QCD input to cosmic rays and compact stellar objects: open questions and next challenges

V. Mantovani Sarti (TUM), M. Pappagallo (Bari U., INFN Bari), A. Gérardin (CPT Marseille)

Open Symposium European Strategy for Particle Physics – Update 2026

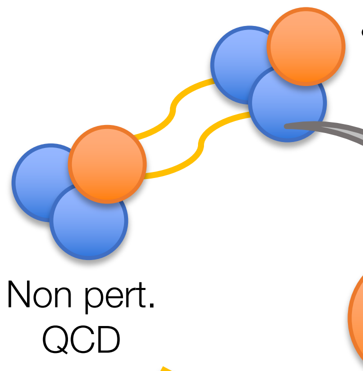
Venice 23-27 June 2025

valentina.mantovani-sarti@tum.de

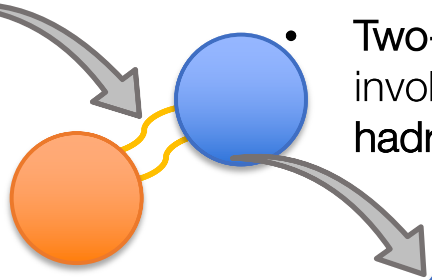
OPEN SYMPOSIUM
European Strategy for Particle Physics
2026 UPDATE
23-27 JUNE 2025

QCD inputs for astrophysics

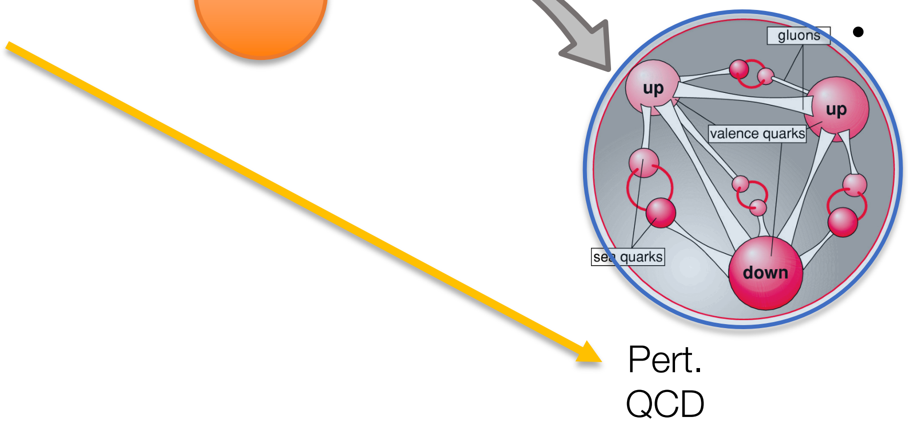
- QCD dynamics entering in several astrophysical processes and areas



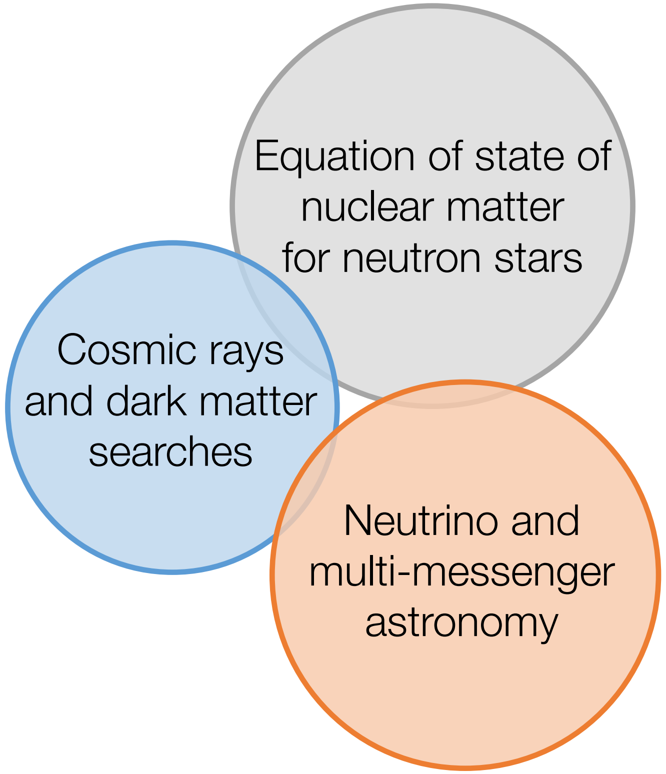
- Three- and many-body forces



- **Two-body interactions** involving **strange hadrons** and nucleons



- Distributions of quarks and gluons inside hadrons



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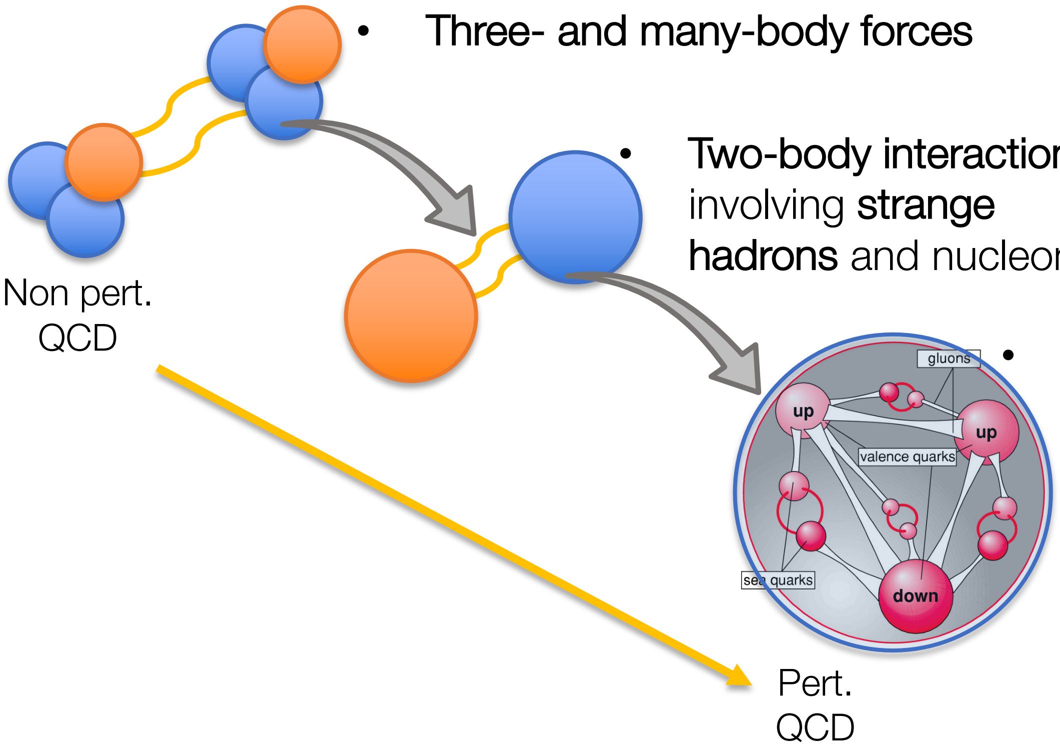

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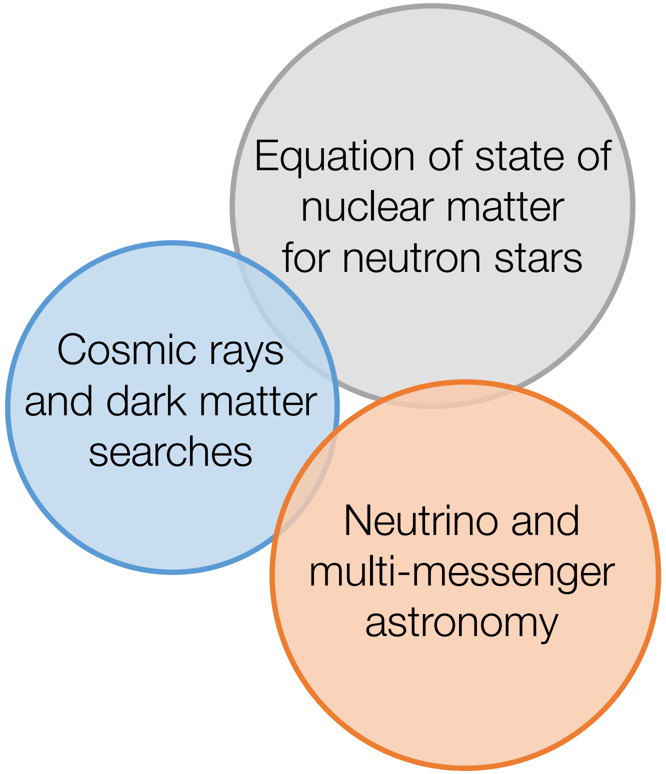

Continuous effort on synergy between astrophysics and QCD required!

QCD connections to astrophysics: open questions

From neutron stars, to cosmic rays and neutrino astronomy

Equation of state of neutron stars (NS)

1. Can we improve the knowledge of the ordinary nucleonic EoS?
   Still large uncertainties on properties of symm/asymm. nuclear matter at $\rho > \rho_0$

2. Are three-body nucleonic forces with strange hadrons the solution to the "hyperon puzzle" in NS?
   Poor knowledge on hyperon-nucleon and hyperon-nucleon-nucleon strong forces, particularly with Σ and multi-strange baryons

QCD

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QCD

Cosmic rays and dark matter (DM)

1. Do we observe an indirect evidence of DM in CRs?

   Focus on light-antinuclei ($\overline{d}, \overline{He}$) fluxes in GCRs as clean signal of DM annihilation/decay

2. Can we provide an explanation to the composition of extended air-showers and primary ultra-high energy CRs?

   Hadronic interactions are key input for simulations of air-showers and CRs studies

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QCD

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Neutrino astronomy

1. Can we improve the modeling of high-energy ν production and its interaction with hadrons?
   More constraints on ν-N (ν-Nucleus), prompt atmospheric ν background (complementary with low-x physics)

Many community inputs:
id89:Precision XS for advancing CRs physics
id106:NuPECC id235:PBC id126:GermanyKAT
id76:INFNCS3 id183:GermanKhUK id117:INFNCS4

Ordinary nucleonic EoS for NS

State-of-the art and future physics goals

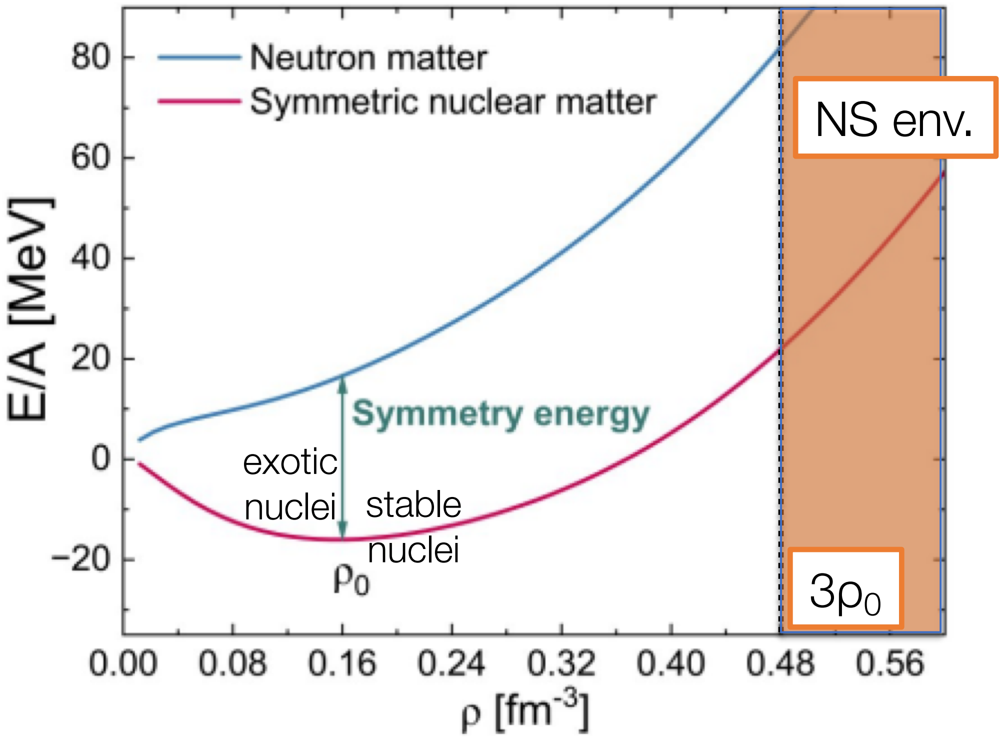
id89:Precision XS for advancing CRs physics
id106:NuPECC id235:PBC

isospin asymmetry

$$\rho_p - \rho_n / \rho$$

$$E(\rho, \delta) = E_0(\rho, 0) + E_{sym}(\rho)\delta^2 + \sigma(\delta^4)$$

- **Knowledge of EoS** as input to **β-stable calculations** of masses and radii of NS (Tolmann-Oppenheimer-Volkoff)
- Broad experimental effort to constrain isoscalar and isovector parameters around ρ_0
  - **Nuclei properties (M,R), nuclear excitations (GMR), Neutron skin**
  - Dedicated **flow measurements in low-energy heavy-ion collisions**
- Still rather large uncertainties on both terms (ΔK_0 up to 30%, ΔL up to 40%,)



Recent reviews and works:
A. Sorensen et al. Prog.Part.Nucl.Phys. 134 (2024)
MUSES Coll. Living Rev.Rel. 27 (2024) 1, 3
S. Huth et al. Nature 606 (2022) 276-280
G.F. Burgio et al. Prog.Part.Nucl.Phys. 120 (2021) 103879

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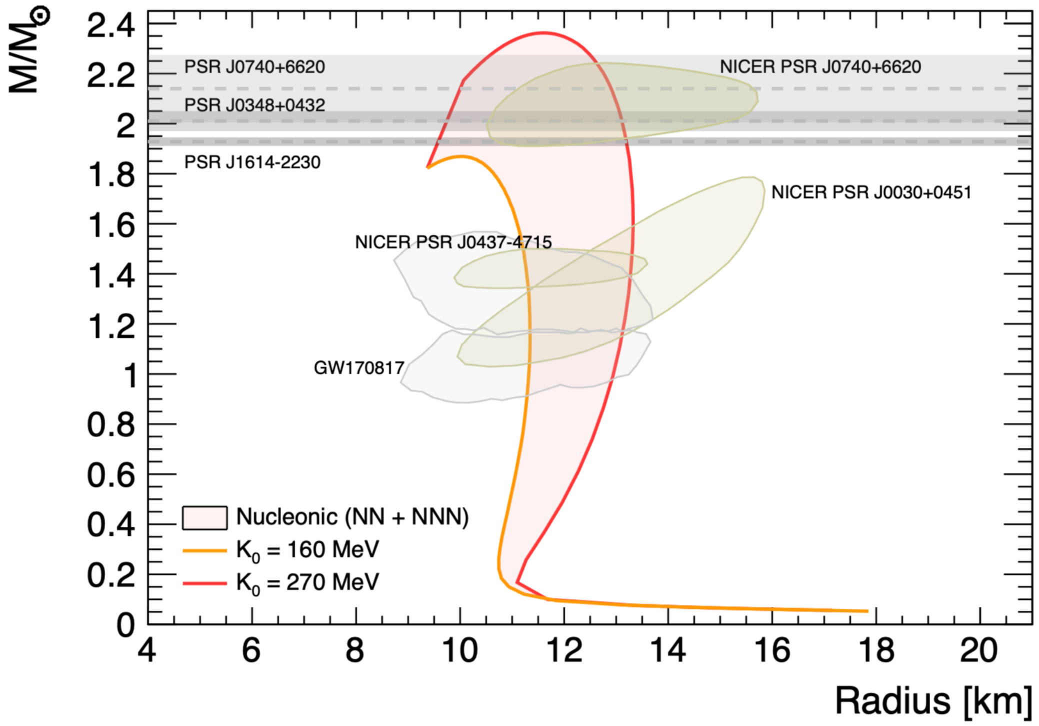
I.Vidaña et al. Eur.Phys.J.A 61 (2025) 3, 59



Inclusion of NN and NNN forces delivers EoS compatible with astrophysical measurements

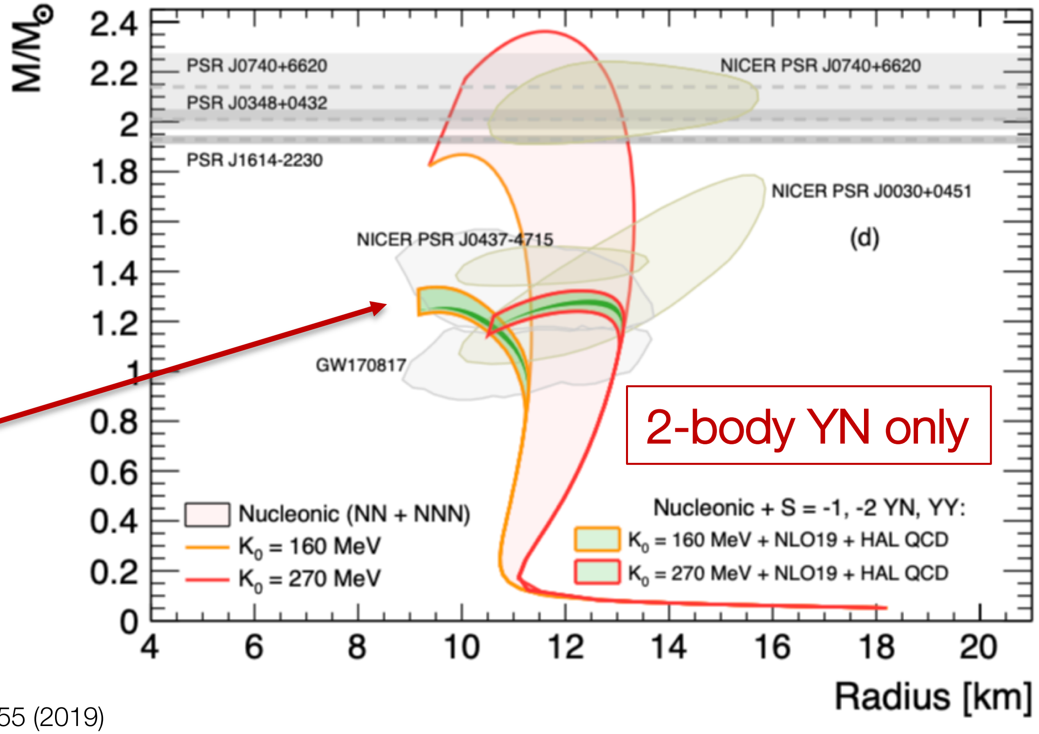
QCD connection to neutron star physics: where are we?

State-of-the art and future physics goals

- Production of hyperons in NS energetically favourable around 2-3 ρ_0
- Appearance of new degrees of freedom
  - Softening of EoS → confirmed by latest studies with YN-only constrained to scattering+correlation data
  - incompatible with heavy measured NS

"Hyperon puzzle"?
Missing ingredients..

I.Vidaña et al. Eur.Phys.J.A 61 (2025) 3, 59



- Three-body ΛNN repulsive forces to stiffen EoS
  - How much repulsion?
    → Model-dependent
    → Need for more experimental constraints

With Λ hyperons: D. Logoteta et al., Eur.Phys.J.A 55 (2019)
No Λ hyperons in NS: D. Gerstung et al., Eur.Phys.J.A 56 (2020)
No bound hypernuclei: D. Lonardoni et al., PRL 114 (2019)

Exploration of more exotic scenarios requires a solid knowledge of the nuclear/hadronic part

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QCD connection to neutron star physics

Physics benchmarks and future experimental opportunities

Nucleonic EoS

Continuing the effort between nuclear physics and HICs

Measurement	Facility/Experiment	Timeline
Properties of exotic nuclei	Low-en. radioactive ion beams ISOLDE HIE-UPGRADE (p from 1.4 to to 2 GeV) id6:ISOLDE	> 2029
Flow, strangeness measurements in HICs	Low-energy $\sqrt{sNN} \sim 2-5$ GeV heavy-ions (HADES@GSI, CBM@FAIR,J-PARC-HI)	> 2028 (CBM)

Hyperonic EoS

Extending the complementarity between different experimental techniques

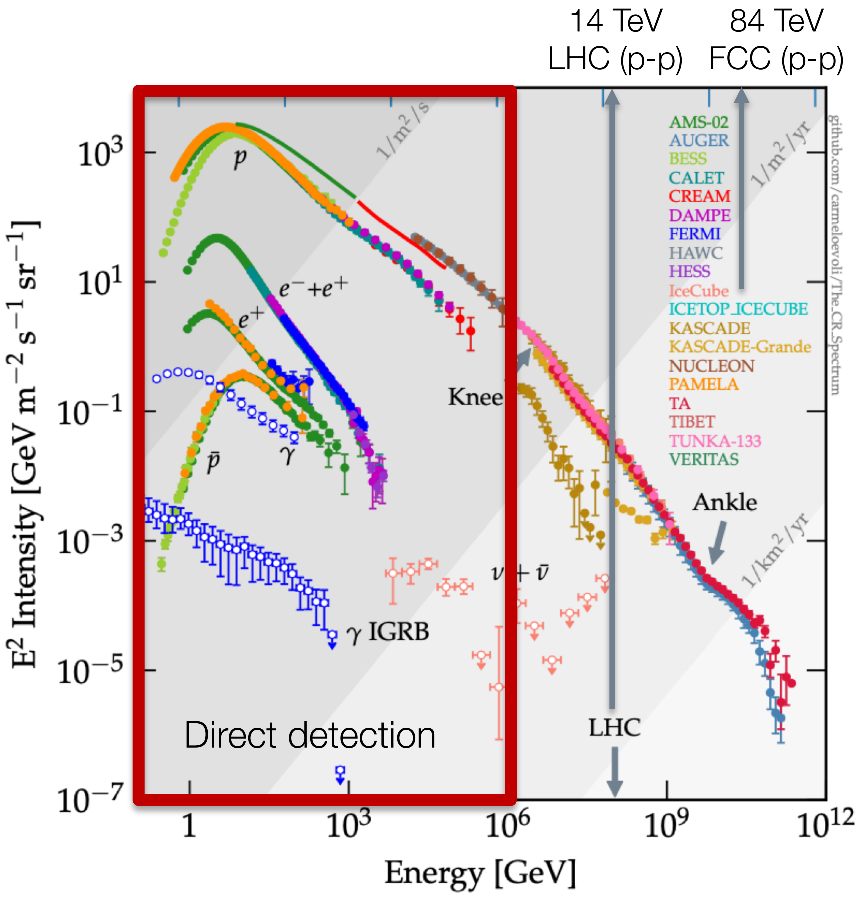
Measurement	Facility/Experiment	Timeline
2-body and 3-body correlations with hyperons (Σ)	ALICE 3, NA61/Shine, J-PARC-HI id68:ALICE id171:NA61/SHINE	>2035 (ALICE 3)
Hypernuclei (n-rich in particular) id126:GermanyKAT id183:GermanKhUK	J-PARC HEF-EX, ALICE 3, Hyperpuma@CERN, Panda@FAIR, …	> 2035 (ALICE 3)
Scattering data, id35:Y.Ichikawa cusp spectroscopy (ΣN)	J-PARC HEF-EX	Operat. in ~2033

Cosmic rays and DM indirect searches: where are we?

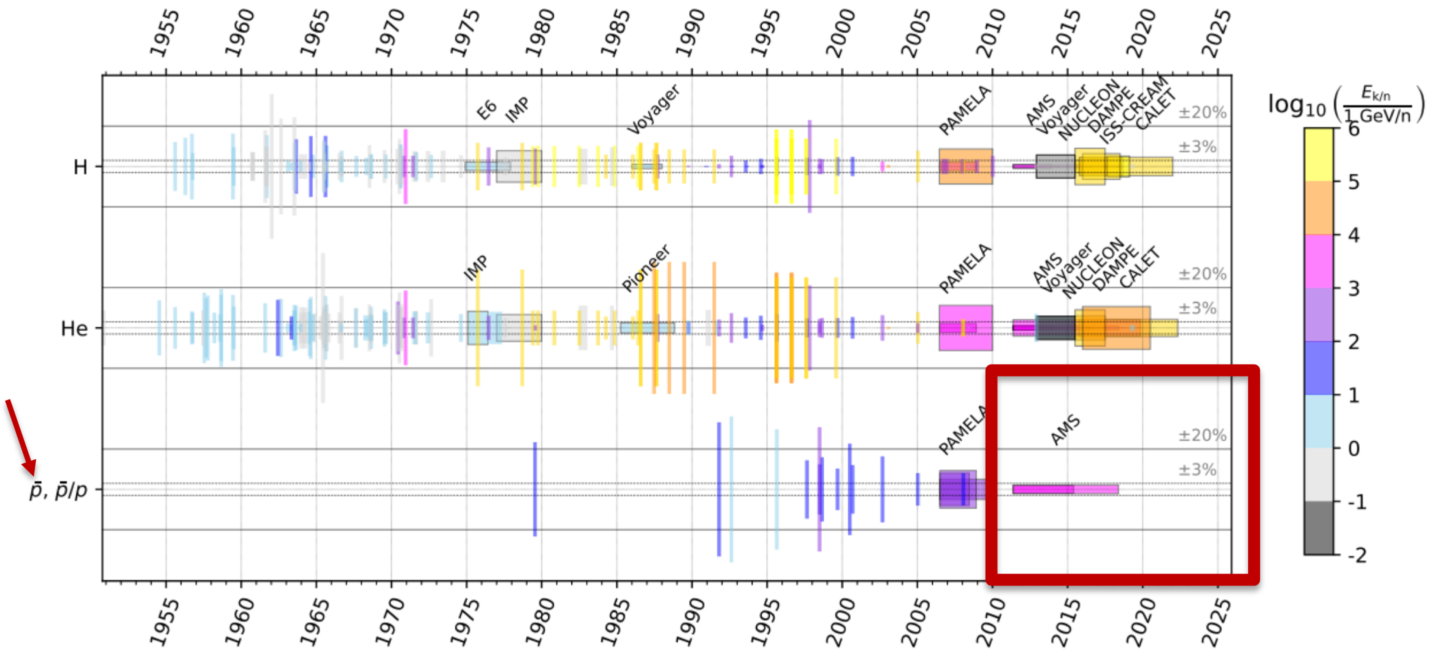
Precision era for CRs physics

[id89:Precision XS for advancing CRs physics](#)
[id106:NuPECC](#) [id235:PBC](#)

- Searching for signatures of indirect DM detection with antimatter in galactic CRs (E~ GeV– 10^3 TeV)
- Precision era with CRs experiments (uncert. below 10%) with data on several CR species



D. Maurin, F. Donato et al. arXiv: 2503.16173



D. Maurin, F. Donato et al. arXiv: 2503.16173

No observation of heavier antinuclei ($\bar{d}$, $^3\overline{He}$) confirmed so far

Preliminary AMS 02 results in AMS Coll. PoS EPS-HEP2019 (2020) 028

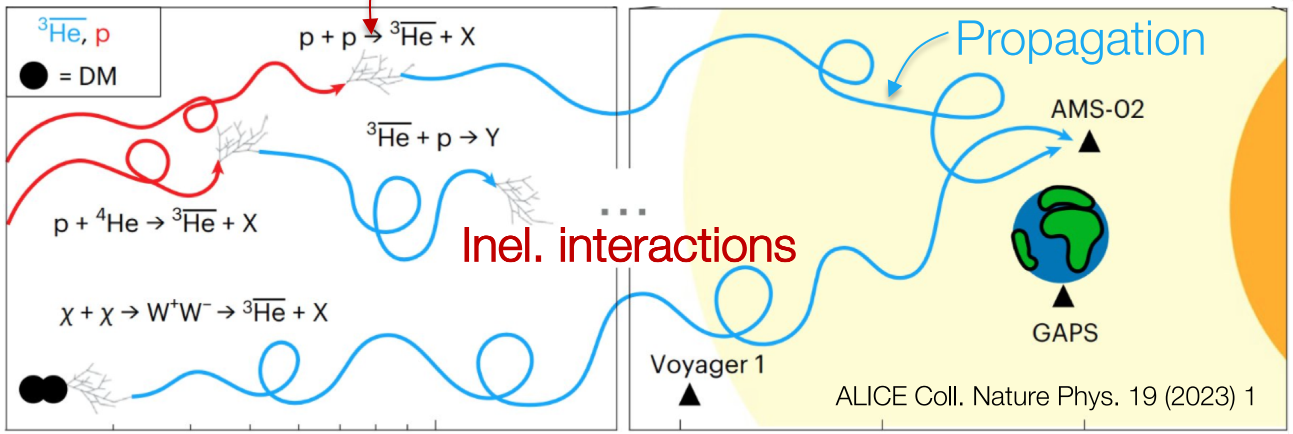
Cosmic rays and DM indirect searches: where are we?

[id89:Precision XS for advancing CRs physics]

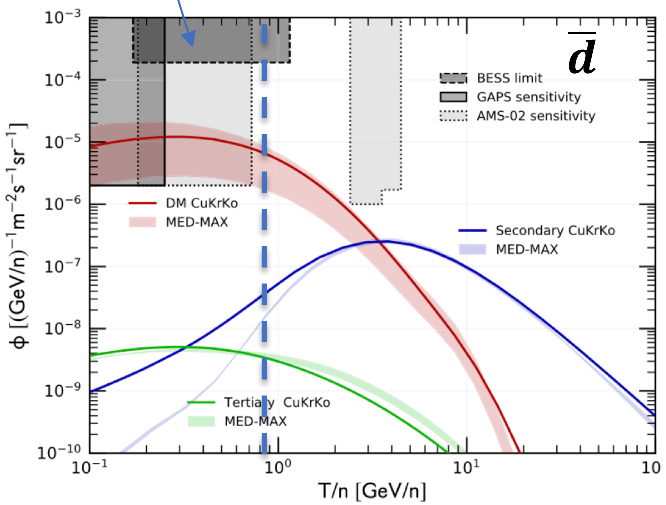
Antinuclei in GCRs

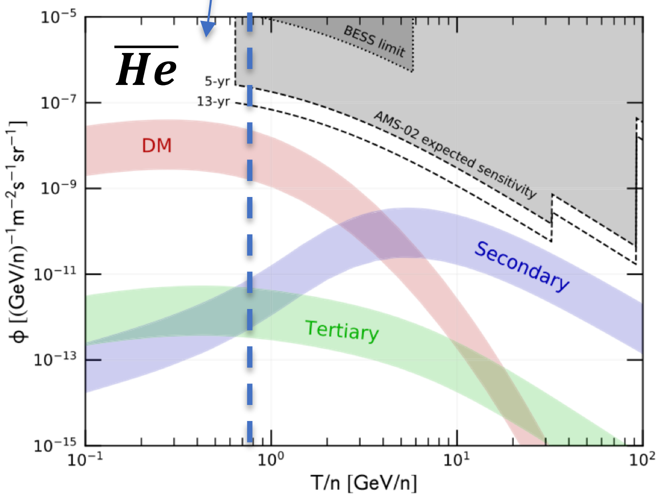
- Antinuclei mainly of secondary origin from primary CRs impinging on InterStellar Medium
  - E_{kin} < GeV: production via GCR-ISM suppressed by at least one order of magnitude wrt to DM models

Production → studied at accel. facilities



Antinuclei ($\overline{d}$,$^3\overline{He}$) fluxes as golden channel for DM annihilation/decay but…





M. Korsmeier, F. Donato, N. Fornengo PRD 97 (2018),10

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id89:Precision XS for advancing CRs physics

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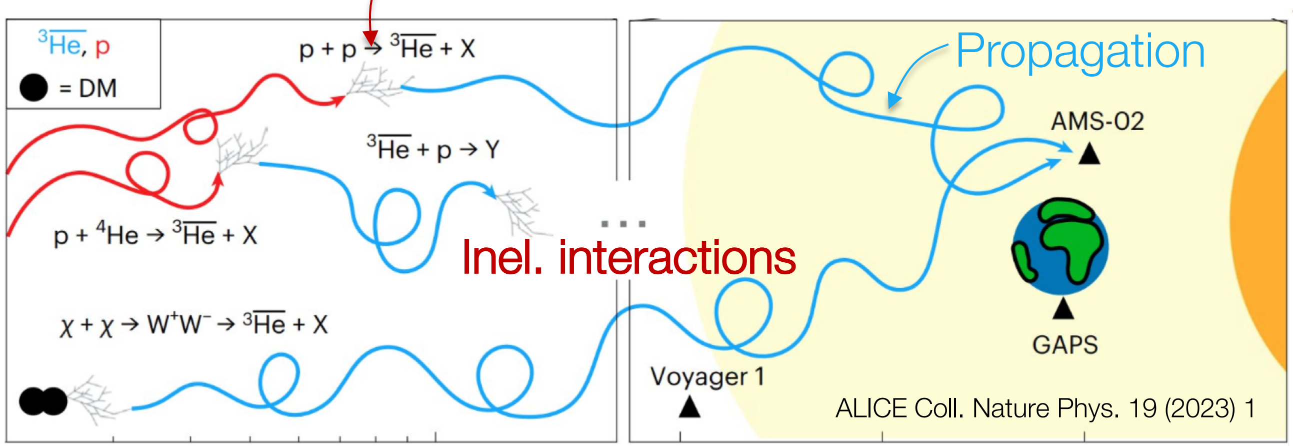
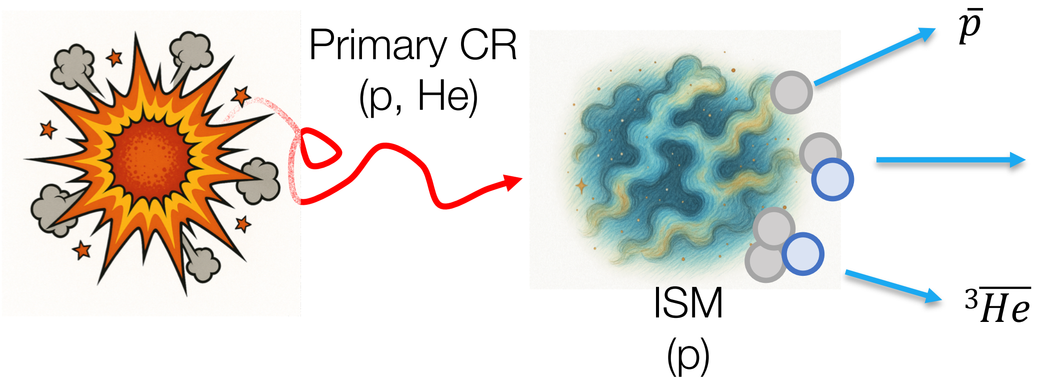




Antinuclei ($\bar{d}$, $^3\overline{He}$) fluxes as golden channel for DM annihilation/decay but…

…secondary production must be fully under control!!

1. High-precision input on production mechanism
2. Data on ($\bar{d}$, $^3\overline{He}$) production cross-sections

Parallel 3:
A. Heijboer
Mon. 14:35

valentina.mantovani-sarti@tum.de

Coalescence modeling of antinuclei

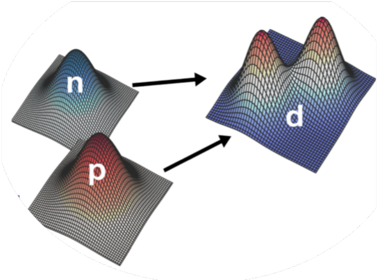
Physics benchmarks and future experimental opportunities

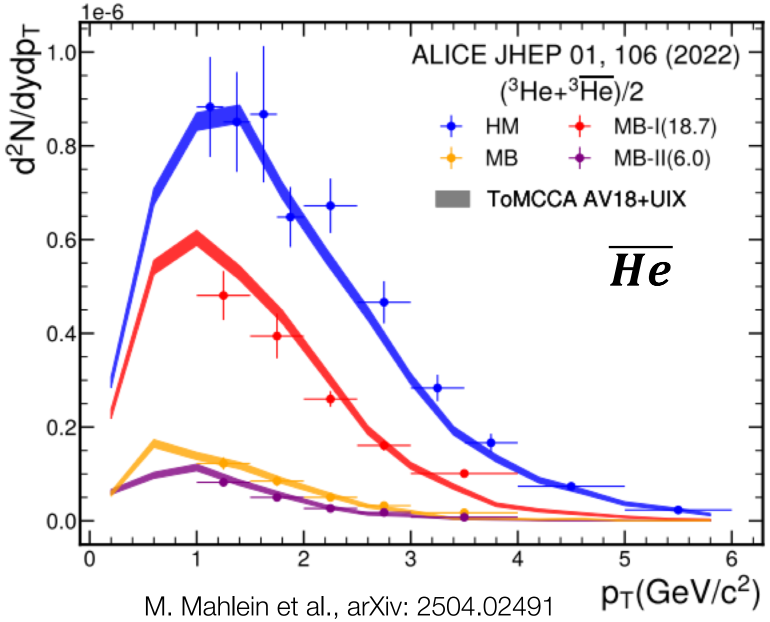
id89:Precision XS for advancing CRs physics
id106:NuPECC id235:PBC

Largest source of uncertainty for secondary antinuclei estimate!!

- Underlying coalescence mechanism leading to the formation of $\bar{d}$ and $^3\overline{He}$
- Recent developments on advanced coalescence modeling at LHC energies
  - based on Wigner formalism and measured femtoscopic radii as input

d: M. Mahlein et al., Eur.Phys.J.C 83 (2023) 9, 804,
M. Mahlein et al., Eur.Phys.J.C 84 (2024) 11, 1136





M. Mahlein et al., arXiv: 2504.02491

Measurement	Experiment	Features	Timeline
$d(\bar{d}), He\ (\overline{He})$ yields/spectra	NA61/Shine id171:NA61/SHINE	Operating at cosmic $\bar{d}$ prod. peak energy (p+p 300 GeV/c)	From 2025 ($\bar{d}$) < 2033
Source size studies via femtoscopy	ALICE 3 id68:ALICE	Unique pointing resolution (few μm) and large acceptance Access to A ≥ 5	> 2035

Cosmic rays and DM indirect searches: production cross-sections

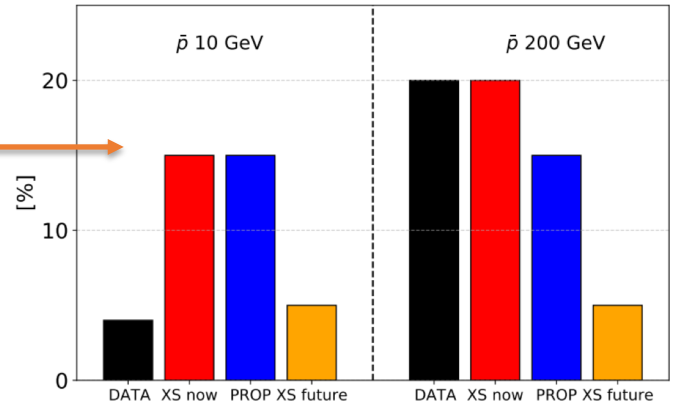
id89:Precision XS for advancing CRs physics

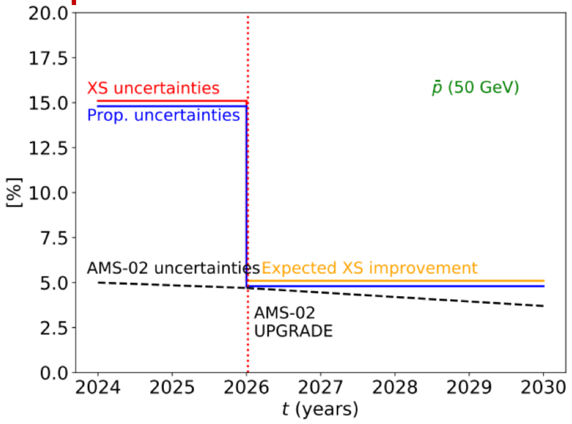
Physics benchmarks and future experimental opportunities

D. Maurin, F. Donato et al. arXiv: 2503.16173

Particle	Reaction	Measurement	$\sqrt{s}$	Sought precision
$\bar{\mathrm{p}}$	$\mathrm{p}+\mathrm{p}\to\bar{\mathrm{p}}+\mathrm{X}$	σ_{inv}	5 to 100 GeV	$<3\%$
	$\mathrm{p}+\mathrm{He}\to\bar{\mathrm{p}}+\mathrm{X}$			$<5\%$
	$\mathrm{p}+\mathrm{p}\to\bar{\Lambda}+\mathrm{X}$			$<10\%$
	$\mathrm{p}+\mathrm{He}\to\bar{\Lambda}+\mathrm{X}$			$<10\%$
	$\mathrm{p}+\mathrm{p}\to\bar{\mathrm{n}}+\mathrm{X}$			$<5\%$
	$\mathrm{p}+\mathrm{n}\to\bar{\mathrm{p}}+\mathrm{X}$			$<5\%$
$\bar{\mathrm{d}}$	$\mathrm{p}+\mathrm{p}\to\bar{\mathrm{d}}+\mathrm{X}$	$\sigma_{\mathrm{inv}}/n_{\mathrm{tot}}$	5 to 100 GeV	(any data)
	$\mathrm{p}+\mathrm{He}\to\bar{\mathrm{d}}+\mathrm{X}$	$\sigma_{\mathrm{inv}}/n_{\mathrm{tot}}$	5 to 100 GeV	(any data)
	$\bar{\mathrm{p}}+\mathrm{p}\to\bar{\mathrm{d}}+\mathrm{X}$	σ_{inv}	2 to 10 GeV	(any data)
$\overline{\mathrm{He}}$	$\mathrm{p}+\mathrm{p}\to\overline{\mathrm{He}}+\mathrm{X}$	$\sigma_{\mathrm{inv}}/n_{\mathrm{tot}}$	5 to 100 GeV	(any data)

$\bar{\mathrm{p}}$ scenario halted by XS precision!!





Input needed for antinuclei!!

Measurement	Experiment	Features	Timeline
Prod. XS for $\bar{d}$, $\overline{He}$	LHCb (fixed targ.) id82:LHCb	Coverage of GCR-ISM energies ($\sqrt{s_{NN}}\in[27{,}113]$ GeV) Already experience on pHe, pH_2, pD_2 with SMOG2	Run 3, until 2026
	AMBER	Access to lower energies wrt to LHCb ($\sqrt{s_{NN}}<21.7$ GeV) Possibility to study energy-dependence	2023-2031
	NA61/Shine	Access to low energies (def.:$\sqrt{s_{NN}}\in[5{,}17]$ GeV)	< 2033

Possibility to also measure nuclear-fragmentation XS for reducing propagation uncertainties (currently at 20-30% wrt ~5% from GCR data)

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Primary (Anti)He from beauty baryons and DM annihilation

[id89:Precision XS for advancing CRs physics](#)

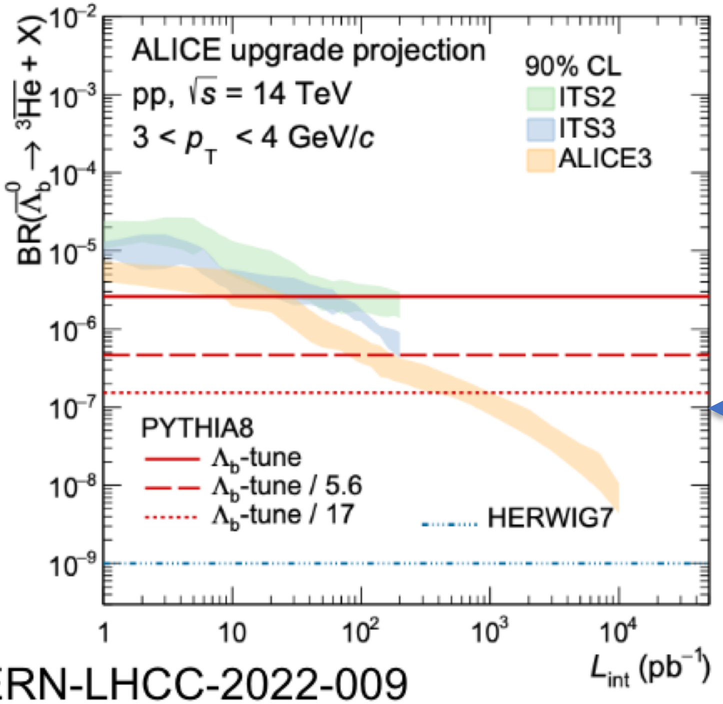
Physics benchmarks and future experimental opportunities

$$\chi + \chi \rightarrow \boxed{\overline{\Lambda}_b + X \rightarrow {}^3\overline{He} + X}$$

Preliminary results from LHCb on BR recently available

CERN-LHCb-CONF-2024-005

[id68:ALICE](#)

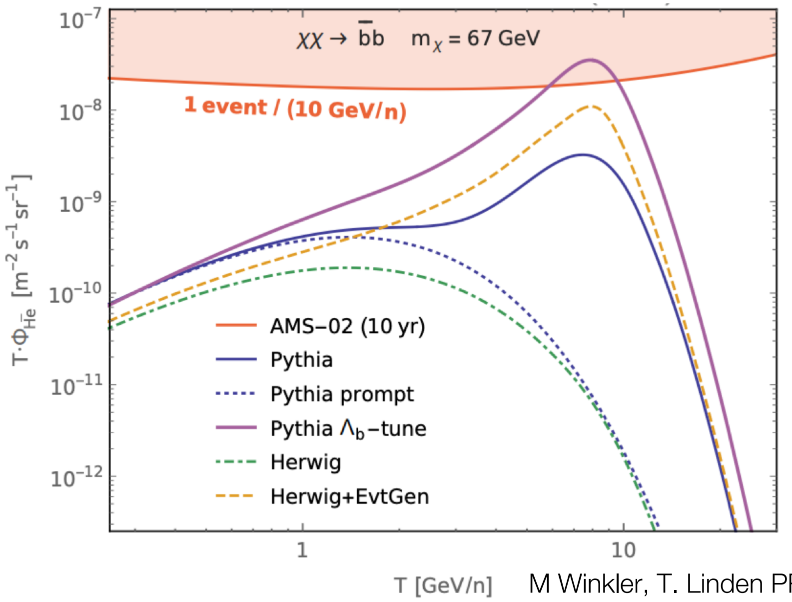


CERN-LHCC-2022-009

Dark Matter Annihilation Can Produce a Detectable Antihelium Flux through $\bar{\Lambda}_b$ Decays

Martin Wolfgang Winkler[1,*] and Tim Linden[1,†]

[1]Stockholm University and The Oskar Klein Centre for Cosmoparticle Physics, Alba Nova, 10691 Stockholm, Sweden



M Winkler, T. Linden PRL 126 (2021)

Possibility to further investigate this channel with ALICE 3

[id68:ALICE](#)

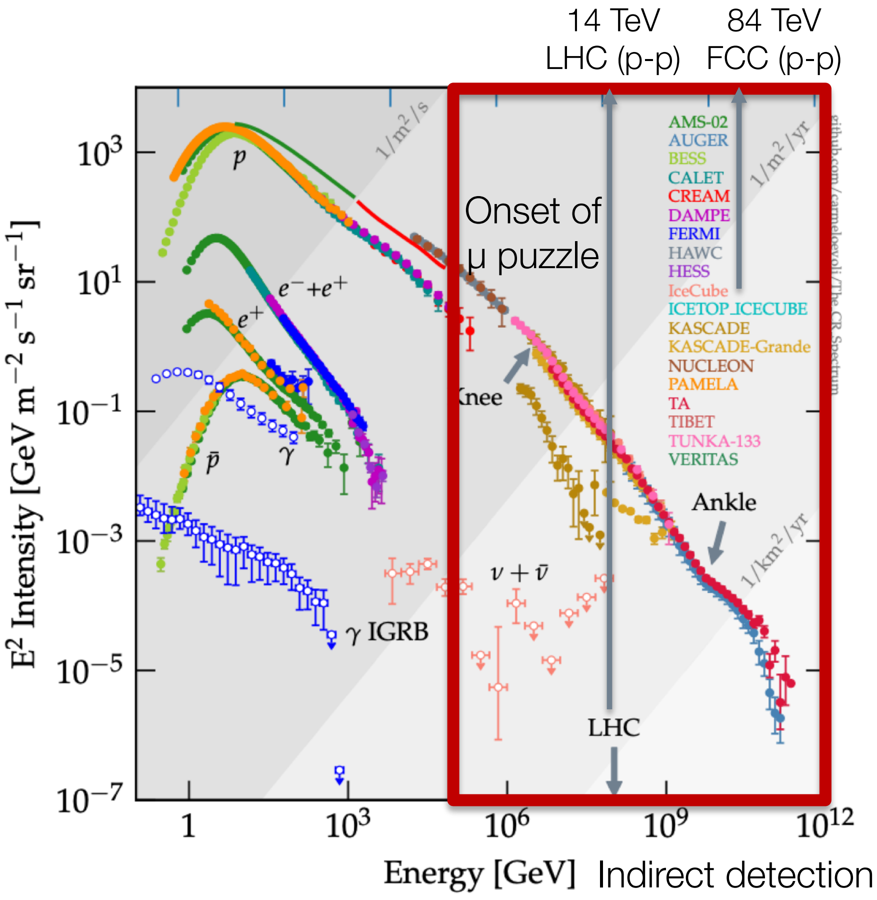
Cosmic rays composition and μ puzzle: where should we go?

Physics benchmarks and future experimental opportunities

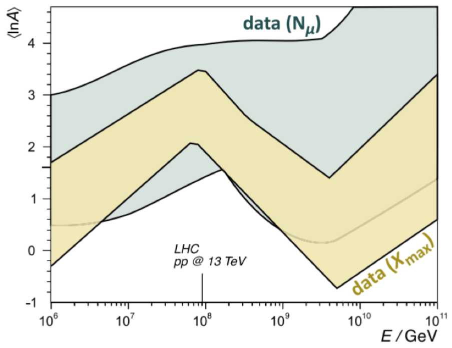
[id201:AUGER Coll.](#) [id224:pALHC](#)
[id89:Precision XS for advancing CRs physics](#)

- Still tension in reproducing the composition of Ultra-High Energy CRs
  - Muon puzzle in EAS but also change from p-dominated composition to heavier species

J. Albrecht et al. Astrophys.Space Sci. 367 (2022) 3, 27
Pierre Auger Coll. Phys.Rev.D 91 (2015) 3, 032003



J. Albrecht et al. Astrophys.Space Sci. 367 (2022) 3, 27



Improved constraints on hadronic interaction description in event generators are needed

Measurement	Experiment	Features	Timeline
Hadron production in pp, pA, AA coll.	pA@HL-LHC pA@FCC-hh id209:FCC	Broad physics reach, Ideal energy region	> 2035 (HL-LHC) > 2047 (FCC)
Hadron production in forward region	FPF id19:FPF	Ideal for test of enhanced forward strang. production	> 2031 (FPF)

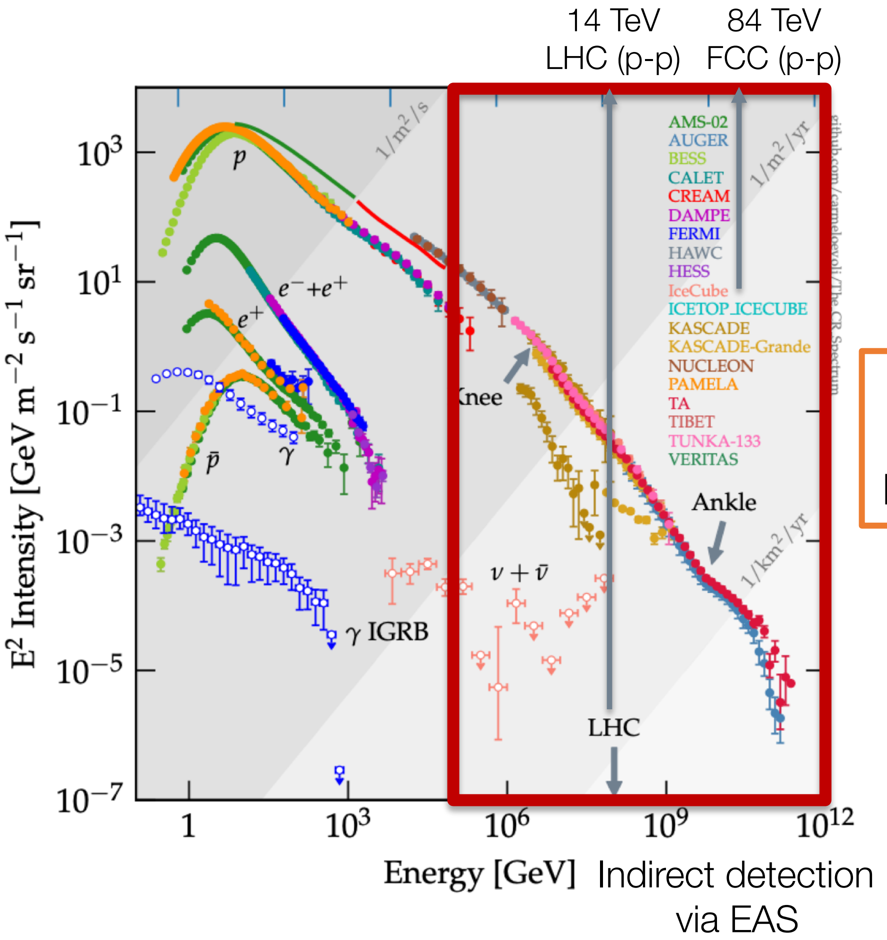
Parallel 3:
A. Heijboer
Mon. 14:35

QCD connection to neutrino and multi-messenger astronomy

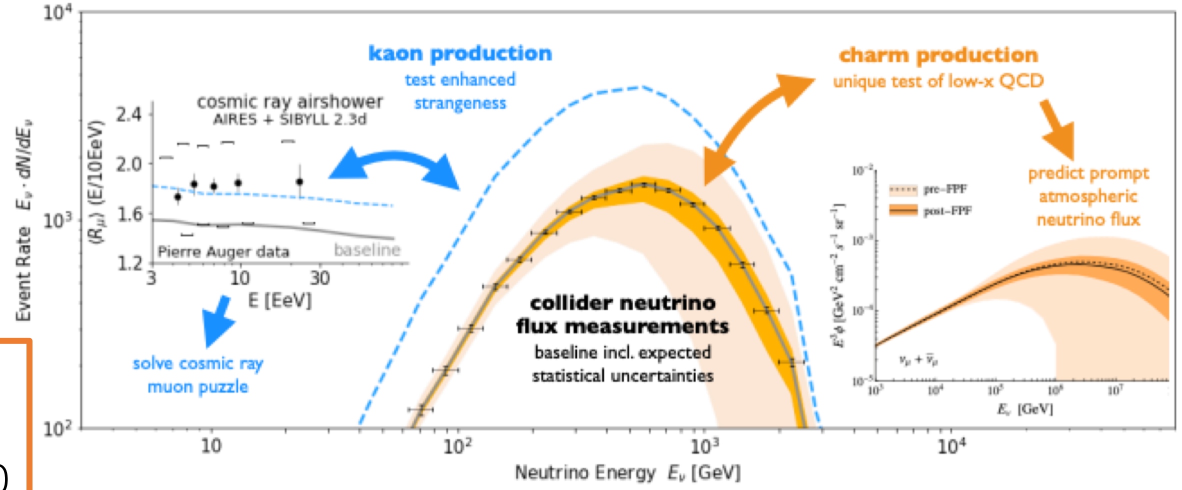
Constraining νN (ν-nucleus) cross-sections and ν from charm

[id201:AUGER Coll.](#) [id224:pALHC](#)
[id89:Precision XS for advancing CRs physics](#)

- **Knowledge of νN cross-section** is one of the main limitations in **understanding high-energy ν production** → Depends on precise knowledge of PDF at small x (~10^{-3} for IceCube <E>~1-30 TeV)



Possibilities at FPF



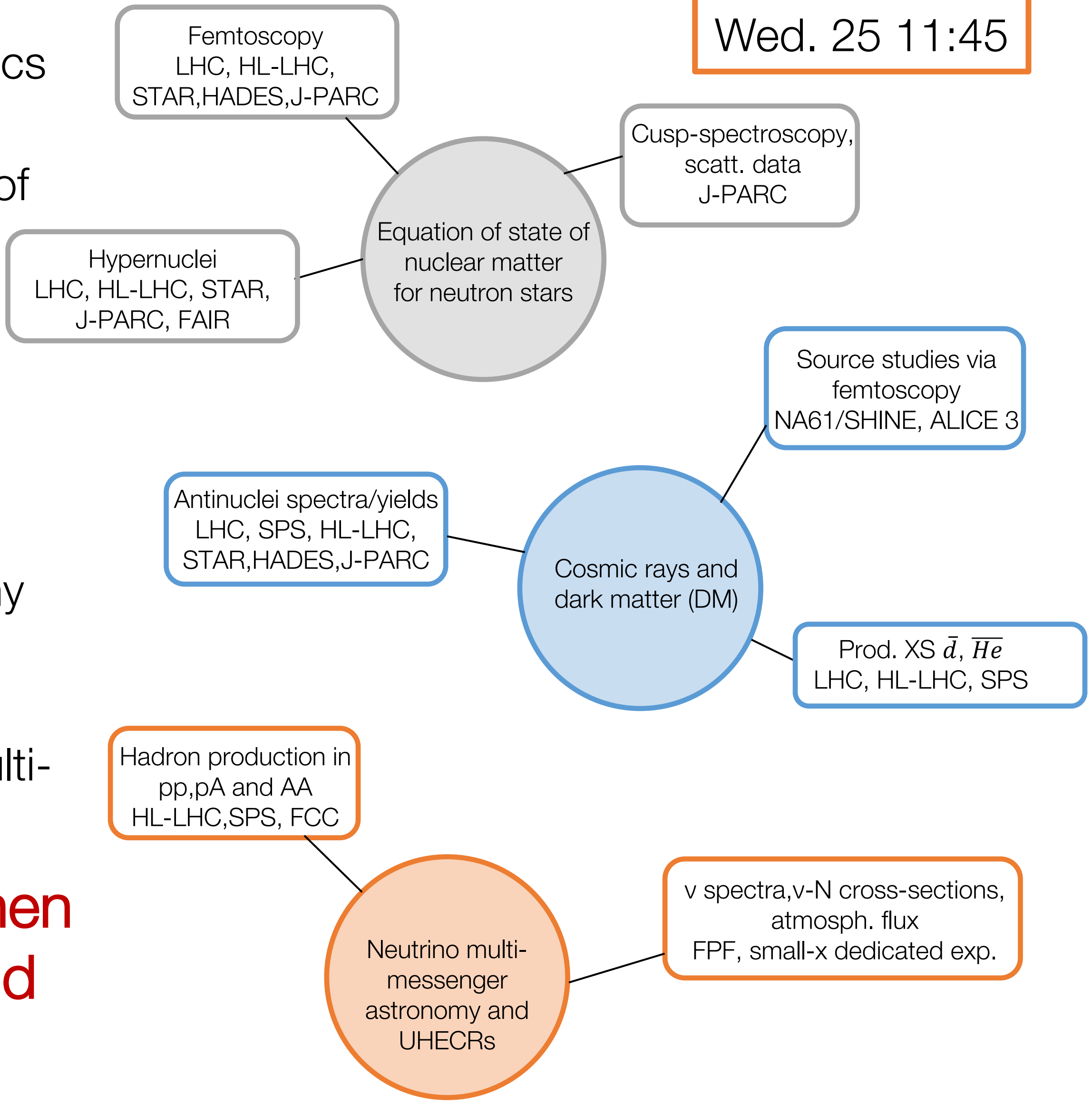
Parallel 3:
I. Esteban
Mon. 12:00

Measurement	Experiment	Features	Timeline
ν energy spectra and ν-N cross-sections	FASER, then FPF (FASERν, FLArE) [id23:FASER](#) [id19:FPF](#)	Increase in statistics of x 100, bridging Ice Cube energies	> 2031 (FPF)
Atmospheric ν background fluxes	FPF, NA61/SHINE-LE	High-statistics, low energy p,mesons (beam mom < 2 GeV/c) on nucl. targets	> 2031 (FPF). Run 4

Take-home messages and synergies

Plenary talk:
A. Dainese
Wed. 25 11:45

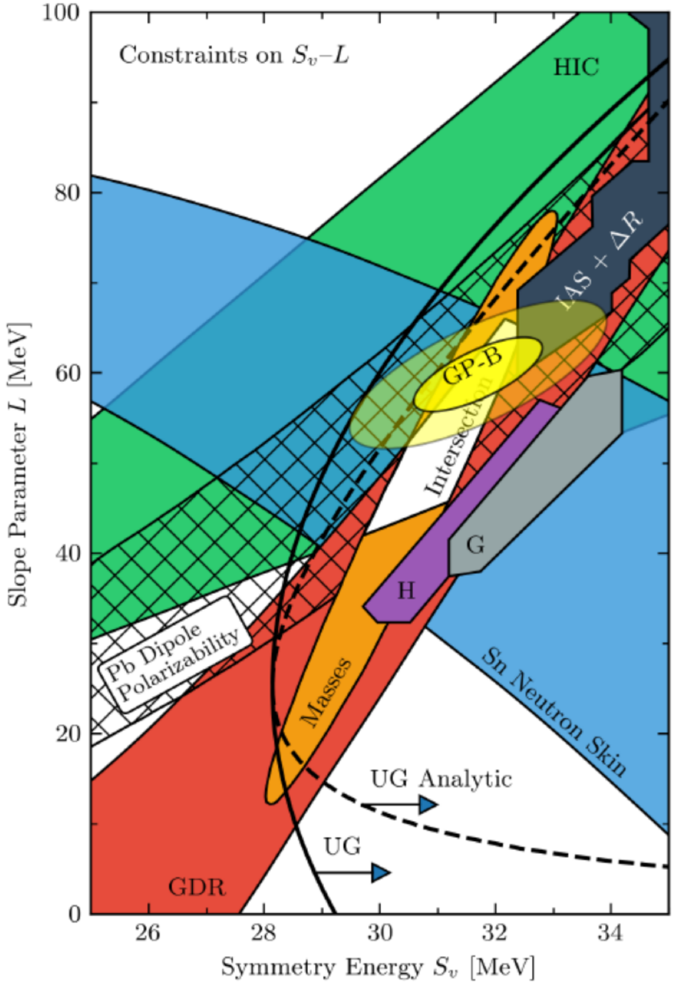
- QCD in action at different facilities and experimental techniques to improve many open question in astrophysics
  - Understanding of EoS, DM in CRs and production of high-energy ν requires a full complementarity & synergy amongst high-energy and low-energy facilities
  - HL-LHC perfect set to address all of the open questions presented
  - Crucial role from nuclear facilities as HIE-ISOLDE and similar, with a broad reach to many astrophysics areas
  - Important role of FPF and FCC-hh for a full understanding of UHECRs and high-energy ν in multi-messenger astronomy



Recommendation to continue and strengthen the cooperation between astrophysics and particle/hadronic/nuclear community

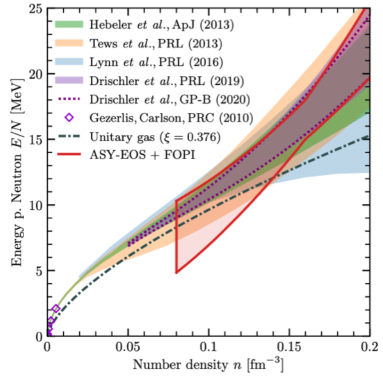
Additional slides

EoS nucleons-only

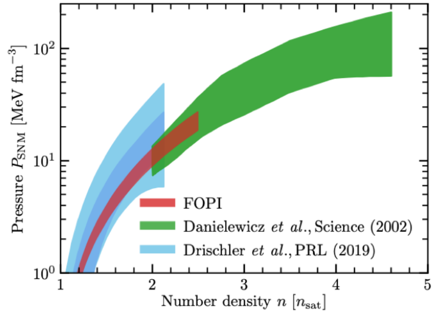


A. Sorensen et al. Prog.Part.Nucl.Phys. 134 (2024) 104080

S. Huth et al. Nature 606 (2022) 276-280



Extended Data Figure 4 | Constraints for pure neutron matter. Energy per particle E/N of neutron matter as a function of density n for various many-body calculations using chiral EFT interactions from Hebeler *et al.*[12], Tews *et al.*[13], Lynn *et al.* (used here)[14], Drischler *et al.* PRL[15] and GP-B[16], and low-density quantum Monte Carlo results from Gezerlis and Carlson[89]. Overall, the results from these calculations are in good agreement with each other. We also show the energy per particle of a unitary Fermi gas of neutrons, which has been proposed as a lower bound for the energy of neutron matter[90]. Finally, we compare the theoretical results with the constraint from the ASY-EOS and FOPI experiments (red), which is used as a constraint for neutron matter in the main work.



Extended Data Figure 5 | Comparison of the pressure of symmetric nuclear matter for experiment and theory. The pressure band from the FOPI experiment[10] at the 1σ level (red) for the incompressibility is consistent with the chiral EFT constraint from Drischler *et al.*[15,59] at N^{2}LO (light blue) and N^{3}LO (dark blue). The experimental uncertainty band is smaller than the theoretical one because the empirical saturation point used for extracting the experimental results has smaller uncertainties compared to theoretical estimates from chiral EFT. Between 2-3n_{sat}, we additionally constrain the FOPI results with the constraint from Danielewicz *et al.*[27] (green), which has no statistical interpretation. This excludes the highest values for the incompressibility K from the FOPI distribution and also influences symmetric matter at smaller densities, which depends on the range of K. However, both constraints are in very good agreement with each other and the impact of the additional Danielewicz *et al.* constraint is small in our analysis.

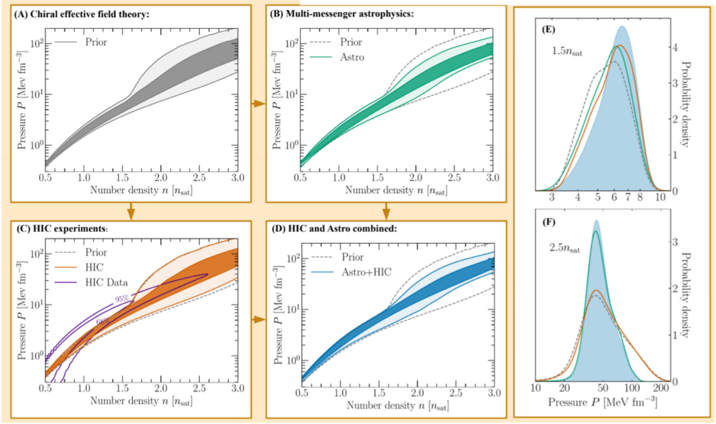


Figure 1 | Constraints on the EOS of neutron-star matter. A-D, Evolution of the pressure as a function of baryon number density for the EOS prior (A, grey), when including only data from multi-messenger neutron-star observations (B, green), when including only HIC data (C, orange), and when combining both (D, blue). The shading corresponds to the 95% and 68% credible intervals (lightest to darkest). The impact of the HIC experimental constraint (HIC Data, purple lines at 95% and 68%) on the EOS is shown in panel C. In B-D, the 95% prior bound is shown for comparison (grey dashed lines). E,F Posterior distributions for the pressure at $1.5n_{sat}$ (E) and $2.5n_{sat}$ (F) at different stages of our analysis (E, F), with the combined Astro+HIC region shaded in light-blue.

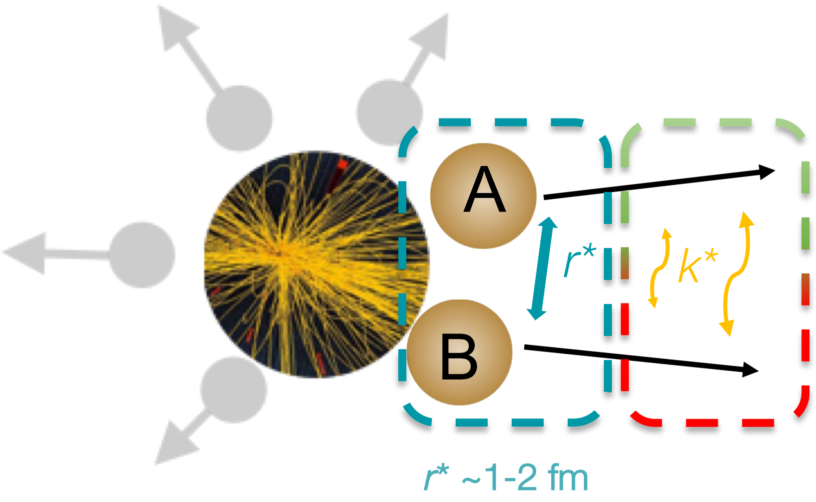
Accessing hadronic interactions with correlations at LHC

Koonin-Pratt equation

S. E. Koonin, Phys. Lett. B 70, 43 (1977)

$$\boldsymbol{C(k^*)} = \mathcal{N}(k^*)\frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)} = \int S(\vec{r}^*)\left|\psi(\vec{k}^*,\vec{r}^*)\right|^2 d^3\vec{r}^*$$

M.Lisa, S. Pratt et al, ARNPS. 55 (2005), 357-402
L. Fabbietti, VMS and O. Vazquez Doce ARNPS 71 (2021), 377-402

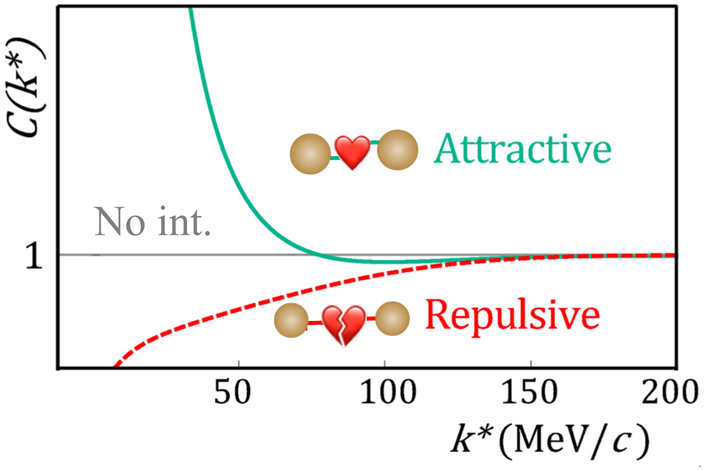


Emitting source

- Average relative r^*_{AB} distances at which particles are produced
- How much $\left|\psi(\vec{k}^*,\vec{r}^*)\right|^2$ do we sample?
- It depends on the collision system

Interaction

ALICE Coll. Nature 588 (2020) 232-238



What ranges of inter-particle distances can we probe at LHC?

DM searches in GCRs

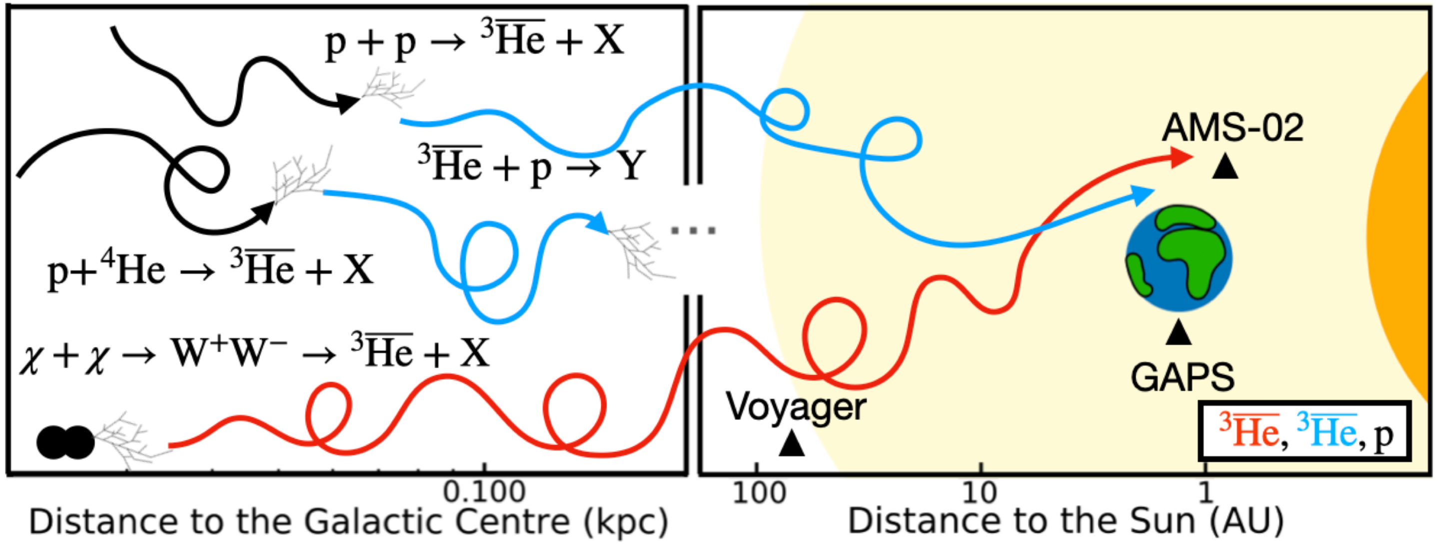
Transport equation

$$\frac{\partial\psi}{\partial t} = \boxed{q(\mathbf{r},p)} + \boxed{\mathbf{div}(D_{xx}\mathbf{grad}\psi - \mathbf{V}\psi) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{\psi}{p^2} - \frac{\partial}{\partial p}\left[\psi\frac{dp}{dt} - \frac{p}{3}(\mathbf{div}\cdot\mathbf{V})\psi\right]} - \boxed{\frac{\psi}{\tau_f} - \frac{\psi}{\tau_r}}$$

Source Function

Propagation: diffusion, convection…

Fragmentation, annihilation



Cusp spectroscopy and more

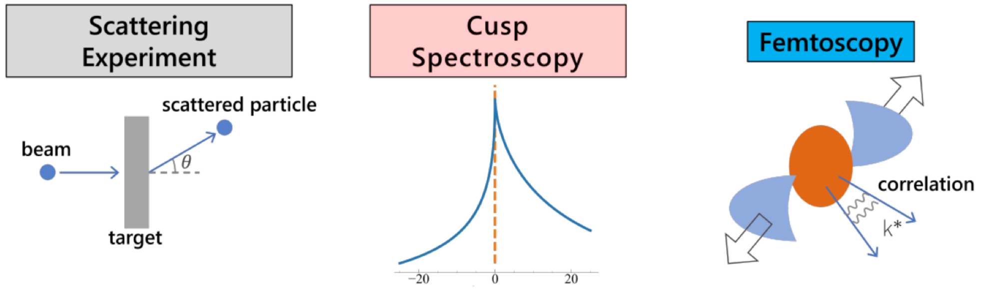


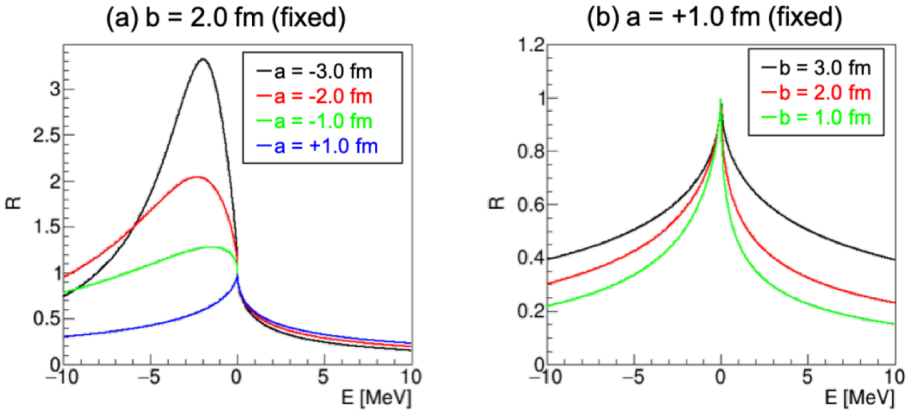
Figure 1: The schematic drawing of the experimental method to study the hadron interaction.

JPARC-E90 experiment is proposed to study ΣN cusp using the d(K⁻, π⁻)Λp reaction

$$K^- + d \rightarrow \pi^- + (\Sigma N)^+ \rightarrow \pi^- + \Lambda + p.$$

$$R_S^t \approx (k_\Sigma \sigma_S^t(\Sigma N \rightarrow \Lambda N)) = \frac{4\pi b}{(1 + k_\Sigma b)^2 + (k_\Sigma a)^2}.$$

In the J-PARC E90 experiment, we aim to measure the ΣN cusp with a 0.4 MeV resolution (σ), owing to the excellent momentum resolution of the S-2S spectrometer and high statistics of 1.0 × 104 events. The J-PARC E90 experiment aims to determine the scattering length through spectrum fitting, with an estimated statistical error of 0.3 fm. The J-PARC E90 experiment aims to perfom the data taking in 2027–2028.



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Novel upper limit from LHCb on $\overline{\Lambda}_b + X \rightarrow {}^3\overline{He} + X$