Heavy ion collisions and cosmology
Different systems – common challenges

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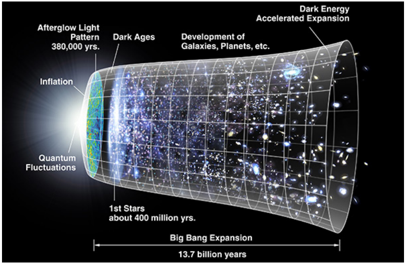
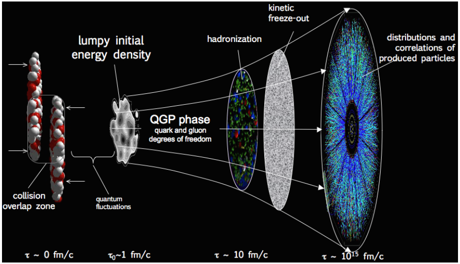
Big bang – little bang: More than an analogy?





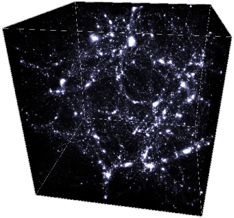
- cosmol. scale: MPc$= 3.1 \times 10^{22}$ m
- Gravity + QED + Dark sector
- one big event

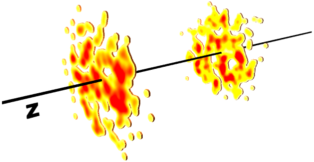
- nuclear scale: fm$= 10^{-15}$ m
- QCD
- very many events

- initial conditions not directly accessible
- all information must be reconstructed from final state
- dynamical description as a fluid

Symmetries in a statistical sense

- Concrete realization breaks symmetry
- Statistical properties are symmetric





Cosmology

- Cosmological principle: universe homogeneous and isotropic
- 3D translation and rotation

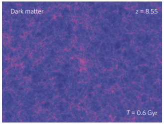
→ 3D Fourier expansion

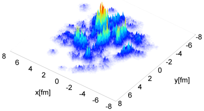
Heavy ion collisions

- 1D azimuthal rotation for central collisions
- 1D Bjorken boost (approximate)

→ Bessel-Fourier expansion [Floerchinger & Wiedemann (2013)]

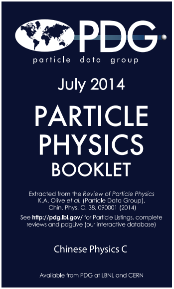
The problem of initial conditions





- Problem for cosmology and heavy ion physics: precise initial conditions for fluid dynamic description not known

	Planck+WP +highL	*Planck*+WP +highL+BAO	*WMAP*9+eCMB +BAO
$\Omega_b h^2$	0.02207 ± 0.00027	0.02214 ± 0.00024	0.02211 ± 0.00034
$\Omega_c h^2$	0.1198 ± 0.0026	0.1187 ± 0.0017	0.1162 ± 0.0020
$100\,\theta_{MC}$	1.0413 ± 0.0006	1.0415 ± 0.0006	–
n_s	0.958 ± 0.007	0.961 ± 0.005	0.958 ± 0.008
τ	$0.091^{+0.013}_{-0.014}$	0.092 ± 0.013	$0.079^{+0.011}_{-0.012}$
$\ln(10^{10}\Delta^2_{\mathcal{R}})$	3.090 ± 0.025	3.091 ± 0.025	3.212 ± 0.029
h	0.673 ± 0.012	0.678 ± 0.008	0.688 ± 0.008
σ_8	0.828 ± 0.012	0.826 ± 0.012	$0.822^{+0.013}_{-0.014}$
Ω_m	$0.315^{+0.016}_{-0.017}$	0.308 ± 0.010	0.293 ± 0.010
Ω_Λ	$0.685^{+0.017}_{-0.016}$	0.692 ± 0.010	0.707 ± 0.010


PDG
particle data group
July 2014
PARTICLE
PHYSICS
BOOKLET
Extracted from the *Review of Particle Physics*
K.A. Olive *et al.* (Particle Data Group),
Chin. Phys. C, 38, 090001 (2014)
See **http://pdg.lbl.gov/** for Particle Listings, complete
reviews and pdgLive (our interactive database)
Chinese Physics C
Available from PDG at LBNL and CERN

- Nevertheless, cosmology is now a precision science!
- How is that possible?

Initial conditions in cosmology

- Perturbations are classified into scalars, vectors, tensors
- Vector modes are decaying, need not be specified
- Tensor modes are gravitational waves, can be neglected for most purposes
- Decaying scalar modes also not relevant
- Growing scalar modes are further classified by wavelength
- For relevant range of wavelength: close to Gaussian probability distribution
- Almost scale invariant initial spectrum

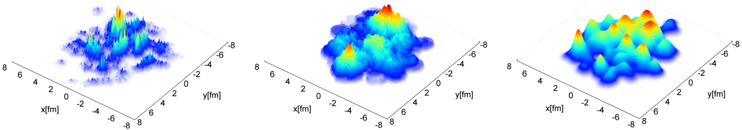
$$\langle \delta(\mathbf{k})\,\delta(\mathbf{k}')\rangle = P(k)\;\delta^{(3)}(\mathbf{k}+\mathbf{k}')$$

with

$$P(k) \sim k^{n_s - 1} \qquad\qquad n_s = 0.968 \pm 0.006$$ [Planck (2015)]

Initial conditions heavy ion collisions

- State of the art: Explicit realizations in terms of Monte-Carlo models



IP-Glasma MC-KLN MC-Glauber

[Schenke, Tribedy & Venugopalan, PRL 108, 252301 (2012)]

- Can we follow the successful approach used in cosmology?
  - Characterize statistical properties rather than explicit realizations
  - Focus on relevant wavelengths

- First attempts in this direction have been made
  [Teaney & Yan (2011), Coleman-Smith, Petersen & Wolpert (2012), Floerchinger & Wiedemann (2013), Yan & Ollitrault (2014), Bzdak & Skokov (2014), ...]

Cosmological inhomogeneities

Cosmological perturbation theory

[Lifshitz, Peebles, Bardeen, Kosama, Sasaki, Ehler, Ellis, Hawking, Mukhanov, Weinberg, ...]

- Solves evolution equations for fluid + gravity
- Expands in perturbations around homogeneous background
- Detailed understanding how different modes evolve
- Diagramatic formalism for non-linear mode-mode interactions

Cosmological fluid

- Very simple equations of state $p = w\,\epsilon$
- Viscosities usually neglected $\eta = \zeta = 0$
- Photons and neutrinos are free streaming

Inhomogeneities in cosmology

- Small initial density perturbations

$$\delta = \frac{\Delta\epsilon}{\bar{\epsilon}} \ll 1$$

- At photon decoupling (CMB)

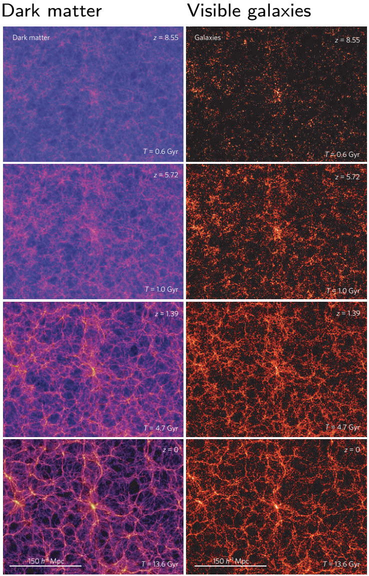
$$\delta \approx 10^{-5}$$

- Structure growth due to attractive gravitational interaction
- Perturbative treatment possible up to

$$\delta \approx 1$$

- For late times and small wavelengths

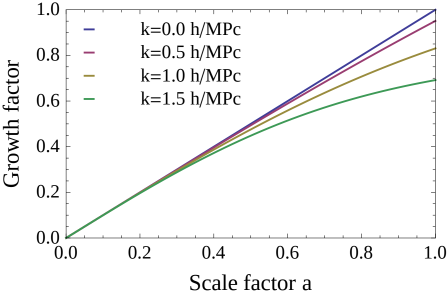
$$\delta \gg 1$$



[Springel, Frenk & White, Nature 440, 1137 (2006)]

Structure formation with viscosities

Viscosities would slow down structure formation for large k



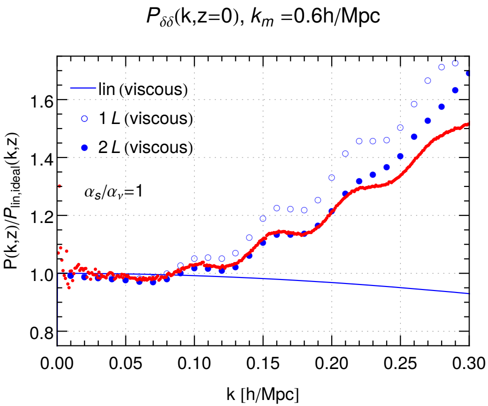
[Blas, Floerchinger, Garny, Tetradis & Wiedemann (2015)]

Two types of viscosities for cosmological fluid

1. Momentum transport by particles or radiation
   - governed by interactions
   - from linear response theory [Green (1954), Kubo (1957)]
2. Momentum transport in the inhomogeneous, coarse-grained fluid
   - governed by non-linear fluid mode couplings
   - determined perturbatively [Blas, Floerchinger, Garny, Tetradis & Wiedemann]
   - heavy ions: anomalous plasma viscosity [Asakawa, Bass & Müller (2006)]
     eddy viscosity [Romatschke (2008)]

Large scale structure and effective viscosities

Dark matter density power spectrum in the BAO range



[Blas, Floerchinger, Garny, Tetradis & Wiedemann (2015)]

- 2 Loop perturbative calculation with effective viscosity and sound velocity
- agrees with N-body simulations up to $k = 0.2\, h/$MPc
  [related: Effective field theory of LSS, Baumann, Nicolis, Senatore & Zaldarriaga (2012), Carrasco, Hertzberg & Senatore (2012), ...]

Dissipation in cosmology

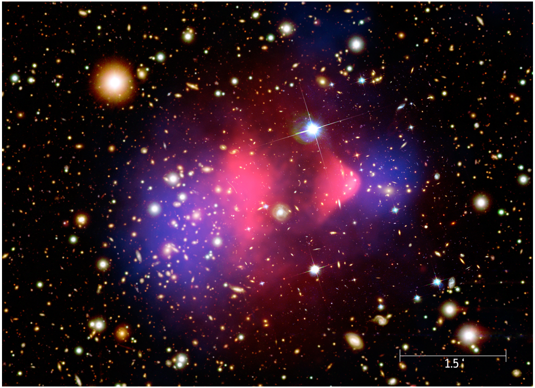
- Current paradigm for dark matter
  - ideal, cold and pressure-less fluid
  - dark matter particles with small or vanishing self-interaction
- What about dissipation / viscosities?
- How does dissipation influence structure formation?
  Fluid velocity gradients grow large...
- Heavy ion collisions

$$\mathscr{L}_{\text{QCD}} \quad \rightarrow \quad \text{fluid properties}$$

- Late time cosmology

$$\text{fluid properties} \quad \rightarrow \quad \mathscr{L}_{\text{dark matter}}$$

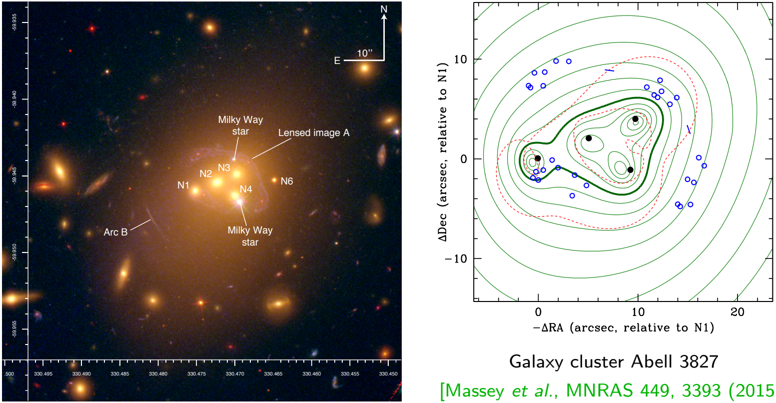
Material properties of dark matter



Gravitational lensing and x-ray image of "bullet cluster" 1E0657-56

- so far: dark matter is non-interacting → can collide without stopping
- Future decade: analysis of colliding galaxy clusters will refine this picture
- Dark energy self interacting
  - → modification of equation of state
  - → dissipation

Is dark matter self-interacting?



Galaxy cluster Abell 3827

[Massey *et al.*, MNRAS 449, 3393 (2015)]

- Offset between stars and dark matter falling into cluster
- Is this a first indication for a dark matter self interaction?

  [Kahlhoefer, Schmidt-Hoberg, Kummer & Sarkar, MNRAS 452, 1 (2015)]

$$\frac{\sigma}{m_{\mathrm{DM}}} \approx 3\,\frac{\mathrm{cm}^2}{\mathrm{g}} \approx 0.5\,\frac{\mathrm{b}}{\mathrm{GeV}} \qquad \text{(under debate)}$$

Precision cosmology can measure shear stress

- Scalar excitations in gravity

$$ds^2 = a^2 \left[-(1+2\psi)d\eta^2 + (1-2\phi)dx_i dx_i \right]$$

  with two Newtonian potentials ψ and ϕ.

- Einsteins equations imply

$$\left(\partial_i\partial_j - \tfrac{1}{3}\delta_{ij}\partial_k^2\right)(\phi-\psi) = 8\pi G_\mathsf{N} a^2 \; \pi_{ij}\big|_\text{scalar}$$

  with scalar part of shear stress

$$\pi_{ij}\big|_\text{scalar} = \left(\partial_i\partial_j - \tfrac{1}{3}\delta_{ij}\partial_k^2\right)\tilde{\pi}$$

- Detailed data at small redshift e.g. from Euclid satellite (esa, 2020) [Amendola *et al.* (2012)]
  - ψ can be measured via acceleration of matter
  - $\psi+\phi$ can be meaured by weak lensing and Sachs-Wolfe effect
  - fluid velocity can be accessed by redshift space distortions
- New quantitative precise insights into fluid properties of dark matter!

Bulk viscosity

- Bulk viscous pressure is negative for expanding universe

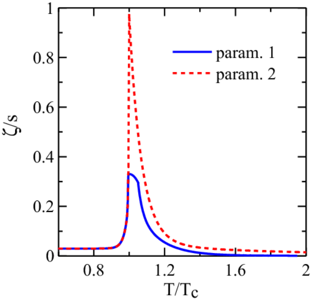
$$\pi_{\text{bulk}} = -\zeta\, \nabla_\mu u^\mu = -\zeta\, 3H < 0$$

- Negative effective pressure

$$p_{\text{eff}} = p + \pi_{\text{bulk}} < 0$$

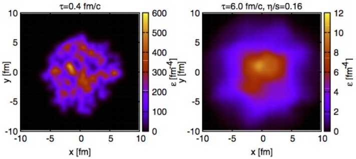
would act similar to dark energy in Friedmann's equations
[Murphy (1973), Padmanabhan & Chitre (1987), Fabris, Goncalves & de Sa Ribeiro (2006), Li & Barrow (2009), Velten & Schwarz (2011), Gagnon & Lesgourgues (2011), ...]

- Is negative effective pressure physical?
- Cavitation: instability for $p_{\text{eff}} < 0$
[Torrieri & Mishustin (2008), Rajagopal & Tripuraneni (2010), Buchel, Camanho & Edelstein (2014), Habich & Romatschke (2015), Denicol, Gale & Jeon (2015)]
- In heavy ion physics
  - ζ/s large close to crossover
  - Cavitation relevant for freeze-out?
- What precisely happens at the instability?



[Denicol, Gale & Jeon (2015)]

Inhomogeneities in heavy ion collisions



[Schenke, Jeon & Gale (2011)]

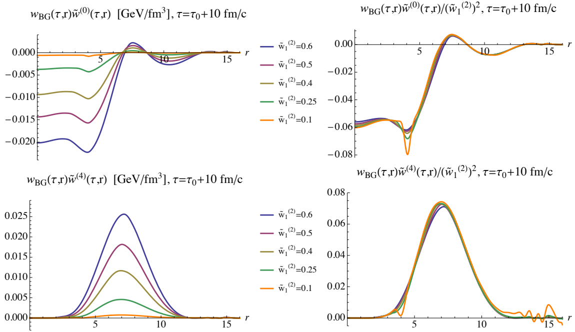
- At initial time density contrast

$$\delta = \frac{\Delta\epsilon}{\bar{\epsilon}} \approx 1$$

- Dissipation leads to damping. At late time

$$\delta = \frac{\Delta\epsilon}{\bar{\epsilon}} < 1$$

- Perturbative expansion similar to cosmological perturbation theory possible
  [Floerchinger & Wiedemann (2013), Floerchinger, Wiedemann, Beraudo, Del Zanna, Inghirami & Rolando (2014)]



The backreaction

- Linear + non-linear response

$$V_4 = \kappa_4^{\mathsf{L}}\ \varepsilon_4 + \kappa_4^{\mathsf{NL}}\ \varepsilon_2^2 + \ldots$$

- Symmetries allow also

$$\frac{dN}{d\eta} = c + \kappa_{0,2}^{\mathsf{NL}}\ \varepsilon_2^*\varepsilon_2 + \kappa_{0,3}^{\mathsf{NL}}\ \varepsilon_3^*\varepsilon_3 + \kappa_{0,4}^{\mathsf{NL}}\ \varepsilon_4^*\varepsilon_4 + \ldots$$

- Perturbations have an effect on the 0-mode: backreaction
- In cosmology this could affect the expansion history
- Backreaction due to non-linearities of gravity: presumably small effect
  [Ellis & Stoeger (1987); Mukhanov, Abramo & Brandenberger (1997); Unruh (1998); Buchert (2000); Geshnzjani & Brandenberger (2002); Schwarz (2002); Wetterich (2003); Räsänen (2004); Kolb, Matarrese & Riotto (2006); Brown, Behrend, Malik (2009); Gasperini, Marozzi & Veneziano (2009); Clarkson & Umeh (2011); Green & Wald (2011); ...]
- Detailed comparison between heavy ion physics and cosmology showed that additional effect comes from viscosities
  [Brouzakis, Floerchinger, Tetradis & Wiedemann (2015)]

Accelerated cosmological expansion from shear and bulk viscosity (?)

[Floerchinger, Tetradis & Wiedemann, PRL 114, 091301 (2015)]

Expectation value of energy density $\bar{\epsilon} = \langle \epsilon \rangle$

$$\tfrac{1}{a}\dot{\bar{\epsilon}} + 3H\left(\bar{\epsilon} + \bar{p} - 3\bar{\zeta}H\right) = D$$

with dissipative backreaction term

$$D = \tfrac{1}{a^2}\left\langle \eta\left[\partial_i v_j \partial_i v_j + \partial_i v_j \partial_j v_i - \tfrac{2}{3}\partial_i v_i \partial_j v_j\right]\right\rangle$$
$$+ \tfrac{1}{a^2}\left\langle \zeta[\vec{\nabla}\cdot\vec{v}]^2\right\rangle + \tfrac{1}{a}\left\langle \vec{v}\cdot\vec{\nabla}\left(p - 6\zeta H\right)\right\rangle$$

- D vanishes for unperturbed homogeneous and isotropic universe
- D has contribution from shear viscosity, bulk viscosity and thermodynamic work done by contraction against pressure gradients
- viscous terms in D are positive semi-definite
- for $\frac{1}{a}\vec{\nabla}\vec{v} \sim H$ backreaction term at same order as background bulk term
- Could account for observed accelerated expansion with $p_{\text{eff}} = 0$ for

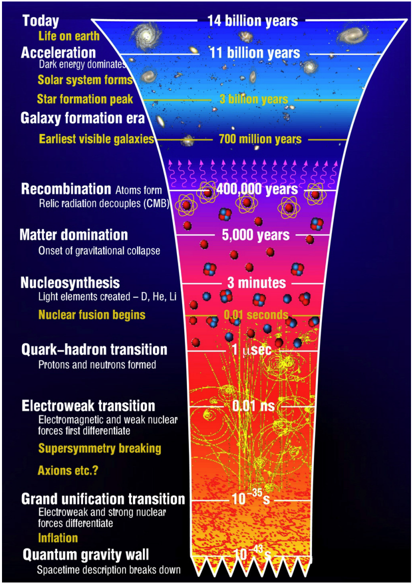
$$\frac{4\pi G_{\mathsf{N}} D}{3H^3} \approx 3.5$$

Conclusions

- For heavy ions and the cosmos, fluctuation analysis can provide detailed information about material properties and expansion history without full control over initial conditions.
- Common challenges require commonalities in analysis techniques.
- Interplay between both fields likely to become more important in the next decade:
- Heavy ion physics aims for more and more differential fluctuation analysis, which is a core competence of cosmology.
- Cosmological precision becomes sensitive to deviations from simple, idealized fluid properties, which is a core competence of heavy ion physics.

Backup slides

The quark gluon plasma in the early universe



- Quark-gluon plasma has filled the universe until $\sim 10^{-6}$ s
- Probably not much information from that era transmitted
- Baryogenesis / Leptogenesis presumably much earlier

Fluid dynamics in cosmology and heavy ion collisions

Cosmology

- Large part of cosmological evolution is governed by equilibrium thermodynamics or ideal fluid dynamics.
- Free-streaming of photons and neutrinos at late times.
- Matter was in equilibrium at early times, drops out of equilibrium later.
- Gravitational interaction is long range and treated explicitely.

Heavy ion collisions

- Expansion governed by viscous fluid dynamics.
- Free streaming of hadrons at late times.
- Strong interactions are confined at low temperature and screened at high temperature, treated implicitely.

Fluid dynamic perturbation theory for heavy ion collisions

Formalism very similar to cosmological perturbation theory could be used for heavy ion collisions

- Expansion in fluctuations around event-averaged solution
- Based on relativistic viscous fluid dynamics
- Compared to cosmology, absence of gauge symmetries reduces technical effort but smaller degree of symmetry increases technical effort
- Leads to linear + non-linear response formalism
- Could allow for more detailed constraints on initial conditions and transport properties
- Extensions of current model might be investigated more easily
  - initial fluid velocity and shear stress fluctuations
  - baryon number and electric change densities
  - magnetic fields
  - thermodynamic fluctuations
- Comparison to cosmology more direct

First steps towards fluid dynamic perturbation or response theory

- Linear perturbations around Bjorken flow [Floerchinger & Wiedemann (2011)]
- Linear perturbations around Gubser solution for conformal fluids
  [Gubser & Yarom (2010), Staig & Shuryak (2011), Springer & Stephanov (2013)]
- More detailed investigation of linear perturbations and first steps towards non-linear perturbations around Gubser solution
  [Hatta, Noronha, Torrieri, Xiao (2014)]
- Linear perturbations around general azimuthally symmetric initial state, realistic equation of state
  [Floerchinger & Wiedemann (2013)]
- Characterization of initial conditions by Bessel-Fourier expansion
  [Coleman-Smith, Petersen & Wolpert (2012), Floerchinger & Wiedemann (2013)]
- Comparison to full numerical solution shows good convergence properties of perturbative expansion
  [Floerchinger, Wiedemann, Beraudo, Del Zanna, Inghirami, Rolando (2013)]
- Related response formalism for expansion in eccentricities
  [Teaney & Yan (2012), Yan & Ollitrault (2015]