Leonardo Senatore (ETH)

Large Scale Structure Cosmology with the Effective Field Theory

Current Picture of Initial Perturbation

• Quantum Vacuum Fluctuations of a field, the inflaton, created the initial perturbations:

credit: NASA/WMAP

- Knowledge of initial conditions and components $\sim 10^{-2}$ or $\sim 10^{-3}$
- Primordial Non-Gaussianities: we know the initial distribution of the fluctuations is Gaussian to about ussian to about $\sim 10^{-3}$
- What does that mean? nat does that mean?

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- What does that mean? $\overline{)}$ 14 000 **km**
12000 **km** $\frac{1}{2000}$ ⌦*^m h k* $\frac{2000}{\pi}$ *As,* ⌦*m, H*0*, b*¹ (5) ln(10¹⁰*As*) ⇠ 8%*,* (8) 0.00005 0.0000107 nat does that mean? Primordial Non-Guassianity *Frobability*
14 000 <u>r</u>
12 000 **f** k_{6000} and k_{6000} and *P*IRresummed(*k*) ⇠ *dq M*(*k, q*) *· P*nonresummed(*q*) (4) 010 *-*0.0000
h As, ⌦*m, H*0*, b*¹ (5) (\$ 8*, f, H*0*, b*1) (6) $k = 0.000010$ $k = 0.000005$ $k = 0.000000$ $k = 0.000005$ $k = 0.0000107$ -0.00010 -0.00005 $+$ 0.00005 0.00010 T 614000 2000 4000 6000 8000 10 000 12 000 14 000 **Probability** -0.00010 -0.00005 $+$ 0.00005 0.00010 δT 0.000107 2000 4000 6000 8000 10 000 12000 14 000 **Probability** -0.00010 -0.00005 0.00000 0.00005 0.00010 δ T 0.000107 2000 4000 6000 8000 10 000 12 000 Diff.Probability

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Quantum Fields at the origin of Universe

- How could we achieve such a Gaussian distribution?
- If Inflation is made of a quantum field

with Cheung *et al.* **2008**

$$
S_{\pi} = \int d^4 \sqrt{-g} \left[\frac{\dot{H} M_{\rm Pl}^2}{c_s^2} \left(\dot{\pi}^2 - c_s^2 (\partial_i \pi)^2 \right) + \frac{\dot{H} M_{\rm Pl}^2}{c_s^2} \left[\dot{\pi} (\partial_i \pi)^2 + \tilde{c}_3 \dot{\pi}^3 \right] \right]
$$

 \bullet in its vacuum state:

$$
|0\rangle\,\,, |\Omega\rangle\,\,, \Psi(\pi)
$$

- and the non-linear term are small. ear term are small.
- Then we can! *k*3 en we can!
	- vacuum quantum fluctuations are Gaussian! .
tı $\ddot{}$ aan quantum nuctuatio ✓*T* \overline{a}
- Less self-interacting than Quantum Electro Dyn. h \overline{a} *T T* $\mathop{\mathrm{im}}\nolimits \mathop{\mathrm{Electro}}\nolimits I$ ✓*k*² χ cting than Quantum Electro Dyn.

Quantum Fields at the origin of Universe

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$$

 \bullet in its vacuum state:

*^d*⁴p*^g* $\overline{}$ *HM*˙ ² $|0\rangle$, $|\Omega\rangle$, $\Psi(\pi)$

-
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The way ahead

Cosmology is a luminosity experiment

- Progress through observation of the primordial fluctuations
- They are statically distributed:

–To increase knowledge: more modes:

 $\Delta({\rm everything})\propto$ 1 $\sqrt{N_{\text{pixel}}}$

credit: SDSS/BOSS credit: SDSS/BOSS

credit: WMAP

Cosmology is a luminosity experiment

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$$
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ser
`M R ^{*GN*} Planck, STPpol, … has observed almost all the modes in CMB

credit: SDSS/BOSS credit: SDSS/BOSS

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 $\text{LagC-3}\text{Cau}$ (LSS)
R ⇢`*vⁱ* $\frac{1}{2}$ (a) $\frac{1}{2}$ (b) $\frac{1}{2}$ (c) $\frac{1}{2}$ (Large-Scale Structure (LSS) offer the only medium-term opportunity

credit: WMAP

credit: SDSS/BOSS credit: SDSS/BOSS

What is the challenge?

– As many modes as possible:

 $N_{\rm modes} \sim$ $\int^{k_{\max}}$ $d^3k \sim k_{\rm m}^3$ $\frac{3}{2}$ max $\frac{1}{2}$ max $\frac{1}{2}$ and $\frac{1}{2}$ a

– Need to understand short distances d short distances *T*

credit: Millenium Simulation, Springel *et al.* (2005)

What is the challenge?

– As many modes as possible:

$$
N_{\rm modes} \sim \int^{k_{\rm max}} d^3 k \sim k_{\rm max}^3
$$

- Need to understand short distances d short distances *T*
	- Like having LHC but not having QCD \overline{a} t not having QCD

credit: Millenium Simulation, Springel *et al.* (2005)

The Observables

$$
\langle n_{\rm gal}(\vec{x}) n_{\rm gal}(\vec{y}) \rangle \quad \Leftrightarrow \quad \langle n_{\rm gal}(\vec{k}) n_{\rm gal}(\vec{k}') \rangle \equiv P(\vec{k}) \, \delta^{(3)} \left(\vec{k} + \vec{k}' \right)
$$

credit: SDSS/BOSS

credit: SDSS/BOSS

Normal Approach: numerics

Large-Scale Structure

credit NASA/ESA

–DESI, Euclid, Vera Rubin, Megamapper…

– Can we use them to make a lot of fundamental physics?

–in CMB, we use simplicity of universe at early time, can we now use its simplicity at long distances?

The Effective Field Theory of Large-Scale Structure: A well defined perturbation theory $\frac{1}{2}$ $\frac{1}{2}$ $\overline{\mathbf{A}}$ a wel *l* defined pe e
C $|\vec{c}|$ $\begin{array}{c} \text{ } & \text{ } \\ \text{ } & \text{ } \end{array}$ int _{α} <u>t</u> Lar ⇢ \overline{a} ◆*i* ⁺ *...*#

n n $\frac{1}{2}$ $\frac{1}{2}$ $\overline{\mathbf{A}}$ a wel *l* defined pe e
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C $|\vec{c}|$ $\begin{array}{c} \text{ } & \text{ } \\ \text{ } & \text{ } \end{array}$ int _{α} <u>t</u> Lar ⇢ \overline{a} matter ◆*i* The Effective Field Theory of Large-Scale Structure:
A well defined perturbation theory A well defined perturbation theory

What is a fluid? *d is a fluid*

wikipedia: credit National Oceanic and Atmospheric Administration/ Department of Commerce

 $\sum_{i=1}^{n}$

1

 ρ_ℓ

 $\left(\rho_\ell v^i_\ell \right)$

 $\partial_i p_\ell = \text{viscous terms}$

–From short to long

- –The resulting equations are simpler \mathbf{r}
- –Description arbitrarily accurate

–construction can be made without knowing the nature of the particles. *n* knowing the nature of the particles.

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

 $\partial_t \rho_\ell + \partial_i$

 $\partial_t v^i_\ell + v^j_\ell \partial_j v^i_\ell +$

Do the same for matter in our Universe

credit NASA

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

$$
\nabla^2 \Phi_{\ell} = H^2 (\delta \rho_{\ell} / \rho)
$$

\n
$$
\partial_t \rho_{\ell} + H \rho_{\ell} + \partial_i (\rho_{\ell} v_{\ell}^i) = 0
$$

\n
$$
\partial_t v_{\ell}^i + v_{\ell}^j \partial_j v_{\ell}^i + \partial_i \Phi_{\ell} = \partial_j \tau^{ij}
$$

-construction can be made without knowing the nature of the particles. Z *^t*

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

$$
\tau_{ij} \sim \delta_{ij} \rho_{\text{short}} \left(v_{\text{short}}^2 + \Phi_{\text{short}}\right)
$$

–From short to long

–The resulting equations are simpler

–Description arbitrarily accurate

Dealing with the Effective Stress Tensor ⇣ $\overline{\mathfrak{c}}$ $\lfloor \cdot \rfloor$ th the *<u>le</u> Effective Stress* ⇣ Tens

- For long distances: expectation value over short modes (integrate them out) $\langle \tau_{ij}(\vec{x},t) \rangle_{\text{long fixed}} = f_{\text{very complicated}} \left(\{ H, \Omega_m, \ldots, m_{\text{dm}}, \ldots, \rho_\ell(x) \}_{\text{past light cone}} \right)$ $\int_{\tau_1}^{t} \left(\frac{d}{dx} t\right) dx$ = $\int_{t_1}^{t} \int_{\theta}^{t} \left(t_1 + t_1\right) \frac{\delta \rho_{\ell}}{\sqrt{d^2} + t_1}$ = 0 (8) $\frac{1}{2}$ *dt*⁰ $f(x)$ to $f(x)$ pans) + *^O* $\left\{ \frac{\mu_{ij}(x, v)}{\log \max} \right\}$ at $\left[\frac{c(v, v)}{\rho} \frac{v}{\log v} + \mathcal{C} \left(\frac{\rho(v, v)}{\rho} \right) \right]$ *x X X Taylor* Expansion *dt*² ⁺ *^k*² *k*2)`($_{\rm ed} = \int$ *P*(*k*1)*P*(*k*2) (3) At *long* wavelengths $\{ \downarrow \}$ Taylor Expansion *long* wavelengths $\left\{\right\}$ dion $_{\rm d} = 1$ *t* $\frac{1}{2}$ $\frac{1}{2}$ $\langle \tau_{ij}(\vec{x},t) \rangle_{\rm long~fixed} =$ vith $\partial_j v$ $\overline{\mathbf{r}}$ modes (integrate them out) ` (*x*⁰ 2) i ong fixed \Box J very complicated $(1^{11}, 4^{\omega}m, \cdots, 1^{10}dm, \cdots, \mathcal{P}\ell(\omega)$ J past light cone \Box At long wavelengths $\sqrt{ }$ Taylor Expansion \int_0^t dt' $\sqrt{ }$ $c(t,t')$ $\delta \rho_\ell$ $\frac{\rho_\ell}{\rho}(\vec{x}_{\rm fl},t') + \mathcal{O}\left((\delta\rho_\ell/\rho)^2\right)$ $\overline{}$
- Equations with only long-modes Γ 29 Equations with only long-modern $\overline{\mathbf{a}}$ *k*

At long wavelengths
$$
\sqrt{}
$$
 Taylor Expansion
\n
$$
\langle \tau_{ij}(\vec{x},t) \rangle_{\text{long fixed}} = \int^t dt' \left[c(t,t') \frac{\delta \rho_{\ell}}{\rho} (\vec{x}_n, t') + \mathcal{O} \left((\delta \rho_{\ell}/\rho)^2 \right) \right]
$$
\n• Equations with only long-modes
\n
$$
\partial_t v^i_{\ell} + v^j_{\ell} \partial_j v^i_{\ell} + \partial_i \Phi_{\ell} = \partial_j \tau^{ij}
$$
\n
$$
\tau_{ij} \sim \delta \rho_{\ell} / \rho + \dots \underbrace{\left\{\begin{array}{c} \mathcal{O}_{\ell \text{UAP}} \\ \text{Nartree} \end{array}\right\}}_{\text{Hartfer}}
$$
\nevery term allowed by symmetries

every term allowed by symmetries *d*4 p_{min} and ved by symmetries

• each term contributes as factor of $\frac{1}{2}$ ern ach te

$$
\frac{1}{2} \text{ is a factor of } \frac{\delta \rho_l}{\rho} \sim \frac{k}{k_{\text{NL}}} \ll 1
$$

Perturbation Theory within the EFT 1922 vis 3

• In the EFT we can solve iteratively $\delta_{\ell}, v_{\ell}, \Phi_{\ell} \ll 1$, where $\delta\rho_{\ell}$ $\delta_{\ell}, v_{\ell}, \Phi_{\ell} \ll 1$, where $\delta_{\ell} = \frac{\delta_{\ell} v_{\ell}}{2}$ $\delta \rho_\ell$ $rac{\rho}{\rho}$

$$
\nabla^2 \Phi_{\ell} = H^2 (\delta \rho_{\ell}/\rho)
$$

\n
$$
\partial_t \rho_{\ell} + H \rho_{\ell} + \partial_i (\rho_{\ell} v_{\ell}^i) = 0
$$

\n
$$
\partial_t v_{\ell}^i + \left(\frac{v_{\ell}^j \partial_j v_{\ell}^i}{v_{\ell}^j}\right) + \partial_i \Phi_{\ell} = \partial_j \tau^{ij}
$$

\n
$$
\tau_{ij} \sim \delta \rho_{\ell} / \rho + \dots
$$

• Two scales:

les:
\n*k* [Mean Free Path Scale] ~
$$
k \left[\left(\frac{\delta \rho}{\rho} \right) \sim 1 \right] \sim k_{\text{NL}}
$$

Perturbation Theory within the EFT

- Solve iteratively some non-linear eq. $\delta_{\ell} = \delta_{\ell}^{(1)} + \delta_{\ell}^{(2)} + \ldots \ll 1$
- Second order:

and order:
\n
$$
\partial^2 \delta_{\ell}^{(2)} = \left(\delta_{\ell}^{(1)}\right)^2 \implies \delta_{\ell}^{(2)}(x) = \int d^4 x' \text{ Greens}(x, x') \left(\delta_{\ell}^{(1)}(x')\right)^2
$$

• Compute observable:

$$
\langle \delta_{\ell}(x_1) \delta_{\ell}(x_2) \rangle \supset \langle \delta_{\ell}^{(2)}(x_1) \delta_{\ell}^{(2)}(x_2) \rangle \sim \int d^4x'_1 d^4x'_2 \text{ (Green's)}^2 \langle \delta_{\ell}^{(1)}(x'_1)^2 \delta_{\ell}^{(1)}(x'_2)^2 \rangle
$$

⇢`

$$
x_2' \to x_1'
$$

- Need to add counterterms from $\tau_{ij} \supset c_s^2 \delta_\ell$ to correct to add c (1) ounterter (2) **e**
*x*₂ *ex e*^{*x*} *ex e*^{*x*} *ex e*^{*x*} *ex e*_{*x*} *ex e*_{*x*} *e*_{*x*} *e*_** $counterterms$ f_1 $\text{C} \text{O} \text{I} \text{I} \quad \text$
- Loops and renormalization applied to galaxies ⇢ nd rei nor $\overline{101117}$ al za $\overline{\mathfrak{u}}$ on app to galax *k* 700

…. lots of work ….

Galaxy Statistics

Senatore **1406** with Lewandowsky *et al* **1512** with Perko *et al.* **1610**

Galaxies in the EFTofLSS Senatore 1406

- On galaxies, a long history before us, summarized by McDonald, Roy 2010.
	- $-$ senatore 1406 provided first complete parametrization.

• Nature of Galaxies is very complicated $\frac{1}{2}$ rature of Galaxies is very complicated

$$
n_{\rm gal}(x) = f_{\rm very\ complicated}\left(\{H,\Omega_m,\ldots,m_e,g_{ew},\ldots,\rho(x)\}_{\rm past\ light\ cone}\right)
$$

Galaxies in the EFTofLSS Senatore 1406

$$
n_{\text{gal}}(x) = f_{\text{very complicated}} \left(\{H, \Omega_m, \dots, m_e, g_{ew}, \dots, \rho(x) \}_{\text{past light cone}} \right)
$$

At long wavelengths

$$
\left(\frac{\delta n}{n} \right)_{\text{gal}, \ell} (x) \sim \int^t dt' \left[c(t, t') \left(\frac{\delta \rho}{\rho} \right) (\vec{x}_{\text{fl}}, t') + \dots \right]
$$

• all terms allowed by symmetries
• all physical effects included
–e.g. assembly bias
•

$$
\left(\frac{\delta n}{n}\right)_{\text{gal},\ell}(x) \sim \int^t dt' \left[c(t,t')\left(\frac{\delta \rho}{\rho}\right)(\vec{x}_{\text{fl}},t') + \ldots\right]
$$

- all terms allowed by symmetries \sim • all terms allowed by symmetries
- all physical effects included an physical effects included
 $-e \sigma$ assembly bias *x*) + @*xⁱ T*(*t,* ~
	- $-e.g.$ assembly bias

• . *f*verycomplicated QFT: Non-Time-Localh`(~ *k*1)`(*k*2)`(r ~ *x*0 ² ! *x*⁰ *✓*ⁿ n* ◆ gal*,*` (*x*) ✓*n n* ◆ gal*,*` (*y*) + = X *n* Coe↵*ⁿ ·* hmatter correlation functioni*ⁿ* h`(*k*1)`(*k*2)`(*k*3)i*^k*1!⁰ ⇠ r ~ (25) *x*0 ² ! *x*⁰

Senatore **1406**

It is familiar in dielectric E&M

• Polarizability:

$$
\vec{P}(\omega) = \chi(\omega)\vec{E}(\omega) \quad \Rightarrow \quad \vec{P}(t) = \int dt' \chi(t - t')\vec{E}(t')
$$

– Here we work in time-Fourier space, and theory is practically linear.

- The EFT of Non-Relativistic binaries Goldberger and Rothstein 2004 is non-local in time time \mathcal{L} of Non-Relativistic binaries 1 Goldberger and Rothstein **2004**
	- Here we solve perturbatively the inspiralling regime, and feed it into the long-
distance theory (again time-Fourier space). distance theory (again time-Fourier space). ,
Fourier s lir ace).

Baryonic effects

• When stars explode, baryons behave differently than dark matter

credit: Millenium Simulation, Springel *et al.* (2005)

• They cannot be reliably simulated due to large range of scales
Baryons $\sum_{n=1}^{\infty}$ $Baryons$

- Idea for EFT for dark matter: than the equality scale. Notice that t **i** \mathbf{r}
	- $-$ Dark Matter moves $1/k_{\rm NL} \sim 10 \,\rm Mpc$
		- \implies an effective fluid-like system with mean free path \sim θ fluid-like system with mean free nath \approx 1/ k_{max} \implies an effective fluid-like system with mean free path $\sim 1/k_{\rm NL}$ *s* $\frac{1}{\sqrt{2}}$ $\frac{1}{\sqrt{2$ $1/k_\mathrm{NL}$
- Baryons heat due to star formation, but move the same: r formation, but move the same. ons heat
- $-$ Universe with CDM+Baryons \implies EFTofLSS with 2 specie **example 18**
k
k
k
c
k
c
c
f
f M+Baryons \implies EFTofLSS with 2 specie \implies EFTofLSS with 2 specie

Baryons

• EFT Equations:

Continuity:
$$
\dot{\rho}_{\sigma} + 3H\rho_{\sigma} + a^{-1}\partial_i \pi_{\sigma}^i = 0
$$
,
\nMomentum: $\dot{\pi}_c^i + 4H\pi_c^i + a^{-1}\partial_j \left(\frac{\pi_c^i \pi_c^j}{\rho_c}\right) + a^{-1}\rho_c \partial_i \Phi = +a^{-1}\gamma^i - a^{-1}\partial_j \tau_c^{ij}$,
\n $\dot{\pi}_b^i + 4H\pi_b^i + a^{-1}\partial_j \left(\frac{\pi_b^i \pi_b^j}{\rho_b}\right) + a^{-1}\rho_b \partial_i \Phi = -a^{-1}\gamma^i - a^{-1}\partial_j \tau_b^{ij}$.

Baryons

• EFT Equations:

Continuity:
$$
\dot{\rho}_{\sigma} + 3H\rho_{\sigma} + a^{-1}\partial_i \pi_{\sigma}^i = 0
$$
,
\nMomentum: $\dot{\pi}_c^i + 4H\pi_c^i + a^{-1}\partial_j \left(\frac{\pi_c^i \pi_c^j}{\rho_c}\right) + a^{-1}\rho_c \partial_i \Phi = \left(\frac{a^{-1}\gamma^i}{\rho_c^i}\right) + a \left(\frac{1}{\rho_f^i \sigma_c^i}\right)$
\n $\dot{\pi}_b^i + 4H\pi_b^i + a^{-1}\partial_j \left(\frac{\pi_b^i \pi_b^j}{\rho_b}\right) + a^{-1}\rho_b \partial_i \Phi = \left(\frac{a^{-1}\gamma^i}{\rho_c^i}\right) + a^{-1}\partial_j \pi_b^{ij}$.
\ndynamical friction effective force
\n $\Phi = \Phi$
\n $\Phi = \Phi$

perature operator

A marginal operator

• Dynamical friction term is indeed needed for renormalization of the theory, i.e. it is generated.

• Dynamical friction is a relevant operator: i.e. it cannot be treated perturbatively: it is an essential part of the linear *equations:*

$$
a^2 \delta_I^{(1)\prime\prime}(a,\vec{k}) + \left(2 + \frac{aH'(a)}{\mathcal{H}(a)}\right) a\delta_I^{(1)\prime}(a,\vec{k}) = \int^a d\mu_1 g(a,a_1) a_1 \delta_I^{(1)\prime}(a_1,\vec{k}) .
$$

–due to the time-translation breaking and actually even non-locality, very very very very very very hard to handle consistently.

• we can make some guesses

• Luckily: it only affect the decaying mode of the isocurvature, which is very very very very very small by the time this effect kicks in.

Predictions for CMB Lensing

• Baryon corrections are detectable in next CMB S-4 experiments. But we can predict it:

Bispectrum at one loop

with D'Amico, Donath, Lewandowski, Zhang **2206**

Bispectrum

• The tree level bispectrum had been already used for cosmological parameter analysis in

with Guido D'Amico, Jerome Gleyzes, Nickolas Kockron, Dida Markovic, Pierre Zhang, Florian Beutler, Hector Gill-Marin **1909**

Philcox, Ivanov **2112**

- ~10% improvement on A_s A_s
- Time to move to one-loop:
	- –Large effort:
		- data analysis with D'Amico, Donath, Lewandowski, Zhang 2206
		- theory model with D'Amico, Donath, Lewandowski, Zhang JCAP 2024
		- theory integration with Anastasiou, Braganca, Zheng **JHEP 2024**

Data Analysis ACDM

- Main result: $\Lambda{\rm CDM}$
	- Improvements:
	- 30\% on σ_8
	- 18% on h
	- 13\% on Ω_m

- Compatible with Planck –no tensions
- Often Planck Comparable

Data Analysis Non-Gaussianities

with D'Amico, Lewandowski, Zhang **2201**

with Cheung *et al.* **2008**

Theory Model with D'Amico, Donath, Lewandowski, Zhang **²²⁰⁶**

• We add all the relevant biases (4th order) and counterterms (2nd order):

$$
P_{11}^{r,h}[b_1], P_{13}^{r,h}[b_1, b_3, b_8], P_{22}^{r,h}[b_1, b_2, b_5],
$$

\n
$$
B_{211}^{r,h}[b_1, b_2, b_5], B_{321}^{r,h,(II)}[b_1, b_2, b_3, b_5, b_8], B_{411}^{r,h}[b_1, \ldots, b_{11}],
$$

\n
$$
B_{222}^{r,h}[b_1, b_2, b_5], B_{321}^{r,h,(I)}[b_1, b_2, b_3, b_5, b_6, b_8, b_{10}],
$$

$$
P_{13}^{r,h,ct}[b_1, c_{h,1}, c_{\pi,1}, c_{\pi v,1}, c_{\pi v,3}], P_{22}^{r,h,\epsilon}[c_1^{\text{St}}, c_2^{\text{St}}, c_3^{\text{St}}],
$$

\n
$$
B_{321}^{r,h,(II),ct}[b_1, b_2, b_5, c_{h,1}, c_{\pi,1}, c_{\pi v,1}, c_{\pi v,3}], P_{321}^{r,h,\epsilon,(I)}[b_1, c_1^{\text{St}}, c_2^{\text{St}}, \{c_i^{\text{St}}\}_{i=4,\ldots,13}],
$$

\n
$$
B_{411}^{r,h,ct}[b_1, \{c_{h,i}\}_{i=1,\ldots,5}, c_{\pi,1}, c_{\pi,5}, \{c_{\pi v,j}\}_{j=1,\ldots,7}], P_{222}^{r,h,\epsilon}[c_1^{(222)}, c_2^{(222)}, c_5^{(222)}].
$$

- IR-resummation:
	- For the power spectrum, we use the correct and controlled IR-resummation.
	- For the bispectrum, we use an approximate method Ivanov and Sibiryakov **2018**

Derivation of theory model

with D'Amico, Donath, Lewandowski, Zhang **2211**

Derivation of theory model vith D'Amico, Donath, Lewandowski, Zhang **2211** *^vk*]*^R* ! [*vⁱ* Derivation of theory model 2211]*Rk^l* + 5 perms.) of theory model $\frac{with D'Amic}{2211}$ *j k^l .*

- Counterterms: major algebraic effort for 4th order and some theoretical subtle aspects. • Counterterms: major algebraic effort for 4th order and some theoretical subtle aspects.
- Renormalization of velocity ization of velocity \bullet **Deparmalization of velocity**
- In the EFTofLSS, the velocity is a composite operator $v^i(x) = \frac{\mu(x)}{\rho(x)}$, so, it possible is a sequence of iterational m the ET TOLESS, the verse
needs to be renormalized: τ to ρ write σ ones to write in terms of the non-renormalized the non-renormalized $\pi^i(x)$ $\frac{1}{\sqrt{2}}$ • In the EFTofI SS the velocity is a composite operator $e^{i(x)} = \pi^{i}(x)$ so it $,$ we wish to have \int \overline{S} *SS*, the velocity is]*R*[*v^j*]*^R* ⁺ *^Oij ^v*² *,* where *^Oij*

$$
v^i(x) = \frac{\pi^i(x)}{\rho(x)} \quad \text{, so, it}
$$

 $\left[\gamma^{i}\right]_{R} \equiv \gamma^{i} + \hat{\gamma}^{i}$ $[v^{i}]_{R} = v^{i} + O_{v}^{i}$, $v^i_R = v^i + \mathcal{O}_v^i$ $+$ \mathcal{O} ^{*i*}

• Under a diffeomorphisms: [*vi vj ^vk*]*^R* ! [*vⁱ vj* [*vi*]*^R* ! [*vⁱ vk*]*^R* + ([*vⁱ* U nder a diffeomorphisms: were the contract of the contr [*vi vj vkv^l*

 $v^i \to v^i + \chi^i \Rightarrow \mathcal{O}_v^i$ is a scalar [*vi vj ^v*² *,* $v^{\iota} \to v^{\iota} + \chi^{\iota} \implies \mathcal{O}_{v}^{\iota}$ is a scalar $v^i \rightarrow v^i + \chi^i \Rightarrow \mathcal{O}_v^i$ is a scalar

• In redshift space, we have local product of velocities, which need to be renormalized but have non-trivial transformations under diff.s: μ ² have local product of velocities, which need to be realized to but have non-trivial transformations under diff.s: In redshift space, we have local product of velocities, which need to be renormalized]*Rk^l* + 5 perms.) *k₁ permits:* $\frac{1}{2}$ *permits:* $\frac{1}{2}$ *permi* shift space, we have local product of velocities, which need to be renormalized

 $[v^iv^j]_R \rightarrow [v^iv^j]_R + [v^i]_R \chi^j + [v^j]_R \chi^i + \chi^i \chi^j$ fields is $\frac{1}{2}$ Γ is the renormalized variety satisfying the satisfying the satisfying the $\Lambda \Lambda$ that other operators could have been used that are not independent from the ones shown, like the ones shown, l
The ones shown, like that are not independent from the ones shown, like the ones shown, like the ones shown, l

• To achieve this, one can do: (so must include products $v^i \cdot \mathcal{O}_v^i$) \overline{C} \overline{C} achieve this, one can do: (so must include products $v^i \cdot \mathcal{O}_v^i$) $[v^i v^j]_B = [v^i]_B[v^j]_B + \mathcal{O}^{ij}$, where \mathcal{O}^{ij} is a scalar + ([*vⁱ*]*R^j k^l* + 3 perms.) + *ⁱ* \overline{a} o achieve this, one can $[v^iv^j]_R = [v^i]_R[v^j]_R + \mathcal{O}_{v^2}^{ij}$, where $\mathcal{O}_{v^2}^{ij}$ is a scalar f his one $R^{i}[\hat{v}^j]_R + \hat{O}^{ij}$ v^2 ^{*/i*} • To achieve this, one can do: (so must include products $v^i \cdot \mathcal{O}_v^i$) $[v^iv^j]_R = [v^i]_R[v^j]_R + \mathcal{O}^{ij}_{v^2}$, where $\mathcal{O}^{ij}_{v^2}$ is a scalar $\frac{1}{2}$ $v^i \cdot \mathcal{O}_v^i$ $\begin{pmatrix} 2 \\ v \end{pmatrix}$

Derivation of theory model with D'Amico, Donath, Lewandowski, Zhang **2211**

- Counterterms: major algebraic effort for 4th order and some theoretical subtle aspects.
- Spatially non-locally-contributing counterterm:
	- This is a normal effect, just strange-looking in the EFTofLSS context.
	- Normally, counterterms are local, but, contributing through non-local Green's functions, they contribute non-locally.

Derivation of theory model with D'Amico, Donath, Lewandowski, Zhang **2211** with D'Amico, Donath, Lewandowski, Zhang Derivation of theory model $\frac{1}{2211}$ $\frac{1}{2211}$ **full power spectrum in the linear contribution in the linear contribution in the linear contribution in the linear power in the linear power in the linear power spectrum in the linear power specific terms in the power spe**

- Counterterms: major algebraic effort for 4th order and some theoretical subtle aspects.
	- Spatially non-locally-contributing counterterm: a density perturbation, \mathbf{a} density perturbation, \mathbf{a} and \mathbf{a} density perturbation, \mathbf{a} α -contributing counterterm: $3.2 ¹ \cdot 11$ bis pectrum in real space 11 space of 11 space 11 space of 11
		- In the EFTofLSS, the Green's function is simple: $\frac{1}{\partial^2}$ s functio $lim_{n \to \infty} \frac{1}{20}$ 1 $\frac{1}{\partial^2}$
- Counterterms typically come with $\partial^2 \mathcal{O}_{\text{local}} \Rightarrow \delta_{\text{counter}} \sim$ • result almost trivial 1 • Counterterms typically come with $\partial^2 \mathcal{O}_{\text{local}} \Rightarrow \delta_{\text{counter}} \sim \frac{1}{\partial^2} \partial^2 \mathcal{O}_{\text{local}} \sim \mathcal{O}_{\text{local}}$ ^ˆ*^j* @*i*@*j*@*k*@*^m* Counterterms typically come with $\partial^2 \mathcal{O}_{local} \Rightarrow \delta_{counter} \sim \frac{1}{\partial^2} \partial^2 \mathcal{O}_{local} \sim \mathcal{O}_{local}$
	- But at second order, and for velocity fields, contracted along the line of sight, derivatives do not simplify, so we get $\frac{1}{2}$ and for velocity fields, c $\boldsymbol{\mathsf{x}},$ contracted alon α *d*3*x* ⁰ 1 *r* (*x*) *x* $orde$ \mathbf{r} and for velocity field bntracte *g* the line of sight,

$$
\delta_{\text{counter}}(\vec{x}) \sim \hat{z}^i \hat{z}^j \partial_i \pi^j_{(2)}(\vec{x}) \sim \hat{z}^i \hat{z}^j \frac{\partial_i \partial_j \partial_k \partial_m}{\partial^2} \mathcal{O}_{\text{local}}
$$

$$
\sim \hat{z}^i \hat{z}^j \frac{\partial_i \partial_j \partial_k \partial_m}{\partial^2} \left(\frac{\partial_k \partial_l}{H^2} \Phi(\vec{x}) \frac{\partial_l \partial_m}{H^2} \Phi(\vec{x}) \right)
$$

- This is truly non-locally contributing, truly non-trivial. s is trury non-locally contributing, trury non-trivial. But the wave contributions contribute to the contributio ^ˆ*^j* @*i*@*j*@*k*@*^m*
- We check that all these terms are *needed and sufficient* for renormalization check that all these terms are *needed and sufficient* for renormalization **The 11/2 does in the 1**/2 does not the final explored in the final expression of the contribution of the contribution

Evaluational/Computational Challenge

with Anastasiou, Braganca, Zheng **2212**

The best approach so far

- Nice trick for fast evaluation of the loops integrals • Nice trick for fast evaluation of the loops integrals
- The power spectrum is a numerically computed function • The power spectrum is a numerically computed function \mathbb{E} is the substitution \mathbb{E} regmark et al. 2002
- Decompose linear power spectrum $\frac{1}{2}$

$$
P_{11}(k) = \sum_{n} c_n k^{\mu + i\alpha n}
$$

• Loop can be evaluated analytically *P*12000 μ **D** μ **EV** μ anary*u* \mathbf{C}^{\prime}

$$
P_{1-\text{loop}}(k) = \int_{\vec{q}} K(\vec{q}, \vec{k}) P_{11}(k-q) P_{11}(q) =
$$

=
$$
\sum_{n_1, n_2} c_{n_1} c_{n_2} \left(\int_{\vec{q}} K(\vec{q}, \vec{k}) k^{\mu + i\alpha n_1} k^{\mu + i\alpha n_2} \right) = \sum_{n_1, n_2} c_{n_1} c_{n_2} M_{n_1, n_2}(k)
$$

- $-$ using quantum field theory techniques here, to keep it simple).]]]
	- $-M_{n_1n_2}$ is cosmology independent \Rightarrow so computed once \hat{M} is cosmology independent \rightarrow so computed once wang manang ma
Manang manang man $M_{n_1 n_2}$ is cosmology independent \Rightarrow so computed once

Computational Challenge

Philcox, Ivanov, Cabass, Simonovic*,* Zaldarriaga **2022**

• Two difficulties: $\frac{1}{2}$

$$
P_{1-\text{loop}}(k) = \int_{\vec{q}} K(\vec{q}, \vec{k}) P_{11}(k-q) P_{11}(q) =
$$

=
$$
\sum_{n_1, n_2} c_{n_1} c_{n_2} \left(\int_{\vec{q}} K(\vec{q}, \vec{k}) k^{\mu + i\alpha n_1} k^{\mu + i\alpha n_2} \right) = \sum_{n_1, n_2} c_{n_1} c_{n_2} M_{n_1, n_2}(k)
$$

- integrals are complicated due to fractional, complex exponents
- many functions needed, the matrix $M_{n_1 n_2 n_3}$ for bispectrum is about 50Gb, so, ~impossible to load on CPU for data analysis With the results of \mathbb{R}^3 the EFTofLSS became ready to became ready to data, in particular to data, in particular to the EFTs became ready to data, in particular to the EFTs became ready to the EFTs became ready to t ctions needed the matrix M_{max} for hispectrum is about 50Gb so chons necuea, the matrix e to load on CPU for data analysis $\overline{}$ *^k* ⇠ const (6)

• In order to ameliorate (solve) these issues, we use a different basis of functions. \bullet In order to ameliorate (solve) these issues we use a different hasis of functions

Complex-Masses Propagators

with Anastasiou, Braganca, Zheng **2212**

• Use as basis: • With just 16 functions: $f(k^2, k_{\text{peak}}^2, k_{\text{UV}}^2, i, j) \equiv$ (k^{2}/k_{0}^{2}) *i* $\sqrt{2}$ $1 + \frac{(k^2 - k_{\rm peak}^2)^2}{k^4}$ $\left(\frac{k_{\text{peak}}^2}{k_{\text{UV}}^4}\right)^2$ ^j, where *k*0, *k*² peak and *k*² 10^4 *^j* are positive integers, with *ⁱ ^j*. We define *^fn*(*k*2) ⌘ *^f*(*k*2*, k*² peak*,n, k*² UV*,n, in, jn*) and use ²⁰*h/*Mpc. The cosmology dependence is encoded in the fitting coecients ↵*n*. *N* is the $\frac{1000}{2}$ for $\frac{1}{2}$ and $\frac{1}{2}$ and *f* as vectors whose *n*-th entry is given, respectively, by the elements ↵*ⁿ* and *fn*. Note $100\frac{1}{5}$ \longrightarrow P_{li} $\frac{30}{\rho}$ ---- P_{fit} ↵ = (*X^T X*) 1*X^T P* lin *,* (2.3) P_{lin} 50 ----- P_{fit} $100 \frac{1}{5}$ 500 $|1000 \}$ 5000 10^4 $P(k)$ 0.001 0.005 0.010 0.050 0.100 0.500 1 $-0.04\frac{5}{5}$ -0.02 0.00 0.02 0.045 $k \left[h/\text{Mpc} \right]$ \blacktriangleleft P/P

COMPICX-MASSES FIOPAGALOIS 2212 Complex-Masses Propagators with Anastasiou, Braganca, Zheng

even if the fit is only performed up to 0*.*6 *h* Mpc¹ , the error is within 5% up to 1 *h* Mpc¹ . propagator-like functions by decomposing the decomposing the following $\mathbf{F}_{\mathbf{d}}$ **2212**

• This basis is equivalent to massive propagators to integer powers basis is equivale uivalent to

¹ $\frac{1}{2}$ **SS** *k* ive propagators to integer powers
 $\frac{1}{2}$ $\frac{4}{3}$

$$
\frac{1}{\left(1+\frac{(k^2-k_{\text{peak}}^2)^2}{k_{\text{UV}}^4}\right)^j} = \frac{k_{\text{UV}}^{4j}}{\left(k^2-k_{\text{peak}}^2-i k_{\text{UV}}^2\right)^j \left(k^2-k_{\text{peak}}^2+i k_{\text{UV}}^2\right)^j},
$$
\n
$$
\frac{k_{\text{UV}}^2}{\left(k^2-k_{\text{peak}}^2-i k_{\text{UV}}^2\right)\left(k^2-k_{\text{peak}}^2+i k_{\text{UV}}^2\right)} = -\frac{i/2}{k^2-k_{\text{peak}}^2-i k_{\text{UV}}^2} + \frac{i/2}{k^2-k_{\text{peak}}^2+i k_{\text{UV}}^2}
$$

• So, each basis function: σ SO, each basis function. • So, each basis function

$$
f(k^2, k_{\text{peak}}^2, k_{\text{UV}}^2, i, j) = \sum_{n=1}^j k_{\text{UV}}^{2(n-i)} k^{2i} \left(\frac{\kappa_n}{(k^2 + M)^n} + \frac{\kappa_n^*}{(k^2 + M^*)^n} \right)
$$

COMPICX-MASSES FIOPAGALOIS 2212 Complex-Masses Propagators

even if the fit is only performed up to 0*.*6 *h* Mpc¹ , the error is within 5% up to 1 *h* Mpc¹ . propagator-like functions by decomposing the decomposing the following $\mathbf{F}_{\mathbf{d}}$ with Anastasiou, Braganca, Zheng **2212**

• This basis is equivalent to massive propagators to integer powers basis is equivale $\frac{1}{2}$ **SS** *k* ive propagators to integer powers
 $\frac{1}{2}$ $\frac{4}{3}$

• This basis is equivalent to massive propagators to integer powers
\n
$$
\frac{1}{\left(1+\frac{(k^2-k_{\text{peak}}^2)^2}{k_{\text{UV}}^4}\right)^j} = \frac{k_{\text{UV}}^{4j}}{\left(k^2-k_{\text{peak}}^2-i\,k_{\text{UV}}^2\right)^j\left(k^2-k_{\text{peak}}^2+i\,k_{\text{UV}}^2\right)^j},
$$
\n
$$
\frac{k_{\text{UV}}^2}{\left(k^2-k_{\text{peak}}^2-i\,k_{\text{UV}}^2\right)\left(k^2-k_{\text{peak}}^2+i\,k_{\text{UV}}^2\right)} = \left(\frac{i/2}{k^2-k_{\text{peak}}^2-i\,k_{\text{UV}}^2} + \frac{i/2}{k^2-k_{\text{peak}}^2+i\,k_{\text{UV}}^2}\right)
$$
\n
$$
\frac{k_{\text{UV}}^2}{\text{Complex-Mass propagator}}
$$

Complex-with propagators with the right hand side of the right hand side (*r.h.s.)* or Eq. (2.6). The right hand side (*r.h.s.)* or Eq. (*r.h.s.)* or Complex-Mass propagator

• So, each basis function: σ SO, each basis function. • So, each basis function

$$
f(k^2, k_{\text{peak}}^2, k_{\text{UV}}^2, i, j) = \sum_{n=1}^j k_{\text{UV}}^{2(n-i)} k^{2i} \left(\frac{\kappa_n}{(k^2 + M)^n} + \frac{\kappa_n^*}{(k^2 + M^*)^n} \right)
$$

C compression we wave the expression of the expression of the some arguments of the some arguments design that is a non- \overline{a} and \overline{b} \overline{c} and \overline{b} and \overline{b} and \overline{a} and \overline{a} \overline{c} \overline{d} \overline{d} \overline{d} \overline{b} \overline{c} \overline{d} \overline{d} \overline{d} \overline{d} \overline{d} \overline{d} \overline{d} \overline{d} \overline{d} \overline *Complex-Masses Propagators* 2212 Complex-Masses Propagators with Anastasiou, Braganca, Zheng section we outline the recursion relation used to reduce *L* when all *nⁱ* = 0 and all *dⁱ >* 0. We

2212

• We end up with integral like this: \sim we can up with

$$
L(n_1, d_1, n_2, d_2, n_3, d_3) = \int_q \frac{(k_1 - q)^{2n_1} q^{2n_2} (k_2 + q)^{2n_3}}{((k_1 - q)^2 + M_1)^{d_1} (q^2 + M_2)^{d_2} ((k_2 + q)^2 + M_3)^{d_3}}
$$

- with integer exponents. α ¹, with integer exponents with the general triangle integral triangle integral triangle integral named after the shape of the corresponding Feynman integral $\frac{1}{2}$
- First we manipulate the numerator to reduce to: \bullet First we manipulate the which is just *L* with all *nⁱ* = 0. We can define

$$
T(d_1, d_2, d_3) = \int_q \frac{1}{((\mathbf{k}_1 - \mathbf{q})^2 + M_1)^{d_1} (\mathbf{q}^2 + M_2)^{d_2} ((\mathbf{k}_2 + \mathbf{q})^2 + M_3)^{d_3}},
$$

• Then, by integration by parts, we find (i.e. QCD teaches us how to) recursion relations $\frac{1}{1}$. Then, by • Then, by integration by parts, we find (i.e. QC $\overline{\mathbf{r}}$

$$
\int_q \frac{\partial}{\partial q_\mu} \cdot (q_\mu t(d_1,d_2,d_3)) = 0
$$

 $\Rightarrow (3 - d_{1223})0 + d_1k_{1s}1^+ + d_3(k_{2s})3^+ + 2M_2d_22^+ - d_1$ \overline{a} ω_{\perp} ^{*n*}₁ $\Rightarrow (3 - d_{1223})\hat{0} + d_1k_{1s}\hat{1} + d_3(k_{2s})\hat{3} + 2M_2d_2\hat{2} + - d_1\hat{1} + \hat{2} - d_3\hat{2} - \hat{3} + = 0$

• relating same integrals with raised or lowered the exponents (easy terminate due to integer exponents). rals wi *·* (*k*2*µt*(*d*1*, d*2*, d*3)) = 0 *.* (4.17) same integrals with raised or lowered the exponents (easy terminate due to

resulting in *L* being a sum of master integrals, which we call Tadpole, Bubble, and Triangle Complex-Masses Propagators with Anastasiou, Braganca, Zheng

2212

• We end up to three master integrals:

• Tadpole:
\n
$$
\mathrm{Tad}(M_j, n, d) = \int \frac{d^3 \mathbf{q}}{\pi^{3/2}} \frac{(\mathbf{p}_i^2)^n}{(\mathbf{p}_i^2 + M_j)^d}
$$

• Bubble:

• Tadpole:

• Bubble:
\n
$$
B_{\text{master}}(k^2, M_1, M_2) = \int \frac{d^3 \mathbf{q}}{\pi^{3/2}} \frac{1}{(q^2 + M_1)(|\mathbf{k} - \mathbf{q}|^2 + M_2)}
$$

• Triangle: 3. Triangle:

$$
T_{\text{master}}(k_1^2, k_2^2, k_3^2, M_1, M_2, M_3) =
$$

$$
\int \frac{d^3 \mathbf{q}}{\pi^{3/2}} \frac{1}{(q^2 + M_1)(|\mathbf{k}_1 - \mathbf{q}|^2 + M_2)(|\mathbf{k}_2 + \mathbf{q}|^2 + M_3)},
$$

Complex-Masses Propagators 2212 with Anastasiou, Braganca, Zheng Complex-Masses Propagators with Anastasiou, Braganca, Zheng **2212**

- The master integrals are evaluated with Feynman parameters, but with great care of branch cut crossing, which happens because of complex masses. The master integrals are evaluated with Feynman parameters, but with great care of branch cut crossing, which happens because of complex masses. *B*
als are evaluated with Fevnman parameters, but with great care of evaluated with Feynman parameters, but with great care of *Find Histor History R2* n happe ^p*|R*2*[|]* ^p(*z*⁺ *^x*) ^p(*^x ^z*)(*^x ^x*0) *.* (5.84)
	- Bubble Master:

• **Bubble Master:**
\n
$$
B_{\text{master}}(k^2, M_1, M_2) = \frac{\sqrt{\pi}}{k} i [\log (A(1, m_1, m_2)) - \log (A(0, m_1, m_2))
$$
\n
$$
- 2\pi i H(\text{Im } A(1, m_1, m_2))H(-\text{Im } A(0, m_1, m_2))],
$$
\n
$$
A(0, m_1, m_2) = 2\sqrt{m_2} + i(m_1 - m_2 + 1),
$$
\n
$$
A(1, m_1, m_2) = 2\sqrt{m_1} + i(m_1 - m_2 - 1),
$$
\n
$$
m_1 = M_1/k^2 \text{ and } m_2 = M_2/k^2
$$

• Triangle Master:
\n
$$
F_{\rm int}(R_2, z_+, z_-, x_0) = s(z_+, -z_-) \frac{\sqrt{\pi}}{\sqrt{|R_2|}} \frac{\arctan\left(\frac{\sqrt{z_+} - x\sqrt{x_0 - z_-}}{\sqrt{x_0 - z_+}\sqrt{x_0 - z_-}}\right)}{\sqrt{x_0 - z_+}\sqrt{x_0 - z_-}} \Big|_{x=0}^{x=1}.
$$

. (5.88)

• Very simple expressions with simple rule for branch cut crossing. provided that the condition (Re(*m*1)*,* Re(*m*2))*>* 0 is satisfied. This interesting observation • Very simple expressions with simple rule for branch cut crossing. ^p*x*(1 *^x*) + *^m*1*^x* ⁺ *^m*2(1 *^x*) + *ⁱ*(*m*¹ *^m*² ²*^x* + 1)*,* (5.24) • Very simple expressions with simple rule for branch cut crossing indeterminacies. We now outline how to incorporate possible branch cut crossings, and later possible branch cu
Incorporate possible branch cut crossings, and later possible branch cut crossings, and later possible branch

Result of Evaluation

with Anastasiou, Braganca, Zheng **2212**

- All automatically coded up.
- For BOSS analysis, evaluation of matrix is 2.5CPU hours and 800 Mb storage, very fast matrix contractions.
- Accuracy with 16 functions:

Back to data-analysis: Pipeline Validation

Scale cut from NNLO with D'Amico, Donath, Lewandowski, Zhang 2206

• We can estimate the k_{max} without the use of simulations, by adding NNLO terms, and seeing when they make a difference on the posteriors.

$$
P_{NNLO}(k,\mu) = \frac{1}{4} c_{r,4} b_1^2 \mu^4 \frac{k^4}{k_{NL,R}^4} P_{11}(k) + \frac{1}{4} c_{r,6} b_1 \mu^6 \frac{k^4}{k_{NL,R}^4} P_{11}(k) ,
$$

\n
$$
B_{NNLO}(k_1, k_2, k_3, \mu, \phi) = 2 c_{NNLO,1} K_2^{r,h}(\vec{k}_1, \vec{k}_2; \hat{z}) K_1^{r,h}(\vec{k}_2; \hat{z}) f \mu_1^2 \frac{k_1^4}{k_{NL,R}^4} P_{11}(k_1) P_{11}(k_2)
$$

\n
$$
+ c_{NNLO,2} K_1^{r,h}(\vec{k}_1; \hat{z}) K_1^{r,h}(\vec{k}_2; \hat{z}) P_{11}(k_1) P_{11}(k_2) f \mu_3 k_3 \frac{(k_1^2 + k_2^2)}{4k_1^2 k_2^2 k_{NL,R}^4} \Big[-2 \vec{k}_1 \cdot \vec{k}_2 (k_1^3 \mu_1 + k_2^3 \mu_2) + 2 f \mu_1 \mu_2 \mu_3 k_1 k_2 k_3 (k_1^2 + k_2^2) \Big] + \text{perm.} ,
$$

• For our k_{max} , we find the following shifts, which are ok:

Scale-cut from simulations with D'Amico, Donath, Lewandowski, Zhang 2206

Scale-cut from simulations with D'Amico, Donath, Lewandowski, Zhang 2206

- Patchy:
	- Volume ~2000 BOSS *P*
	- safely within $\sigma_{\text{data}}/3$
- After phase-space correction

BOSS data

Data Analysis ACDM

- Main result: $\Lambda{\rm CDM}$
	- Improvements:
	- 30\% on σ_8
	- 18% on h
	- 13\% on Ω_m

- Compatible with Planck –no tensions
- Remarkable consistency –of observables

Data Analysis Non-Gaussianities

with D'Amico, Lewandowski, Zhang **2201**

Comment on Large non-Gaussianities

with Donath **in progress**

 $(\partial \phi)^2 + \frac{(\partial \phi)^4}{\Lambda}$

 Λ^4

- Emerged that we can continue probing large non-Gaussianities. thanks to LSS
- Are they viable?
- Large non-Gaussianities means that breaking of Lorentz invariance is strong: inflationary solution is non-perturbatively far from the Lorentz invariant vacuum.
	- Slow-roll inflation is when the solution is close.
- Explains why hard to find solutions with large non-Gaussianities.
	- $-\sim$ as discovering liquid Helium out of the standard model Lagrangian

source Wikipedia

–Easier to discover the EFT for the fluctuations (and indeed this is the EFTofI)

• To have
\n
$$
S_{\pi} = \int d^4 \sqrt{-g} \left[\frac{\dot{H} M_{\rm Pl}^2}{c_s^2} \left(\dot{\pi}^2 - c_s^2 (\partial_i \pi)^2 \right) + \frac{\dot{H} M_{\rm Pl}^2}{c_s^2} \left[\dot{\pi} (\partial_i \pi)^2 + \tilde{c}_3 \dot{\pi}^3 \right] \right]
$$
\n
$$
f_{\rm NL}^{\rm equil}, f_{\rm NL}^{\rm orthog} \gtrsim 1 \iff \left(\Lambda_{\rm cutoff}^{\rm EFT} \right)^4 \lesssim \dot{H} M_{\rm Pl}^2
$$

Comment on Large non-Gaussianities

with Donath **in progress**

• Is it so hard?

–At field theory level, there are two models that can derive the inflationary solution out of the Lorentz invariant vacuum:

• slow roll inflation

$$
(\partial \phi)^2 + \frac{(\partial \phi)^4}{\Lambda^4}
$$

$$
\sqrt{1 - \frac{(\partial \phi)^2}{\Lambda^4}}
$$

- DBI inflation
- At string-theory level
	- unclear if one is better than the other h and h a at h and h

• Summary: I do not currently see any theoretical prejudice towards the fact that inflation should have small non-Gaussianities

–as much as I have no theoretical prejudice against the existence on liquid helium, though it is harder to find.

No tensions?!

No Tensions!!

with Pierre Zhang, Guido D'Amico, Cheng Zhao, Yifu Can 2110 0*.*⁰⁰⁶⁷ ⁰*.*⁶⁷⁷⁶ *[±]* ⁰*.*⁰⁰⁴⁶ ⁰*.*⁶⁷⁸⁰ *[±]* ⁰*.*⁰⁰⁴³ with Pierre Zhang, Guido D'Amico, Cheng Zhao, Yifu Can 2110 0*.*⁰¹⁵⁰ ⁰*.*³⁰⁹⁷ *[±]* ⁰*.*⁰⁰⁶⁰ ⁰*.*³⁰⁹⁰ *[±]* ⁰*.*⁰⁰⁵⁶

The Hubble Tension as of yesterday

How fast is the universe expanding? Scientists can't agree-and that's a problem

CMB with Planck
- SILERT LACT : 57,49 + 0.53

Balkenhol et al. (2021), Planck 2018+SPT+ACT: 67.49 ± 0.53 Pogosian et al. (2020), eBOSS+Planck Ω_m H²: 69.6 ± 1.8
Pogosian et al. (2020), eBOSS+Planck Ω_m H²: 69.6 ± 1.8
Aghanim et al. (2020), Planck 2018: 67.27 ± 0.60 Ade et al. (2016), Planck 2015, $H_0 = 67.27 \pm 0.66$

 \bullet .

CMB without Planck

Dutcher et al. (2021), SPT: 68.8 ± 1.5
Aiola et al. (2020), ACT: 67.9 ± 1.5 Aiola et al. (2020), WMAP9+ACT: 67.6 ± 1.1 Zhang, Huang (2019), WMAP9+BAO: 68.36+0.53
2.Ehang, Huang (2019), WMAP9+BAO: 68.36+0.53
2.2.Etinshaw et al. (2013), WMAP9: 70.0 ± 2.2

No CMB, with BBN

D'Amico et al. (2020), BOSS DR12+BBN: 68.5 ± 2.2
Colas et al. (2020), BOSS DR12+BBN: 68.7 ± 1.5 Philcox et al. (2020), $P_t + BAO + BBN$: 68.6 ± 1.1 Ivanov et al. (2020). ROSS+BBN: 67.9 + 1.1 Alam et al. (2020), BOSS+eBOSS+BBN: 67.35 ± 0.97

$P₁(k) + CMB$ lensing

Philcox et al. (2020), $P_1(k)$ +CMB lensing: 70.6 $^{+3.7}_{-5.0}$

Cepheids - SNIa

Riess et al. (2020), R20: 73.2 \pm 1.3
Breuval et al. (2020): 72.8 \pm 2.7 Riess et al. (2020), R20: 73.2 ± 1.3
Breuval et al. (2020): 72.8 ± 2.7
Riess et al. (2019), R19: 74.0 ± 1.4 –
Camarena, Marra (2019): 75.4 ± 1.7 Riess et al. (2019), R19: 74.0 ± 1.4
Camarena, Marra (2019): 75.4 ± 1.7
Burns et al. (2018): 73.2 ± 2.3 Dhawan, Jha, Leibundgut (2017), NIR: 72.8 ± 3.1 Follin, Knox (2017): 73.3 ± 1.7
Feeney, Mortlock, Dalmasso (2017): 73.2 ± 1.8 Riess et al. (2016), R16: 73.2 \pm 1.7 – Cardona, Kunz, Pettorino (2016), HPs: 73.8 ± 2.1
Freedman et al. (2012): 74.3 ± 2.1

TRGB - SNIa

Soltis, Casertano, Riess (2020): 72.1 \pm 2.0 Solids, Caservallo, Niess (2020): 69.6 ± 1.9
- Freedman et al. (2020): 69.6 ± 1.9
- Freedman et al. (2019): 69.8 ± 1.9
- Freedman et al. (2019): 69.8 ± 1.9 Yuan et al. (2019): 72.4 \pm 2.0 Jang, Lee (2017): 71.2 ± 2.5

Miras - SNIa Huang et al. (2019): 73.3 ± 4.0

Masers

Pesce et al. (2020): 73.9 ± 3.0

Tully - Fisher Relation (TFR) Kourkchi et al. (2020): 76.0 ± 2.6
Schombert, McGaugh, Lelli (2020): 75.1 ± 2.8

Surface Brightness Fluctuations Blakeslee et al. (2021) IR-SBF w/ HST: 73.3 ± 2.5

Khetan et al. (2020) w/ LMC DEB: 71.1 ± 4.1

de Jaeger et al. (2020): 75.8^{+5.2}

HII galaxies Fernández Arenas et al. (2018): 71.0 ± 3.5

Lensing related, mass model - dependent -

Denzel et al. (2021): 71.8⁺³³
rer et al. (2020), TDCOSMO+SLACS: 67.4⁺⁴³/₂, TDCOSMO: 74.5⁺²⁴³
Yang, Birrer, Hu (2020): 74.5⁺²⁴³
Millon et al. (2020): 73.5+5²³
Millon et al. (2020), TDCOSMO: 74.2+1.6
Baxter et al $Qi et al. (2020): 73.6^{+1.8}_{-1.6}$

Liao et al. (2020): 73.6 $^{+1.8}_{-1.6}$

Liao et al. (2029): 72.8 $^{+1.8}_{-2.7}$

Shajib et al. (2019), STRIDES: 74.2 $^{+2.7}_{-1.7}$

Wong et al. (2019), HOLICOW 2019: 73.3 $^{+1.9}_{-1.7}$

Wong et a Birrer et al. (2018), HOLICOW 2018: 72.5⁺²
Bonvin et al. (2018), HOLICOW 2018: 72.5⁺²

Optimistic average

Valentino (2021): 72.94 ± 0.75
ra – conservative, no Cepheids, no lensing entino (2021): 72.7 ± 1

GW related

Gayathri et al. (2020), GW190521+GW170817: 73.4+69
Mukherjee et al. (2020), GW170817+ZTF: 67.6+4:
Mukherjee et al. (2019), GW170817+VLBI: 68.3+4: Abbott et al. (2017), GW170817: 70.0 $^{+12}_{-81}$
JWST sheds light

• 3 methods

• Most important:

- Cepheids are systematically offset
	- wrt JAGB
- $-I$ do find Riess et al, 2024 addresses this
- To me, they should address/decide on these systematics.

Direct Measurement of formation time of galaxies

with Donath and Lewandowski **2307**

Galaxies in the EFT of LSS
\n
$$
n_{\text{gal}}(x) = f_{\text{very complicated}} \left(\{H, \Omega_m, \dots, m_e, g_{ew}, \dots, \rho(x) \}_{\text{past light cone}} \right)
$$
\nAt long wavelengths
\n
$$
\left(\frac{\delta n}{n} \right)_{\text{gal},\ell} (x) \sim \int^t dt' \left[c(t, t') \left(\frac{\delta \rho}{\rho} \right) (\vec{x}_n, t') + \dots \right]
$$
\n• all terms allowed by symmetries
\n• all physical effects included
\n–e.g. assembly bias
\n•
\n
$$
\left(\left(\frac{\delta n}{n} \right)_{\text{gal},\ell} (x) \left(\frac{\delta n}{n} \right)_{\text{gal},\ell} (y) \right) =
$$
\n
$$
\sum_{n=1}^{\infty} \sum_{n=1}^{\infty} \binom{n}{n} \binom{n}{n}
$$

- all terms allowed by symmetries \sim h*n*gal(~ • all terms allowed by symmetries
- all physical effects included an physical effects included
 $-e \sigma$ assembly bias *x*) + @*xⁱ T*(*t,* ~
	- $-e.g.$ assembly bias

$$
\left\langle \left(\frac{\delta n}{n} \right)_{\text{gal},\ell} (x) \left(\frac{\delta n}{n} \right)_{\text{gal},\ell} (y) \right\rangle =
$$
\n
$$
= \sum_{n} \text{Coeff}_n \cdot \left\langle \text{matter correlation function} \right\rangle_n
$$
\n
$$
\left\langle \left(\frac{\delta n}{n} \right)_{\text{gal},\ell} (x) \left(\frac{\delta n}{n} \right)_{\text{gal},\ell} (y) \right\rangle
$$

Consequences of non-locality in time ϵ **Consequence** *n*=1 where the expression at $\frac{1}{2}$ and $\frac{1}{2}$ order is given by the non- $\cos \theta$ the gas \int the gas \int can differ the times sequences of hon-focality in this \mathbf{Con} the remaining case **n** \mathbf{r} **1** \mathbf ences of non-locality in time

- Mathematics again: *Notes* We work in the Newtonian approxima**o** Mathematics again:
- non-local in time: \overline{a} for a derivative with respect to \overline{a}

• **Mathematics again:**
\n• non-local in time:
$$
\underbrace{\delta_g^{(n)}(\vec{x},t)}_{\mathcal{O}_m} = \sum_{\mathcal{O}_m} \int^t dt' H(t') c_{\mathcal{O}_m}(t,t') \times [\mathcal{O}_m(\vec{x}_H(\vec{x},t,t'),t')]^{(n)},
$$
\n
$$
\mathcal{O}_{m=3} \supset \delta^2 \theta, \delta^3, \dots
$$

• local in time:
$$
\underbrace{\delta_{g,\text{loc}}^{(n)}(\vec{x},t)}_{\mathcal{O}_m} = \sum_{\mathcal{O}_m} c_{\mathcal{O}_m}(t) \mathcal{O}_m^{(n)}(\vec{x},t),
$$

Consequences of non-locality in time

• This means that one *does not* get the same terms as in the local-in-time expansion

- If we could measure one of these terms, we could *measure* that Galaxies take an Hubble time to form. We have never measured this: we take pictures of different galaxies at different stages of their evolution. But we have never *seen* a galaxy form in an Hubble time.
	- –This would be the first direct evidence that the universe lasted an Hubble time.
- So, detecting a non-local-in-time bias would allow us to measure that, and from the size, the formation time. Unfortunately, so far, not yet.

Consequences of non-locality in time Consequen density in time. ecients and the contract of *locality in tir* $\frac{1}{2}$

$$
\delta_{g,\text{loc}}^{(n)}(\vec{x},t) = \sum_{\mathcal{O}_m} c_{\mathcal{O}_m}(t) \mathcal{O}_m^{(n)}(\vec{x},t) , \qquad \delta_g^{(n)}(\vec{x},t) = \sum_{\mathcal{O}_m} \sum_{\alpha=1}^{n-m+1} c_{\mathcal{O}_m,\alpha}(t) \mathbb{C}_{\mathcal{O}_m,\alpha}^{(n)}(\vec{x},t)
$$

- it turns out that up to 4th order, the two basis of operators were identical. *cal.* the urns out that up to 4th order, the two basis of operators were identify
- but at 5th order they are not! o but at 5th order they are not!
	- out of 29 independent operators, 3 cannot be written as local in time ones. tually straightforward, it can be practically quite cumbers, 3 cannot be written as local in time ones. ^h(5) *^g*¹ (~ *x*1)(1) *^g*² (~ *x*2)(1) *^g*³ (~ *x*3)(1) *^g*⁴ (~ *x*4)i *,* (29)
- \Rightarrow By looking at, eg, \Rightarrow By looking at, eg, \geq By looking at, eg,

 $(y^{\omega}g_5)(\omega_0)$ δ $g_{\vec{e}}$ $\frac{1}{2}$ (w_0) *^Om,*↵(~*x, t*) *,* (12) λ \rightarrow $\langle \delta_{g_1}^{(5)}(\vec{x}_1) \delta_{g_2}^{(1)}(\vec{x}_2) \delta_{g_3}^{(1)}(\vec{x}_3) \delta_{g_4}^{(1)}(\vec{x}_4) \delta_{g_5}^{(1)}(\vec{x}_5) \delta_{g_6}^{(1)}(\vec{x}_6) \rangle$

• we can detect these biases, and, from their size, determine: • we can detect these biases, and, from their *C*_m and their size, determine: where no detect these hisses and from their size determine: di↵erent tracer samples (each of which can have a di↵er-

- the order of magnitude of the formation time of galaxies - the order of magnitude of the formation time of galaxies - the order of magnitude of the formation time of galaxies

-direct evidence that the universe lasted 13 Billion years

Peeking into the next Decade

with Donath, Bracanga and Zheng **2307**

Next Decade

- After validating our technique against the MCMC's on BOSS data, we Fisher forecast for DESI and Megamapper
- Prediction of one-loop Power Spectrum and Bispectrum
- Here, and in the NG analysis, introduce a *`perturbativity prior'*: impose expected size and scaling of loop

• Also a *`galaxy formation prior'*, 0.3 in each EFT-parameter data,CMASS (grey). As an example of a typical MCMC, the BOSS CMASS *P*⁰

 $\overline{2}$ $\overline{0}$ C_4

 $\overline{2}$

Results: Non-Gaussianities

 400

 0.66

 $0.67 1.0$

 1.1

 $\overline{12}$

 $\overline{0}$

 -400

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 -1

 $\overline{0}$

 C_4

 $\overline{1}$

• Just using perturbativity prior, potentially a factor of 20, 5, 6 over Planck!!

Results: Curvature and Neutrinos BOSS:(*·*) *h* ln(10¹⁰*As*) ⌦*^m n^s* ⌦*^k* Pulte: Curvature and Neutre **P** $\frac{1}{2}$ **P** $\frac{1}{2}$ *P* $\frac{1}{2}$ *P* $\frac{1}{2}$ *<i>P* $\frac{1}{2}$ *P* $\frac{1}{2}$ *<i>P* $\frac{1}{2}$ *P* $\frac{1}{2}$ *P* $\frac{1}{2}$ *<i>P* $\frac{1}{2}$ *P* $\frac{1}{2}$ *P* $\frac{1}{2}$ *<i>P* $\frac{1}{2}$ *P* $\frac{1}{2}$ *P \frac{1}{* $D_{\text{coul-to}}$ C_{tum} of use of λ to uters of RUSU

- Just using perturbativity prior, potentially factor of 5 over Planck! turbativity prior, potentially fector of $\overline{5}$ ever D lenekl ally prior, potential
	- Important for the landscape of string theory. *,* (11)
- Neutrinos: guaranteed evidence/detection:

$$
2\sigma\ \text{DESI},\qquad 14\sigma\ \text{MegaMapper}
$$

MegaMapper *k*min = 0*.*02*h* Mpc¹ for the bispectrum, as well as *k* = 0*.*005*h* Mpc¹ for the power spectrum and *k* = 0*.*02*h* Mpc¹ for the bispectrum. Again, to reduce binning e↵ects, we evaluate on *k*e↵. to results obtained without shot noise (left) and with biases fixed or with a "galaxy-formation prior" (g.p.) (right). **P** \overline{P} **b** \overline{P} **b** \overline{P} **b** \overline{P} **b** \overline{P} **d** \overline{P}

Summary

- After the initial, successful, application to BOSS data:
	- –measurement of cosmological parameters
	- –new method to measure Hubble
	- –perhaps fixing tensions
- the EFTofLSS is starting to look ahead to
	- –higher-order and higher-n point functions
	- –enlightening what next surveys could do, and how to design them
		- an eye to BSM: primordial non-Gaussianities, neutrinos, curvature, etc..
	- –learning about some astrophysics, qualitative facts on the universe