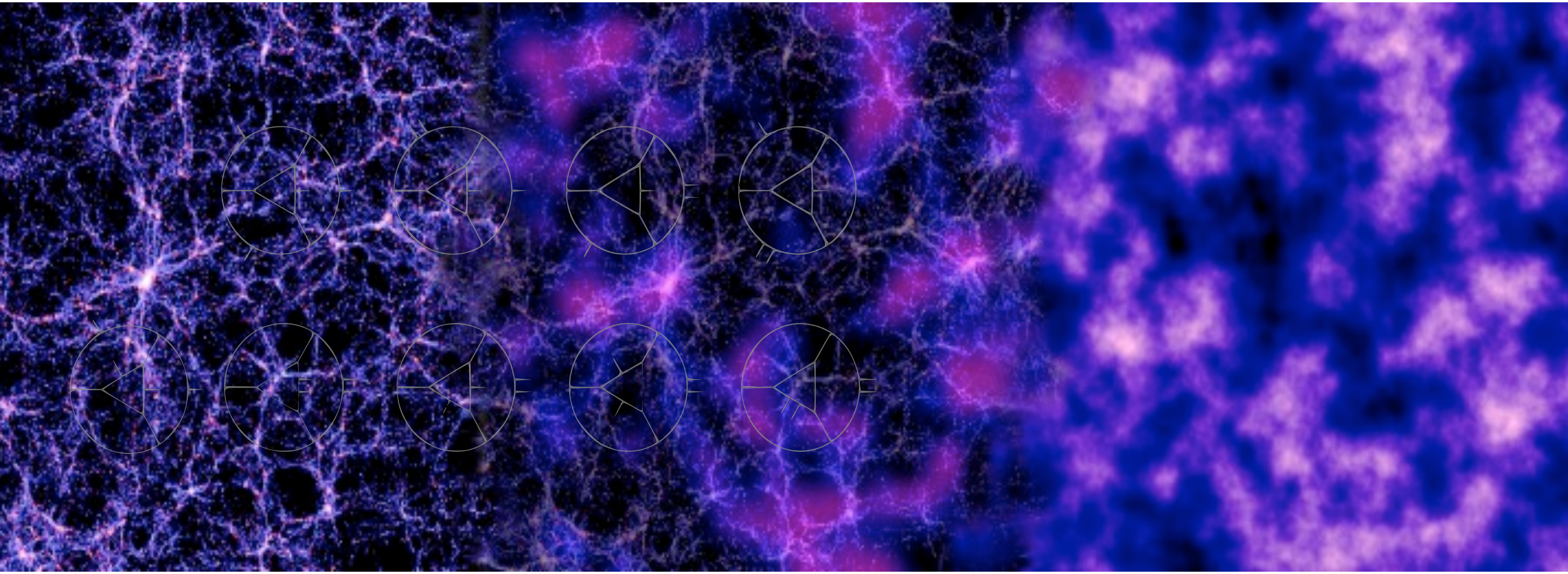
The largest effective field theory in the universe

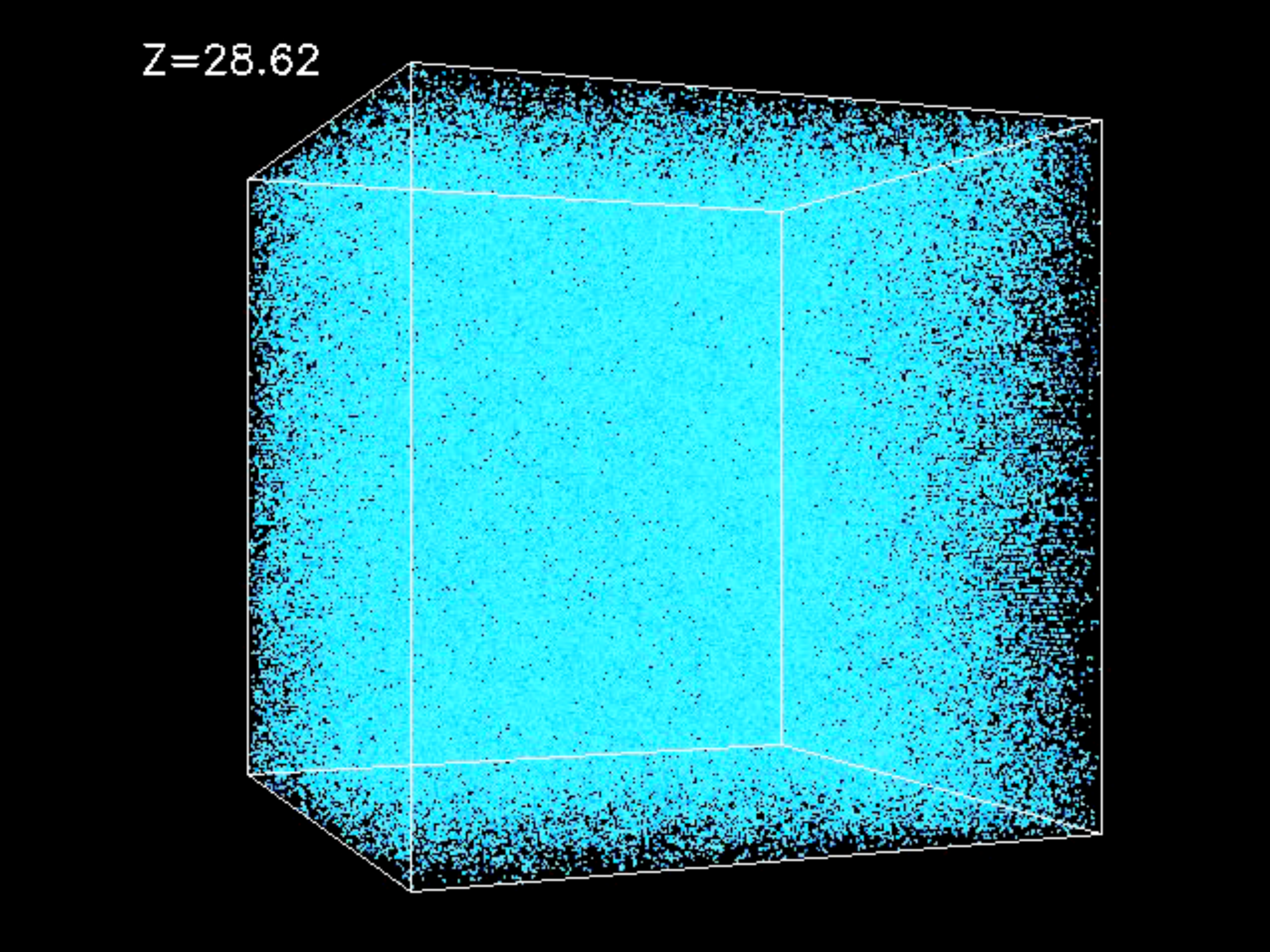


Stanford Institute for Theoretical Physics

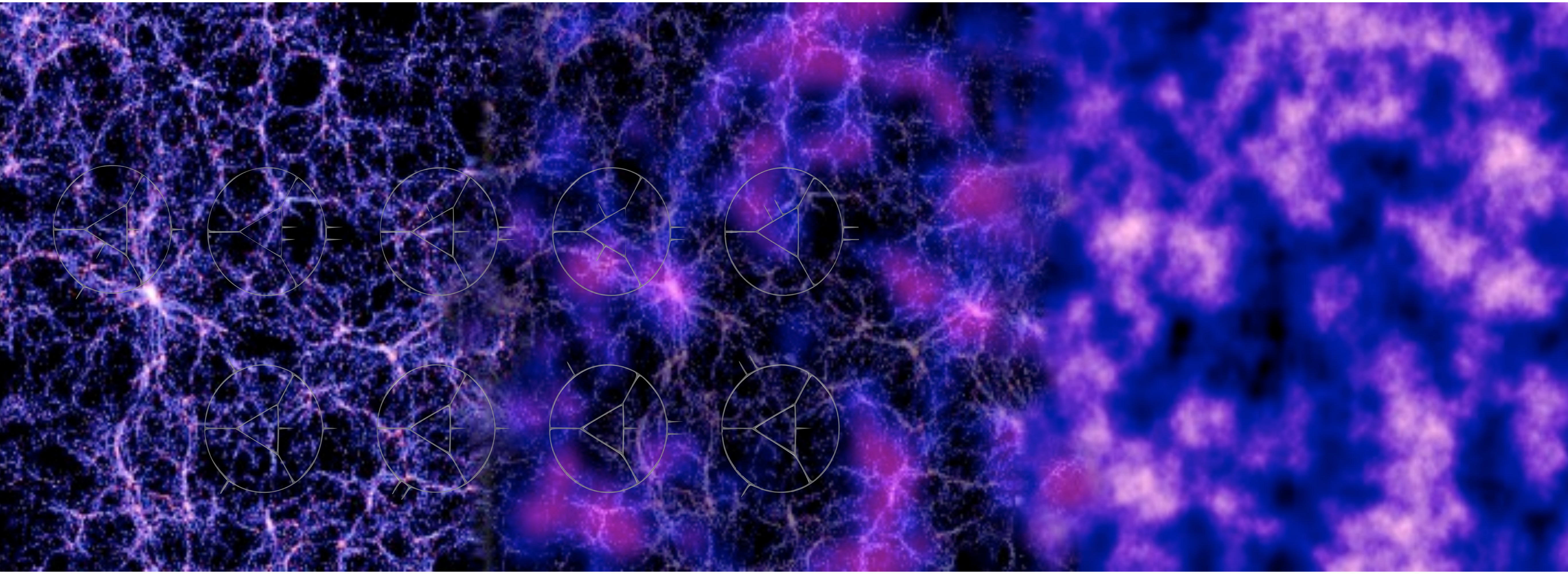
Bay Area Particle Theory Seminar

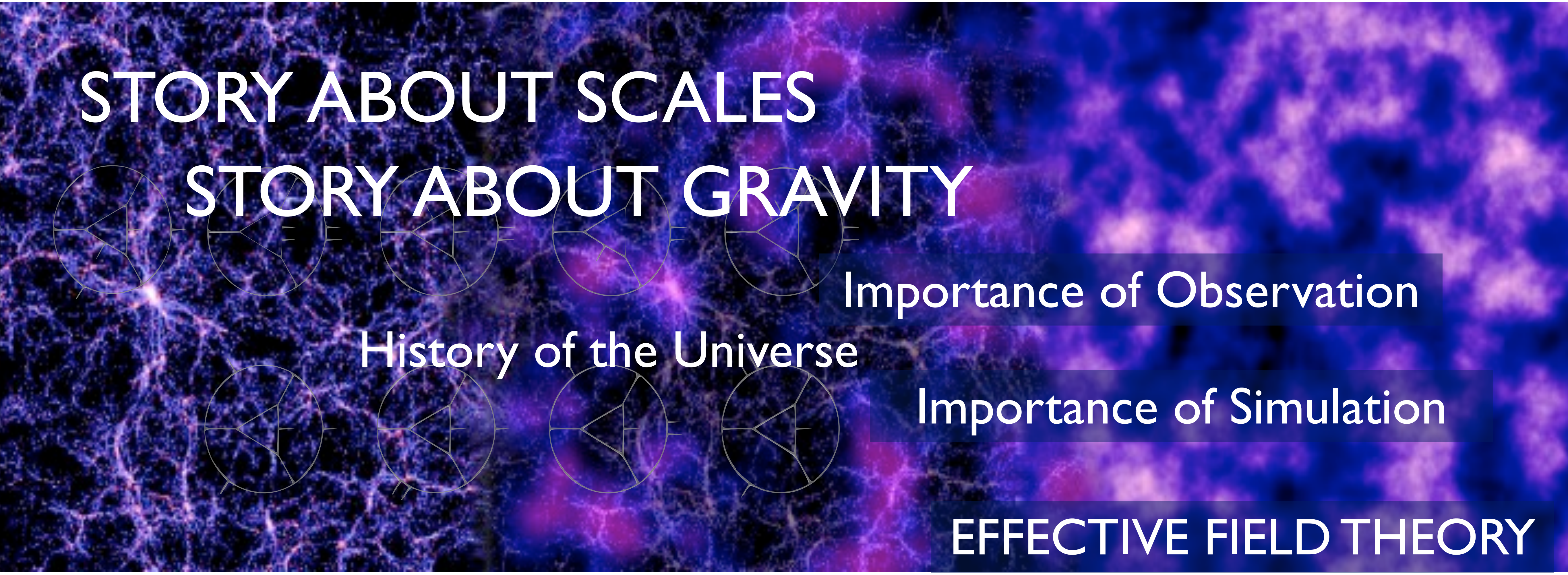
Friday, 14 March 2014

Work done with Foreman, Green, Hertzberg, Senatore.


Z=28.62

(OUTLINE)





COSMOLOGICAL LARGE SCALE STRUCTURE

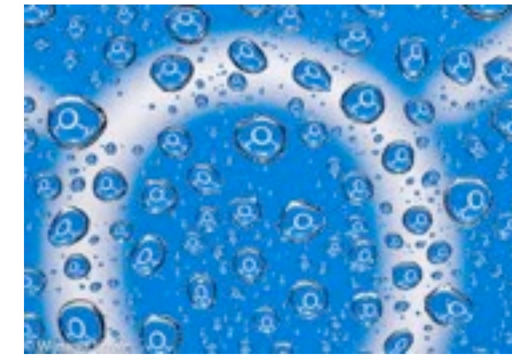
ULTIMATE GOAL: SOLVE THE SYSTEM!
ABILITY TO MAKE PREDICTIONS
RELEVANT TO THE SCALES OF INTEREST

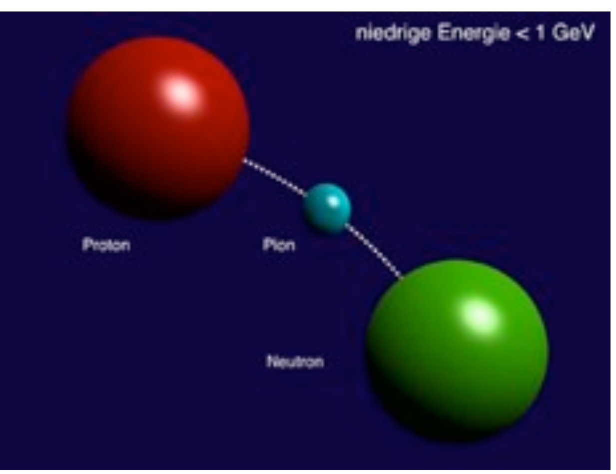
IR UV

Scales

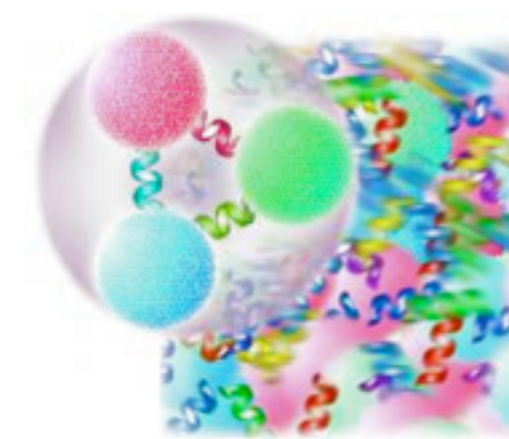
IR

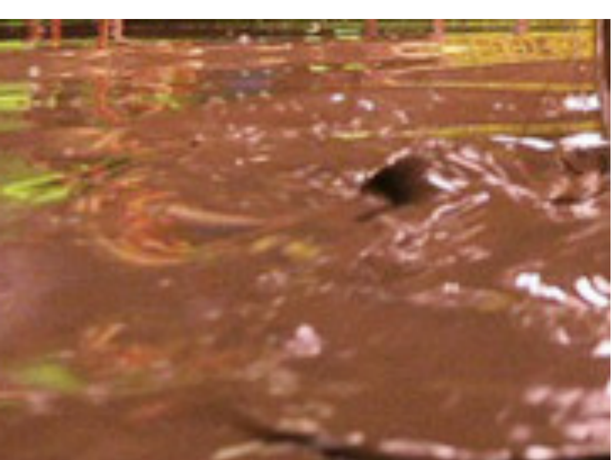
UV

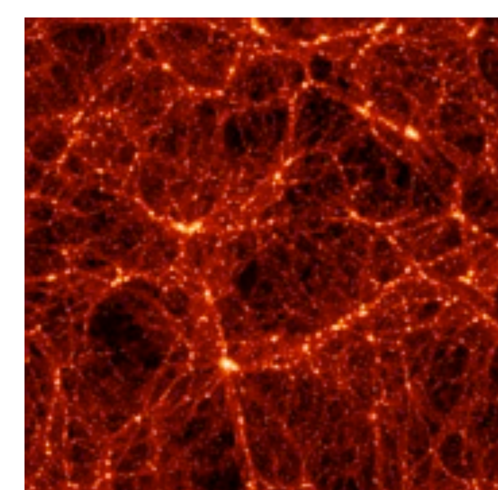




Scales







WHAT DO WE KNOW ABOUT GRAVITY?

$$F = m g$$

constant force pulling us down

g ~ 9.8 m/s^2

WHAT DO WE KNOW ABOUT GRAVITY?

$$F = m\,g$$

constant force pulling us down

How to extend to other scales?

WHAT DO WE KNOW ABOUT GRAVITY?

$$F = mg$$

constant force pulling us down

How to extend to other scales?

$$F = mg + Ah + Bh^2 + Ch^3 \cdots$$

WHAT DO WE KNOW ABOUT GRAVITY?

$$F = mg$$

constant force pulling us down

How to extend to other scales?

$$F = mg + Ah + Bh^2 + Ch^3 \cdots$$

$$F = mg\,(1 - 2\alpha h + 3\alpha^2 h^2 - 4\alpha^3 h^3 \cdots)$$

WHAT DO WE KNOW ABOUT GRAVITY?

$$F = m\,g$$

constant force pulling us down

How to extend to other scales?

$$F = mg + Ah + Bh^2 + Ch^3 \cdots$$

$$F = mg\,(1 - 2\alpha h + 3\alpha^2 h^2 - 4\alpha^3 h^3 \cdots)$$

$$F = \frac{gm}{(1+\alpha h)^2}$$

WHAT DO WE KNOW ABOUT GRAVITY?

$$F = mg$$

constant force pulling us down

How to extend to other scales?

$$F = mg + Ah + Bh^2 + Ch^3 \cdots$$

$$F = mg\left(1 - 2\alpha h + 3\alpha^2 h^2 - 4\alpha^3 h^3 \cdots\right)$$

$$F = \frac{gm}{(1+\alpha h)^2} \qquad \alpha \to 1/R_E \qquad g \to GM_E/R_E^2$$

$$\vec{F} = -\frac{Gm_1 m_2}{R^2}\hat{r}$$

Force pulling planets to the Sun
(and each other)

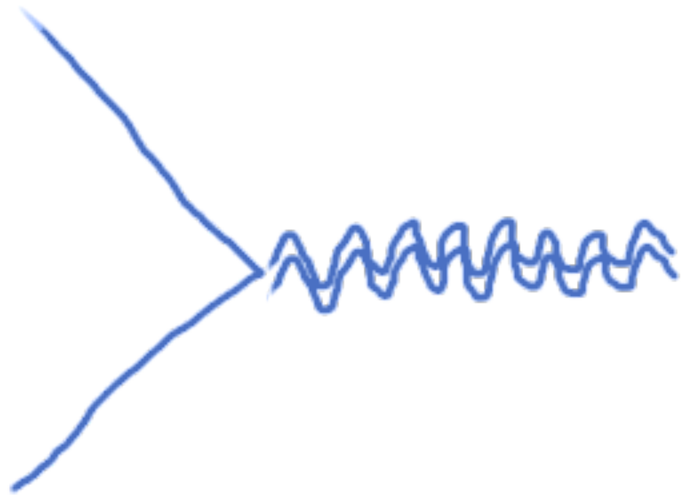
What about more fundamental description?

"Venusian approach"

(Feynman)

- Given success of standard model natural to think about field theory

- Start with scalars -- what type of mediating field gives me inverse R potential?



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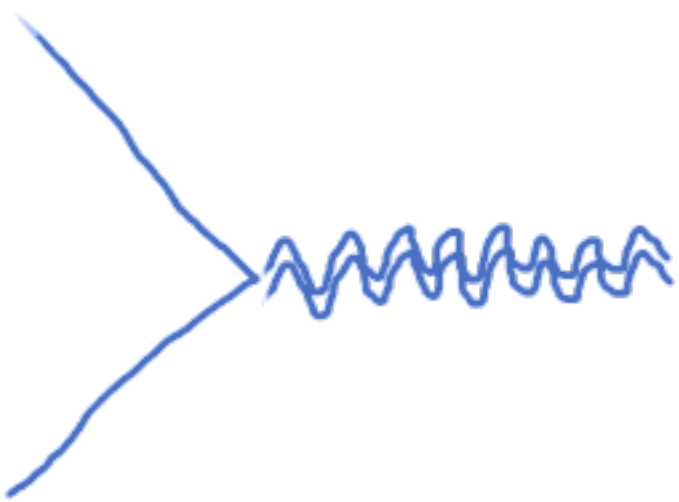
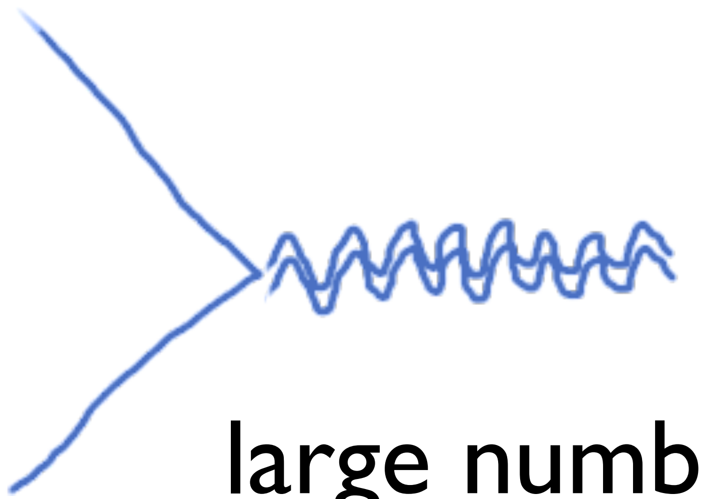
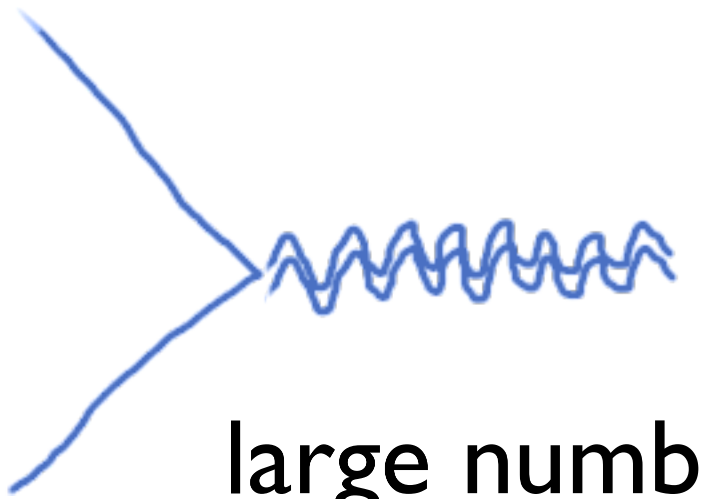


enough to get Newton's law



$$\vec{F} = -\frac{Gm_1m_2}{R^2}\hat{r}$$

large number of scales, lots of predictions



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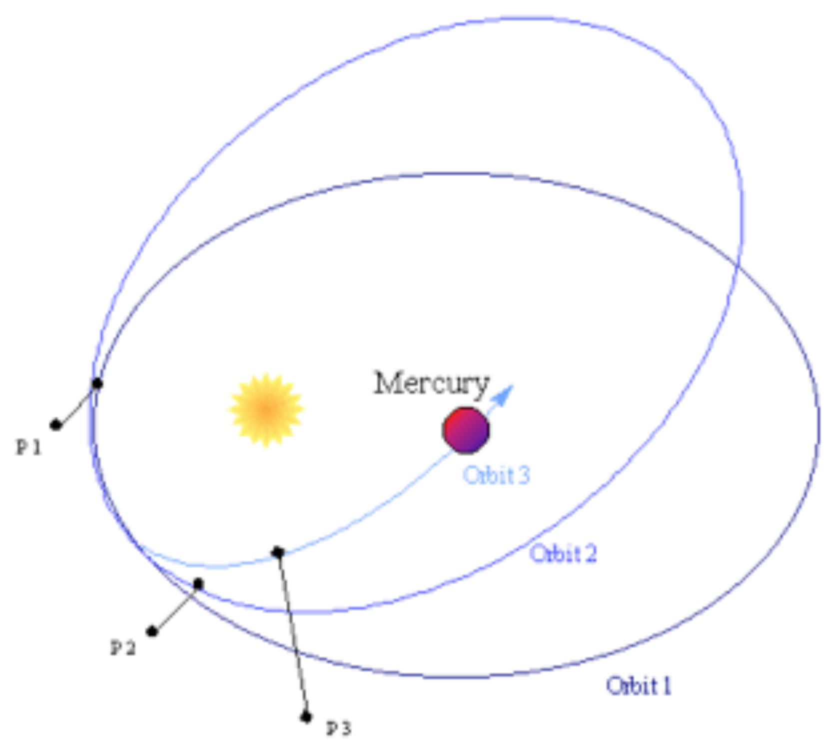

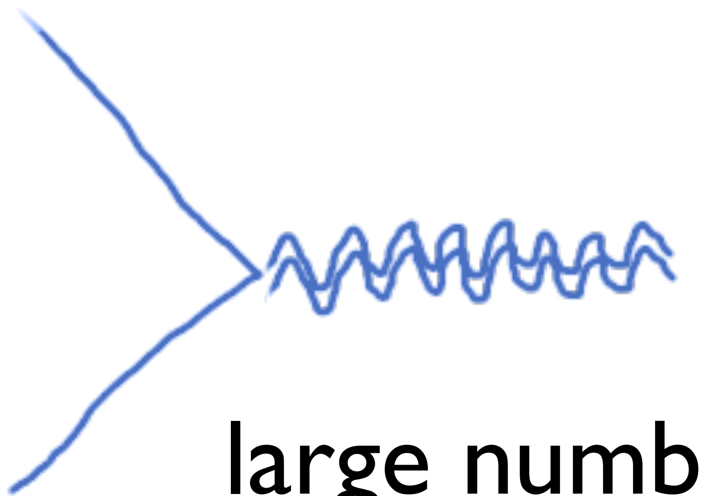

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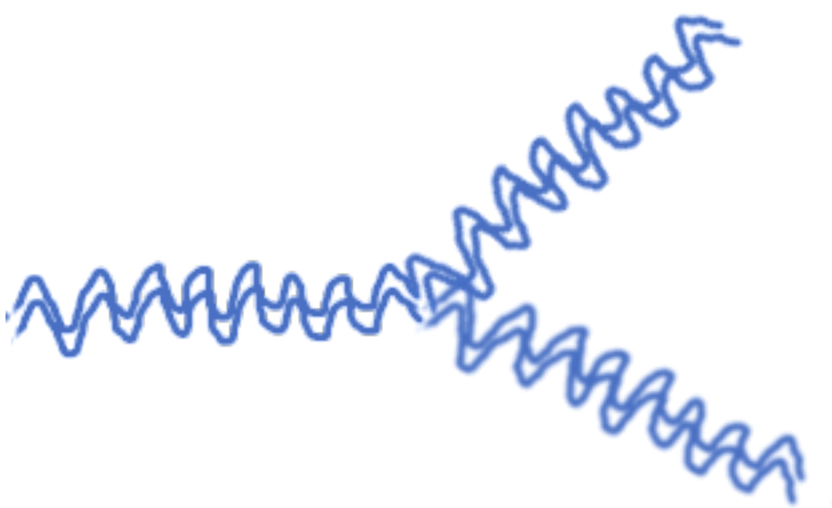
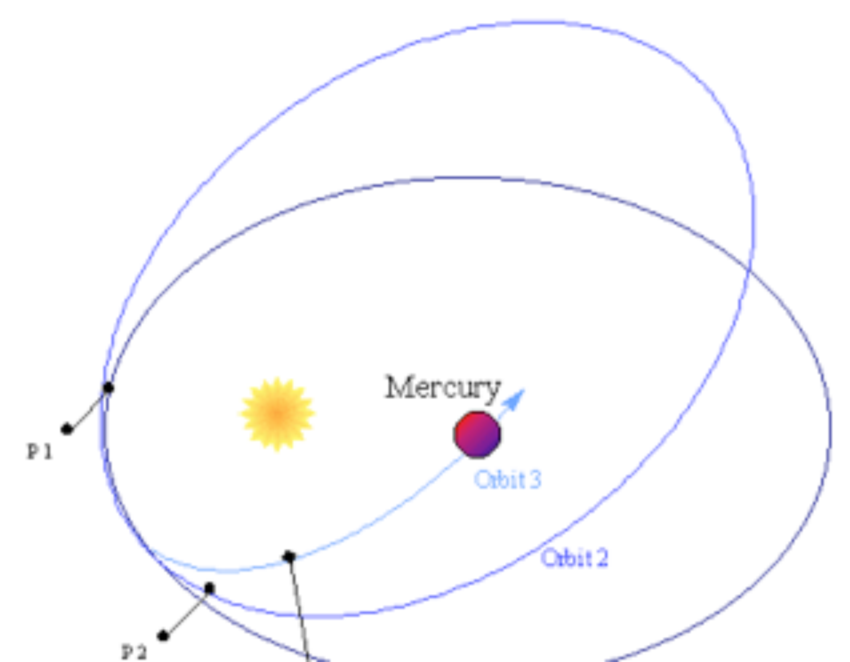


+ buddies

Self-energy gets you to
Einstein-Hilbert action

Seems valid on all
large scales,
firmament of modern
cosmology

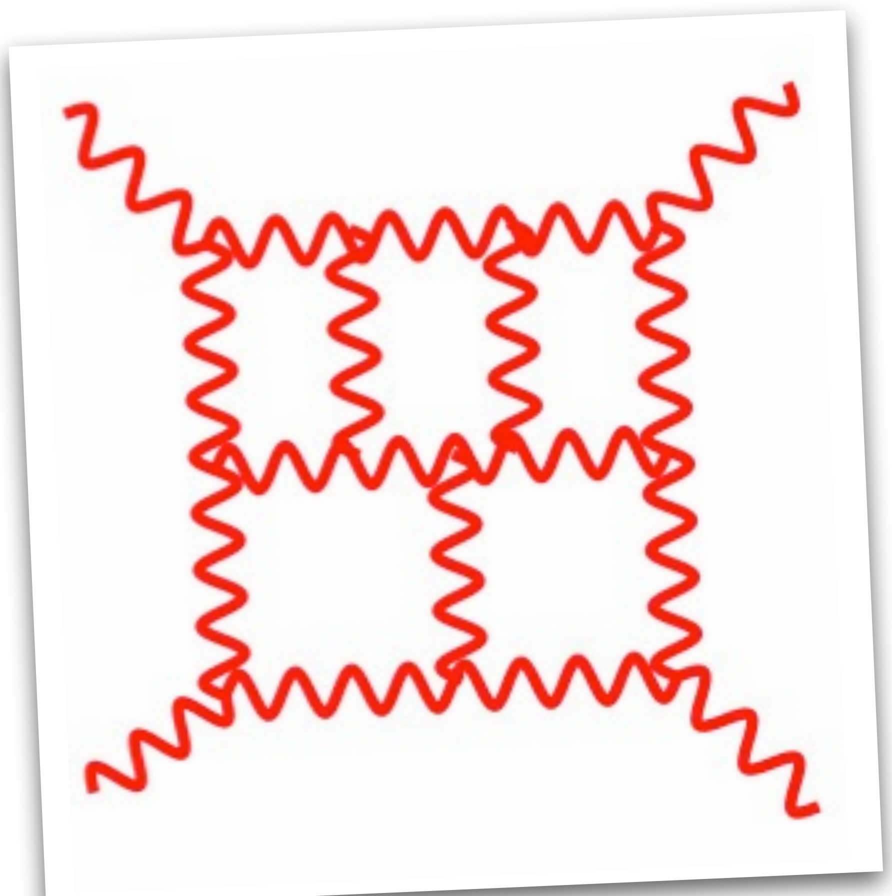


Sidebar: Can you quantize it?

Perturbative quantization should run into trouble at some loop level for (almost) all point-like quantum field theories

Why surprising if finite:

Dimensionful coupling: $\kappa \sim m_{pl}^{-1}$ → non-renormalizable



Any responsible mechanism would fundamentally impact our understanding of gravity

No known structure to make up diff btw

$$\frac{(\kappa\, p^\mu p^\nu)\cdots}{\text{propagators}}$$ gravity

and

$$\frac{(g\, p^\mu)\cdots}{\text{propagators}}$$ gauge

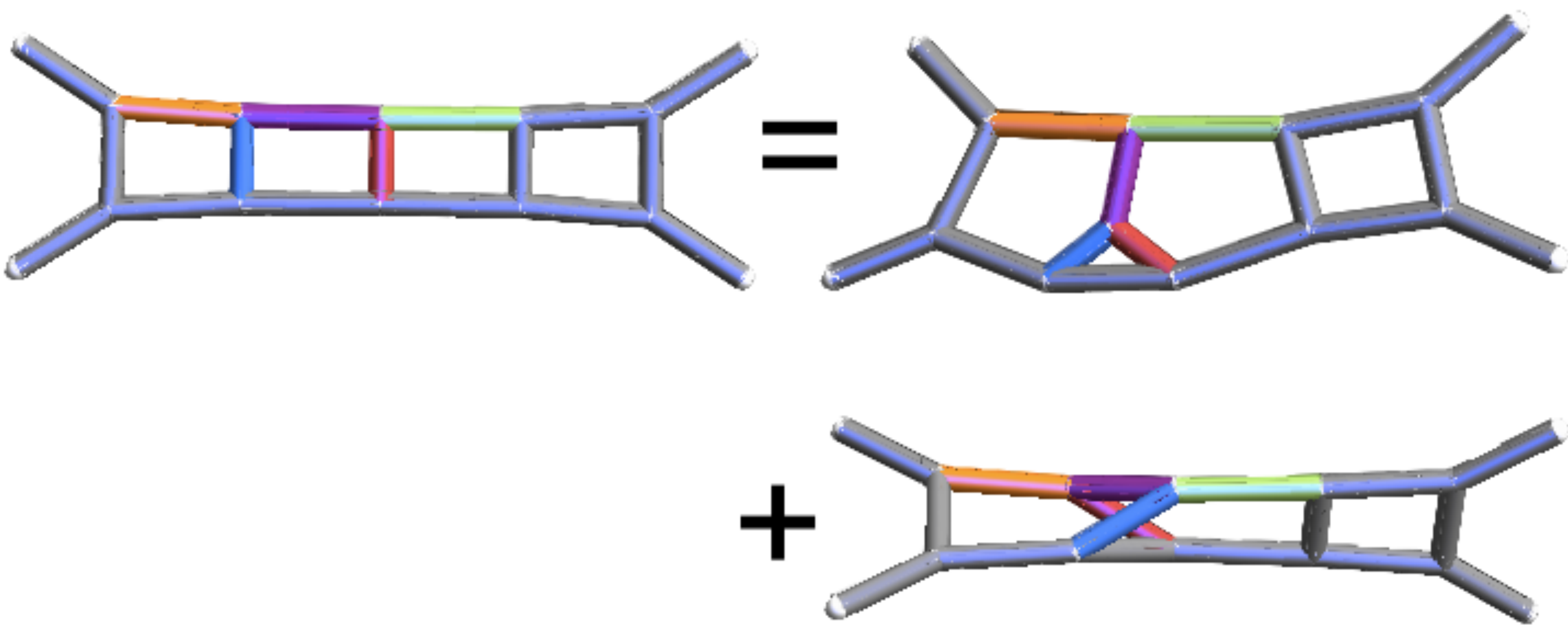
Sidebar: Can you quantize it?

So, barring possible exceptions of special supergravity theories (e.g. N>=5 SG), even these Einstein-Hilbert type actions are some sort of effective field theories -- to be completed in the UV

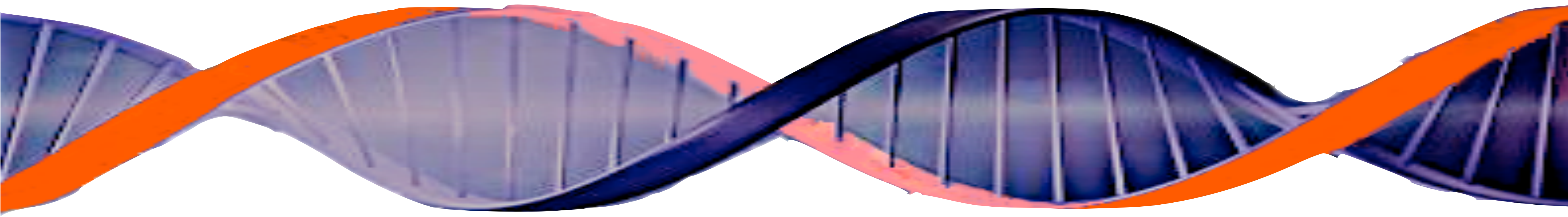
Hints as to the structure?

Sidebar: Can you quantize it?

So, barring possible exceptions of special supergravity theories (e.g. N>=5 SG), even these Einstein-Hilbert type actions are some sort of effective field theories -- to be completed in the UV

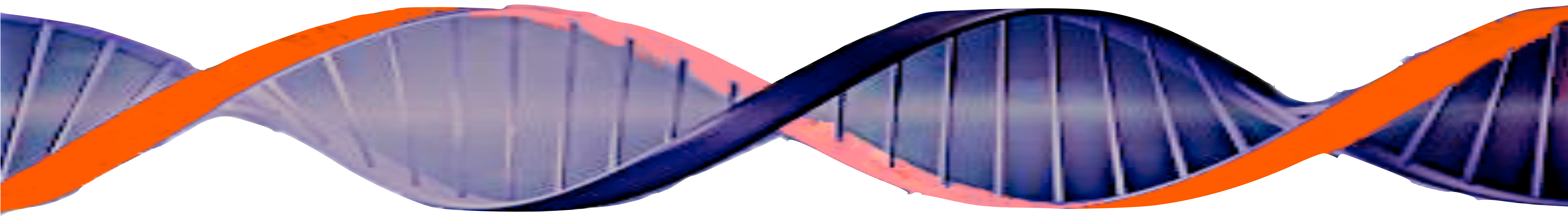


$$\frac{(-i)^L}{g^{n-2+2L}}\mathcal{A}^{\text{loop}} = \sum_{\mathcal{G}\in\text{cubic}} \int \prod_{l=1}^{L} \frac{d^D p_l}{(2\pi)^D} \frac{1}{S(\mathcal{G})} \frac{n(\mathcal{G})c(\mathcal{G})}{D(\mathcal{G})}$$



DOUBLE COPY

$$\frac{(-i)^L}{g^{n-2+2L}}\mathcal{A}^{\text{loop}} = \sum_{\mathcal{G}\in\text{cubic}} \int \prod_{l=1}^{L} \frac{d^D p_l}{(2\pi)^D} \frac{1}{S(\mathcal{G})} \frac{n(\mathcal{G})c(\mathcal{G})}{D(\mathcal{G})}$$



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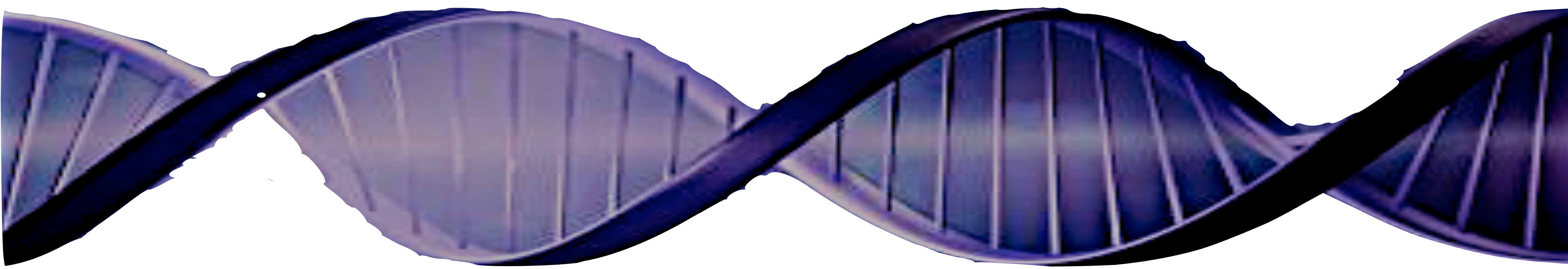
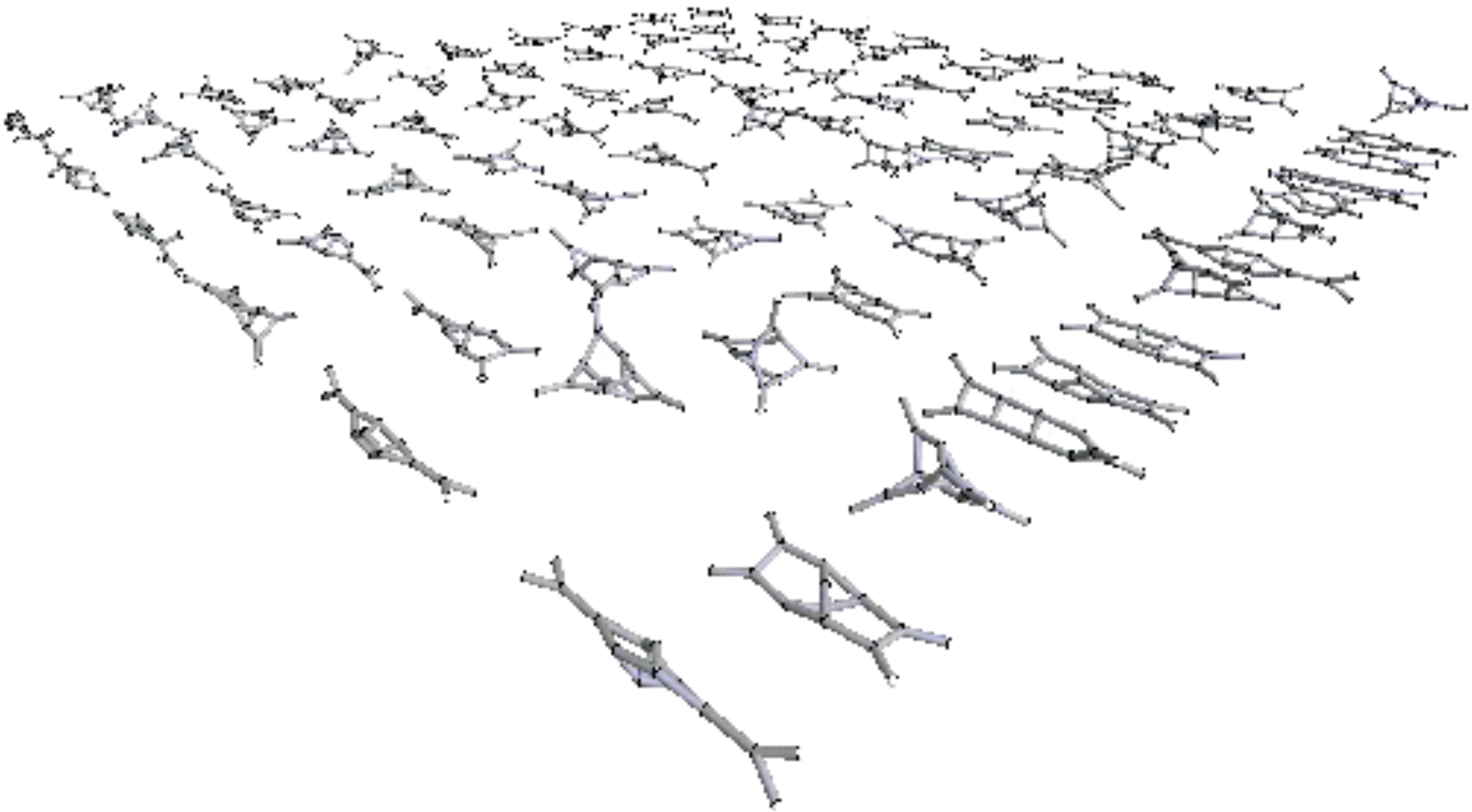


$$\frac{(-i)^{L+1}}{(\kappa/2)^{n-2+2L}}\mathcal{M}^{\text{loop}} = \sum_{\mathcal{G}\in\text{cubic}} \int \prod_{l=1}^{L} \frac{d^D p_l}{(2\pi)^D} \frac{1}{S(\mathcal{G})} \frac{n(\mathcal{G})\tilde{n}(\mathcal{G})}{D(\mathcal{G})}$$

Bern, JJMC, Johansson

Only need to focus on a small number of graphs

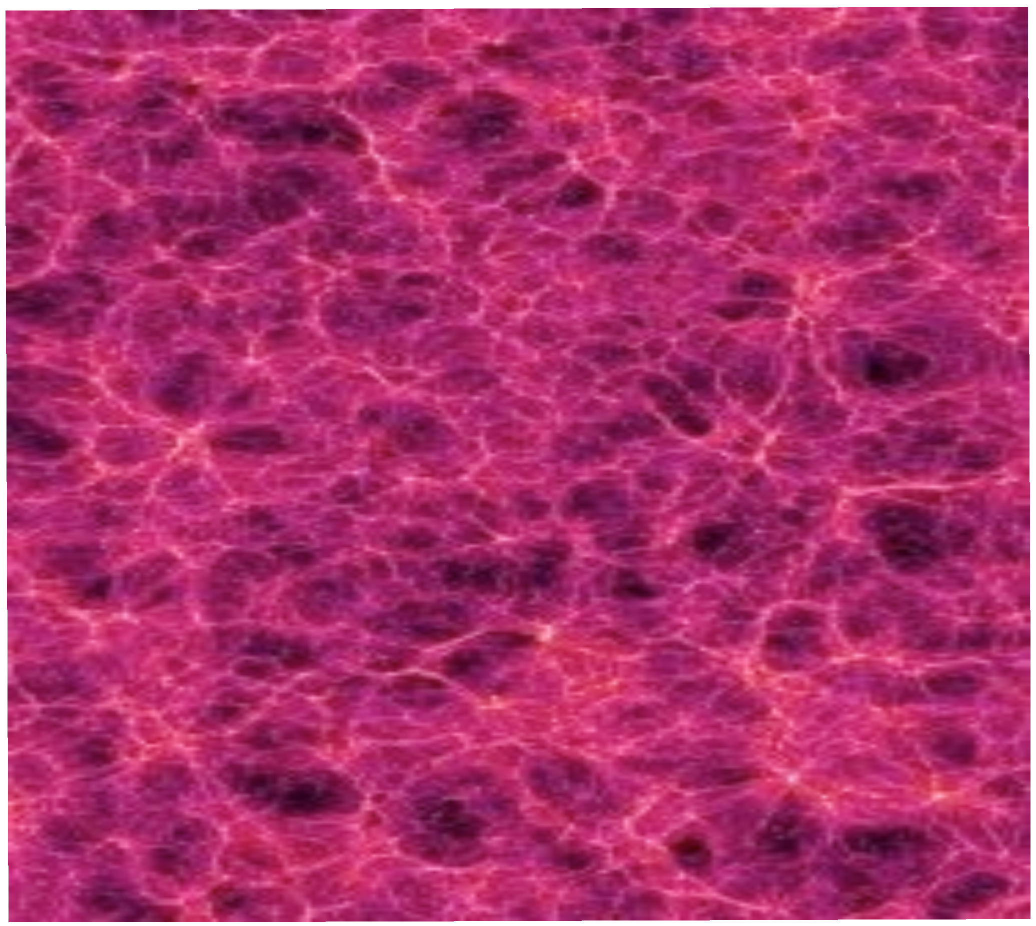


Bern, JJMC, Dixon, Johansson, Roiban

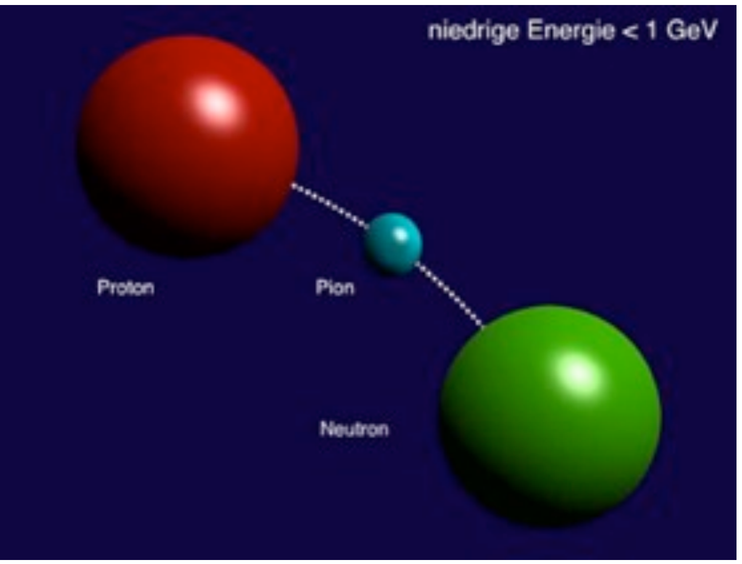
PHYSICAL PROBLEM of cosmological matter distribution

Distribution of matter smooth

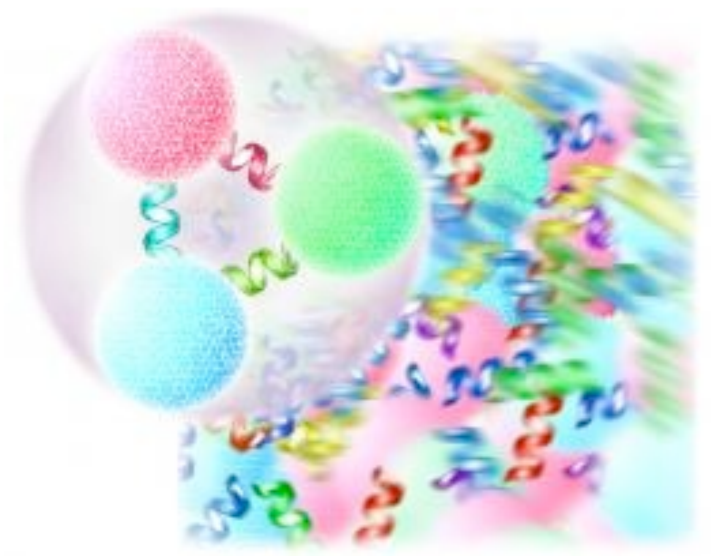
Distribution of matter in the universe is very lumpy



IR Homogenous | Inhomogenuous UV



Chiral Lagrangian

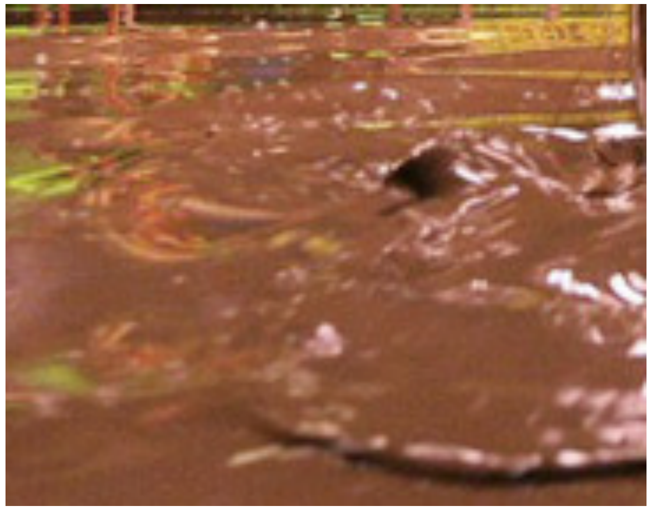


QCD

Lessons from QCD for looking at Cosmological Large Scale Structure

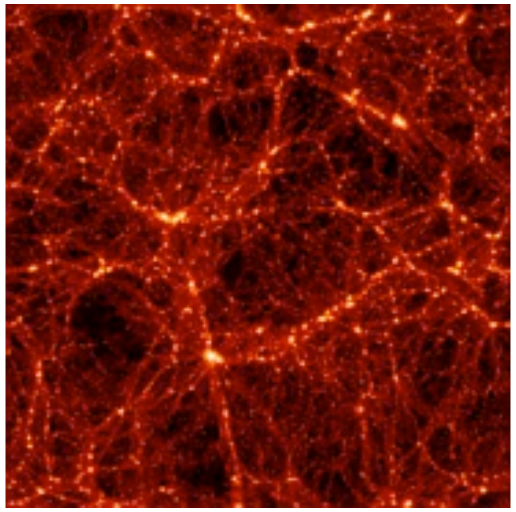
Effective fluid

Dark matter under gravity

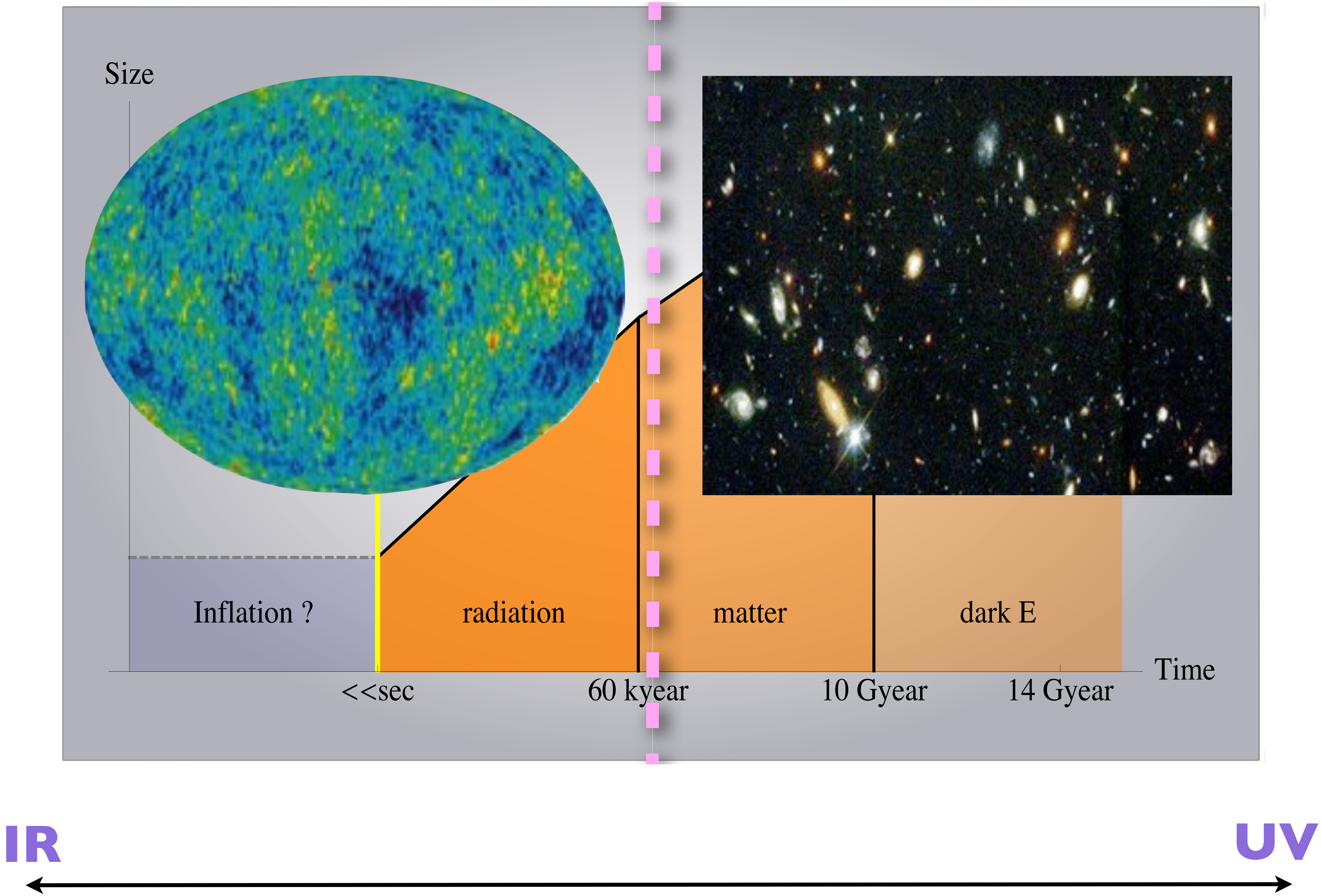


JJMC, Hertzberg, Senatore

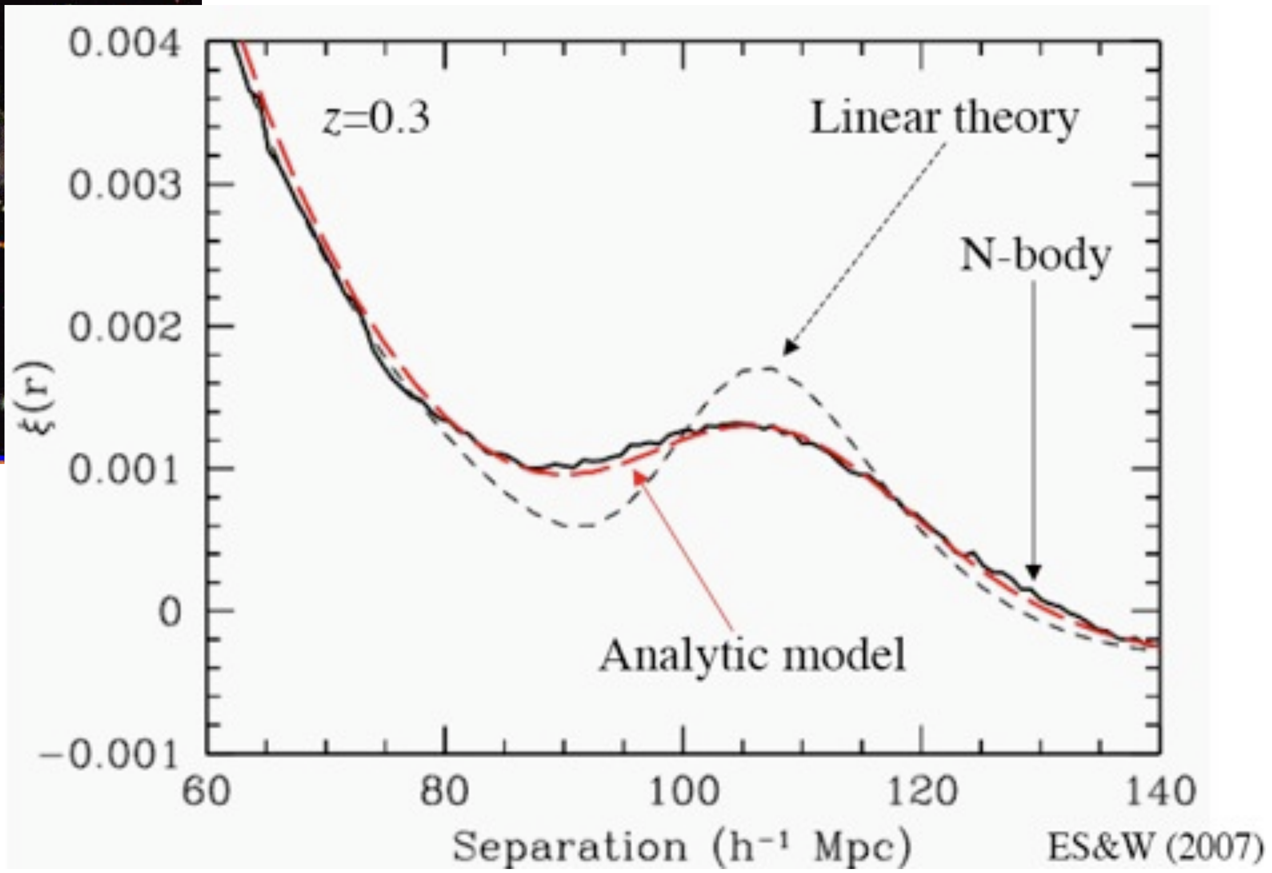
(JJMC, Foreman, Green, Senatore)^2



IR ⟷ **UV**


Size
Inflation ?
radiation
matter
dark E
Time
<<sec
60 kyear
10 Gyear
14 Gyear
IR
UV

- Observe the correlation of Galaxies

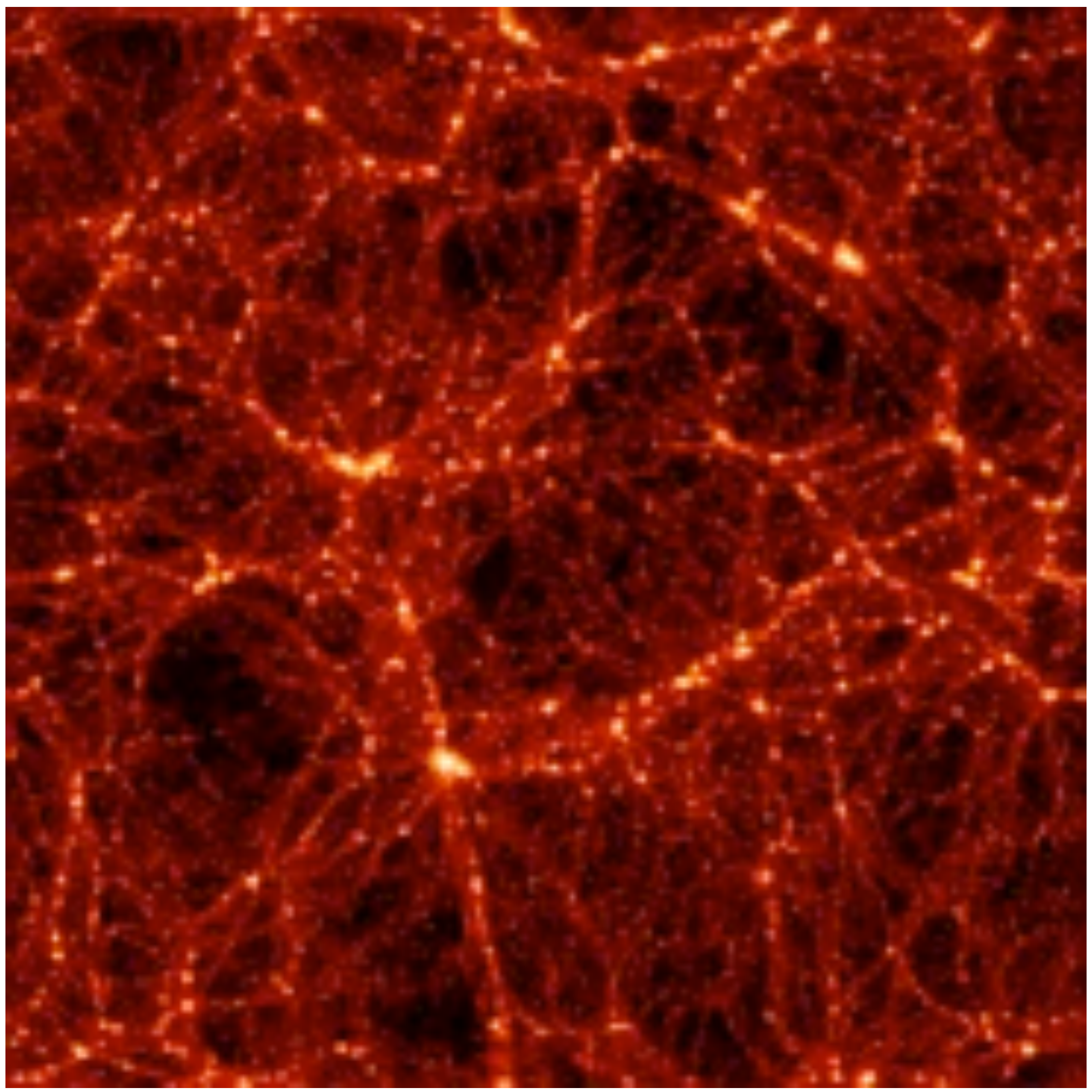


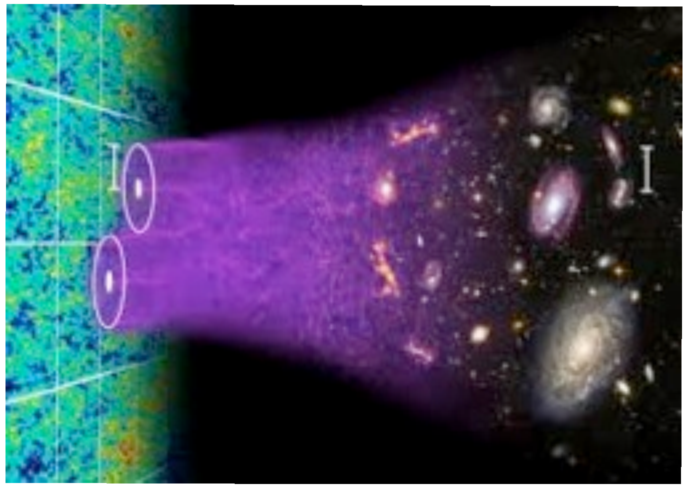
Analogous to CMB peaks

- Information about Dark Energy, Non-Gaussiantiy, ...

PHYSICAL PROBLEM of cosmological matter distribution

Large Scale Structure surveys promise tremendous amount of information in the IR





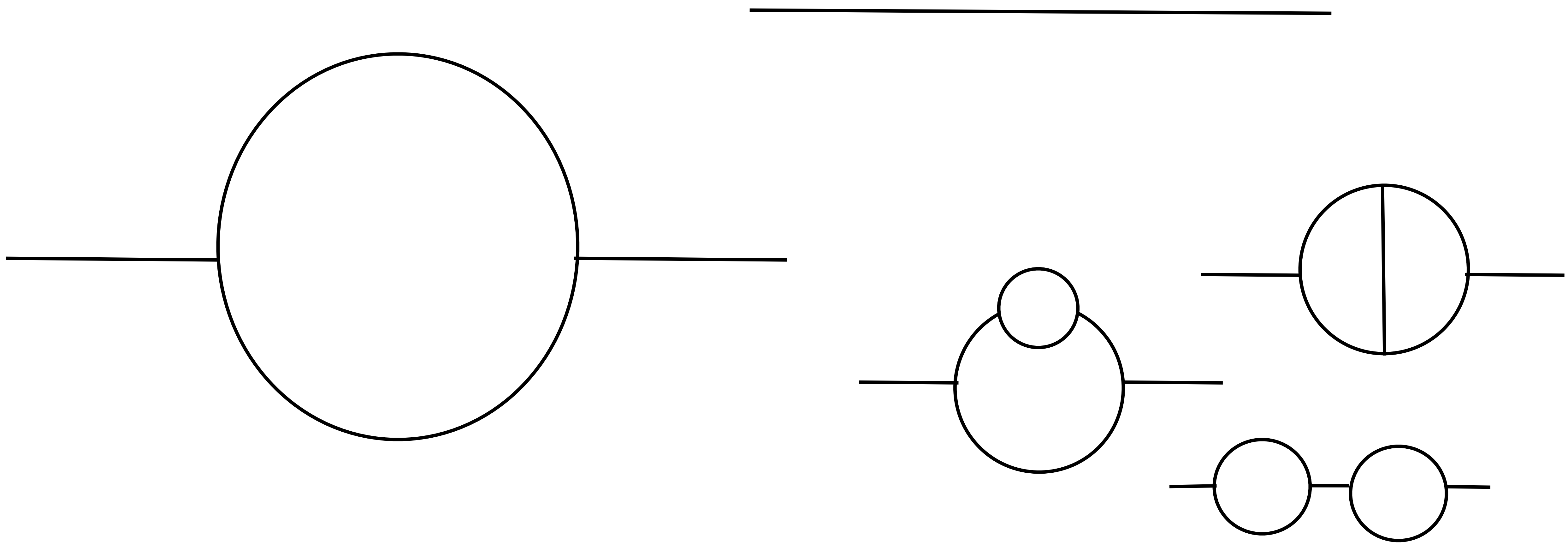
UV of CDM under-control and predictive (through simulations -- where they *can* excel!!)

(UV including Baryons?)

Can have a rigorous calculable IR theory.

IR complex & expensive | theory under control & predictive **UV**

Calculations

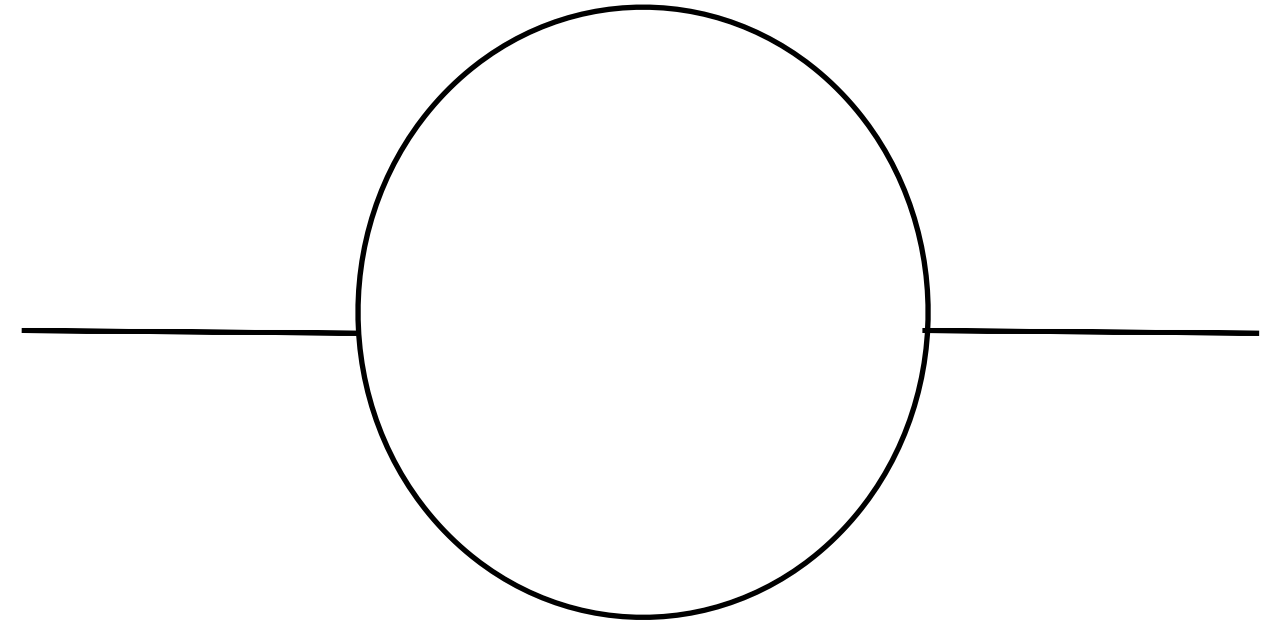


...in a classical (stochastic) field theory...

relevant on scales > 10 megaparsecs

$(< 10^{-30} eV)$

classical



?

Review of classical ϕ^3 perturbation theory

Simple Equation of Motion: $$(\Box + m^2)\phi = g\phi^2$$

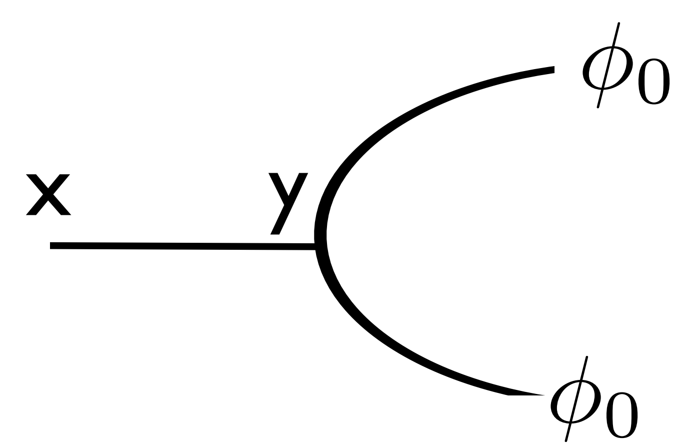
Ansatz: $\phi = \sum_{n=0}^{\infty} \phi_n g^n \qquad (\Box + m^2)\phi_0 = 0$

Collect power's of g, can recursively solve for ϕ_n in terms of Green's function evolved $\phi_{m<n}$

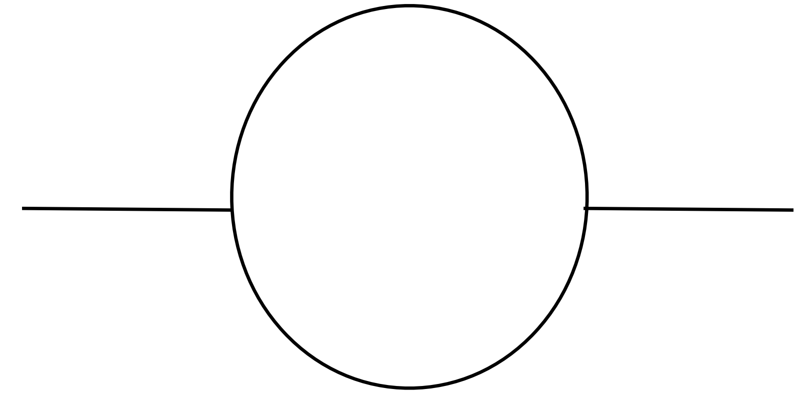
$$(\Box + m^2)\mathcal{G}(x) = \delta(x)$$

$$(\Box + m^2)\phi_1 = \phi_0^2$$

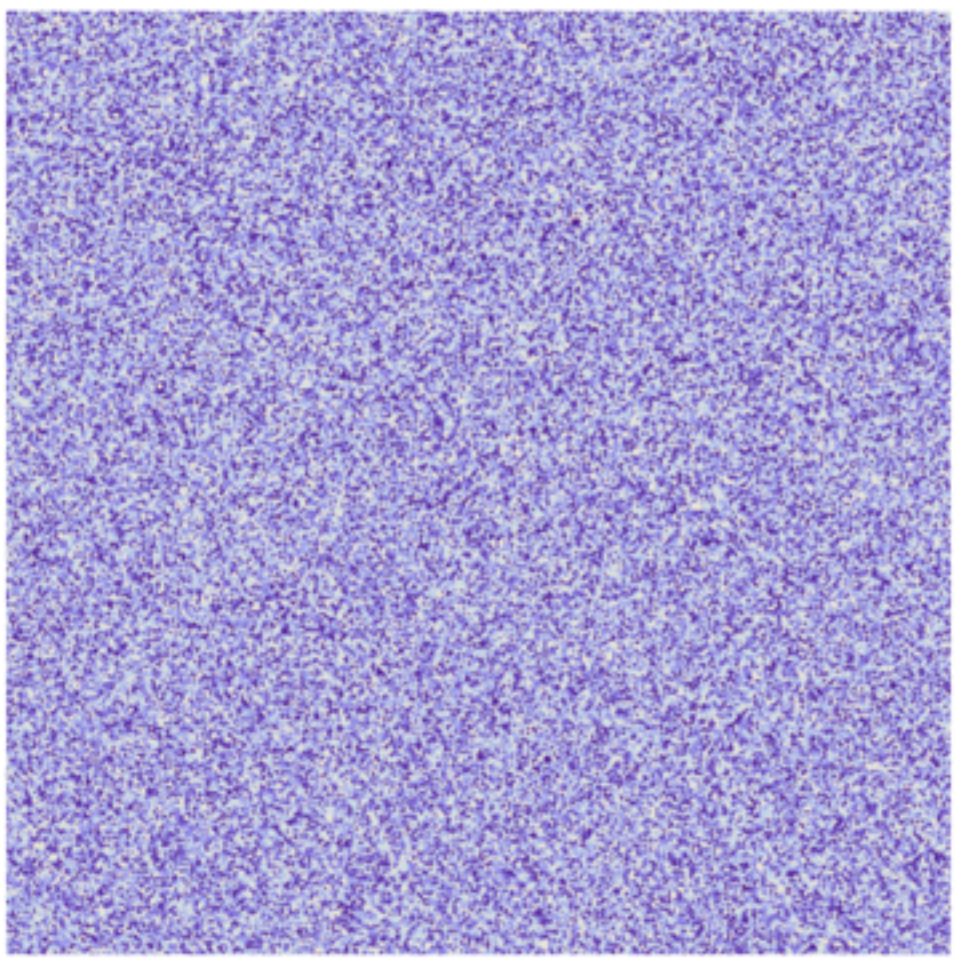
$$\phi_1(x) = \int dy\, \mathcal{G}(x-y)\phi_0(y)^2$$



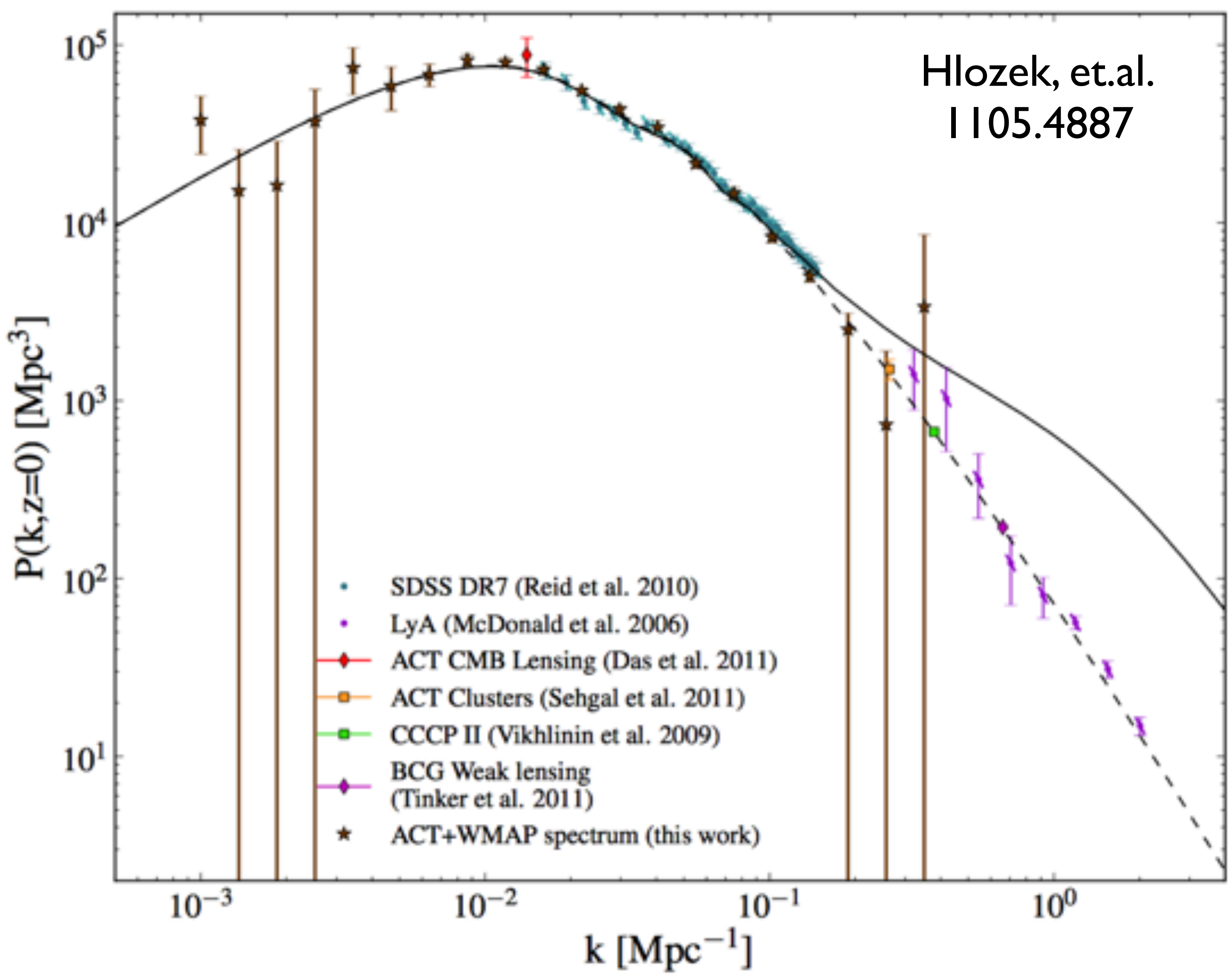
classical



Density fluctuations

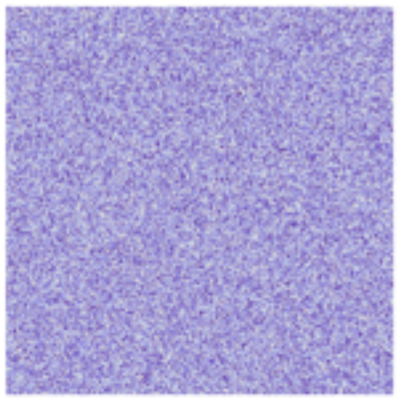


Powerspectrum: 2-pt Correlation in Freq space



classical

Density fluctuations



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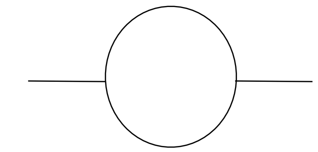
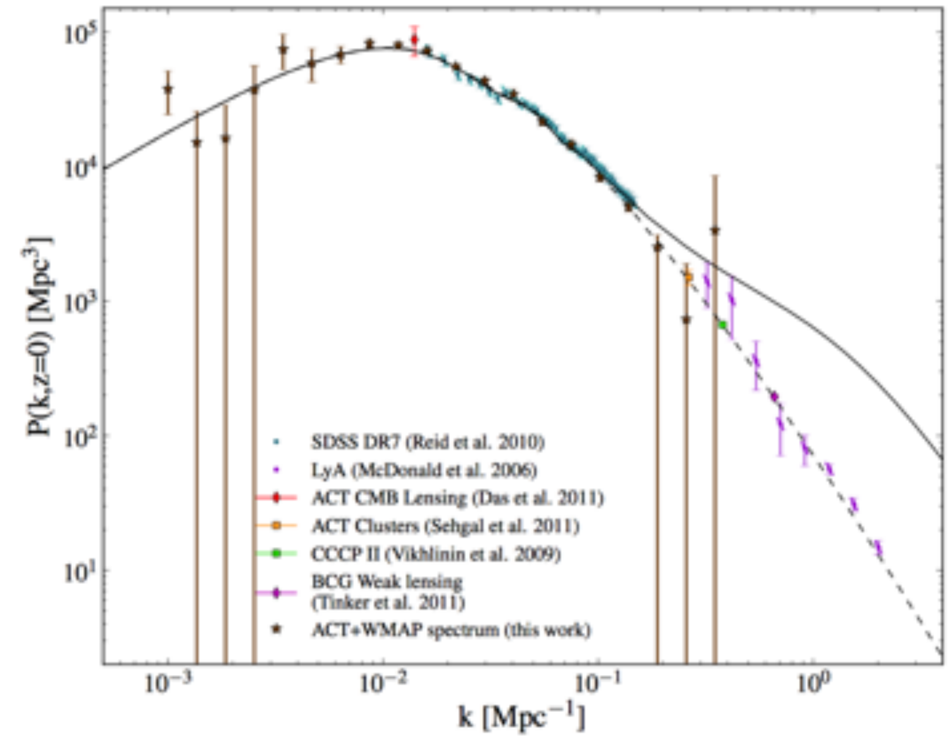
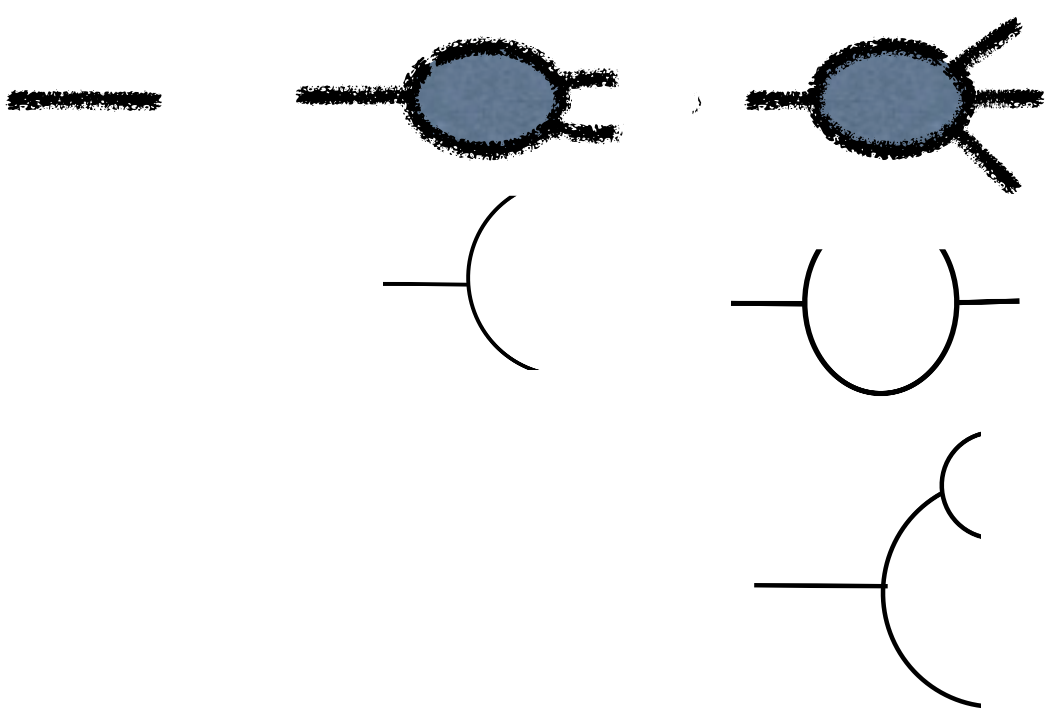




Perturbative solution to equations of motion:



classical

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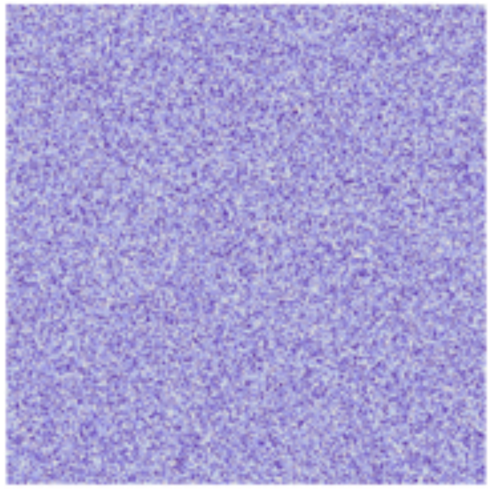

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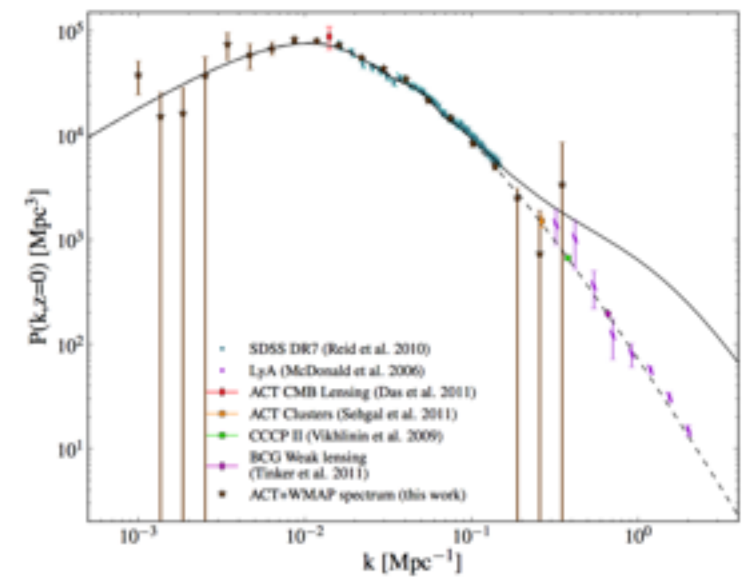
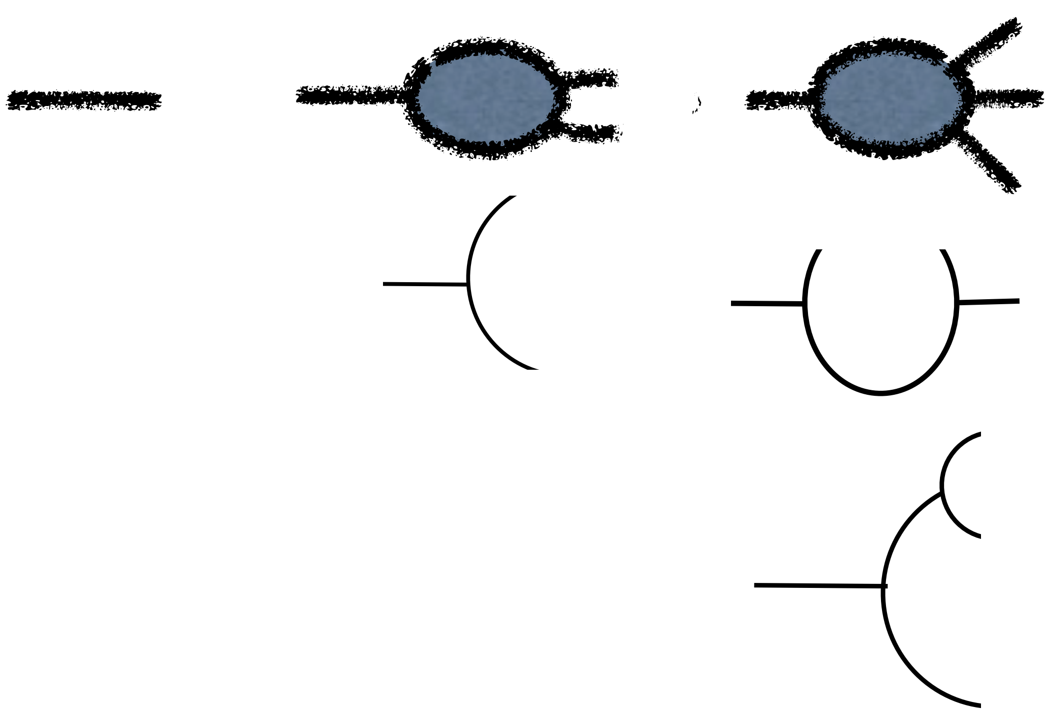
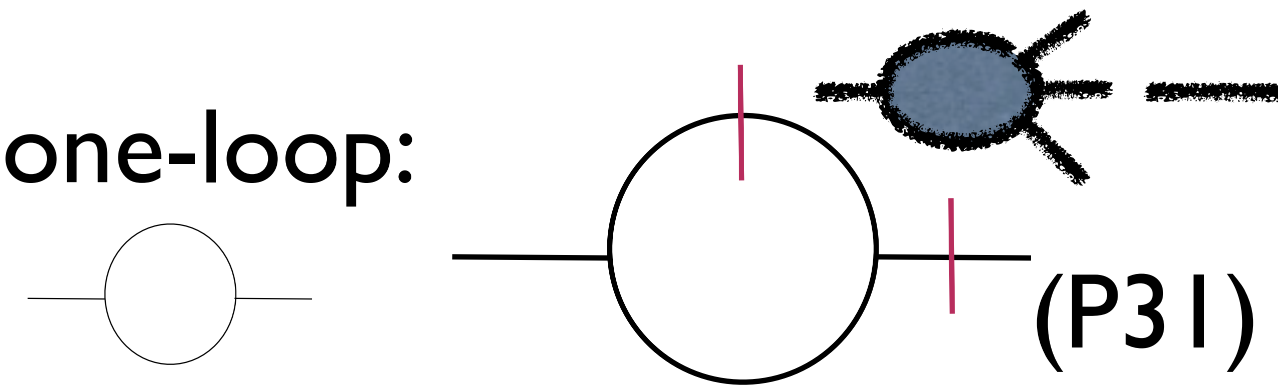


linear: P11

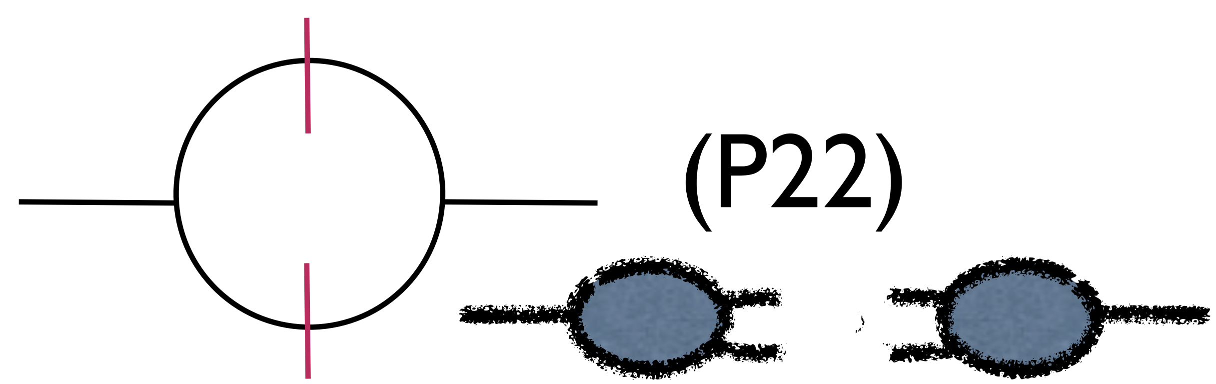
Perturbative solution to EOM:



one-loop:



(P31)



(P22)

How to arrive at a rigorous prediction of large scale matter distribution?

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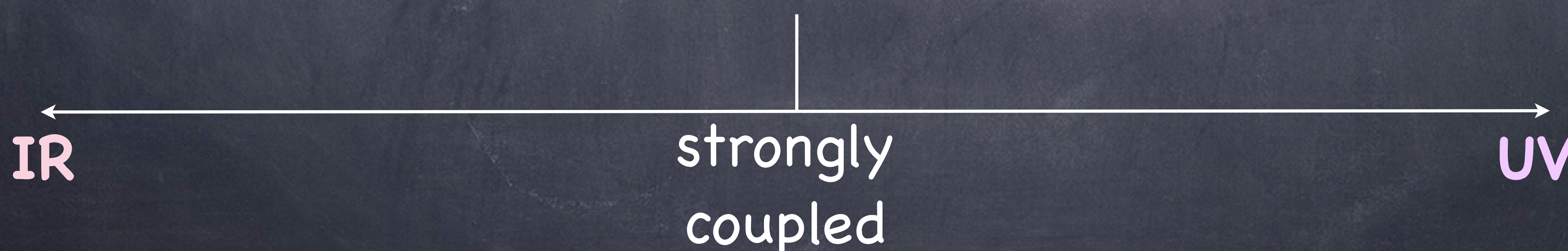
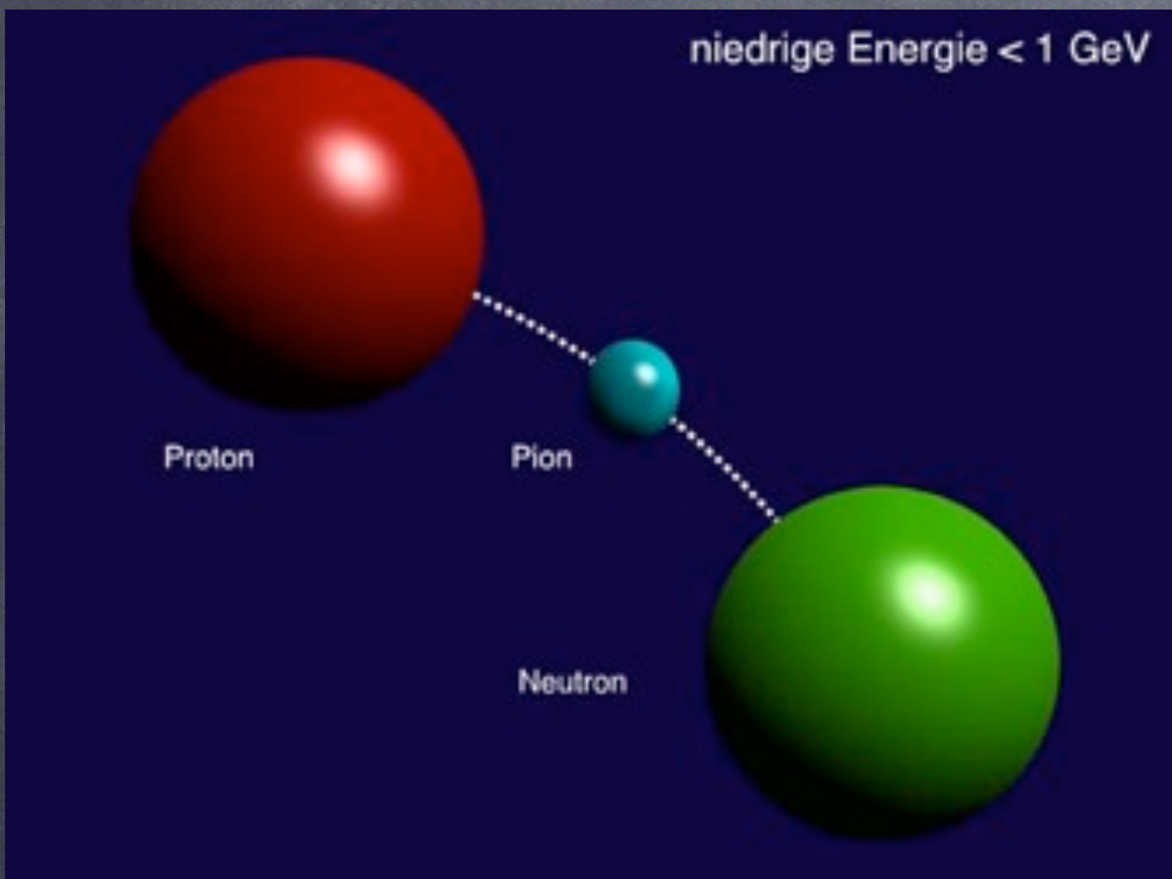
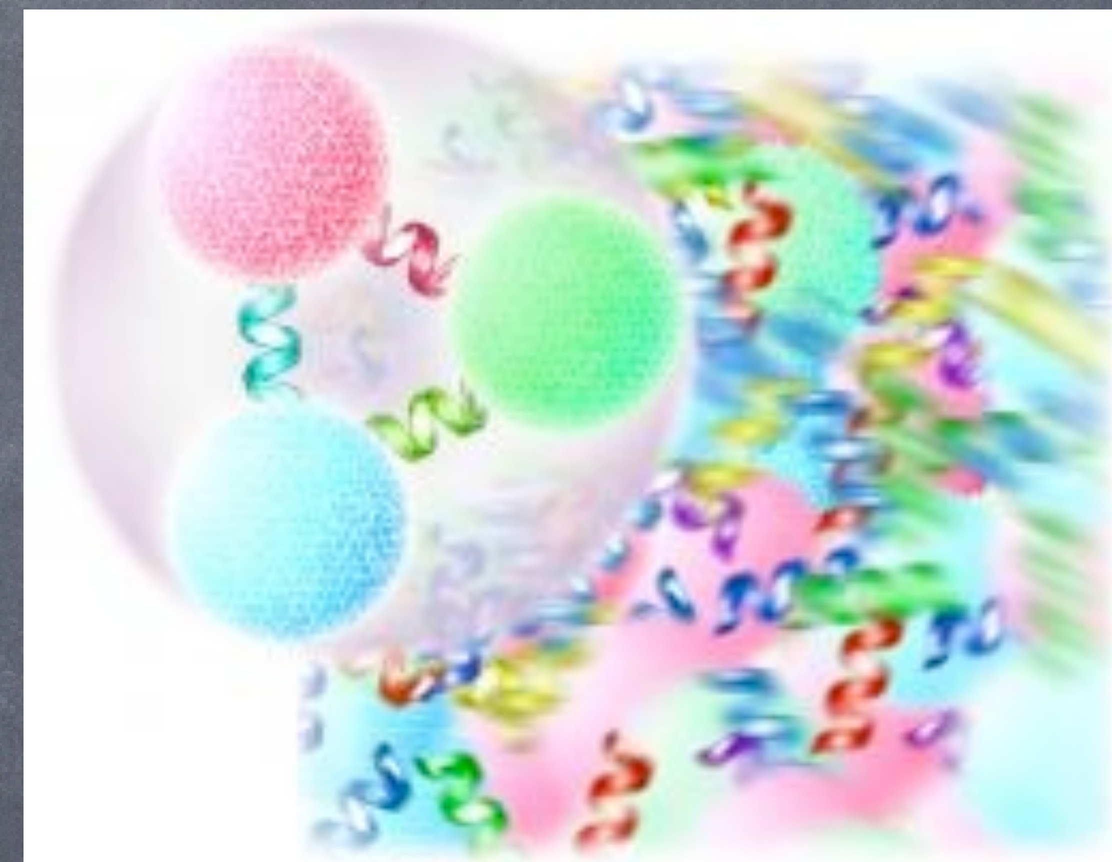


How to arrive at a rigorous prediction of large scale matter distribution?





Chiral Lagrangian Effective Theory

$4\pi F_\pi \approx 1$ GeV

QCD

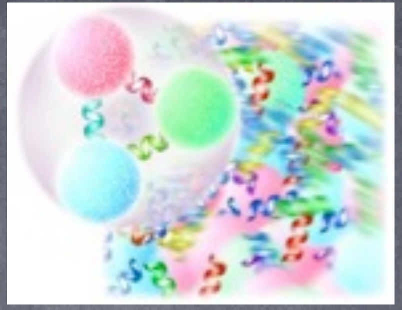
IR

weakly interacting pions

strongly coupled

UV

Pions strongly coupled



weakly interacting pions

IR

Chiral Lagrangian Effective Theory

UV

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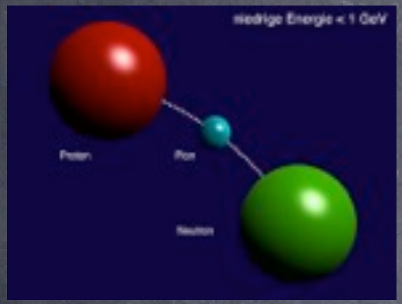
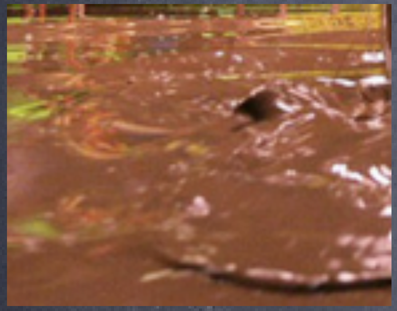




Nonlinear Scale

Fluid-like description

$k_{\rm NL}$

IR

small matter fluctuations

UV

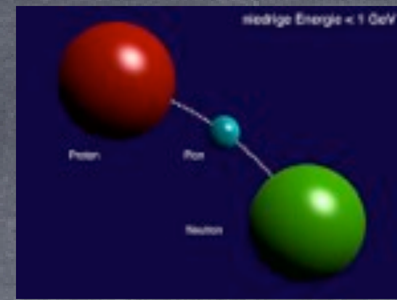
EFT coupling: $$\frac{\mathbf{k}}{\mathbf{k}_{NL}} \sim \left(\frac{\delta\rho}{\rho}\right)$$

GR effects

Grav. collapse overtakes expansion

JJMC, Hertzberg, Senatore

weakly interacting pions



Lattice calculations

IR

Chiral Lagrangian Effective Theory

$4\pi F_\pi \approx$ 1 GeV

UV

QCD

Must be well described by rigorous perturbative methods - predictive after input from UV physics

Effective Fluid description

$k_{\rm NL}$

IR

small matter fluctuations

UV

speed of sound, viscosity

GR effects

N-body simulations

JJMC, Hertzberg, Senatore

EFT DERIVATION

Cosmological Non-linearities as an Effective Fluid

Baumann, Nicolis, Senatore and Zaldarriaga **JCAP 2012**

Effective Field Theory of Large Scale Structure

JJMC, Hertzberg, and Senatore JHEP 2012

The 2-loop power spectrum and the IR safe integrand

JJMC, Foreman, Green, and Senatore **1304**

The EFT of LSS at 2-loops

JJMC, Foreman, Green, and Senatore **1310**

EFT DERIVATION

Cosmological Non-linearities as an Effective Fluid

Baumann, Nicolis, Senatore and Zaldarriaga **JCAP 2012**

Effective Field Theory of Large Scale Structure

JJMC, Hertzberg, and Senatore JHEP 2012

The 2-loop power spectrum and the IR safe integrand

JJMC, Foreman, Green, and Senatore **1304**

The EFT of LSS at 2-loops

JJMC, Foreman, Green, and Senatore **1310**

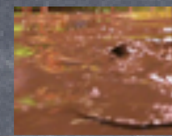
The Lagrangian EFT of LSS

Porto, Senatore, and Zaldarriaga **1311**

IR Resummed EFT of LSS

Senatore, and Zaldarriaga **(In Progress)**

Fluid description k_{NL}

IR | small matter fluctuations  Λ | larger matter fluctuations | **UV**

Effective cutoff!

Smoothing with length scale $\mathbf{\Lambda}^{-1}$

stochastic description by Boltzmann eqn for NR matter in expanding FRW background

effective fluid **continuity** & **Euler eqns** with stress tensor ($[\tau^{ij}]_\Lambda$) sourced by short (UV) modes

$$\partial_{i'}\phi(\mathbf{x}')\,\partial_{j'}\phi(\mathbf{x}')$$

BUT we want EFT params!!

$$\dot{\rho}_l + 3H\rho_l + \frac{1}{a}\partial_i(\rho_l v_l^i) = 0 \ ,$$

$$\dot{v}_l^i + Hv_l^i + \frac{1}{a}v_l^j\partial_j v_l^i + \frac{1}{a}\partial_i\phi_l = -\frac{1}{a\rho_l}\partial_j\left[\tau^{ij}\right]_\Lambda$$

effective fluid **continuity** & **Euler eqns** with stress tensor ($[\tau^{ij}]_\Lambda$) sourced by short (UV) modes

take expectation value on long wavelength background & Taylor expand in long mode fluctuations δ_l

$$\langle [\tau^{ij}]_\Lambda \rangle_{\delta_l} = \langle [\tau^{ij}]_\Lambda \rangle_0 + \left. \frac{\partial \langle [\tau^{ij}]_\Lambda \rangle_{\delta_l}}{\partial \delta_l} \right|_0 \delta_l + \ldots$$

parameterize UV physics dependence:

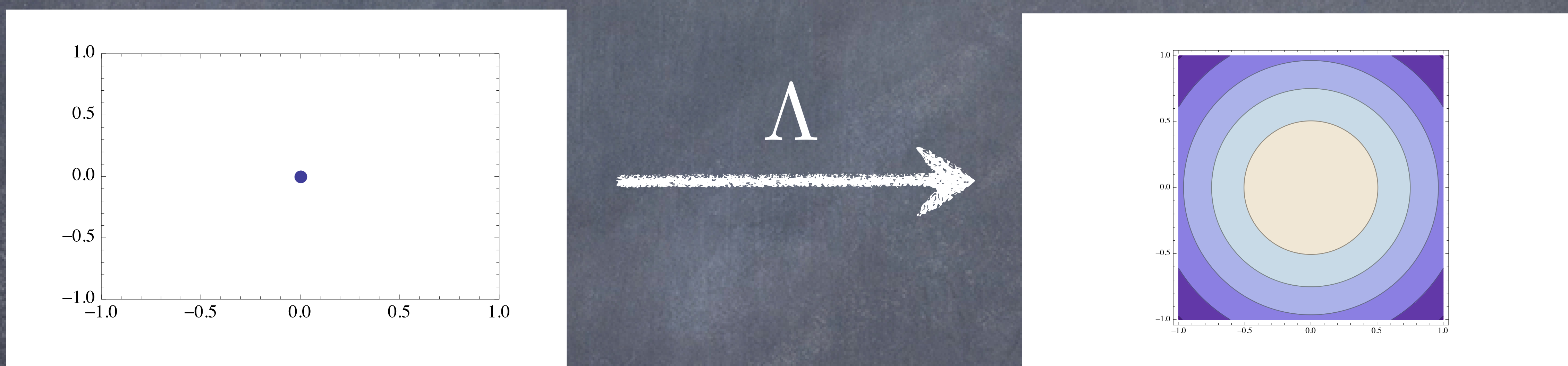
$$c_s^2, c_{sv}^2, c_{bv}^2$$

IR Λ UV

LATTICE!

Fluid parameters: $c_s^2, c_{sv}^2, c_{bv}^2$

measurable from output of simulations by taking appropriate correlations of **fields** defined by smoothing out positions



e.g. $\rho_l = \Lambda\text{–Gaussian smoothed particle positions}$

$\phi_l = \text{Newtonian grav potential sourced by } \rho_l$

IR Λ UV

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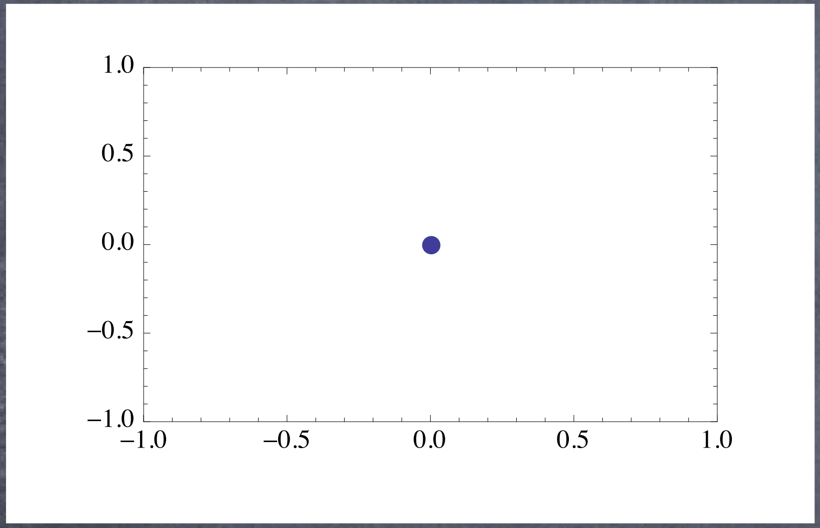
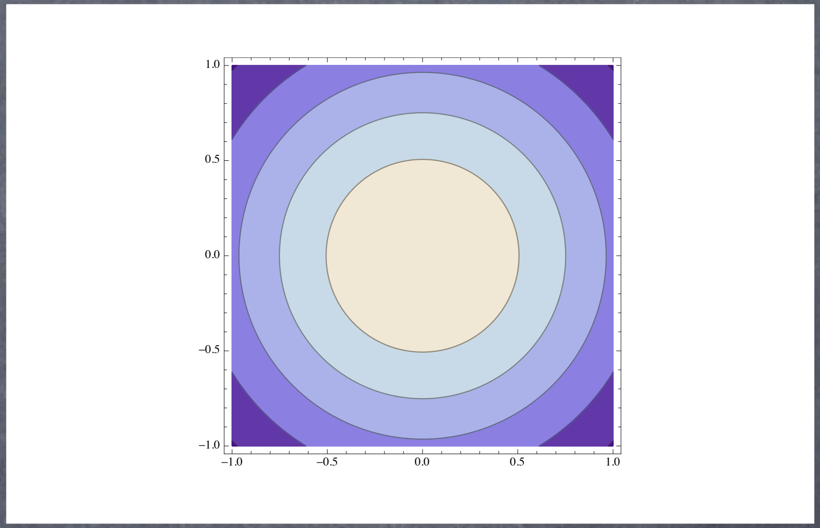


Λ



e.g. $\rho_l = \Lambda\text{−Gaussian smoothed particle positions}$

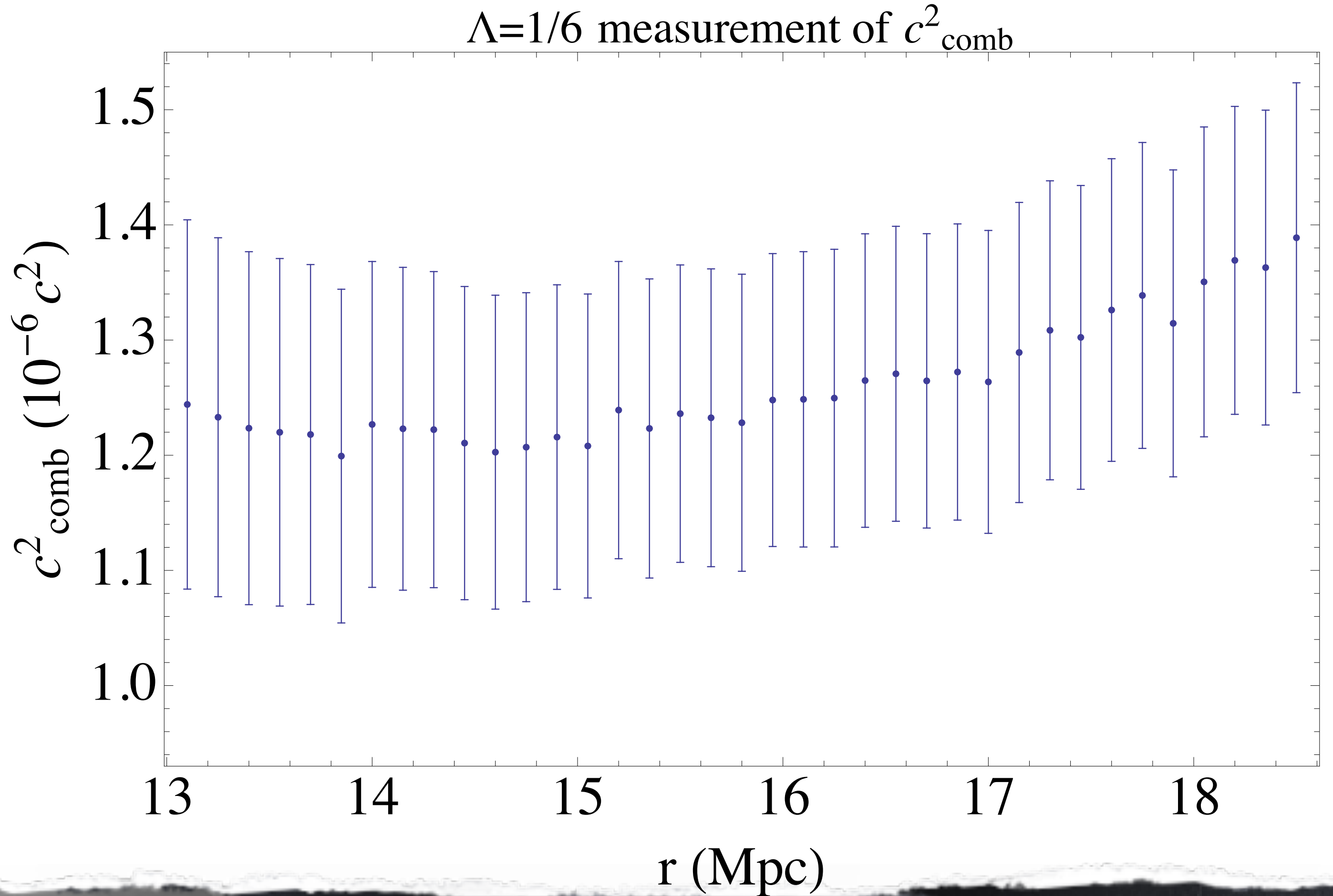
$\phi_l = \text{Newtonian grav potential sourced by } \rho_l$

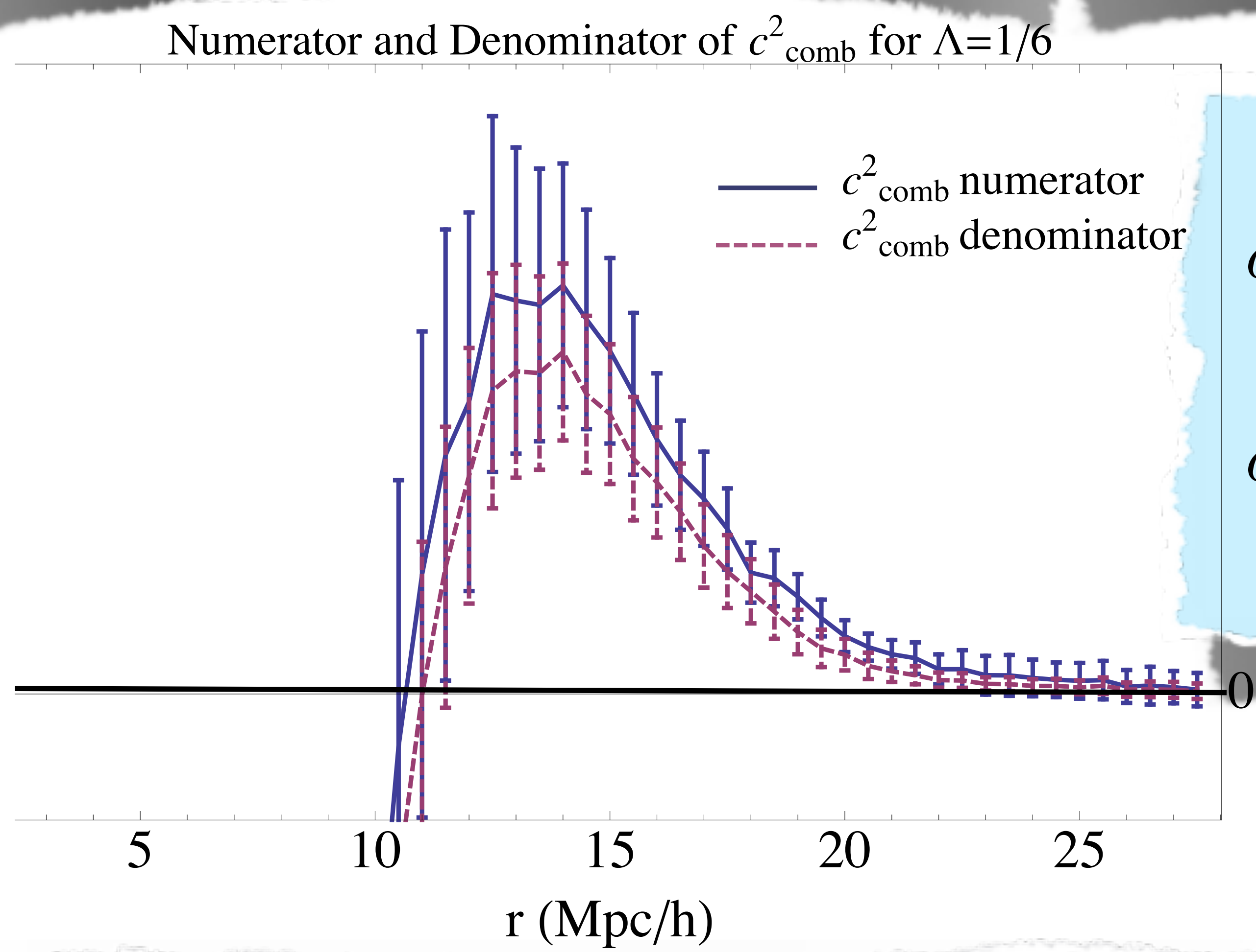
Consuelo:
10^9 particles, in (420 Mpc)^3

Parameter measurement efficiently parallelizable from a 10^6 particle downsample in the UV (<20 Mpc)

Consuelo data from Busha & Wechsler / LASDAMAS Collab (McBride, et. al. 2012 in prep)

$$P_{A\delta}(x) = \langle A_l(\vec{x}' + \vec{x})\delta_l(\vec{x}')\rangle\ ,$$
$$P_{A\Theta}(x) = \langle A_l(\vec{x}' + \vec{x})\Theta_l(\vec{x}')\rangle\ ,$$
$$P_{A^{ki}\Theta_{ki}}(x) = \langle A_l^{ki}(\vec{x}' + \vec{x})\Theta_{lki}(\vec{x}')\rangle\ ,$$
$$P_{B\Theta}(x) = \langle B_l(\vec{x}' + \vec{x})\Theta_l(\vec{x}')\rangle\ ,$$
$$P_{\delta\delta}(x) = \langle \delta_l(\vec{x}' + \vec{x})\delta_l(\vec{x}')\rangle\ ,$$
$$P_{\delta\Theta}(x) = \langle \delta_l(\vec{x}' + \vec{x})\Theta_l(\vec{x}')\rangle\ ,$$
$$P_{\Theta\Theta}(x) = \langle \Theta_l(\vec{x}' + \vec{x})\Theta_l(\vec{x}')\rangle\ ,$$
$$P_{\Theta^{ji}\Theta_i^k}(x) = \langle \Theta_l^{ji}(\vec{x}' + \vec{x})\Theta_{l\ i}^{k}(\vec{x}')\rangle\ ,$$



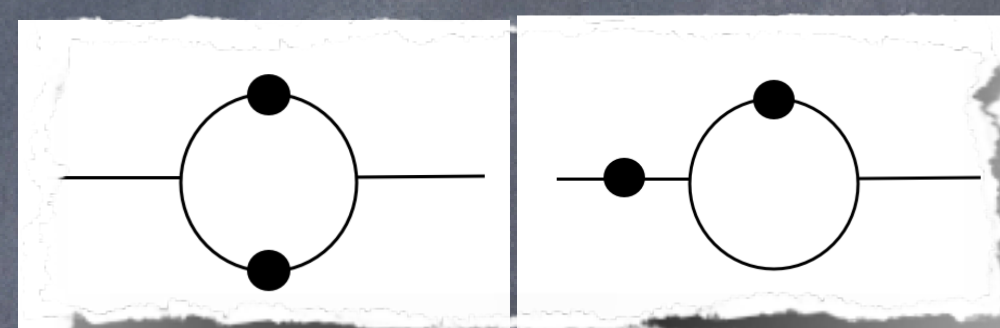


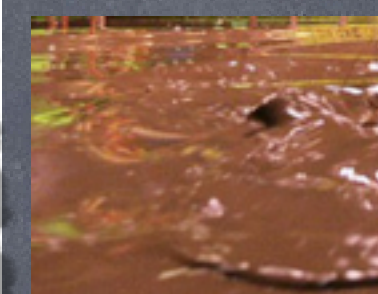
$$c_s^2 = a^2 \frac{P_{A\Theta}(x)\partial^2 P_{\delta\Theta}(x) - P_{A\delta}(x)\partial^2 P_{\Theta\Theta}(x)}{\left(\partial^2 P_{\delta\Theta}(x)\right)^2 - \partial^2 P_{\delta\delta}(x)\partial^2 P_{\Theta\Theta}(x)}$$
$$c_v^2 = a^2 \frac{P_{A\delta}(x)\partial^2 P_{\delta\Theta}(x) - P_{A\Theta}(x)\partial^2 P_{\delta\delta}(x)}{\left(\partial^2 P_{\delta\Theta}(x)\right)^2 - \partial^2 P_{\delta\delta}(x)\partial^2 P_{\Theta\Theta}(x)}$$

IR Λ UV

GO STRAIGHT TO OBSERVATION, using the
EFT perturbative calculation

can measure the physical parameter c^2_{comb}
through observations of **powerspectrum** at some scale
-- **all other scales predictive**





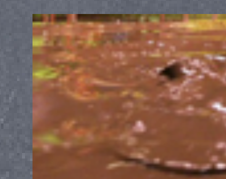
$$P^{1-\text{loop}}_{\delta\delta} = P_{11}(k,a) + \left(P_{22}(k,a) + P_{13}(k,a) + P_{13,c^2_{\text{comb}}}\right)$$

(linear) ("1-loop")

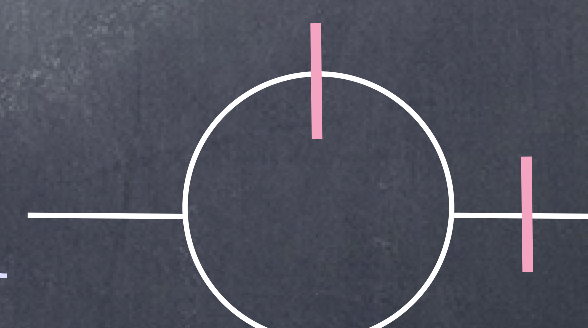
$$P_{11}(k, a_0) = \langle \delta(\vec{k}, a_0)\delta(\vec{q}, a_0)\rangle' \ ,$$
$$P_{22}(k, a_0) = \langle \delta^{(2)}(\vec{k}, a_0)\delta^{(2)}(\vec{q}, a_0)\rangle' \ ,$$
$$P_{13}(k, a_0) = 2\langle \delta^{(3)}(\vec{k}, a_0)\delta^{(1)}(\vec{q}, a_0)\rangle' \ ,$$
$$P_{13,\, c^2_{\rm comb}}(k, a_0) = 2\langle \delta^{(3)}_{c_{\rm comb}}(\vec{k}, a_0)\delta^{(1)}(\vec{q}, a_0)\rangle'$$

given in terms of smoothed P_{11}

Λ-dependent!!



But this cutoff dependence cancels for physical observables -- the **counterterm** $P_{13,c^2_{\rm comb}}$ exists to eat up the UV cutoff dependence of P_{13}

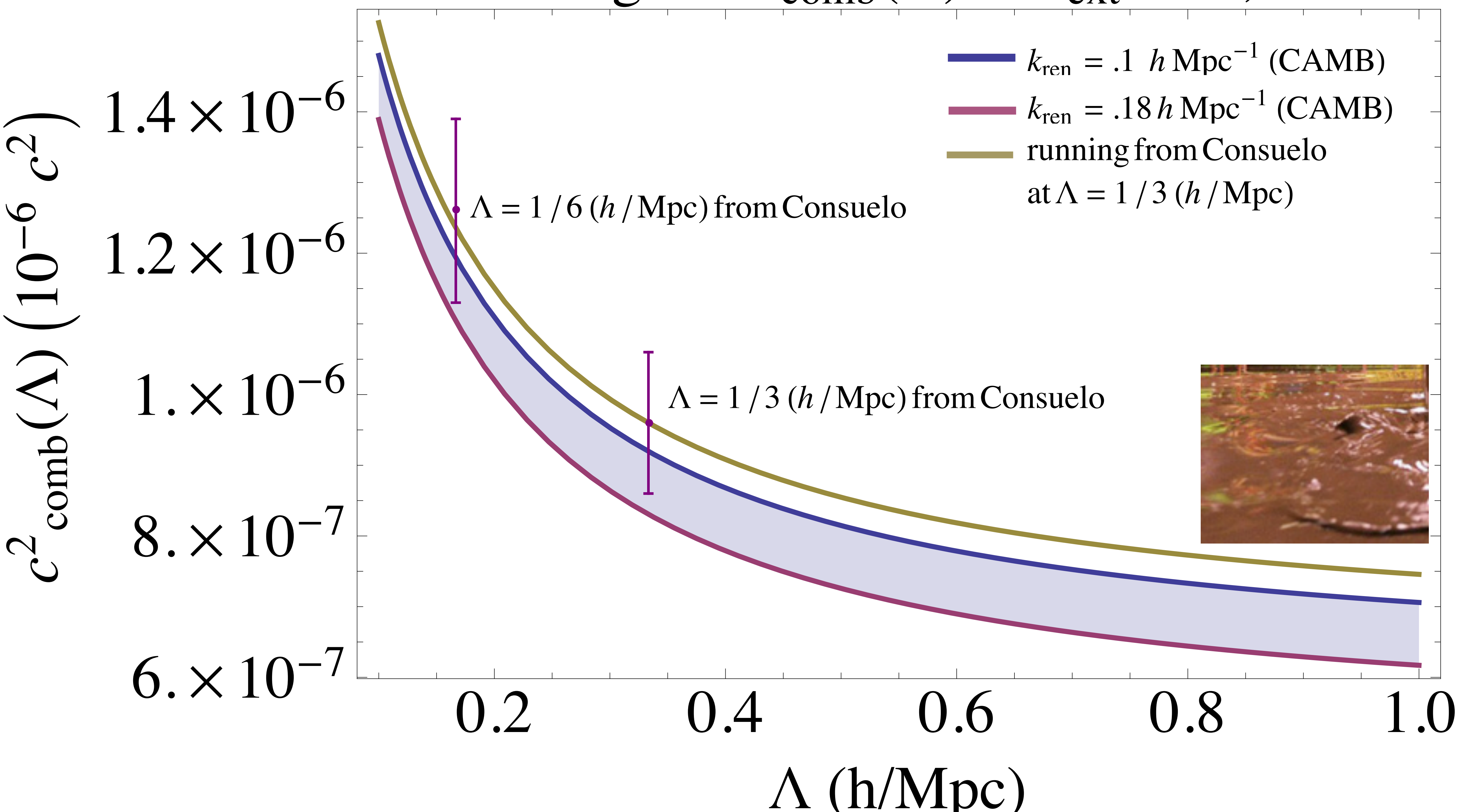
$$\partial_\Lambda c^2 = \partial_\Lambda$$ 

Can measure params at finite Λ and **renormalize** by taking $\Lambda \to \infty$

Measuring fluid parameters

JJMC, Hertzberg, Senatore

Running of $c^2_{comb}(\Lambda)$ at k_{ext}=.01 , a=1



Consuelo data from Busha & Wechsler / LASDAMAS Collab
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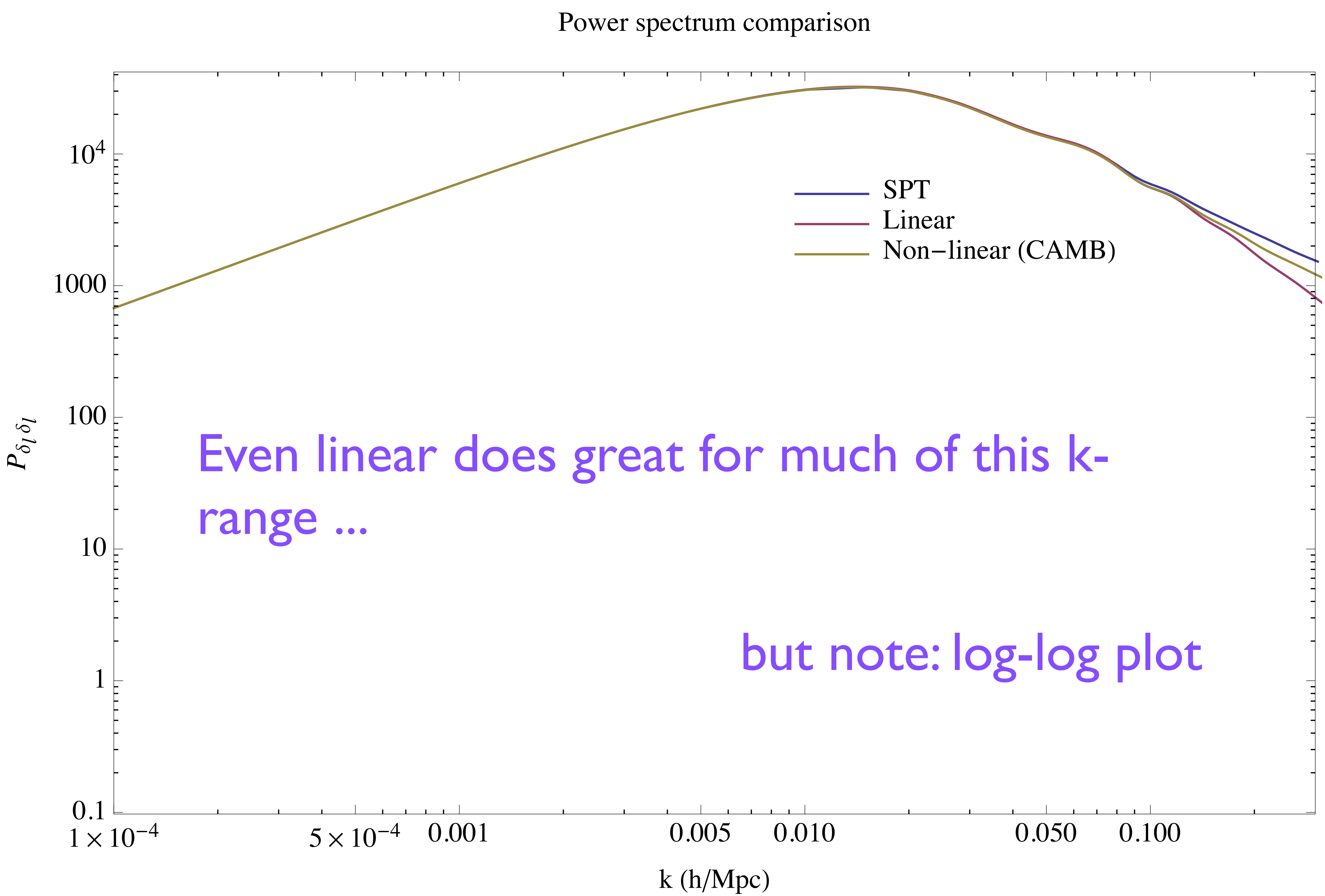
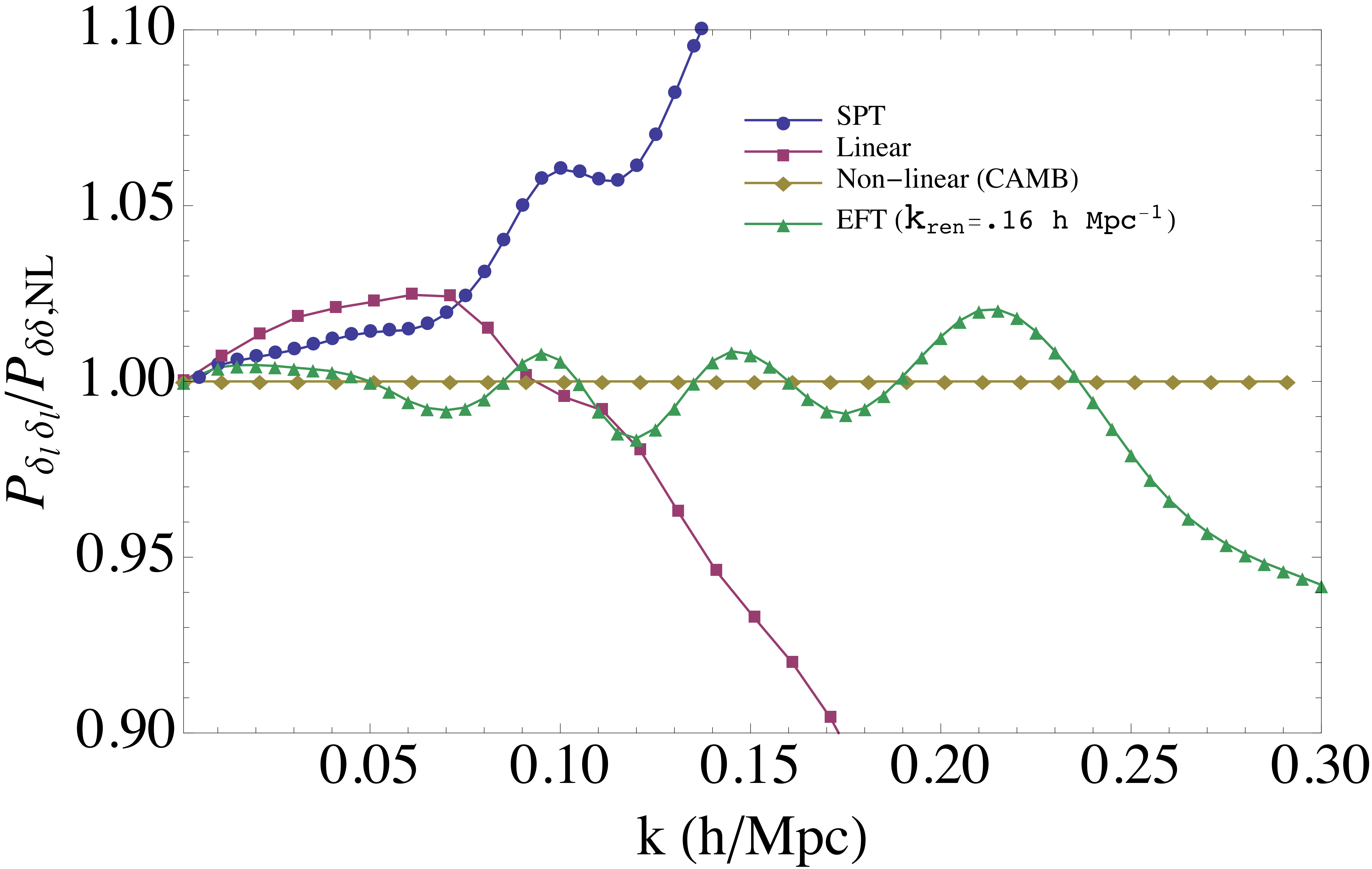


Even linear does great for much of this k-range ...

but note: log-log plot

JJMC, Hertzberg, Senatore

Comparison with nonlinear power spectrum (CAMB):
nonlinear power spectrum normalized.



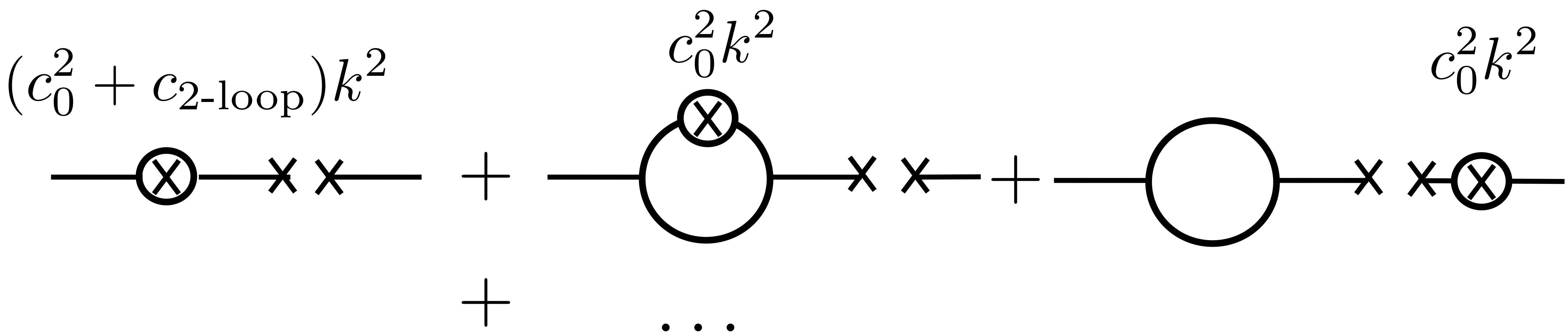
What counterterms to include at 2-loops?

Whose contributions are more significant than 3-loops?

From scaling universe, at 2-loops we have

$$\partial_i \partial_j \tau^{ij} = (c_0^2 + c_{2\text{-loop}}) \frac{\partial^2}{k_{\rm NL}^2} \delta$$

These terms are evaluated at different orders!



c_0^2 counts as 1-loop and $c_{2\text{-loop}}$ counts as 2-loops

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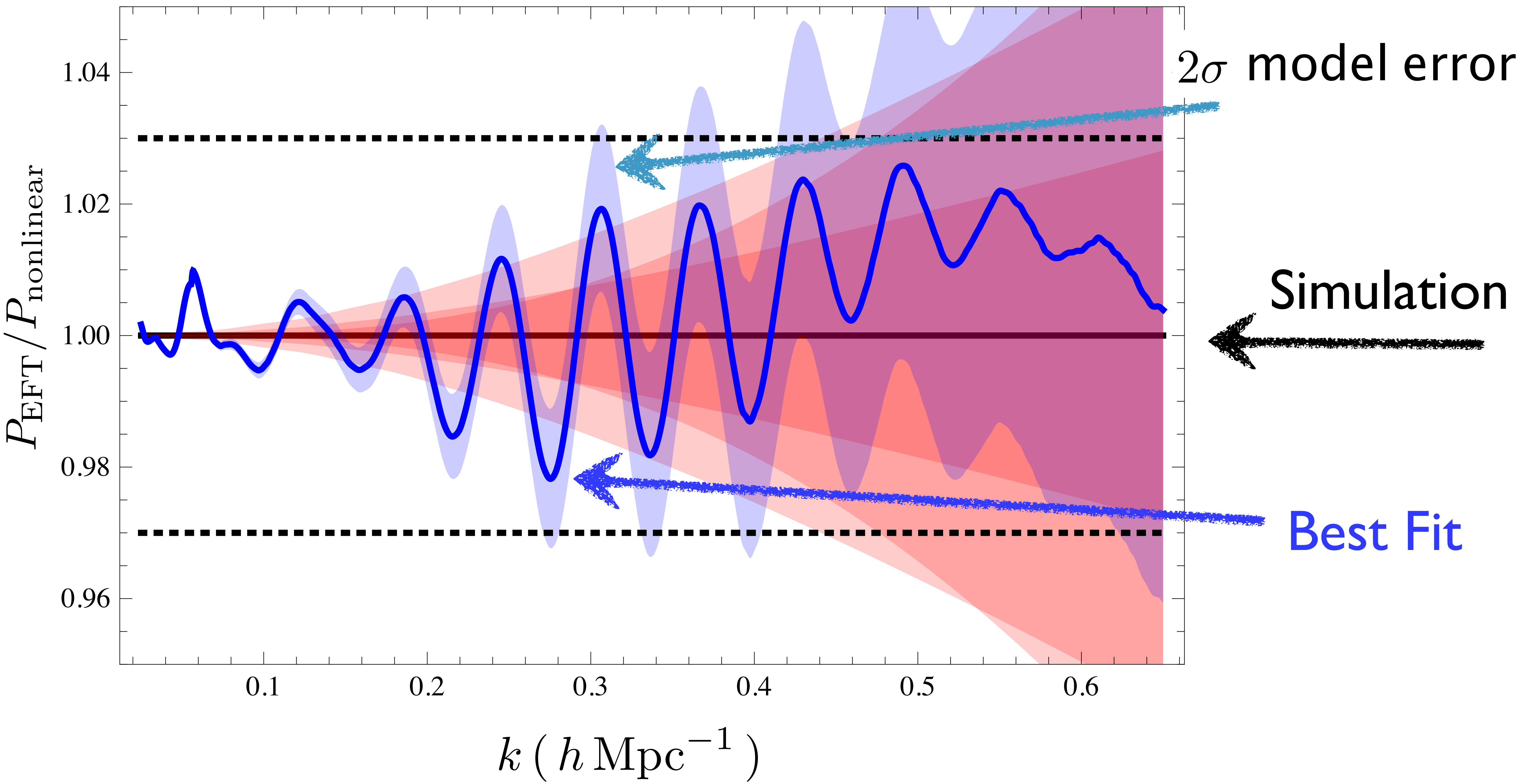
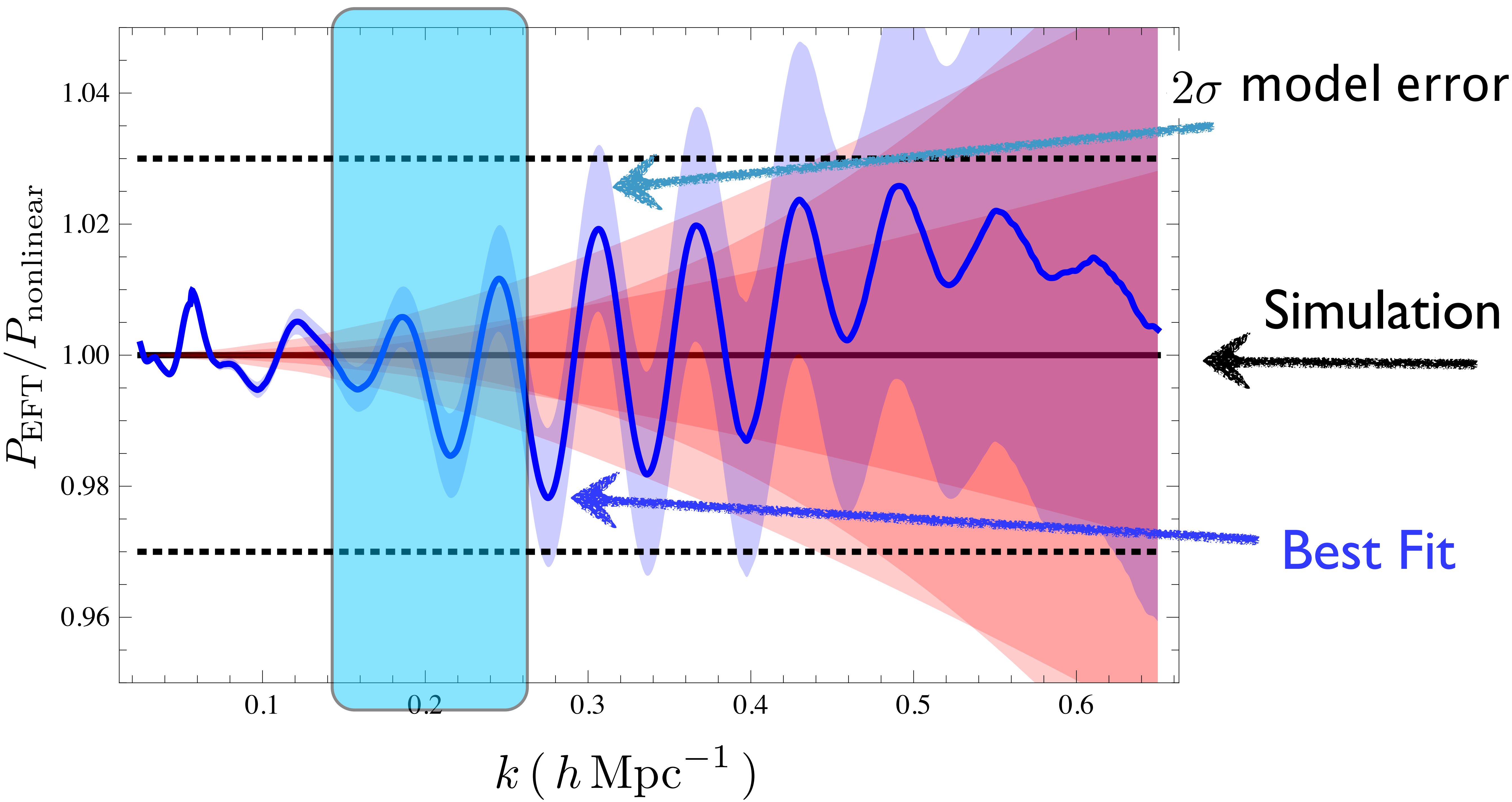


JJMC, Foreman, Green, Senatore

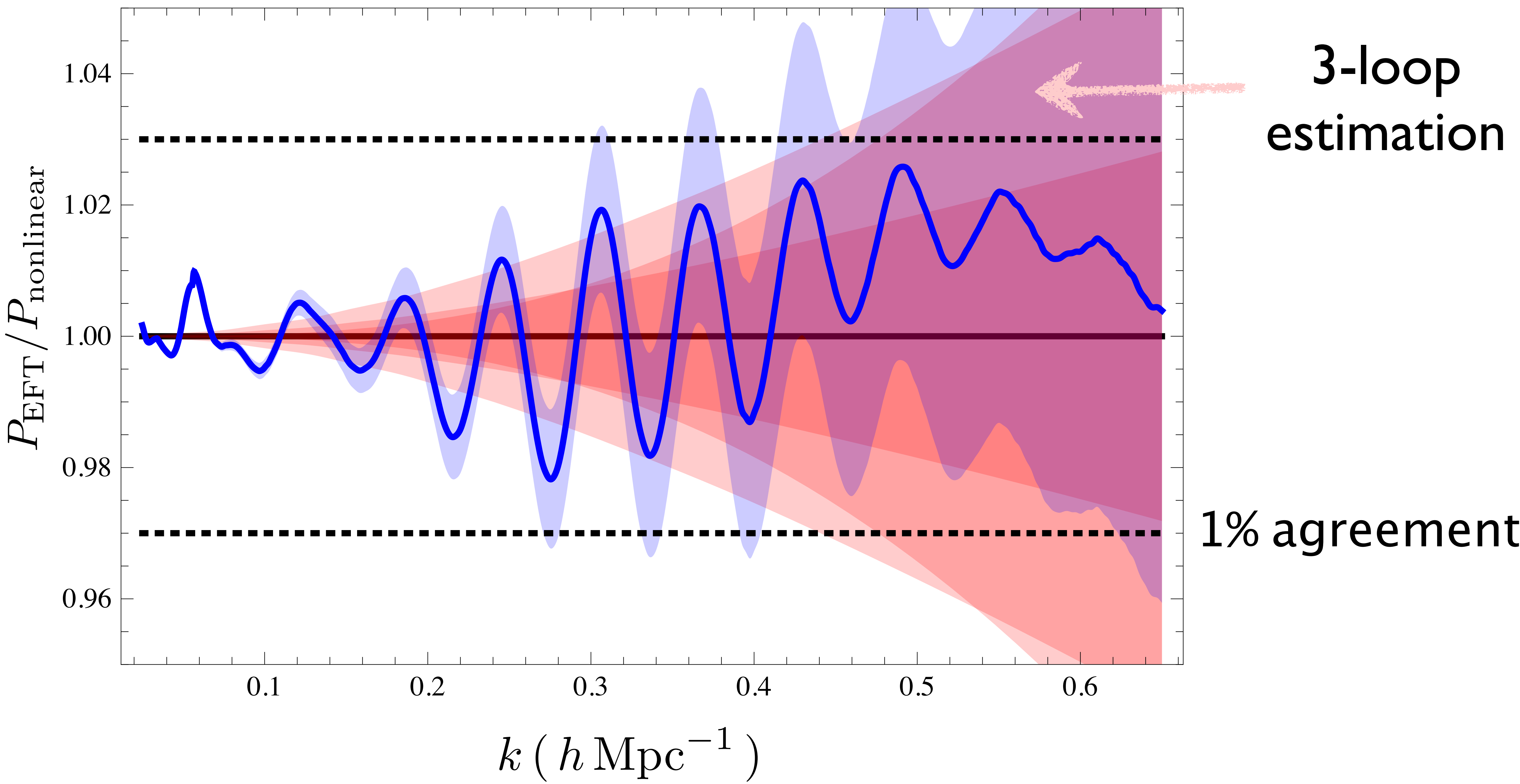


$$.15\,h\,{\rm Mpc}^{-1} < k_{\rm fit} < .25\,h\,{\rm Mpc}^{-1}$$

JJMC, Foreman, Green, Senatore

$$c^2_{s(1)} = (1.62 \pm 0.03) \times \frac{1}{2\pi} \left(\frac{k_{\rm NL}}{h\,{\rm Mpc}^{-1}} \right)^2 \qquad (1\text{-}\sigma).$$

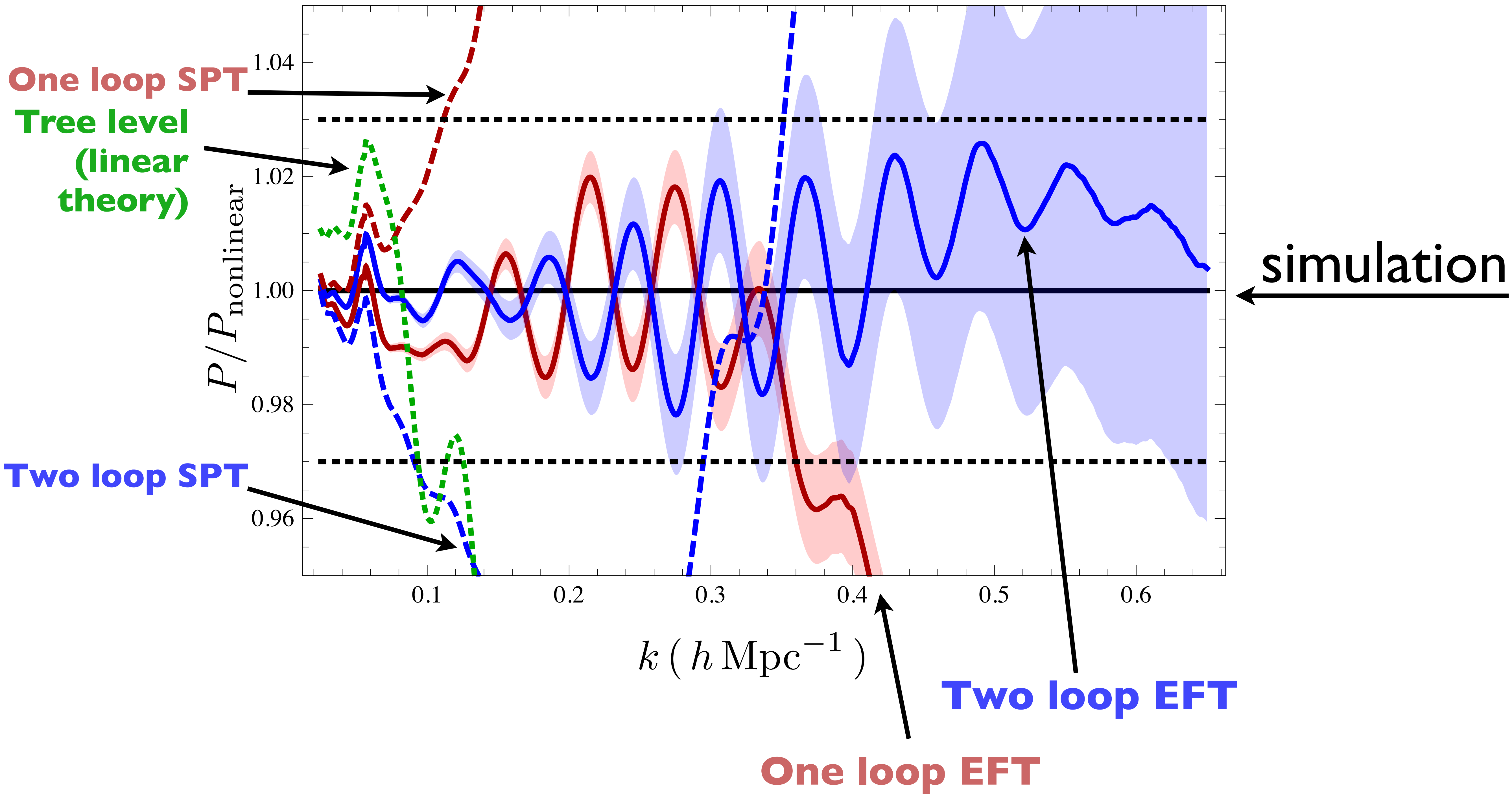
$$c^2_{s(2)} = (-3.316 \pm 0.002) \times \frac{1}{2\pi} \left(\frac{k_{\rm NL}}{h\,{\rm Mpc}^{-1}} \right)^2 \qquad (1\text{-}\sigma).$$



$$.15\,h\,\mathrm{Mpc}^{-1} < k_{\mathrm{fit}} < .25\,h\,\mathrm{Mpc}^{-1}$$

JJMC, Foreman, Green, Senatore

Comparison to not including counterterms



JJMC, Foreman, Green, Senatore

EFT of LSS
February 27 - March 1
PCTS Princeton

http://www.sns.ias.edu/~baldauf/EFTofLSS/

Thursday, February 27

8:45-9:00	Welcome Remarks
9:00-9:30	Talk: General Introduction to LSS D. Spergel
9:30-10:30	Talk: Introduction to EFTofLSS L. Senatore
10:30-11:00	Coffee
11:00-12:00	Talk: LEFT M. Zaldarriaga
12:00-14:00	Lunch
14:00-15:00	Discussion: Eulerian vs. Lagrangian PT S. Tassev
15:00-16:00	Talk: EFTofLSS at two Loops J. Carrasco
16:00-16:30	Coffee
16:30-17:30	Discussion: Non-Locality in Time E. Pajer, J. Pollack
17:30	Reception

Friday, February 28

9:00-10:00	Talk: Analytical Tools for LSS R. Scoccimarro
10:00-11:00	Discussion: Parameters from Simulations T. Baldauf, M. Pietroni, E. Schaan
11:00-11:30	Coffee
11:30-12:30	Discussion: Vorticity and Small Scale Effects E. Pajer, R. Scoccimarro
12:30-14:30	Lunch
14:30-15:30	Talk: Theory meets Observations M. Crocce
15:30-16:00	Coffee
16:00-17:00	Discussion: What are SPT and EFTofLSS good for? D. Spergel, L. Senatore, M. Crocce

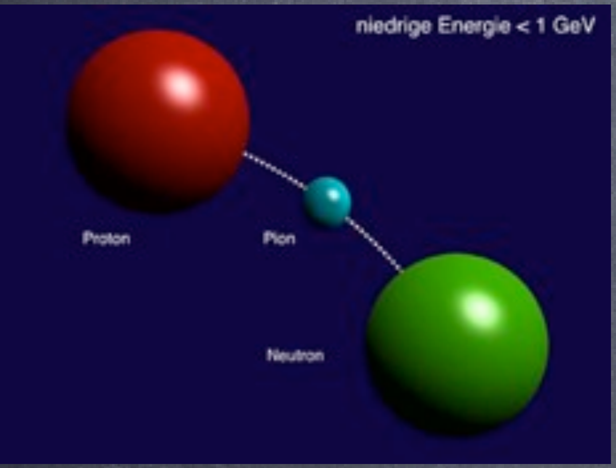
Saturday, March 1

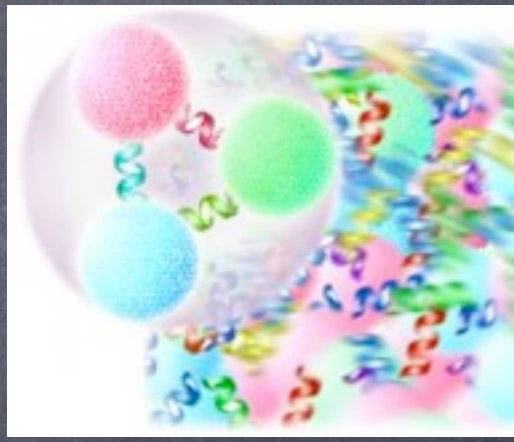
9:00-10:00	Talk: Introduction to Bias F. Schmidt
10:00-11:00	Talk: EFT for Biased Tracers D. Green
11:00-11:30	Coffee
11:30-12:30	Discussion: What's next? D. Baumann, M. Zaldarriaga
12:30-14:30	Lunch

IR UV

There's a very physical story here --
and this is the way we do science, finding the right description for the scale of interest

IR UV





POTENTIAL ACCESS TO MANY MANY MODES--LOTS TO DO!

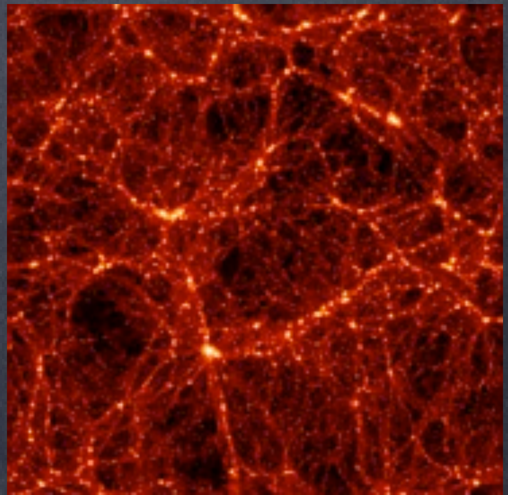
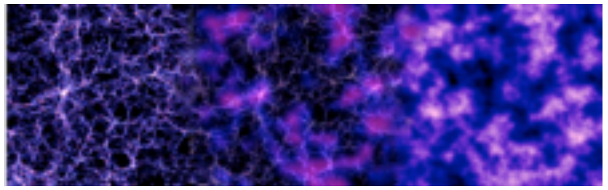
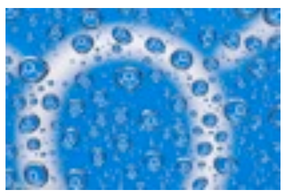


Image attribution

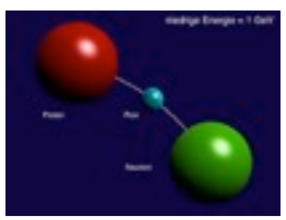


http://4.bp.blogspot.com/_fLNIKNbFuVU/TKtmoqLmj9I/AAAAAAAAAH8/8tySo3V-kA8/s1600/quantum-foam-2.jpg

http://nees.oregonstate.edu/killer_wave/characteristics.htm



http://lovoto.nl/water-molecules/



http://www.kph.tuwien.ac.at/element/index_e.html

http://newscenter.lbl.gov/feature-stories/2010/01/14/jet/