Overview of Low energy nuclear physics and FRIB

William Lynch

- Low energy physics:
  - not JLAB or RHIC
- How has the field evolved?
- What are some of the new scientific objectives?
  - Will not discuss everything.
  - More focus will be on topics that have some reaction dynamics component.

John was my thesis advisor and gets the “credit” for getting me started in nuclear physics

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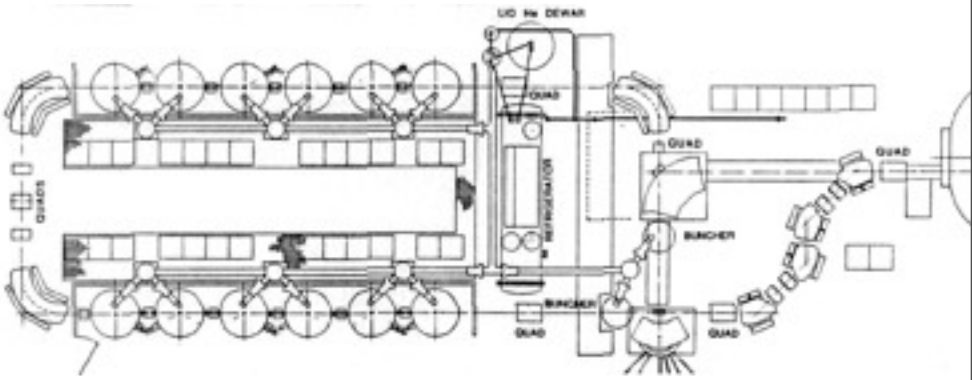
CHAOS BRIAN SHUSTER

"Oh, and I suppose it was me who said 'what harm could it be to give the chickens a book on nuclear physics?'"

In 1975-1980, one frontier was physics with HI beams

NPL Booster Linac



New Physics

- Heavy Ion reactions
- Nuclear mean field at high density.
- Nuclear structure at high spin.

New Instruments

- Heavy Ion accelerators

  Superconducting Linacs and Cyclotrons: (Ex. UW booster)

  HI stripping and transport
- 4π γand charged particle arrays
- Fragmentation studies motivated new use for these accelerators

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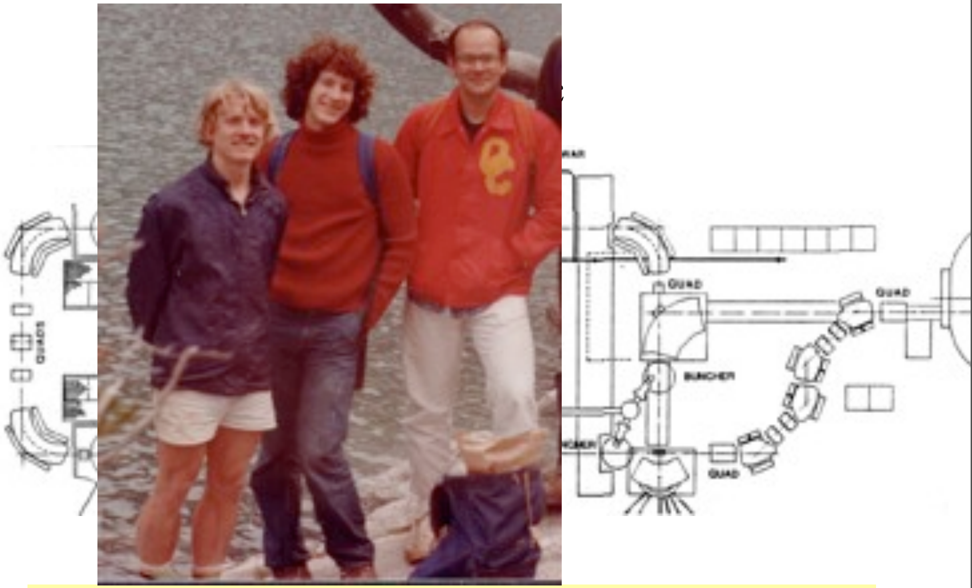

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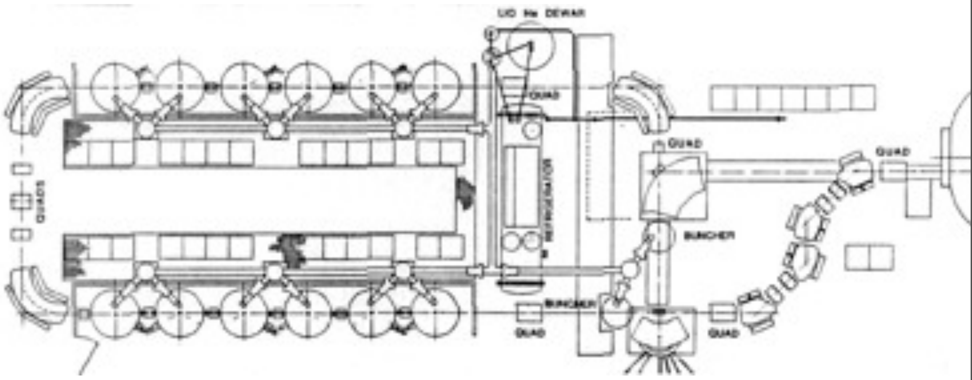

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“Low Energy” Frontier 2009: Physics with rare isotope beams

New Physics

- Structure of very neutron-rich nuclei.
- Mean field potential for neutron-rich matter.
- Nuclear Astrophysics in explosive environments and neutron stars.

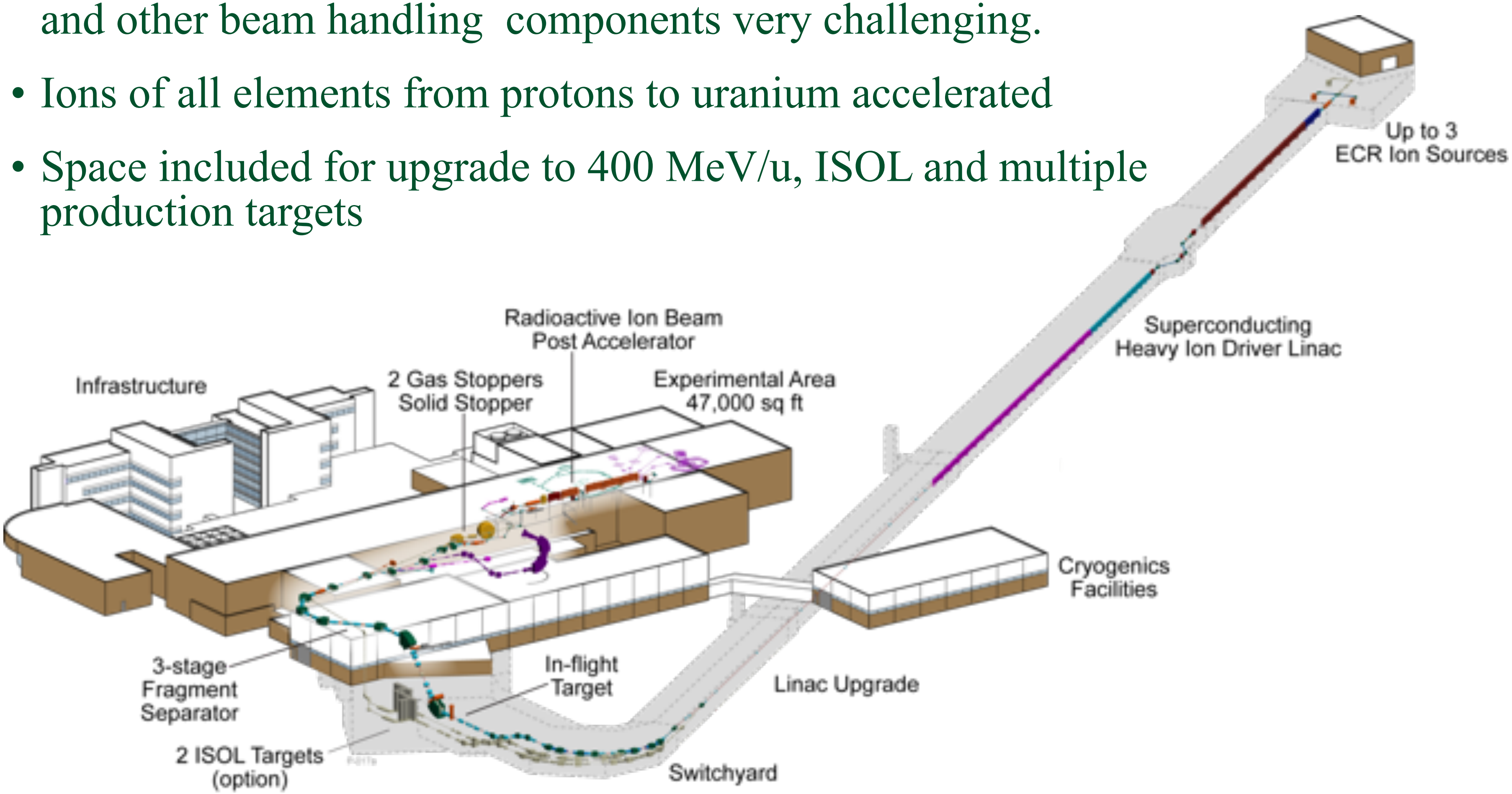
New Instruments

- Rare isotope beam “factories” to produce neutron-rich systems for study:

  Examples: FAIR (Darmstadt), RIBF (Wakoshi), FRIB (East Lansing)
- Highly efficient detection systems to overcome low RI intensities.

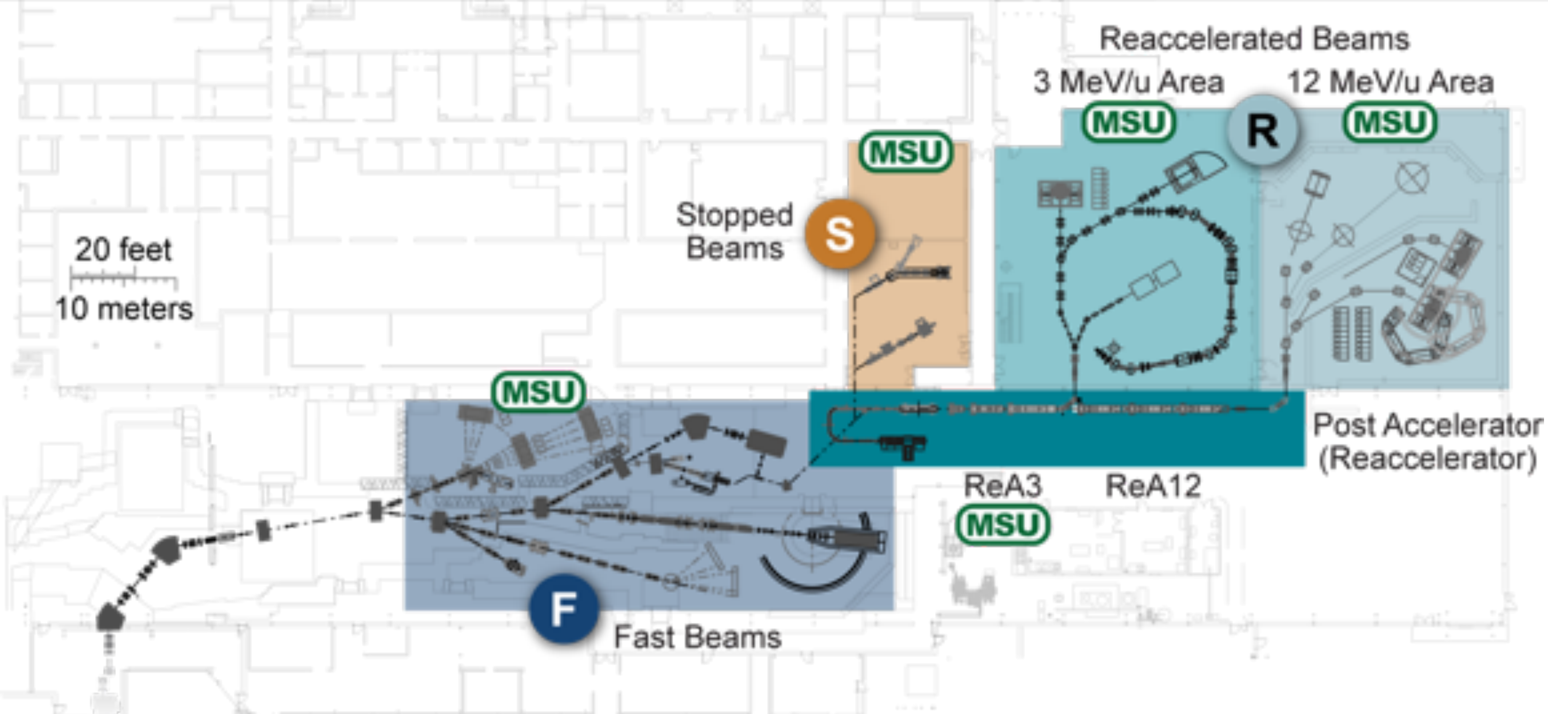
FRIB General Features

- Driver linac with 400 kW and greater than 200 MeV/u for all ions.
- High power makes requirements of stripper, target, beam dump and other beam handling components very challenging.
- Ions of all elements from protons to uranium accelerated
- Space included for upgrade to 400 MeV/u, ISOL and multiple production targets



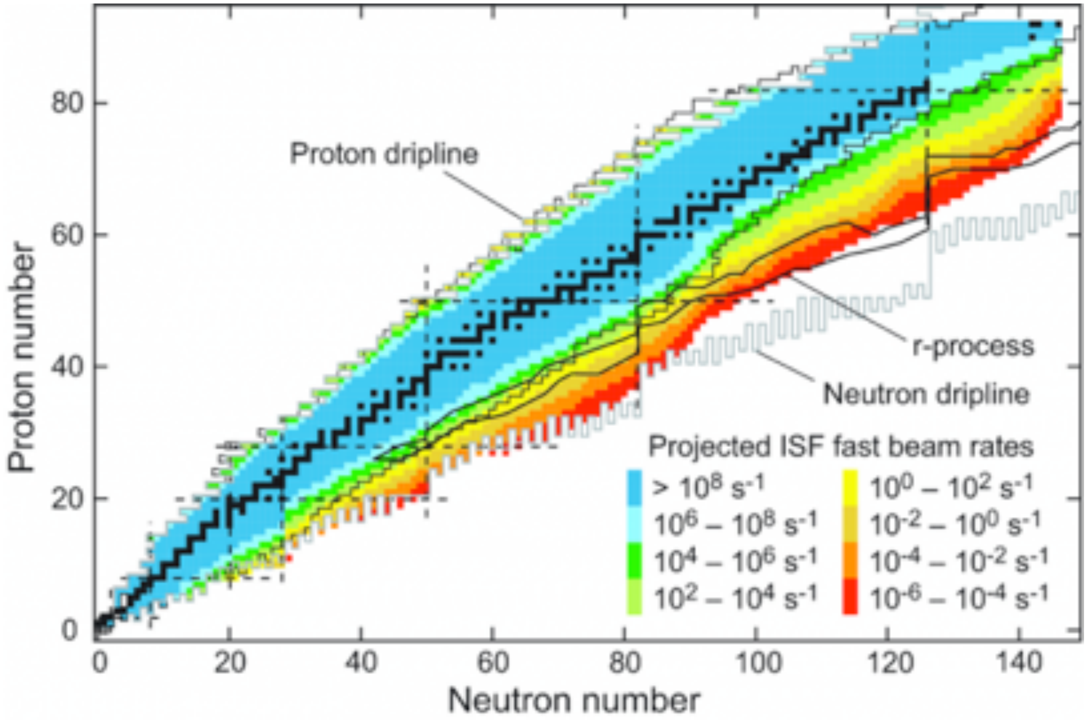
ReA12 and Experimental Areas

- A full suite of experimental equipment will be available for fast, stopped and reaccelerated beams
- New equipment
  - Stopped beam area (LASERS)
  - ISLA Recoil Separator
  - Solenoid spectrometer
  - Active Target TPC



What new capabilities will be enabled by the driver linac specifications?

- FRIB with 400 kW for all beams and minimum energy of 200 MeV/u will have secondary beam rates for some isotopes of up to 100 times higher than other world leading facilities
- FRIB intensity will allow the key benchmark nuclei ^{54}Ca (reaccelerated beams) and ^{60}Ca (fast beams) to be studied, for example, as well as many of the important nuclei along the r-process.



Beam intensity estimates from the ISF facility should be similar to those for FRIB

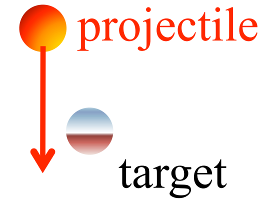
Some selected topics
(I will skip much more than I discuss.)

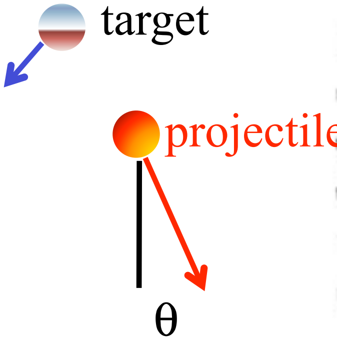
- Will discuss selected topics related to:
  - Mean field potential for neutron-rich matter.
  - Nuclear Astrophysics in explosive environments and neutron stars.
  - Structure of nuclei far from stability.
- Will not discuss:
  - Fundamental symmetries studies
  - Applications
  - Many exciting scientific opportunities will not be discussed

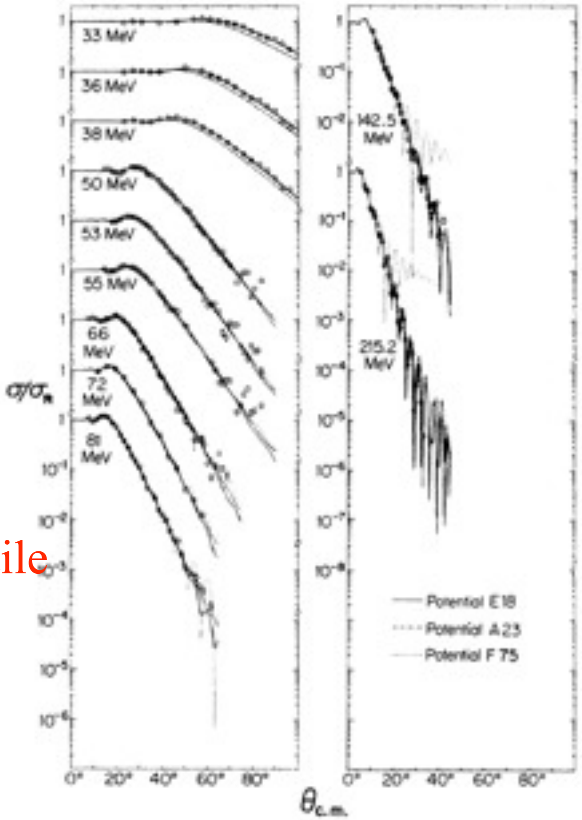
Mean field potential and EOS for neutron-rich matter.

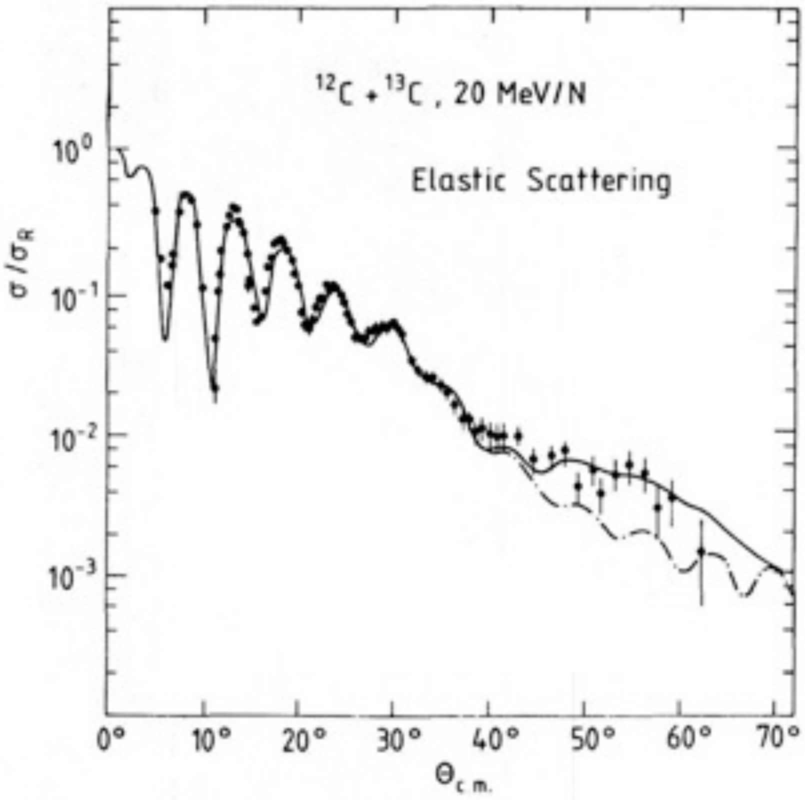
- Structure and astrophysics issue: How does the mean field potential and EOS vary with density and isospin?
- Reactions issue: How does one probe the mean field at supra-saturation density.

1975-1980 John Cramer: HI Optical potential







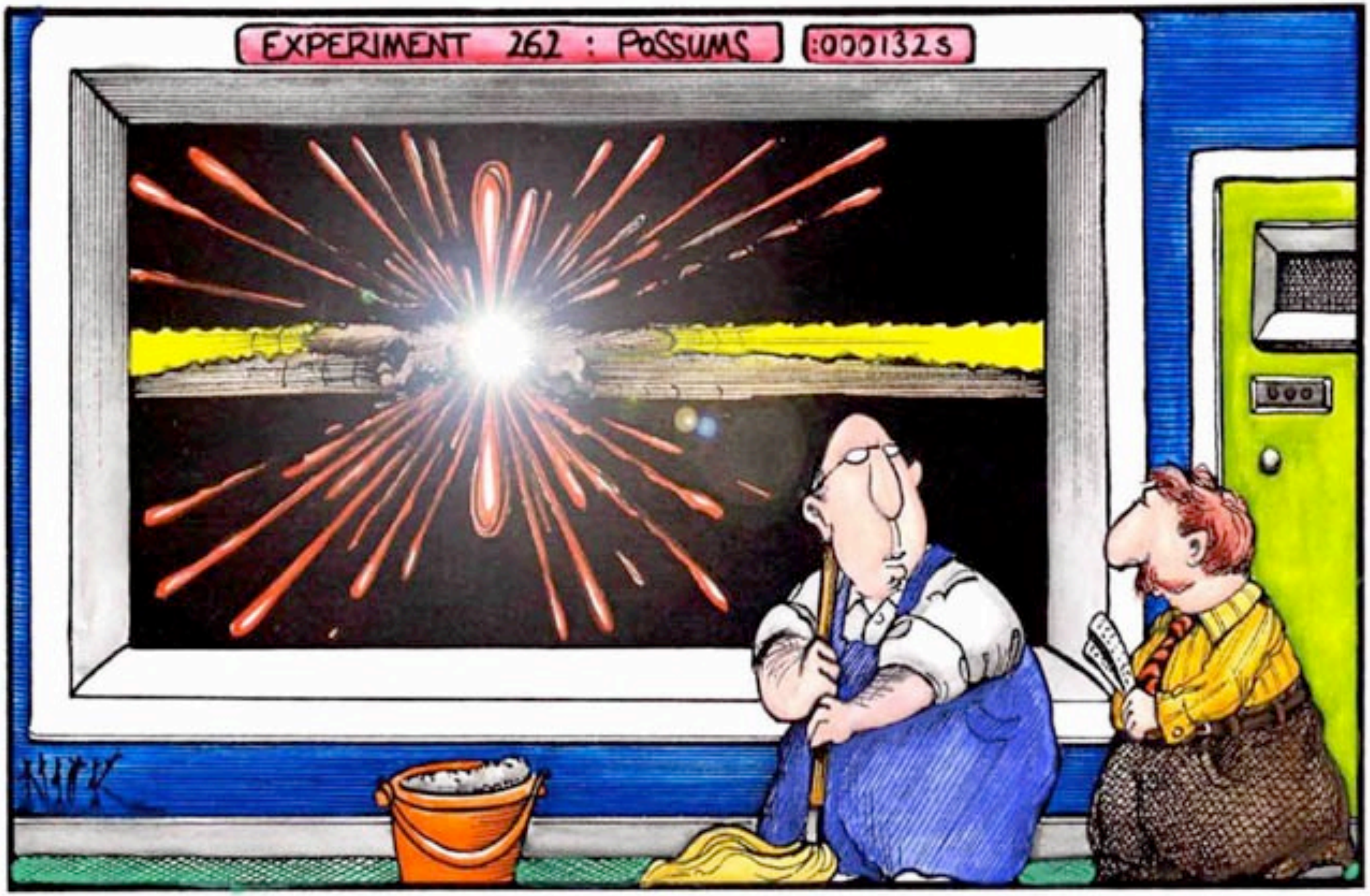


- Strong absorption limits sensitivity to mean field a high density in the center of nucleus.
- Lighter ions, higher energies exhibit rainbow scattering and provide sensitivity to interior.

- “Notch” sensitivity tests indicate that sensitivity to the interior can be achieved with lighter nuclei.
- Subsequent measurements place constraint on the mean field at $\rho \approx 2\rho_0$, “consistent with $K_{nm} \approx 250$ MeV.”

Higher densities

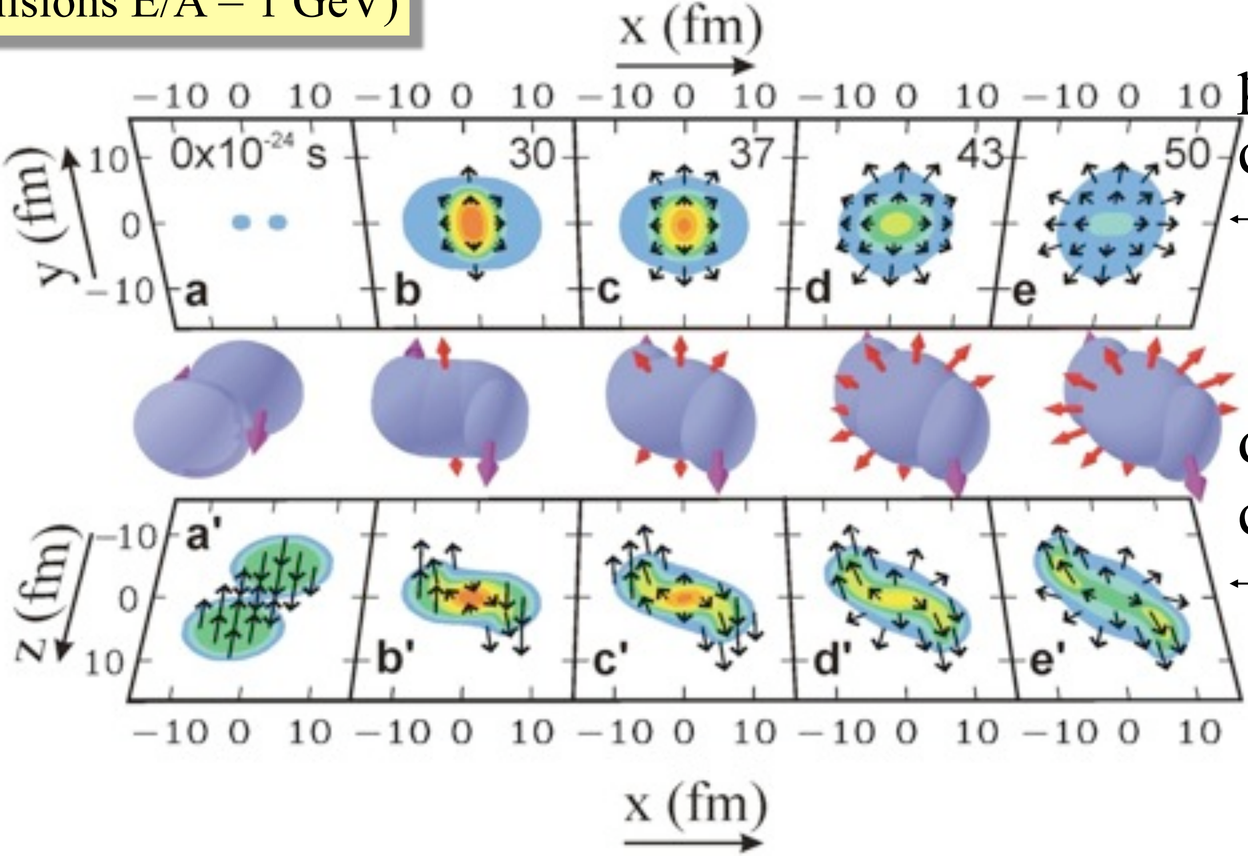
- To probe higher densities, one must collide complex nuclei.
- Higher densities are momentarily achieved by inertial confinement.
- Idea initially generated some skepticism



"Sure been a heap more work for ME around here since those Biologists got granted research time on the ol' Supercollider..."

Constraining the EOS at $\rho > 2\rho_0$ by nuclear collisions

Au+Au collisions E/A = 1 GeV)



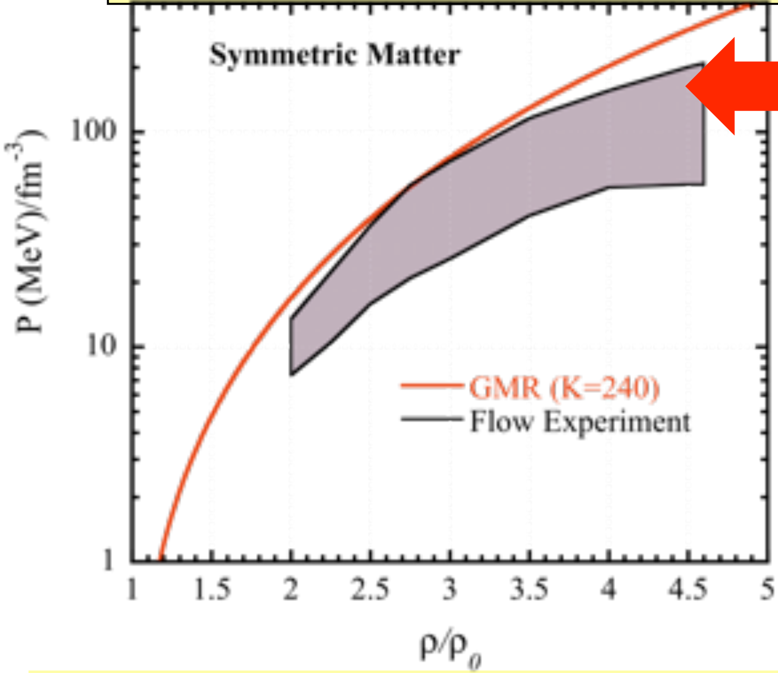
pressure contours

density contours

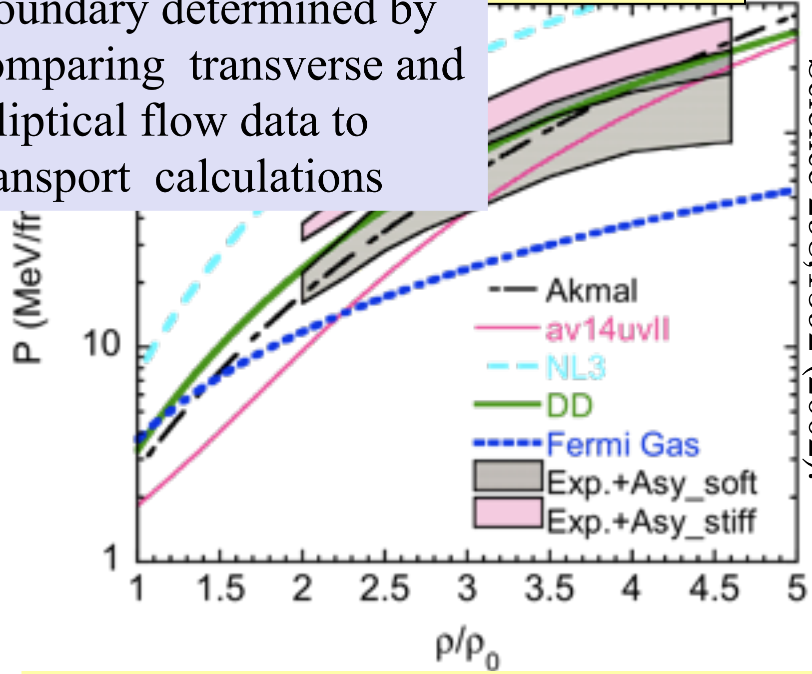
- Two observable consequences of the high pressures that are formed:
  - Nucleons deflected sideways in the reaction plane.
  - Nucleons are “squeezed out” above and below the reaction plane. .

Example: Constraints on symmetric matter EOS at $\rho > 2\,\rho_0$.

$E/A\,(\rho, \delta) = E/A\,(\rho,0) + \delta^2 \cdot S(\rho)$ $\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A \approx 1$



Boundary determined by comparing transverse and elliptical flow data to transport calculations



Danielewicz et al., Science 298,1592 (2002).

- Flow confirms the softening of the EOS at high density.
- Constraints from kaon production are consistent with the flow constraints and bridge gap to GMR constraints.
- Note: analysis requires additional constraints on m* and σ_{NN}.

- The symmetry energy dominates the uncertainty in the n-matter EOS.
- Both laboratory and astronomical constraints on the density dependence of the symmetry energy are urgently needed.

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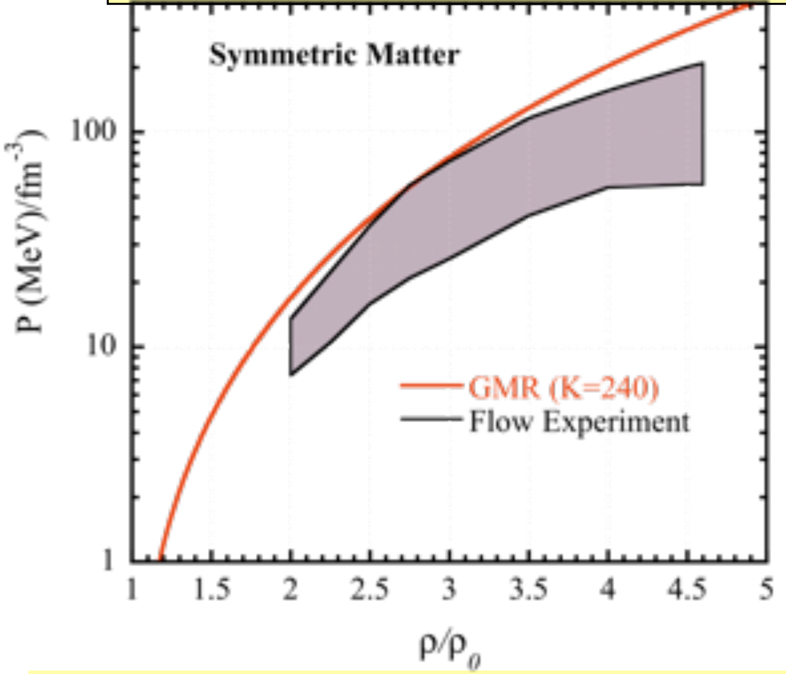

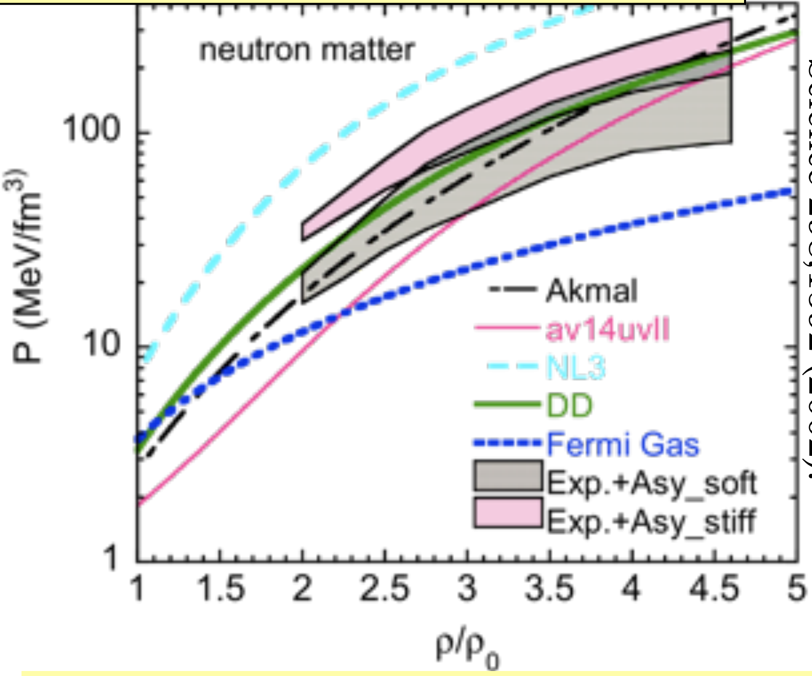

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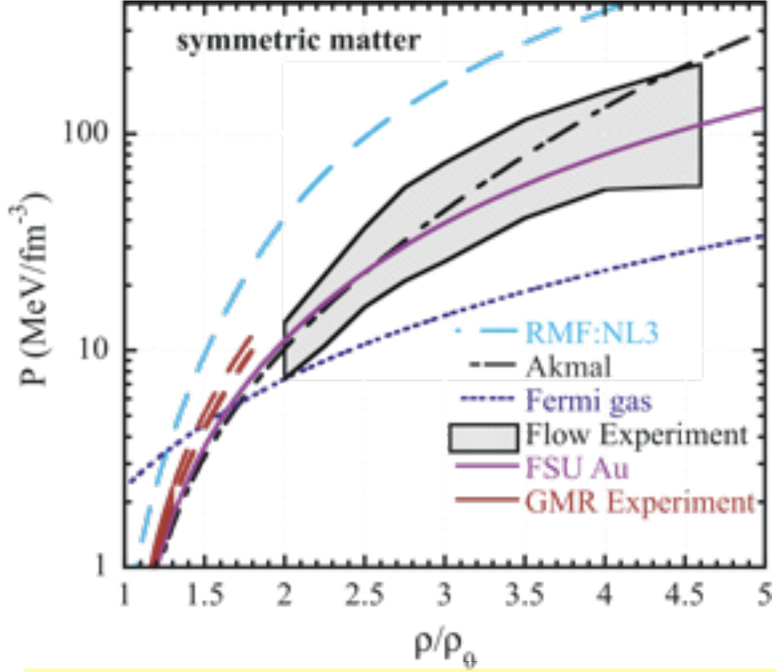

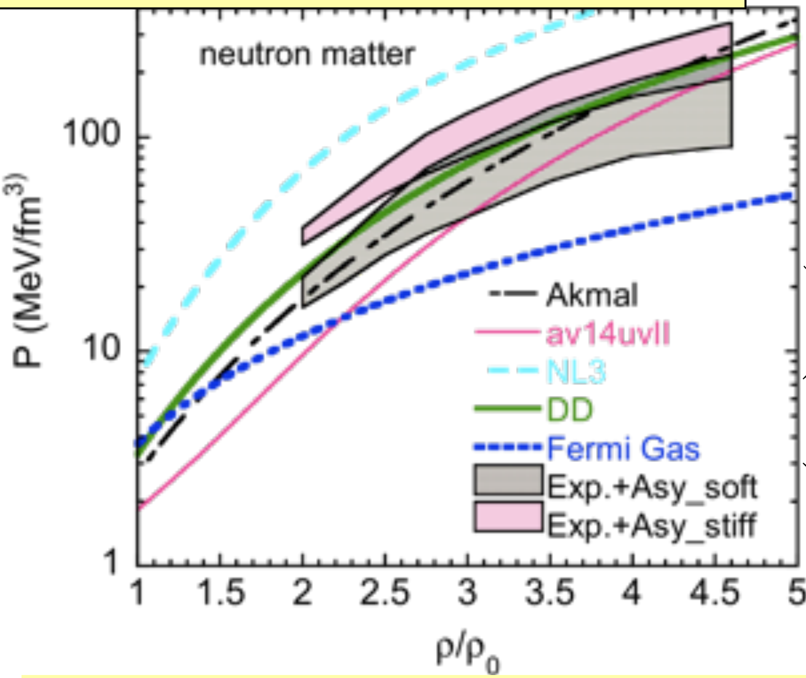

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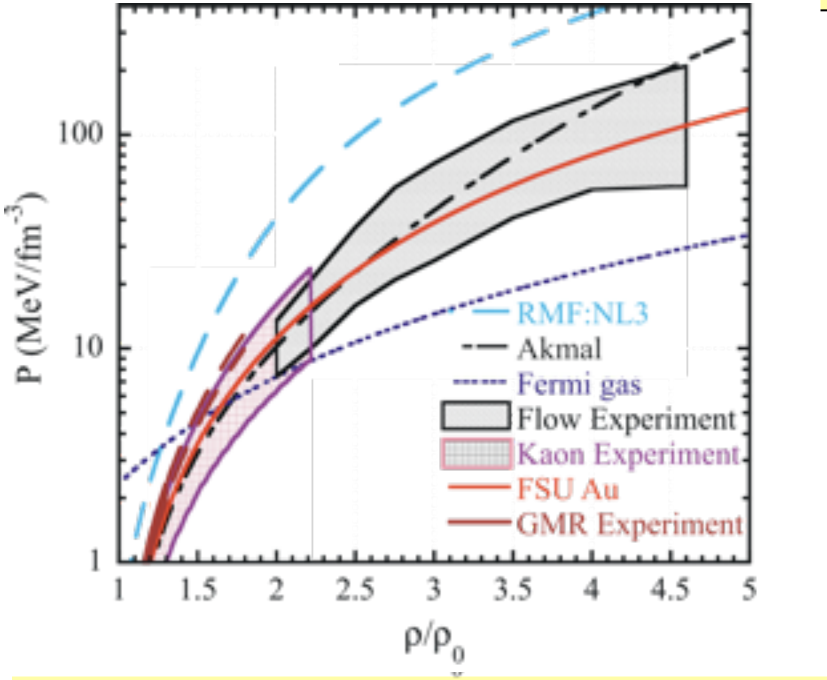

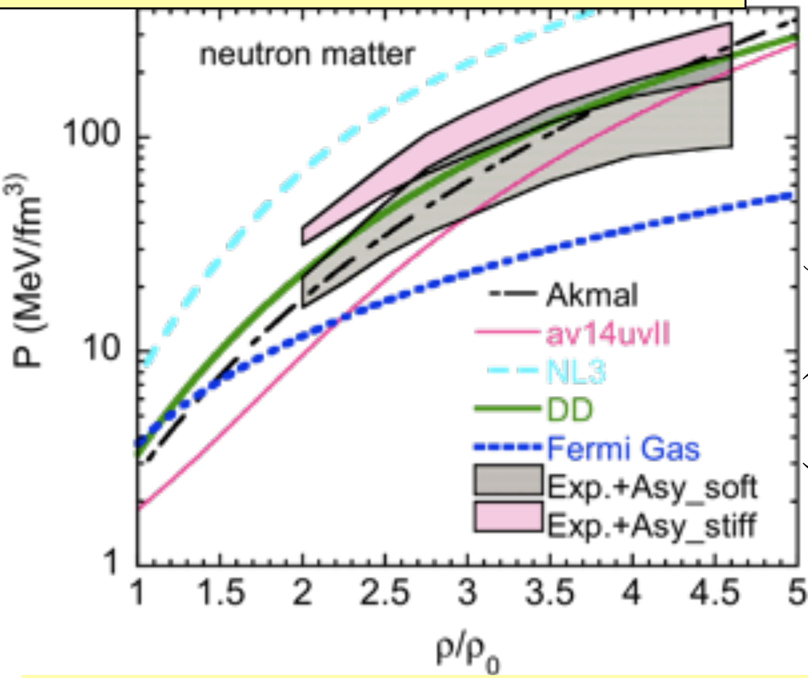

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Probe: Isospin diffusion in peripheral collisions

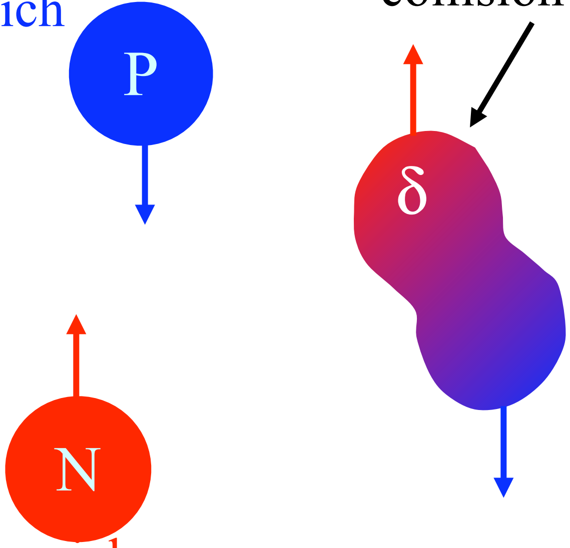
- Collide projectiles and targets of differing isospin asymmetry
- Probe the asymmetry δ=(N-Z)/(N+Z) of the projectile spectator during the collision.
- The use of the isospin transport ratio $R_i(\delta)$ isolates the diffusion effects caused by multi-nucleon transfer between projectile and target:

$$R_i(\delta) = 2\times\frac{\delta-(\delta_{both\_neut.-rich}+\delta_{both\_prot.-rich})/2}{\delta_{both\_neut.-rich}-\delta_{both\_prot.-rich}}$$

- Useful limits for R_i for ^{124}Sn+^{112}Sn collisions:
  - R_i =±1: no diffusion
  - R_i ≈0: Isospin equilibrium

Systems
mixed ^{124}Sn+^{112}Sn
n-rich ^{124}Sn+^{124}Sn
p-rich ^{112}Sn+^{112}Sn

Example:



proton-rich target

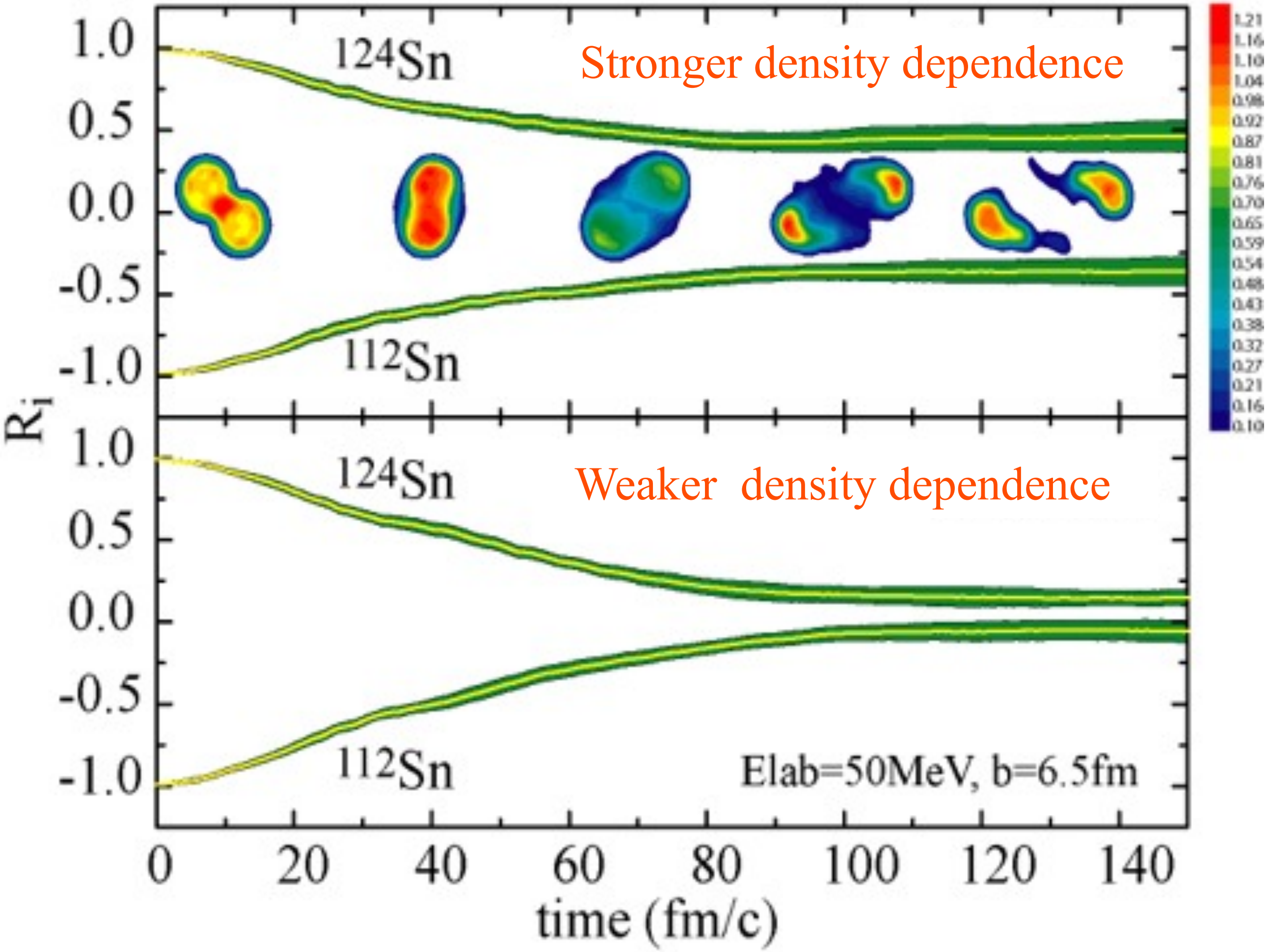
neutron-rich projectile

measure asymmetry after collision

Sensitivity to symmetry energy

$$R_i(\delta) = 2\times\frac{\delta - (\delta_{Neutron-rich} + \delta_{Proton-rich})/2}{\delta_{Neutron-rich} - \delta_{Proton-rich}}$$

- The asymmetry of the spectators can change due to diffusion, but it also can changed due to pre-equilibrium emission.
- The use of the isospin transport ratio $R_i(\delta)$ isolates the diffusion effects:



Lijun Shi, thesis

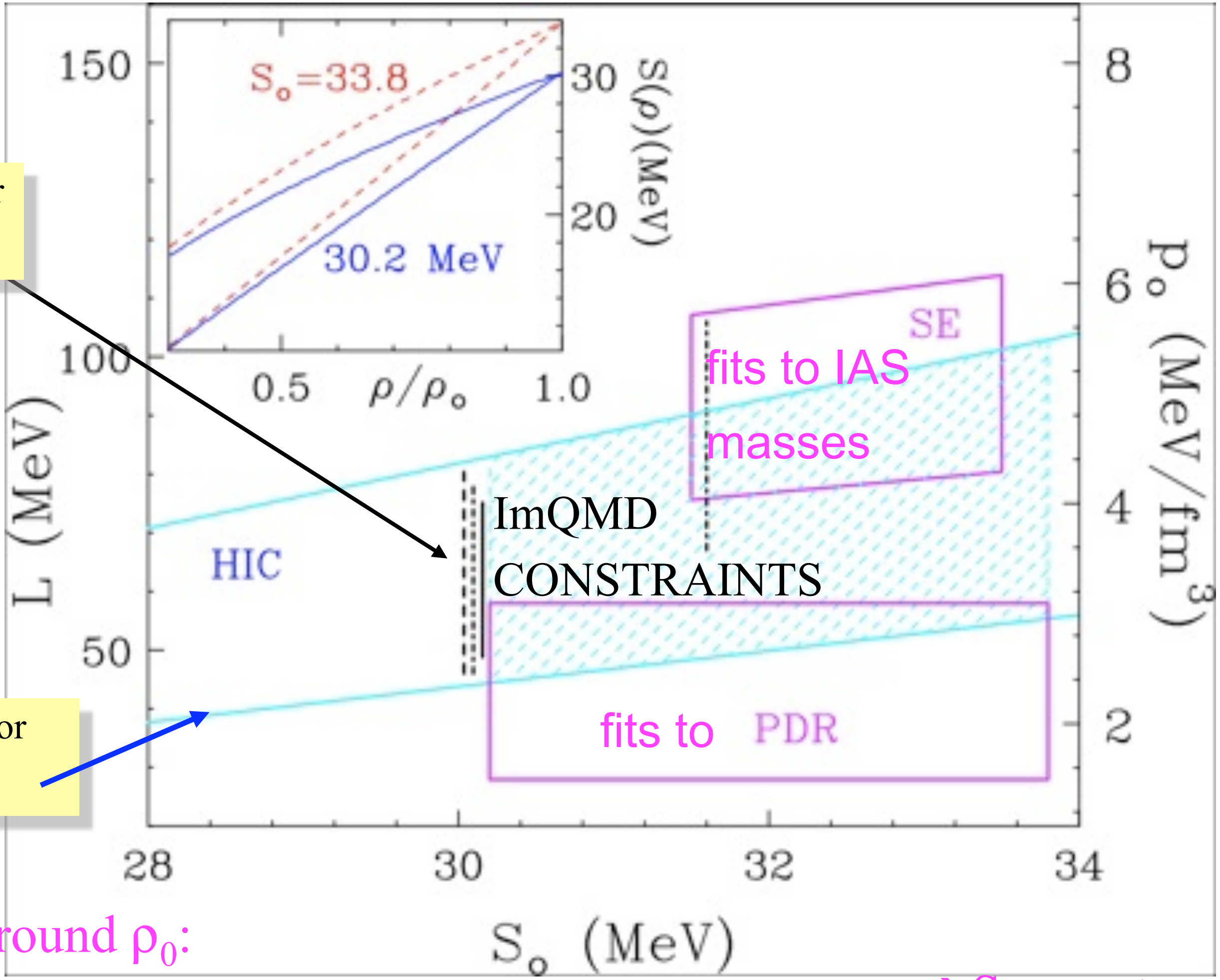
Tsang et al., PRL92(2004)

Diffusion is sensitive to S(0.4ρ), which corresponds to a

Tsang et al., PRL 102, 122701 (2009).

ImQMD fits for S_0=30.1 MeV

ImQMD fits for variable S_0



Expansion around ρ_0:

→Symmetry slope L & curvature K_{sym}

$$E_{sym} = S_o + \frac{L}{3}\left(\frac{\rho_B - \rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho_B - \rho_0}{\rho_0}\right)^2 + \ldots$$

→Symmetry pressure P_{sym}

$$L = 3\rho_0 \left.\frac{\partial E_{sym}}{\partial \rho_B}\right|_{\rho_B=\rho_0} = \frac{3}{\rho_0} P_{sym}$$

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GDR: Trippa,
PRC77, 061304

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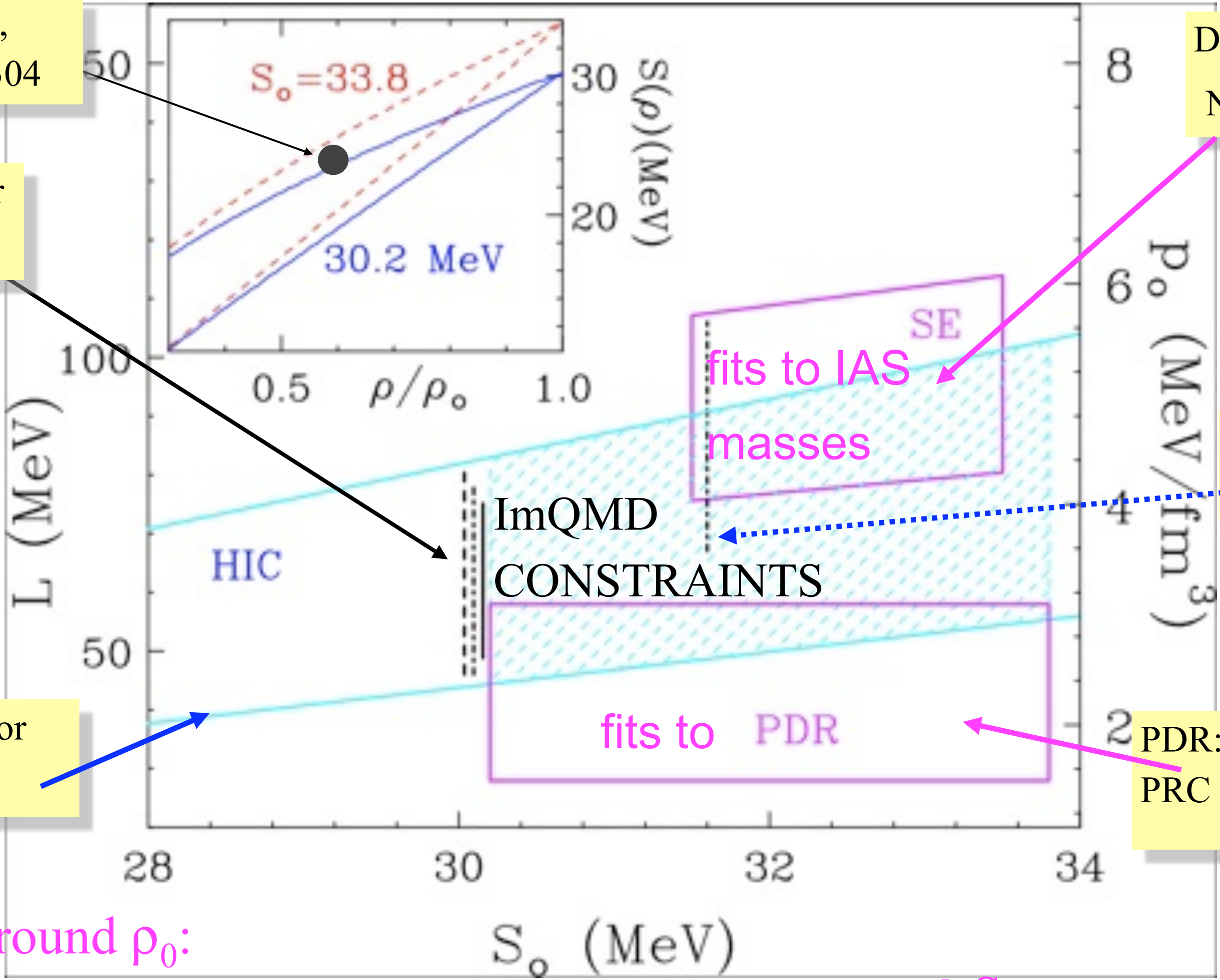
Danielewicz, Lee,
NPA 818, 36 (2009)

Bao-An Li et al., Phys. Rep. 464, 113 (2008).

PDR: A. Klimkiewicz,
PRC 76, 051603 (2007).



fits to IAS
masses

ImQMD
CONSTRAINTS

fits to

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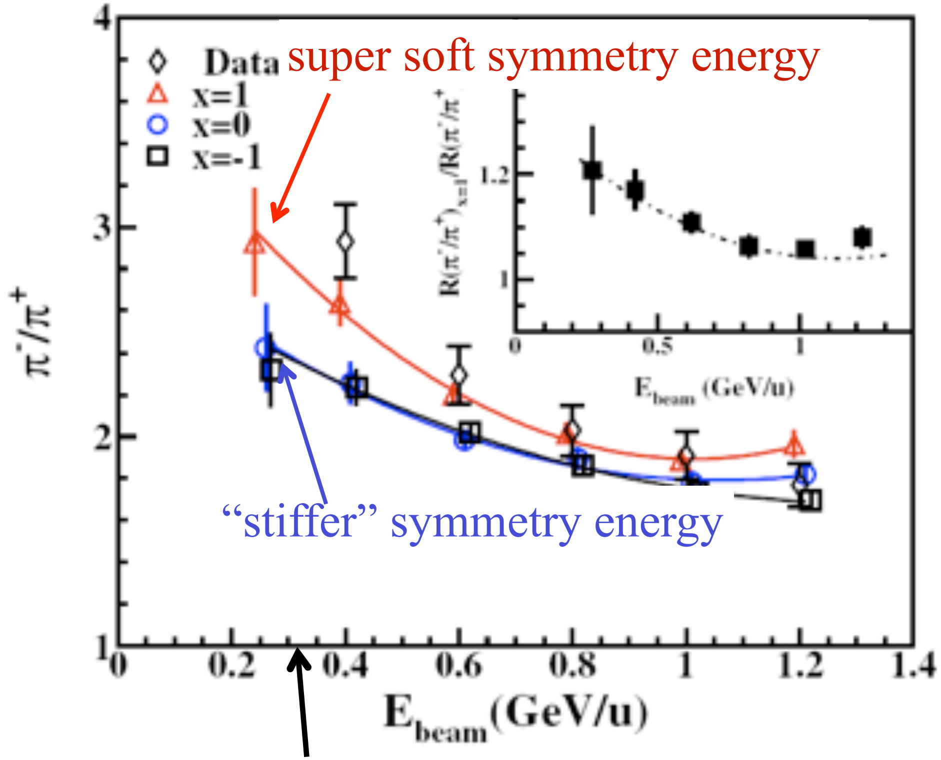
Results from Fopi and Future Prospects

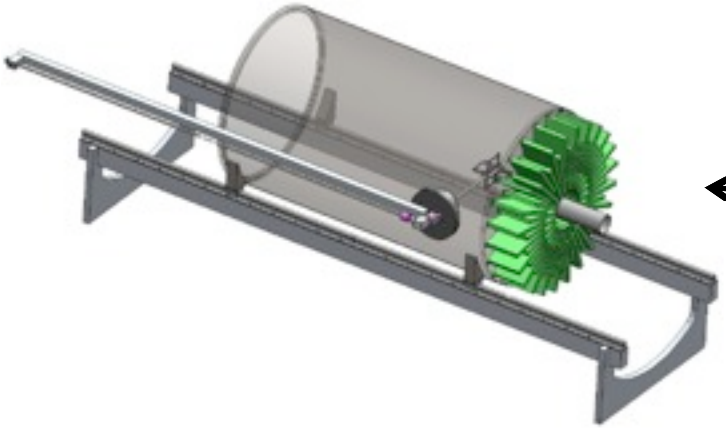
- Calculations suggest that the π^-/π^+ ratios for Au+Au Fopi data are consistent with very soft symmetry energy at $\rho > 2\rho_0$
- To separate effects of Coulomb and symmetry energies, measurements with rare isotope beams would be useful.

Zhigang Xiao et al., LANL arXiv:0808.0186



super soft symmetry energy

“stiffer” symmetry energy



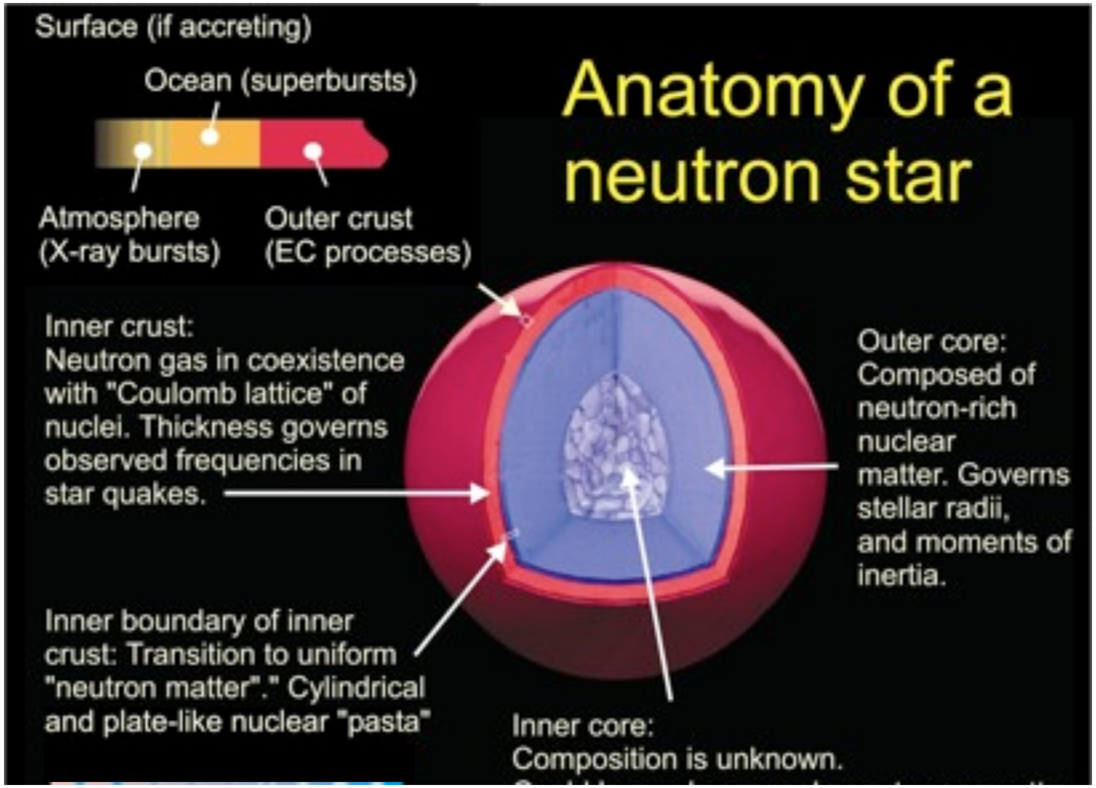
Can be probed at RIKEN or at MSU/FRIB with AT-TPC

Nuclear Astrophysics in explosive environments and

- Astrophysics questions :
  - What are the masses, radii and internal structures of selected neutron stars.
  - What are the conditions required for supernovae and neutron star formation?
  - What is the site (or sites) of the r-process?
  - What causes x-ray bursts or super-bursts?
- Structure questions:
  - What are the electron-capture rates relevant for core-collapse supernovae?
  - What are the nuclear masses, lifetimes and reaction rates that are relevant for explosive r-process and rp-process.
- Reactions question:
  - How does one probe the mean field at supra-saturation density?
  - How does one determine the relevant electron-capture rates?

EOS, Symmetry Energy and Neutron Stars

- Influences neutron Star stability against gravitational collapse
- Stellar density profile
- Internal structure: occurrence of various phases.
- Observational consequences:
  - Cooling rates of proto-neutron stars
  - Cooling rates for X-ray bursters.
  - Stellar masses, radii and moments of inertia.
    - Possible study of low mass X-ray binaries



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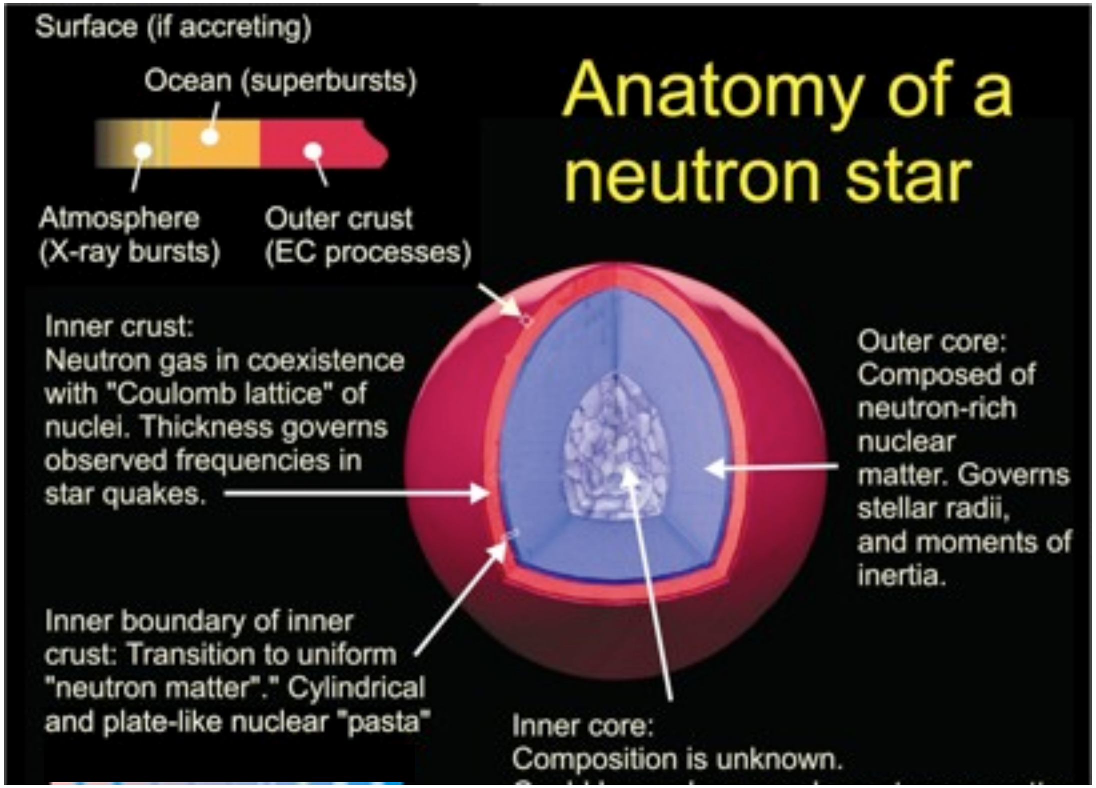
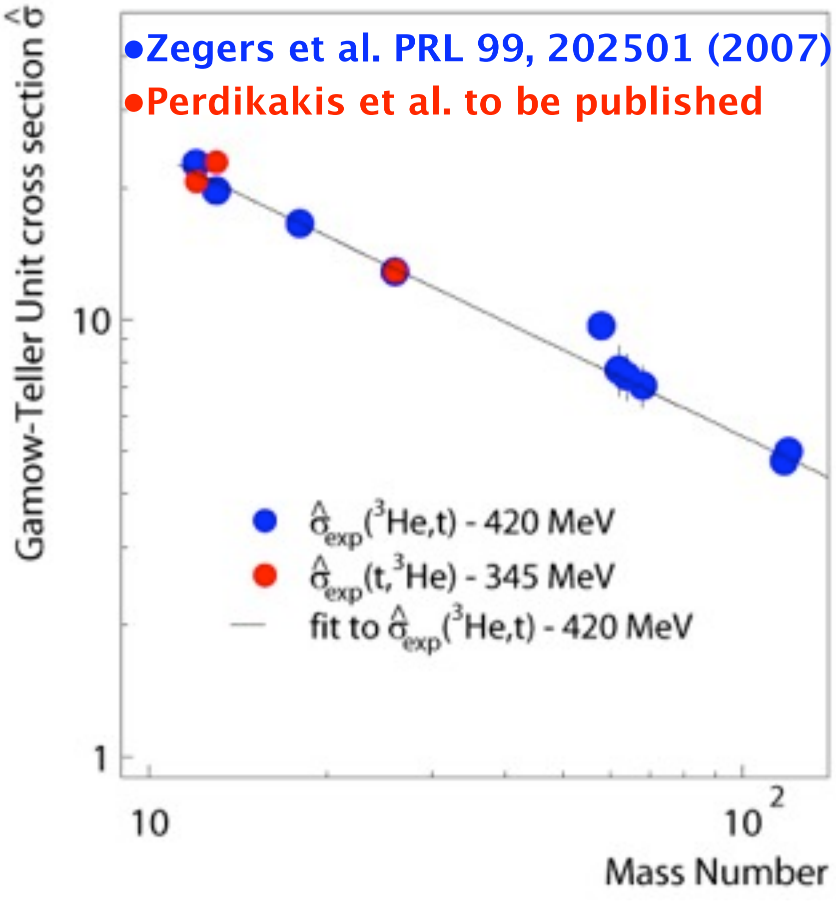


- Beyond capabilities of Chandra or XMM.
- Requires "International X-ray Observatory"
  - Cost ~ $2B RY: Possible launch date 2020.
- In the interim, observers will still focus on the EOS

⇒It is important to obtain laboratory constraints.

Weak interaction rates for supernova

- electron capture ⇔ β^+ direction on neutron-rich nuclei decreases electron pressure and accelerates collapse
- Overall supernova dynamics and neutrino signal are modified.
- Pauli-blocking reduces capture rate
- Possible charge exchange probes:
  - (t,^{3}He) on stable nuclei
  - (d,2p) on unstable nuclei:



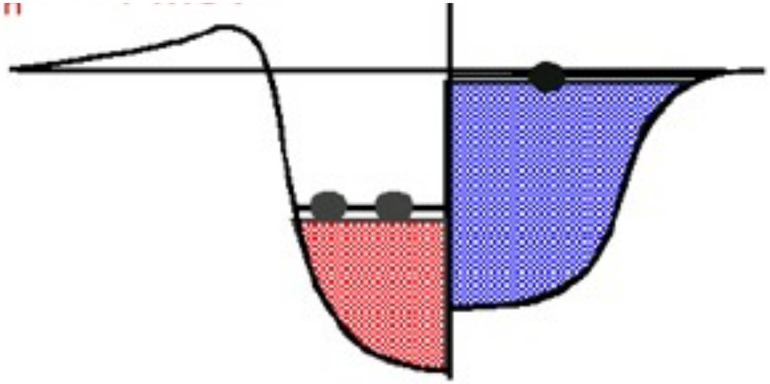
•Zegers et al. PRL 99, 202501 (2007)

•Perdikakis et al. to be published

$$\left(\frac{d\sigma}{d\Omega}(q=0)\right)_{(t,^3He)} = \hat{\sigma}\, B(GT)$$

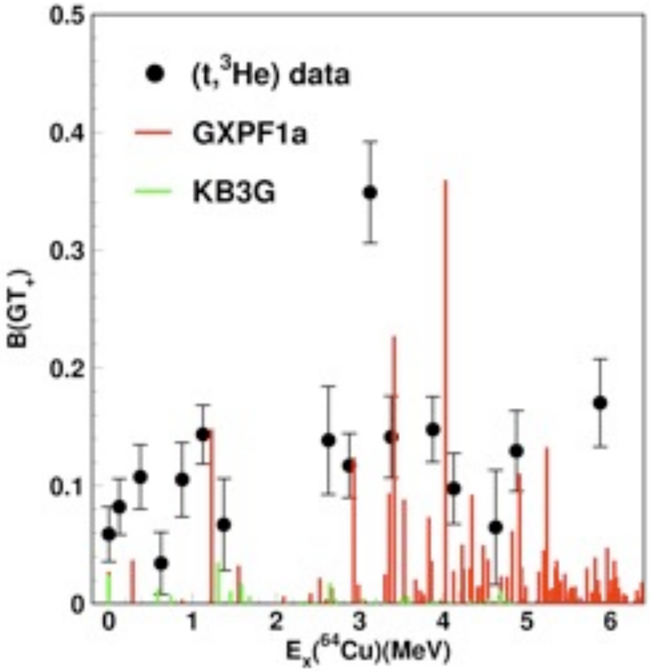
Neutron-rich nuclei:

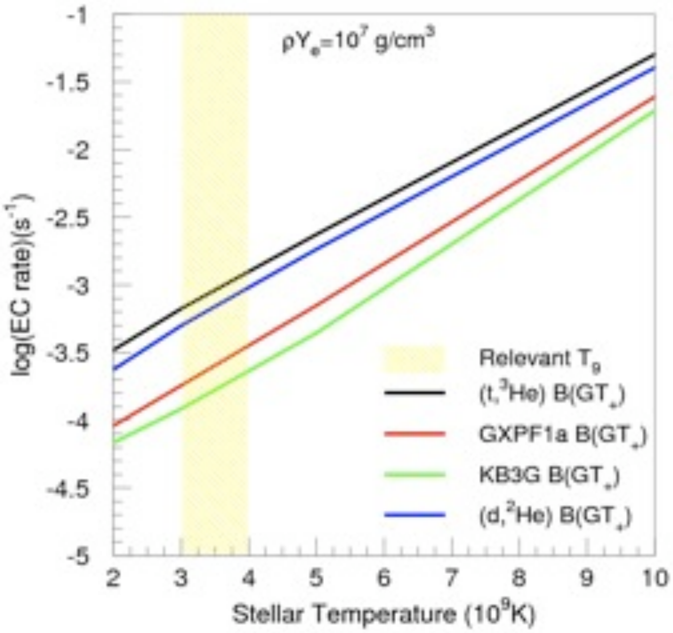
capture is pauli blocked



Charge exchange with RI beams

- Thesis by G.W. Hitt (Jan ’09) & to be published





- Large discrepancy to shell model
  - Quantitative picture of uncertainties
  - Part of body of data needed to improve shell model

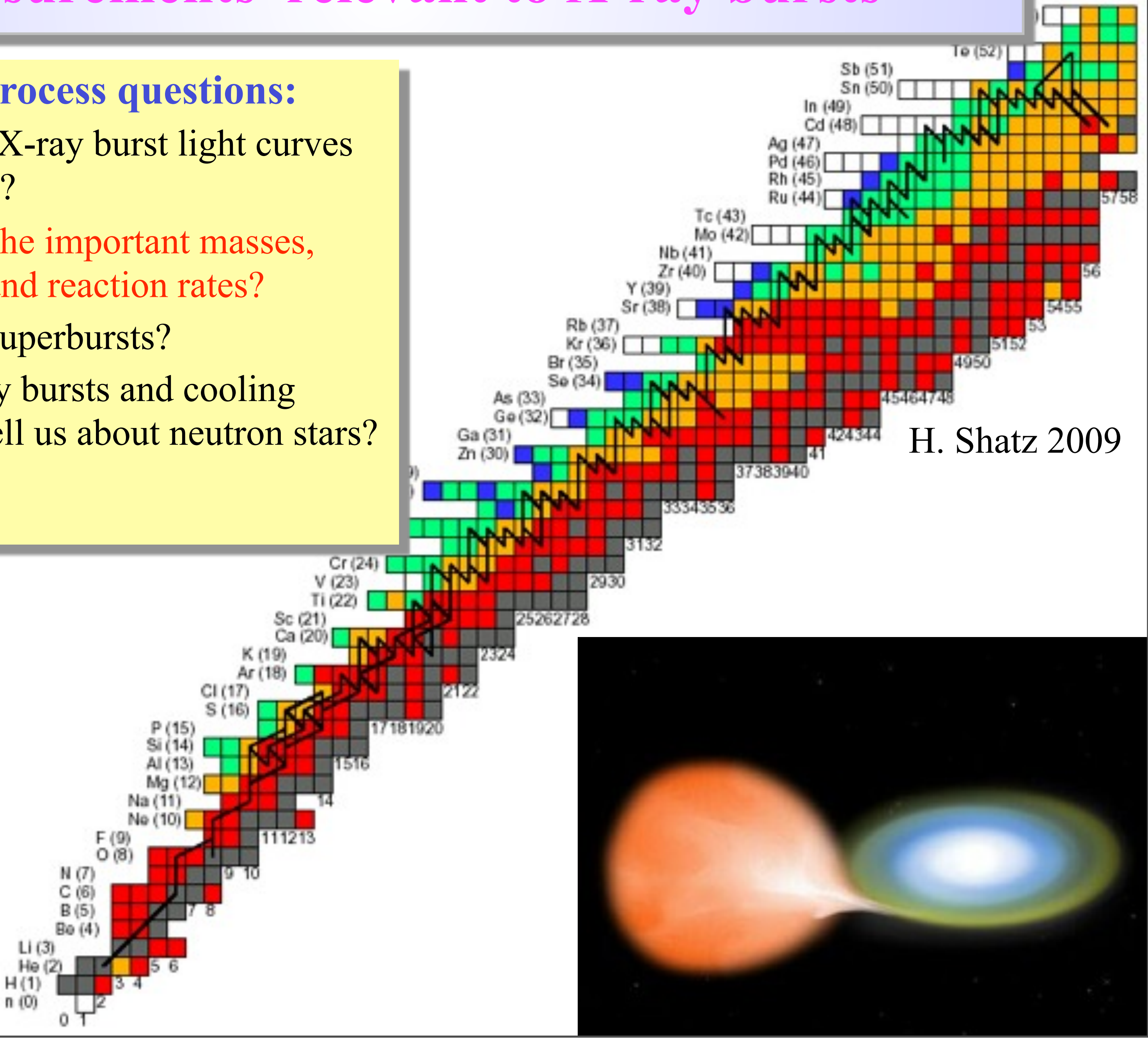
- Significant enhancement of electron capture rate over shell model calculations

  Improvement is clearly needed.

Measurements relevant to X-ray bursts

rp-process / crust process questions:

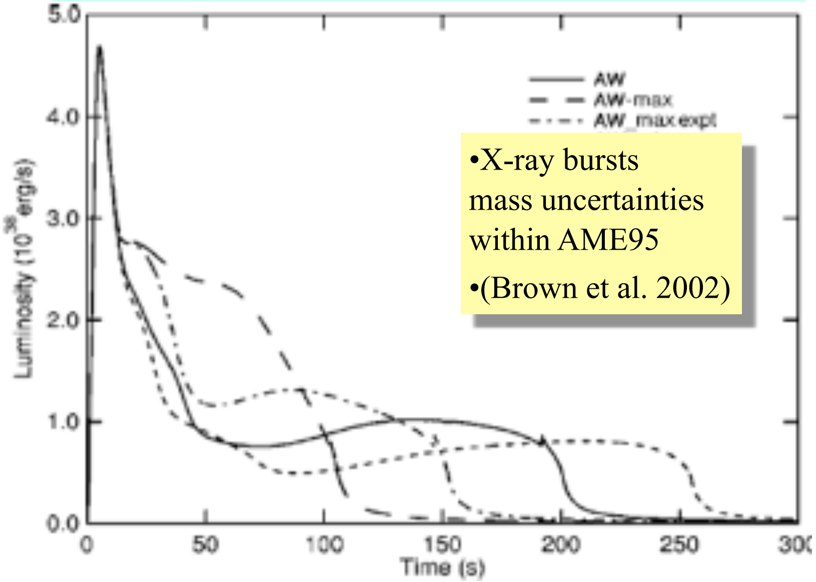
- What governs X-ray burst light curves and recurrence?
  - What are the important masses, lifetimes and reaction rates?
- What causes superbursts?
- What do X-ray bursts and cooling observations tell us about neutron stars?



H. Shatz 2009

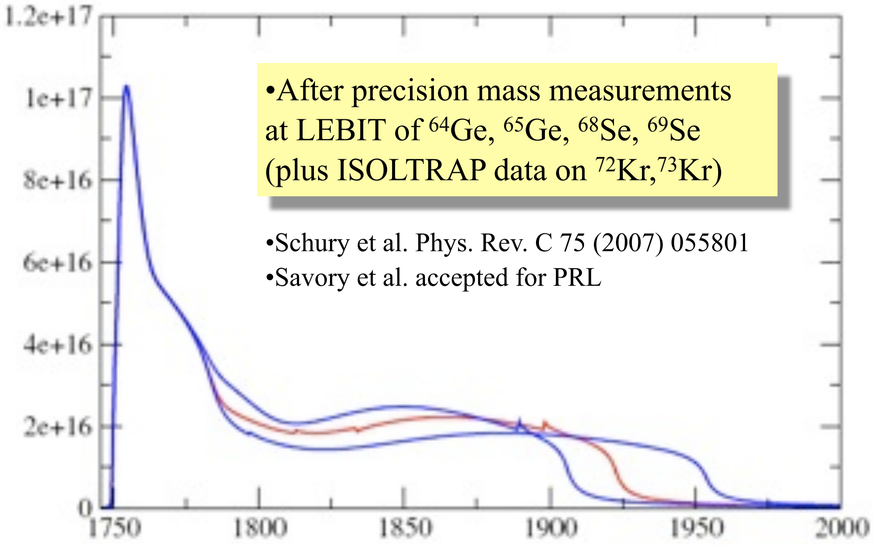
Importance of waiting point masses

- **Using AME95 mass estimates:**



- X-ray bursts mass uncertainties within AME95
- (Brown et al. 2002)

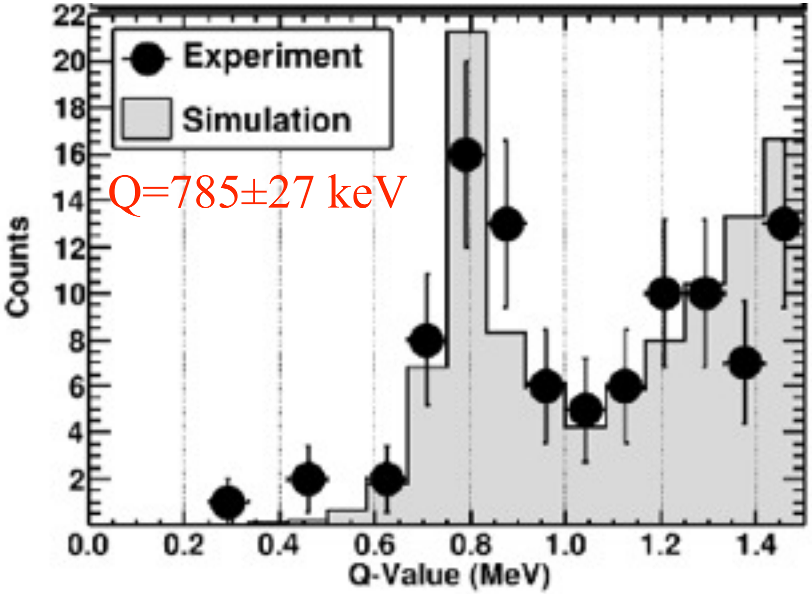
- **After LEBIT mass measurements :**



- After precision mass measurements at LEBIT of ^{64}Ge, ^{65}Ge, ^{68}Se, ^{69}Se (plus ISOLTRAP data on ^{72}Kr,^{73}Kr)

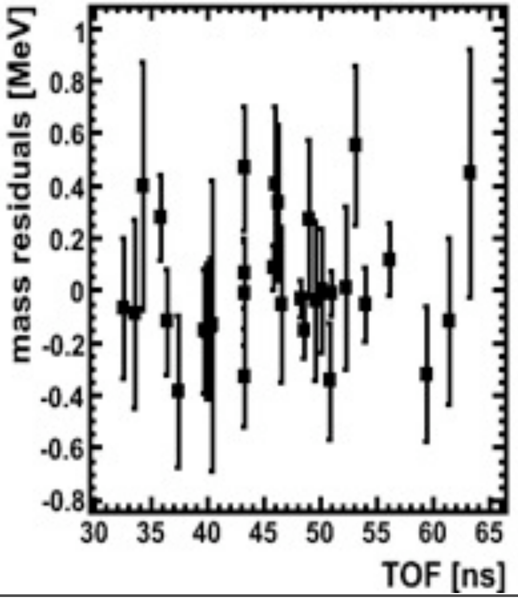
- Schury et al. Phys. Rev. C 75 (2007) 055801
- Savory et al. accepted for PRL

- **p decay of ^{69}Br (Rogers, Famiano, Lynch)**



Q=785±27 keV

- **TOF mass measurements** (Matos, Estrade ,Shatz)



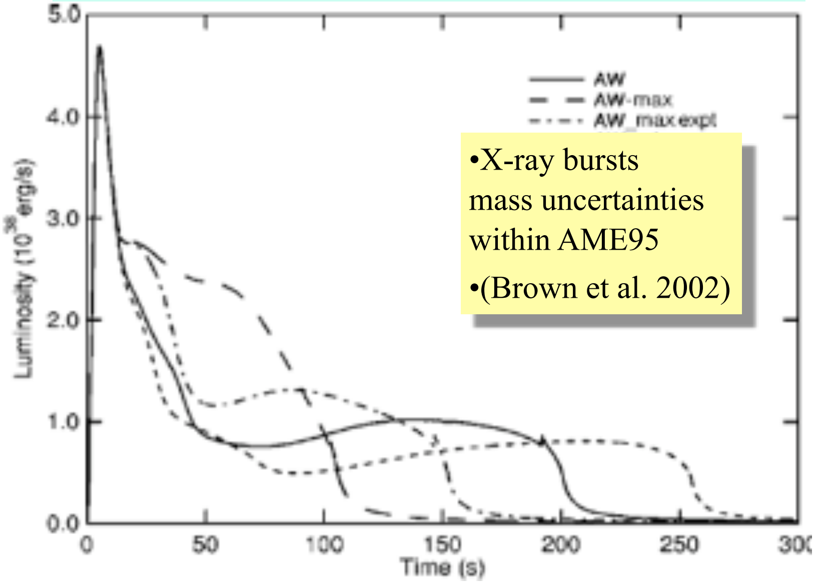
→ ~100 keV systematic error

→ 4 new masses
4 improved masses

→ ready for broader application

Importance of waiting point masses

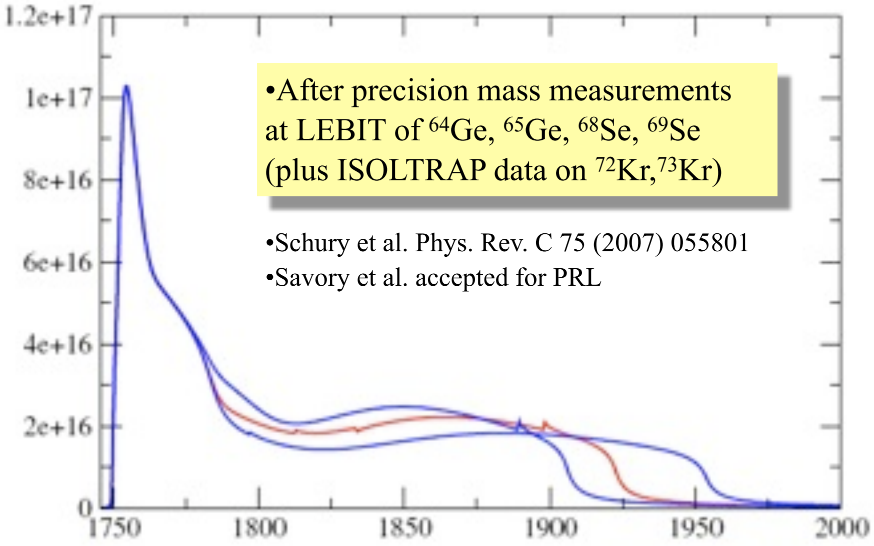
•Using AME95 mass estimates:



•X-ray bursts mass uncertainties within AME95

•(Brown et al. 2002)

•After LEBIT mass measurements :

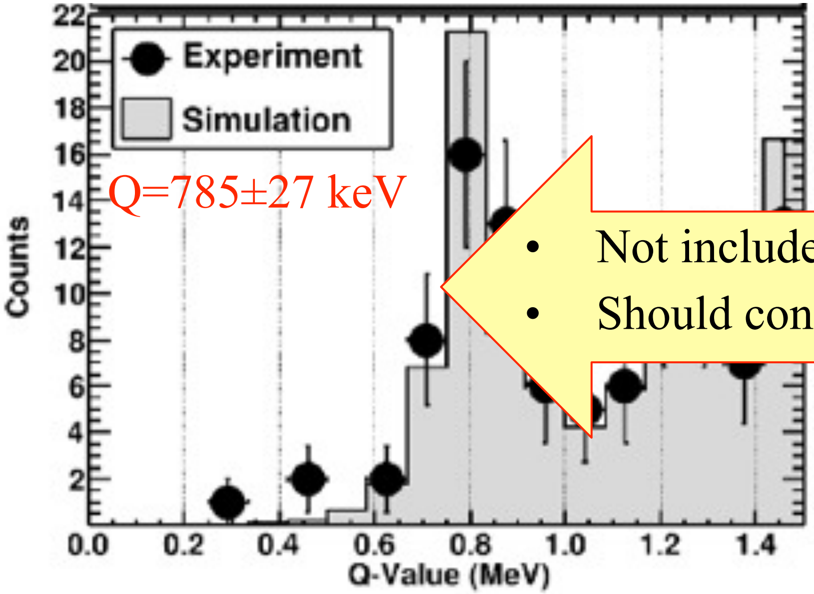


•After precision mass measurements at LEBIT of ^{64}Ge, ^{65}Ge, ^{68}Se, ^{69}Se (plus ISOLTRAP data on ^{72}Kr,^{73}Kr)

•Schury et al. Phys. Rev. C 75 (2007) 055801

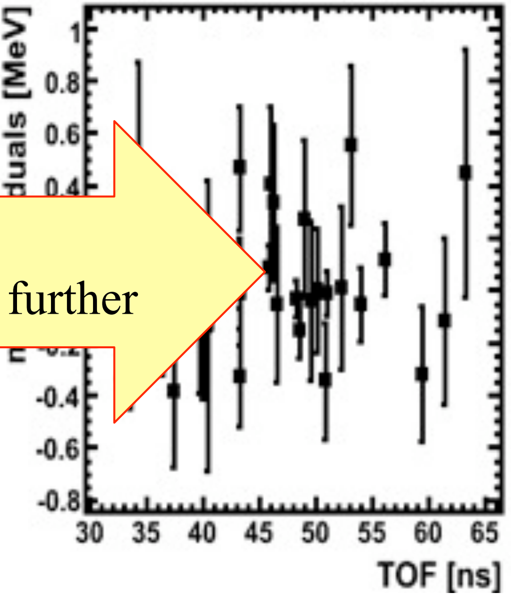
•Savory et al. accepted for PRL

•p decay of ^{69}Br (Rogers, Famiano, Lynch)



Q=785±27 keV

•TOF mass measurements (Matos, Estrade ,Shatz)



- Not included yet
- Should constrain further

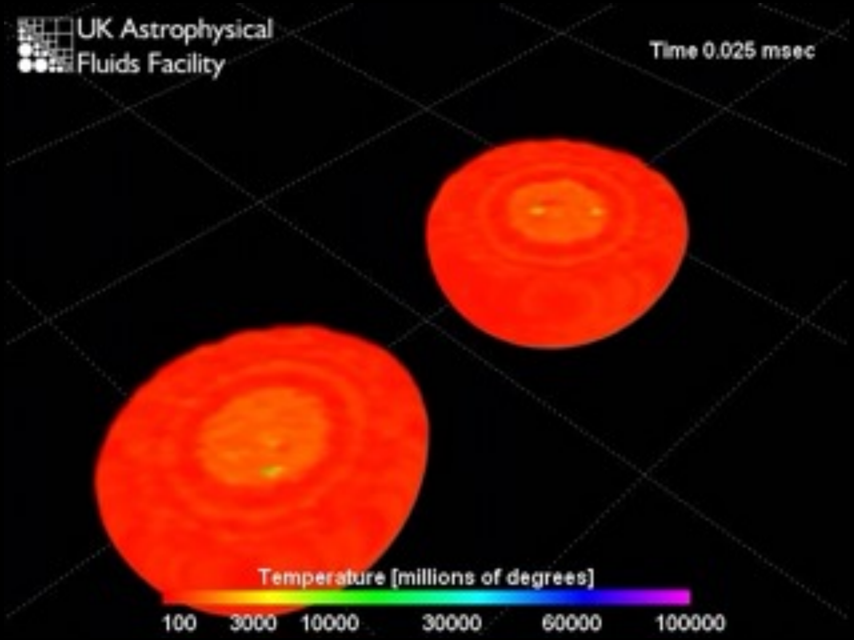
→ ~100 keV systematic error

→ 4 new masses
4 improved masses

→ ready for broader application

Question:

- What is the origin of the heavy elements in the cosmos?



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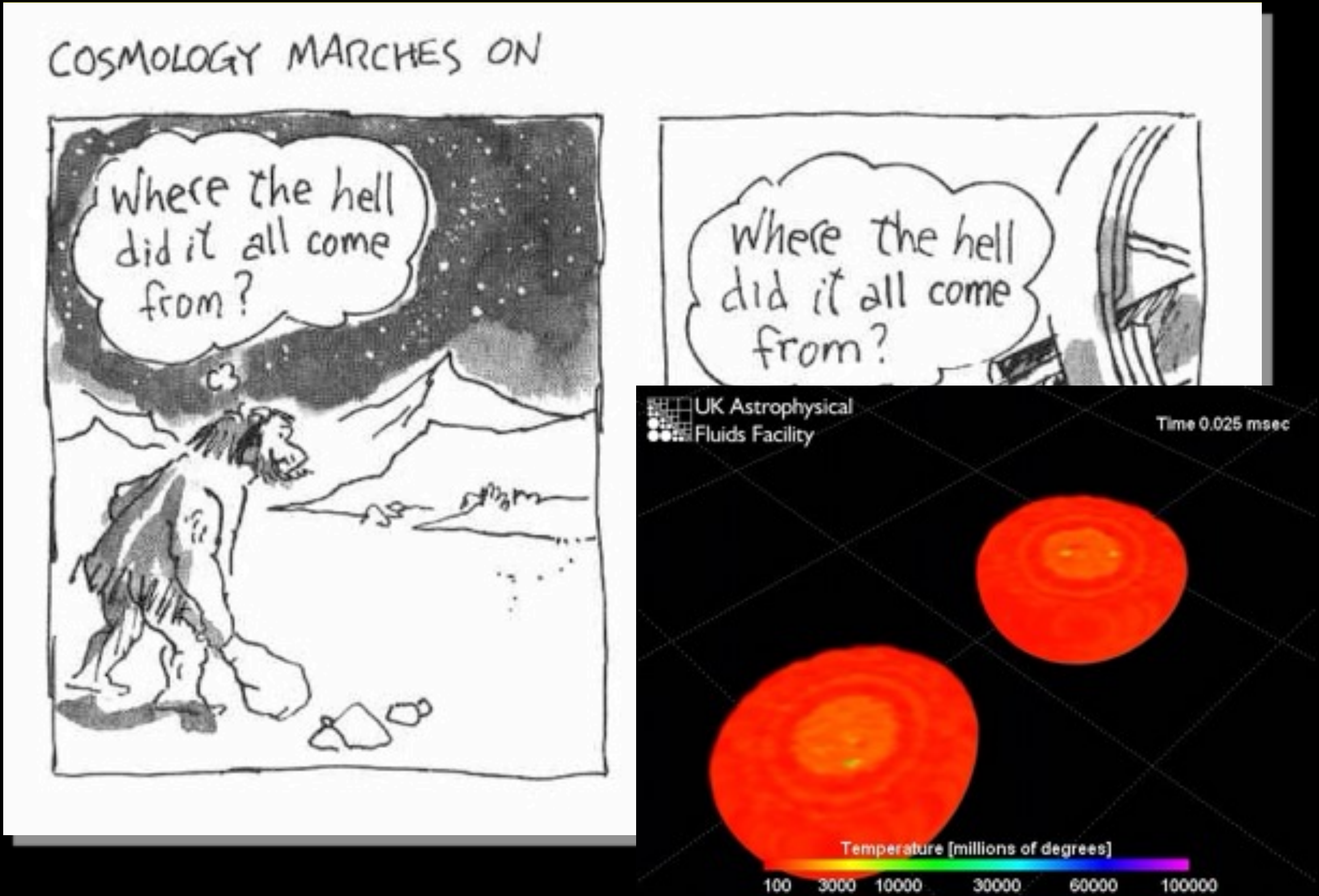

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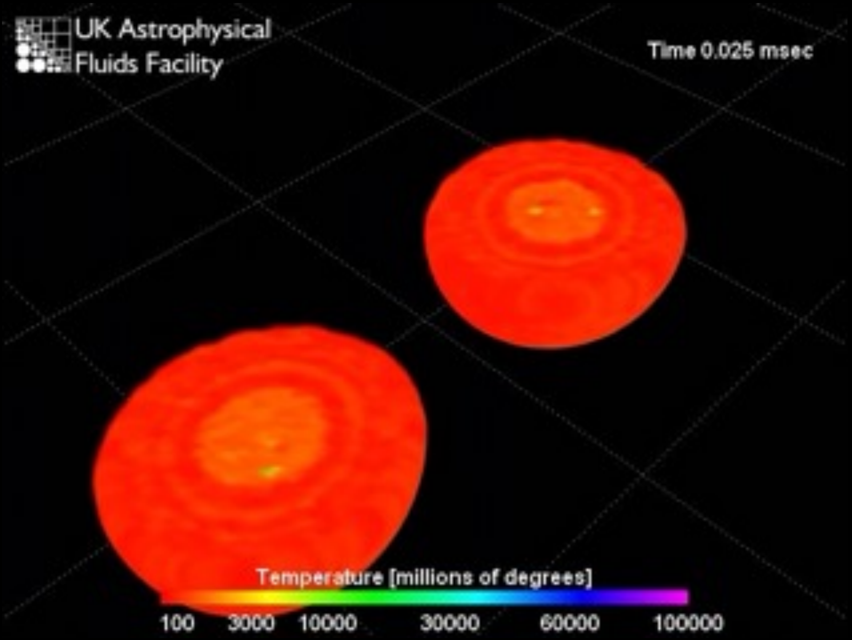
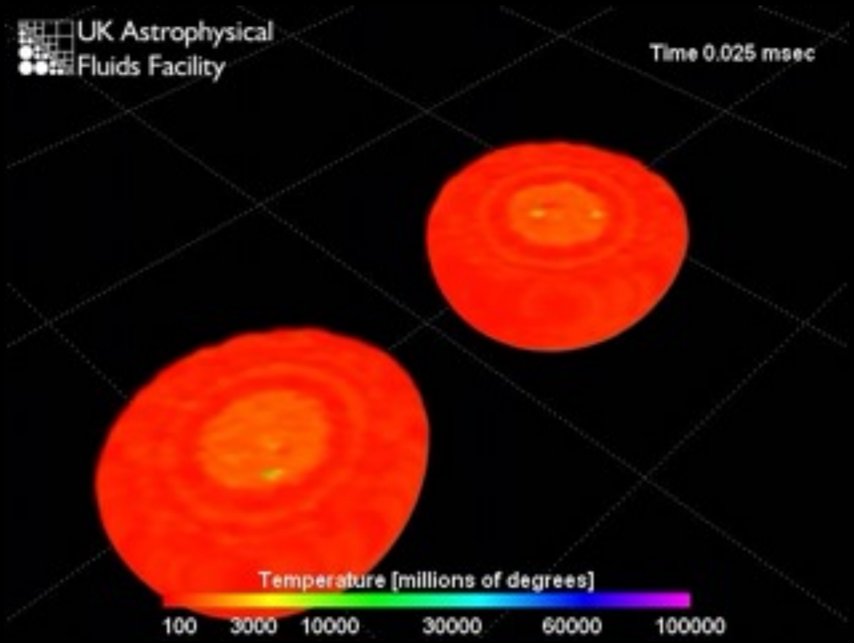


Questions:

- What is the origin of the heavy elements in the cosmos?
  - Multiple processes?
  - Multiple sites?



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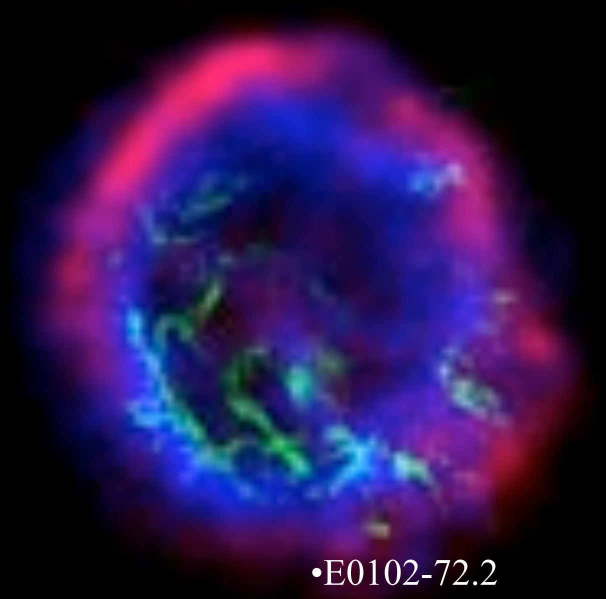
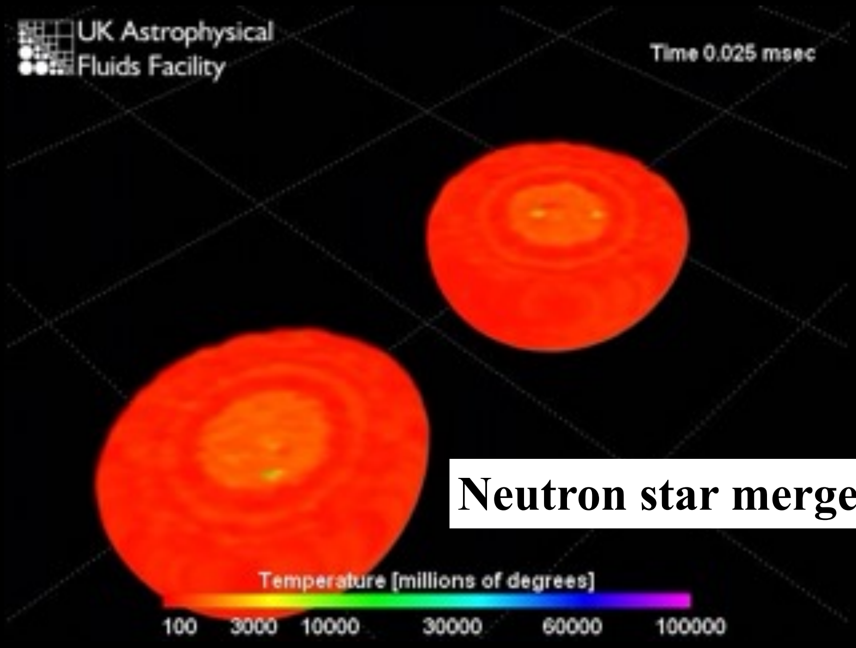


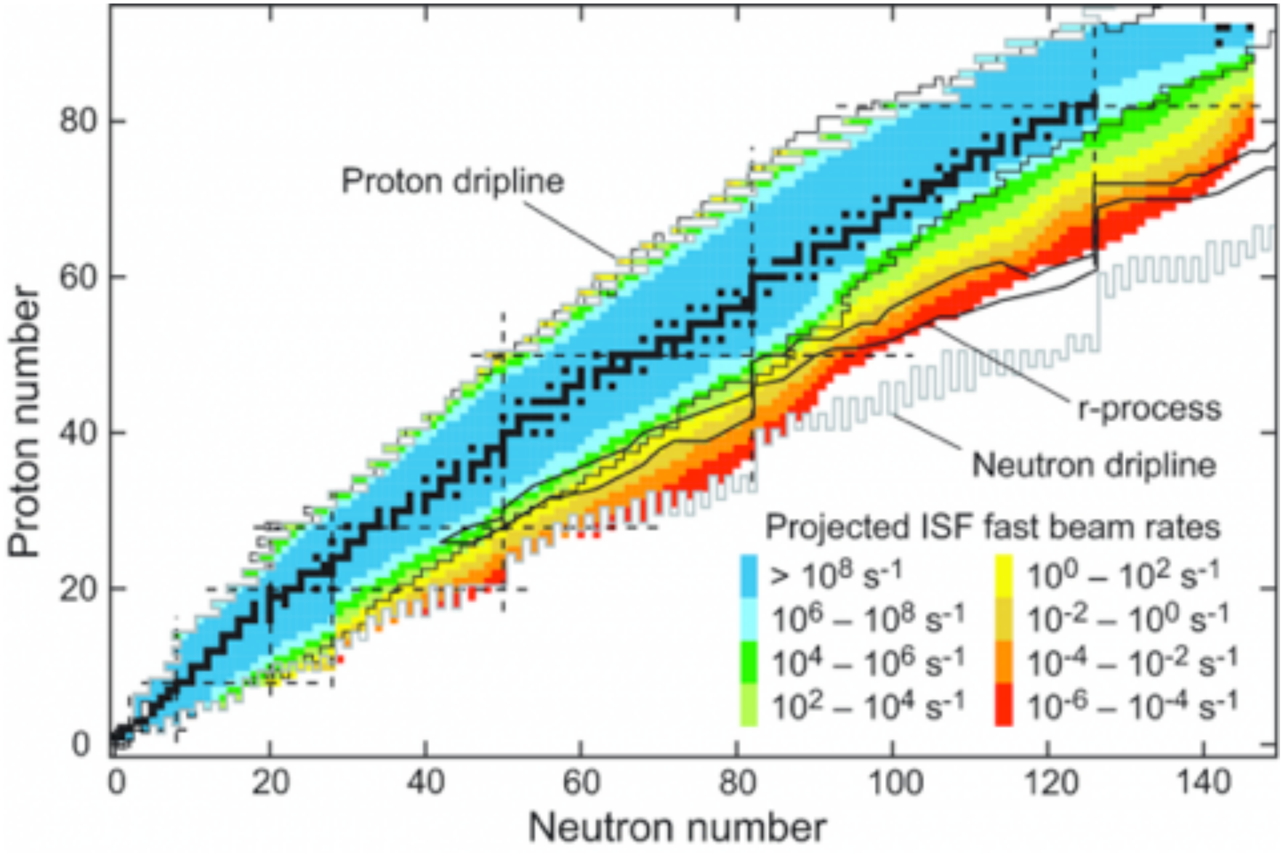
•E0102-72.2

•Supernovae ?



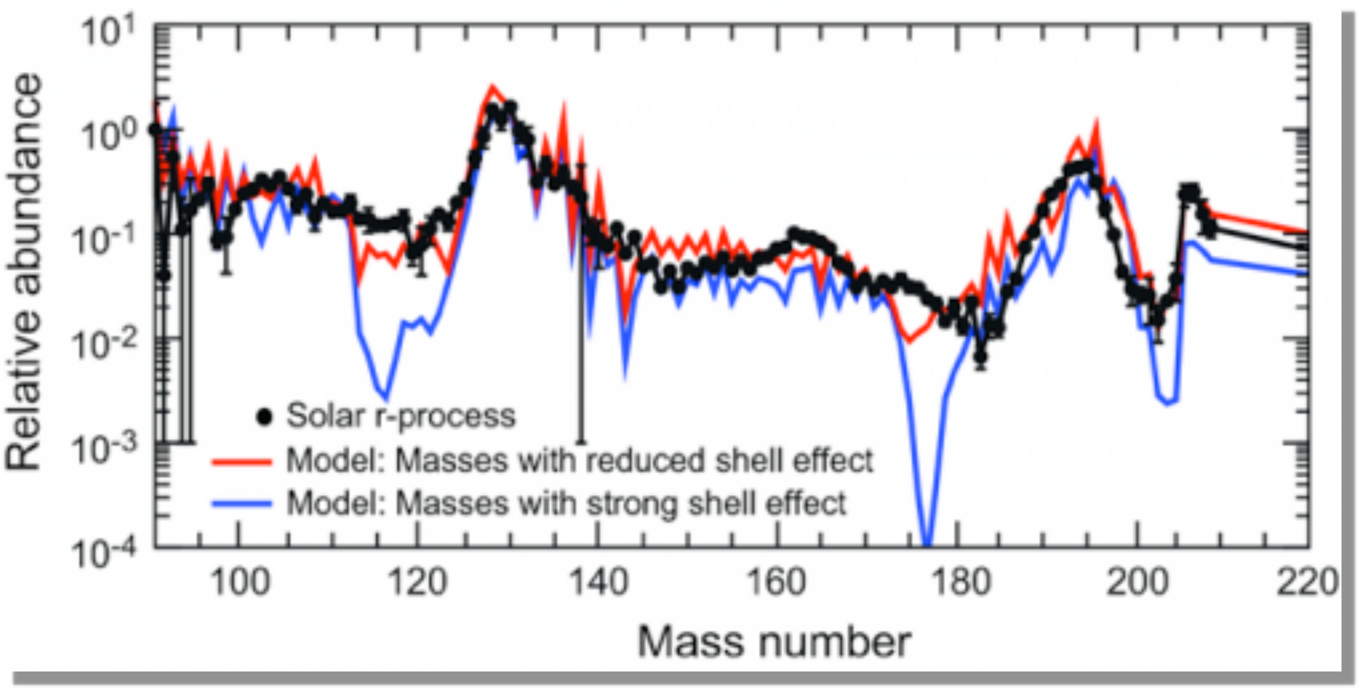
Neutron star mergers ?

r-process nucleo-synthesis



- Large nucleon flux dictates n-γequilibrium centered at large neutron excess.
- Mass determines the most probable isotope.
- Beta decay allow increase in Z.
- At end of r-process, nuclei beta decay back to stability.
- Masses and Beta decay lifetimes are necessary properties to measure.

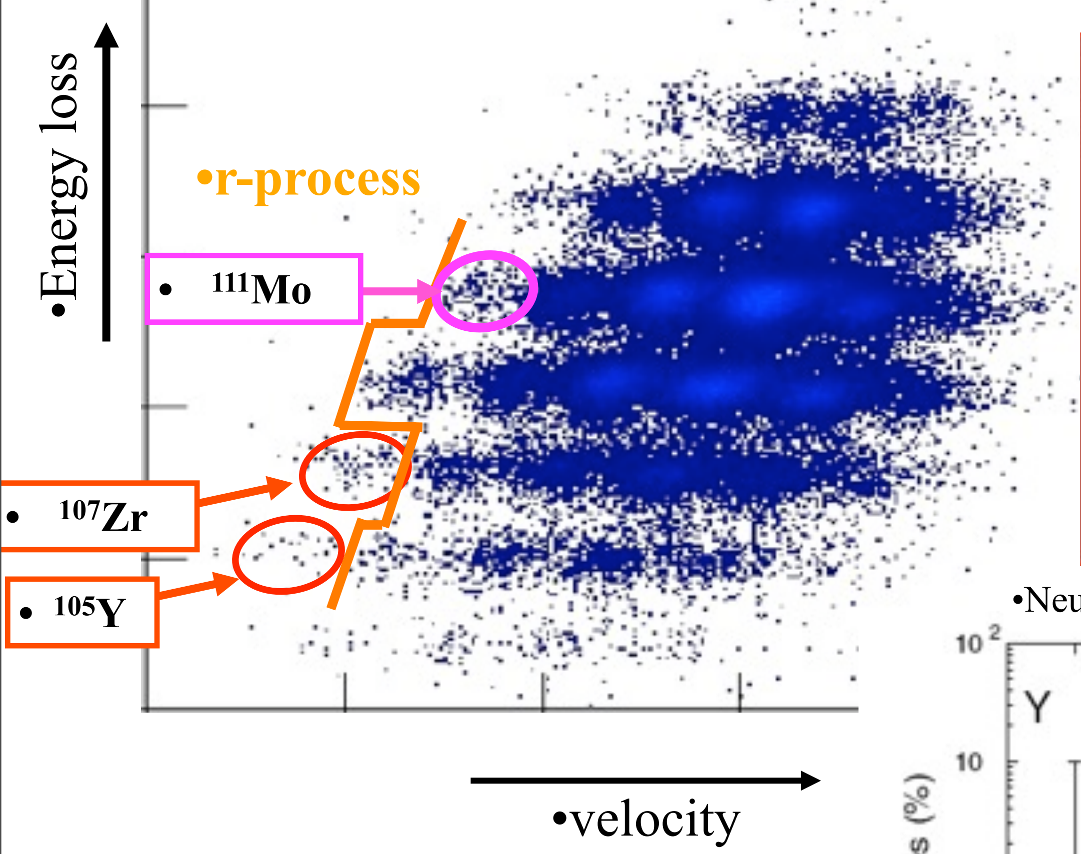
r-process abundance peak: Evidence for reduced shell



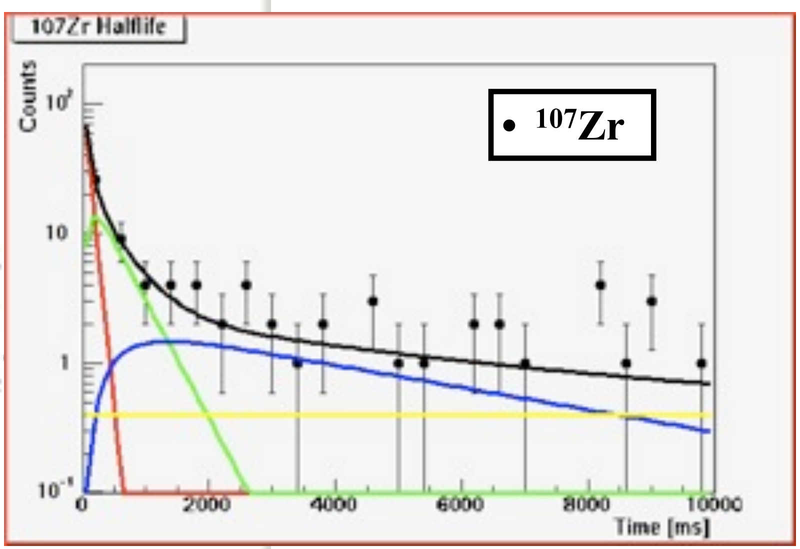
- Calculations predict abundance peaks near A≈130 and A≈190 to originate from enhancements of hot r-process nuclei near N=82 and N=126 close shells.
- Observed abundances are better fitted by reducing the size of the shell effects (enhanced binding).
  - Mass measurements needed to verify this.

Another important issue: lifetimes of r-process elements

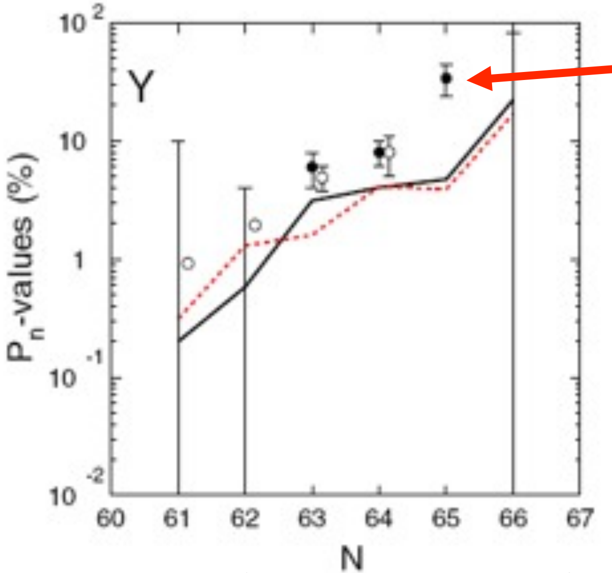
- ^{136}Xe beam on Be target



- Half life fits



- Neutron emission ratios



- ^{104}Y discrepancy could be resolved with
- smaller deformation than expected

- RI beam particles stop in silicon telescope and subsequently decay
- Detectors:
  - Beta Counting Station BCS
  - Neutron detector NERO

- J. Pereira et al. Phys. Rev. C 79 (2009) 035806

Figure from H. Schatz

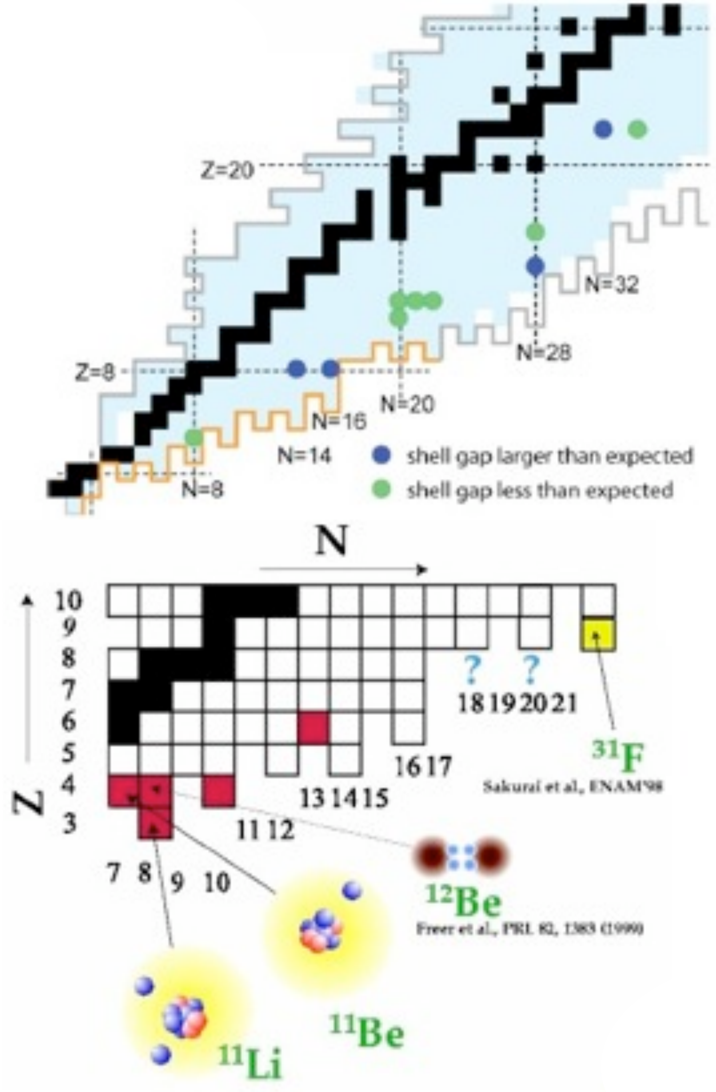
Structure of nuclei far from stability.

- New closed shells and disappearance of conventional magic numbers.
- New regions of deformation
- New correlations
    - neutron-proton pairing
    - neutron halos and skins
    - cluster states

Evolution of Shell structure with asymmetry

- Shell change as one approaches the neutron drip-line.
  - Some shell gaps decrease.
  - New shell gaps emerge.

- Intruder orbits lower and become valence.
- New cluster structures become relevant.

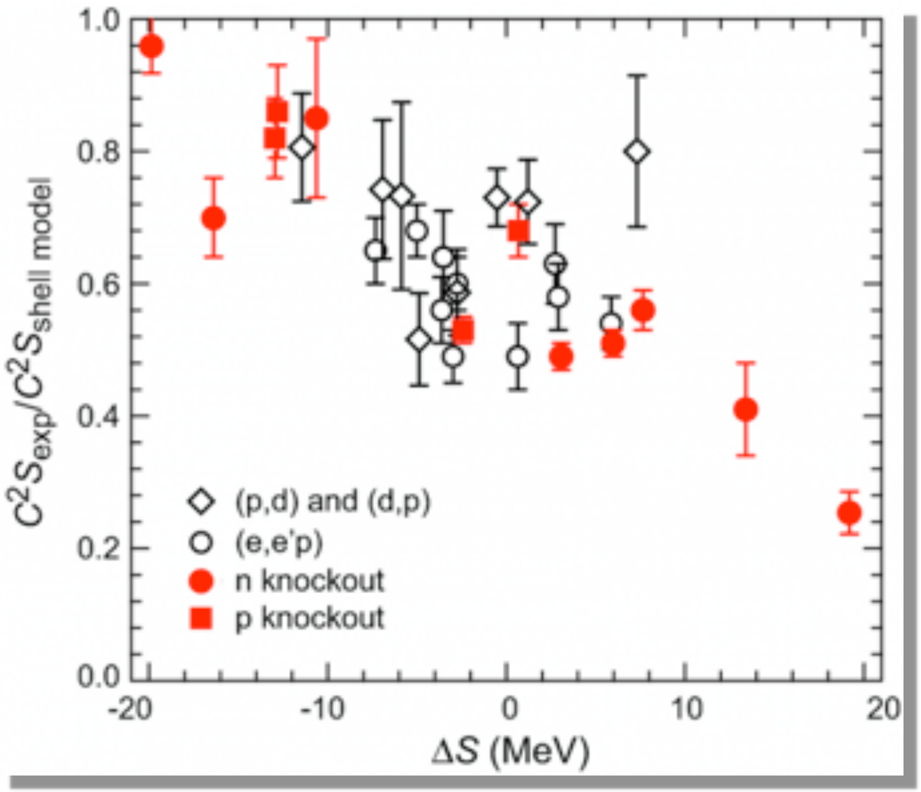


Figures from C/K/Gelbke

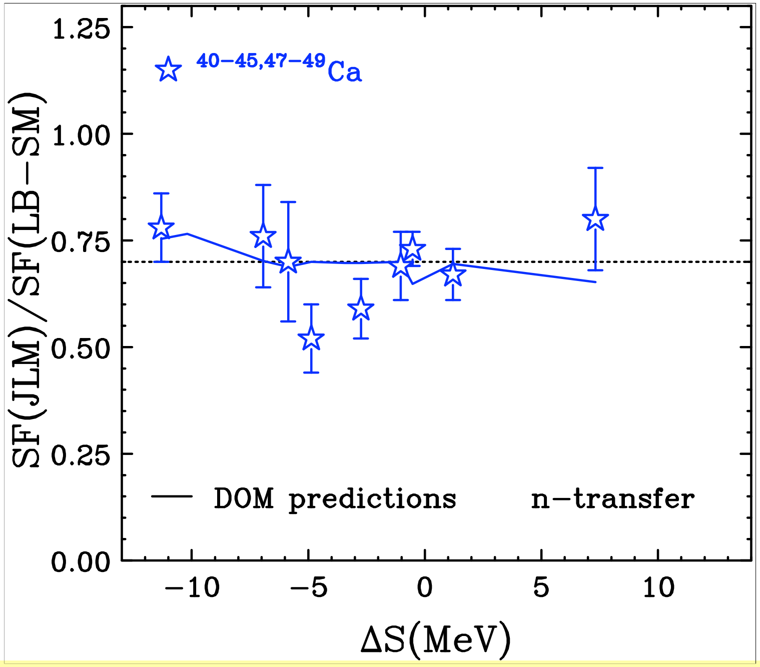
Spectroscopic factor puzzle

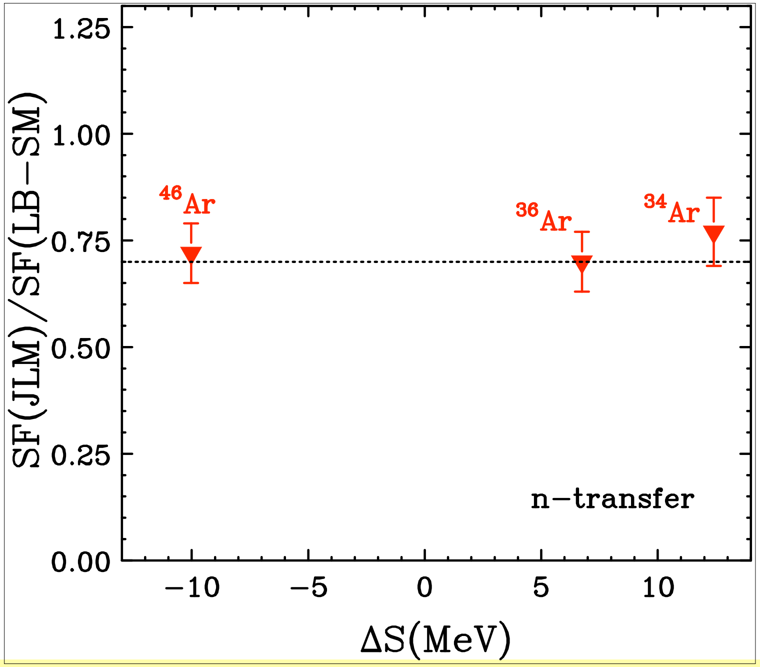
- Spectroscopic factors (SF's) reveal the dominant valence orbits.
- Residual interactions reduce SF's below unity near the Fermi Surface.
  - Short-range nucleon-nucleon repulsion
  - Long-range particle-vibration coupling, etc.
- (e,e'p) reactions indicate a 30% reduction for valence orbits.
- n and p knockout reactions suggest a strong dependence on the separation energy of the removed nucleon.

•Gade, Lee



Results from other probes





Dispersive optical potential

- The interactions that reduce SF's are the source of the imaginary potential in nucleon optical potentials.

  Fits elastic scattering data enable predictions for the SF reduction

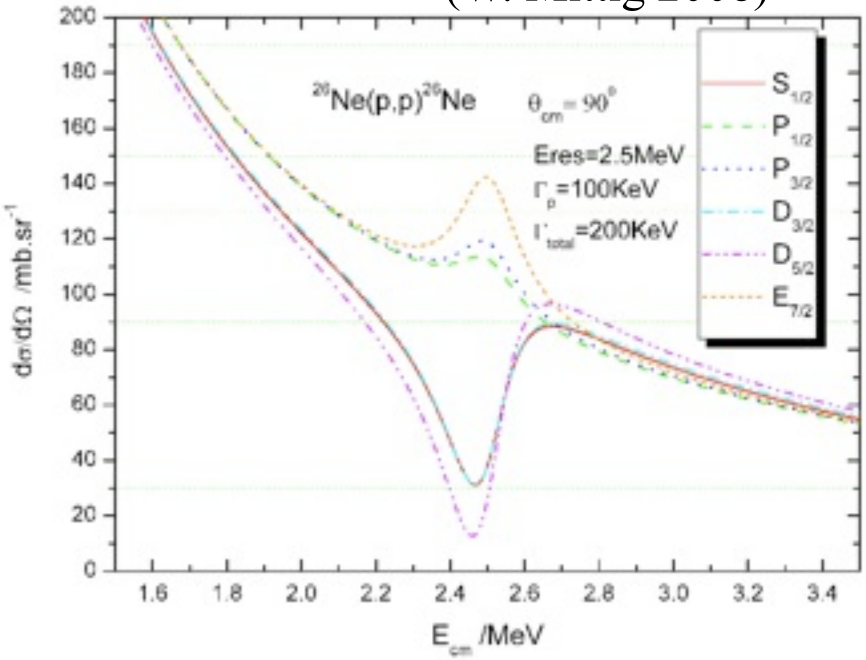
  Line show two predictions; both show much weaker trends than that of the knock-out data.

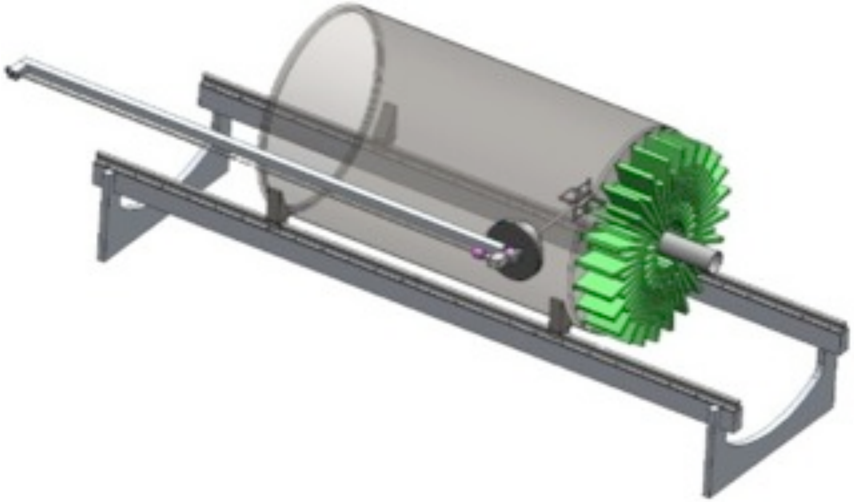
(p,d) reactions

- New (p,d) transfer data for ^{34}Ar, ^{36}Ar and ^{46}Ar do not show strong depend on asymmetry or neutron separation energy.
- Sensitivity tests should be done to reveal the relative contributions of the surface and the interior.
- Discrepancy between knockout and other probes presents a puzzle

Another tool: isobaric analog resonances

(W. Mittig 2008)



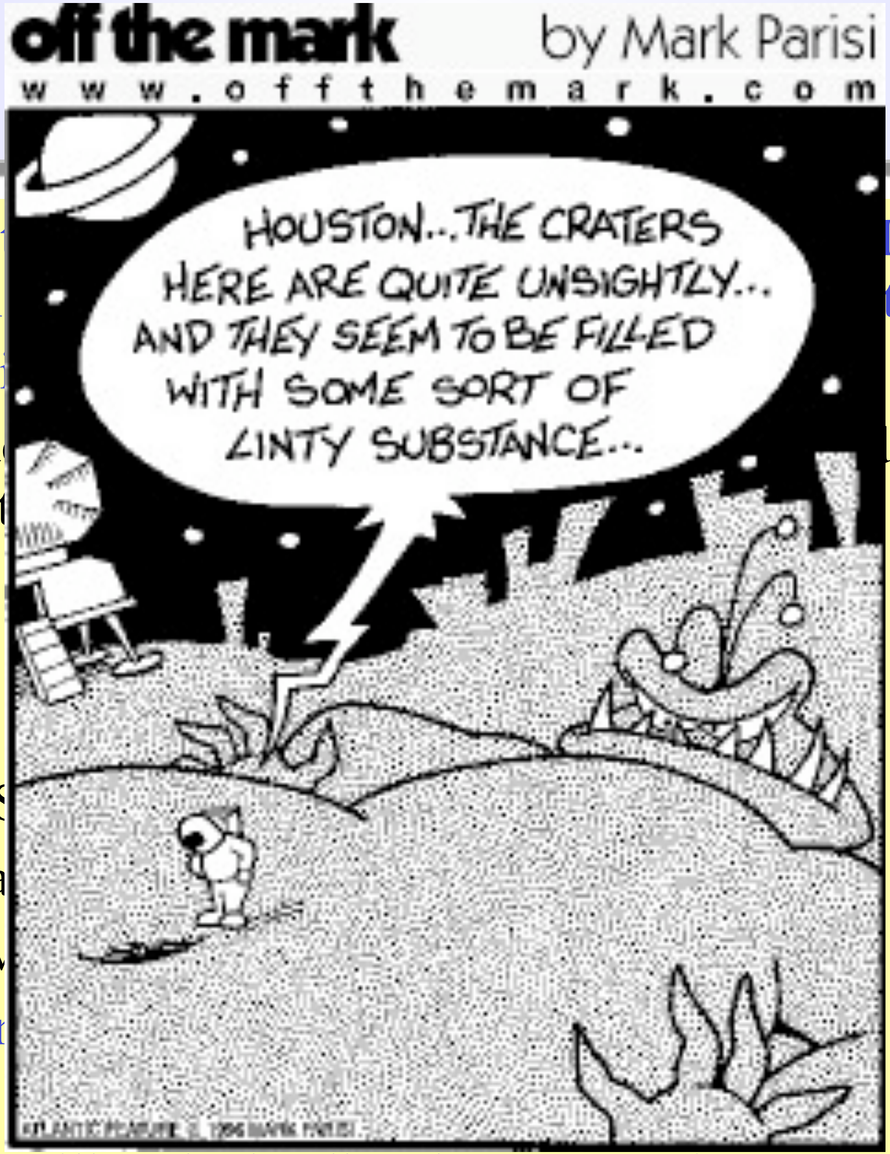


- Isobaric analog resonances in proton elastic scattering on a exotic nucleus (Z,A) can provide information about the analog states in the nucleus (Z-1,A).

- Experiment can be performed in inverse kinematics using low intensity rare isotope beams (>100 p/s) incident on an active hydrogen target.

Summary and outlook

- Next generation rare isotope facilities such FRIB, FAIR and RIBF (at RIKEN) will address a broad array of scientific objectives.
- Some of which were discussed:
  - The structure and excitations of neutron –rich and neutron deficientnuclei
    - new shell structures
    - new regions of deformation.
    - new correlations.
  - The EOS of asymmetric matter.
  - The creation of the heavy elements.
  - Explosive astrophysical environments.
- Some were not discussed:
  - Tests of fundamental symmetries
- Future work will undoubtedly advance greatly our perspectives of these matters, which are somewhat limited at present.



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