A brief review of inflation

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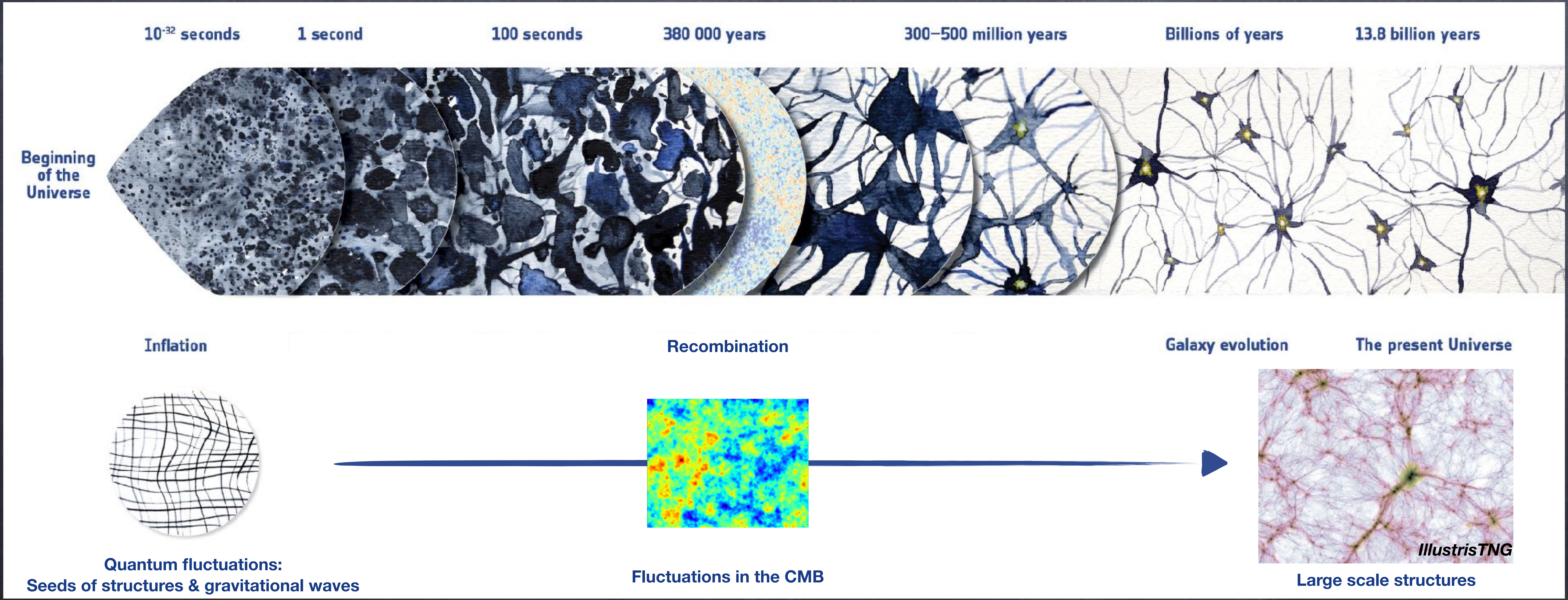
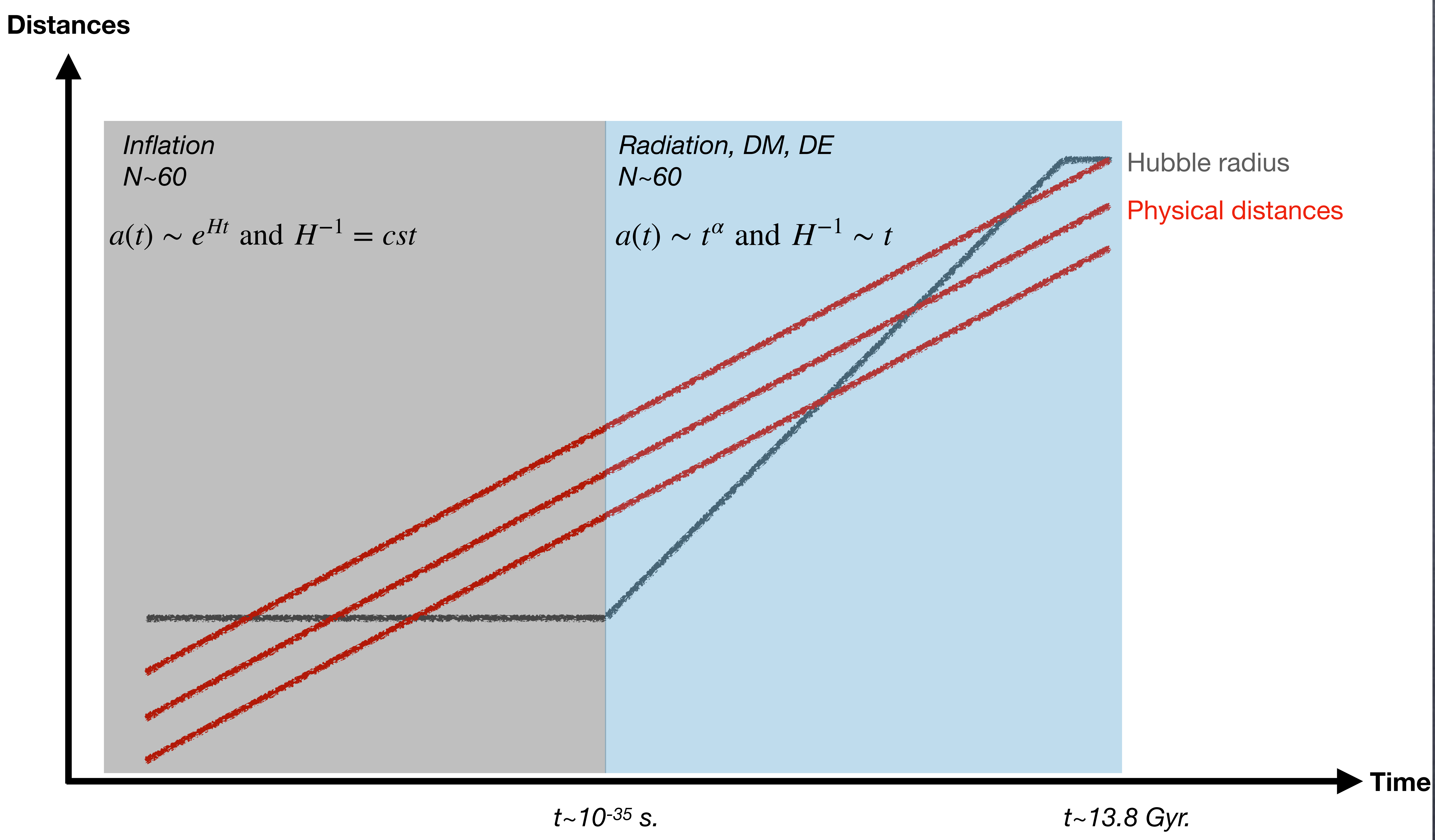


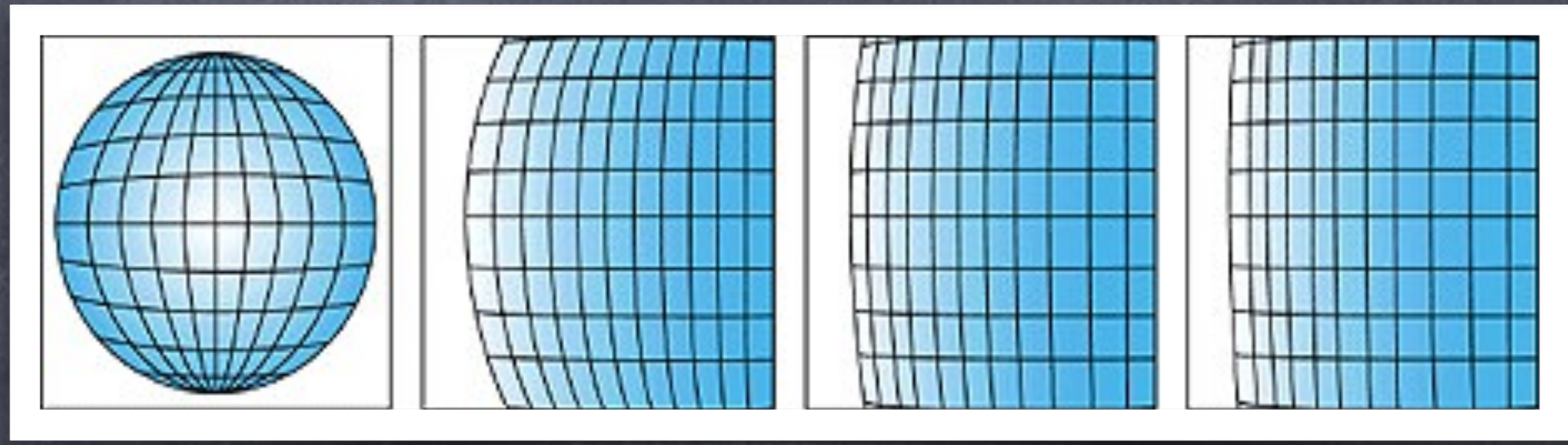
Inflation: Accelerated expansion in the very early Universe

Physical scales grows exponentially faster than Hubble radius



- Observable universe contained in one Hubble patch
  —> Homogeneity of CMB

- Spatial curvature is 'diluted' $\Omega_K(t) \sim 1/(aH)^2$
  —> exponentially suppressed



- High-energetic phenomenon

$$N_{inf} = H \times \Delta t$$

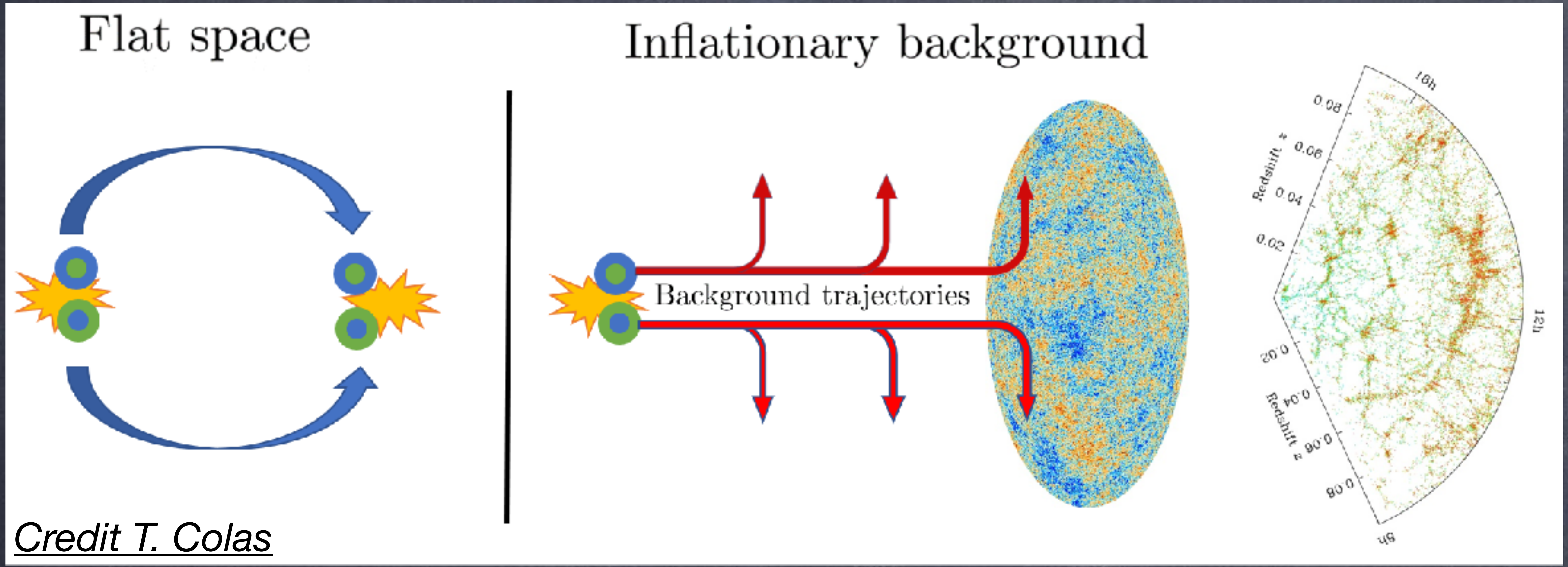
$$\Longrightarrow H \simeq 10^{16}\,\mathrm{km\,.\,s^{-1}Mpc^{-1}} = 10^{10}\,\mathrm{GeV}$$

Inflation & the origin of cosmic structures

Inhomogeneities extracted out of the quantum fluctuations of density & gravitational fields

- Linearize Einstein's equation: density waves and gravitational waves
- QFT in an expanding Universe: initial vacuum for fluctuations

➡ Instability at horizon radius crossing $\omega_k^2(t) \sim k^2/a^2(t) - H^2$



Cosmological observables

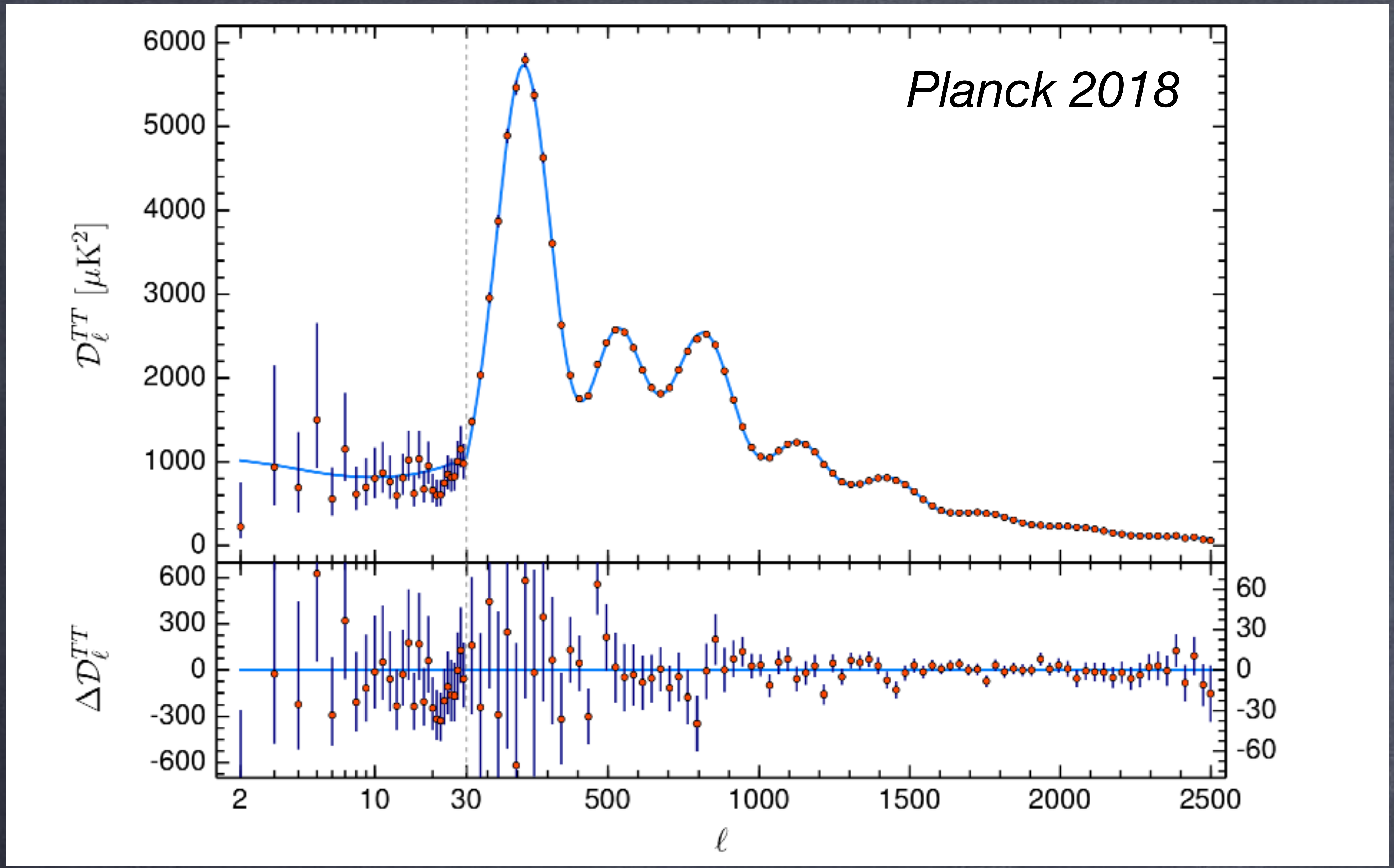
- *N*-pt correlation functions
- Abundance of structures
- Full PDF of cosmic fluctuations

Why studying inflation:

- *Sets up initial conditions for structure formation: detailed statistics*
- *High-energy physics beyond SM: number of fields, nature, couplings*
- *Laboratory for QM: QFT in curved spaces, 'classicalization', linear quantum gravity*

The origin of cosmic structures: what we know

Planck: Aghanim et al. 20
Planck: Akrami et al. 20



Density inhomogeneities:

✓ Superhorizon
✓ Adiabatic
✓ Almost scale-invariant
✓ Gaussian

$$P_\zeta(k) \sim (2\times 10^{-9})\left(\frac{k}{k_\star}\right)^{-0.035}$$

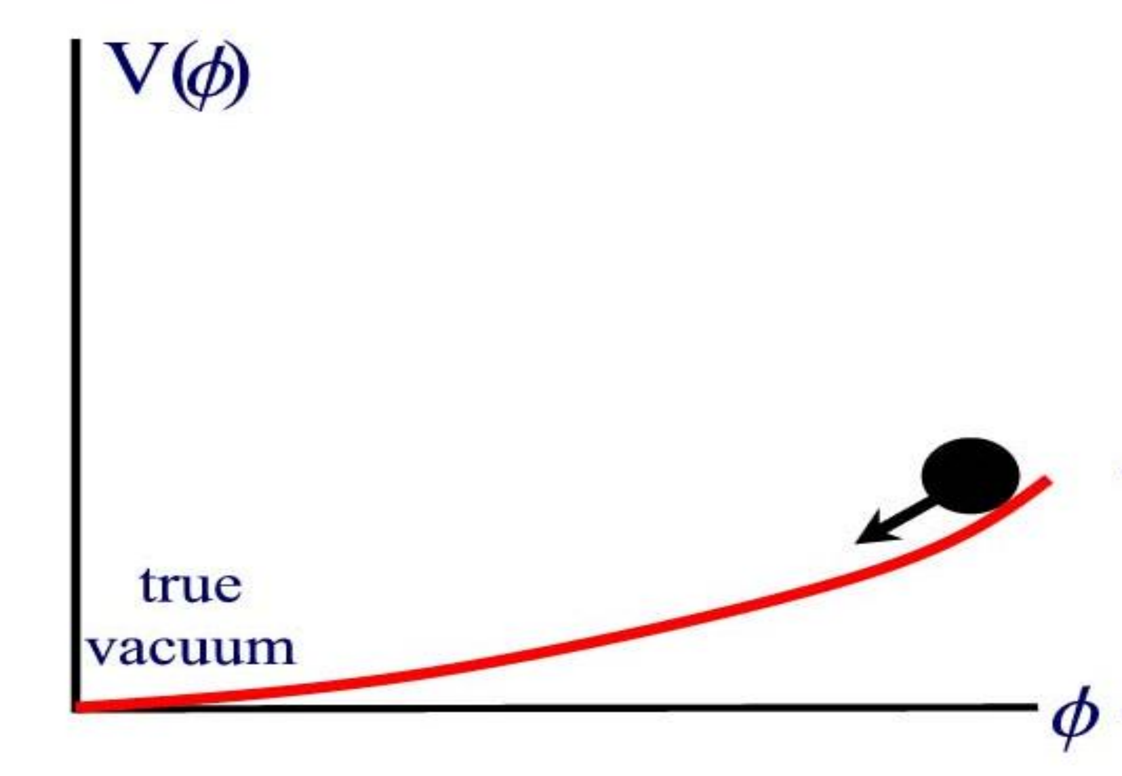
$$f_{\rm NL}^{\rm local} = -\,0.9 \pm 5.1$$
$$f_{\rm NL}^{\rm equil} = -\,26 \pm 47$$
$$f_{\rm NL}^{\rm ortho} = -\,38 \pm 68$$

Primordial gravitational waves:

✓ Not yet detected
✓ Upper bound

$$P_{GW}(k) \le 10^{-10}$$

$\boxed{\text{--> Single-field model in slow-roll}}$

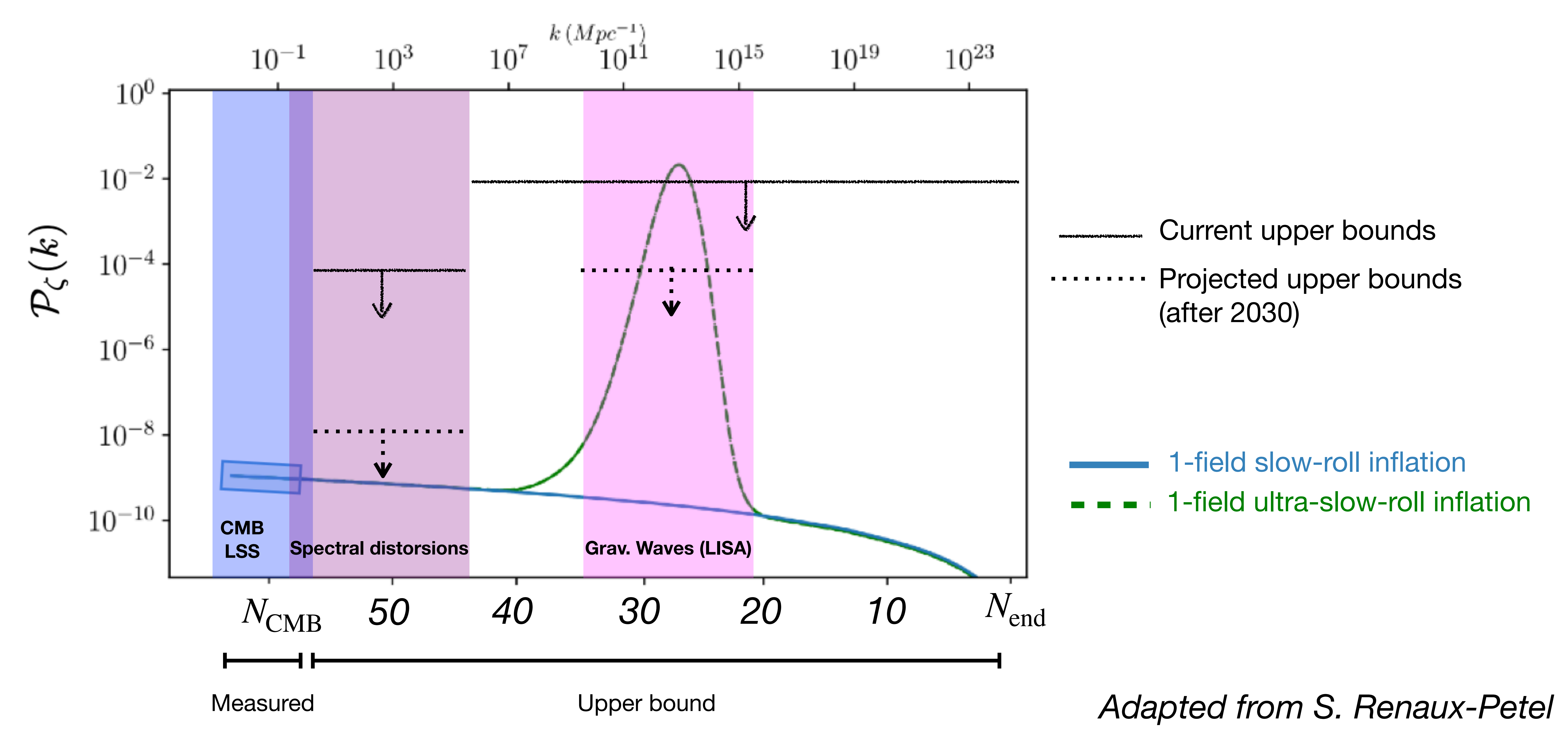


➡ *Complemented with LSS (SDSS, BOSS, DES)*

Eisenstein et al 05
Delubac et al. 15
Colas et al. 19
Doux et al. 22
D'Amico et al. 22
Cabass et al. 22
Riquelme et al. 22

The origin of cosmic structures: what we know

✓ *Type:* Gravitational waves not detected yet
✓ *Scales:* **~4** observed over **~26** predicted
✓ *Amplitude:* large-fluctuation regime not explored
✓ *Character:* quantumness not tested yet



Adapted from S. Renaux-Petel

Large-scale structures:

Prim. NG
Parity-odd N-pt

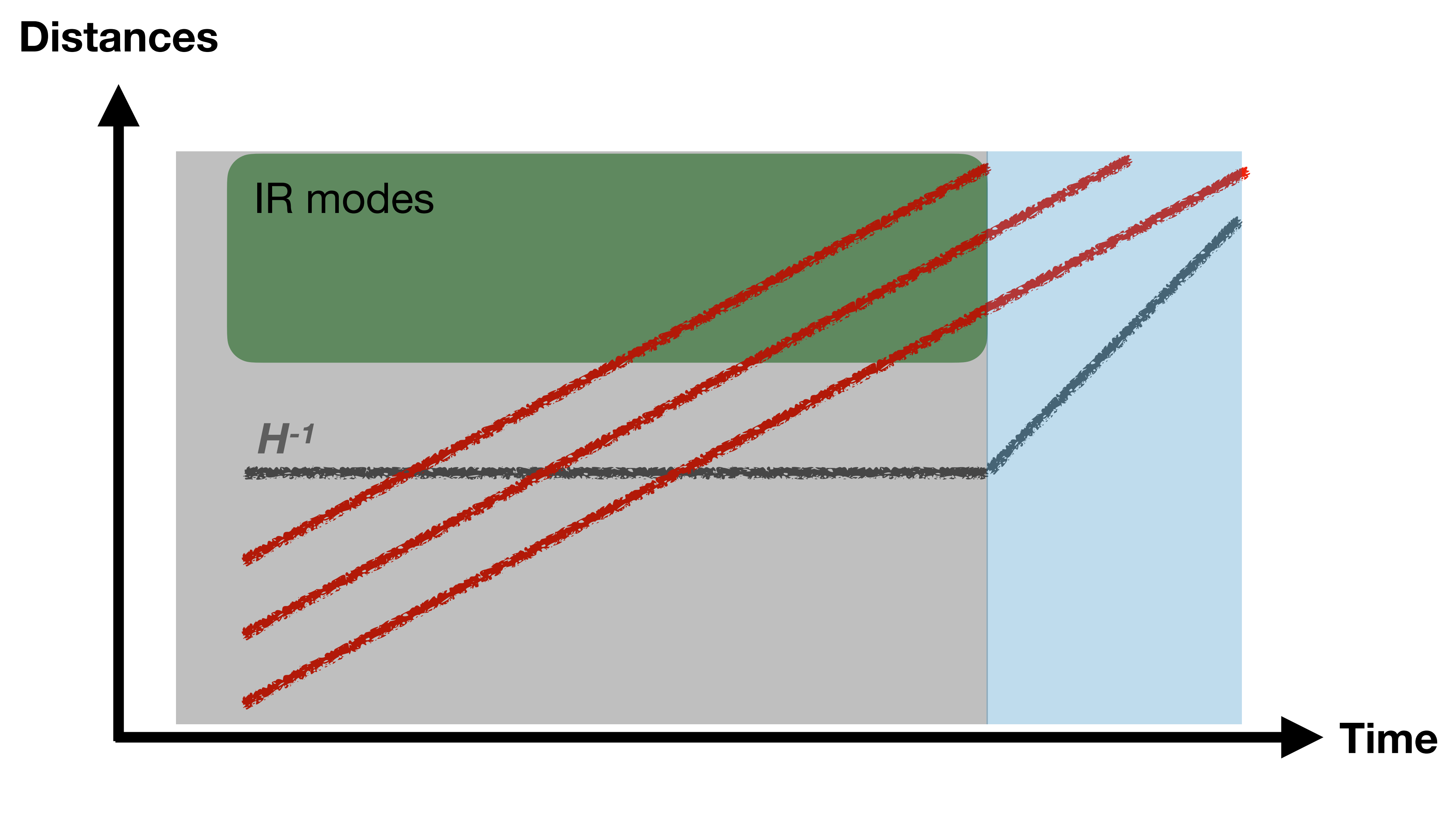
CMB:

B-mode
Spectral distorsions

Gravitational waves:

Stochastic background
Search for PBHs

Stochastic inflation & large fluctuations



Inflow of quantum fluctuations (UV) towards large-scale perturbations (IR)
—> Quantum modifications of the superhorizon dynamics

Stochastic inflation:
Effective classical and stochastic theory for coarse-grained fields

Test scalar field in inflation:

Coarse-grained field

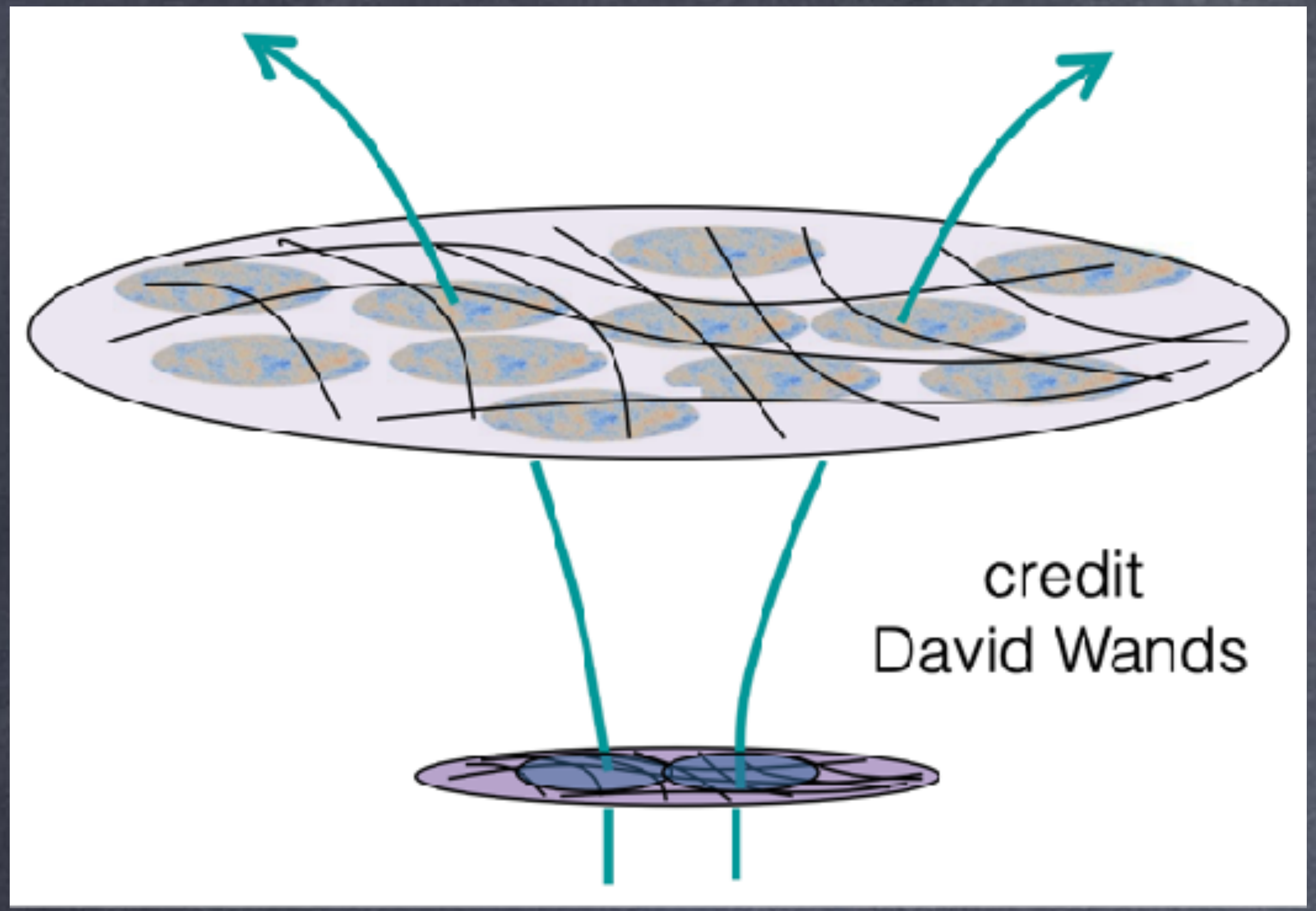
Gaussian white noise
(Inflow of UV quantum fluct. to IR)

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}\phi \\ \pi\end{pmatrix} = \begin{pmatrix}\pi/a^2(t) \\ -a^4(t)V_{,\phi}(\phi)\end{pmatrix} + \begin{pmatrix}\xi_\phi \\ \xi_\pi\end{pmatrix}$$

Classical drift
(Homog. & isotrop. evolution but *non-linear*)

Starobinksy 86
Nakao et al. 88
Habib 92
Grain, Vennin 17

Stochastic inflation & large fluctuations



Many superhorizon regions evolving like *separate universes* but *randomly* corrected by quantum fluctuations

Quantum-to-classical transition:
Quantum fluctuations treated as classical noise

Separate universe approximation:
Inhomog. & anisotropic perturbations matched to homogeneous & isotropic variations at large scales

Fokker-Planck Eq.: $\frac{\partial P(\varphi)}{\partial N} = \left[\mathscr{L}_{\mathrm{drift}} + \mathscr{L}_{\mathrm{diff}}\right] \cdot P(\varphi)$

Non-linear dynamics   « Quantum » diffusion

$P[N(\varphi)]$

PDF of duration of inflation within patches given an initial value for the inflaton

➡ Full PDF of curvature perturbation

$$\zeta = N - \langle N \rangle$$

Starobinsky 83
Wands et al 00
Fujita et al 13
Vennin, Starobinsky 15
Pattison et al. 19
Pinol, Renaux-Petel, Tada 19, 21
Tanaka, Urakawa 21
Artigas, Grain, Vennin 22

Stochastic inflation & large fluctuations

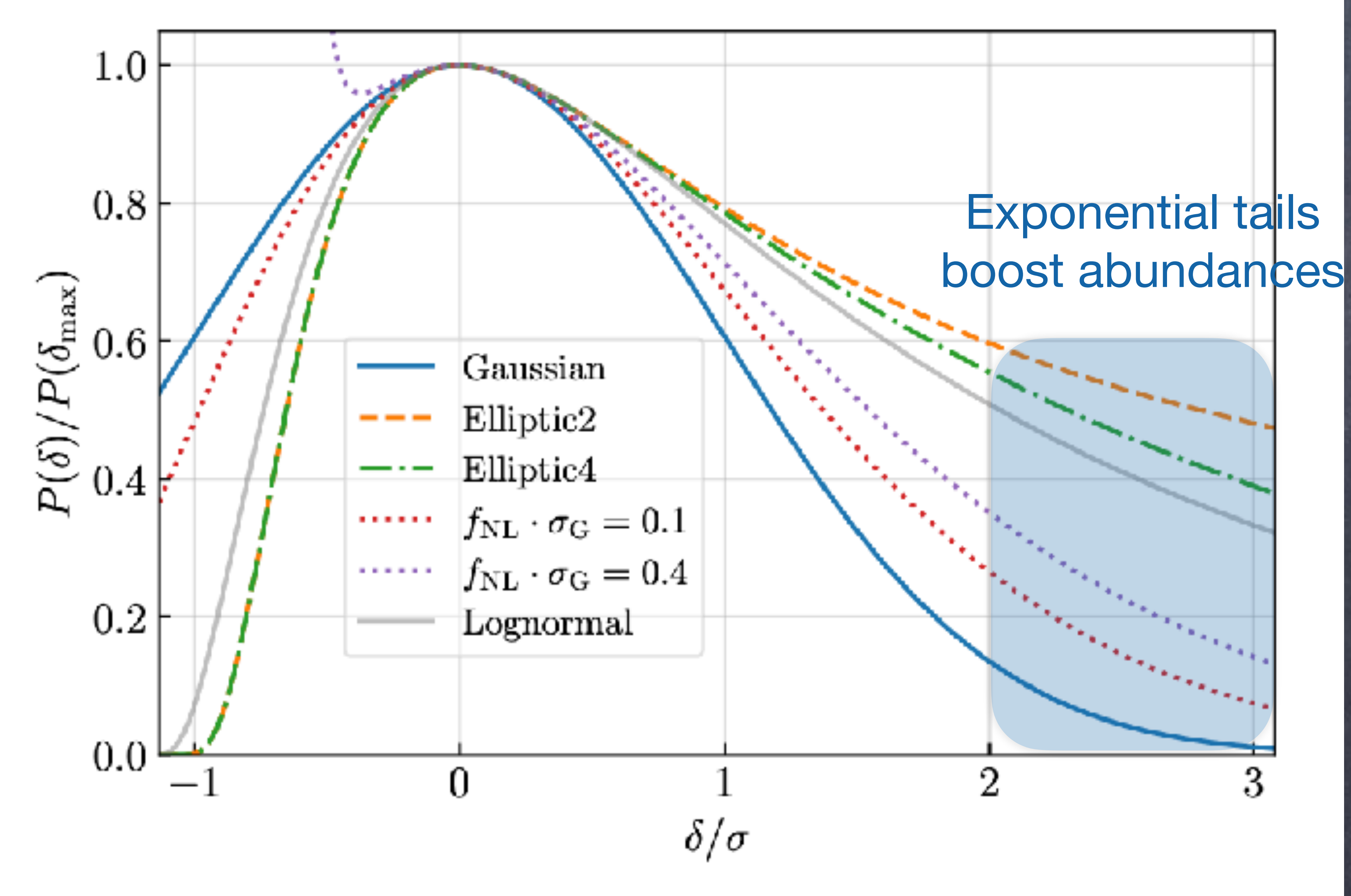
Ezquiaga, Garcia-Bellido, Vennin 20
Figueroa et al. 21, 22
Biagetti et al. 21

In the large-fluctuation regime: exponential tails instead of Gaussian

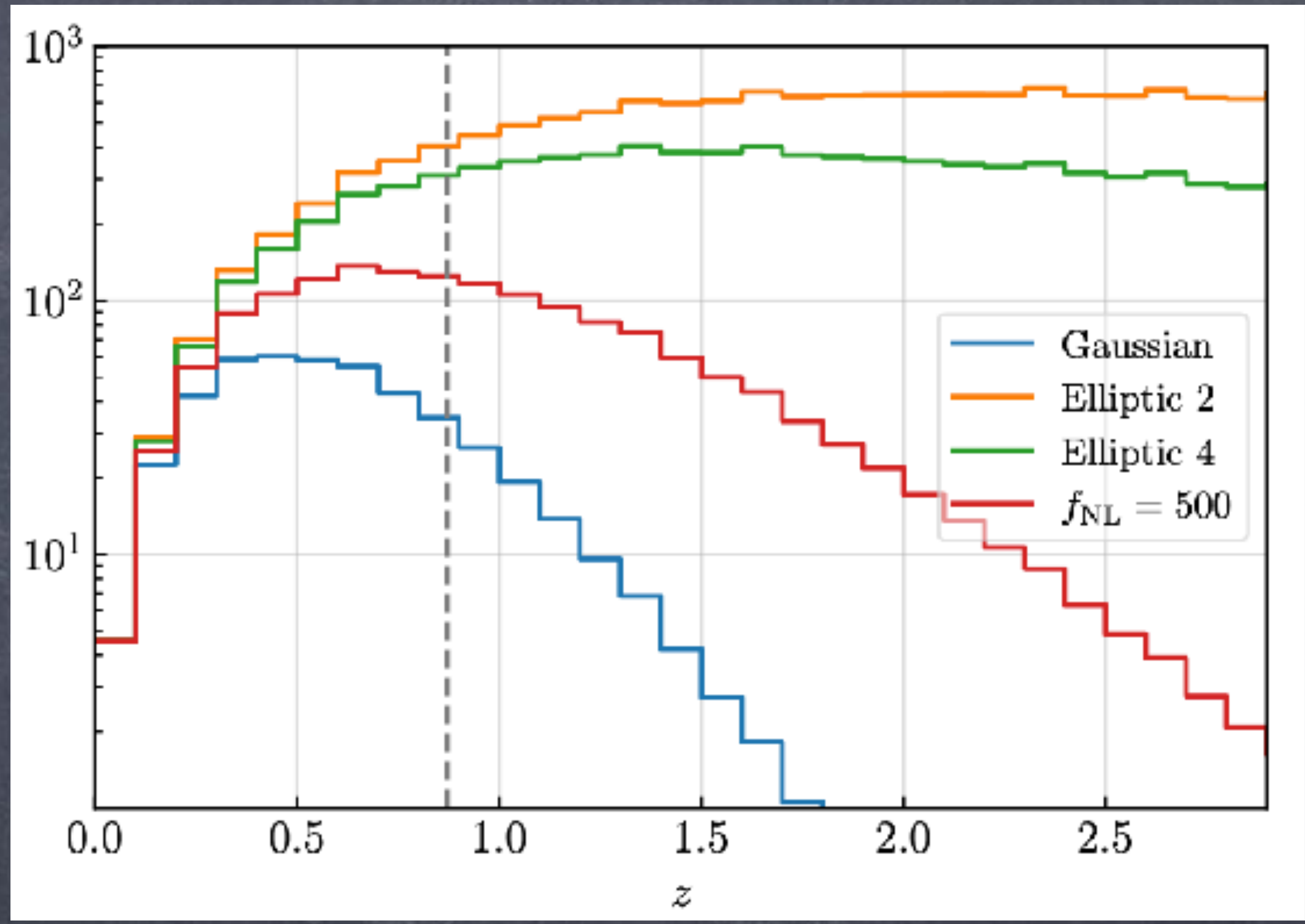
- ➡Generic prediction (*i.e.* valid in SR and Non-SR inflation)
- ➡More important in models with boosts in the *P(k)*
- ➡Impact on abundance of collapse objects (PBHs and DM haloes)

Gravitational collapse: $\delta\rho > \delta_c$

$$\beta = \mathrm{Prob}(\delta\rho > \delta_c) \Longrightarrow \frac{dn}{d\ln M}$$



Ezquiaga, Garcia-Bellido, Vennin 22



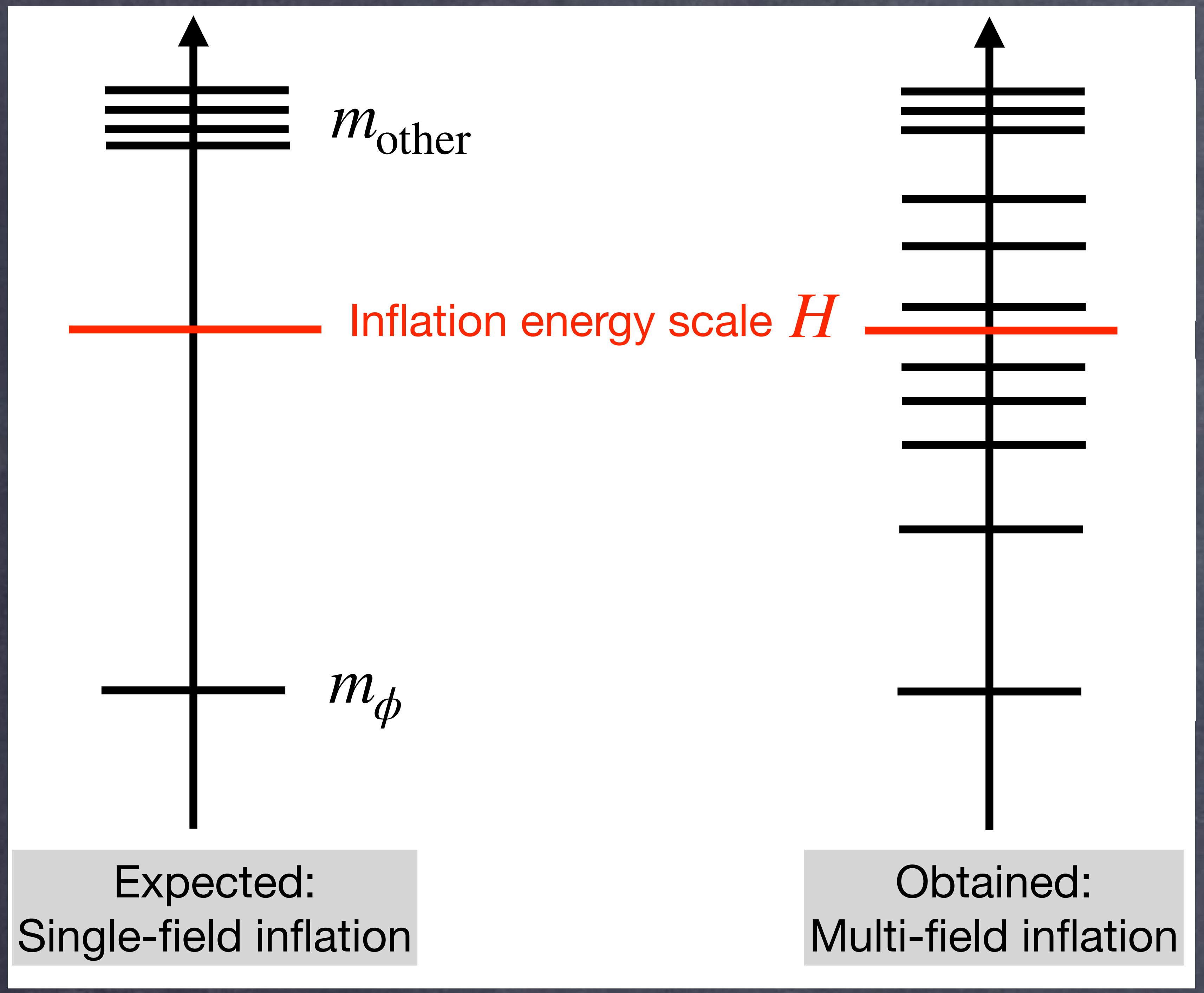
Num. haloes $M > 10^{15}$ Sol.Mass.

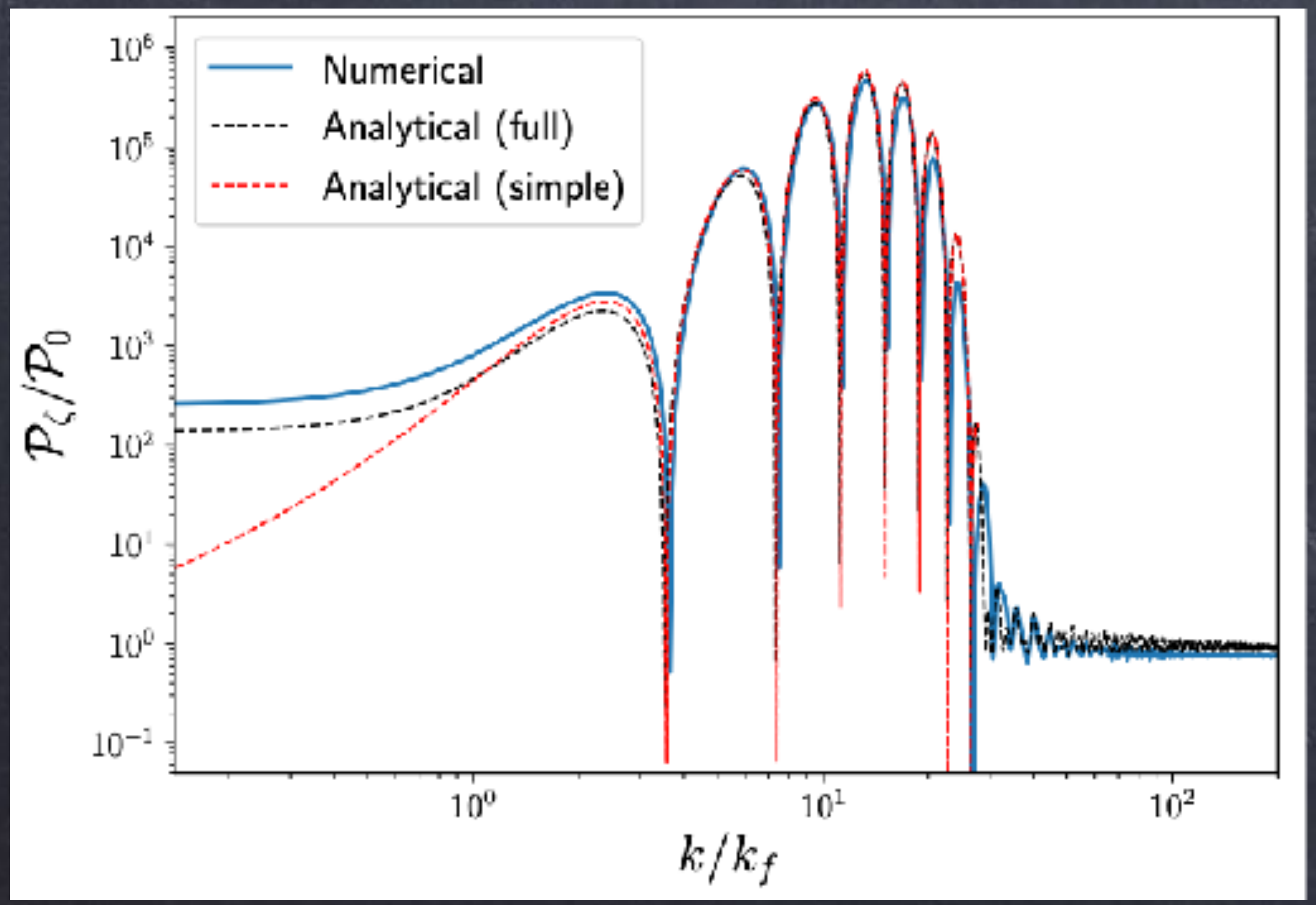
- ➡Explore inflationary models
- ➡*N*-pt correlators of LSS (halo model)
- ➡Interplay with low-*z* *vs.* high-*z* tensions
- ➡Other structures in the cosmic web

Multiple fields in inflation

Renaux-Petel, Turzynski 16
Fumagalli et al. 19
Garcia-Saenz, Pinol, Renaux-Petel 20
Pinol 20
Pinol, Aoki, et al. 21

Planck: 1-field inflation
High-energetic building: multiple fields, large couplings





Curved-field space: $S_{mat} = \int d^4x\sqrt{-g}\left[-G_{IJ}(\phi^K)g^{\mu\nu}\partial_\mu\phi^I\,\partial_\nu\phi^J - V(\phi^I)\right]$

Covers a large class of HE constructions
Use to explore the rich phenomenology of multi-field inflation

Boosts in the power spectrum (small scales):

- Curvature pert. coupled to entropic mode
- Q_S: Transient instability for bended trajectories
- Transferred to curvature perturbations

$$\mathcal{L}_{int} \sim \dot{\zeta}\, Q_s$$
$$m_s^2 = V_{,s,s} - H^2\eta_\perp^2 + \epsilon H^2 M_{Pl}^2 R_{fs}$$

Broad turn: featureless peak (enhance the production of PBHs)

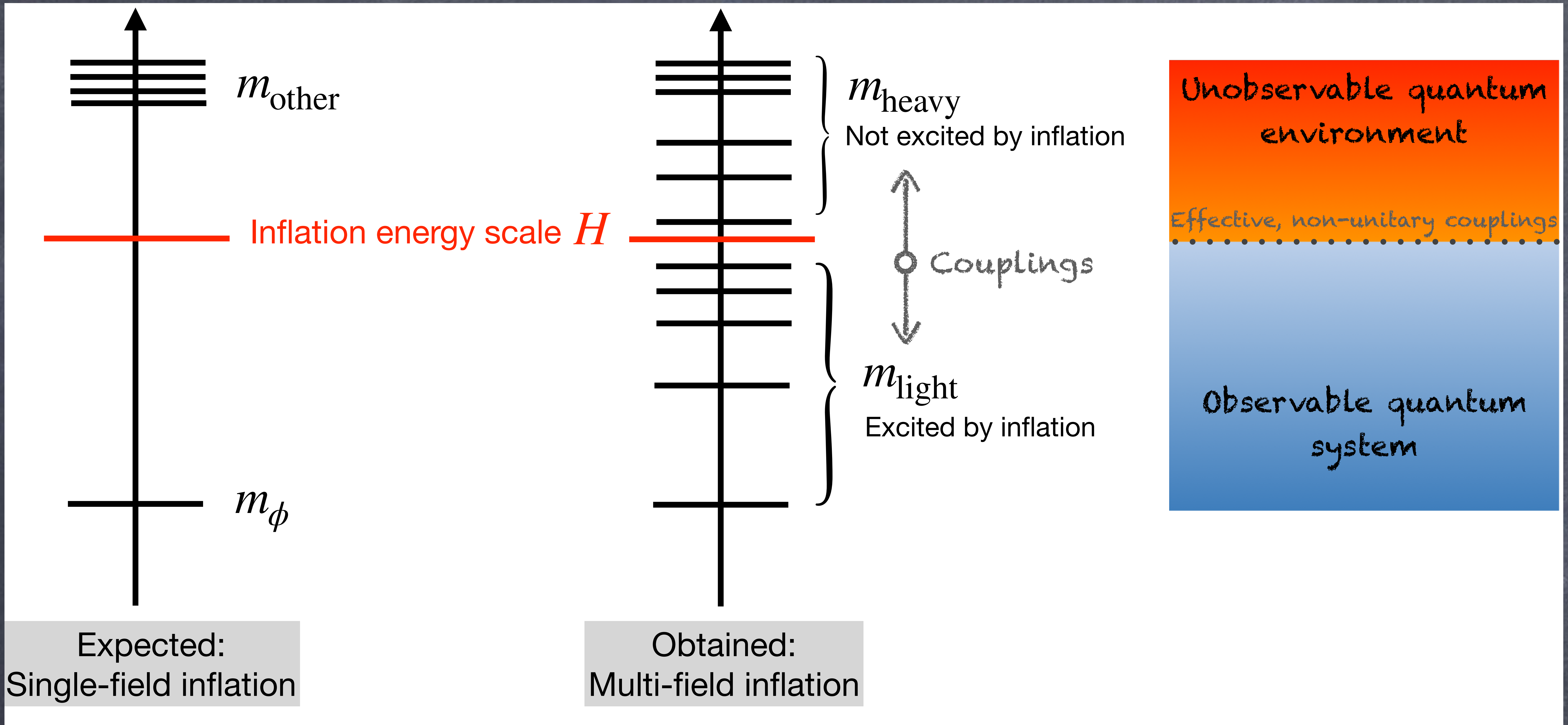
Fumagali, Renaux-Petel et al. 20

Sharp turn: peak and oscillatory features (excited states)
—> Transfer to secondary GW

Fumagali, Renaux-Petel et al. 21, 21, 22

Multiple fields in inflation

Many approches: 1-field effective theory, cosmological collider & bootstraps
➡***Open quantum system*** techniques



Boyanovsky 15
Martin, Vennin 18, 18
Colas, Grain, Vennin, 21, 22, 22
Martin, Micheli, Vennin 22
Burgess et al. 22
Bartolo, Daddi Hamou 22

- Keep track of quantum properties
- Explore decoherence channels
- Resum secular effects

➡ ***Promising theoretical tool: cosmological observables & quantum properties***

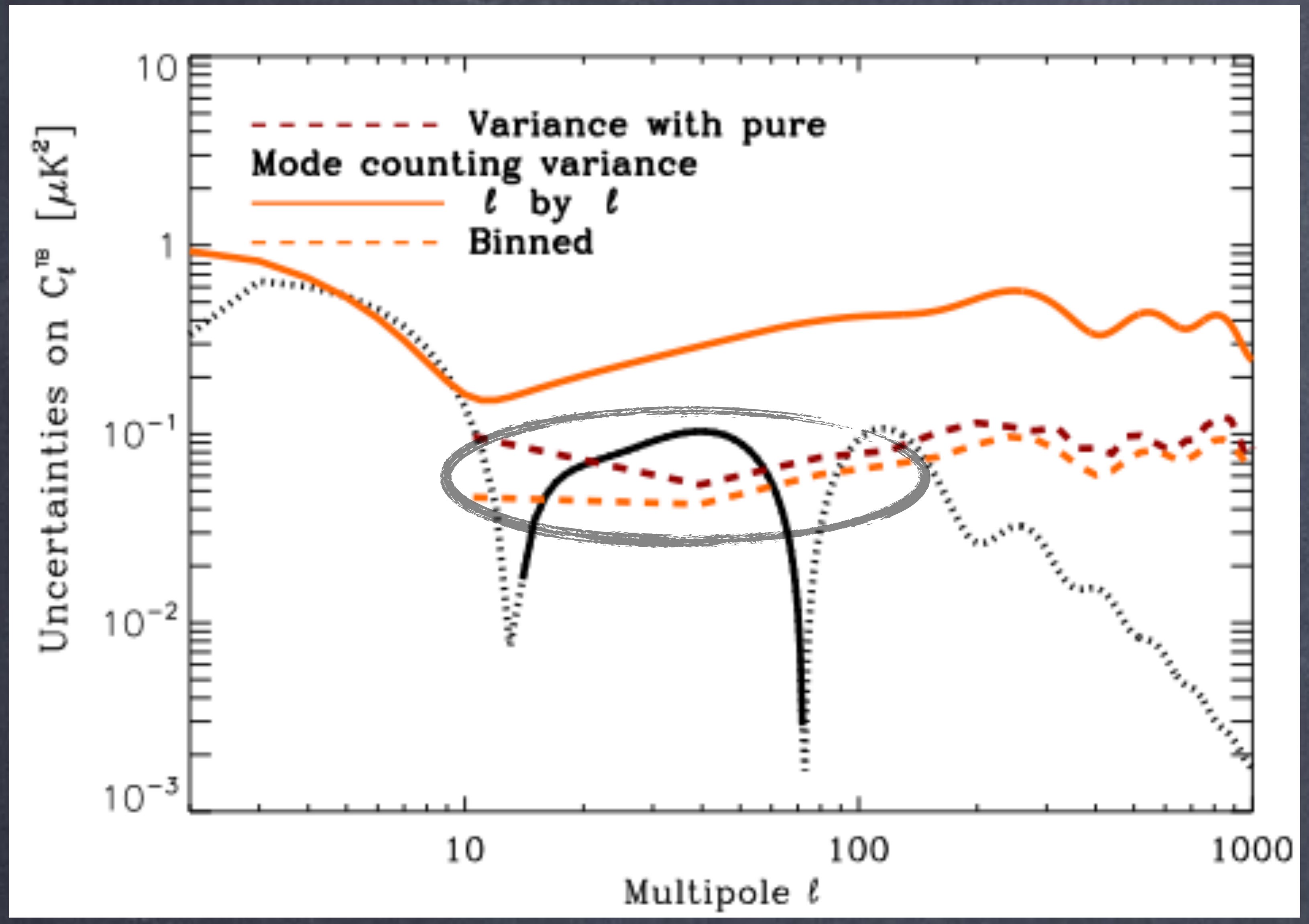
Parity violation during inflation

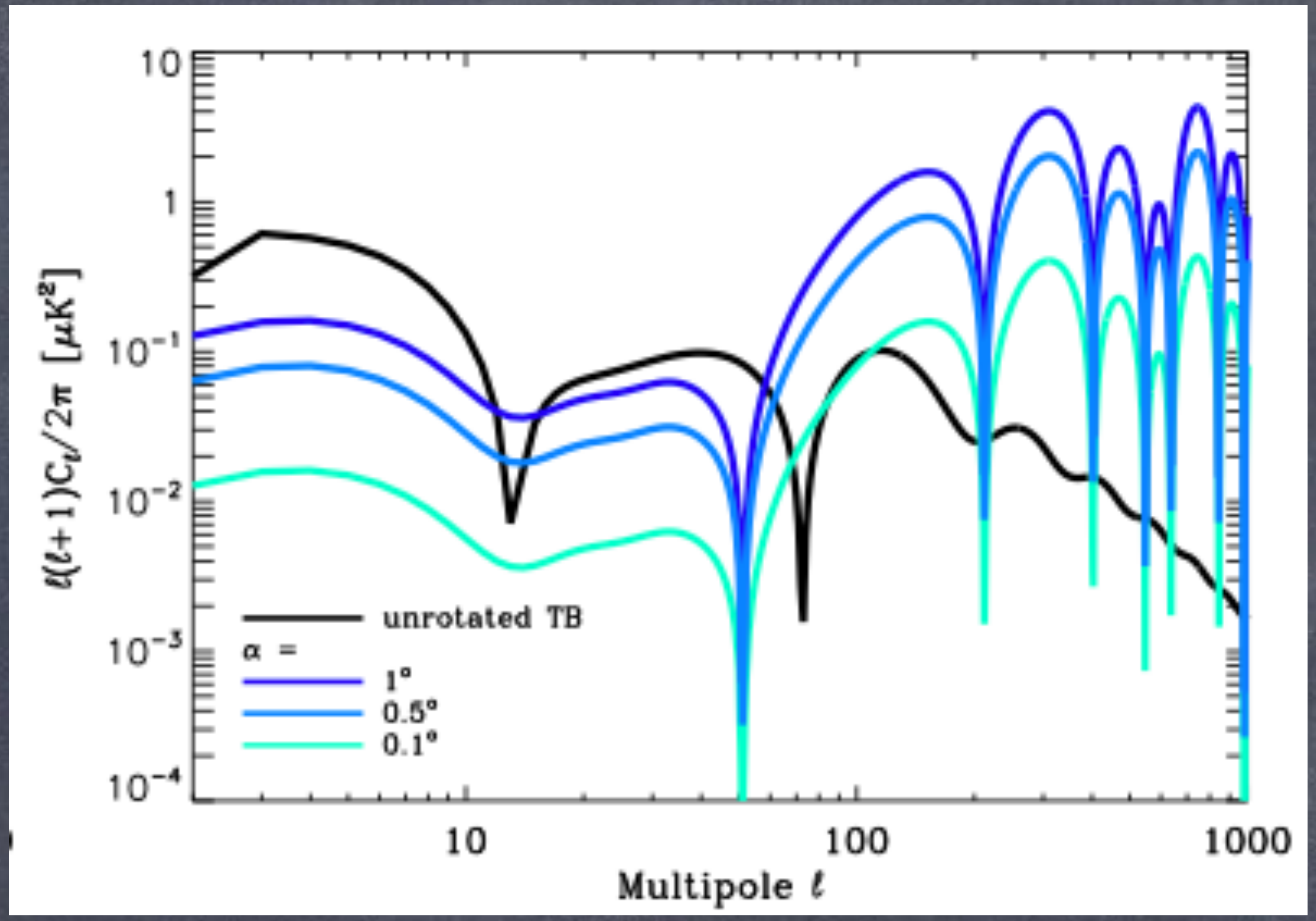
Lue et al. 99
Alexander, Yunes 09
Bartolo et al. 15
Bordin, Cabass 20
Shiraishi 12
Cook, Sorbo 12
Arkani-Hamed, Maldacena 15
Gluscevic, Kamionkowski 10
Schmidt et al. 15

Scalar-field: parity-invariant *N*-pt functions —> *TB* and *EB* are vanishing $C_\ell^{XB} \sim \int \mathrm{d}k\Delta(k)\left[P_l(k) - P_r(k)\right]$

Parity violation: magnetic fields, vector perturbations, Chern-Simons couplings, exchange of particles etc.

A simple model: right-handed GW only w. *r=0.05*





Rotation of the polarization plane
- L.O.S. effect (magnetic fields, Chern-Simons)
- Miscalibration of pol. angle of detector

➡*E* mixes into *B*: non-zero *TB* and *EB*

At CMB scales: no detection with power spectrum unless a full knowledge of angle and observed from space

At small scales: direct detection of GW bumps at $k \sim 10^{11\text{-}13}$ Mpc.$^{-1}$

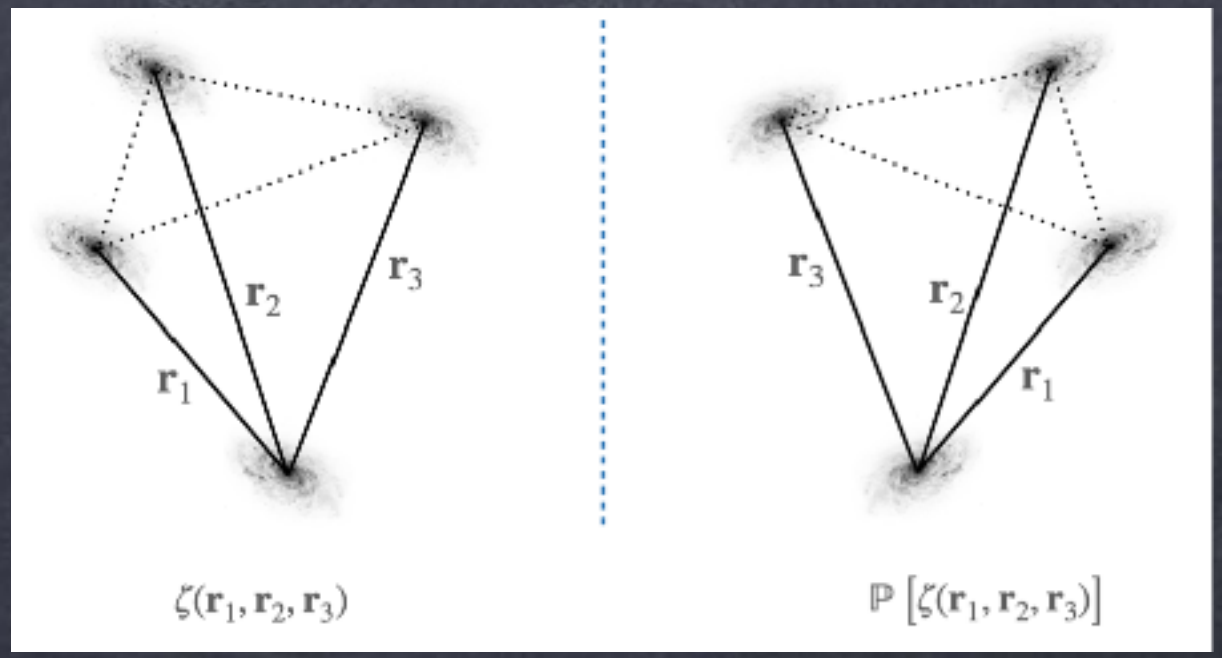
Ferte, Grain 15
Thorne et al. 18
Eskilt, Komatsu 22

Scalar perturbations: *4*-pt correlation (Parity [2-pt & 3-pt] = rotation)

2.9-sigma detection in BOSS

$$\mathscr{L}_{CS} \sim f(\phi)\left[F_{\mu\nu}F^{\mu\nu} - \gamma F_{\mu\nu}\widetilde{F}^{\mu\nu}\right]$$

	ρ_E/ρ_ϕ	
- CMB spectrum	$<10^{-13}$	
- CMB bispectrum	$<10^{-16}$	*Shiraishi 16*
- Odd trispectrum	$<10^{-19}$	*Philcox 22*



Conclusion

-Why inflation

Cosmology: Initial conditions for LSS
High-energy physics: beyond SM
Quantum mechanics: beyond lab-based exp.

-Theoretical constructions anchored on Planck obs.

BUT

-Obs. limited to large scales and small amplitude
-Anchor to be complemented with GW (energy scale of inflation)

-Many models w. rich phenomenology (Multi field, axion-inflation)
-New theoretical tools are developed (Open EFT, bootstraps, non-pertur.)

Large-scale structures

CMB

Gravitational waves