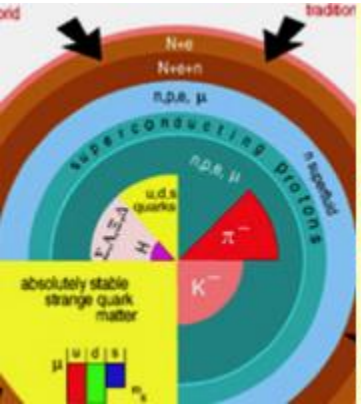
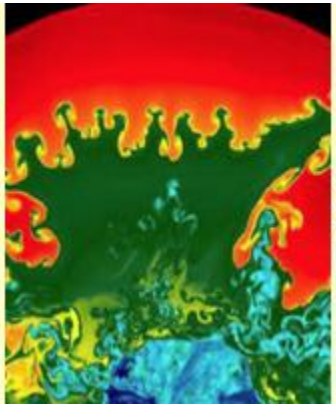
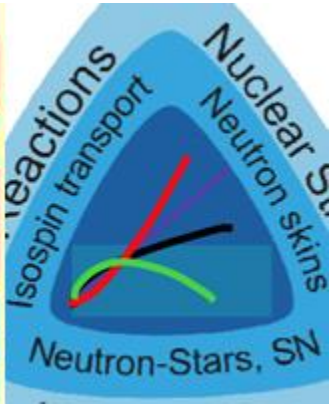
NuSYM11 International Symposium on Nuclear Symmetry Energy
Smith College, Northampton MA (USA), 17-20 June 2011



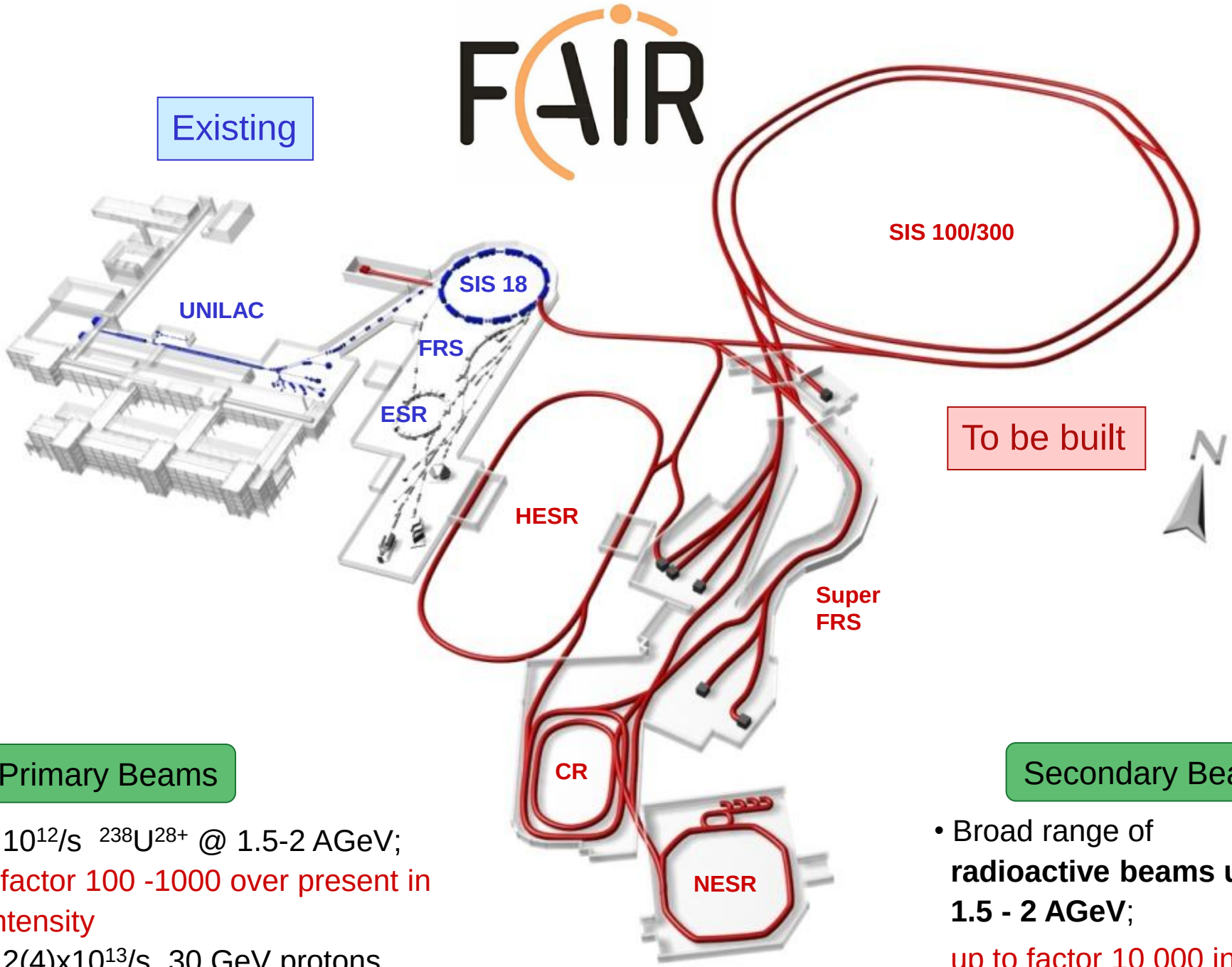
Future Studies of the Symmetry Energy with the R^{3}B Experiment at FAIR

Marielle Chartier

UNIVERSITY OF LIVERPOOL

The Future International Facility FAIR
Beams of Ions and Antiprotons

FAIR
Facility for Antiproton and Ion Research



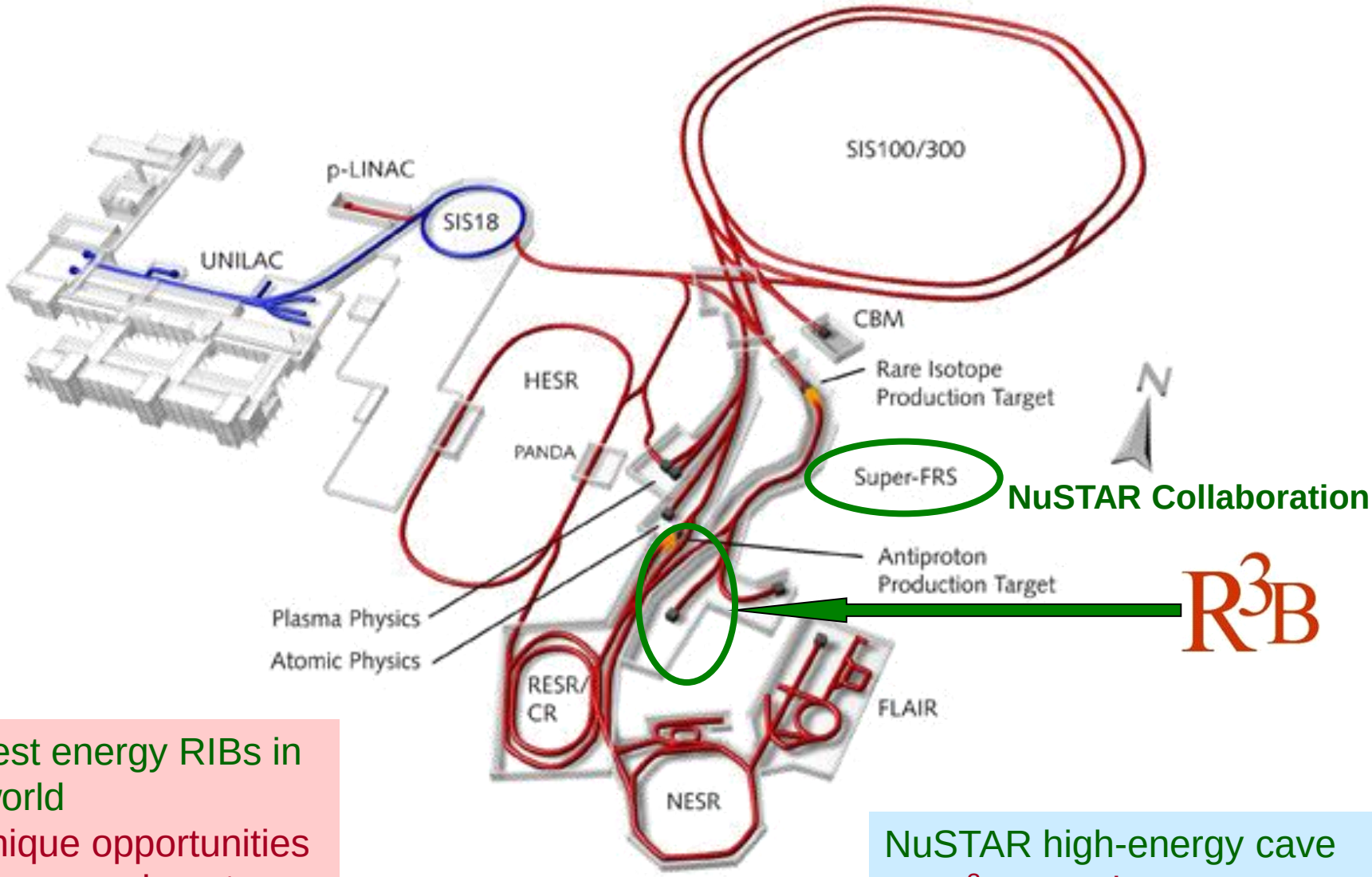
Primary Beams

- 10^{12}/s $^{238}U^{28+}$ @ 1.5-2 AGeV;
  factor 100 -1000 over present in intensity
- 2(4)x10^{13}/s 30 GeV protons
- 10^{10}/s $^{238}U^{73+}$ up to 25 (-35) AGeV

Secondary Beams

- Broad range of **radioactive beams up to 1.5 - 2 AGeV**;
  up to factor 10 000 in intensity over present

High-Energy Radioactive Beams

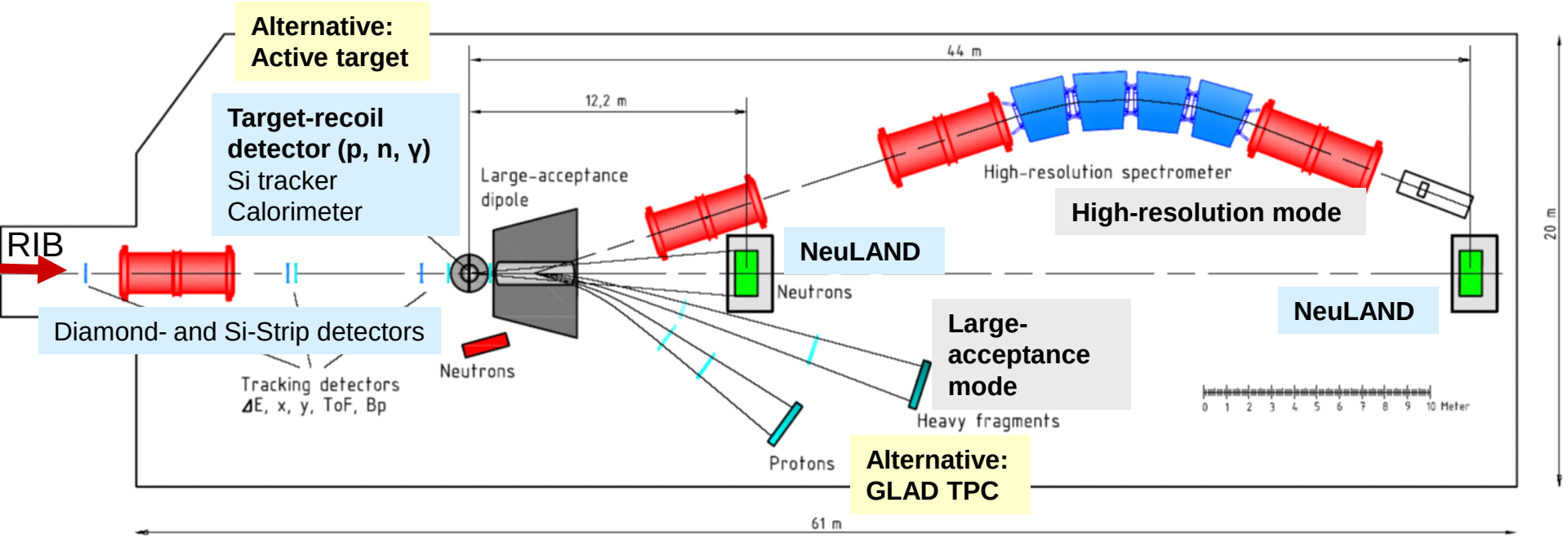


Highest energy RIBs in the world
=> unique opportunities for new experiments

NuSTAR high-energy cave
=> R^3B experiment

The R³B Experiment at FAIR

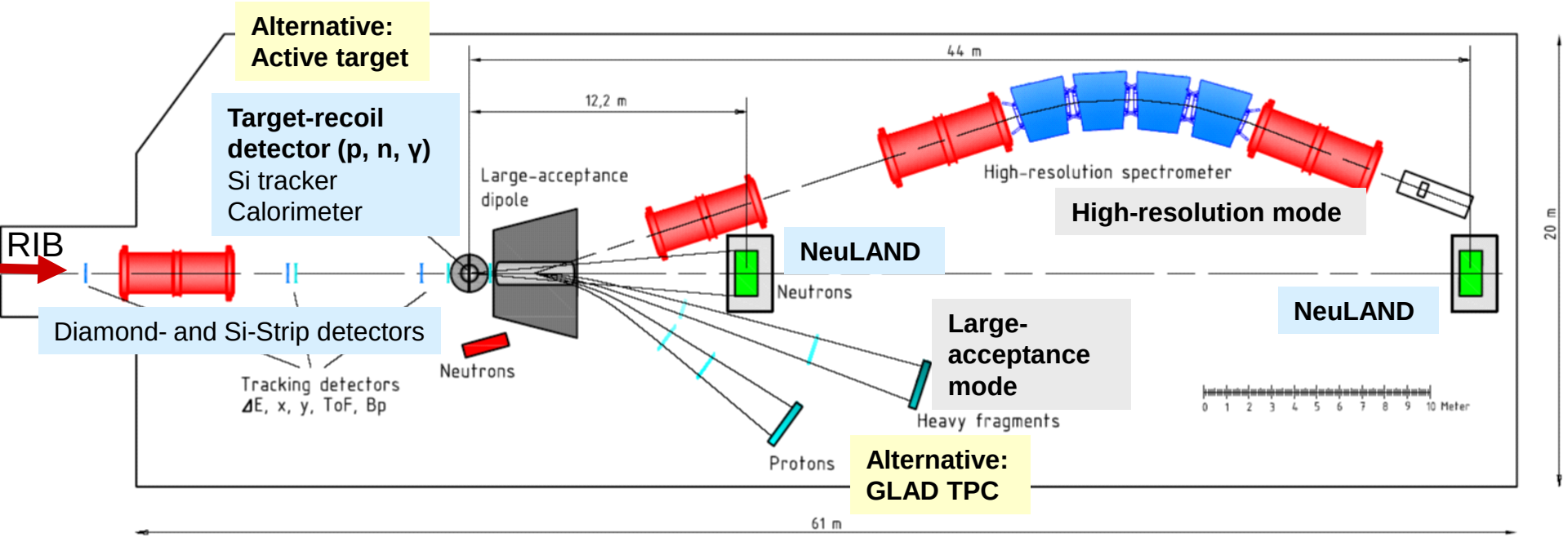
Universal setup for kinematically complete measurements of reactions with high-energy RIBs



Experiments	Physics goals
➢ elastic scattering	radii, matter distribution
➢ knockout and quasi-free scattering	single-particle occupancies, spectral functions, correlations, clusters, resonances beyond the drip lines
➢ electromagnetic excitation	single-particle occupancies, astrophysical reactions (S factor), soft coherent modes, giant resonance strength, B(E2)
➢ charge-exchange reactions	Gamov-Teller strength, spin-dipole resonance, neutron skins
➢ fission	shell structure, dynamical properties
➢ spallation	reaction mechanism, applications (waste transmutation, ...)
➢ fragmentation	γ-ray spectroscopy, isospin-dependence in multifragmentation, EOS

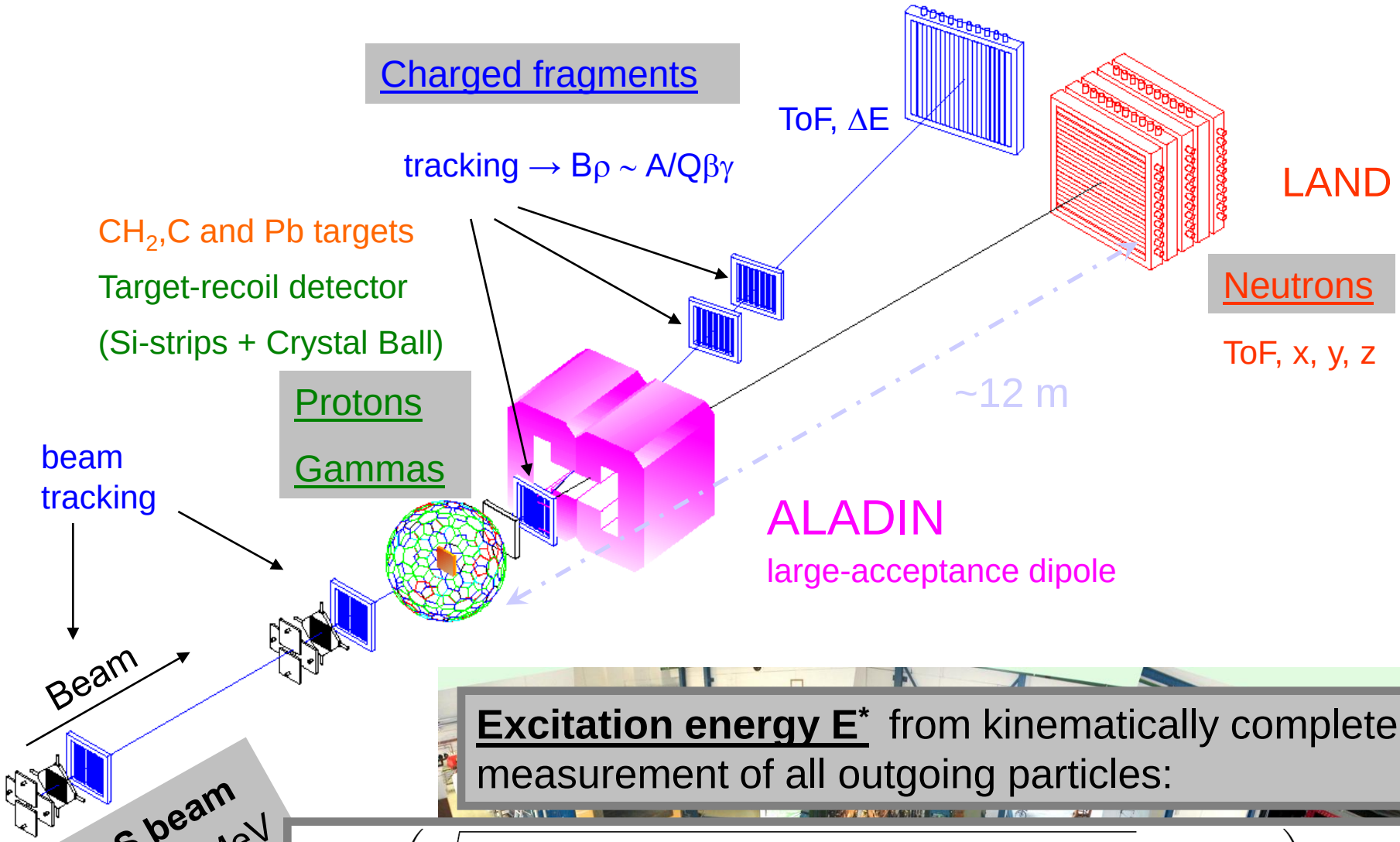
The R³B Experiment at FAIR

Universal setup for kinematically complete measurements of reactions with high-energy RIBs



- identification and beam "cooling" (tracking and momentum measurement, $\Delta p/p \sim 10^{-4}$)
- exclusive measurement of the final state:
  - identification and momentum analysis of fragments
    (large acceptance mode: $\Delta p/p \sim 10^{-3}$, high-resolution mode: $\Delta p/p \sim 10^{-4}$)
  - coincident measurement of neutrons, protons, gamma-rays, light recoil particles
- **applicable to a wide class of reactions**

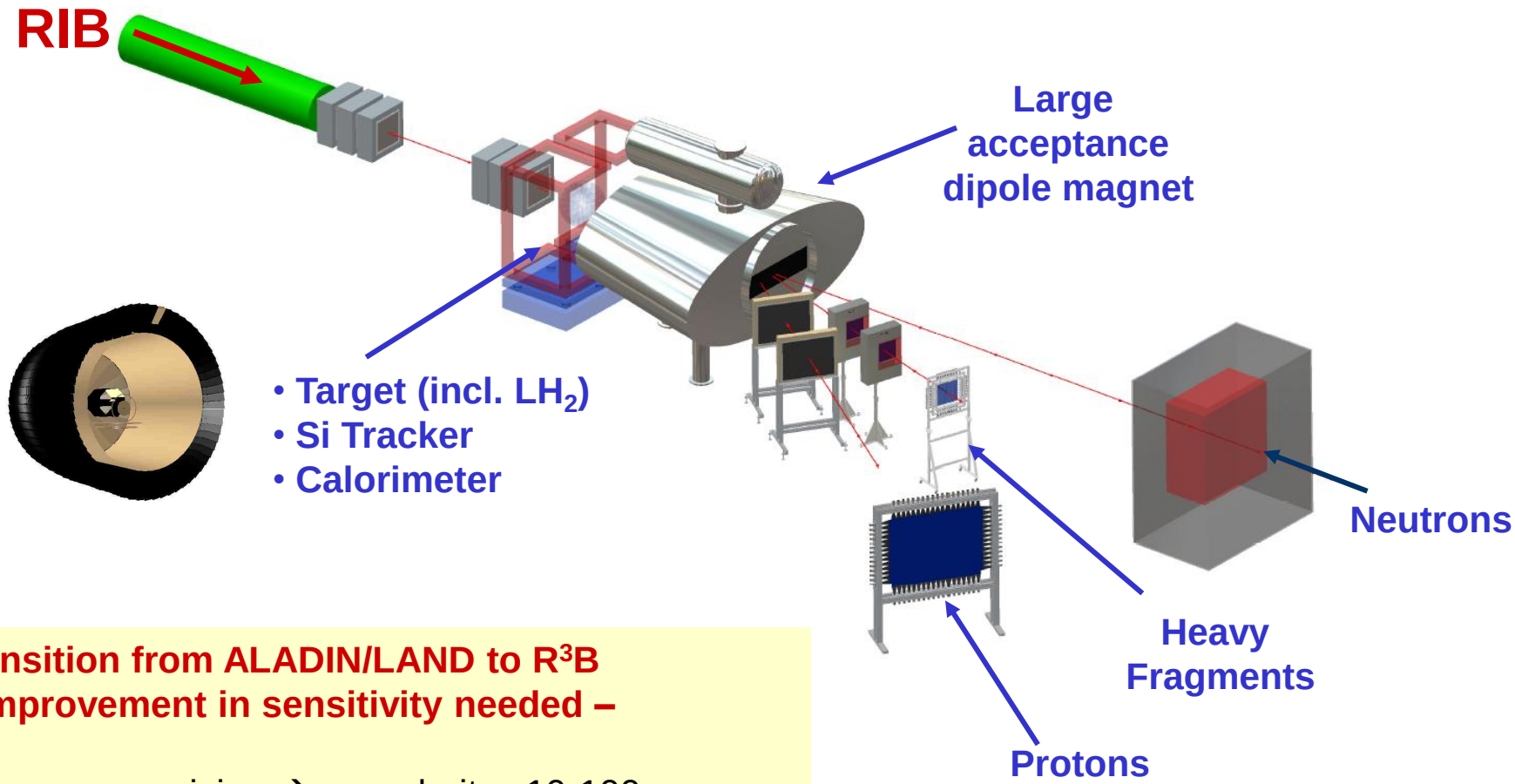
The ALADIN/LAND Set-up at GSI



Excitation energy E* from kinematically complete measurement of all outgoing particles:

$$E^* = \left(\sqrt{\sum_i m_i^2 + \sum_{i\neq j} m_i m_j \gamma_i \gamma_j (1 - \beta_i \beta_j \cos\theta_{ij})} - m_{proj}\right)c^2 + E_\gamma$$

R^3B – The Startup Version



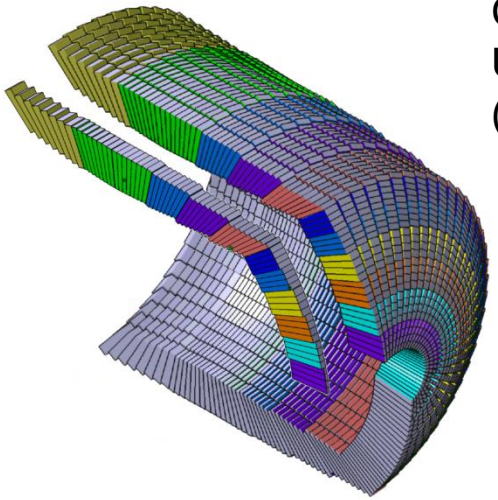
Transition from ALADIN/LAND to R^3B
– improvement in sensitivity needed –

- increase precision → granularity x10-100
- adapt to higher rates → 20 kHz dead-time free incoming ID
- adapt to higher energies → strong dipole magnet → x-ray suppression

The CALIFA Calorimeter

CALIFA
Calorimeter (and spectrometer) for γ-rays and protons
- sum energy as well as individual particles or γ-rays
- large dynamic range: 50 keV to 300 MeV

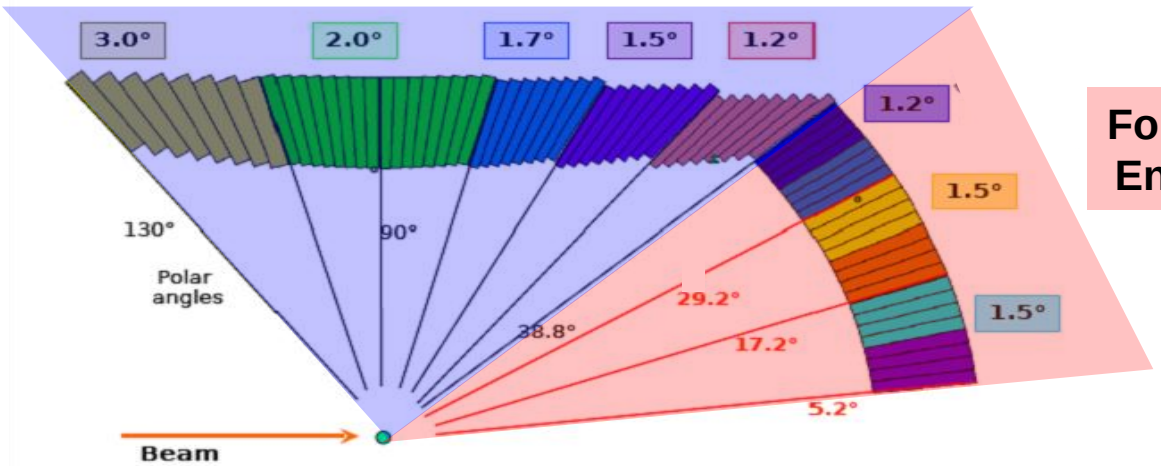
Technical implementation based on scintillation detectors



Coordinator: D. Cortina Gil, Univ. Santiago de Compostela (Spain)

Large Doppler effects … tiling with small slabs

Barrel

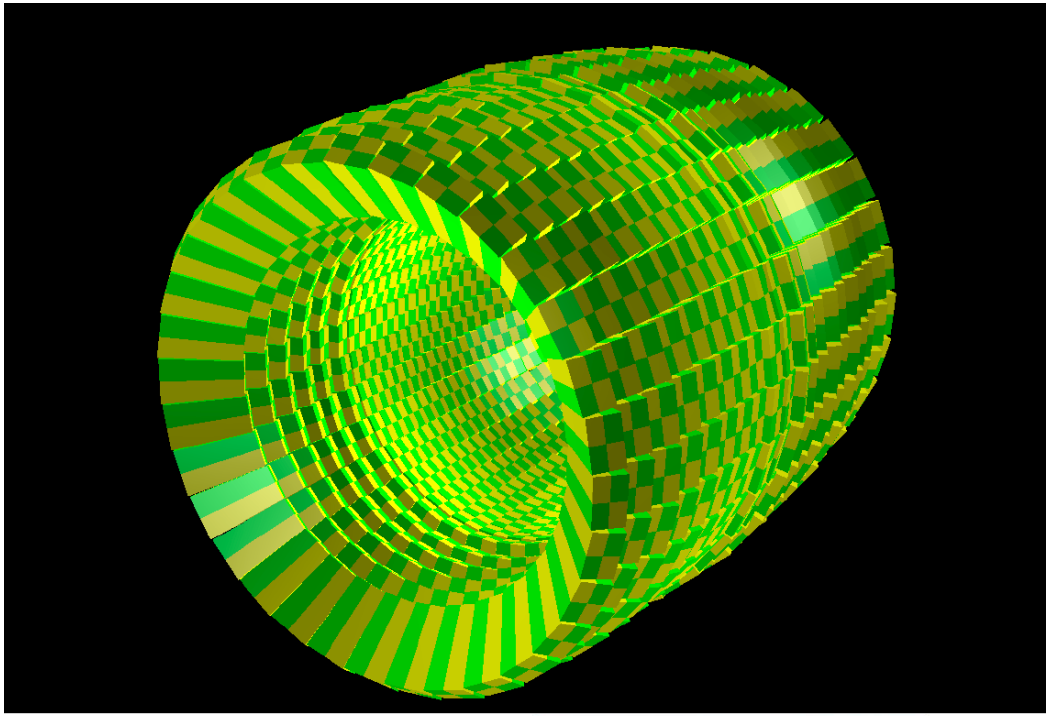


Forward Endcap

CALIFA Barrel

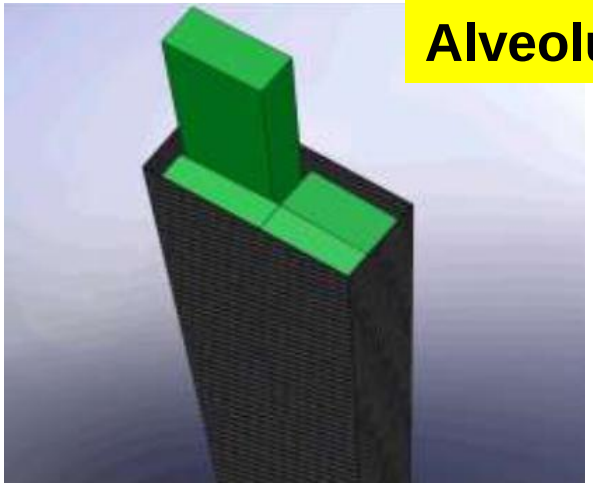
CsI(Tl) crystals

Crystals	2560
Crystals by Ring	64
Crystals by polar direction	40
Crystals by alveolus	4
Alveoli	640
Alveoli by Ring	32
Alveoli by polar direction	20



H. Alvarez Pol et al., Univ. Santiago de Compostela (Spain)

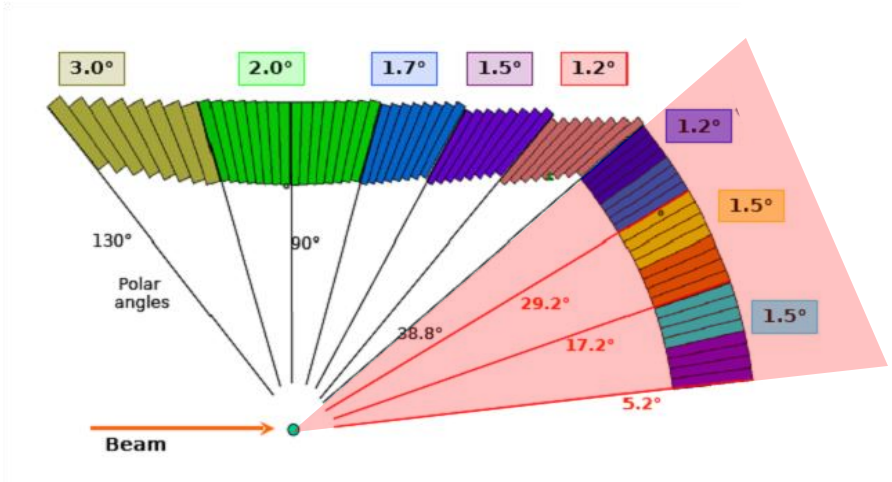
Alveolus

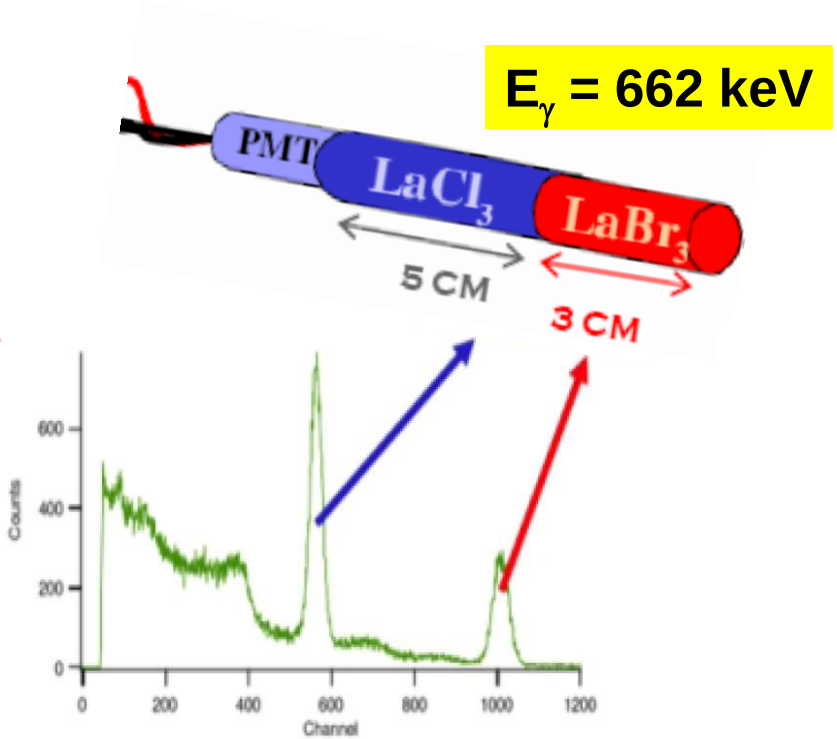


300 µm wrapping
300 µm carbon fibre

USC, Lund
CSIC/IEM

CALIFA Front Endcap





Large Doppler effect
- Higher γ-ray energies
- Lorentz boost

- CsI or $LaBr_3$/$LaCl_3$?
- Phoswich solutions?
- No PMT because of GLAD
  → APD readout!

… by pulse shape analysis!

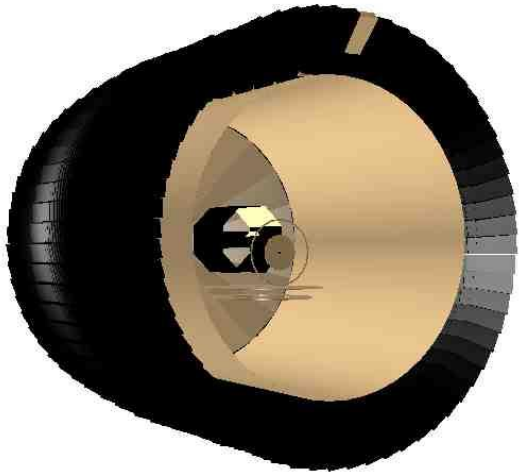
O. Tengblad et al.,
IEM/CSIC Madrid (Spain)

The Silicon Recoil Tracker

❖ Multiple layers of Si microstrip detectors to track outgoing protons from LH_2 target in QFS reactions e.g. (p,2p), (p,pn)
❖ Aims for separation-energy resolution of ~1 MeV and angular resolution ~1 mrad

❖ Sits inside the CALIFA calorimeter
❖ New ASIC designed by RAL (UK)

Coordinator: R. Lemmon, STFC Daresbury Lab (UK)



Design constraints studied with Monte Carlo simulations (R3BRoot) – geometry, strip pitch, Si thickness... => Impact on energy resolution, efficiency, mechanics, FEE...

- Must detect protons at most forward angles
- Inner layer as thin as possible (~100um)
- At least 3 layers – strip redundancy
- Inner layer as close to target as possible – accurate determination of reaction vertex
- No shielding between detector and target

∅ 70 mm, 61 mm thickness

LH_2 target
CEA Saclay
A. Obertelli et al.

The Silicon Recoil Tracker

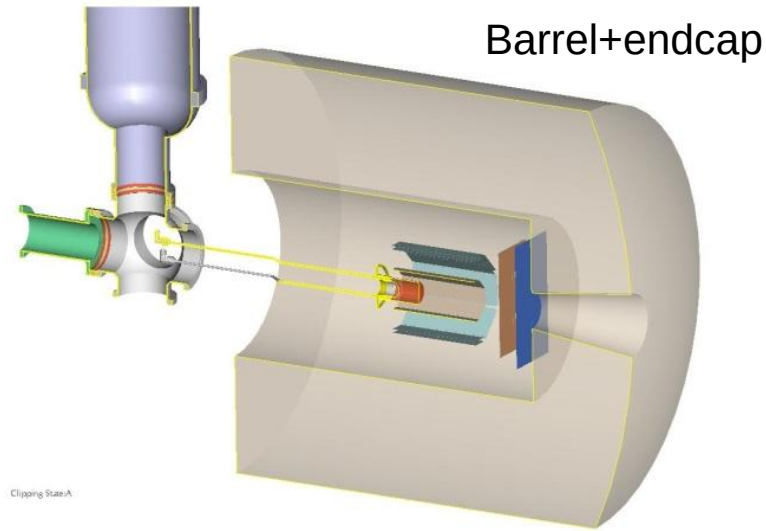
Two design options studied:

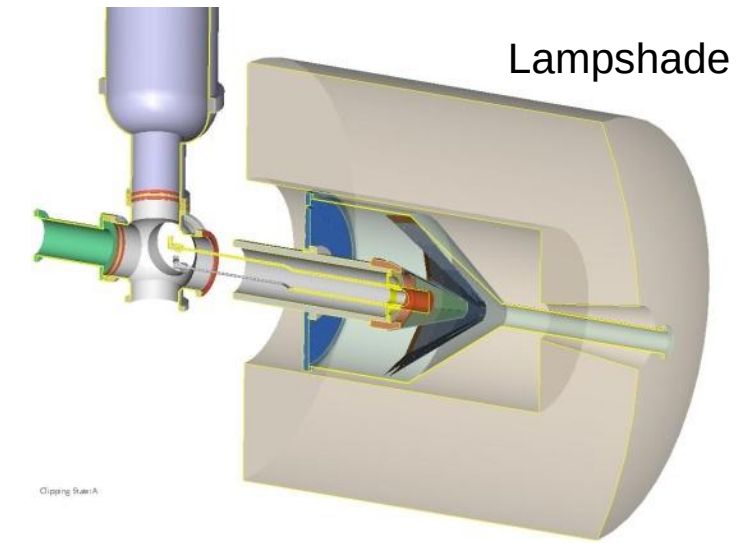
- **Barrel+endcap**
- **Trapezoidal shape (lampshade)**

Resolution almost the same for both but advantages for lampshade design:

- sensors easier to make with high yield (no double metallisation required)
- less noisy on both sides
- no endcap required
- all FEE (incl. cooling) and mechanical support at one end (backward angles)

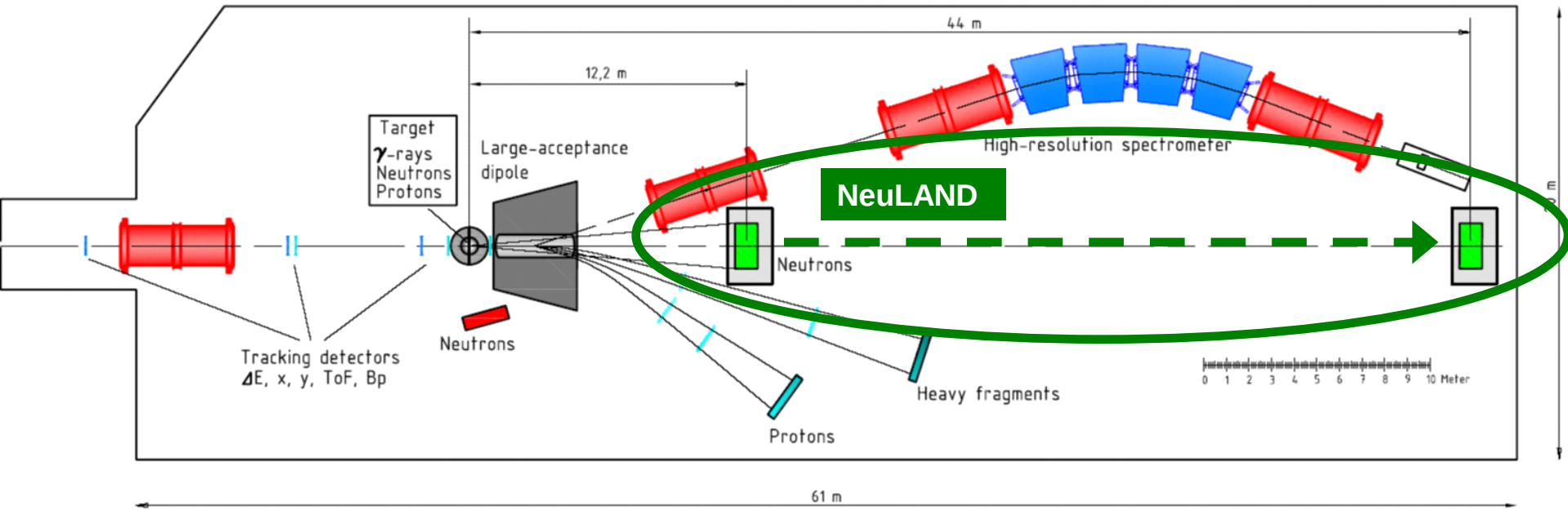
Number of channels ~100k
50um strip pitch
Stereo angle (diamond pixel)





Design by Daresbury/Liverpool, UK

NeuLAND – New Large Area Neutron Detector



- >90% efficiency for 200-1000 MeV neutrons
- Time resolution **σ <** 100 ps
- Acceptance 80 mrad @ 12 m distance: active area 200 cm x 200 cm
- Multi-hit capability for up to 5 neutrons

Example invariant-mass resolution: NeuLAND-target distance 30 m

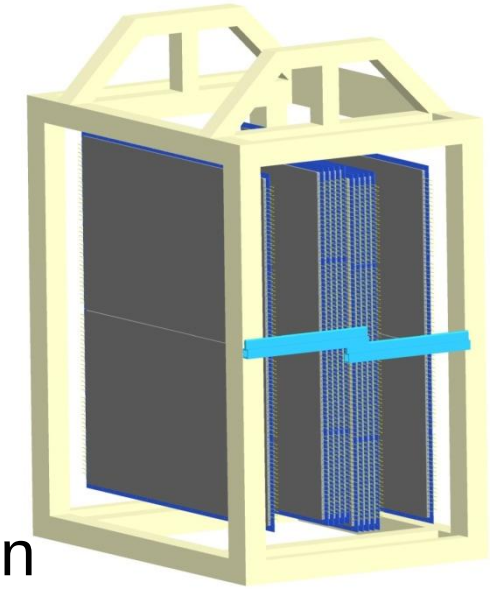
$\Delta E \approx 20$ keV above the neutron threshold

Coordinator: K. Boretzky, GSI (Germany)

NeuLAND Detector Design: 2 Alternatives

NeuLAND based on MRPC's:

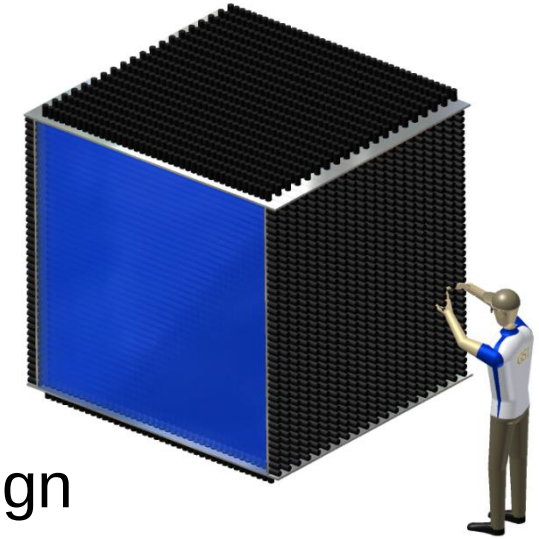
- Alternating layers of passive converter material and Resistive Plate Chambers (RPC) for the detection of secondary particles
- **Detector size 2*2*~1 m^3**
- ~7.000-8.000 channels



HZDR design

NeuLAND based on organic scintillator:

- Full active detector
- Bar structure read out from two sides by PMs/APDs
- **Detector size 2*2*~2-3 m^3**
- ~3.200-5.000 channels



GSI Design

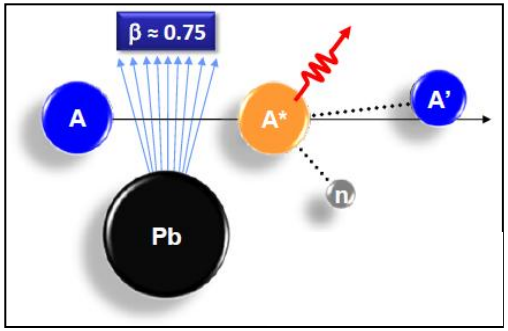
Symmetry Energy and R³B

Possible future measurements with R³B

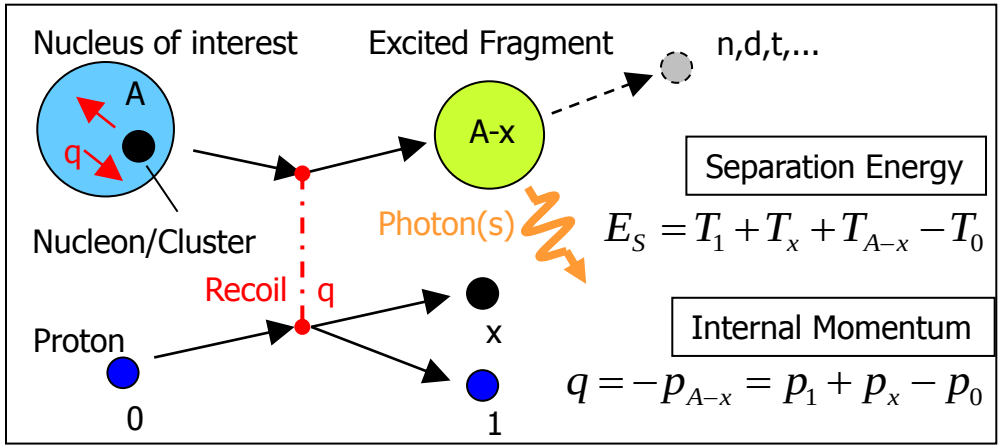
1) Nuclear structure measurements

- Neutron skins:
  - Giant resonances
  - Matter distributions
- Correlations in nuclei:
  - Hadronic quasifree scattering

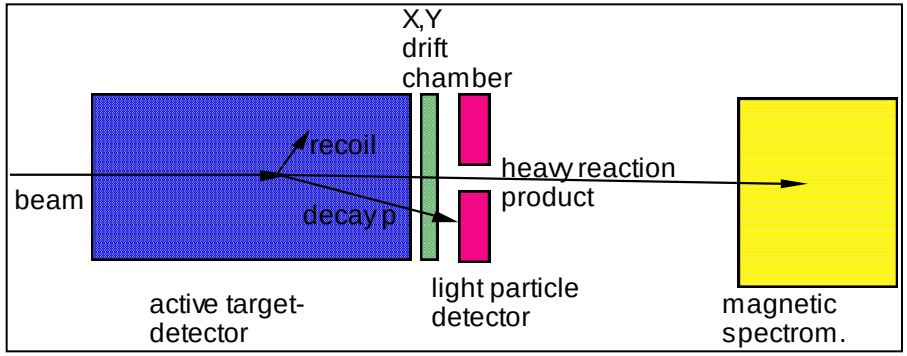
Heavy-ion induced electromagnetic excitation



p-induced QFS e.g. (p,2p) and (p,pn)

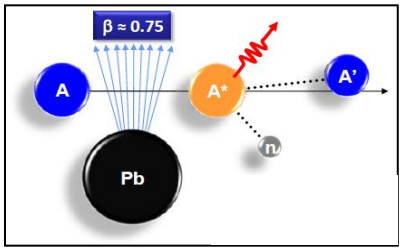


p elastic scattering with an active target (low-momentum transfer)



Heavy-Ion Induced Electromagnetic Excitation

See D. Rossi's presentation at NuSYM10

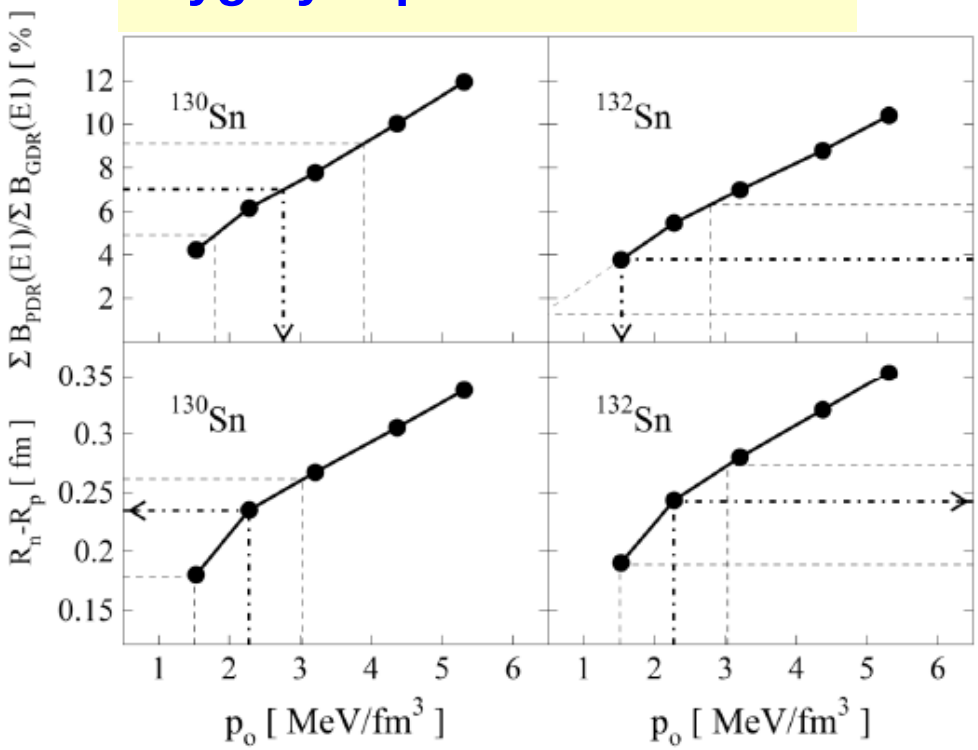


$$E(\rho,\alpha) = E(\rho,0) + S_2(\rho)\alpha^2 + O(\alpha^4)\,,\ \alpha = \frac{N-Z}{A}$$

$$E(\rho,0) = -a_V + \frac{K_0}{18\rho_0^2}(\rho-\rho_0)^2 + \ldots$$

$$S_2(\rho) = \frac{1}{2}\frac{\partial^2 E(\rho,\alpha)}{\partial\alpha^2}\Big|_{\alpha=0} = a_4 + \frac{p_0}{\rho_0^2}(\rho-\rho_0) + \frac{\Delta K_0}{18\rho_0^2}(\rho-\rho_0)^2 + \ldots$$

Pygmy Dipole Resonances



A. Klimkiewicz, N. Paar *et al.*, Phys. Rev. C **76**, 051603(R) (2007)

a_4: symmetry energy per nucleon in pure neutron matter
p_0: symmetry energy pressure

❖ RQRPA calculations performed by N. Paar

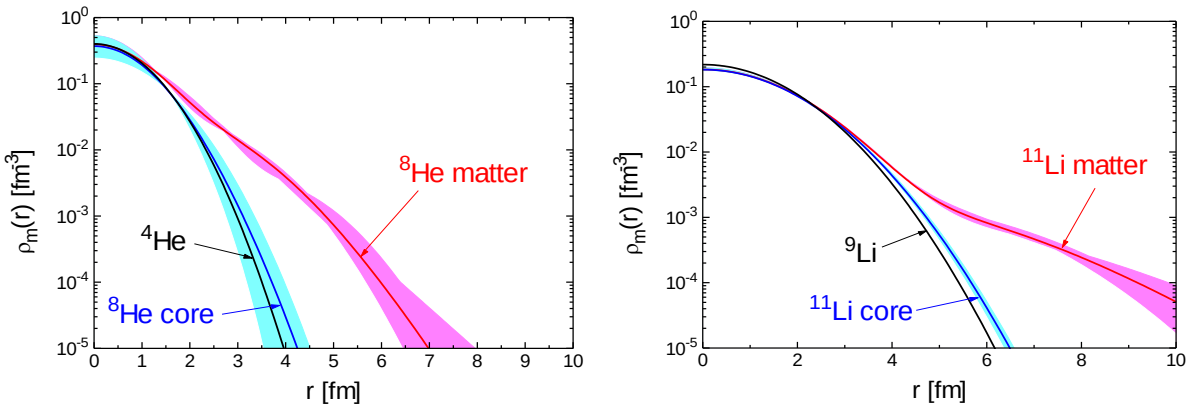
❖ Analysis of ^{130,132}Sn provide mean EOS parameters:
⇒ $\langle a_4 \rangle$ = 32.0(1.8) MeV
⇒ $\langle p_0 \rangle$ = 2.3(0.8) MeV/fm^3

❖ Values of the neutron skin thickness also obtained:
⇒ ^{130}Sn: 0.23(4) fm
⇒ ^{132}Sn: 0.24(4) fm

Elastic Proton Scattering from Halo Nuclei

Investigation of nuclear matter density distributions of halo nuclei by elastic proton scattering at low momentum transfer **with the active target IKAR and ALADIN magnet setup at GSI**

- Extended neutron distribution in ^{8}He and ^{11}Li obtained
- Size of core, halo and total matter distributions determined with high accuracy
- *with charge radius from laser spectroscopy (R. Sanchez et al.) neutron radius and neutron skin (halo) determined



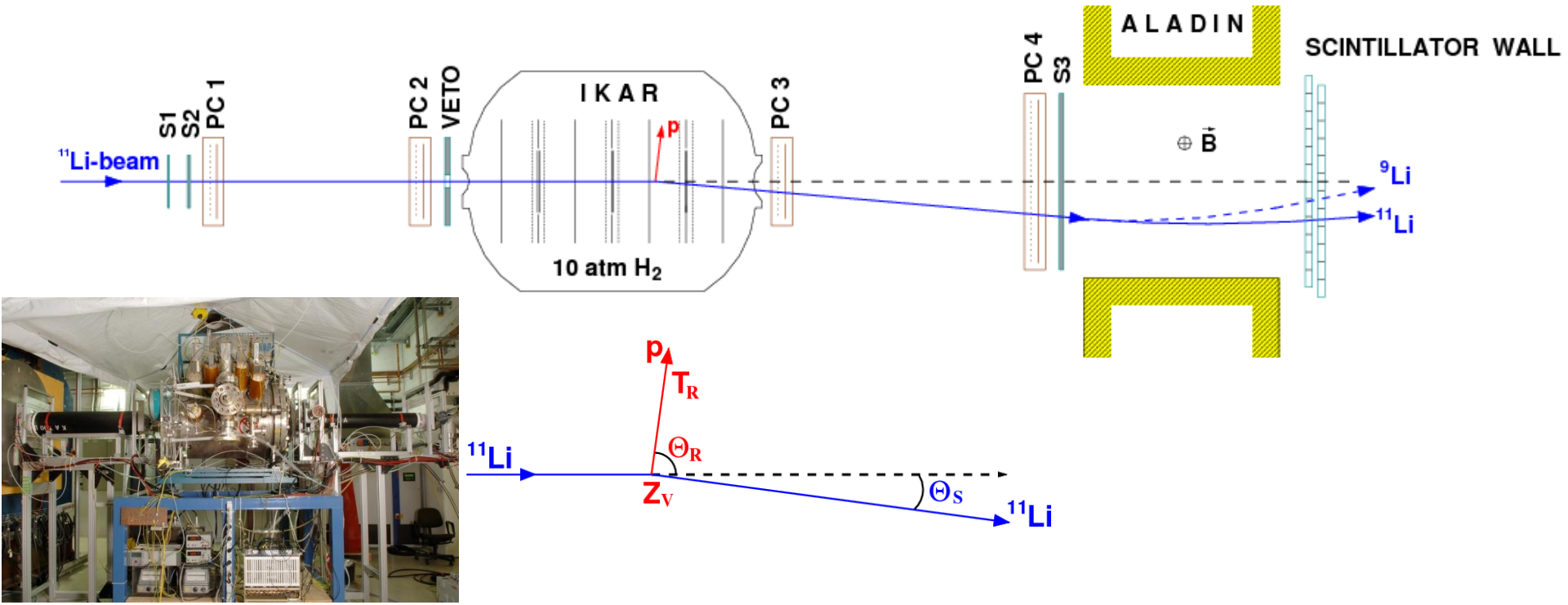
A. Dobrovolsky *et al.*, Nucl. Phys. A 766 (2006) 1.

nucleus	R_{matter}, fm	R_{core}, fm	R_{halo}, fm	R_n*, fm	R_n-R_p*, fm
^{4}He	1.49 (3)	--	--	--	--
^{8}He	2.45 (7)	1.55 (15)	3.08 (10)	--	--
^{9}Li	2.43 (7)	--	--	2.59 (9)	0.48 (9)
^{11}Li	3.62 (19)	2.55 (12)	6.54 (38)	4.06 (23)	1.73 (23)

P. Egelhof et al.

Elastic Proton Scattering with IKAR

Active Target IKAR and Aladin Magnet



Active Target is foreseen as alternative recoil detector for R^3B

⇒ advantage:

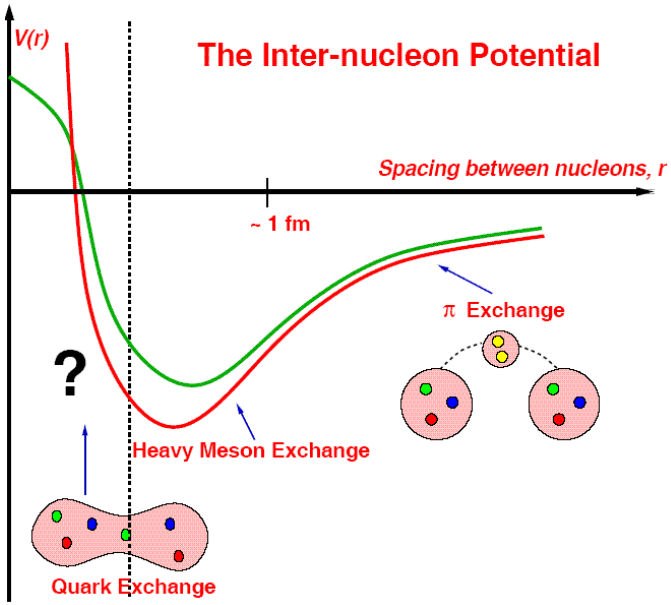
- low threshold
- high detection efficiency (rel. thick target)

⇒ well suited as alternative technique to EXL for:

- short lifetimes ($T \leq 1$ sec)
- low RIB intensities ($\leq 10^4$ sec^{-1})

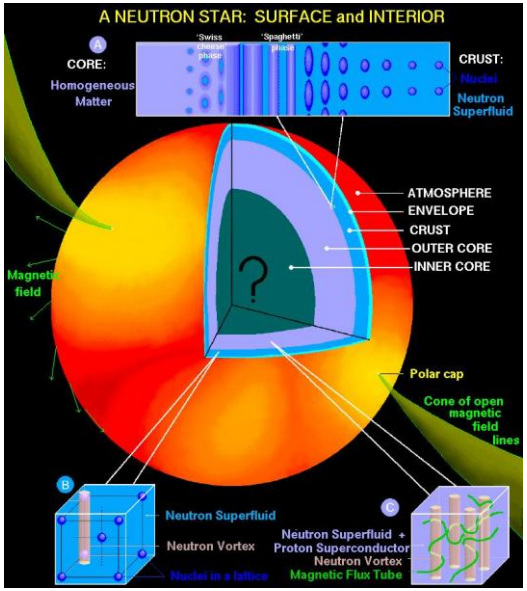
Beyond the Nuclear Mean-Field

Nucleon-Nucleon correlations:
Short-range (SRC)
Tensor
Long-range (LRC)



Modification of NN correlations as a function of density, temperature, isospin asymmetry determine the nature of many-body systems

- Finite nuclei, nuclear structure
- Extended nuclear matter, EOS
- Compact astrophysical object e.g. neutron stars



Very challenging theoretically to incorporate correlations in the nuclear many-body system starting from bare NN interactions

- Experimental studies crucially needed

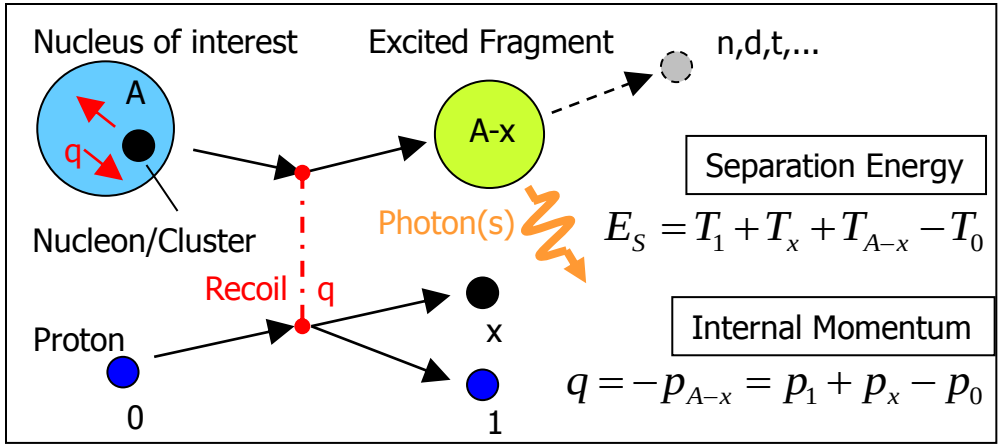
Hadronic Quasifree Scattering

❖ **Proton and electron induced quasifree scattering (QFS) e.g. (e,e'p), (p,2p), (p,pn)...**

Most direct experimental probes to investigate single-particle properties of nuclei and the role of nucleon-nucleon correlations

❖ **Construct spectral functions for bound nucleons**
(probability that a nucleon as a certain energy and momentum within the nucleus)

Integrated strength => spectroscopic factors, occupation probabilities



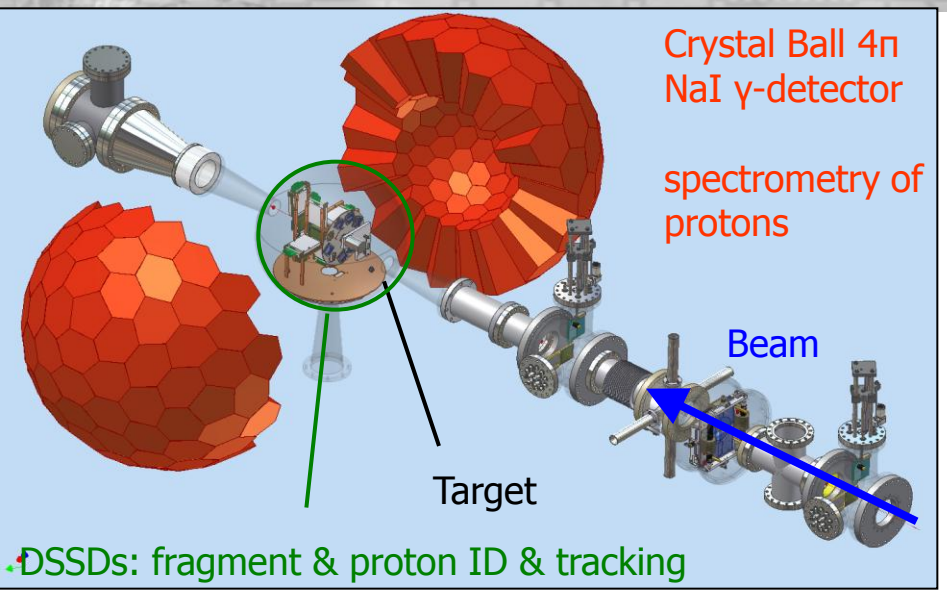
To probe SRC (short distance scales)
=> high energy and momentum
=> **Need high energy beams**

Both valence and deeply-bound nucleons can be removed
⇒ different densities probed
⇒ disentangle LRC and SRC

High-energy, high-intensity radioactive ion beams at GSI (and in future at FAIR)
➡ **opportunity to perform such studies with isospin asymmetric nuclei**

T. Aumann, M. Chartier, R. Lemmon et al.

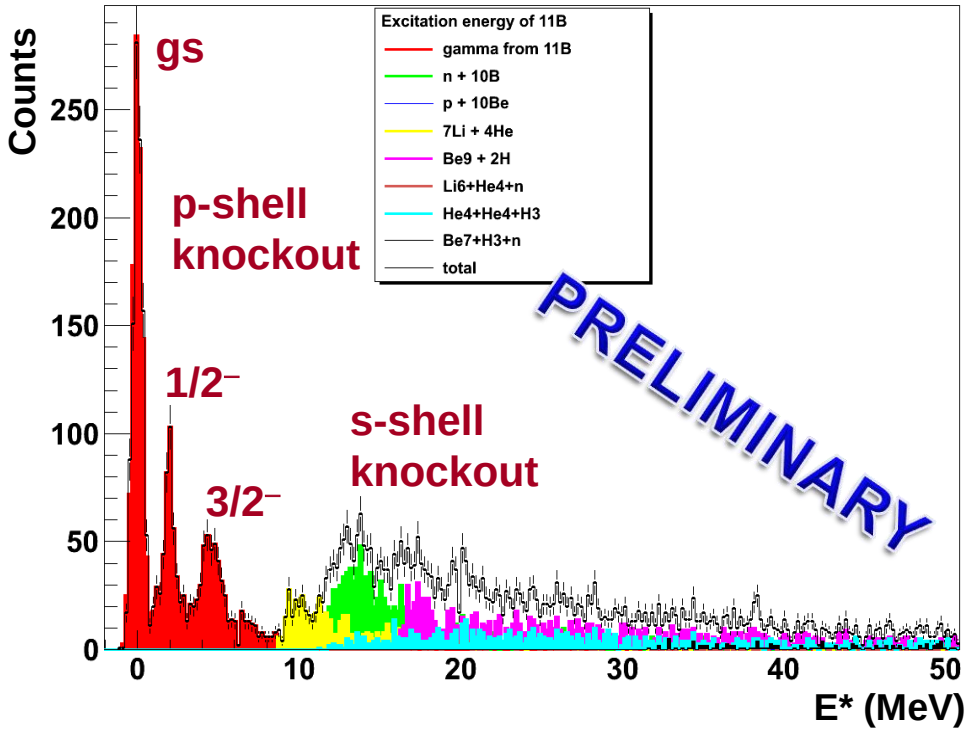
$^{12}C(p,2p)^{11}B$ in Inverse Kinematics



PhD Thesis J. Taylor, Univ. Liverpool (UK) and V. Panin, TU Darmstadt (Germany)

Excitation energy spectrum for ^{11}B reconstructed by invariant mass method

$$E^* = \sqrt{\sum_i m_i^2 + \sum_{i \neq j} \gamma_i \gamma_j m_i m_j (1 - \beta_i \beta_j cos\vartheta_{ij})} + E_\gamma - m_{proj}$$



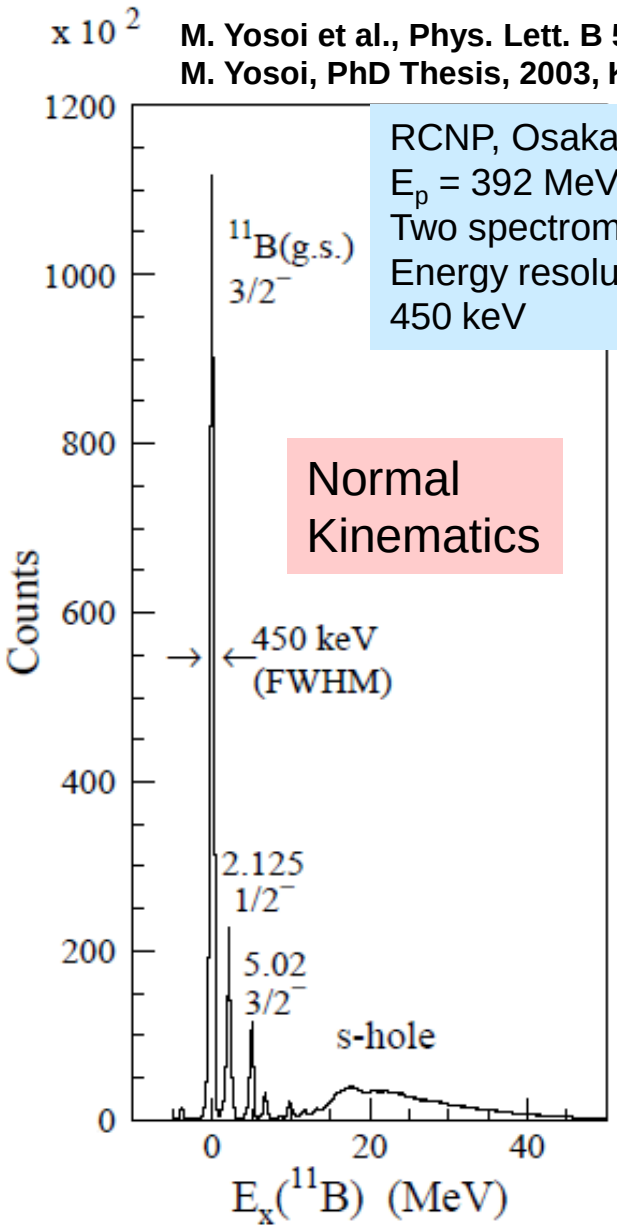
Decays from bound states:
γ-rays detected in the Crystal Ball

2- and 3-body $^{12}C(p,2p)X$ channels included in the reconstruction of the s-state:

$^{12}C(p,2p)^{10}B+n$	$^{12}C(p,2p)^{10}Be+p$
$^{12}C(p,2p)^{9}Be+d$	$^{12}C(p,2p)^{7}Li+\alpha$
$^{12}C(p,2p)^{6}Li+\alpha+n$	$^{12}C(p,2p)\alpha+\alpha+t$

$^{12}C(p,2p)^{11}B$ in Inverse Kinematics

M. Yosoi et al., Phys. Lett. B 551, 255 (2003).
M. Yosoi, PhD Thesis, 2003, Kyoto University



RCNP, Osaka
E_p = 392 MeV
Two spectrometer measurement
Energy resolution (FWHM) ≈ 450 keV

Normal Kinematics

PhD Thesis J. Taylor, Univ. Liverpool (UK) and V. Panin, TU Darmstadt (Germany)

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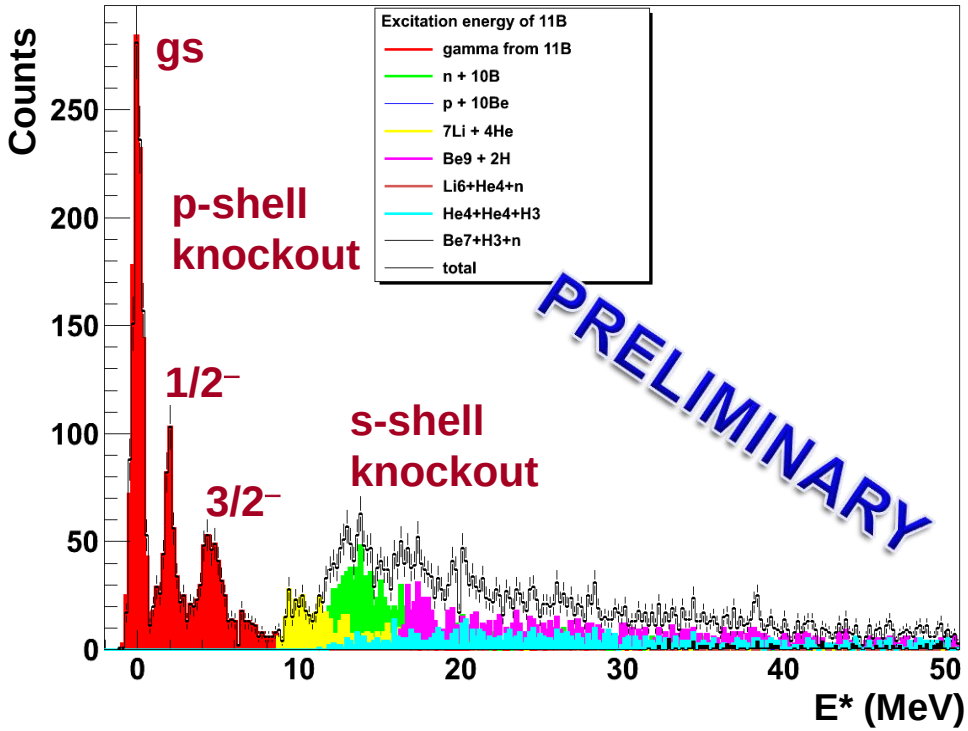
$$E^* = \sqrt{\sum_i m_i^2 + \sum_{i \neq j} \gamma_i \gamma_j m_i m_j (1 - \beta_i \beta_j cos\vartheta_{ij})} + E_\gamma - m_{proj}$$



Symmetry Energy and R^{3}B

Possible future measurements with R^{3}B

2) Heavy-ion collision measurements:

❖ Collective flows, particle ratios and yields, particle production (π^+/π^-, K^+/K^0, Σ^-/Σ^+)...

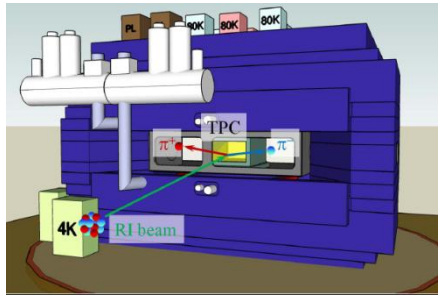
High densities, maximise isospin asymmetry in reaction, reduce Coulomb effects through double ratios and differences
e.g. ^{106}Sn+^{112}Sn and ^{132}Sn+^{124}Sn

See talks by R. Lemmon and P. Russotto et al. (ASYEOS)

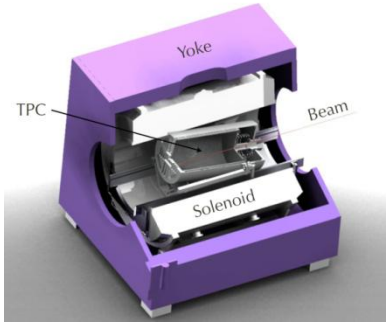
FAIR will provide the highest energy RIBs in the world
=> Unique opportunity to probe higher densities!

Short meeting tonight?
If interested to discuss, see myself or R. Lemmon

SAMOURAI



MSU Active Target



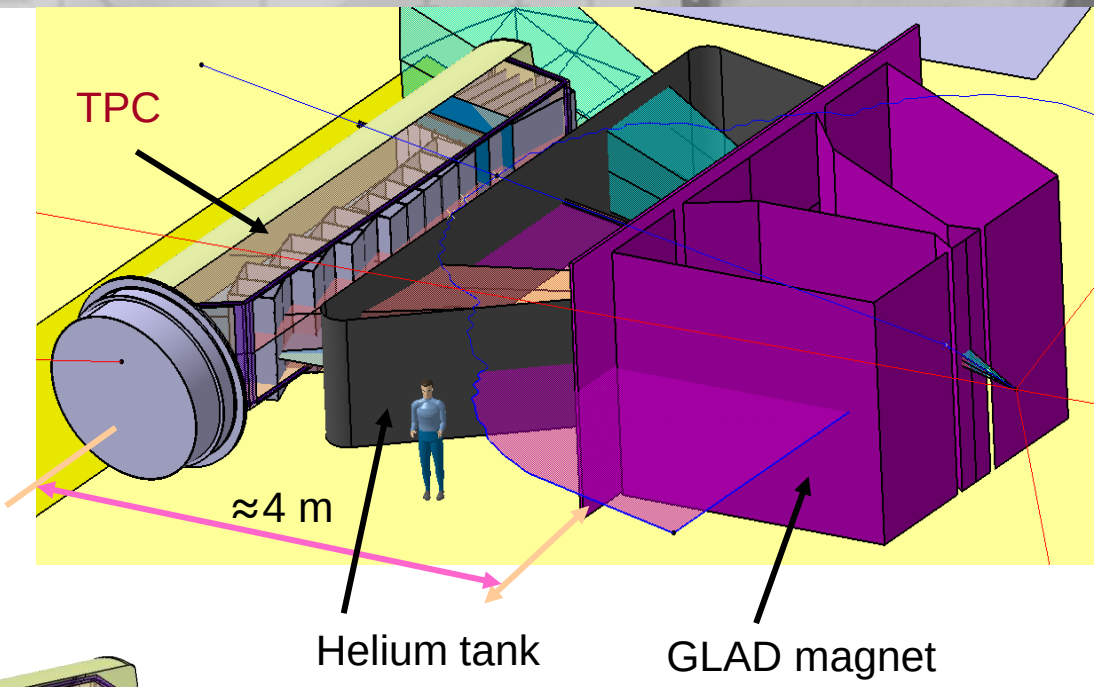
❖ **New detectors needed, opportunities for new projects**
e.g.
GLAD TPC or other
TPC at target position + TOF wall (FOPI-like)
Active target/TPC working group recently formed

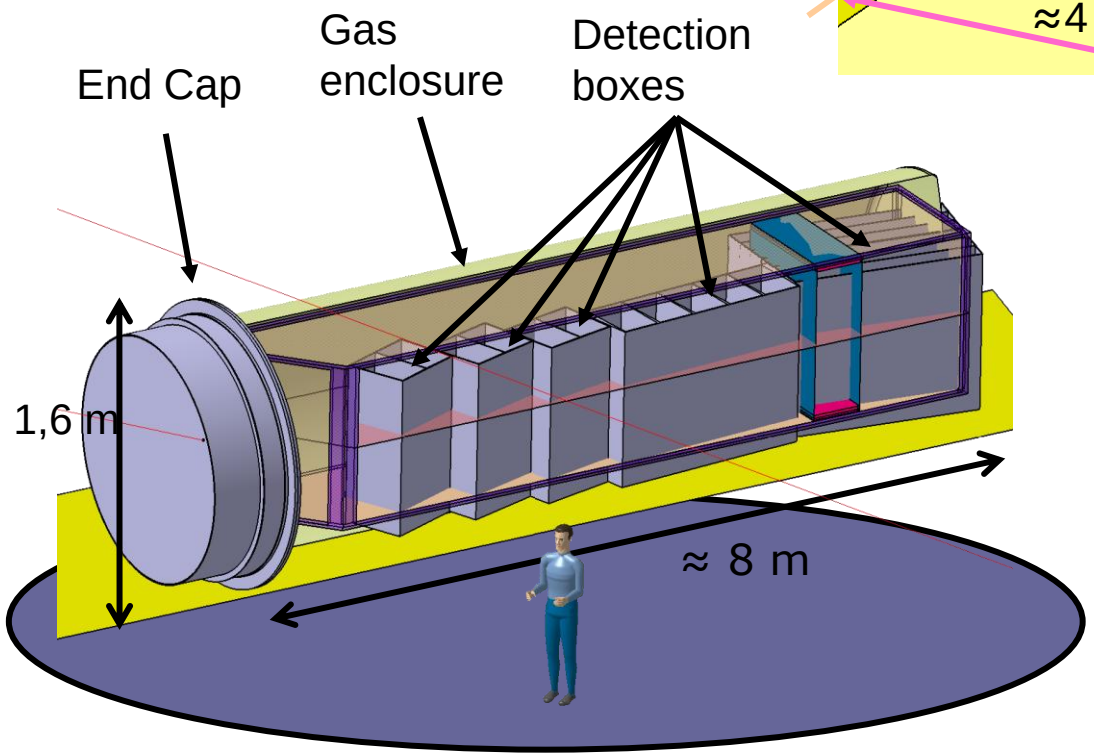
❖ **Collaboration open to new collaborators and new ideas!**

❖ **Synergies with other projects around the world**

The GLAD TPC

- A prototype is being constructed at Saclay
- Collaborators welcome





For details during this symposium, see R. Lemmon (R^3B Technical Coordinator)

CEA Saclay (France)
plegou@cea.fr

Summary

The R^3B experiment is being designed to exploit the future RIBs from the Super-FRS at FAIR
⇒ A universal set-up for kinematically complete measurements of reactions with high-energy RIBs
Applicable to a wide class of reactions

Possible future measurements relating to the Symmetry Energy with R^3B:
Nuclear structure measurements
Heavy-ion collision measurements

FAIR will provide the highest energy RIBs in the world
⇒ New experiments to perform hadronic QFS and study correlations
⇒ Unique opportunity to probe higher densities in HIC with large isospin asymmetries
⇒ Optimum for proton elastic scattering or giant resonances for skin measurements
⇒ ...
New detectors needed (e.g. active target/TPC or other)
New ideas and new collaborators welcome!

The R3B Collaboration

A next generation experimental setup for studies of

Reactions with **R**elativistic **R**adioactive **B**eams

Spokesperson: Tom Aumann

>50 institutes
20 countries
>220 participants
embedded in NUSTAR

http://www.gsi.de/forschung/kp/kr/R3B_e.html

Thank you for your attention!