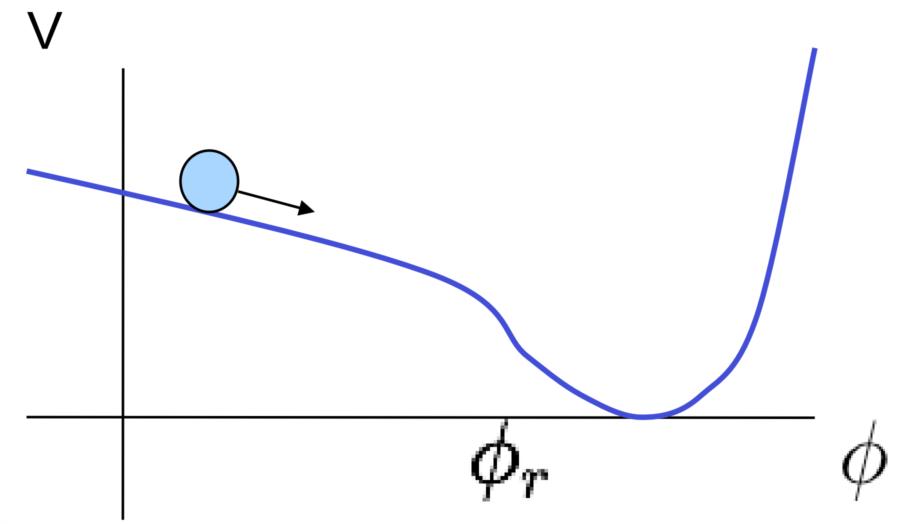
Leonardo Senatore (Stanford)

Some aspects of Theoretical Cosmology

How Inflation begins
and
a connection to Differential Geometry

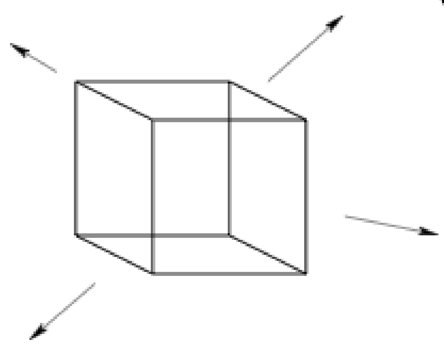
The Problem

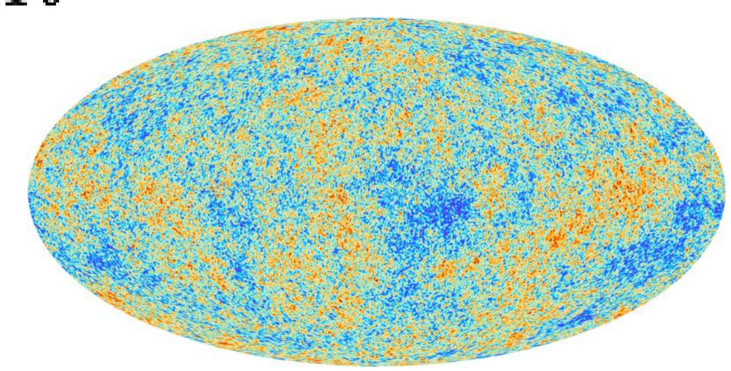


– If we have the inflaton on top of his potential

– and the space is homogeneous on a $H_I^2 \sim \frac{V(\phi)}{M_{\rm Pl}^2}$ patch

– then inflation starts $a(t) \sim e^{Ht}$





• Question: how likely is to have an homogenous patch of this size?

– If we imagine random initial condition, since overdensities lead to collapse, every point will tend to collapse into a black hole by the time start inflation, compelling argument (at least to me) implies that if

$$H_I \ll M_{\rm Pl} \quad \Rightarrow \quad {\rm Prob} \sim (H_I/M_{\rm Pl})^{\#}$$

– this is the so-called \`initial patch problem'

• Particularly relevant for low energy models

– and we will show that this argument is not really correct

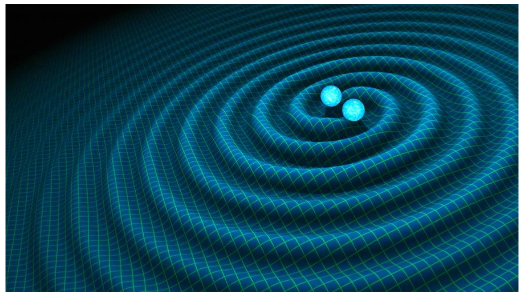
Highly Debated

How did inflation start?

with Kleban **JCAP 2016**

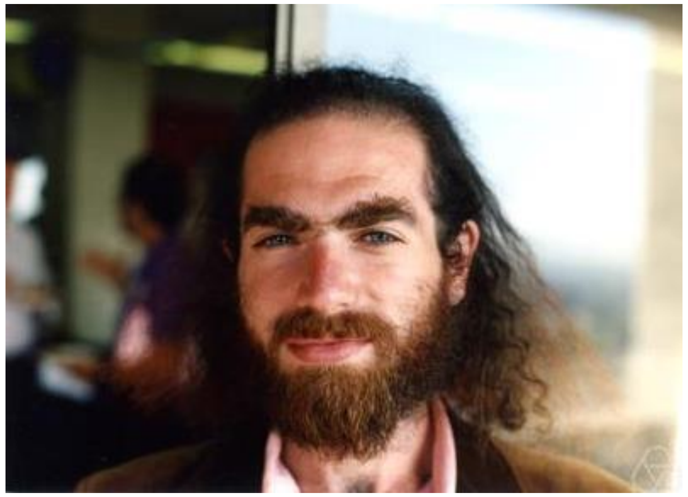
- Hard to make progress: evolution in completely inhomogenous universe leads to singularities, difficult to describe

- However, recently progress was made in two unrelated aspects of science
  - numerical codes that can handle singularities Pretorious **2005**



  - the Thorston Geometrization Classification (i.e. the Poincarè Hypothesis), has been proven

Thorston, Hamilton, Perelman
Fields Medal 2006

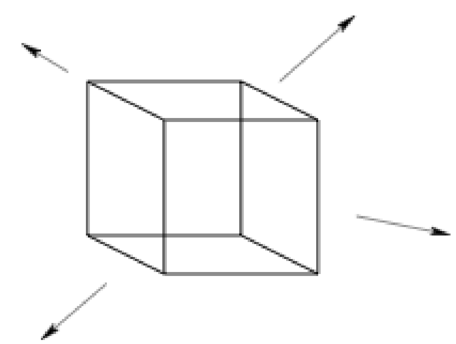


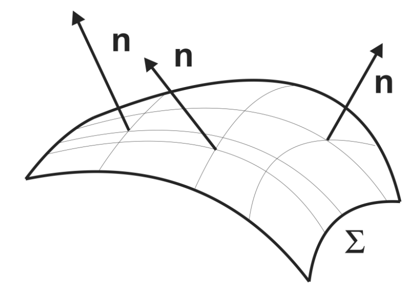
Numerical Experiment

with East, Linde and Kleban **JCAP1609**
Clough, Lim, di Nunno, Fishler, Flauger, Paban **JCAP1709**
Clough, Flauger, Lim **JCAP1805**

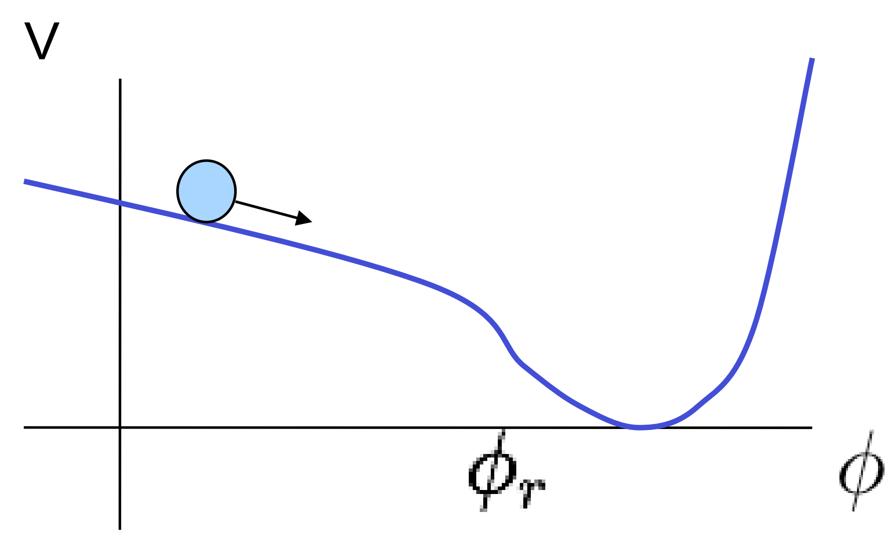
- We start with an highly inhomogenous configuration:

$$\phi(t=0,\mathbf{x}) = \phi_0 + \delta\phi \left[\sum_{1 \le |\mathbf{k}L/2\pi|^2 \le N} \cos(\mathbf{k}\cdot\mathbf{x} + \theta_{\mathbf{k}}) \right],$$





- And find that inflation starts

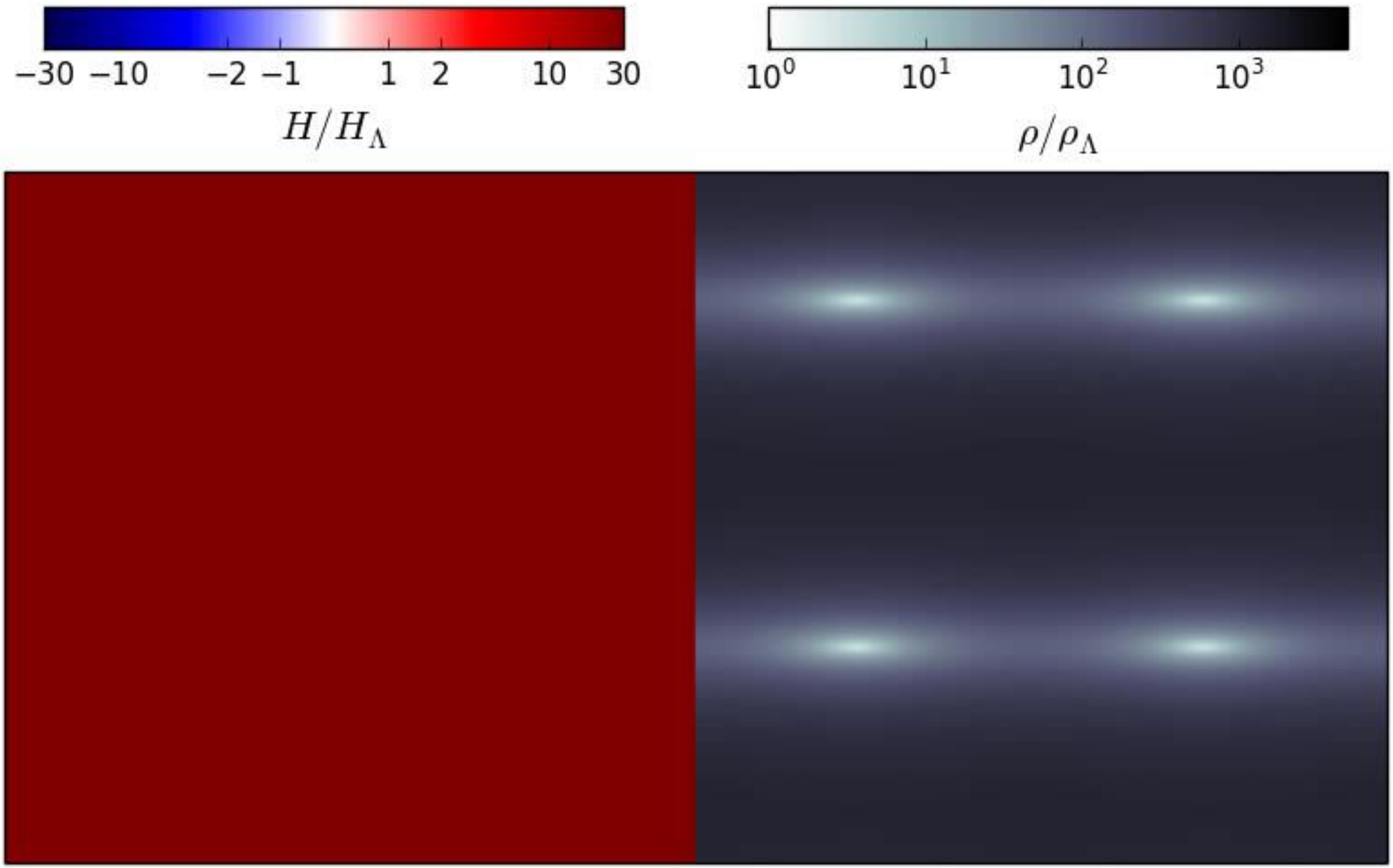


Simulation

with East, Linde and Kleban **JCAP1609**

– Inflation starts

– BH emit GW

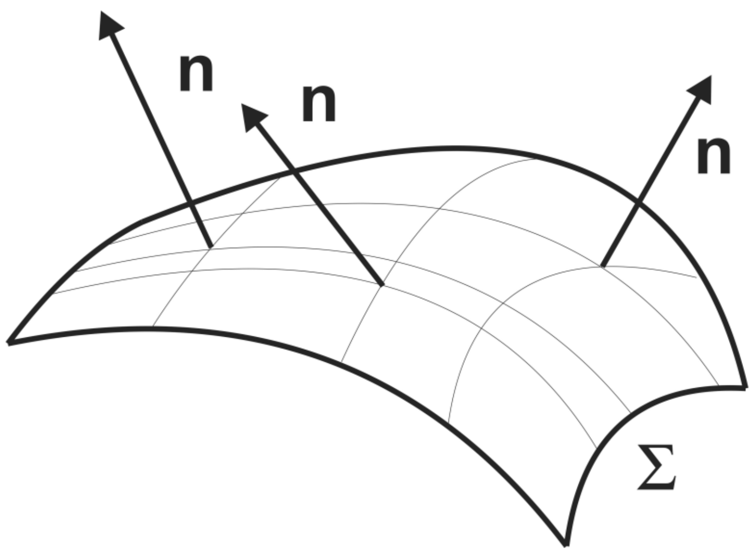


Analytically:A no Big-Crunch theorem

with Kleban, **JCAP 2016**
see also Barrow and Tippler **1985**
with Creminelli and Vasy **2019**

- Consider a cosmological spacetime with an initial surface expanding everywhere.
- Can the universe globally collapse?
- Since $\mathcal{L}_n \log \sqrt{h} = K,$ $\quad K_{\mu\nu} = \nabla_\mu n_\nu$
- $\Longrightarrow$ there must exist a maximal surface, where

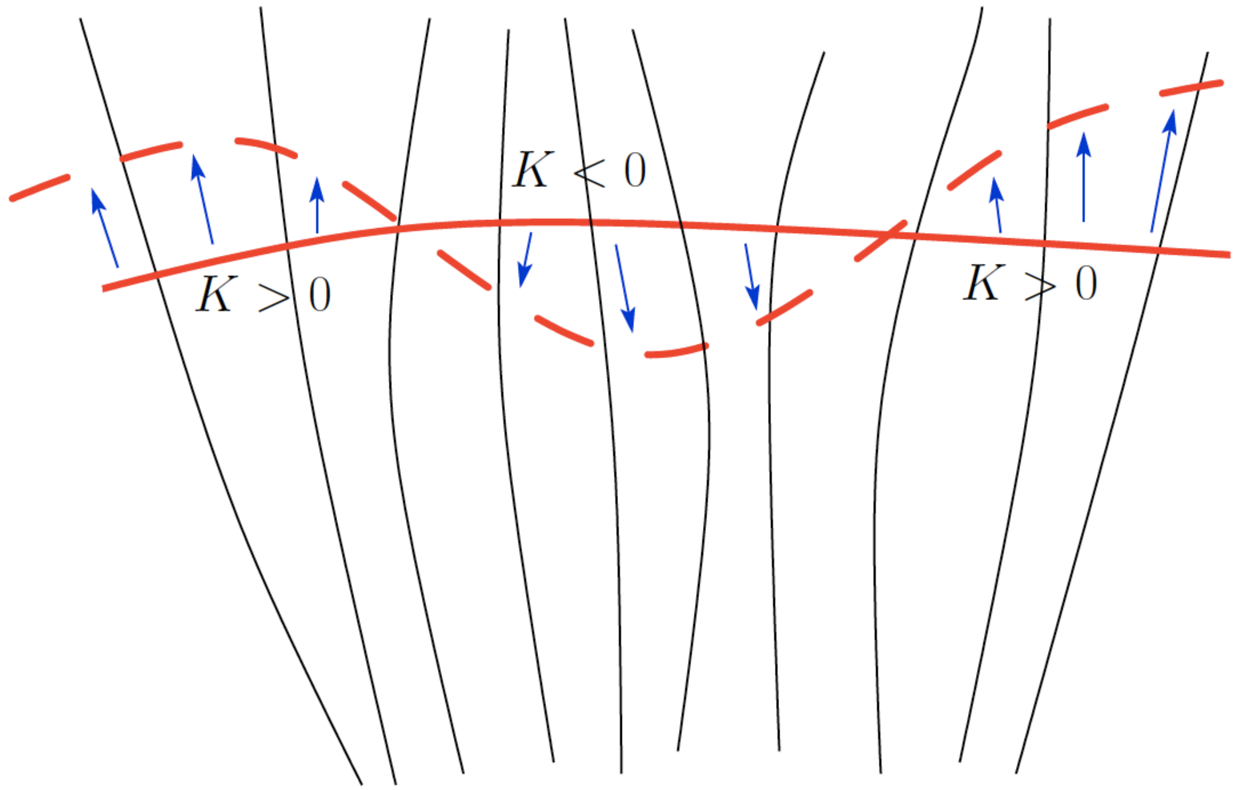
$$K = 0 \quad \text{everywhere}$$



Mean-Curvature Flow

with Kleban, **JCAP 2016**
with Creminelli and Vasy **2019**

– Take a surface, and deform it forward or backward according to sign of K



– The change of volume: $$\frac{\partial V}{\partial \lambda} = \int d^3x K^2 \sqrt{h} \equiv \langle K^2 \rangle \geq 0$$

– So this procedure either converges to an extremal surface, if it can exist, with $K = 0$ everywhere

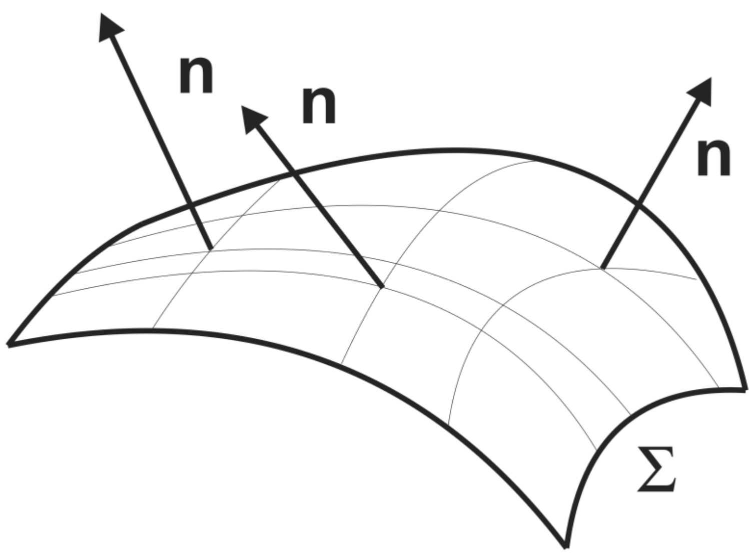
– or it gives a surface of larger volume indefinitely

– The surface will never its a spacetime singularity nor become singular.

– This is a field of Mathematics, and now it has a new connection to Physics

A no Big-Crunch theorem

with Kleban, **JCAP 2016**
see also Barrow and Tippler **1985**
with Creminelli and Vasy **2019**



- To have a global recollapse,
- $\Rightarrow$ there must exist a maximal surface, where

$$K = 0 \quad \text{everywhere}$$

- Consider the following linear-combination of Einstein Equations

$$n^\mu n^\nu \left(8\pi G_N T_{\mu\nu} = G_{\mu\nu}\right) n^\mu n^\nu$$

- Using Gauss-Codazzi

$$16\pi G_N T_{\mu\nu} n^\mu n^\nu = R^{(3)} + \frac{2}{3} K^2 - \sigma_{\mu\nu}\sigma^{\mu\nu}$$

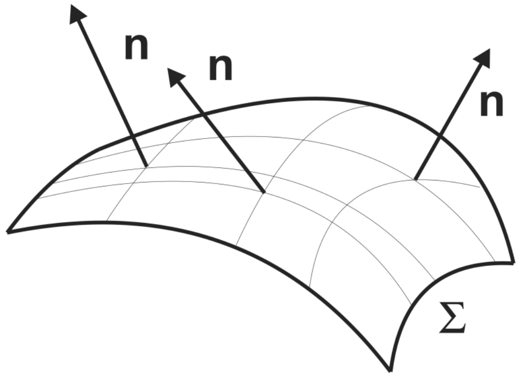
–where $K = \nabla_\mu n^\mu \,, \qquad \sigma_{\mu\nu} = K_{\mu\nu} - \frac{1}{3} K h_{\mu\nu}$

- On Extremal surface

$$16\pi G_N T_{\mu\nu} n^\mu n^\nu = R^{(3)} - \sigma^{\mu\nu}\sigma_{\mu\nu}$$

A no Big-Crunch theorem

with Kleban, **JCAP 2016**
see also Barrow and Tippler **1985**
with Creminelli and Vasy **2019**



- If we impose Weak Energy Condition

$$\underbrace{16\pi G_N T_{\mu\nu} n^\mu n^\nu}_{\geq 0 \text{ by WEC}} = R^{(3)} \underbrace{-\sigma^{\mu\nu}\sigma_{\mu\nu}}_{\leq 0}$$

$T_{\mu\nu}t^\mu t^\nu \geq 0$ (i.e. "$\rho \geq 0, \rho + p > 0$") , for any t^μ timelike

- If there is a topological condition such that $R^{(3)} \leq 0$ at least at one point
- $\Rightarrow$ The equation cannot be satisfied, $\Rightarrow$ extremal surface does not exists

- The Thorston Geometrization Classification, indeed shows that "most" of 3-manifold must have $R^{(3)} \leq 0$ at least at one point
  - for these topologies, some regions of the universe keep expanding, notwithstanding the development of singularities

Thorston Geometrization Classification

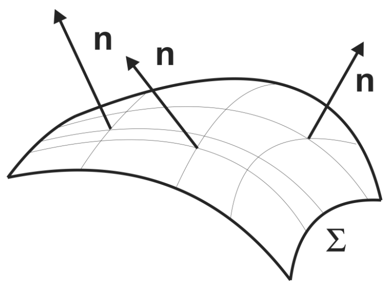
Thorston, Hamilton, Perelman

– To determine which manifolds must have $R^{(3)} \leq 0$ at least at one point, consider that all compact oriented 3-manifold fall into one of these three classes

- (i) ``Closed'': any function on M_t can be the $R^{(3)}$ of a smooth metric on M_t
  - ex: $S^3,\ S^2 \times S^1,\ S^3/\Gamma(\text{with } \Gamma \in SO(4)), RP^3$
    - and connected sums
- (ii) ``Flat'': a function on M_t can be the $R^{(3)}$ of a smooth metric on M_t if it is negative somewhere or zero everywhere
  - ex: R^3/Γ (with Γ an isometry of R^3)
    - and connected sums
- (iii) ``Open'': a function on M_t can be the $R^{(3)}$ of a smooth metric on M_t if it is negative somewhere
  - ex: $H^3/\Gamma,\ H^2 \times R, nil, sol, \widetilde{SL}(2, R)$
- Any connected sum of (i) and (ii) with a factor of (iii) is of kind (iii)

A no Big-Crunch theorem

with Kleban, **JCAP 2016**
see also Barrow and Tippler **1985**



- Therefore, in most manifolds (fast) expansion has to continue.
  - this, and some additional results using mean curvature flow, suggests that
  - it is *extremely likely* that expansion continues, volume reaches infinity, inhomogenous energy dilutes, potential energy (which does not dilutes) dominates, inflation starts notwithstanding the formation of singularities.
  - partial, stronger, results in 3+1d

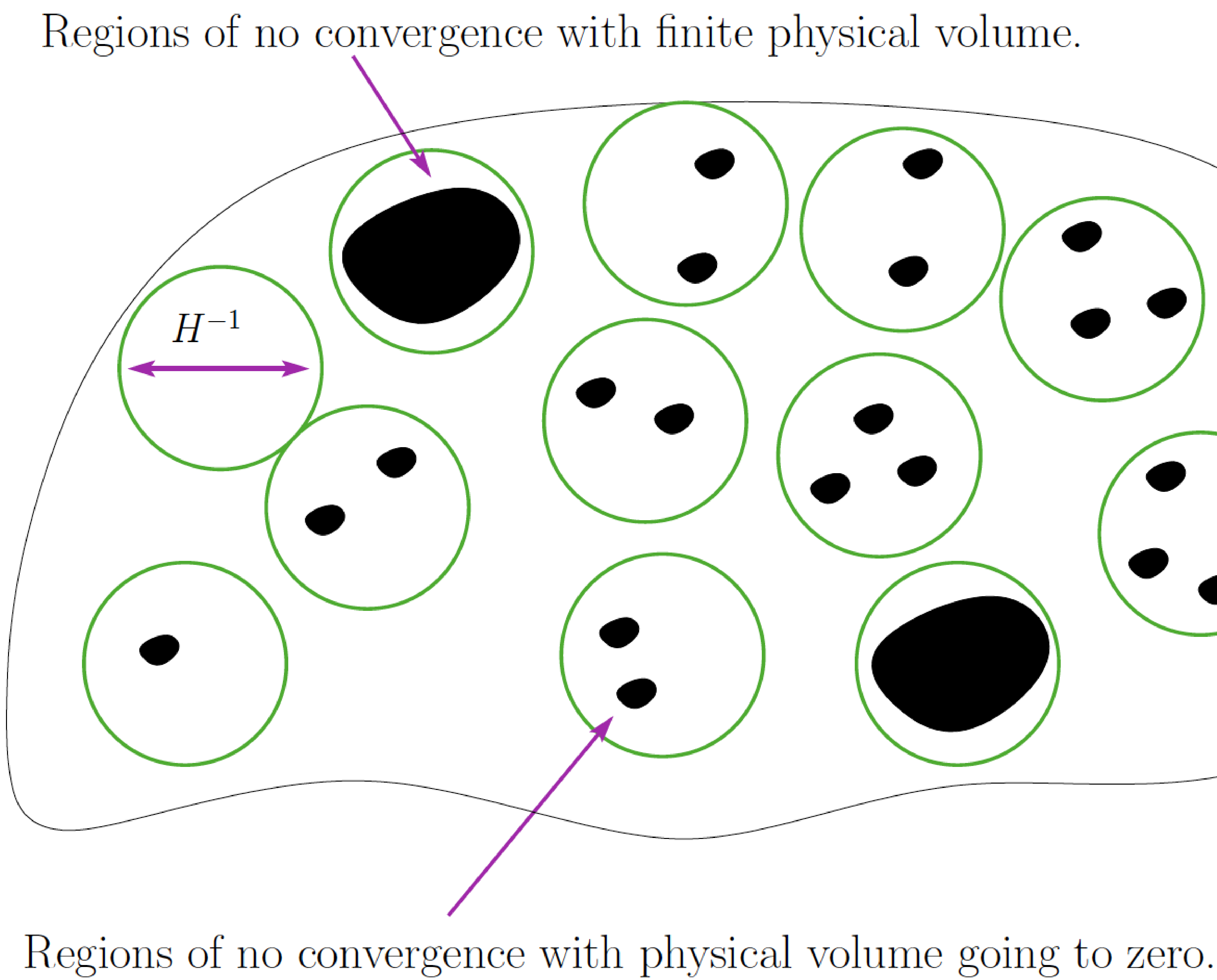
with Creminelli, Kleban, Vasy **in progress**

- In 2+1d, this statement as recently been rigorously proved by
  - using the expertise of the Math Department Professor

with Creminelli, Vasy **2019**

The Cow

–Pictorial representation of the late time manifold



Summary on starting Inflation

- For ~ 30 years, widely believed: to start inflation, need an homogenous H_I patch.
  - This seemed to require fine tuning: `initial patch problem'
- By using numerical GR simulations that are able to handle singularities and horizons
- & less-usual mathematical techniques such as mean curvature flow and topology
- we have shown that inflation starts very often, and actually seems always to start in some topologies:
  - 2+1d proved
  - 3+1d partial-statements proved

- these results are apparently appealing also for mathematicians

- So, we can take that inflation starts….

… but we mentioned Black Holes…

… we cannot think to LIGO/VIRGO…

Lessons for Fundamental Physics from LIGO/VIRGO

An EFT for testing extensions of GR with Gravitational Waves

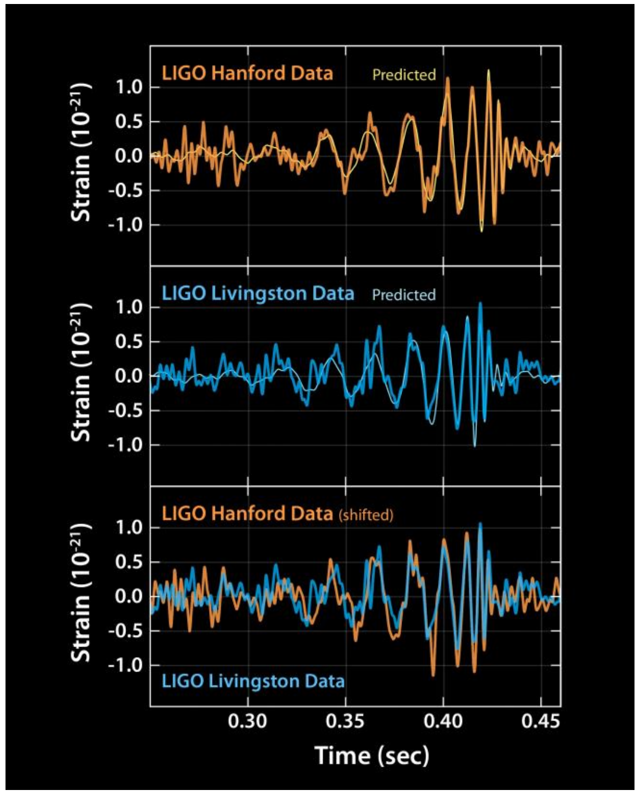
with Endlich, Huang and Gorbenko

2017

with Sennett, Brito, Buonanno and Gorbenko

in completion

An EFT for probing extensions of GR at LIGO



- Gravity waves have just been discovered.
  - An amazing lesson of perseverance for whole mankind

- They will teach us a lot about astrophysics compact objects
- Can these observations teach us something about the fundamental nature of gravity?
- The most general parametrization (*i.e.* EFT) for doing that with the following requirements:
  - testable at LIGO/VIRGO
  - no additional degree of freedom
  - no violation of locality (superluminality, etc.)
  - in no conflict to other GR experiments

An EFT for probing extensions of GR at LIGO/VIRGO

- The most general such a Lagrangian is with Endlich, Huang, Gorbenko **2017**

$$S_{\rm eff} = 2M_{\rm pl}^2 \int d^4x\sqrt{-g}\left(-R + \frac{\mathcal{C}^2}{\Lambda^6} + \frac{\tilde{\mathcal{C}}^2}{\tilde{\Lambda}^6} + \frac{\tilde{\mathcal{C}}\mathcal{C}}{\Lambda_-^6} + \dots\right)$$

$$\mathcal{C} \equiv R_{\alpha\beta\gamma\delta}R^{\alpha\beta\gamma\delta}, \quad \tilde{\mathcal{C}} \equiv R_{\alpha\beta\gamma\delta}\,\epsilon^{\alpha\beta}{}_{\mu\nu}\,R^{\mu\nu\gamma\delta}\ ,$$

- No superluminality $\sim\Rightarrow$ No $R^3_{\mu\nu\rho\sigma}$ Camanho, Edelstain, Maldacena, Zhiboeadov **2016**
- Testable at LIGO $\Rightarrow$ $\Lambda \sim 10^{-1}\ \text{Km}^{-1}$
- Not ruled out by GR tests

$$\Rightarrow \quad \delta g^{\mu\nu}T_{\mu\nu} = \text{as in GR} \quad \& \quad \text{amplitudes saturate when UV enters}$$

  – this `soft' UV complition is the same that happens in WW scattering when the Higgs enters: the amplitude soft growing

  – in all test prior LIGO/VIRGO, at UV scale $R_{\mu\nu\rho\sigma}\Delta x^2 \ll 1$

An EFT for probing extensions of GR at LIGO/VIRGO

- The most general such a Lagrangian is

$$S_{\rm eff} = 2M_{\rm pl}^2 \int d^4x\sqrt{-g}\,\left(-R + \frac{\mathcal{C}^2}{\Lambda^6} + \frac{\tilde{\mathcal{C}}^2}{\tilde{\Lambda}^6} + \frac{\tilde{\mathcal{C}}\mathcal{C}}{\Lambda_-^6} + \dots\right)$$

$$\mathcal{C} \equiv R_{\alpha\beta\gamma\delta}R^{\alpha\beta\gamma\delta}, \quad \tilde{\mathcal{C}} \equiv R_{\alpha\beta\gamma\delta}\,\epsilon^{\alpha\beta}{}_{\mu\nu}\,R^{\mu\nu\gamma\delta}\ ,$$

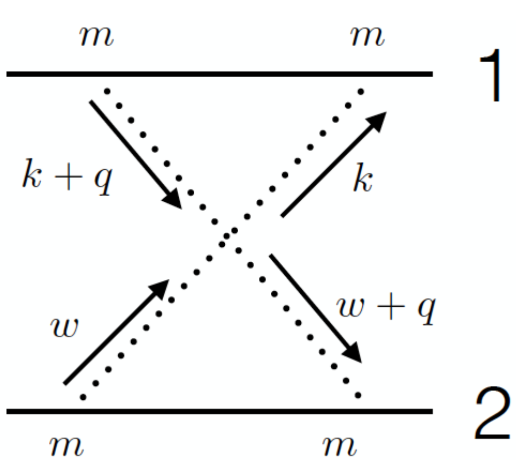
- In this way, information from LIGO/VIRGO can be mapped into parameters of a fundamental physics Lagrangian $\Lambda,\ \Lambda_-,\ \tilde{\Lambda}$
  - similar to what we do in particle physics at colliders (Precision EW tests, or the LHC Brazilian-flag plots)
- instead of into some arbitrary and potentially-unphysical rescaling of the post-Newtonian parameters of the templates $\omega(r) = \sum_n c_n\, v^n$
  - this was suboptimal
  - explored physically uninteresting regions such as superluminal ones.

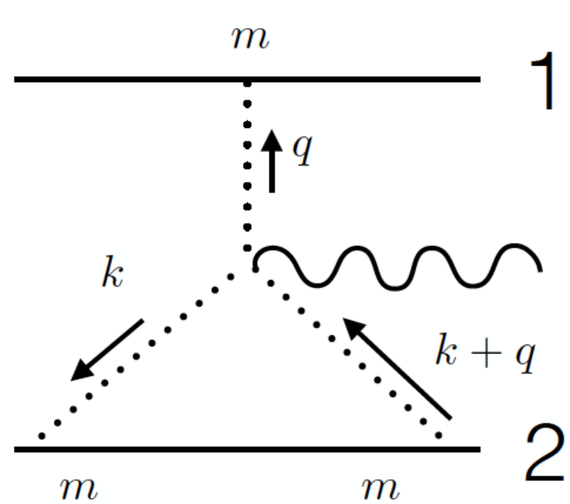
An EFT for probing extensions of GR at LIGO/VIRGO

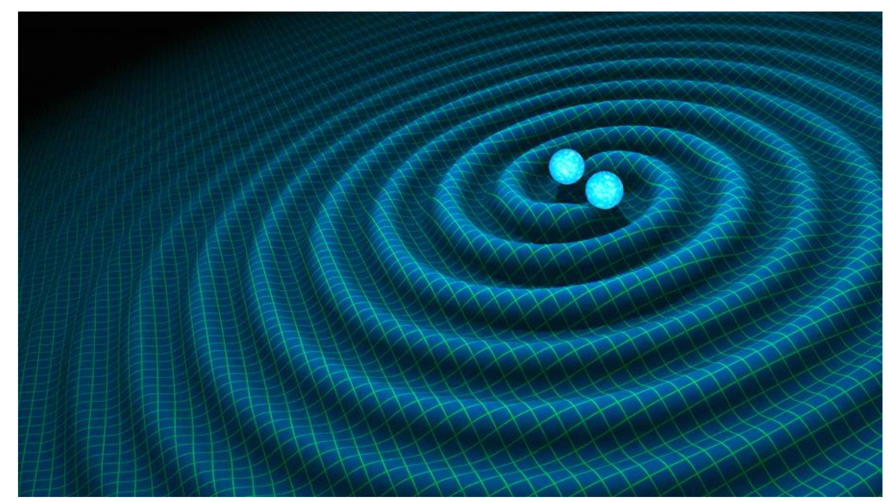
- Predictions

$$S_{\rm eff} = 2M_{\rm pl}^2 \int d^4x\sqrt{-g}\,\left(-R + \frac{\mathcal{C}^2}{\Lambda^6} + \frac{\tilde{\mathcal{C}}^2}{\tilde{\Lambda}^6} + \frac{\tilde{\mathcal{C}}\mathcal{C}}{\Lambda_-^6} + \dots\right)$$

- For $r_s \lesssim 1/\Lambda$, leading signal is in In the insparalling phase:
  - Using the EFT of Goldberger and Rothstein **2004**, change the potential energy of the two bodies, and their single-body effective radiation multipoles







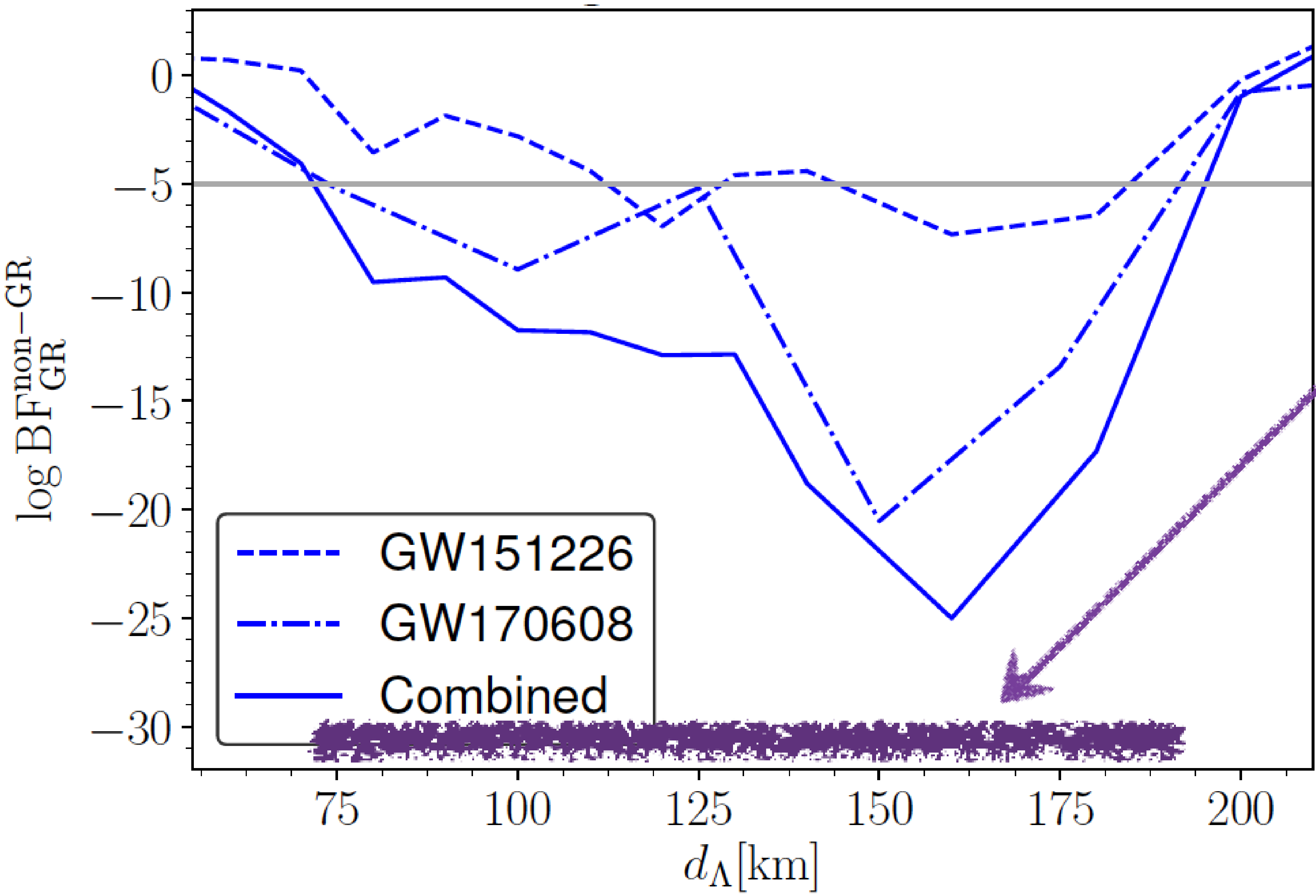
- For $r_s \gtrsim 1/\Lambda$, leading signal is in the modification of Black Hole geometry and quasi normal modes spectrum with Cardoso, Kimura, Maselli **2018**
- Similar considerations apply to the exchange of axions in neutron-neutron merger

Huang, Johnson, Samunski, Sakellariadu, Zhang **2018**

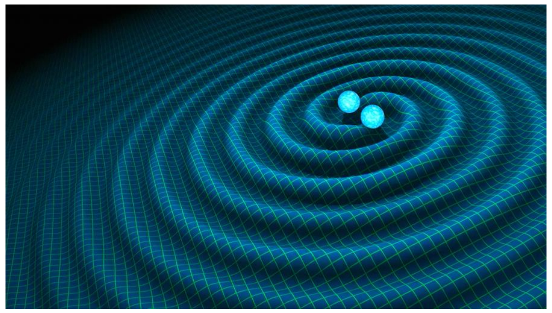
First bounds on fundamental Lagrangian from LIGO data

with Sennett, Brito, Buonanno, Gorbenko, Senatore
in completion

- LIGO members, preliminary



Excluded!



$$S_{\rm eff} = 2M_{\rm pl}^2 \int d^4x\sqrt{-g}\,\left(-R + \frac{\mathcal{C}^2}{\Lambda^6} + \frac{\tilde{\mathcal{C}}^2}{\tilde{\Lambda}^6} + \frac{\tilde{\mathcal{C}}\mathcal{C}}{\Lambda_-^6} + \dots\right)$$

Lessons on Dark Energy from LIGO/VIRGO

Creminelli, Vernizzi, **2017**
Sakstein, Jain, **2017**
Ezquiaga, Zumalacarregui, **2017**
Baker etal, **2017**
Copeland etal **2018**
Creminelli, Lewandowski, Tambalo, Vernizzi **2018**

The universe is Accelerating

- Many people, especially outside of Europe, and including me, have a favorite explanation:

The universe [illegible] Accelerating

- Many people, especially outside of Eu[illegible]nd including me, have a favorite explanation:

$$\Lambda$$

The universe [illegible] Accelerating

- Many people, especially outside of Eu[illegible]nd including me, have a favorite explanation:

$$\Lambda$$

- it agrees with data to ~4%

Weinberg probably got it right (again)

- S. Weinberg, prior the detection of the acceleration of the universe, predicted, based on Anthropic reasoning, the value of the observed cosmological constant. It worked.
  - In a universe dominated by cosmological constant, structures do not form any longer
  - $\Rightarrow$ for experimentalists to be there, cosmological constant better dominate after structure form
  - If there is a landscape with lots of local values of Λ, observes will be where structures are, and so where Λ is small enough.
  - But since it is hard to make Λ small, most likely Λ will be closed to threshold: it will dominate just after structure formed
- This is exactly where we found Λ
- This interpretation finds support in the presence of the Landscape, and in the Higgs tuning.
- There are issues of, to me, detail, and, also, this is truly revolutionary point of view.

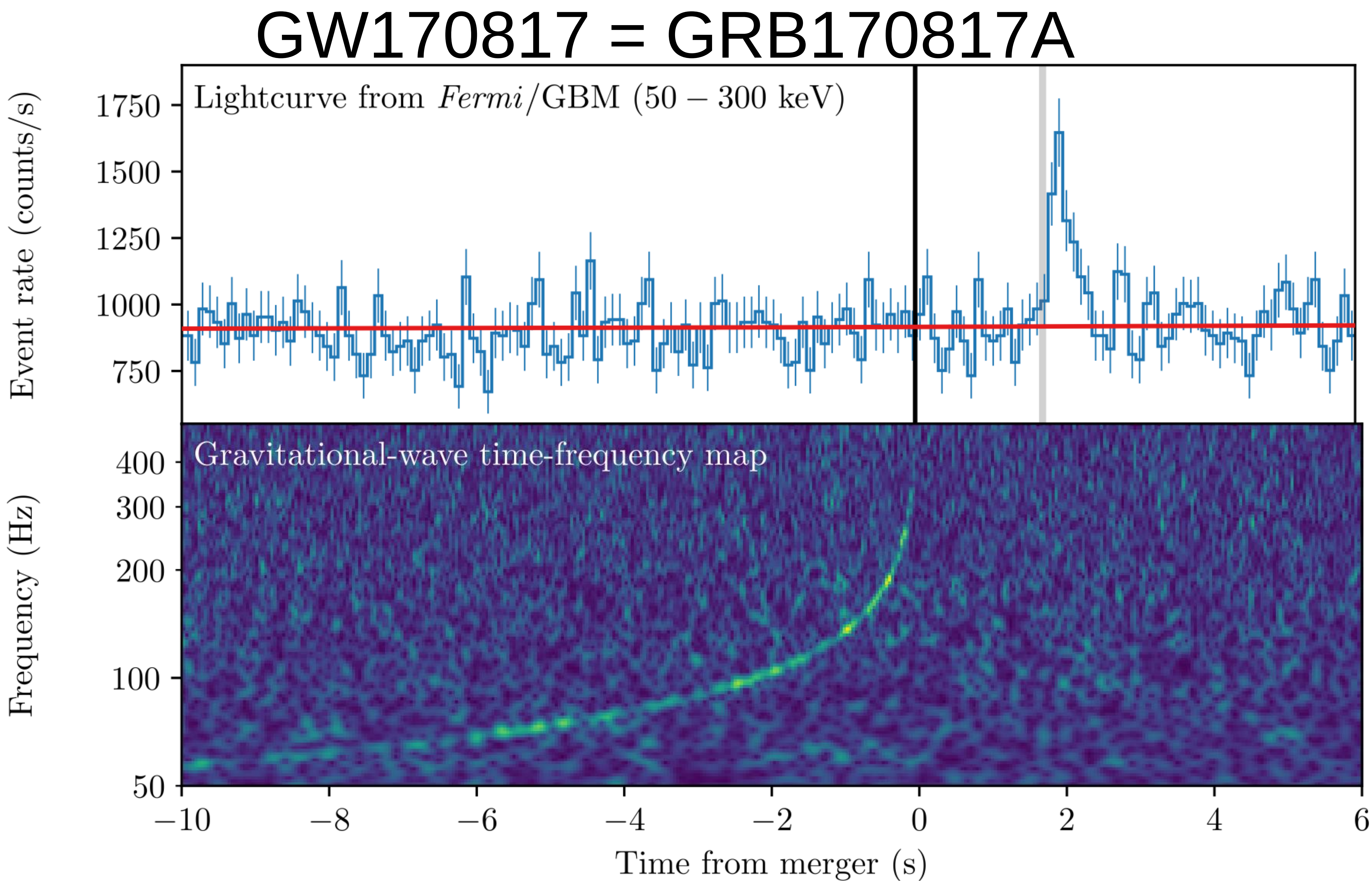
Observational side

- Due to such a revolutionary change of point of view, and due to the fact that, observationally, we are probing with unprecedented precision the low-redshift universe, many people have started focusing of theories that tend to modify gravity.
  - it is unclear if any of them actually addresses the Cosmological Constant problem

- These are just theories where one adds a degree of freedom that, due to FRW spacetime, spontaneously breaks time translation.

- There is an extremely large field, especially in Europe.
- And tremendous progress in this field has come from the following experimental fact

Black-Hole Neutron-Star merger



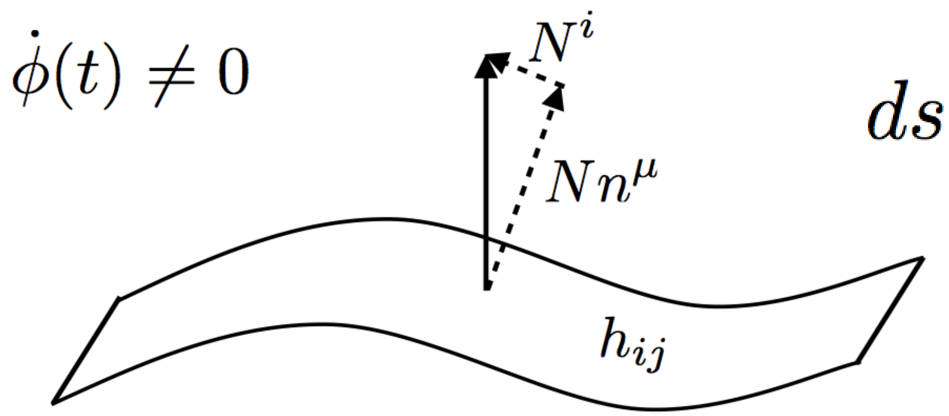
Black-Hole Neutron-Star merger

GW170817 = GRB170817A

$$-3 \cdot 10^{-15} \leq c_g/c - 1 \leq 7 \cdot 10^{-16}$$

The EFT of Dark Energy

- It is possible to write down the most general theory for the fluctuations



$$ds^2 = -N^2 dt^2 + h_{ij}(N^i dt + dx^i)(N^j dt + dx^j)$$

- Assume that time-translation are spontaneously broken, there is preferred slicing, write the most general Lagrangian

$$S = \int d^4x \sqrt{-g} L[t; N, K^i_j, {}^{(3)}R^i_j, \ldots]$$

with Creminlli, Luty and Nicolis, **2006**
Vernizzi, Piazza, + many others

- Action contains all possible scalar under spatial diffs, oder by number of perturbations and derivatives

The EFT of Dark Energy

- At level of fluctuations

$$S=\int d^4x\sqrt{-g}\Big[\frac{M_*^2}{2}f^{(4)}R-\Lambda-cg^{00}+\frac{m_2^4}{2}(\delta g^{00})^2$$
$$-\frac{m_3^3}{2}\delta K\delta g^{00}-m_4^2\delta\mathcal{K}_2+\frac{\tilde{m}_4^2}{2}\delta g^{00}R-\frac{m_5^2}{2}\delta g^{00}\delta\mathcal{K}_2$$
$$-\frac{m_6}{3}\delta\mathcal{K}_3-\tilde{m}_6\delta g^{00}\delta\mathcal{G}_2-\frac{m_7}{3}\delta g^{00}\delta\mathcal{K}_3\Big]\,.$$

$$\delta\mathcal{K}_2\equiv\delta K^2-\delta K_\mu^\nu\delta K_\nu^\mu\,,\qquad \delta\mathcal{G}_2\equiv\delta K_\mu^\nu R_\nu^\mu-\delta KR/2\,,$$
$$\delta\mathcal{K}_3\equiv\delta K^3-3\delta K\delta K_\mu^\nu\delta K_\nu^\mu+2\delta K_\mu^\nu\delta K_\rho^\mu\delta K_\nu^\rho\,.$$

- $m_2^4=\alpha_K H^2M_*^2$ for LSS, we are interested in $\alpha\sim 0.1$

The EFT of Dark Energy

- At level of fluctuations

Dark Energy speed of sound

Quintessence and Brans-Dicke

DGP and brading

Galileon, Hordensky and

Beyond Hordensky

$$S = \int d^4x \sqrt{-g} \left[\frac{M_*^2}{2} f^{(4)} R - \Lambda - c g^{00} + \frac{m_2^4}{2} (\delta g^{00})^2 - \frac{m_3^3}{2} \delta K \delta g^{00} - m_4^2 \delta \mathcal{K}_2 + \frac{\tilde{m}_4^2}{2} \delta g^{00} R - \frac{m_5^2}{2} \delta g^{00} \delta \mathcal{K}_2 - \frac{m_6}{3} \delta \mathcal{K}_3 - \tilde{m}_6 \delta g^{00} \delta \mathcal{G}_2 - \frac{m_7}{3} \delta g^{00} \delta \mathcal{K}_3 \right] .$$

Non-linear terms, screening

$$\delta \mathcal{K}_2 \equiv \delta K^2 - \delta K^\nu_\mu \delta K^\mu_\nu , \qquad \delta \mathcal{G}_2 \equiv \delta K^\nu_\mu R^\mu_\nu - \delta K R/2 ,$$

$$\delta \mathcal{K}_3 \equiv \delta K^3 - 3 \delta K \delta K^\nu_\mu \delta K^\mu_\nu + 2 \delta K^\nu_\mu \delta K^\mu_\rho \delta K^\rho_\nu .$$

- $m_2^4 = \alpha_K H^2 M_*^2$ for LSS, we are interested in $\alpha \sim 0.1$
- All models unified in one Lagrangian

The EFT of Dark Energy

- At level of fluctuations

$$S=\int d^4x\sqrt{-g}\left[\frac{M_*^2}{2}f^{(4)}R-\Lambda-cg^{00}+\frac{m_2^4}{2}(\delta g^{00})^2\right.$$
$$-\frac{m_3^3}{2}\delta K\delta g^{00}-m_4^2\delta\mathcal{K}_2+\frac{\tilde m_4^2}{2}\delta g^{00}R-\frac{m_5^2}{2}\delta g^{00}\delta\mathcal{K}_2$$
$$\left.-\frac{m_6}{3}\delta\mathcal{K}_3-\tilde m_6\delta g^{00}\delta\mathcal{G}_2-\frac{m_7}{3}\delta g^{00}\delta\mathcal{K}_3\right].$$

Changes the speed of sound of gravity waves

$$\dot\gamma_{ij}^2 \subset \quad \delta\mathcal{K}_2\equiv\delta K^2-\delta K_\mu^\nu\delta K_\nu^\mu\,,\qquad \delta\mathcal{G}_2\equiv\delta K_\mu^\nu R_\nu^\mu-\delta KR/2\,,$$
$$\delta\mathcal{K}_3\equiv\delta K^3-3\delta K\delta K_\mu^\nu\delta K_\nu^\mu+2\delta K_\mu^\nu\delta K_\rho^\mu\delta K_\nu^\rho\,.$$

- $m_2^4=\alpha_K H^2 M_*^2$ for LSS, we are interested in $\alpha\sim 0.1$
- All models unified in one Lagrangian

The EFT of Dark Energy

- At level of fluctuations

$$S=\int d^4x\sqrt{-g}\left[\frac{M_*^2}{2}f^{(4)}R-\Lambda-cg^{00}+\frac{m_2^4}{2}(\delta g^{00})^2 -\frac{m_3^3}{2}\delta K\delta g^{00}-m_4^2\delta\mathcal{K}_2+\frac{\tilde{m}_4^2}{2}\delta g^{00}R-\frac{m_5^2}{2}\delta g^{00}\delta\mathcal{K}_2 -\frac{m_6}{3}\delta\mathcal{K}_3-\tilde{m}_6\delta g^{00}\delta\mathcal{G}_2-\frac{m_7}{3}\delta g^{00}\delta\mathcal{K}_3\right].$$

$\tilde{m}_4^2 = m_5^2$

$$\dot{\gamma}_{ij}^2 \subset \quad \delta\mathcal{K}_2\equiv\delta K^2-\delta K_\mu^\nu\delta K_\nu^\mu\,,\qquad \delta\mathcal{G}_2\equiv\delta K_\mu^\nu R_\nu^\mu-\delta KR/2\,,$$

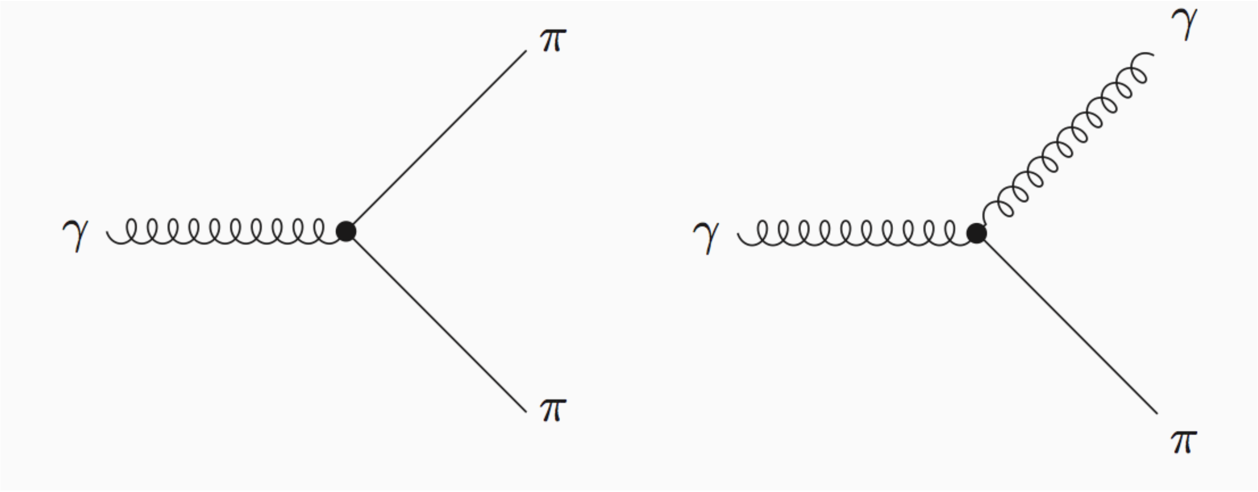
$$\delta\mathcal{K}_3\equiv\delta K^3-3\delta K\delta K_\mu^\nu\delta K_\nu^\mu+2\delta K_\mu^\nu\delta K_\rho^\mu\delta K_\nu^\rho\,.$$

- $m_2^4=\alpha_K H^2M_*^2$ for LSS, we are interested in $\alpha\sim 0.1$
- All models unified in one Lagrangian

The EFT of Dark Energy

- The non-relativistic dynamics allows also gravitational waves to decay into dark energy.

$$\frac{\tilde{m}_4^2}{2}\delta g^{00}\left({}^{(3)}R - \delta\mathcal{K}_2\right)$$



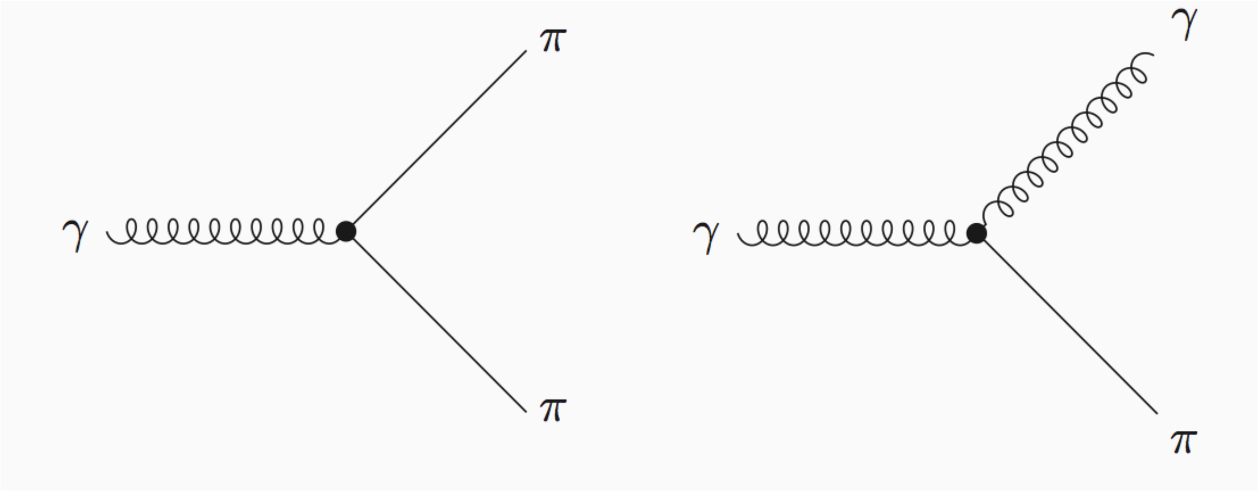
$$\alpha_{\rm H} \equiv \frac{2\tilde{m}_4^2}{M_{\rm Pl}^2} \lesssim 10^{-10}$$

- Irrelevant for LSS observations

The EFT of Dark Energy

- The non-relativistic dynamics allows also gravitational waves to decay into dark energy.

$$\frac{\tilde{m}_4^2}{2}\delta g^{00}\left({}^{(3)}R - \delta\mathcal{K}_2\right)$$



$$\alpha_{\rm H} \equiv \frac{2\tilde{m}_4^2}{M_{\rm Pl}^2} \lesssim 10^{-10}$$

- Irrelevant for LSS observations

The EFT of Dark Energy

- Somewhat unexpectedly, the discovery of gravitational waves has hit very heavily the theories of dark energy.
- Some theories are surviving (at least so far), but, to me, we are talking of corners.
- Plus, we already have a theory that works very well: Λ
  - and which goes well together in what we are seeing in the standard model Higgs.
- So, we go back to the early universe, where, with Inflation,. we definitely have something to better understand.

The way ahead

Cosmology is a luminosity experiment

- Tremendous progress has been made through observation of the primordial fluctuations
- We are probing a statistical distribution:
  - In order to increase our knowledge of Inflation, apart for one expetion, we need more modes:
    $$\Delta(\text{everything}) \propto \frac{1}{\sqrt{N_{\text{modes}}}}$$
- Planck has just observed almost all the modes from the primordial CMB
- Large-Scale Structure offer the only medium-term place for hunting for more modes
  - but we are compelled to understand them better
    - Lots of applications for
      - astrophysics, inflation, dark energy, neutrinos, dark matter, etc.

What is next?

- LSST, Euclid and Chime are the next big missions: this is our next chance
  - we need to understand how many modes are available

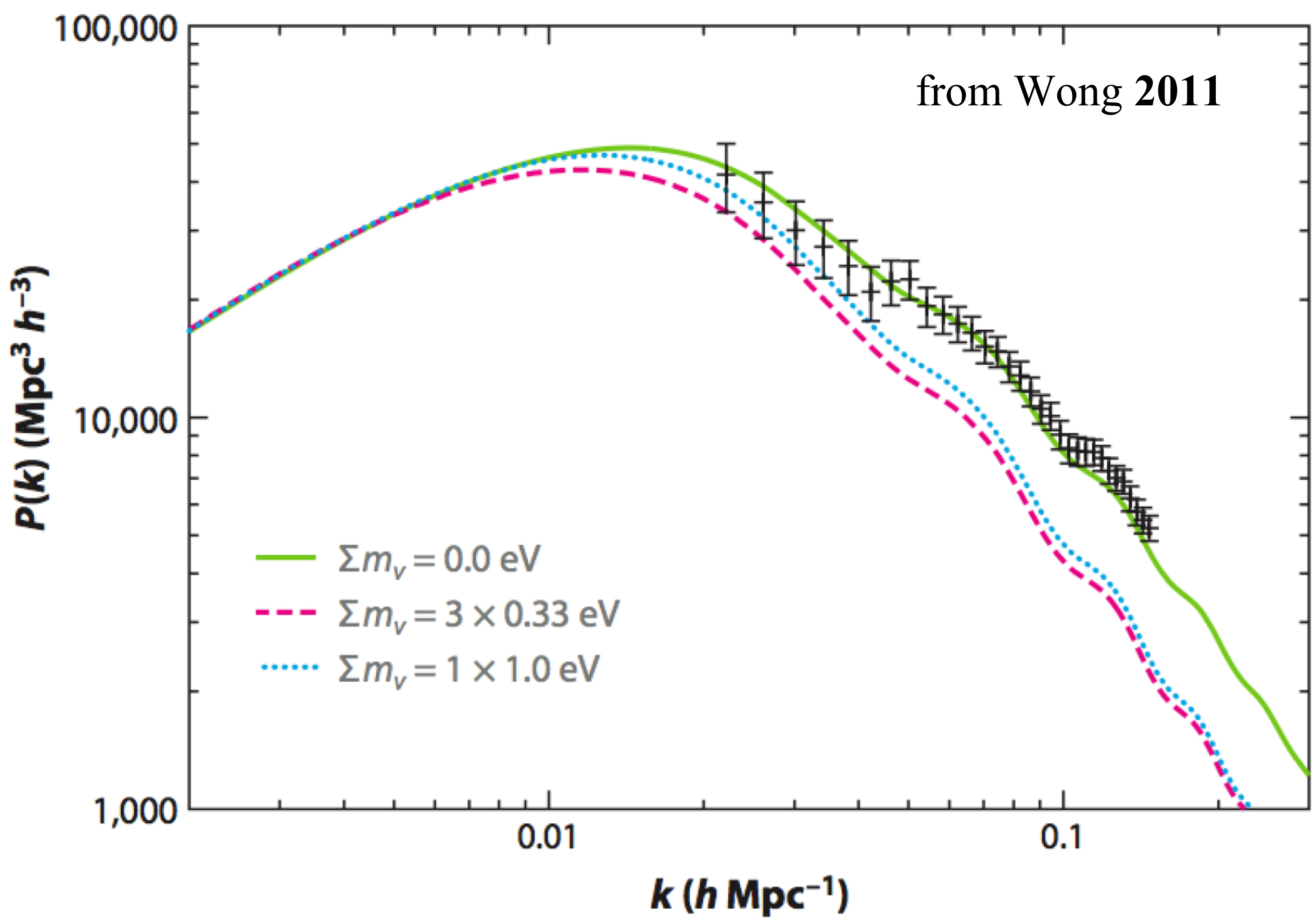
$$\text{Number modes} \sim V_{\text{survey}}\, k_{\text{max}}^3$$

  - Need to understand short distances

Massive Neutrinos

Nobel Prize and Breakthrough prize **2015**

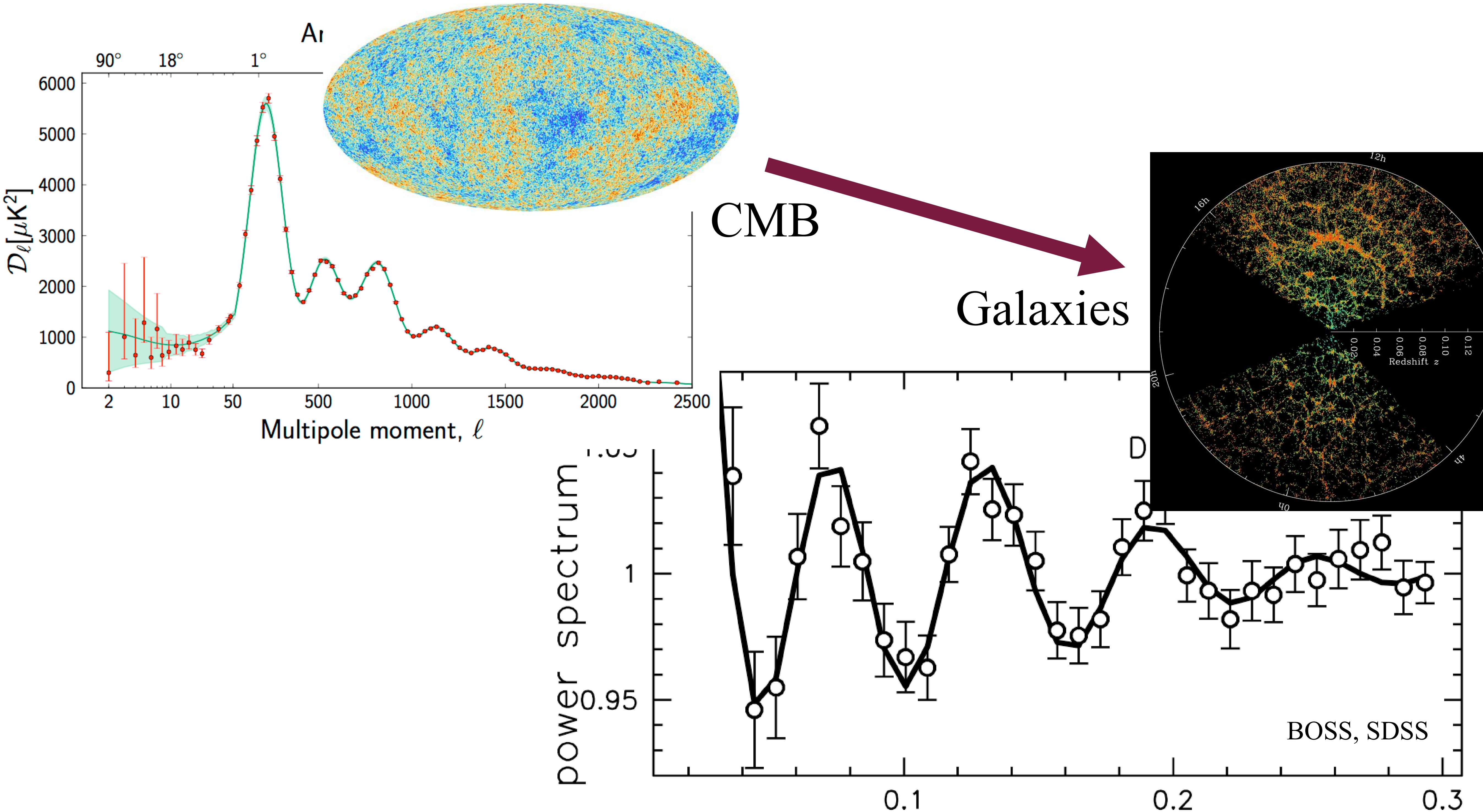
- Not only inflation
- Neutrinos have a mass, their energy affects the gravitational clustering
- By understanding the clustering, we can measure their mass



- We need to understand these curves

Some marvelous results already achieved

- Baryon Acoustic Oscillations in Galaxies distribution

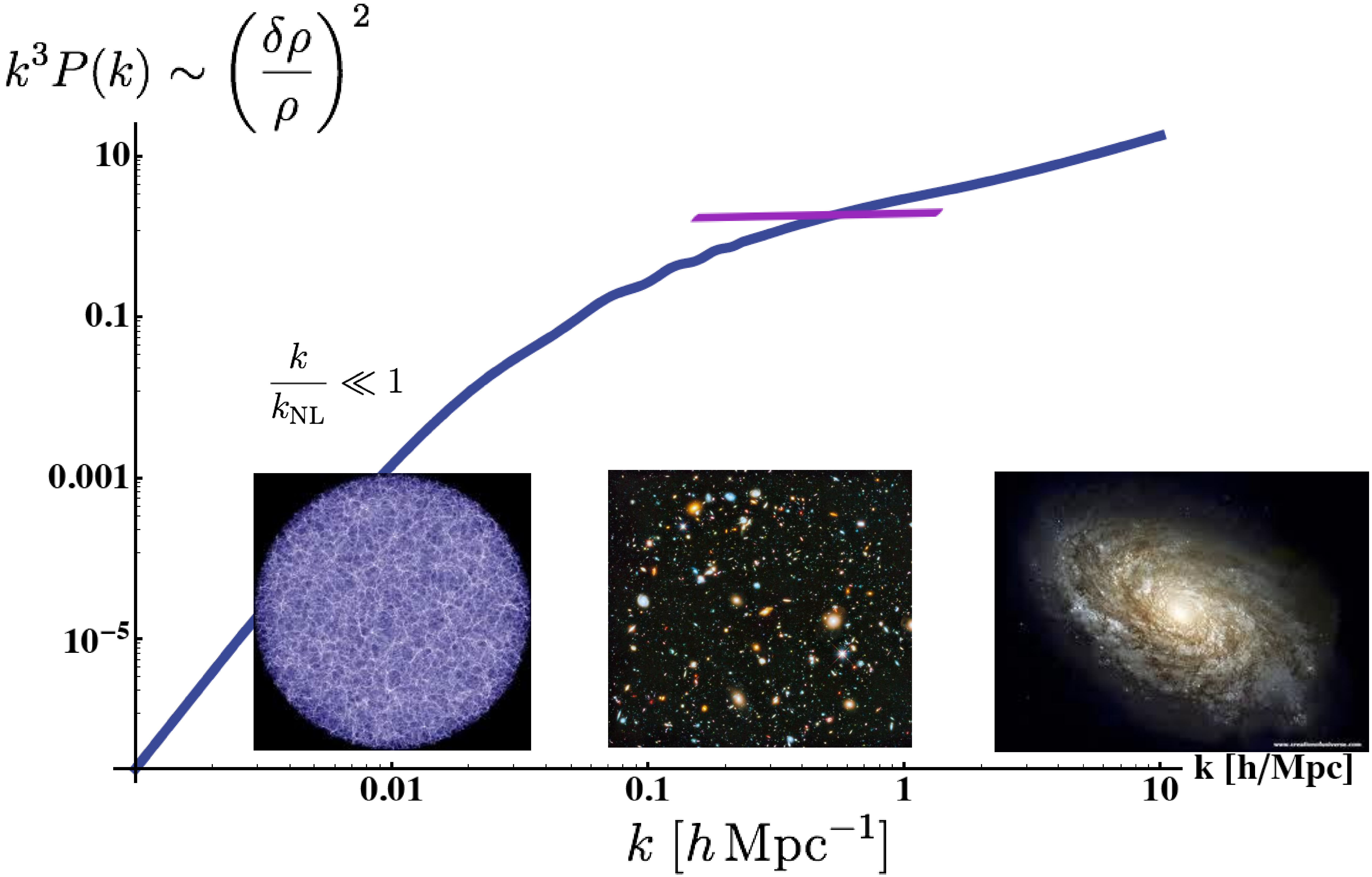


- But most new information is just about low-z universe
- Wherever CMB was not degenerate, it dominates

The Effective Field Theory
of
Large-Scale Structure

The EFTofLSS: A well defined perturbation theory

- Non-linearities at short scale



A long, long journey

– Dark Matter & Baryons

– Galaxies

– Redshift space

– IR-resummation

– Of course, none of this would have been possible without the precedent work of people like Bernardeau, Bond, Boucher, Kaiser, Matsubara, MacDonald, Peebles, Refregier, Scheth, Scoccimarro, Seljak, Wechsler, White, and Zeldovich…

– But the EFTofLSS provides the first (and only) rigorous, convergent formalism to the true answer for $k \ll k_{\rm NL}$

- to do fundamental physics, we have to be very accurate, and therefore rigorous.

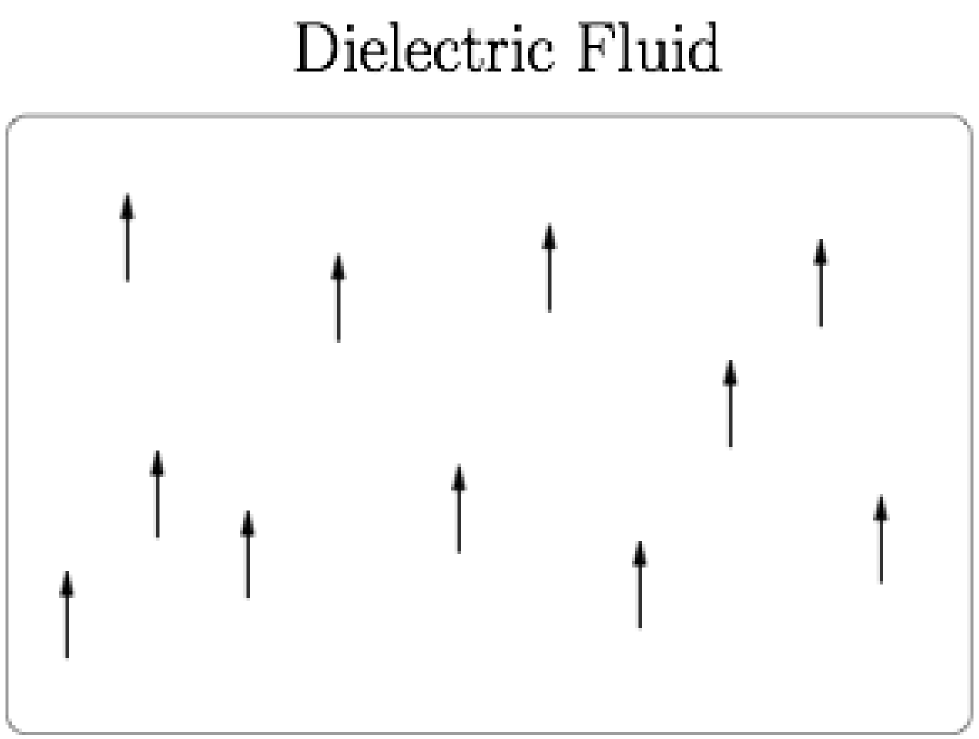
The EFTofLSS and Dieletric Materials

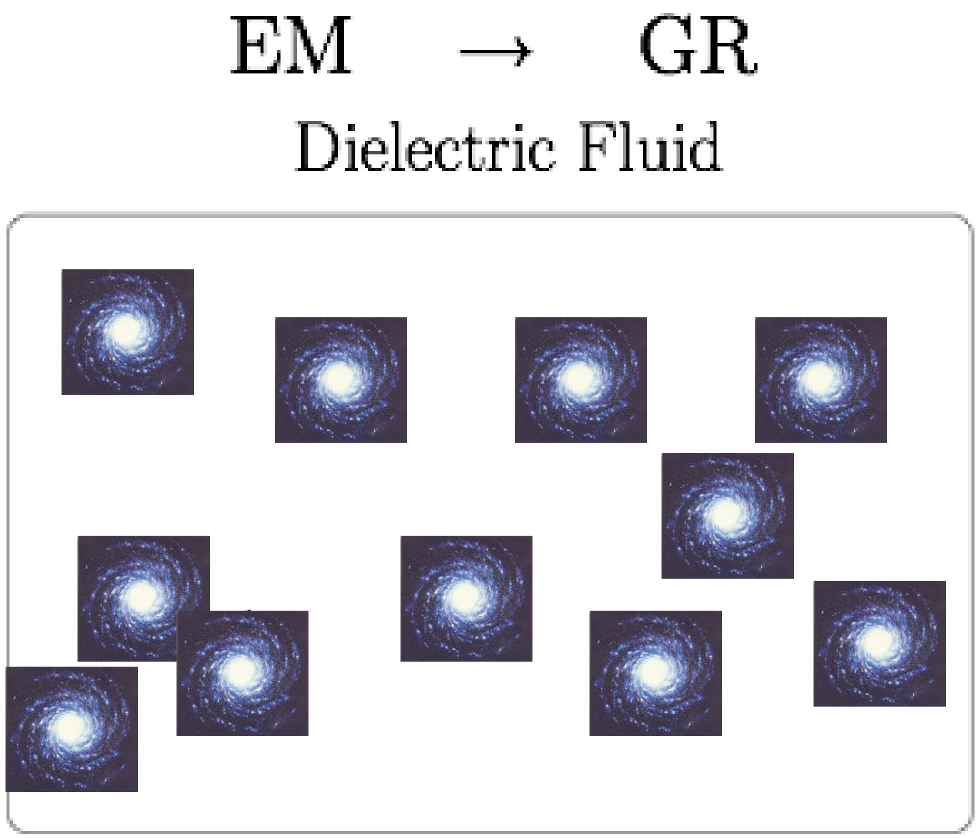
– The theory of dielectric materials is the theory of a massless spin-one object (light) interacting with composite objects (atoms)

– Very similarly, the EFTofLSS is the theory of massless spin-two object (gravity), interacting with composite objects (galaxies)

  - so it is conceptually quite easy

– It is also similar to the Chiral Lagrangian





The Effective ~Fluid

– In history of universe Dark Matter moves about $1/k_{\rm NL} \sim 10\,{\rm Mpc}$

  – it is an effective fluid-like system with mean free path ~ $1/k_{\rm NL} \sim 10\,{\rm Mpc}$

• Skipping many subtleties, the resulting equations are equivalent to fluid-like equations

$$\nabla^2\Phi_l = H^2\frac{\delta\rho_l}{\rho}$$

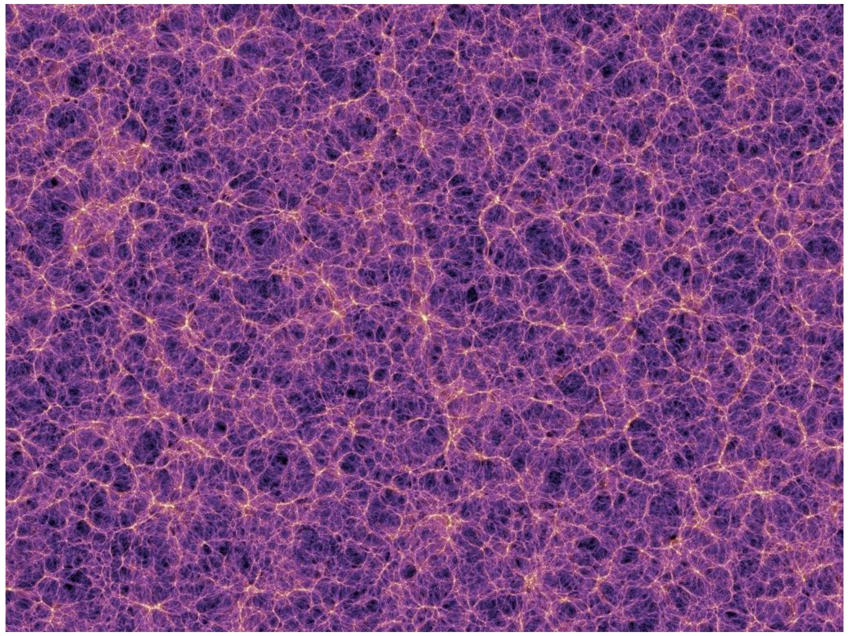
$$\partial_t\rho_l + H\rho_l + \partial_i\left(\rho_l v_l^i\right) = 0$$

$$\dot v_l^i + H v_l^i + v_l^j\partial_j v_l^i = \frac{1}{\rho}\partial_j\tau_{ij}$$

with Baumann, Nicolis and Zaldarriaga **JCAP 2012**
with Carrasco and Hertzberg **JHEP 2012**
with Porto and Zaldarriaga **JCAP 2014**

– short distance physics appears as a non trivial stress tensor for the long-distance fluid

$$\tau_{ij} \sim \delta_{ij}\,\rho_{\rm short}\,\left(v^2_{\rm short} + \Phi_{\rm short}\right)$$



Dealing with the Effective Stress Tensor

- For dealing with long dist., expectation value over short modes (integrate them out)

$$\langle \tau_{ij}(\vec{x},t)\rangle_{\text{long fixed}} = f_{\text{very complicated}}\left[\{H(t'),\Omega_{\text{dm}}(t'),\ldots,\rho_{\text{dm}}(x',t'),\ldots,m_{\text{dm}},\ldots\}|_{\text{on past light cone}}\right]$$

- At long-wavelengths, the only fluctuating fields have small fluctuations: Taylor expand

$$\Rightarrow \quad \langle \tau_{ij}(\vec{x},t)\rangle_{\text{long fixed}} \sim c_s^2 \delta\rho(\vec{x},t) + \mathcal{O}(\delta\rho^2)$$

- We obtain equations containing only long-modes

$$\nabla^2 \Phi_l = H^2 \frac{\delta\rho_l}{\rho}$$

$$\partial_t \rho_l + H\rho_l + \partial_i\left(\rho_l v_l^i\right) = 0$$

$$\dot{v}_l^i + H v_l^i + v_l^j \partial_j v_l^i = \frac{1}{\rho}\partial_j \tau_{ij}$$

every term allowed by symmetries

$$\langle \tau_{ij}\rangle_{\text{long-fixed}} \sim \delta_{ij}\left[p_0 + c_s\,\delta\rho_l + \mathcal{O}\left(\frac{\partial}{k_{\text{NL}}}, \partial_i v_l^i, \delta\rho_l^2, \ldots\right) + \Delta\tau\right]$$

- How many terms to keep?

  –each term contributes as an extra factor of $\dfrac{\delta\rho_l}{\rho} \sim \dfrac{k}{k_{\text{NL}}} \ll 1$

Perturbation Theory
with the EFT

Perturbation Theory within the EFT

- In the EFT we can solve iteratively $\delta_\ell, v_\ell, \Phi_\ell \ll 1$, where $\delta = \dfrac{\delta\rho}{\rho}$

$$\nabla^2 \Phi_l = H^2 \frac{\delta\rho_l}{\rho}$$

$$\partial_t \rho_l + H\rho_l + \partial_i \left(\rho_l v_l^i\right) = 0$$

$$\dot{v}_l^i + H v_l^i + v_l^j \partial_j v_l^i = \frac{1}{\rho} \partial_j \tau_{ij}$$

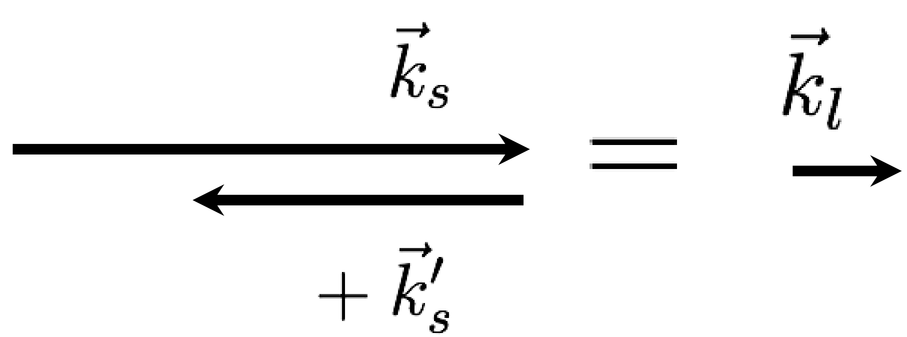
$$\langle \tau_{ij} \rangle_{\text{long-fixed}} \sim \delta_{ij} \left[p_0 + c_s \, \delta\rho_l + \mathcal{O}\left(\frac{\partial}{k_{\text{NL}}}, \partial_i v_l^i, \delta\rho_l^2, \ldots \right) + \Delta\tau \right]$$

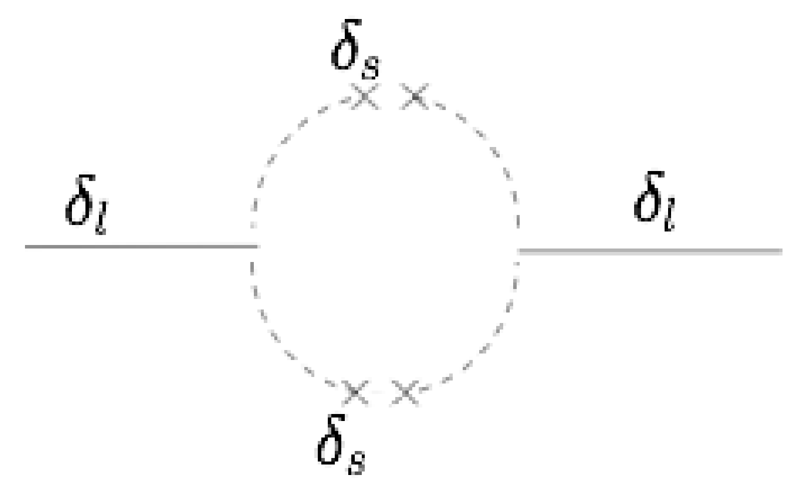
Perturbation Theory within the EFT

- Solve iteratively in $\delta = \dfrac{\delta\rho}{\rho}$
- Since equations are non-linear, we obtain convolution integrals (loops)

$$\delta^{(n)} \sim \int \text{GreenFunction} \times \text{Source}^{(n)}\left[\delta^{(1)}, \delta^{(2)}, \ldots, \delta^{(n-1)}\right]$$

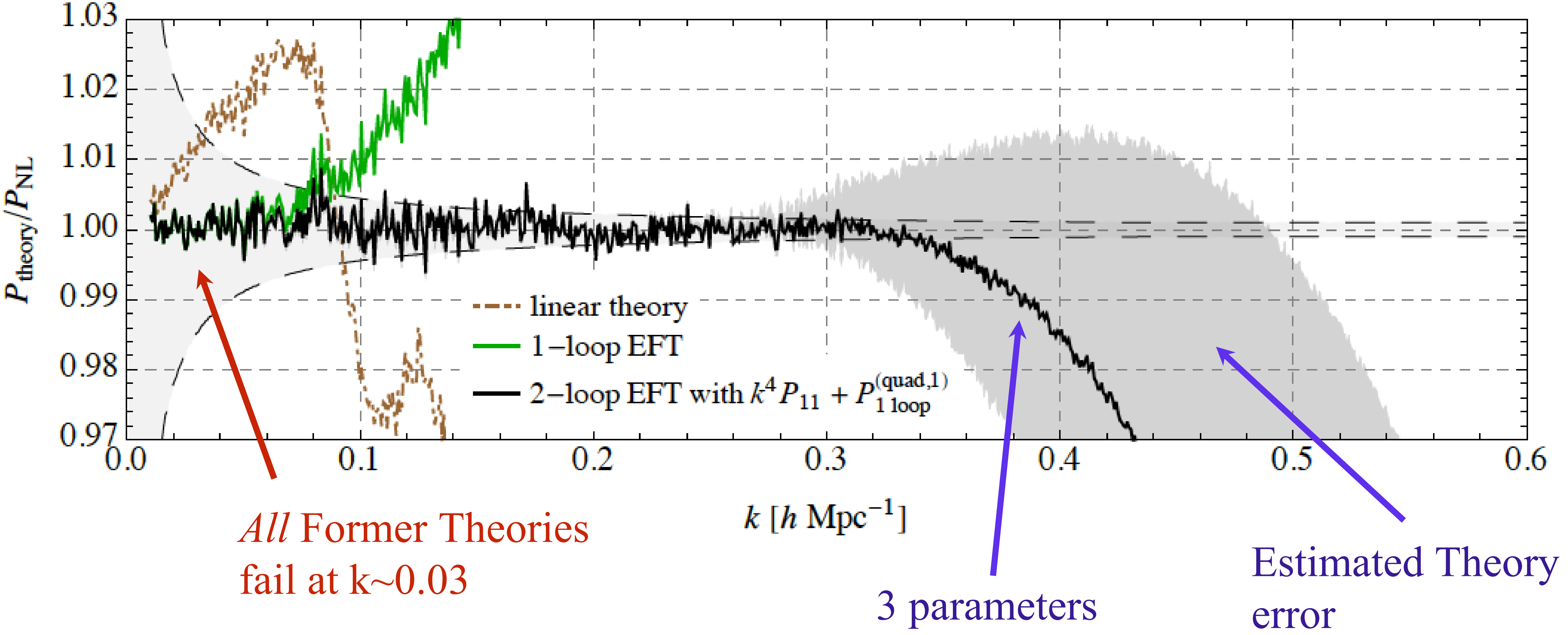
$$\Rightarrow \quad \delta^{(2)}(k_l) \sim \int d^3k_s\, \delta^{(1)}(k_s)\, \delta^{(1)}(k_l - k_s)\ , \quad \Rightarrow \quad \langle \delta_l^2 \rangle \sim \int d^3k_s\, \langle \delta_s^{(1)2} \rangle^2$$





- Integrand has support at high wavenumber where expressions do not make sense
- Need to add counterterms from $\tau_{ij} \supset c_s^2\, \delta\rho$ to make the result finite and correct
- we just found loops and renormalization applied to galaxies

EFT of Large Scale Structures at Two Loops



- Order by order improvement $\left(\frac{k}{k_{\rm NL}}\right)^L$
- Theory error estimated
- k-reach pushed to $k \sim 0.34\, h\, {\rm Mpc}^{-1}$
- Huge gain wrt former theories

with Carrasco, Foreman and Green **JCAP1407**
with Zaldarriaga **JCAP1502**
with Foreman and Perrier **1507**
see also Baldauf, Shaan, Mercolli and Zaldarriaga **1507, 1507**

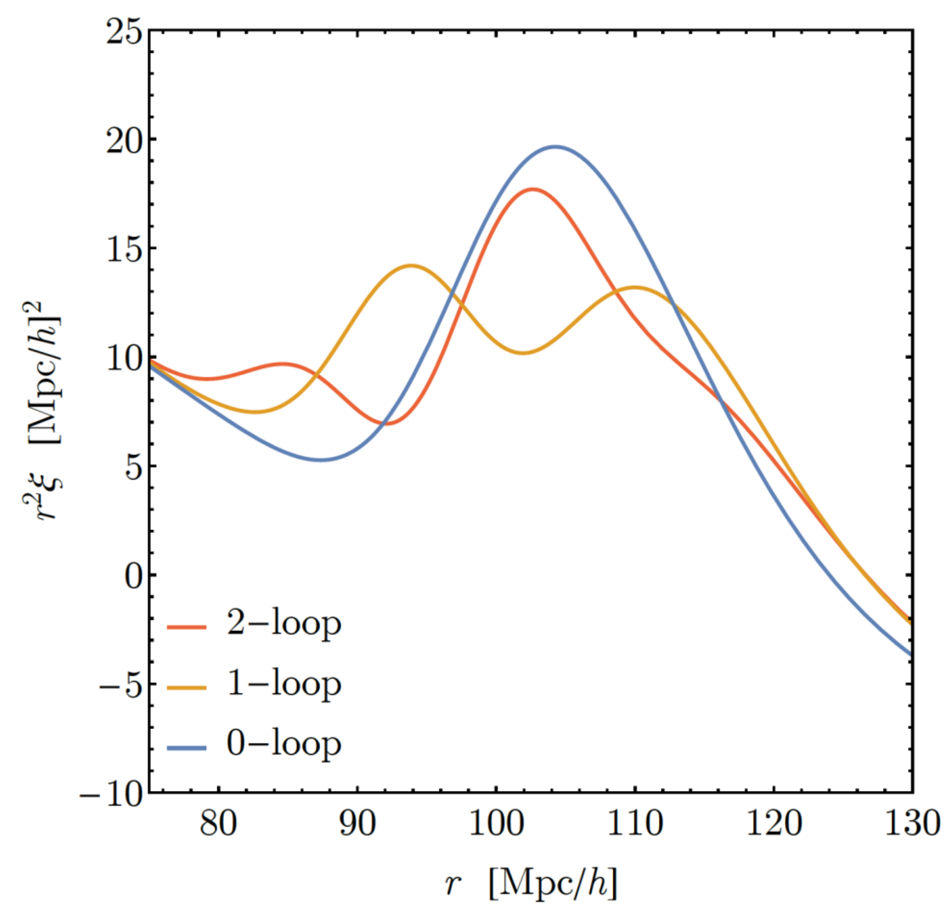
IR-resummation and the BAO peak

- Perturbation theory is extremely slow to converge due to the effect of IR-displacements. They affect the feature in real space named BAO peak

- The first, and in a sense unique, consistent way to resum the IR-displacements was obtained in with Zaldarriaga **JCAP2015**

$$P_{\rm IR-resummed}(k) \sim \int dq\; M(k,q)\cdot P_{\rm non-resummed}(q)$$

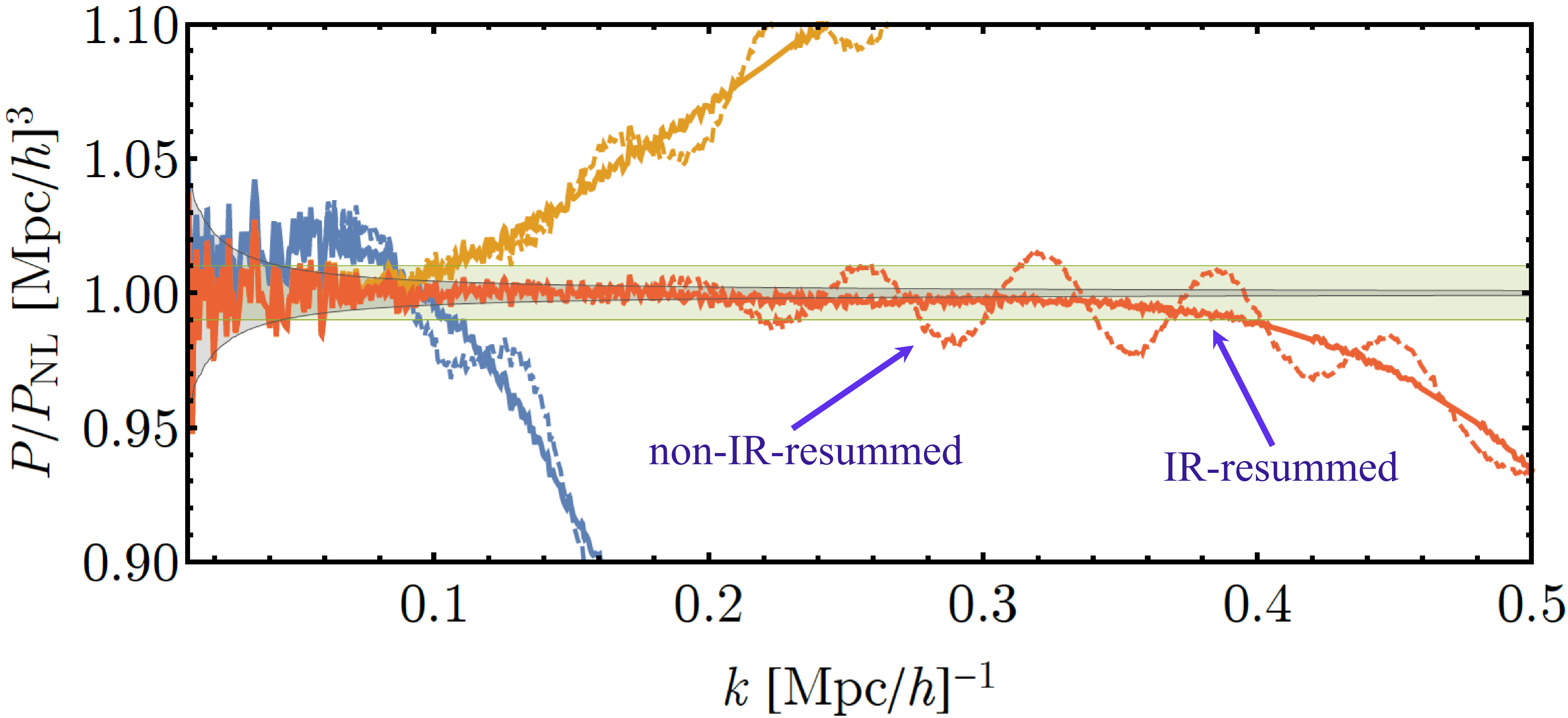
- ~Similar to soft photons



IR-resummation and the BAO peak

- It works very well

with Zaldarriaga **JCAP2015**
with Trevisan **JCAP1805**



- Similarly well in redshift space

with Lewandowski et al **PRD2018**

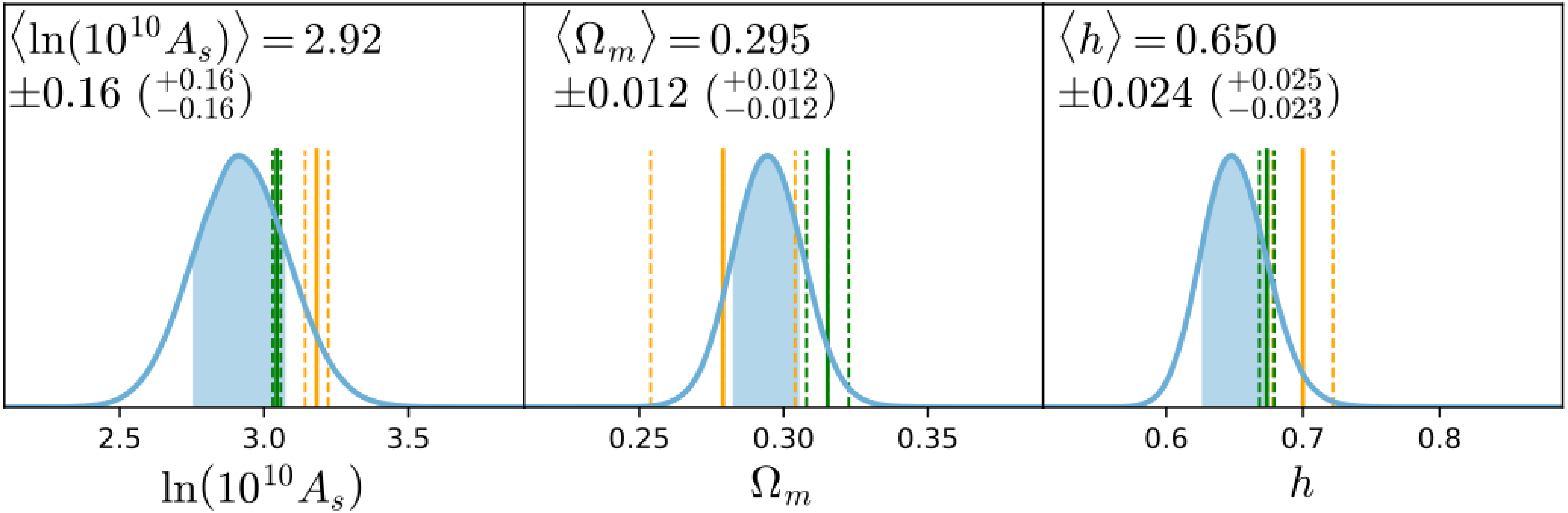
Analysis of the BOSS/SDSS data

Jerome Gleyzes, Nickolas Kockron, Dida Markovic, Leonardo Senatore, Pierre Zhang,
Florian Beutler, Hector Gill-Marin

in completion

Analysis of the SDSS/BOSS data

–*Preliminary* results of the power spectrum analysis of the CMASS&low-z samples



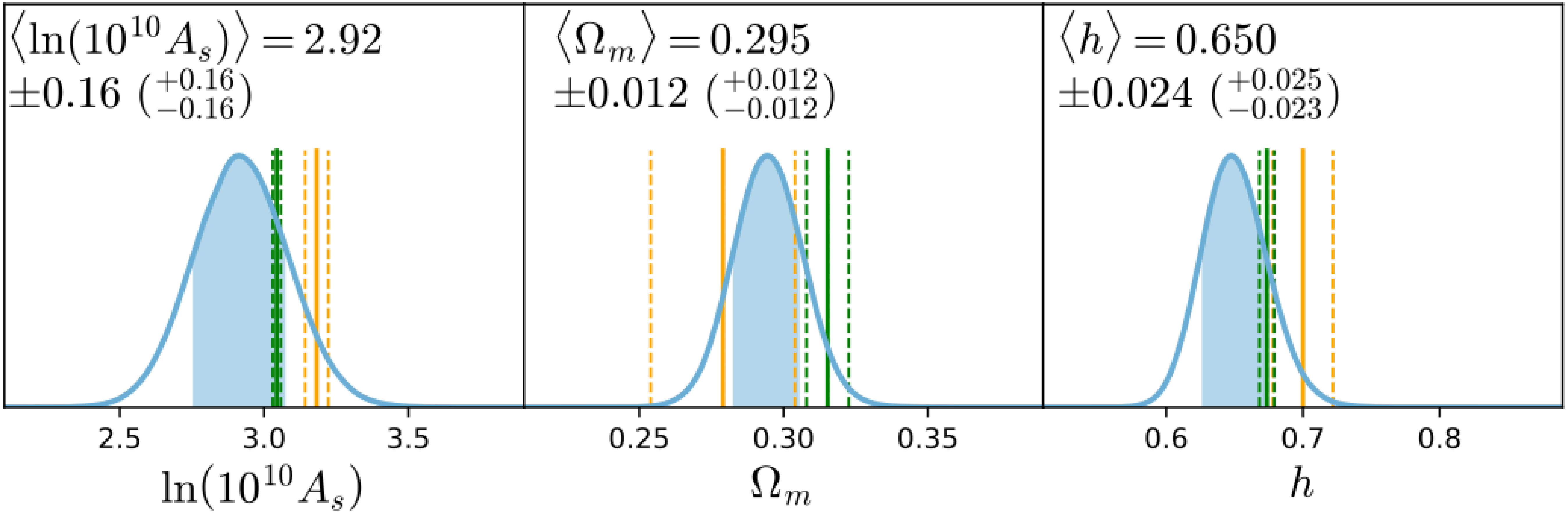
–some results are preliminary

–more checks, plots, runs, still to do

- We assume flat $\Lambda\mathrm{CDM}$ and Planck's n_s & Ω_b/Ω_m
- and measure $A_s, \ \Omega_m, \ H_0, \ b_1 \quad \leftrightarrow \quad f, \sigma_8, \ H_0, \ b_1$
- These *preliminary* results, if confirmed, tell us that there is the potentiality of much improving the whole *legacy* of SDSS.

Analysis of the SDSS/BOSS data

– *Preliminary* results of the power spectrum analysis of the CMASS&low-z samples



– Major improvement with respect to what done before

– Error bars comparable to CMB

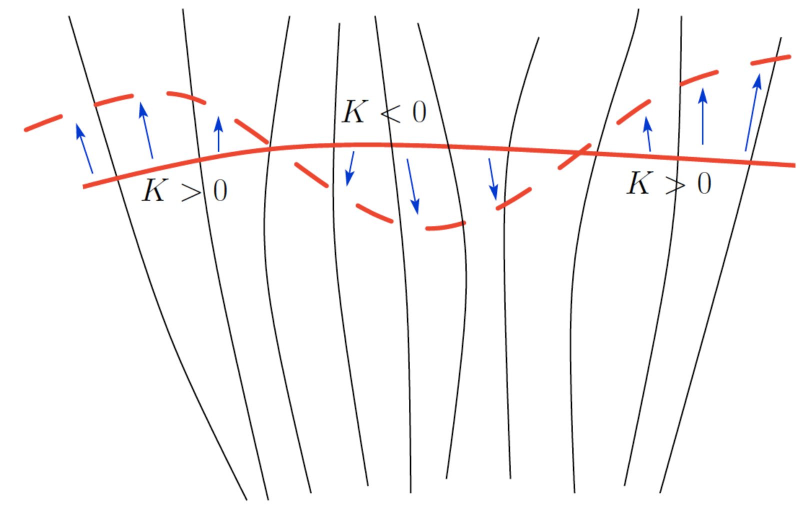
– New way to measure H_0 , and a further data point in the `tension'.

Summary

• Several aspects of physics in cosmology:

• Numerical GR and unusual Math

–to explain how the universe started



• LIGO/VIRGO

$$S_{\rm eff} = 2M_{\rm pl}^2 \int d^4x \sqrt{-g} \left(-R + \frac{\mathcal{C}^2}{\Lambda^6} + \frac{\tilde{\mathcal{C}}^2}{\tilde{\Lambda}^6} + \frac{\tilde{\mathcal{C}}\mathcal{C}}{\Lambda_-^6} + \dots \right)$$

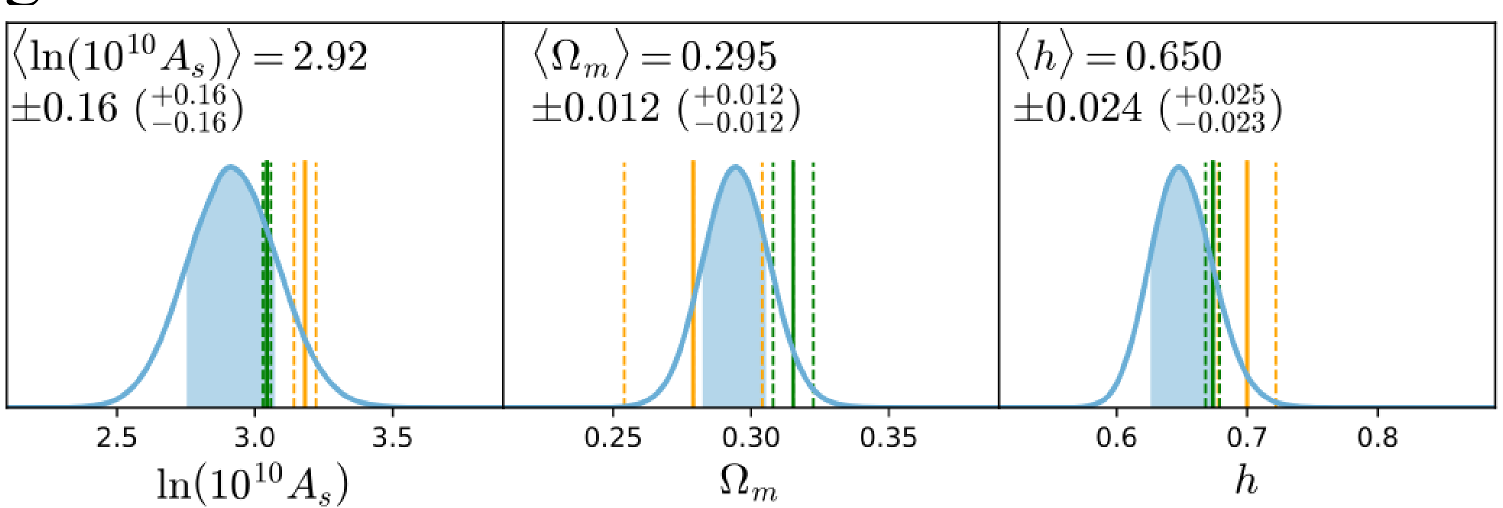
• the nature of gravity

• hitting hard Dark Energy

• The Effective Field Theory of Large Scale Structure

• The `Chiral Lagrangian' for galaxies

• applied to data: it works!



Proof in 2+1 dimensions

– We would like to prove that an initial expanding topologically-non-closed 2+1dim cosmology, with a positive cosmological constant and matter satisfying suitable energy conditions, reaches de Sitter space almost everywhere.

– In 2+1 dimensions, the usual Einstein equation:

$$n^\mu n^\nu G_{\mu\nu} = 8\pi G \left(T_{\mu\nu} + \Lambda g_{\mu\nu}\right) n^\mu n^\nu$$

$$\Longrightarrow \; {}^{(2)}R + \frac{1}{2}K^2 - \sigma^2_{\mu\nu} = \frac{1}{2}K^2_\Lambda + 16\pi G T_{\mu\nu} n^\mu n^\nu \quad \text{where} \quad K^2_\Lambda = 32\pi G \Lambda$$

– On MCF-surfaces: $d/d\lambda = H \cdot d/dt$

$$\frac{dV}{d\lambda} = \int d^2x\sqrt{h}\, K^2 = \int d^2x\sqrt{h}\left(32\pi G T_{\mu\nu} n^\mu n^\nu + K^2_\Lambda + 2\sigma^2_{\mu\nu} - 2\cdot {}^{(2)}R\right) \geq$$

$$K^2_\Lambda \int d^2x\sqrt{h} - 2\int d^2x\sqrt{h}\,{}^{(2)}R = K^2_\Lambda V - 8\pi\chi\,.$$

– here we assumed WEC

- The solution reads $V(\lambda) \geq \frac{8\pi\chi}{K^2_\Lambda} + e^{K^2_\Lambda \lambda}\left(V(0) - \frac{8\pi\chi}{K^2_\Lambda}\right) \underset{\chi \leq 0}{\Longrightarrow} V(\lambda) \geq V(0)\, e^{K^2_\Lambda \lambda} \to \infty$

– for all topologies but the sphere, the volume goes to infini