General relativistic non-linearities in cosmology

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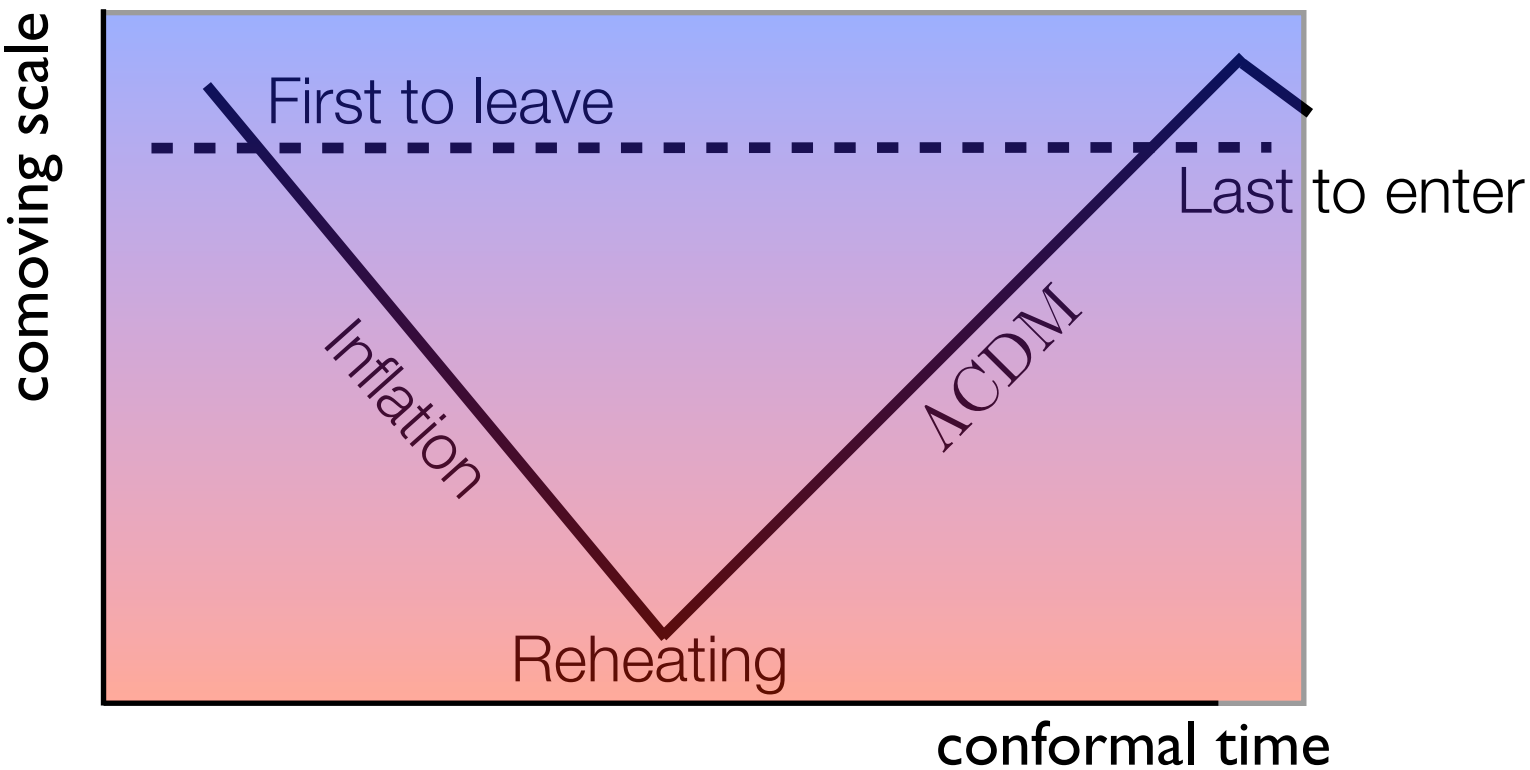
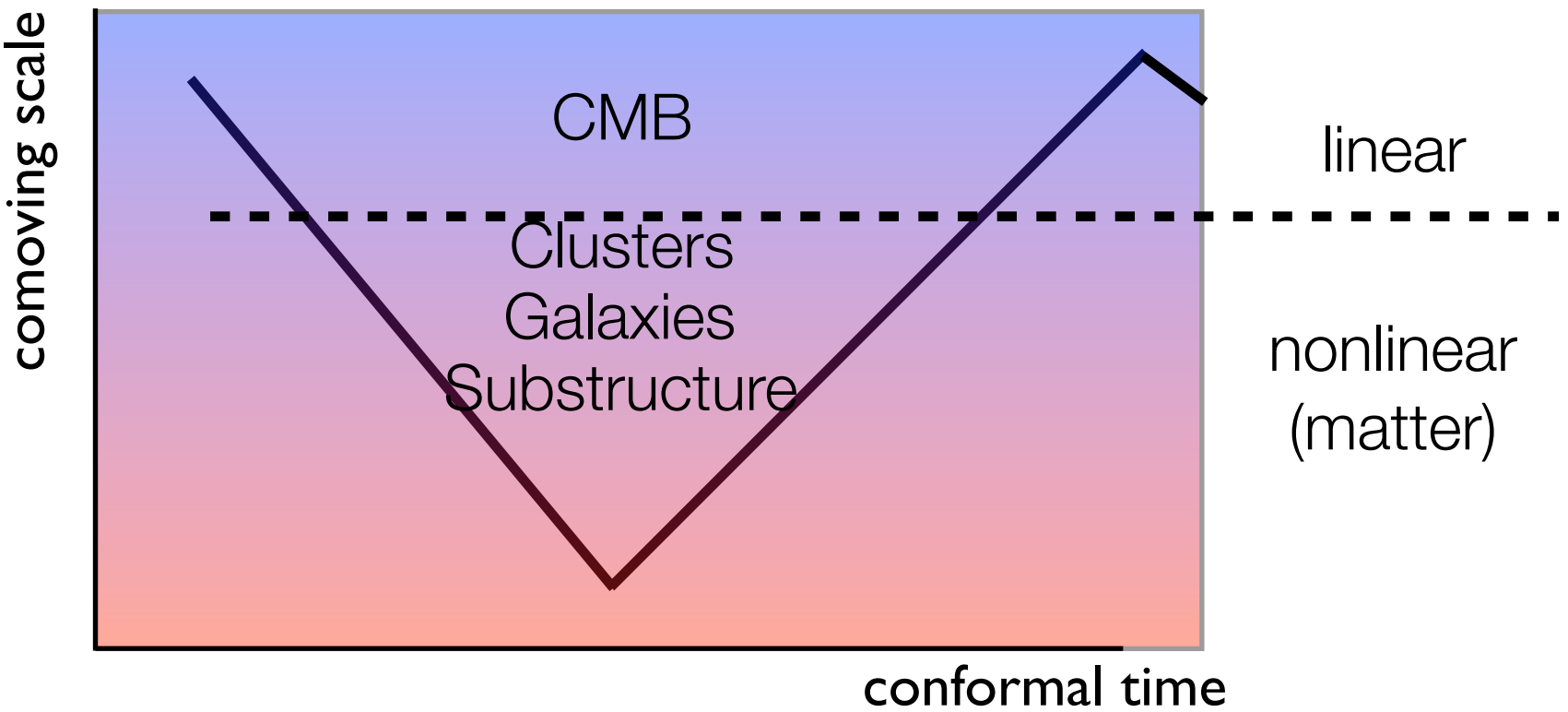
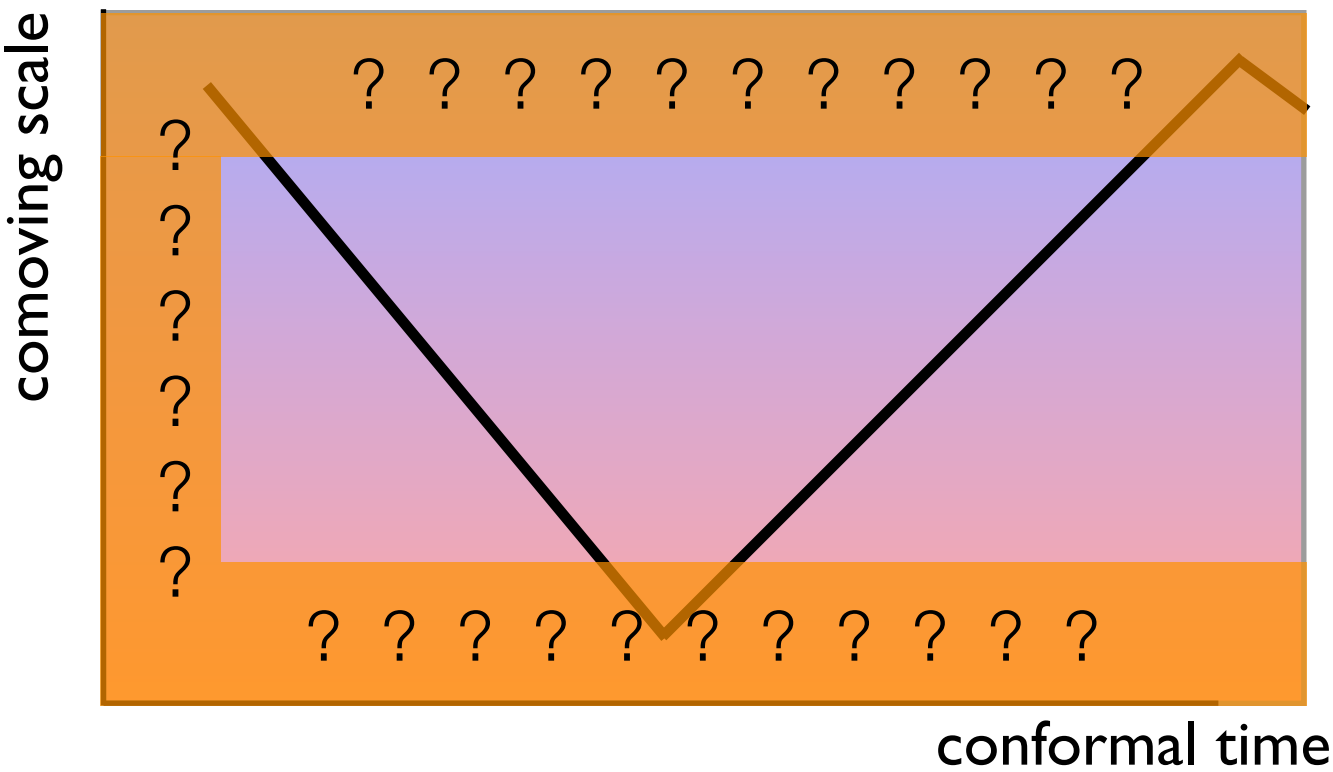
The linear Universe



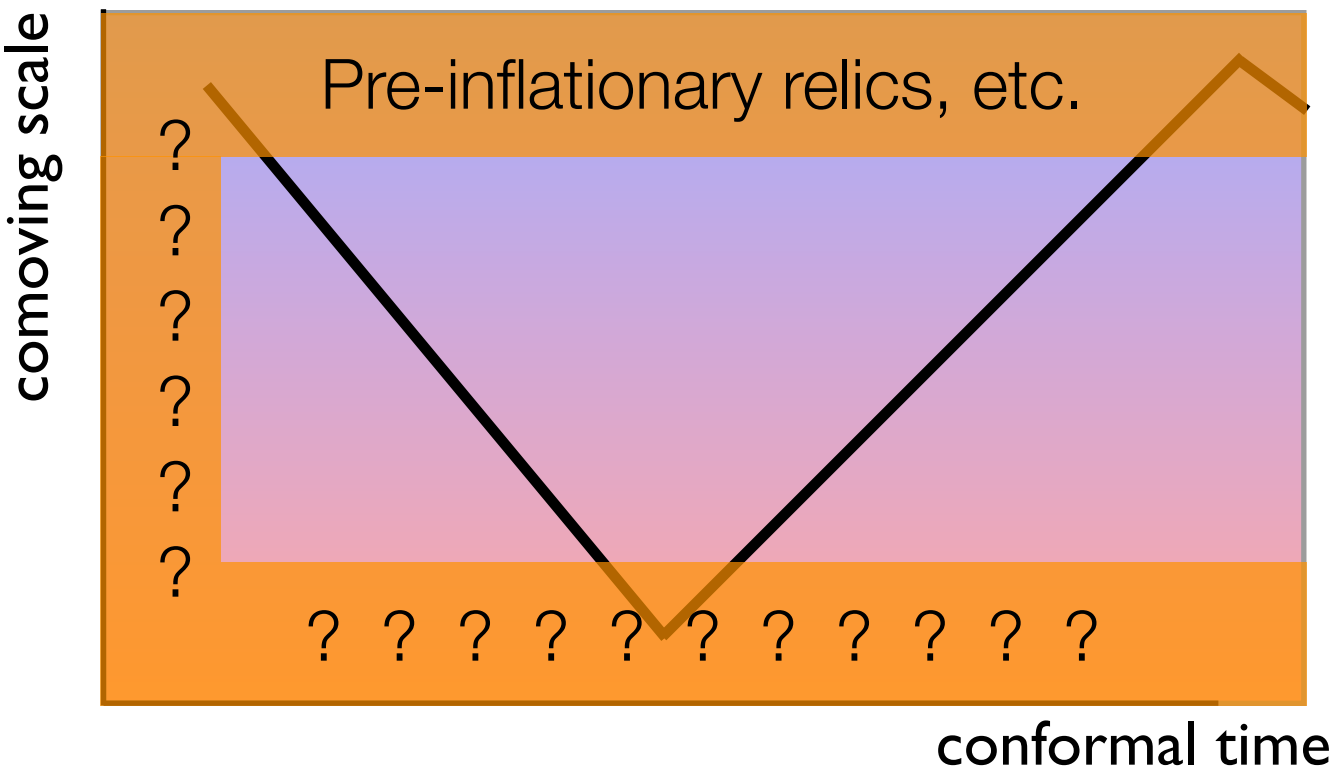
The linear Universe



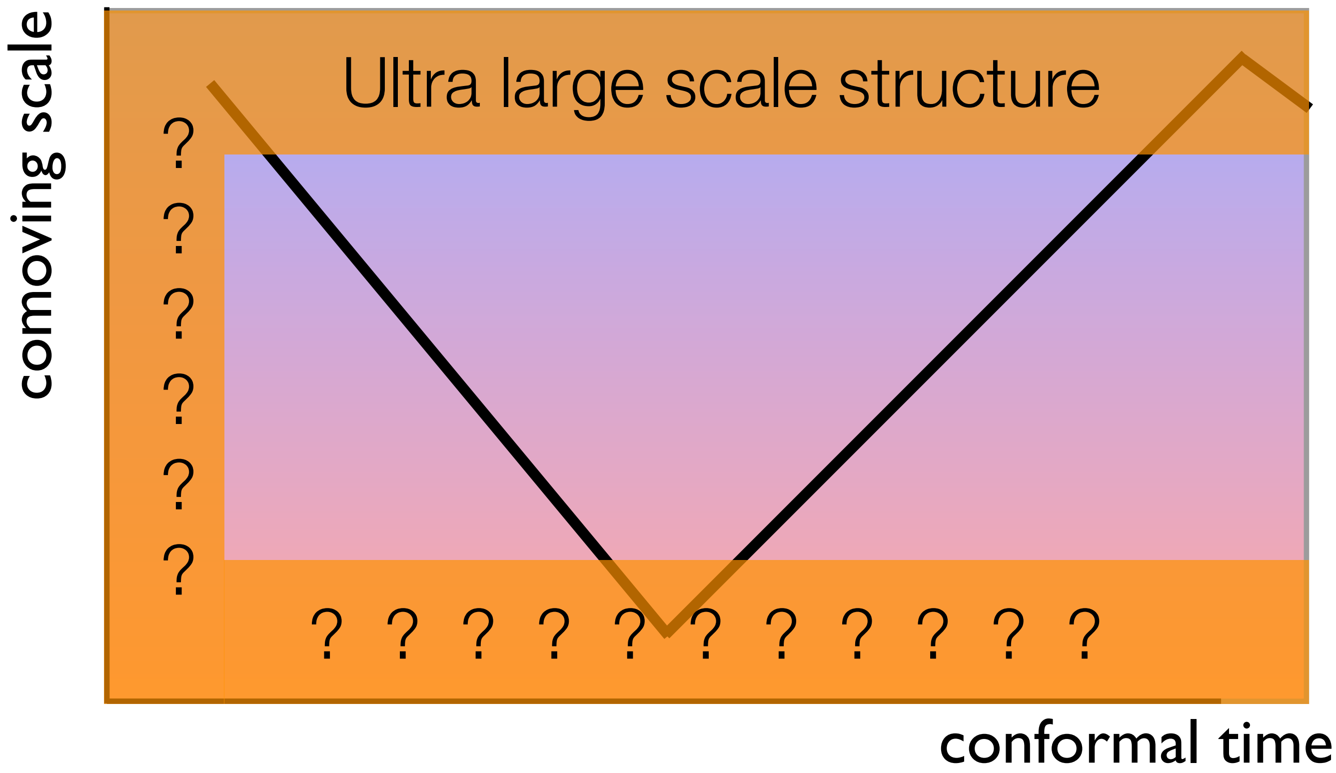
The non-linear Universe



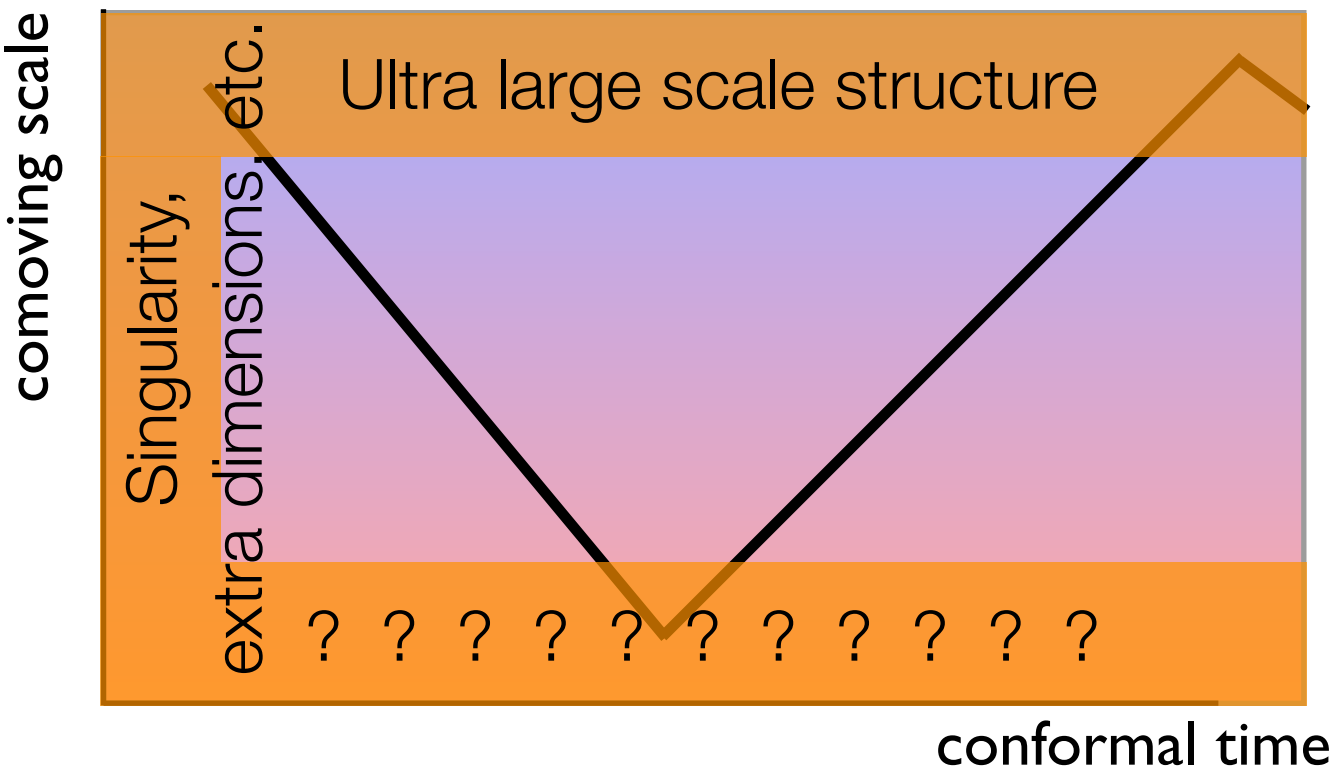
The non-linear Universe



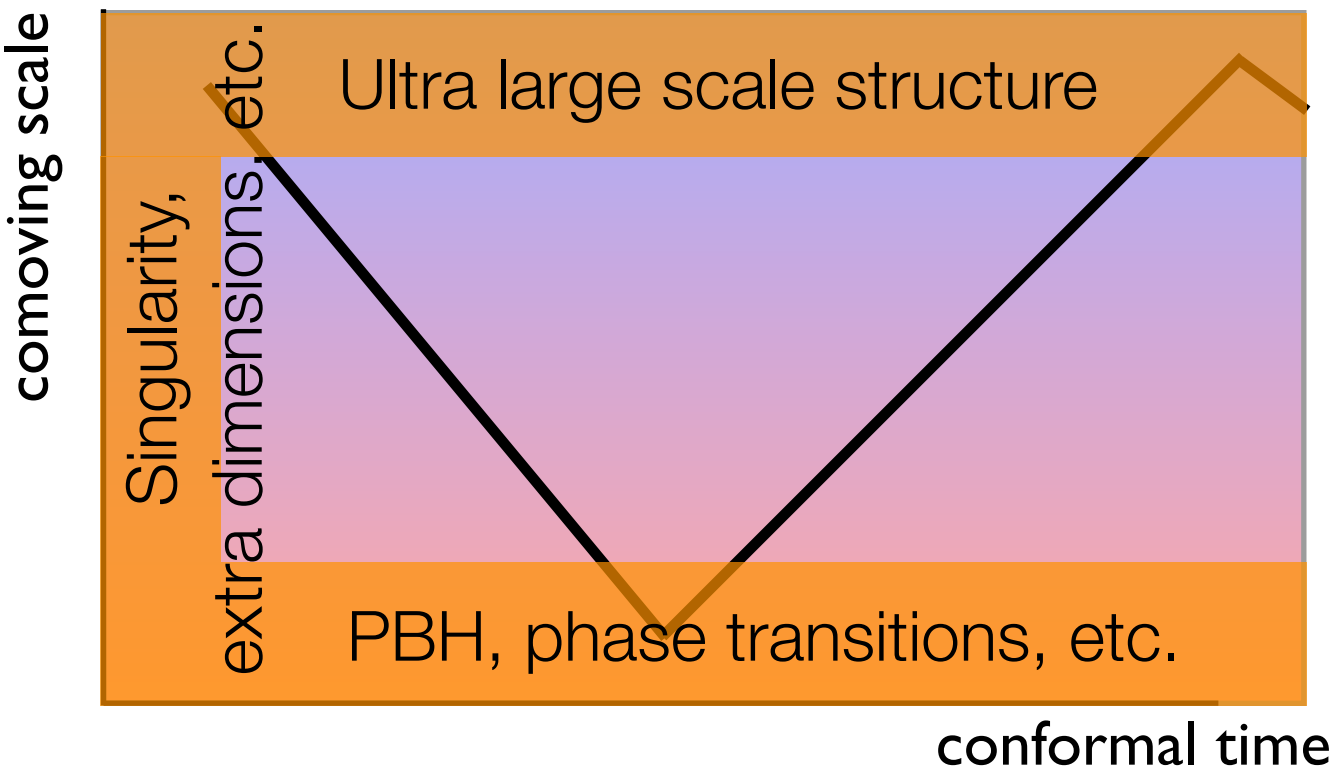
The non-linear Universe



The non-linear Universe



The non-linear Universe



The non-linear Universe

- On very large scales, very small scales, and at early times, gravitational non-linearities are key to answering a number of fundamental questions:

  - What were the initial conditions for inflation and are there any observable relics?
  - How did inflation end and are there any observable relics?
  - How do sub-horizon and horizon-scale modes couple?
  - What role to do extra dimensions play in early Universe cosmology?

The non-linear Universe

- **On very large scales, very small scales, and at early times, gravitational non-linearities are key to answering a number of fundamental questions:**

An invitation: Lots of interesting questions, many technical challenges, rare combination of theory, numerics, and observation.

The non-linear Universe

- **On very large scales, very small scales, and at early times, gravitational non-linearities are key to answering a number of fundamental questions:**

  - What were the initial conditions for inflation and are there any observable relics?

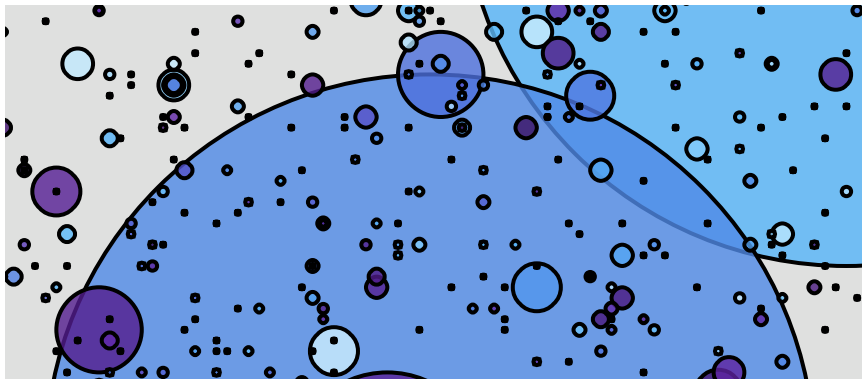
Check out talks by:
Jonathan Braden: B4, Tuesday, 4:30-6:30.
Will East: B2, Thursday 4:30-6:30.

Eternal Inflation: is this our universe?

Observational Tests of Eternal Inflation

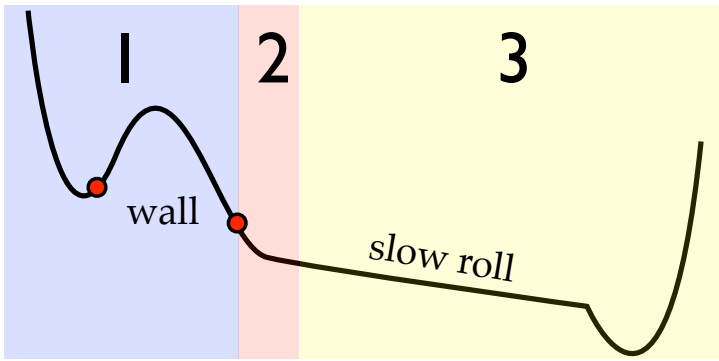
- But is eternal inflation experimentally verifiable?

Our bubble does not evolve in isolation....

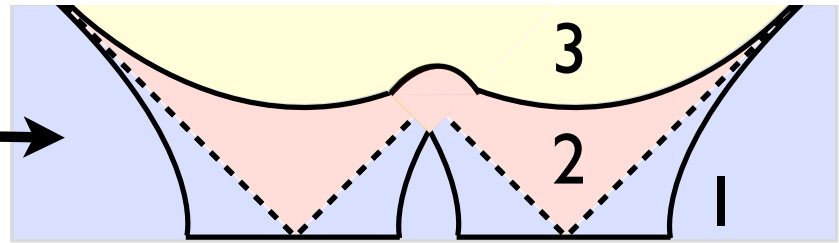


The collision of our bubble with others provides an observational test of eternal inflation.

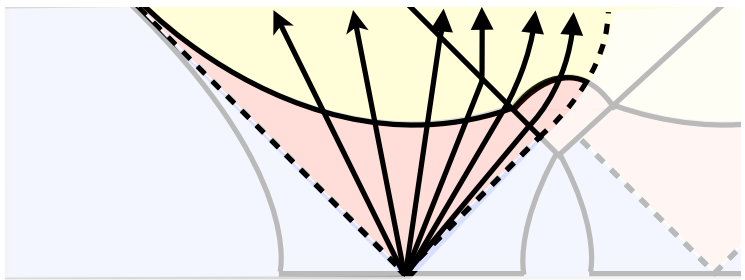
How do we find the signature of bubble collisions?



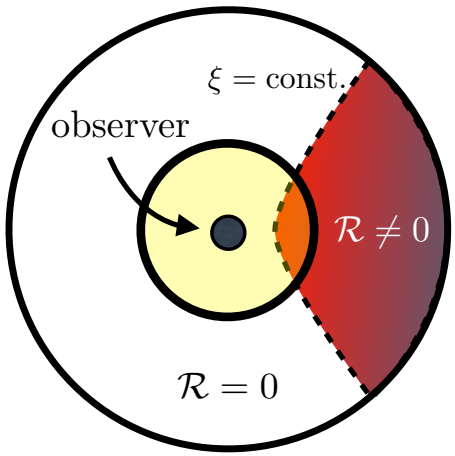
Model



Collision Simulation

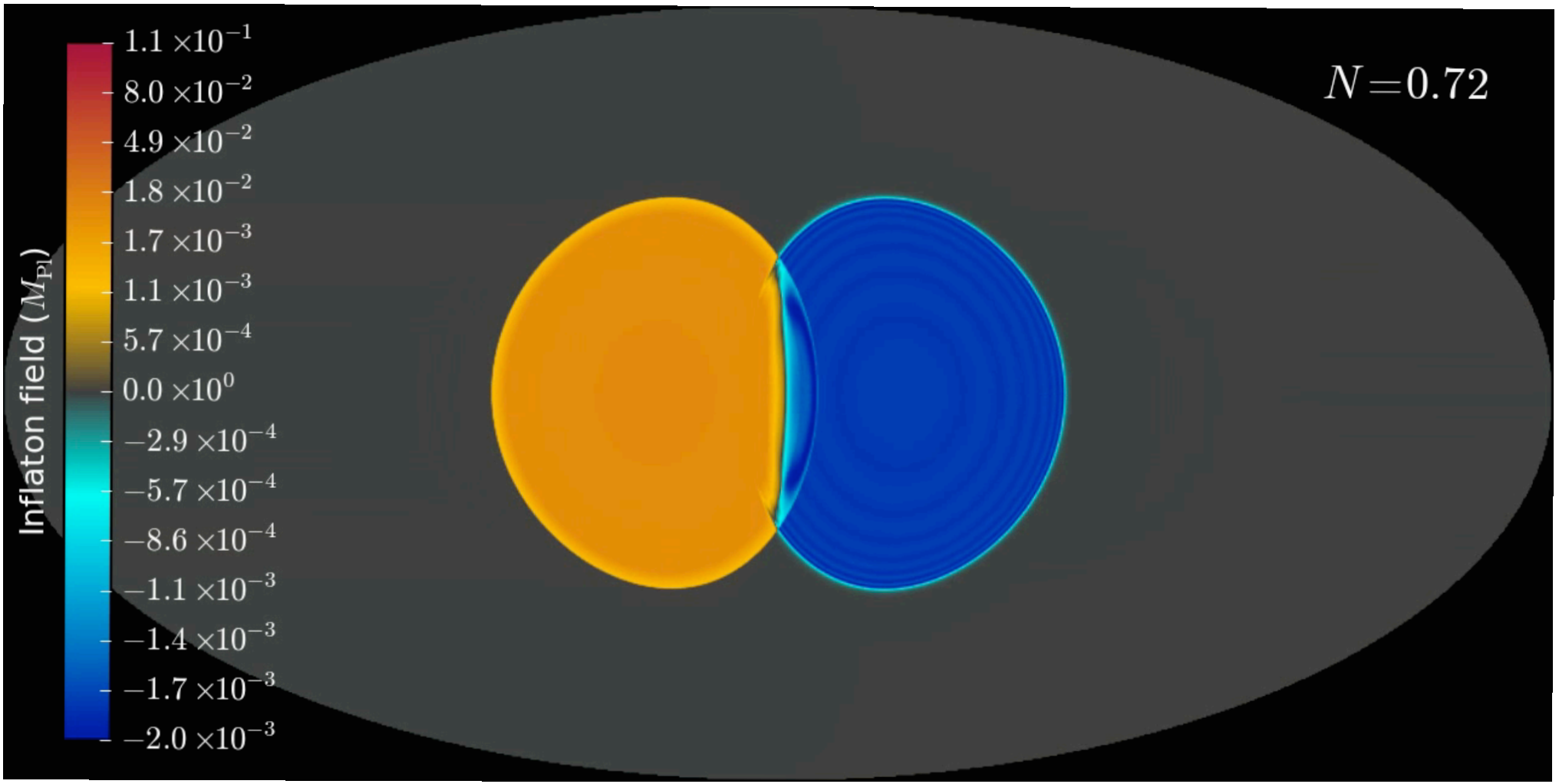


Metric Reconstruction



Cosmological Signatures

Determining the collision spacetime: numerical GR



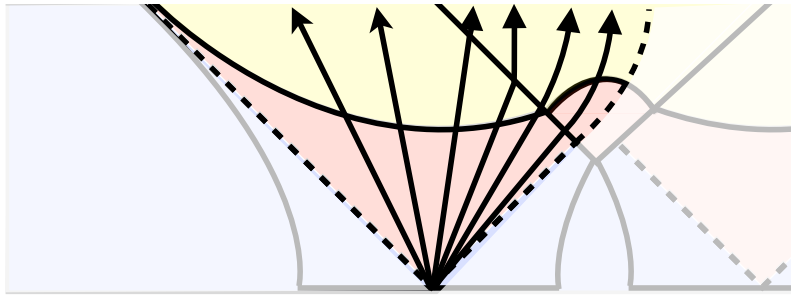
Mollweide projection of closed foliation of de Sitter space.

Local vs global

- **A key challenge: how do you extract locally FRW patches from a very inhomogeneous Universe on large scales?**

- **Brute force:**

  (linear)



Solve geodesic equation

Perturbed FRW in synchronous gauge, centered on fiducial geodesic:

$$ds^2 = -d\tau^2 + a^2(\tau)\left[(1-2\Psi) + E_{ij}\right] dX^i dX^j$$

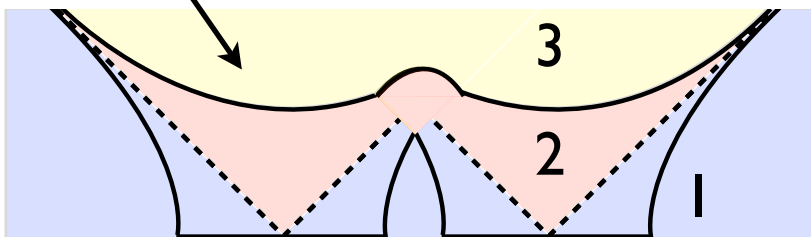
Local vs global

- A key challenge: how do you extract locally FRW patches from a very inhomogeneous Universe on large scales?

- Geometrical:

  (linear)

$$R^{(3)}(\xi) = -6 + 4\nabla^2\mathcal{R}$$



Perturbed FRW in comoving gauge on spatial slices:

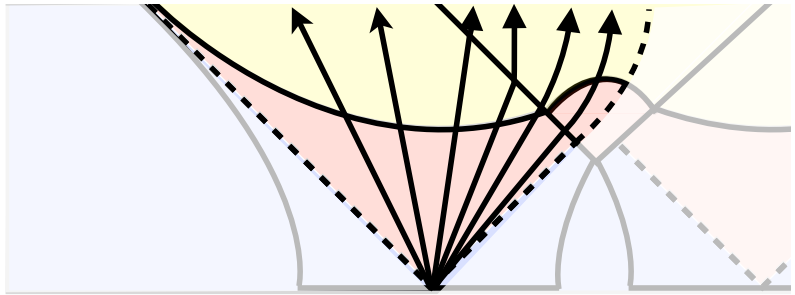
$$ds_3^2 = a^2(\tau)\,(1-2\mathcal{R})\,\delta_{ij}dX^i dX^j$$

Local vs global

- A key challenge: how do you extract locally FRW patches from a very inhomogeneous Universe on large scales?

- Delta N:

(non-linear)



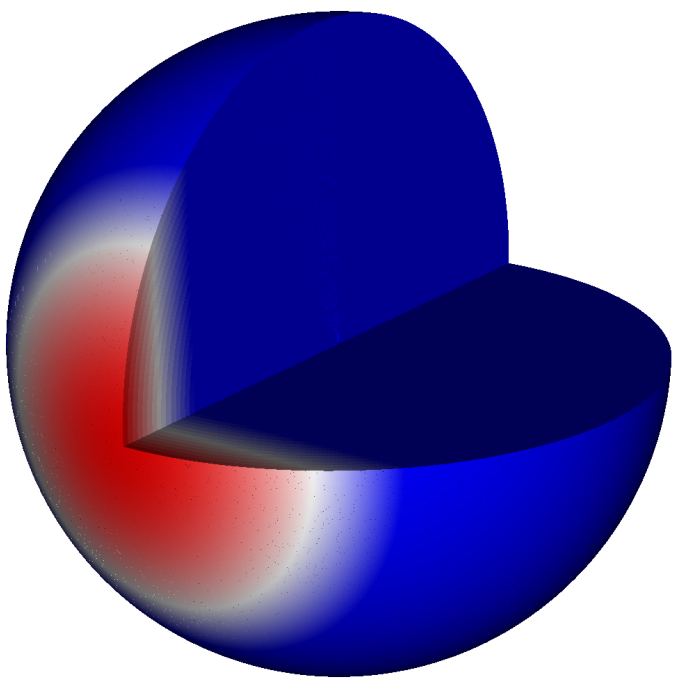
$$\zeta \equiv \frac{1}{6} \log \det g_{ij} \Big|_{\text{begin}}^{\text{end}}$$

Perturbed FRW in comoving gauge on spatial slices:

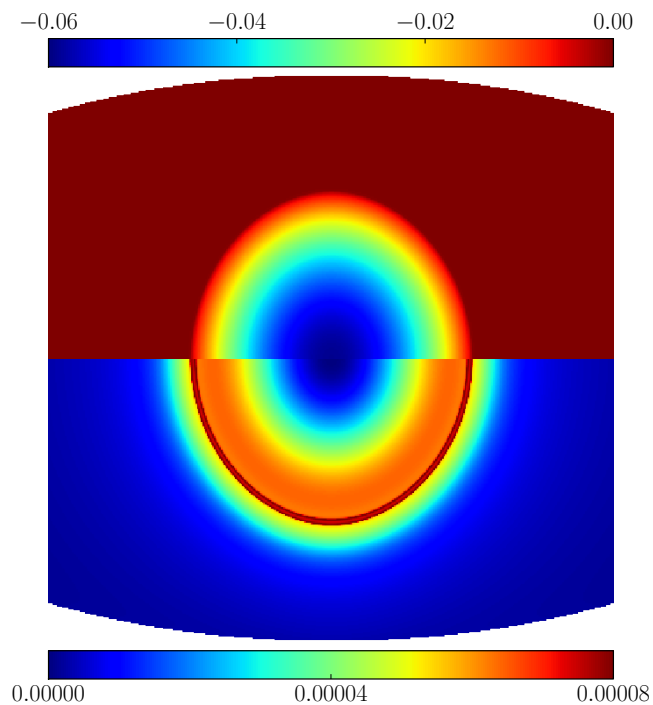
$$ds_3^2 = e^{2\zeta} \delta_{ij} dX^i dX^j$$

CMB observables

- Observables are computed at many different vantage points in the simulations, e.g. CMB temperature and polarization:



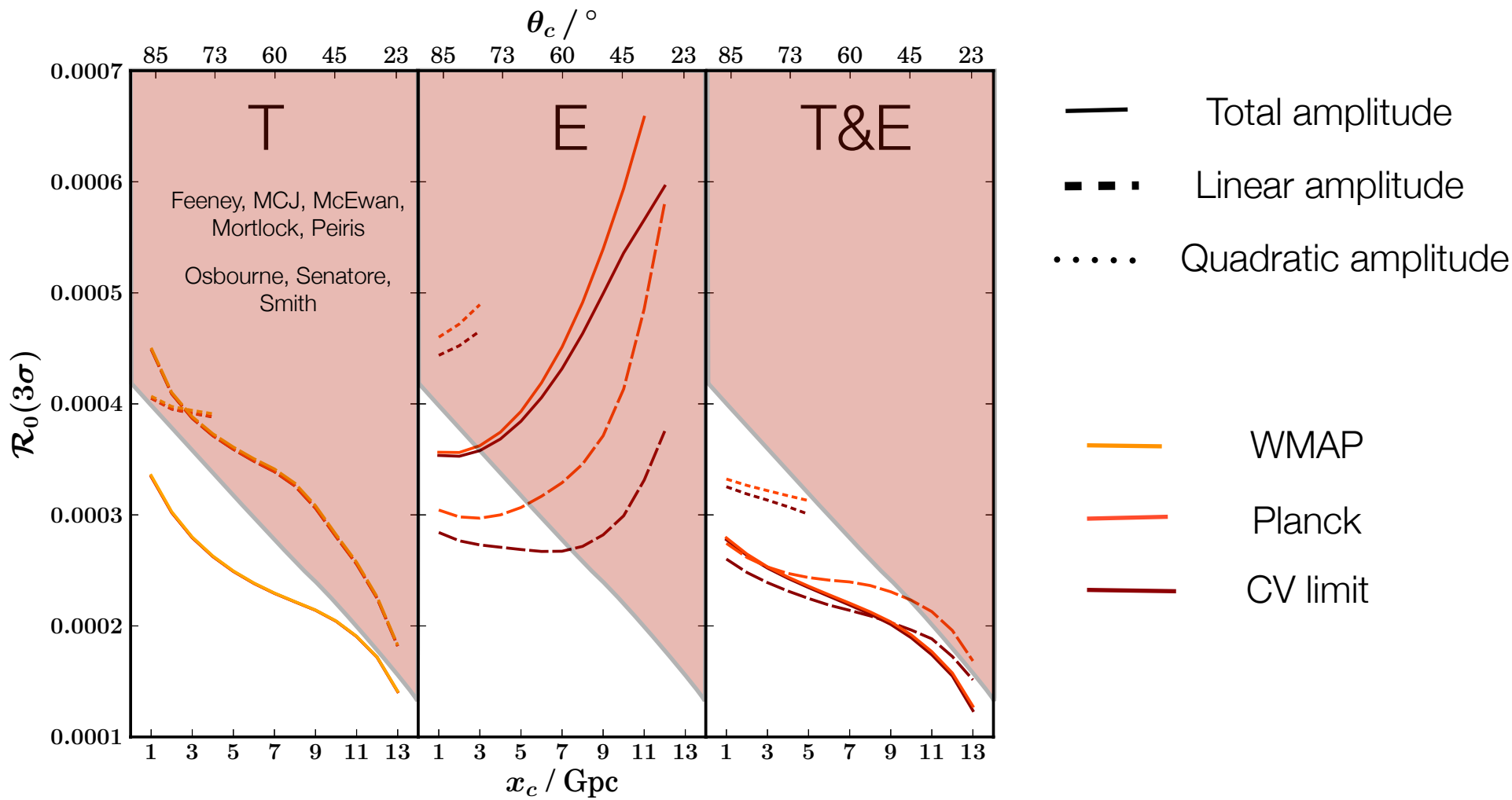
$\mathcal{R}$



$\Theta^{T,E}$

CMB constraints

- With a prediction, we can forecast and do data analysis:



Conclusions

- Proof of principle that non-linear early Universe physics can be constrained using combination of theory, numerics, and observation.
- Other scenarios: inhomogeneous inflation (Braden, East), extra dimensions in early Universe, primordial black holes, large scale structure, etc.
- New tools: extracting cosmological observables from simulations in arbitrary gauge, simulation techniques, data analysis techniques, motivation for new observational techniques, etc.

Thanks!