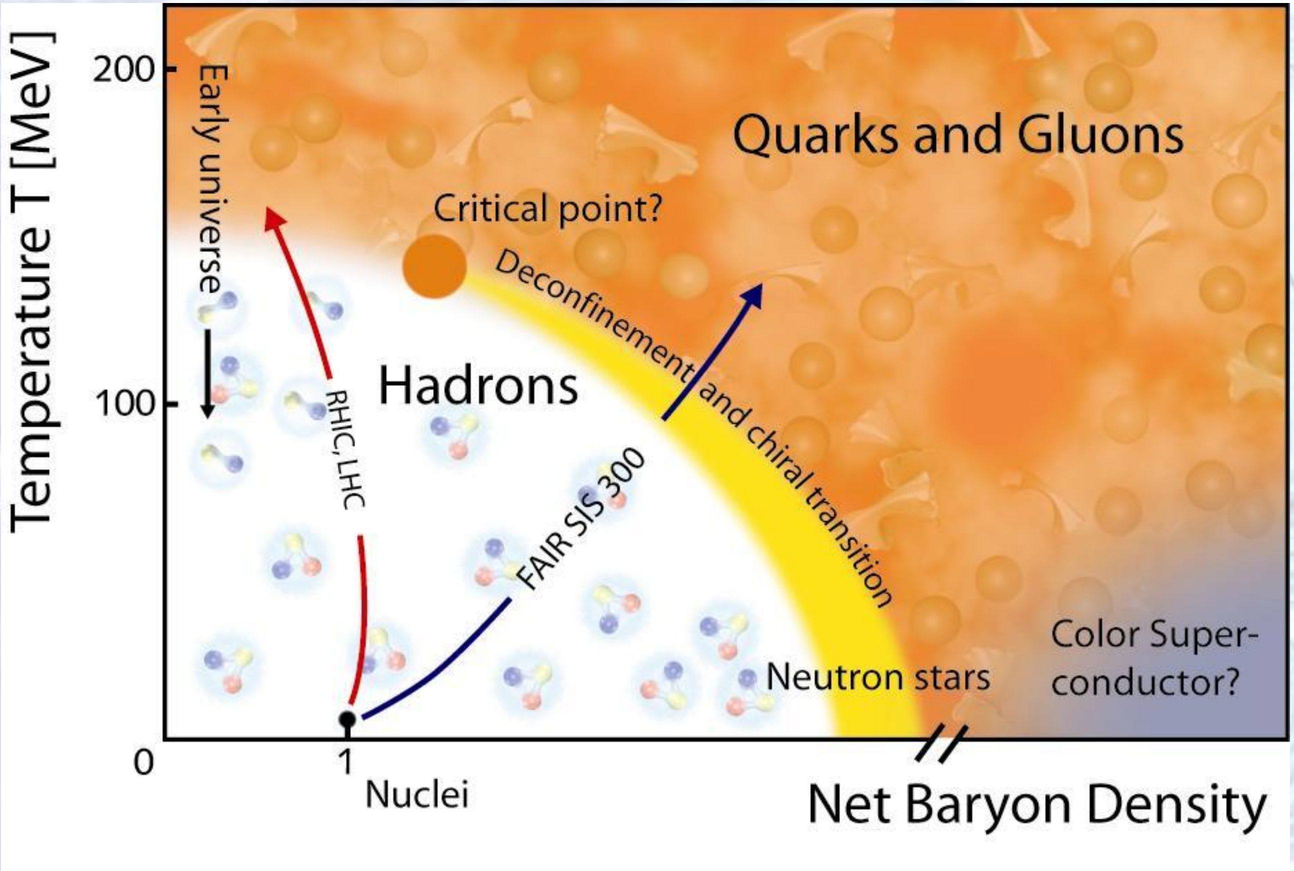
ASYEOS: ASYMMETRIC EQUATION OF STATE and the S394 experiment at GSI

Measuring flow to constrain the symmetry energy of the nuclear equation of state

Zoe Matthews for Liverpool University and the ASYEOS Collaboration

Phase Diagram of Strongly Interacting Matter



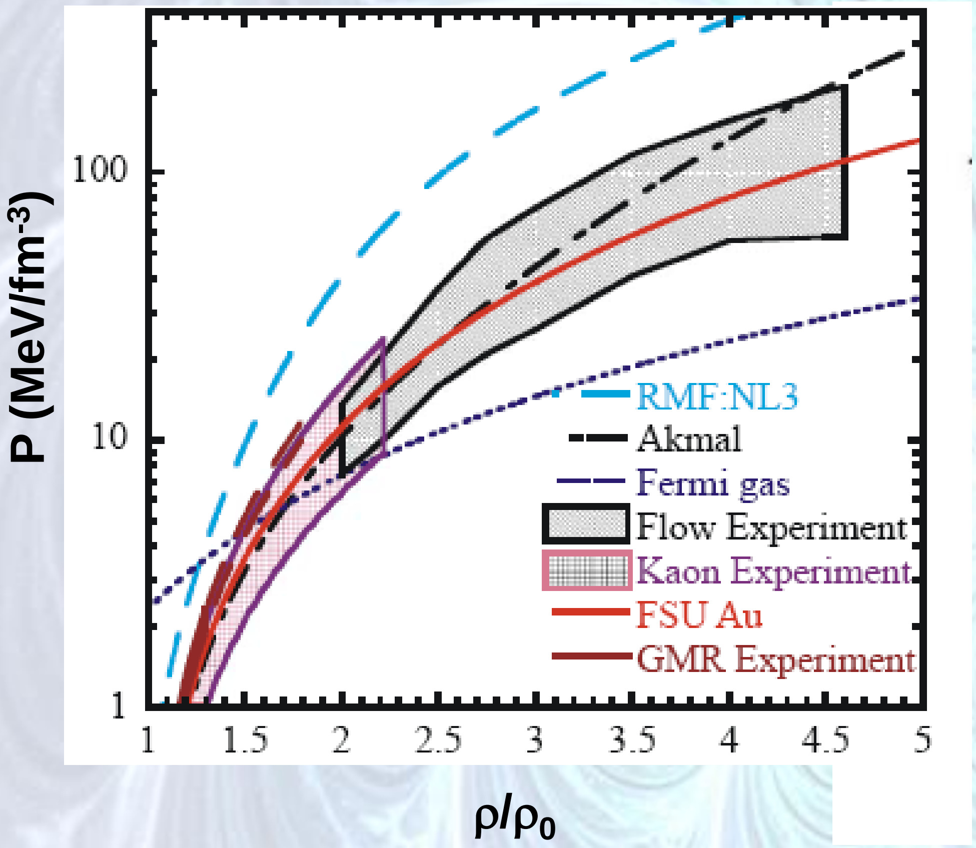
Compact Astrophysical Objects e.g. Neutron Stars:
- Low Temperature
- High Density
- Strong isospin asymmetry

Heavy Ion Collision Experiments Explore Phase diagram

Nuclear Equation of State

- EOS describes relationship between Energy E, Pressure P, Temperature T, Density ρ and Isospin Asymmetry δ

Symmetric



- Experimental constraints from:
  - collective flow
  - sub-threshold kaon production
  - giant monopole resonance

Nuclear Equation of State

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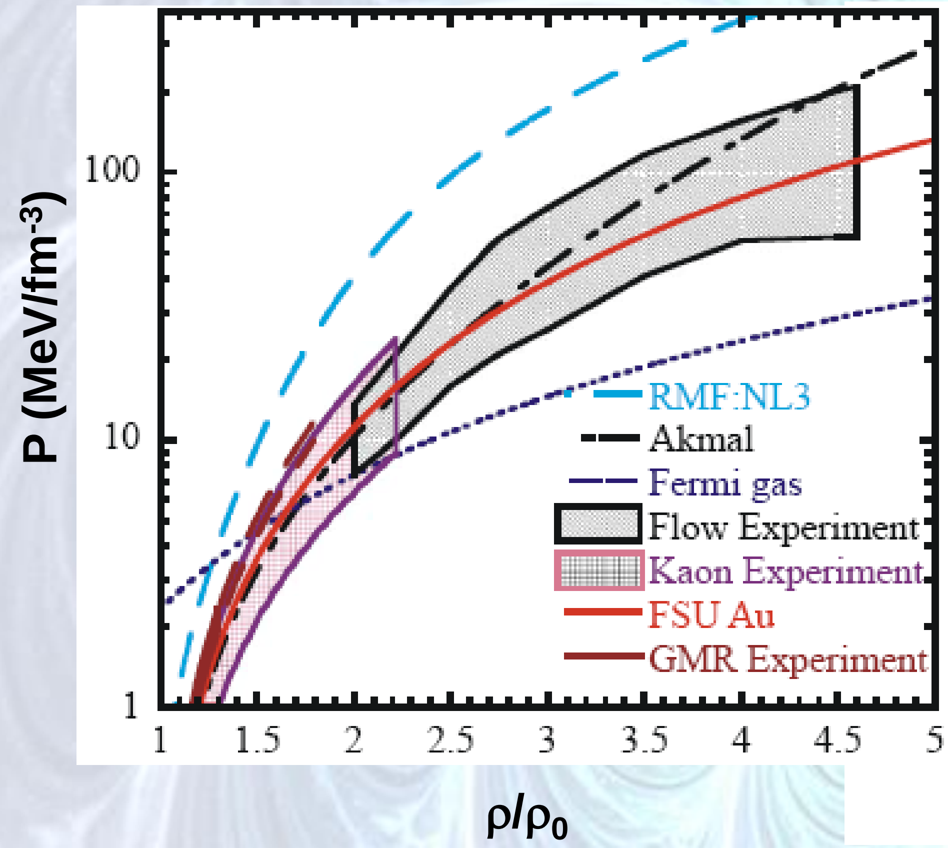
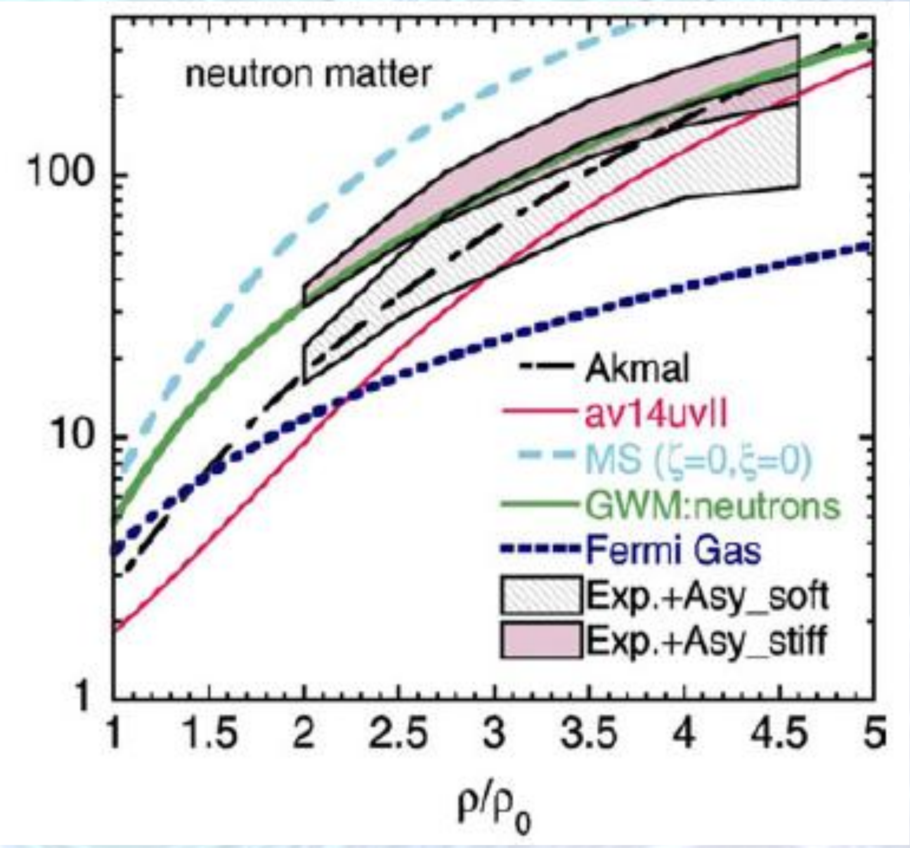
Symmetric



Asymmetric



Nuclear Equation of State

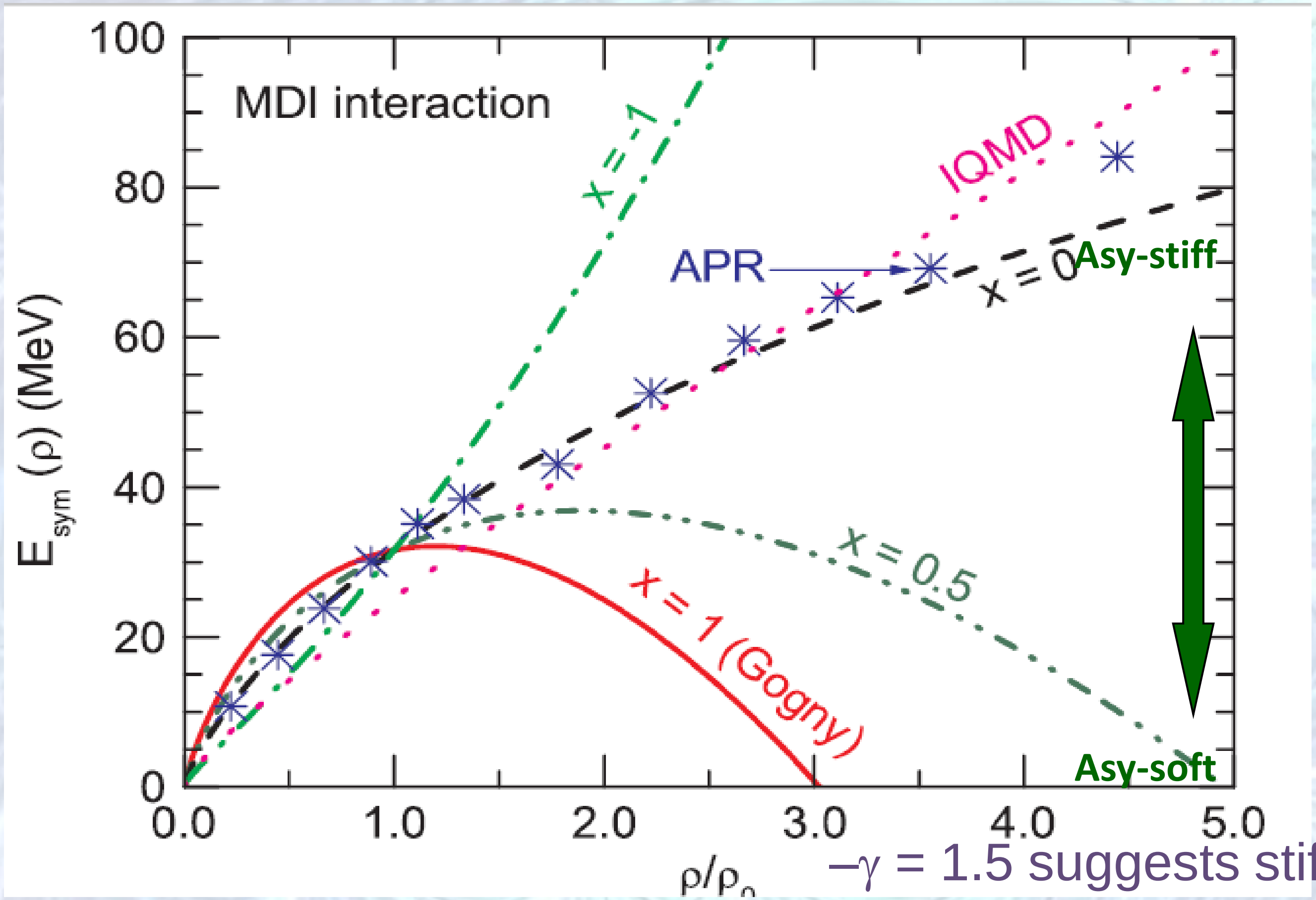
- EOS describes relationship between Energy E, Pressure P, Temperature T, Density ρ and Isospin Asymmetry δ
- Few constraints in isospin-asymmetric system

$$\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A$$

E/A(ρ,δ) = E/A(ρ,0) + Isospin Asymmetric part, $\delta^2 * S(\rho)$

Nuclear Equation of State

- EOS describes relationship between Energy E, Pressure P, Temperature T, Density ρ and Isospin Asymmetry δ



–γ = 1.5 suggests stiff S(ρ)

–γ = 0.5 suggests soft S(ρ)

PRL 102, 062502 (2009)

Nuclear Equation of State

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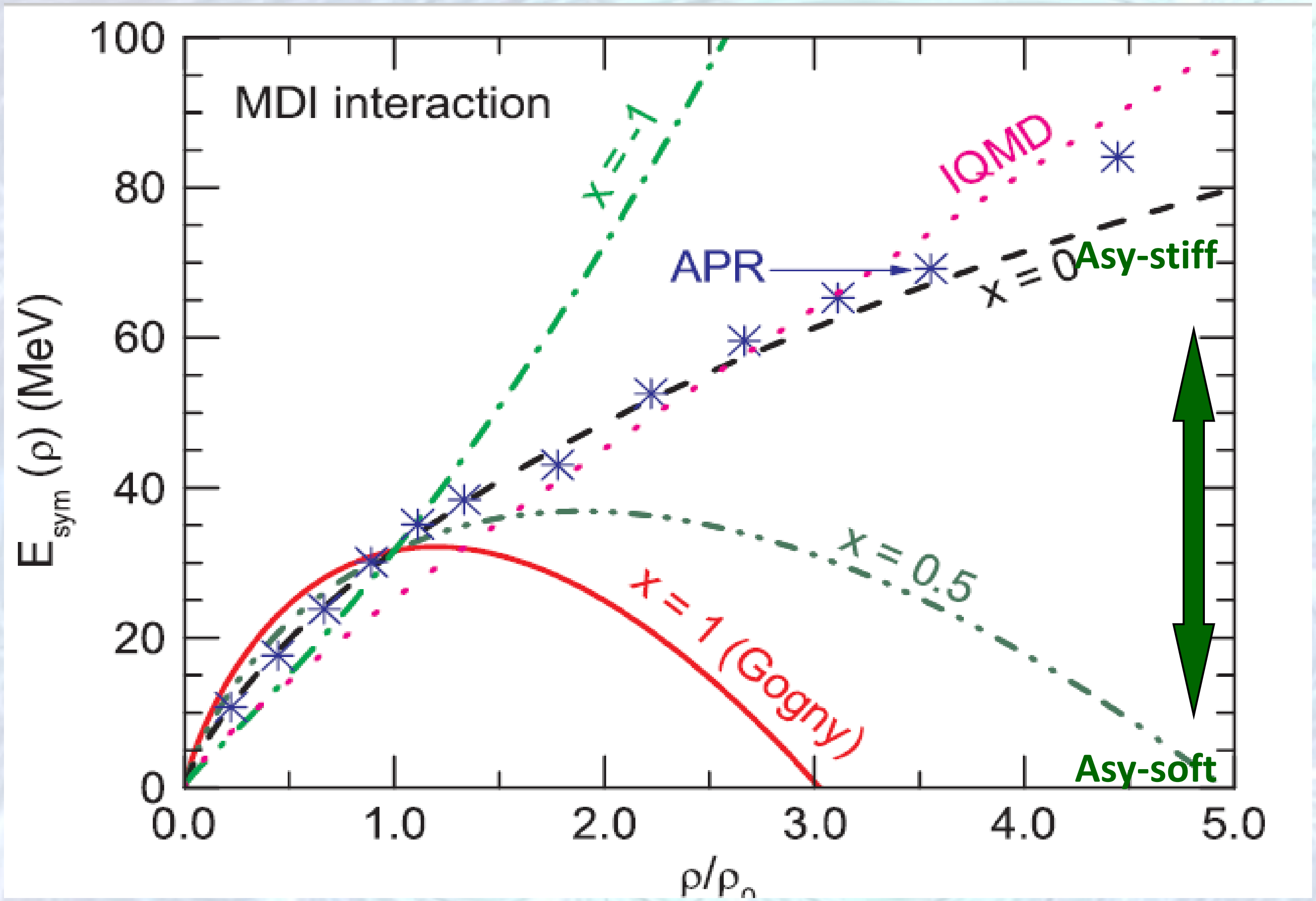
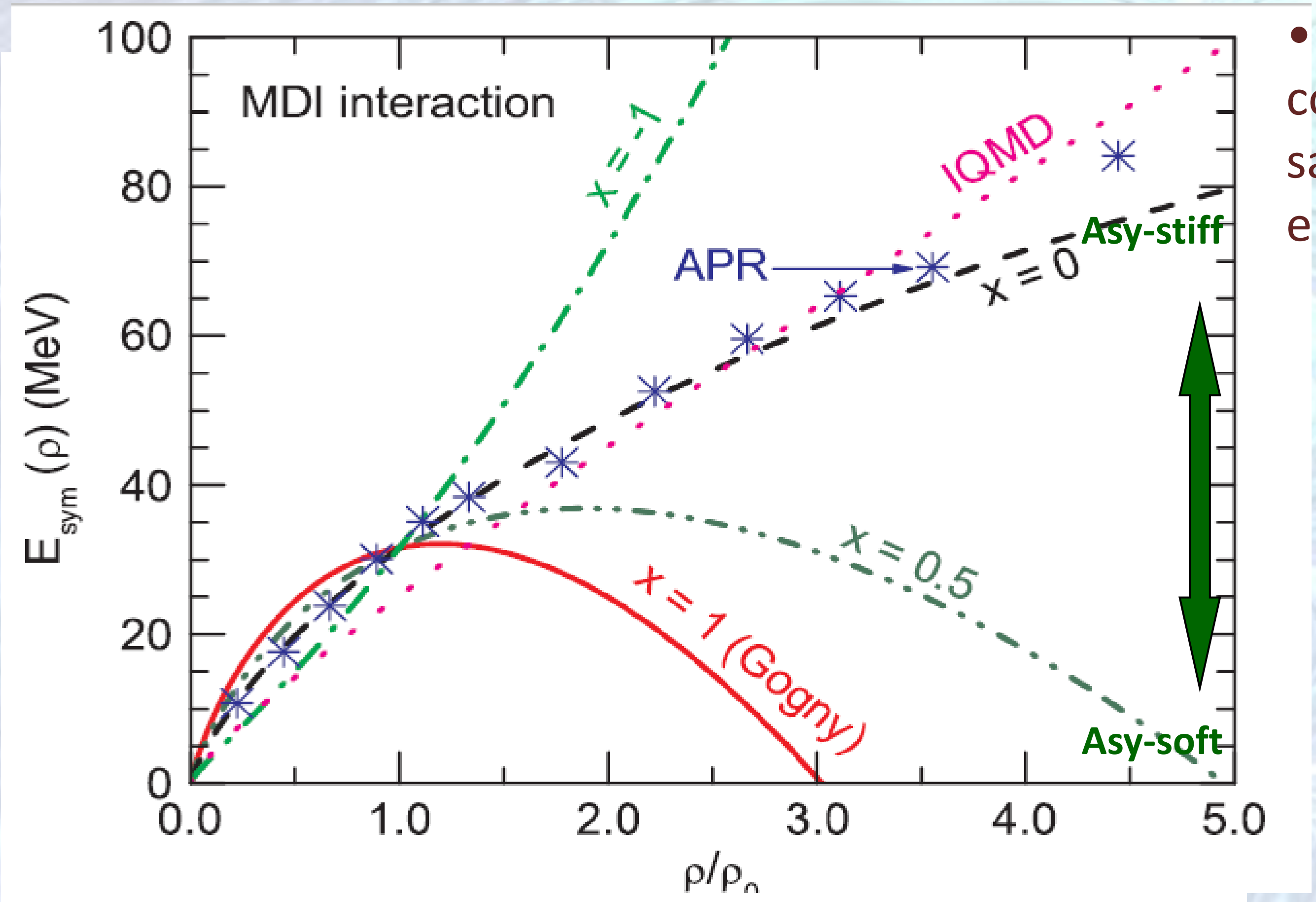


- Experimental constraints, sub-saturation density e.g.
  - –Low Energy (< 100 AMeV) Heavy Ion Collisions: Isospin Diffusion Neutron/Proton Ratios

PRL 102, 062502 (2009)

Nuclear Equation of State

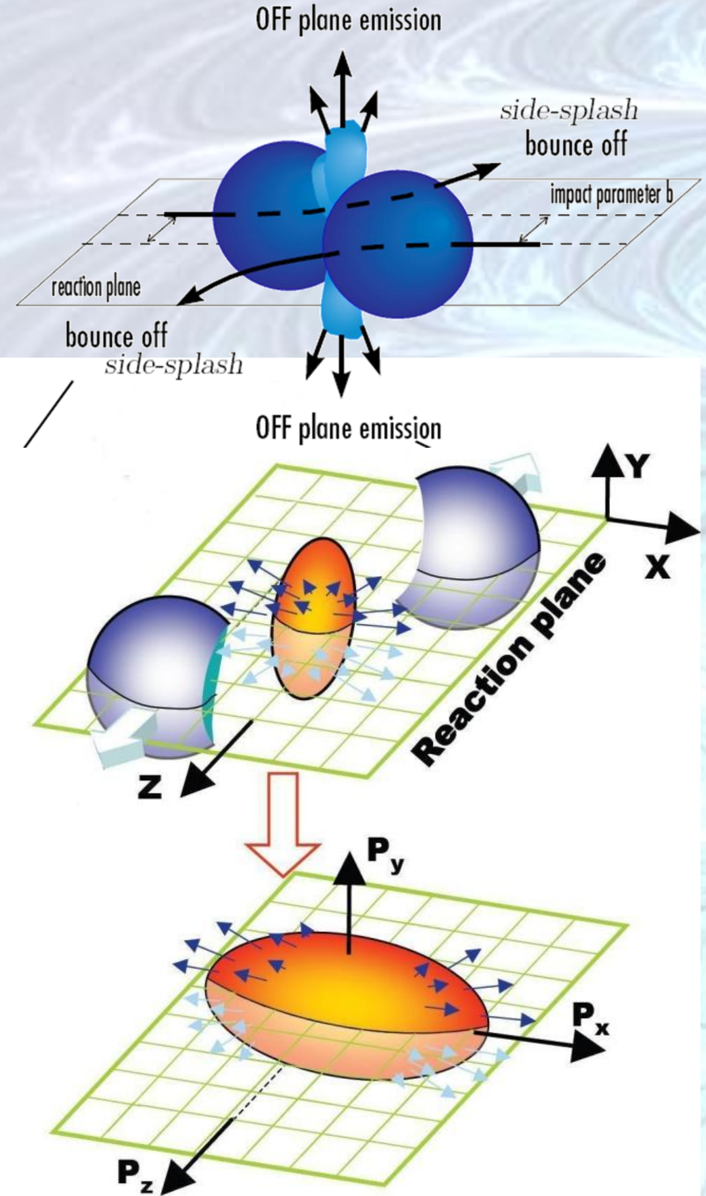
- EOS describes relationship between Energy E, Pressure P, Temperature T, Density ρ and Isospin Asymmetry δ



- Experimental constraints, supra-saturation density e.g.
  - – neutron /proton spectra and flows
  - –fragment ratios: t/3He
  - – particle production: π^+/π^-, K^+/K^-, Σ^+/Σ^-

PRL 102, 062502 (2009)

Flow in heavy ion collisions

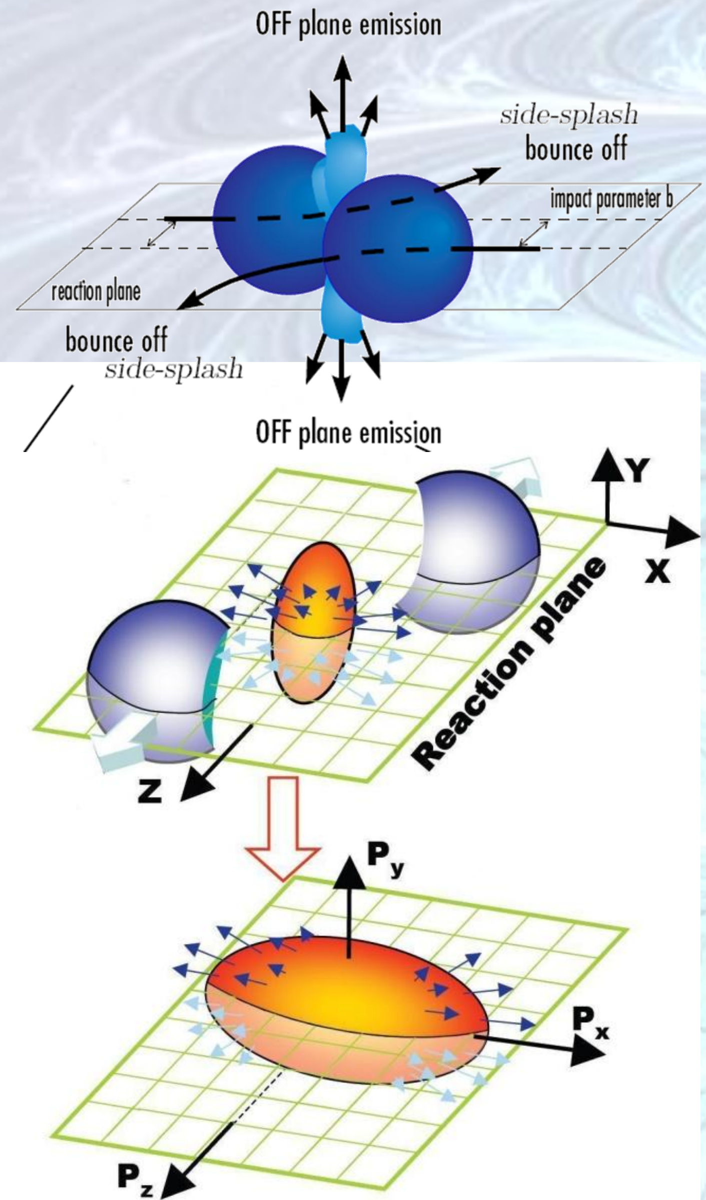


- These effects are measured in detectors as azimuthal anisotropy with respect to the reaction plane, and can be described via a Fourier expansion

$$\frac{dN}{d(\varphi_R-\varphi)}=\frac{N_0}{2\pi}\left(1+2\sum_{n\geq 1}v_n\cos n(\varphi_R-\varphi)\right)$$

- V1=Directed Flow: in-plane, larger at large rapidity
- V2=Elliptic Flow: large and negative (off-plane) at mid-rapidity

Flow in heavy ion collisions



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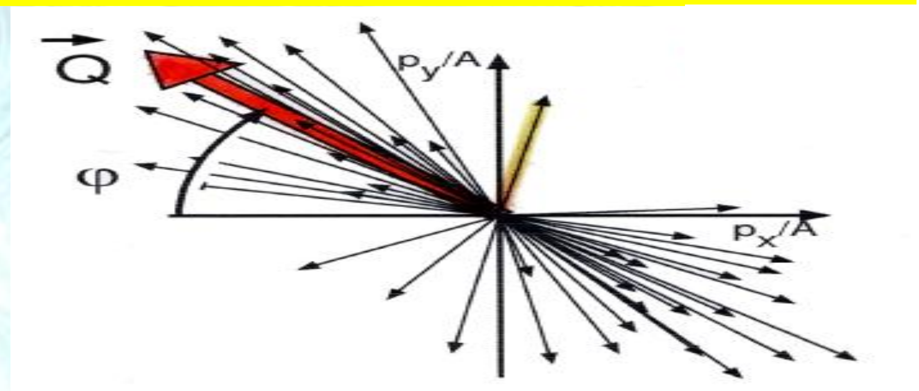
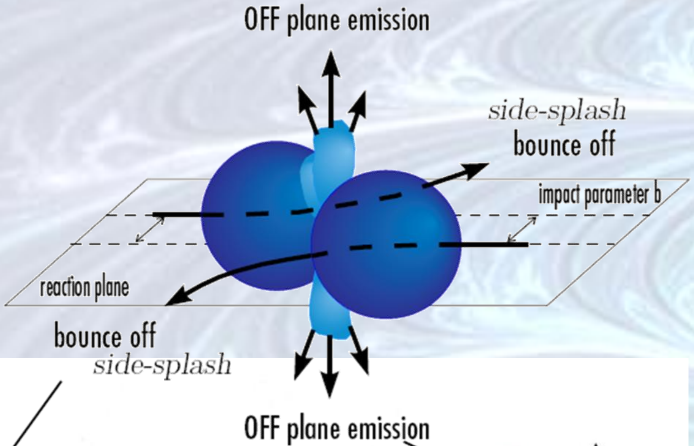
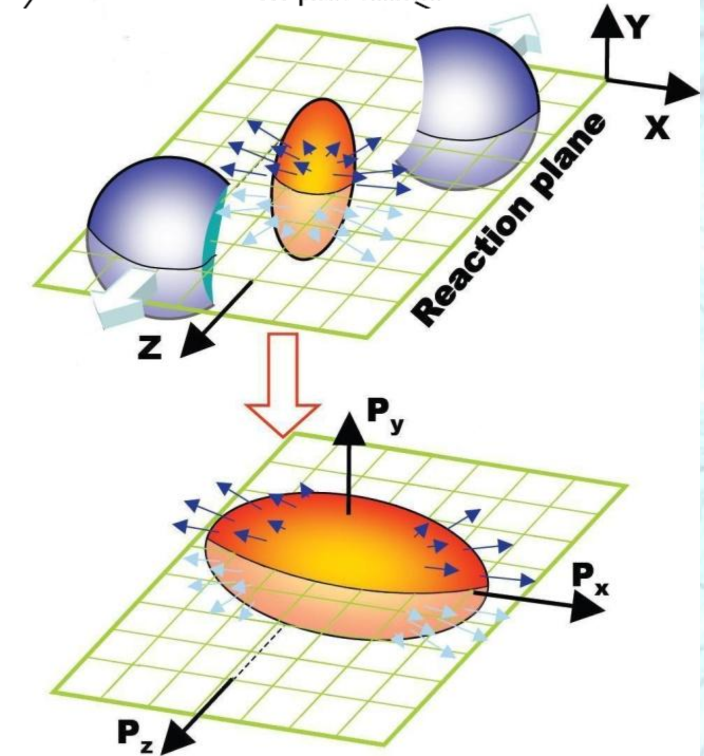
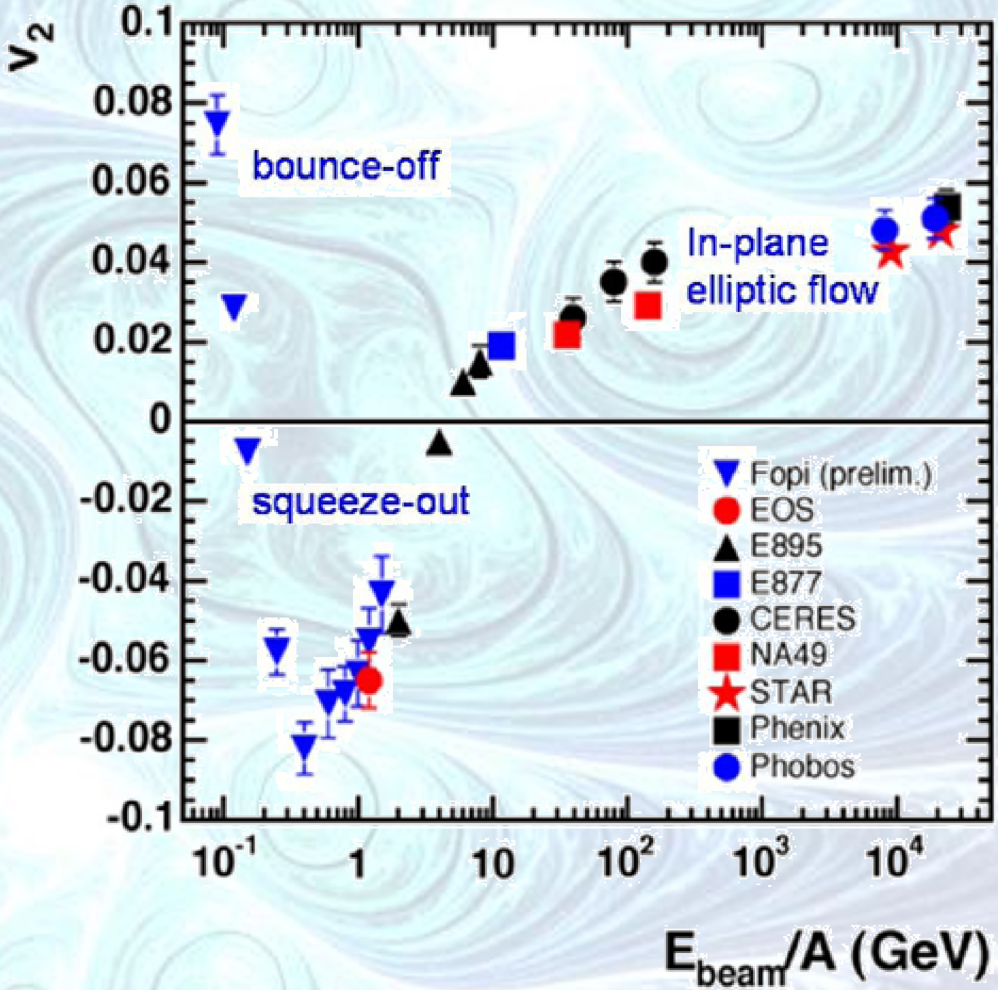


- “Q-vector” used to measure flow

Flow in heavy ion collisions





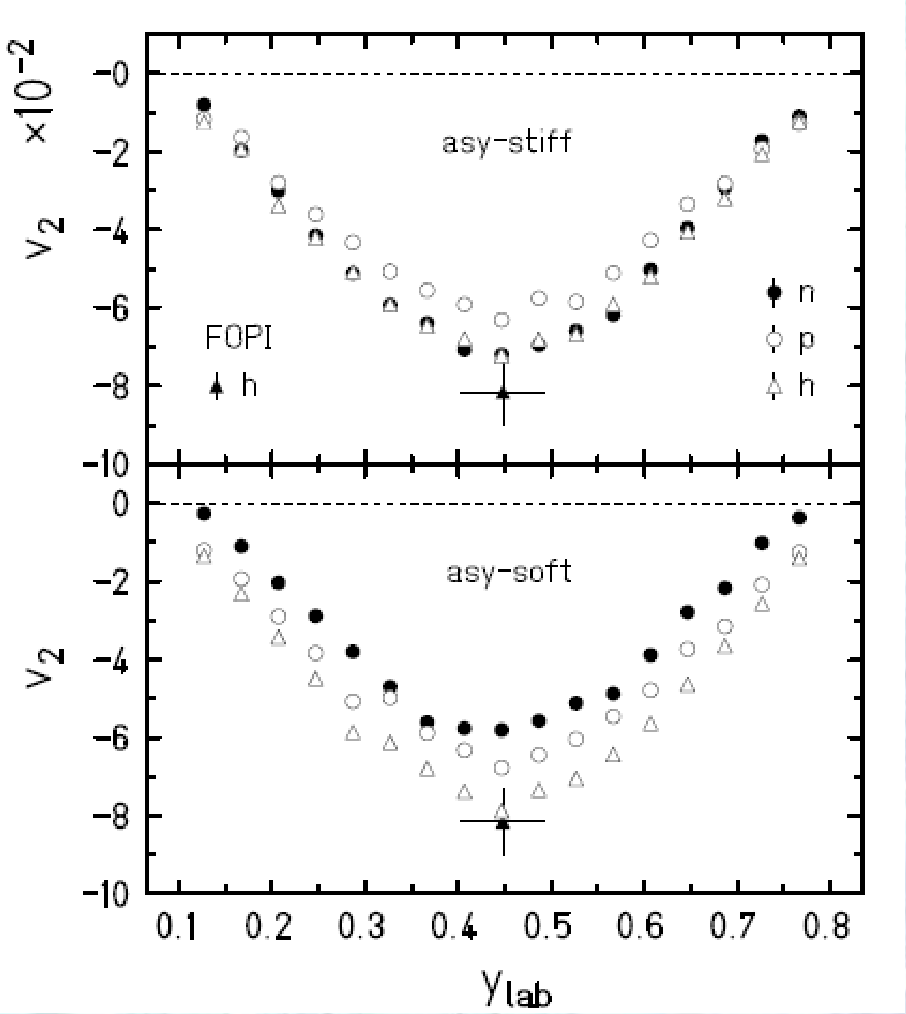


- Largest effect from v2 at 400 MeV/u

Flow and Isospin Asymmetry

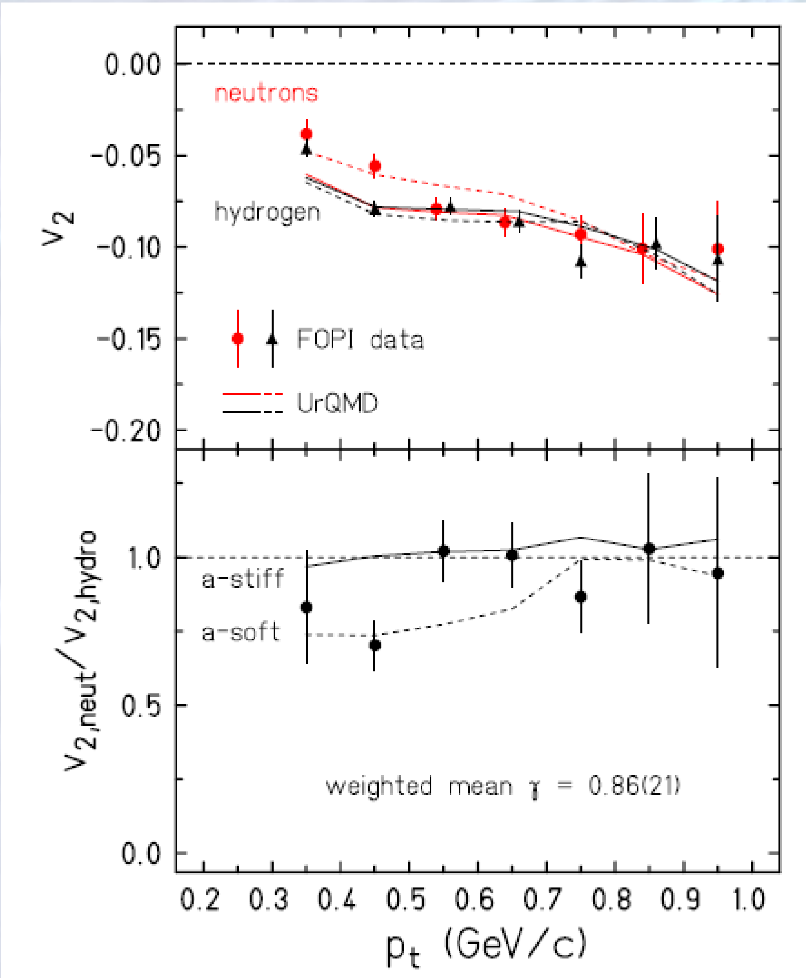
- Flow of n vs p at high density, sensitive to symmetry energy
- Compare measured data with model predictions to establish “stiffness”

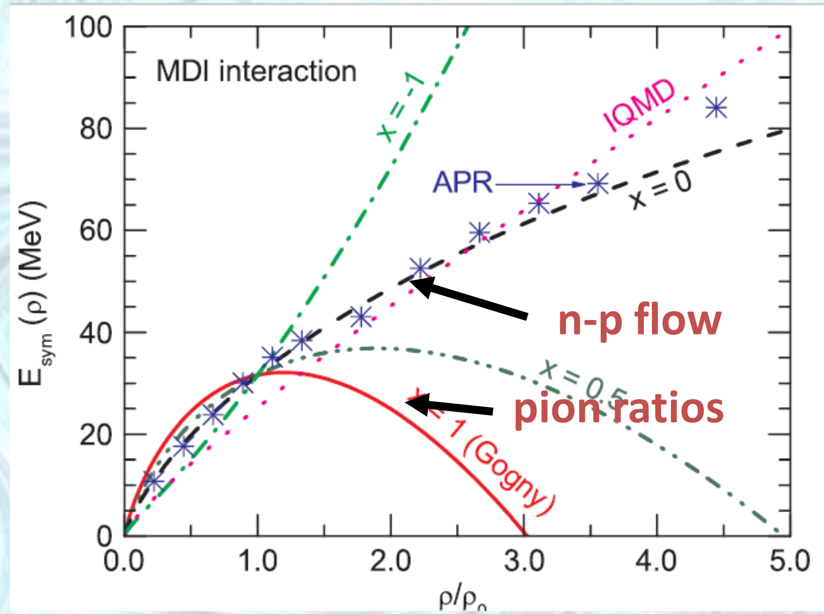
Symmetry energy from elliptic flow in ^{197}Au ^{197}Au
P. Russotto et al, Physics Letters B 697, 471 (2011)



UrQMD predictions for n, p and h v_2 for soft vs stiff density dependence

Measurements using FOPI data





Asy-stiff

Asy-soft

- SIS@GSI, LAND + FOPI forward wall
- Au+Au at 400, 600, 800 AMeV
- Re-analysis of data sets and comparison to UrQMD transport models
- PhD topic of Pete Wu, Liverpool University

Comparison of neutron-proton elliptic flow data to UrQMD model gives moderately soft symmetry energy (x=0; γ = 0.86 (21)) at $\rho/\rho_0 \sim 2$

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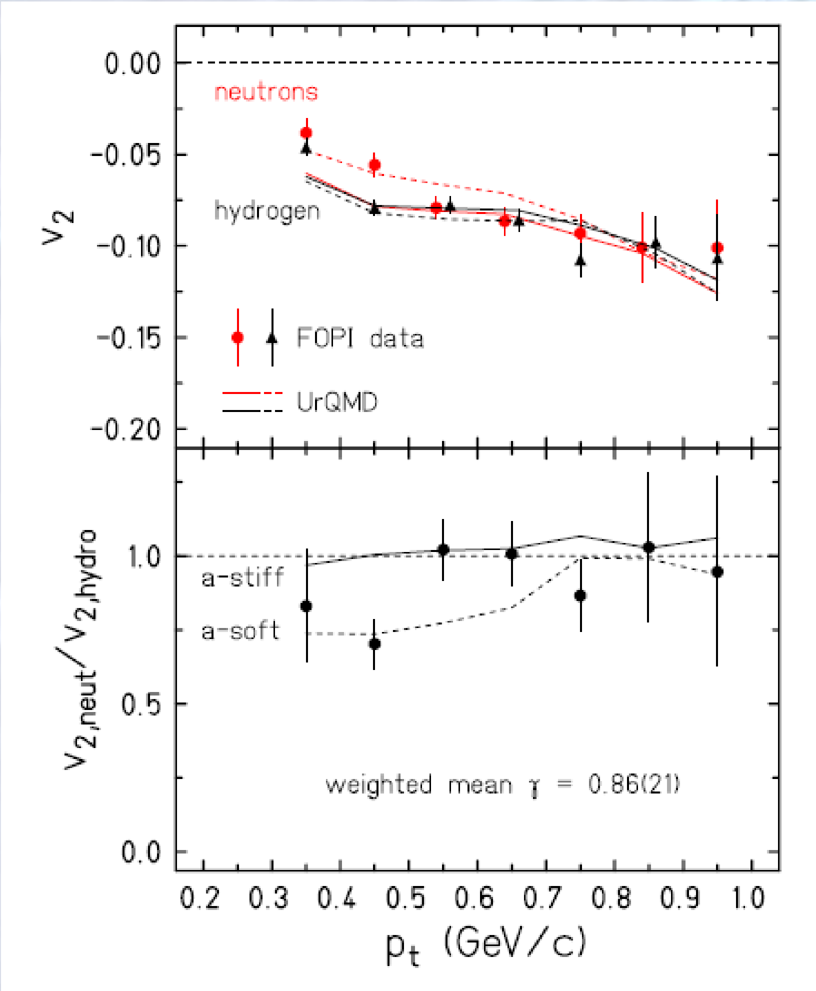
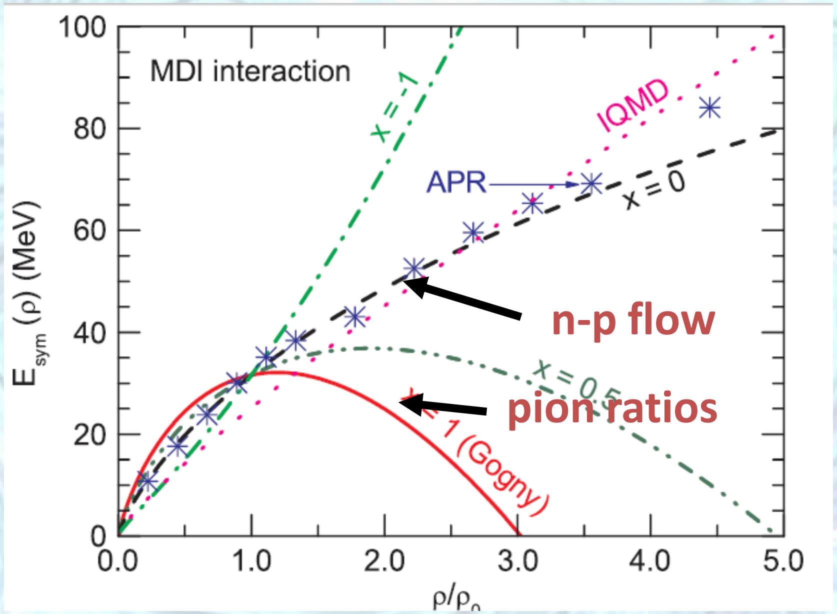
Measurements using FOPI data





Asy-stiff

Asy-soft

However...comparison of FOPI π^-/π^+ ratios to IBUU04 transport model gives super-soft symmetry energy (x=1; $\gamma < 0.5$)

Comparison of neutron-proton elliptic flow data to UrQMD model gives moderately soft symmetry energy (x=0; $\gamma = 0.86$ (21)) at $\rho/\rho_0 \sim 2$

Conflicting results !!!
Need new experiments, smaller systematic errors, more sensitivity

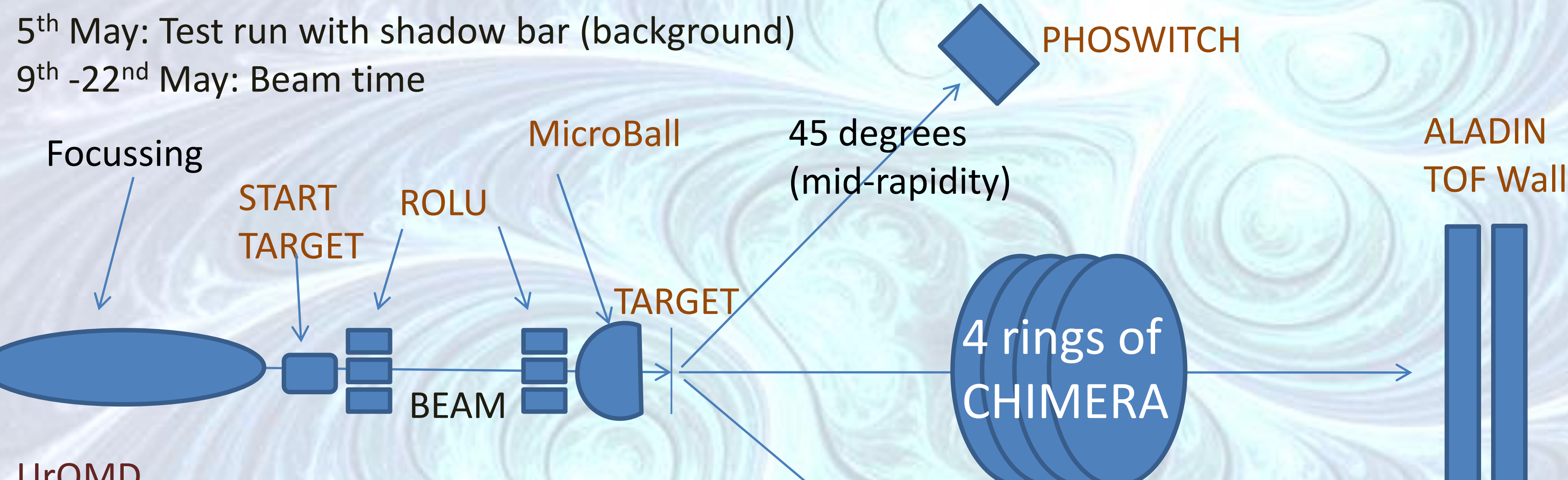
ASYEOS 'S394' Experiment

SIS@GSI, ^{197}Au-^{197}Au, ^{96}Ru-^{96}Ru, ^{96}Zr-^{96}Zr, 400 MeV/u

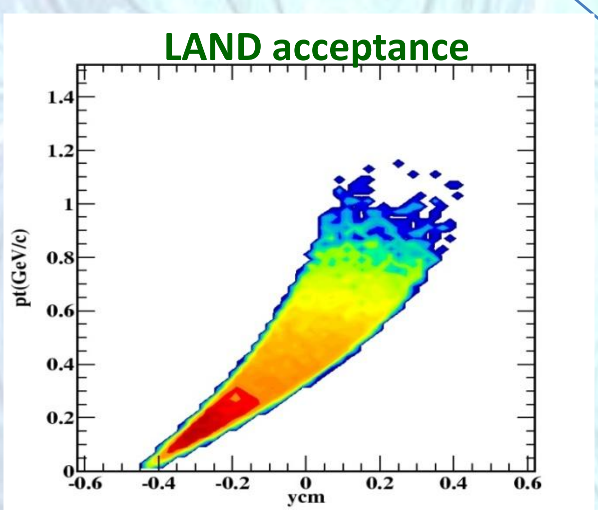
Dates:

5th May: Test run with shadow bar (background)

9th -22nd May: Beam time



UrQMD simulations predict, using Q-vector method, reaction plane resolution of $\Delta\phi$~21 degrees χ~1.9



From proposal submitted to GPAC 2009

Large Area Neutron Detector (LAND)

- Plastic scintillator / Fe converter sandwich structure, 200 paddles
- VETO Wall: plastic scintillator stripes ,in front of LAND
- Simultaneous n/p detection

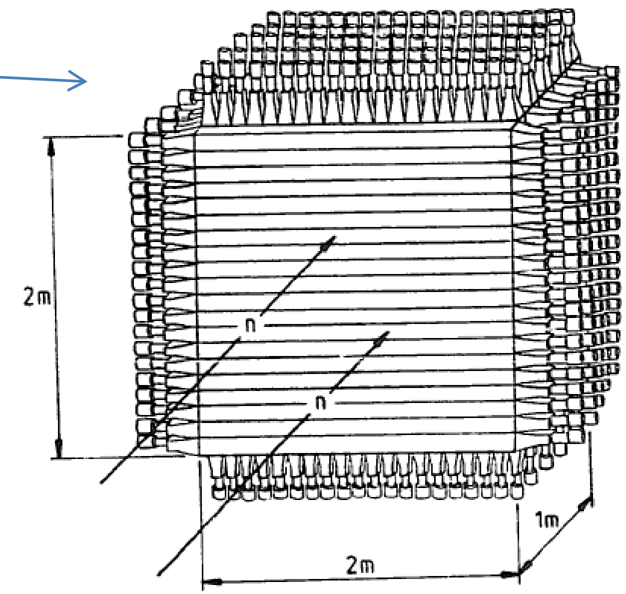
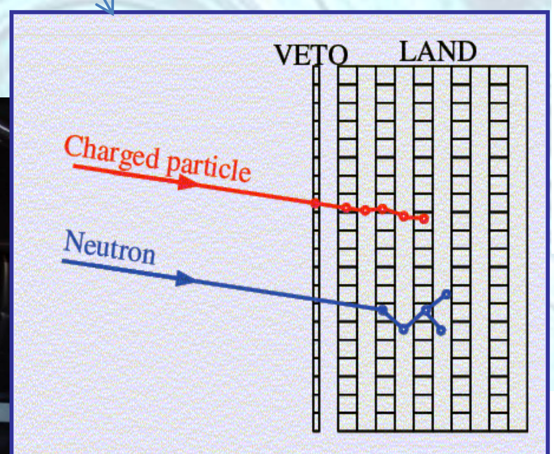
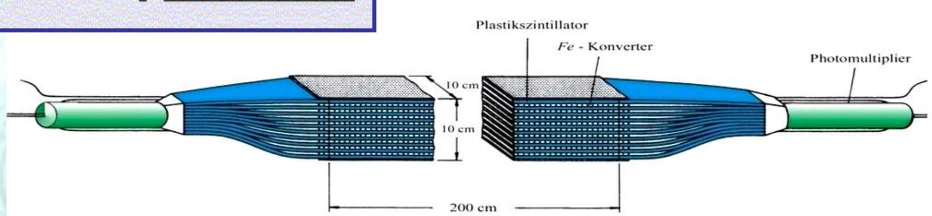


Fig. 4. Sketch of the full neutron detector (without veto detector).

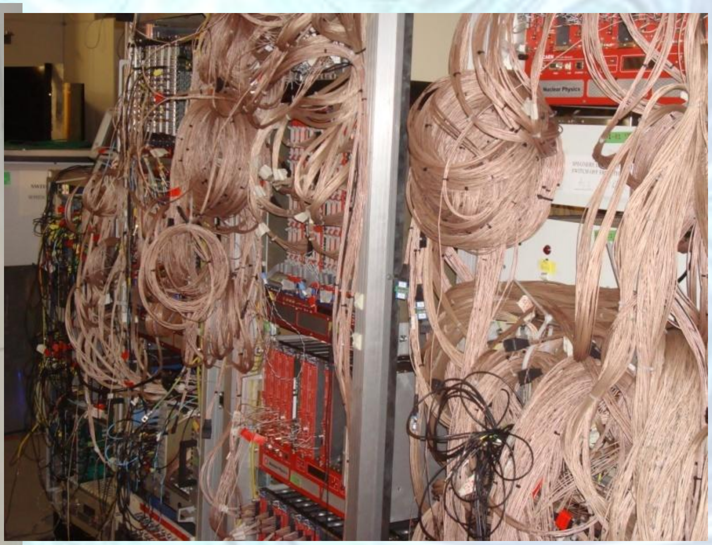
$\sigma_t < 250$ ps, $\sigma_{x,y,z} \approx 3$ cm



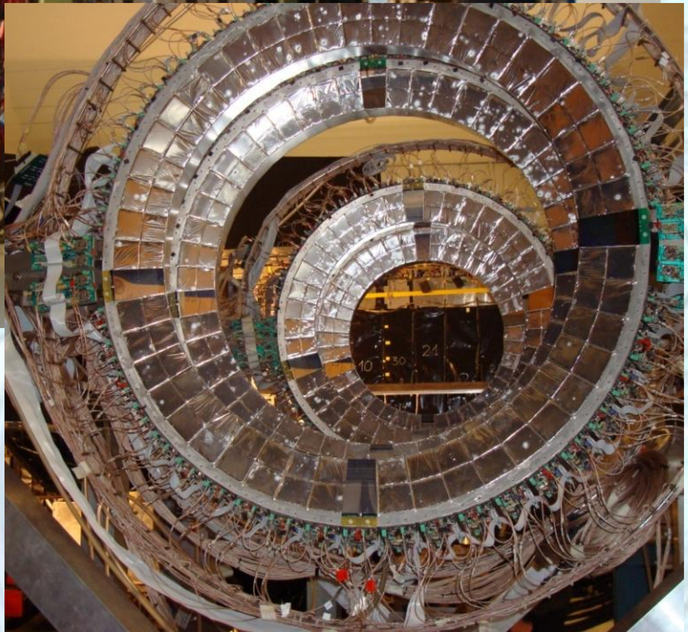


Th. Blaich *et al.*, NIM A 314,136 (1992).

Status of Experiment (in pictures)



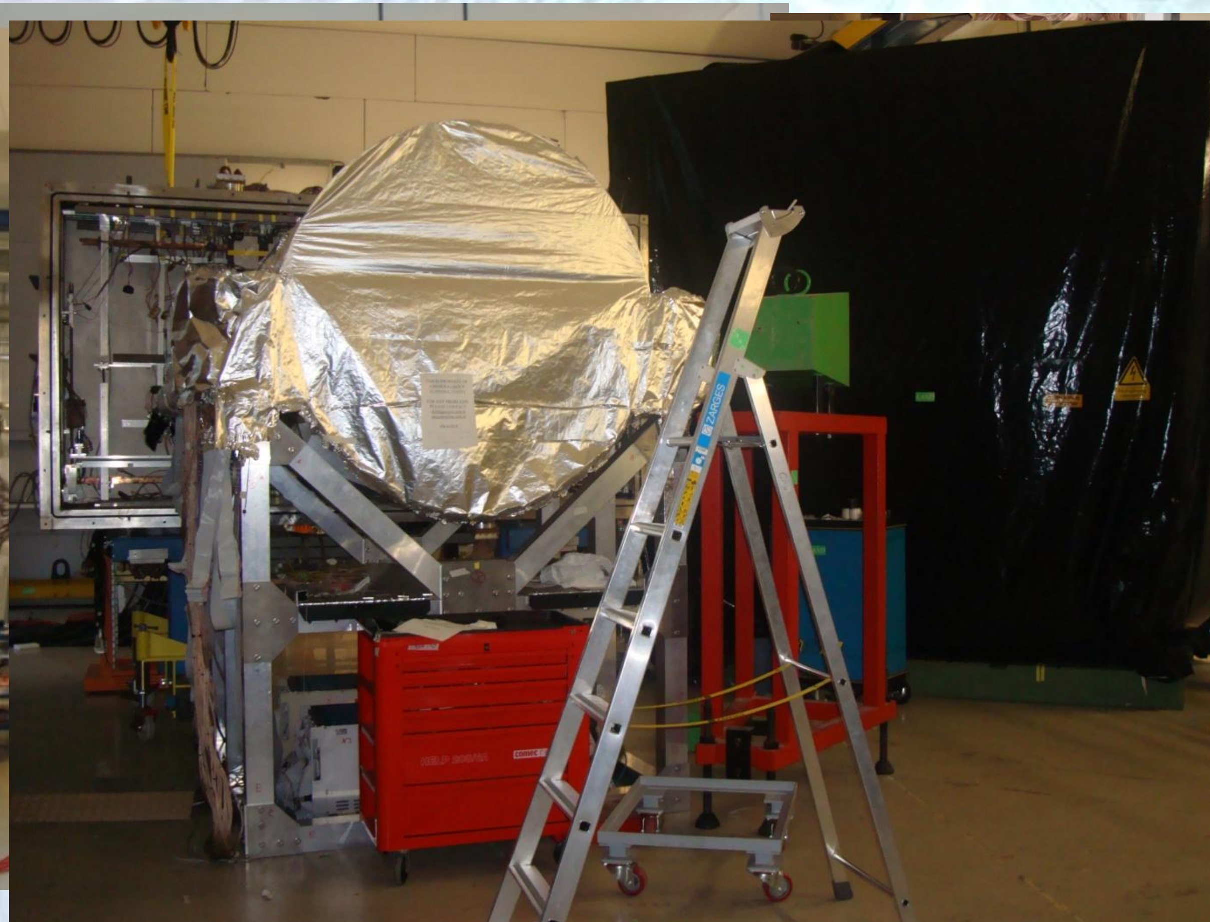
2 weeks ago...

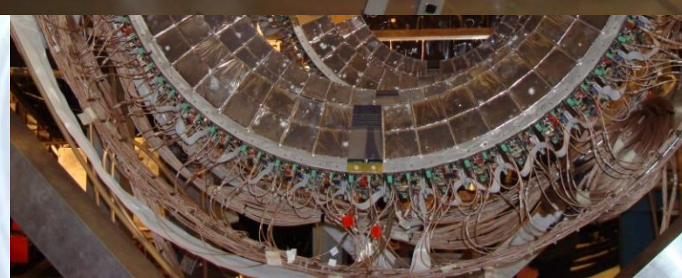


Last week...

- Microball and Krakow to be delivered end of month
- Other detectors being moved, tested, installed etc
- Cave closes on 10^{th} April for 2 weeks

Status of Experiment (in pictures)





2 weeks ago...

Last week...

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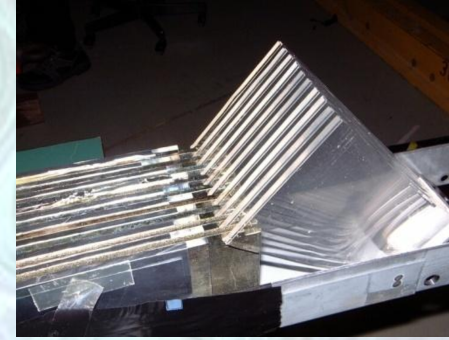
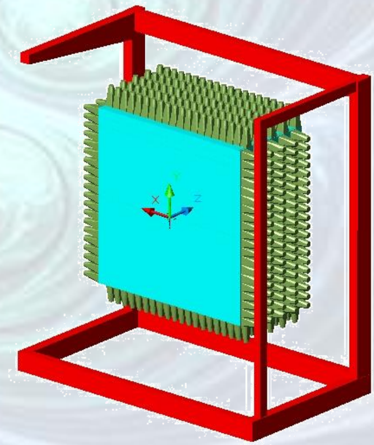
Last week...

Summary and Outlook

- Symmetry energy, part of the nuclear EOS, needs to be constrained
- In particular, density dependence poorly understood at high density
- Measuring n vs p collective flow in high density heavy ion systems can tell us something about symmetry energy
- ASYEOS S394 Experiment runs 5^{th}-22^{nd} May 2011
- FAIR beams will provide more isospin-asymmetric systems (stronger symmetry-energy dependence) and higher density systems



ASYEOS



BACKUPS

Zoe Matthews for Liverpool University and the ASYEOS Collaboration

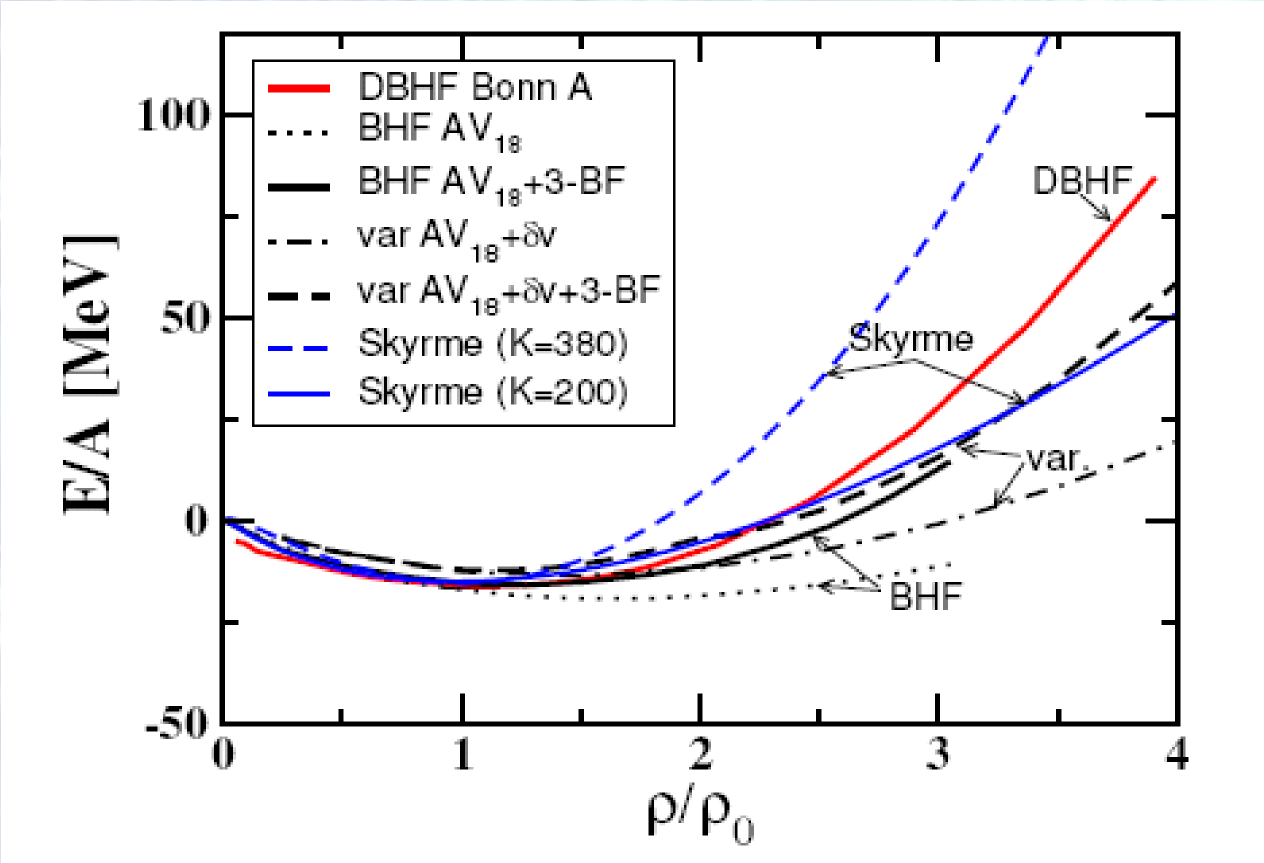
UNIVERSITY OF LIVERPOOL

Outline

- Symmetry Energy and the nuclear EoS
- Flow in heavy ion collisions
  - What is flow? What can we learn from flow?
  - How do we measure flow?
- Flow measurements to constrain symmetry energy at supra-saturation densities
  - Initial studies using FOPI data
  - The ASYEOS S394 Experiment 2011
    - Setup, detectors
    - Preparation and status
  - Looking to the future: FAIR
- Summary

Nuclear Equation of State

- EOS describes relationship between Energy E, Pressure P, Temperature T, Density ρ and Isospin Asymmetry δ

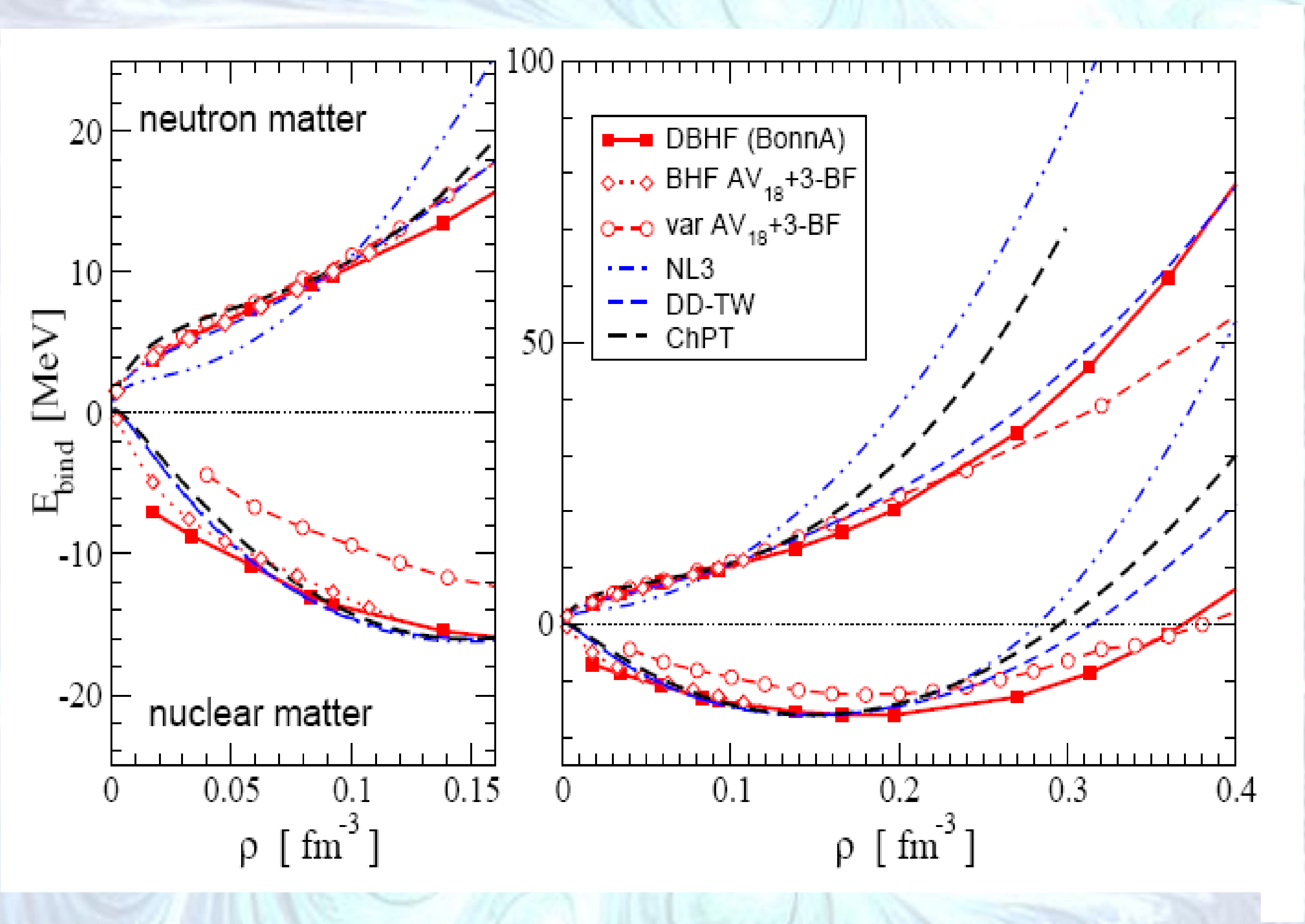


PRL 102, 062502 (2009)

E/A(ρ,δ) = E/A(ρ,0) + Isospin Asymmetric Term, δ^2 * S(ρ)

Symmetry Energy

C. Fuchs and H.H. Wolter, Eur. Phys. J. A 30 (2006) 5.



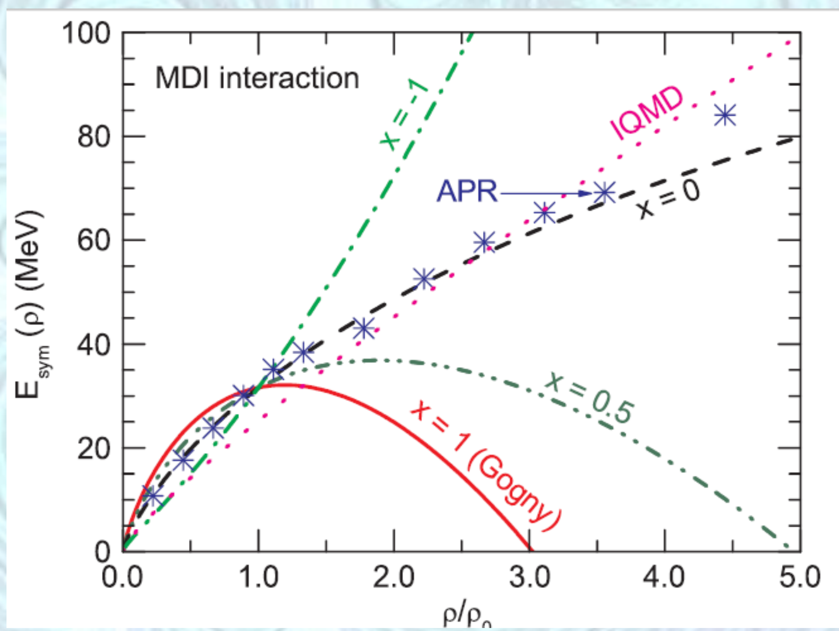
Symmetry Energy

- Symmetry Energy S and dependence on density, takes some form:

$$S(\rho) \propto C(\rho/\rho_0)^{\gamma}$$

- Nuclear EOS Models diverge at high density because unknown γ term dominates!
  - γ = 1.5 suggests stiff $S(\rho)$
  - γ = 0.5 suggests soft $S(\rho)$

Using data as input to transport models helps constrain γ



Asy-stiff

Asy-soft

PRL 102, 062502 (2009)

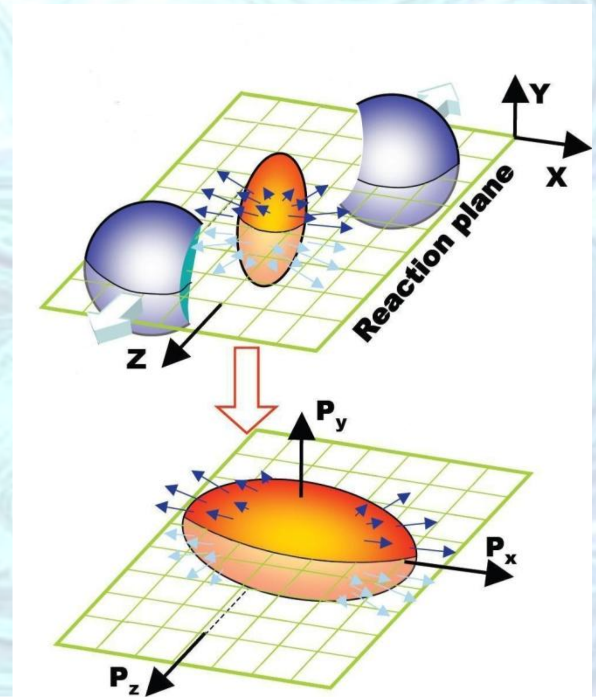
Symmetry Energy

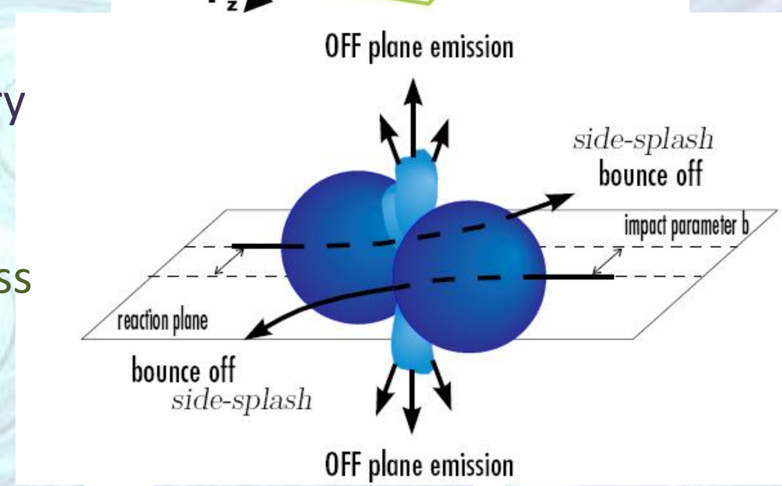
Constraints on Symmetry Energy:

- Sub-saturation Density
  - Neutron skins
  - Giant and pigmy dipole resonances
  - Isobaric analogue states and masses
  - Low Energy (< 100 AMeV) Heavy Ion Collisions: Isospin Diffusion, Neutron/Proton Ratios
- Supra-saturation Density
  - Astrophysical observations
  - Heavy ion collisions: neutron/proton spectra and flows
  - fragment ratios: t/3He
  - particle production: π^+/π^-, K^+/K^-, Σ^+/Σ^-

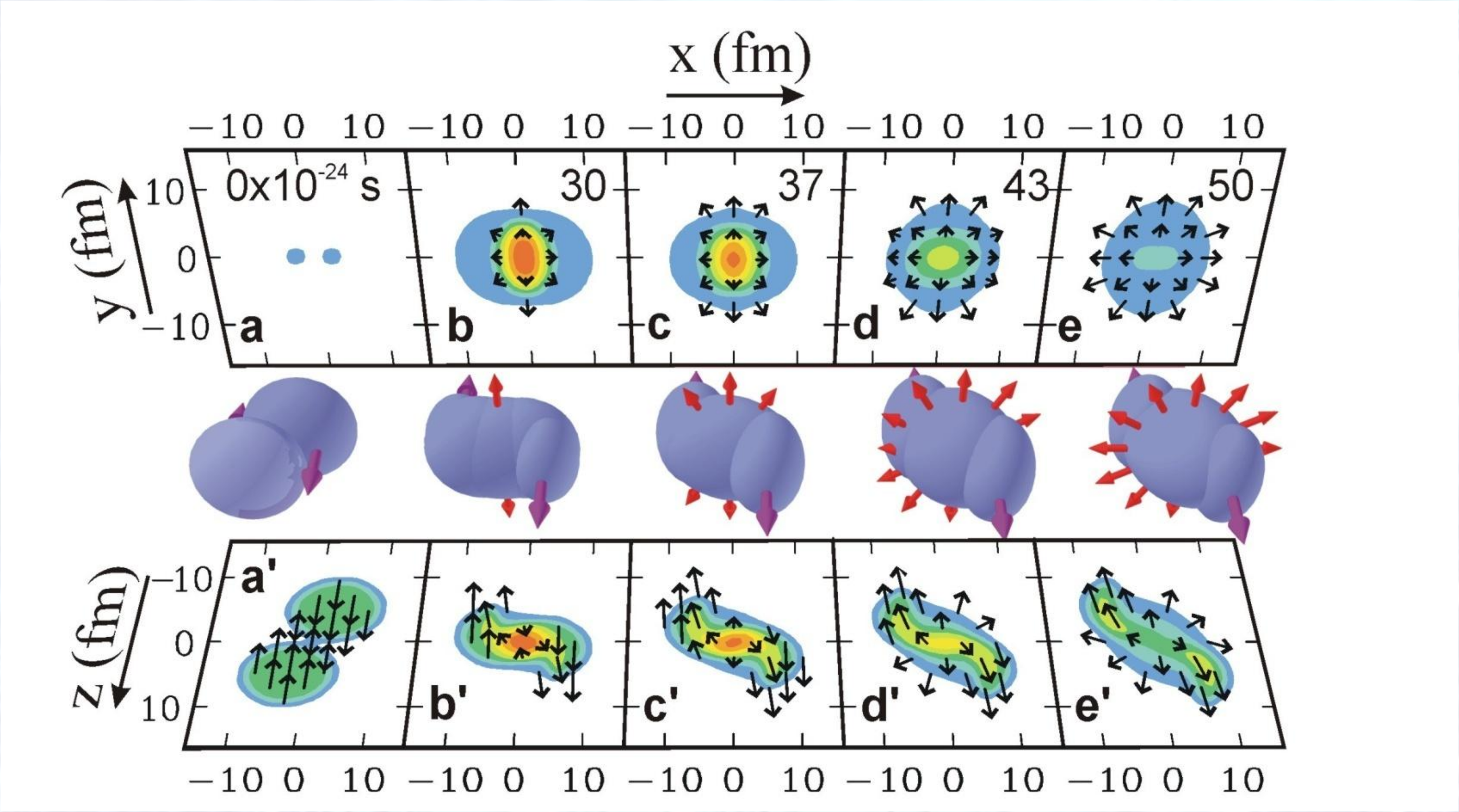
Flow in heavy ion collisions

- Semi-central heavy ion collisions have an initial spatial anisotropy, orientated by the reaction plane, z (beam direction) vs x (axis defined by impact parameter b)
  - Pressure gradients translate this anisotropy from coordinate space to momentum space
  - At mid-rapidity (for middling, up to 1 A GeV energies), stopping power of the “spectator” nucleons cause off-plane elliptic flow (“squeeze out”)
    - **High density – interesting!**
  - At larger rapidities, initial spatial asymmetry leads to preferred direction of “flow” of particles (directed flow)
  - Smaller elliptic flow at higher rapidity as less stopping (or even in-plane at higher, >10 A GeV energy)





Flow in heavy ion collisions



Measuring Flow

- These effects are measured in detectors as azimuthal anisotropy with respect to the reaction plane, and can be described via a Fourier expansion:

$$\frac{dN}{d(\varphi_R - \varphi)} = \frac{N_0}{2\pi}\left(1 + 2\sum_{n\geq 1} v_n \cos n(\varphi_R - \varphi)\right)$$

- V1=Directed Flow (in-plane, p_x/p_T), larger at large rapidity
- V2=Elliptic Flow

(positive in-plane, negative off-plane, $p_x^2 - p_y^2 / p_x^2 + p_y^2$), large and negative at mid-rapidity

Measuring Flow

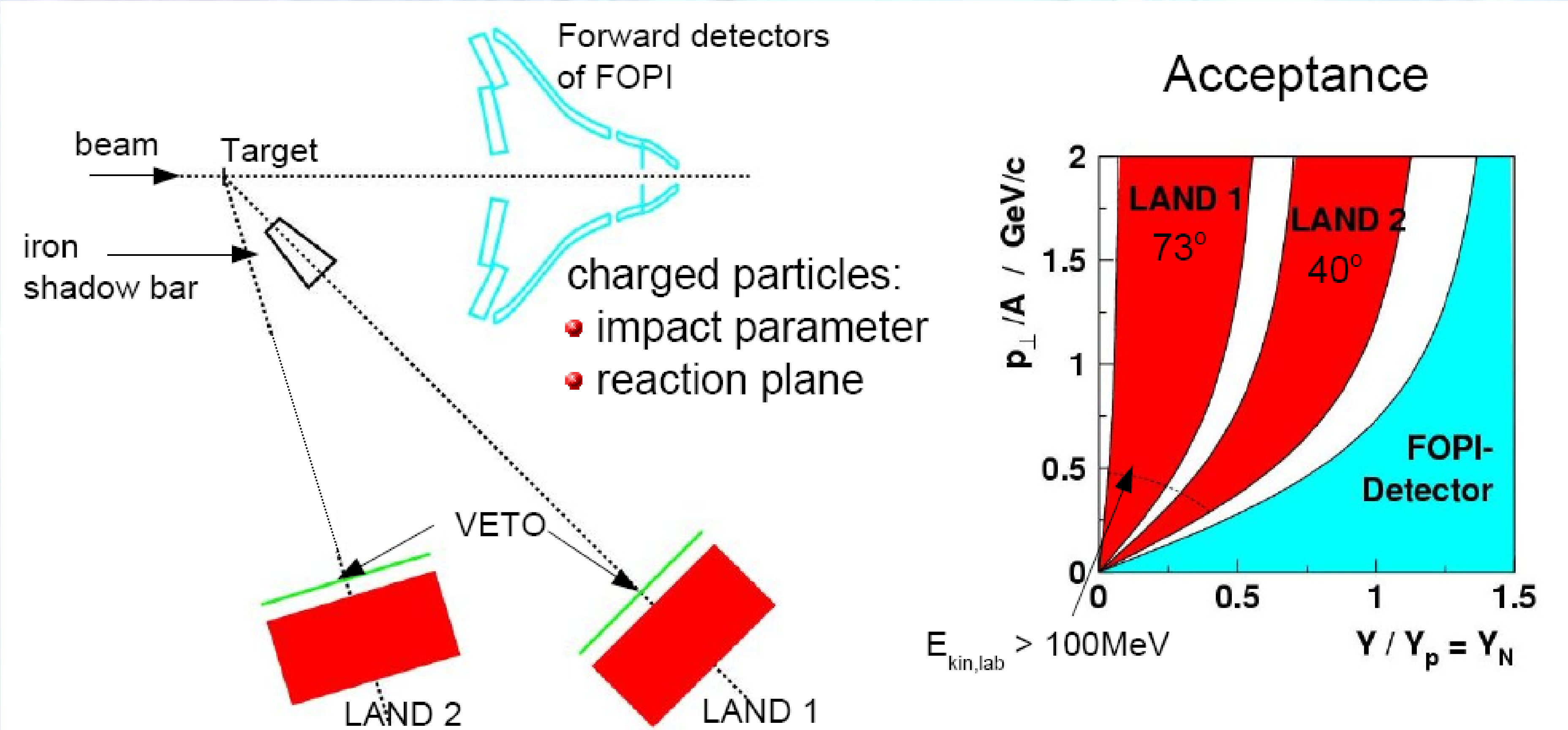
- "Event Plane" method:
  - Reaction plane angle constructed event-by-event using Q-vector method (average transverse momentum of emitted particles)
  - Uses anisotropy itself to find reaction plane, one harmonic at a time
  - Limitations
    - **Reaction plane resolution depends on multiplicity and signal: $\chi = v_2\sqrt{M}$**
    - **"Non-flow" effects from e.g. resonances, jets. "Mixed harmonics" method can reduce this but also reduces resolution**
    - **"Participant plane" (fluctuation from reaction plane, flow seems bigger)**

Measuring Flow

- Bessel and Fourier Transforms, Cumulants (some-particle correlations), Lee Yang Zeros (all-particle correlations)
  - Several methods that focus on collective flow wrt other particles
  - E.g. Lee Yang Zeros, compute value of generating function/product generating function, find minimum, derive collective flow. Designed to remove all orders of auto-correlations and non-flow
  - Limitations
    - **Require minimum multiplicity and signal or errors blow up: χ>0.8**

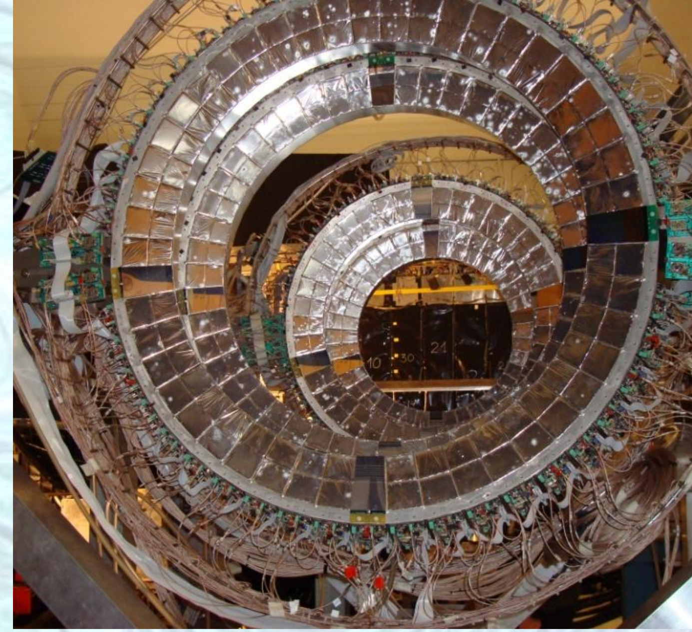
Measurements using FOPI data

- SIS@GSI, LAND + FOPI forward wall
- Au+Au at 250, 400, 600, 800 AMeV
- Re-analysis of data sets and comparison to UrQMD transport models
- PhD topic of Pete Wu, Liverpool University



Y. Leifels et al., Phys. Rev. Lett 71, 963 (1993).
D. Lambrecht et al., Z. Phys. A 350, 115 (1994).

Charged Heavy Ion Mass and Energy Resolving Array (CHIMERA)



- CsI detector scintillator rings, full coverage in ϕ, forward coverage from 7 to 20 degrees in θ
- Bethe Bloche info for atomic and mass numbers of fragment emissions
- Data used to find impact parameter vector, centrality

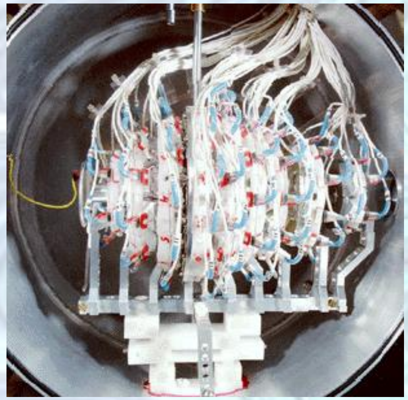
ALADIN Time of Flight (TOF) Wall

- (2 layers) 12 modules (8 scintillator rods each) for x-positioning
- TOF (up-down) information for y-axis positioning,
- E loss information, Nch multiplicity
- Forward coverage 8 degrees in θ (1 degree overlap with CHIMERA)
- Data used to find impact parameter vector, centrality

HIGH EFFECTIVE GRANULARITY

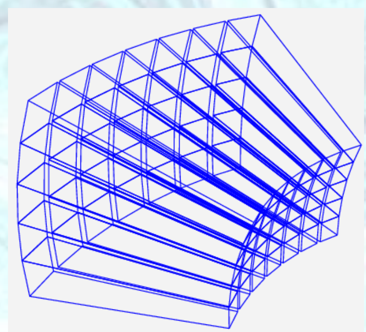
Microball

- Back-angle target hodoscope rings, 95 CsI(Tl) Scintillators
- To distinguish between beam-target and beam-air interactions
- Trigger on back-angle fragments from mass symmetric beam-target interactions



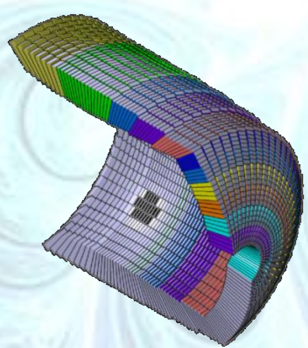
Krakow Phoswitch

- 36 CsI modules orientated 6x6 or 7x5, to measure light fragments



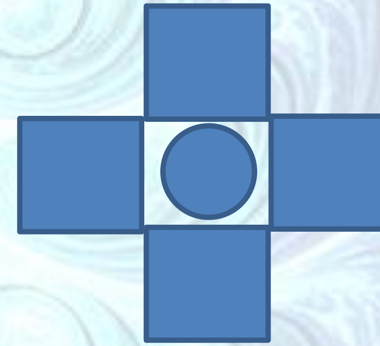
CALIFA: R3B Prototype

- CsI(Tl) crystals to measure light fragments
- (prototype will run in standalone)



ROLU

- "Right, Over, Left, Under" HALO detectors
- Scintillating material surrounding beam
- Active coincidence trigger for beam halo events



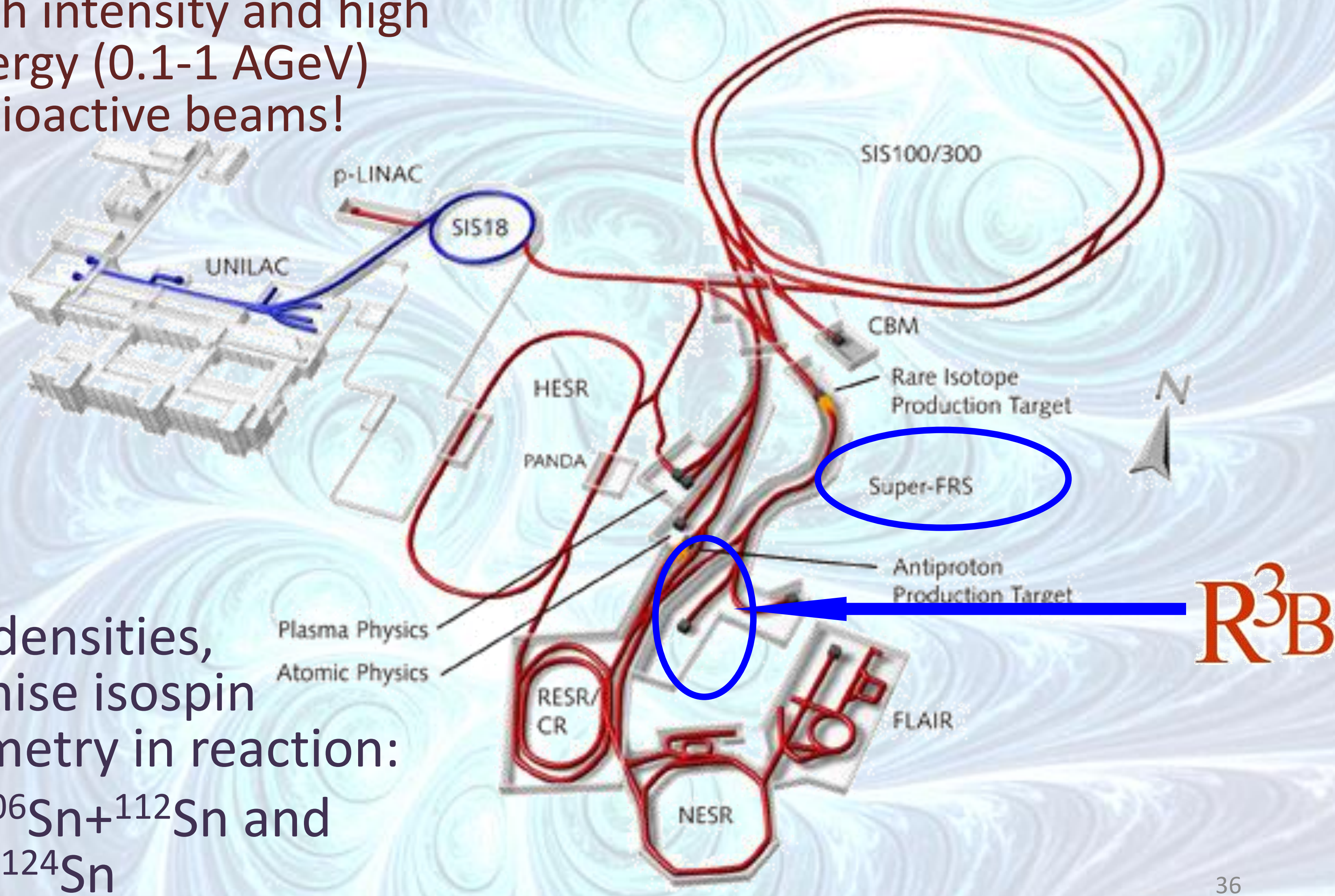
Shadow Bar

Neutrons scattered from surrounding material - approximately 20% of total neutron yields in LAND for Au-Au. Have distinct, azimuthally asymmetric shape

- Intense runs with iron shadow-bar covering neutrons from target to estimate background

FAIR: The future of the project

- High intensity and high energy (0.1-1 AGeV) radioactive beams!



- High densities, maximise isospin asymmetry in reaction:
- e.g. $^{106}Sn+^{112}Sn$ and $^{132}Sn+^{124}Sn$