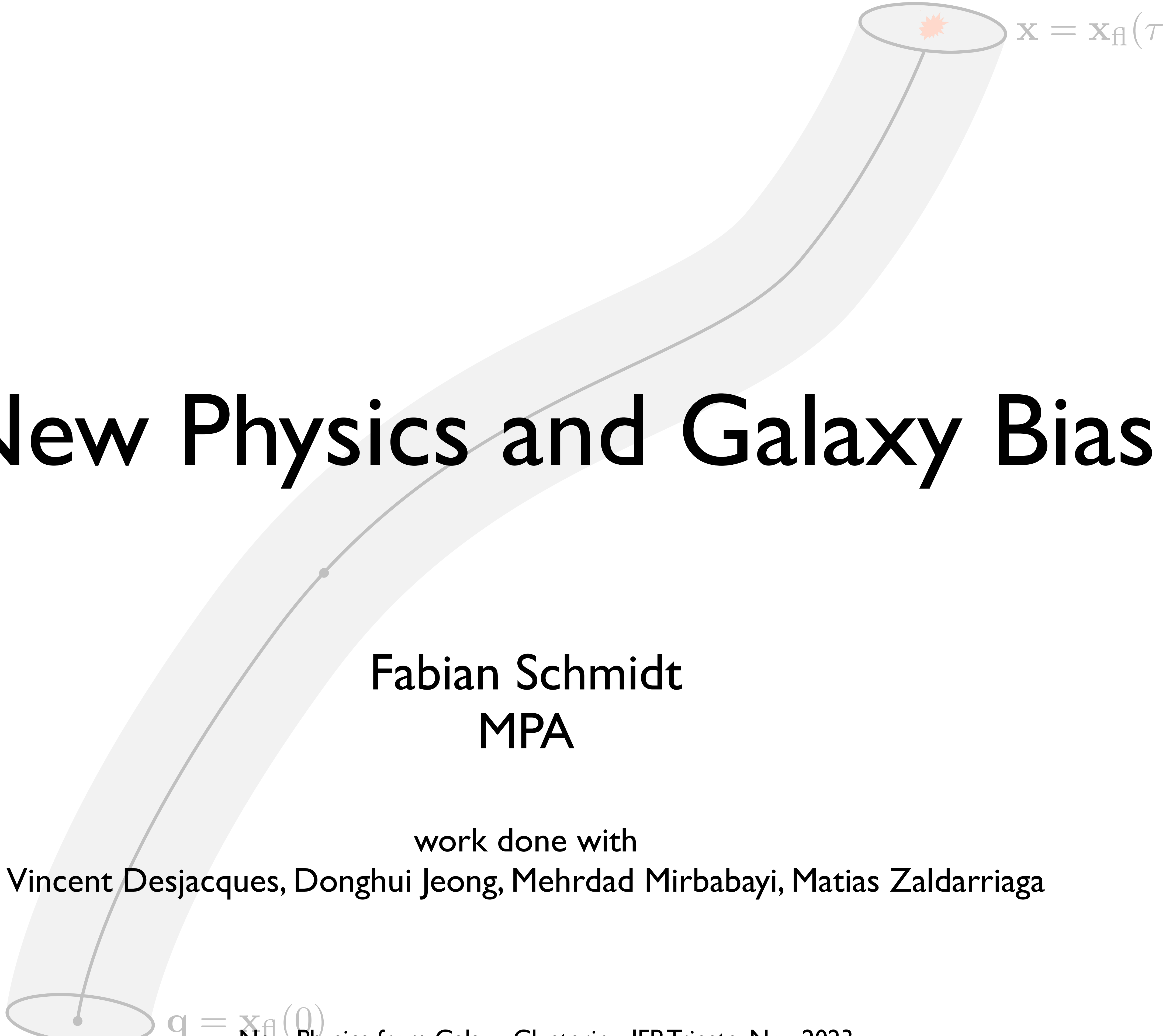


New Physics and Galaxy Bias

Fabian Schmidt
MPA

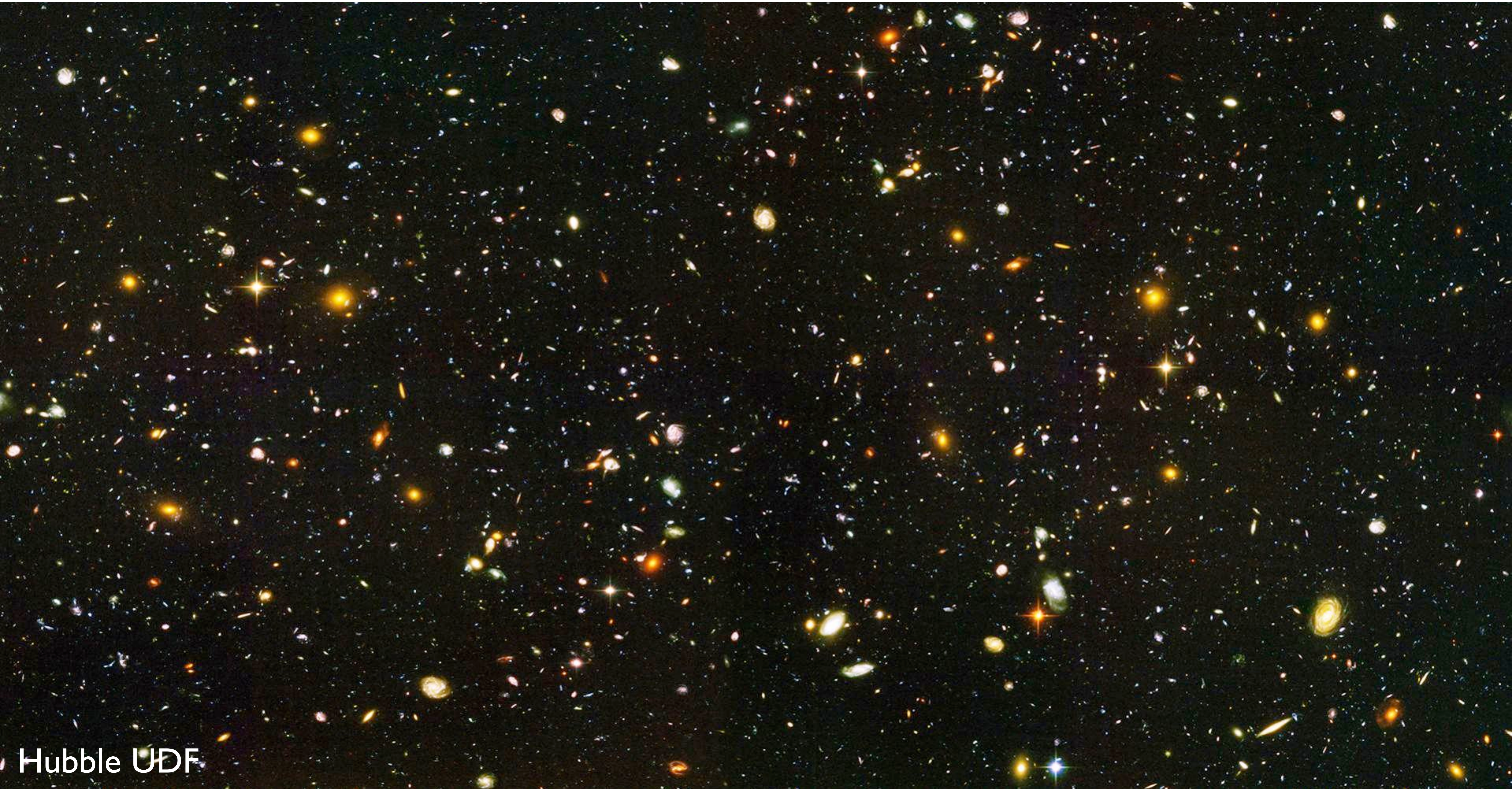
work done with
Vincent Desjacques, Donghui Jeong, Mehrdad Mirbabayi, Matias Zaldarriaga

New Physics from Galaxy Clustering, IFP Trieste, Nov 2023

Outline

- Bias expansion
  - Nonlocality in time
  - Terms and conditions
- Modified gravity
  - SEP and WEP violating
- Different species
  - Baryons
  - Neutrinos
- Caveats (other new scales)

Theory of galaxy clustering



Theory of galaxy clustering

- We cannot yet simulate the formation of galaxies* fully realistically
- Need to abstract from the incomplete understanding on small scales
  - Only hope for rigorous results is on scales $k < k_{NL}$

* Of course, everything in following will apply to any tracer of LSS.

Theory of galaxy clustering

- We cannot yet simulate the formation of galaxies* fully realistically
- Need to abstract from the incomplete understanding on small scales
  - Only hope for rigorous results is on scales $k < k_{NL}$
- Goal: describe galaxy clustering up to a given scale and accuracy using a finite number of free bias parameters b_O:

$$\delta_g(\mathbf{x}) = \sum_O b_O \, O(\mathbf{x})$$ (at fixed time)

* Of course, everything in following will apply to any tracer of LSS.

Cf. Pierre Zhang's talk

EFT approach in LSS

- Effective field theory: write down all terms (in Lagrangian or equations of motion) that are consistent with symmetries
  - Gravity: general covariance
  - Galaxy density: 0-component of 4-vector (momentum density)
- Order contributions by perturbative order, and number of spatial derivatives

EFT approach in LSS

- LSS is non-relativistic: velocities v << c
- Only relevant metric component is time-time component: gravitational potential Φ
- Relevant remaining gauge symmetries:

$$\tau \to \tau + c(\tau) \Leftrightarrow \Phi \to \Phi + C(\tau)$$

Time rescaling

$$x^i \to x^i + \xi^i(\tau) \Leftrightarrow \Phi \to \Phi + A_i(\tau) x^i$$

$$v^i \to v^i + \xi^{i\prime}(\tau)$$

Time-dependent Lorentz boost ("generalized Galilei transformation")

$$x^i \to \boldsymbol{R}^i{}_j x^j$$

Rotations

EFT bias expansion

$$\tau \to \tau + c(\tau) \Leftrightarrow \Phi \to \Phi + C(\tau)$$

$$x^i \to x^i + \xi^i(\tau) \Leftrightarrow \Phi \to \Phi + A_i(\tau) x^i$$

$$v^i \to v^i + \xi^{i\prime}(\tau)$$

$$x^i \to \boldsymbol{R}^i{}_j x^j$$

- What can (and thus has to) appear?
  - Stress-energy (matter):

$$\delta\,,\ \delta^2\,,\ \nabla^2\delta\,,\ \theta = \partial_i v^i\,,\ \frac{D\delta}{D\tau}\,,\ \cdots$$

    - But not velocity (forbidden by gauge symmetry)

$$\delta \equiv \frac{\rho_m - \bar{\rho}_m}{\bar{\rho}_m}$$

    - Time derivatives have to be convective: $\frac{D}{D\tau} = \partial_\tau + v^i \partial_i$

  - Gravity (potential):

$$\nabla^2\Phi\,,\ (\partial_i\partial_j\Phi)^2\,,\ \frac{D}{D\tau}\nabla^2\Phi\,,\ \cdots$$

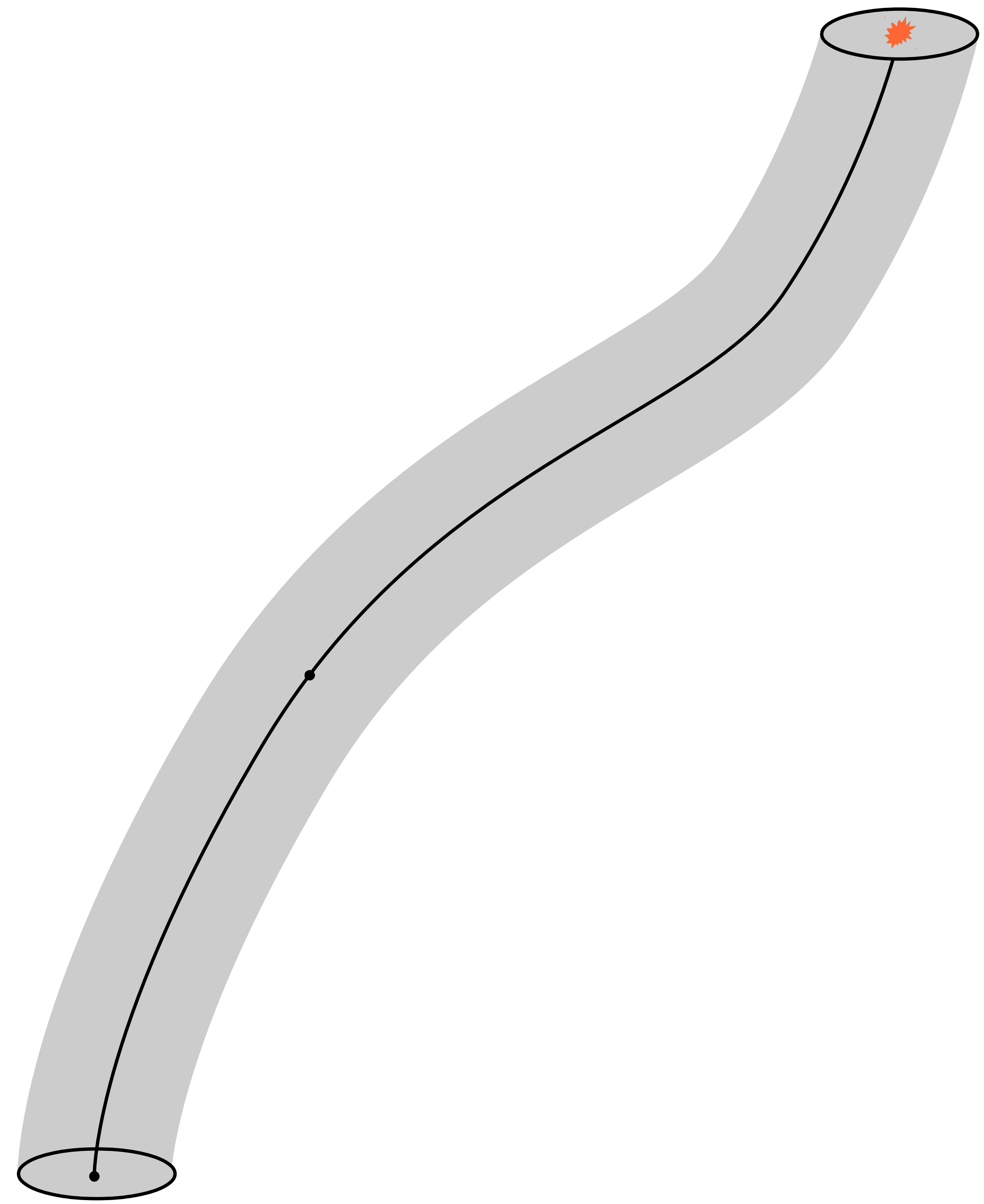
    - But not Φ or $\nabla\Phi$

EFT bias expansion

- We are not done yet however… Two issues:
- Many terms are redundant, as they are related through the equations of motion for matter and gravity (continuity, Euler, Poisson)
  - Cumbersome, but no problem - can eliminate redundant terms order by order in perturbations
- So far, we have written the EFT as local in time and space
  - Only makes sense if spatial and time derivatives are suppressed
  - True for spatial derivatives, but not for time derivatives! Galaxies form over many Hubble times (as does matter field)
  - Theory is *nonlocal in time*.

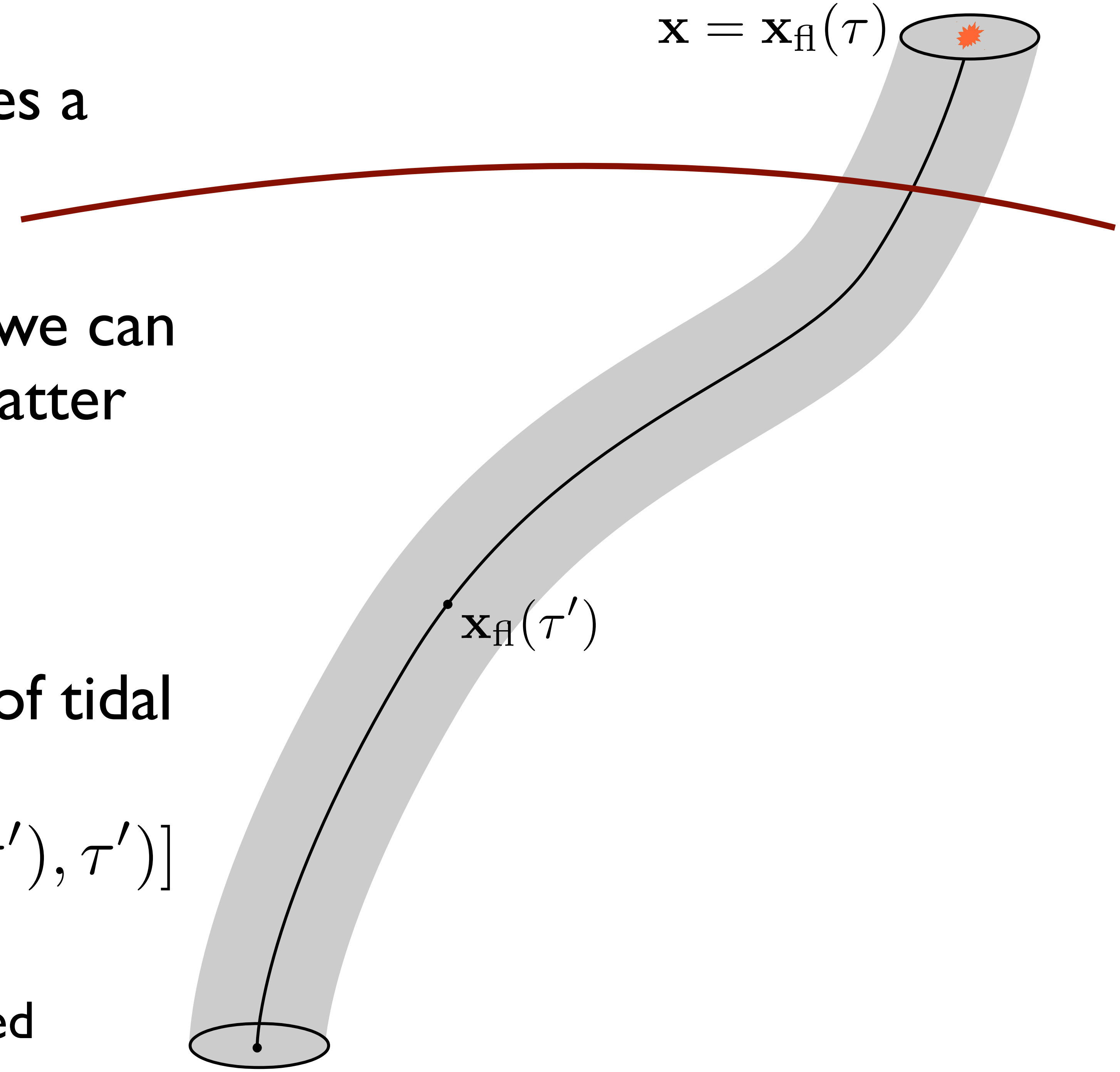
Galaxy formation

- Consider coarse-grained (large scale) view of region that forms a galaxy at conformal time τ
- Formation happens over long time scale, but small spatial scale R_*
  - For halos, expect $R_* \lesssim R_L$



Galaxy formation

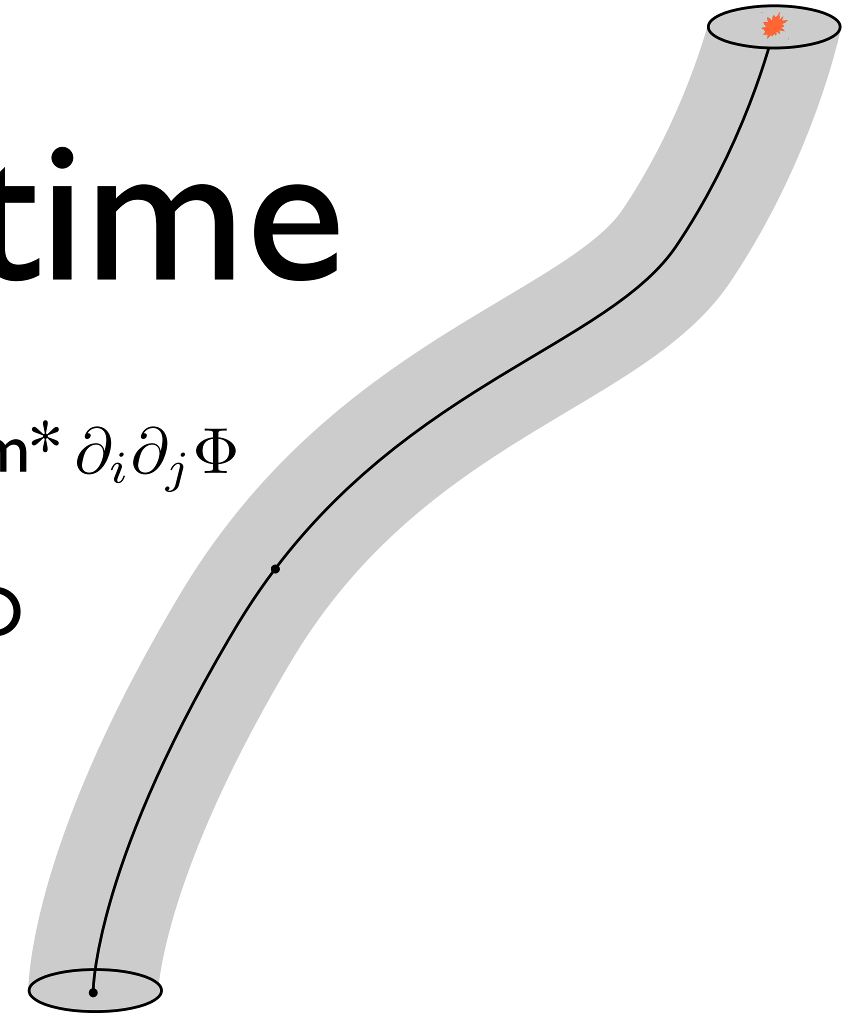
- Consider large-scale perturbations
- Galaxy density then becomes a local function *in space**
- Using equations of motion, we can eliminate dependence on matter density and velocity
- We are left with nonlinear, nonlocal-in-time functional of tidal tensor:
  $n_g(\mathbf{x},\tau) = F_g\left[\partial_i\partial_j\Phi(\mathbf{x}_{\rm fl}(\tau'),\tau')\right]$



* higher spatial derivatives are suppressed by $(\lambda/R_*)^2$ -> later

Mirbabayi, FS, Zaldarriaga '14

Non-locality in time



- Consider operator (field) O(x,t) that is constructed from* $\partial_i \partial_j \Phi$
- For simplicity, consider linear dependence of galaxy on O
- Linear functional in time:

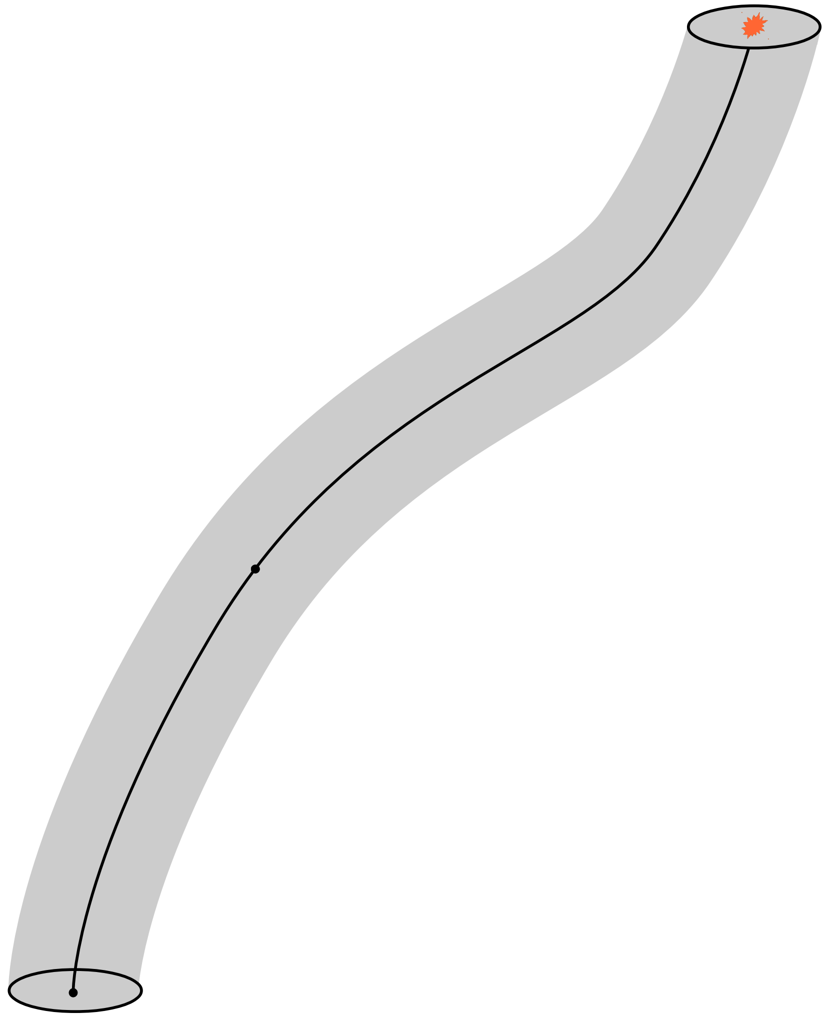
$$n_g(\boldsymbol{x},\tau) \supset \int_{\tau_{\rm in}}^{\tau} \mathrm{d}\tau' \, f_O(\tau,\tau') O(\boldsymbol{x}_{\rm fl}(\tau'),\tau')$$

- In perturbation theory, we know the *convective* time evolution of all these operators.
- Morally, at *n*-th order, there at most *N(n)* different time dependences (with *N*=*n* for EdS), and hence *<= N independent terms!*
  - Equivalently: arbitrarily high time derivatives can be written in terms of <= *N* terms

* From Poisson equation, $\delta \propto \nabla^2 \Phi$, so this includes "local bias" terms δ^n

Senatore '14; Mirbabayi, FS, Zaldarriaga '14

Non-locality



- *Ignore convective/fluid* trajectory part for now.
- In PT, we can generally write

$$O^{(\leq n)}(\boldsymbol{x}, \tau) = \sum_\alpha D_\alpha(\tau) O_\alpha(\boldsymbol{x}, \tau_0)$$

- Then, for any kernel f_O, time integral becomes

$$\begin{aligned} n_g(\boldsymbol{x}, \tau) &\supset \int_{\tau_{\rm in}}^{\tau} {\rm d}\tau' \, f_O(\tau, \tau') O(\boldsymbol{x}_{\rm fl}(\tau'), \tau') \\ &= \sum_\alpha \left[\int_{\tau_{\rm in}}^{\tau} d\tau' f_O(\tau, \tau') D_\alpha(\tau') \right] O_\alpha(\boldsymbol{x}, \tau_0) \\ &= b_{O_\alpha}(\tau) O_\alpha(\boldsymbol{x}, \tau_0) \end{aligned}$$

- We have absorbed time non-locality into a finite set of bias coefficients $b_{O\alpha}$

Senatore '14; Mirbabayi, FS, Zaldarriaga '14

Lagrangian picture

$$n_g(\boldsymbol{x},\tau) \supset \int_{\tau_{\rm in}}^{\tau} \mathrm{d}\tau' \; f_O(\tau,\tau') O(\boldsymbol{x}_{\rm fl}(\tau'),\tau')$$

- In practice, need to expand operators in convective time derivatives:

$$O(\boldsymbol{x}_{\rm fl}(\tau'),\tau') = \sum_{n=0}^{\infty} \frac{1}{n!}(\tau'-\tau)^n \left(\frac{D}{D\tau}\right)^n O(\boldsymbol{x},\tau)\Big|_{\tau}$$

- A bit cumbersome in Eulerian frame. Things much easier conceptually in Lagrangian frame:

$$\boldsymbol{x}_{\rm fl}(\tau) = \boldsymbol{q} + \boldsymbol{s}(\boldsymbol{q},\tau) \quad \Rightarrow \quad \frac{D}{D\tau} = \frac{\partial}{\partial\tau}$$

Lagrangian picture

$$\boldsymbol{x}_{\rm fl}(\tau) = \boldsymbol{q} + \boldsymbol{s}(\boldsymbol{q},\tau) \quad \Rightarrow \quad \frac{D}{D\tau} = \frac{\partial}{\partial\tau}$$

- Claim: complete set of bias expansion consists of all scalars constructed out of

$$\{(\partial_\tau)^n M_{ij}(\boldsymbol{q},\tau)\}_{n=0}^{\infty}$$

where

$$M_{ij}(\boldsymbol{q},\tau) \equiv \partial_{q,(i}s_{j)}(\boldsymbol{q},\tau)$$

Equation of motion (geodesic equation):

$$\left(\frac{\partial^2}{\partial\tau^2} + \mathcal{H}\frac{\partial}{\partial\tau}\right)\boldsymbol{s}(\boldsymbol{q},\tau) = -\boldsymbol{\nabla}\Phi\Big(\boldsymbol{q}+\boldsymbol{s}(\boldsymbol{q},\tau),\tau\Big)$$

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Relation to Eulerian observables

- Non-perturbative, local-in-time relations between M_{ij} and velocity shear:

$$v_i(\boldsymbol{x}_{\rm fl},\tau) = \dot{s}(\boldsymbol{q},\tau) \longrightarrow \frac{\partial v_i}{\partial x_j} = \frac{\partial q_k}{\partial x_j}\frac{\partial \dot{s}_i}{\partial q_k}$$

$$J = |\mathbf{1} + \boldsymbol{M}| = (1+\delta_m)^{-1}$$

$$= \frac{\epsilon_{kmn}\epsilon_{jpl}}{2J}(\delta_{pn}+M_{pn})(\delta_{lm}+M_{lm})\dot{M}_{ik}$$

- M_{ij} and tidal field:

$$\ddot{s}_i + \mathcal{H}\dot{s}_i = -\frac{\partial \phi}{\partial x_i} \longrightarrow \frac{\partial^2\phi}{\partial x_i \partial x_j} = -\frac{\partial q_k}{\partial x_j}(\ddot{M}_{ik} + \mathcal{H}\dot{M}_{ik})$$

$$= \frac{\epsilon_{kmn}\epsilon_{jpl}}{2J}(\delta_{pn}+M_{pn})(\delta_{lm}+M_{lm})(\ddot{M}_{ik} + \mathcal{H}\dot{M}_{ik})$$

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Complete bias expansion

- Start with Einstein-de Sitter (EdS):

$$M_{ij}^{(n)}(\boldsymbol{q},\tau) = D^n(\tau) M_{ij}^{(n)}(\boldsymbol{q},\tau_0)$$

- Simple to write down all Lagrangian bias terms:

$1^{\rm st}$	$\mathrm{tr}[M^{(1)}]$
$2^{\rm nd}$	$\mathrm{tr}[(M^{(1)})^2]\,,\ (\mathrm{tr}[M^{(1)}])^2$
$3^{\rm rd}$	$\mathrm{tr}[(M^{(1)})^3]\,,\ \mathrm{tr}[(M^{(1)})^2]\,\mathrm{tr}[M^{(1)}],\ (\mathrm{tr}[M^{(1)}])^3\,,\ \mathrm{tr}[M^{(1)}M^{(2)}]$
$4^{\rm th}$	$\mathrm{tr}[(M^{(1)})^4]\,,\ \mathrm{tr}[(M^{(1)})^3]\,\mathrm{tr}[M^{(1)}]\,,\ \left(\mathrm{tr}[(M^{(1)})^2]\right)^2\,,\ (\mathrm{tr}[M^{(1)}])^4\,,$
	$\mathrm{tr}[M^{(1)}]\,\mathrm{tr}[M^{(1)}M^{[2]}]\,,\ \mathrm{tr}[M^{(1)}M^{(1)}M^{(2)}]\,,\ \mathrm{tr}[M^{(1)}M^{(3)}]\,,\ \mathrm{tr}[M^{(2)}M^{(2)}]\,.$

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Complete bias expansion for *general expansion history*

- Equations of motion in GR for *any* expansion history:

$$
\begin{aligned}
\mathcal{D}_{3/2}(\lambda)\sigma^{(n)}(\boldsymbol{q},\lambda) = \sum_{m_1+m_2=n} &\Big\{ \operatorname{tr}\Big[\boldsymbol{H}^{(m_1)}(\boldsymbol{q},\lambda)\mathcal{D}_{3/4}(\lambda)\boldsymbol{H}^{(m_2)}(\boldsymbol{q},\lambda)\Big] \\
&\quad - \operatorname{tr}\Big[\boldsymbol{H}^{(m_1)}(\boldsymbol{q},\lambda)\Big]\mathcal{D}_{3/4}(\lambda)\operatorname{tr}\Big[\boldsymbol{H}^{(m_2)}(\boldsymbol{q},\lambda)\Big]\Big\} \\
&- \frac{1}{2}\sum_{m_1+m_2+m_3=n} \varepsilon_{ijk}\varepsilon_{lmn} H_{il}^{(m_1)}(\boldsymbol{q},\lambda)H_{jm}^{(m_2)}(\boldsymbol{q},\lambda)\mathcal{D}_{1/2}(\lambda)H_{kn}^{(m_3)}(\boldsymbol{q},\lambda) \\
\mathcal{D}_0(\lambda)(\boldsymbol{t}^{(n)})^i = \sum_{m_1+m_2=n} &\varepsilon^{ijk}\Big(\boldsymbol{H}^{(m_1)}\mathcal{D}_0\boldsymbol{H}^{(m_2)\top}\Big)_{jk}\,, \qquad (2.10)
\end{aligned}
$$

where

$$
\begin{aligned}
\gamma(\lambda) &\equiv \frac{\Omega_m(\lambda)}{f^2(\lambda)} - 1; \quad \lambda \equiv \ln D \\
\mathcal{D}_c &\equiv \frac{\partial^2}{\partial\lambda^2} + \frac{1}{2}[1+3\gamma(\lambda)]\frac{\partial}{\partial\lambda} - c[1+\gamma(\lambda)] \quad \text{for any } c\in\mathbb{R}. \qquad (2.11)
\end{aligned}
$$

$M_{ij} \equiv H_{(ij)}, \quad H_{ij} = \partial_i s_j$

$\sigma \equiv \boldsymbol{\nabla}\cdot\boldsymbol{s} \quad \boldsymbol{t} = \boldsymbol{\nabla}\times\boldsymbol{s}$

Rampf, 2012; Matsubara, 2015; FS, arXiv:2012.09837

Complete bias expansion for *general expansion history*

- Can be solved iteratively, given *a(t)*
- Schematic contributions:

n	Shapes contributing to $\boldsymbol{H}^{(n)}$ (schematic)
1	$H^{(1)}$
2	$H^{(1)}H^{(1)}$
3	$H^{(1)}H^{(2)}$, $H^{(1)}H^{(1)}H^{(1)}$
4	$H^{(1)}H^{(3,1)}$, $H^{(1)}H^{(3,2)}$, $H^{(2)}H^{(2)}$, $H^{(1)}H^{(1)}H^{(2)}$

- Again, in EdS time dependence is the same at each order. In practice, time dependence in ΛCDM-like universe extremely similar,

FS, arXiv:2012.09837

Complete bias expansion for *general expansion history*

- Bias operators constructed out of these shapes:

1. We first construct all scalar invariants up to including n-th order out of the $\boldsymbol{M}^{(m,p)}$. Given the restriction on $\mathrm{tr}[\boldsymbol{M}^{(m,p)}]$, and since these are symmetric 3-tensors, the invariants at order m consist of the set

$$\begin{aligned} \mathcal{I}^{(m)} = \Big\{ & \mathrm{tr}[\boldsymbol{M}^{(1)}], \quad \{\mathrm{tr}[\boldsymbol{M}^{(m_1,p_1)}\boldsymbol{M}^{(m_2,p_2)}]\}^{p_1,p_2}_{m_1+m_2\leq m}, \\ & \{\mathrm{tr}[\boldsymbol{M}^{(m_1,p_1)}\boldsymbol{M}^{(m_2,p_2)}\boldsymbol{M}^{(m_3,p_3)}]\}^{p_1,p_2,p_3}_{m_1+m_2+m_3\leq m} \Big\} \\ \equiv & \left\{ I_s^{(m)} \right\}_{s=1}^{N_{\mathcal{I}}(m)} . \end{aligned} \tag{3.4}$$

2. We then construct all independent products

$$\begin{aligned} & I_{s_1}^{(m_1)} \cdots I_{s_k}^{(m_k)}, \quad 1 \leq k \leq n, \\ & \text{with} \quad m_1 + \cdots + m_k = n; \quad s_i \in \{1, \ldots, N_{\mathcal{I}}(m_i)\}. \end{aligned} \tag{3.5}$$

Technically, this is done iteratively by running over the set of partitions of n, and then, for each partition $\{m_i\}_{i=1}^k$, constructing products of all combinations of the $\{s_1, \ldots s_k\}$.

Only symmetric part of H, i.e. M needed in bias expansion.

FS, arXiv:2012.09837

LEFTfield

Complete bias expansion for *general expansion history*

- Bias operators constructed out of the shapes $M^{(\alpha=n,p)}$
- First effect on bias expansion at fourth order:

$$\mathrm{tr}[\boldsymbol{M}^{(3,1)}\boldsymbol{M}^{(1)}], \quad \mathrm{tr}[\boldsymbol{M}^{(3,2)}\boldsymbol{M}^{(1)}]$$

FS, arXiv:2012.09837

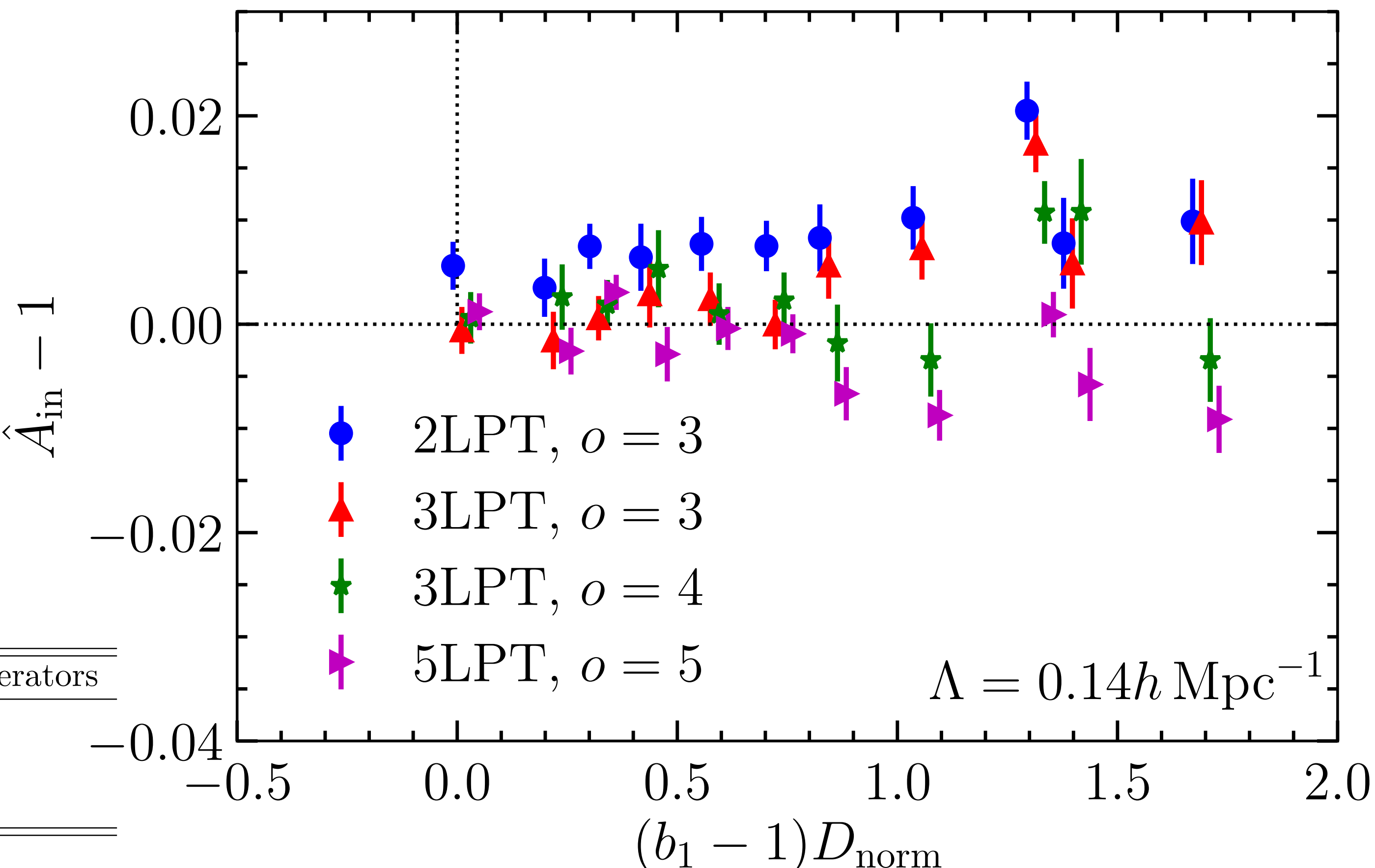
Inference on dark matter halos with fixed initial conditions

Relative deviation of maximum-likelihood value of σ_8 from ground truth, for different perturbative orders

L_{box} = 2000 Mpc/h

$$A_{\rm in} \equiv \frac{\sigma_8}{\sigma_8^{\rm fid}}$$

Results for all mass bins and redshifts for $\Lambda = 0.14h\ \mathrm{Mpc}^{-1}$



Proxy for higher-order bias terms

Order	Leading bias operators	Higher-derivative operators	Total number of operators
$o = 3$	[7, Eq. (3.6)]	$\nabla^2\delta$	8
$o = 4$	[15, Eq. (3.6)]	$\nabla^2\delta$, $(\boldsymbol{\nabla}\delta)^2$, $\nabla^2 O^{(2)}$ [4]	19
$o = 5$	[29]	[13]	42

Table 1. Number of relevant operators at each order, following Eq. (3.12) and Eq. (3.13). The numbers in brackets give the total number of operators in each case. $O^{(2)}$ stands for the two second-order bias operators (second line in Eq. (3.6)), but after displacement to Eulerian space).

FS, arXiv:2009.14176

Complete *Eulerian* bias expansion

There exists an analogous expansion in Eulerian coordinates:

$$
\begin{array}{ll}
1^{\rm st} & \mathrm{Tr}[\Pi^{[1]}] \\
2^{\rm nd} & \mathrm{Tr}[(\Pi^{[1]})^2],\ (\mathrm{Tr}[\Pi^{[1]}])^2 \\
3^{\rm rd} & \mathrm{Tr}[(\Pi^{[1]})^3],\ \mathrm{Tr}[(\Pi^{[1]})^2]\mathrm{Tr}[\Pi^{[1]}],\ (\mathrm{Tr}[\Pi^{[1]}])^3,\ \boxed{\mathrm{Tr}[\Pi^{[1]}\Pi^{[2]}]} \\
4^{\rm th} & \mathrm{Tr}[(\Pi^{[1]})^4],\ \mathrm{Tr}[(\Pi^{[1]})^3]\mathrm{Tr}[\Pi^{[1]}],\ \mathrm{Tr}[(\Pi^{[1]})^2]\mathrm{Tr}[(\Pi^{[1]})^2],\ (\mathrm{Tr}[\Pi^{[1]}])^4,\ \boxed{\mathrm{Tr}[\Pi^{[1]}\Pi^{[3]}]}, \\
 & \boxed{\mathrm{Tr}[\Pi^{[2]}\Pi^{[2]}]}
\end{array}
$$

Time derivatives <~>
"Nonlocality in time"

where $\Pi^{[1]}_{ij} = \partial_i\partial_j\Phi(\mathbf{x},\tau)$

$$\Pi^{[n]}_{ij} \propto \frac{D}{D\tau}\Pi^{[n-1]}_{ij}$$

starts at n-th order in pert. theory

Small-scale modes lead to *stochastic* contributions:

$$
\begin{array}{ll}
1^{\rm st} & \epsilon_1 \\
2^{\rm nd} & \epsilon_2\,\mathrm{Tr}[\Pi_{ij}] \\
3^{\rm rd} & \epsilon_3\,\mathrm{Tr}[(\Pi_{ij})^2]\,,\ \epsilon_4\,(\mathrm{Tr}[\Pi_{ij}])^2 \\
 & \ldots
\end{array}
$$

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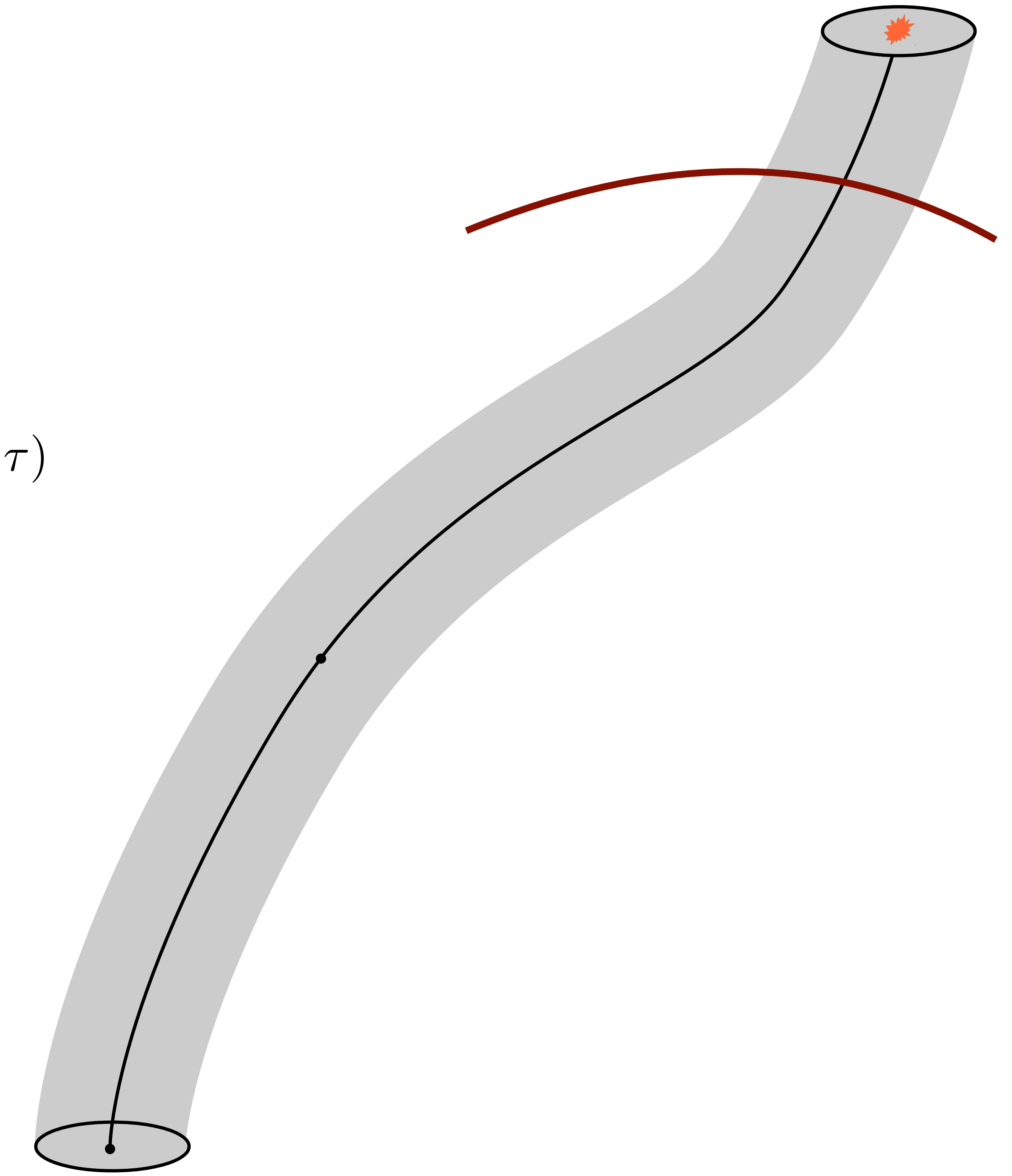
Remarks / Discussion points

- Bias expansions in different coordinates at fixed order in PT should be equivalent
  - I.e. related by unitary transformation
- Order at which "time non-locality" appears in bias expansion is mostly semantics
  - E.g. whether velocity potential included
  - But could also include acceleration potential…
- Impact of non-EdS expansion history appears at 4th order (3d order for galaxy shapes)
  - In principle, allows for probing history of structure formation
- All of the individual bias terms are locally observable (tidal field and its time derivatives as measured by comoving observer). Any conclusion on formation time of galaxies must rely on making *specific assumptions about the kernels f_O*.

$$b_{O_\alpha} = \int_{\tau_{\rm in}}^{\tau} d\tau' f_O(\tau,\tau') D_\alpha(\tau')$$

Spatial nonlocality and scale-dependent bias

- Beyond large-scale limit: need to expand *spatial nonlocality* of galaxy formation
- Higher derivative biases are suppressed with scale R_*
- E.g., $R_*^2 \nabla^2 \delta \longrightarrow \delta_g(\mathbf{k}, \tau) = \left(b_1 + b_{\nabla^2\delta} k^2 R_*^2\right) \delta(\mathbf{k}, \tau)$
- This also allows for baryonic physics, which *has to come with additional derivatives*
    - Example: pressure perturbations $\delta p = c_s^2 \delta \rho$
    - Pressure force: $\boldsymbol{F} = \boldsymbol{\nabla} \delta p \propto \boldsymbol{\nabla} \delta$
- At higher order in derivatives, time evolution no longer determined by gravity alone



Velocity bias

- Galaxy velocities are important probe of cosmology - but how related to matter velocity?
- Recall that bias expansion for galaxy density cannot include $\nabla\Phi$
- The same is true for any observable - in particular also the relative velocity between matter and galaxies
- Hence, relative velocity can be written as

$$v_g^i - v^i = \partial^i \left\{ \delta\,,\ (\partial_i\partial_j\Phi)^2\,,\ \cdots \right\}$$

- Necessarily higher derivative ~ R_*^2 ! Cf. pressure forces $\boldsymbol{F} = \boldsymbol{\nabla}\delta p \propto \boldsymbol{\nabla}\delta$
  - Also small-scale stochastic velocities, with power spectrum ~ k^4, which captures virial motions

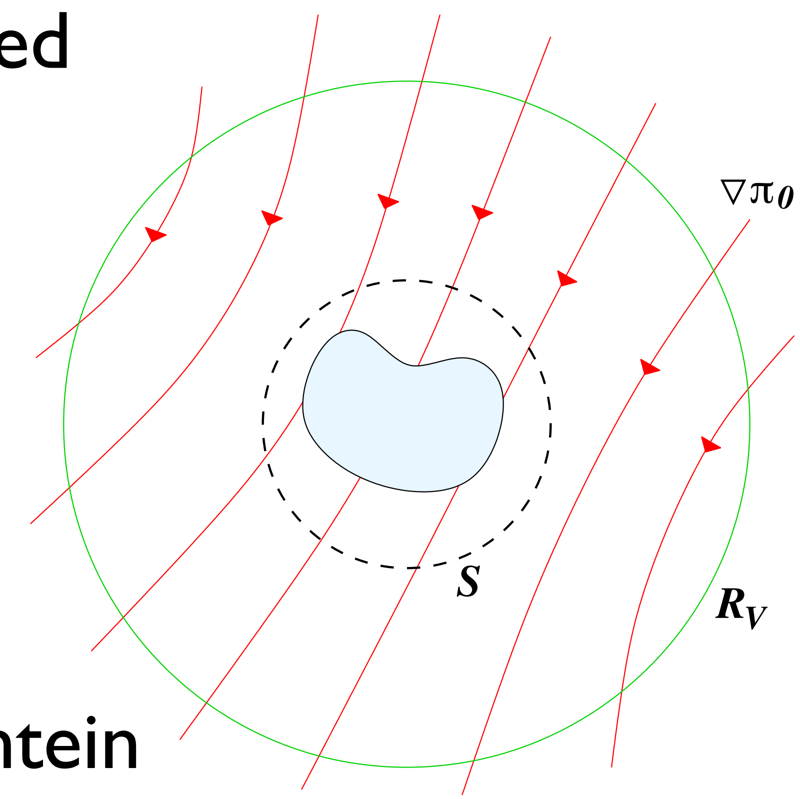
- Summary: Galaxy velocities are unbiased on large scales.

Modified gravity: ~~SEP~~, ~~WEP~~

- One example: long-range dark forces
- Violation of weak equivalence principle generally leads to relative displacement between galaxies and matter
- Cf. Salvatore B. / Marco C.'s talks

Modified gravity: ~~SEP~~, WEP

- Widely discussed MG models generally preserve weak equivalence principle, but violate strong equivalence principle
  - Strongly-gravitating objects (black holes, screened bodies) in general fall differently than weakly gravitating objects
- EP violation for screened objects
  - Most easily shown in Einstein-Infeld-Hoffmann approach
  - Present for chameleon screening, but not Vainshtein screening



Hui, Nicolis, Stubbs (2009)

Modified gravity: ~~SEP~~, WEP

- Phenomenology of chameleon-screened MG:
  - Interesting effects, but only within Compton length of fifth force
  - Already constrained to be in nonlinear regime; e.g., $m_{f(R)} \lesssim 10\,\mathrm{Mpc}$
  - On large scales, effects scale as k^2/m^2

Additional species: baryons

Linear evolution of baryons and CDM

- Standard treatments of structure formation (perturbation theory, N-body simulations) neglect radiation and anisotropic stress (accurate at z <~ 100). We will do the same here.
- Then, baryons and CDM are described by continuity and Euler equations, and at linear order:

$$\frac{\partial}{\partial \tau}\delta_s = -\theta_s\,, \quad s \in \{b,\, c\}$$

$$\frac{\partial}{\partial \tau}\theta_s + \mathcal{H}\theta_s = -\frac{3}{2}\Omega_m(a)\mathcal{H}^2\delta_m\,,$$

$$\mathcal{H} = aH$$

- Only coupled by gravity, via $\delta_m = f_b\delta_b + (1 - f_b)\delta_c$

$$f_b = \Omega_b/\Omega_m$$

Galaxy clustering and baryon-CDM perturbations

- Four modes: adiabatic growing (~$D(t)$) and decaying (~$H(t)$), relative density (*const*) and relative velocity (~a^{-1})
  - Neglect adiabatic decaying
- Distinguish three physical effects (partially historic reason):
  - Constant mode δ_{bc}
  - Decaying relative velocity divergence θ_{bc}
  - Uniform relative velocity v_{bc}^2

Galaxy clustering and baryon-CDM perturbations

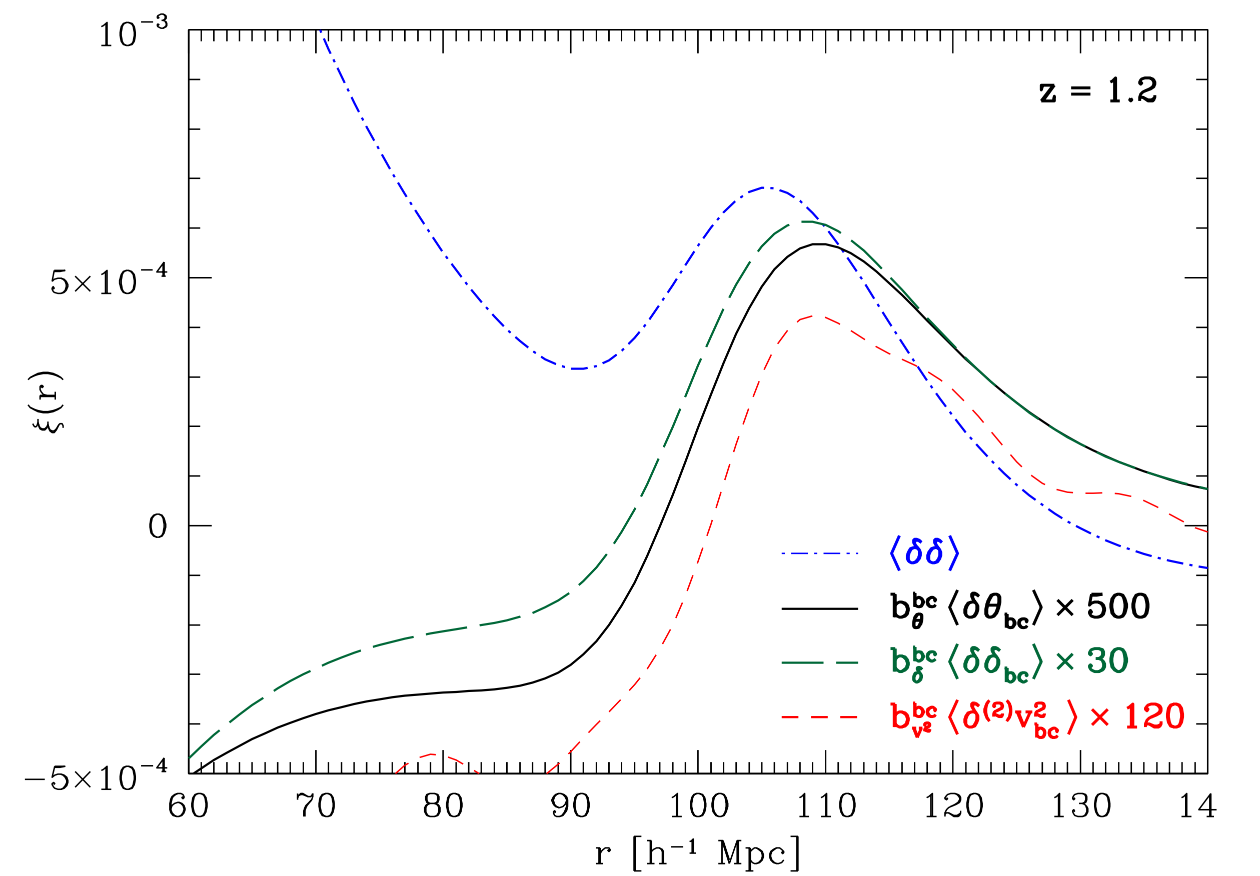
- Galaxies form from baryons, hence we need to include them in the bias expansion used to describe galaxy clustering on large scales:

$$\delta_g(\mathbf{x},\tau) = b_1\delta_m(\mathbf{x},\tau) + b_\delta^{bc}\delta_{bc}(\mathbf{q}) + b_\theta^{bc}\theta_{bc}(\mathbf{q}) + b_{v^2}^{bc}\mathbf{v}_{bc}^2(\mathbf{q}) + \cdots$$

- Straightforward to systematically include at higher order in bias expansion.
  - Evaluate at Lagrangian position
  - No time derivatives as these modes are not coupled to gravity

What is the impact of these modes ?

- Contribution of bc modes rapidly becomes small compared to growing mode in the matter perturbation
- However, because they are sourced by the acoustic waves in the plasma, they have a prominent BAO feature in their two-point function
- Relevant for galaxy clustering using BAO as standard ruler



FS, 2016

$$P_g(k) = b_1^2 P_{mm}(k) + 2b_1 b_\delta^{bc} P_{m\delta_{bc}}(k) + 2b_1 b_\theta^{bc} P_{m\theta_{bc}}(k) + b_1 b_{v^2}^{bc} \mathcal{I}^{\delta^{(2)},v^2}(k) + \cdots$$

What is the impact of these modes ?

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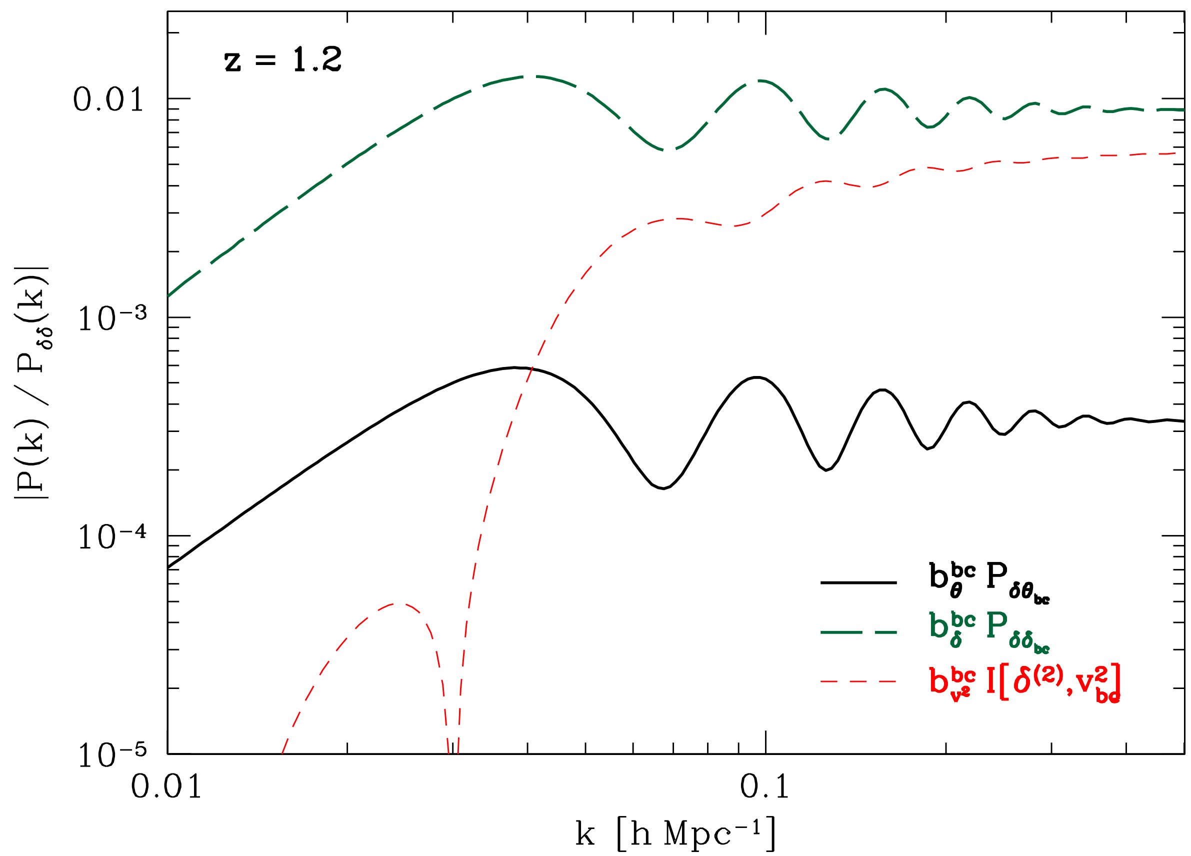
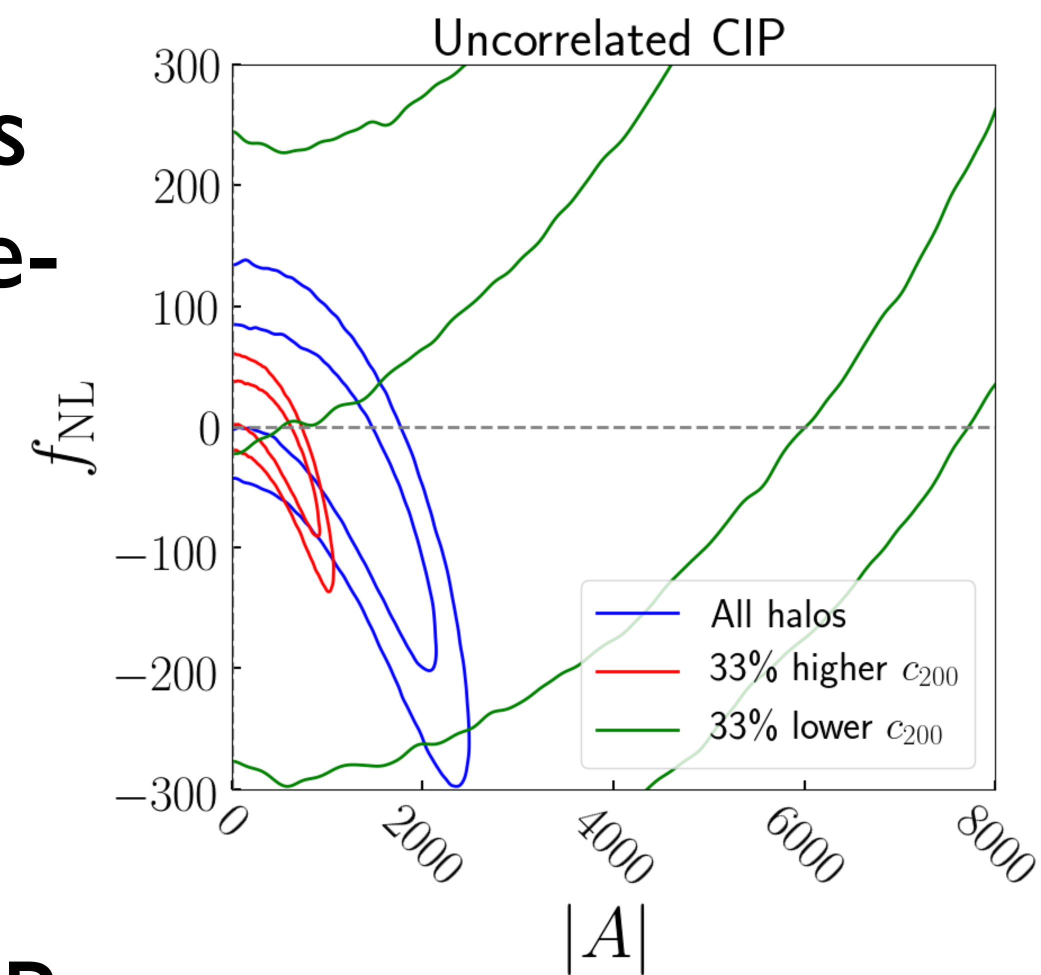


FS, 2016

$$P_g(k) = b_1^2 P_{mm}(k) + 2b_1 b_\delta^{bc} P_{m\delta_{bc}}(k) + 2b_1 b_\theta^{bc} P_{m\theta_{bc}}(k) + b_1 b_{v^2}^{bc} \mathcal{I}^{\delta^{(2)},v^2}(k) + \cdots$$

Primordial baryon-CDM isocurvature perturbations

- Scale-invariant isocurvature perturbations between baryons and CDM lead to fNL-like scale-dependent bias
- Tight constraints (and $b_{\delta bc}$ is arguably better understood than b_{ϕ})
  - Factor of ~2 better than CMB



Barreira et al 2020a,b ; Barreira, arXiv:2302.01927

Additional species: neutrinos

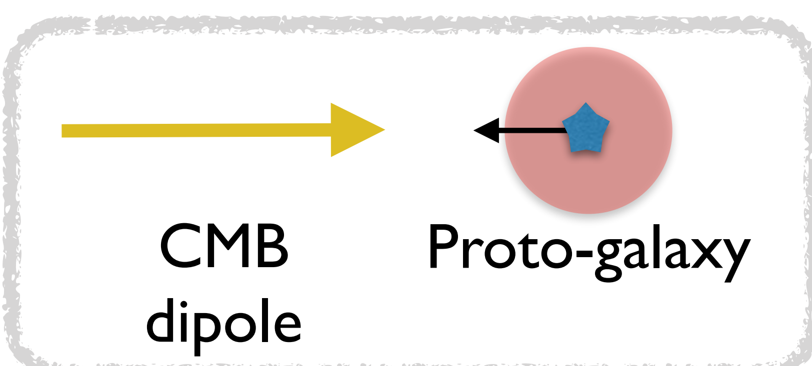
- Cf. Marilena's talk
- Introduce an additional large scale: k_{fs}
- Strictly, EFT expansion only valid for $k << k_{fs}$, but suppression of gravitational effect by f_ν helps a lot of course.

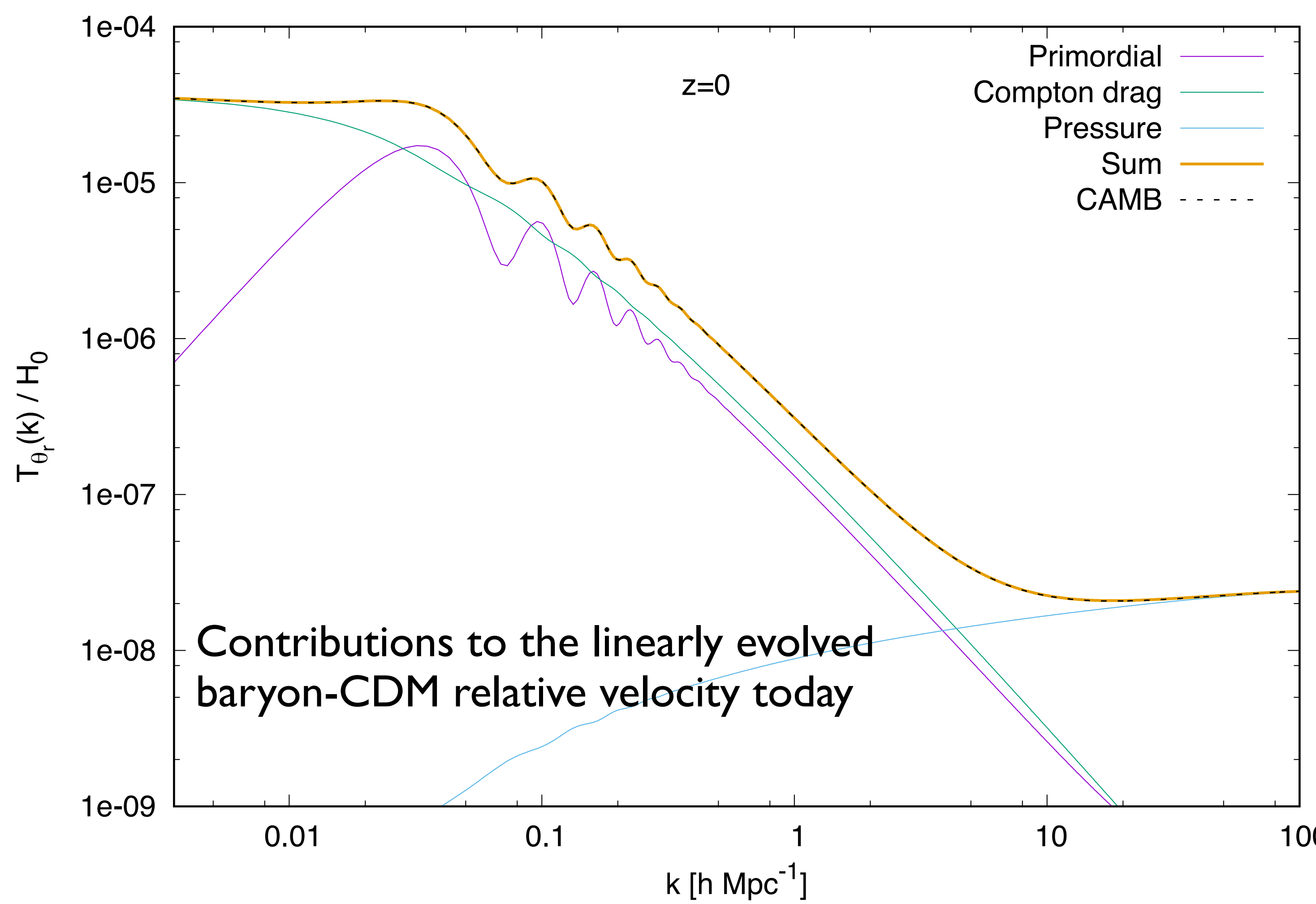
Caveat: Reionization

- Two interesting effects:
  - Compton drag
  - Radiative transfer effects

Caveat: Reionization

- Compton drag

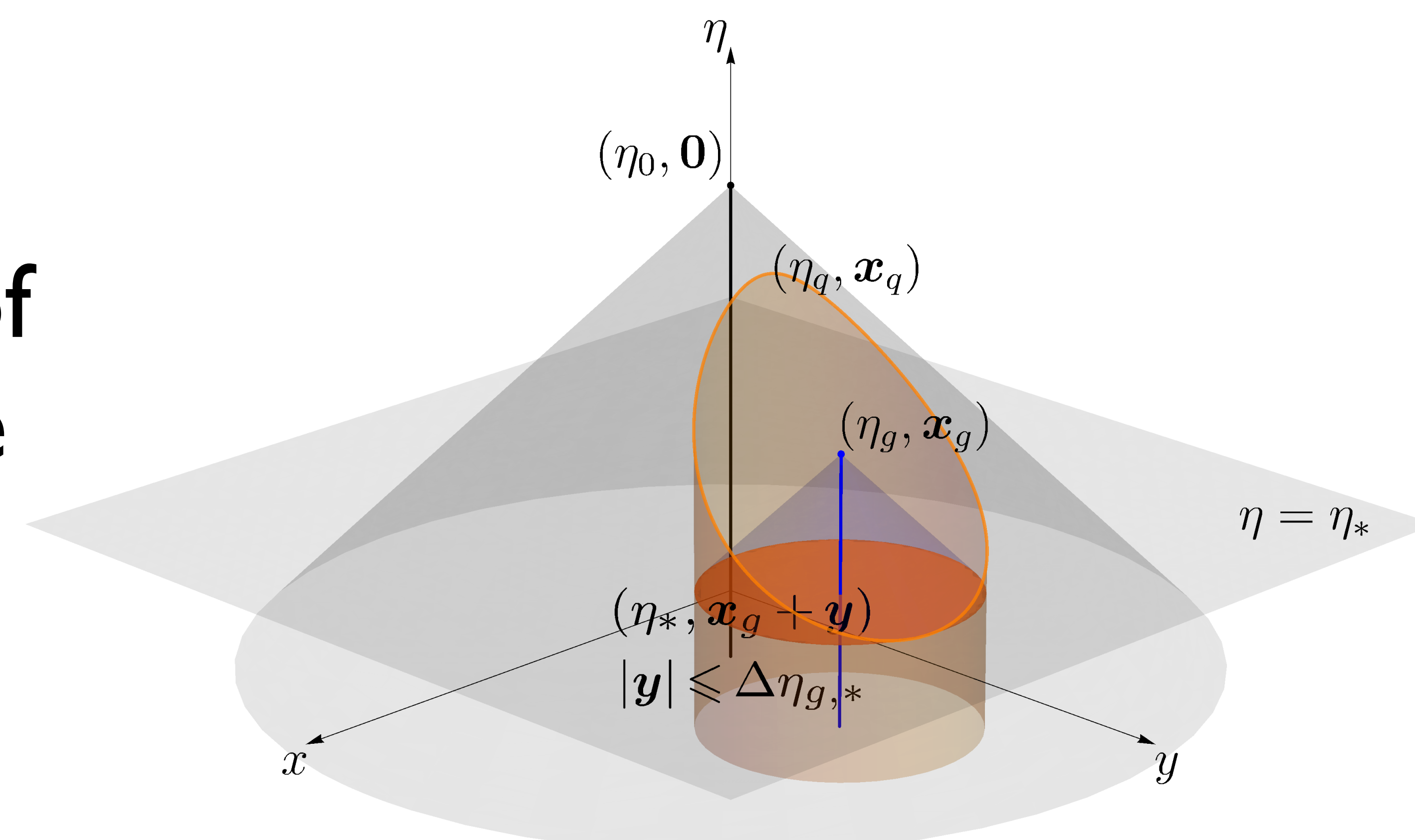




FS, F. Beutler, arXiv:1705.07843

Radiative transfer effects

- MFP of ionizing radiation increases dramatically during reionization
- If formation efficiency of galaxies depends on the local flux of ionizing radiation, number of galaxies *depends on distribution of matter within this MFP*



Cabass, FS (2018); see also Pontzen (2014), Meiksin & McQuinn (2018), Sanderbeck et al (2018)

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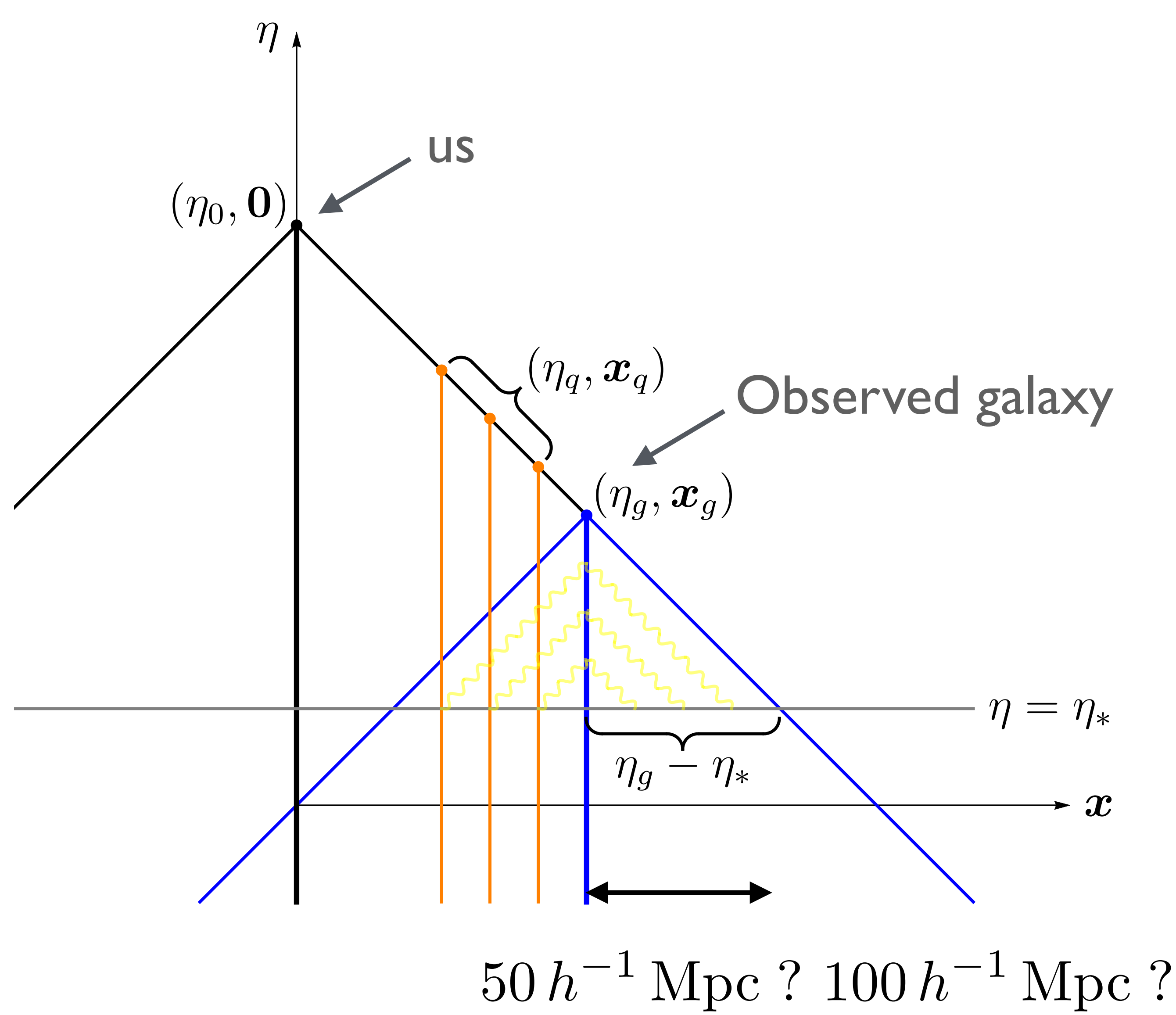

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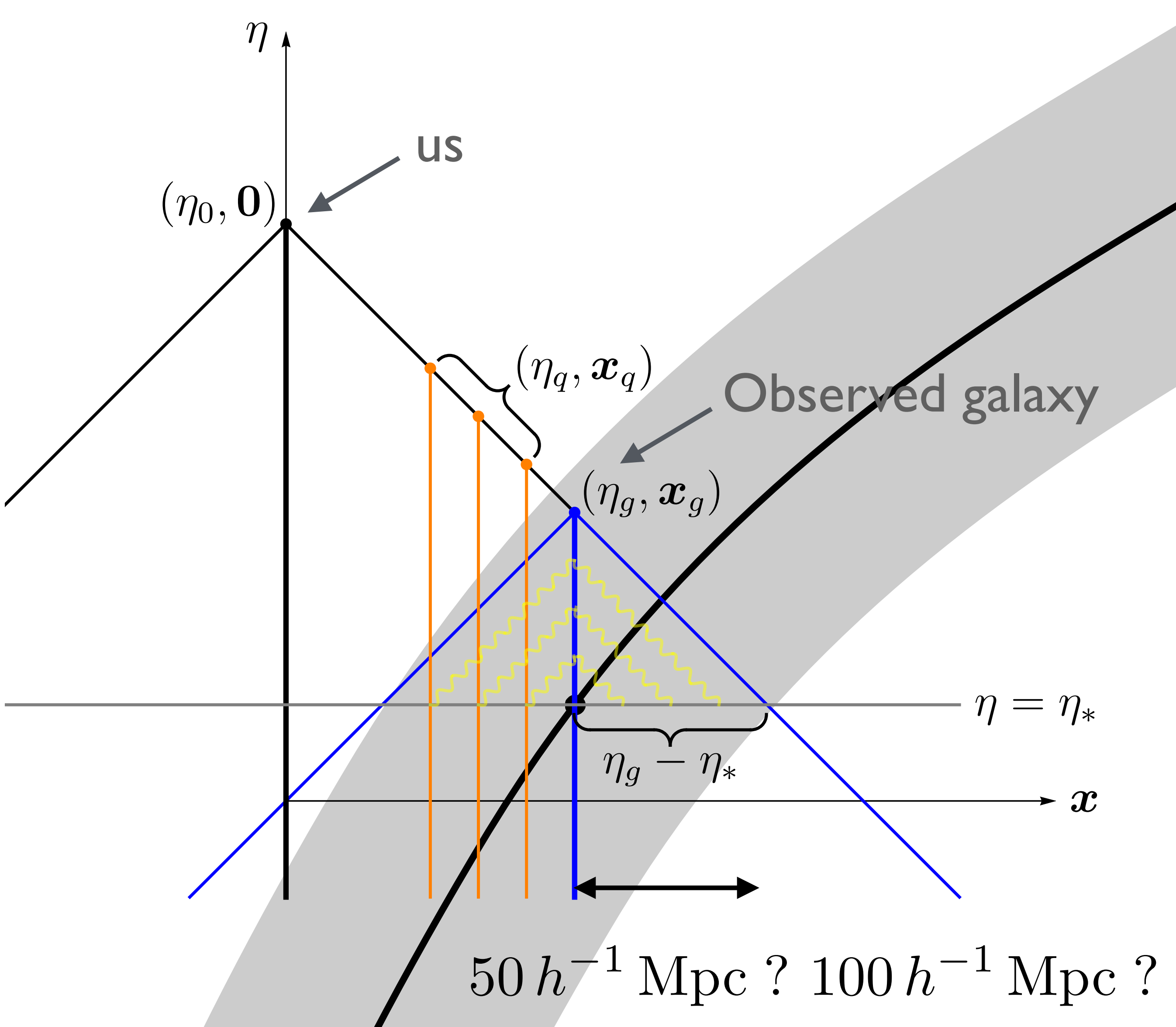

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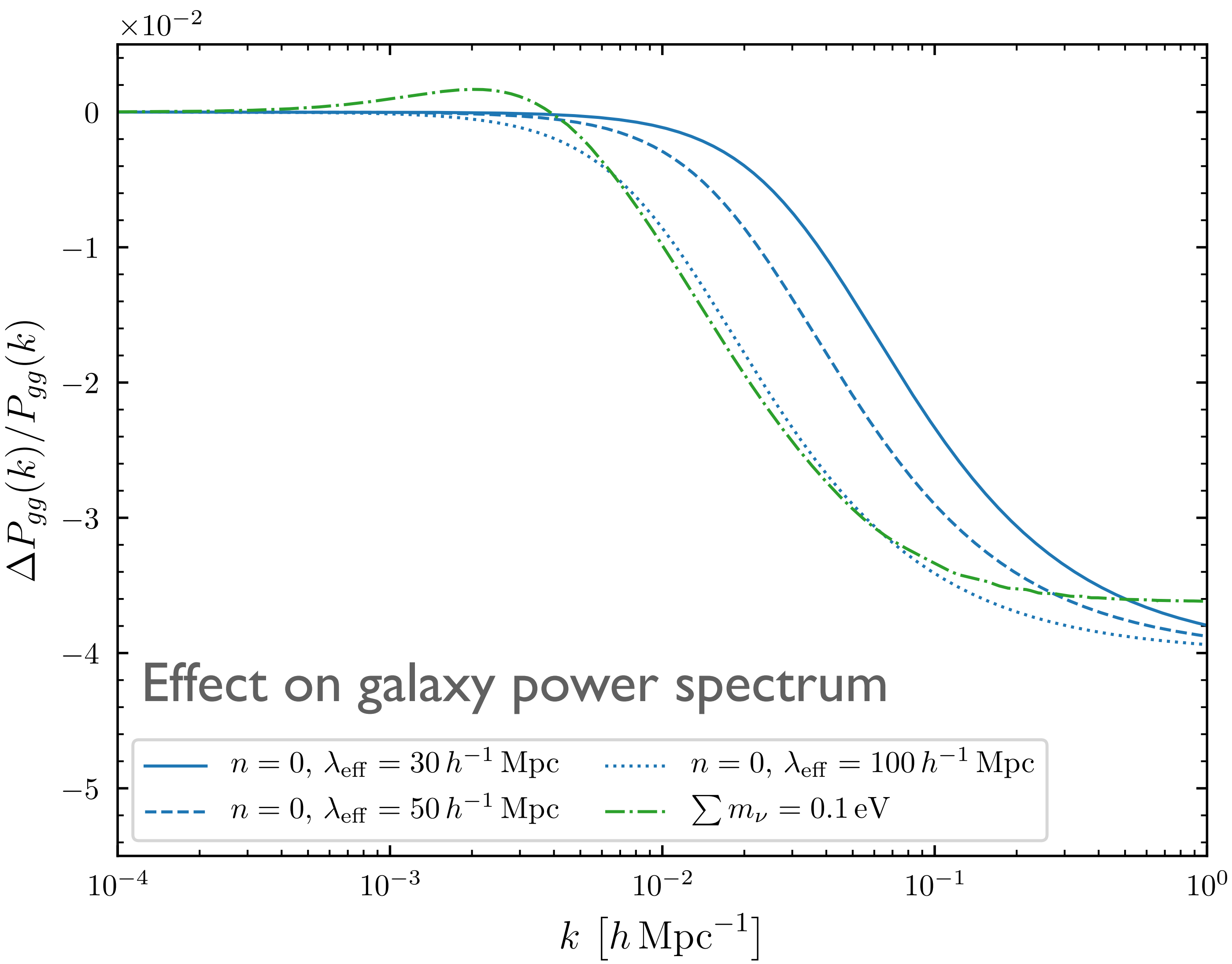
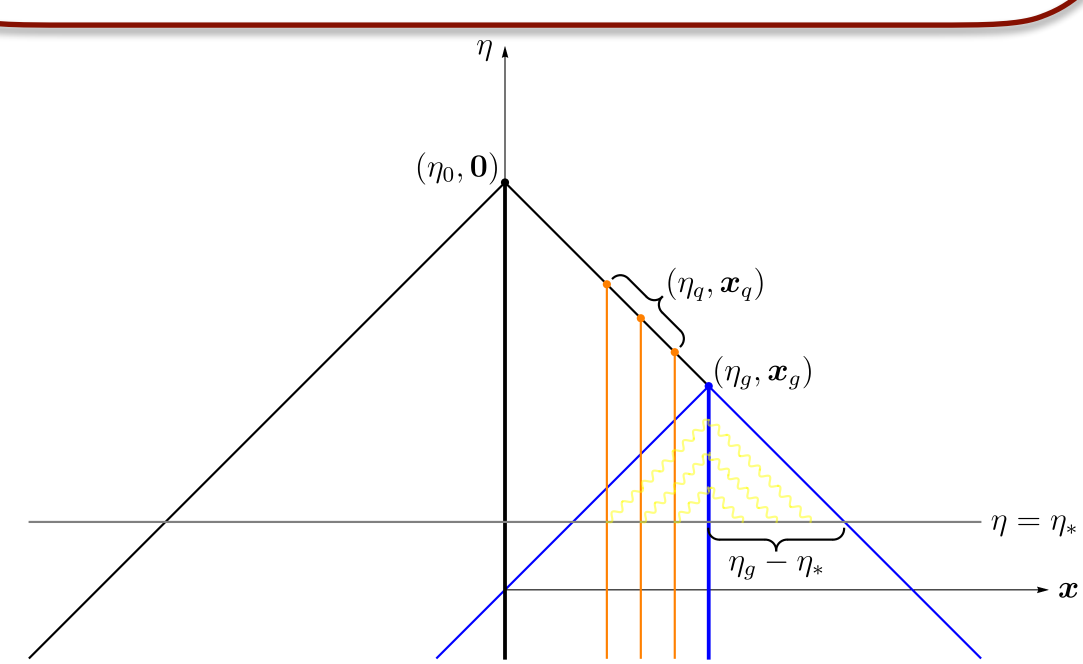


When can this effect be described rigorously (in EFT sense) ?

$\delta\tau = 0$	$\Delta\eta_G \ll \mathcal{H}^{-1}$	$\Delta\eta_G \sim \mathcal{H}^{-1}$
$\Delta\eta_{\rm em} \ll \mathcal{H}^{-1}$	✓	✓
$\Delta\eta_{\rm em} \sim \mathcal{H}^{-1}$	✓	✗

Same as Tab. 1, but taking into account the inhomogeneities in the optical depth.

$\delta\tau \neq 0$	$\Delta\eta_G \ll \mathcal{H}^{-1}$	$\Delta\eta_G \sim \mathcal{H}^{-1}$
$\Delta\eta_{\rm em} \ll \mathcal{H}^{-1}$	✓	✗
$\Delta\eta_{\rm em} \sim \mathcal{H}^{-1}$	✗	✗



Cabass, FS (2018)

Primordial non-Gaussianity

- Two effects:
  - Contribution to n-point functions inherited from matter ($\sim b_1^n$)
  - Scale-dependent bias from long/short mode coupling
    - Determined by squeezed-limit scaling of primordial correlators: $(k_L/k_S)^\Delta$ -> scale-dependent bias $\sim k^{\Delta-2}$.
- Note: parity-violating signatures suppressed in squeezed limit.

FS, Kamionkowski; Assassi, Baumann, FS

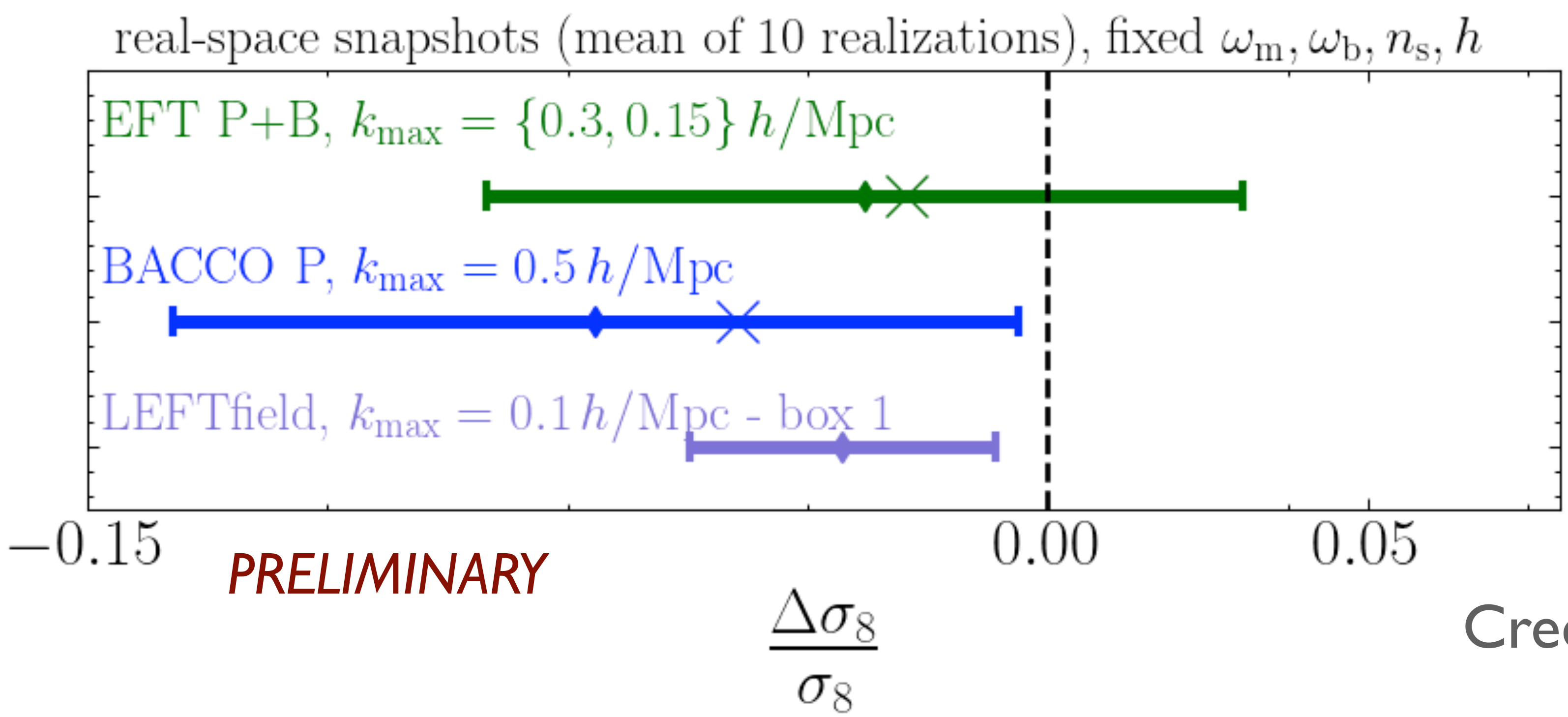
cf. Ben Wallisch's talk

Summary

- EFT allows for rigorous incorporation of all local-in-space, nonlocal-in-time physics of structure formation
  - Effects of non-EdS expansion history appear at 4th order, but likely extremely small in real world
- Isocurvature perturbations, primordial non-Gaussianity can likewise be incorporated
- Strictly, only real show-stopper are additional large spatial scales:
  - Neutrino free-streaming scale
  - Mean free path of ionizing radiation (memory effect of high-z/reionization)
  - Very reasonable that these have very small amplitude, but how small?

P.S. On field-level inference…

- EFT-based full field-level inference on blind catalogs from beyond 2-pt challenge:



Credit: Minh Nguyen

Thanks to Y. Kobayashi, A. Salcedo, E. Krause, and M. Ivanov, M. Pellejero !

LEFTfield