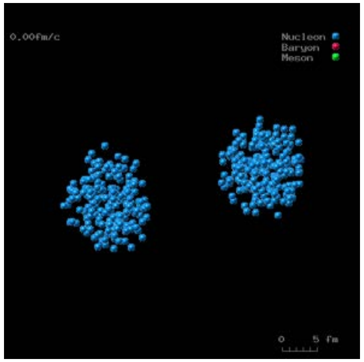
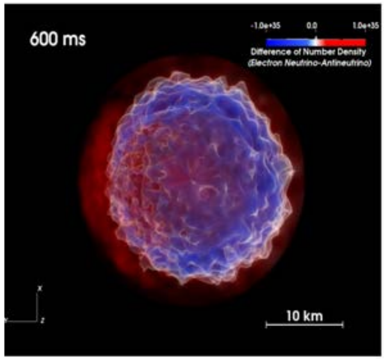
Connector 7: Matter under Extreme Conditions

Laura Fabbietti (TUM)

Heavy Ion Collisions at GeV energies

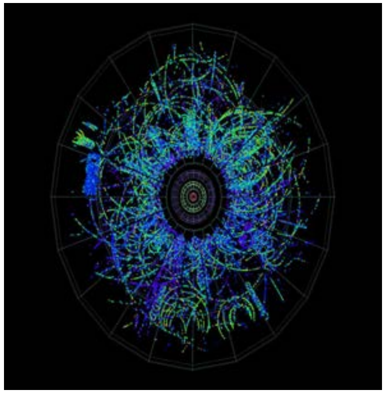


3D Simulation Supernovae
(R. Glas)

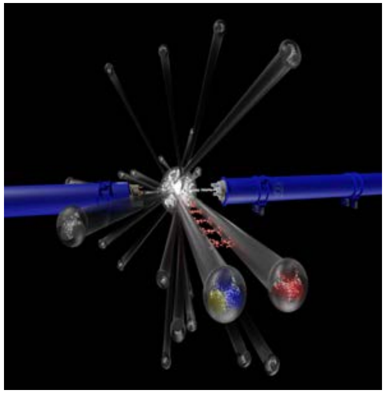


Supernovae Explosion

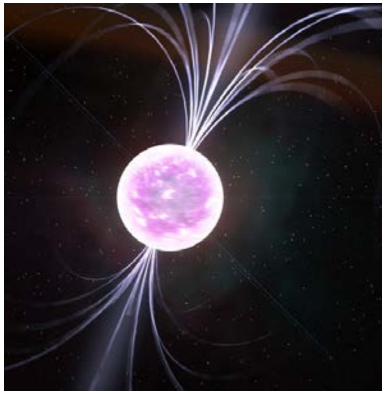
Heavy Ion Collisions at TeV energies



Interaction Measurements
(B. Hohlweger)

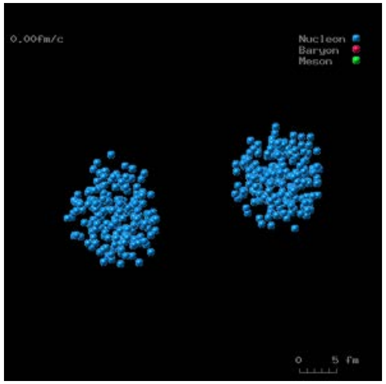


Neutron Stars



Transport Codes for the Investigation of Extreme Matter in Heavy-Ion Collisions

Hermann Wolter (LMU) and the Transport Model Evaluation Project (TMEP)



Goal: Extract the energy and density dependence of the **Symmetry Energy** (energy variation of the nuclear system when the number of neutrons increases-> Relevant for Neutron Stars)

Transport Codes for the Investigation of Extreme Matter in Heavy-Ion Collisions

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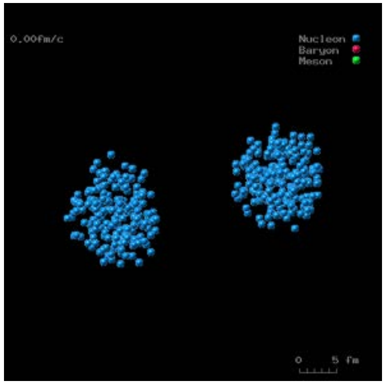


connection via

→ Transport theory: 2 families

→ BUU (1-body phase space dynamics)

→ QMD (N-body molecular dynamics)

non-equilibrium, highly non-linear

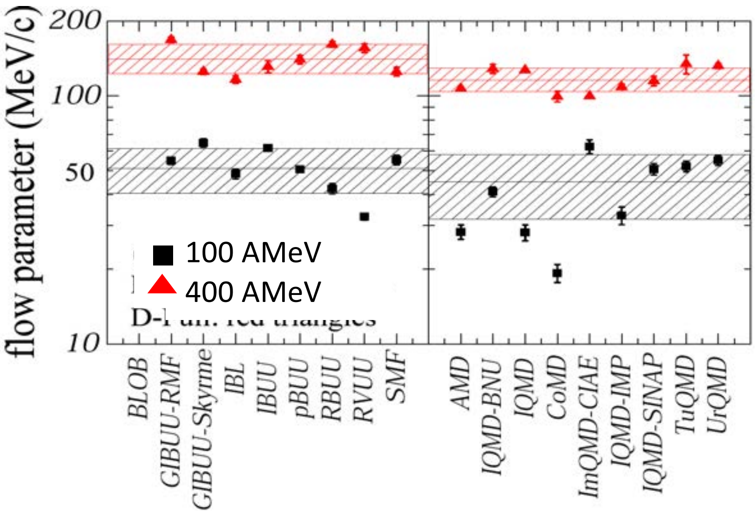
solved by complex simulations.

Reliability? Not always!

test with Transport Model Evaluation Project:

1st stage: identical phys. input; most import transport codes

Au+Au, b=7 fm, E/A=100,400 MeV (J. Xu et al., PRC 93, 064609 (2016))



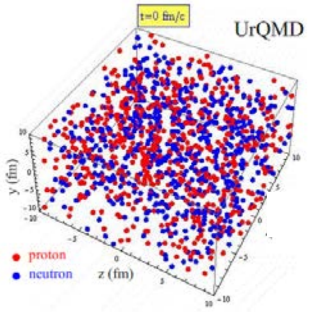
-> deviation in flow (slope of transverse flow at mid-rapidity) too large (~30% at 100MeV, 13% at 400 MeV)

-> difficult to disentangle diff. effects (mean field, collisions, Pauli blocking, etc)

-> simplify set-up: calculations in a periodic box,

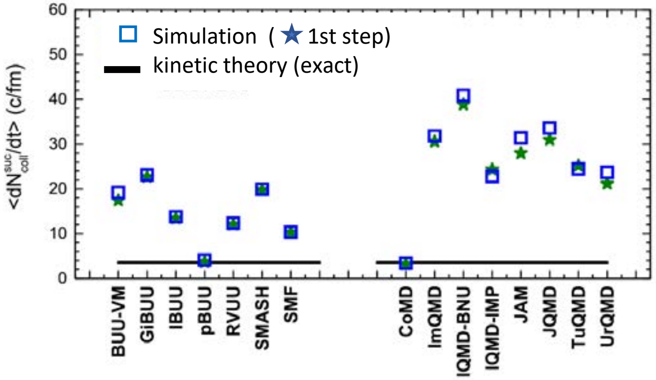
2nd stage: Box calculation comparison

simulation of the static system of infinite nuclear matter,
→ check different aspects of transport separately, e.g.



1. Collision integral:

collision rates in Cascade calculation,compared to exact kinetic theory,
Y.X.Zhang, et al-.Phys. Rev. C 97,034625 (2018)



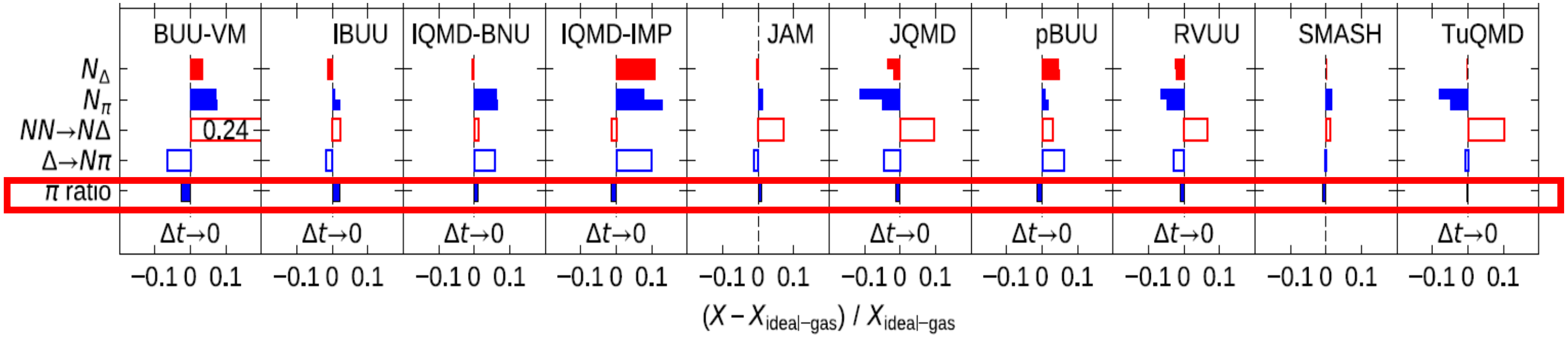
Reaction rates too high. Pauli blocking not effective enough (partic. in QMD)

Reason: fluctuations

2. π,Δ production

Cascade calculation at T=60 MeV, extropolated to timestep Δt =0
A. Ono, et al., Phys. Rev. C 100, 044617 (2019)

Differences in π,Δ numbers and reaction rates,
but π–/π+ ratio consistent



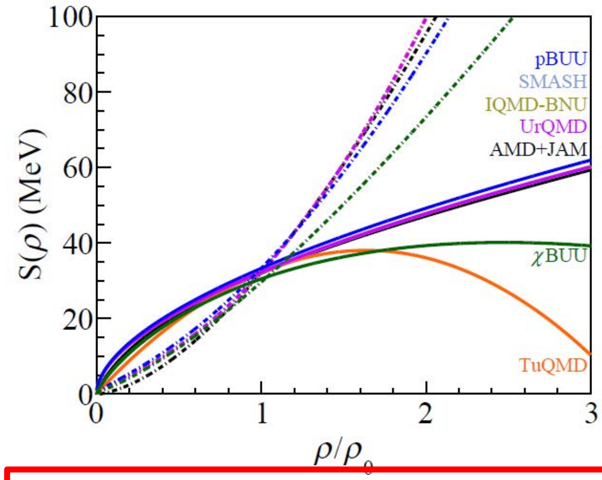
Differences in box calculation are understood and are tollerable. Now back to real HIC!

SπRIT Experiment: ^{132,112,108}Sn+^{124,112}Sn, 270 AMeV, central collisions,
p, light cluster and π yields and spectra (RIKEN, MSU TPC)

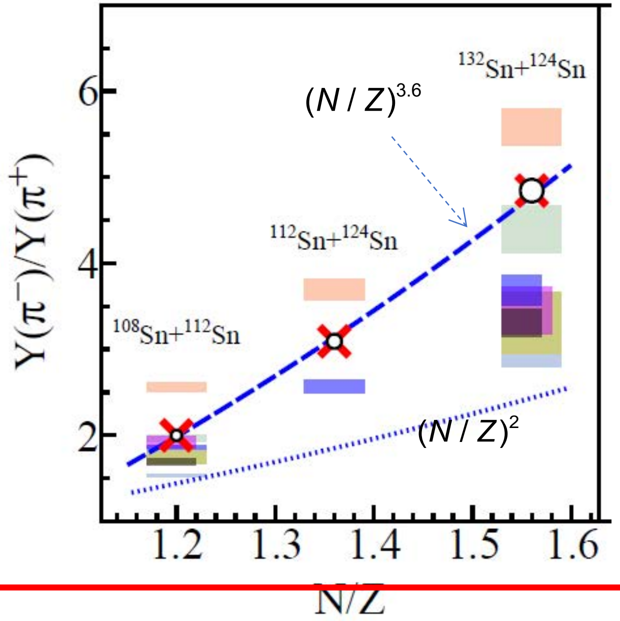
$\pi^{\pm}$ yields and yield ratios, symmetry energy at about $1.5\rho_0$

Transport calculations: predictions!
but now using realistic input, different in the codes, with two choices of the symmetry energy

soft and stiff symmetry energies used in the calculations
(solid and dashed curves for each codes (diff. colors))

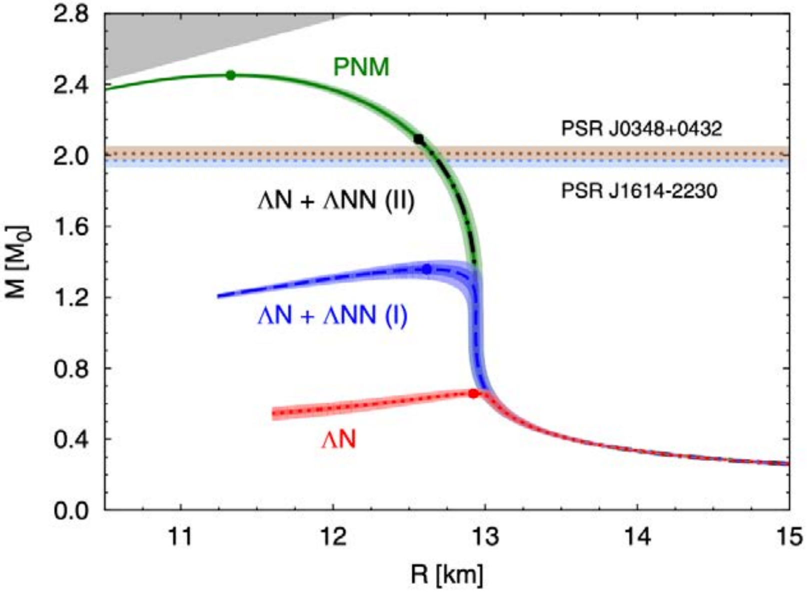


pion ratios
(height of boxes: diff. between soft snd stiff symm. energy)



findings:
- spread of calculations large, reason: treatment of π,Δ potentials, threshold effects,etc matter,
- sensitivity of calculations to symmetry energy small, expected to be better for spectra
- investigation in more detail in progress

Strangeness in Neutron Stars



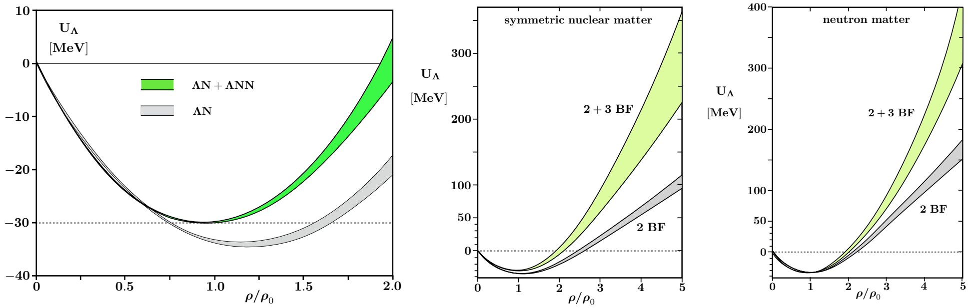
D. Lonardoni *et al.*, Phys. Rev. Lett **114** (2015) 092301.

- Presently available hypernuclei data do not provide stringent constraints on the three-body ΛNN interaction

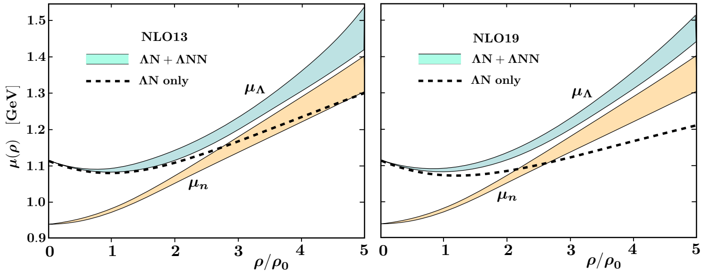
Hyperon-Nucleon Three body Forces and Strangeness in Neutron Stars

[D. Gerstung, N. Kaiser, W. Weise, Eur. Phys. J. A56 (2020) 175]

- ΛN interaction and ΛNN three-body forces from chiral EFT at NLO
- Convert ΛNN three-body forces into density-dependent ΛN potentials
- Solve coupled channel Bethe-Goldstone equation $\rightarrow$ single-particle potential $U_\Lambda(\rho)$ of Λ-hyperon in nuclear or neutron matter
- Constraint from hypernuclear phenomenology $U_\Lambda(\rho_0) \simeq -30\,\text{MeV}$

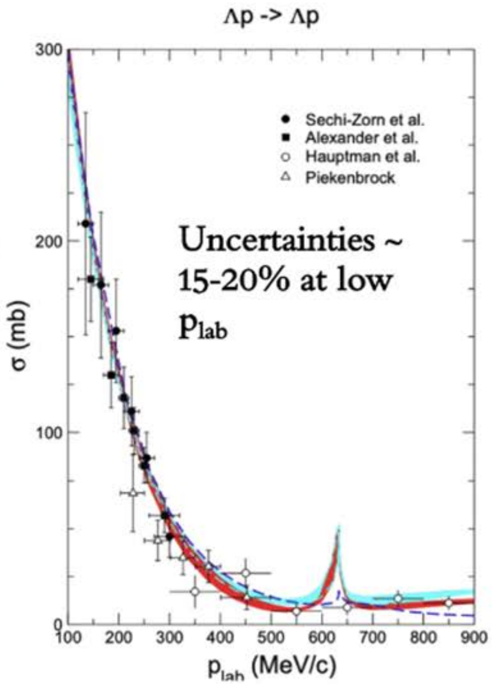


- With increasing density, ΛNN 3-body forces provide strong repulsion
- Λ formation in neutron star matter: $\mu_n(\rho) \geq \mu_\Lambda(\rho) = M_\Lambda + U_\Lambda(\rho)$



- Within errors: Λ formation may be pushed to very high densities $\rho > 5\rho_0$

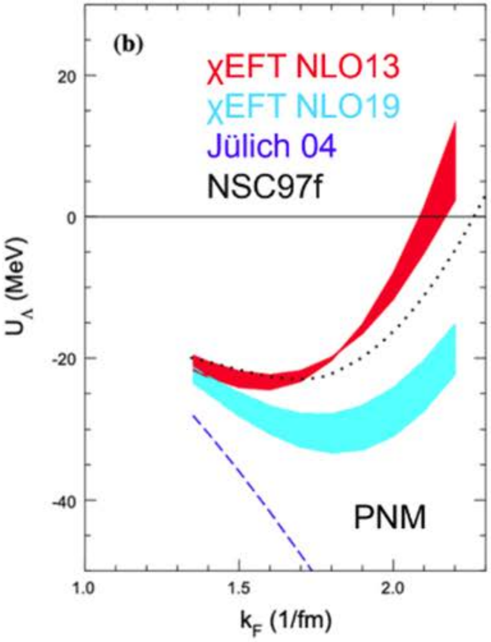
|S|=1: pΛ Interaction and role of the ΣN coupling



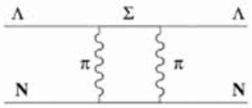
Uncertainties ~ 15-20% at low p_{lab}

NLO13: J.Haidenbauer, N.Kaiser et al., NPA 915, 24 (2013)

NLO19: J.Haidenbauer, U. Meiβner, Eur.Phys.J.A 56 (2020)



- pΛ interaction:
  - low-statistics scattering data and hypernuclei, not available at low momenta (plab> 100 MeV/c)
  - 2-body coupling to ΣN is experimentally not (**yet**) measured
- ΣN coupling strength deeply affects the behaviour of Λ at finite density



  - Relevance for EoS in NS ("hyperon puzzle") and for connection to role of ΛNN three-body interaction
- Updated NLO19 with weaker coupling strength in NΛ-NΣ leading to different Λ properties in nuclear matter

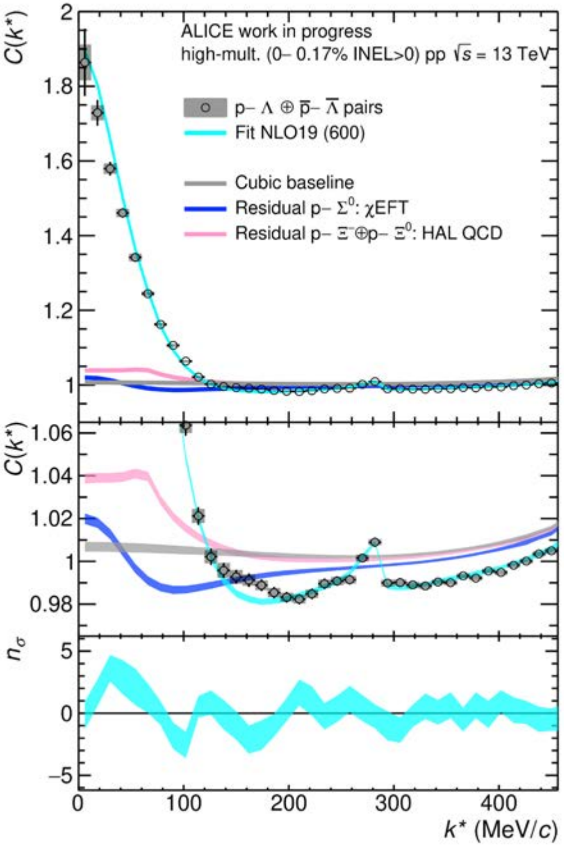
New p-Λ Measurements

A. Mihaylov, V. Mantovani-Sarti, L. Fabbietti (TUM)

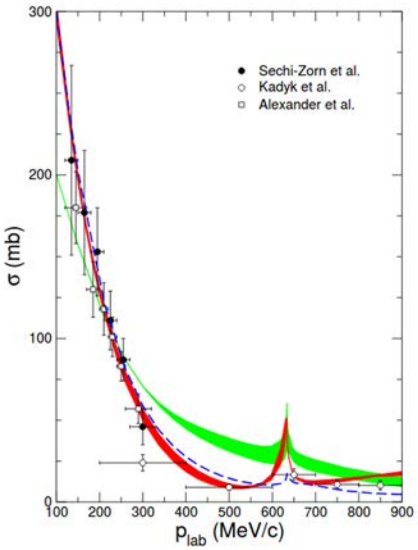
- Low statistics available in scattering data.
- Additional constraints from hypernuclei.
- Femto is the only high-precision tool!

First experimental observation of the coupling to N-Σ

Paper in preparation

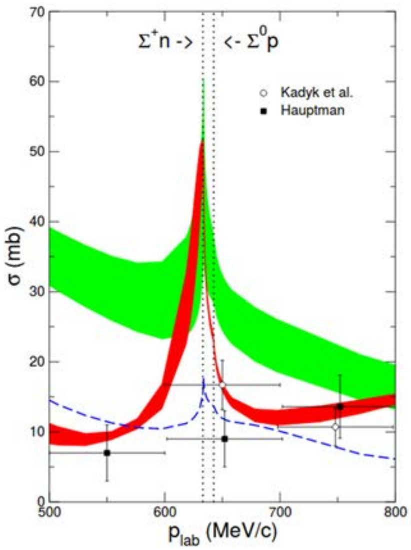


Λp -> Λp



Nucl.Phys.A 915 (2013) 24-58

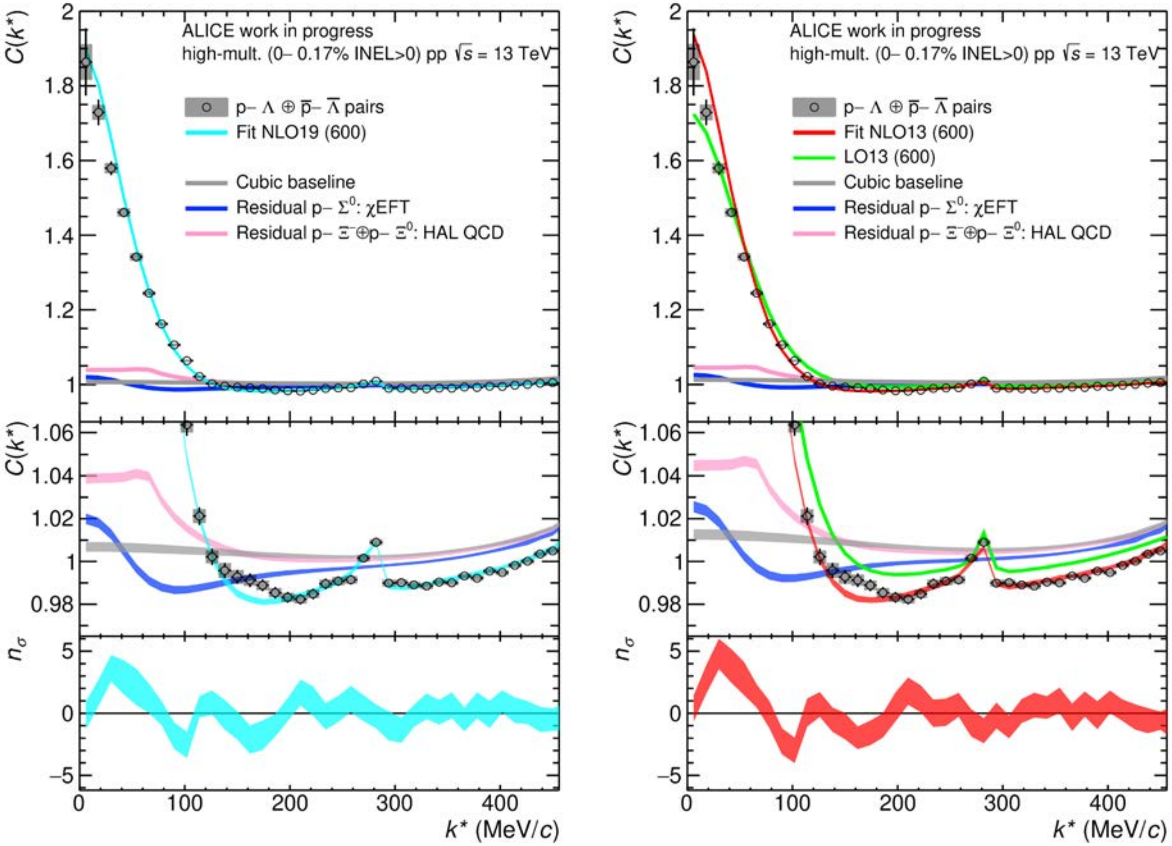
Λp -> Λp



Constraining power on χEFT

In p-Λ correlations

A. Mihaylov, V. Mantovani-Sarti, L. Fabbietti (TUM)

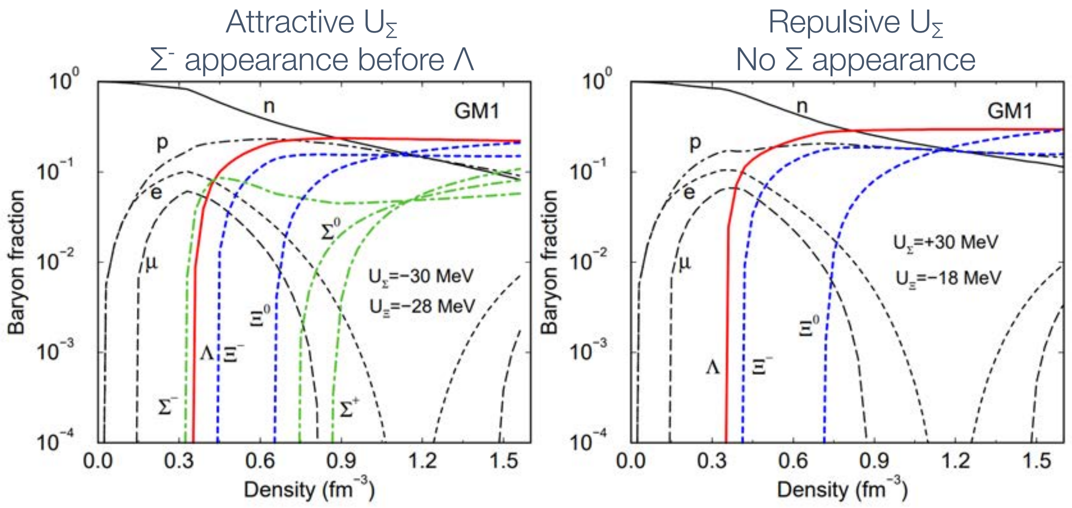


Paper in preparation

$p–\Sigma^0$ (→) $p–\Lambda$ (↓)	**χEFT**	Flat
LO13-600	3.4 (4.7)	7.0 (9.9)
NLO13-500	4.6 (7.4)	2.8 (3.2)
NLO13-550	2.7 (3.9)	1.6 (1.6)
NLO13-600	3.5 (3.5)	2.1 (2.2)
NLO13-650	3.3 (3.3)	2.6 (3.0)
NLO19-500	3.4 (4.4)	2.0 (2.0)
NLO19-550	2.7 (2.6)	1.4 (1.6)
NLO19-600	2.3 (2.4)	1.3 (2.0)
NLO19-650	2.3 (2.3)	1.7 (2.5)

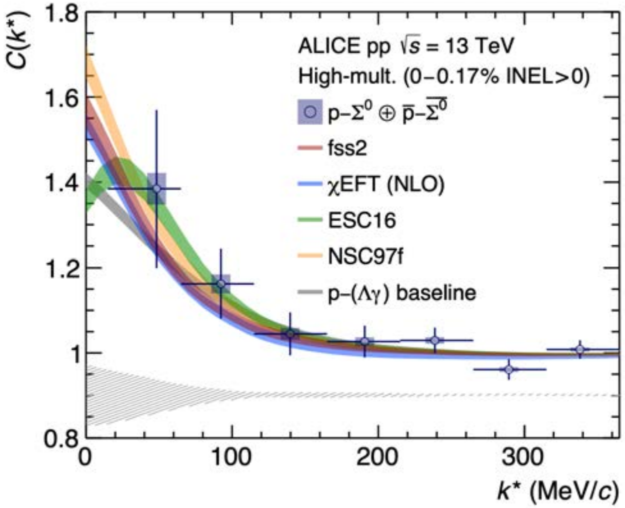
First measurement of the p–Σ^0 correlation function @ CERN

A. Mathis, L. Fabbietti (TUM)



J. Schaffner-Bielich, *Nucl. Phys.* A835 (2010) 279.

Phys. Lett. **B** 805 (2020) 135419

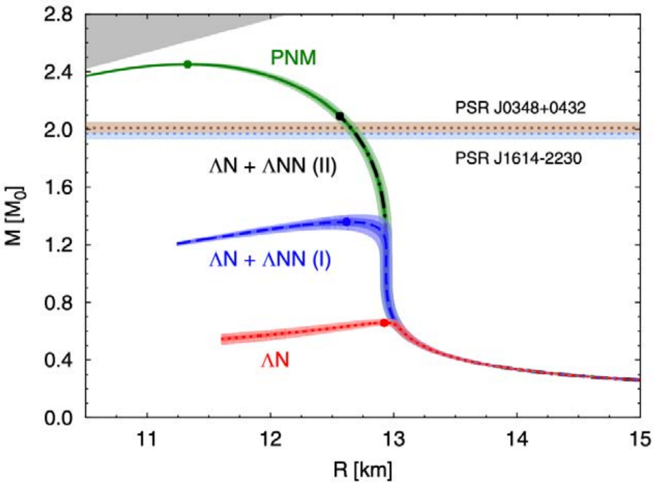


- **First measurement of the p–Σ^0 correlation function**
  - Challenging reconstruction of the decay $\Sigma^0 \rightarrow \Lambda\gamma$
  - p–Σ^0 interaction only shallow
    - Significant impact on neutron star EoS
  - Decisive measurements in LHC Run 3 and 4

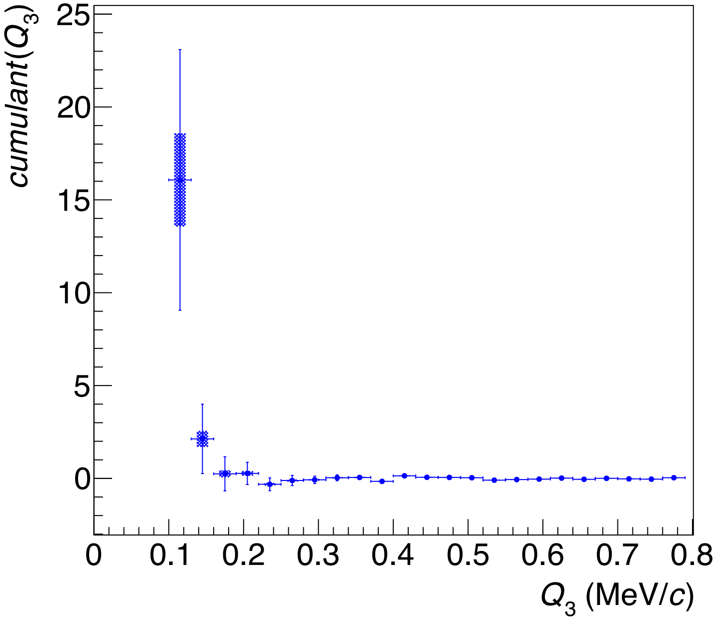
Model	U_Σ (MeV)	n_σ ($k^* < 150$ MeV/c)
NSC97f	-16.1	0.2 – 0.6
ESC16	-3.3	0.1 – 0.5
p–(Λγ) baseline		0.2 – 0.8
fss2	7.5	0.2 – 0.9
χEFT (NLO)	17.1	0.3 – 1.0

Three-body p–p–Λ femtoscopy

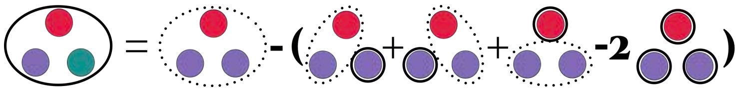
A. Mathis, L. Serksnyte, R. Del Grande, L. Fabbietti (TUM)



D. Lonardoni *et al.*, Phys. Rev. Lett **114** (2015) 092301.



- Presently available hypernuclei data do not provide stringent constraints on the three-body ΛNN interaction
- Non-zero cumulant demonstrates genuine three-body final-state interaction
  - First experimental results for the genuine 3-body force
- Improvement of the triplet count by dedicated trigger in LHC Run 3 by a factor ~800



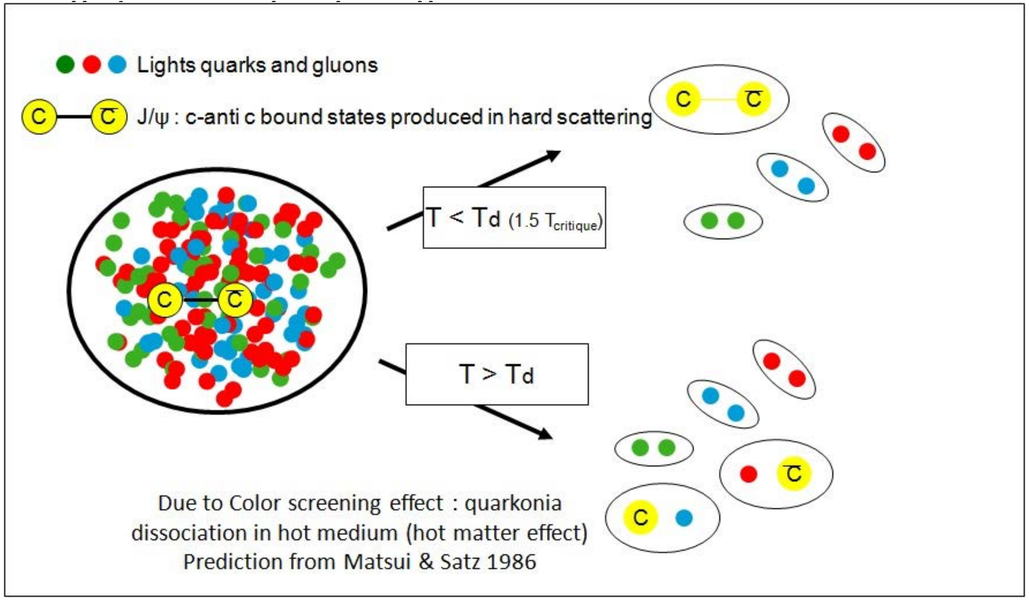
Quark Gluon Plasma and the Early Universe

The QGP refers to a state of matter where quarks and gluons are still interacting but not confined anymore

Why Extreme? Confinement Temperature T_C at which this deconfiment occurs ~160 MeV

Tc= 160 MeV <-> ~10.000 K (Sun Temperature = 6000 K)

It corresponds to the situation of few μs after the Big Bang and it can be recreated at



Due to Color screening effect : quarkonia dissociation in hot medium (hot matter effect)
Prediction from Matsui & Satz 1986

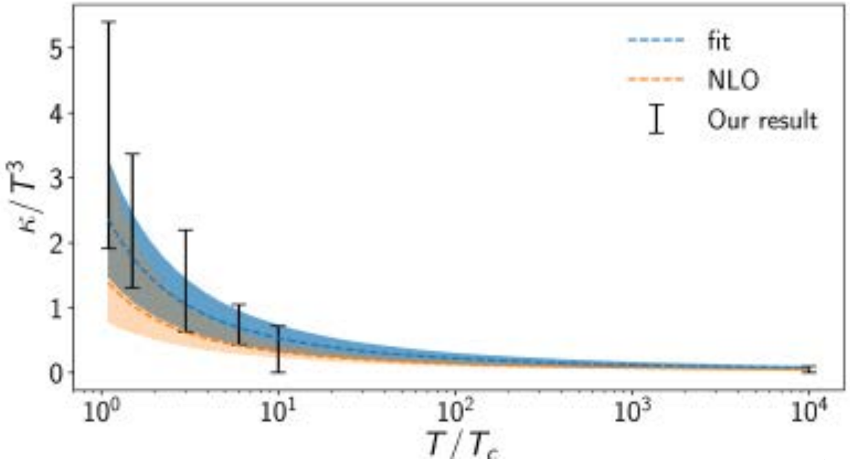
Hadrons containing only charm quarks (Quarkonia) are used to study the properties of the QGP, since c quarks are produced at the QGP formation point and they travel throught the QGP

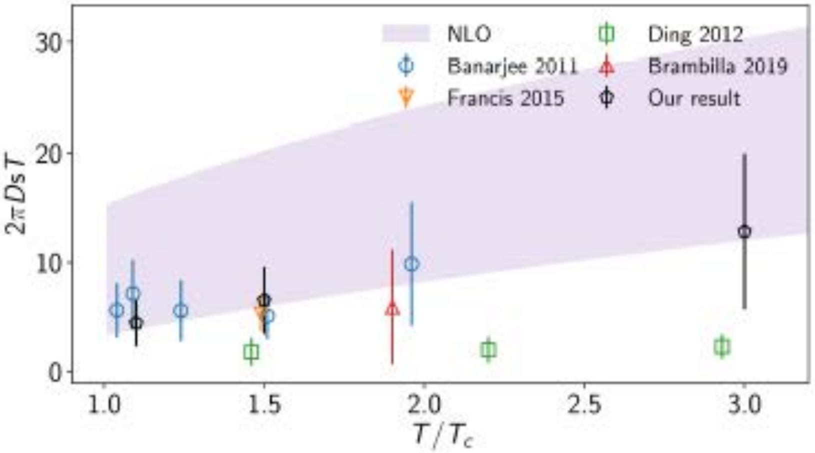
Heavy Quark Momentum Diffusion Coefficient from Lattice

N. Brambilla, V. Leino, P. Pétreczky, A. Vairo

Phys.Rev.D 102 (2020) 7, 074503

- Heavy quark behaves like Brownian particle in Quark Gluon Plasma.
- Experimental results for nuclear suppression factor R_{AA} and elliptic flow ν_2 can be explained by models depending on spatial diffusion coefficient D_{s}.
- We measure momentum diffusion coefficient $\kappa = 2T^2/D_{\mathrm{s}}$ with lattice simulations at C2PAP.
- Cannot be measured directly, instead measure Euclidean correlator and numerically estimate κ.





- Measure κ at unprecedented temperature range $T = 1.1 - 10^4\,T_{\mathrm{c}}$. T_{c} being the confinement temperature.

$$\frac{\kappa^{\mathrm{NLO}}}{T^3} = \frac{g^4 C_{\mathrm{F}} N_{\mathrm{c}}}{18\pi}\left[\ln\frac{2T}{m_{\mathrm{E}}} + \xi + C\frac{m_{\mathrm{E}}}{T}\right].$$

- The NLO perturbative estimate for κ (C=2.3302) is close to our results.
- We can fit temperature dependence of κ and get C=3.81(1.33)

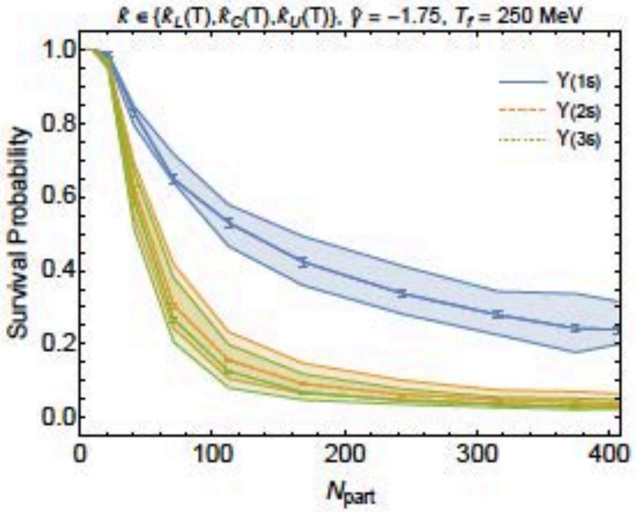
Heavy Quarkonium in Medium: Simulation Methods

N. Brambilla, M. Escobedo, M. Strickland, A. Vairo, P. Vander Griend, J. Weber

- heavy quarkonium states exhibit an inherent hierarchy of scales making them ideal probes of the medium formed in heavy ion collisions
- in a strongly coupled medium, evolution of the density matrix describing a bottomonium state takes the form of a Lindblad equation (Phys. Rev. D 97, 074009 (2018))

  $\frac{d\rho}{dt} = -i[H, \rho] + \sum_n \left(C_n \rho C_n^\dagger - \frac{1}{2}\{C_n^\dagger C_n, \rho\} \right)$

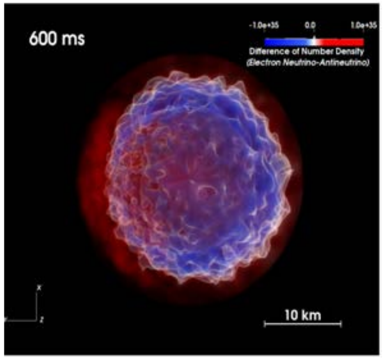
  where H is the quarkonium Hamiltonian and C_n are related to interactions with the medium
- the quantum trajectories method allows for a probabilistic solution to the Lindblad equation using Monte Carlo methods

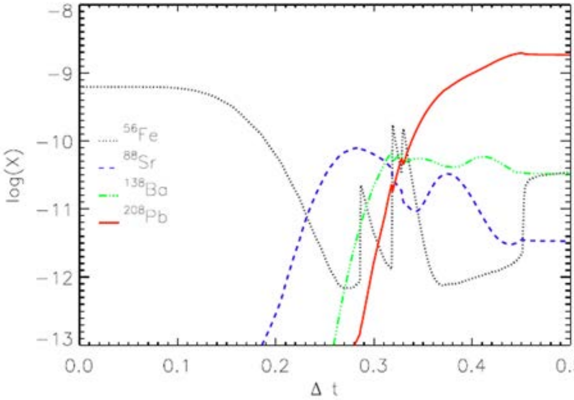


Preliminary results for R_{AA} of the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ using the quantum trajectories method (TUM-EFT 140/20).

- many individual wave functions are simulated and averaged to arrive at a solution of the Lindblad equation
- highly parallelizable allowing for less computationally expensive results

Which aspects of the Supernovae are we studying?





Study of neutrino gas

->Occurs in core-collapse SNe and binary NS mergers where matter is so dense that neutrinos are temporarily trapped

-> Flavor evolution strongly affected by nu-nu interaction: Nonlinear evolution

3D Simulations of SN explosion

-> Focus on the role played by neutrinos flavour conversion within the process

-> Muons-Axions coupling ?

Nucleus synthesis following Supernovaee

Collective Neutrino Conversion (MPP Group G. Raffelt)

- “Matter” under extreme conditions: Here refers to neutrino gas
- Occurs in core-collapse SNe and binary NS mergers where matter is so dense
  that neutrinos are temporarily trapped
  (only astrophys. environments where neutrinos form a gas in thermal equilibrium)
- Flavor evolution strongly affected by nu-nu interaction: Nonlinear evolution

Questions:

- Practical effects in compact objects (cc explosion, nucleosynthesis, detection)
  → Collaboration with Janka group at MPA
- Theoretical description
  (e.g. mean-field kinetic equation adequate description?
  related to nuclear many-body systems, studied by nuclear theorists such as
  Volpe, Balantekin, Fuller, …, i.e. methodological relation to nuclear physics)
- Collective modes of propagation in linear regime (studied at MPP group)
  Which conditions (spectrum, angle distribution) support collective modes?
  e.g. “fast modes” driven by appropriate angle-distribution
- Role of matter background (e.g. turbulence couples different modes)

Collective Nu Conversion (MPP Group 2019–2020)

- T. Stirner,
  Fast neutrino flavour conversions: Stability analysis in the linear regime,
  PhD Thesis, July 2020, LMU

- F. Capozzi, G. Raffelt & T. Stirner:
  Fast neutrino flavor conversion: Collective motion vs. decoherence,
  JCAP 1909 (2019) 002 [1906.08794]

- R. Glas, H.-Th. Janka, F. Capozzi, M. Sen, B. Dasgupta, A. Mirizzi & G. Sigl,
  Fast neutrino flavor instability in the neutron-star convection layer of three-dimensional supernova models, PRD 101 (2020) 063001 [1912.00274]

- F. Capozzi, M. Chakraborty, S. Chakraborty & M. Sen:
  Fast flavor conversions in supernovae: The rise of mu-tau neutrinos [2005.14204]

- S. Abbar:
  Searching for fast neutrino flavor conversion modes in core-collapse supernova simulations,
  JCAP 05 (2020) 027 [2003.00969]

- S. Abbar:
  Turbulence fingerprint on collective oscillations of supernova neutrinos [2007.13655]

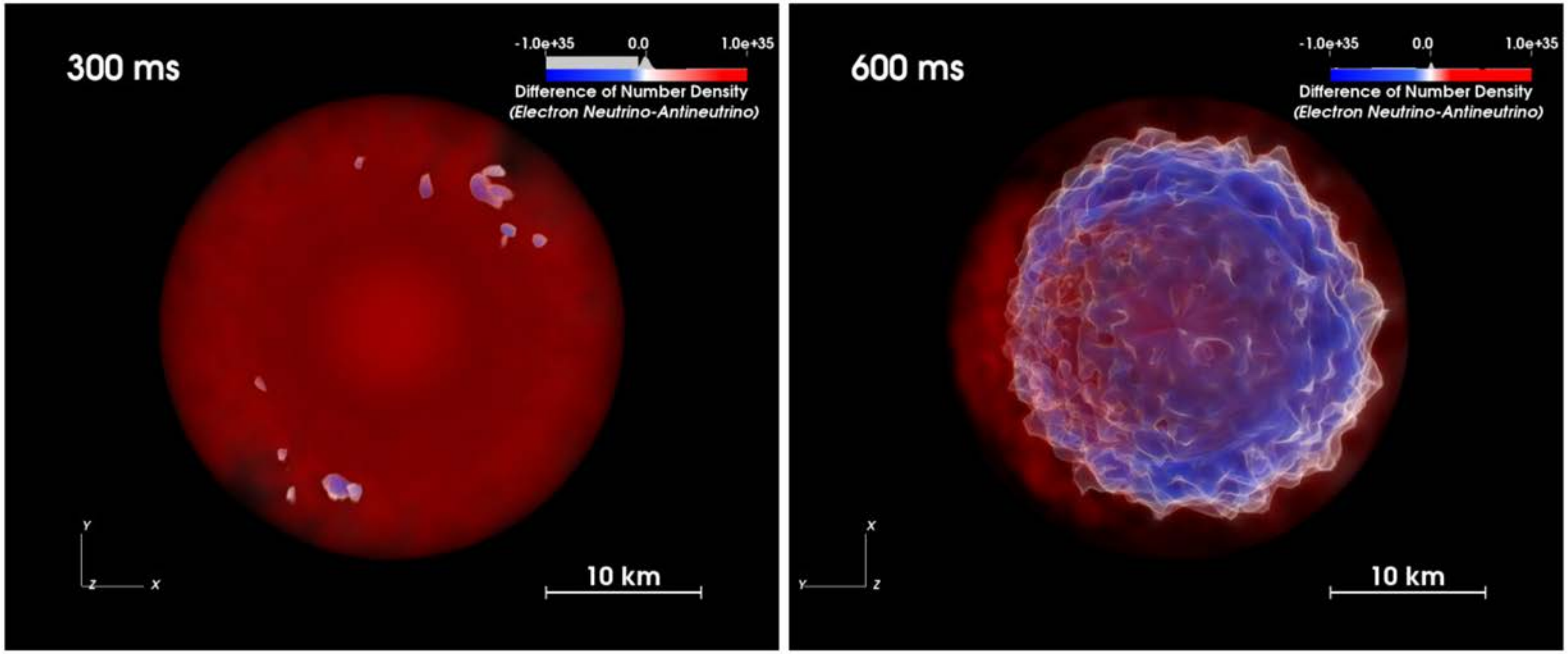
Fast Flavor Conversion in Dense Neutrinos?

- Neutrino flavor conversion *not included* in traditional transport simulations (core-collapse SNe, neutron star mergers)
- Potentially relevant for energy transfer (explosion mechanism), nucleosynthesis in neutrino-driven outflows, and for nu signal of next SN
- Large matter effect suppresses traditional flavor conversion in deep layers, MSW conversion at hundreds km studied by post-processing

- However, interacting dense neutrino gas supports collective flavor modes
- Nontrivial angle-distribution of neutrinos supports "fast flavor modes" with instabilities on scales of meters
- Amounts to pair conversion of neutrino-antineutrino pairs of different flavors on refractive level (order G_F)
- Relevant conditions fulfilled in realistic simulations?
- Do we have the right criteria?
- If effect is real, how does it impact practical core-collapse physics?

Evidence for Fast Flavor Instability in 3D Supernova Models

(T. Janka, R. Glas MPA)

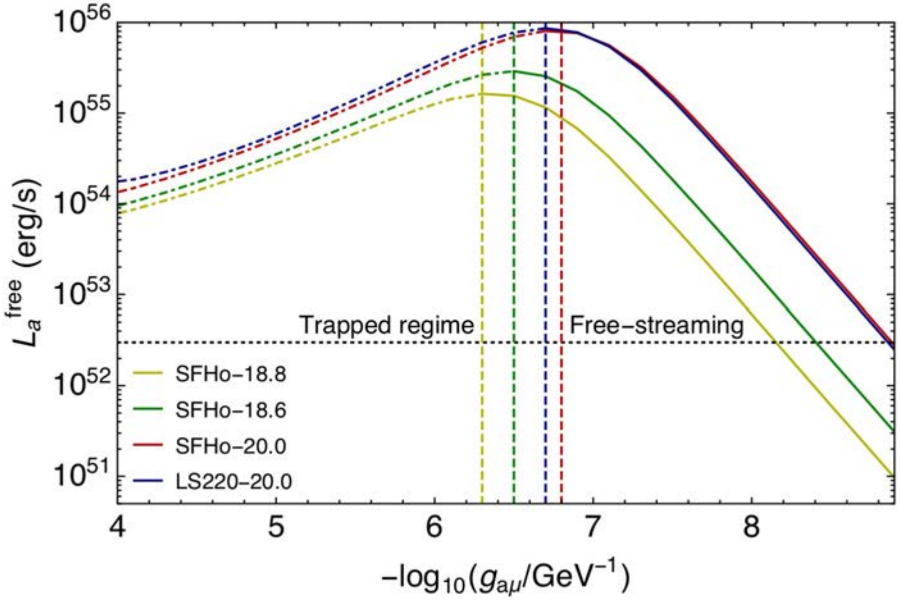


Glas et al., PRD 101 (2020) 063001

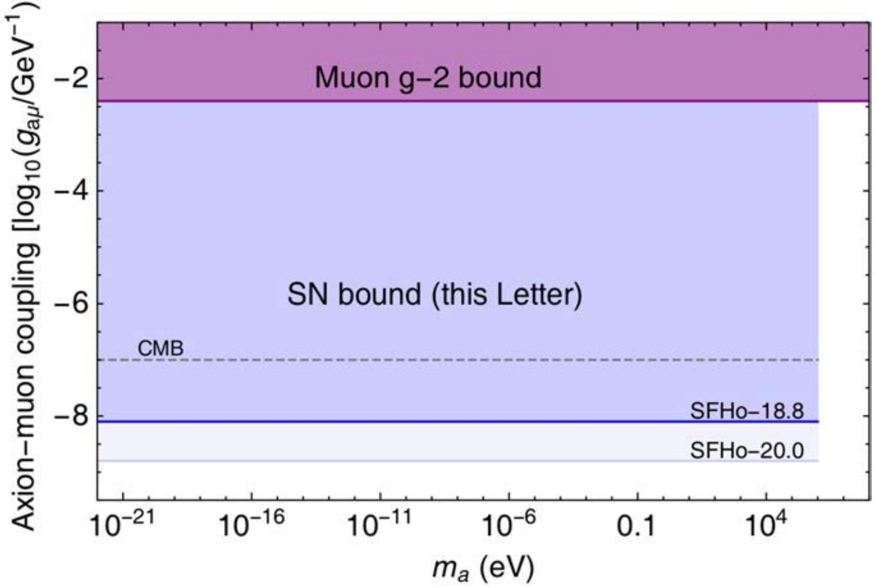
- Fast flavor instability is diagnosed inside of newly formed neutron stars (NSs).
- Instability regions are thin boundary layers of volumes where n($\bar{\nu}_e$) > n(ν_e)
- Regions grow with time in convective shell of the NS, favored by decreasing electron fraction and high temperatures.

Muons in Supernovae:
Implications for the Axion-Muon Coupling

(Janka, Bollig (MPA))



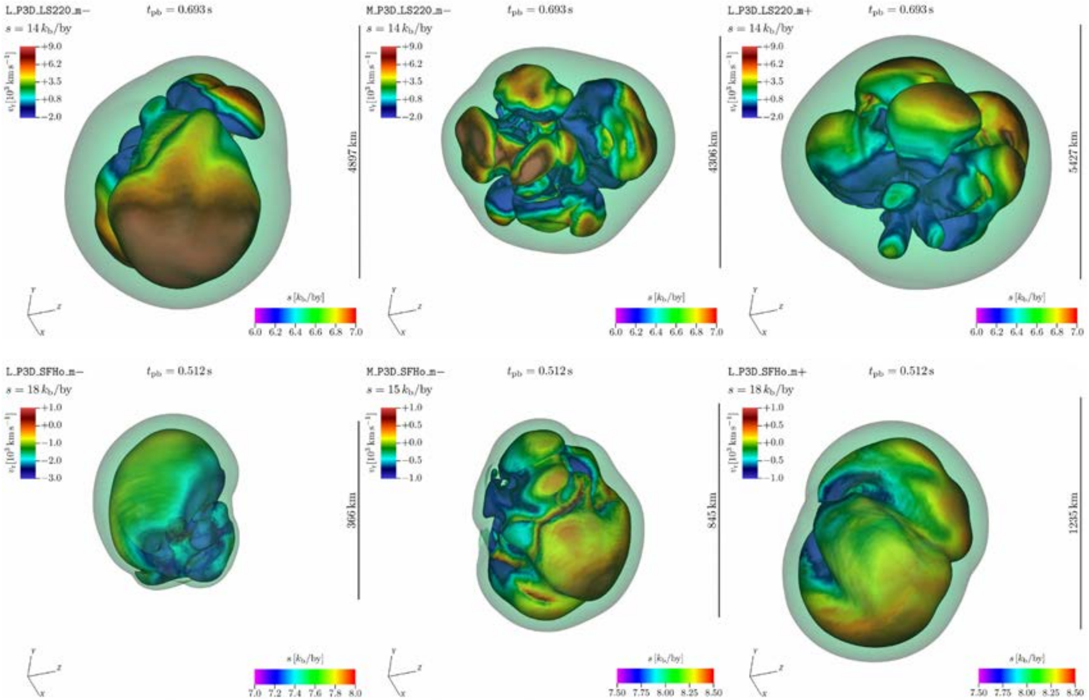
Bollig et al., PRL 125 (2020) 051104



- High temperature and electron degeneracy in supernova allow for large abundance of muons in newly formed neutron star.
- Axions, coupling to muons, could be copiously emitted (mainly by Compton scattering and muon-proton bremsstrahlung) and thus cool the supernova core.
- Observation of the cooling rate of Supernova 1987A (“cooling constraint”) places robust bound on axion-muon coupling 6 orders of magnitude stronger than current experiments.

Muons in Supernovae: Implications for the Explosion Mechanism

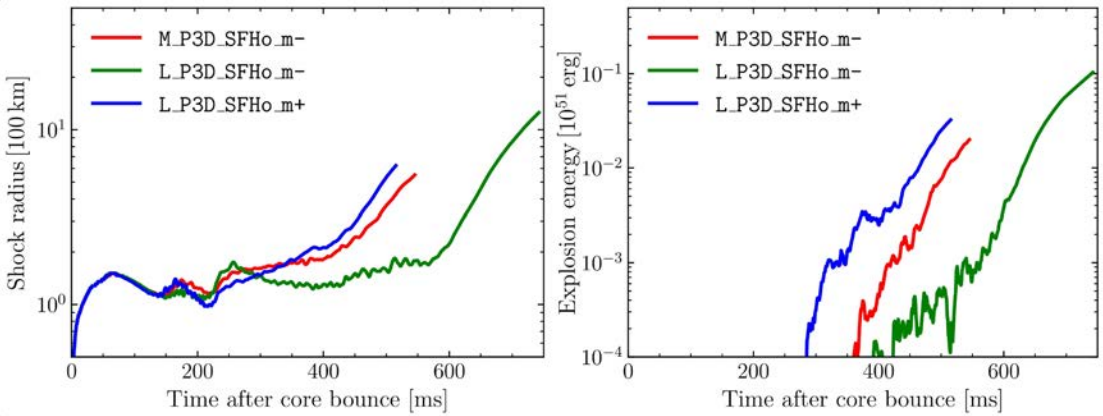
(Janka, Bollig (MPA))



No muons **No muons** **With muons**

Bollig et al., in preparation

- Muons accelerate the onset of the explosion.
- Muons facilitate a faster rise of the explosion energy.
- Muons over-compensate the delay of the explosion by low resolution.

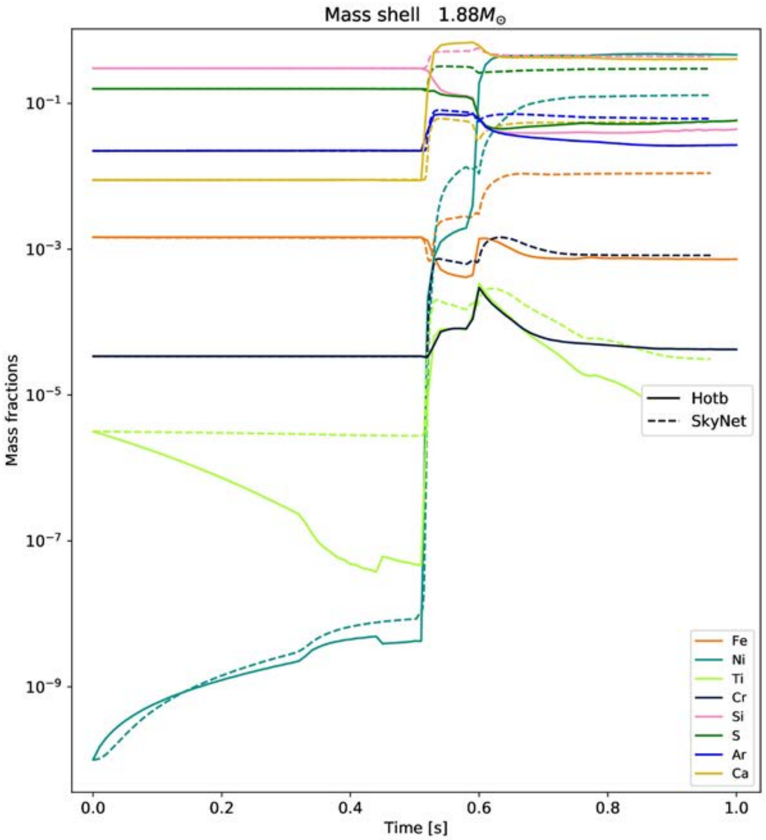


- **Green:**
  Low resolution (4 degrees), no muons
- **Red:**
  2 degree angular resolution, no muons
- **Blue:**
  4 degree resolution with muons

Stellar astrophysics and the origin of elements

Nucleosynthesis in type II supernovae

(Liliya Imasheva, Janka, Weiss)



For global view about element production in SNII simulations for large range of mass and composition parameters needed. Possible only with 1d-models and artificial explosions (several options)

Goal: investigate variations, uncertainties, robust results

example nucleosynthesis over time in selected mass shell in a “piston-driven” SNII explosion model for built-in and post-processed, extended nuclear network

Stellar astrophysics and the origin of elements

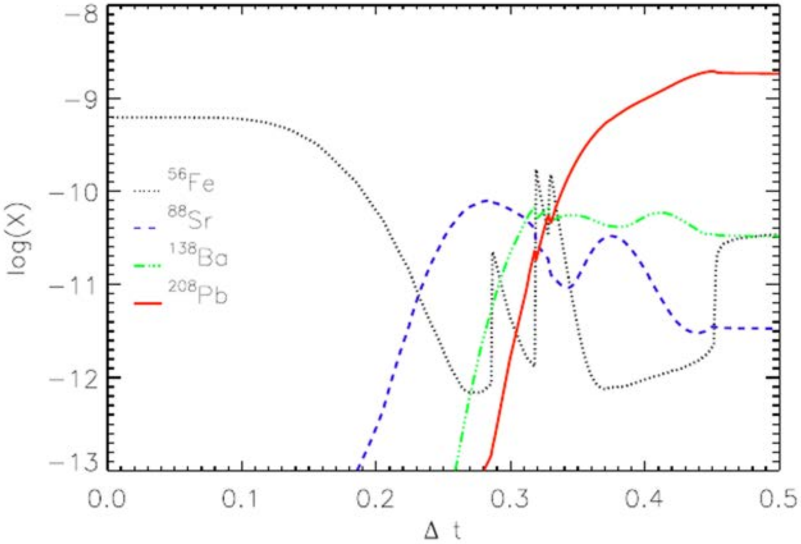
Slow neutron capture processes to produce elements in AGB stars

(Bryce Remple, Weiss)

(PhD starting 01/2021)

Asymptotic Giant Branch stars produce heavy elements in n-capture processes, but models suffer from uncertainties in mass loss, atmospheric conditions, mixing processes, and nuclear reaction rates

Goal: develop updated stellar models and investigate
influence of n-capture rate uncertainties

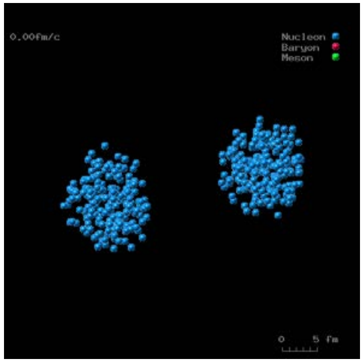


s-process element production in low-mass, low-metallicity star;
Sr, Ba, Pb are key elements
for three s-process components

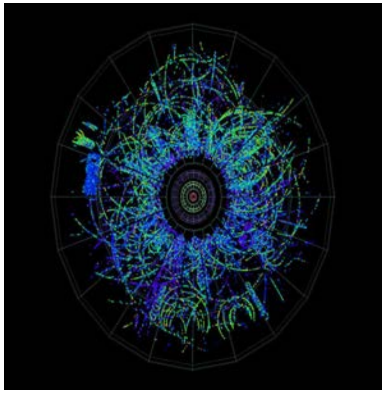
Note: both types of stars are site of C, N, O, S, P production!

Connector 7: Matter under Extreme Conditions

Heavy Ion Collisions at GeV energies



Heavy Ion Collisions at TeV energies



- Several step forward achieved in 2020
- New people starting in 2021
- Plan to work even more on connections between the projects

Supernovae Explosion

Neutron Stars