Synergies and Fundamental Physics from the Large-Scale Structure

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Excelencia María de Maeztu

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H_0 tension

LSS & Galaxy Surveys

Primordial Black Holes

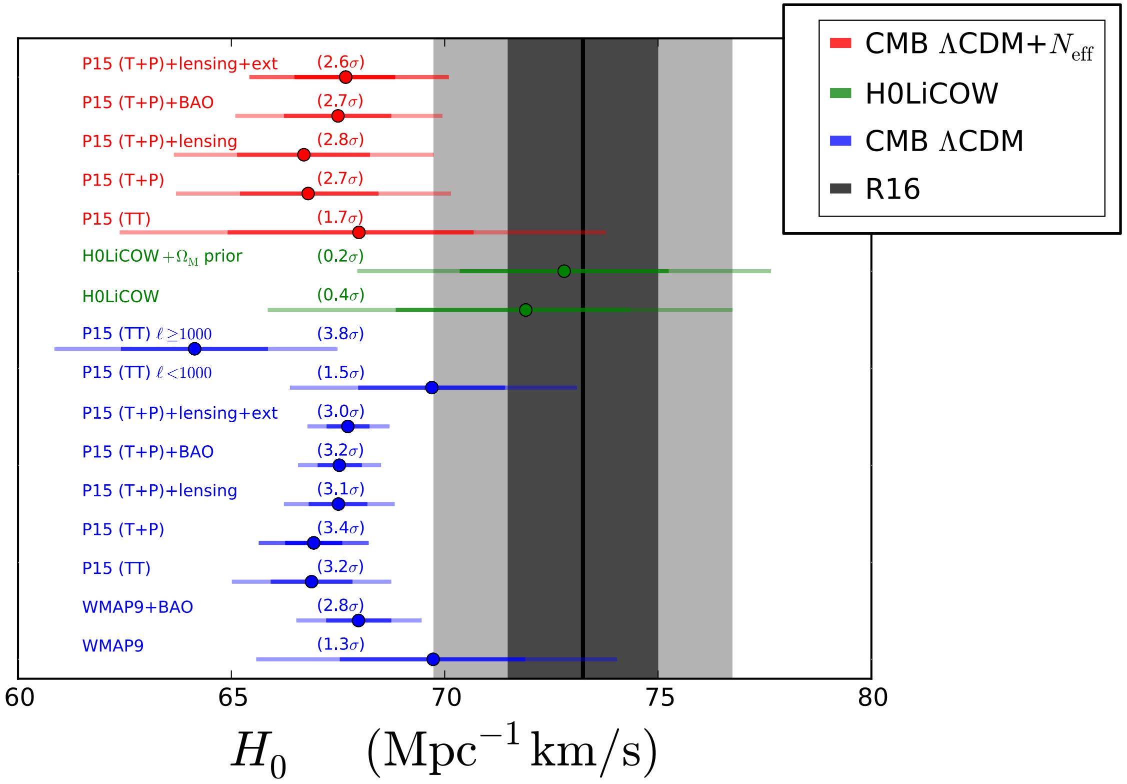
SYNERGIES

José Luis Bernal

LBNL

JLB, Verde, Riess (2016)
Verde, JLB, et al. (2017)

H_0 Tension



- Model dependent tension

JLB, Verde, Riess (2016)
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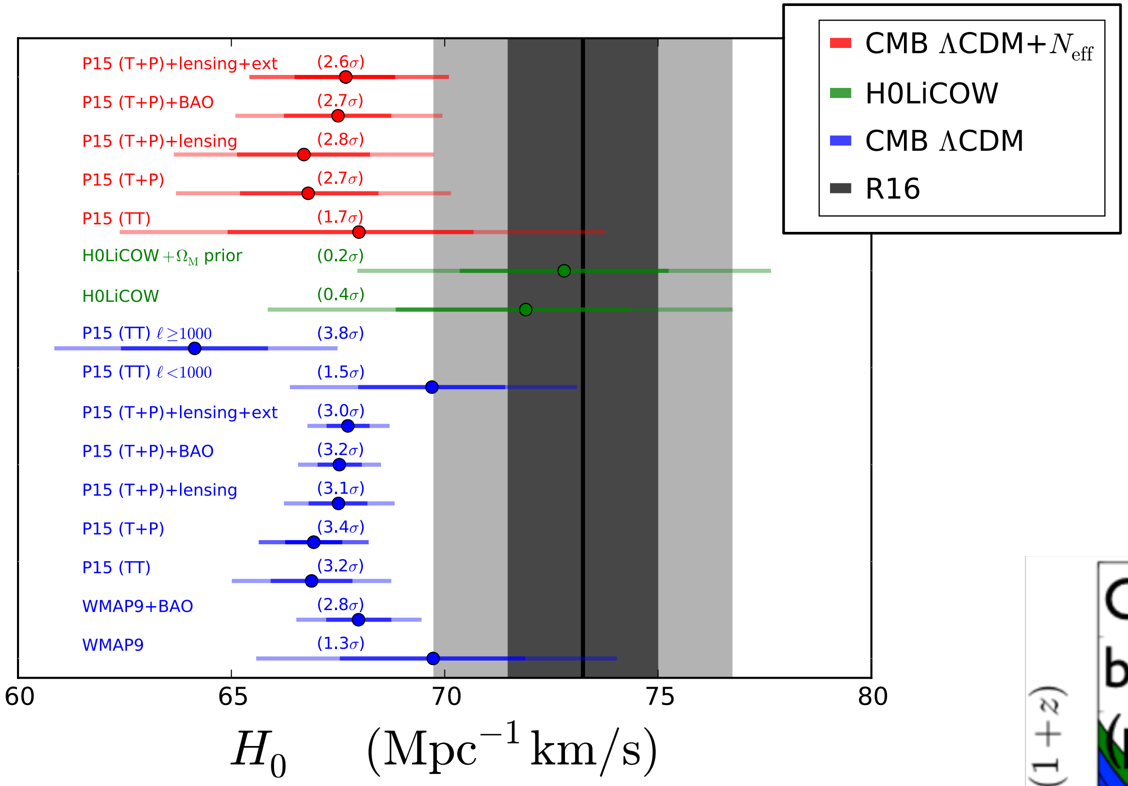
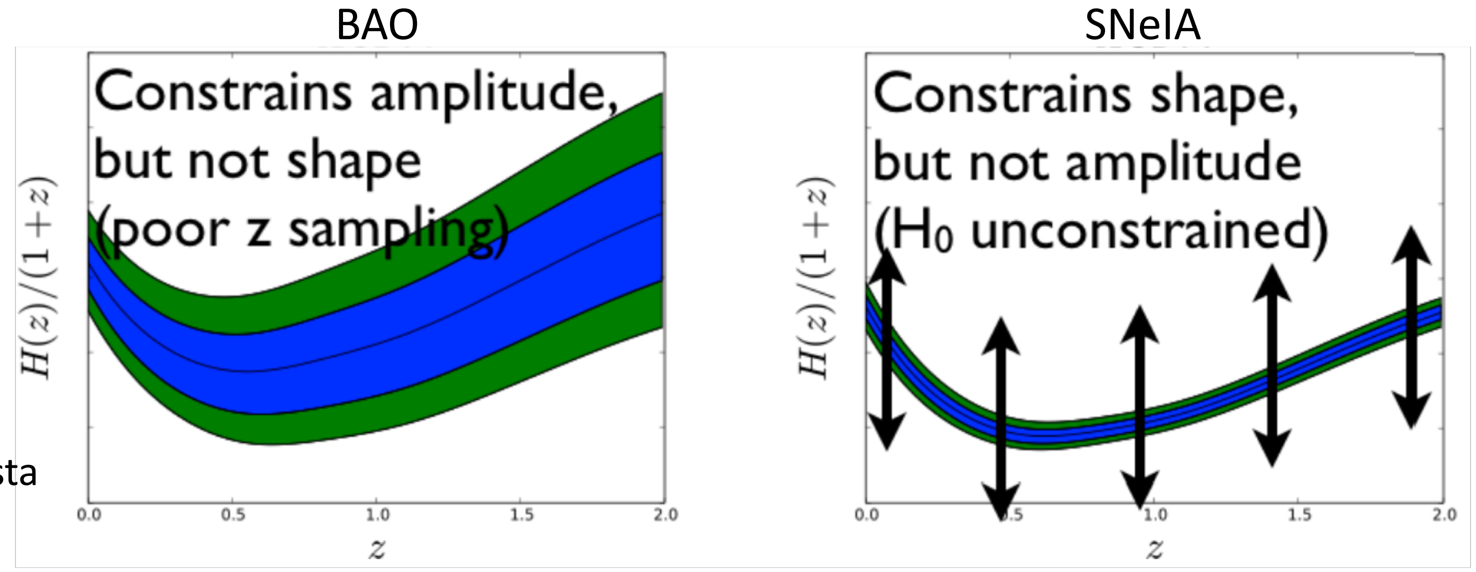


- Model dependent tension
- Agnostic approach to the $\sim 3.6\sigma$ tension:
  Model independent analysis of low z expansion
  $H(z)$ parametrized with cubic splines



A. J. Cuesta

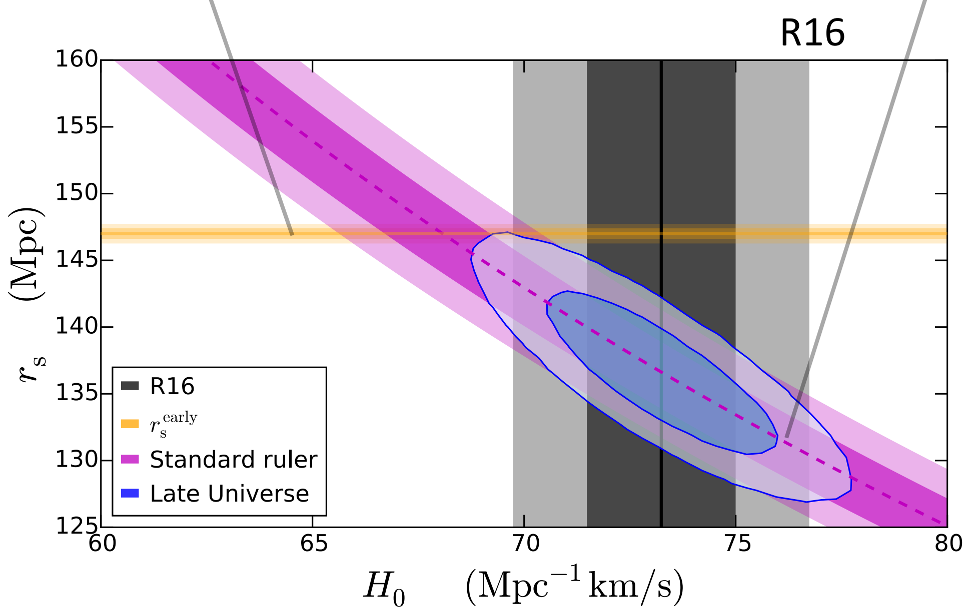
Normalization $\propto r_s \times H_0$

H_0 Tension

JLB, Verde, Riess (2016)
Verde, JLB, et al. (2017)

CMB (only early Universe)
Verde+ 2017

BAO (free r_s)+SN+R16



- BAO+SN constrain:
  - Expansion to be ΛCDM-like (dev. < 5%)
  - $r_s \times H_0$ below 2% precision
- Mismatch between the two anchors of the cosmic distance ladder (r_s & H_0)

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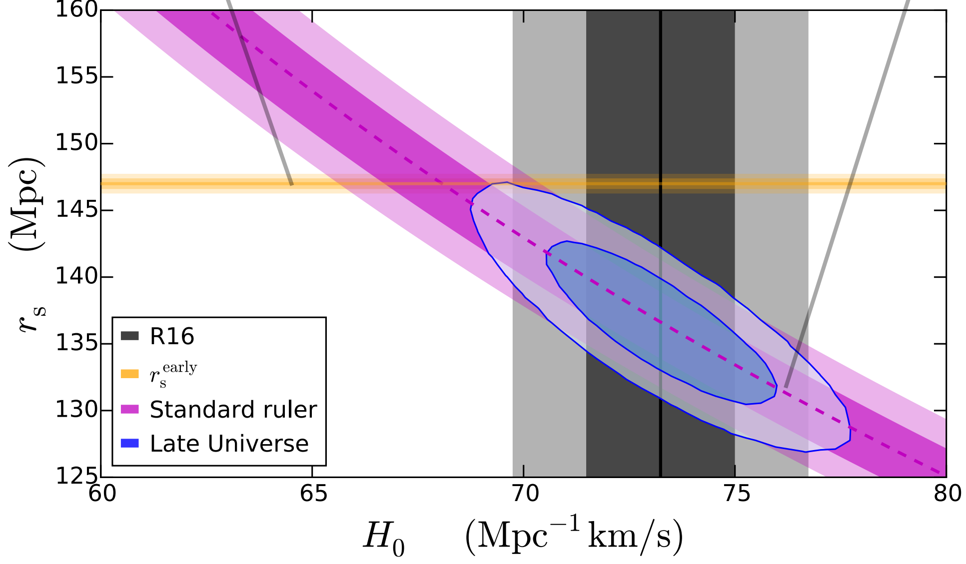

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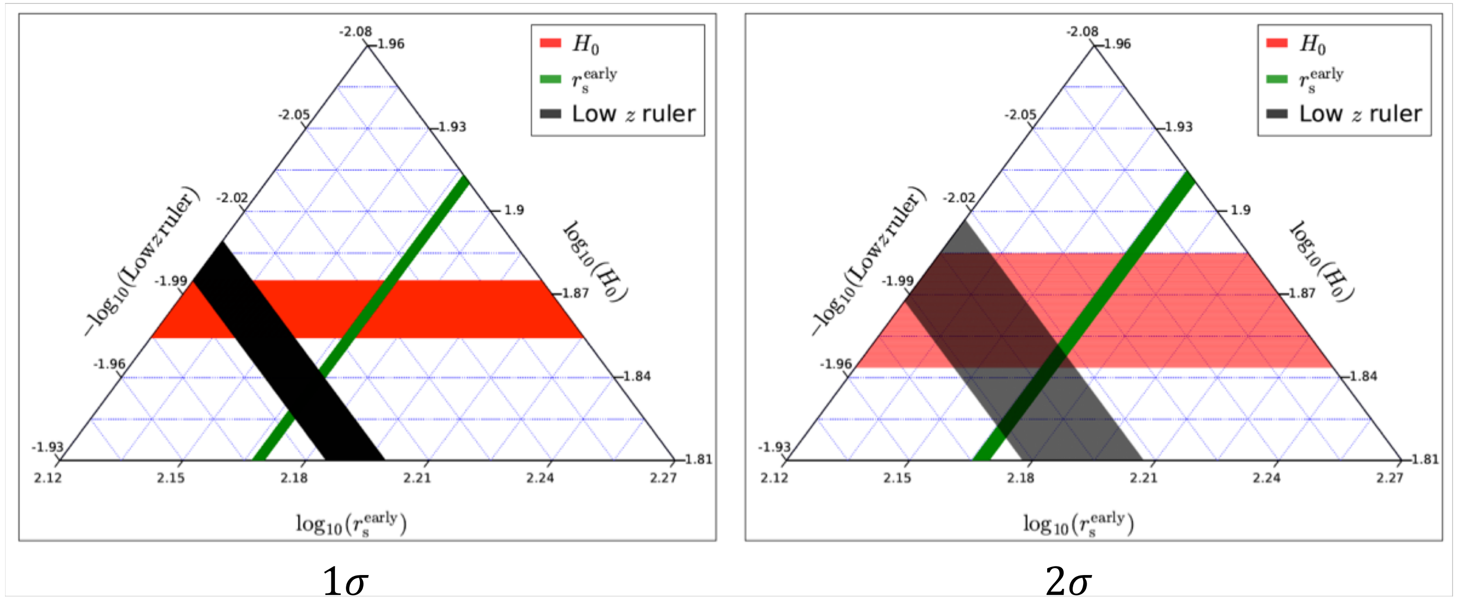
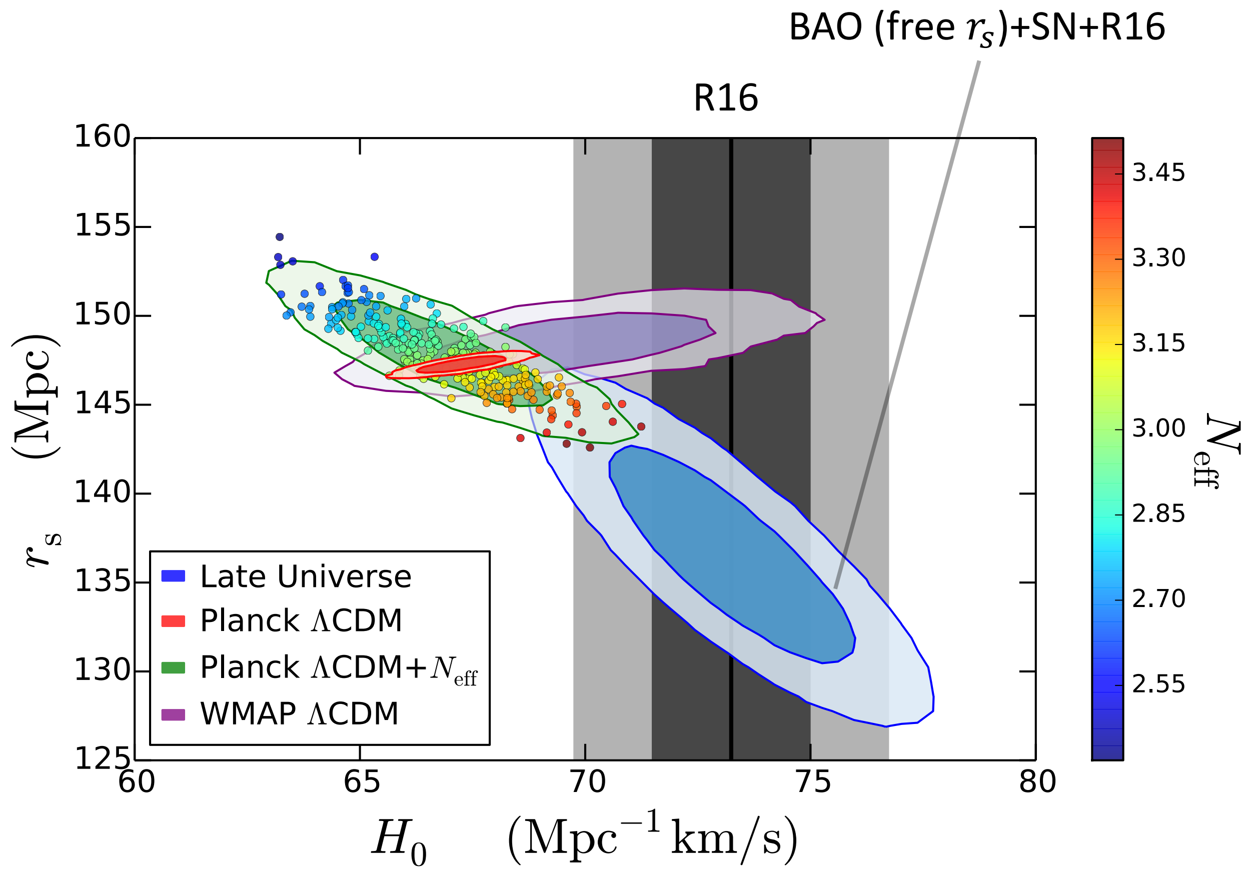


- New versión of the cosmic triangle

JLB, Verde, Riess (2016)
D'Eramo, Ferreira, Notari & JLB (2018)

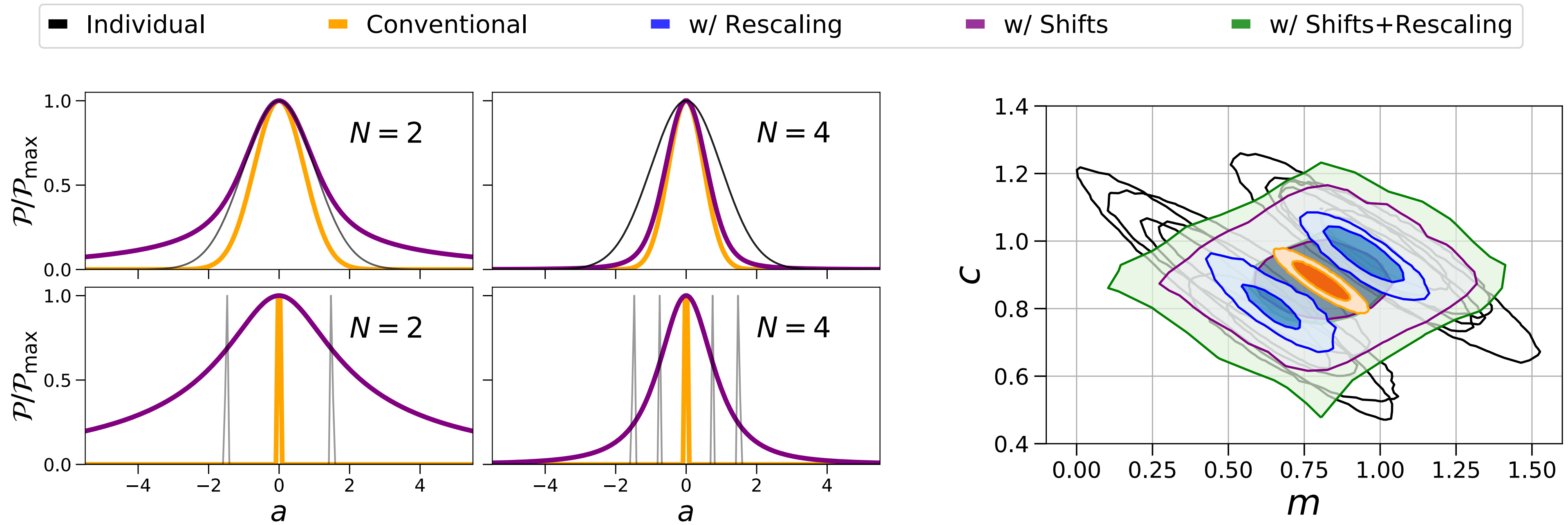
H_0 Tension



- ΔN_{eff} doesn't help, not even theory motivated models such as hot QCD axions (Planck constraints)
- Early Universe mods that shift r_s without changing CMB
- Large changes in $H(z)$ during $2 < z < 1000$

JLB & Peacock (2018)

BACCUS (or how to be conservative)

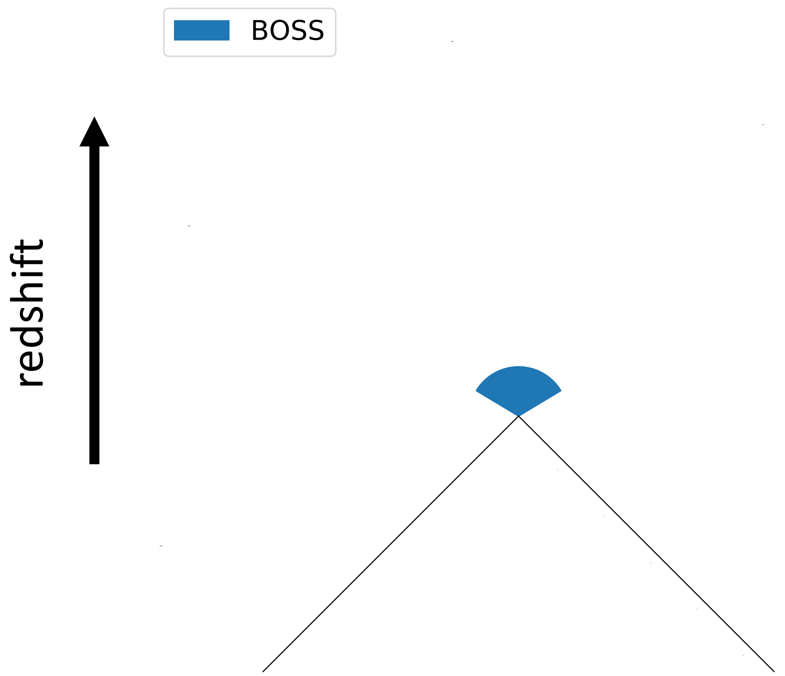


- Combine discrepant data sets to obtain conservative constraints.
- Introduction of "shift" hyperparameters (i.e. $a^i_{th} = a_{par} + \Delta^i_a$)
- Marginalize over hyperparameters to account for posible systematics
- Hyperparameters to evaluate the discrepancy
- BACCUS: code available at github

New opportunity: the Ultra Large Scales

Why ULSS

- Galaxy surveys have focused mainly in BAO scales (~147 Mpc)
- There is much more information in the galaxy clustering
- Non linear scales: Tons of modes but difficult to model



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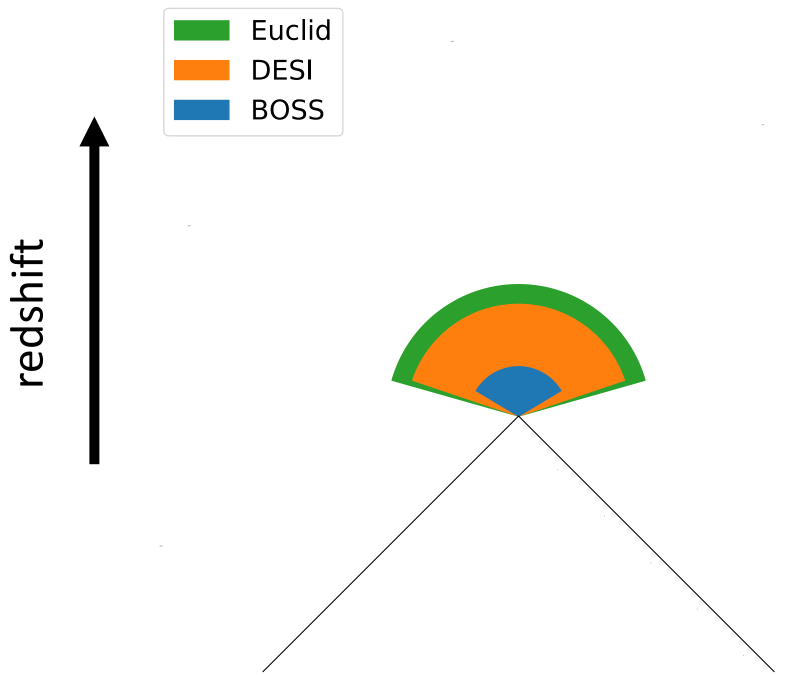
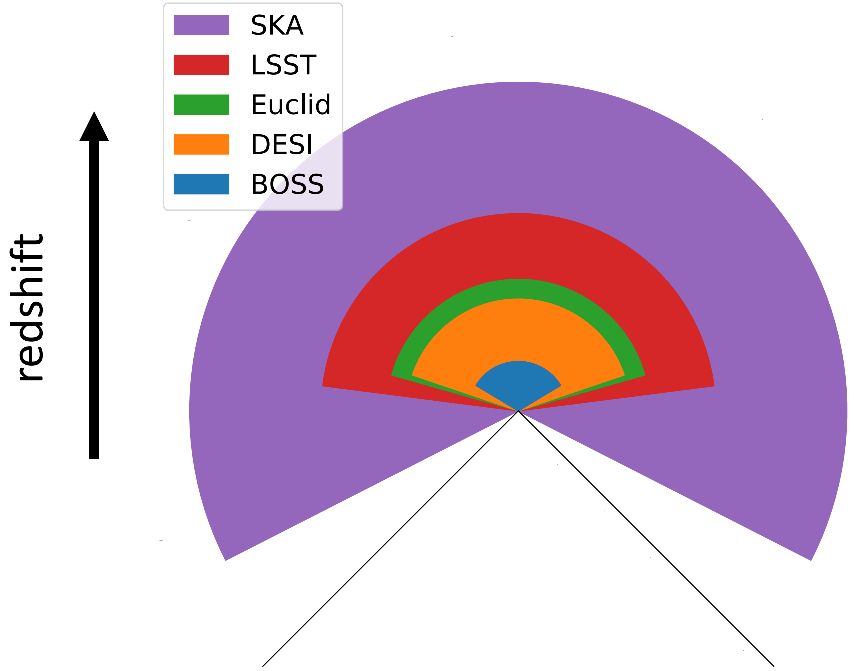


New opportunity: the Ultra Large Scales

Why ULSS

- Galaxy surveys have focused mainly in BAO scales (~147 Mpc)
- Independent, extra and new information not accessible in other ways
- Non linear scales: Tons of modes but difficult to model
- In a couple of years, much larger volumes will be observed
- Should be exploited!!

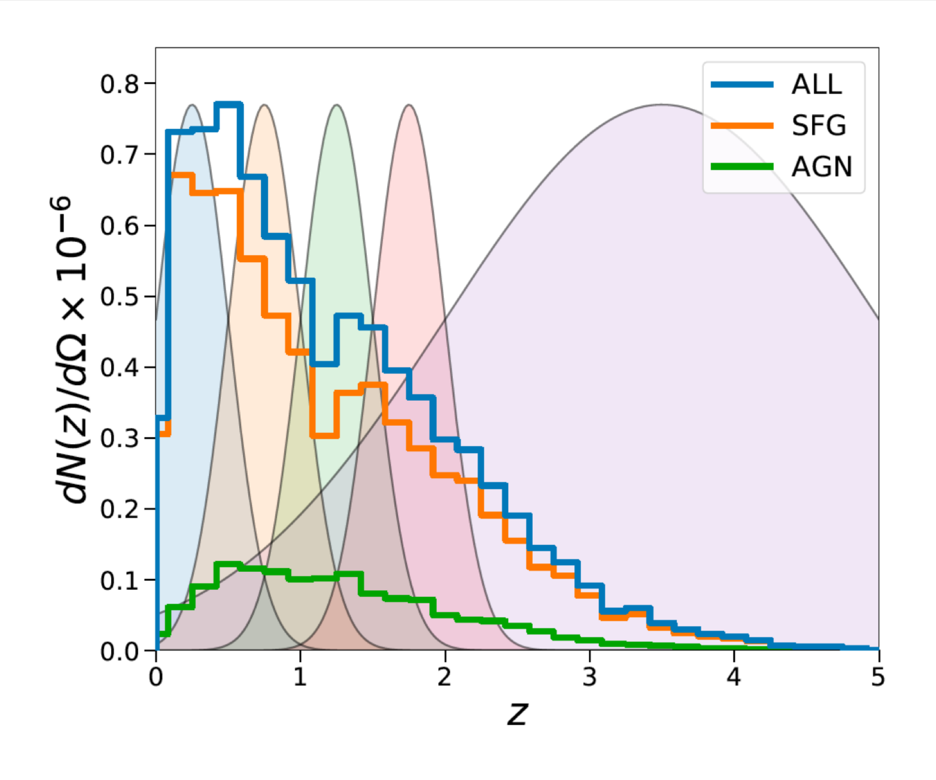


What can we gain?

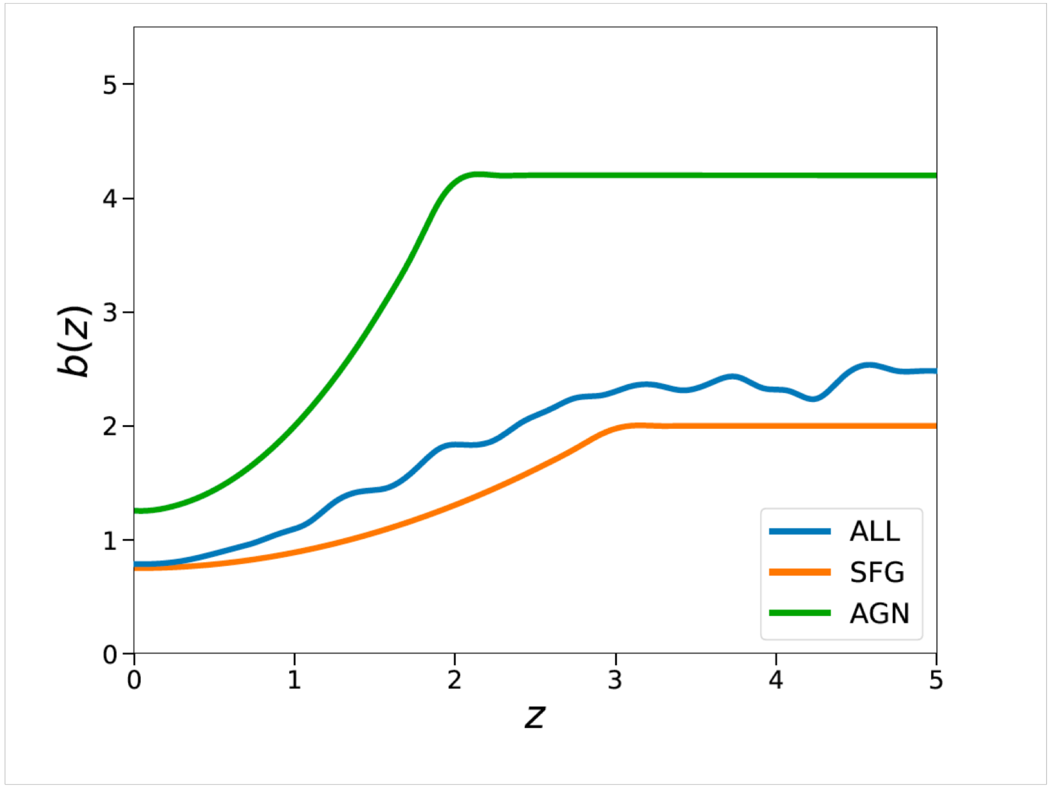
- These scales are there.. Why not?
- Better understanding of galaxy clustering (i.e. bias)
- Cross checks of smaller scales measurements
- Relativistic effects arising at horizon scales
- Primordial Non Gaussianity: galaxy bias $\propto k^{-2}$ if $f_{\rm NL} \neq 0$
- Spatial curvature
- Dark energy and Modified Gravity
- Dark matter
- …

Evolutionary Map of the Universe

- EMU: SKA pathfinder already observing (all sky)
- Radio continuum survey: external data to bin in redshift



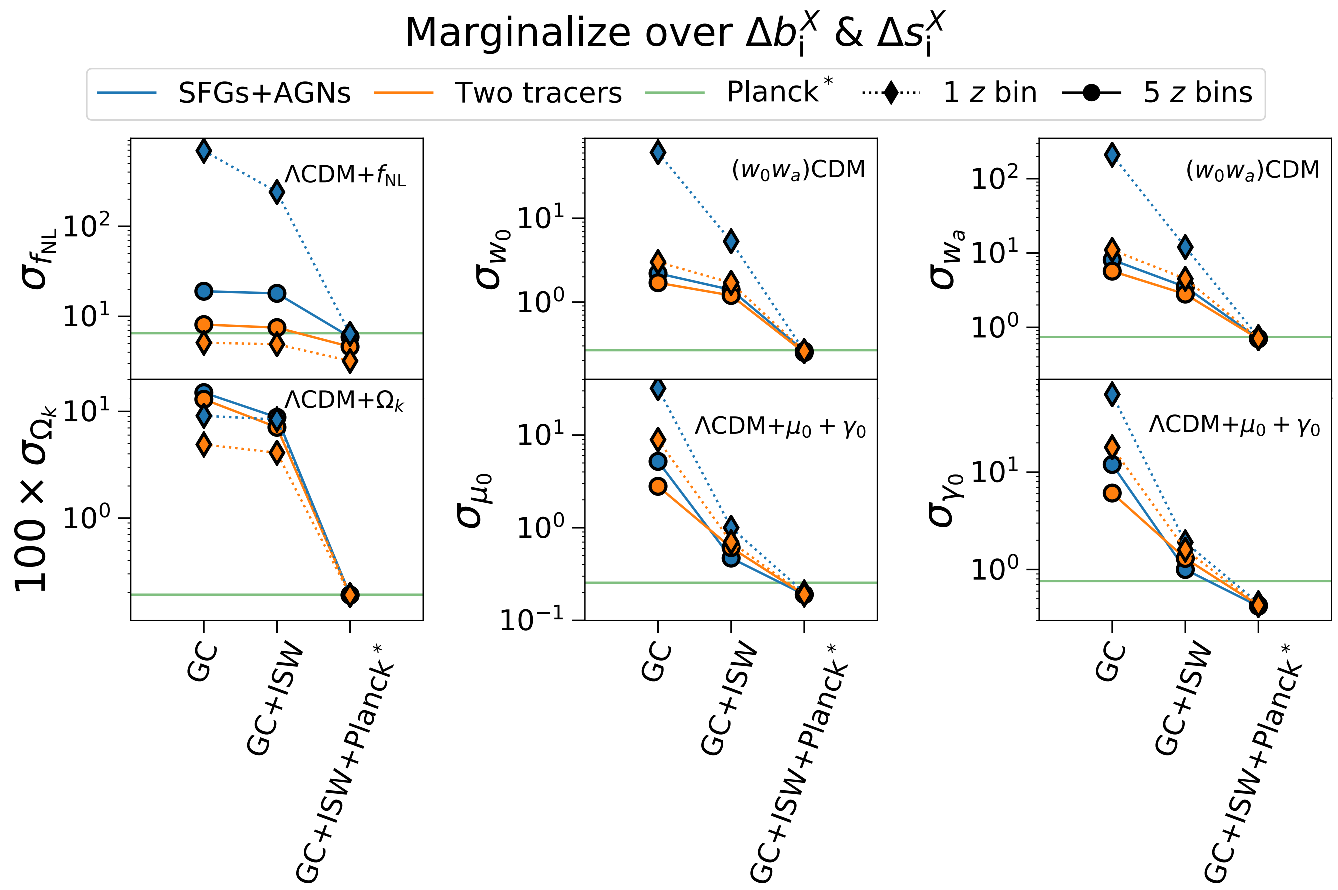
Multitracer: AGN & SFG



Weighted mean

JLB, Raccanelli, Kovetz, et al. (2018)

Constraining ΛCDM using EMU



- Forecast constraints for extended models with different assumptions.
  - $f_{NL}, w_0 w_a, \Omega_k$ & MG
- Galaxy angular power spectrum and ISW
  - Multitracer analysis too
- Improvement for PNG and MG

Multi_CLASS: public soon!

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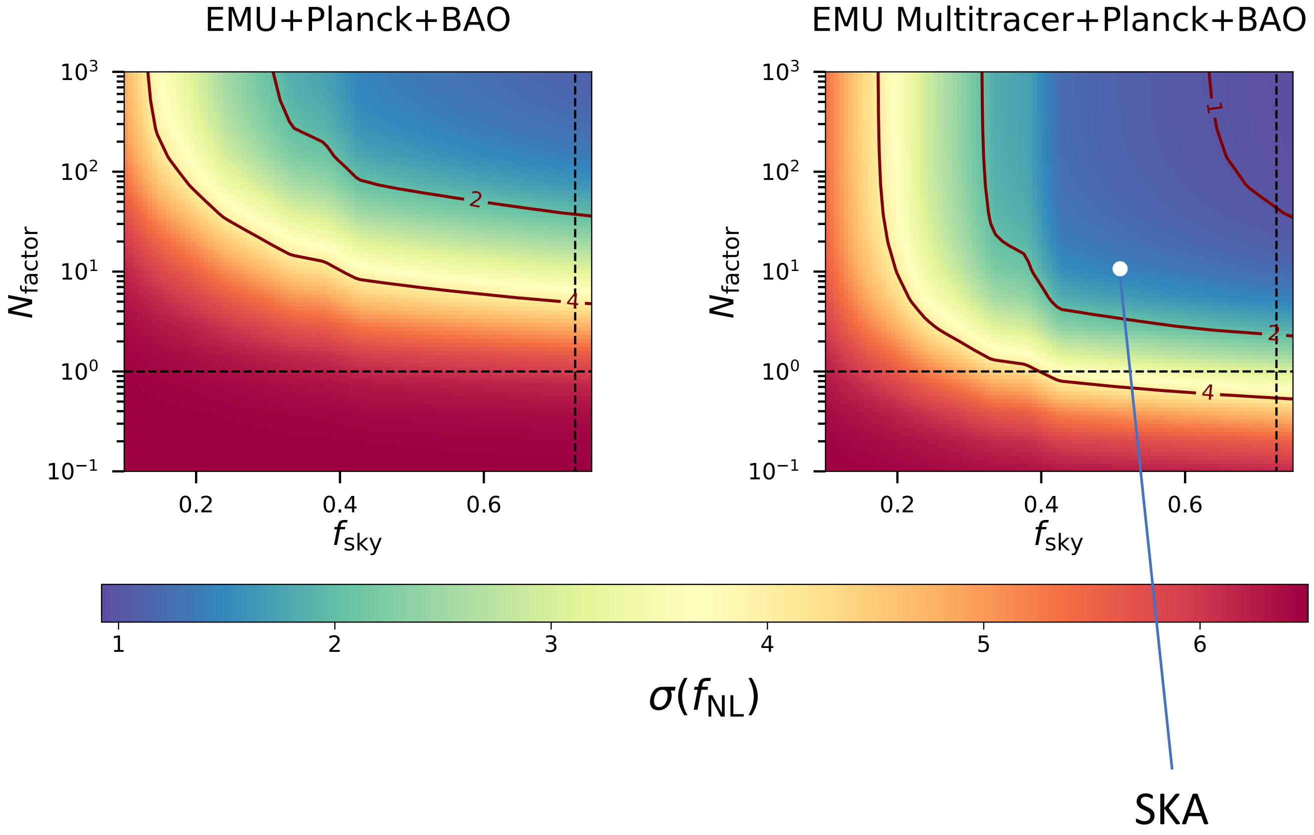

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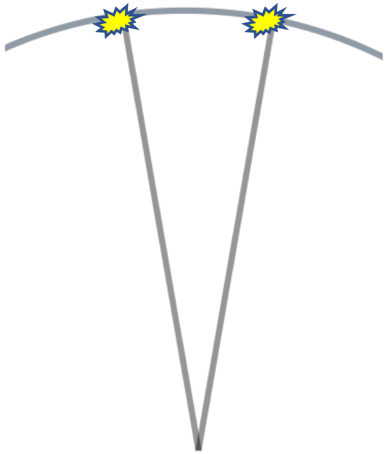
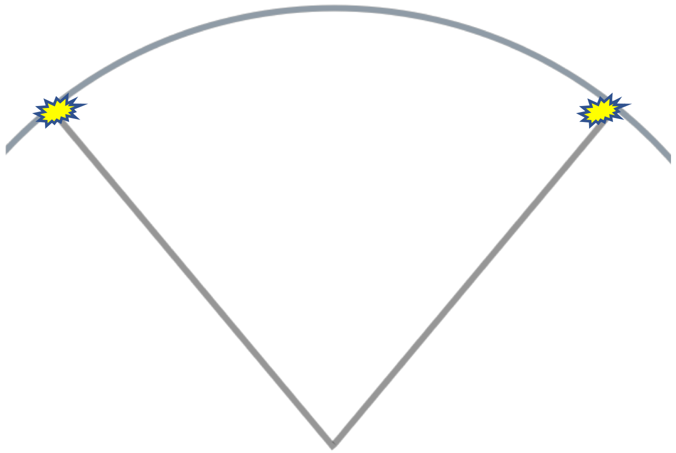
How can we go beyond?





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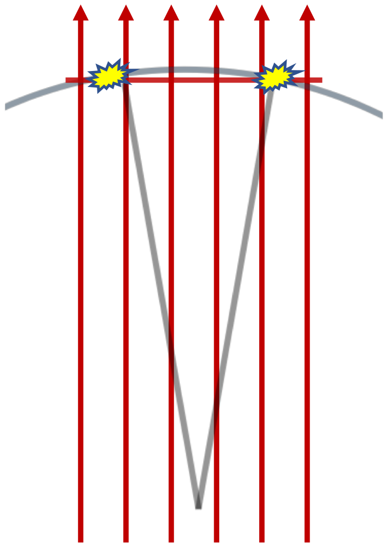
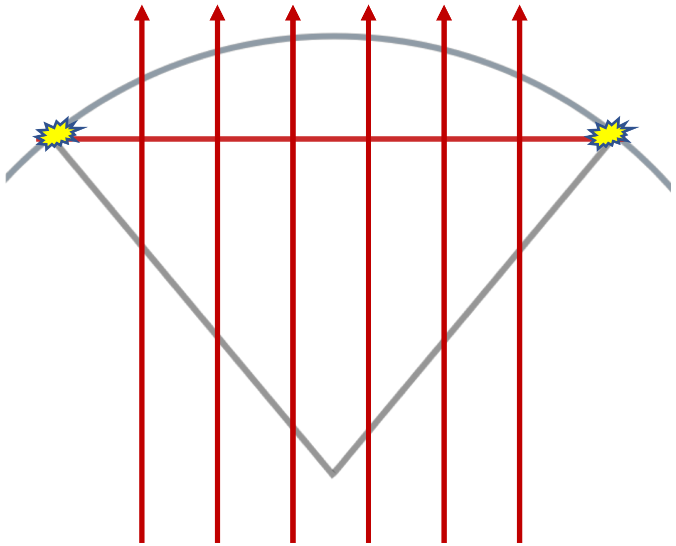


Geometrical set up
of distances and orientations



Flat-sky and plane-parallel approximations do not work in this regime

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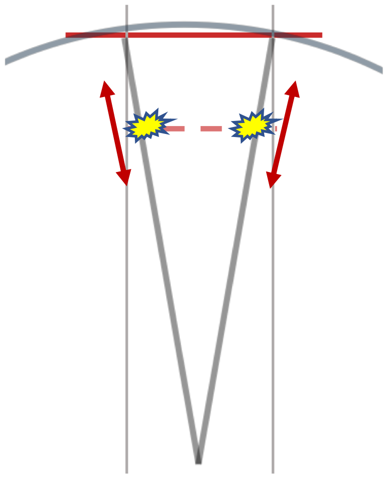
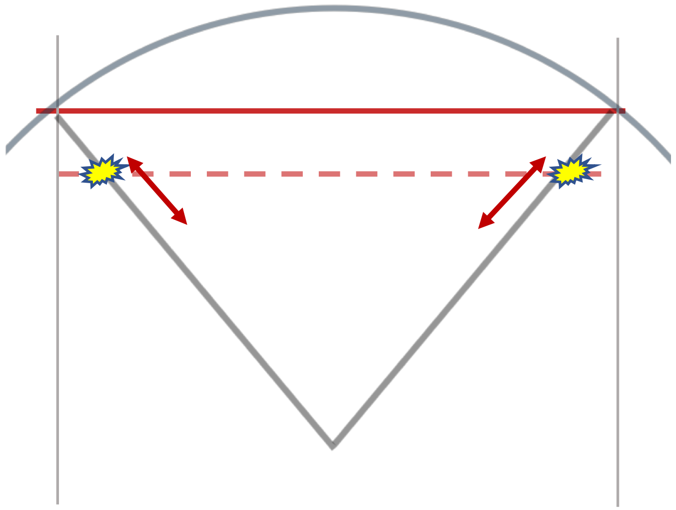


RSD change apparent positions
along the LoS



Flat-sky and plane-parallel approximations do not work in this regime

Complete observed clustering

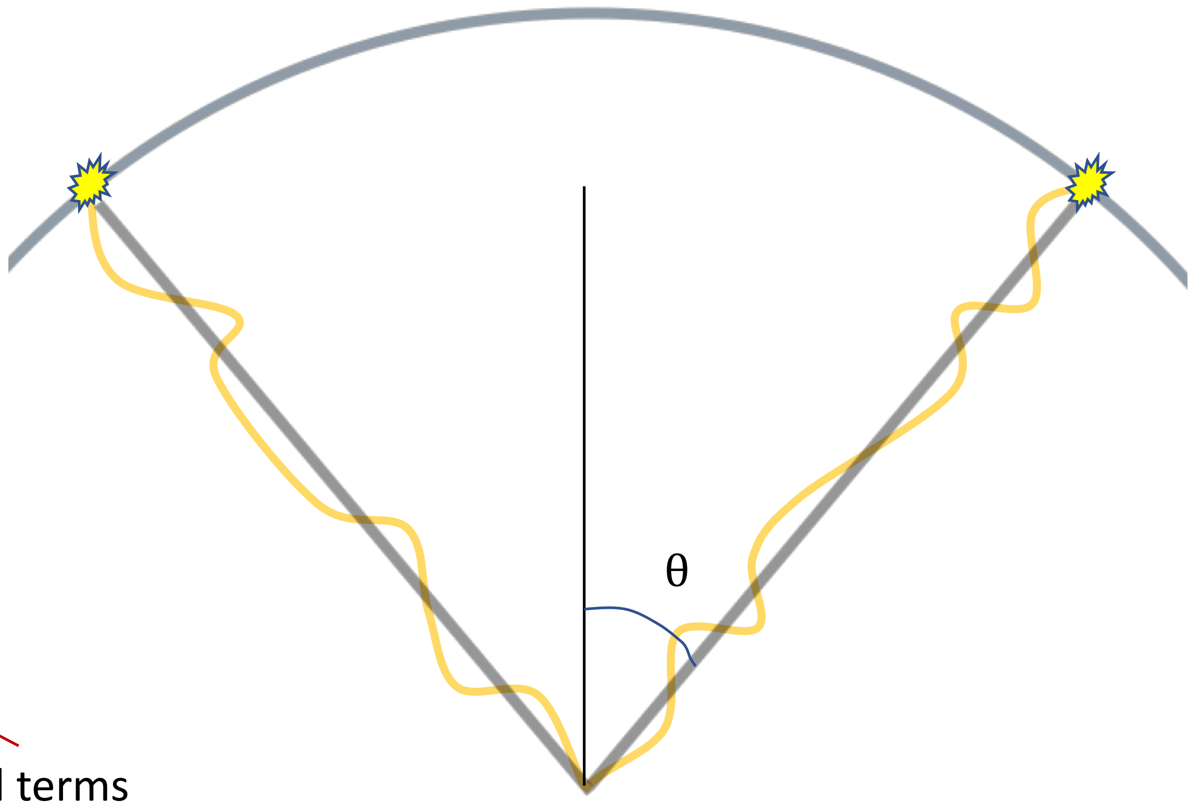
$$\xi(\vec{x}_1\vec{x}_2) = \langle \Delta_{\rm obs}(\vec{x}_1)\Delta_{\rm obs}(\vec{x}_2)\rangle$$

$$\Delta_{\rm obs} = \Delta_{\rm den} + \Delta_{\rm rsd} + \Delta_{\rm wa} + \Delta_{\rm vp} + \Delta_{\kappa} + \Delta_{\rm ISW} + \Delta_{\rm td}$$

Standard terms ($\Delta_{\rm den} + \Delta_{\rm rsd}$)

Local terms ($\Delta_{\rm den} + \Delta_{\rm rsd} + \Delta_{\rm wa} + \Delta_{\rm vp}$)

Integrated terms ($\Delta_{\kappa} + \Delta_{\rm ISW} + \Delta_{\rm td}$)



GR effects at scales of the horizon

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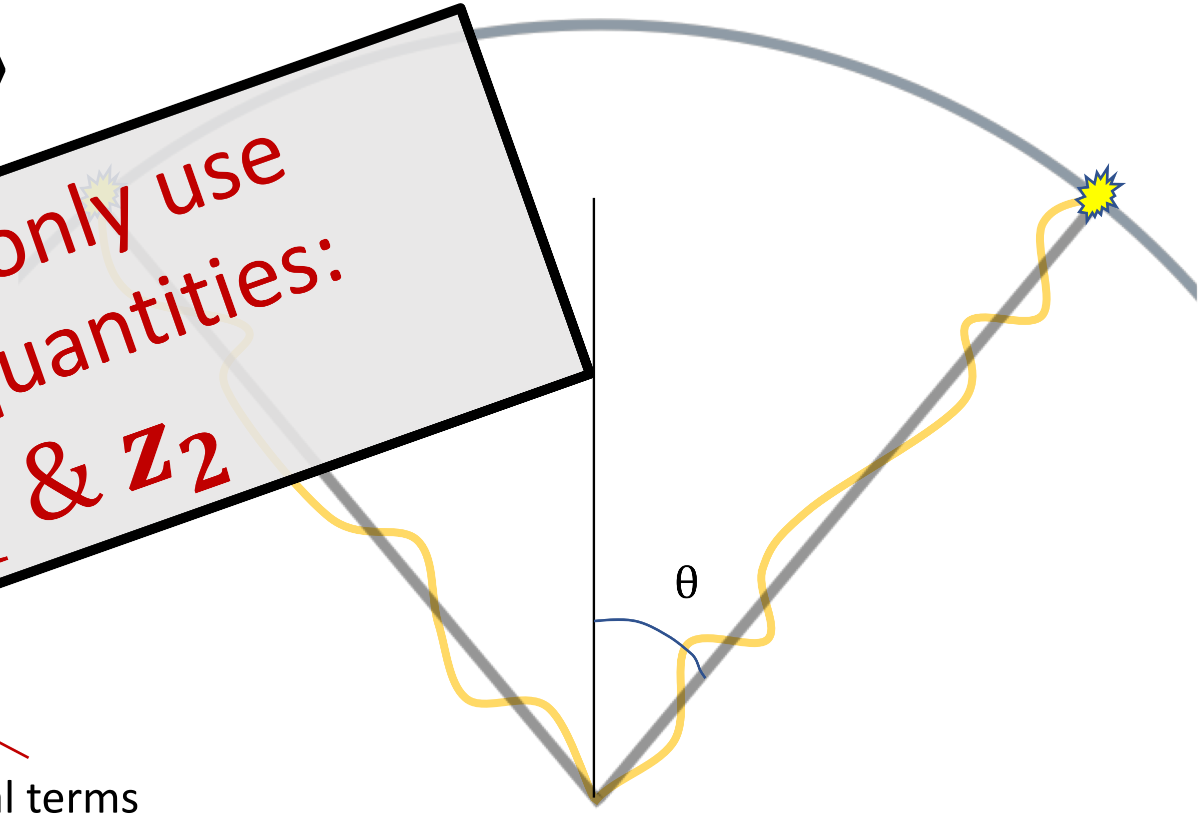
We should only use observed quantities:

$\boldsymbol{\theta, z_1 \ \& \ z_2}$

Standard terms

Local terms

Integrated terms



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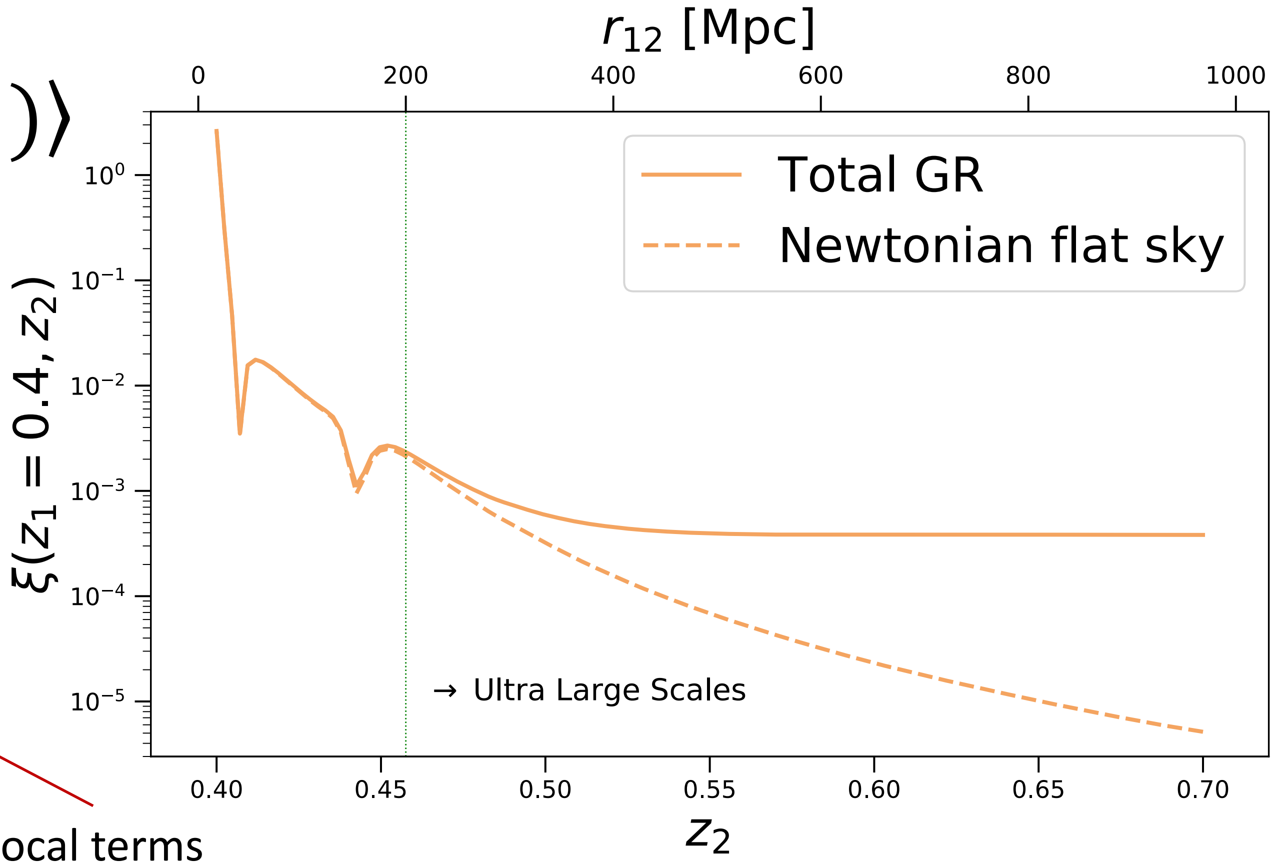


GR effects at scales of the horizon

Challenges for ULSS

- **Foregrounds & inhomogeneous noise:** dealing with complex mask in configuration space is easier. Map-based foreground removal (Kalus+ 2018)

- **Pre-processing galaxy catalogue:** work directly with observed quantities (RA, DEC, z) $\rightarrow$ cleaner

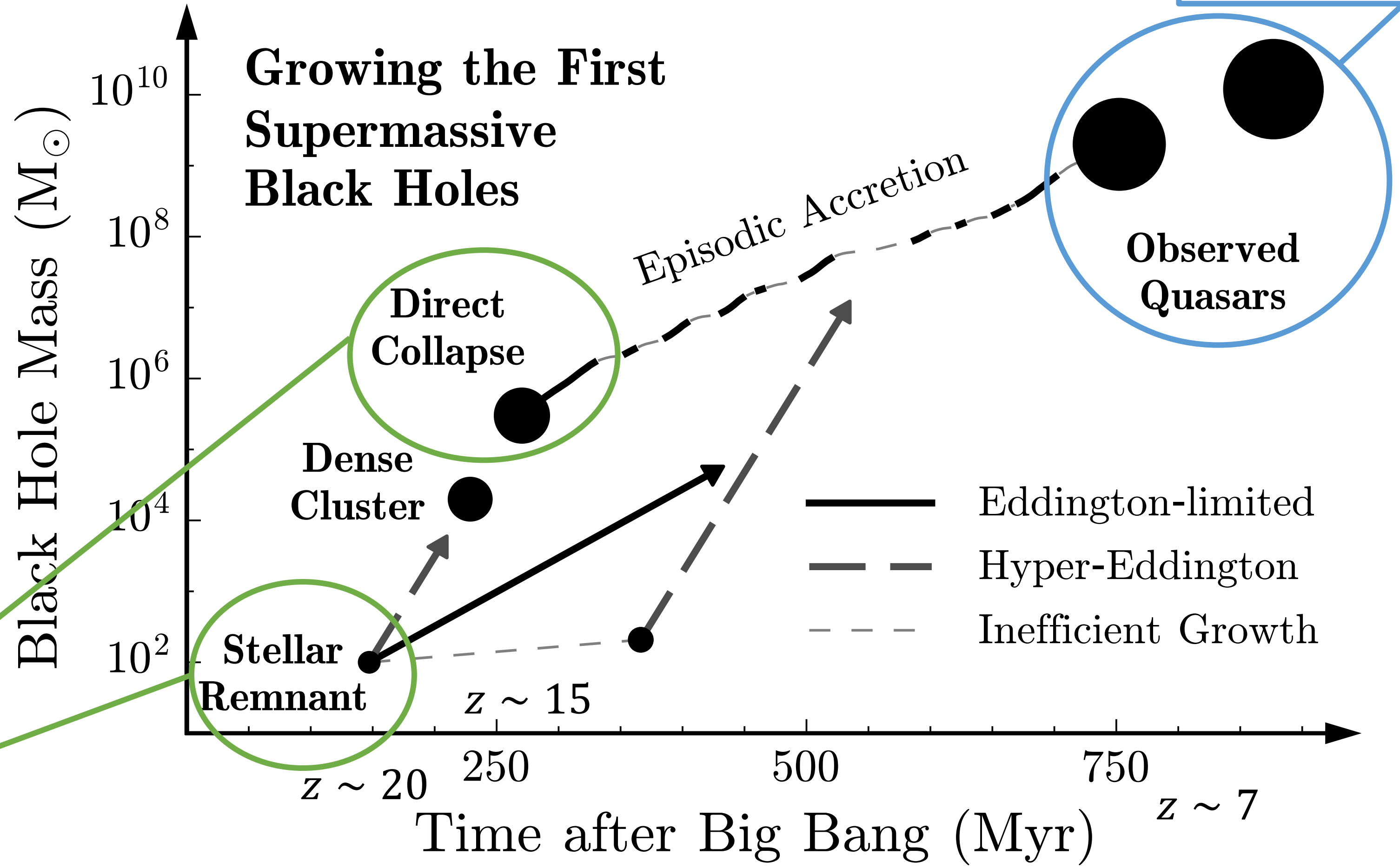
- **Cosmic variance:** Multitracer techniques

- **Modelling of the covariance:** Simulations

- **Including GR in simulations:** LIGER (Borzyszkowski+ 2019).

How SMBHs formed?

Impossible to explain
With standard merger
or accretion history



Seeds of the SMBHs

Smith+ (2017)

How SMBHs formed?

- Formed with $\sim 10^3 - 10^4 M_\odot$
- $f \sim 10^{-8}$ is enough
- Allowed by current constraints

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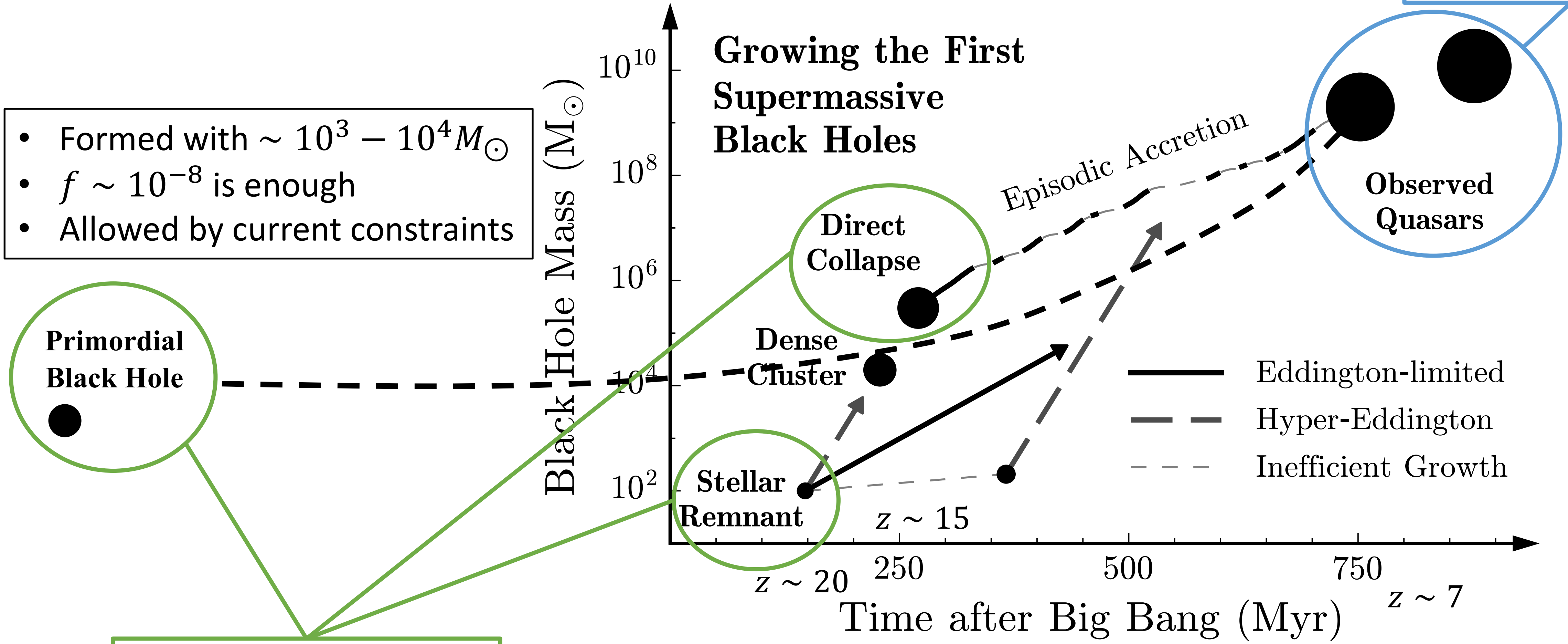

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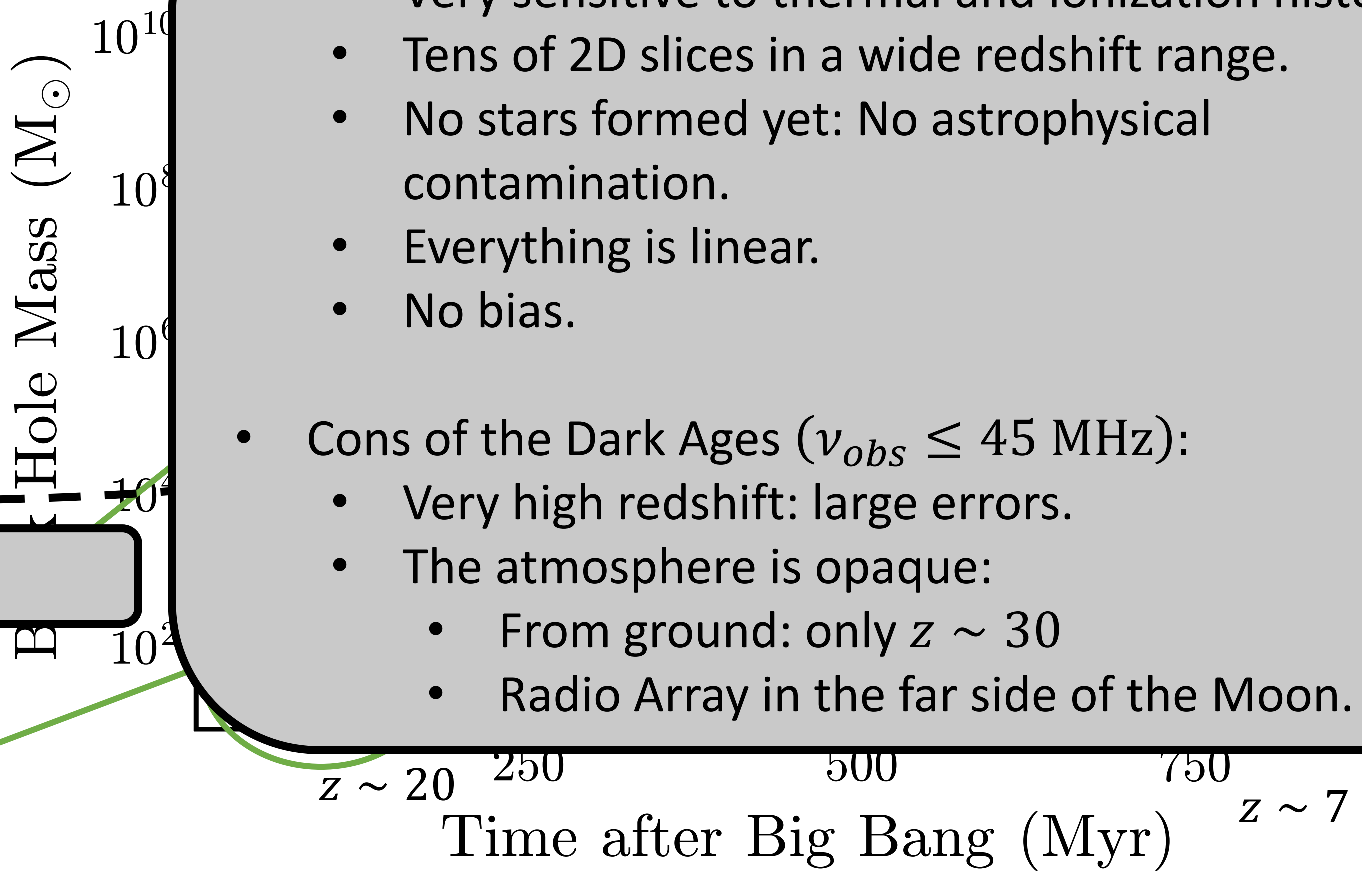
Primordial Black Hole

DARK AGES



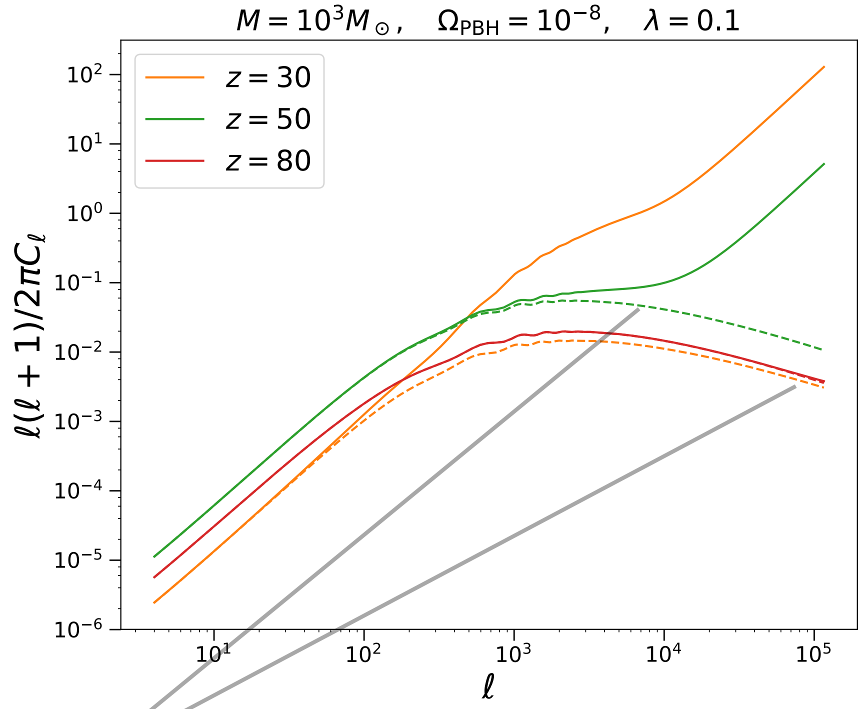
- Pros of the Dark Ages ($z \sim 30 - 200$):
  - Very sensitive to thermal and ionization history
  - Tens of 2D slices in a wide redshift range.
  - No stars formed yet: No astrophysical contamination.
  - Everything is linear.
  - No bias.
- Cons of the Dark Ages ($\nu_{obs} \leq 45$ MHz):
  - Very high redshift: large errors.
  - The atmosphere is opaque:
    - From ground: only $z \sim 30$
    - Radio Array in the far side of the Moon.

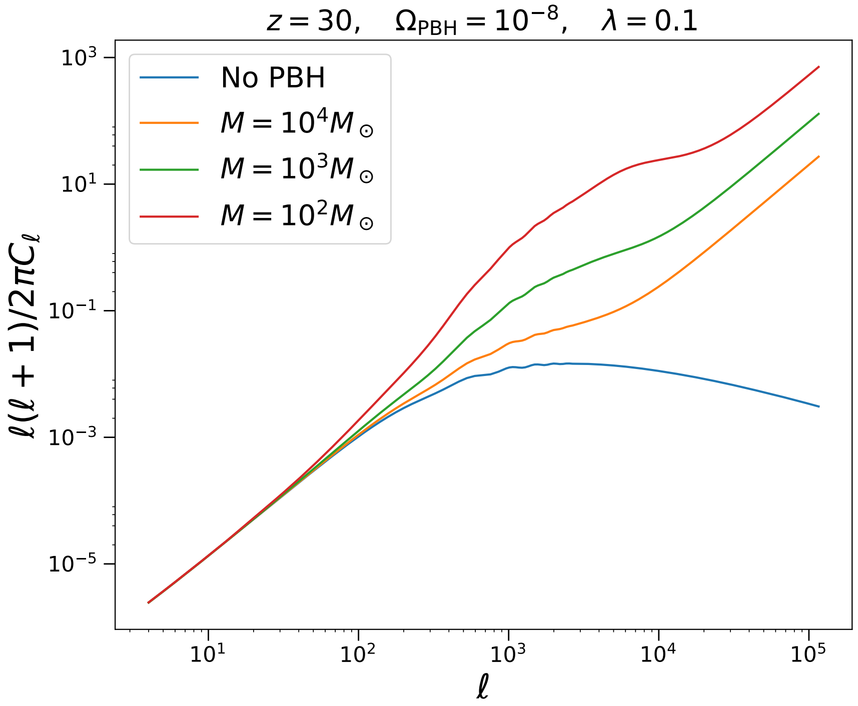
Seeds of the SMBHs

Smith+ (2017)

JLB, Raccanelli, Verde & Silk 2018

21cm IM power spectrum





No PBHs

Predictions of detectability with future telescopes

Difficult with SKA, Lunar Radio Array needed

Conclusions

- The low redshift standard ruler, $r_s H_0$, is very constrained by only SNeIa+BAO.
- Early-late Universe tension? Mismatch in the anchors of the distance ladder.
- The tension in H_0 is not related with deviations in the late time expansion history.
- ΔN_{eff} doesn't help, even with theory motivated models.
- New physics to shift H_0 or r_s?
- Better measurements are coming.

Conclusions

- Next generation surveys = Access to the ULSS.
- EMU+current observations will improve significantly the current constraints, thanks to multitracer and tomography
- $f_{NL}<1$ very very difficult (x40 number density!)
- More precise modelling needed: Wide angle effects and GR corrections in 2PCF.
- New estimators: map-based direct likelihood calculation.
- Ongoing work: stay tuned!

Conclusions

- 21cm IM from the Dark Ages: perfect to probe exotic energy injection.
- Characterization of PBH as SMBH seeds (1st time accounting for full scale dependence)
- Enhancement of the power spectrum at small scales, quickly decaying with redshift.
- Very difficult to detect with SKA: need of a Lunar Radio Array
- Very promising results for exotic dark matter models.
- What else do we want to explore?

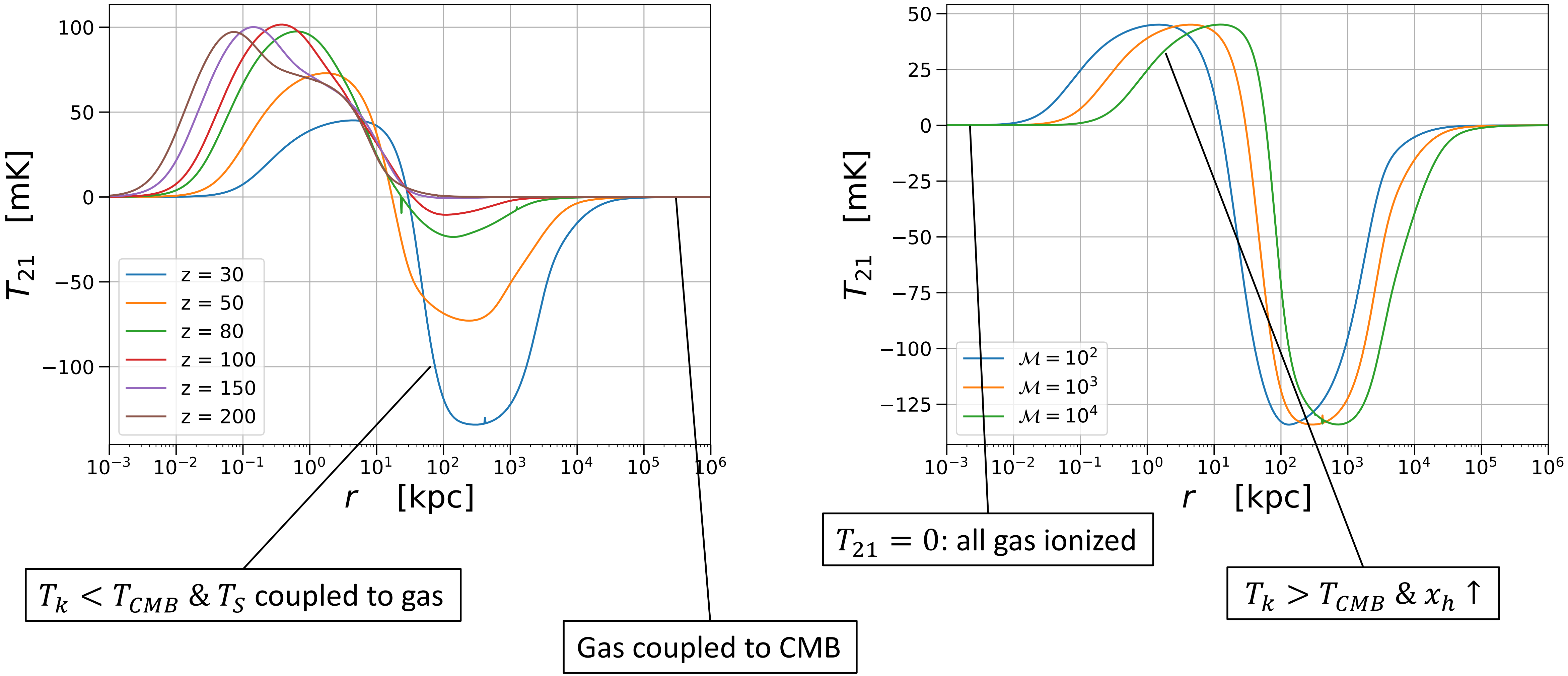
EXTRA SLIDES

JLB, Raccanelli, Verde & Silk 2018

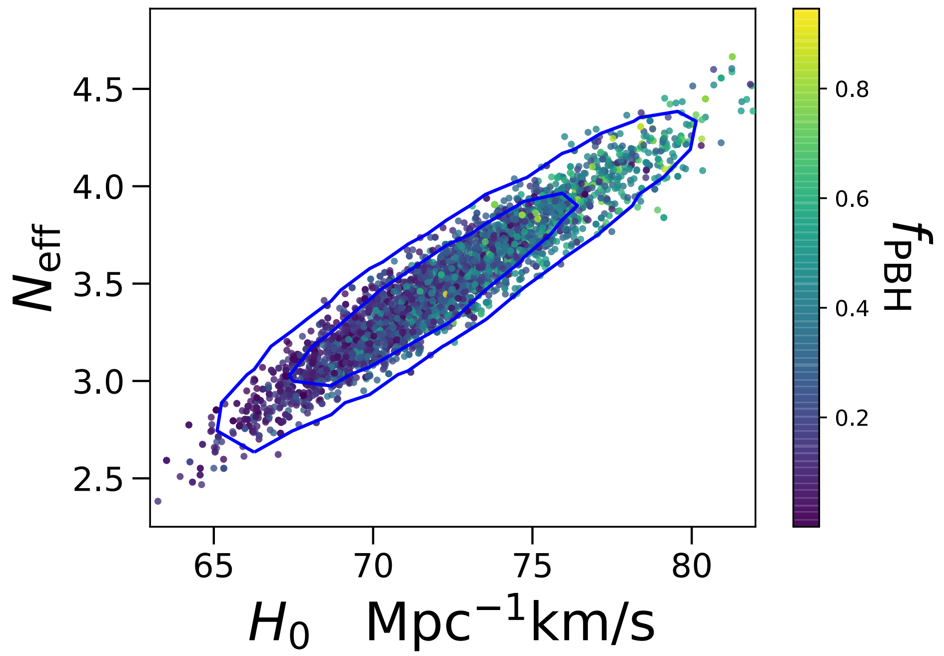
Isolating the signal from a single PBH

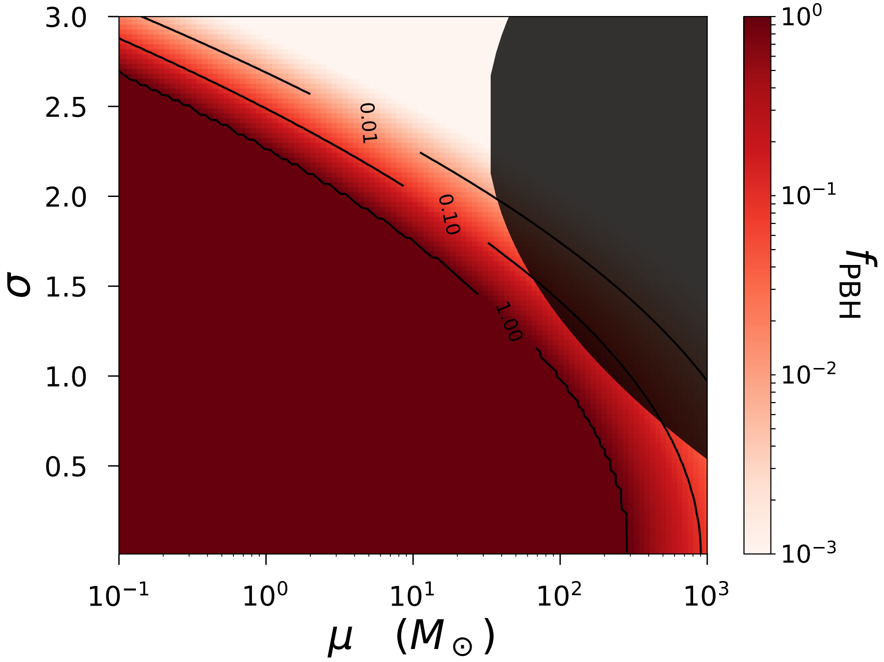
Fixed $\mathcal{M} = M\lambda = 10$

Fixed $z = 30$



PBHs as dark matter





- Degeneracies between f_{PBH} and cosmo params from CMB observations
  - May be important even for low values of f_{PBH}
- Easy translation from monochromatic constraints to cases with extended mass distributions

JLB, Bellomo, Raccanelli, Verde JCAP10(2017)052
Bellomo, JLB, Raccanelli, Verde, JCAP01(2018)004

PBHs: extended mass distributions

$$\frac{d\,f_{PBH}}{d\,M} \equiv f_{PBH}\frac{d\,\Phi_{PBH}}{d\,M}$$

Observable: $\int dM \frac{d\,f_{PBH}}{d\,M} g(M,\{p\})$

$$f_{PBH,1}\int dM \frac{d\,\Phi_{PBH,1}}{d\,M} g(M,\{p\}) = f_{PBH,2}\int dM \frac{d\,\Phi_{PBH,2}}{d\,M} g(M,\{p\})$$

$$f_{PBH}^{MMD} g(M_{eq},\{p\}) = f_{PBH}^{EMD}\int dM \frac{d\,\Phi_{PBH}}{d\,M} g(M,\{p\})$$

Bellomo, JLB, Raccanelli, Verde, JCAP01(2018)004

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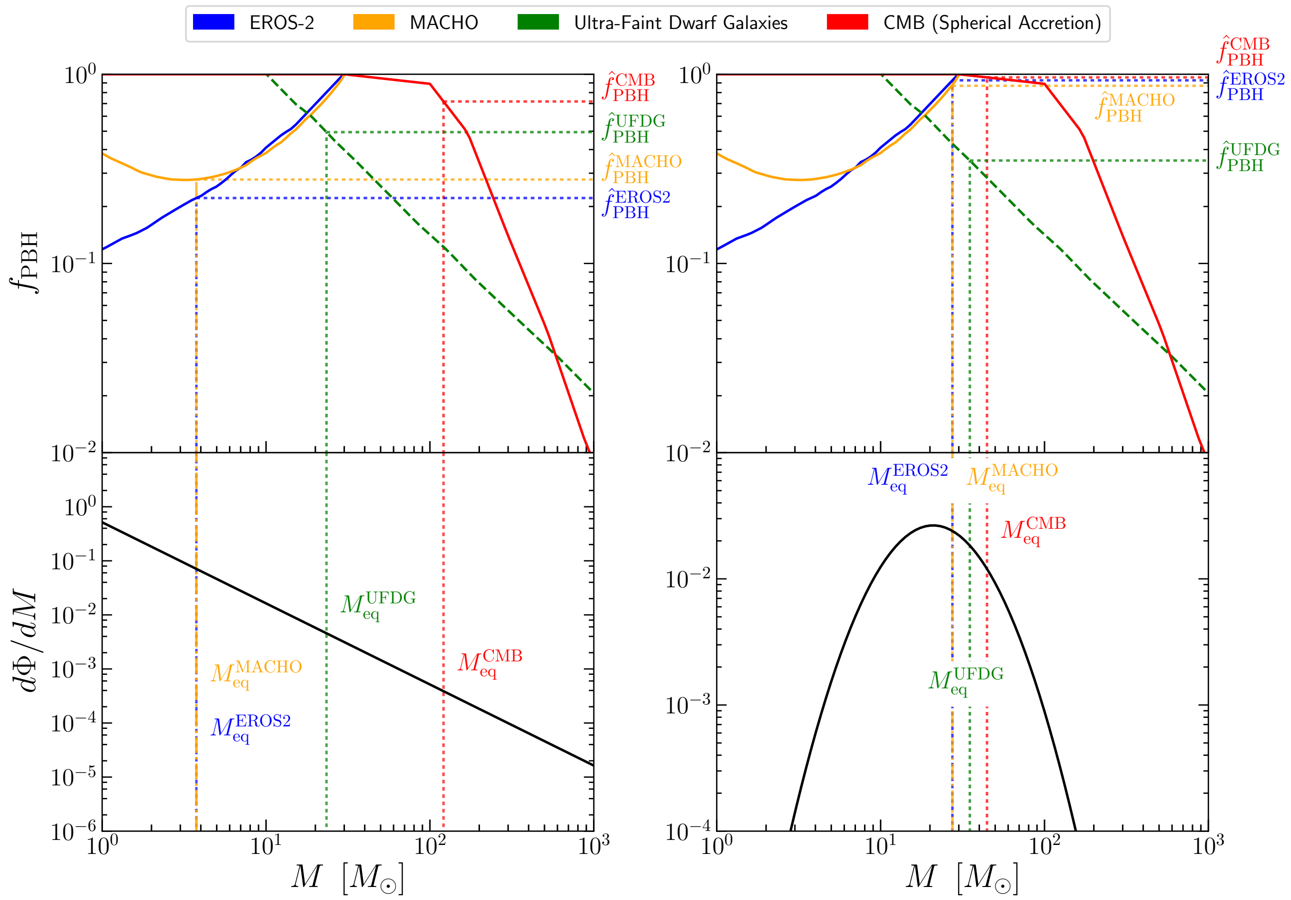

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