Summary: Neutron skins of nuclei

- Thank you for coming and participating.
- Thanks to MITP
- Thanks to MITP staff
- Thanks to Laura, Stefano, Jorge… for taking such good care of me.
- Many many thanks to Concettina!

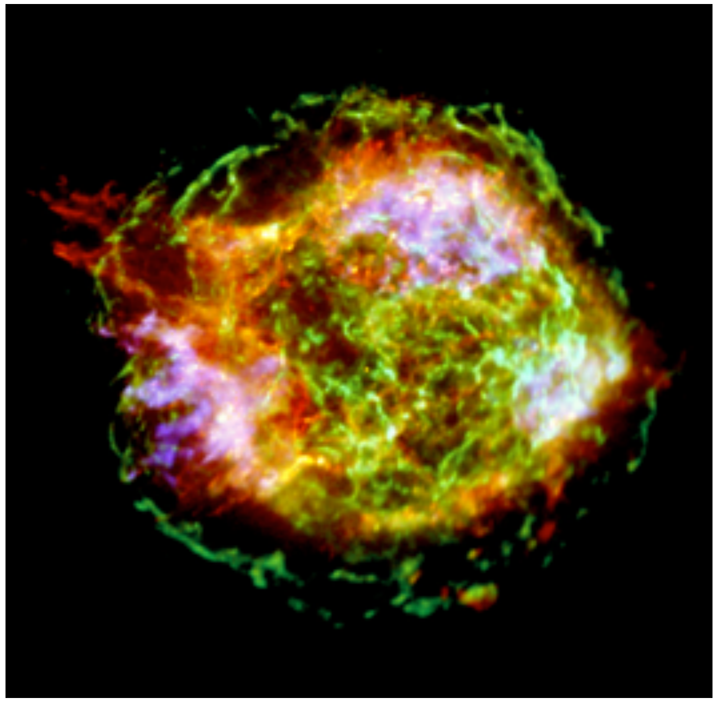
Neutron skins, halos, wings, and tails

$\bar{p}$

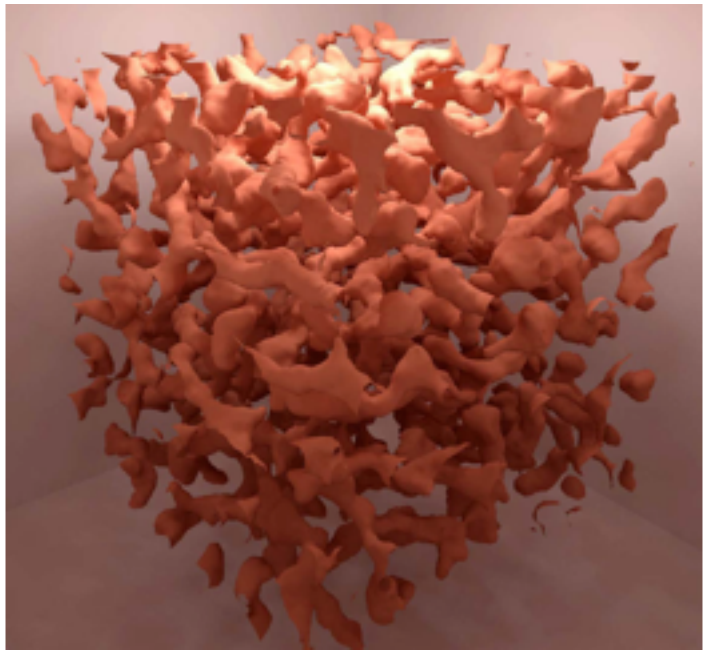
Astrophysics Motivation

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...*



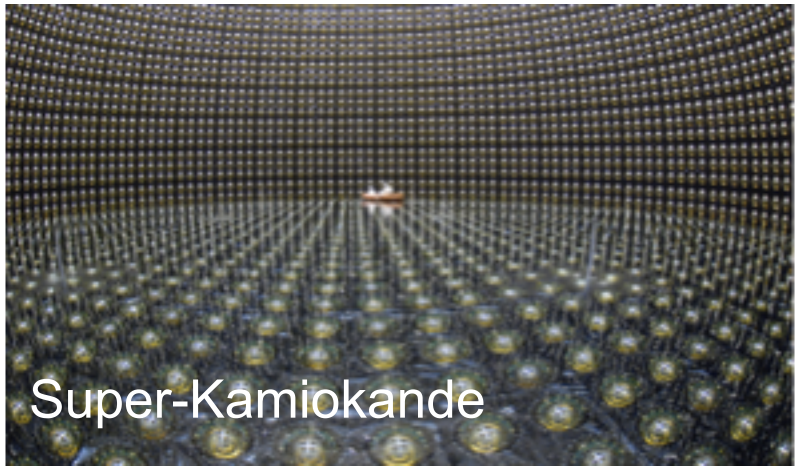
Supernova remanent Cassiopea A in X-rays



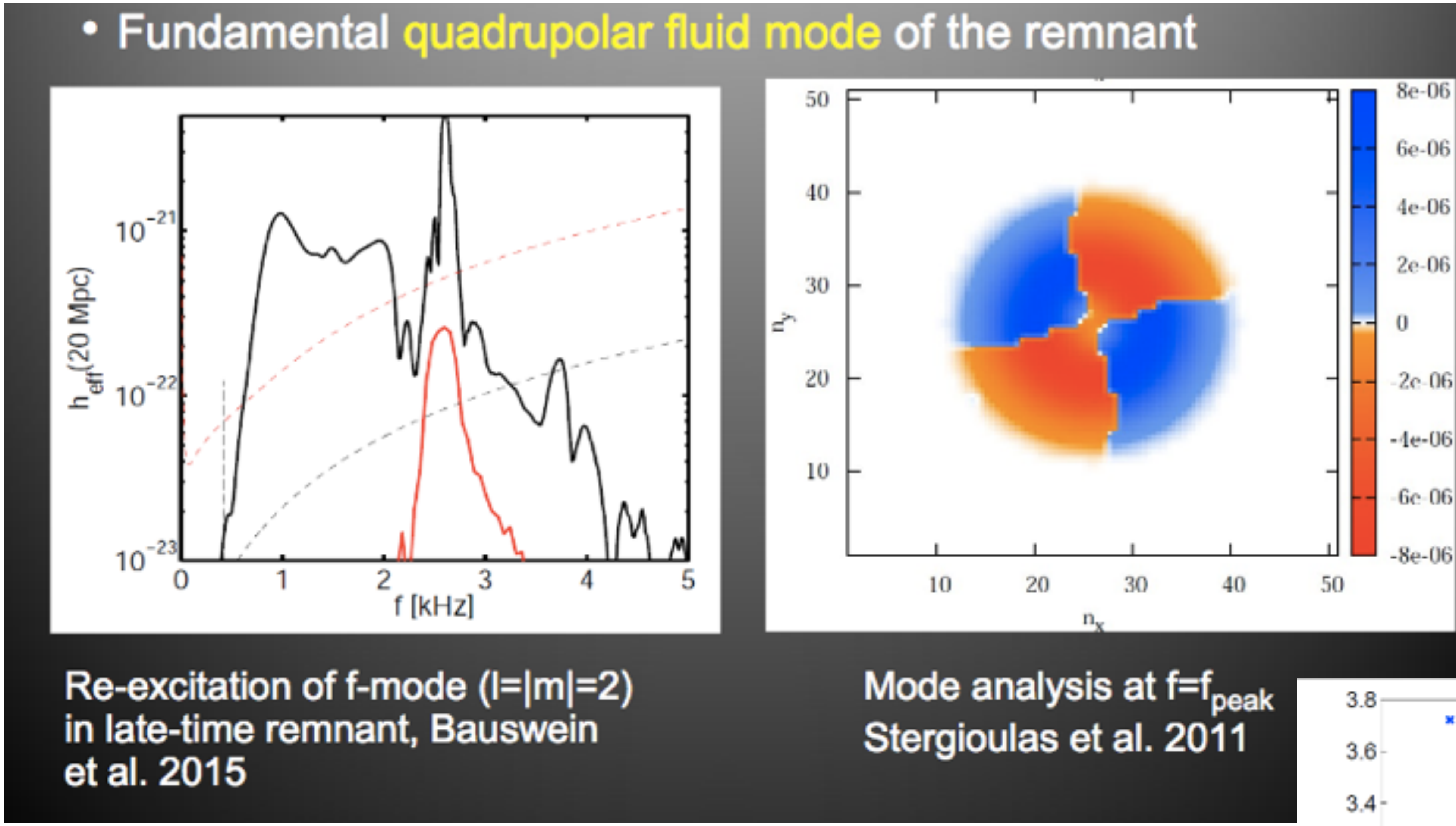
MD simulation of Nuclear Pasta with 100,000 nucleons

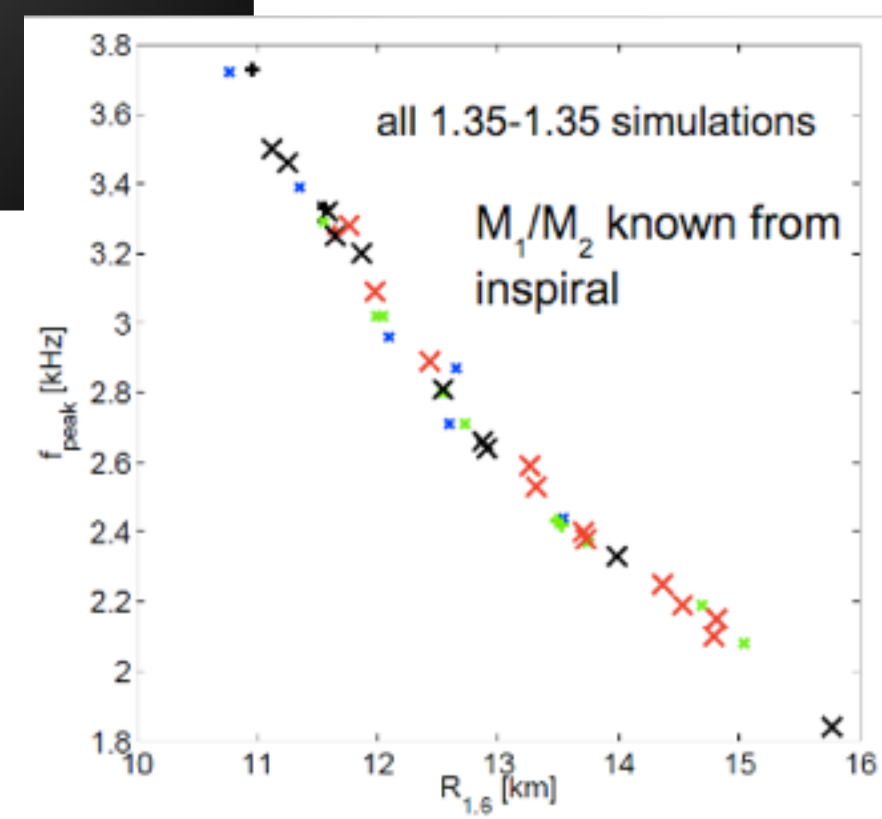
Study n rich matter

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



Gravitational waves and EOS



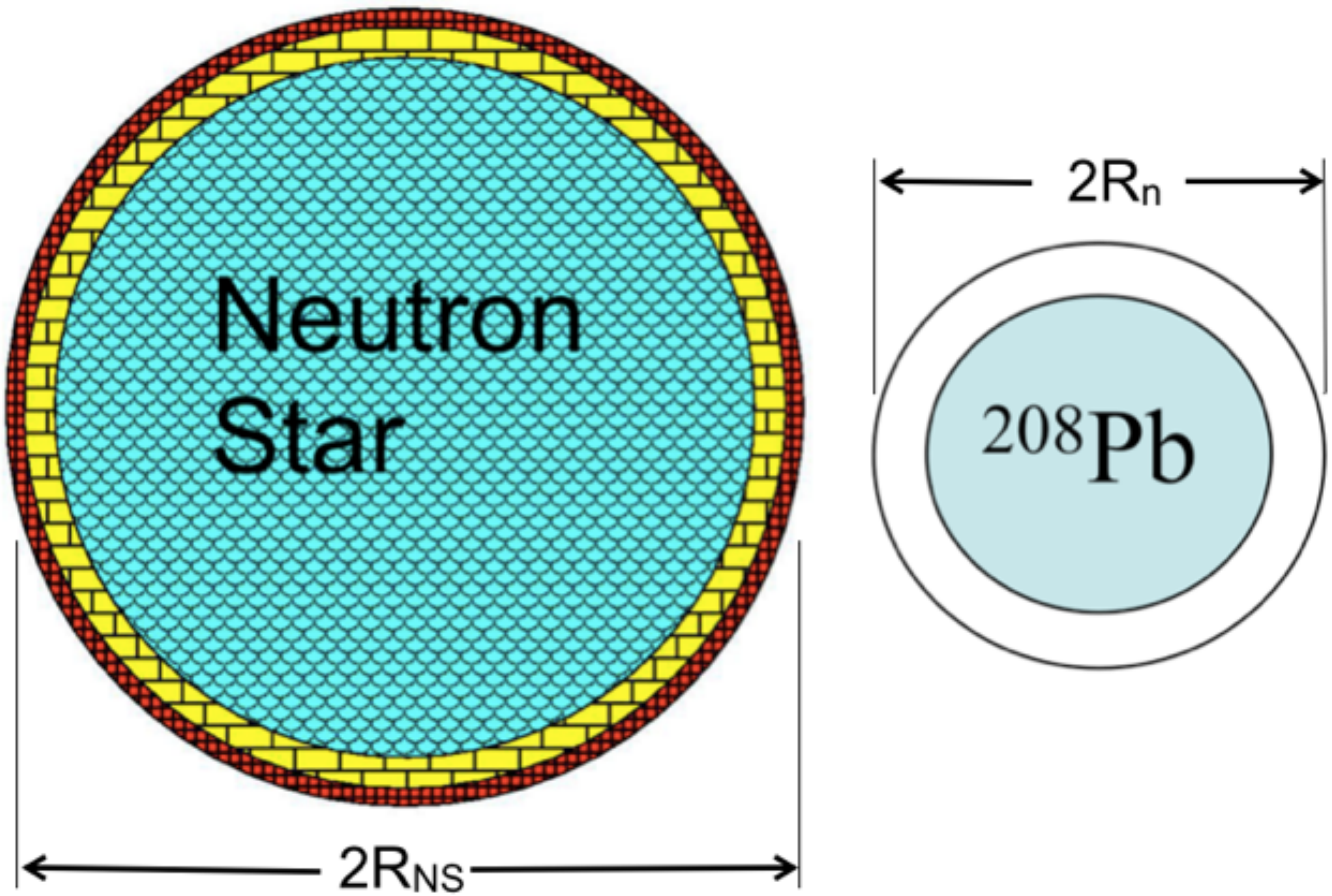


Frequency of oscillation of hyper massive NS during merger provides information on EOS

Andreas Bauswein

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 near ρ_0
- Radius of (~1.4M_{sun}) NS depends on P at medium densities > ρ_0.
- Maximum mass of NS depends on P at high densities.
- These three measurements constrain density dependence of EOS.

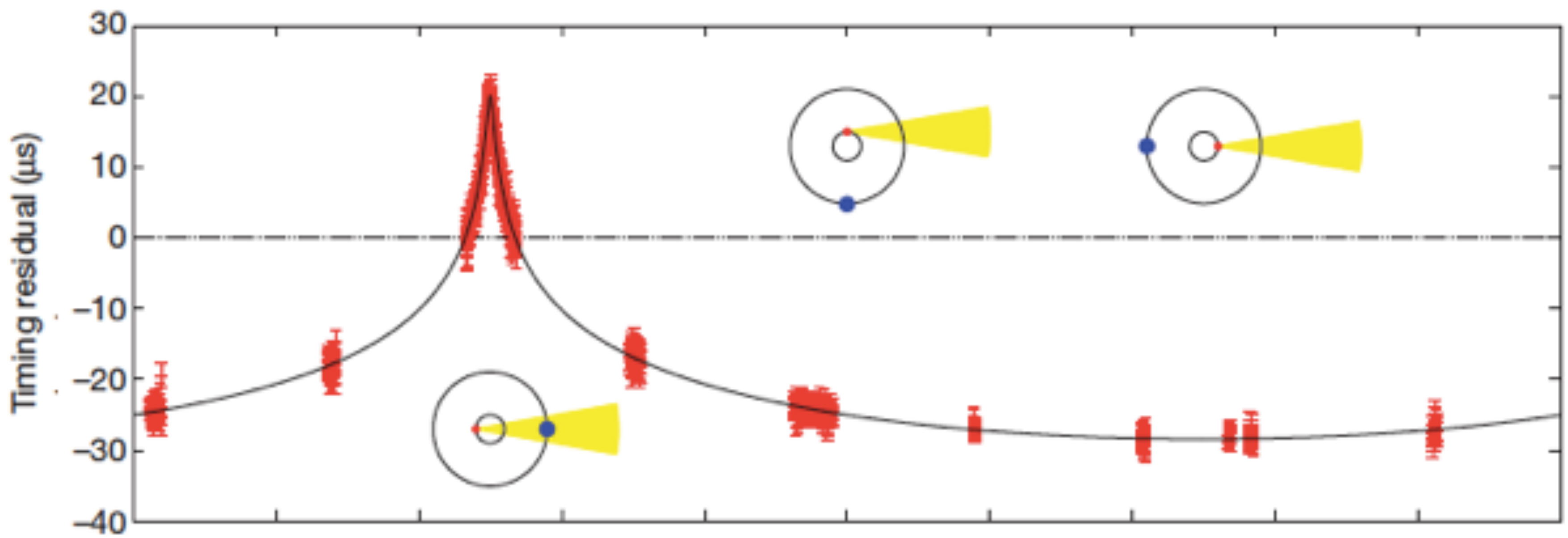


Neutron star is 18 orders of magnitude larger than Pb nucleus but has same neutrons, strong interactions, and equation of state.

Discovery of $2M_{sun}$ Neutron Star

Demorest et al: PSR J1614-2230 has 1.97+/- 0.04 M_{sun}.

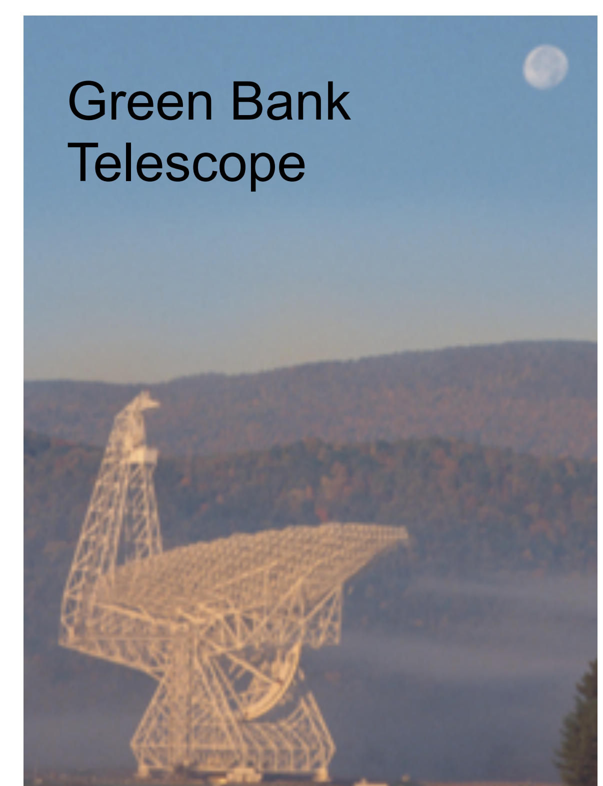
Delay in pulse arrival



NS + White Dwarf Binary

Orbital phase

- The equation of state of neutron rich matter (pressure vs density) at high densities must be stiff enough (have a high enough p) to support this mass against collapse to a black hole. *All soft EOS are immediately ruled out!*
- *However this does not tell composition of dense matter be it neutron/ proton, quark, hyperon...*
- *NS cooling (by neutrinos) sensitive to composition.*



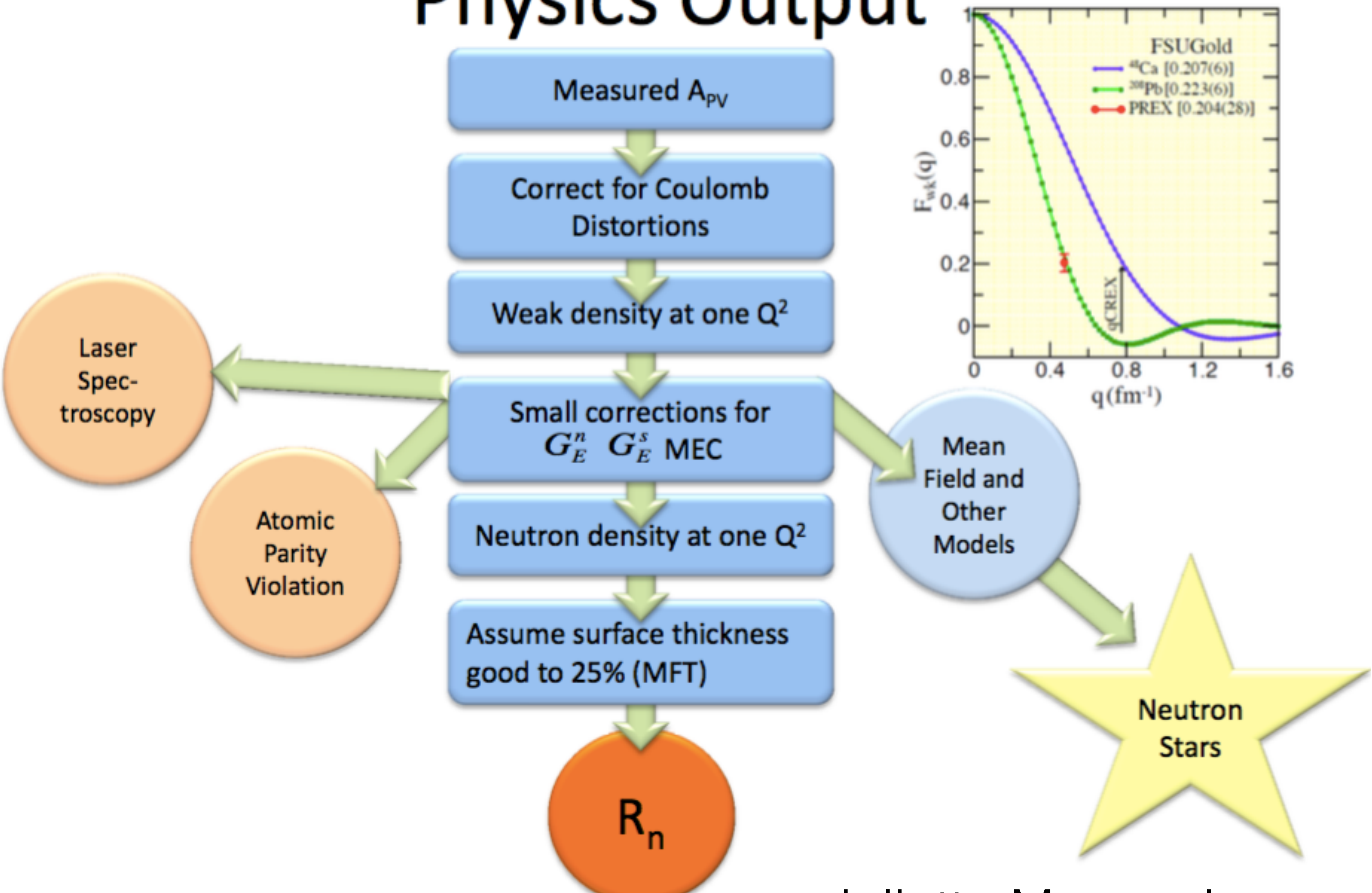
Definition of Neutron Skin

- Expect a neutron rich region near the surface of a heavy nucleus. I call this surface region the neutron skin.
- This allows one to study neutron rich matter in the laboratory.
- The thickness of the n skin can be characterized by R_n-R_p.
- By convention, a very extended density from very weakly bound neutrons is called a halo.

Probes of neutron skin

- It is subtle to probe neutron-rich subregion of nucleus. Premium on accuracy of probe.
- Experimental probes we considered: protons, antiprotons, coherent pi0, parity violation, dipole polarizability, atomic parity.
- Some probes are only for stable nuclei while others also work for radioactive beams.
- First step in determining error for a given probe is drawing a flow diagram of analysis procedure and assigning errors to steps.

Physics Output



Different Kinds of Errors

- **Statistical** (hard to reduce for PV)
- **Systematic** (For PV: helicity correlated beam properties, normalization, measuring Q^2…)
- **Reaction mechanism** (Most important for hadronic probes! For PV: uncertainties in radiative corrections -> likely very small)
- **Model** (errors associated with unmeasured features of the neutron density. For PV need surface thickness to get R_n-R_P.)

Model errors

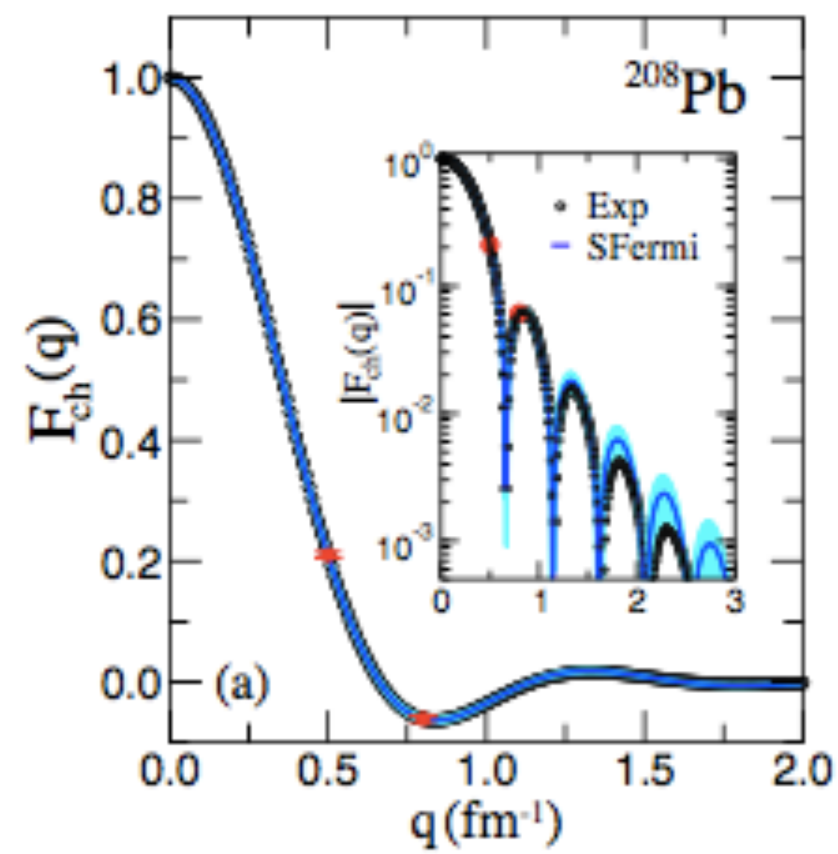
- Can be minimized or avoided if
- Experimentalists can say with precision exactly what is measured.
- Theorists calculate the same quantity.
- For PV, clean reaction mechanism sharply defines measured quantity $F_w(q)$ or $F_{ch}(q)$-$F_w(q)$. If these are compared to theory, PV is very largely model independent.

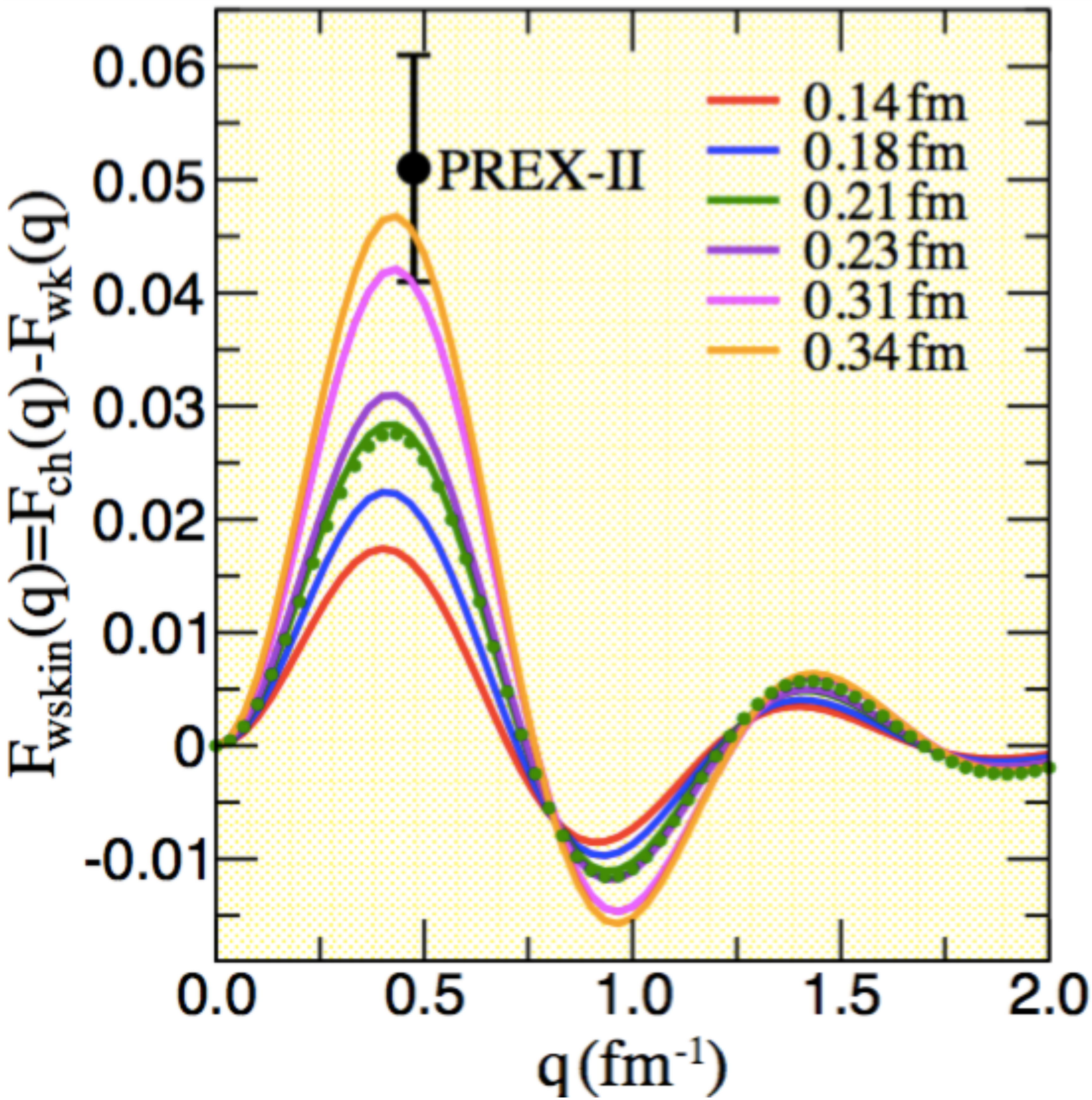
Model error for antiprotons

- Clearly antiprotons measure property of tail of neutron density.
- If experiment is reproduced using a neutron density expressed as a 2P Fermi function and this is used to calculate R_n —> likely introduces a large model error. *The tail is wagging the dog.*
- Instead we should have theory calculate appropriately waited tails of their neutron densities and these can be compared cleanly to antiproton data.

Model error PREX

- Jorge wants to use PREX II and correlation between R_n-R_p and L to determine L.
- Expensive solution: measure at 2nd Q^2 point to constrain surface thickness to remove model error in R_n-R_p.
- Alternative: Correlate L with finite q version of neutron skin in ^{208}Pb: R_n-R_p—> $F_{ch}(q)$-$F_w(q)$

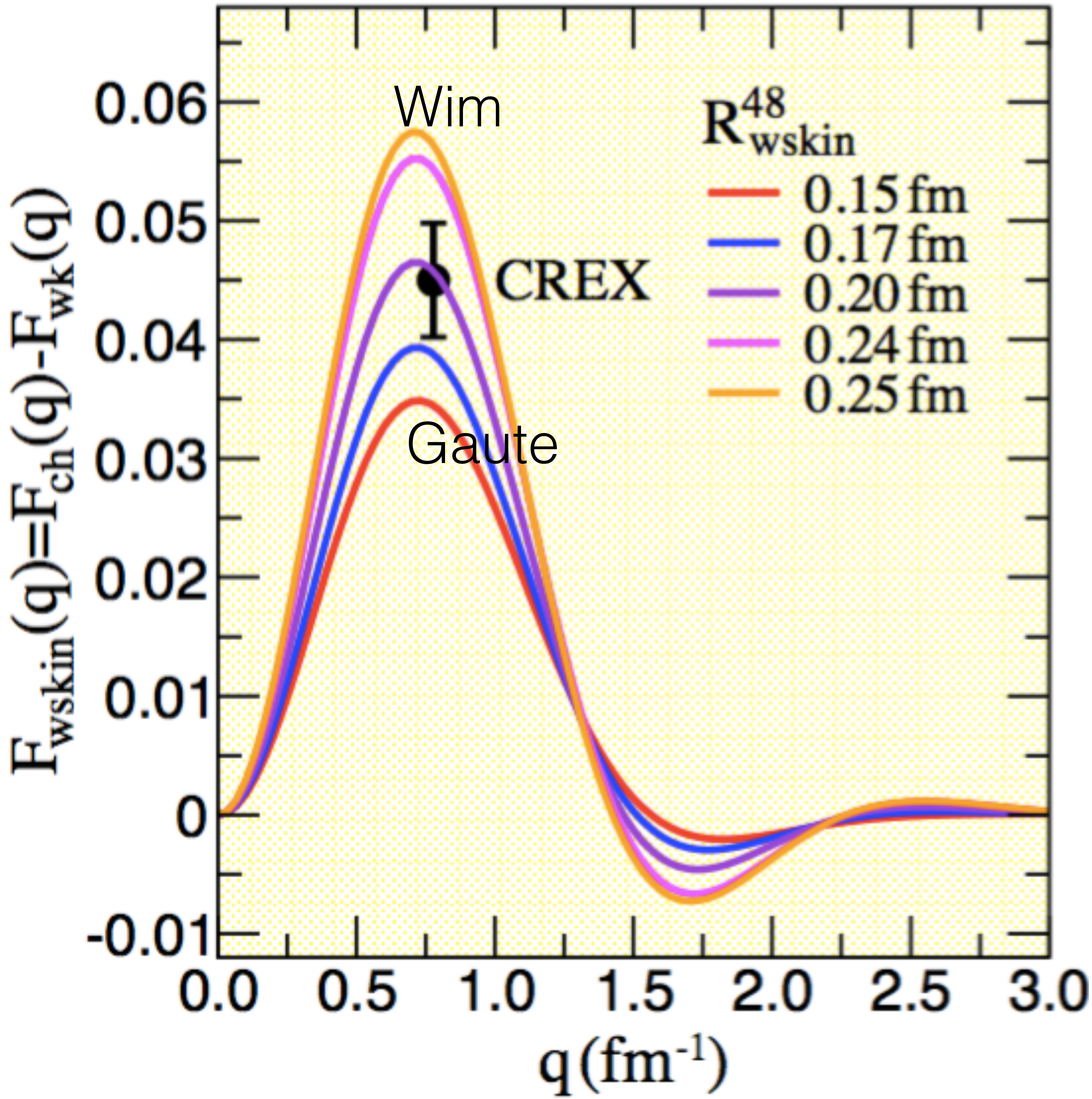




0.14 fm
0.18 fm
0.21 fm
0.23 fm
0.31 fm
0.34 fm
PREX-II
$F_{wskin}(q)=F_{ch}(q)-F_{wk}(q)$
q (fm^{-1})
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
0.0
0.5
1.0
1.5
2.0

Model Error CREX

- Gaute calculated very sharp R_n-R_p for ^{48}Ca precise to +/- 0.015 fm. [CREX +/- 0.02 fm]
- But nuclear saturation is subtle and gives large correlated error between R_n and R_p.
- As a results his R_n is only good to +/-0.06 fm! and therefore his $F_w(q)$ is not very precise. Comparing this to CREX is only a weak test!
- Instead Gaute should calculate $F_{ch}(q)$-$F_w(q)$ where correlated error in R_n and R_p cancels.

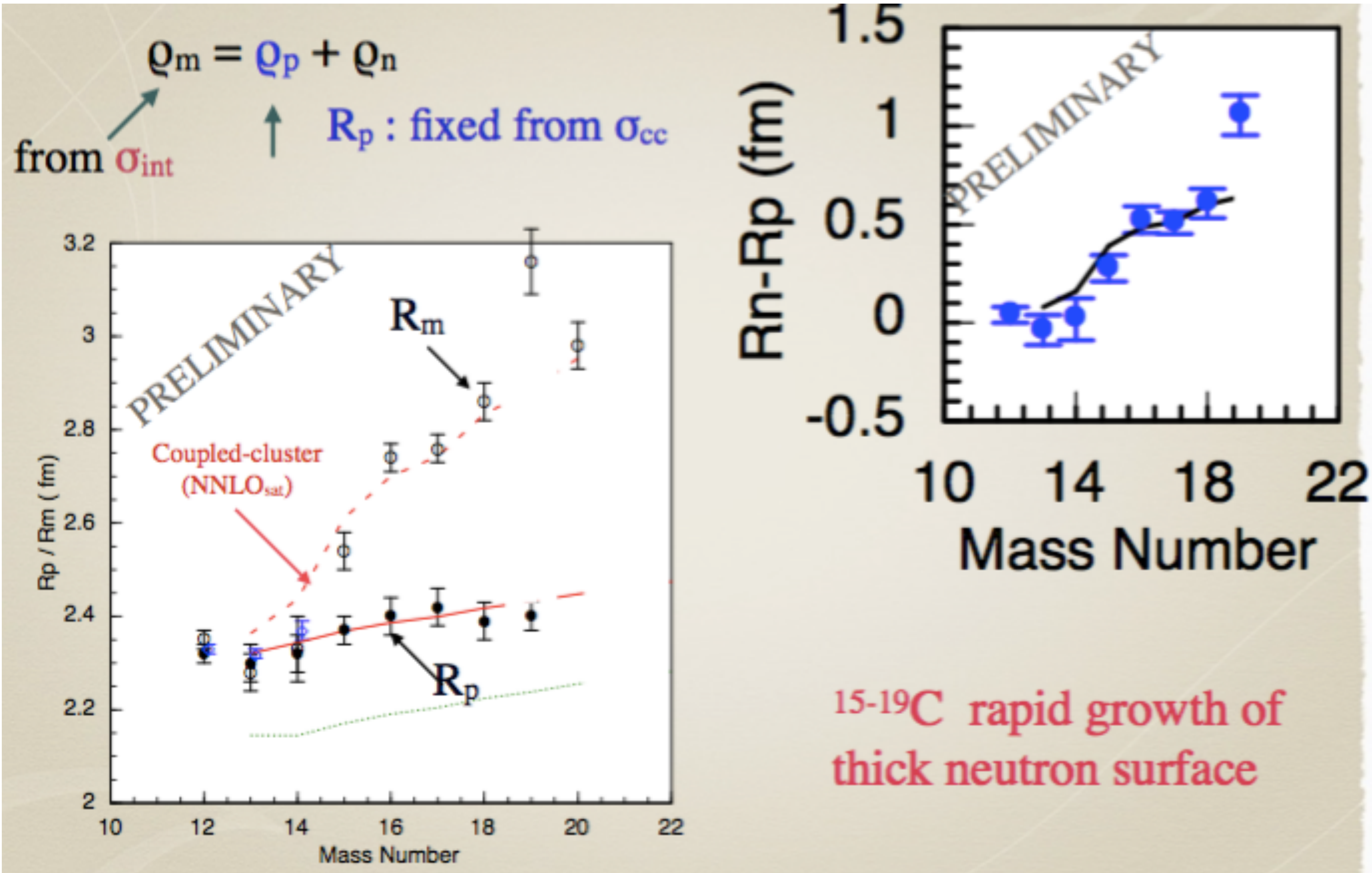


Wim
CREX
Gaute
R^{48}_{wskin}
0.15 fm
0.17 fm
0.20 fm
0.24 fm
0.25 fm
$F_{wskin}(q)=F_{ch}(q)-F_{wk}(q)$
q (fm^{-1})
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
0.0
0.5
1.0
1.5
2.0
2.5
3.0

Reaction mechanism: hadronic probes

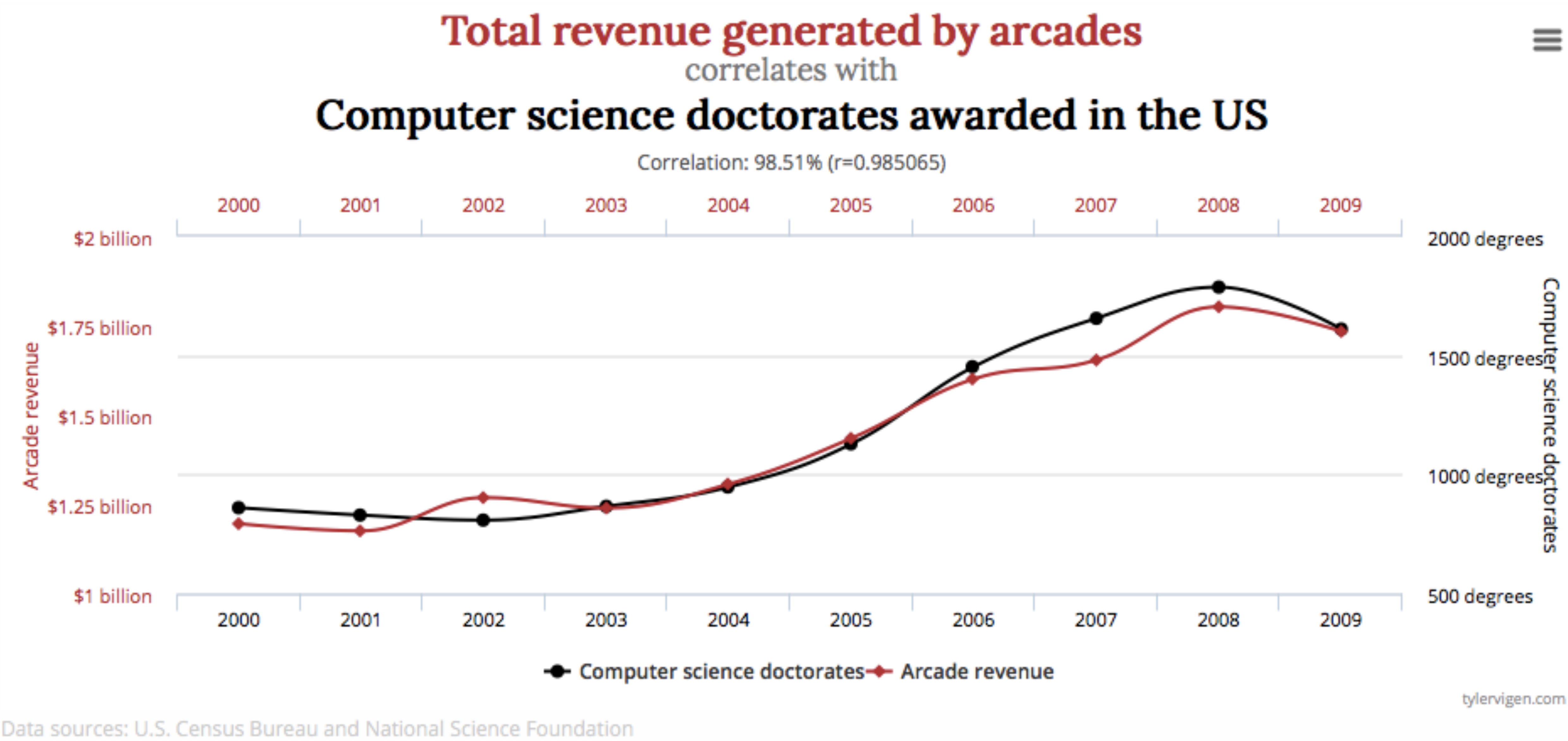
- List some kinds of Rxn error that should be addressed.
- Example: proton elastic scattering at E/A~300 MeV at GSI (Kanungo).
- Optical pot in t rho apprx: $U_{opt}=\rho(q)t(q)$
- Some errors: momentum dep. of t, density dependance (Pauli blocking …), higher order interactions (multiple scattering …)

N rich carbon isotopes



- Compare radii of coupled cluster calculations of Hagen et al with Kanungo et al proton scattering.

Correlations



- One of several correlations that was suggested to me by a conference participant.

Correlations with L

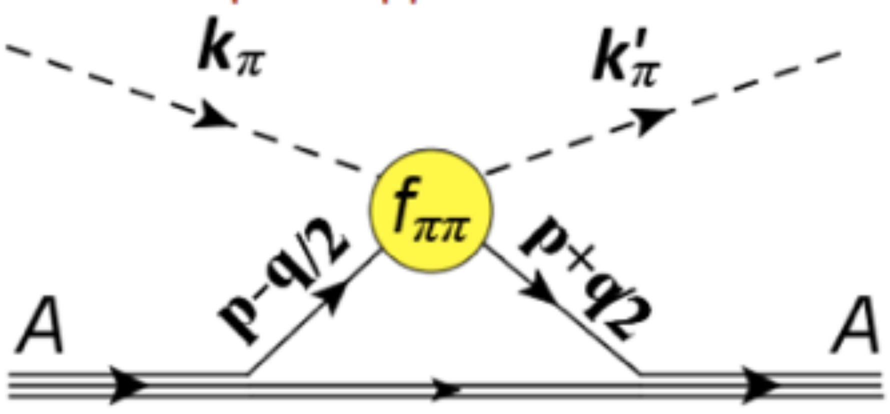
- R_n-R_p in ^{208}Pb sharply correlated with L.
- R_n-R_p in ^{48}Ca correlated but less sharply with L.
- R_n-R_p in ^{19}C likely correlated even less sharply with L. "Complete set of models" could lead to a very fat plot??? (That is my guess)

Coherent pi0

- Reaction mechanism errors need to be further explored / documented.
- What is density dependance of pi production amplitude? Does it depend on delta-hole model??
- Could be sensitive to even a small amount of pion production on two nucleons because q^2 dependence is different.
- Charged pion production, followed by charge exchange scattering can contribute coherently.

Pion-nucleus scattering: tρ potential

Impulse approximation:



$$T(\bar{k}',\bar{k}) = \langle \bar{k}'|T_{IA}^{\pi A}|\bar{k}\rangle = \sum_{\alpha\beta}\langle \bar{k}',\alpha|t_{IA}^{\pi A \mathrm{c.m.}}|\bar{k},\beta\rangle\langle\Phi_A|\hat{c}_\alpha^\dagger\hat{c}_\beta\Phi_B\rangle = \quad (1)$$

$$\sum_{\alpha<F}\int\frac{d^3\bar{p}}{(2\pi)^3}\phi_\alpha^*(\bar{p}+\bar{q}/2)\phi_\alpha(\bar{p}-\bar{q}/2)t_{\pi N}^{\pi A\mathrm{c.m.}}(\bar{k}',\bar{p}+\bar{q}/2;\bar{k},\bar{p}-\bar{q}/2)$$

Factorization approximation:

$$\langle \bar{k}'|T_{IA}^{\pi A}|\bar{k}\rangle = \rho(\bar{q})t_{\pi N}^{\pi A\mathrm{c.m.}}(\bar{k}',\bar{k};\bar{q}) \quad (2) \qquad \rho(\bar{q}) = \int\frac{d^3\bar{p}}{(2\pi)^3}\phi_\alpha^*(\bar{p}+\bar{q}/2)\phi_\alpha(\bar{p}-\bar{q}/2), \quad \rho(0)=A \quad (3)$$

$$t_{\pi N}^{\pi N\mathrm{c.m.}}(\bar{k}'_{\mathrm{c.m.}},\bar{k}_{\mathrm{c.m.}};\bar{q}_{\mathrm{c.m.}}) = -4\pi(b_o + c_o\bar{k}'_{\mathrm{c.m.}}\cdot\bar{k}_{\mathrm{c.m.}}) \quad (4)$$

$$\bar{k}'_{\mathrm{c.m.}}\cdot\bar{k}_{\mathrm{c.m.}} \approx \frac{1}{(1+\varepsilon)^2}\left[\bar{k}'\cdot\bar{k}-\frac{\varepsilon}{2}\bar{q}^2\right], \quad \varepsilon=\omega/m_N \quad (5)$$

$$\langle \bar{k}'|T_{IA}^{\pi A}|\bar{k}\rangle = -4\pi\rho(\bar{q})\left((1+\varepsilon)b_o + \frac{c_o}{1+\varepsilon}\left[\bar{k}'_{\mathrm{c.m.}}\cdot\bar{k}_{\mathrm{c.m.}}-\frac{\varepsilon}{2}\bar{q}^2\right]\right) \quad (6)$$

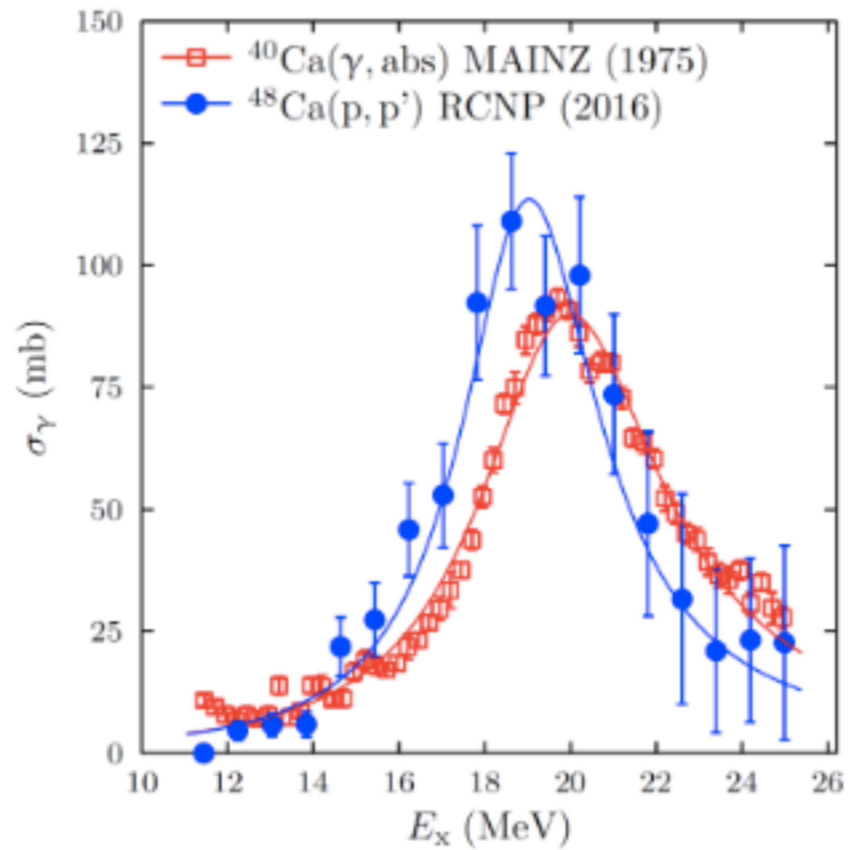
Slava Tsaran

Null tests on symmetric N=Z nuclei

- Test for some things, but can miss many errors such as leaving the lens cover on.
- Example: $U_{opt} = a\ (\rho_p+\rho_n) + b\ (\rho_n-\rho_p)$. Finding R_n-R_p small in ^{40}Ca does not test b term at all. Better to fit a nonzero skin as measured with PREX or CREX.

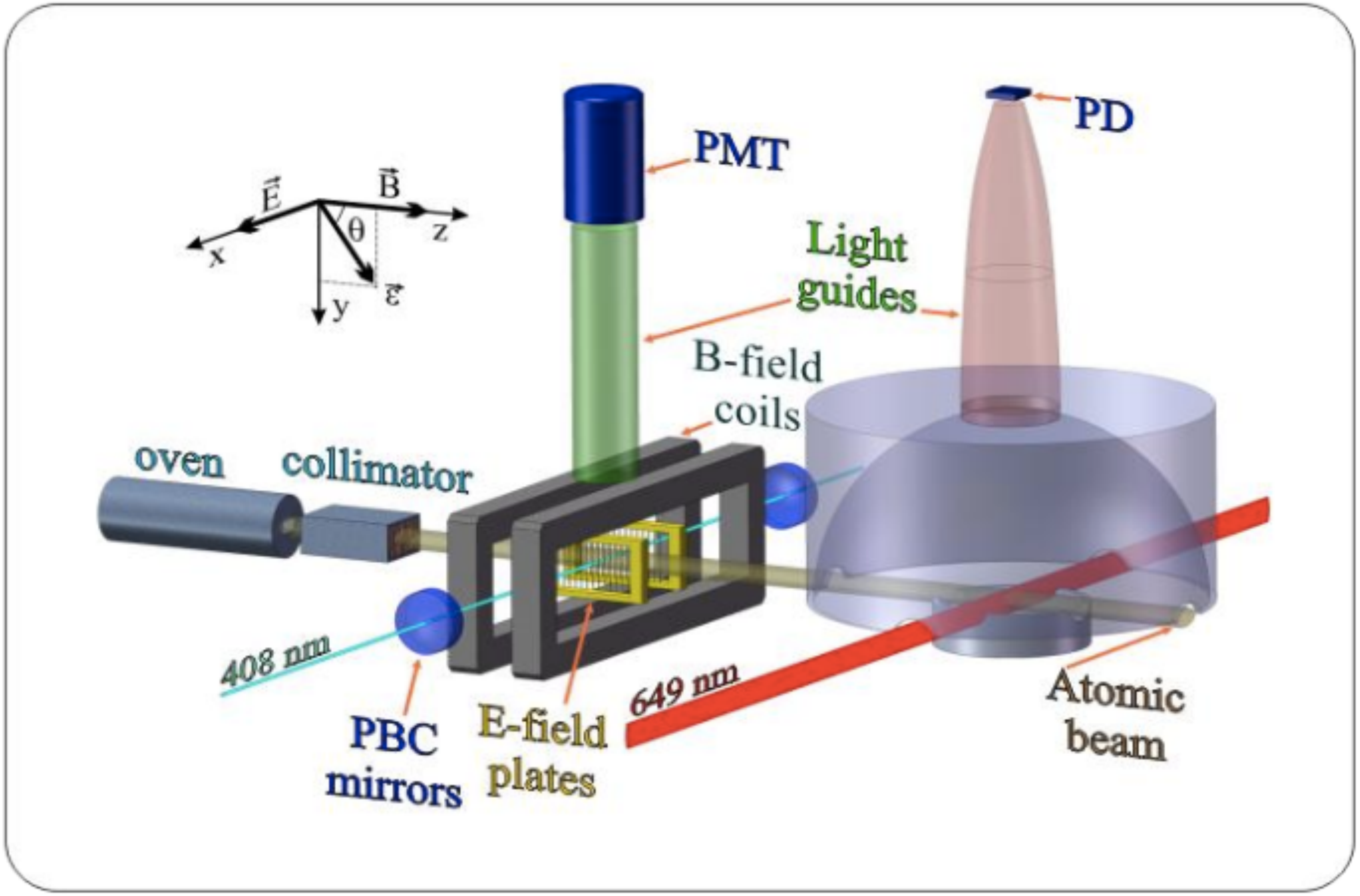
^{48}Ca Dipole polarizability

- We thank Peter Von Neumann-Cosel et al for sharing preliminary results! And we eagerly await final results.
- Tamii et al may have set very high bar with accuracy of ^{208}Pb data.



■ ^{48}Ca: $\alpha_D = (2.07 \pm 0.22)$ fm^3

The Yb PV Experiment



Rotational Invariant: $\left(\vec{\varepsilon}\cdot\vec{B}\right)\left(\vec{E}\times\vec{\varepsilon}\cdot\vec{B}\right)$

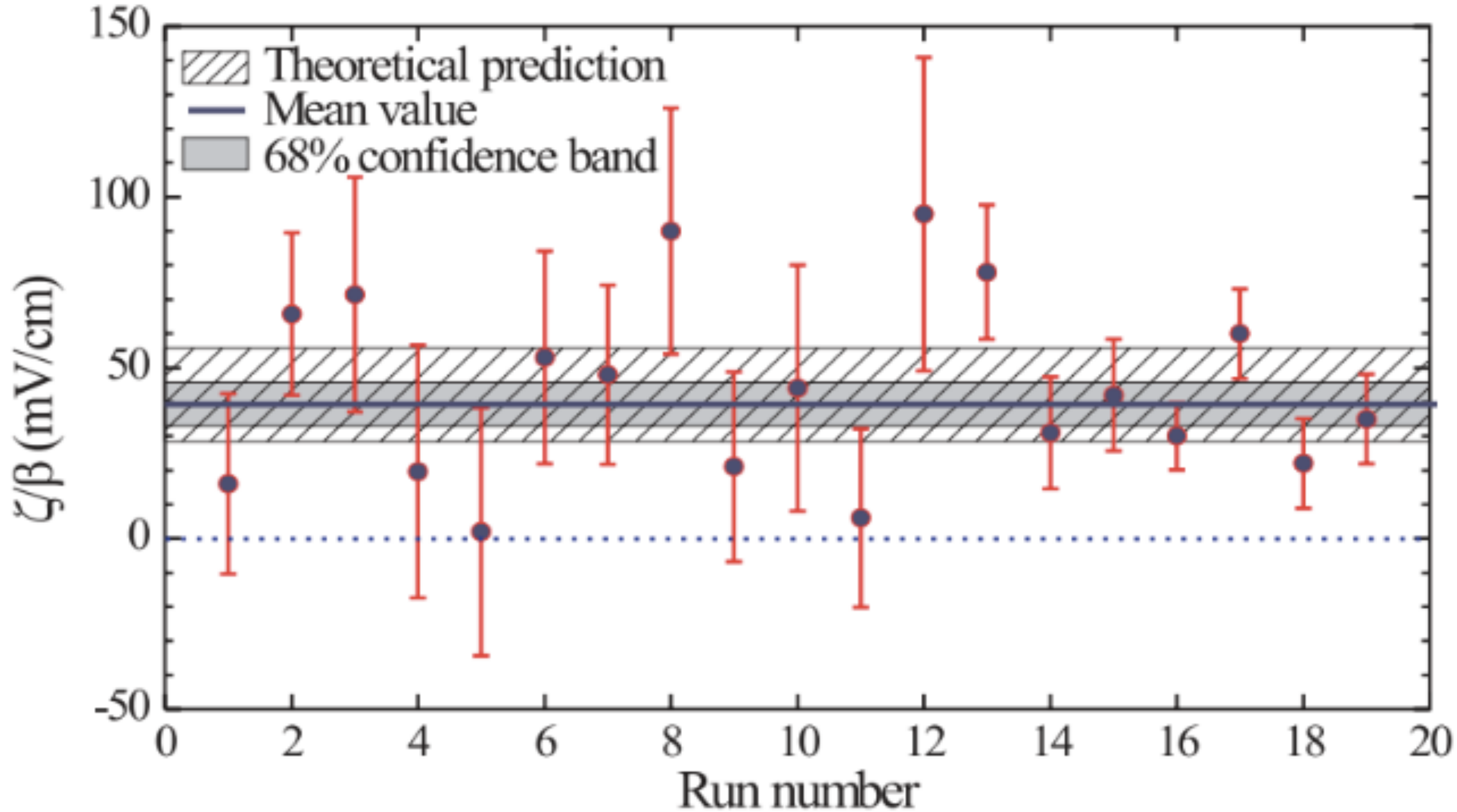
PRL **103,** 071601 (2009)

Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS

week ending
14 AUGUST 2009

Observation of a Large Atomic Parity Violation Effect in Ytterbium

K. Tsigutkin,[1,*] D. Dounas-Frazer,[1] A. Family,[1] J. E. Stalnaker,[1,†] V. V. Yashchuk,[2] and D. Budker[1,3]

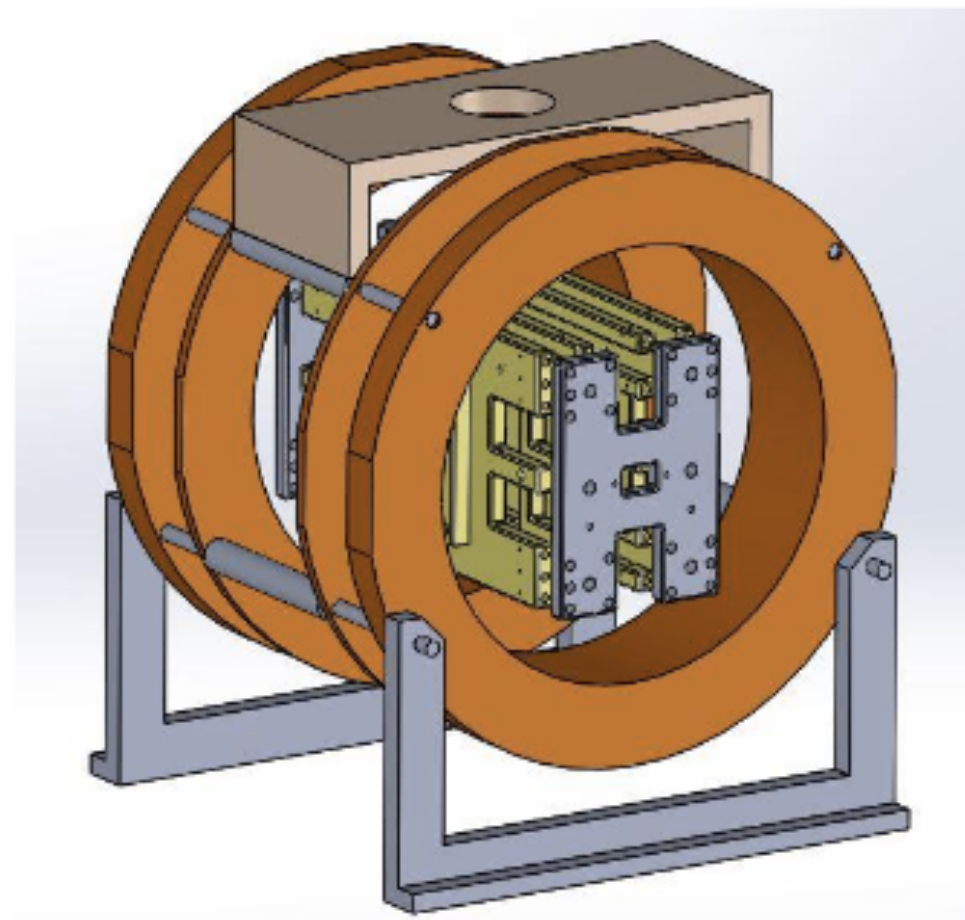


Mean value: $39(4)_{\text{stat}}(5)_{\text{syst}}$ mV/cm, $|\zeta| = 8.7 \pm 1.4 \times 10^{-10} ea_0$

Yb reincarnation in Mainz

Apparatus upgrades

- New, more **powerful** 408 nm laser
- Improved interaction region design to minimize electric field imperfections
- Currently achieving **SNR ~ 0.5/√Hz** in PNC amplitude (laser noise limited)



Roadmap

- Verify expected isotopic dependence of E_{PNC} (0.5% accuracy) - 6 months
- Probe anapole moment (~0.2 %) - (1 year)
- Neutron distributions/Standard model check (~0.1%) - 2 years

Atomic parity

- I was impressed with the thought, care, and effort that has gone into systematic errors and with the progress!
- It is time for theorists to revisit anapole moments. An experimental result will incite a great deal of theoretical work.
- For neutron skins, a new model error: how does the skin in nucleus X depend on the skin in Y?
- Very poor overlap between good PV e scattering nuclei and good atomic PNC atoms. Possible exception Ba???

Theoretical Nuclear Structure Program

- How accurately can we calculate structure of Fr or Yb … isotopes and their neutron skins given charge radii and PREX II, CREX results?
- Probably not so badly, limited by knowledge of isotopes structure.
- An atomic PNC measurement of a neutron skin will stimulate much theoretical work along these lines!
- Theoretical errors on skin likely fine for standard model test.

Neutron skins, halos, wings, and tails

$\bar{p}$

Summary: Neutron skins of nuclei

- Thank you for coming and participating.
- Many many thanks to Concettina!

C. J. Horowitz, Indiana University, Mainz, May 2016