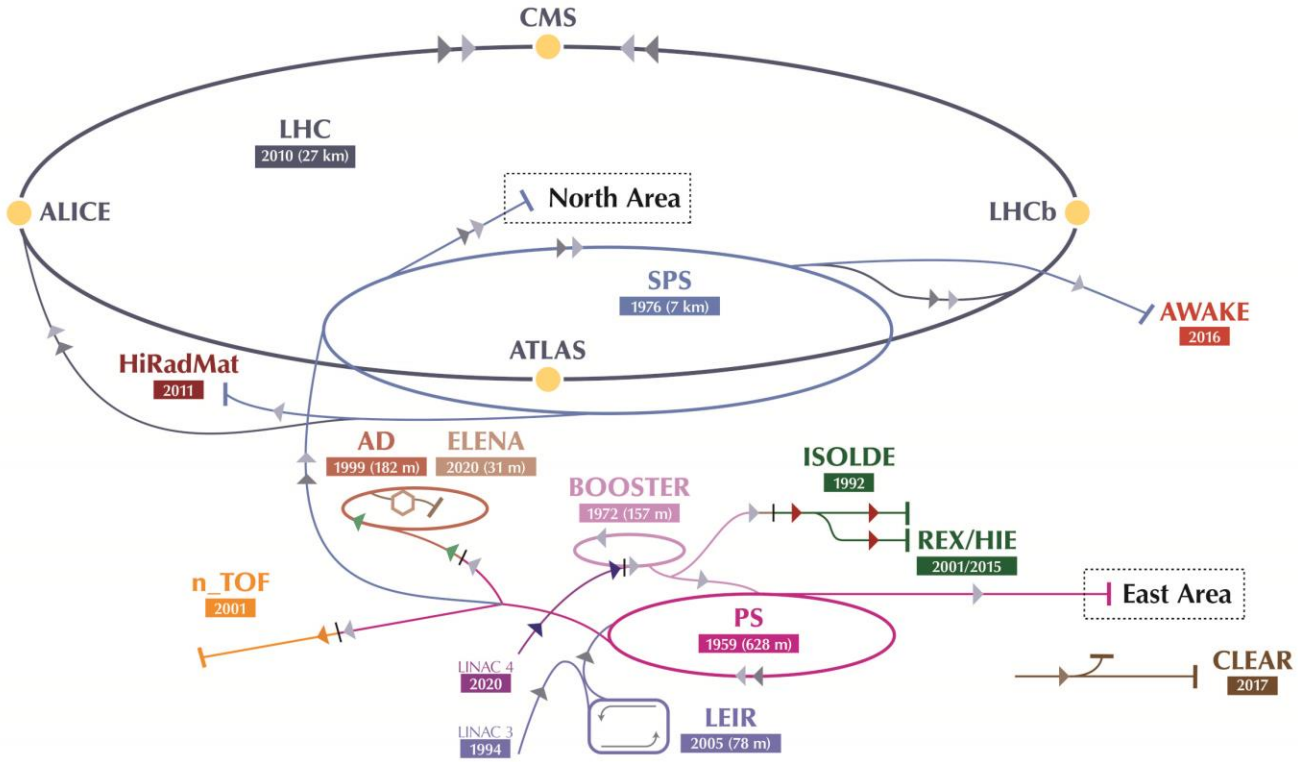
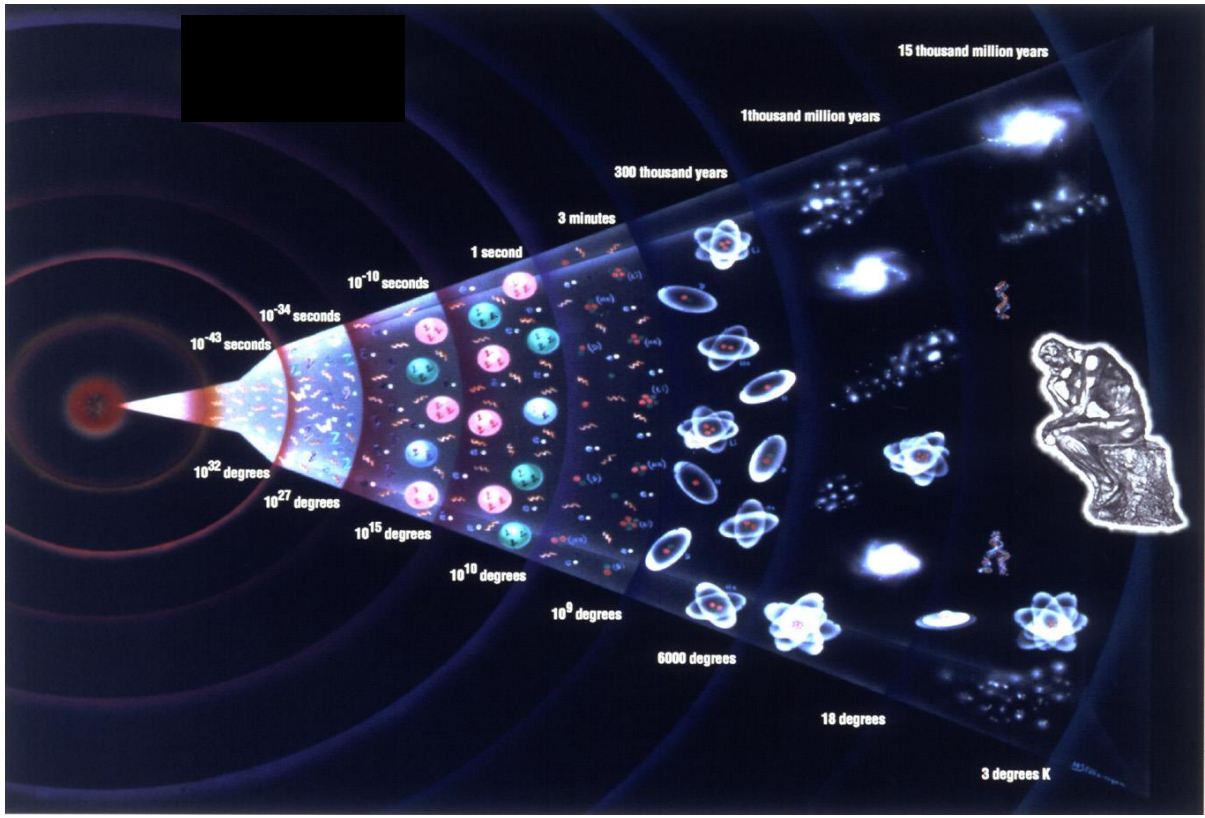
Relating lab-based and space-based science at CERN

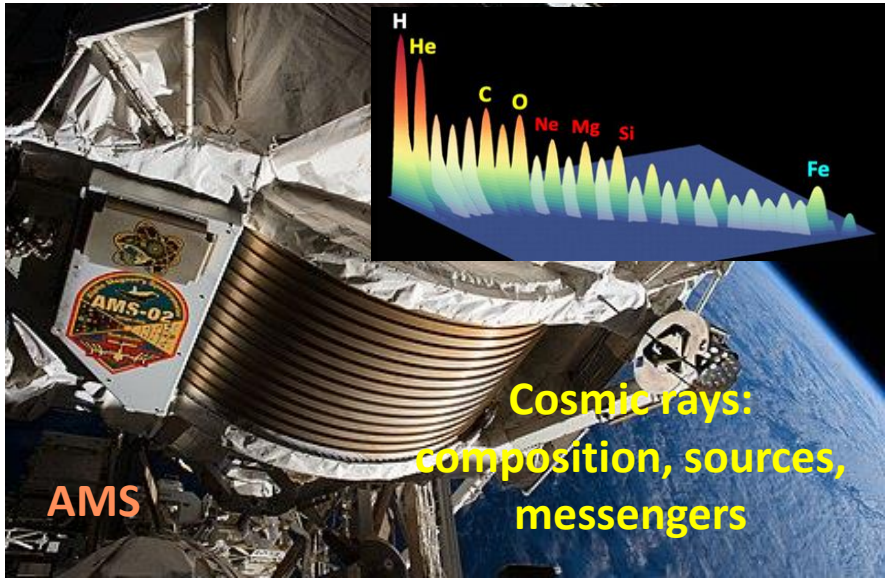


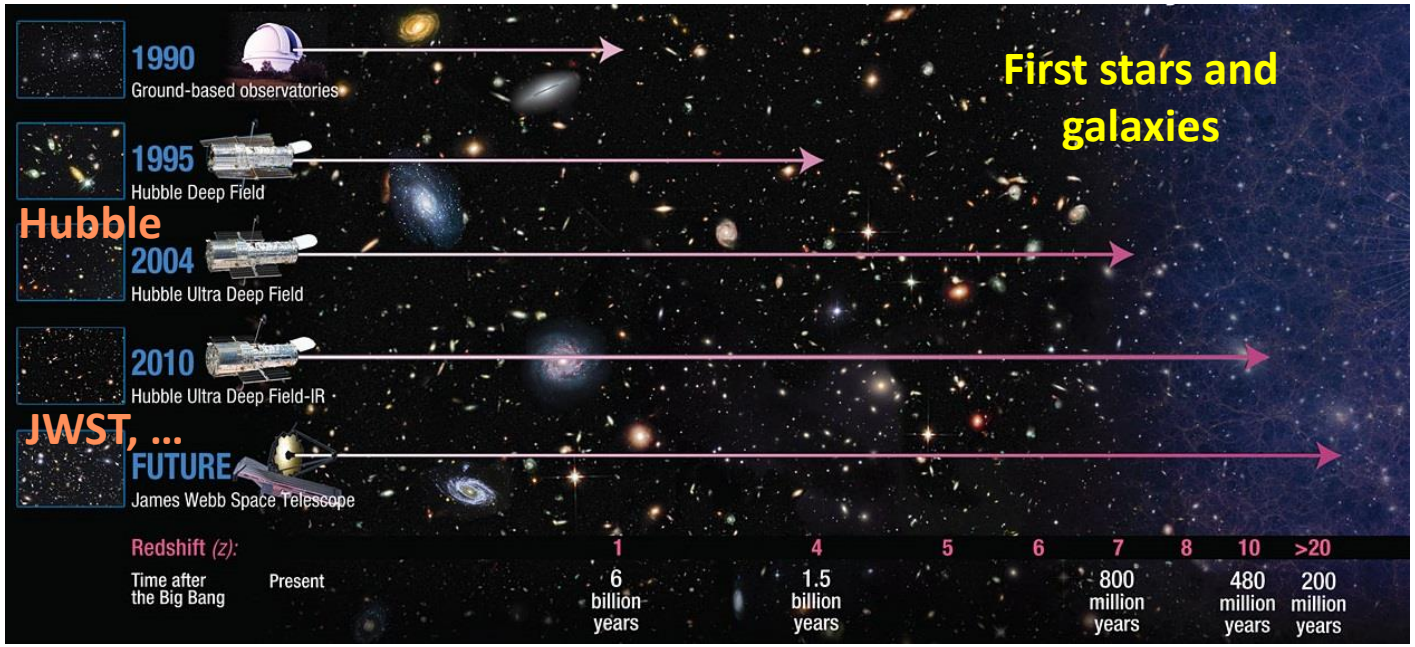


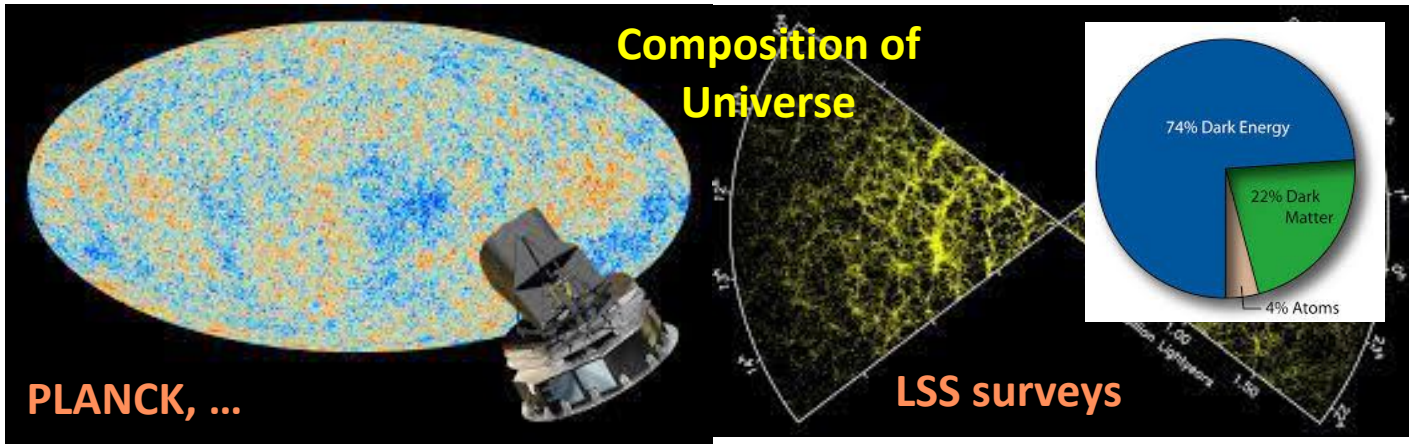
Urs Achim Wiedemann

NPA-X, CERN, 5 Sept 2022

Precision astrophysics ⇔ precision nuclear & particle physics







and more …

Георгій Антонович Гамов

George Gamow

* Одéса, 1904 -- Boulder Colorado 1968

Father of BBN

The Universe at a redshift of a billion

All four fundamental forces are at work:

- **Gravity**
  determines the expansion rate
- **Weak Interactions**
  determine n/p balance
- **Strong Interactions**
  fuse nuclei
- **Electromagnetic repulsion**
  shuts fusion off

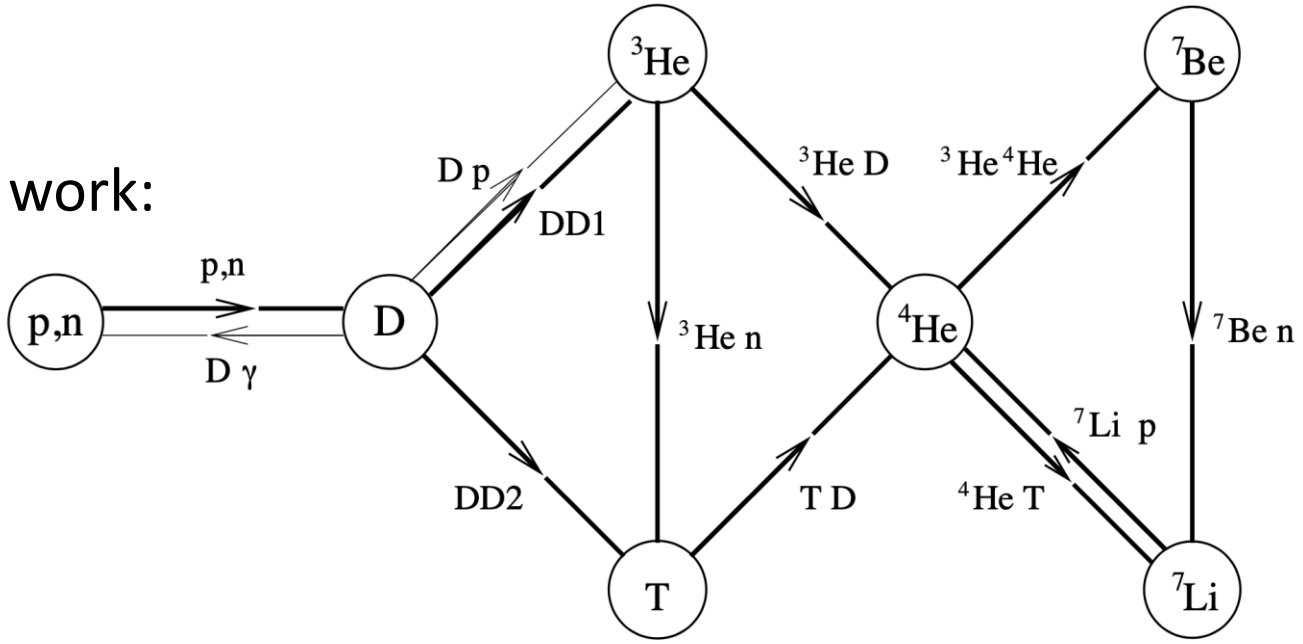
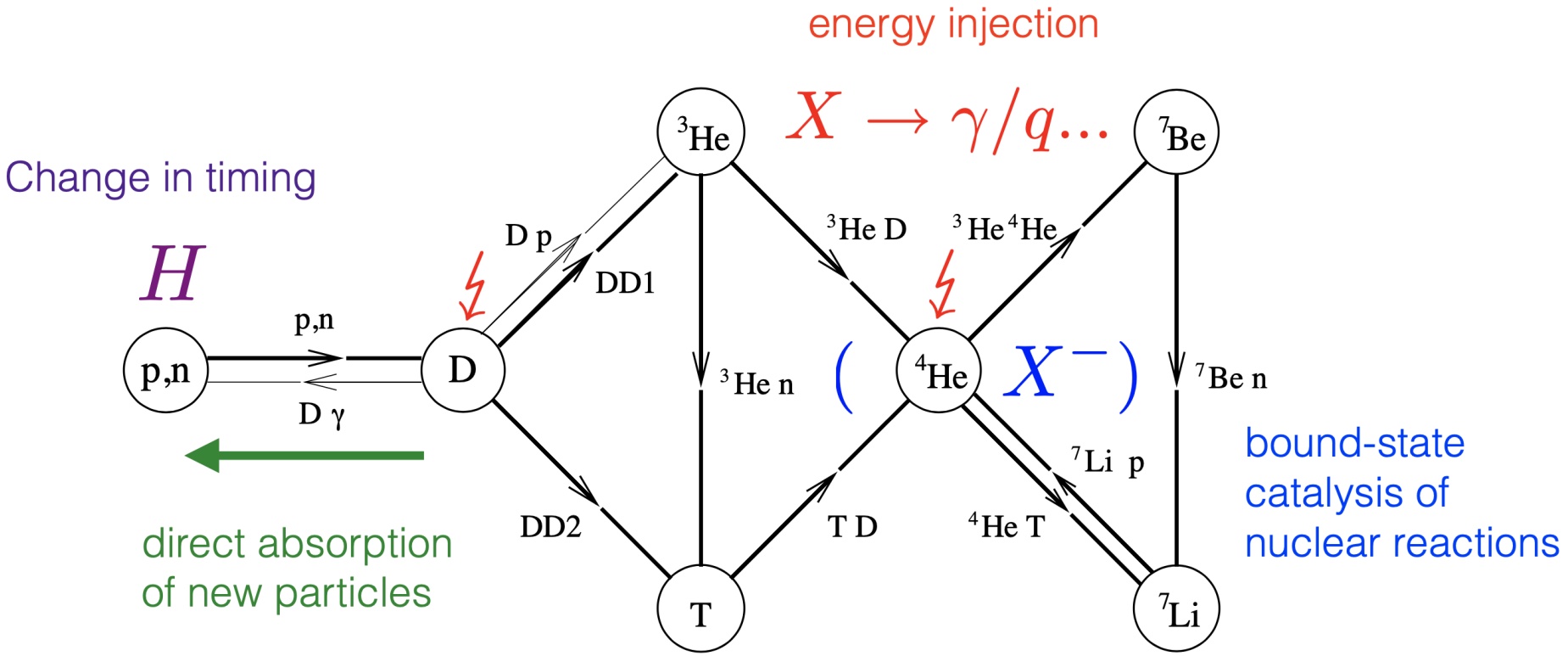


Fig. from Mukhanov "BBN without a computer"

Precision measurements of nuclear reactions + Baryon/ γ ratio from CMB

BBN = parameter free theory (in "Standard Model")

BBN highly sensitive to new physics (BSM)



Metalicity floor of old stars

- **Li- problem? (He-problem)?**
- **systematics - problem ?**

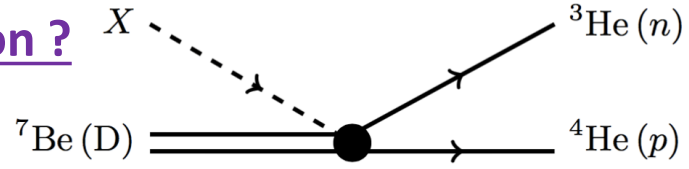
Challenge for precision nuclear physics + astrophysical modeling

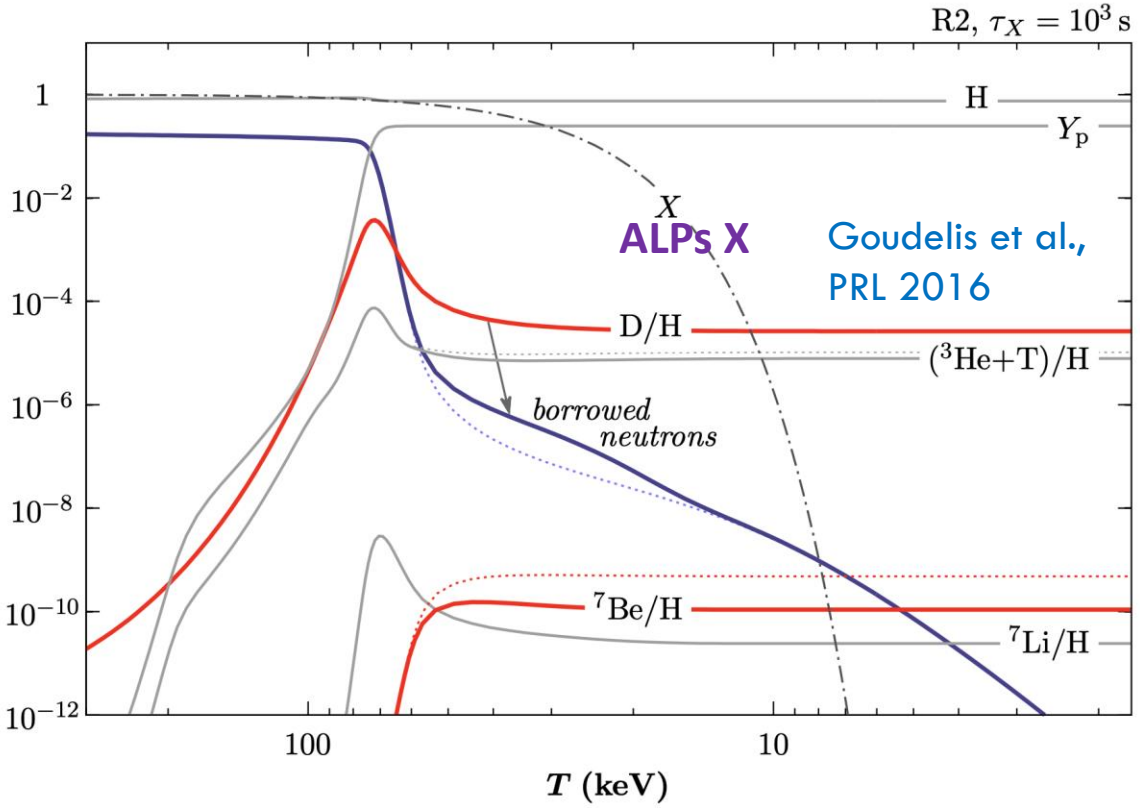
Hints for new physics ?

and if the problem is not NP (nuclear physics) but NP (new physics)...

BSM sources for additional neutrons during BBN epoch, many scenarios conceivable

- **Direct absorption ?**
- **Decay of X ?**

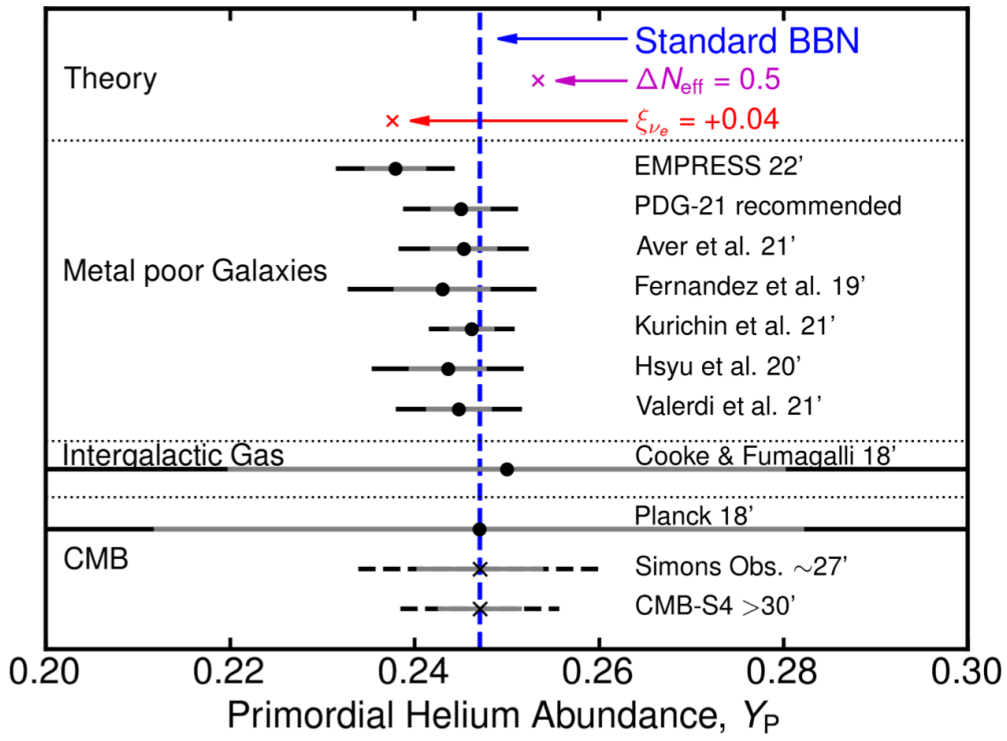




- **Leptogenesis ?**

Neutrino chemical potential

$$Y_P(\xi_{\nu_e}) \simeq Y_P|_{SBBN} \times e^{-0.96\,\xi_{\nu_e}}$$



Escudero et al., 2208.03201

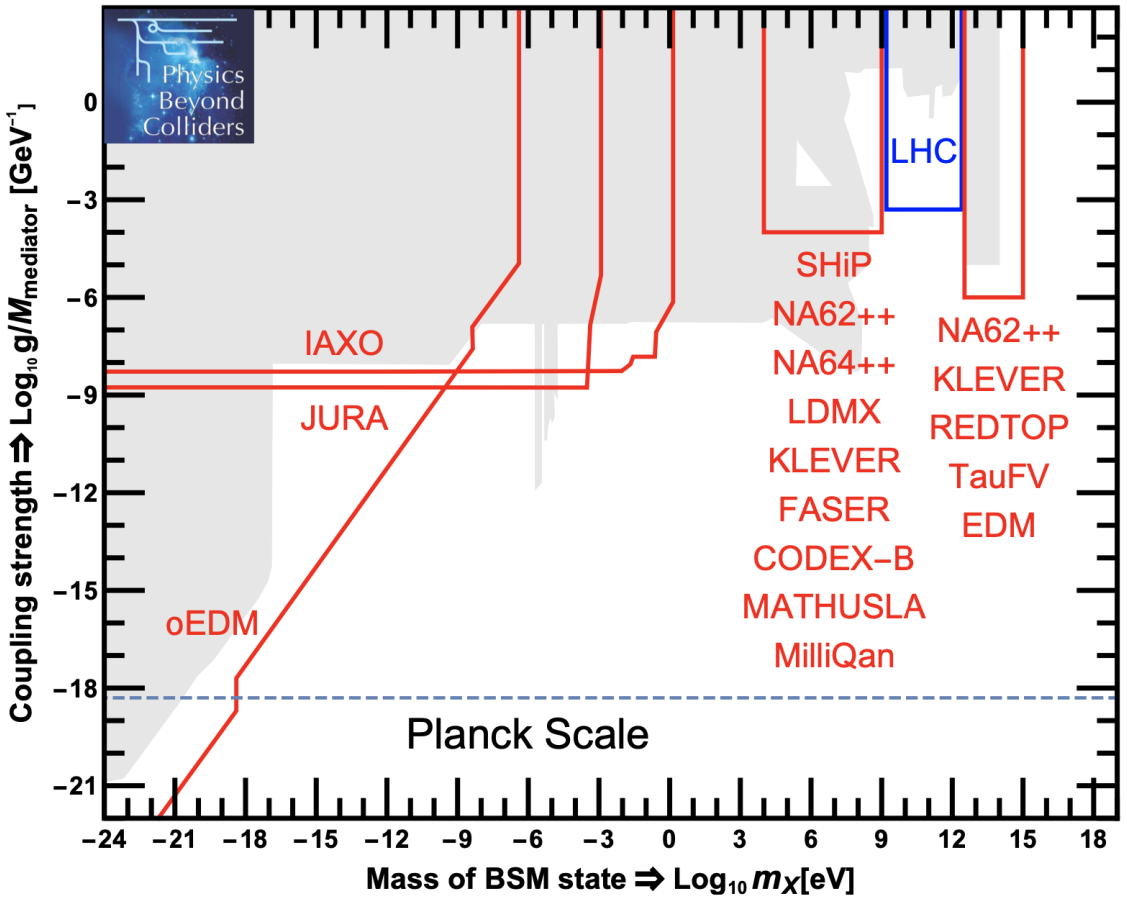
Physics beyond Colliders @ CERN

- The **portal framework** classifies BSM models for "dark sector" DS

$$\mathcal{L}_{\text{portal}} = \sum O_{\text{SM}} \times O_{\text{DS}}$$

Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Axion, a	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Sterile Neutrino, N	$y_N L H N$

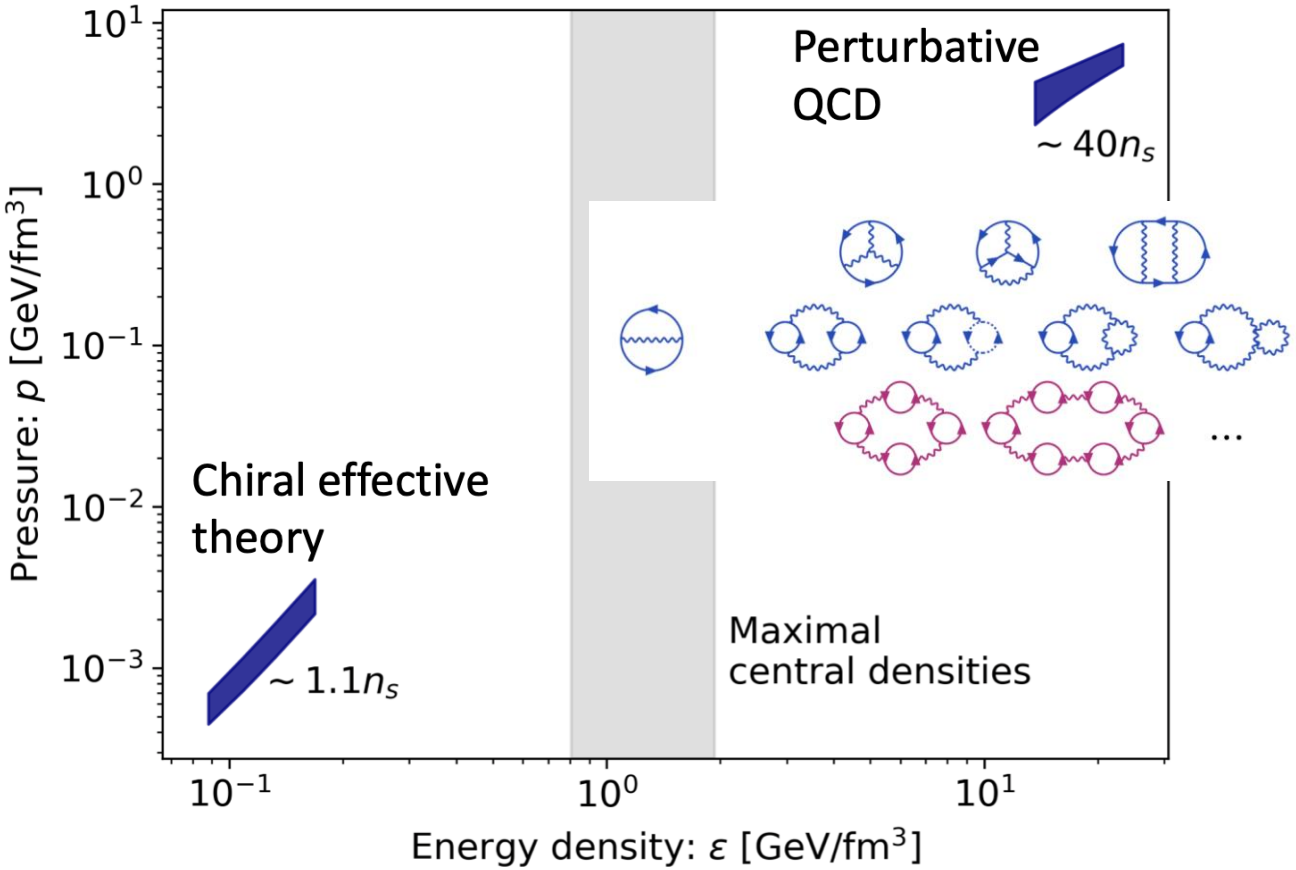
- Opportunities for lab-based discoveries evaluated in community-wide studies*



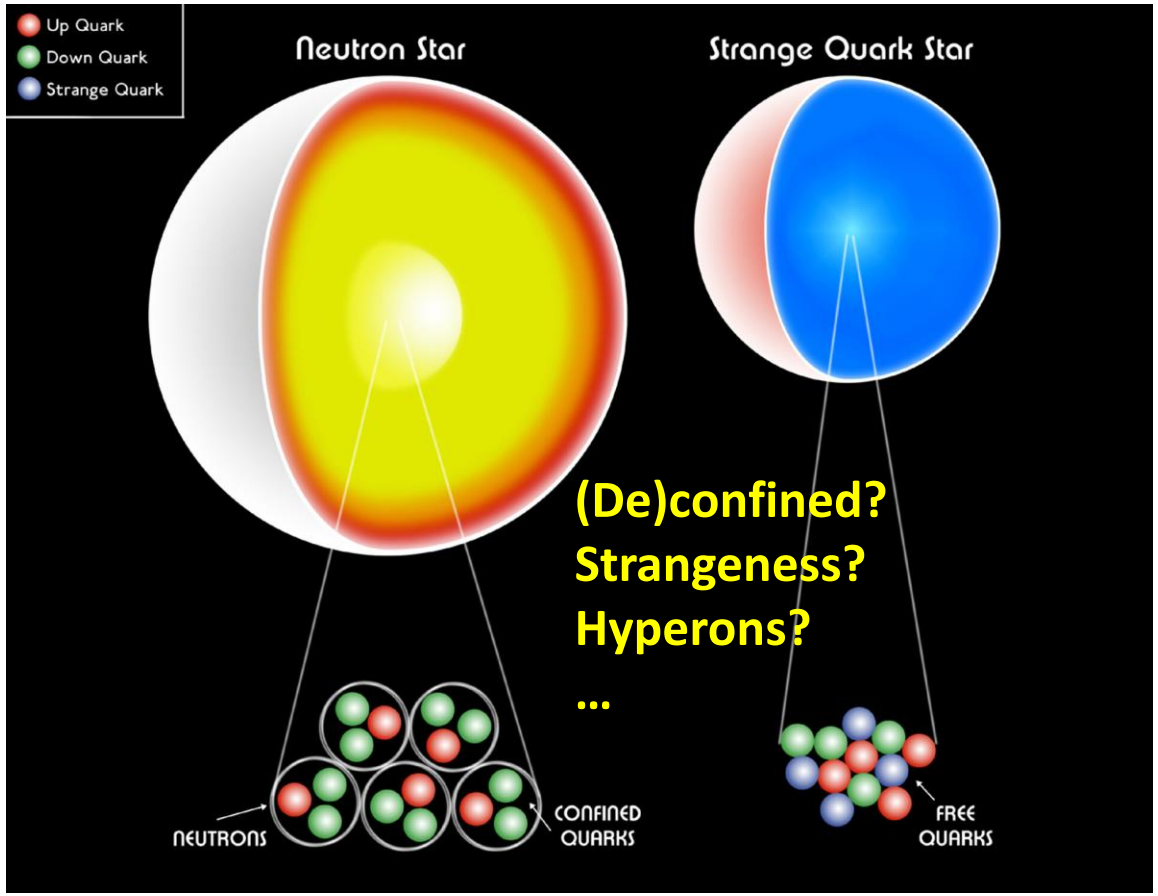
*PBC initiative, J.Phys.G 47 (2020) 1, arXiv:1901.

Neutron stars: QCD equation of state

- What we know for sure w/o astrophysics



- What we want to know



Figs.: LHS: A. Kurkela, RHS: ESA webpage

pQCD: Freedman & McLerran, PRD 16 (1977), Kurkela , Vuorinen, PRL 117 (2016), Gorda et al. PRD 104 (2021)

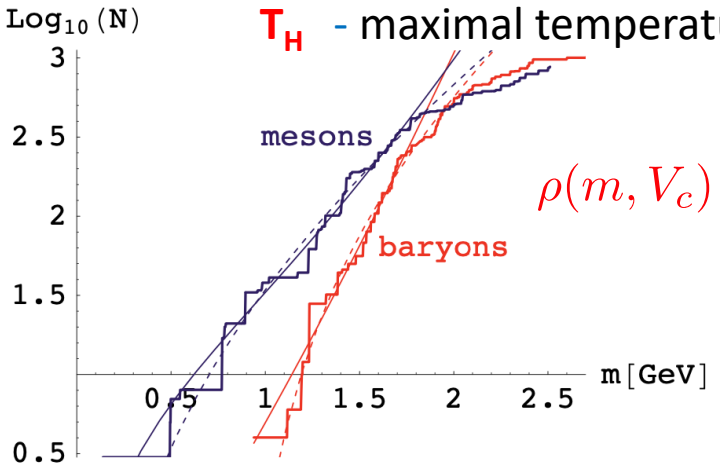
The inevitability of partons at high T

1965 R. Hagedorn's Statistical Bootstrap

1972 W. Nahm, analytical solution of statistical bootstrap

QCD

T_H - maximal temperature of hadron gas



$$\rho(m, V_c) = \frac{\text{const}}{m^3} \exp\left[\frac{m}{T_H}\right]$$

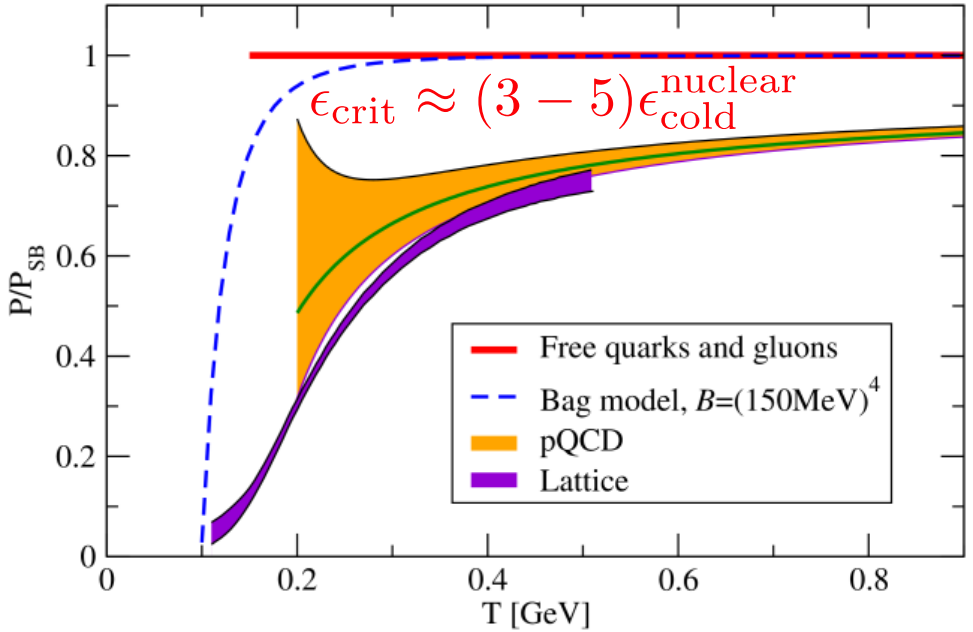
1975 Cabbibo and Parisi:

T_H - temperature of phase transition

1990-2020 Lattice QCD*

Combining perturbative QCD** and non-perturbative Lattice QCD*

=> **rigorous theoretical understanding of QCD phase transition**

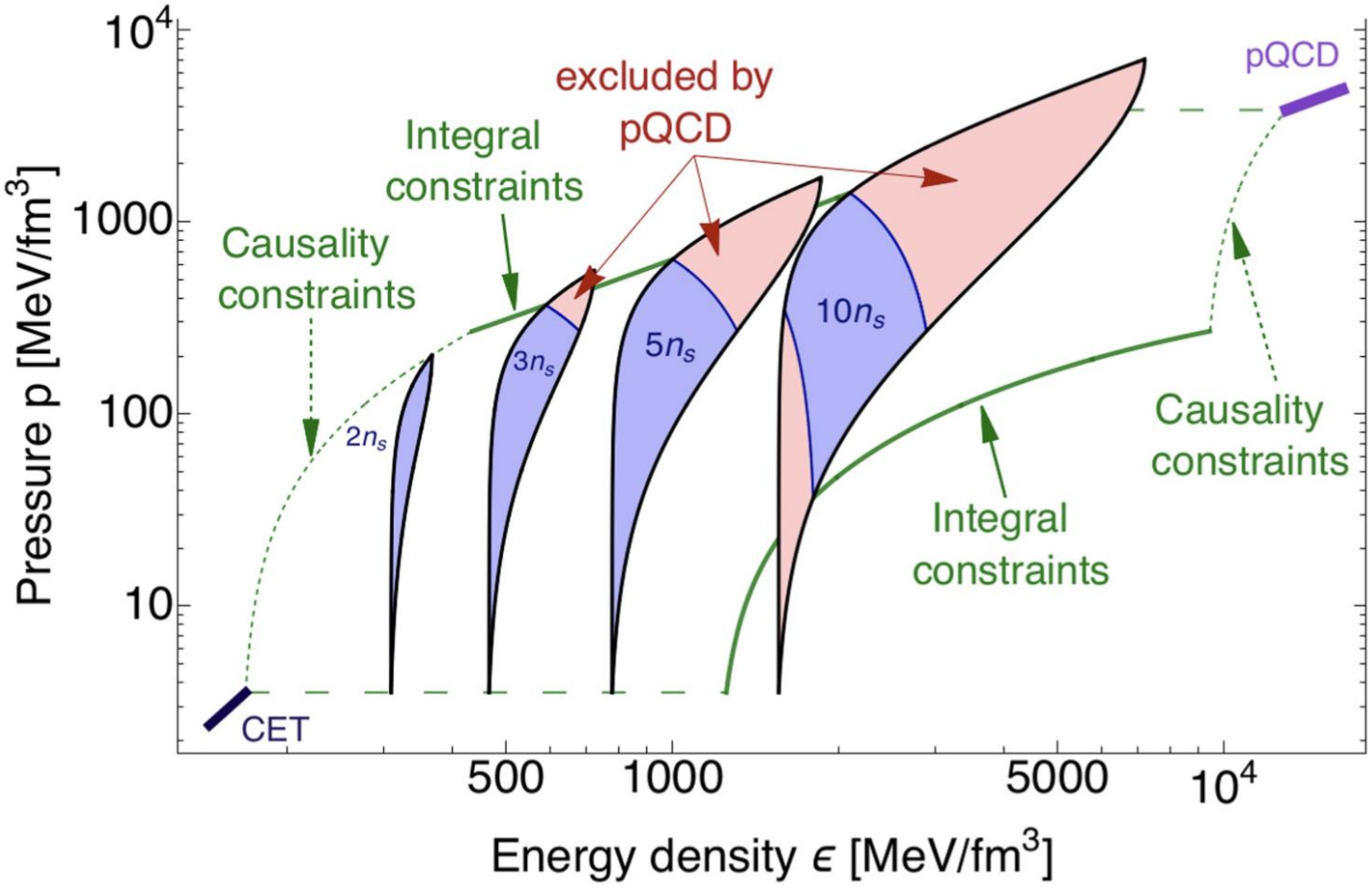


*D. Bazavov et al, Phys. Rev. D90 (2014) 094503
S. Borsanyi et al, JHEP 09 (2010) 073

**K. Kajantje, M. Laine, K. Rummukainen, Y. Schroder, PRD67 (2003)

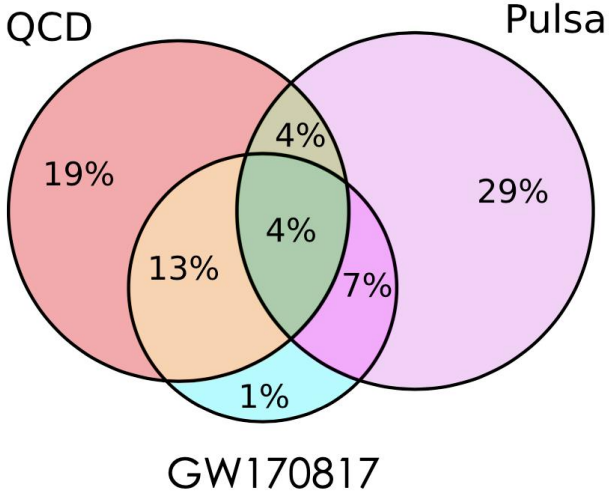
Constraining neutron star eos with theory

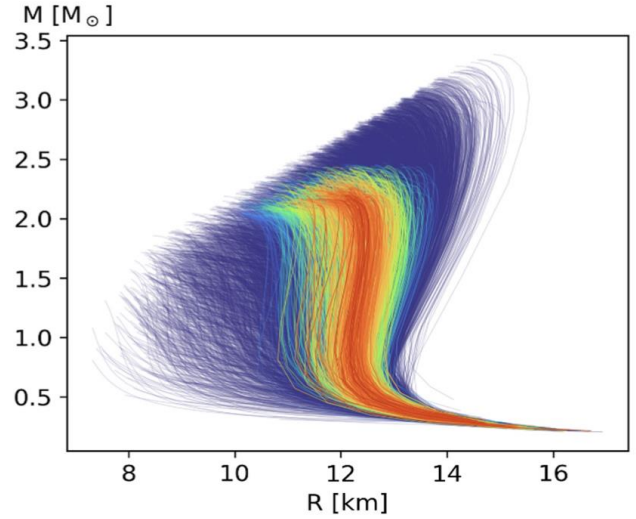
Causality and thermodynamic **stability** yield model-independent constrains the eq. of state

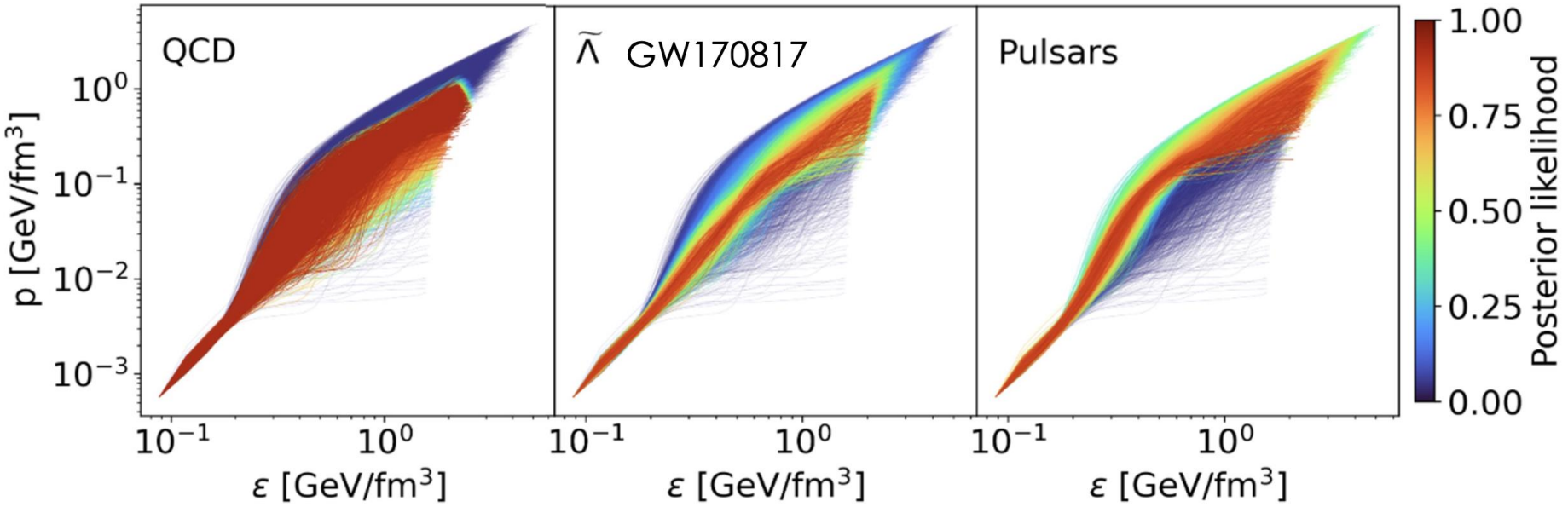


**Komoltsev Kurkela, PRL 128 (2022)

Constraints from theory, GWs and astrophysics

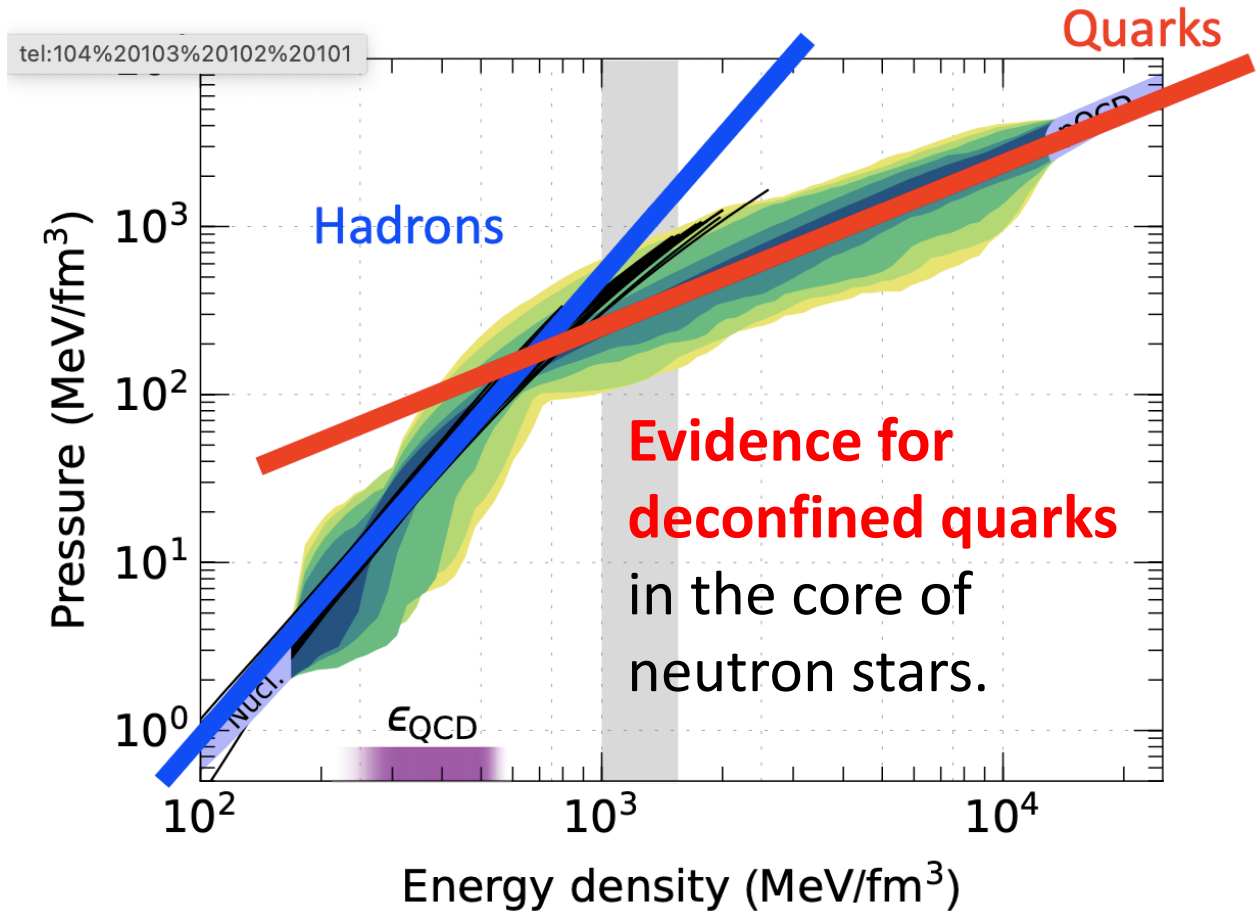




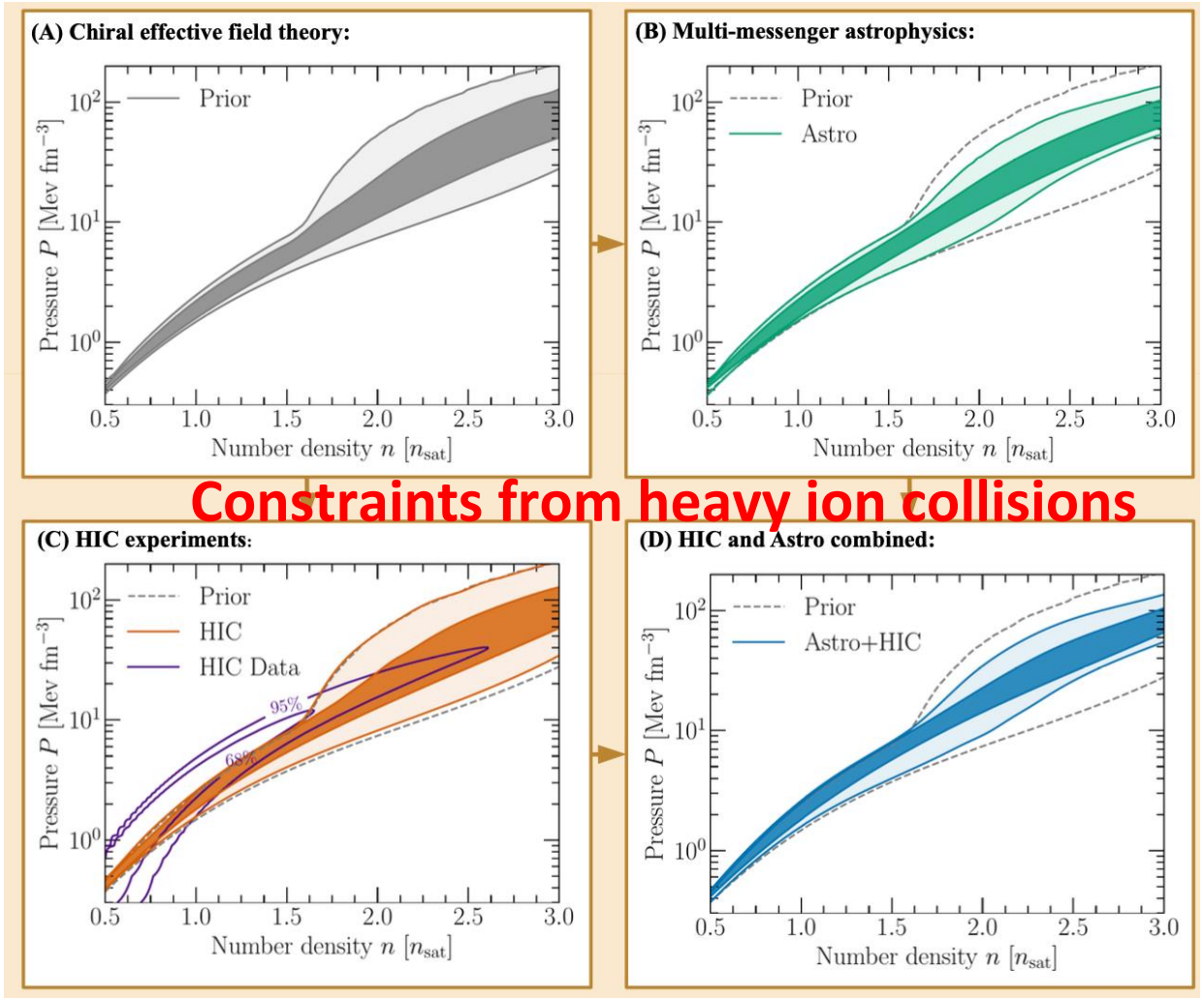


**Gorda et al. 2204.11877

Neutron star equation of state



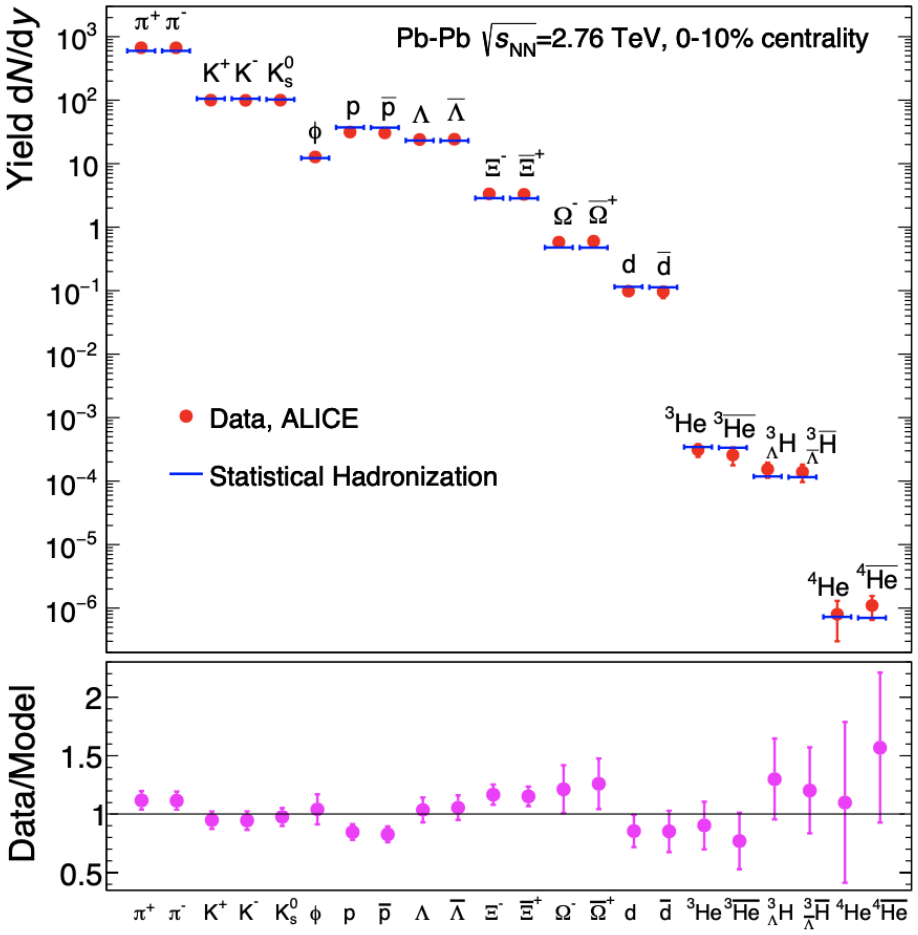
Annala et al.,
Nature Physics 16 (2020) 9

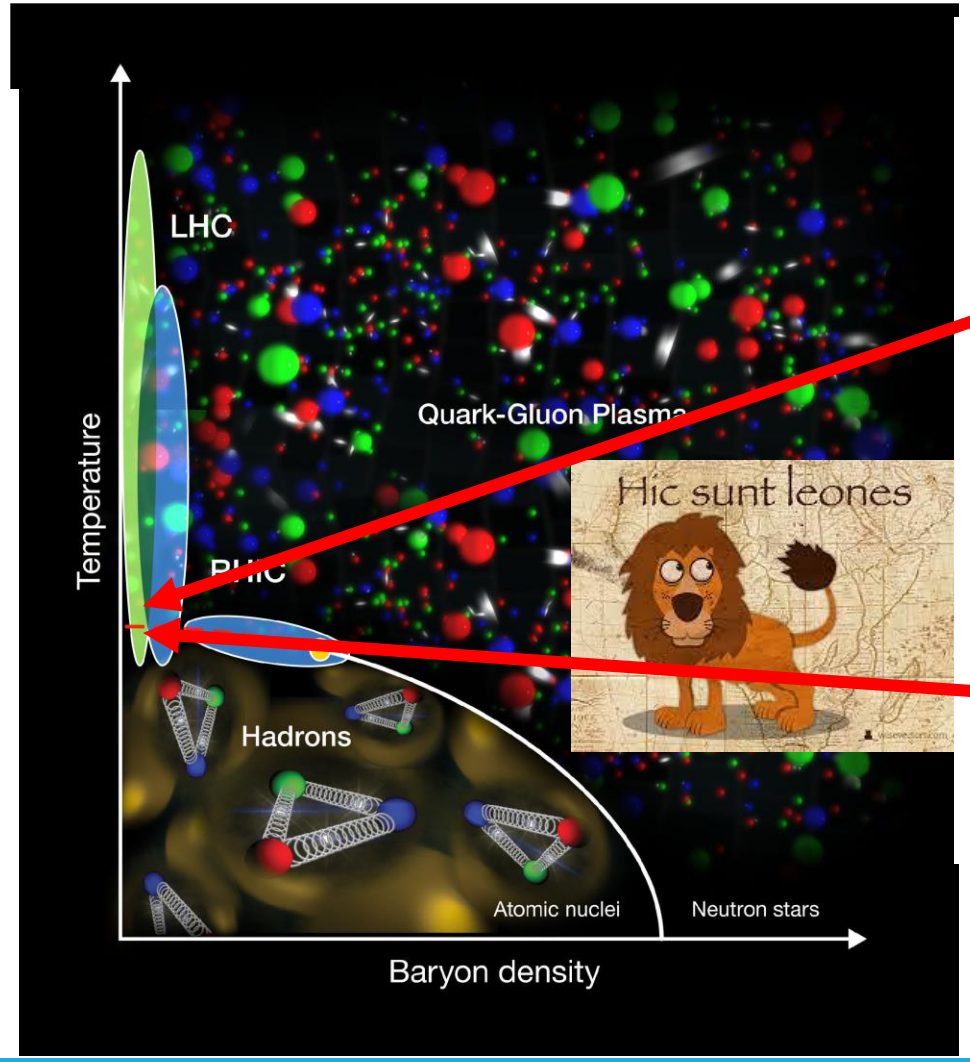


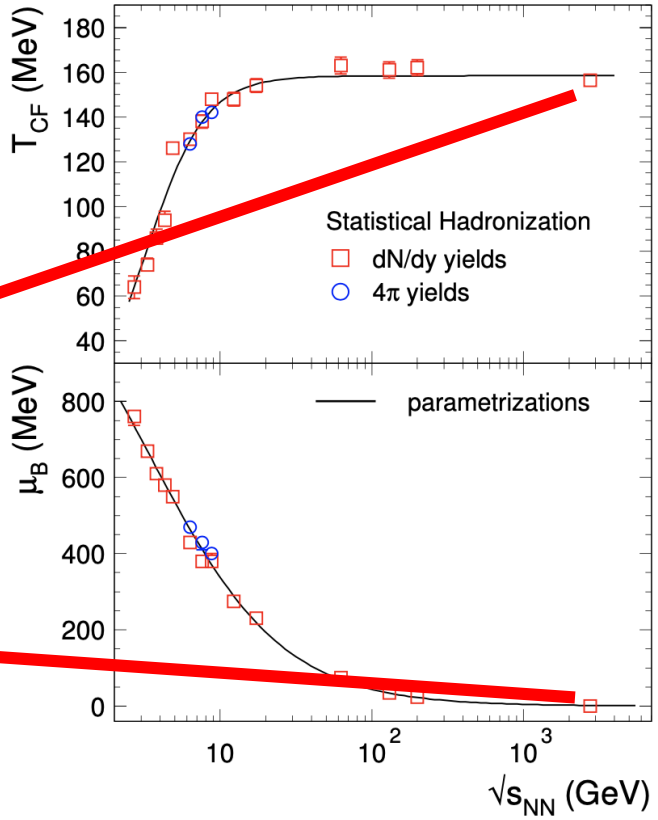
Huth et al., Nature 606 (2022) 276

QCD equation of state

Hadrochemistry at the LHC

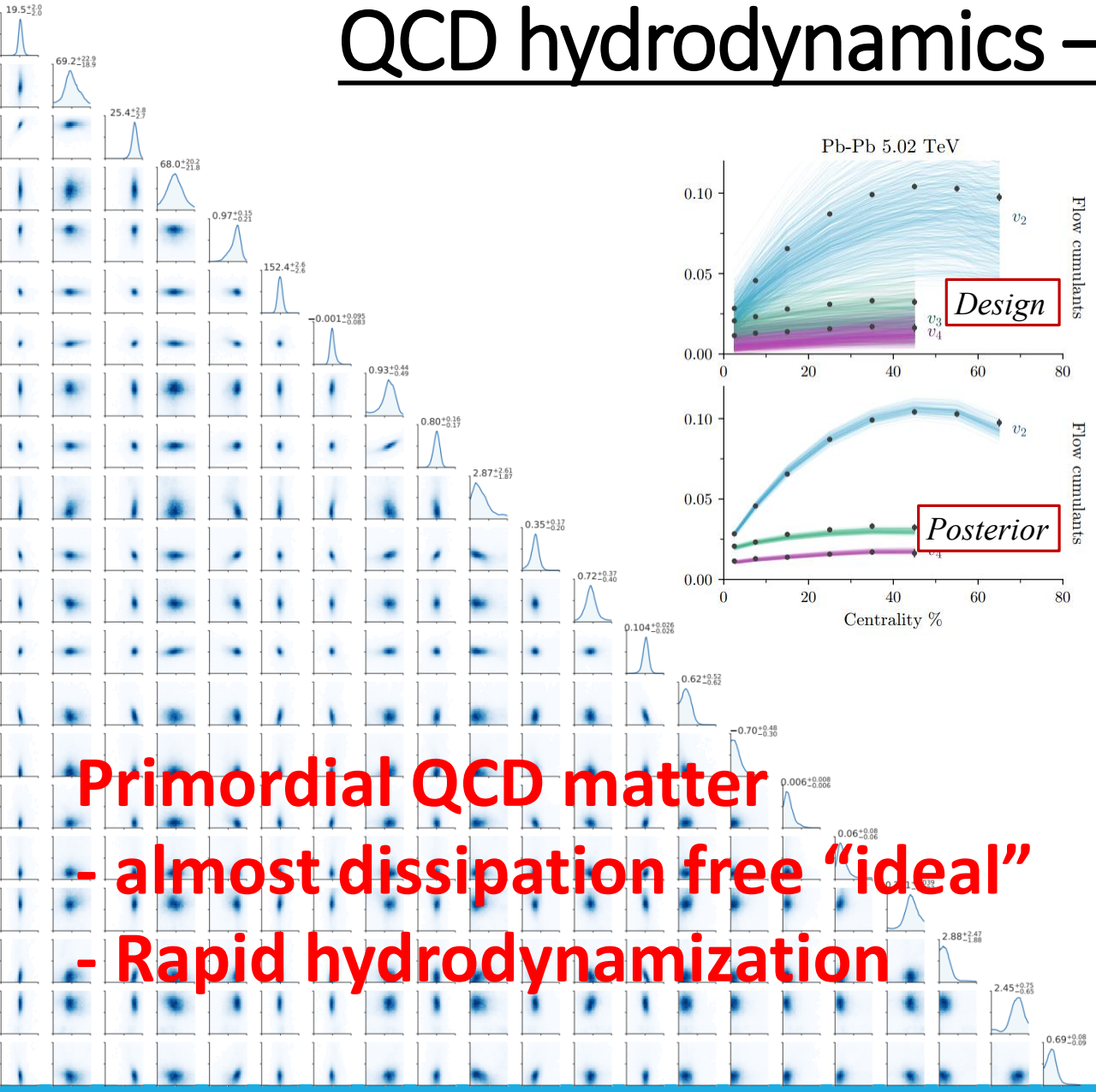






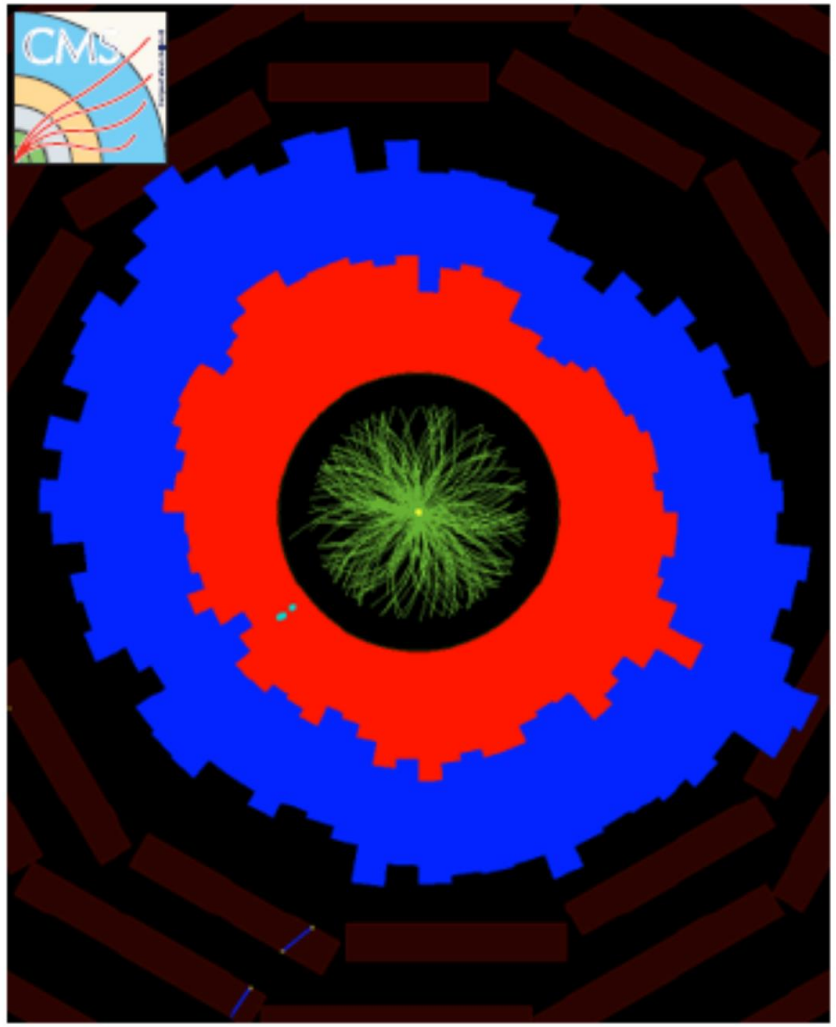
Andronic et al.,
Nature 561 (2018) 321

QCD hydrodynamics – constraints from LHC



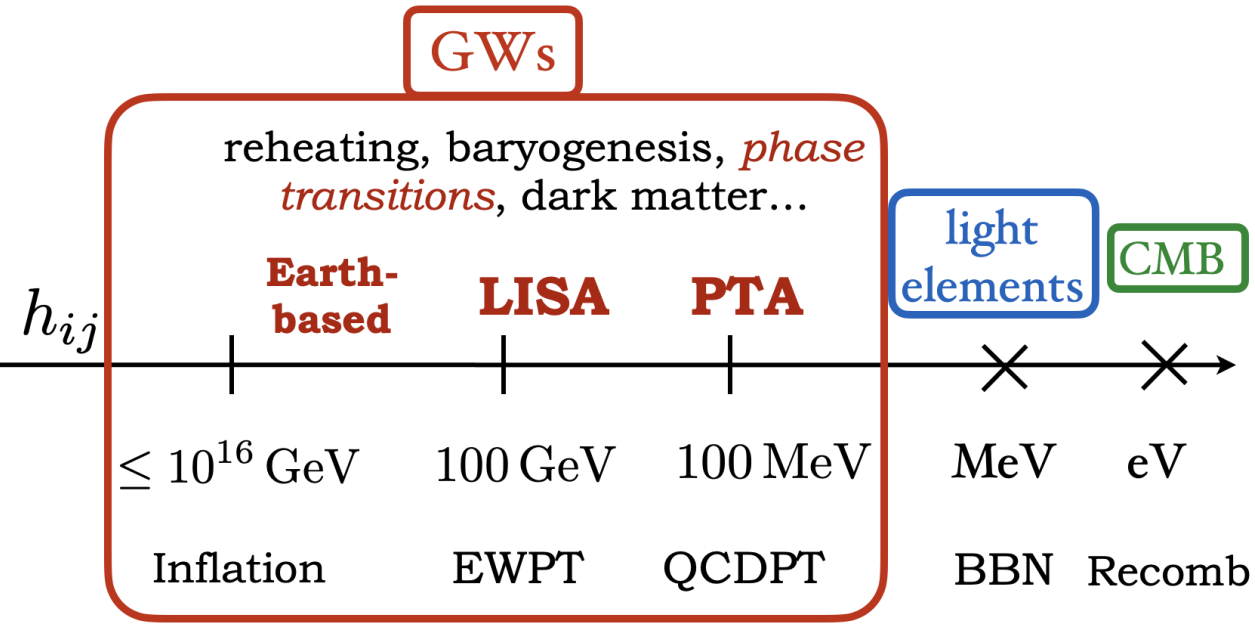
Primordial QCD matter
- almost dissipation free "ideal"
- Rapid hydrodynamization

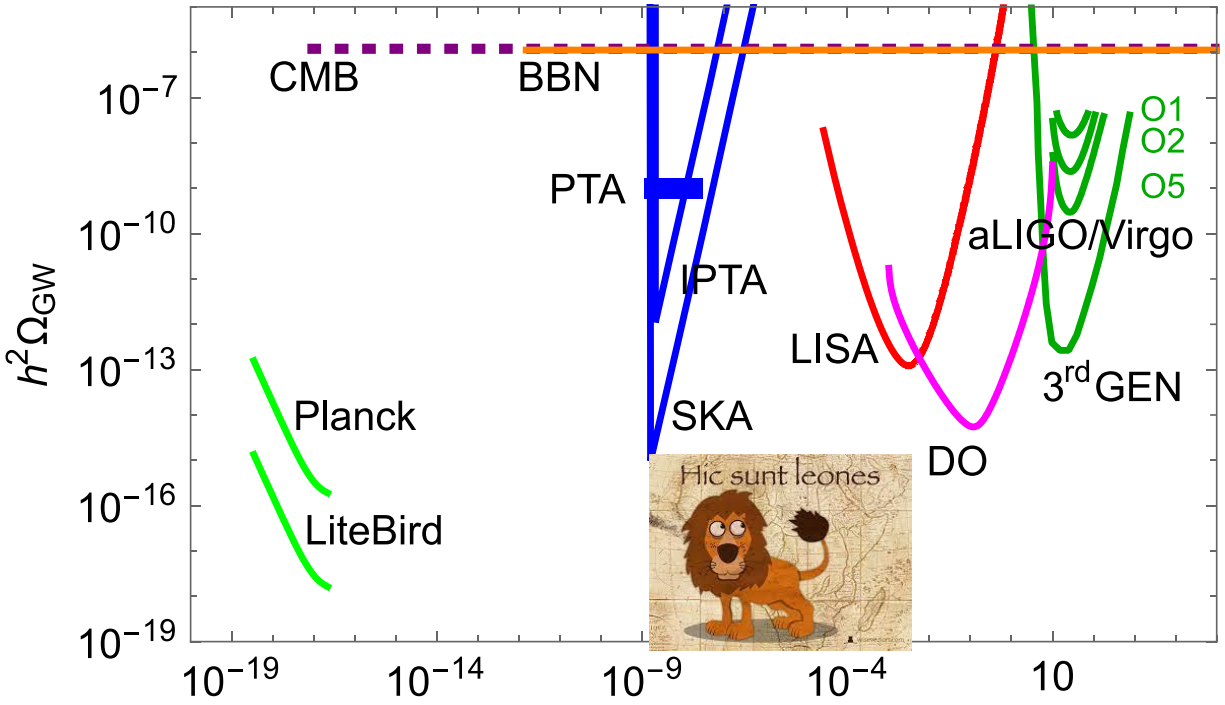
Pb+Pb @ LHC => 10'000 charged particles



Steffen Bass, A data-driven approach to quantifying the shear viscosity of nature's most ideal liquid, https://www.youtube.com/watch?v=MGE8K8IY4cg
*G. Nijs, U. Gursoy, W. v.d. Schee, R. Snellings, arXiv:2010.15130, arXiv:2010.15134

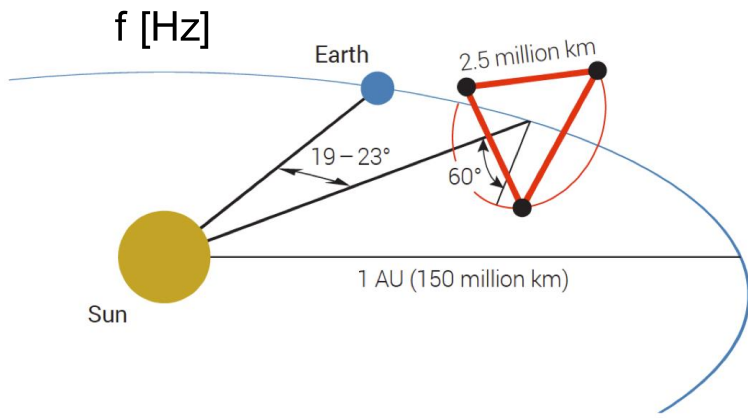
Seeing farther with gravitational waves





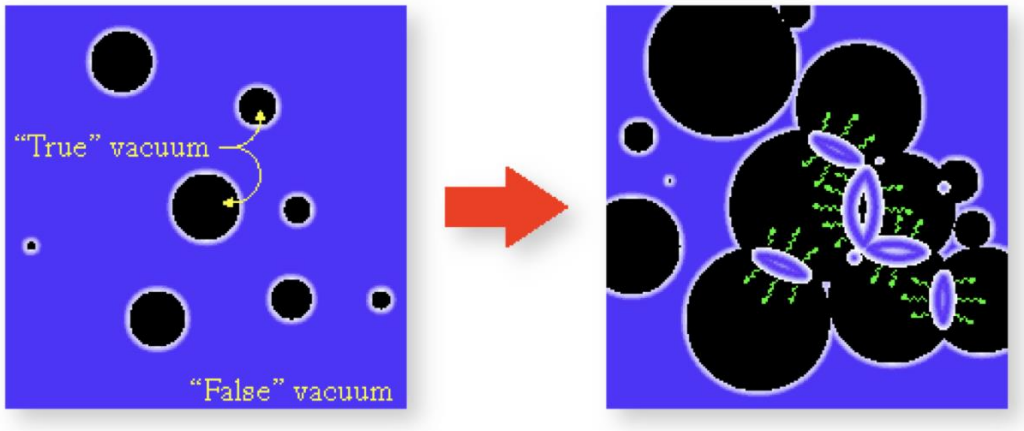
- GW **stochastic sources** include
  - Density perturbations
  - Bulk fluid motion
  - El.magn. fields

$$\ddot{h}_{ij} + 3H\,\dot{h}_{ij} + k^2\,h_{ij} = 16\pi G\,\Pi_{ij}^{TT}$$



GW signals of primordial phase transitions (PTs)?

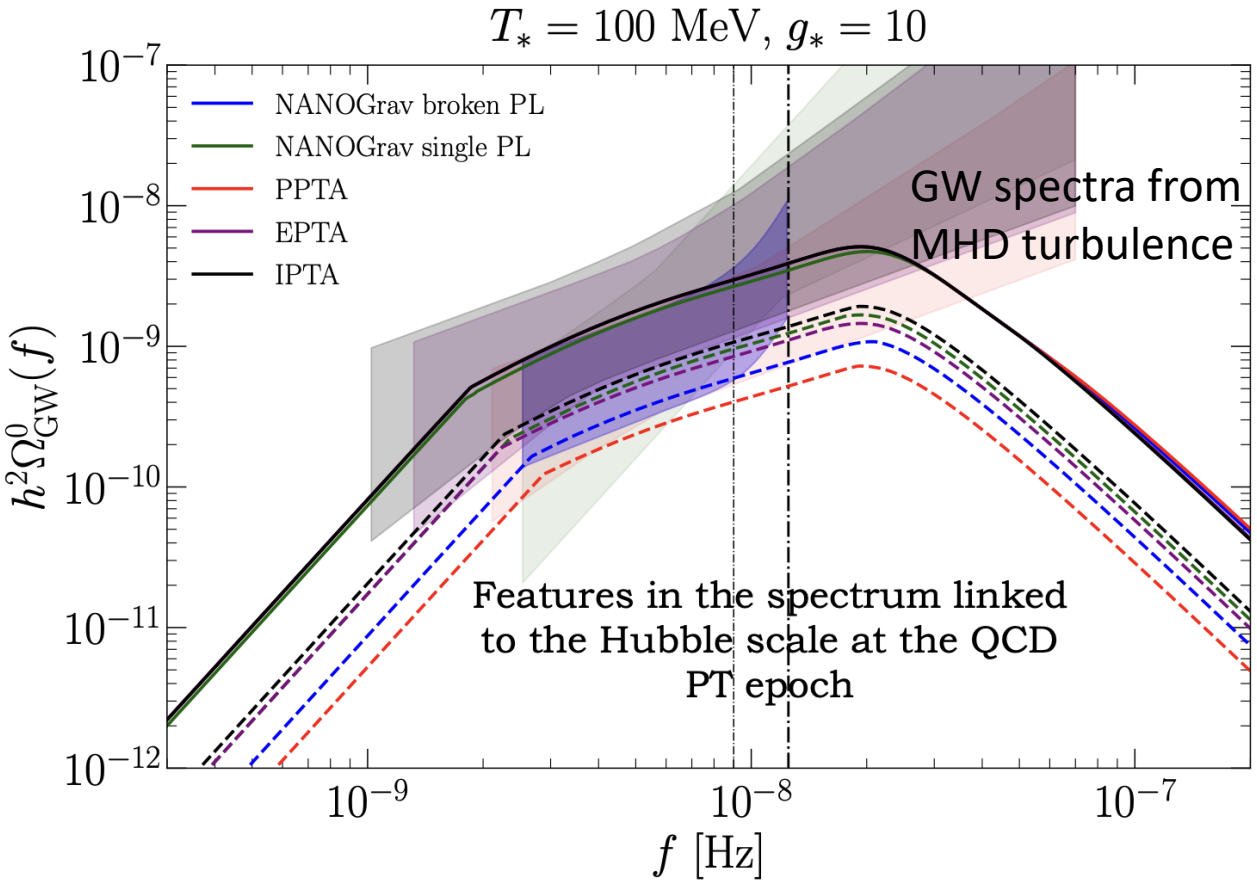
- If PT strongly 1st order, then GW signals from bubble nucleation



Schwarz + Stucke, J. Cosmol. Astropart. Phys. 11 (2009)

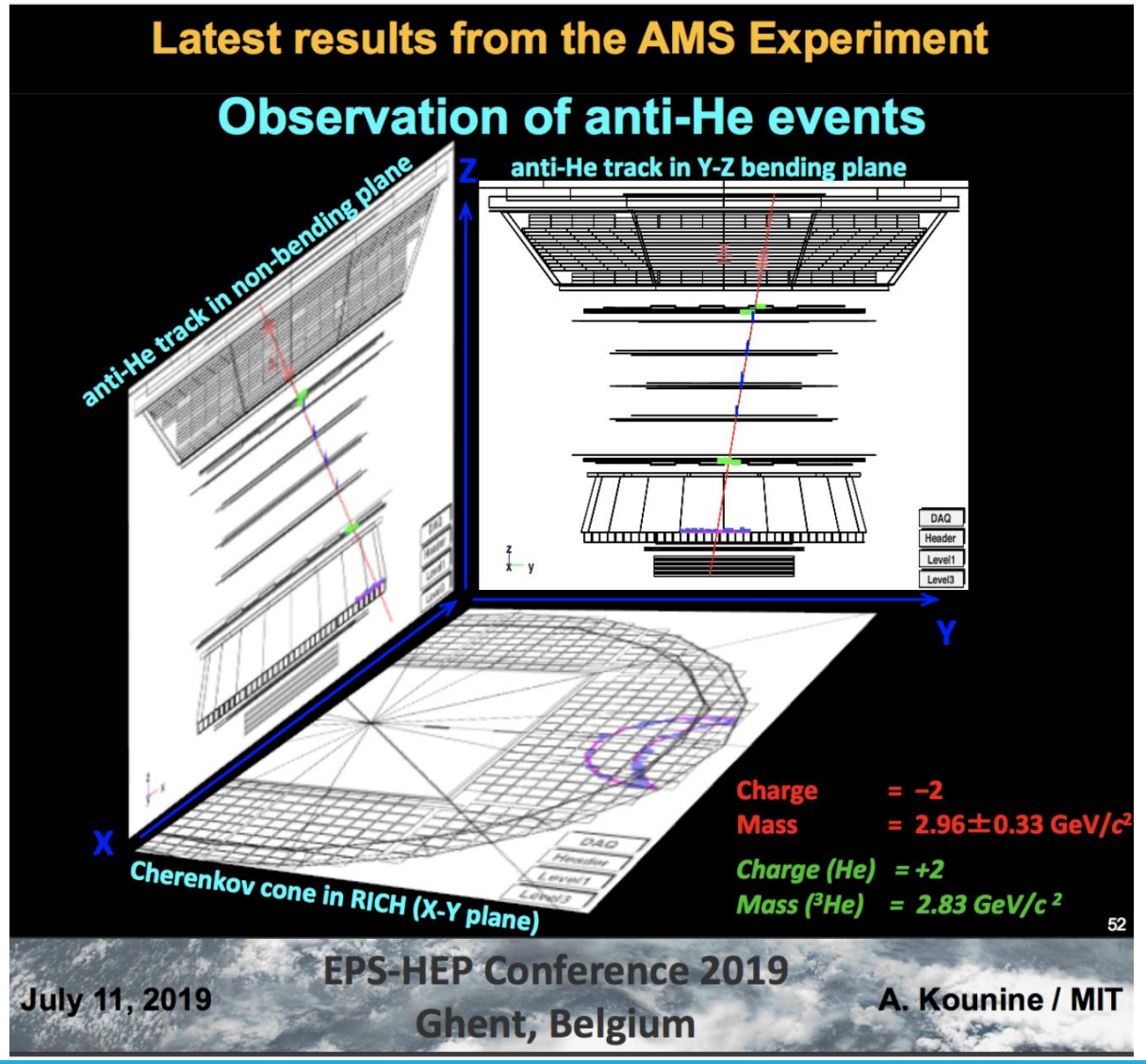
- MHD turbulence at QCD scale may lead to GW noise excess seen in Pulsar Timing Arrays

Roper Pol et al., arXiv:2201.05630



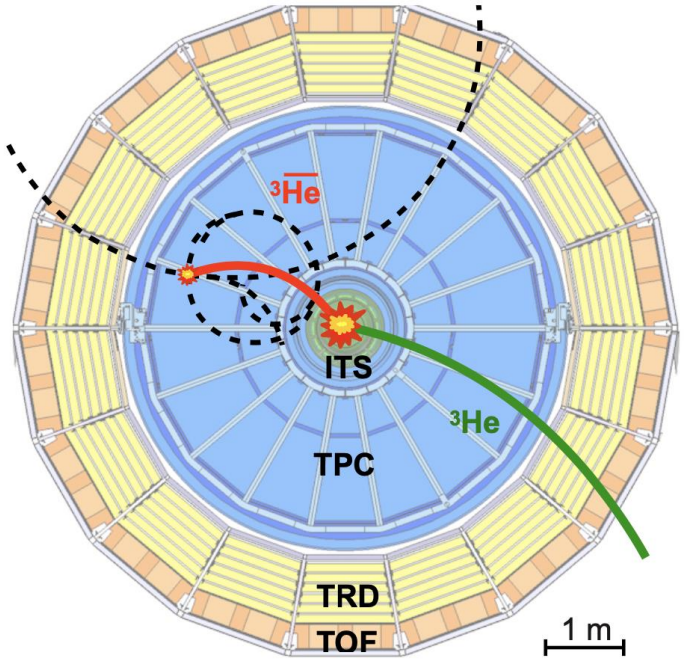
PTA laboratories (NANOGrav,Parkes,European) report noise excess: arXiv: 2009.04496, 2107.12112, 2110.13184

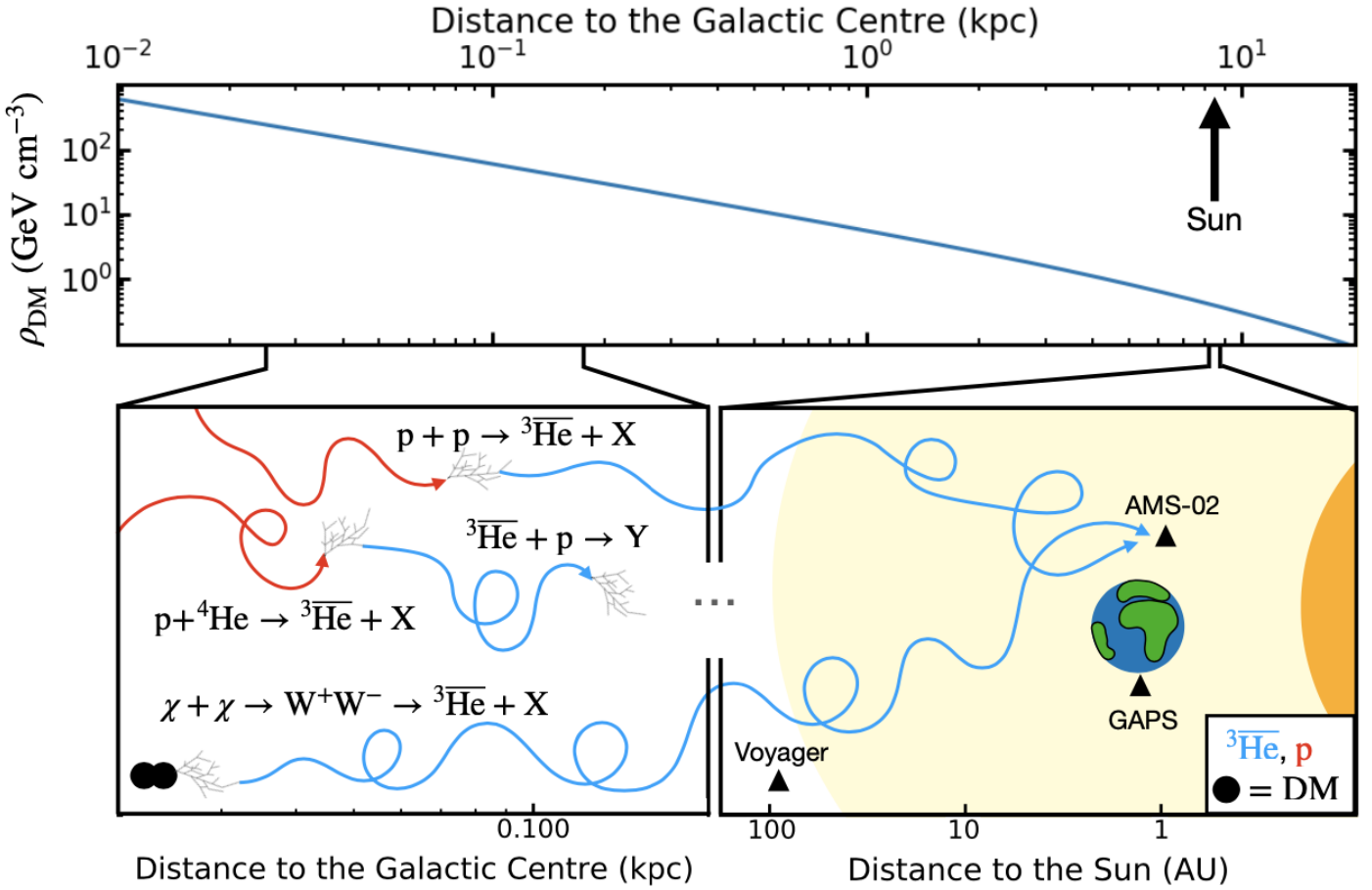
Anti-matter in Cosmic Rays



Anti-matter in Cosmic Rays

- Observation of light anti-nuclei may be signature of dark matter annihilation*
- Collider experiments produce $\overline{d}$, $^3\overline{\mathrm{He}}$, $^4\overline{\mathrm{He}}$
- First $^3\overline{\mathrm{He}}$ absorption measurement informs propagation through galaxy



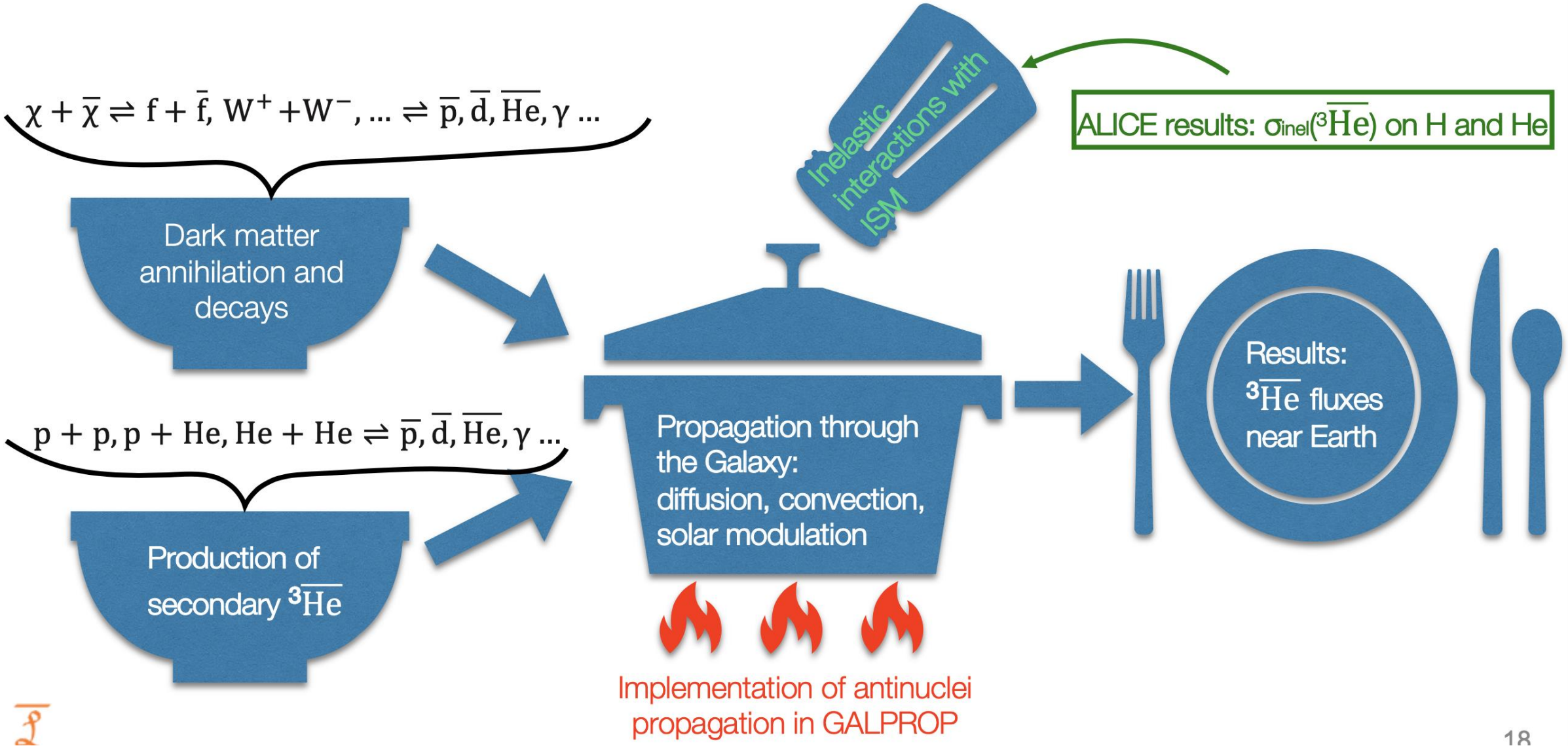


ALICE Coll., arXiv:2202.01549

*Ibarra + Wild, JCAP02 (2013) 021; Winkler+Linden PRL126 (2021)

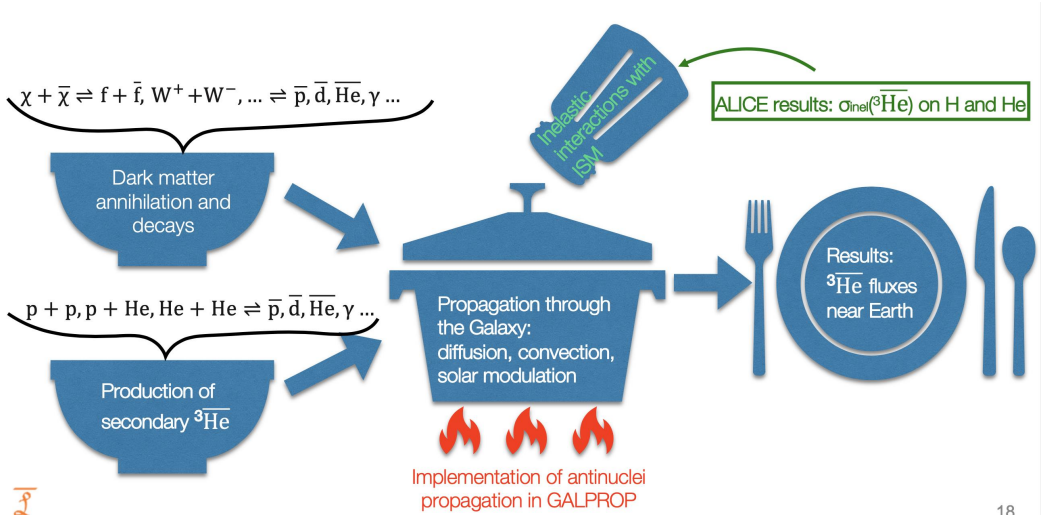
(cf. ALICE Coll., PRL 125 (2020) on anti-deuteron absorption)

Cooking anti-nuclei fluxes

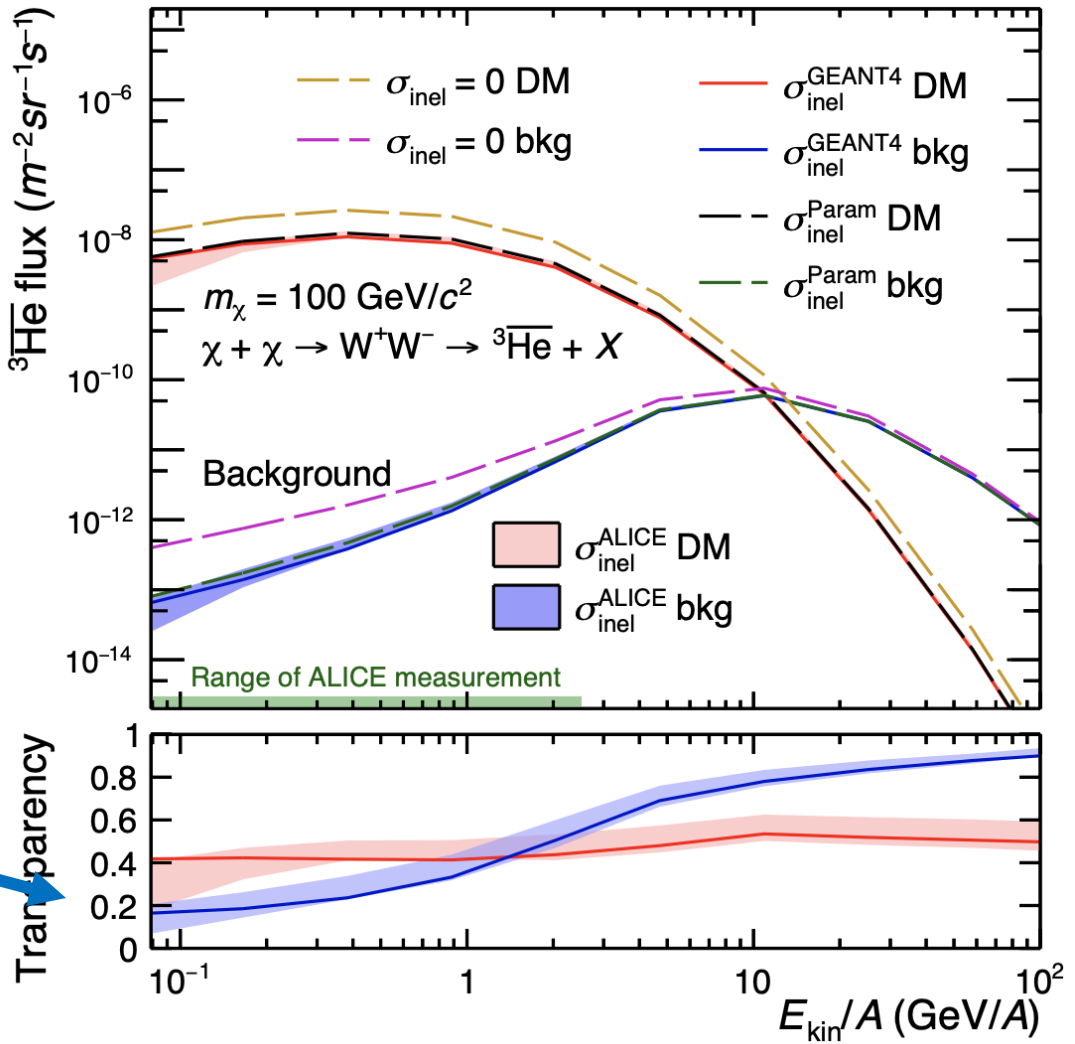


Slide: Laura Fabbietti

Cooking anti-nuclei fluxes

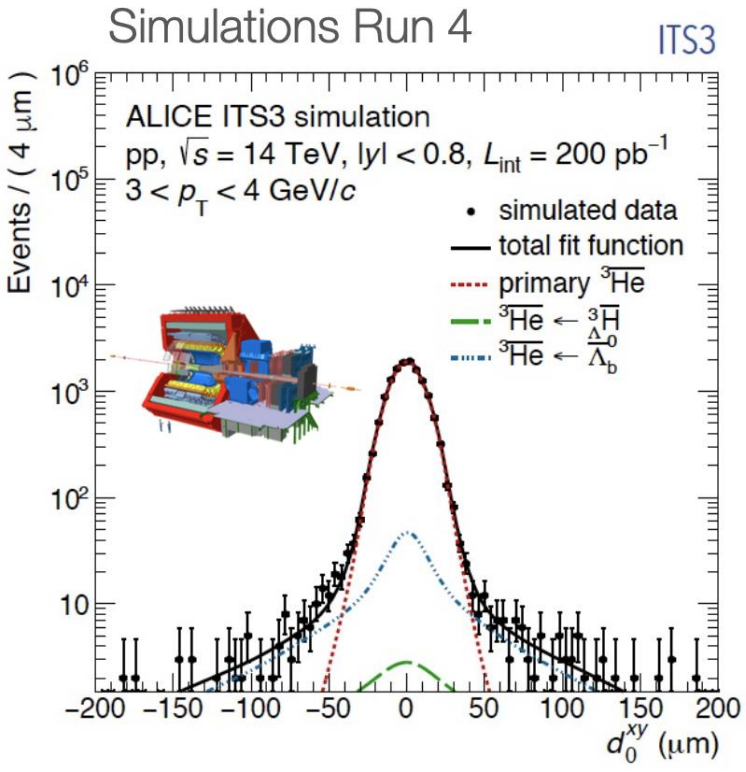


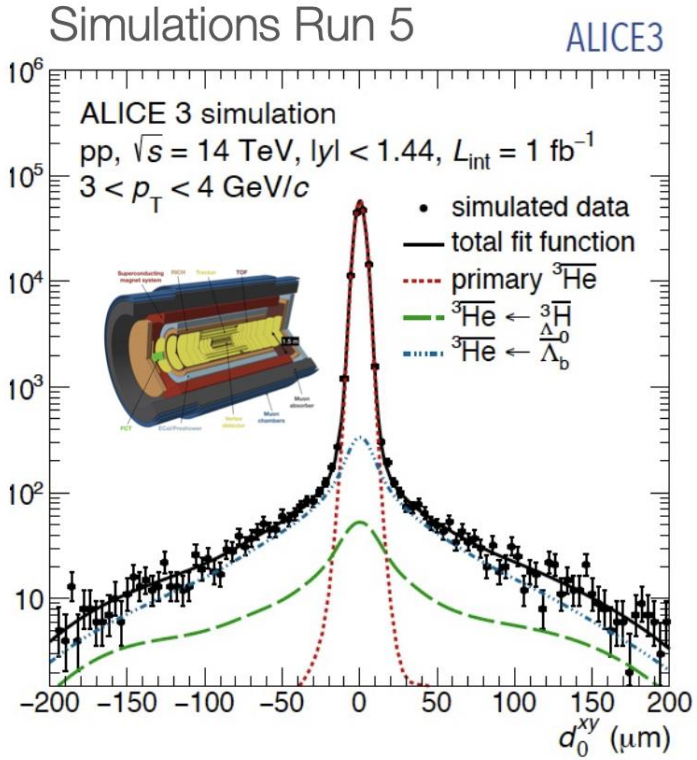
- Absorption reduces known background by factor up to 5

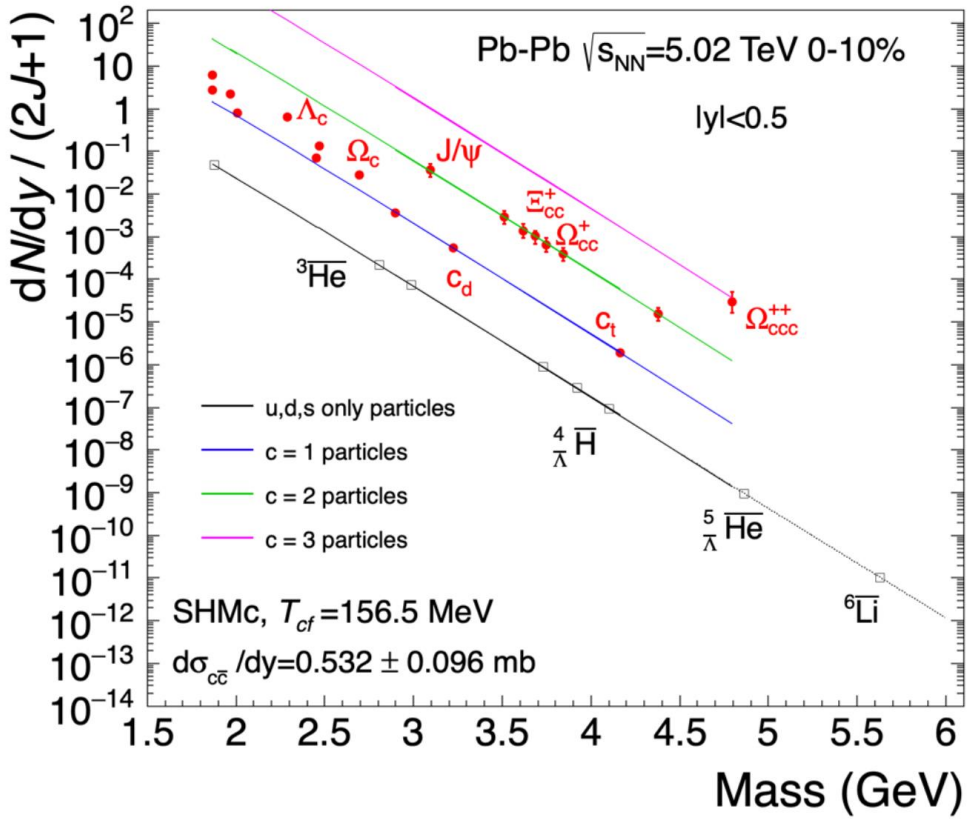


ALICE Coll., arXiv:2202.01549

Future opportunities at the LHC (ALICE + LHCb)







Strong PID+ high rate
+ wide acceptance
+ excellent vertexing

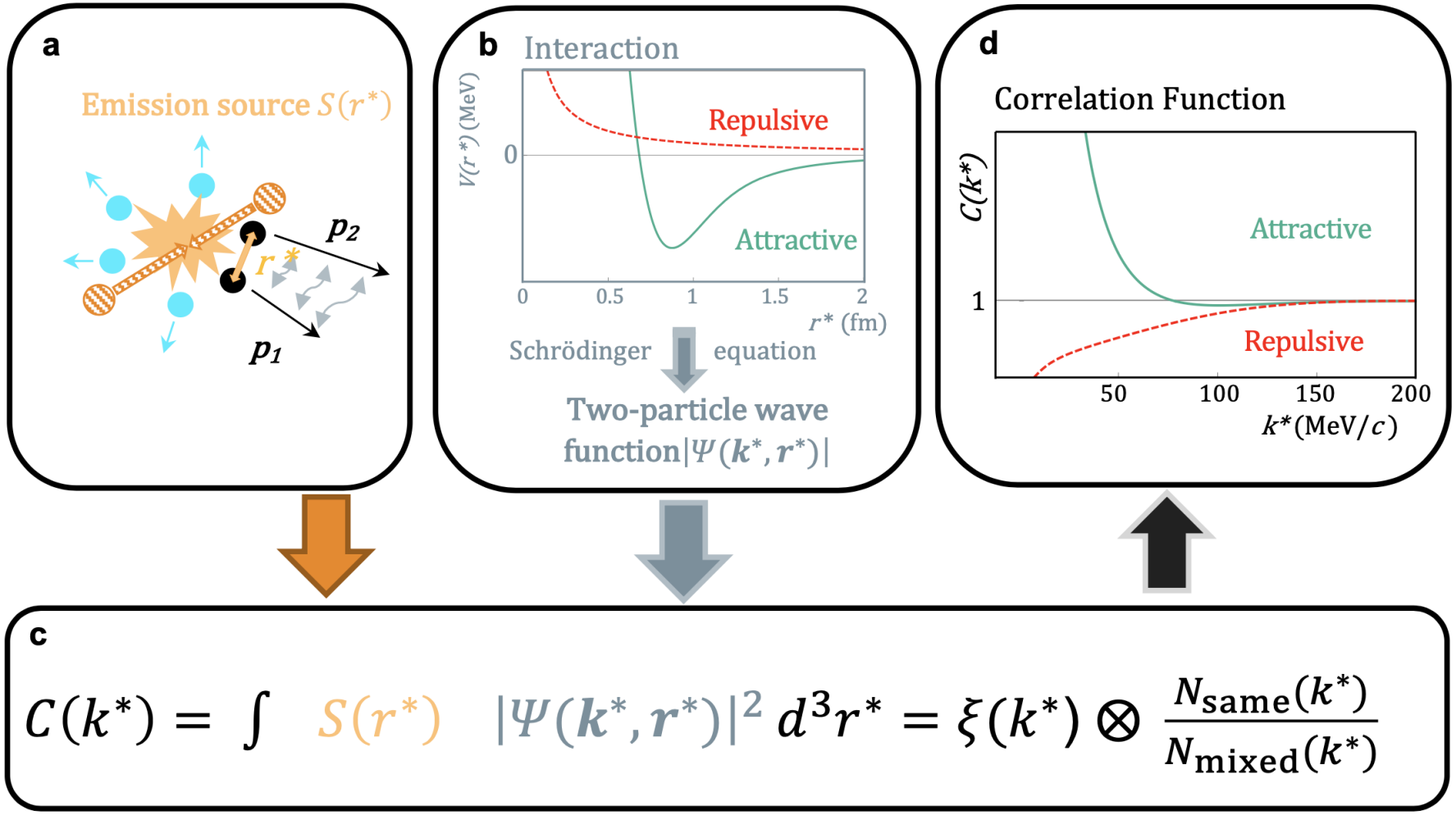
→ Search for exotic anti-, hyper- and super-nuclei

"Super-nuclei" in reach
- Charmed deuterium
- Charmed triton $c_t \rightarrow t + K^- + \pi^+$

One future of hadron physics at the LHC

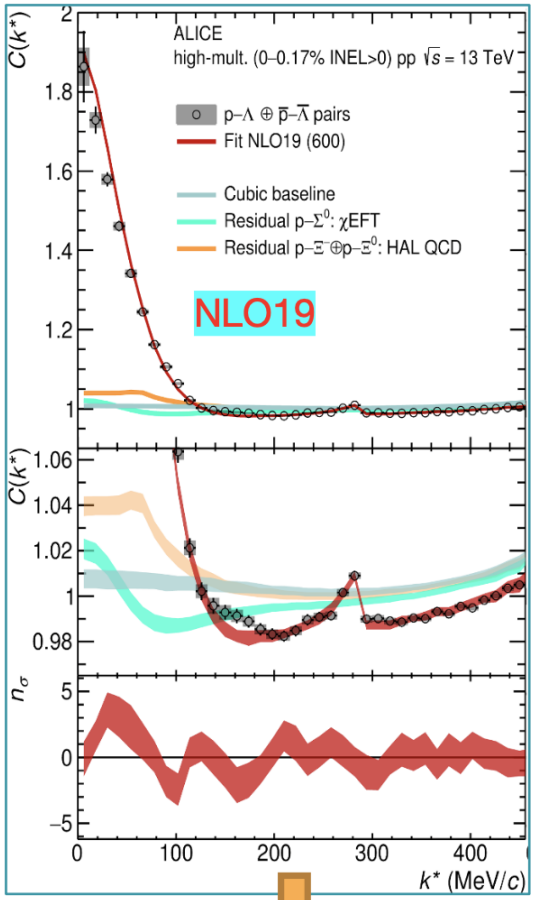
Strong PID+ high rate
+ wide acceptance
+ excellent vertexing

2- (3-) body potentials
hadronic resonances



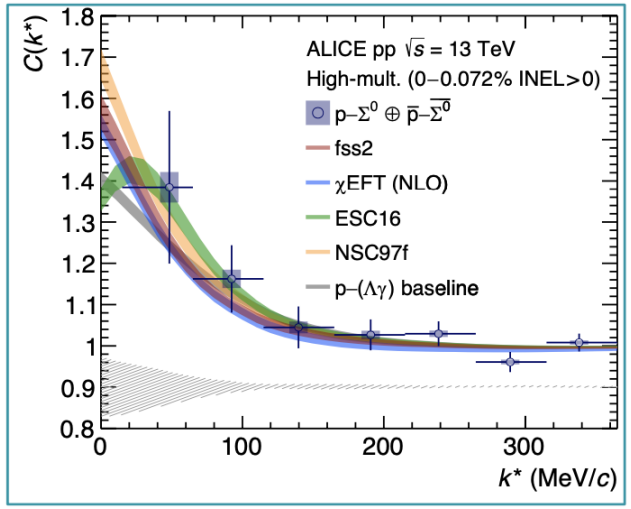
One future of hadron physics at the LHC … cont'd

ALICE Coll. arXiv:2104.04427



U_Λ

ALICE Coll. PLB 805 (2020)

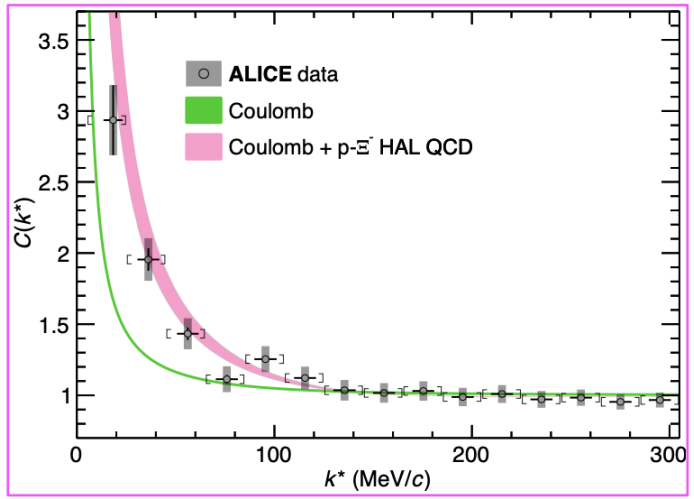


Data compared with χEFT and other models

J. Haidenbauer et al. EPJ A 56 (2020)
J. Haidenbauer et al. PLB 829 (2022)

U_Σ

ALICE Coll. Nature 588 (2020)



Data compared with lattice QCD calculations

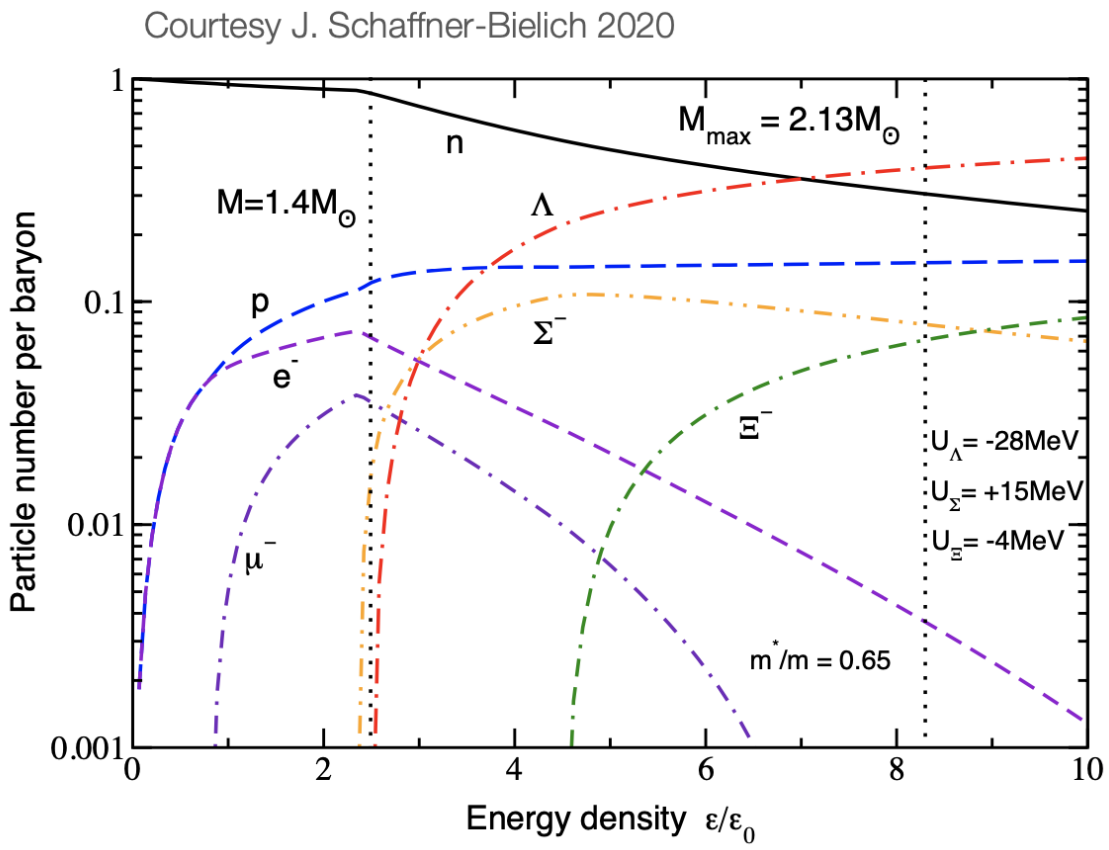
HAL QCD NPA 998 (2020)
Y. Kamya et al. PRC 105 (2022)

U_Ξ

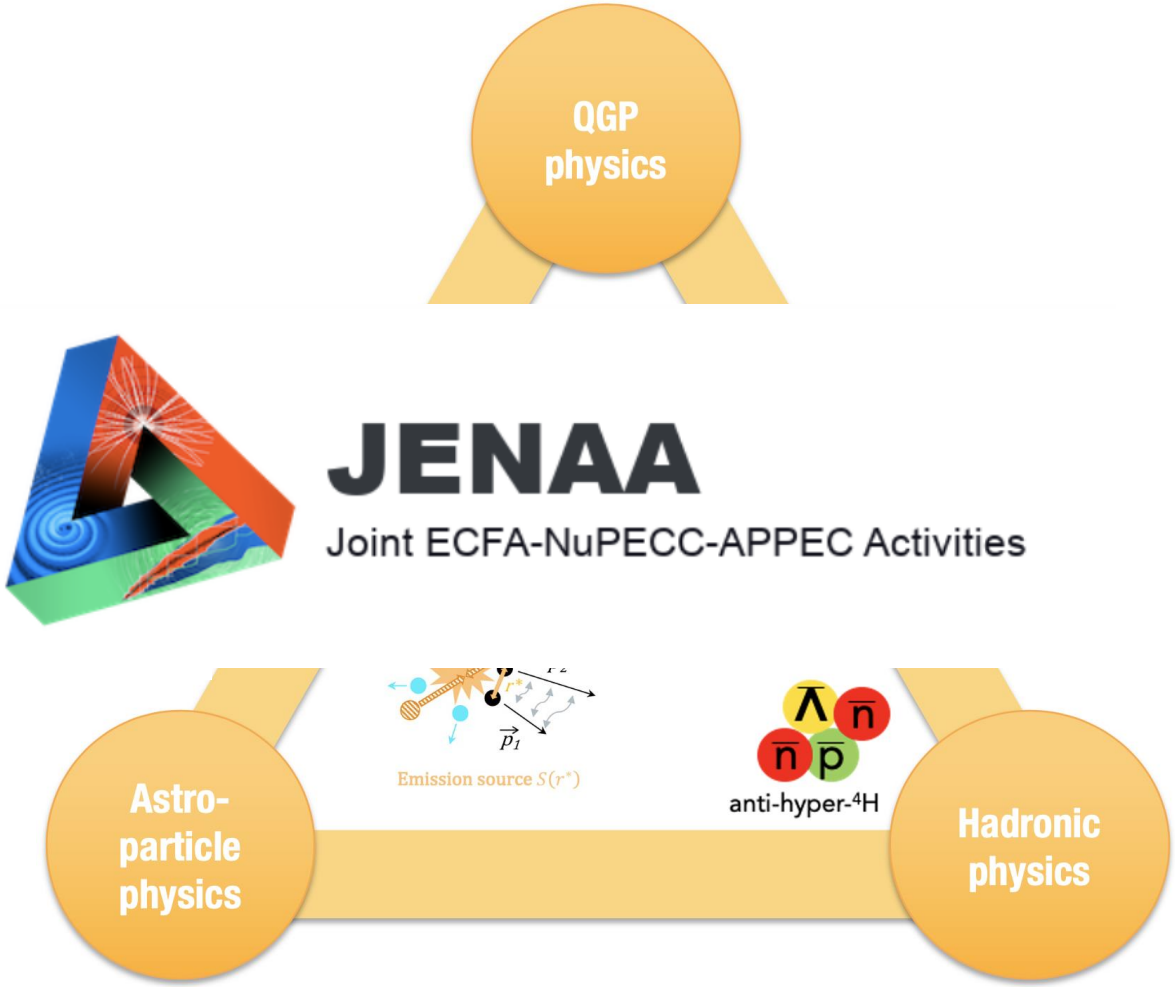
2-body potentials

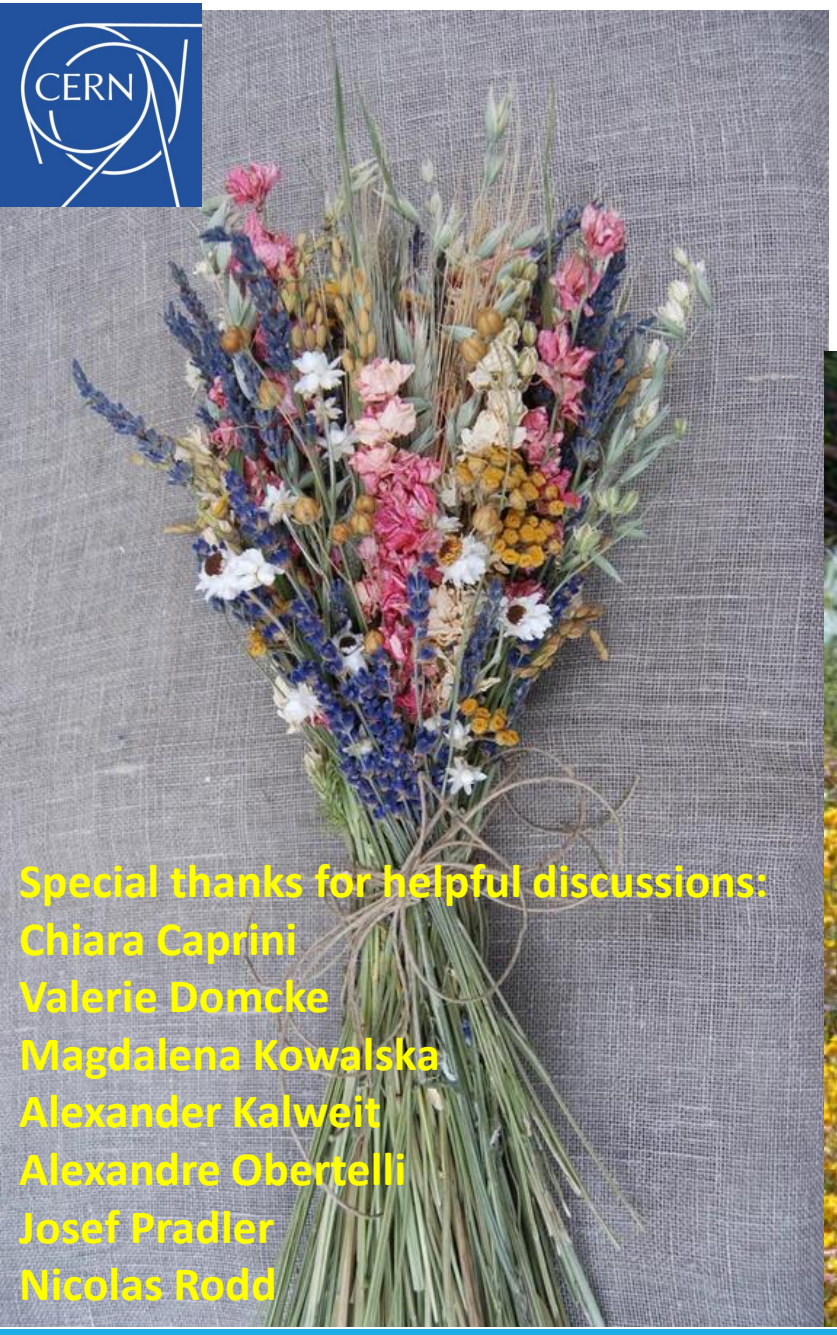
One future of hadron physics at the LHC … cont'd

- The role of hadronic interaction potentials in dense matter



- Interdisciplinary initiatives





Special thanks for helpful discussions:
Chiara Caprini
Valerie Domcke
Magdalena Kowalska
Alexander Kalweit
Alexandre Obertelli
Josef Pradler
Nicolas Rodd
…

- I presented only a small pick from a wide field

THE END