# EFT in the era of sub-percent precision: progress and open questions

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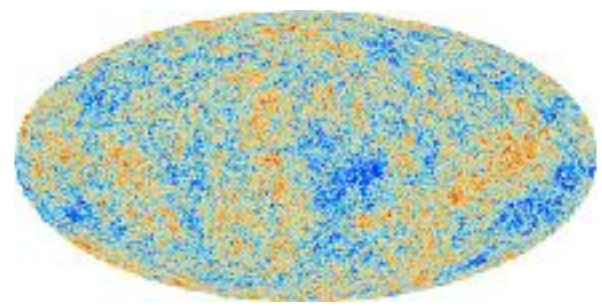
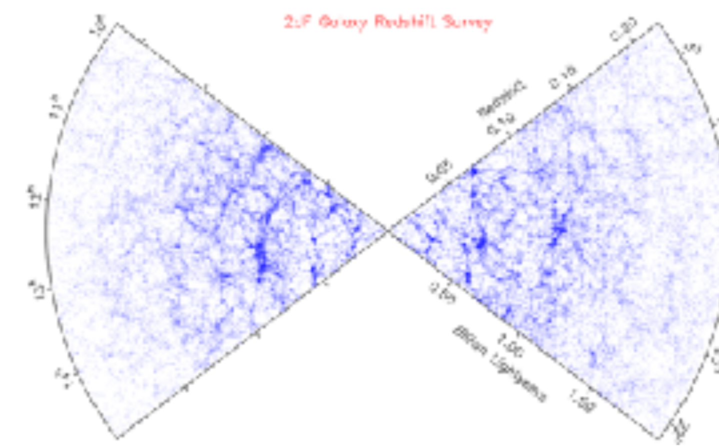
CTP/LNS/MIT

"New Physics from galaxy surveys" 11/06/2023

# Cosmology



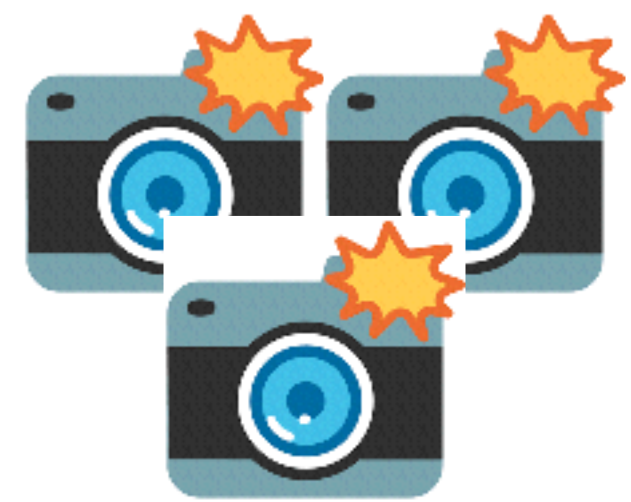


CMB

galaxies

inflation

$$E \lesssim 10^{16}\ \mathrm{GeV}$$



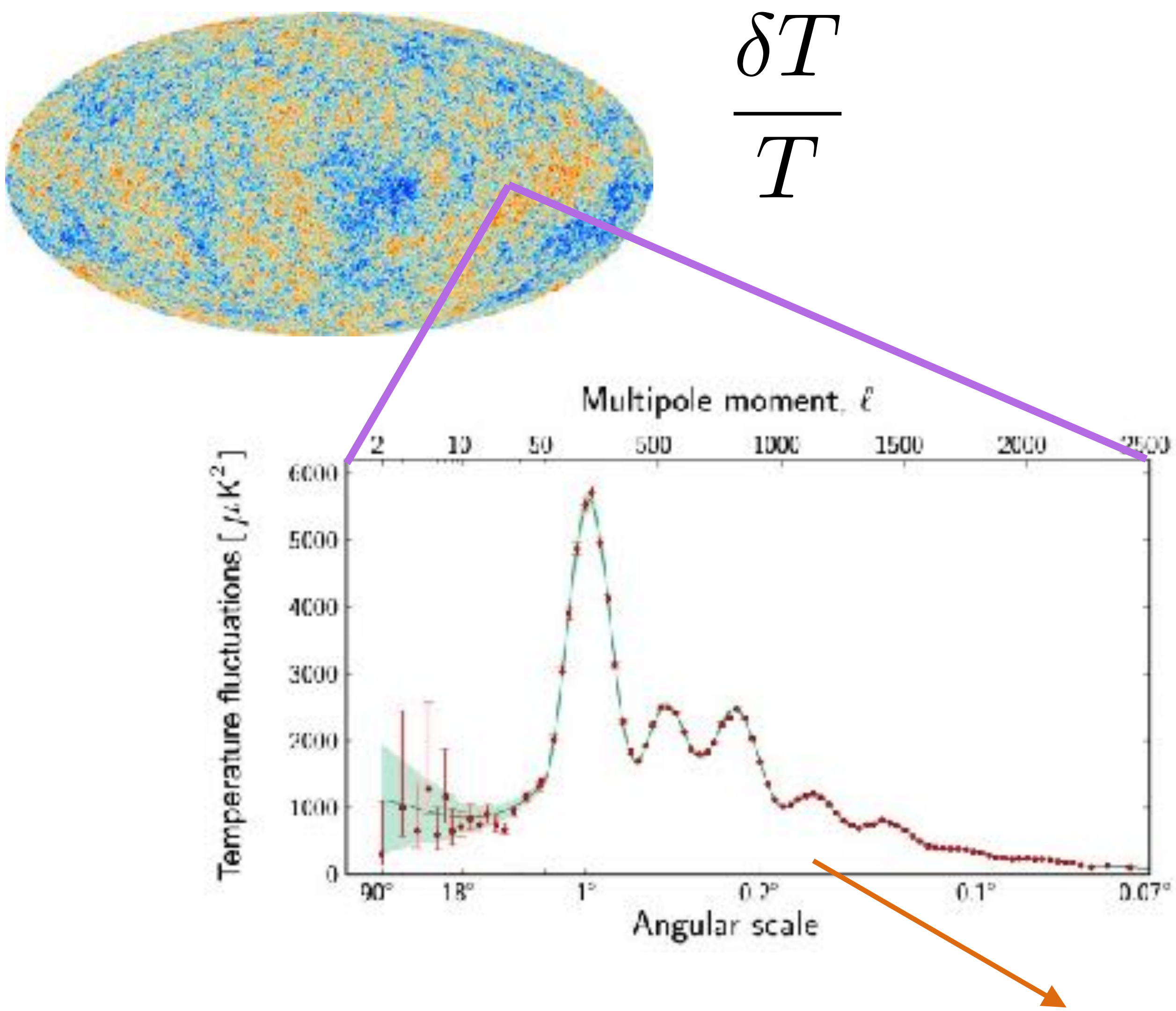
$\Lambda\mathrm{CDM}$ : Inflation, Cold Dark Matter, Lambda

Known Unknowns:
What was inflation, exactly?
DM? etc.

Unkown Unknowns:
Surprises ?

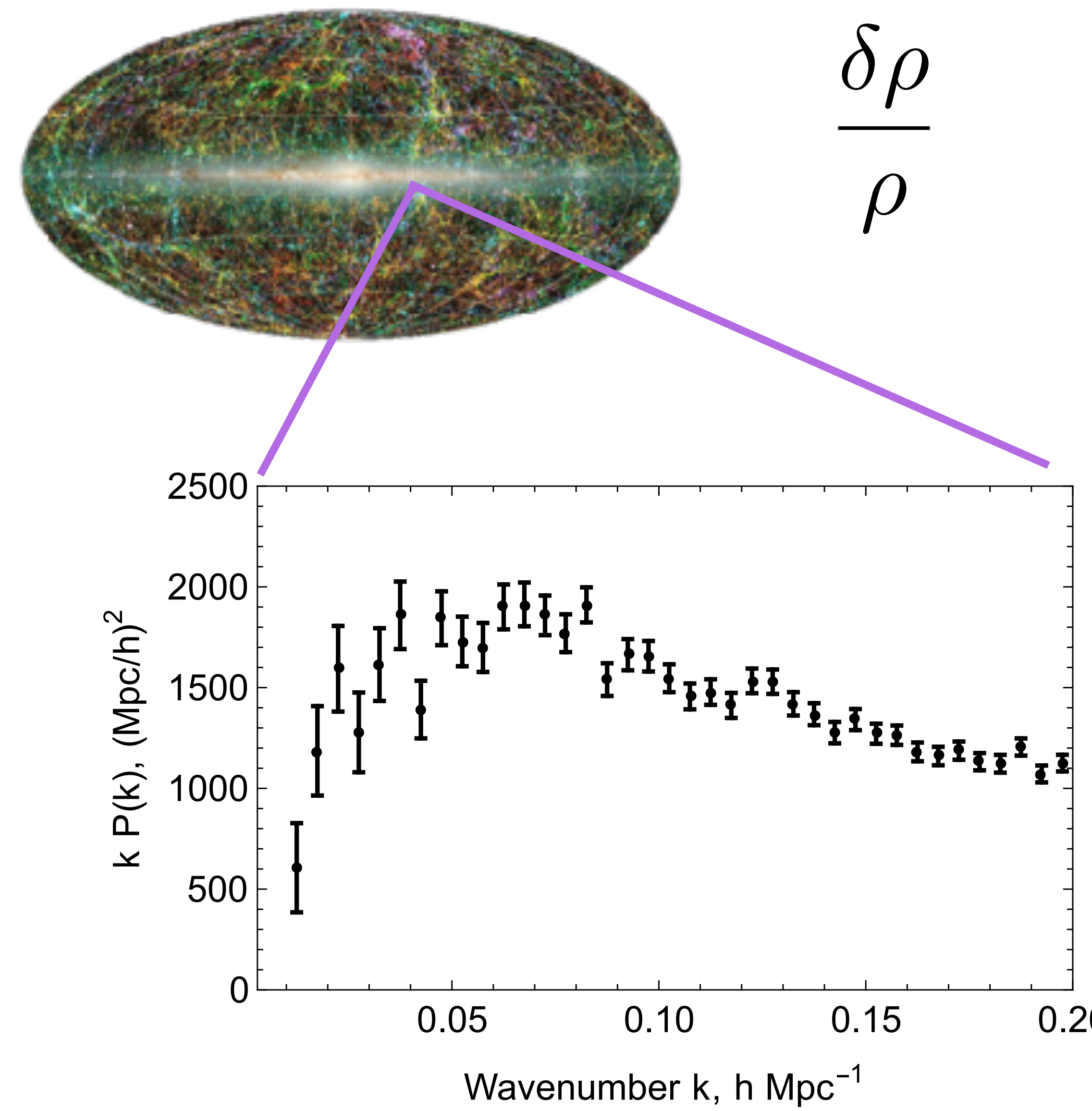
# Full-shape analysis

CMB:




$$\frac{\delta T}{T}$$

LSS:

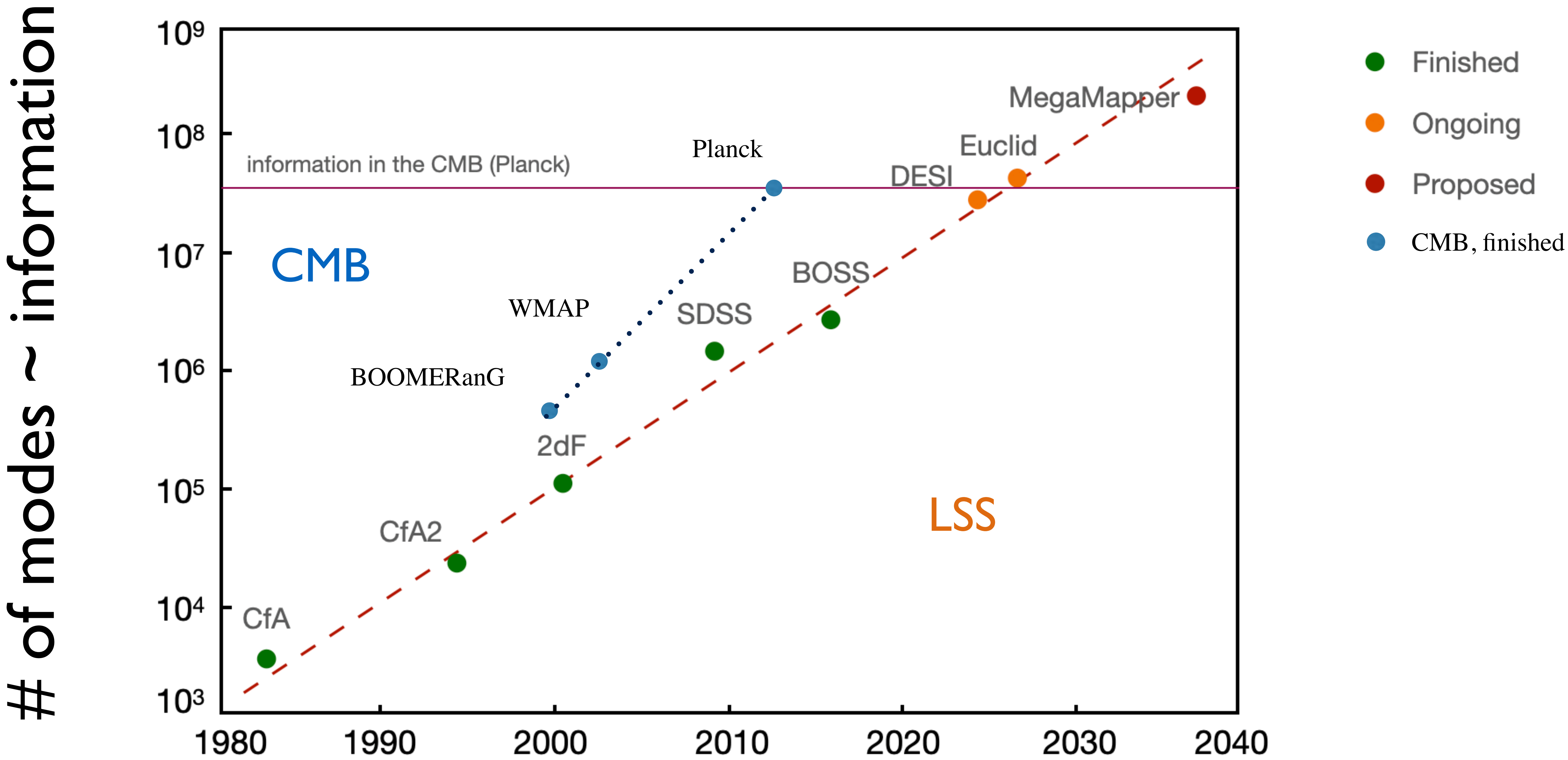



$$\frac{\delta \rho}{\rho}$$

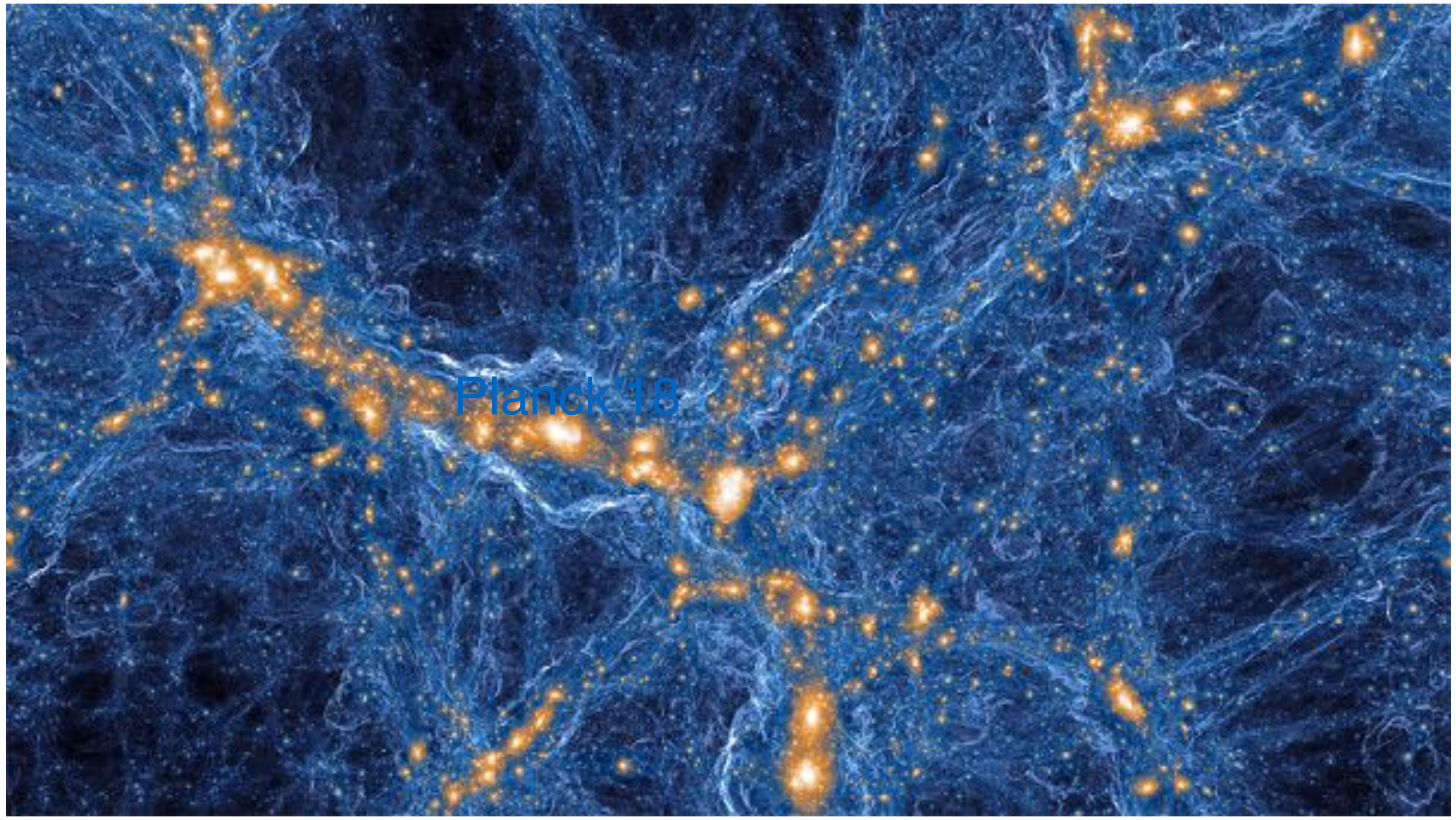
Parameters: $\rho_{\rm dm}, \cdots$

- CMB and LSS probe different scales, different epochs (redshifts) different physics !
- LSS is 3d —> contains orders of magnitude more information

# Large-Scale Structure: mode counting



# Sources of non-linearity




IllustrisTNG

- Clustering of dark matter
- Galaxy - DM connection
- Baryonic feedback
- Redshift space distortions

$$\delta_{\rm g} = b_1\delta + b_2\delta^2 + b_{\mathcal{G}_2}(\nabla_{\langle i}\nabla_{j\rangle}\Phi)^2 + \ldots$$

McDonald, Roy (2009), ++

Desjacques, Jeong, Schmidt (2016)

Nuisance parameters: $b_1, b_2, b_{\mathcal{G}_2}, \ldots$

# Numerics/Analytics

## Simulations

- ✓ matter clustering
- ✓ unlimited range
- ✗ galaxy formation
- ✗ time-consuming

credit: lineartestpilot

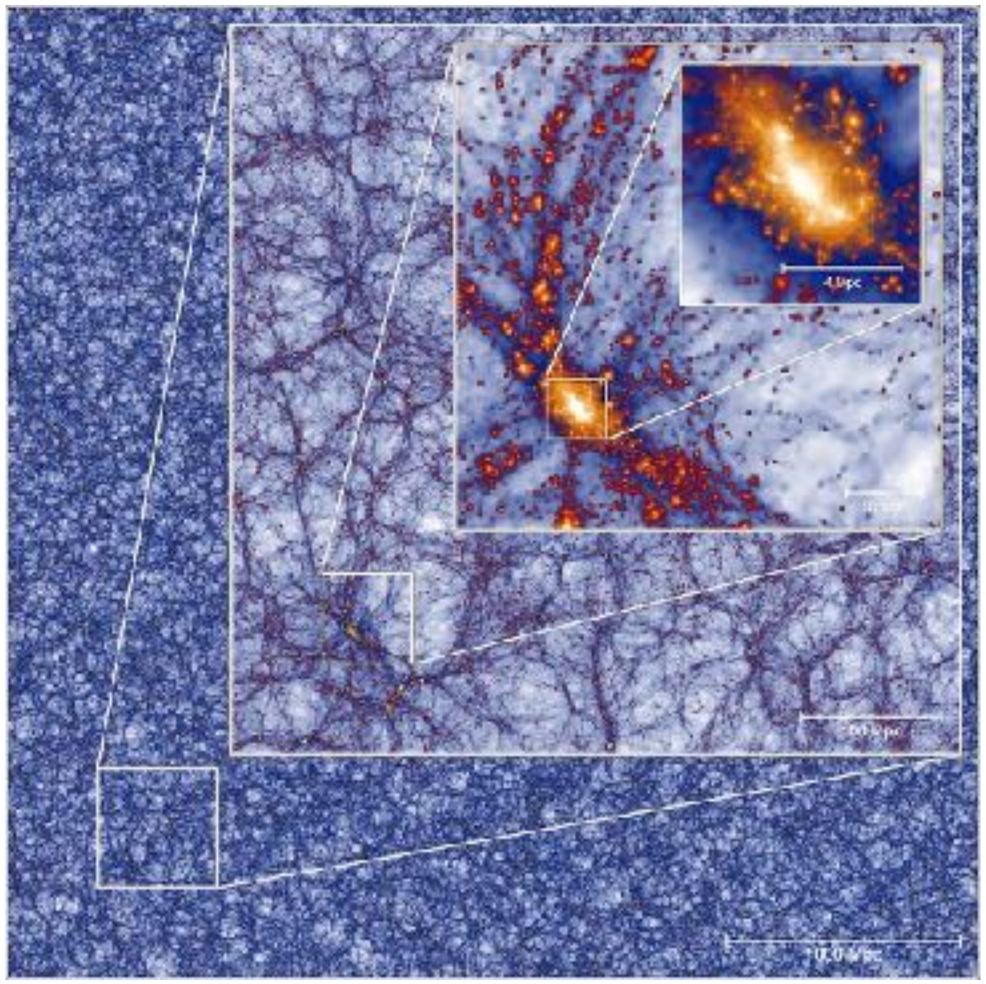
## Perturbation theory

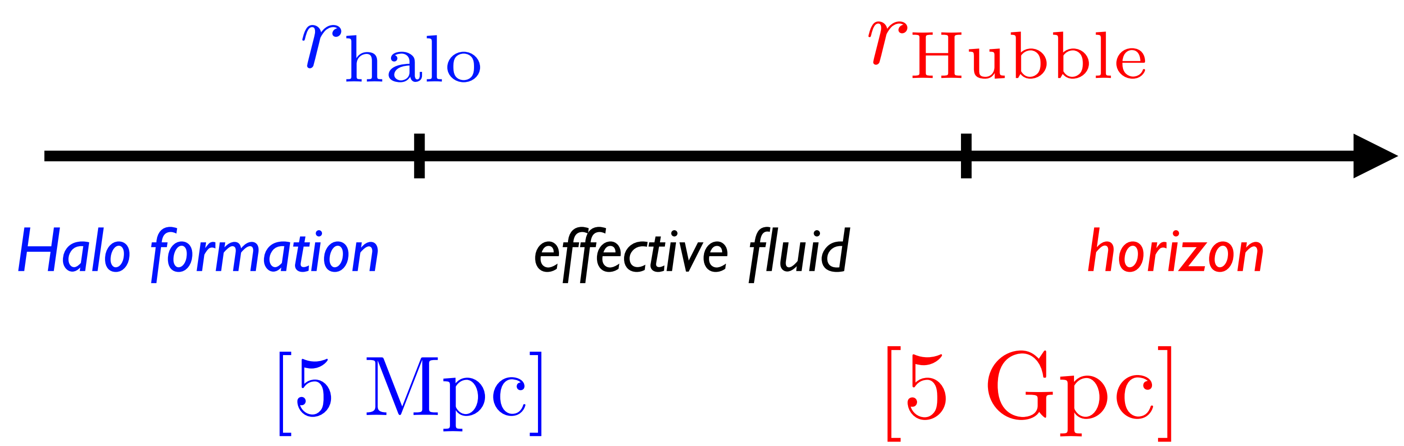
- ✗ limited range
- ✓ precision & accuracy
- ✓ fast/ cheap - beyond LCDM
- ✓ marg. over gastrophysics

State-of-the-art equipment for theoretical physicist

credit: CartoonStock

# Large-scale structure theory






- EFT of Large Scale Structure:

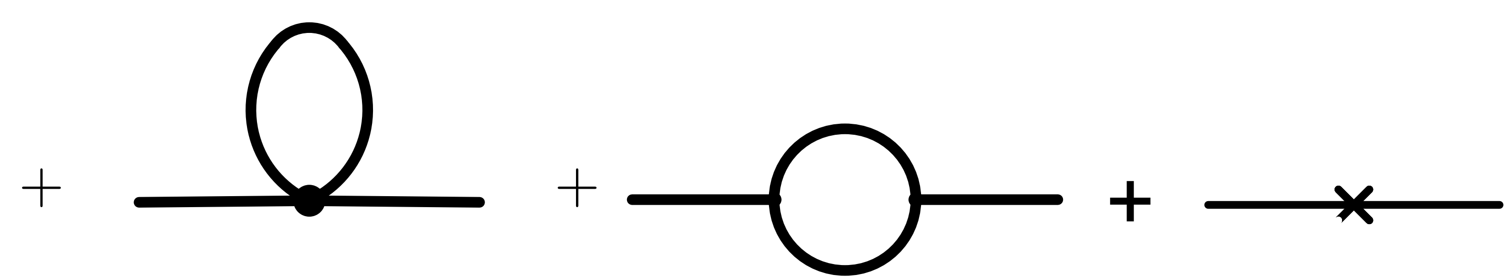
  *Baumann, Carrasco, Senatore, Zaldarriaga, Pajer, Schmidt, Castorina, Sefusatti, Scoccimarro, Porciani, Garny White, Chen, Vlah, Schmidt, Mirbabayi, Lewandowski, ++*

- TSPT: IR resumm.
  for arbitrary n-pf at any order

*Time-sliced perturbation theory (TSPT)*

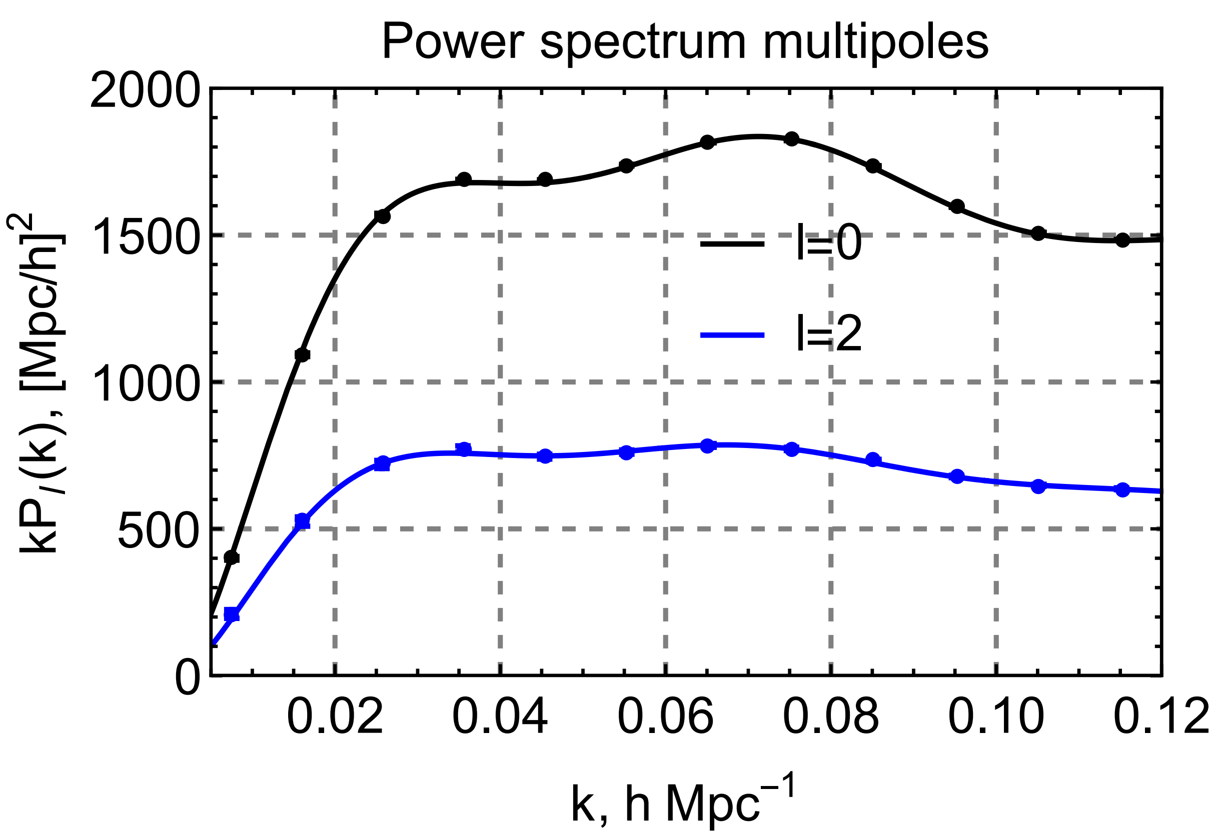
*Path Integral Formulation of EFT of Large-Scale Structure*

*Blas, Garny, MI, Sibiryakov (2015)*

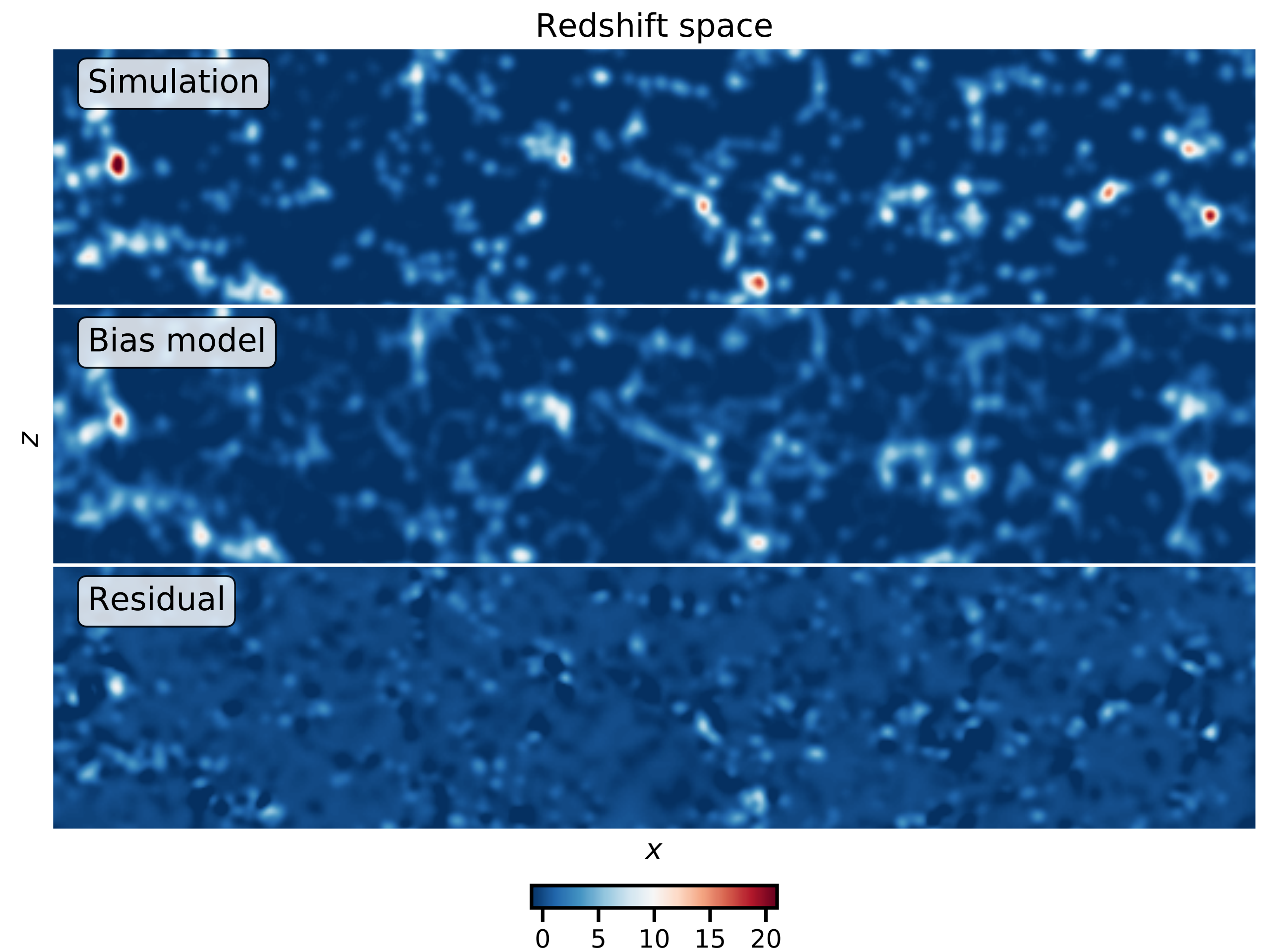


# Are we sure PT is correct ?

- From math - that's the only option
- Checks: blind challenges, EFT at the field level




*Nishimichi, Takada, MI, d'Amico, Simonovic ++ (2020)*




Schmittfull++'18 Schmittfull, Simonovic, MI++'20
Schmidt, Cabass, Jasche++'20, ++

0.1% precision!

# Codes

*Many codes in the market:* *PBJ, Velociraptor, Spinosourus, CLASS-PT, PiBird, CLASS-1loop, FAST-PM, etc.*

real space: Pmm, Pgm, Pgg

*e.g.: lensing, photometric clustering*

redshift space: P0,P2,P4,++

*Assassi'14*
*MI, Sibiryakov' 18*
*Perko+'16*

*e.g.: spectroscopic surveys*

RSD Bispectrum: tree +1loop*

*MI, Philcox ++'21'22*

*Oddo++'21'22, Rizzo++'22, Alkhanishvilli++'21, d'Amico'22*

PNG fNL loops

*Cabass, MI, Philcox ++'22*
*Moradinezhad ++'21*

LOS-dependent operators

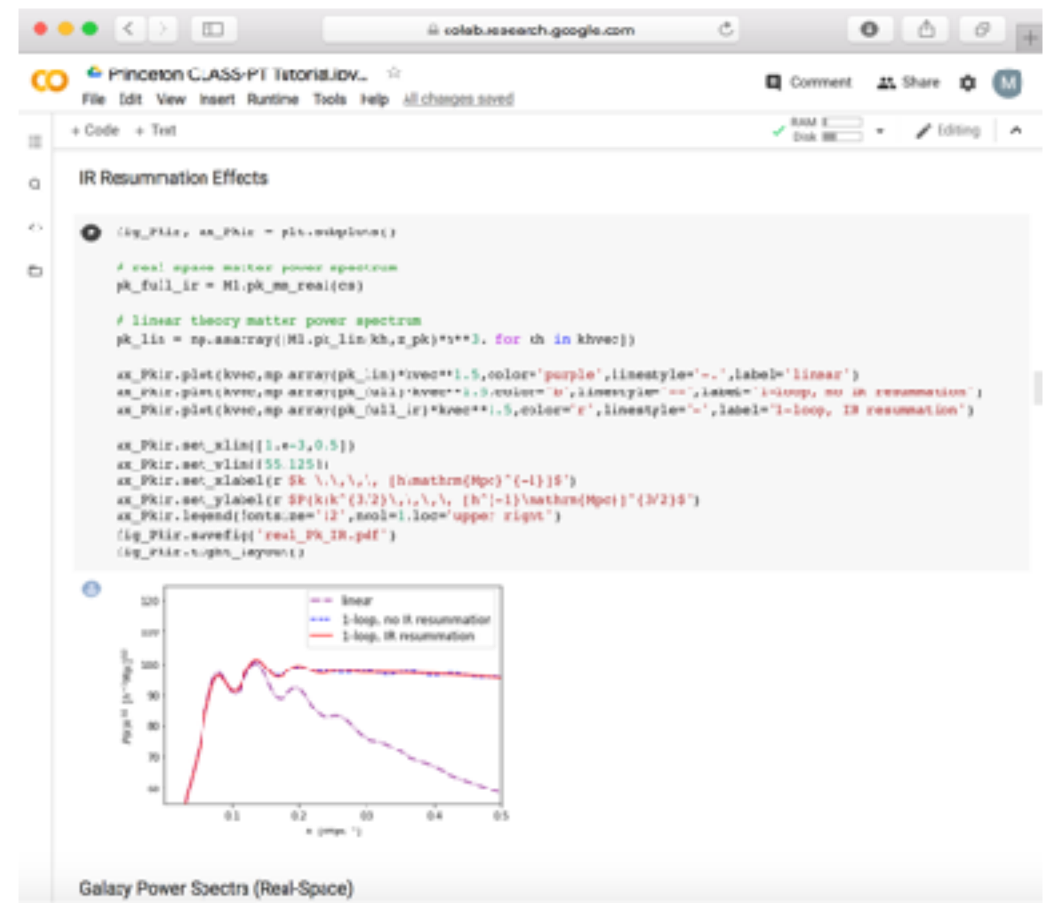
*MI'21*

*e.g.: LyA forest* *Desjasques, Jeong, Schmidt'18*

all in 1second!

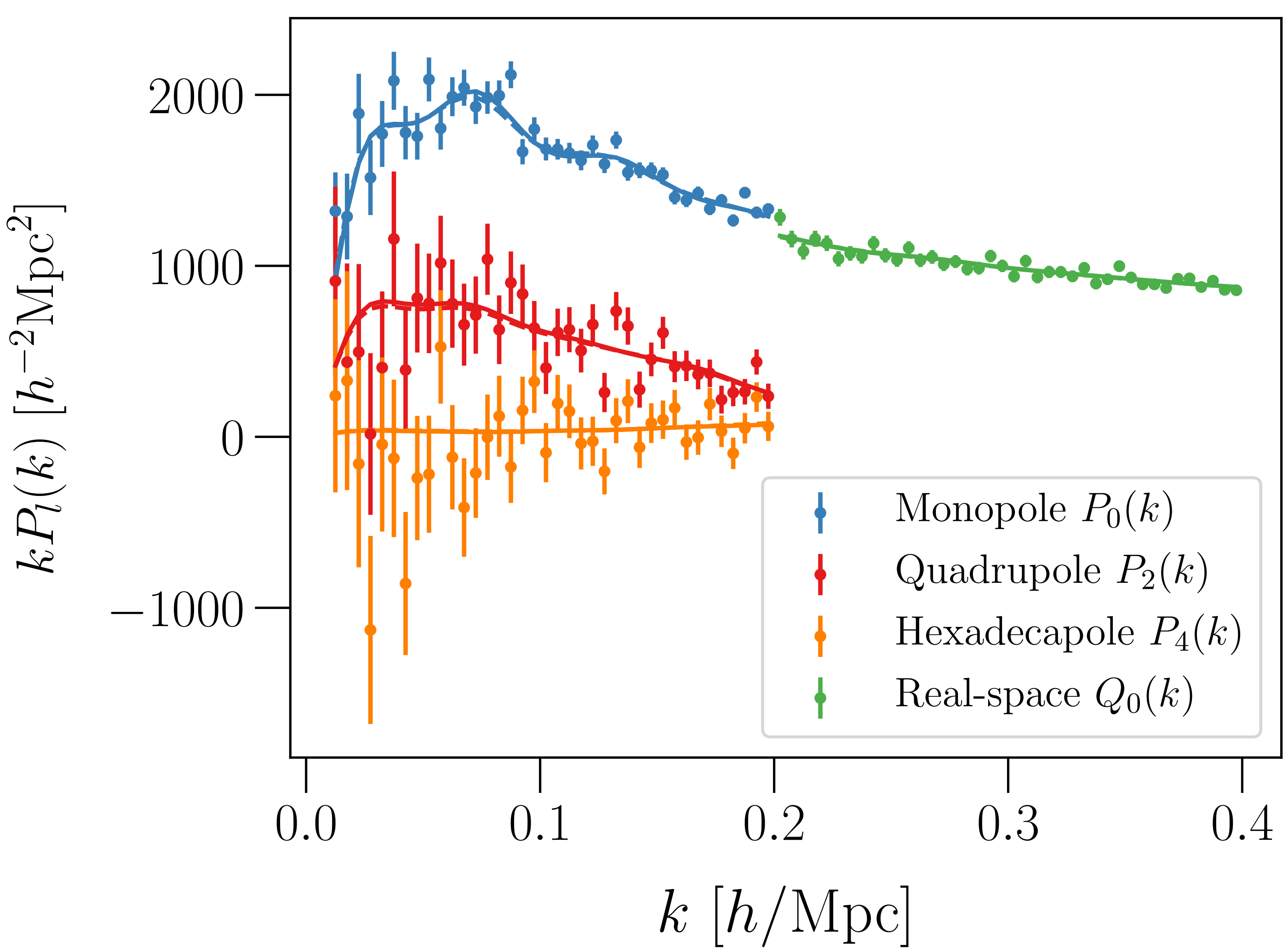
*Simonovic ++'17*
*Chudaykin, MI ++'18*

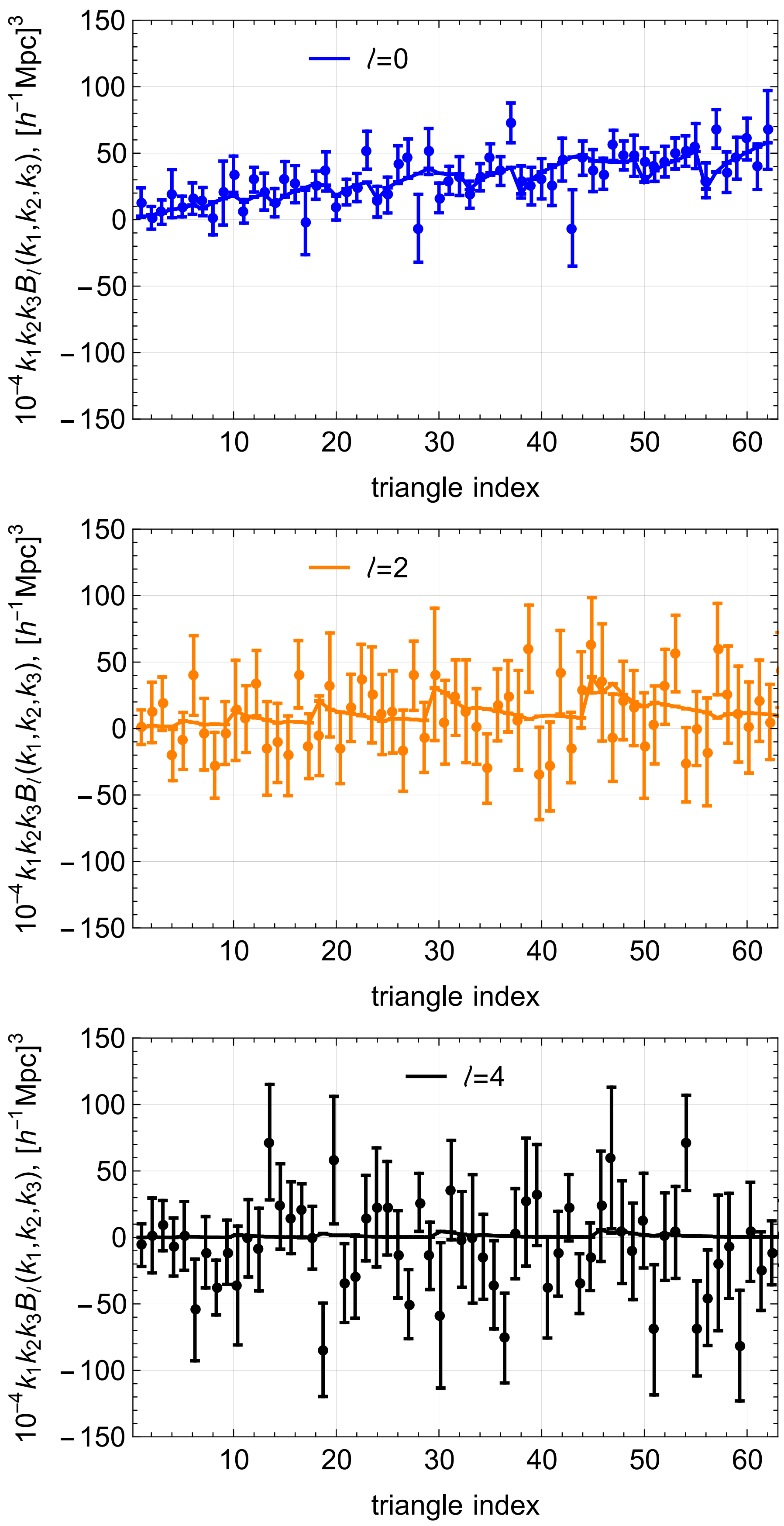
https://github.com/Michalychforever/CLASS-PT




a universal
LSS calculator !

# BOSS data:




Power spectra: $P_0, P_2, P_4,\ Q_0$

Post-reconstructed BAO: $\alpha_{\|}, \alpha_{\perp}$

Bispectra: $B_0, B_2, B_4$

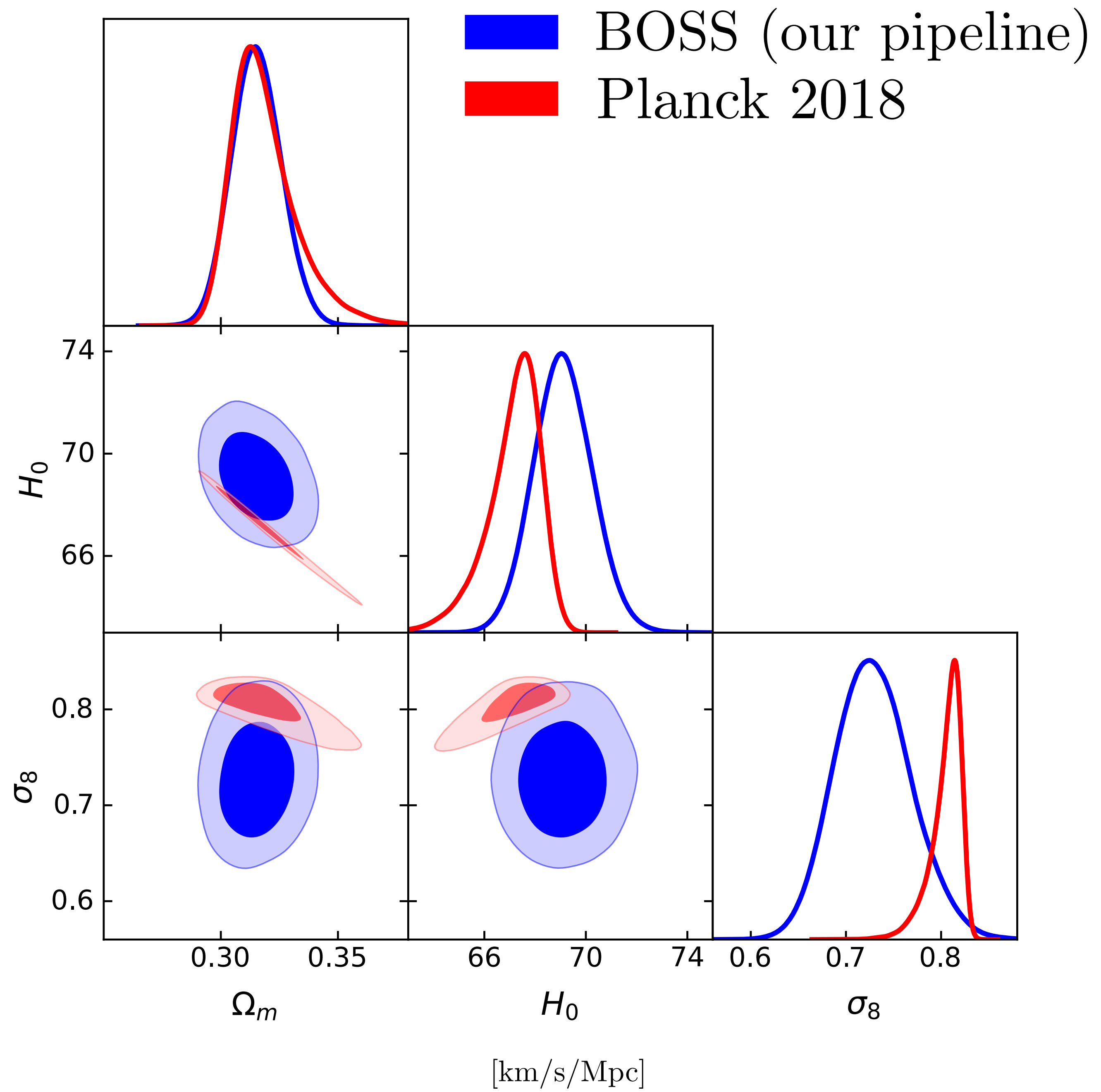
covariance: Patchy mocks + analytic

# Re-analysis of public BOSS data

| $P_\ell + Q_0 + B_\ell$ | |
|---|---|
| Parameter | 68% limits |
| $\omega_{cdm}$ | $0.1303 \pm 0.0055$ |
| $H_0$ | $68.19 \pm 0.78$ |
| $ln10^{10}A_s$ | $2.740 \pm 0.091$ |
| $S_8$ | $0.771 \pm 0.039$ |
| $\Omega_m$ | $0.3296 \pm 0.0095$ |
| $\sigma_8$ | $0.736 \pm 0.033$ |

strongest PT constraints!

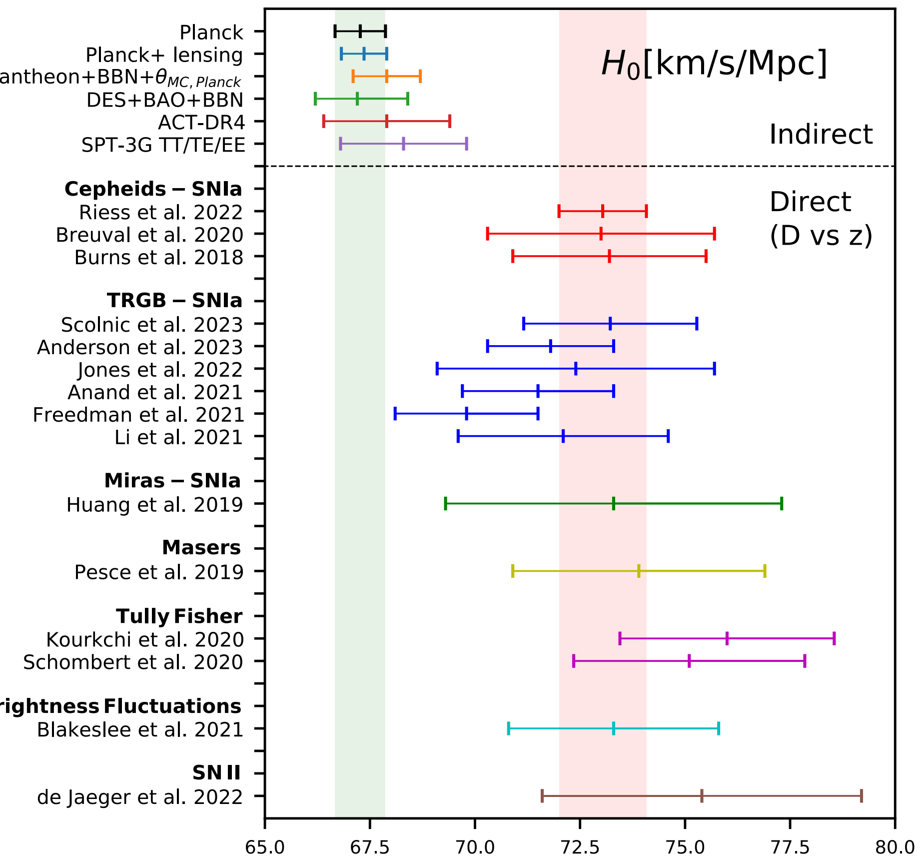
consistent w/Planck @2sigma




*MI, Simonovic, Zaldarriaga (2019), Philcox, MI (2021) ++*
*MI, Philcox ++ (2023)*
*D'Amico, Kokron++(2019), Chen, White, Vlah (2021)*

# Applications

## testing LCDM:




## Dark Sectors

*M. Loverde, K. Rogers, F-Y. Cyr-Racine talks*

## testing inflation

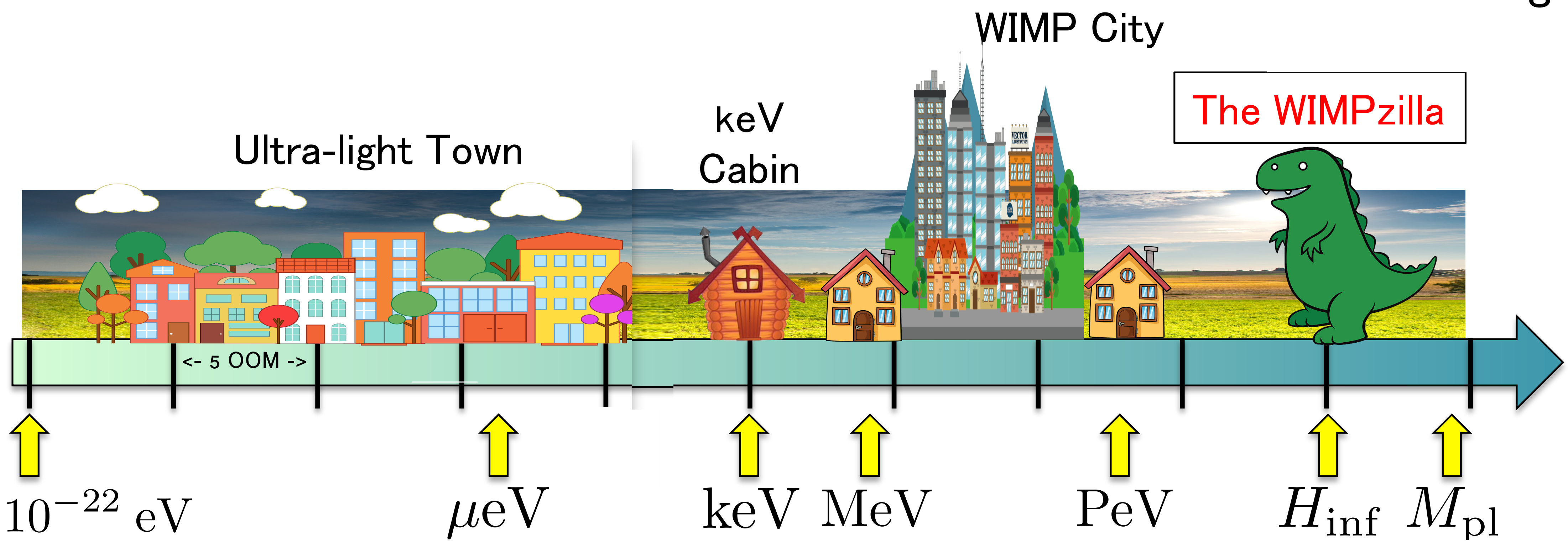
Ghost inflation!

© Philcox w/Midjourney

*O.Philcox, B.Wallisch, A. Moradinezhad talks*

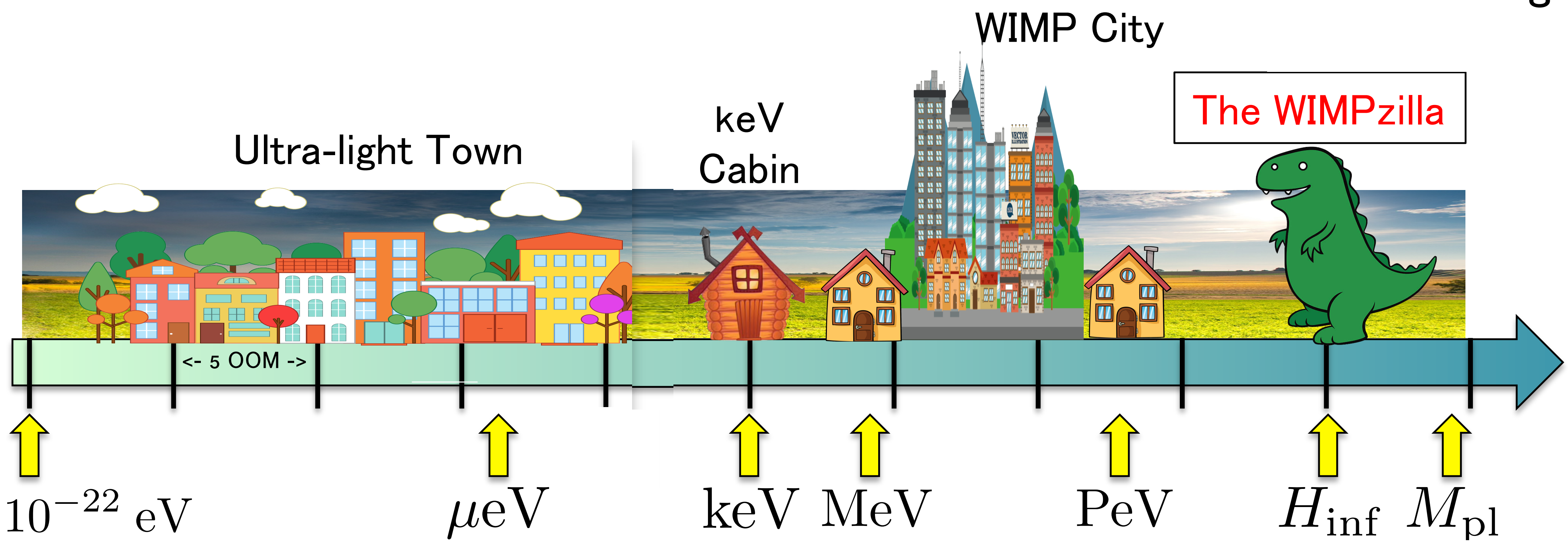
# Dark Matter

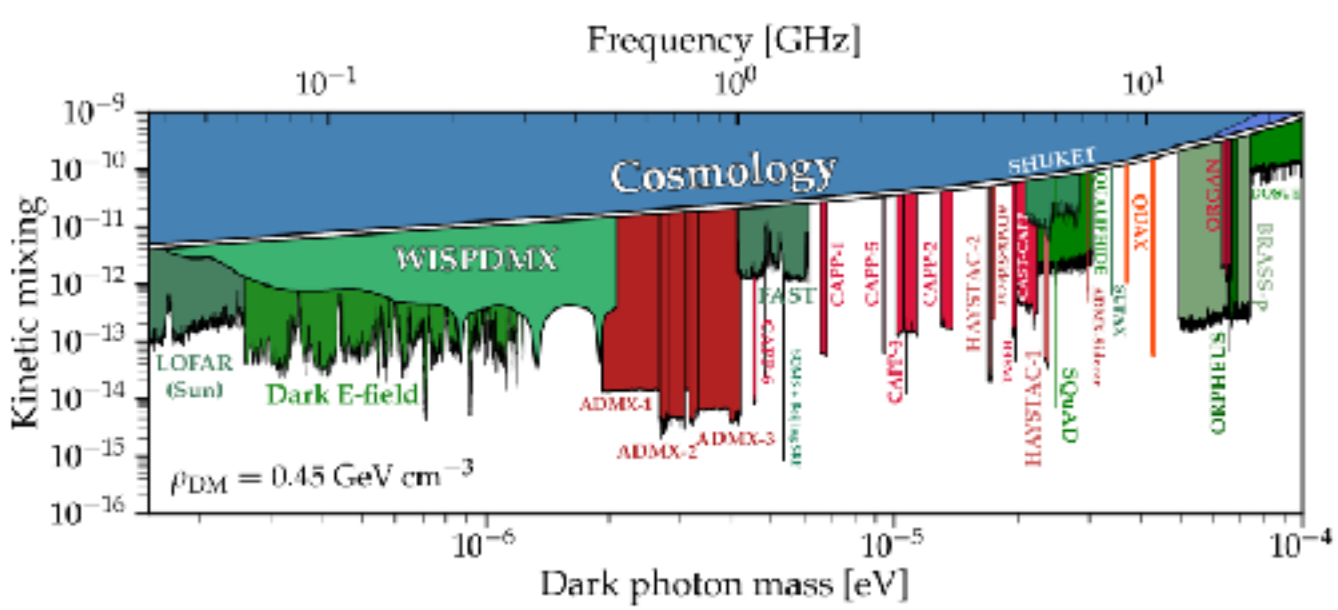


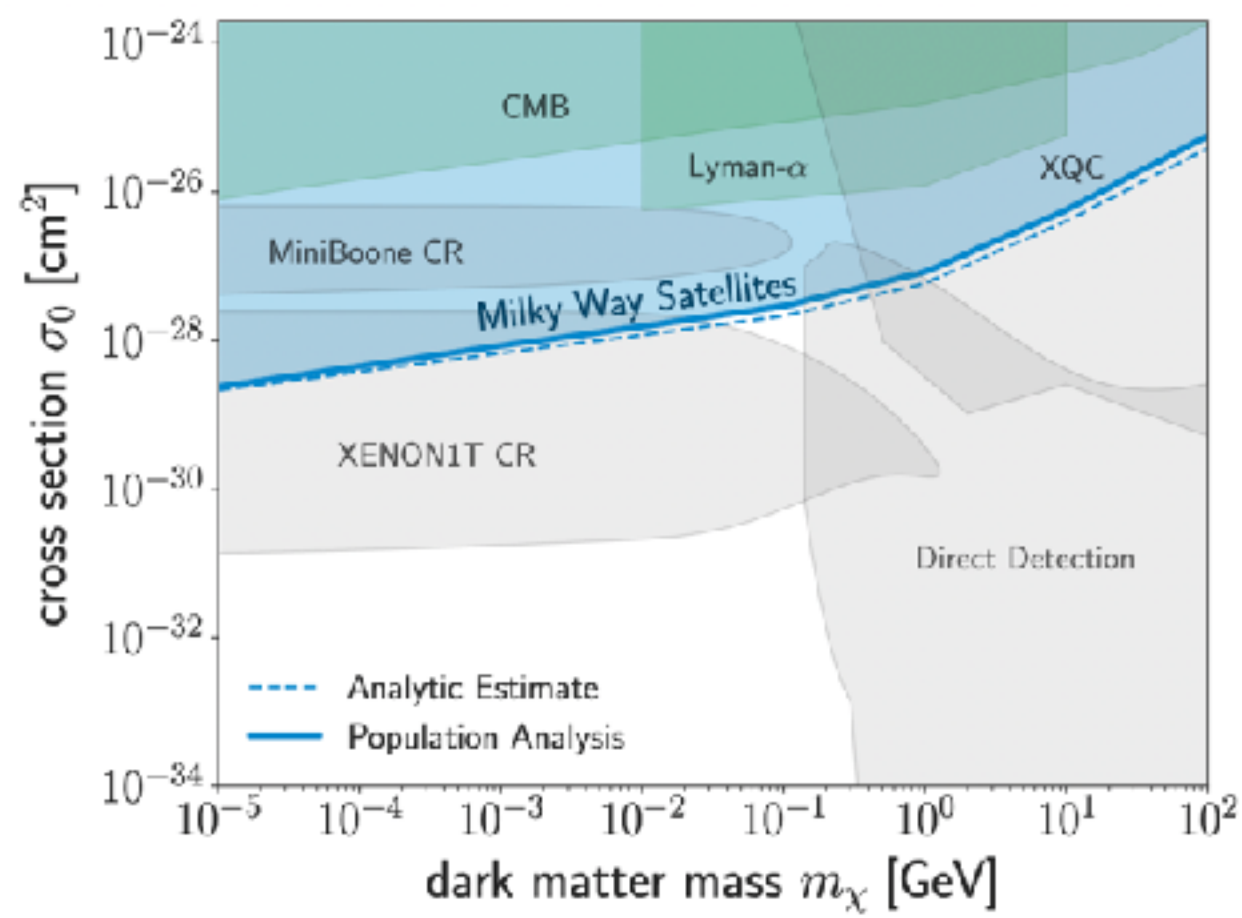

WIMP City
The WIMPzilla
keV
Cabin
Ultra-light Town
<- 5 OOM ->
$10^{-22}$ eV
$\mu$eV
keV
MeV
PeV
$H_{\rm inf}$
$M_{\rm pl}$

# Dark Matter

© A. Long @LWD



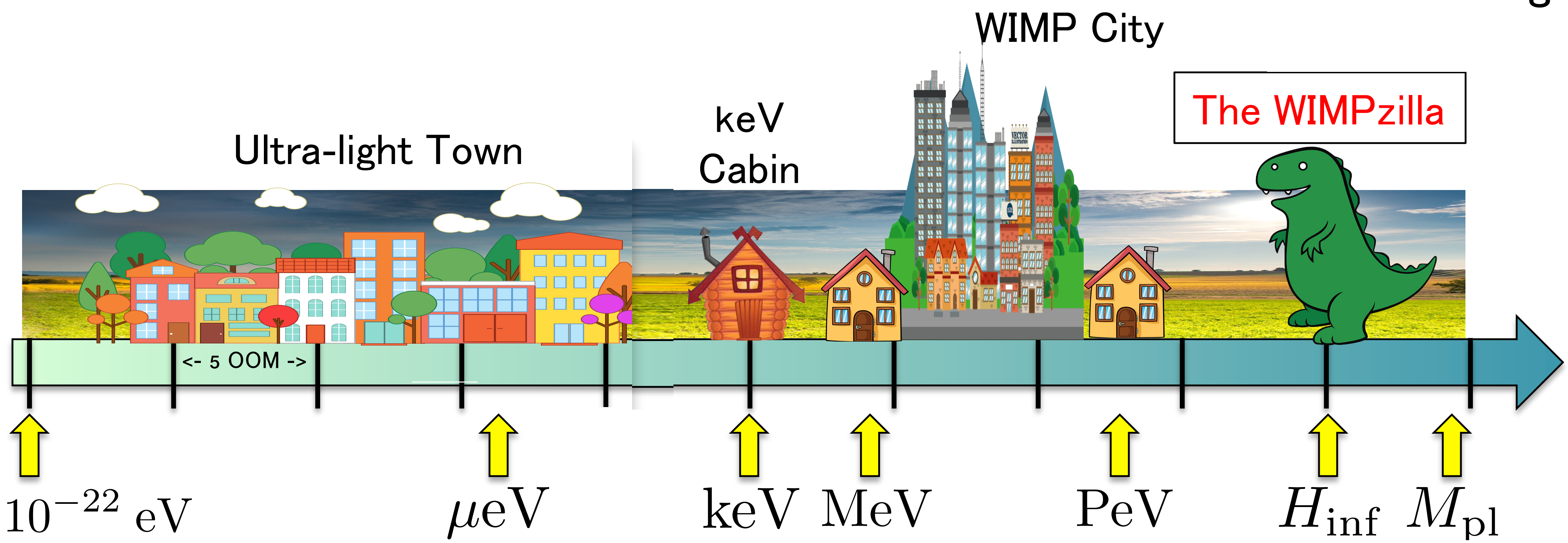



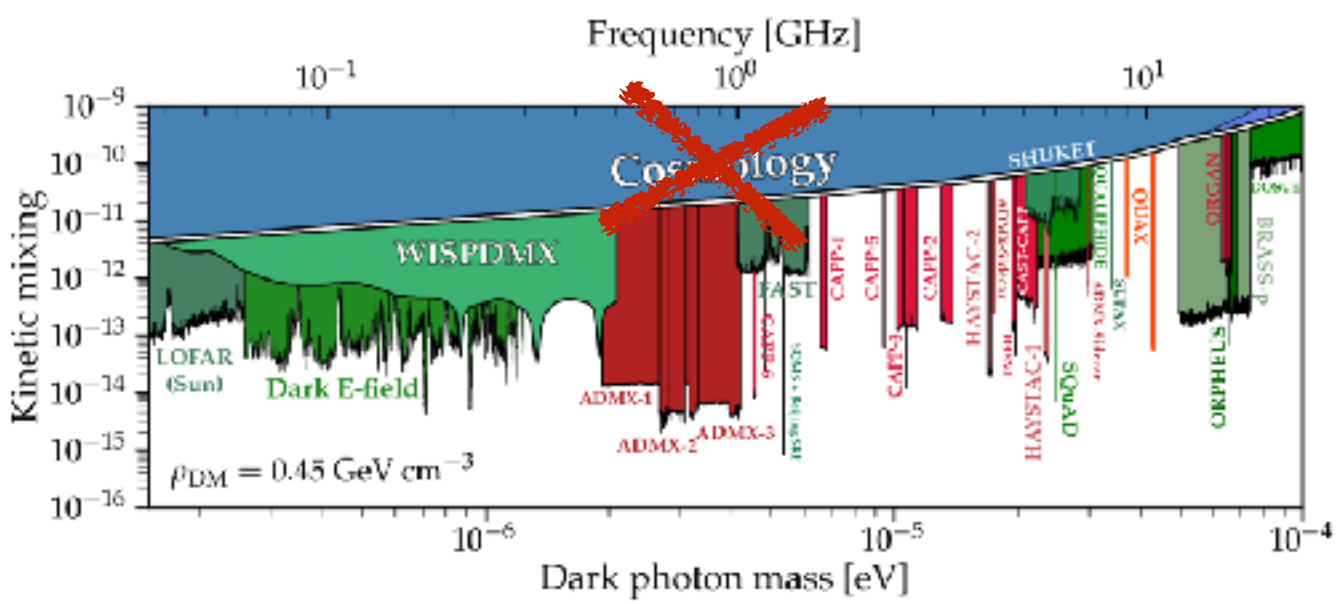

https://cajohare.github.io/AxionLimits/

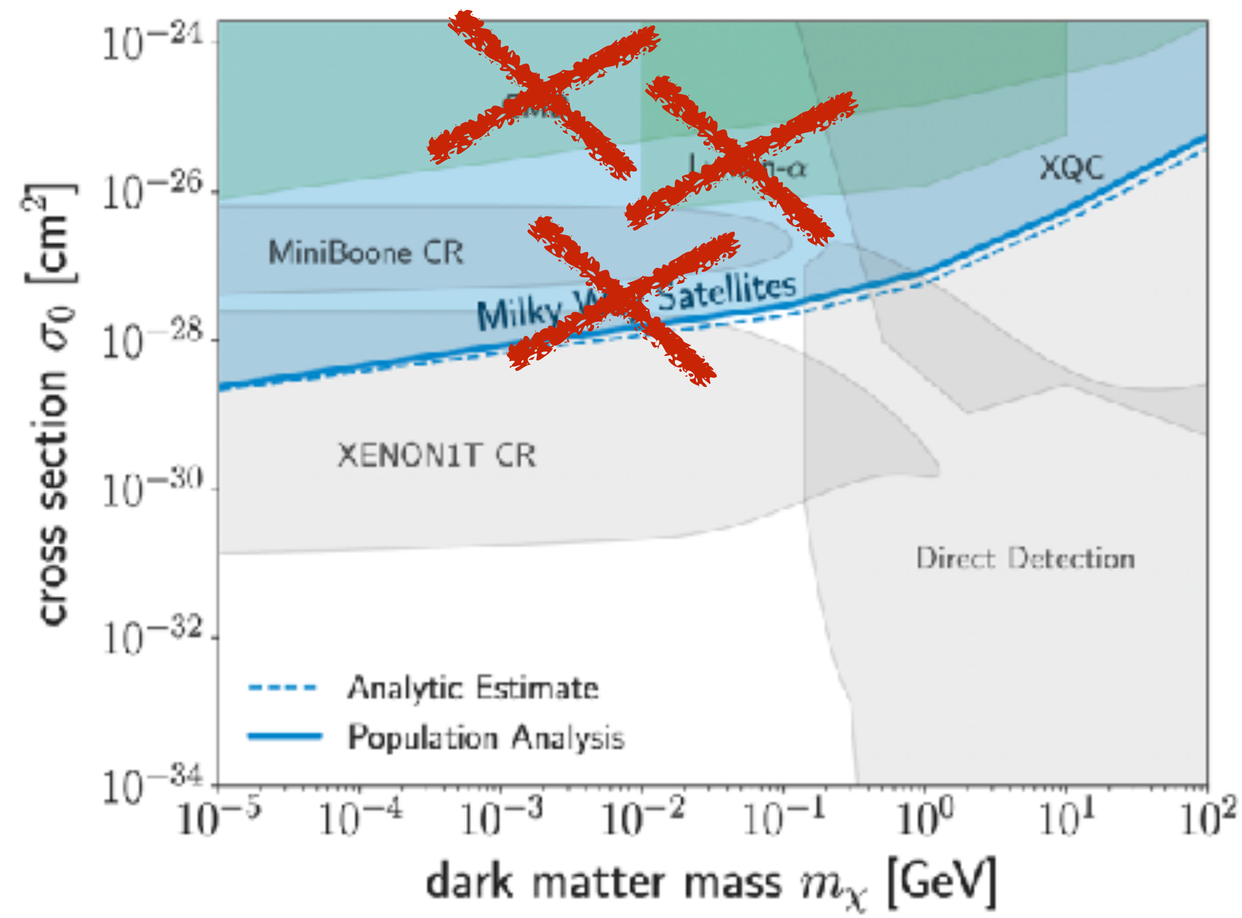
*Nadler ++ (2020)*

# What if there are many DMs ?

© A. Long @LWD



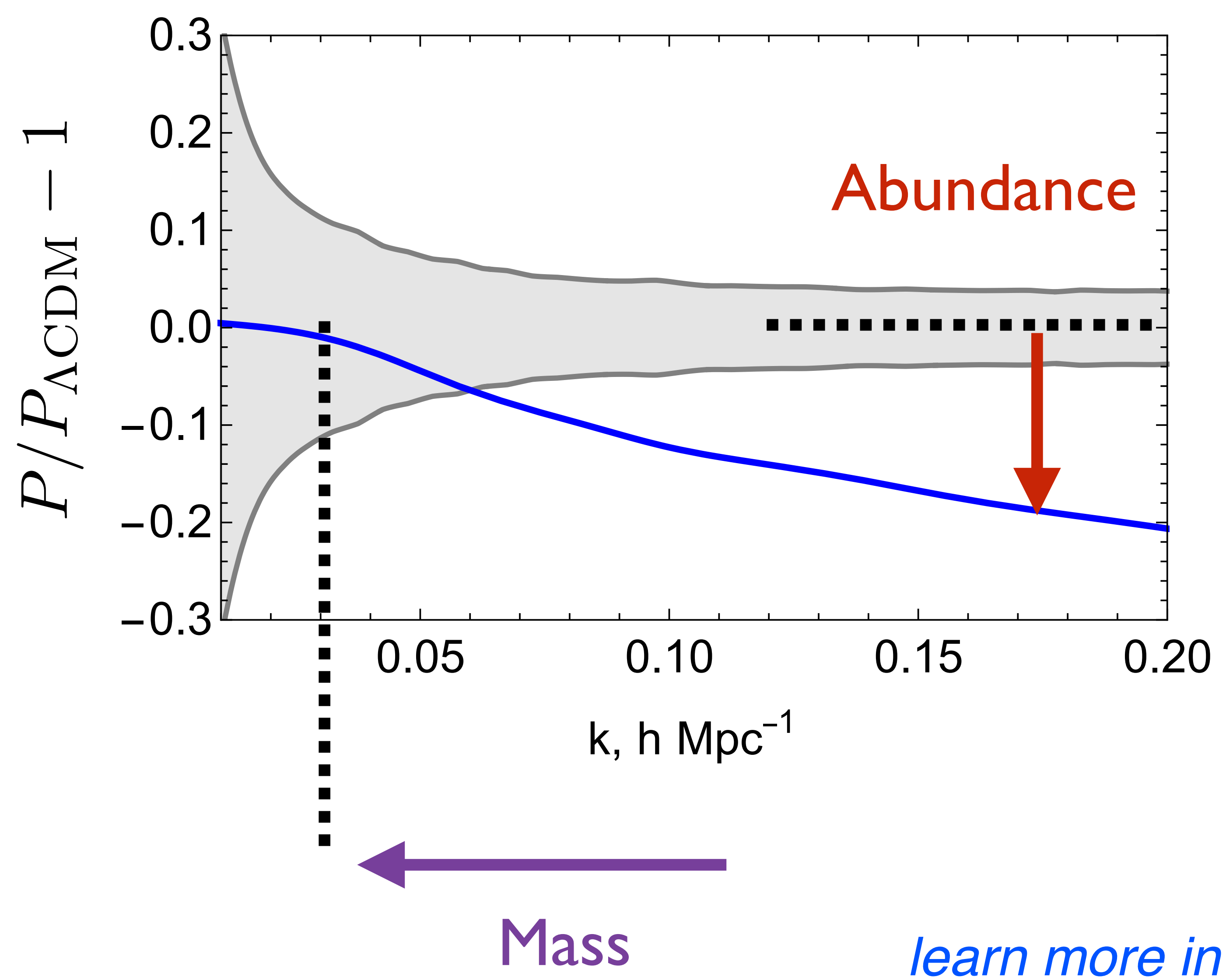




https://cajohare.github.io/AxionLimits/

*Nadler ++ (2020)*

# We can do better with Galaxies!

- Imagine two DM components, one is not exactly cold
- ~ there's a Jeans scale beyond which it won't cluster!




*learn more in Keir Roger's talk !*

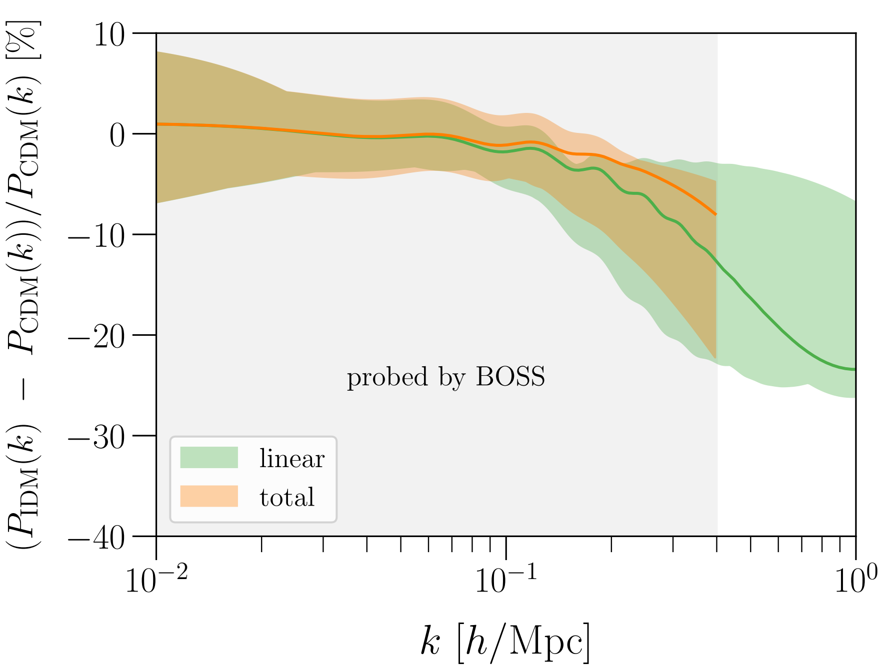
# DM - baryon interactions: apparent evidence ?

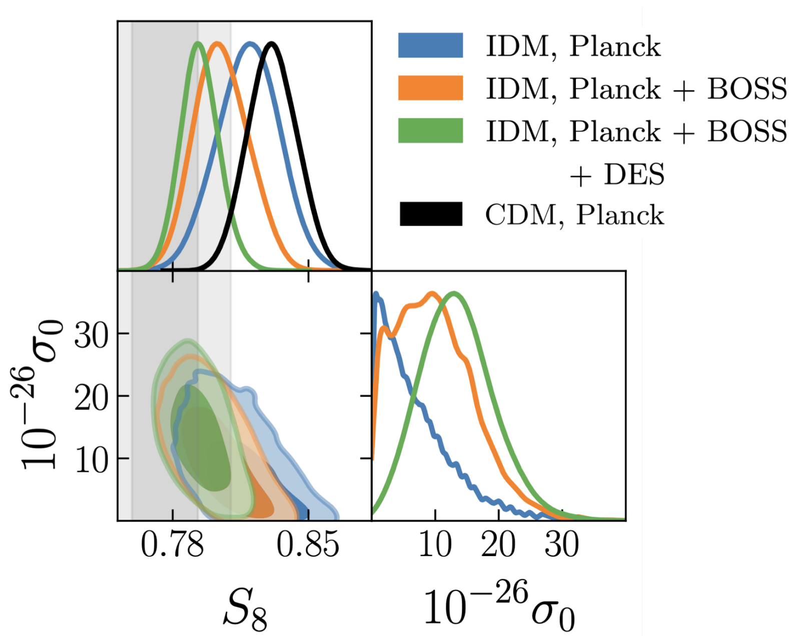
- motivated by direct detections

*Dvorkin, Blum, Kamionkowski ++ (2014)*
*Gluscevic, Boddy (2018)*
*Slatyer, Wu (2018)*

$\sim 10\%$ of DM ~ $m_\chi \sim 1$ MeV interacts w/ baryons

$$\sigma_0 = 1.34^{+0.51}_{-0.67} \times 10^{-25}\ \mathrm{cm}^2$$





*Adam He, MI, Rui, Gluscevic (2023)*

# Technical part

- Recently there've been some concerns about priors, marginalization effects, kmax

*V. Poulen ++(2022)*

- We have thoroughly studied these effects in the past:

even further shifted w.r.t. the true values. This shows that for the BOSS errorbars the marginalization effects are more significant than the theory-systematic error.

*MI, Simonovic, Zaldarriaga (2019)*

The largest systematic shift is observed for $\sigma_8$, which, if one rescales the full NSERIES-volume constraint to the BOSS volume, reaches the level of $0.4\sigma$. Whilst not insignificant, this is likely inflated by (a) the non-independence of the NSERIES mocks, and (b), the non-Gaussianity of the posterior surface, which will drive the mean away from the best-fit value. We may also consider the marginalization bias, *i.e.* the difference between the means in the two analyses; this is equal to $0.6\sigma$ for $\sigma_8$ (using BOSS error-bars) and less than $0.3\sigma$ for other parameters. These two biases cancel each other for $\sigma_8$, such that the resulting shift is only $0.2\sigma$. These results agree with previous studies [23, 47].

*Philcox, MI (2021)*

- Let me address these concerns now

# On the Priors

- Zurich and Princeton groups: different priors, but only one really matters

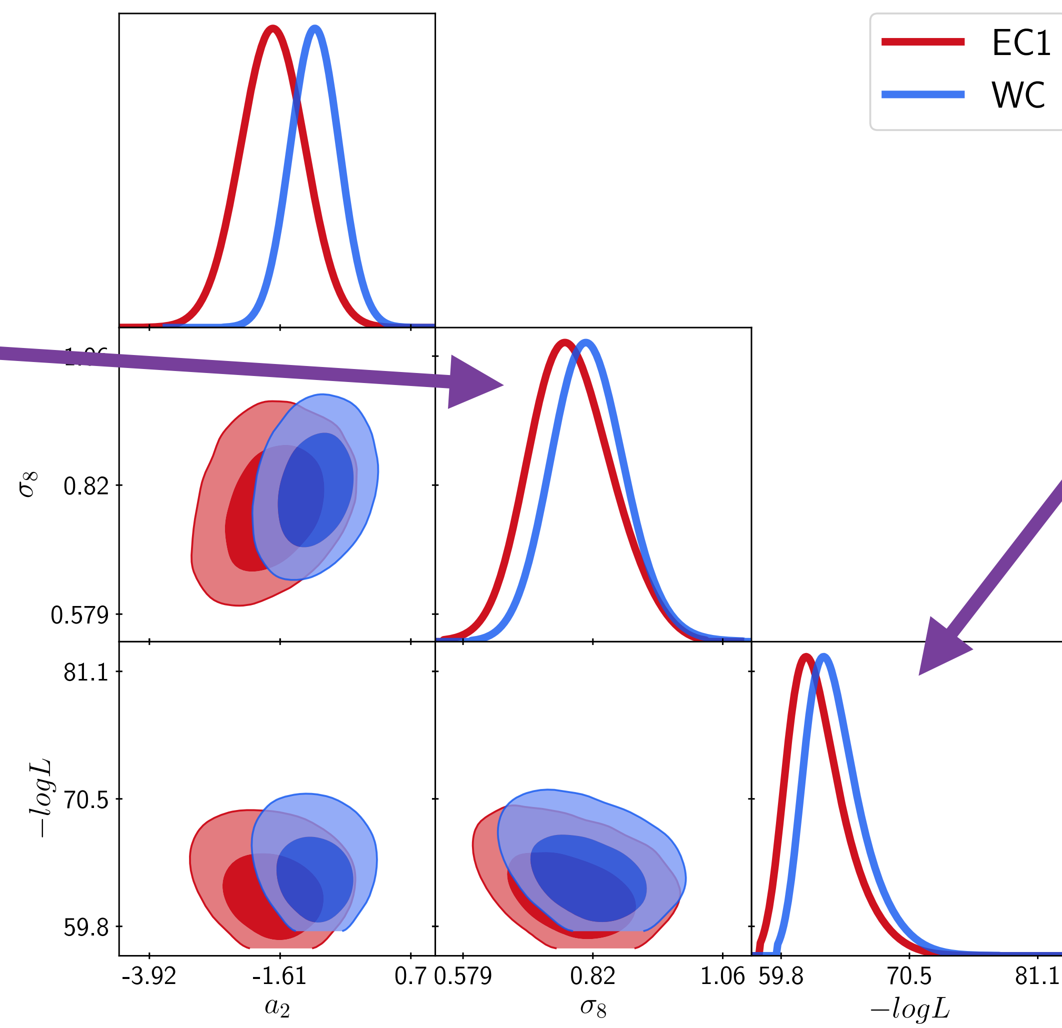
$$P_2^{\rm stoch.} = a_2 \frac{k^2}{k_{\rm FoG}^2} \frac{1}{\bar{n}} \qquad k_{\rm FoG} \simeq (f\sigma_v)^{-1} \simeq 0.4\ h{\rm Mpc}^{-1}$$

Senatore et al: $a_2 \lesssim 0.5$

*D'Amico, Senatore++'19*

if relaxed (us):

lower $\sigma_8$




better fit!

$\Delta\chi^2 \approx -3$

low S8 is real!

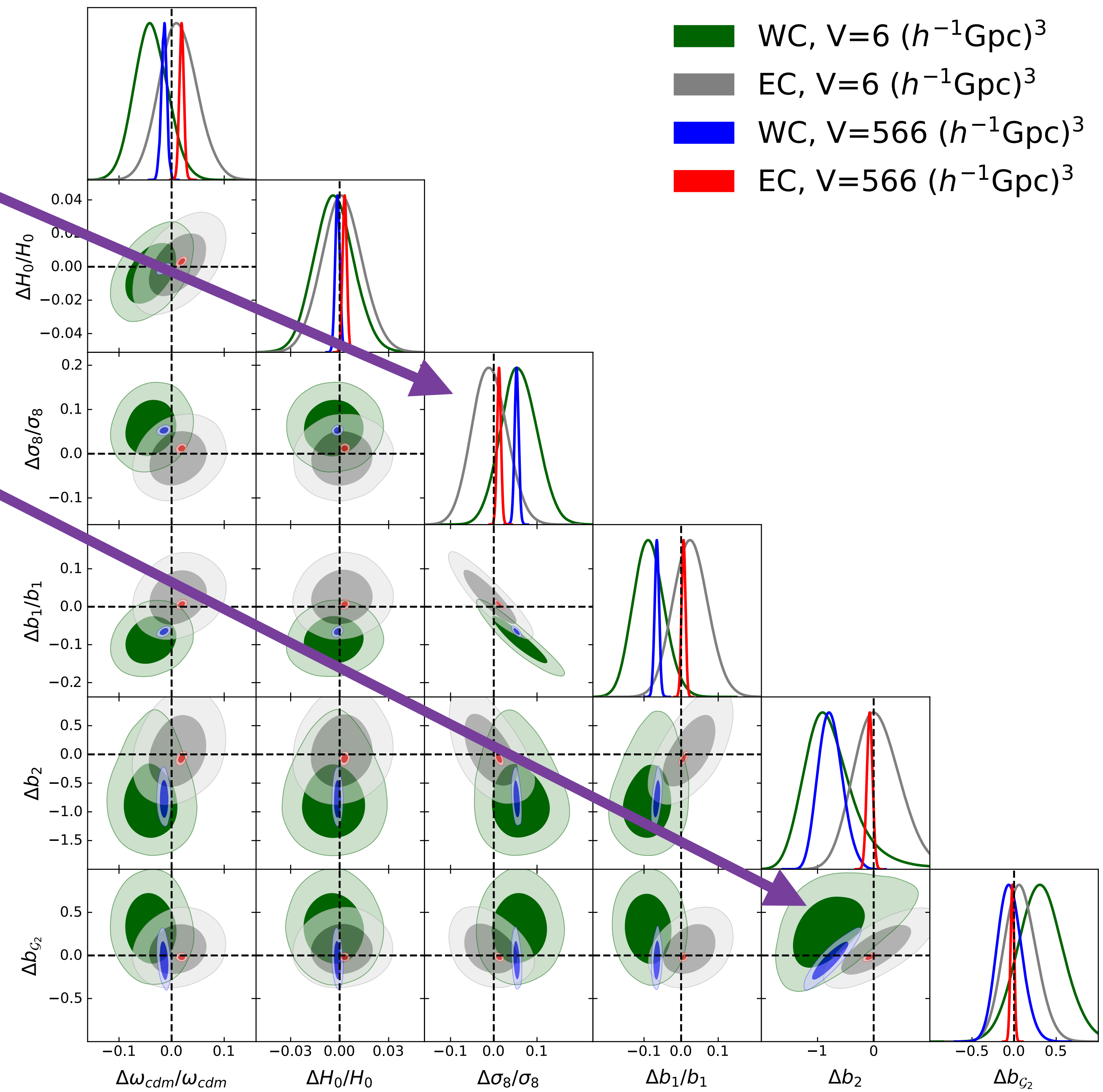
*MI++'19*
*Philcox, MI'21*
*Chen, White, Vlah (2021)*
*MI'23*

- Both Bayesian & frequentist Effect driven by the Likelihood!

# On the Priors: parameter recovery tests*

- overoptimistic priors bias cosmology
- overoptimistic priors bias bias
- problems in the bispectrum analysis
- optimistic priors artificially enforces larger $\sigma_8$

$\sim 5\%$

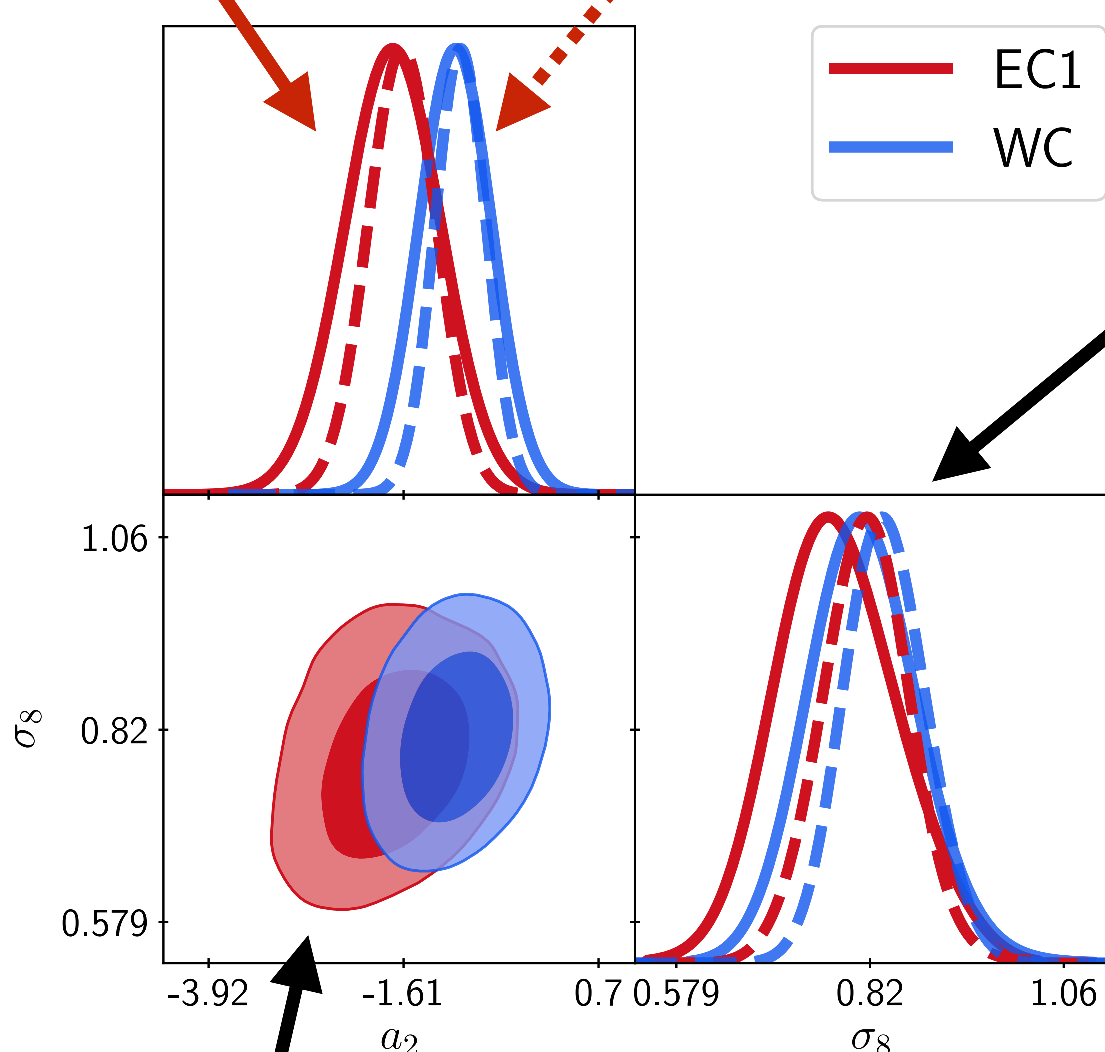



*Add data and codes are publicly available!

# On ~~Prior volume~~ marginalization

mean

likelihood profile




tail: NG posterior

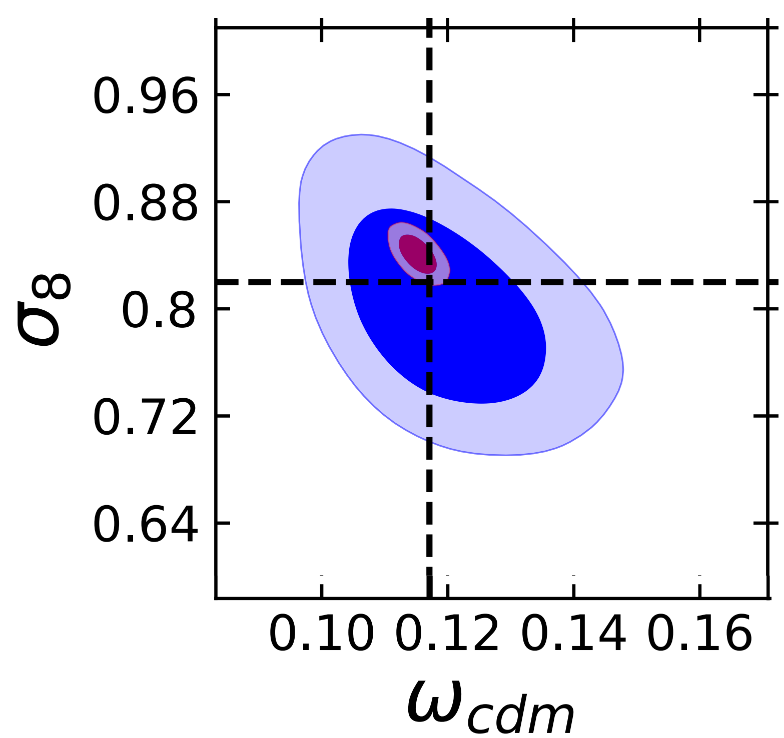
projection of the NG tail

- BF $\neq$ Max Posterior if distrib. is non-Gaussian
- NOT prior volume: Likelihood >> Prior
- 1D marg. limits do not fully reflect the distribution !
- Q: is the parameter recovery unbiased w.r.t. distribution ?
- Our pipeline: yes (e.g blind challenges)

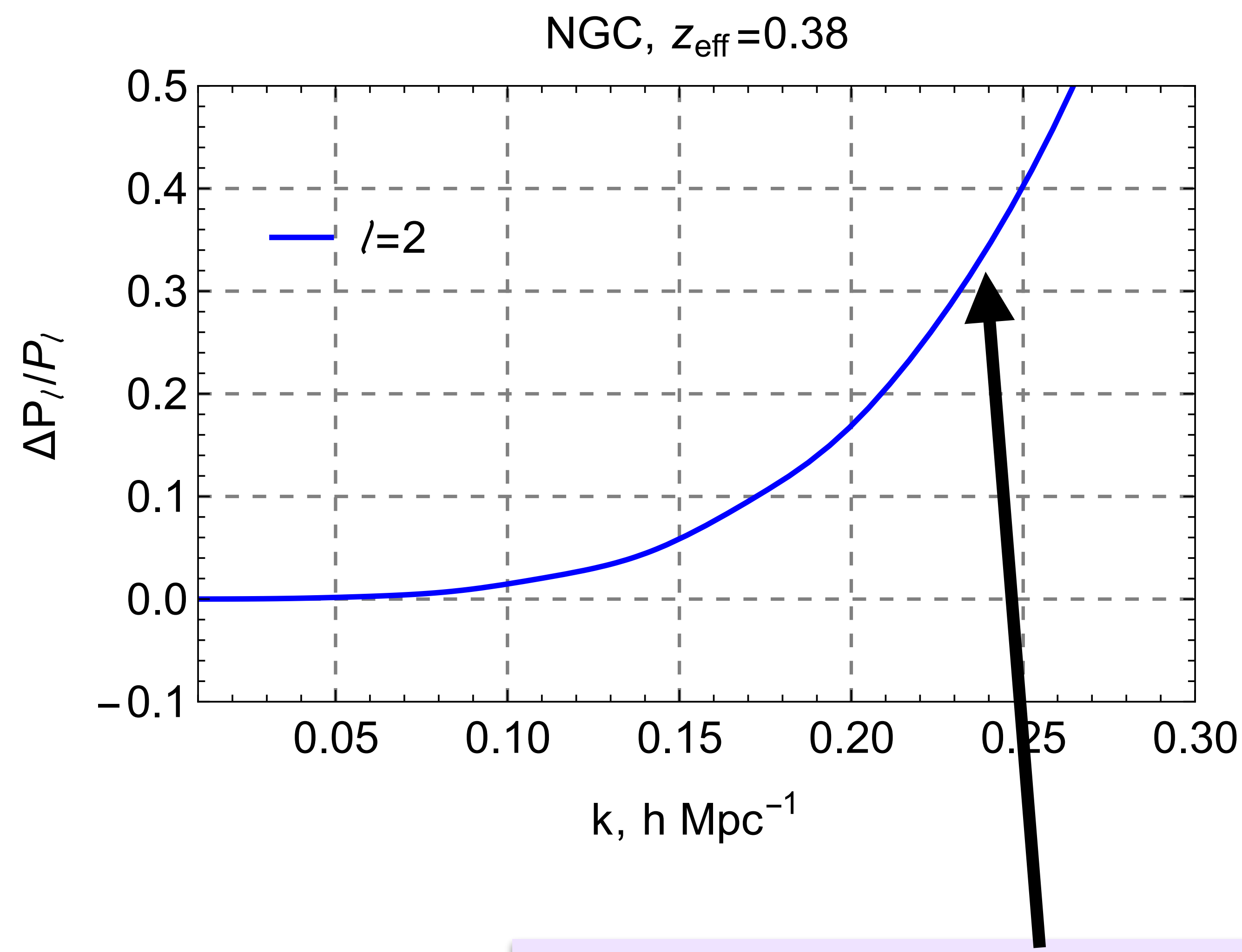
*MI, Simonovic, Zaldarriaga (2019), Dolgikh, ++MI (2020) Philcox, MI (2021), MI (2023)*

# Choice of kmax

- Perturbative assumptions are OK
- Systematic error << Statistic error




$$k_{\rm max} = 0.2\ h\ {\rm Mpc}^{-1}$$




Theory Error blows up

- Changing kmax is a good test

*e.g. Camarena, Cyr-Racine, Houghteling '23*

From data: $k_{\rm FoG} \simeq 0.25\ h\ {\rm Mpc}^{-1}$

# Upshot of the technical part:

- Use conservative priors

→ overoptimistic priors bias parameter inference

- Marginalization effects are sub-sigmish, and reduce w/ survey volume

→ no problem for current & future surveys

- Determination of kmax is an important problem

→ kmax - independent analysis from Theoretical Error :

*Baldauf, Simonovic ++(2016), Chudaykin, MI, Simonovic (2021)*

# Cosmology with the Bispectrum

Bispectrum contains significant information

*Scoccimarro'94 Sefusatti'06'09, Oddo+'19'21, Hahn+'19, Moradinezhad++'20, Rizzo'23*

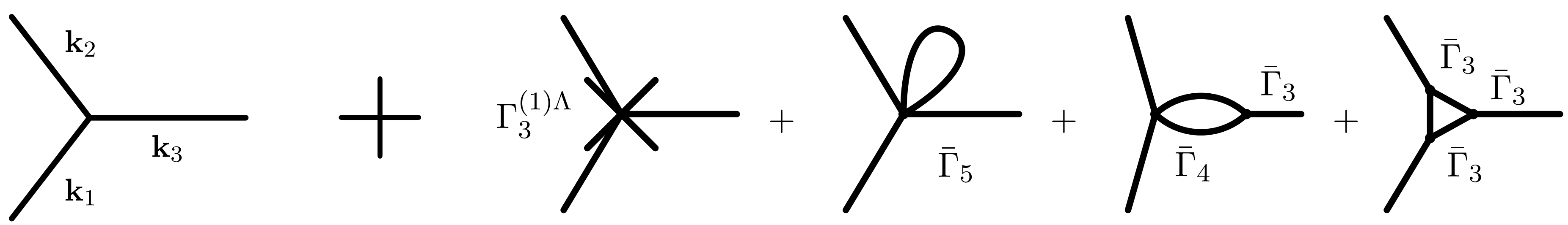
*Philcox (2021)*
*Philcox, MI (2021)*
*MI, Philcox, ++ (2021)*
*Philcox, MI ++ (2022)*

New pipeline:

New mask-free estimator
+ discreetness weights (c.f. k_eff_mean)

*NB.* bin integration is a bad approximation

Tree-level and one-loop EFT model:




FFTLog: 0.1% precision of the 1-loop calculation
Code can be boosted is precision is reduced

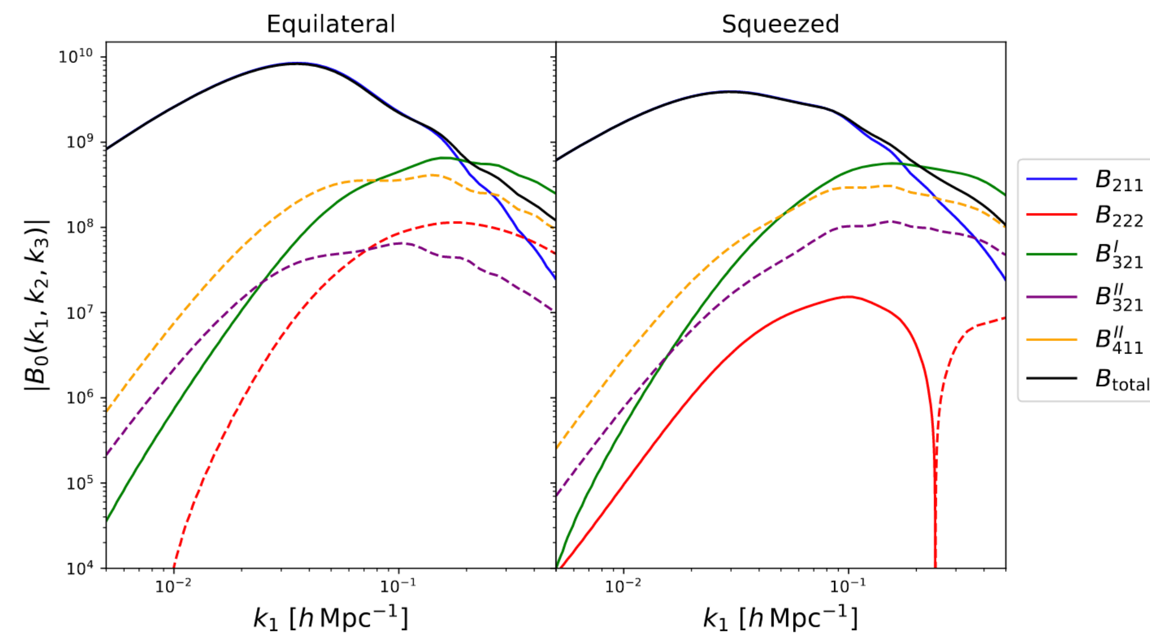
oliverphilcox / **OneLoopBispectrum** Public

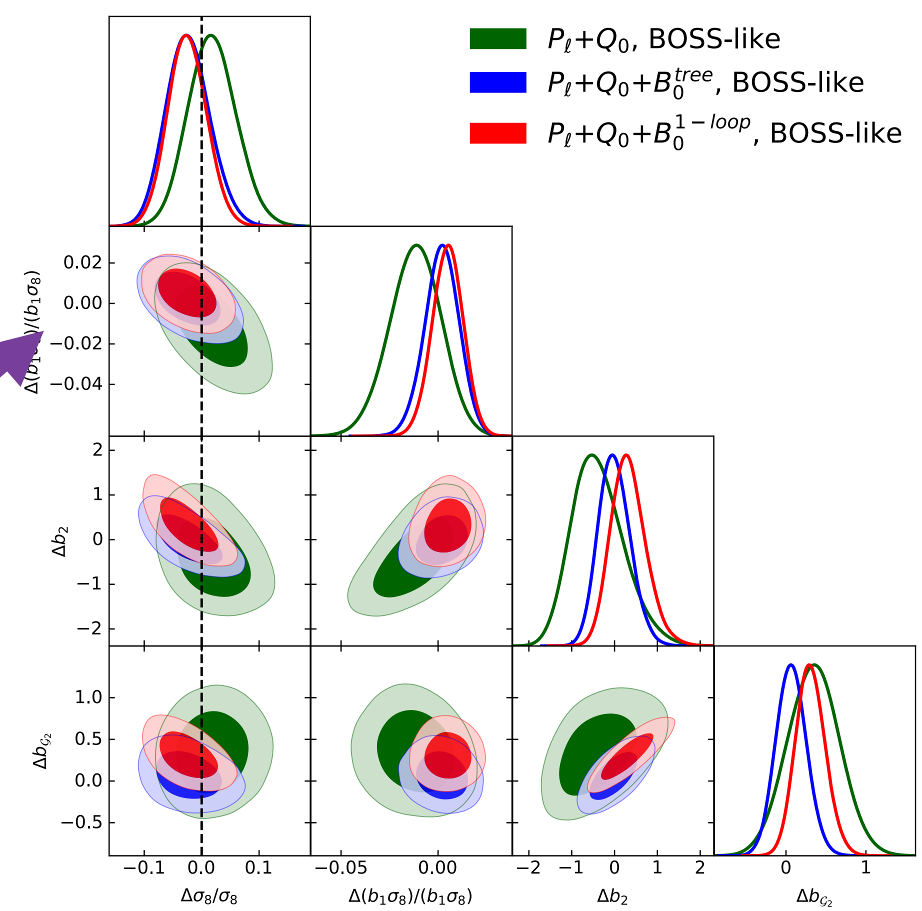
# Cosmology with the 1-loop Bispectrum

$$B_{1-\mathrm{loop}}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3) = B_{211} + \left[B_{222} + B_{321}^{I} + B_{321}^{II} + B_{411}\right] + B_{\mathrm{ct}} + B_{\mathrm{stoch}}$$

- 4th order bias, RSD, conunterterms, IR resumm.
- 44 free parameters (+2)
- Many high precision tests passed! e.g. 0.1%, real space, etc.
- Cosmo param's don't improve even @ kmax = 0.2 h/Mpc
- fNL does not improve either

*NB.* no "prior volume" bias




*Philcox, MI ++ (2022)*

# Future of EFT of LSS


- Forecasts suggest a bright future:

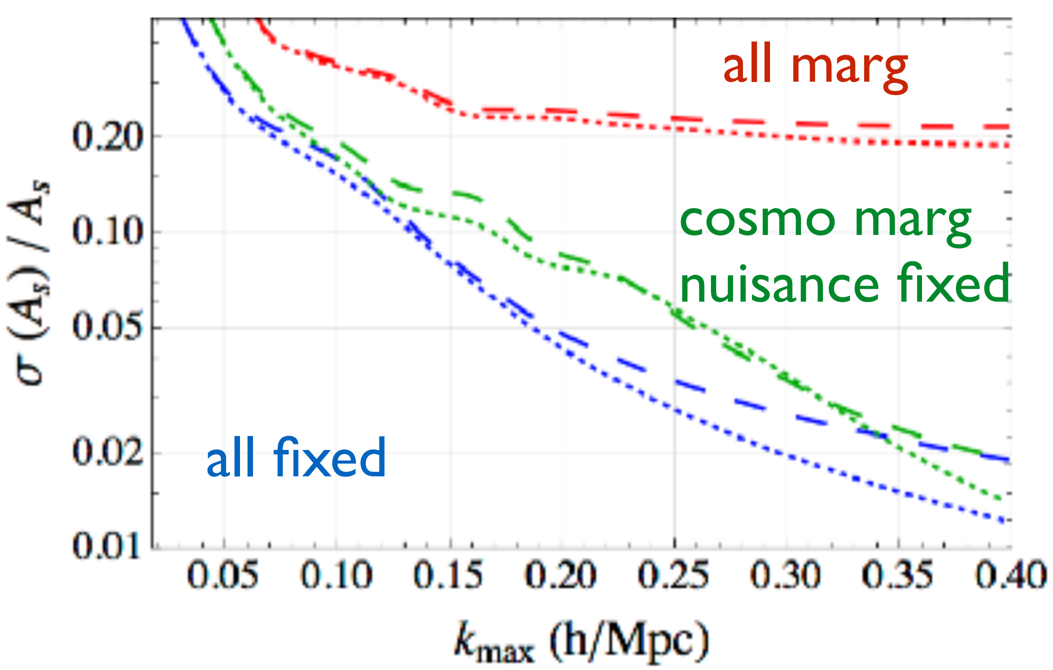
  Hubble, Neutrinos, fNL, …

  *Chudaykin, MI'19   Sailer, Castorina++'21,   Philcox, MI++'22, Braganca'23*

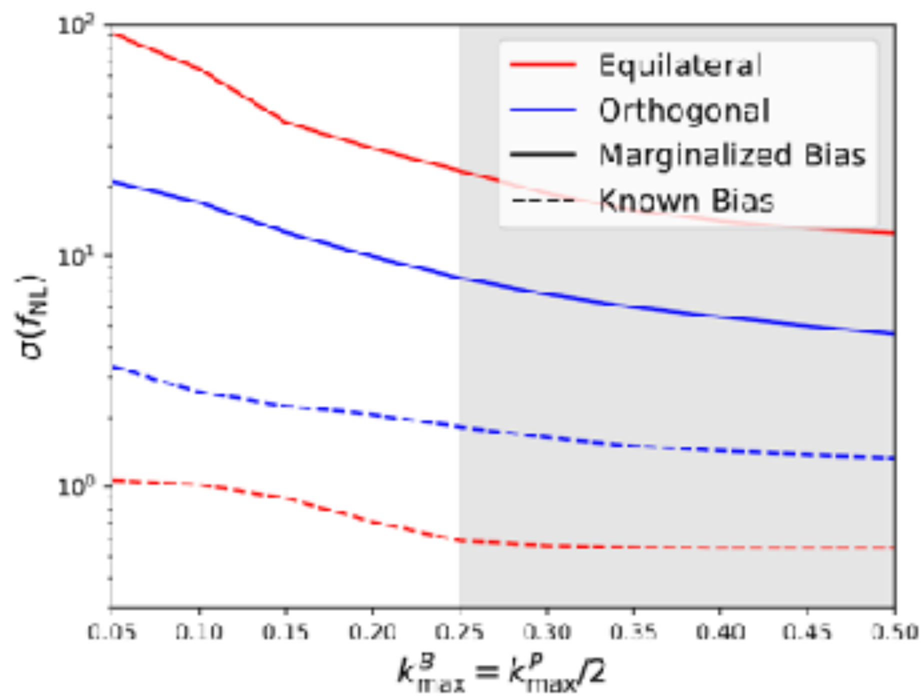
- Can we get even better with higher order EFT ?

# Future of the high loop EFT?

- EFT "party line" example:
  "we get 5-loop trispectrum and it will be great!"
- We see evidence that this will not be that simple
- Nuisance parameters are the bottleneck




Wadekar, MI, Scoccimarro (2020)




Philcox, Cabass, MI, Simonovic, Zaldarriaga (2022)

- Knowing nuisance parameters >> higher loops
- An even bigger problem at higher orders!

# Blast from the past: CHPT

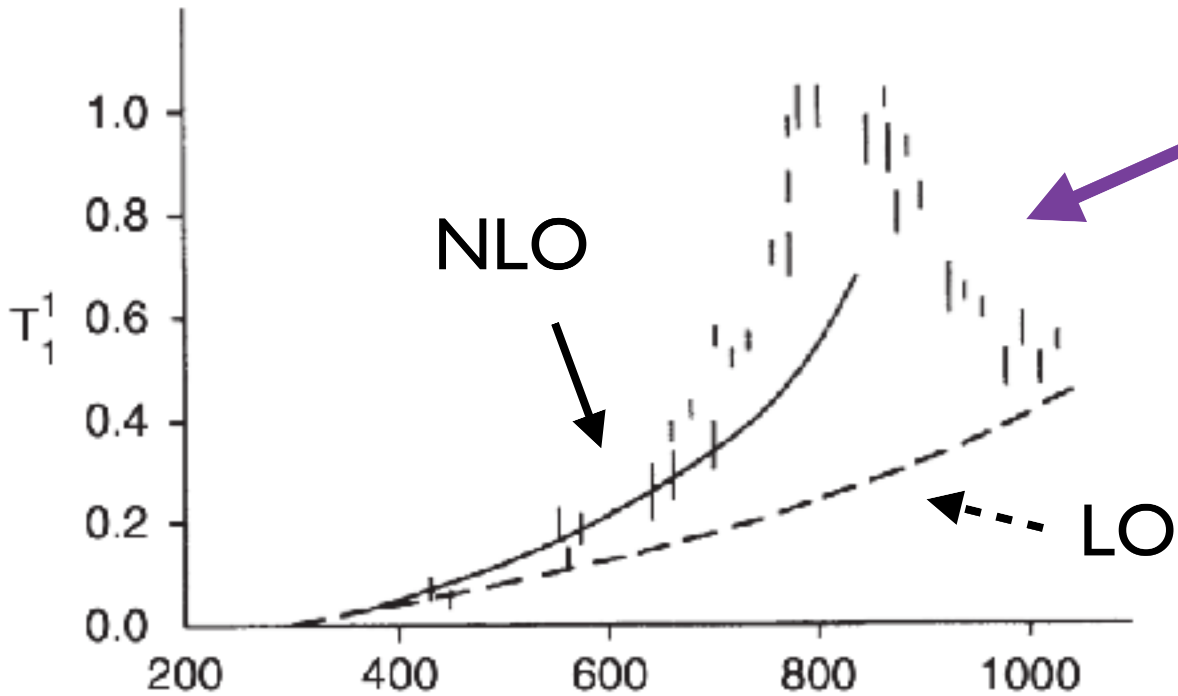



Fig. VII–4 Scattering in the $I = 1, \ell = 1$ channel.

*© Donaghue, Golowich, Holstein SM textbook*

$$G_\pi(q^2) = -\frac{m_\rho^2}{q^2 - m_\rho^2 + i m_\rho \Gamma_\rho(q)\theta(q^2 - 4m_\pi^2)}$$

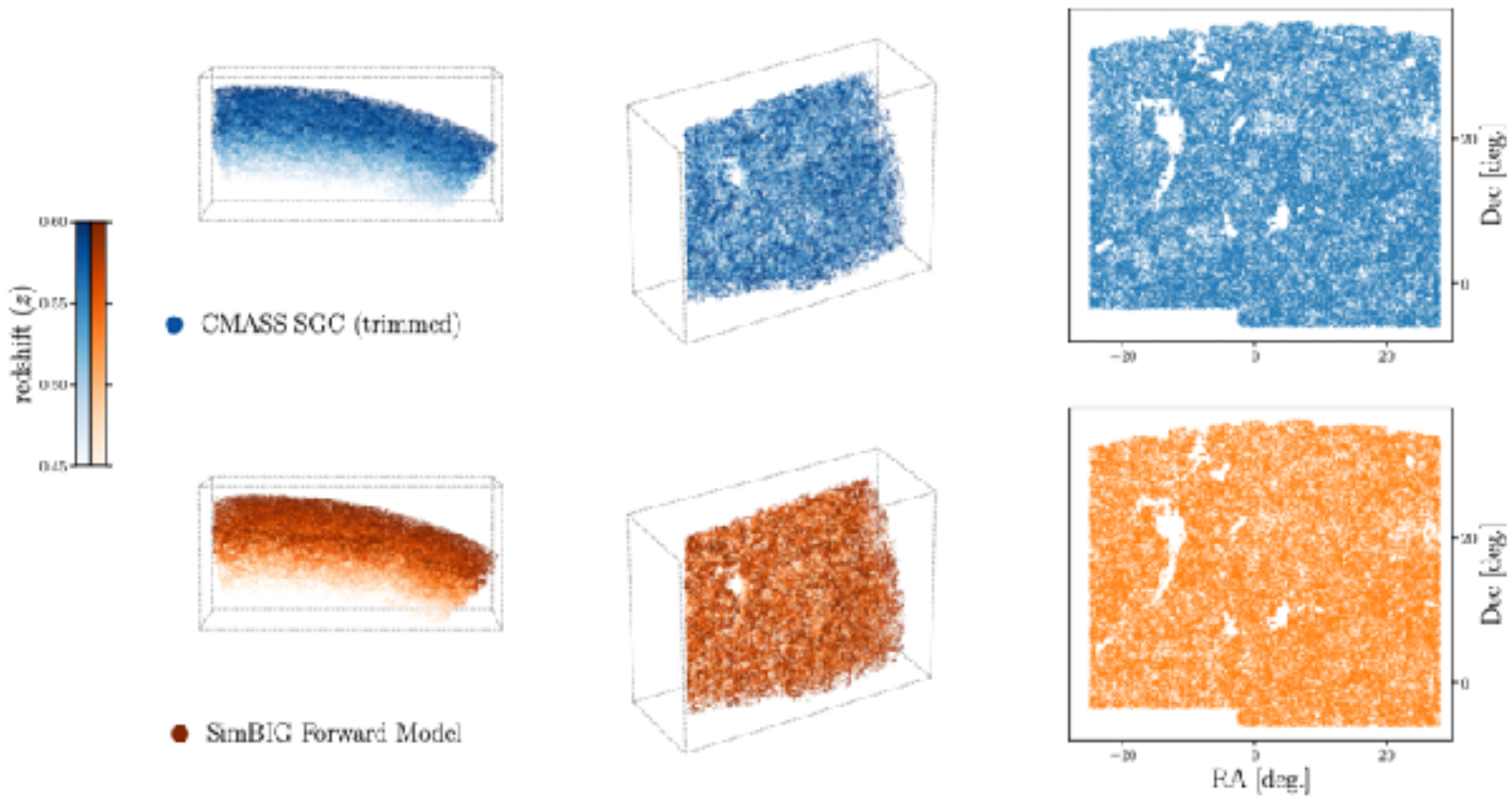
infinite loops can't capture a simple Breit-Wigner!

- Proliferation of LEC (nuisance param's) is the main reason CHPT wasn't successful beyond 1-loop (>100 LEC @NNLO)
- This may be the fate of the EFT of LSS

*Baldauf ++(2015), Konstandin++(2019) , Philcox, MI++(2022)*

# Alternative: Simulation-based inference

*e.g.: C. Cuesta-Lazaro'23, Hanh ++'22,23, Dvorkin++'22,23, etc.*




*© Hanh ++'23*

- HOD: ~10 parameters only (cf. ~46 for 1-loop B)
- All N-point functions are reproduced on all scales!
- future of EFT will depend on how we use this information

# Summary

- PT (EFT) - robust analytic tool for LSS
- Cosmo. parameters competitive with CMB
- Novel ways to test new physics, e.g. mixed DM
- Huge improvements in the future
- Non-perturbative information will be key

Thank you!