Microphysics in Binary Neutron Star Mergers: Present Status and Future Challenges

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Astrophysical neutrinos and the origin of the elements, INT 23-2, Seattle

Introduction

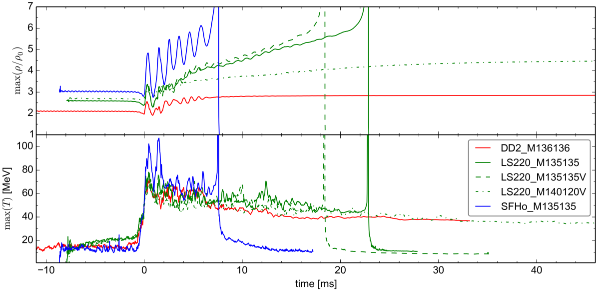
Microphysics in BNS mergers

During a BNS merger …

- ...dense matter becomes hot

$$T_F \sim 30 \text{ MeV} \left(\frac{\rho}{3 \times 10^{14} \text{ g cm}^{-3}} \right)^{2/3}$$

- … weak reactions activate & ν emission is the most relevant source of cooling
- … τ_ν ranges between ~ 0 and $\sim 10^4$ for relevant neutrino energies: transport problems
- … non-trivial effect on matter composition: $n \leftrightarrow p$ through charged current processes



Perego, Bernuzzi, Radice 2019 EPJA

BNS mergers on thermodynamics diagrams

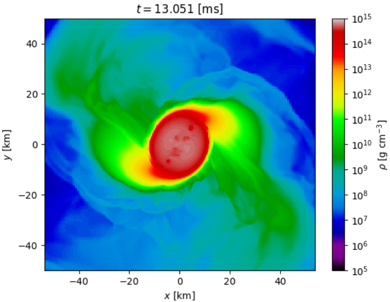
BNS simulation performed with the WhiskyTHC code

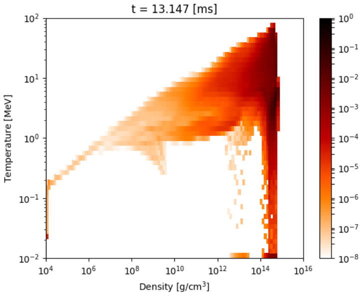
Radice+ 12,14,15

$$M_1 = M_2 = 1.364\, M_\odot$$

DD2 EOS, leakage+M0 scheme for neutrinos

at each time, mass weighted histograms in the ρ-T-Y_e or ρ-s-Y_e plane

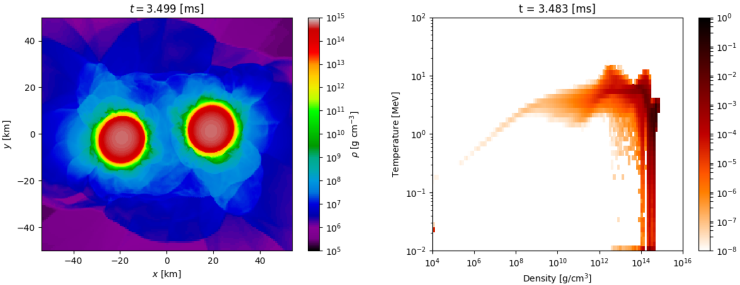




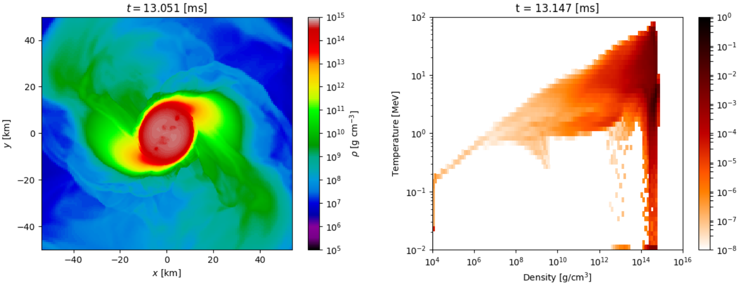
movies at www.youtube.com/channel/UChmn-JGNa9mfY5H5938jnig

BNS mergers on thermodynamics diagrams

inspiral

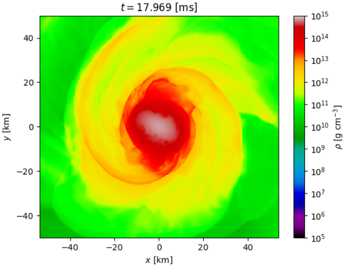


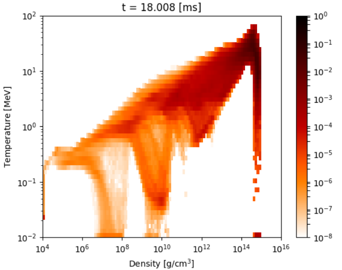
$t(T_{\rm peak})$



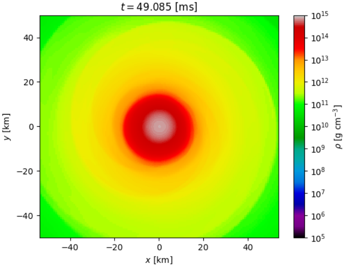
BNS mergers on thermodynamics diagrams

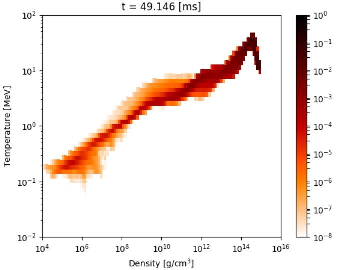
$t \gtrsim t_{\rm dyn}$





$t \gg t_{\rm dyn}$





Perego,Bernuzzi,Radice EPJA 2019

Which EOSs for BNS merger simulations?

finite-T, composition dependent EOSs in Nuclear Statistical Equilibrium

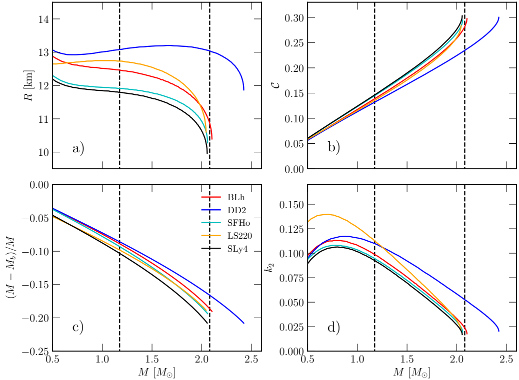
- relevant ranges
  - baryon density
$$10^{-12} n_0 \lesssim n_b \lesssim 10 n_0$$
$(n_0 \approx 0.16 \text{ fm}^{-3} \rightarrow \rho_0 \approx 2.6 \times 10^{14} \text{g cm}^{-3})$
  - temperature:
$$0.1 \text{ MeV} \lesssim T \lesssim 150\text{MeV}$$
  - isospin asymmetry:
$$0.01 \lesssim Y_p \lesssim 0.5$$
- relevant particle content
  - minimal content:
$$n \quad p \quad e^{\pm} \quad \gamma$$
  - additional (possibly relevant) content:
$$\text{hyperons} \quad \text{quarks} \quad \mu^{\pm} \quad \pi^{\pi,0}$$
- usually, in tabulated form

Which EOSs for BNS merger simulations?

So far, relatively reduced amount of EOSs for simulations

- relativistic mean field, e.g. HS(DD2) or SFHo — Hempel+ ApJ 12, Steiner+ ApJ 13
- Skyrme interaction, e.g. LS220 or SRO(SLy4) — Lattimer& Swesty NuPhA 91,Schneider+ PRC 19
- microscopic approaches (e.g. BHF extension at finite T, e.g. Bethe-Goldstone approach), e.g. BLh — Logoteta+ A&A 2021

$T = 0$ and ν-less weak equilibrium EOS:



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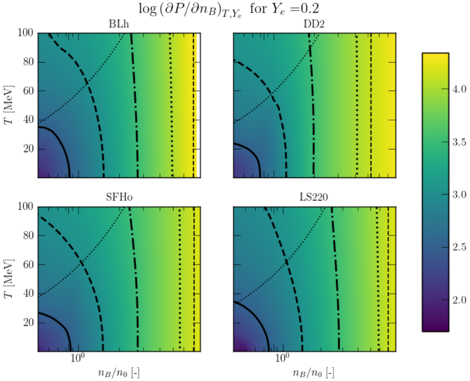
$T > 0$ and arbitrary composition EOS



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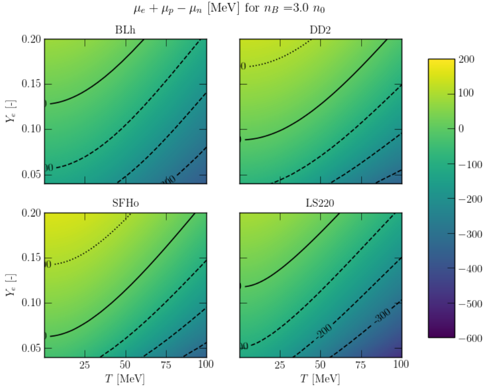


Which ν transport for BNS merger simulations?

transport scheme

- leakage schemes (LKs)

  e.g. O'Connor & Ott 2011,Perego+ 2015 ApJS
- hybrid moment schemes (LK+M0, LK+M1)

  e.g. Sekiguchi+ 2014 PRD, Radice+ 2016,2018 MNRAS
- gray two moments (M1) scheme

  e.g. Foucart+ 2014 PRD, Radice+ 2022 MNRAS
- spectral two moments (M1) scheme

  e.g. Kuroda+ ApJS 16, Cheong+ ApJS 22
- Monte Carlo schemes

  e.g. Richers+ ApJS 2015,Foucart+ ApJ 2020,2021

rates & opacities

- minimal set of reactions

$$p + e^- \leftrightarrow n + \nu_e$$

$$n + e^+ \leftrightarrow p + \bar{\nu}_e$$

$$N(+N) + \nu \leftrightarrow N(+N) + \nu$$

$$N + N \leftrightarrow N + N + \nu + \bar{\nu}$$

$$e^- + e^+ \leftrightarrow \nu + \bar{\nu}$$

- other (relevant?) reactions
  - scattering off $e^{\pm}$
  - reactions on μ's, π's, hyperons & quarks
- energy dependent → grey rates?
- often, simplified expressions or tabulated rates at equilibrium

Outline of the (rest of the) talk

- microphysics is a crucial and unavoidable ingredient of BNS merger simulations to correctly interpret observations
- BNS mergers and their multimessenger observables are unique laboratory for dense matter physics

1. impact of microphysics on observed event modeling
    - Sr and He production in GW170817

   Perego+ ApJ 2022

2. probing nuclear incompressibility in ultra-dense matter

   Perego+ PRL 2022

toward end-to-end modeling of observed events:

GW170817

Strontium (or Helium) in AT2017gfo early spectra?

- observed spectra from AT2017gfo
  - 1.5-4.5 day: identification of P-Cygni lines in spectrum
  - possible lines: SrII or HeII line
- spectra modeling to estimate Sr/He mass in GW170817 ejecta
  - Watson *et al*, Nature, 2018:

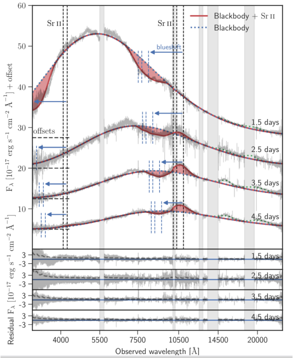
$$M_{\rm Sr} \sim 1 - 5 \times 10^{-5} M_\odot$$

  - Gillanders *et al* MNRAS 2022:

$$M_{\rm Sr} \gtrsim 1.2 \times 10^{-5} M_\odot$$

  - Tarumi *et al* arxiv 2023:

$$M_{\rm Sr} \sim 4 \times 10^{-4} M_\odot \quad \text{or} \quad M_{\rm He} \sim 8 \times 10^{-5} M_\odot$$



Sr in AT2017gfo spectra: Watson *et al* Nature 2018

- do we expect Sr or He in GW170817 ejecta? If yes, how much? Does this say something about this event?

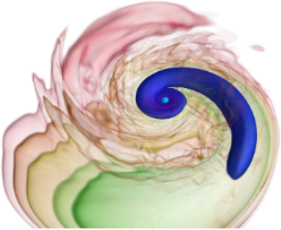
Modeling of GW170817

Simulations targeted to GW170817 ($\mathcal{M}_{\rm chirp} = 1.188 M_\odot$):

Nedora+ 2021 ApJ, Bernuzzi+2020 MNRAS

- 2 distinct binaries, $q = M_B/M_A = [1, 0.56]$
- GRHD (WhiskyTHC code) Radice+ 2011,13,14
- finite-T, composition dependent nuclear EOSs: HS(DD2) & BLh

  CompOse & stellarcollapse websites, Logoteta *et al* 2021
- neutrino treatment Radice 2016 MNRAS
  - leakage in opt. thick conditions
  - M0 in opt. thin conditions
- w and w/o effective treatment for turbulent viscosity (GRLES) Radice 2018 ApJL
- multiple resolutions

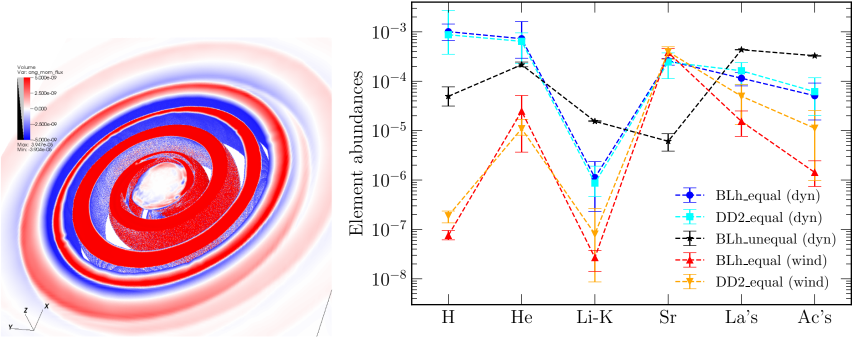


Bernuzzi *et al.* MNRAS 2020

Nucleosynthesis in the ejecta

- all models produce dynamical ejecta
- $q = 1$ models produce long-lived remnant & spiral wave wind ejecta
- extraction of dynamical and spiral wave wind ejecta properties
- calculation of expected nucleosynthesis yields using `Skynet`

Lippuner & Roberts ApJSS 2017



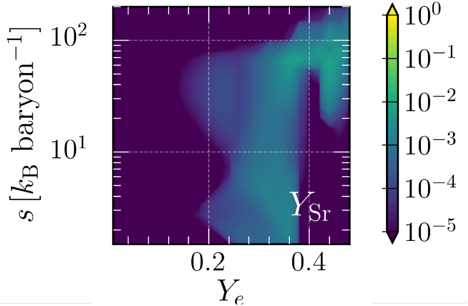
Left: Nedora *et al*, ApJL 2019; Right: Perego *et al*, ApJ 2022

A constraint on GW170817 remnant survival time?

How much Sr is produced in targeted simulations?

- Sr robustly produced for $0.2 \lesssim Y_e \lesssim 0.4$

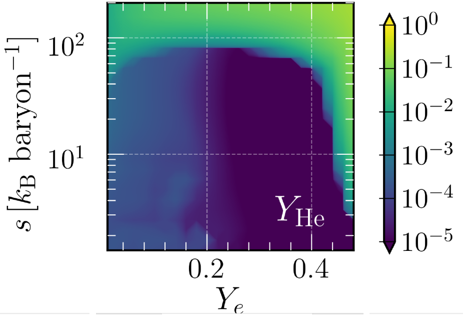
  Sr abundance for $\tau \sim 10$ ms →



- $q = 1$ models: $m_{\rm Sr,dyn} \approx 3 \times 10^{-5} M_\odot$
- $q \ll 1$ models: $m_{\rm Sr,dyn} \approx 3 \times 10^{-6} M_\odot$ → BNS model disfavored
- wind contribution ($\dot{M}_{\rm wind} \approx 0.16 M_\odot$/s and $X_{\rm Sr,wind} \approx 0.034$):
  - if $m_{\rm Sr} \sim 5 \times 10^{-5} M_\odot$, $\Delta t_{\rm wind} \lesssim 4$ ms
  - if $m_{\rm Sr} \sim 4 \times 10^{-4} M_\odot$, $\Delta t_{\rm wind} \lesssim 69$ ms
- our results suggest GW170817 remnant survived only a few tens of ms

He in kilonova spectra?

- He production mechanism(s):
  1. high entropy or high Y_e conditions
     - α-rich freeze-out
  2. low entropy, low Y_e conditions
     - β-decay of n, producing $d \rightarrow t \rightarrow {}^4\mathrm{He}$
     - α-decay of very heavy elements

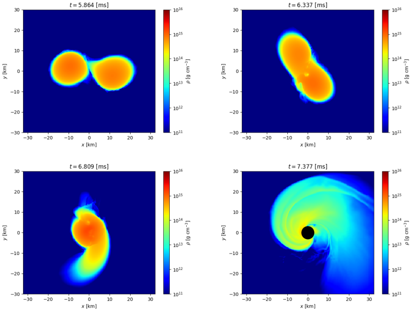


- He amount in $q = 1$ models:
  1. $m_{\rm He,dyn} \approx$ 3-8 $\times 10^{-6} M_\odot$
  2. $X_{\rm He,wind} \approx 0.1\%$
- He observable features:
  - no visible signature using `TARDIS` in LTE or NLTE tuned to SNIa
    Kerzendorf & Sim MNRAS 2014, Vogl *et al* 2020 A&A
  - He spectral features require strong NLTE effects & ×10 more mass Tarumi+ 23

Probing nuclear incompressibility through prompt collapses

The relevance of prompt collapse (PC)

- PC: sudden BH formation at merger
  - absence of remnant bounce: GW-quiet post merger
  - peculiar EM counterparts
    - symmetric BNS: EM quiet
    - highly asymmetric BNS: BHNS-like kilonova
- very likely …
  - …GW170817 was not a PC
  - …GW190425 was a PC



snapshots around merger for 1.305 $M_\odot$-1.535 $M_\odot$ simulation with SFHo EOS

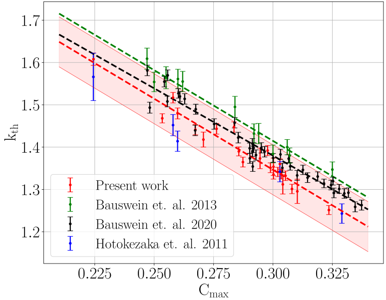
When does PC occur?

$q = 1$, non-spinning ($\chi = 0$) BNSs:

$$M > M_{\rm th} = k_{\rm th} M_{\rm max}^{\rm TOV}$$

$k_{\rm th}$ correlates with several EOS-dependent NS properties, e.g. $C_{\rm max}$ or $R_{1.6}$

Hotokezaka+11 PRD, Bauswein+12 PRL, Koeppel+19 ApJL, Kashyap+22 PRD



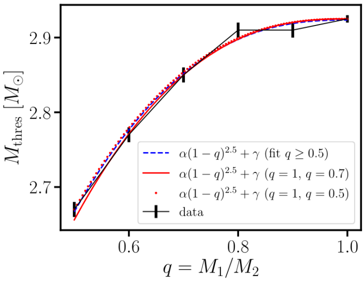
Kashyap+22 PRD

$q \neq 1$, $\chi \neq 0$ BNSs

$$M > M_{\rm th}(q,\chi) = k_{\rm th}(q,\chi) M_{\rm max}^{\rm TOV}$$

- $M_{\rm th}$ decreases for small q & χ, due to lower rotational support
- quasi-universal behavior?
- non-monotonicity at $q \lesssim 1$?

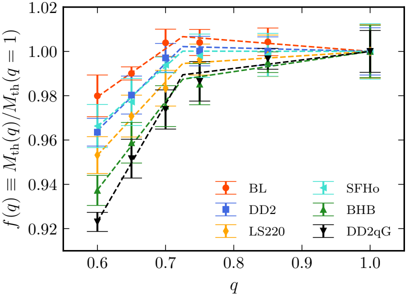
Bauswein+20,21 PRL & PRD; Tootle+21 ApJL, Kölsch+22 PRD



Bauswein+21 PRD

PC in asymmetric, irrotational BNSs

- large simulation campaign (~ 250) to determine $M_{\rm th}(q)$
- 6 EOSs and 6 mass ratios
- two regimes, separated by $\tilde{q} \approx 0.725$
- global decrease for decreasing q, but
  - non-trivial EOS dependence
  - clear non-monotonic behavior for $q > \tilde{q}$ for some EOSs
- double linear fit



Perego et al PRL 2022

$$f(q) = \begin{cases} \alpha_l q + \beta_l & \text{if } q < \tilde{q}\,, \\ \alpha_h q + \beta_h & \text{if } q \geq \tilde{q}\,. \end{cases}$$

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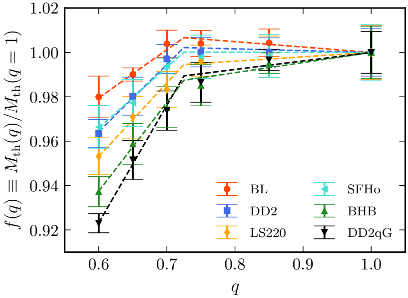
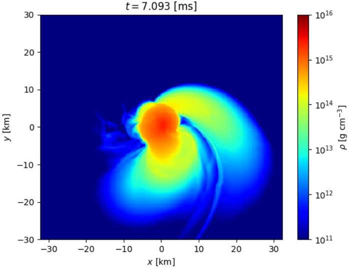


Perego et al PRL 2022



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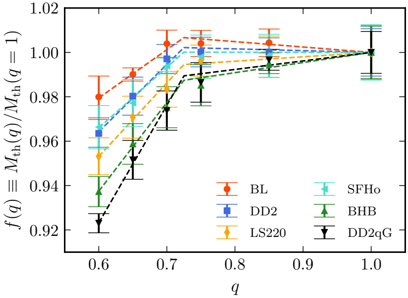

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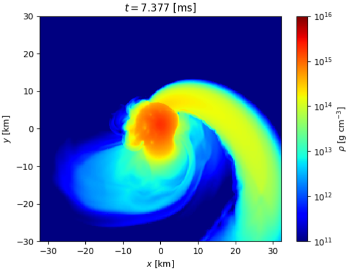


The role of nuclear incompressibility

What is missing?

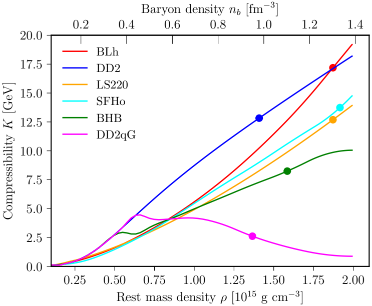
- (prompt) collapse: competition between gravity and matter incompressibility
- nuclear incompressibility:

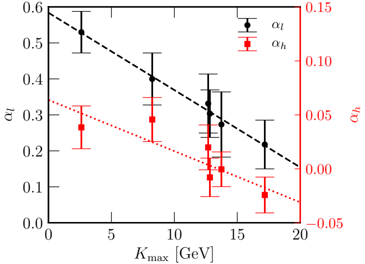
$$K(n_b,\delta) \equiv 9 \frac{\partial P}{\partial n_b}\bigg|_{T=0,\delta=\mathrm{const}} .$$

- clear correlation of α's with

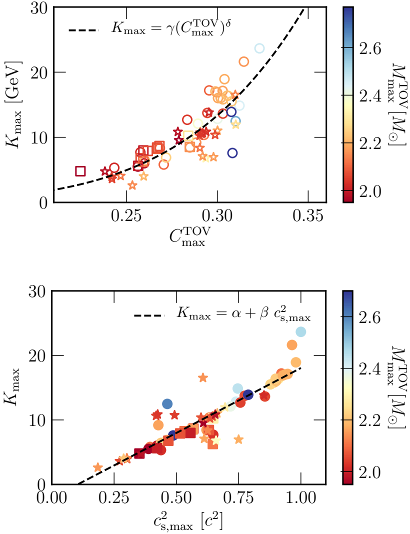
$$K_{\mathrm{max}} = K(n_{b,\mathrm{max}}^{\mathrm{TOV}}, \delta_{\mathrm{eq}})$$

- measurement of M_{th} at two q's directly provide K_{max}





Quasi-universal relations involving incompressibility



- $K_{\rm max}$ correlates with NS and EOS properties, e.g.
  - $C_{\rm max}$
  - $c^2_{\rm s,max}$
- $K_{\rm max}$ possibly provides information on high density composition:
  - $K_{\rm max} \gtrsim 15$GeV points to purely hardonic EOSs
  - possibly, $K_{\rm max} \gtrsim 12$GeV