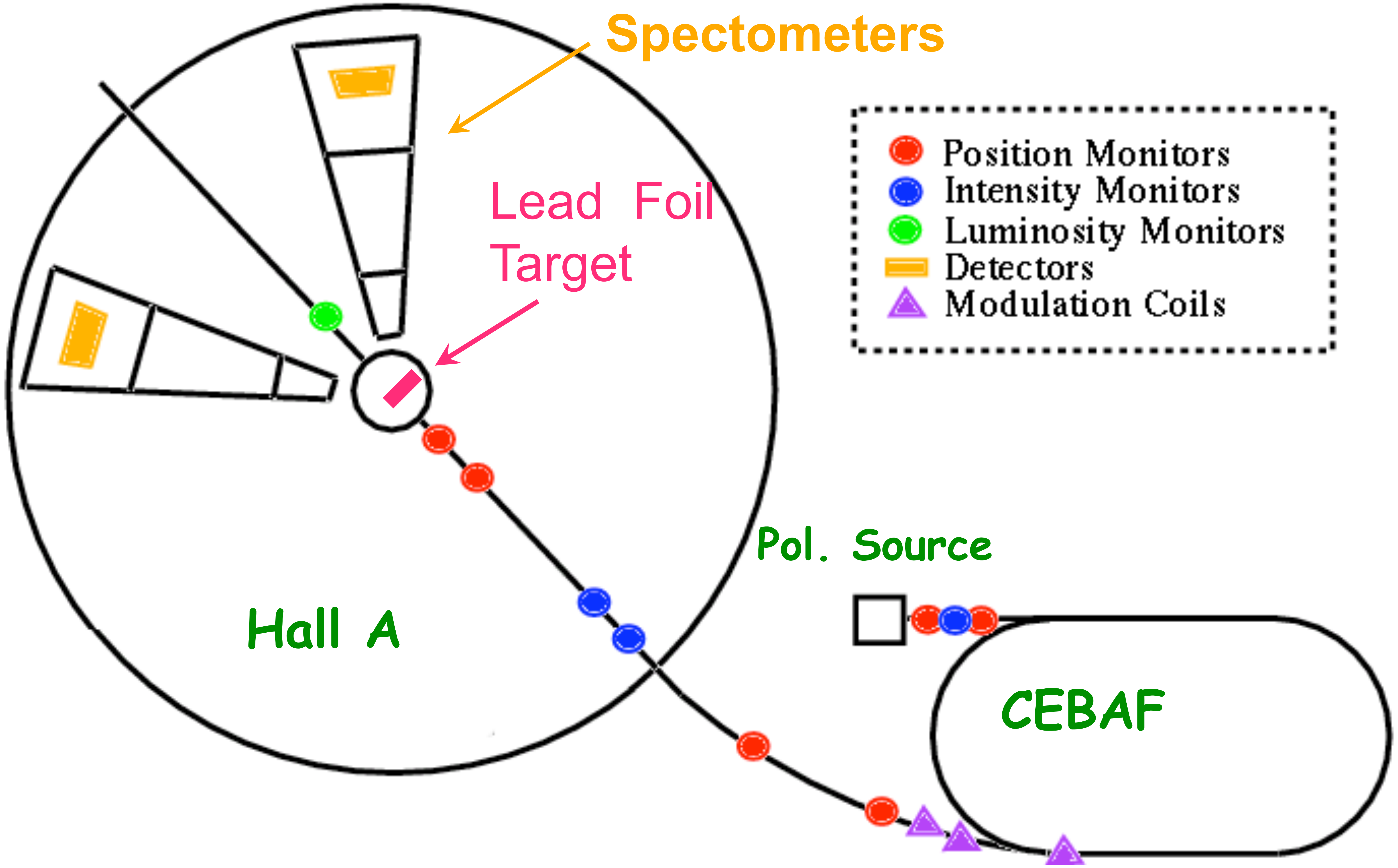
- Model independently map out distribution of weak charge in a nucleus.
- **Electroweak reaction free from most strong interaction uncertainties.**

$$A_{pv} = \frac{d\sigma/d\Omega_+ - d\sigma/d\Omega_-}{d\sigma/d\Omega_+ + d\sigma/d\Omega_-} \approx \frac{G_F Q^2 |Q_W|}{4\pi\alpha\sqrt{2}Z}\frac{F_W(Q^2)}{F_{ch}(Q^2)}$$

PREX in Hall A at JLab

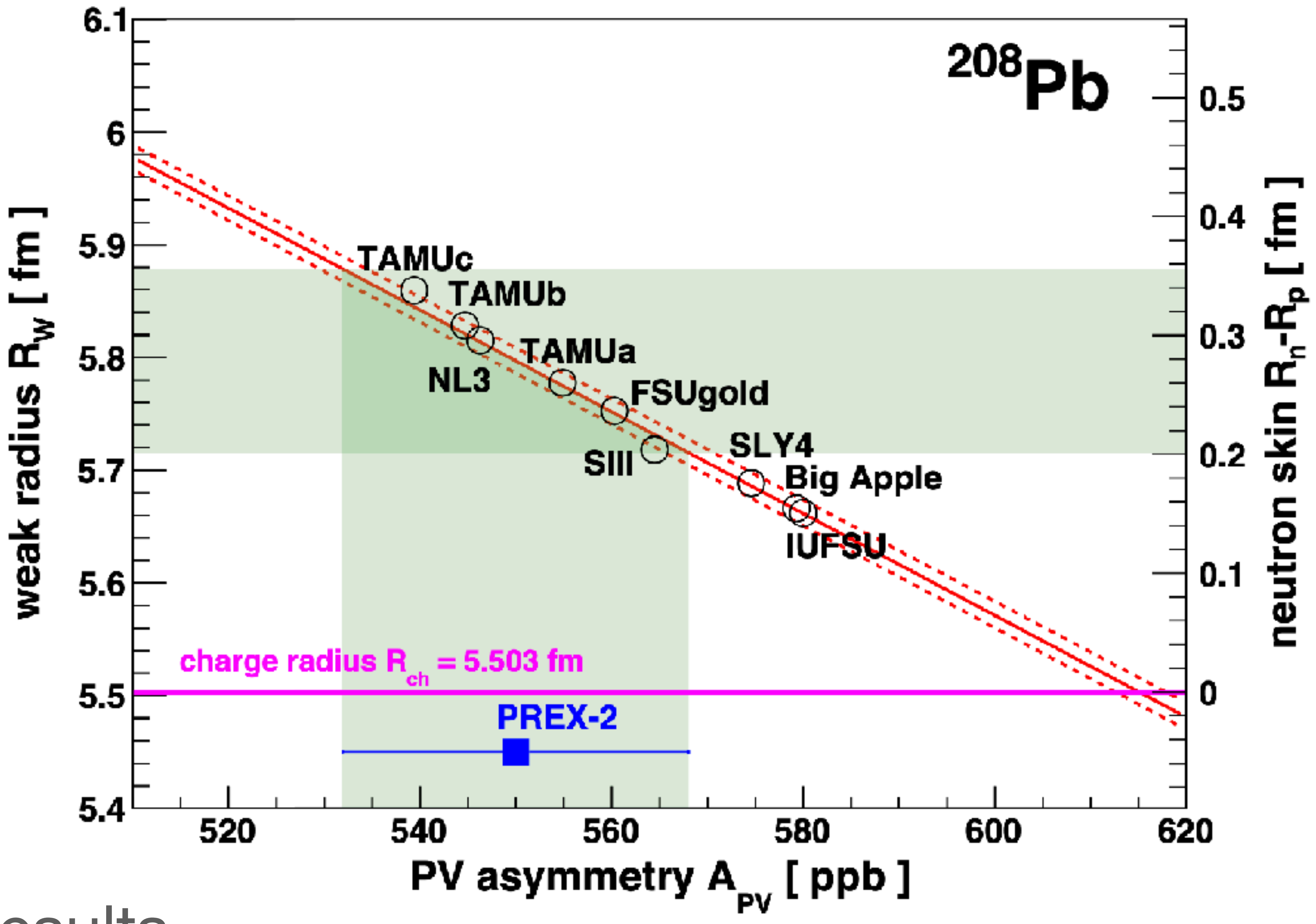






R. Michaels

PREX-II



PREX-I+II Results

^{208}Pb Parameter	Value
Weak radius (R_W)	5.800 ± 0.075 fm
Interior weak density (ρ^0_W)	-0.0796 ± 0.0038 fm^{-3}
Interior baryon density (ρ^0_b)	0.1480 ± 0.0038 fm^{-3}
Neutron skin ($R_n - R_p$)	0.283 ± 0.071 fm

PREX-2 weak form factor:
$F_W(q=0.398\text{fm}^{-1})=0.3676+/-.0125$

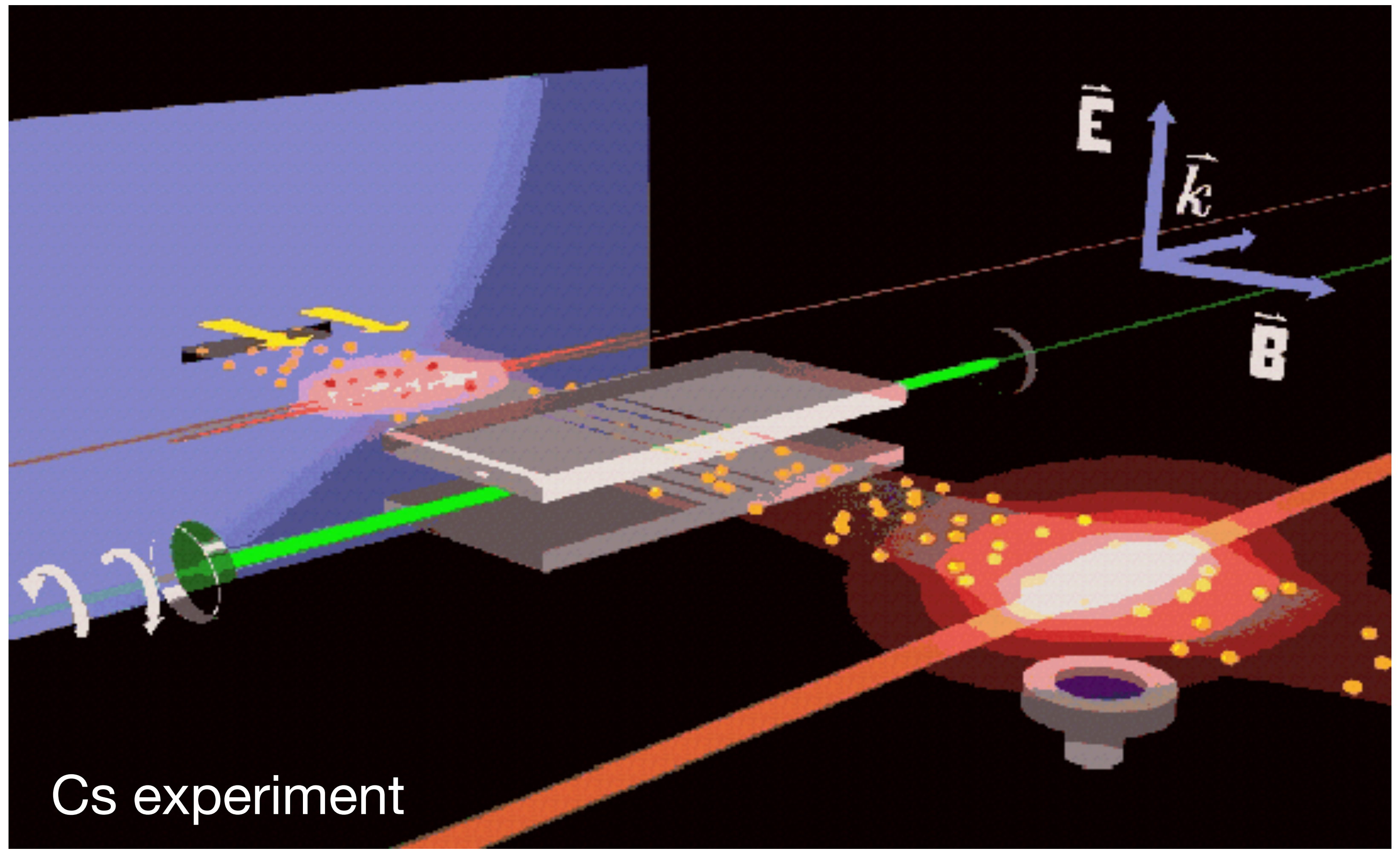
Atomic Parity Nonconservation

- Atomic PNC depends on overlap of electrons with neutrons in nucleus.

- Cs experiment good to 0.3%. Not limited by R_n but future 0.1% exp would need R_n to 1%

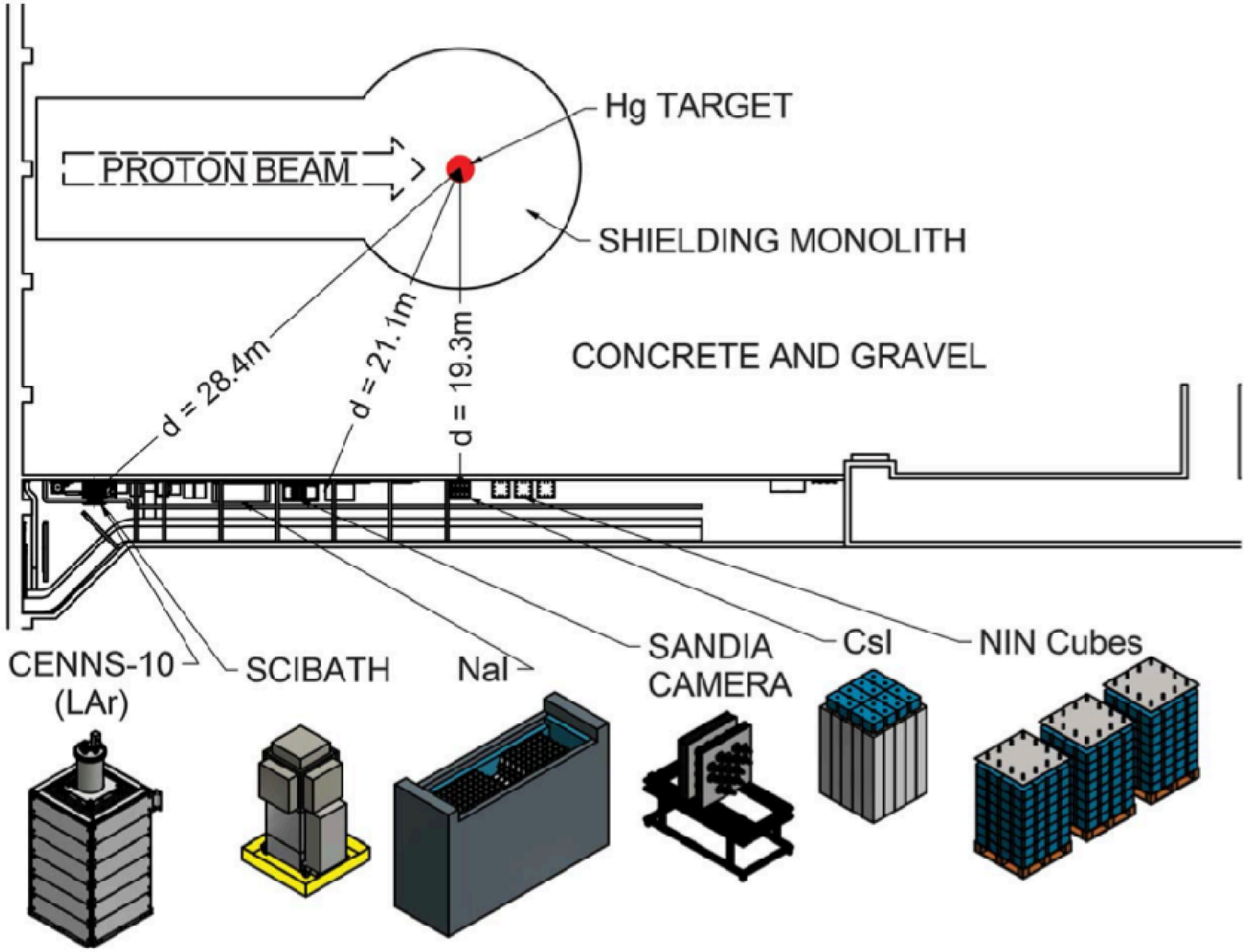
- Measurement of R_n in ^{208}Pb and ^{48}Ca constrains nuclear theory for R_n in other atomic PNC nuclei.

- Combine neutron radius from PV e scattering with an atomic PNC exp for strong low energy test of standard model.



- Atomic PNC Experiments:
  - Berkeley/ Mainz Yb experiment can look at PNC for isotope ratios.
  - PNC in radioactive Fr is x18 larger than for Cs because of higher electron density at nucleus of high Z nucleus.

Neutrino nucleus elastic scattering



COHERENT experiment at SNS in Oak Ridge, TN
Rex Tayloe and others at IU

Neutrino nucleus scattering involves same weak form factor as PV electron scattering

$$\frac{d\sigma}{dT}(E,T) = \frac{G_F^2}{2\pi} M \frac{Q_W^2}{4} F^2(Q^2) \times \left[2 - \frac{2T}{E} + \left(\frac{T}{E}\right)^2 - \frac{MT}{E^2}\right]$$

Coherent probed CsI average R_n to ~15%

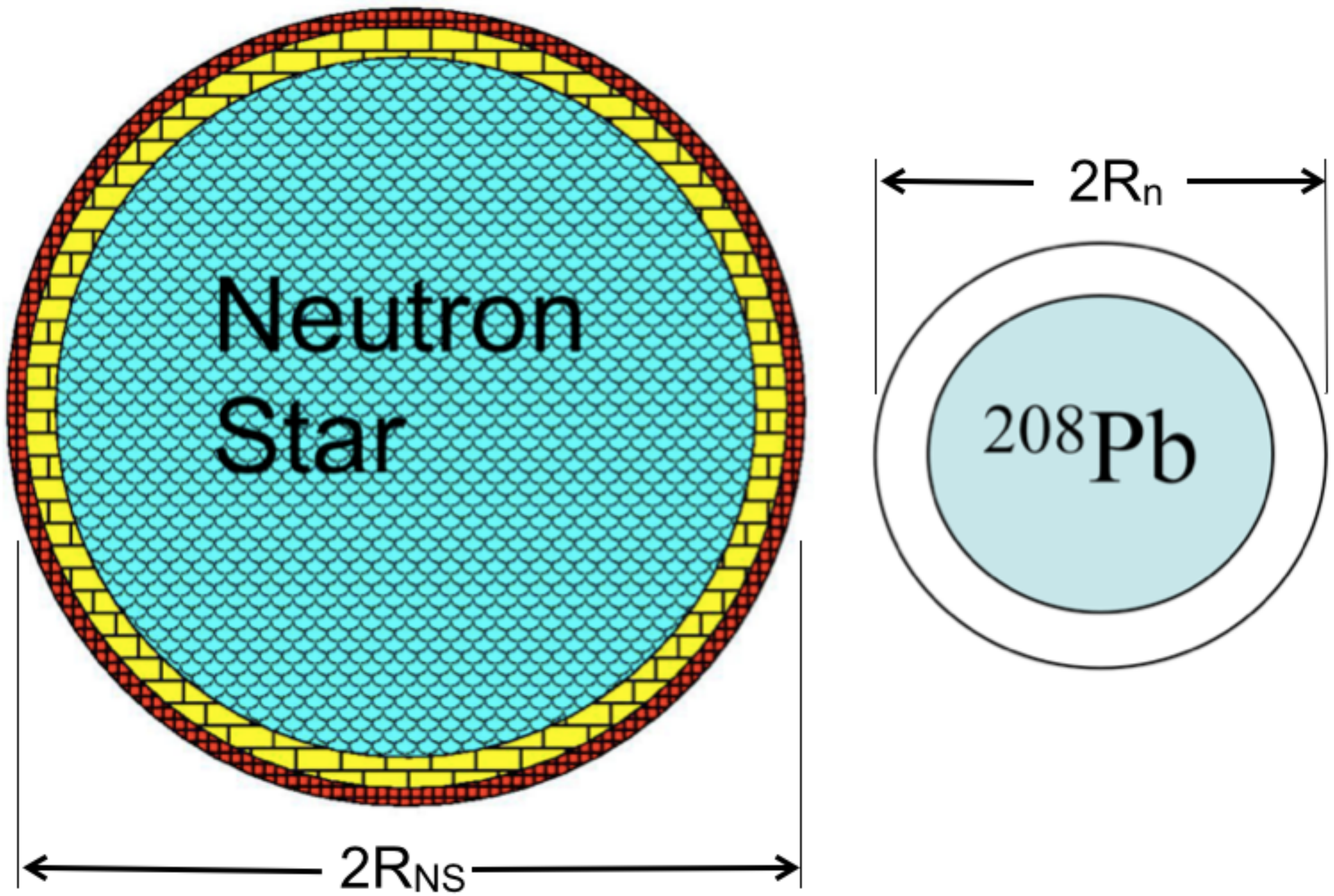
PREX measured $R_w(^{208}Pb)$ to 1.3%
CREX probed $R_w(^{48}Ca)$ to 0.7%
Qweak measured $R_n(^{27}Al)$ to 3.8%

Use PV to constrain nuclear structure. This allows coherent neutrino scattering to probe non-standard neutrino interactions.

Neutron Stars

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 both involve neutron rich matter at similar densities with the same strong interactions and equation of state.

Nuclear measurement vs Astronomical Observation

To probe equation of state

PREX, CREX measure neutron radius of ^{208}Pb and ^{48}Ca. Clean electroweak rxn.

NICER measures NS radius from X-ray light curve. Some systematic errors.

Electric **dipole polarizability** from coulomb excitation. Potential systematic error from sum over excited states. Encourage ab initio calculations.

LIGO measured **gravitational deformability** (quadrupole polarizability) of NS from tidal excitation. Statistics limited but systematic errors controllable.

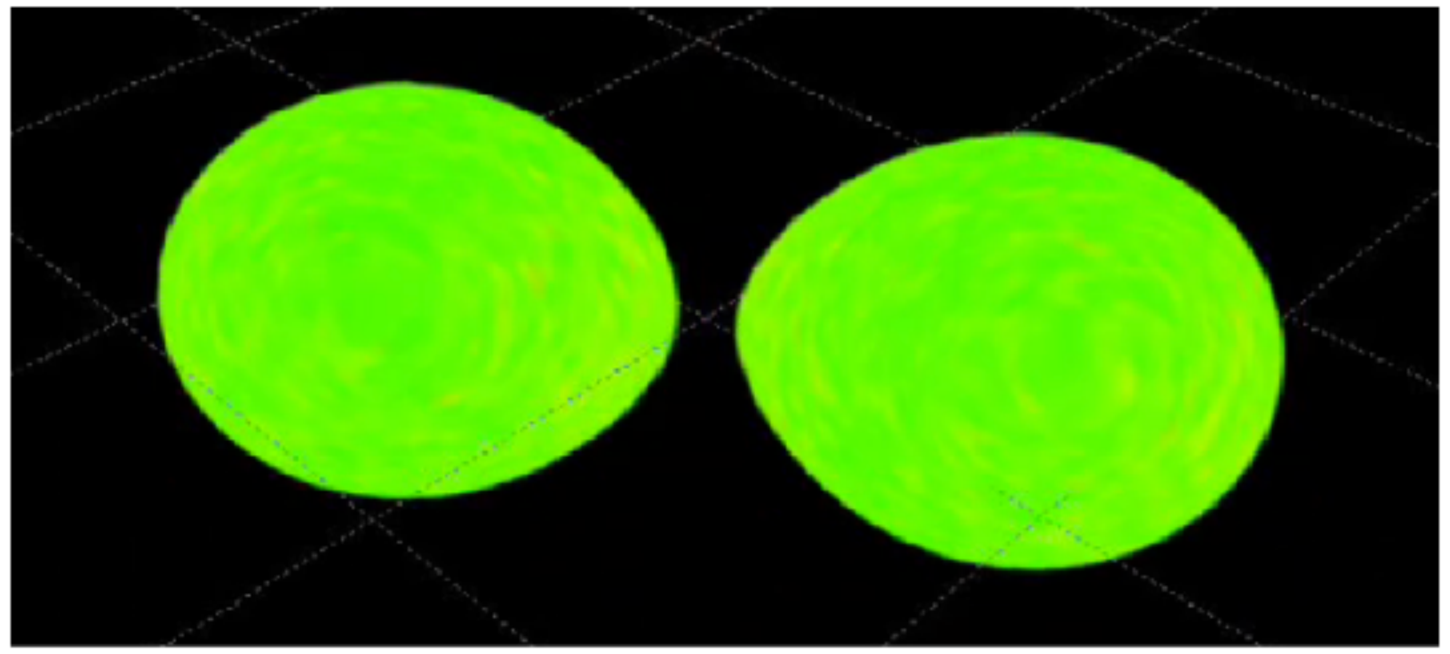
	Laboratory measurements on nuclei	Astronomical observations of neutron stars
Radius	PREX, CREX	NICER
Polarizability	Electric dipole	Gravitational deformability

Spectacular event GW170817

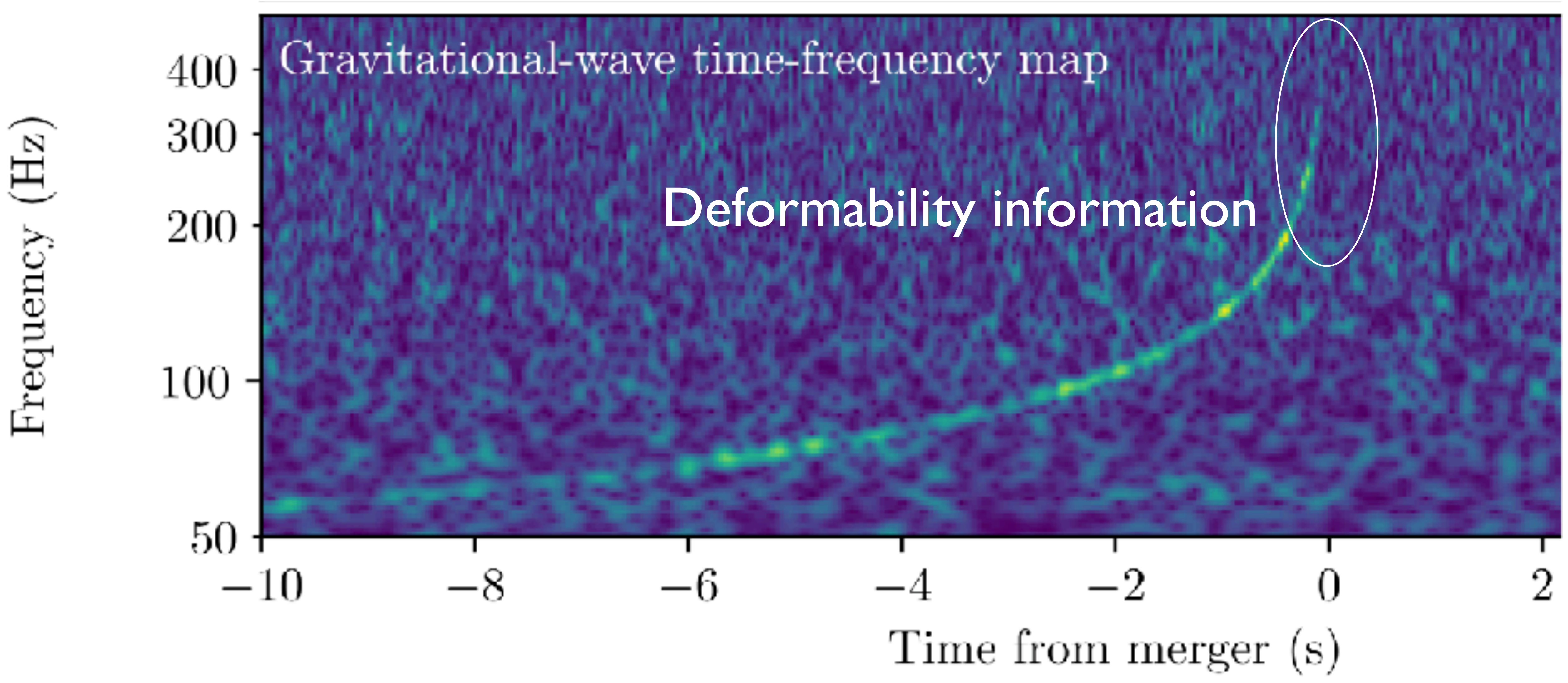
- On Aug. 17, 2017, the merger of two NS observed in GW by the LIGO and Virgo detectors.
- The Fermi and Integral spacecrafts independently detected a short gamma ray burst.
- Extensive follow up observed this event at X-ray, ultra-violet, visible, infrared, and radio wavelengths.
- Gravitational deformability (or quadrupole polarizability) of a neutron star scales as R5.

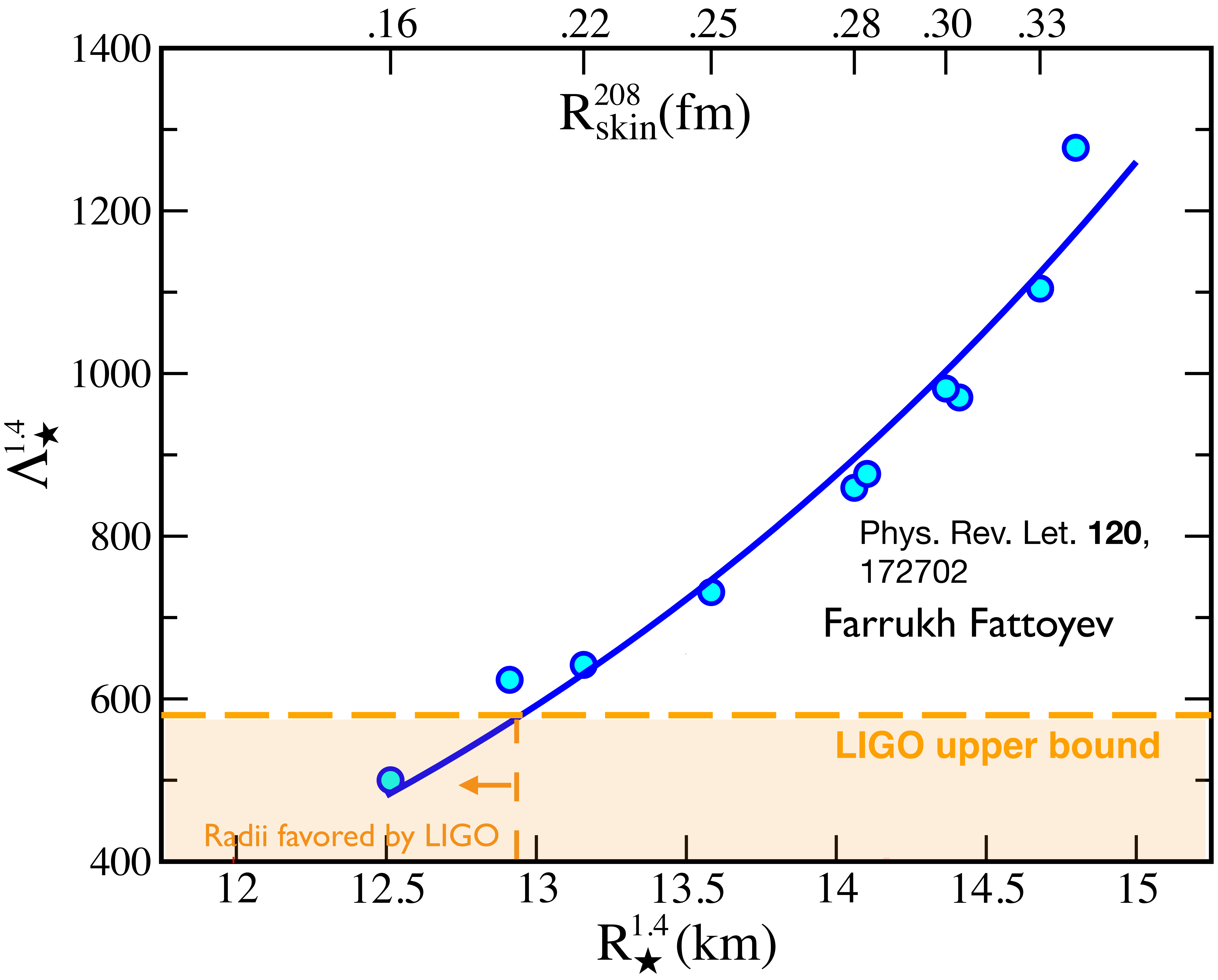
$$\Lambda \propto \Sigma_f \frac{|\langle f|r^2 Y_{20}|i\rangle|^2}{E_f - E_i} \quad \propto \quad R^5$$

- GW170817 observations set upper limit on Λ.



Gravitational tidal field distorts shapes of neutron stars just before they merge.

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R_{skin}^{208}(fm)
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$\Lambda_\star^{1.4}$
Phys. Rev. Let. **120**, 172702
Farrukh Fattoyev
LIGO upper bound
Radii favored by LIGO
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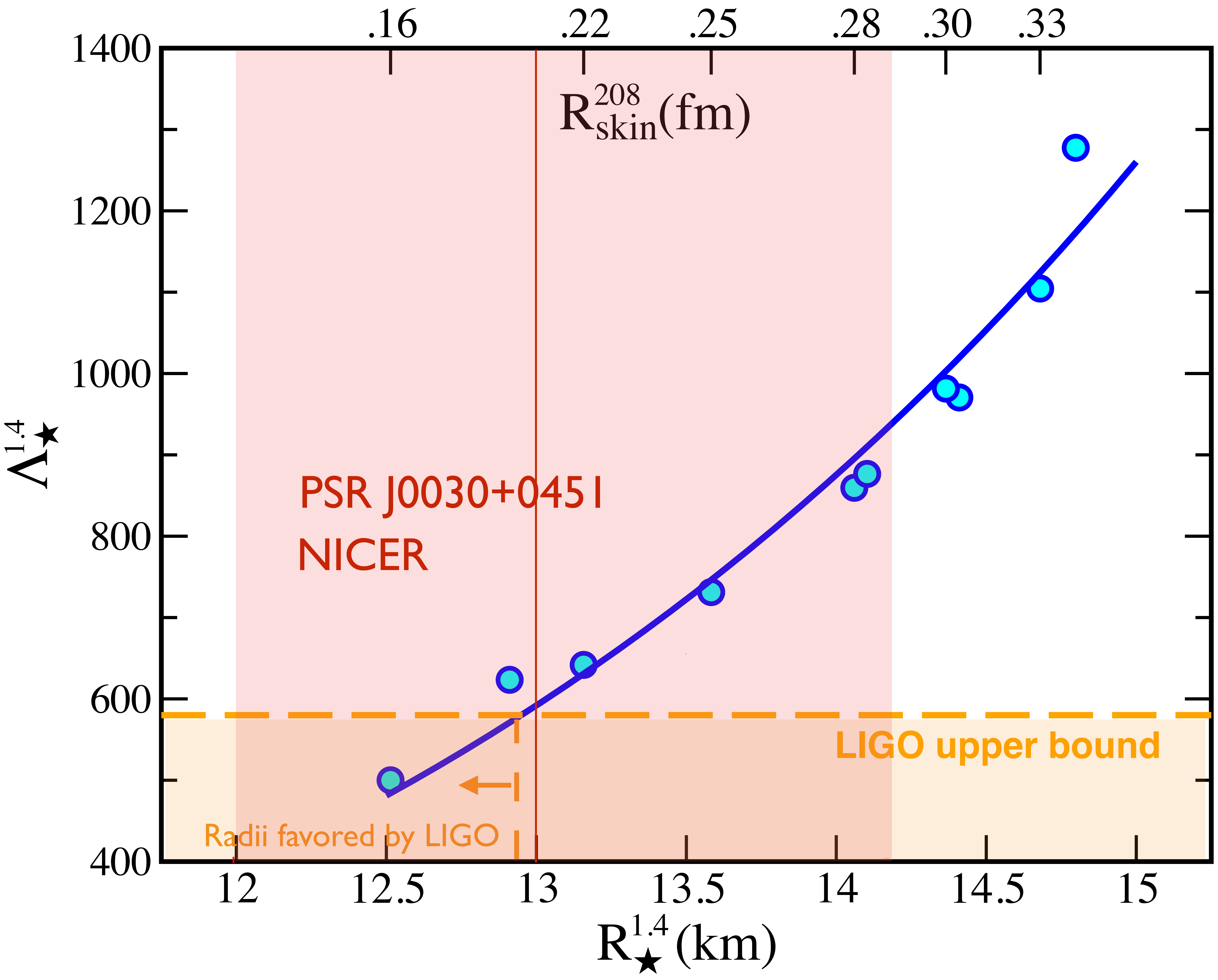
$R_\star^{1.4}$(km)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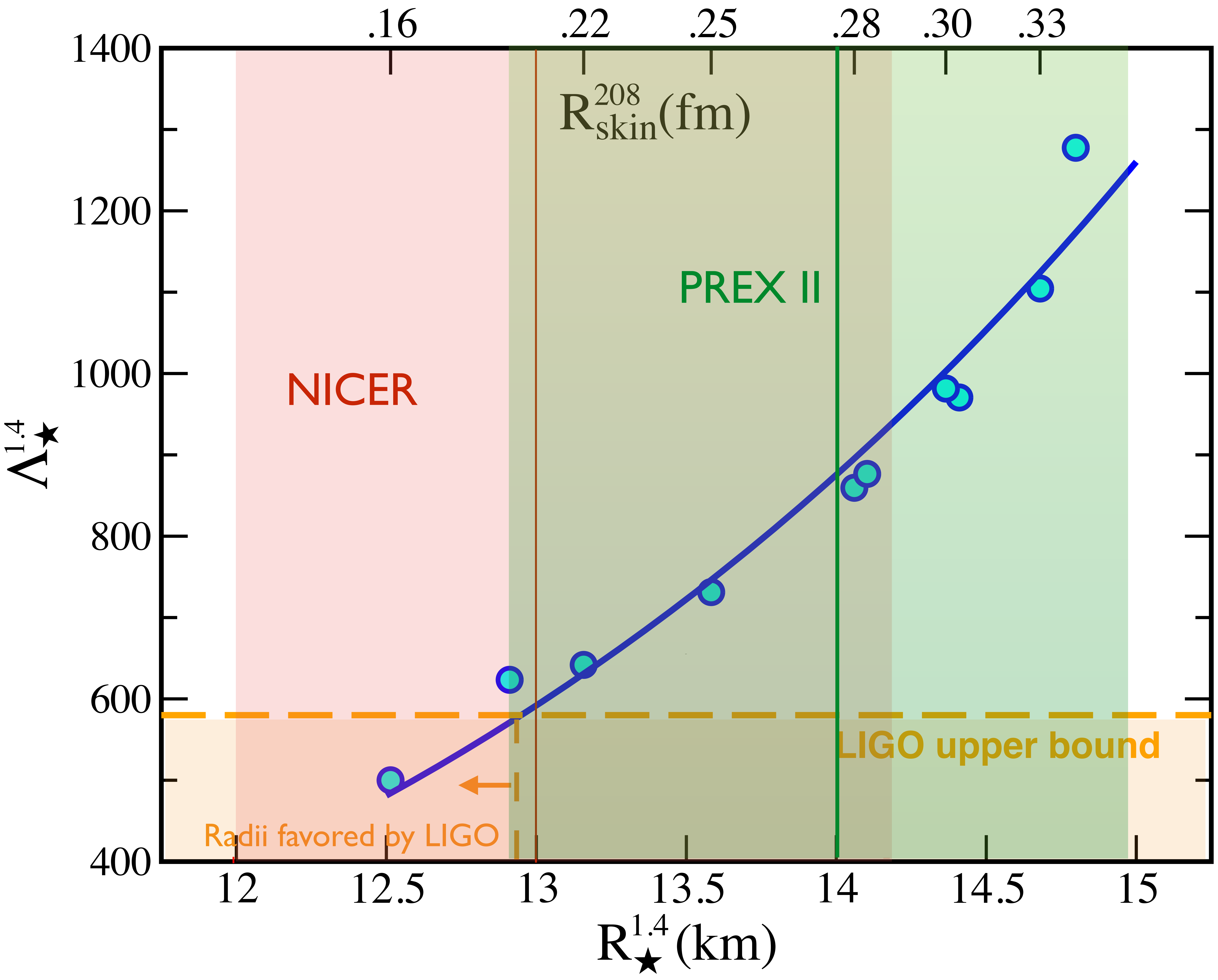

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R_{skin}^{208}(fm)
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$\Lambda_\star^{1.4}$
LIGO upper bound
Radii favored by LIGO
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$R_\star^{1.4}$(km)

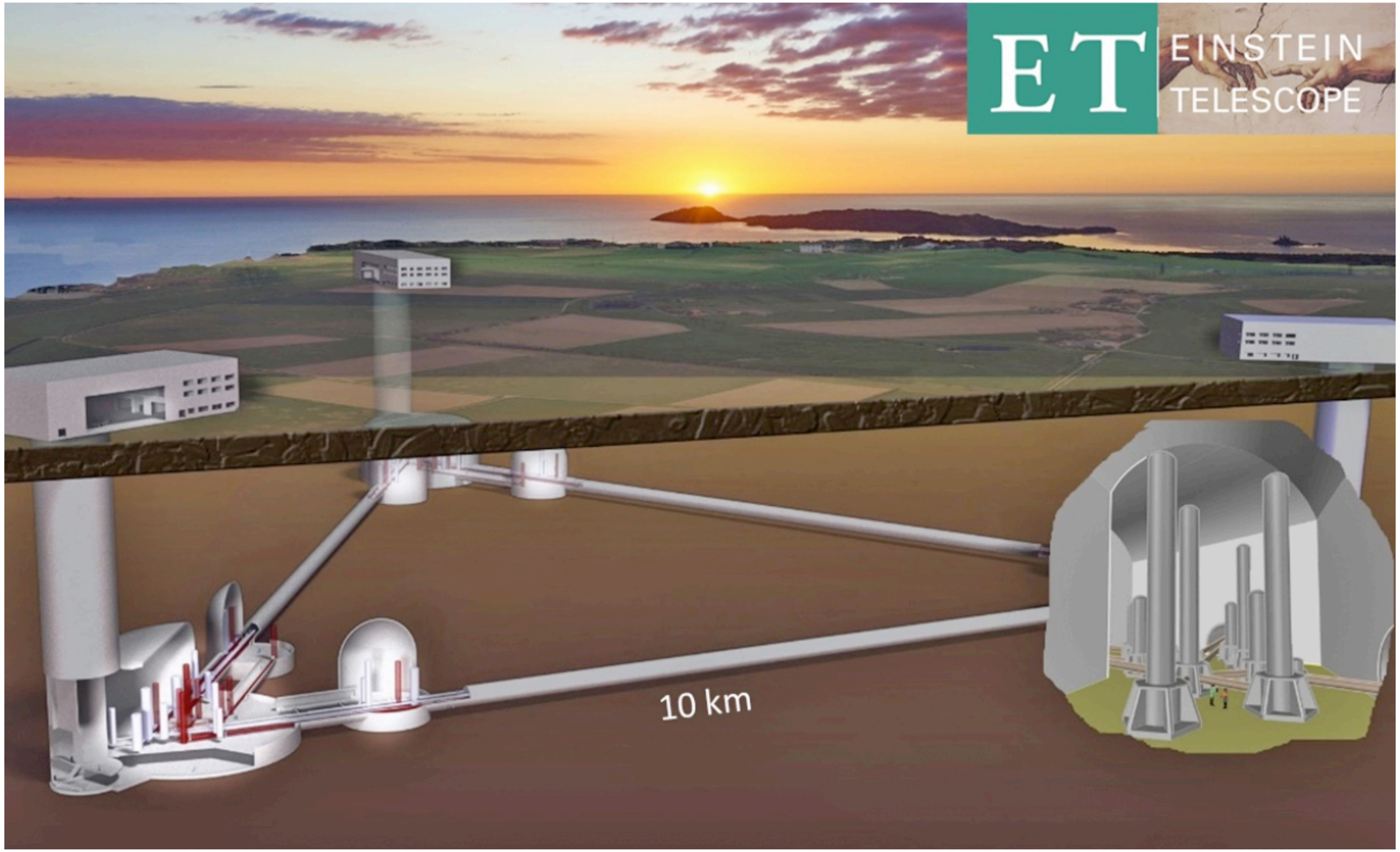
Next generation gravitational wave observatories

- The Einstein Telescope is proposed GW detector to be built at Dutch-Belgian-German border or in Sardinia.

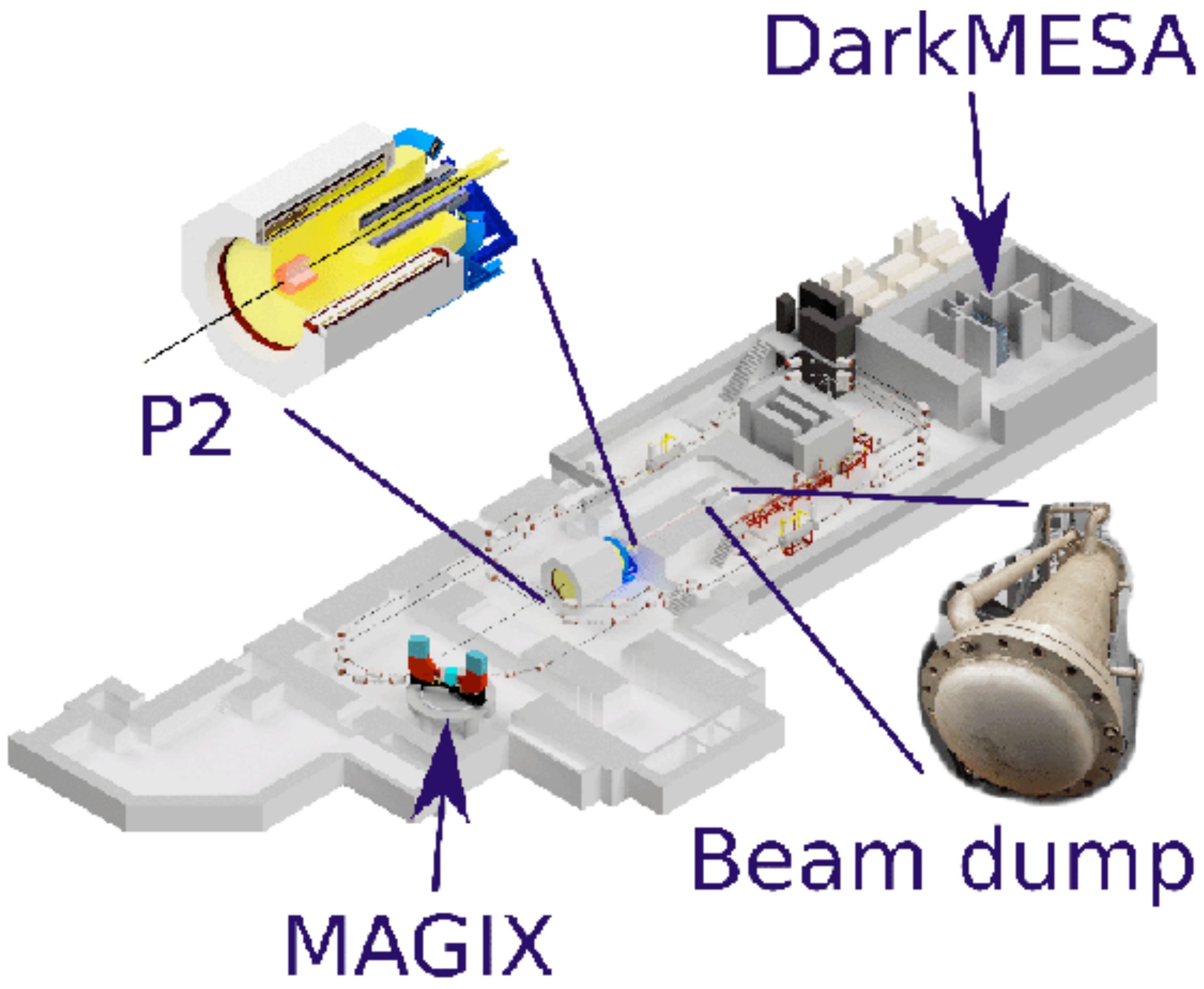
- Cosmic Explorer is proposed US detector with 40 km arms.

- 10 times more sensitive, 1000 x detection rate, of existing LIGO and VIRGO.

- LIGO is a BH machine, CE and ET will detect more NS than BH and accurately measure deformability of neutron stars.



MREX experiment at Mainz

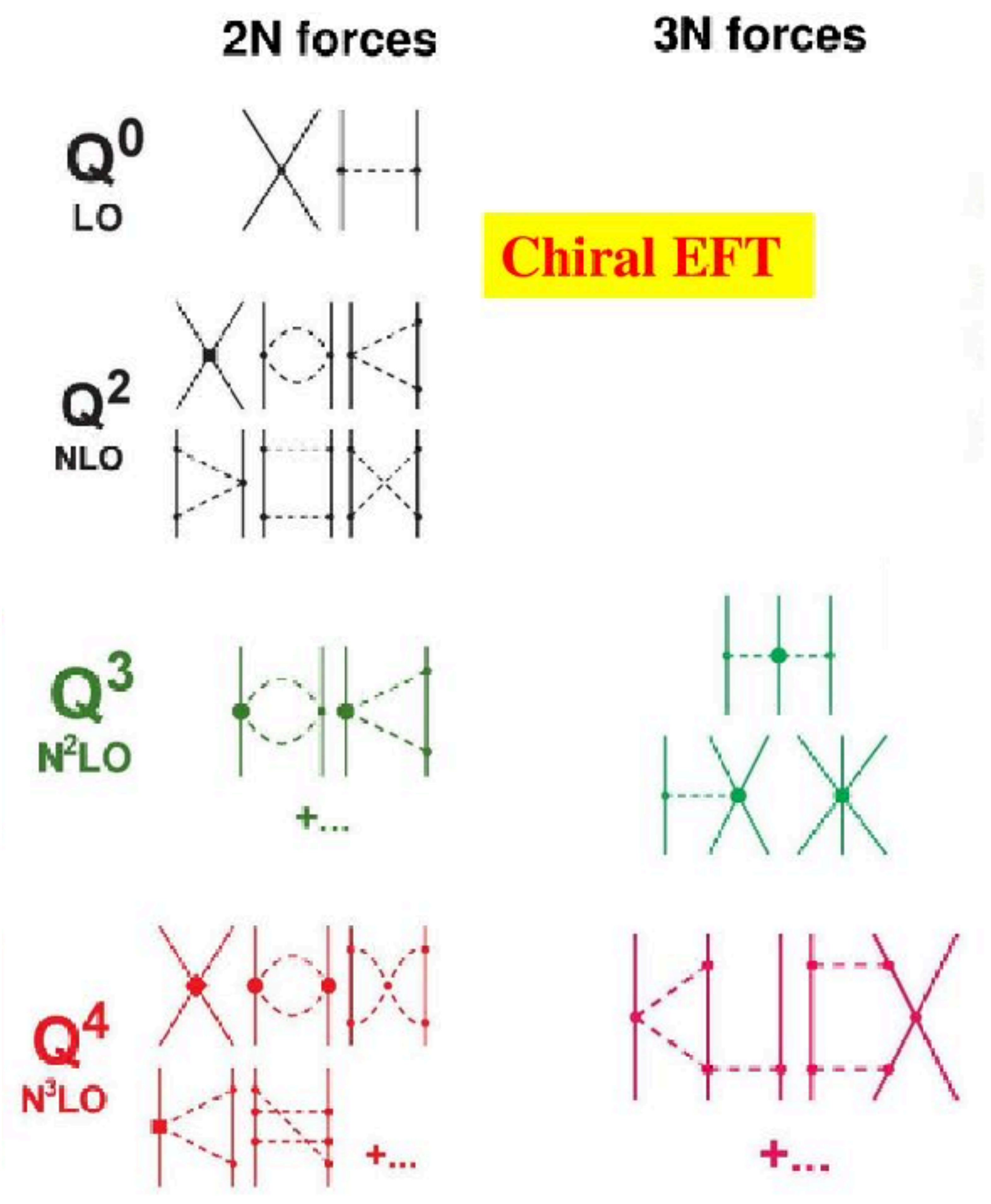


- MESA is high current low energy electron accelerator being built at Mainz.
- Mainz Radius Experiment (MREX) will use MESA and large acceptance P2 detector to measure the neutron skin of ^{208}Pb more accurately than PREX.
- PREX measured R_n to 1.3% (+/- 0.07 fm), MREX goal 0.5% (+/- 0.03 fm)

beam energy	155 MeV
beam current	150 μA
target density	0.28 g/cm^2
polar angle step size	$\Delta\theta = 4°$
polar angular range	30° to 34°
degree of polarization	85 %
parity violating asymmetry	0.66 ppm
running time	1440 hours
systematic uncertainty	1 %
$\delta A^{PV}/A^{PV}$	1.39 %
$\delta R_n/R_n$	0.52 %

CREX on ^{48}Ca and Chiral EFT

- Chiral EFT expands 2, 3, … nucleon interactions in powers of momentum transfer over chiral scale.
- **Three neutron forces** are hard to directly observe. They increase the pressure of neutron matter and the neutron skin thickness of both ^{208}Pb and ^{48}Ca.
- Only stable, neutron rich, closed shell nuclei are ^{48}Ca and ^{208}Pb.
- PREX for ^{208}Pb better for inferring pressure of neutron matter and structure of neutron stars.
- CREX measures neutron skin in ^{48}Ca. Smaller system allows direct comparison to Chiral EFT calculations and very sensitive to 3 *neutron* forces.



PREX and CREX Collaborations

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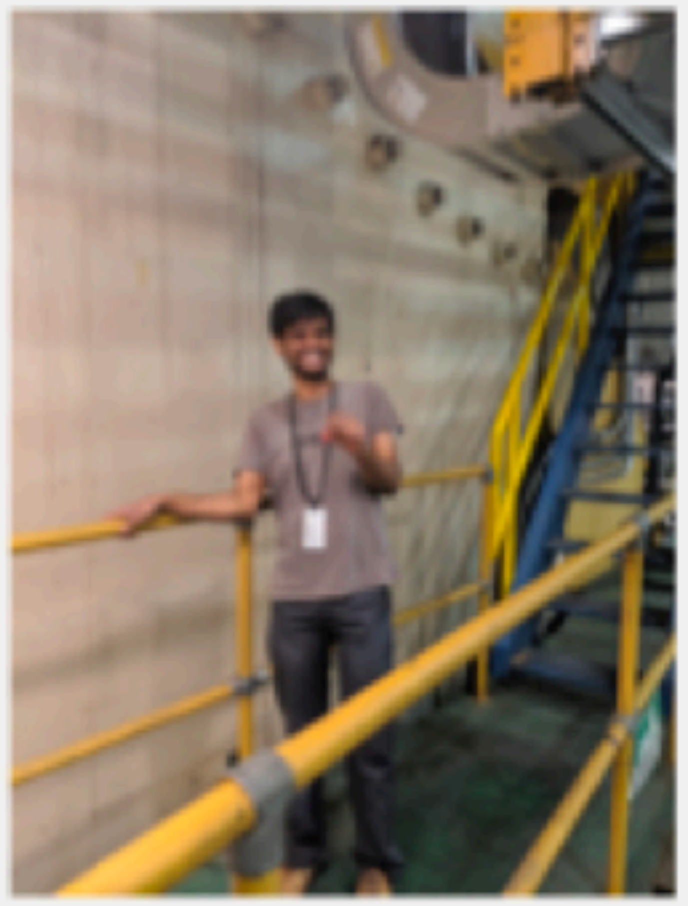


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Spokespeople: Kent Paschke (contact), Krishna Kumar, Robert Michaels, Paul A. Souder, Guido M. Urciuoli

Thanks to the Hall A techs, Machine Control, Yves Roblin, Jay Benesch and other Jefferson Lab staff

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