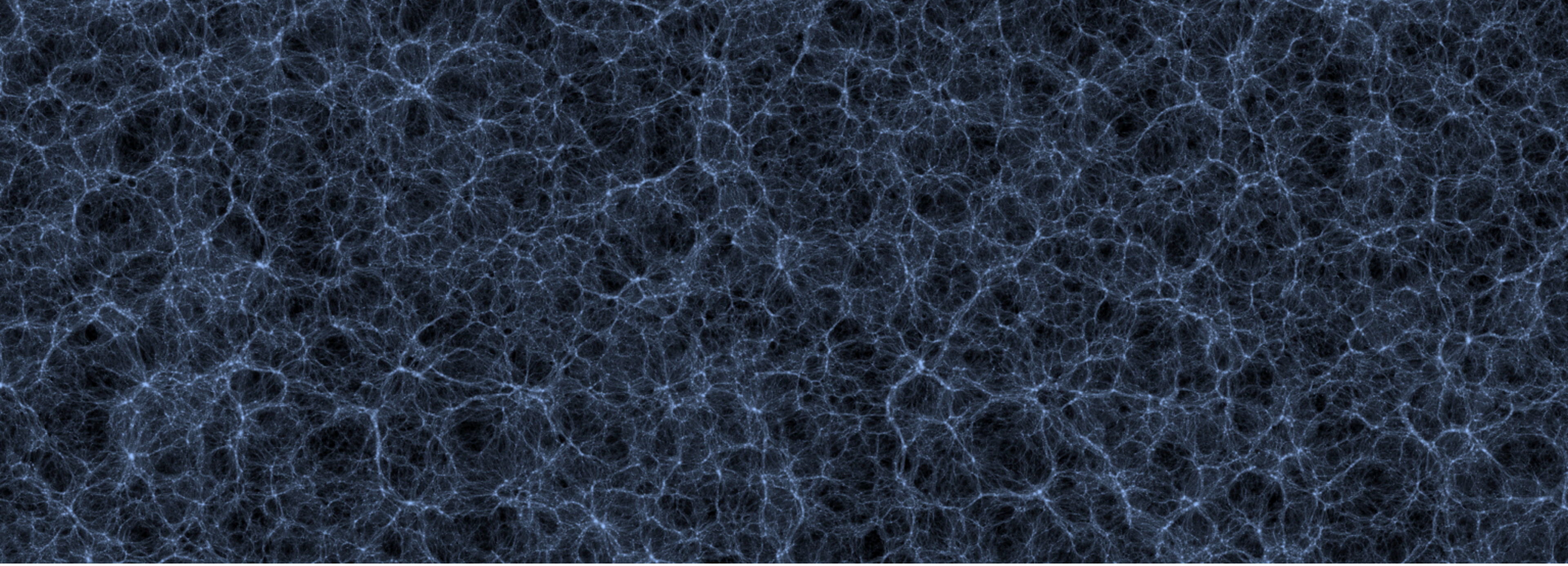


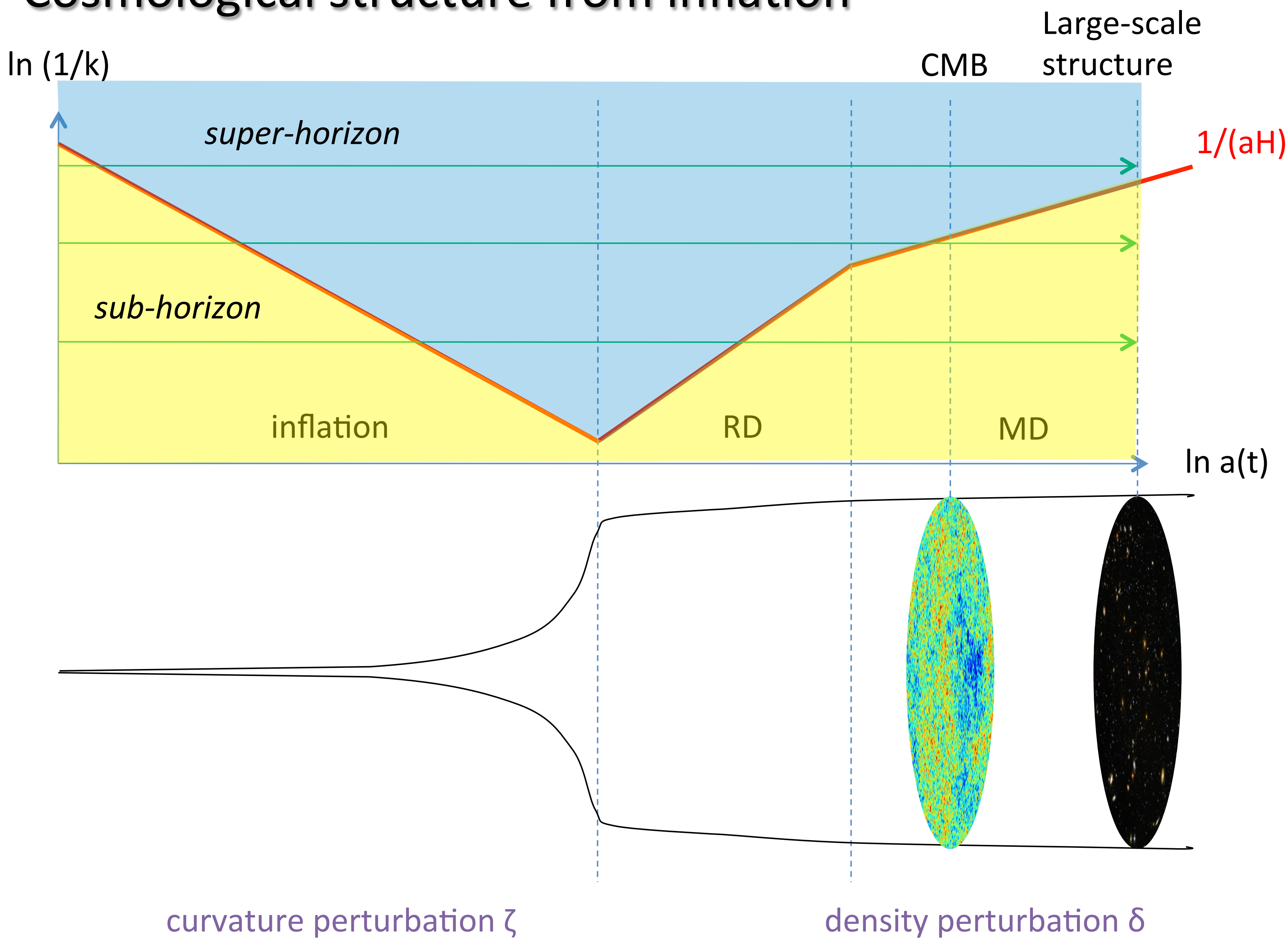
Millennium Simulation of the large-scale structure

Separate universes and large-scale clustering

Liang Dai (IAS)

Presentation at the Einstein Fellowship Symposium, Oct 2015

Cosmological structure from inflation



Primordial non-gaussianity

Departure from Gaussian statistics reveals physics beyond single-field inflation

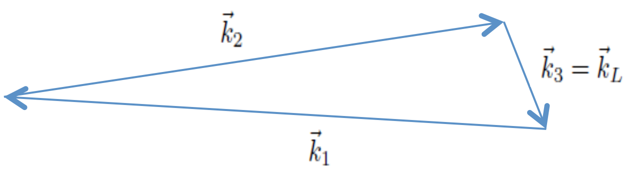
(1) nonlinear coupling (negligible in minimal model)

(2) new degrees of freedom

$$\left\langle \phi_{\rm ini}\left(\vec{k}_1\right)\phi_{\rm ini}\left(\vec{k}_2\right)\phi_{\rm ini}\left(\vec{k}_3\right)\right\rangle = B_{\phi\phi\phi}\left(\vec{k}_1,\vec{k}_3\right)(2\pi)^3\,\delta_D\left(\vec{k}_1+\vec{k}_2+\vec{k}_3\right)$$

	bispectrum scaling	CMB constraint from *Planck* 2015
squeezed	$B_{\phi\phi\phi}\left(\vec{k}_L,\vec{k}_S\right)\sim f_{NL}P_\phi\left(k_S\right)P_\phi\left(k_L\right)$	fNL = 0.8±5.0
equilateral	$B_{\phi\phi\phi}\left(\vec{k}_L,\vec{k}_S\right)\sim f_{NL}\frac{k_L^2}{k_S^2}P_\phi\left(k_S\right)P_\phi\left(k_L\right)$	fNL = -4±43
folded	$B_{\phi\phi\phi}\left(\vec{k}_L,\vec{k}_S\right)\sim f_{NL}\frac{k_L^2}{k_S^2}P_\phi\left(k_S\right)P_\phi\left(k_L\right)$	fNL = -26±21

squeezed

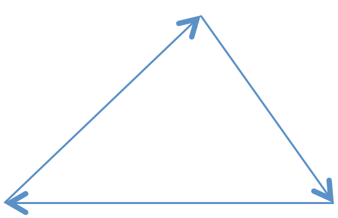


$k_L \ll k_S$

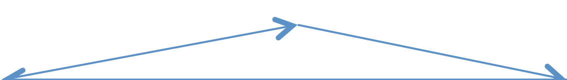
$\vec{k}_1 \approx -\vec{k}_2 \approx \vec{k}_S$

equilateral

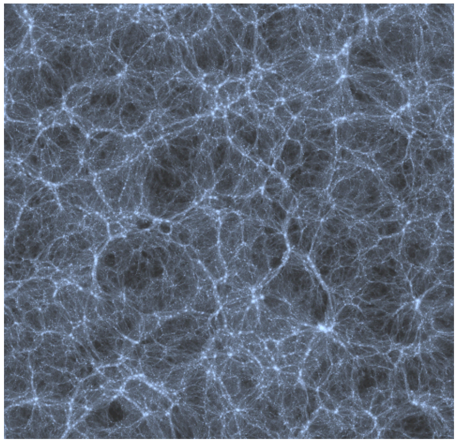
Need σ(fNL)~O(1) to distinguish between models (Alvarez *et al* 2014)



folded



Probing non-gaussianity with large-scale structure



Dark Matter or galaxy perturbation trace primordial perturbation

$$\delta\left(\vec{x},t\right)=\rho\left(\vec{x},t\right)/\bar{\rho}\left(t\right)-1$$

We can measure LSS bispectrum:

$$\left\langle \delta\left(\vec{k}_1,z\right)\delta\left(\vec{k}_2,z\right)\delta\left(\vec{k}_3,z\right)\right\rangle$$

Primordial NG imprinted

End of inflation

source redshift

present

clustering under (nonlinear) gravity

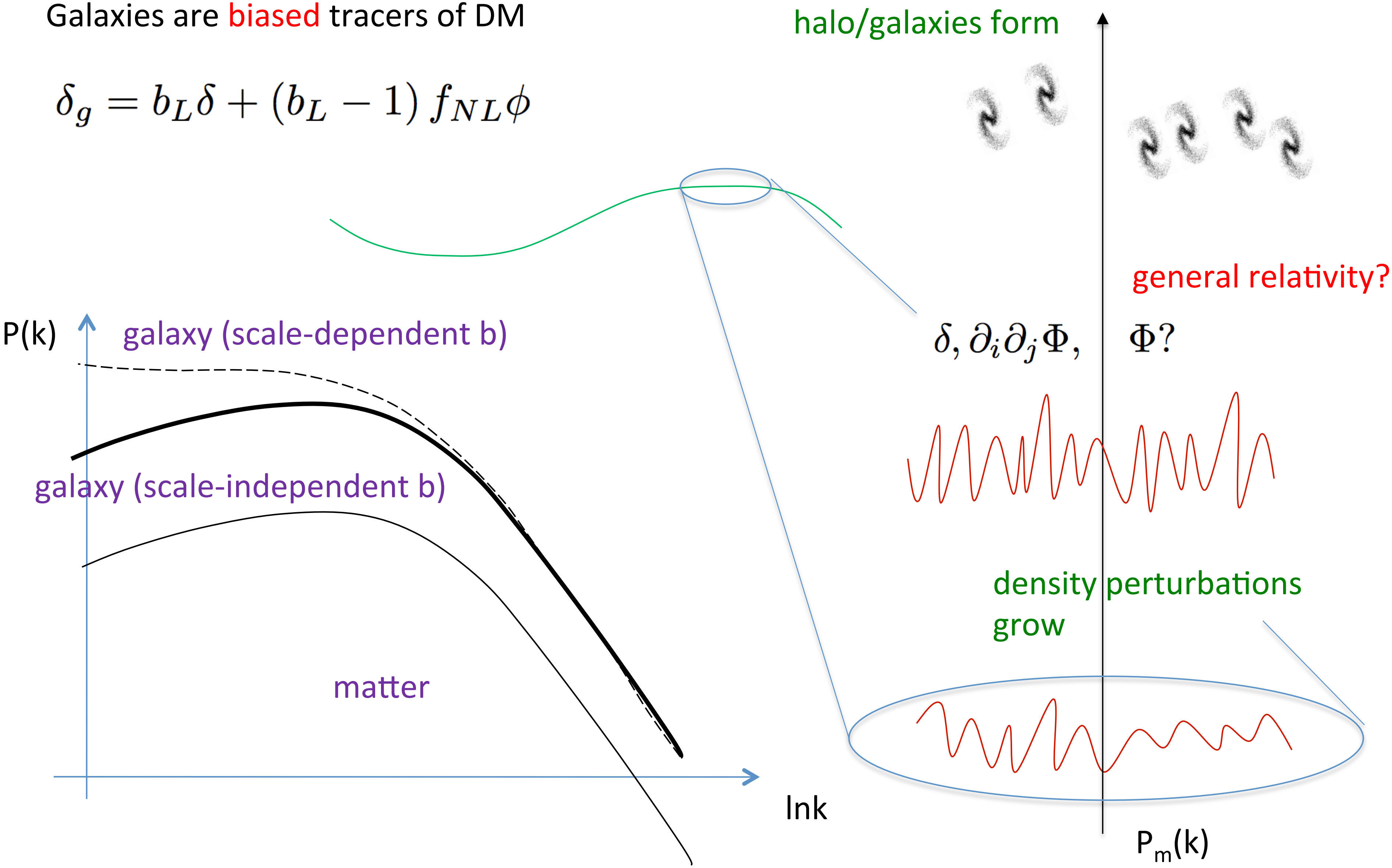
projection: RSD, lensing, Sachs-Wolfe, etc.

Scale-dependent galaxy bias

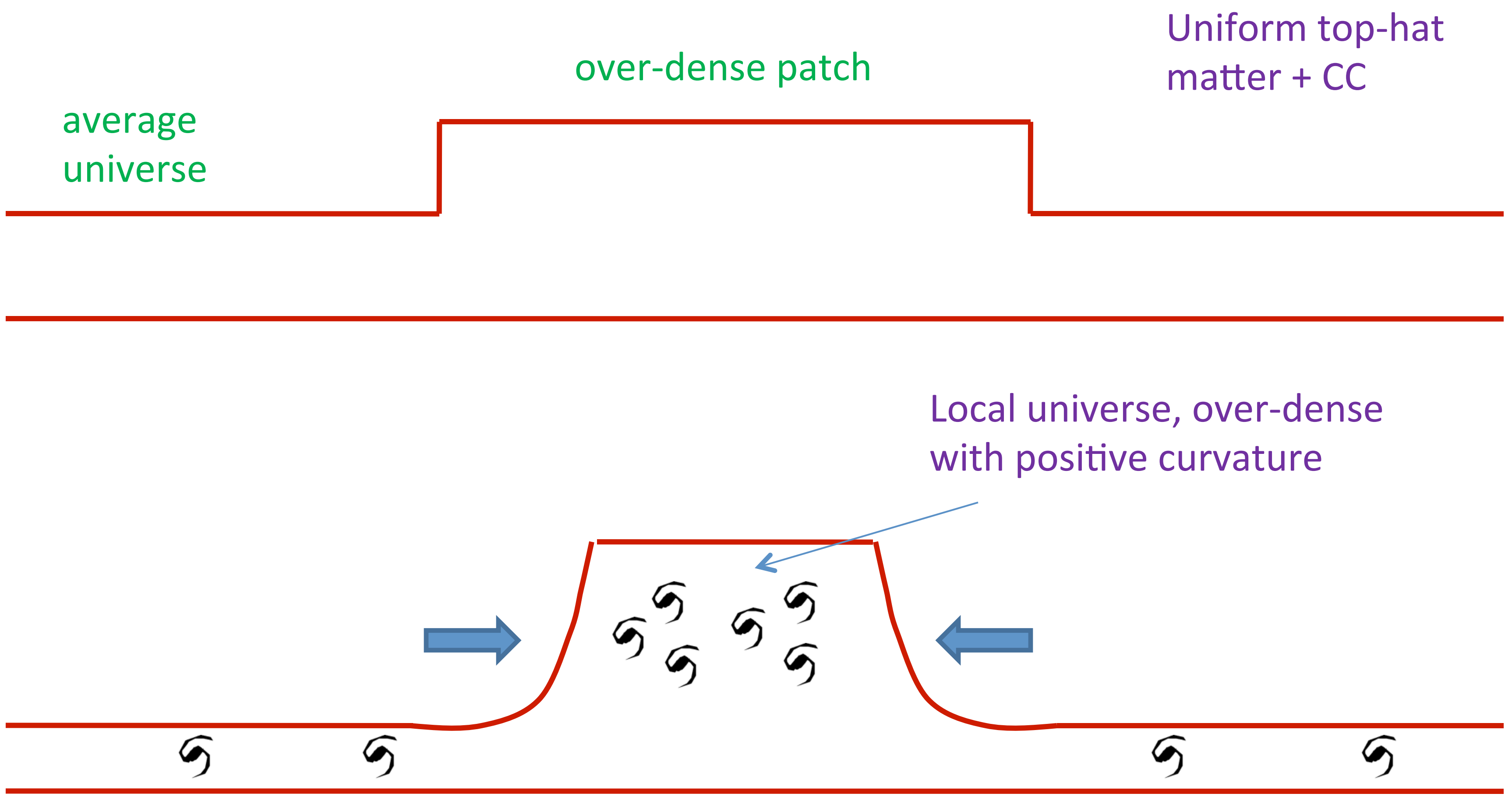
(Dalal, Dore, Huterer & Shirokov 2008)

Galaxies are biased tracers of DM

$$\delta_g = b_L \delta + (b_L - 1)\, f_{NL} \phi$$



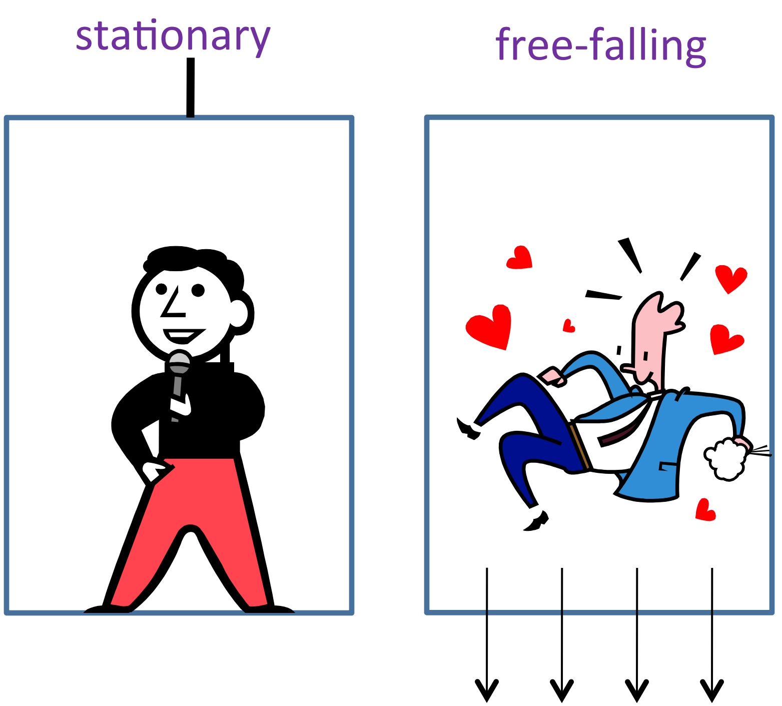
Separate universe: spherical top-hat overdensity



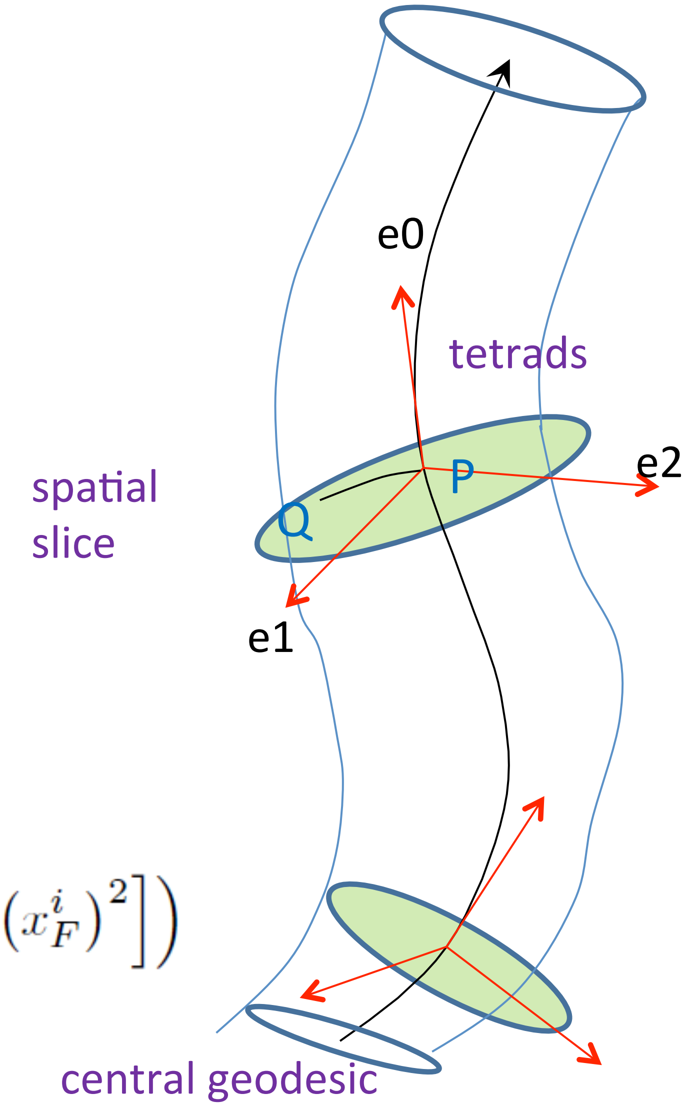
Valid in full general relativity!

Conformal Fermi Coordinates (CFC) (LD, Pajer & Schmidt 2015)

Einstein's elevator
Fermi Normal Coordinates
(FNC) (Manasse & Misner 1963)



Coarse-grain first !



$$(g_F)_{\mu\nu}\left(\tau_F, x_F^i\right) = a_F^2\left(\tau_F\right)\left(-\eta_{\mu\nu} + \mathcal{O}\left[\left(x_F^i\right)^2\right]\right)$$

Separate universe in CFC

(LD, Pajer & Schmidt 2015)

The usual **FNC**

homogeneous expansion

$$ds^2 = -\left[1 - \left(\dot{H} + H^2\right) r^2\right] dt^2 + \left[1 - \frac{1}{2}\left(H^2 + \frac{K}{a^2}\right) r^2\right] \delta_{ij} dx^i dx^j$$

$$+ \,\text{Newtonian tidal terms} \sim \partial\partial\Phi,\ \partial \cdot V$$

Newtonian terms

$$+ \,\text{General relativistic corrections} \sim \ddot{\Phi},\ H\dot{\Phi},\ H\partial\Phi$$

GR "correction"

ALL ``GR corrections'' absorbed into **a_F**, **H_F** and **K_F**

$$ds^2 = \boxed{a_F^2\left(\tau_F\right)} \left[-\left(1 + \boxed{r_F^2 \left(\partial_k \partial_l - \frac{1}{3}\delta_{kl}\partial^2\right)\Phi}\right) d\tau_F^2 + \left(1 - r_F^2\left(\partial_k \partial_l - \frac{1}{3}\delta_{kl}\partial^2\right)\Psi\right)\frac{\delta_{ij} dx_F^i dx_F^j}{\left(1 + \boxed{K_F} r_F^2/4\right)^2}\right]$$

Advantages compared to FNC:

- Ability to extrapolate to (super-)horizon scales
- Physical definition of local expansion rate

Conditions for separate universe

- **Local curvature**

$$K_F = \frac{2}{3}\partial^2\mathcal{R}$$

  Consider multiple fluids I = 1,2,3,…

$$\frac{dK_F}{d\tau} = -\mathcal{H}^2\left[\sum_I (1+w_I)\,\Omega_I\partial^2\left(V_I - V_o\right)\right] + \frac{2}{3}\mathcal{H}\partial^2\left(\Phi - \Psi\right)$$

- Exact “local universe” conditions (always true for matter + CC):
  - NO anisotropic stress
  - ALL fluids co-move along geodesics (free-falling)
  - Non-adiabatic pressure allowed

- Approximate conditions:
  - Sound horizons small
  - “Dark energy” component $w \approx -1$

Calculating in CFC: squeezed matter bispectrum

First add small-scale perturbations

$$ds^2 = a_F^2(\tau_F)\left\{ -\left[1 \boxed{+2\phi} + \left(\partial_k\partial_l\Phi - \frac{1}{3}\delta_{kl}\partial^2\Phi\right)x^k x^l\right] d\tau_F^2 + \left[1 \boxed{-2\psi} - \left(\partial_k\partial_l\Psi - \frac{1}{3}\delta_{kl}\partial^2\Psi\right)x^k x^l\right] \frac{\delta_{ij}dx^i dx^j}{(1+K_F r^2/4)^2} \right\}$$

Usual Euler-Poisson system

$$\partial^2\phi = \frac{3}{2}\mathcal{H}_F^2\Omega_m^F\delta$$

$$\delta' + \partial_i\left[(1+\delta)\,v^i\right] = 0$$

$$v_i' + \mathcal{H}_F v_i + v^j\partial_j v_i + \partial_i\phi = \boxed{-K_{ij}^\Phi x^j}$$

k_S << aH, but k_L arbitrary !

tidal tensor

$$K_{ij}^\Phi = \left(\partial_i\partial_j - \frac{1}{3}\delta_{ij}\right)\Phi$$

Formally identical to Newtonian, but extrapolate to **k_L < aH** :

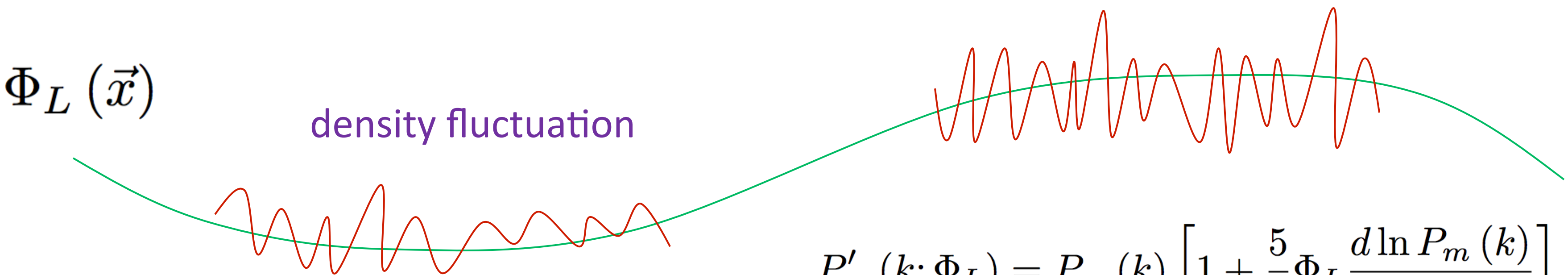
- equal proper time
- proper wavelength

$$\langle\delta(\mathbf{k}_1)\delta(\mathbf{k}_2)\Delta_{\rm sc}(\mathbf{k}_L)\rangle' = \left[\frac{26}{21} + \left(\mu_{SL}^2 - \frac{1}{3}\right)\left(\frac{8}{7} - \frac{d\ln P_\delta(k_S)}{d\ln k_S}\right)\right]P_{\rm sc}^\Delta(k_L)P_\delta(k_S)$$

A previous confusion is resolved

Scale-dependent biasing from general relativity? $f_{NL}^{local} = -5/3$

Argument: nonlinear relation between initial density and initial curvature in full GR.



$$P'_m(k;\Phi_L) = P_m(k)\left[1 + \frac{5}{3}\Phi_L \frac{d\ln P_m(k)}{d\ln k}\right]$$

What was overlooked: (LD, Pajer & Schmidt 2015; de Putter, Dore & Green 2015)
short-wavelength is not measured in proper units; a long-wavelength metric perturbation modulates local proper distance measure.

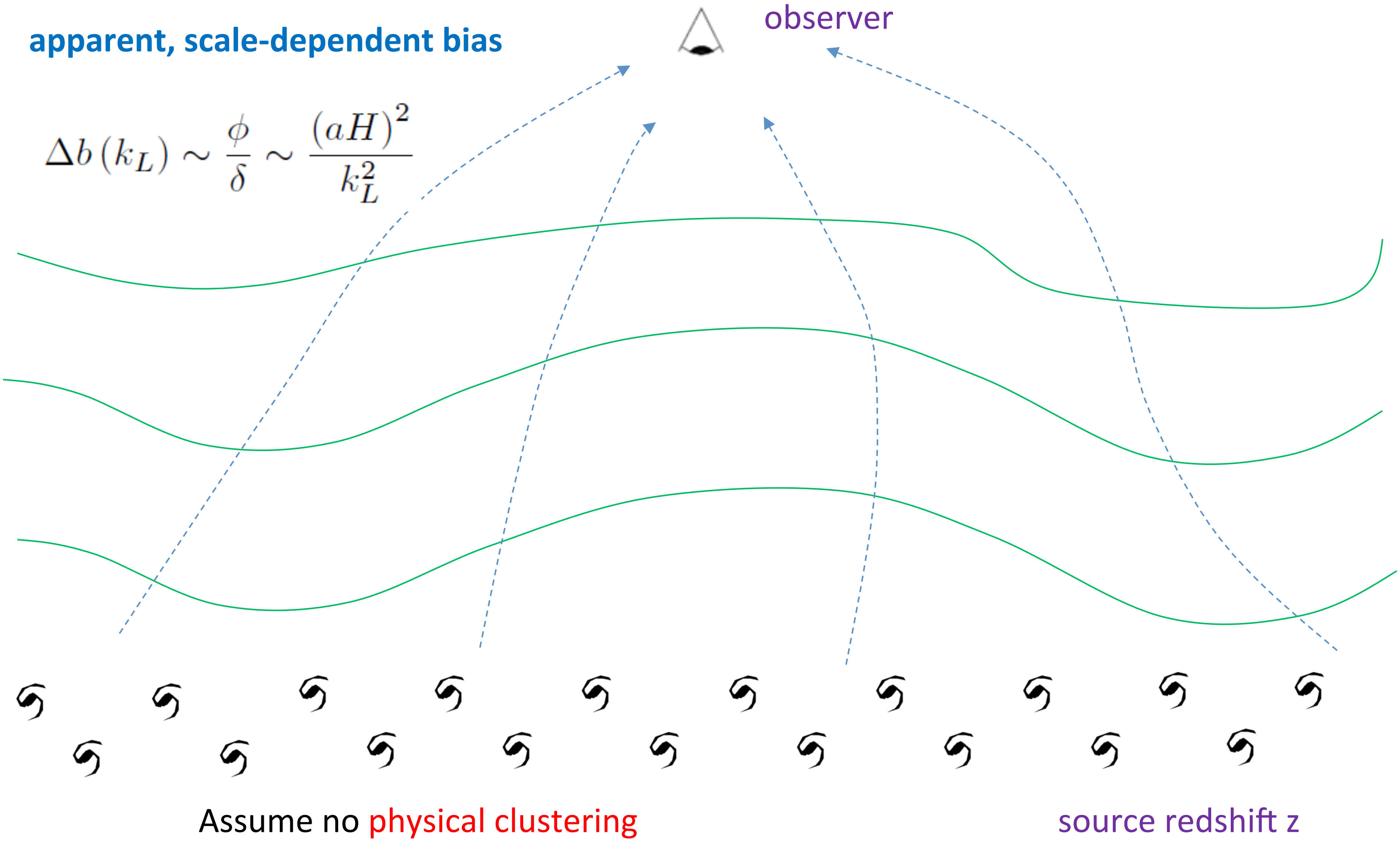
NO scale-dependent bias from GR (Baldauf, Seljak, Senatore & Zaldarriaga 2015)
NO scale-dependence in halo/galaxy shape correlation induced by GR
(Schmidt, Chisari & Dvorkins 2015)
Or any other correlation in halo/galaxy properties at linear order in metric

Projection effects

(e.g. Jeong, Schmidt & Hirata 2012
Camera, Santos & Maartens 2015)

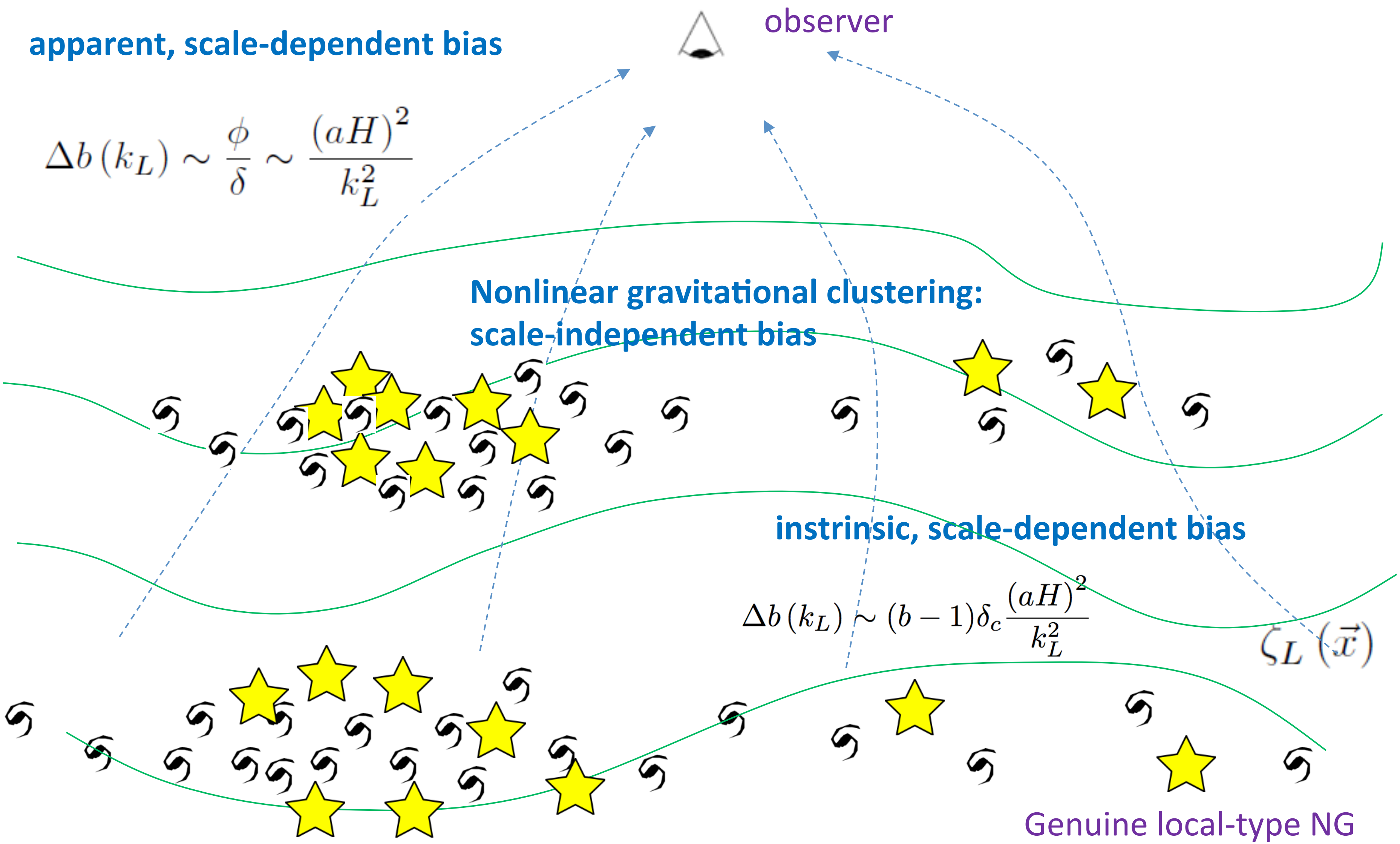
apparent, scale-dependent bias

$$\Delta b\left(k_L\right) \sim \frac{\phi}{\delta} \sim \frac{\left(aH\right)^2}{k_L^2}$$



Overview of large-scale clustering

CAVEAT: projection can also be tracer dependent --- magnification bias, evolution bias, etc.



Conclusion

- Galaxy clustering on large scales is a promising probe of (local-type) primordial non-gaussianity. $\sigma(f_{NL}) \sim O(1)$ requires accurate description in general relativity.

- We construct CFC in which local dynamical effects of a long-wavelength perturbation on structure formation is isolated. In full general relativity, the effect is equivalent to a modified expansion rate and curvature, plus a tidal force.

- We disprove a scale-dependent biasing caused by general relativistic dynamics. Detection of nonzero scale-dependent bias, if not explained by relativistic projection effects, is a smoking gun of new physics beyond single-field inflation.


Thank You!