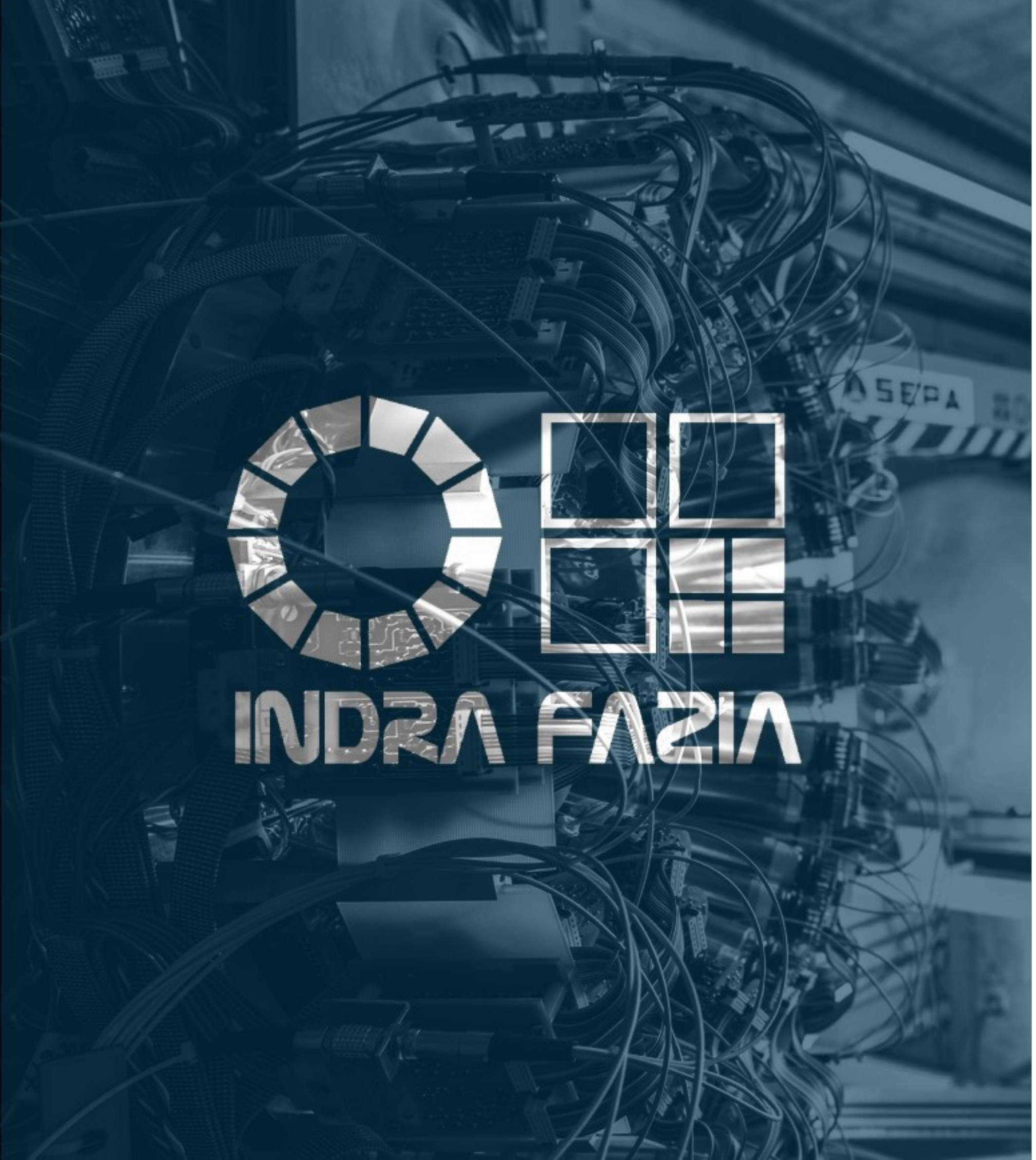


INDRA-FAZIA@GANIL data exclude direct Urca cooling in low mass neutron stars

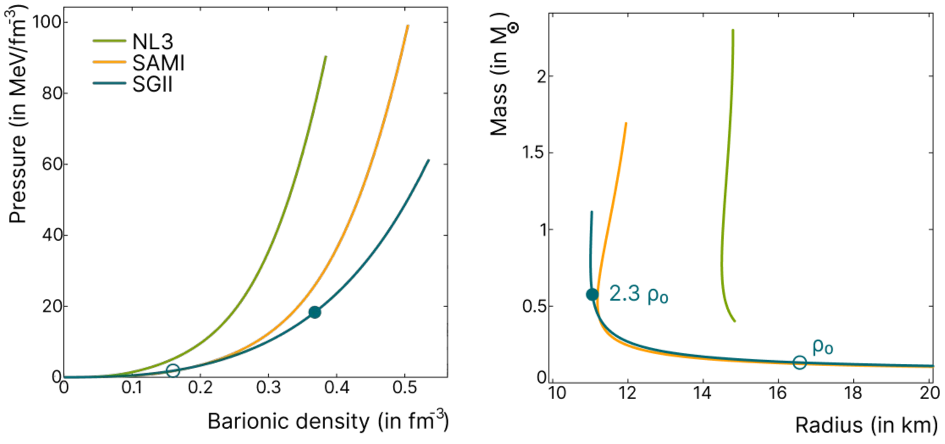
Diego Gruyer
for the INDRA-FAZIA Collaboration

Laboratoire de Physique Corpusculaire (LPC), and
Grand Accélérateur National d'Ions Lourds (GANIL),
Caen, France

Neutron stars

Laboratory to test general relativity, dense matter phases, nucleo-synthesis and neutron-rich environment

Relativistic hydrostatic TOV equation: balance between gravitational attraction and nuclear pressure



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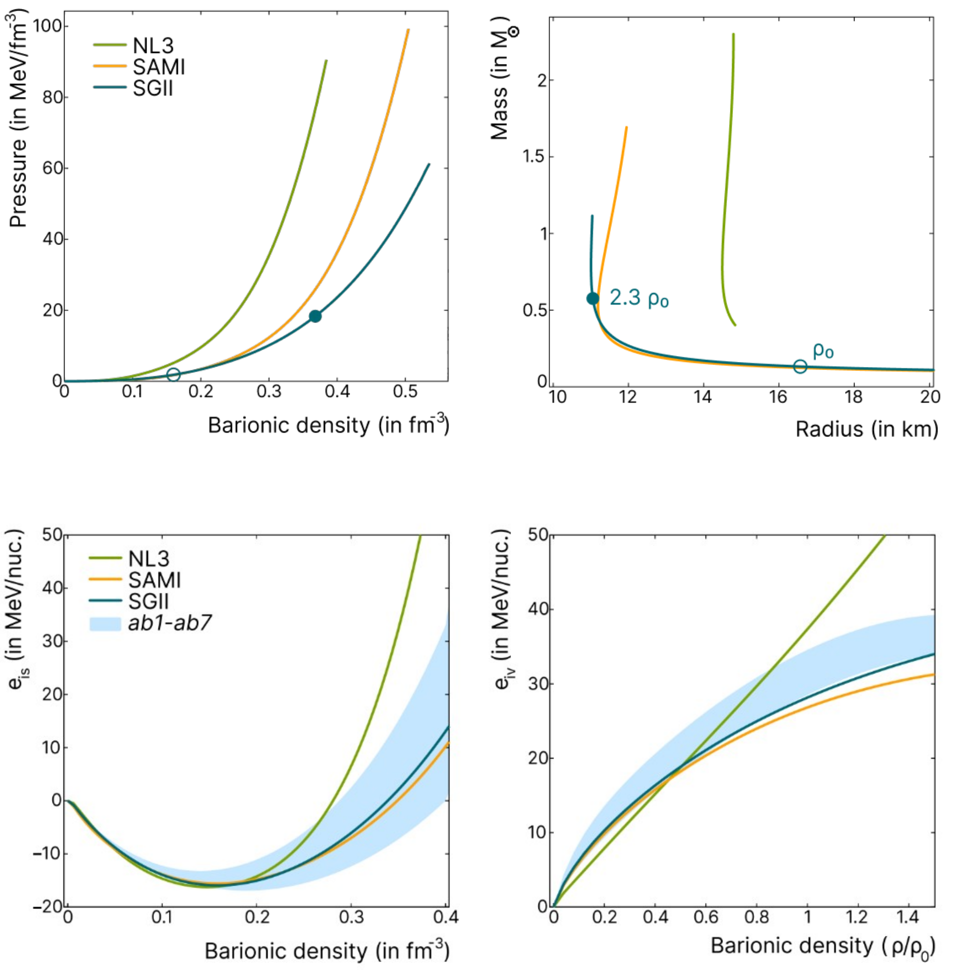
$$P_\beta(\rho) = \rho^2 \frac{de(\rho,\delta_\beta)}{d\rho}$$

with $e(\rho,\delta) = e_{\rm is}(\rho) + e_{\rm iv}(\rho)\delta^2$, and $\delta_\beta(\rho) \approx f(e_{iv}(\rho)^3/\rho)$

→ Neutron star bulk observables depends only on $P_\beta(\rho)$

→ $e_{is}(\rho)$ and $e_{iv}(\rho)$ contributes to β-equilibrated pressure

→ $e_{iv}(\rho)$ drives the composition of β-equilibrated matter (δ)



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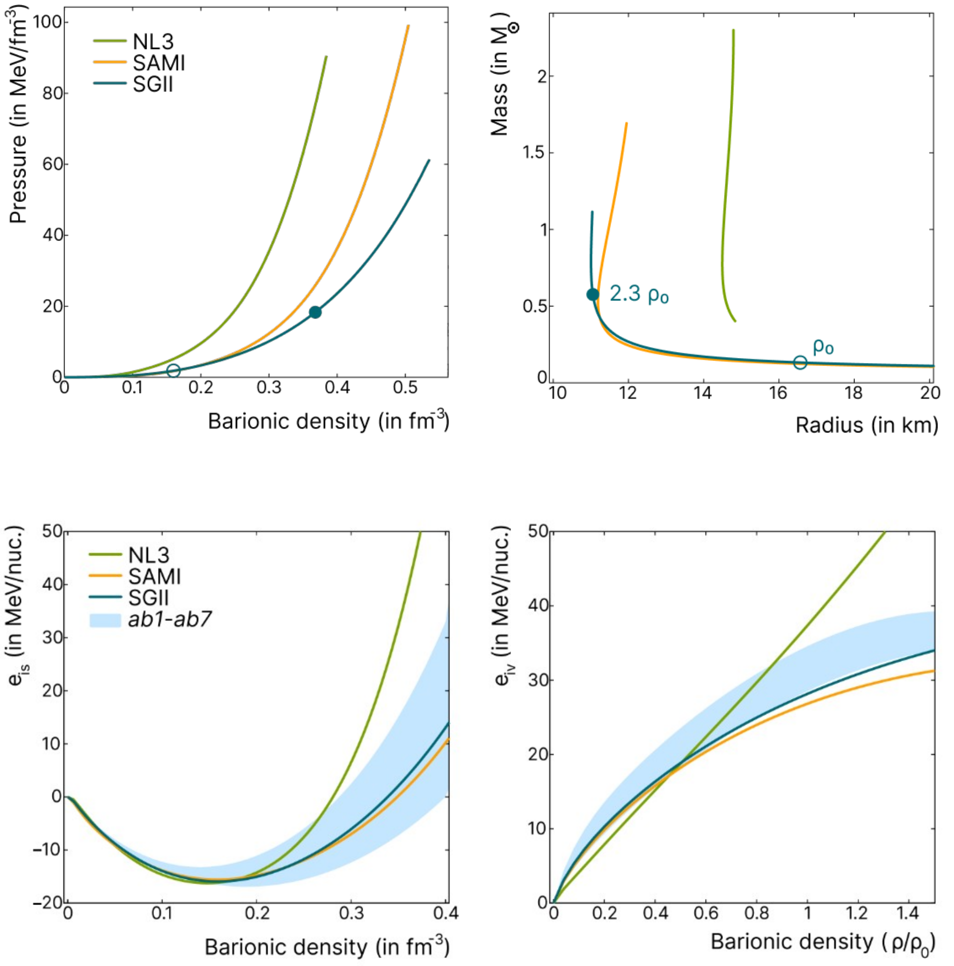
Neutron star cooling

Direct Urca cooling (neutrino emission after neutron β-decay and electron capture) requires a "large" fraction of proton at any point in the neutron star :

$$x_n(\rho)^{1/3} \leq x_p(\rho)^{1/3} + x_e(\rho)^{1/3} \quad \rightarrow \quad \delta_\beta(\rho) \leq \frac{7}{9}$$



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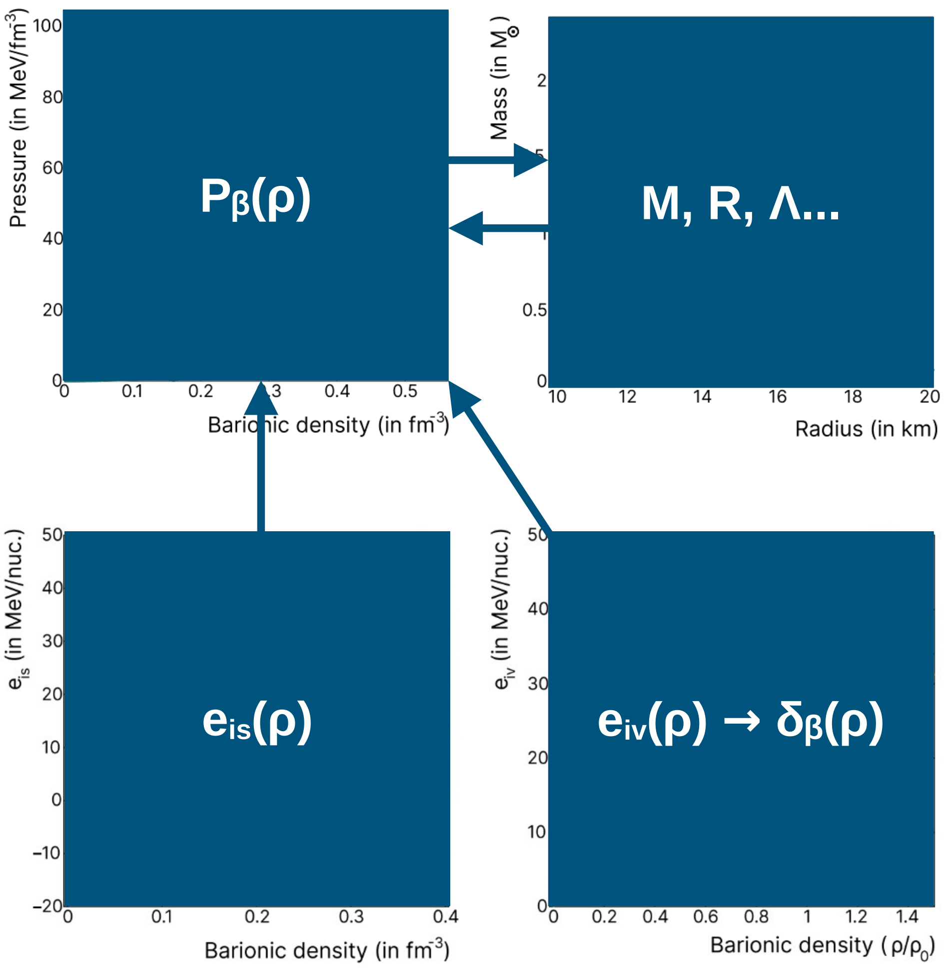

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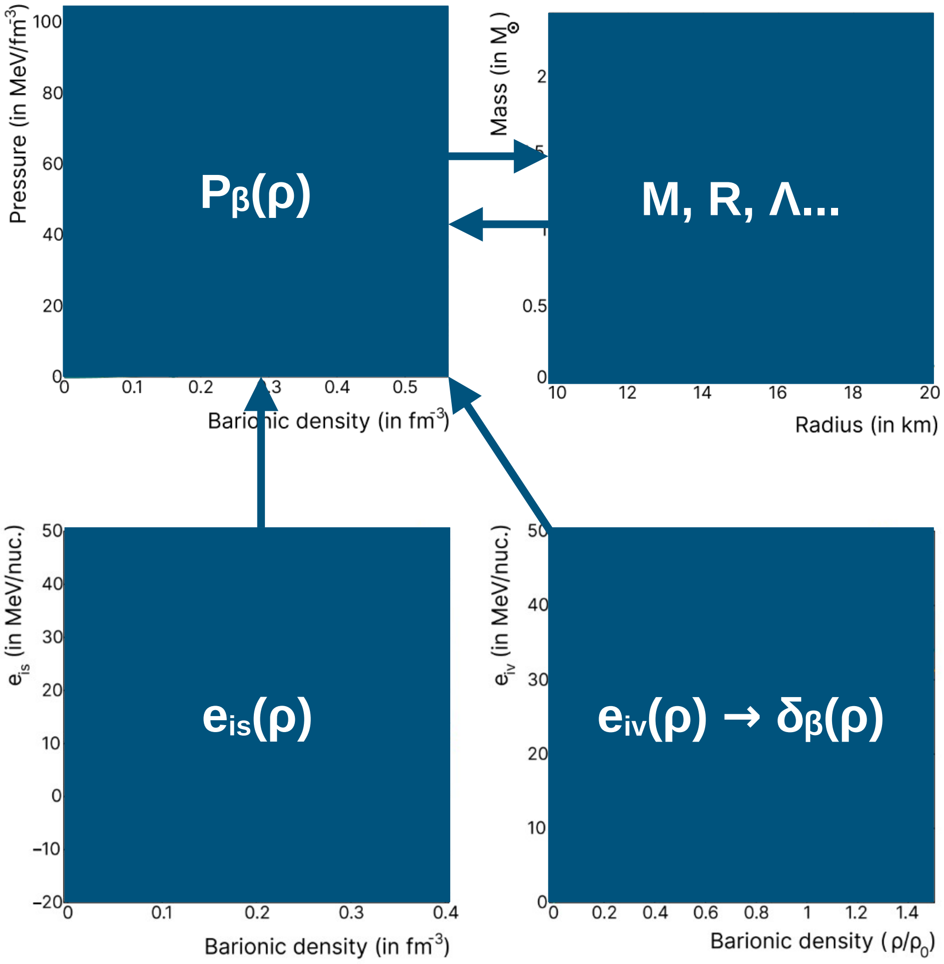

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→ Needs for constraints on $e_{iv}(\rho)$ from nuclear data !

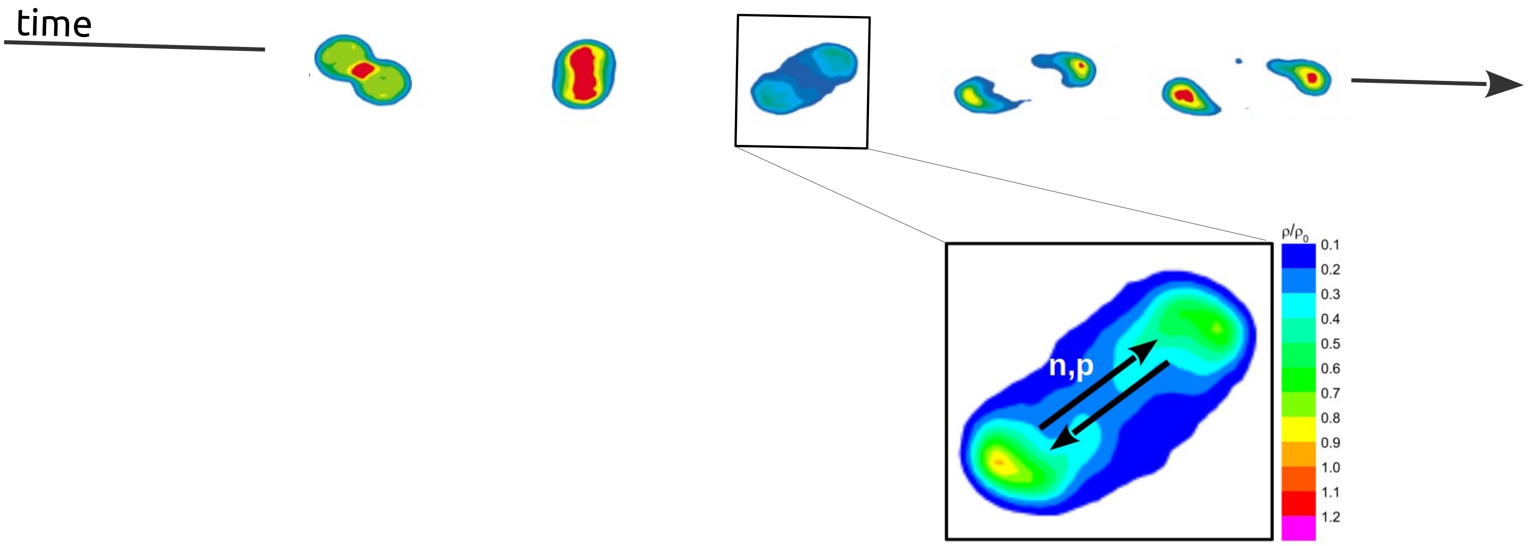
INDRA-FAZIA constraint

→ **Caterina Ciampi**, **John D. Frankland**, D. Gruyer, N. Le Neindre, S. Mallik, R. Bougault, A. Chbihi, et al.
Phys. Rev. C **111** (2025) 044601

→ **Caterina Ciampi**, **Swagata Mallik**, F. Gulminelli, D. Gruyer, J. D. Frankland, N. Le Neindre, R. Bougault, A. Chbihi, et al.
Phys. Lett. B **868** (2025) 139815

Isospin diffusion experiment

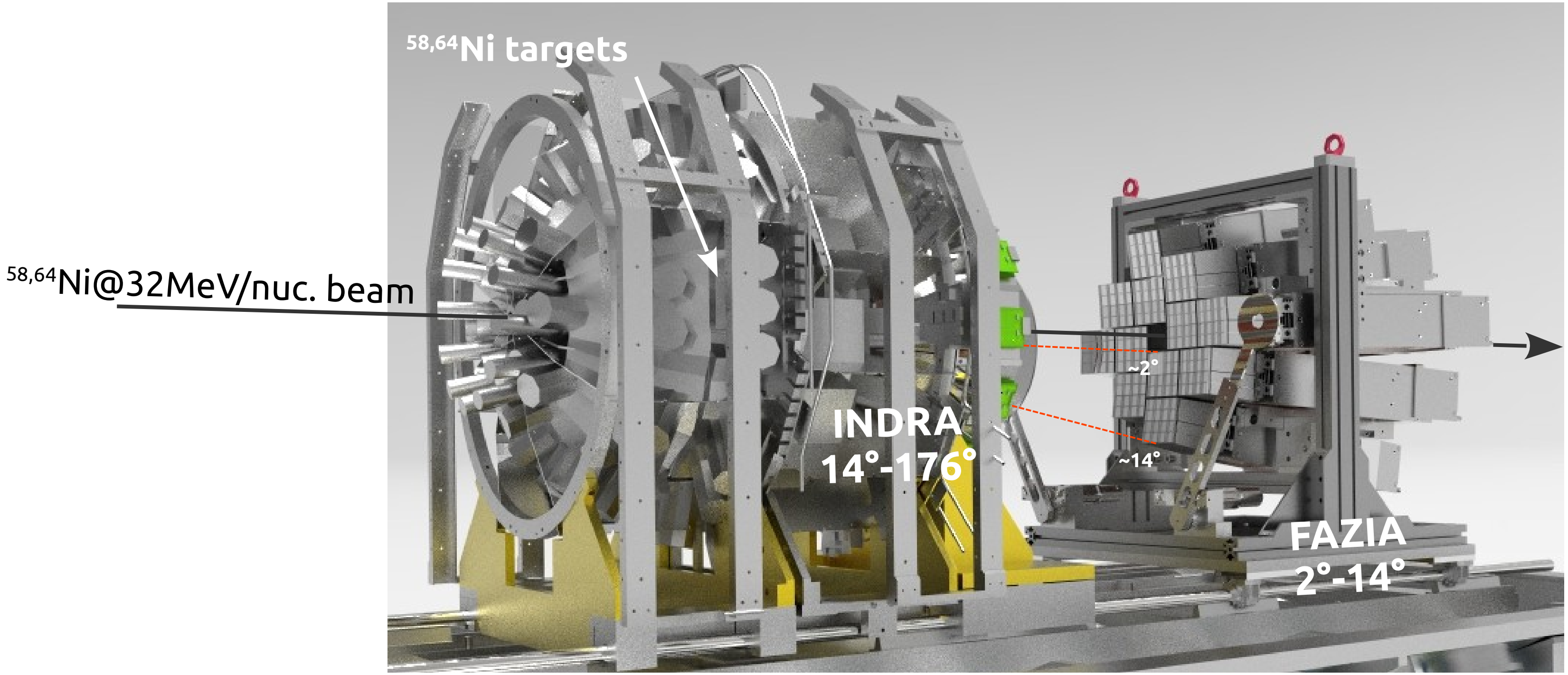
N/Z equilibration in peripheral heavy-ion collision only sensitive to $e_{iv}(\rho)$



Isospin diffusion experiment

N/Z equilibration in peripheral heavy-ion collision only sensitive to $e_{iv}(\rho)$

$^{58,64}Ni + ^{58,64}Ni$ at 32 MeV/nuc. with INDRA-FAZIA at GANIL



→ FAZIA : isospin content of quasi-projectile (charge and mass)

→ INDRA : impact parameter from the total multiplicity (Frankland et al., PRC 104 (2021) 034609)

Isospin transport ratio

Highlights isospin diffusion and attenuate the effects acting similarly on the four systems (Rami PRL (2000) 84, 1120)

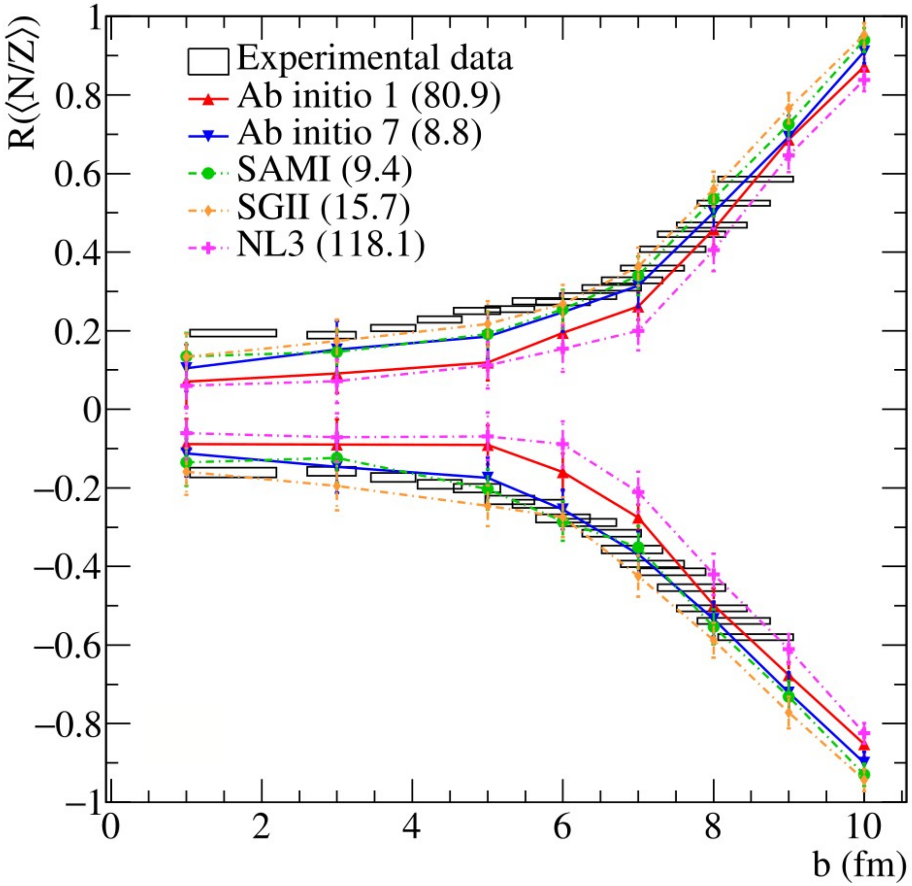
- ^{64}Ni + ^{64}Ni (AA) and ^{58}Ni + ^{58}Ni (BB) define the scale
- ^{64}Ni + ^{58}Ni and ^{58}Ni + ^{64}Ni quantify the equilibration

→ R = ±1 correspond no equilibration at all

→ R = 0 means full N/Z equilibration

$$R(x) = \frac{2x_i - x_{AA} - x_{BB}}{x_{AA} - x_{BB}}$$

→ Model independent isospin transport ratio versus impact parameter (Ciampi, PRC 111 (2025) 044601)



Isospin transport ratio

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$$R(x) = \frac{2x_i - x_{AA} - x_{BB}}{x_{AA} - x_{BB}}$$

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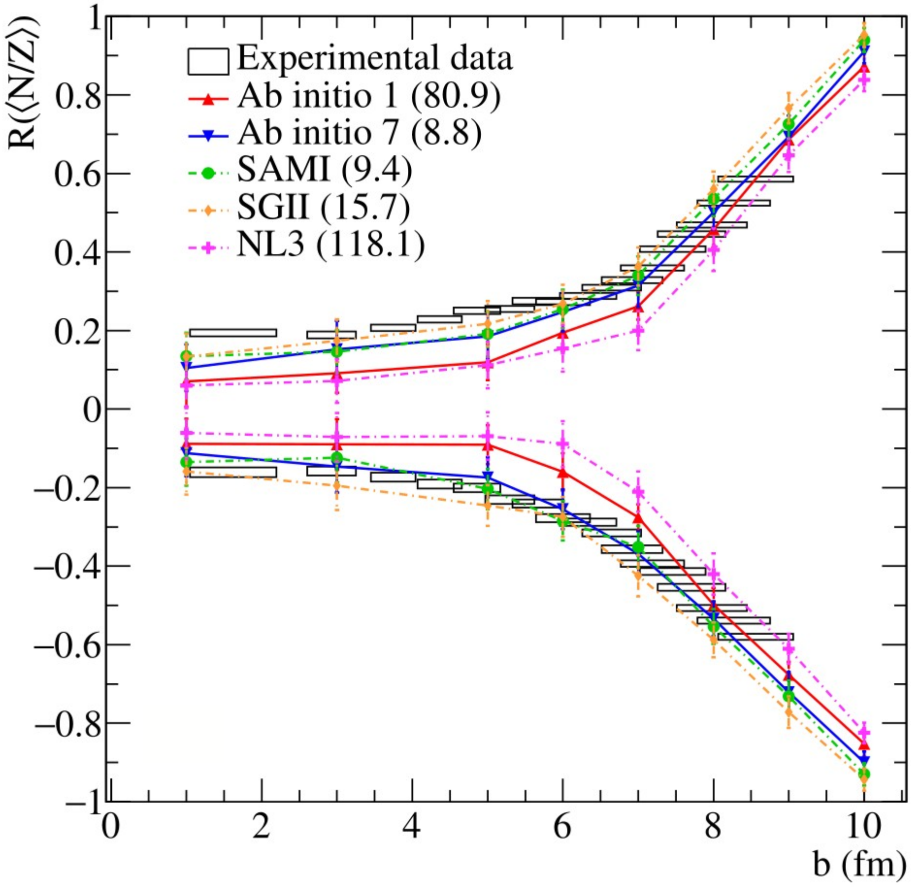
Transport model calculation

BUU@VECC-McGill to simulate the heavy-ion dynamics

Bulk part of the potential expressed in terms of the ELFc metamodel (Margueron, PRC 97 (2018) 025805)

- 2 chiral-EFT energy densities (ab-1 and ab-7)
- 2 Skyrme and 1 RMF interactions (SAMi, SGII and NL3)

→ Mallik, Universe 12(7) (2026) 202



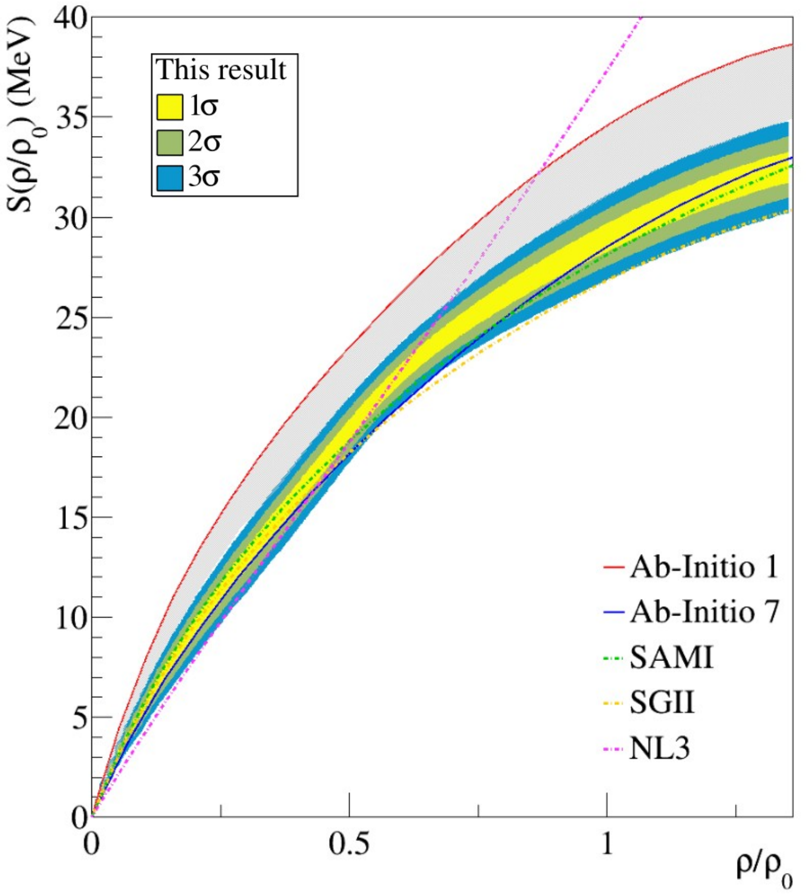
Isovector energy band

Extract confidence bands in the S(ρ)-ρ plane using gaussian likelihood L(S(ρ))

→ Overlaps with the χ-EFT interactions band

→ Tends to favor rather soft symmetry energy

→ What density region are we probing ?



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→ **What density region are we probing ?**

Density and current dynamics

For each time-step, we compute the density and isospin current density along the principal axis in a 3fm sphere

→ Dynamical processes do not probe a single density !

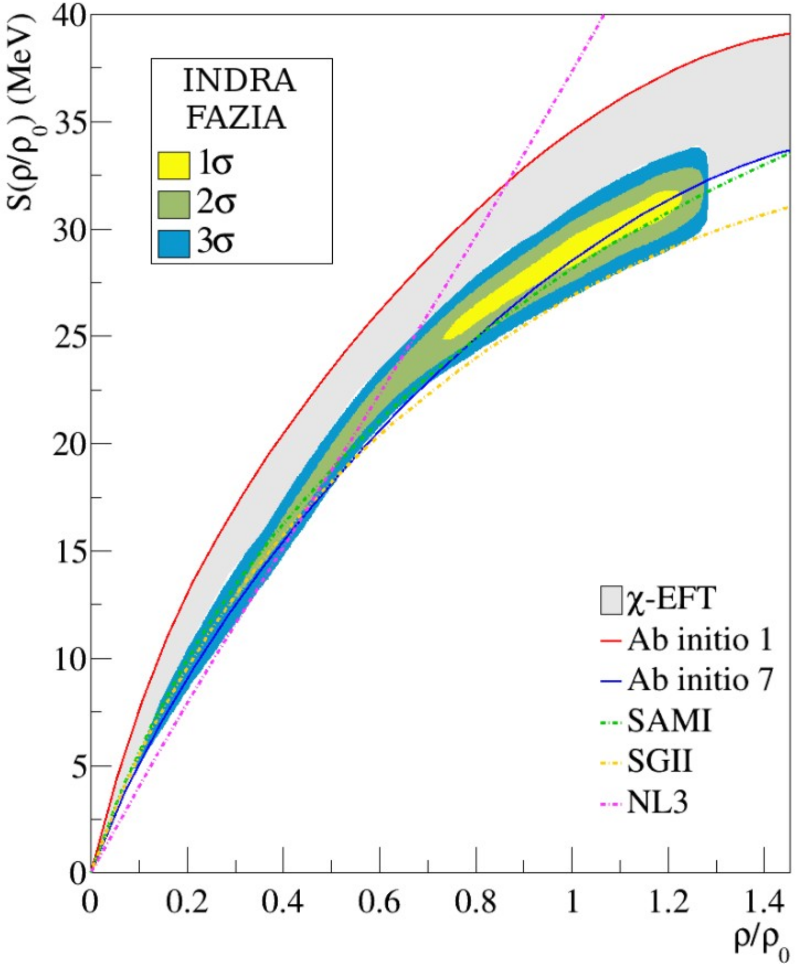
→ Density weight by integrating the differential n, p current density over time for each value of the density

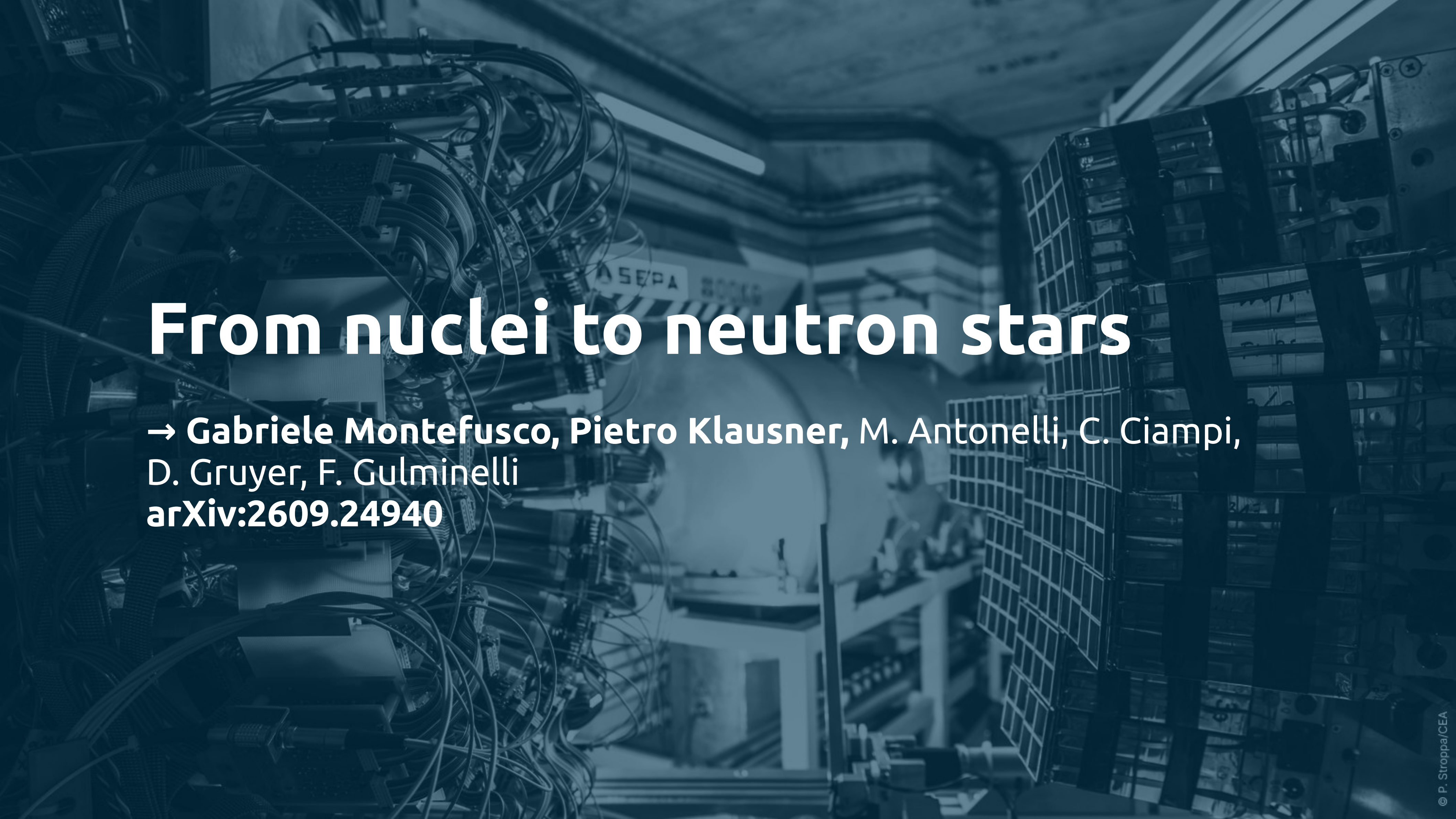
Isovector energy constraint

Bidimentional isovector energy-density posterior based on the weighted likelihood **L(S,ρ) = w(ρ) x L(S(ρ))** :

→ Sensitivity close to saturation (max at $\rho = 1.01\rho_0$)

→ **Ciampi, PLB 868 (2025) 139815**





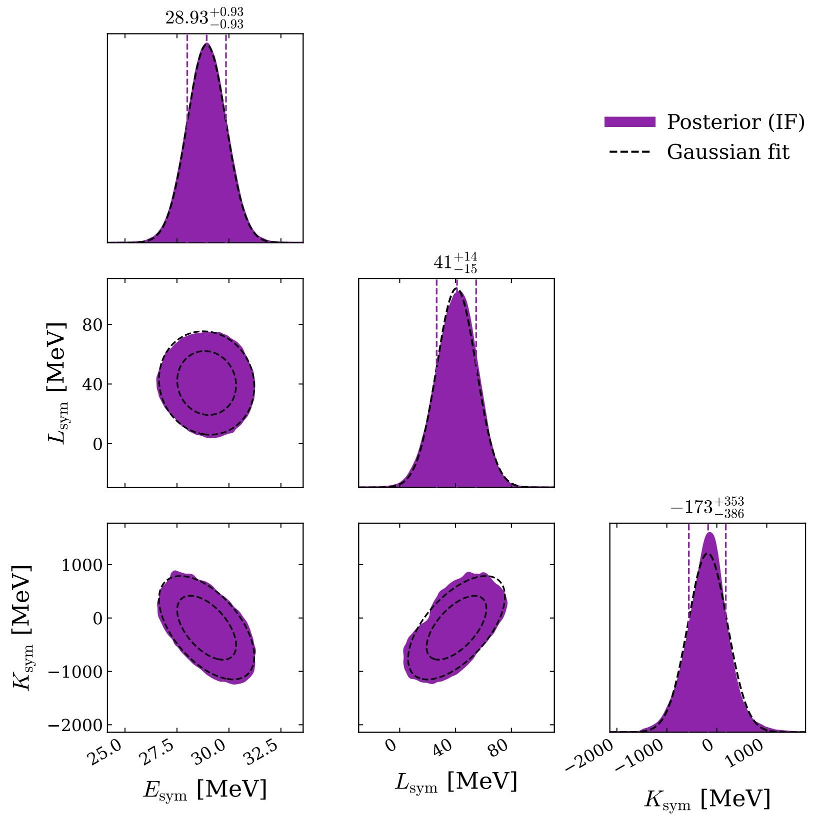
From nuclei to neutron stars

→ **Gabriele Montefusco, Pietro Klausner,** M. Antonelli, C. Ciampi, D. Gruyer, F. Gulminelli
arXiv:2609.24940

Nuclear Matter Parameter posterior

The INDRA-FAZIA (S,ρ) posterior was projected onto the Nuclear Matter Parameter (NMP) space of the asymptotically causal metamodel of **Montefusco et al., arXiv:2604.00196**

→ INDRA-FAZIA NMPs posterior (IF)



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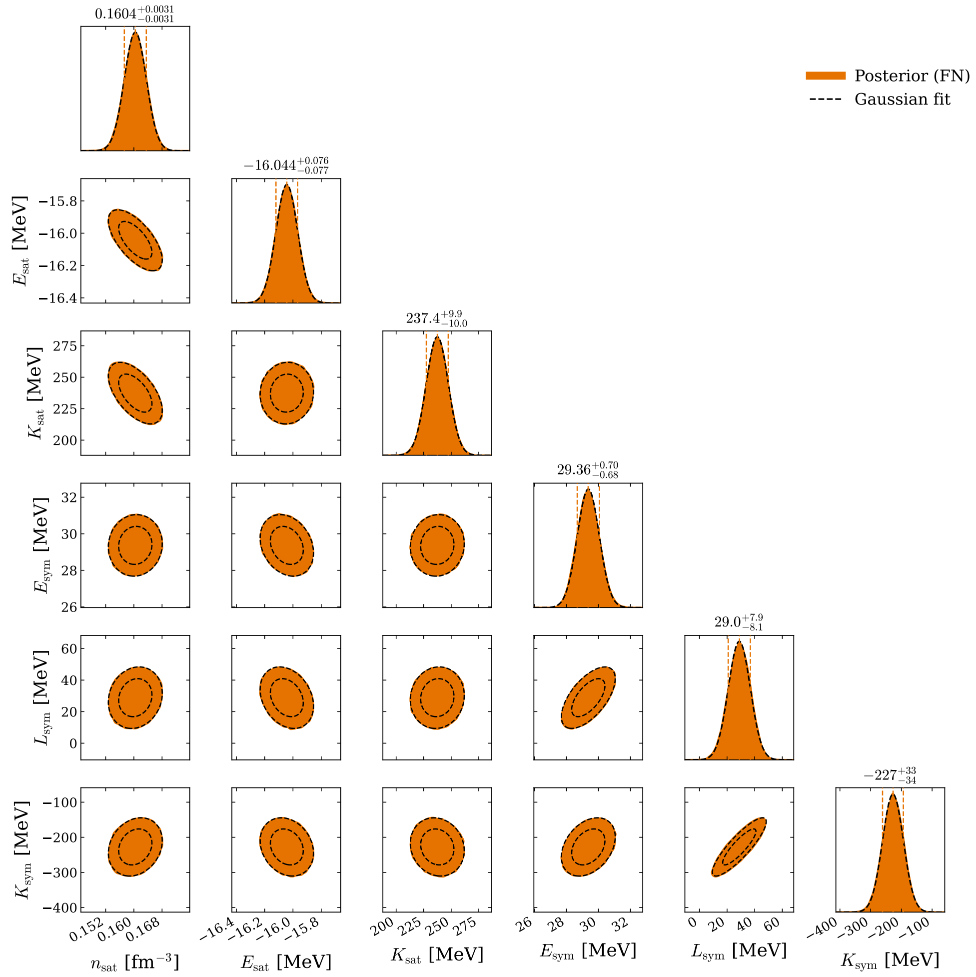
Improved laboratory constraint

The IF NMPs posterior was then combined with the nuclear structure data NMPs posterior from spherical qRPA-BCS code of **Klausner et al., arXiv:2604.11358**

→ B(Z,A), radii, collective modes, s-o splittings, dipole polarizability, parity violating scattering of ^{48}Ca and ^{208}Pb

→ Nuclear Structure Data NMPs posterior (NSD)



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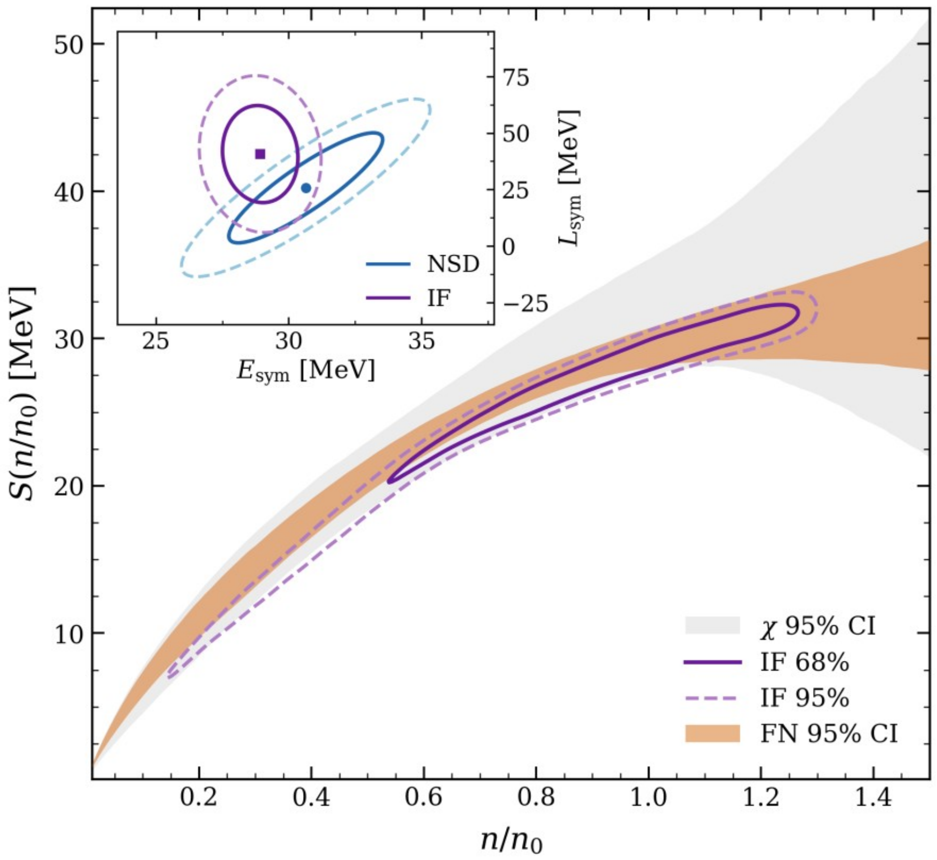
$$P_{\rm FN}\,(\theta) \propto \pi(\theta)\,\mathcal{L}_{\chi\rm EFT}(\theta)\,\mathcal{L}_{\rm IF}(\theta)\,\mathcal{L}_{\rm NSD}(\theta).$$

→ Full-nuclear isovector energy band using chiral prior !



Astrophysical filters

Standard set of astrophysical constraints :
→ maximal mass of PSR J0348+0432, PSR J0740+6620,
→ tidal deformability from GW170817,
→ mass-radius estimates for PSR J0030+0451, PSR J0437-4715, PSR J0740+6620, PSR J0614-3329.

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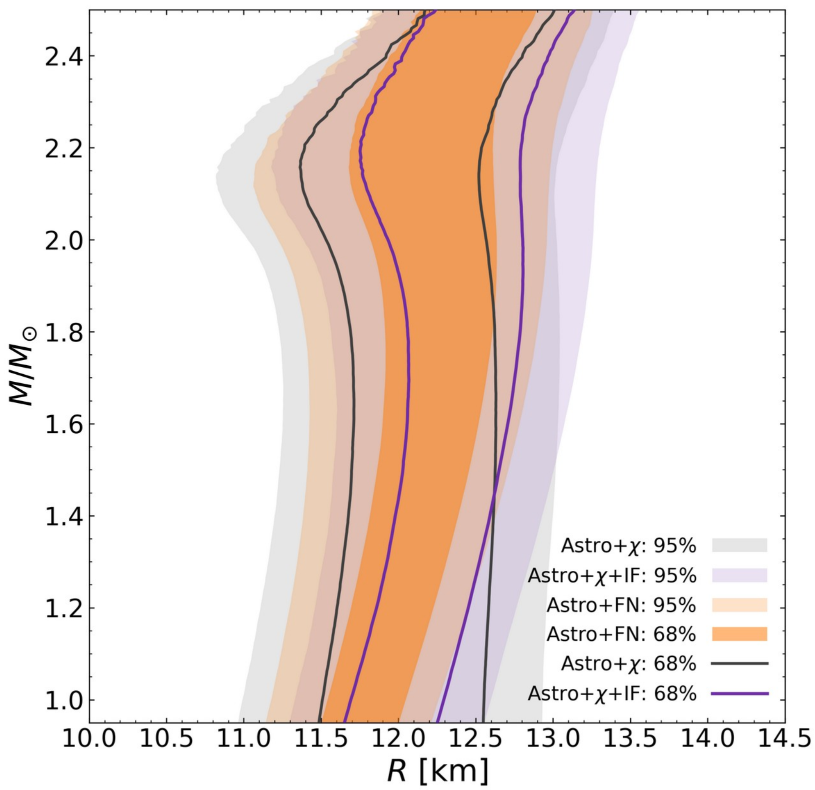
Mass-Radius posterior

Narrowing of the posterior radius for low mass stars

Little effect on massive neutron stars

→ Increased information around and below saturation



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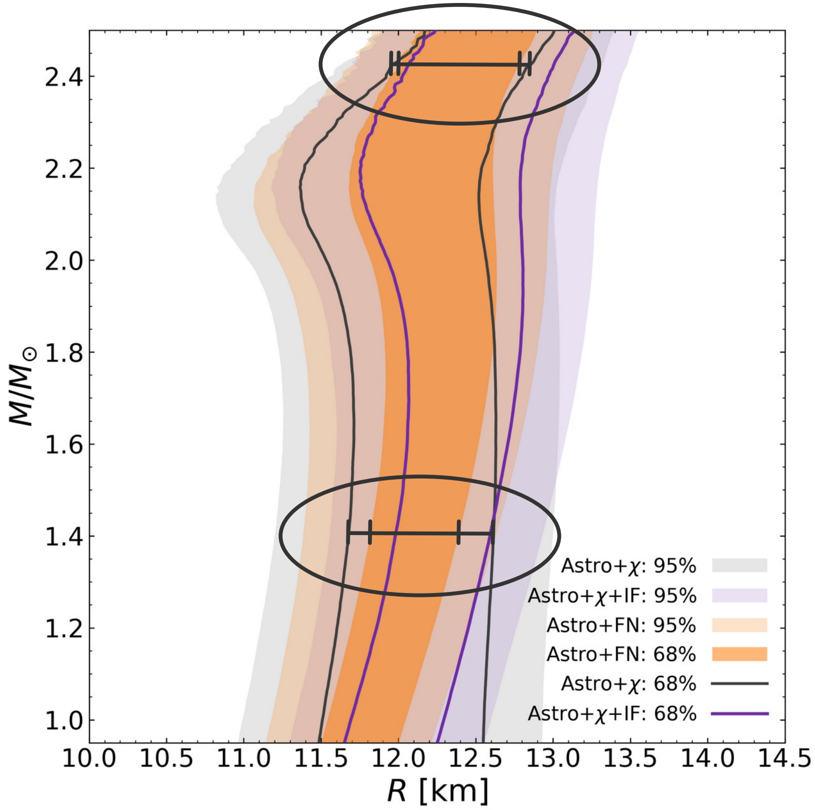

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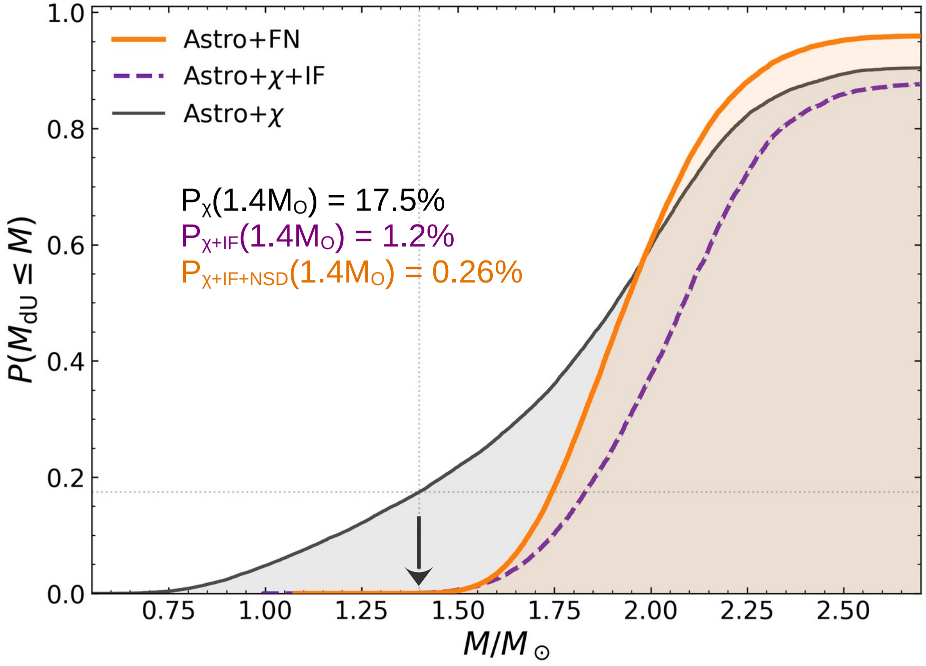
Composition and dUrca threshold

Better constraint on the isovector energy produces more neutron-rich stars (smaller central proton fraction)

Strong effect on the posterior distribution of the minimal mass allowing for nucleonic direct Urca cooling.



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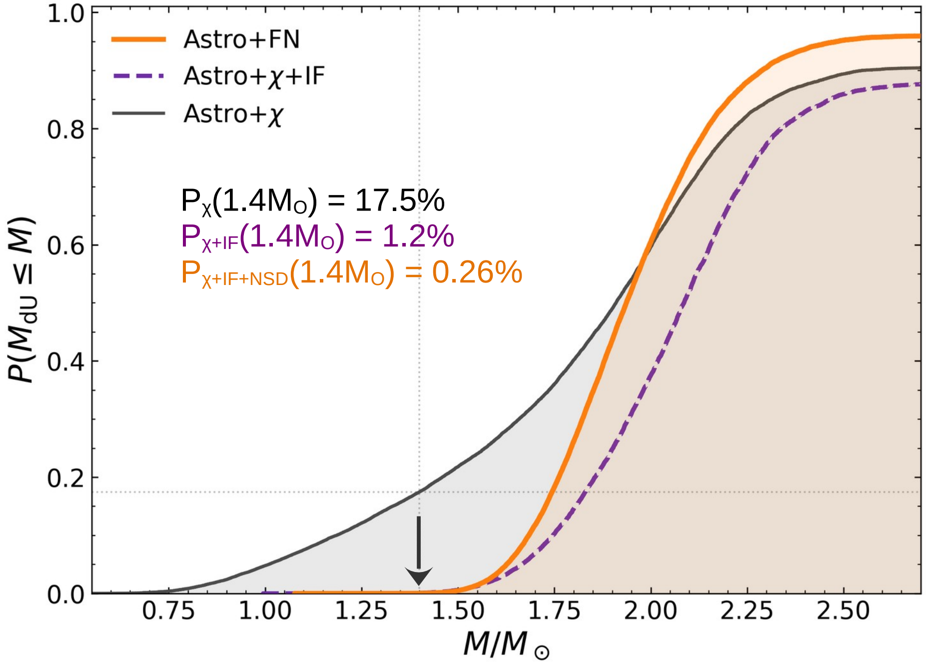

→ Improved laboratory constraints exclude the possibility for nucleonic dUrca cooling for $M \leq 1.4\ M_{\odot}$

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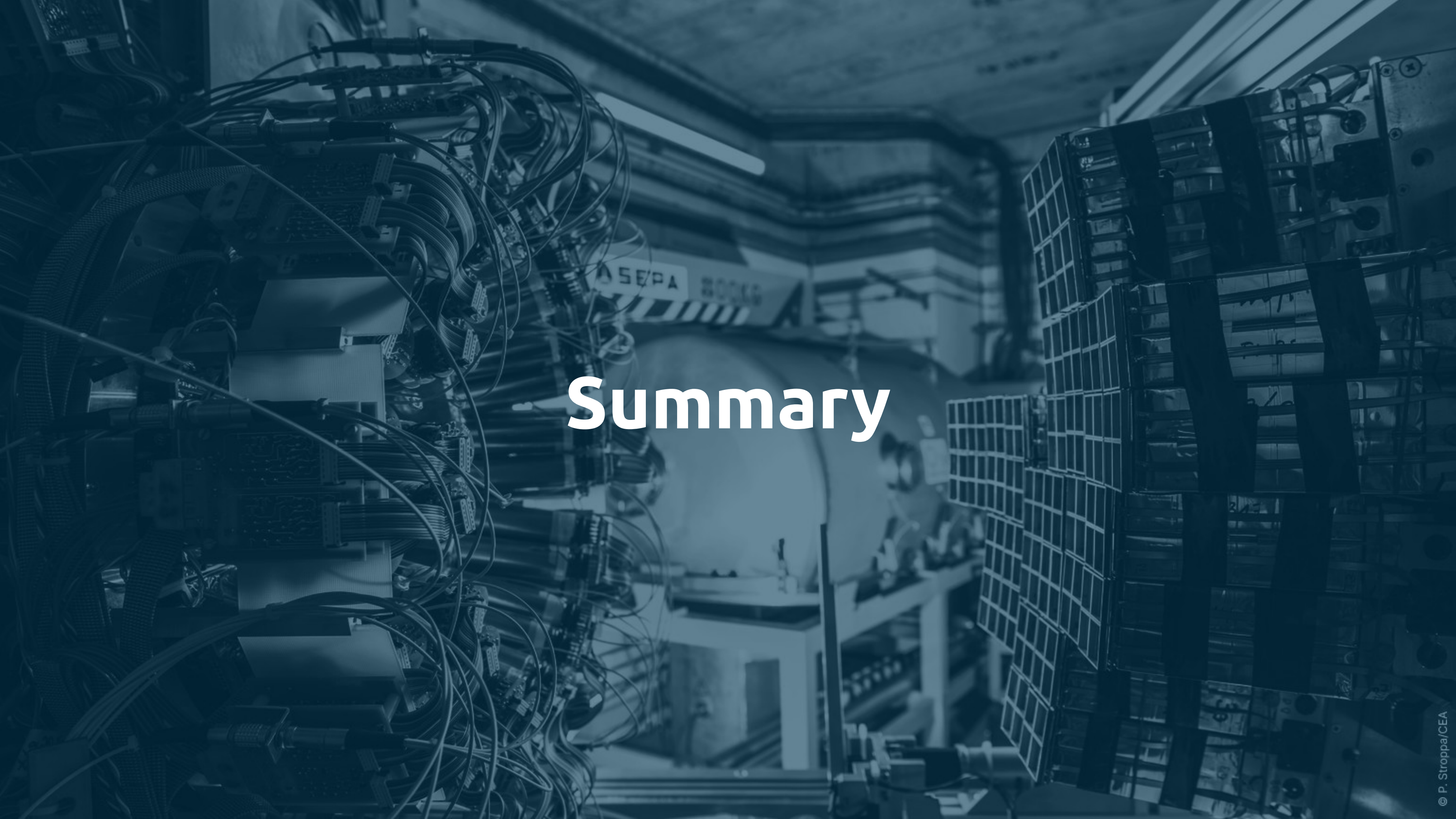
Summary



INDRA-FAZIA constraint

New constraint on e_{iv}-ρ plane by comparing isospin transport ratio measured with INDRA-FAZIA at GANIL and BUU calculations
→ FAZIA : isospin content of quasi-projectile
→ INDRA : model independent impact parameter distribution
→ Huge effort to define consistently the sensitive density region

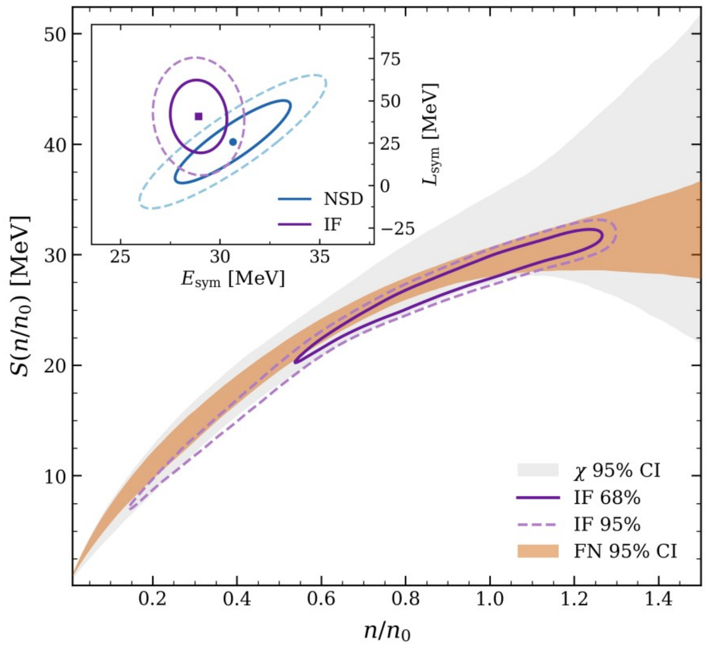
Improved laboratory constraint

The INDRA-FAZIA NMP posterior was combined with a recent nuclear structure data analysis using chiral-informed prior
→ Full-nuclear symmetry energy band propagated throught the asymptotically causal metamodel

From HIC+NSD to NS

After incorporation of the standard astro filter :
→ Narrowing of the posterior radius for low mass stars
→ Smaller central proton fraction posterior for low mass stars

→ Improved laboratory constraints exclude the possibility for nucleonic dUrca cooling for $M \leq 1.4\, M_\odot$



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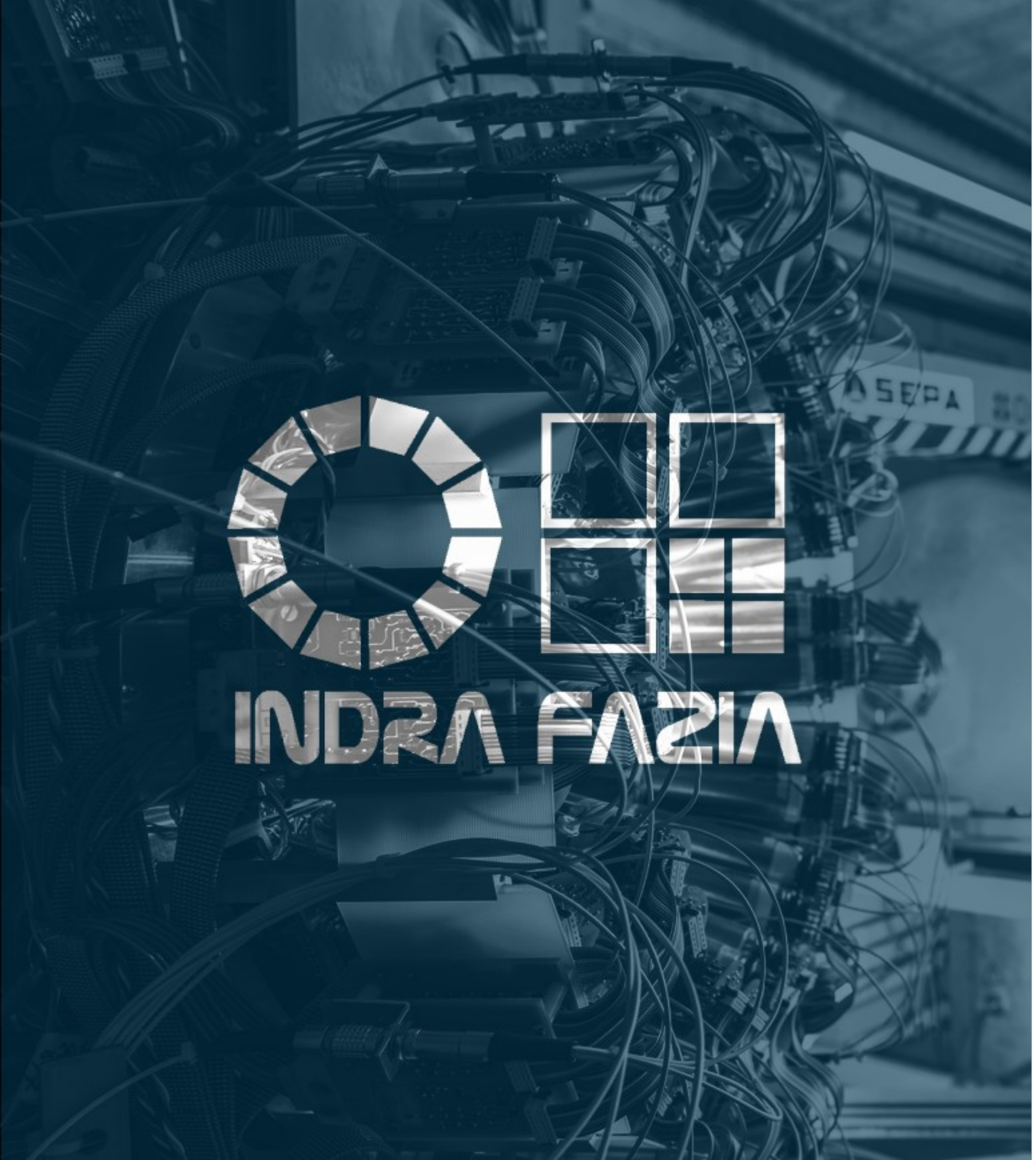

C. Ciampi, S. Mallik, G. Montefusco, P. Klausner,
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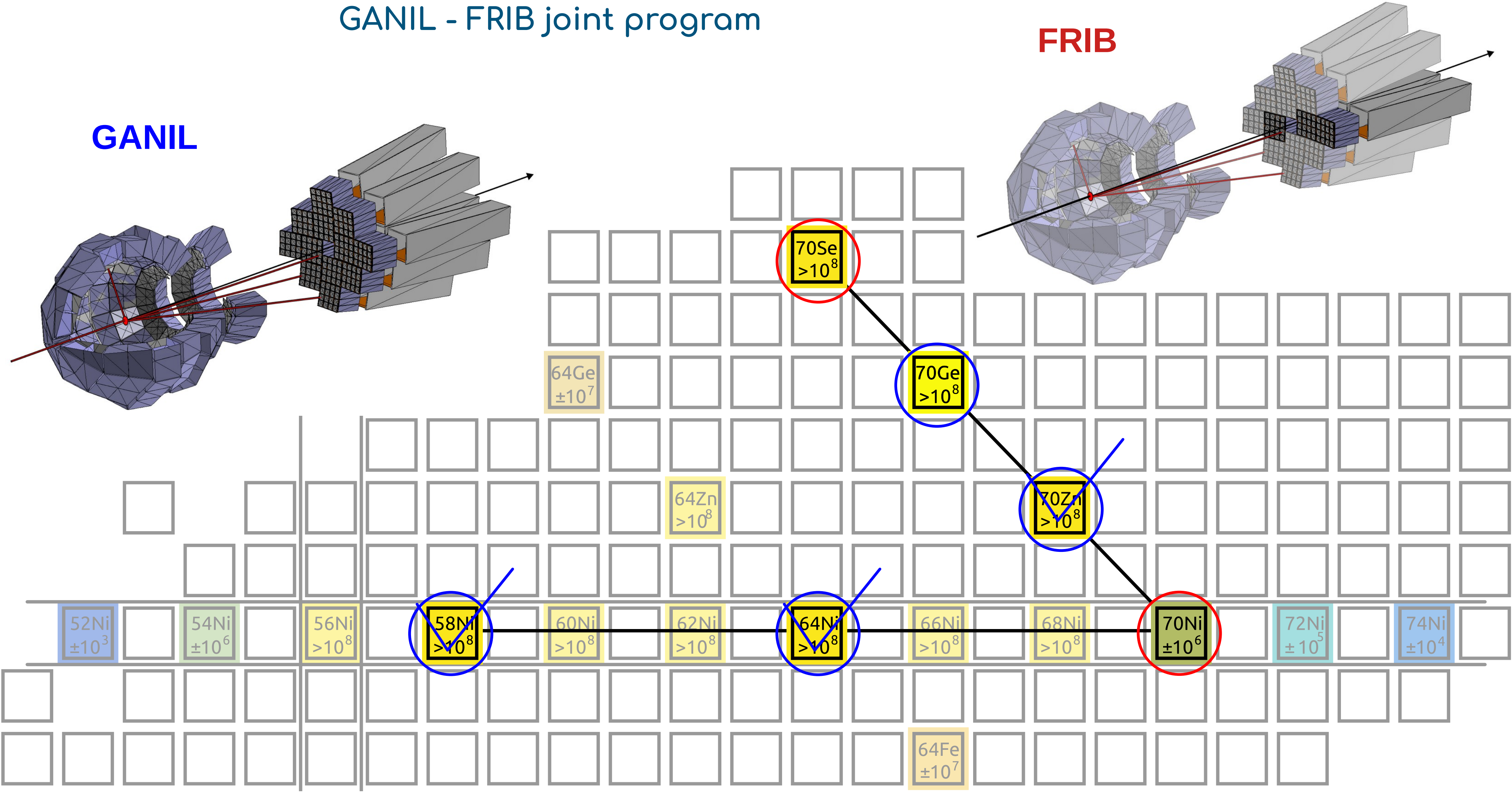
(INDRA and FAZIA Collaborations)

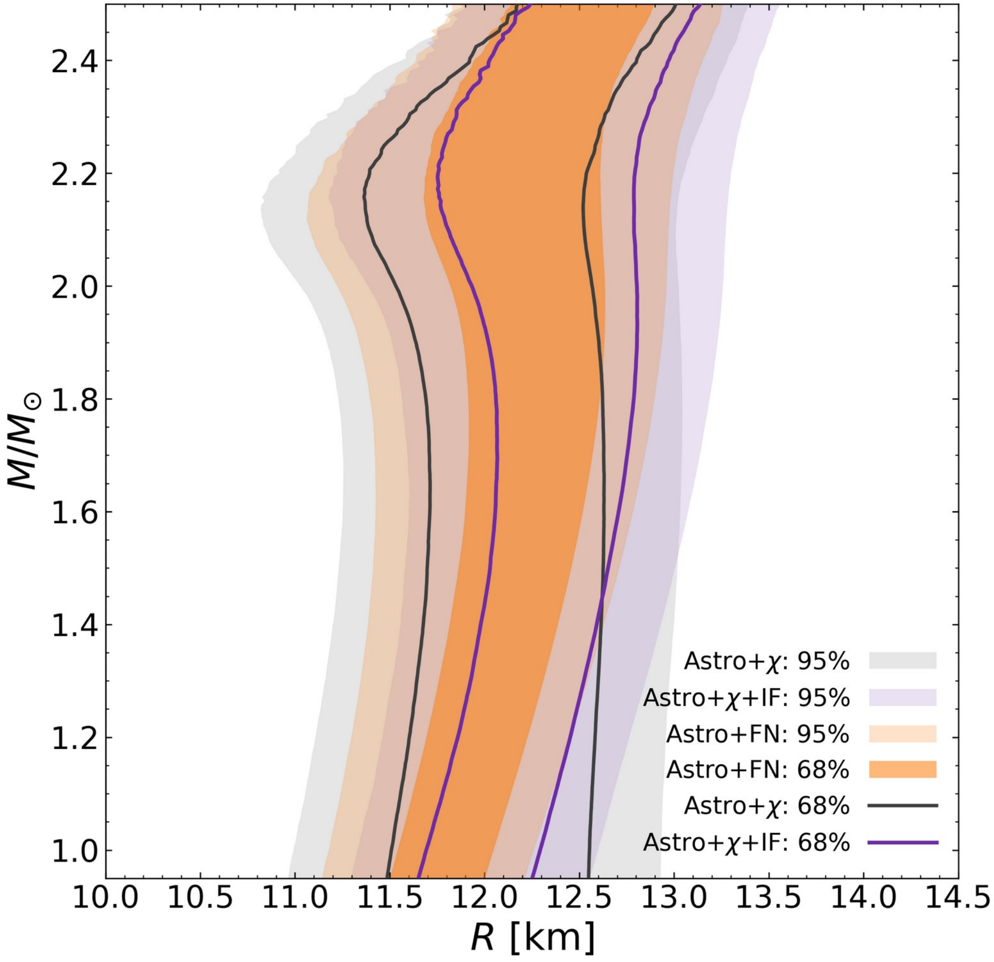
Prospects

→ FAZIA LoI submitted to the FRIB PAC

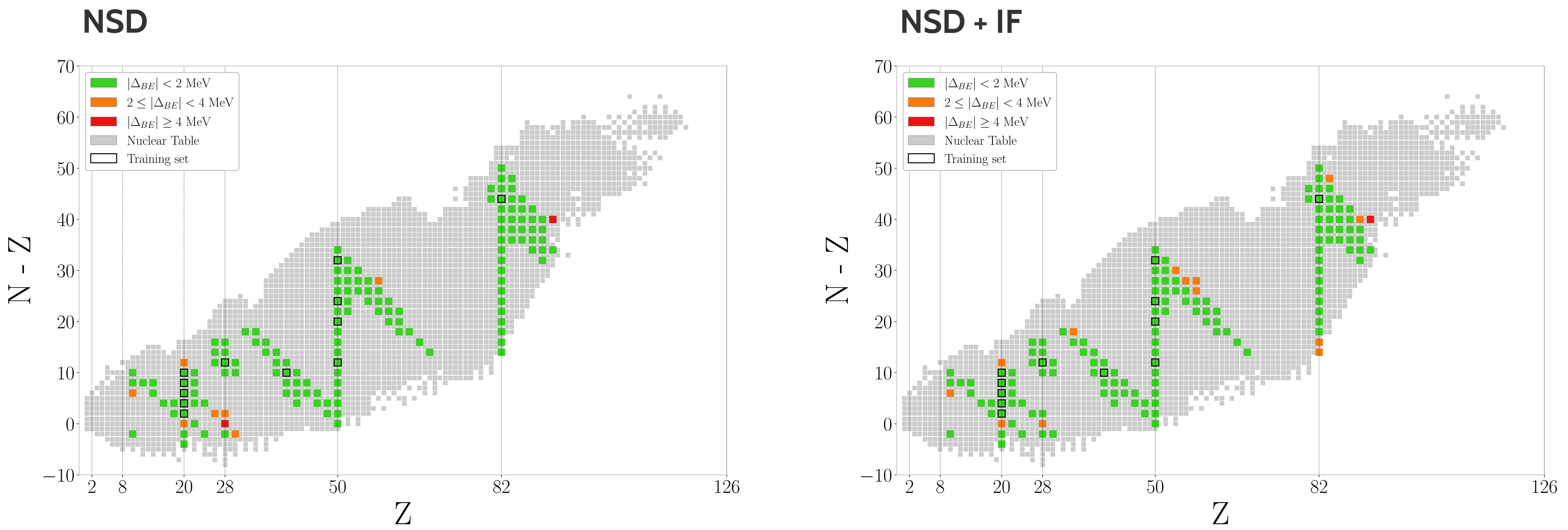
GANIL - FRIB joint program




SEPA



$M/M_\odot$
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
10.0
10.5
11.0
11.5
12.0
12.5
13.0
13.5
14.0
14.5
R [km]
Astro+χ: 95%
Astro+χ+IF: 95%
Astro+FN: 95%
Astro+FN: 68%
Astro+χ: 68%
Astro+χ+IF: 68%


NSD
NSD + IF
$|\Delta_{BE}| < 2$ MeV
$2 \leq |\Delta_{BE}| < 4$ MeV
$|\Delta_{BE}| \geq 4$ MeV
Nuclear Table
Training set
N - Z
Z
2
8
20
28
50
82
126
−10
0
10
20
30
40
50
60
70