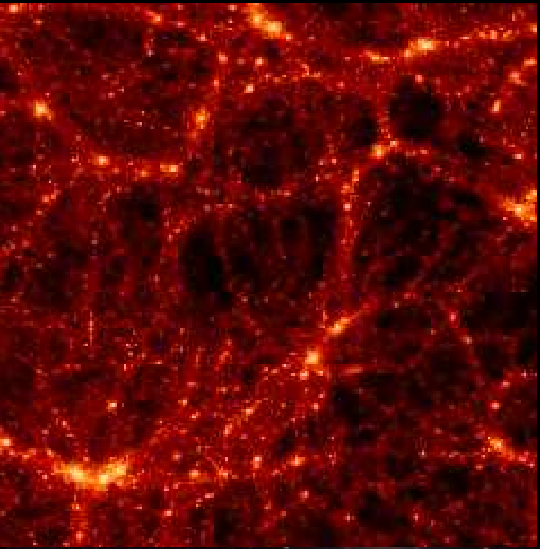

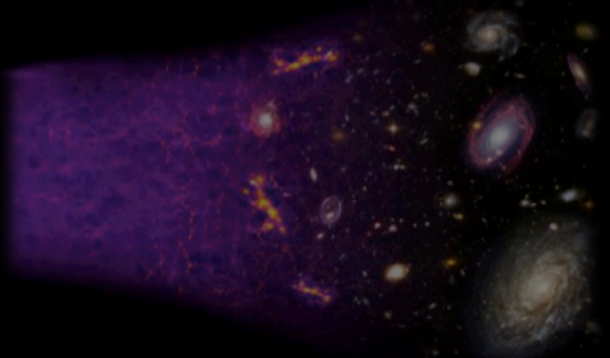


# Licia Verde

ICREA & ICC-UB
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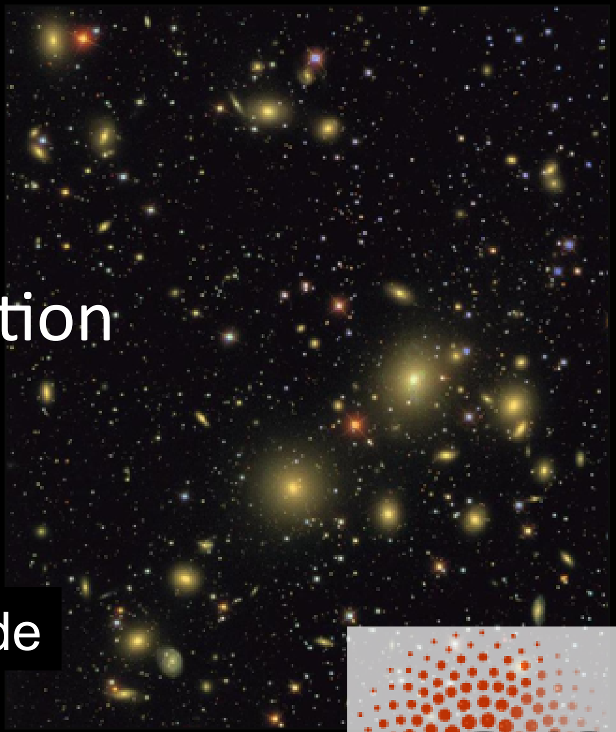

## Primordial Back Holes: the cosmology connection

http://icc.ub.edu/~liciaverde

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erc

Say that there is a population of PBH floating around…

**How do they affect cosmology?**

CMB

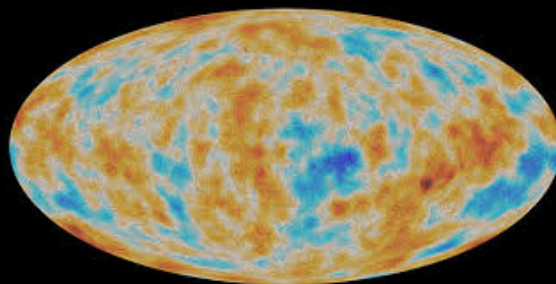
Lyalpha

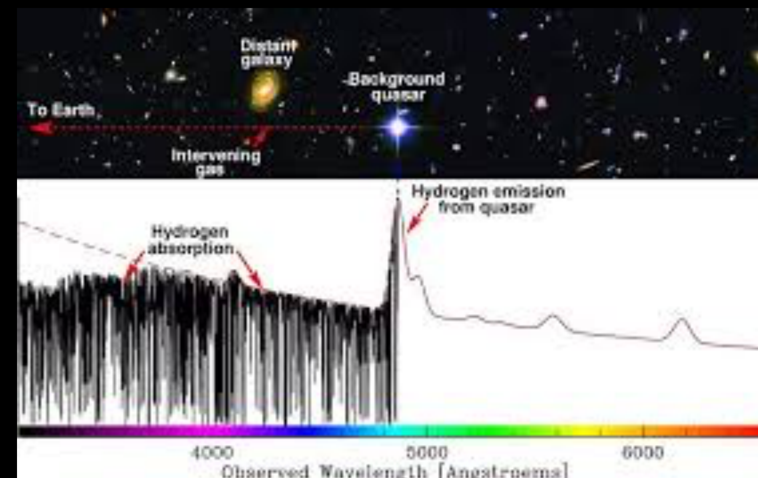
Dark matter

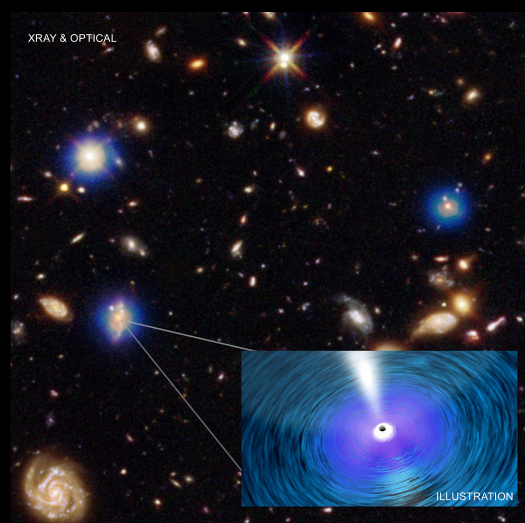
Seeds for SMBH

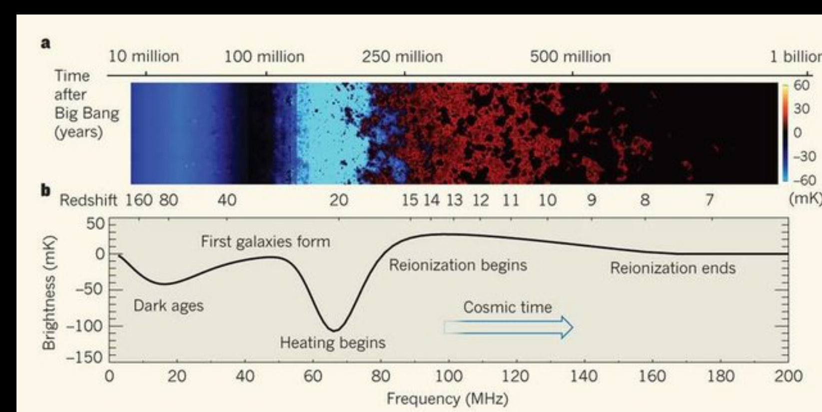
Help with IMBH

21 cm





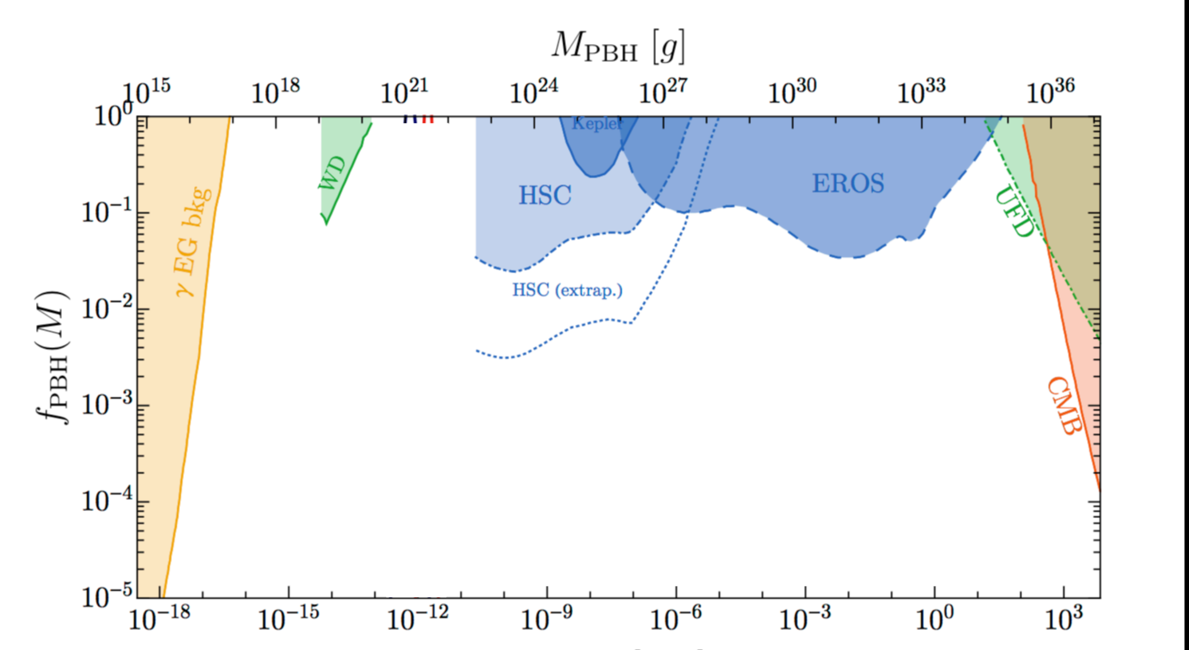



# Constraints on PBH abundance

Different type of constraints:

- Dynamical
- Lensing
- Accretion
- LSS




Adapted from Bartolo et al 18

$$f_{PBH} = \rho_{PBH} / \rho_{CDM}$$

# References

- Chasing the progenitors of merging binary black holes, 2018
  Giulio Scelfo, Nicola Bellomo, A. Raccanelli, S. Matarrese, LV

- Primordial Black holes as dark matter: Converting constraints from monochromatic to extended mass distributions , 2017
  Nicola Bellomo, Jose Luis Bernal, A. Raccanelli, LV

Connecting Primordial Black Holes abundance to the primordial power spectrum,
Alba Kalaja, Nicola Bellomo, et al. in prep.

# Is the PBH scenario compatible with merger rates?

Assuming that DM halos are made of PBH the merger rate is compatible with LIGO observed one.

$\mathcal{R}_{\text{today}}^{\text{Late Primordial}} \simeq 4 \text{ Gpc}^{-3}\text{yr}^{-1}.$ VS $\mathcal{R}_{\text{today}}^{\text{LIGO}} \simeq 9 - 240 \text{ Gpc}^{-3}\text{yr}^{-1},$ VS $\mathcal{R}_{\text{today}}^{\text{Stellar}} \simeq 150 \text{ Gpc}^{-3}\text{yr}^{-1},$

But the predicted merger rate for primordial binaries could be as high as

$$\mathcal{R}_{\text{today}}^{\text{Early Primordial}} \simeq 10^5 \text{ Gpc}^{-3}\text{yr}^{-1}$$

But see Raidal et al. 18

With large uncertainty

...So large that something like this is still OK:

$$\mathcal{R}_{\text{today}}^{\text{Early Primordial}} \simeq 200 \text{ Gpc}^{-3}\text{yr}^{-1}$$

1812.01930

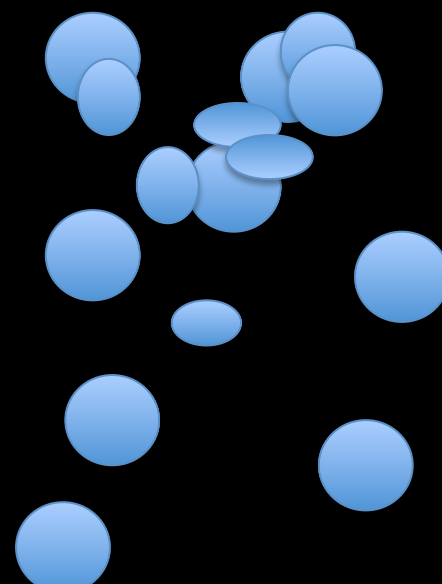
# Merging binary black holes: stellar or primordial?

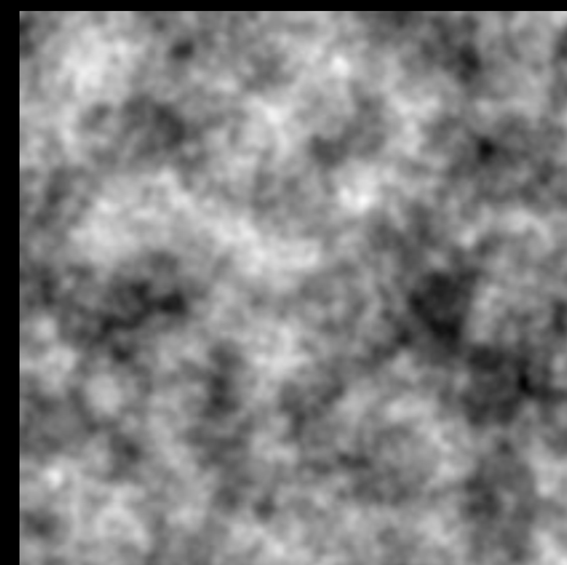
Scelfo, Bellomo et al. 2018

In a not too  distant future we wiill have…

galaxies

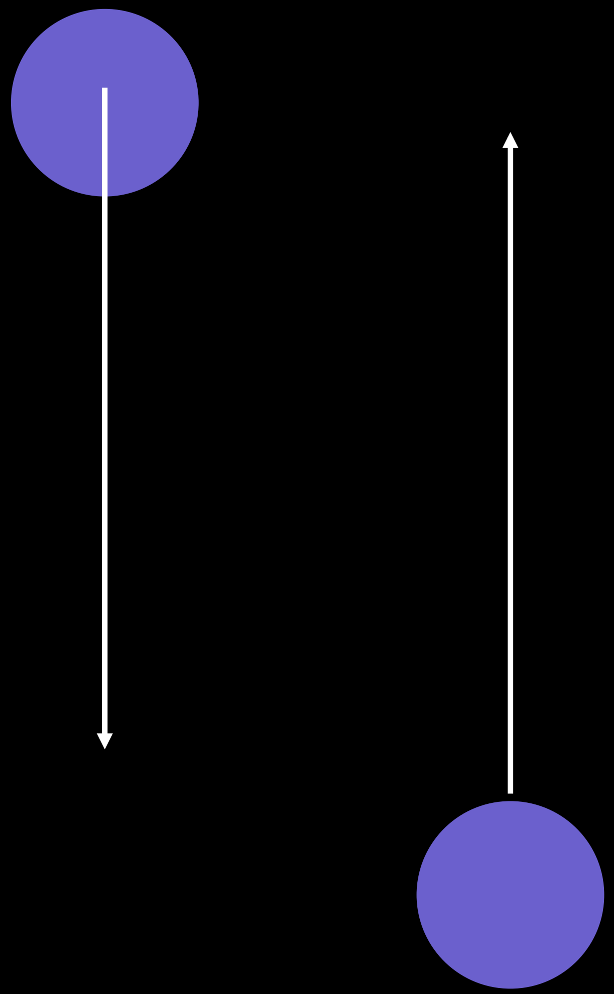
GW events → Low resolution map





In several z bins

# Big halos



Courtesy of AlviseRaccanelli

# Small halos

How small?

majority of events

in $M<10^{6}\,M_\odot$

Courtesy of Alvise Raccanelli

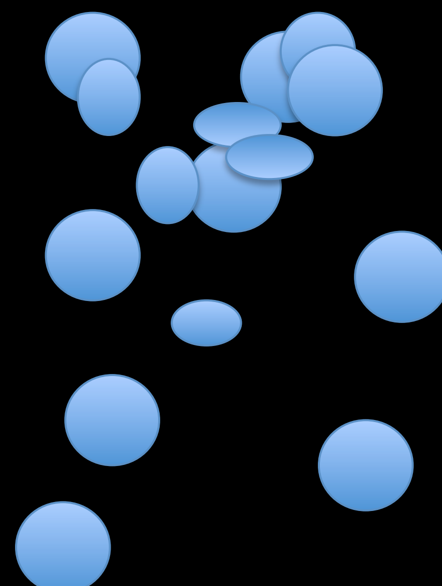
# Merging binary black holes: stellar or primordial?

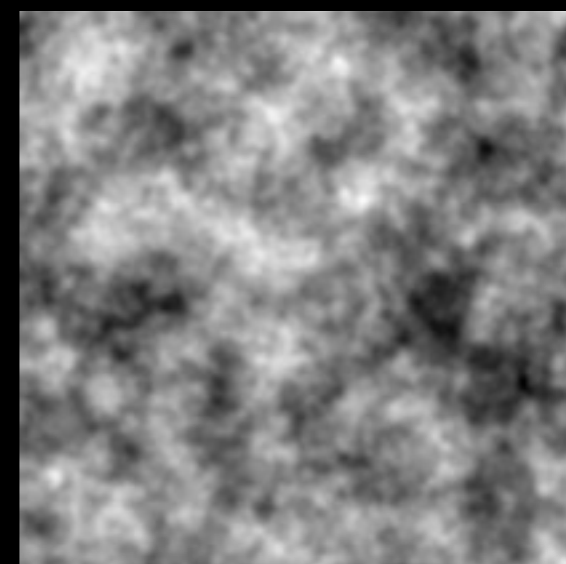
Scelfo, Bellomo et al. 2018

Cross correlation!

galaxies

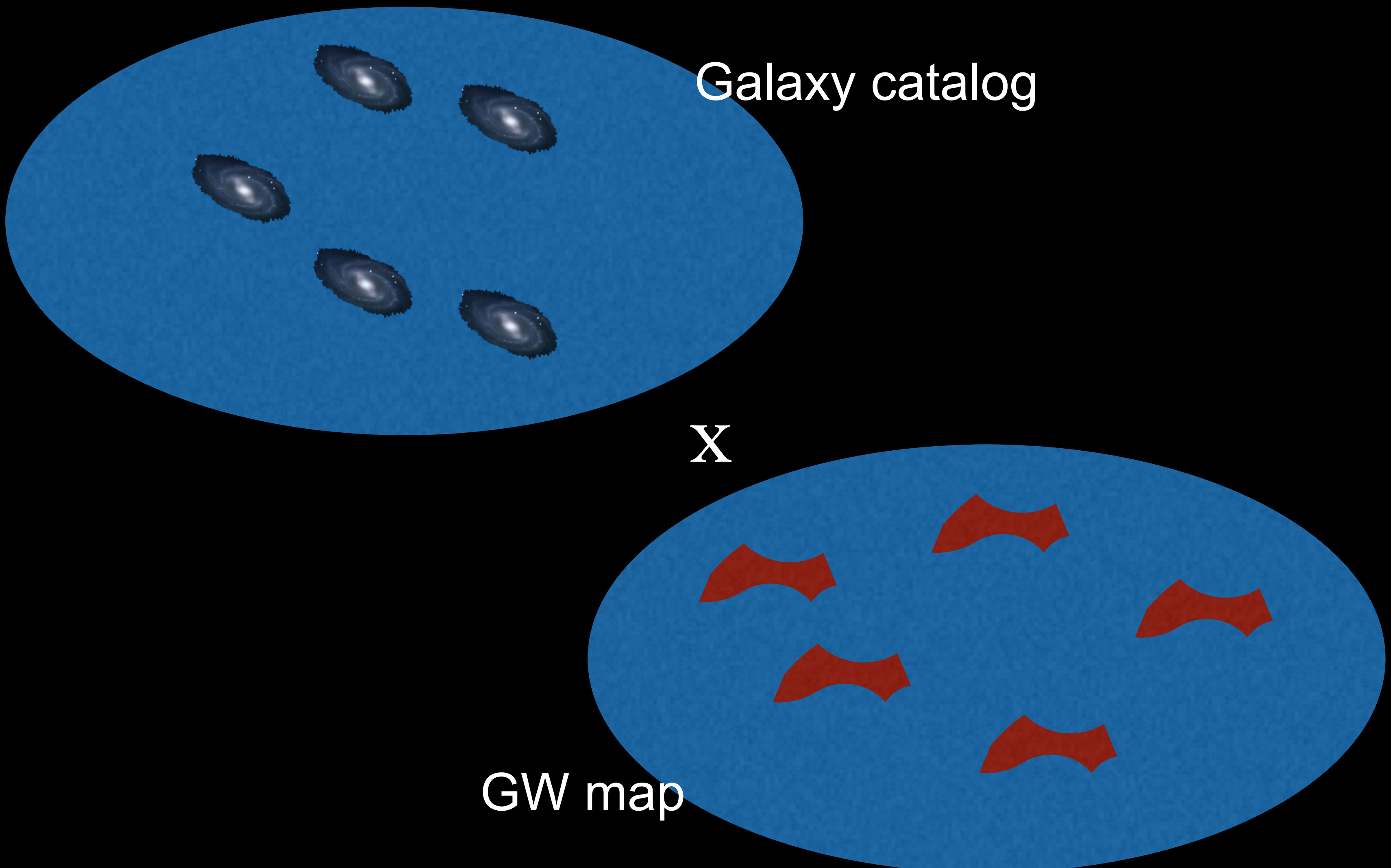
GW events → Low resolution map





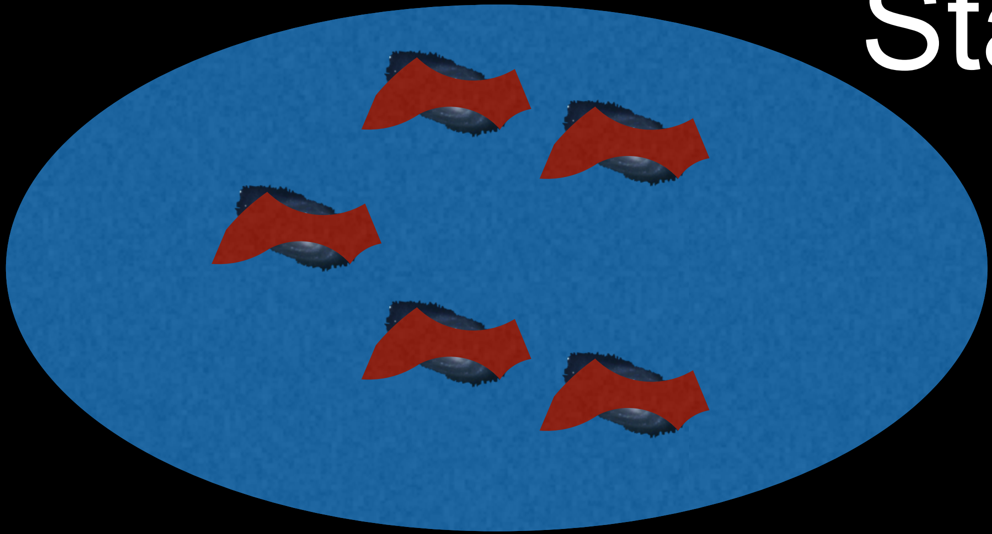
In several z bins

# Cross-correlation




Courtesy of AlviseRaccanelli

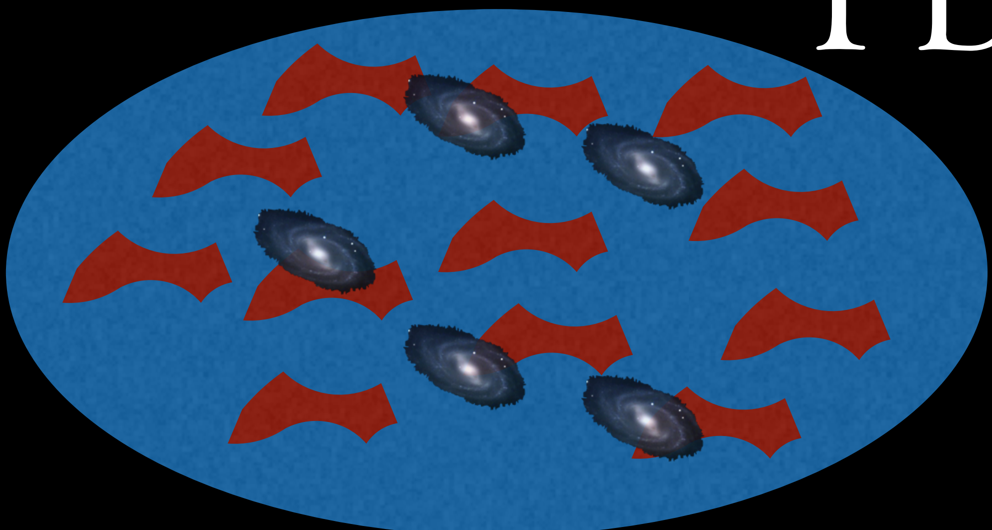
# Cross-correlations



Stars

Courtesy of AlviseRaccanelli

# Cross-correlations



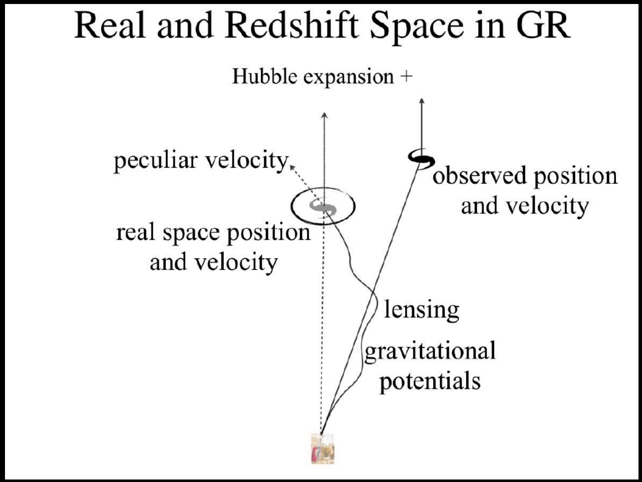
PBHs!

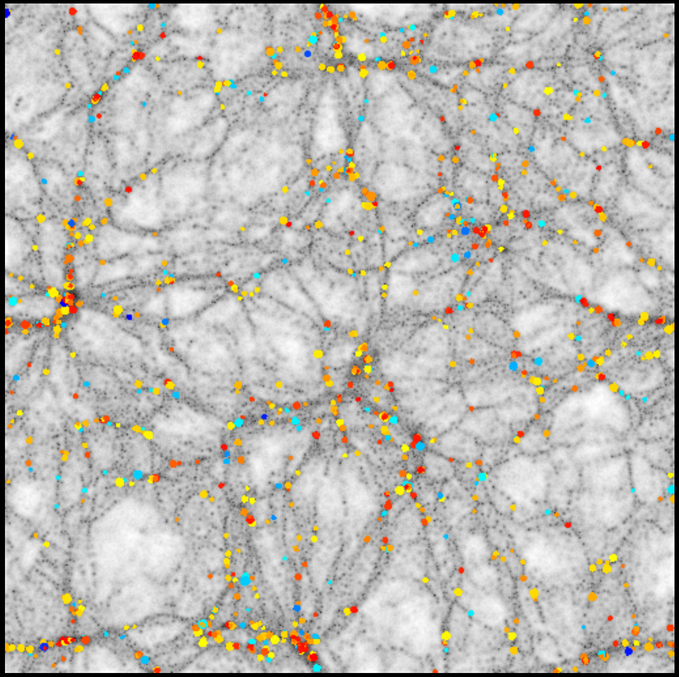
# Technicalities

Develop cross correlation description in different z bins including z-bins cross correlations

This is multi-tracers

Must include GR effects,
lensing and and magnification



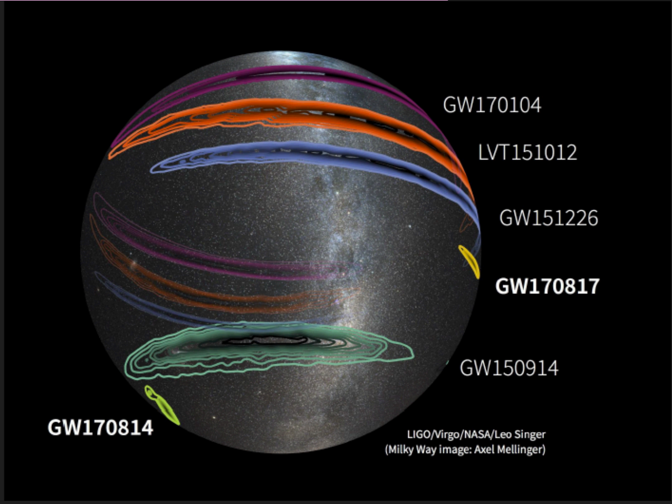
**Different bias parameters:**

Low mass halos b=0.5
DM b=1
High mass halos b=1.5

# More technicalities

Events are poorly localised

| Detectors | Resolution |
|---|---|
| ALIGO+VIRGO | $9^o$ |
| ALIGO+VIRGO+LIGO-India+KAGRA | $4^o$ |
| Einstein Telescope | $2^o$ |




We use angular power spectra Cl with lmax~180/θ

Null hypothesis testing comparing the two cases
(primordial or stellar origin)
S/N in specific cases

**Can't ignore projection effects**
(e.g., Magnification bias)

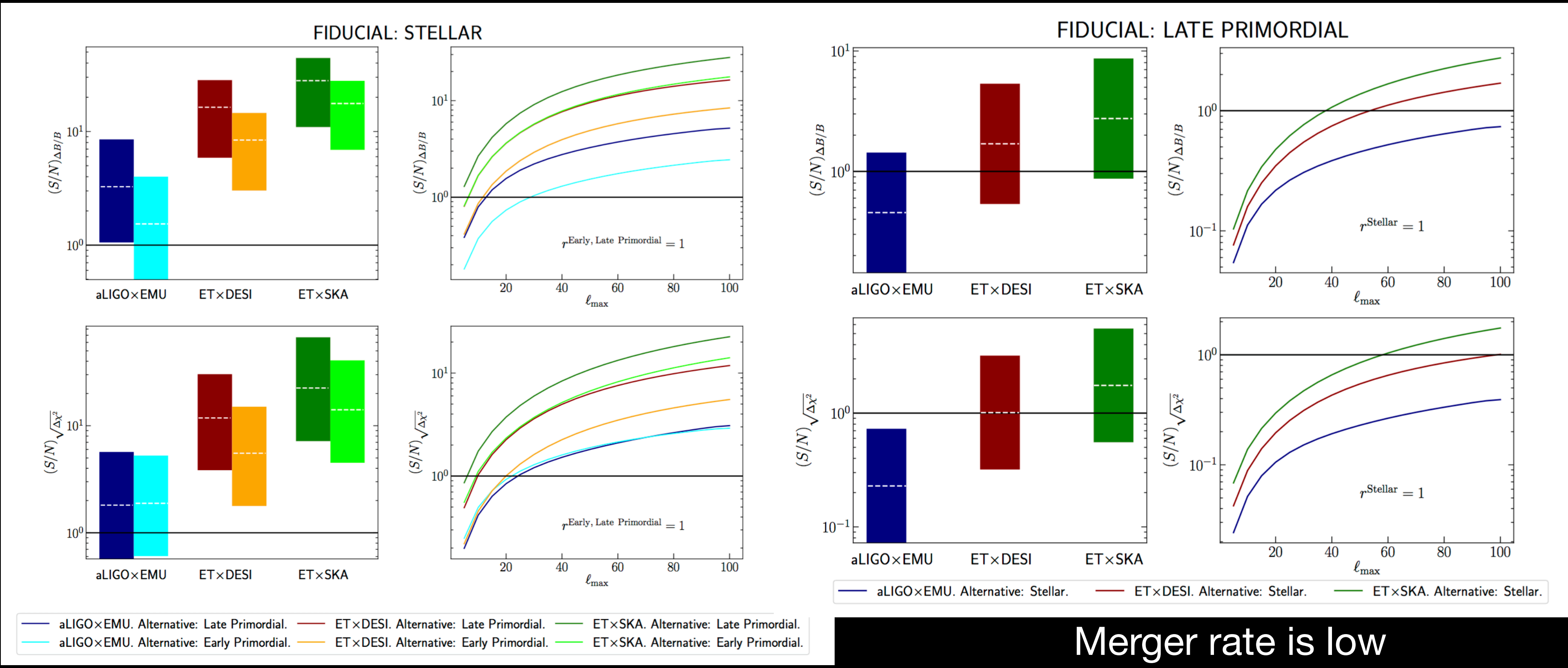
# Uncertainties ….

$$r^{\text{Late Primordial}} = \frac{T_{\text{obs}}}{10\text{ years}} \times f_{\text{PBH}}^2 \times \frac{\mathcal{M}_{\text{PBH}}^{\text{Extended}}}{\mathcal{M}_{\text{PBH}}^{\text{Monochromatic}}} \times \left\langle F_{\text{GW}}^{\text{detectable}} \right\rangle \times \frac{\mathcal{R}}{\mathcal{R}_{\text{today}}^{\text{Late Primordial}}},$$

$$r^{\text{Early Primordial}} = \frac{T_{\text{obs}}}{10\text{ years}} \times \frac{\mathcal{R}}{\mathcal{R}_{\text{today}}^{\text{Early Primordial}}},$$

$$r^{\text{Stellar}} = \frac{T_{\text{obs}}}{10\text{ years}} \times \frac{\mathcal{R}}{\mathcal{R}_{\text{today}}^{\text{Stellar}}},$$

# RESULTS: Forecasts




Merger rate is low

**r in [0.1,10]**

This is a promising approach, can probe big part of parameter space

## The devil is in the details

This is all analytic

Simplified bias assumptions

The merger rate depends also on the metallicity
not just on the host mass

Large uncertainties in e.g., Merger rates, star formation rates,

....

# Converting constraints between MMD and EMD

What is the effective MMD for an EMD?

$$\frac{df_{\rm PBH}}{dM} \equiv f_{\rm PBH}\frac{d\Phi_{\rm PBH}}{dM}$$

Normalization shape

$$\frac{d\rho_{\rm PBH}}{dM} = \frac{dn_{\rm PBH}}{d\log M} = f_{\rm PBH}\rho_{\rm dm}\frac{d\Phi_{\rm PBH}}{dM}$$

Physics is here

To compute observational consequences of PBH you need $\int dM \frac{df_{\rm PBH}}{dM} g(M, \{p_j\})$

Two distributions, 1, 2, give the same observational consequence if

$$f_{\rm PBH,1}\int dM \frac{d\Phi_1}{dM} g(M, \{p_j\}) = f_{\rm PBH,2}\int dM \frac{d\Phi_2}{dM} g(M, \{p_j\})$$

Hence if 1 is a $\delta^D$

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

Defines equivalent mass

**SOLVE THIS:**

$$g(M_{\rm eq}, \{p_j\}) = r_f \int dM \frac{d\Phi_{\rm EMD}}{dM} g(M, \{p_j\})$$

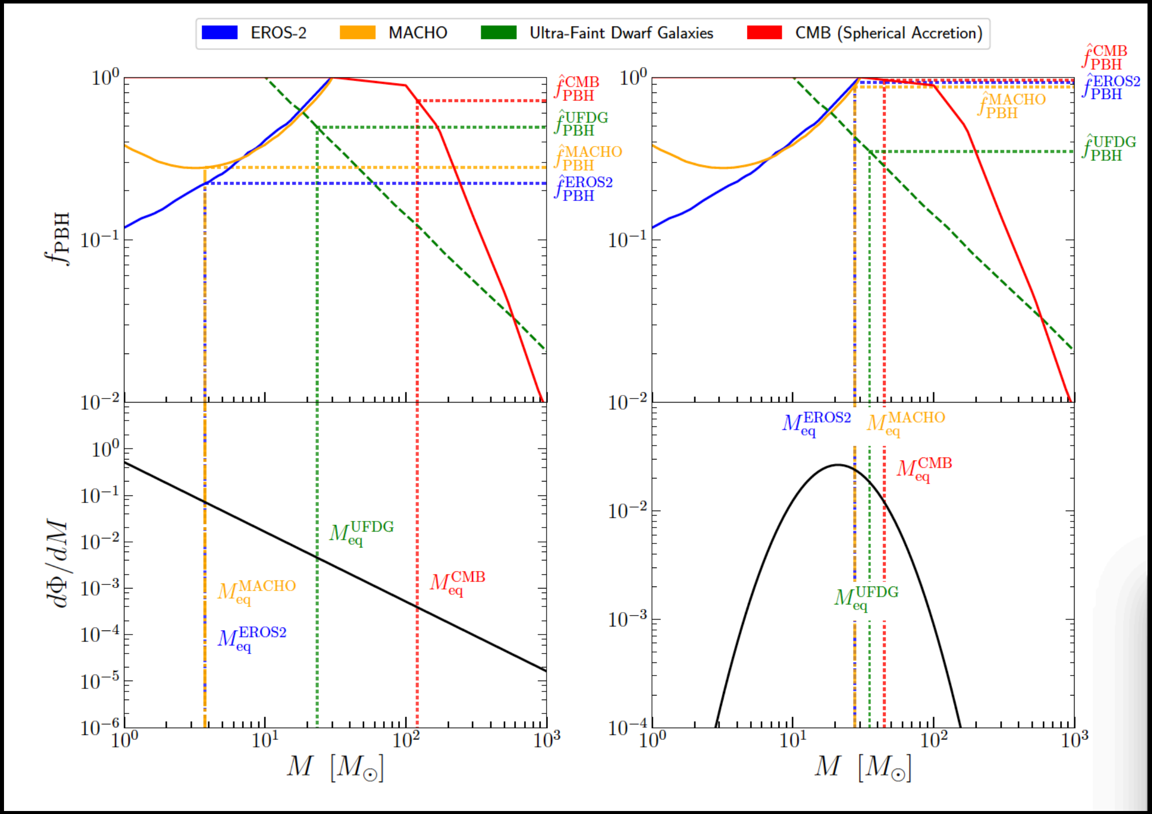
$$r_f = f_{\rm PBH}^{\rm EMD} / f_{\rm PBH}^{\rm MMD}$$

# So now you have….

$$M_{\rm eq}(r_f, \{\zeta_j\})$$

$$f_{\rm PBH}^{\rm EMD}(\{\zeta_j\}) = r_f f_{\rm PBH}^{\rm MMD}\left(M_{\rm eq}(r_f, \{\zeta_j\})\right)$$

largest allowed abundance for a MMD with M = Meq



# Examples of Extended Mass Distributions

Power law

$$\frac{d\Phi_{\rm PBH}}{dM} = \frac{\mathcal{N}_{PL}}{M^{1-\gamma}}\Theta(M - M_{\rm min})\Theta(M_{\rm max} - M),$$

$$\gamma = -\frac{2w}{1+w}$$

$$\mathcal{N}_{PL}(\gamma, M_{\rm min}, M_{\rm max}) = \begin{cases} \dfrac{\gamma}{M_{\rm max}^{\gamma} - M_{\rm min}^{\gamma}}, & \gamma \neq 0, \\ \log^{-1}\left(\dfrac{M_{\rm max}}{M_{\rm min}}\right), & \gamma = 0. \end{cases}$$

Lognormal

$$\frac{d\Phi_{\rm PBH}}{dM} = \frac{e^{-\frac{\log^2(M/\mu)}{2\sigma^2}}}{\sqrt{2\pi}\sigma M}$$

**You need g and Meq…**

# Where the physics is…

**For microlensing**

$$g(M) = M^{-1/2}$$

**For CMB**

$$\dot{\rho}_{\rm inj} = \rho_{\rm dm} f_{\rm PBH} \int dM \frac{d\Phi}{dM} \frac{\langle L(M) \rangle}{M}$$

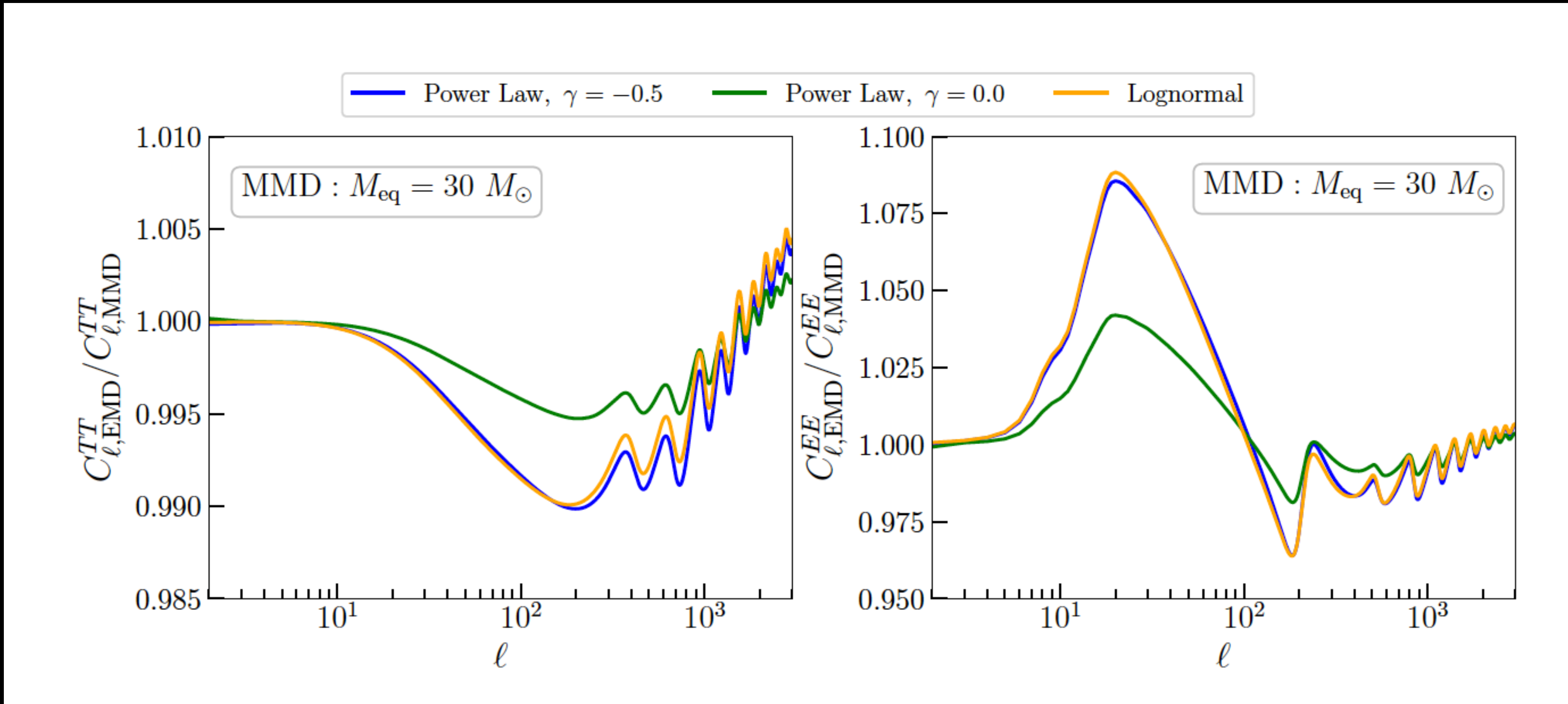
Rate of energy injection

$$g(M, \{p_j\}) = \frac{\langle L(M) \rangle}{M}.$$

$$\frac{\langle L \rangle}{M} \propto \frac{L}{M} \propto \frac{\dot{M}^2 / L_{\rm Edd}}{M} \propto \frac{M^4 \lambda^2(M)/M}{M} = M^2 \lambda^2(M),$$

$\lambda$ is accretion rate ~ M $^{\alpha/2}$

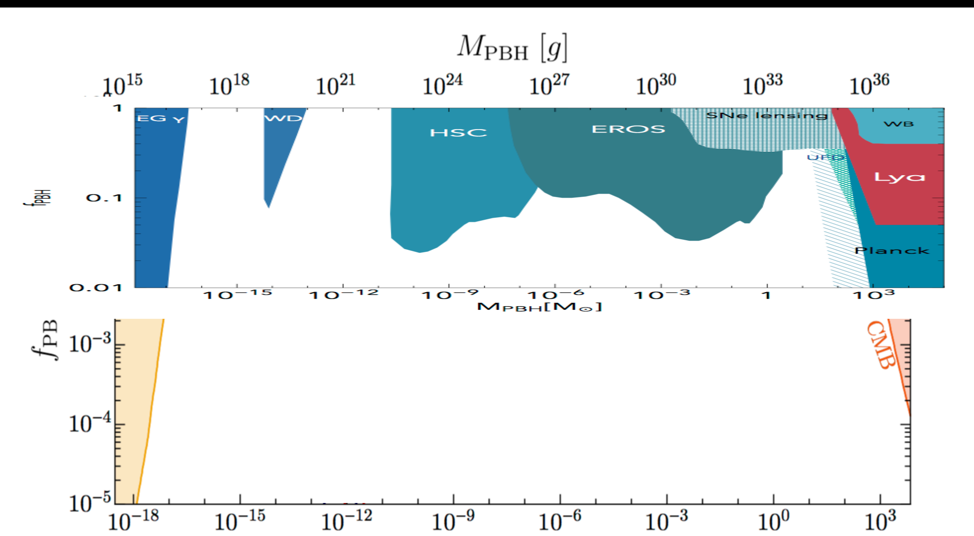
$$M_{\rm eq}^{2+\alpha} = r_f \begin{cases} \mathcal{N}_{PL} \dfrac{M_{\rm max}^{\gamma+2+\alpha} - M_{\rm min}^{\gamma+2+\alpha}}{\gamma + 2 + \alpha}, & PL, \\ \mu^{2+\alpha} e^{\frac{(2+\alpha)^2 \sigma^2}{2}}, & LN. \end{cases}$$



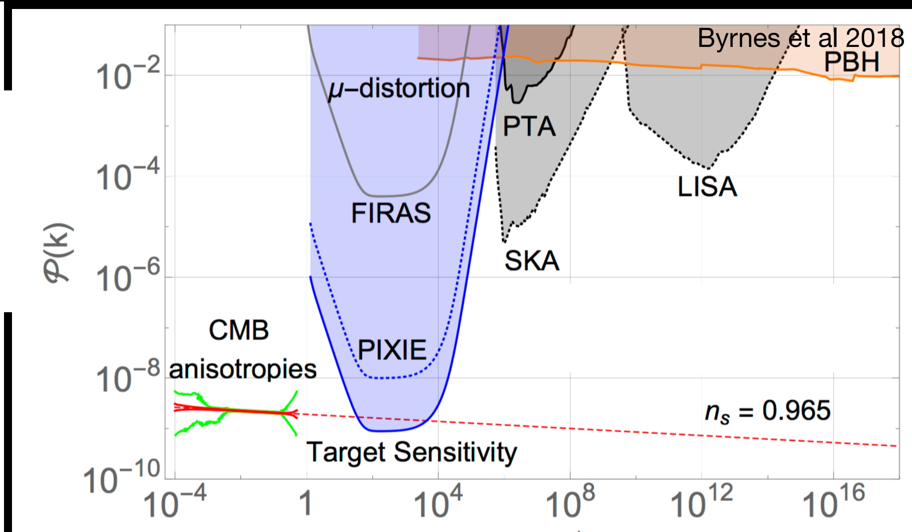

**Good practice:**
the adopted modelling defines a mass range of validity; outside this range, results (if any) are not reliable or unphysical.

# Connecting Primordial Black Holes abundance to the primordial power spectrum

**It is established how to connect abundance of clusters to the primordial P(k)**



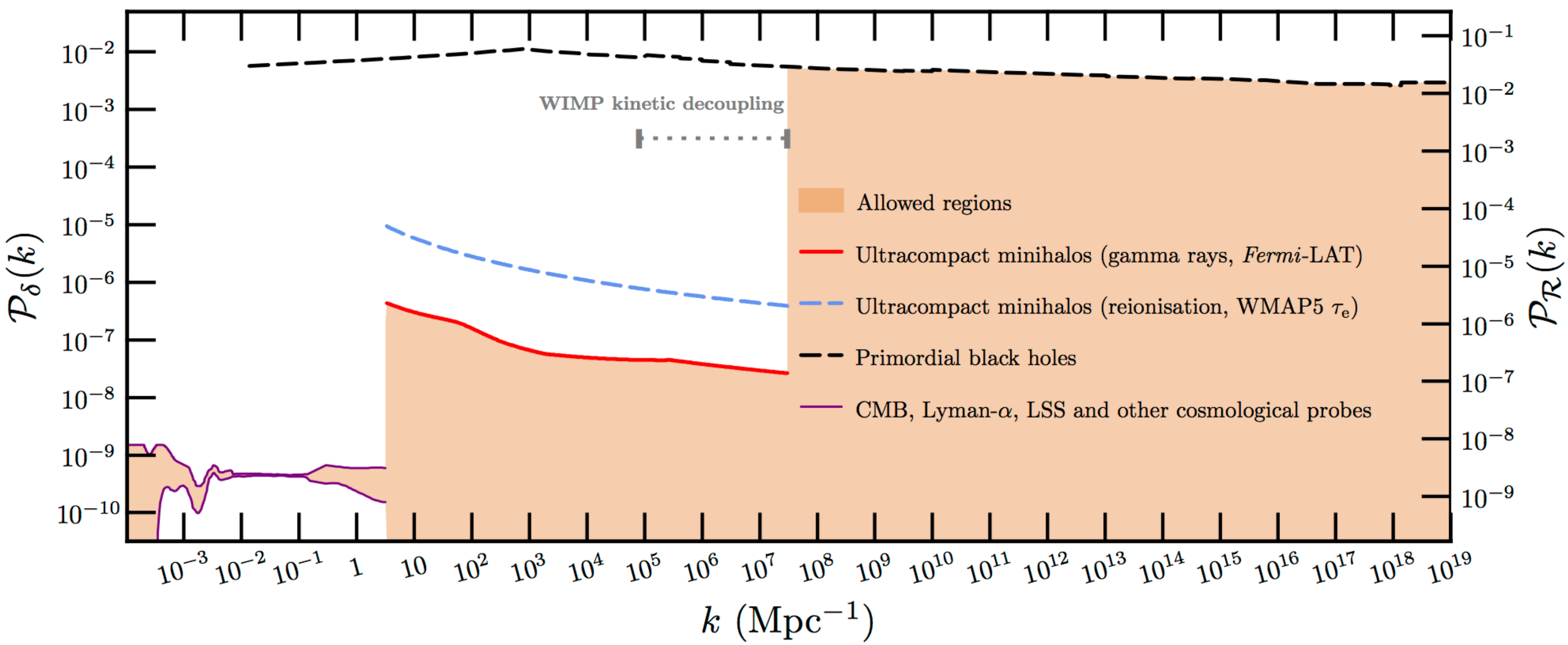
Adapted from Bartolo et al 18



Chluba et al 2019

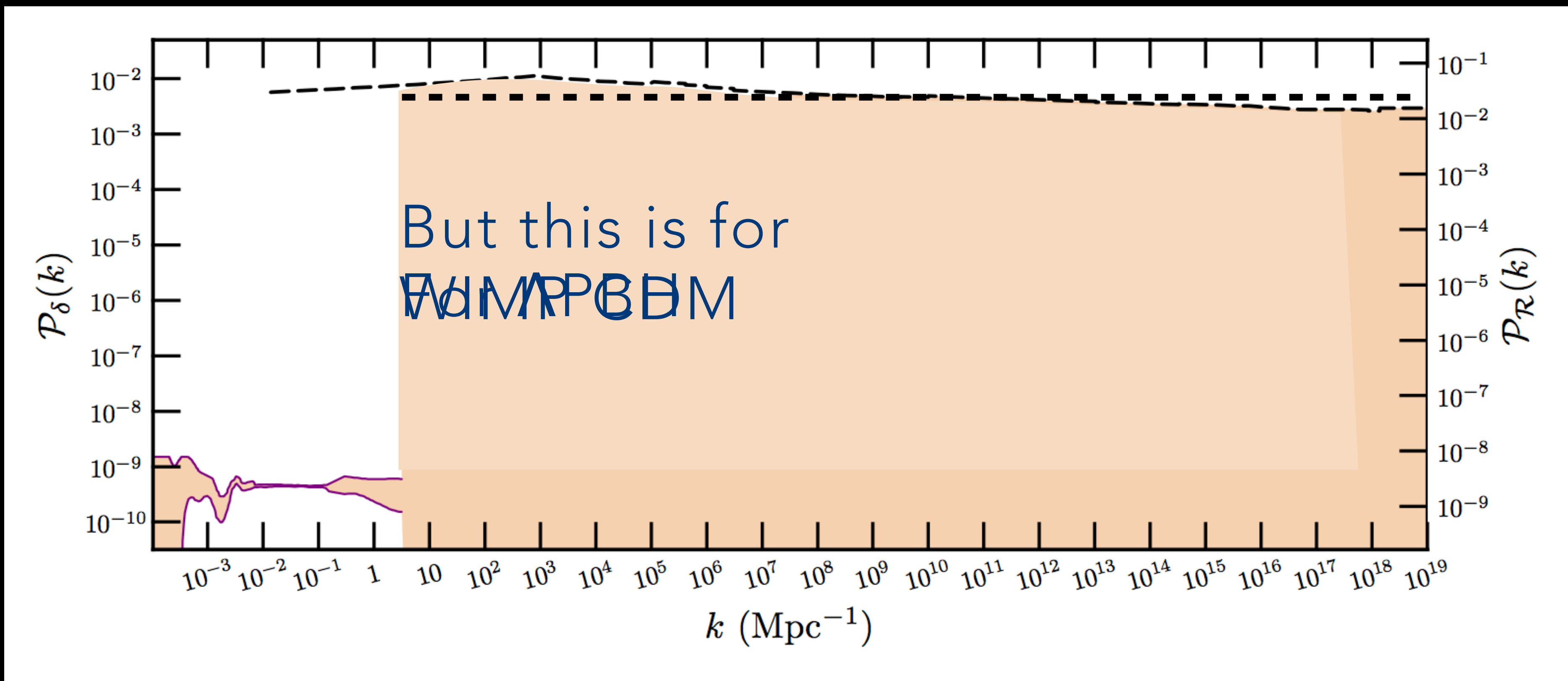
**Why not for PBH? And what would it take?**

# This is not new…




Bringmann et al arXiv:1110.2484

# Early Universe physics with PBHs




Curtesy of A. Raccanelli

# Motivation and background

Primordial Black Holes form in the early Universe from the gravitational collapse of large density perturbations generated during inflation.

Radiation domination era: at first approximation PBHs mass depends on the time of formation $m_{PBH} \simeq m_{Hor} = c^3 t_f / G$

- $t_f \approx 10^{-45} s \Rightarrow m_{PBH} \approx 10^{-39}\,\mathrm{M}_\odot$
- $t_f \approx 1 s \Rightarrow m_{PBH} \approx 10^{5}\,\mathrm{M}_\odot$

High peaks in the density field: the statistics is specified by the power spectrum

$\downarrow$

constraints on inflationary models.

# Ingredients

## PBH formation

Say you have a (primordial)  (curvature) perturbation in radiation era…
The relation between curvature and density is non linear
Threshold for collapse might be affected
GR simulations (Ilia Musco)

## Cosmological analogy

# BBKS Statistics of Gaussian random fields

THE ASTROPHYSICAL JOURNAL, **304**:15–61, 1986 May 1


## THE STATISTICS OF PEAKS OF GAUSSIAN RANDOM FIELDS

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*Received 1985 July 25; accepted 1985 October 9*

## ABSTRACT

Cosmological density fluctuations are often assumed to be Gaussian random fields. The local maxima of such fields are obvious sites for the formation of nonlinear structures. The statistical properties of the peaks can be used to predict the abundances and clustering properties of objects of various types. In this paper, we derive (1) the number density of peaks of various heights $\nu\sigma_0$ above the rms $\sigma_0$; (2) the factor by which the peak density is enhanced in large-scale overdense regions; (3) the $n$-point peak-peak correlation function in the limit that the peaks are well separated, with special emphasis on the two- and three-point correlations; and (4) the density profiles centered on peaks. To illustrate the predictive power of this semianalytic approach, we apply our formulae to structure formation in the adiabatic and isocurvature $\Omega = 1$ cold dark matter (CDM) models. We assume bright galaxies form only at those peaks in the density field (smoothed on a galactic scale) that are above some global threshold height $\nu_t \approx 3$ fixed by normalizing to the galaxy number density. We find, for example, that the shapes of the peak-peak two- and three-point correlation functions for the adiabatic CDM model agree well with observations before any dynamical evolution, just due to the propensity of the peaks to be clustered in the initial conditions. Only moderate dynamical evolution is required to bring the amplitude of the correlations up to the observed level. The corresponding redshift of galaxy formation $z_g$ in the isocurvature model is too recent ($z_g \approx 0$) for this model to be viable. Even for the adiabatic models $z_g \approx$ 3–4 is predicted. We show that the mass-per-peak ratio in clusters, and thus presumably the cluster mass-to-light ratio, is substantially lower than in the ambient medium, alleviating the $\Omega$ problem. We also confirm that the smoothed density profiles of collapsing structures of height $\sim \nu_t$ are inherently triaxial.

*Subject headings:* early universe — galaxies: clustering — galaxies: formation

# Ingredients

## PBH formation

Say you have a (primordial)  (curvature) perturbation in radiation era…
The relation between curvature and density is non linear
Threshold for collapse might be affected
Ilia Musco simulations

## Cosmological analogy

“mutatis mutandis”:
Works (of course) but one has to be carerful to recognize the relevant physics
Define wisely  the characteristic scale of the perturbation

## Peaks theory

Average profile shape
Improve approximations to connect to P(k)

## Power spectrum reconstruction

Given the above and fPBH from observations

# PBH formation

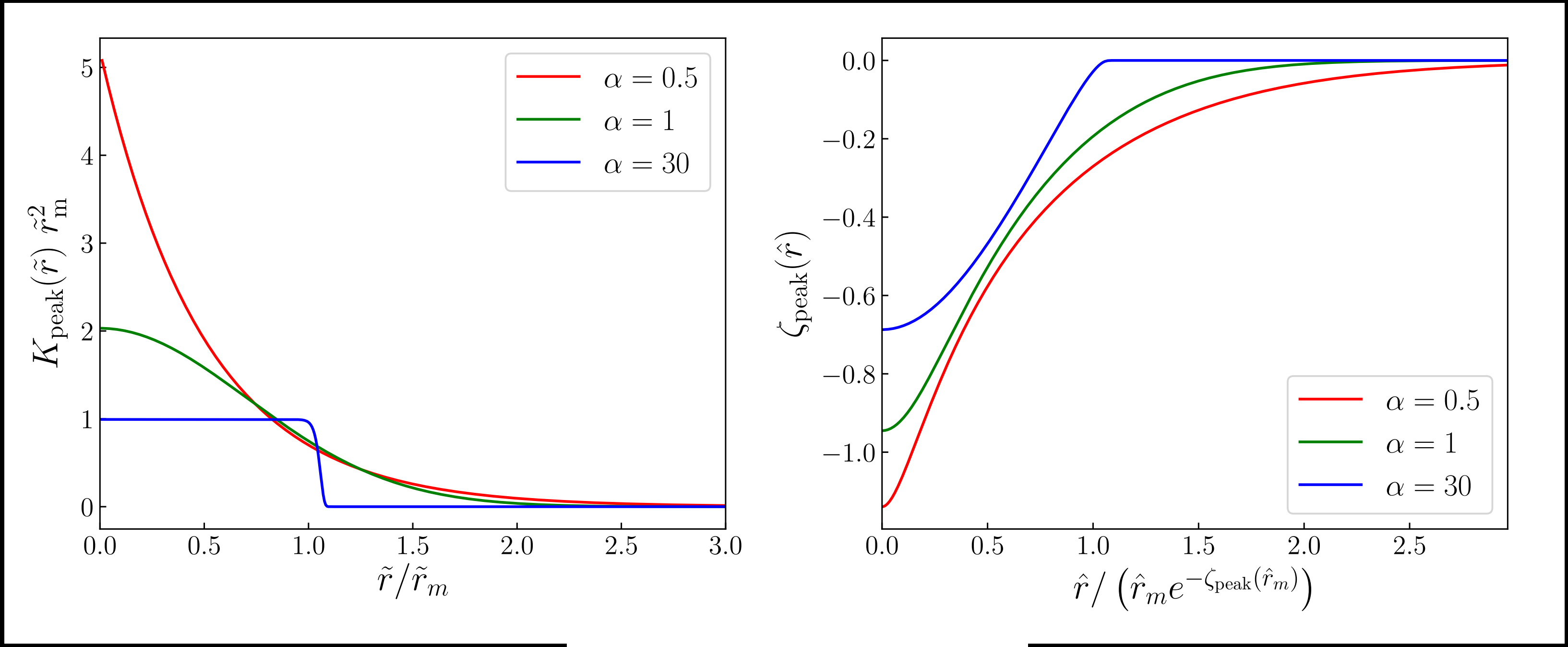
**Ilia Musco**

Start simulations on super horizon scales (all “frozen”)

Parameterization of perturbation **initial conditions**

Synchronous metric: curvature

Cosmo: curvature perturbation
on uniform energy density hypersurfaces




$$\tilde{r} = \hat{r} e^{\mathcal{R}(\hat{r})} \simeq \hat{r} e^{-\zeta(\hat{r})}$$

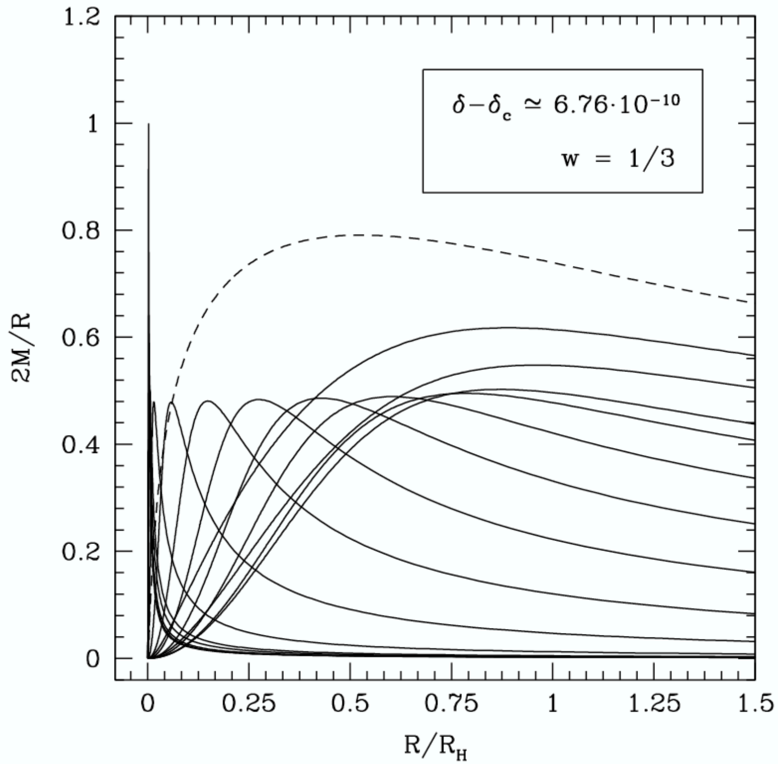
$r_m$ typical scale of the perturbation >> horizon (at ti)

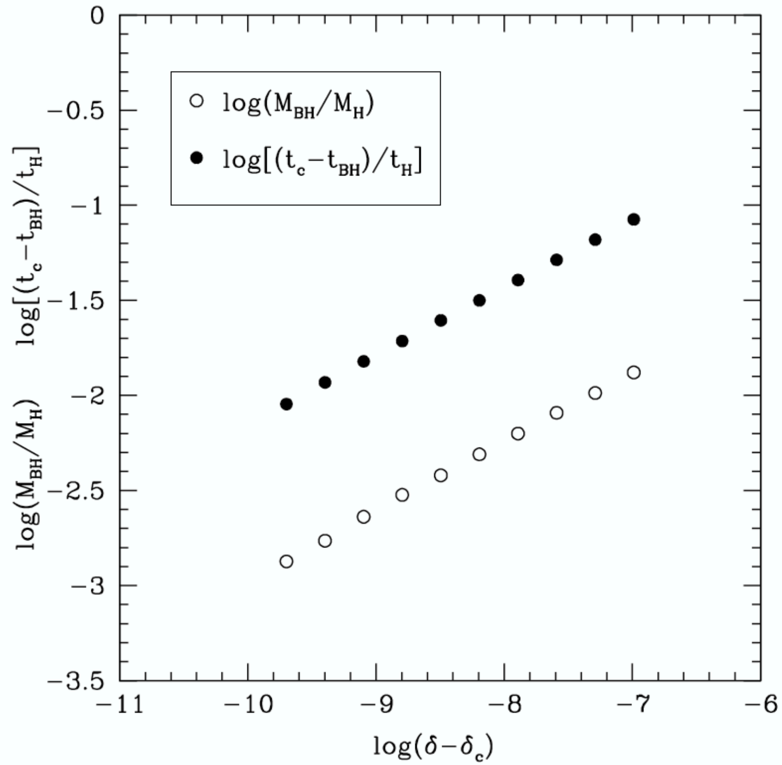
See: arXiv:1809.02127

# Numerical Results: PBH formation

$$\boxed{R(r,t) = 2M(r,t)}$$

$$\boxed{M_{PBH} = \mathcal{K}(\delta - \delta_c)^\gamma M_H}$$




IM, J. Miller et al. - CQG (2005, 2009, 2012)

**Ilia Musco**

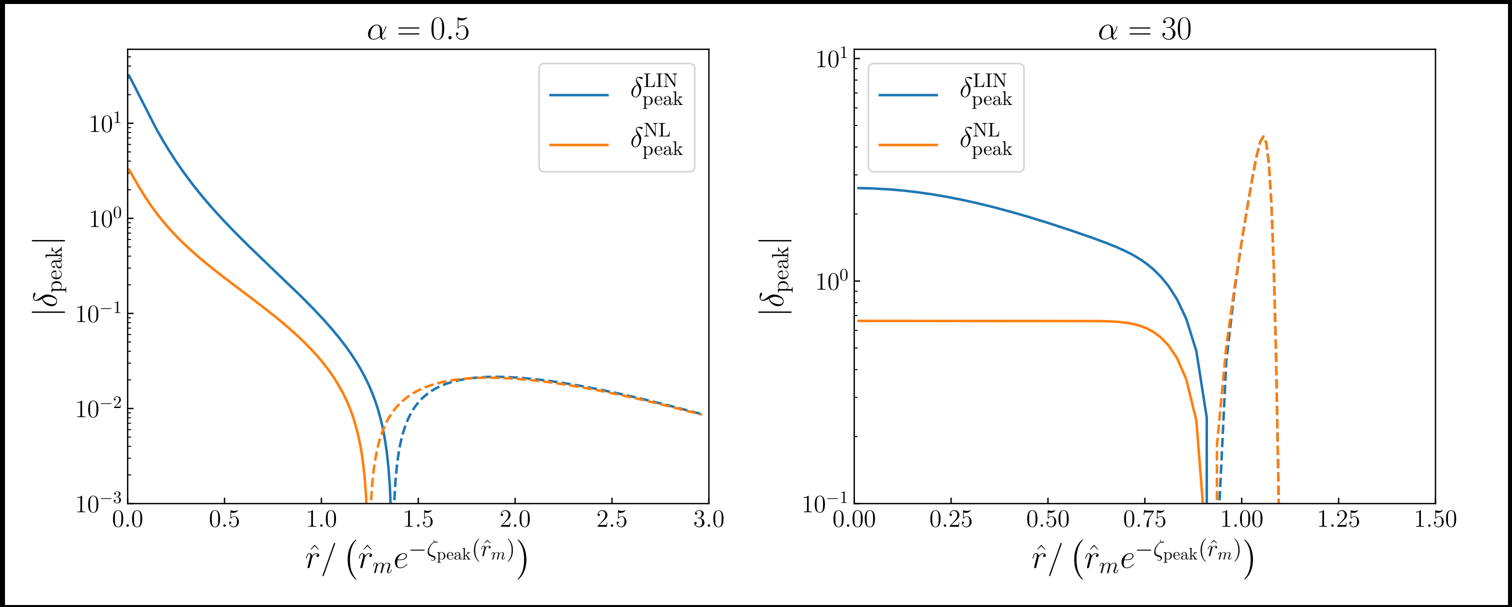
# PBH formation

Some subtelties: over density

w=1/3

$$\delta_{\rm peak}(t,\hat r) = \frac{3(1+w)}{5+3w}\left(\frac{1}{aH}\right)^2\left(-\frac{4}{3}\right)e^{5\zeta_{\rm peak}(\hat r)/2}\nabla^2 e^{-\zeta_{\rm peak}(\hat r)/2}$$
$$= \frac{4}{9}\left(\frac{1}{aH}\right)^2 e^{2\zeta_{\rm peak}(\hat r)}\left[\nabla^2\zeta_{\rm peak}(\hat r) - \frac{1}{2}\nabla\zeta_{\rm peak}(\hat r)\cdot\nabla\zeta_{\rm peak}(\hat r)\right]$$

$$\delta^{\rm LIN}_{\rm peak} = \frac{4}{9}\left(\frac{1}{aH}\right)^2\nabla^2\zeta_{\rm peak}$$




NL effects damp and shrink the density profile

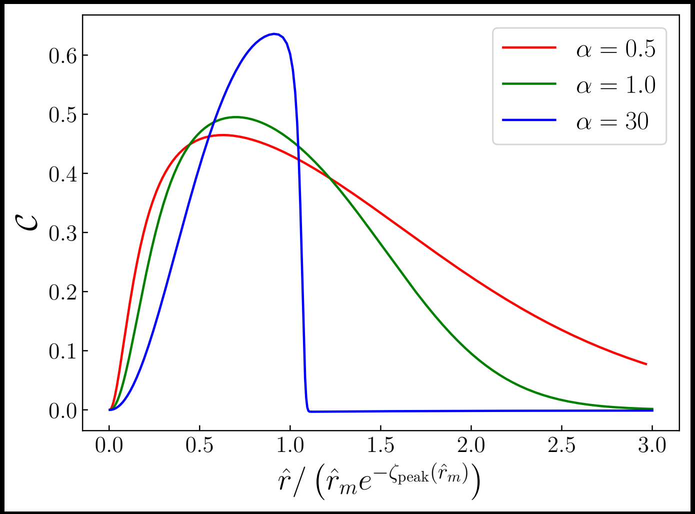
# Collapse threshold

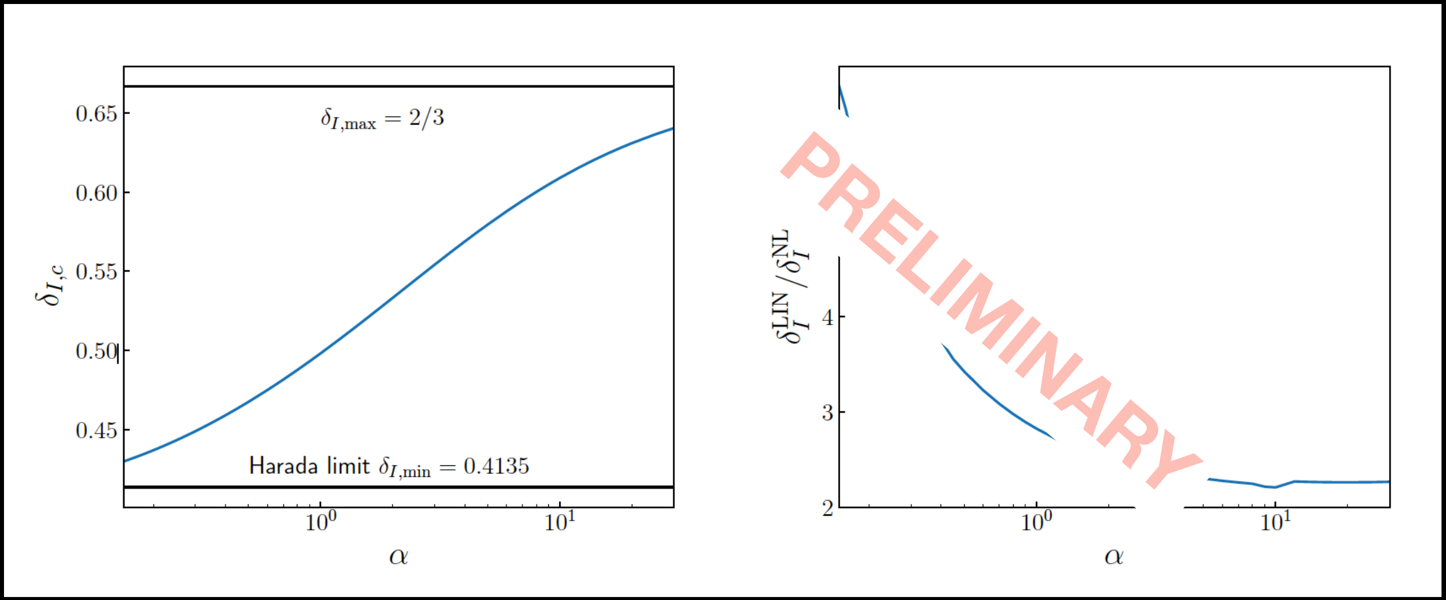
(Musco '18, Harada et al '15, Shibata Sasaki 99)

$$\mathcal{C}(t,R) = 2(\delta M/R)$$

Compaction function has a max (at Rm), when this is above a threshold PBH forms

$$\mathcal{C}(t_m, R_m) = \delta_I(t_m, R_m) > \delta_{I,c}(\alpha),$$



# How many peaks above the threshold value for a given P(k)?

**BBKS used** in matter domination, no pressure forces, factorize scale and time dependence.

Not here in radn domination

Can still use BBKS result

$$\frac{dn^{\mathrm{com.}}_{\mathrm{peak}}}{d\nu} = \frac{1}{(2\pi)^2 R_\star^3} e^{-\nu^2/2} G(\gamma, \gamma\nu)$$

To compute the collapse fraction

$$\beta_{\mathrm{f}} := \frac{\rho_{\mathrm{PBH}}(\tau_{\mathrm{f}})}{\rho_{\mathrm{r}}(\tau_{\mathrm{f}})}$$

The average peak profile is related to the correlation function of the density field

$$\xi_S(r) = \sigma_0^2 \frac{\bar{\delta}_{\mathrm{peak}}(r)}{\bar{\delta}_{\mathrm{peak}}(0)}$$

# And what's the mass?

Time when perturbation crosses horizon

$$M_{\mathrm{PBH}}(\nu, \tau_{\mathrm{m}}) = \mathcal{K}_{\mathrm{peak}} M_{\mathrm{hor}}(\tau_{\mathrm{m}})(\delta_{\mathrm{peak,0}} - \delta_{\mathrm{peak,0,c}})^{\Gamma}$$

Result of GR numerical simulations

# Connect to P(k)

## Two regimes

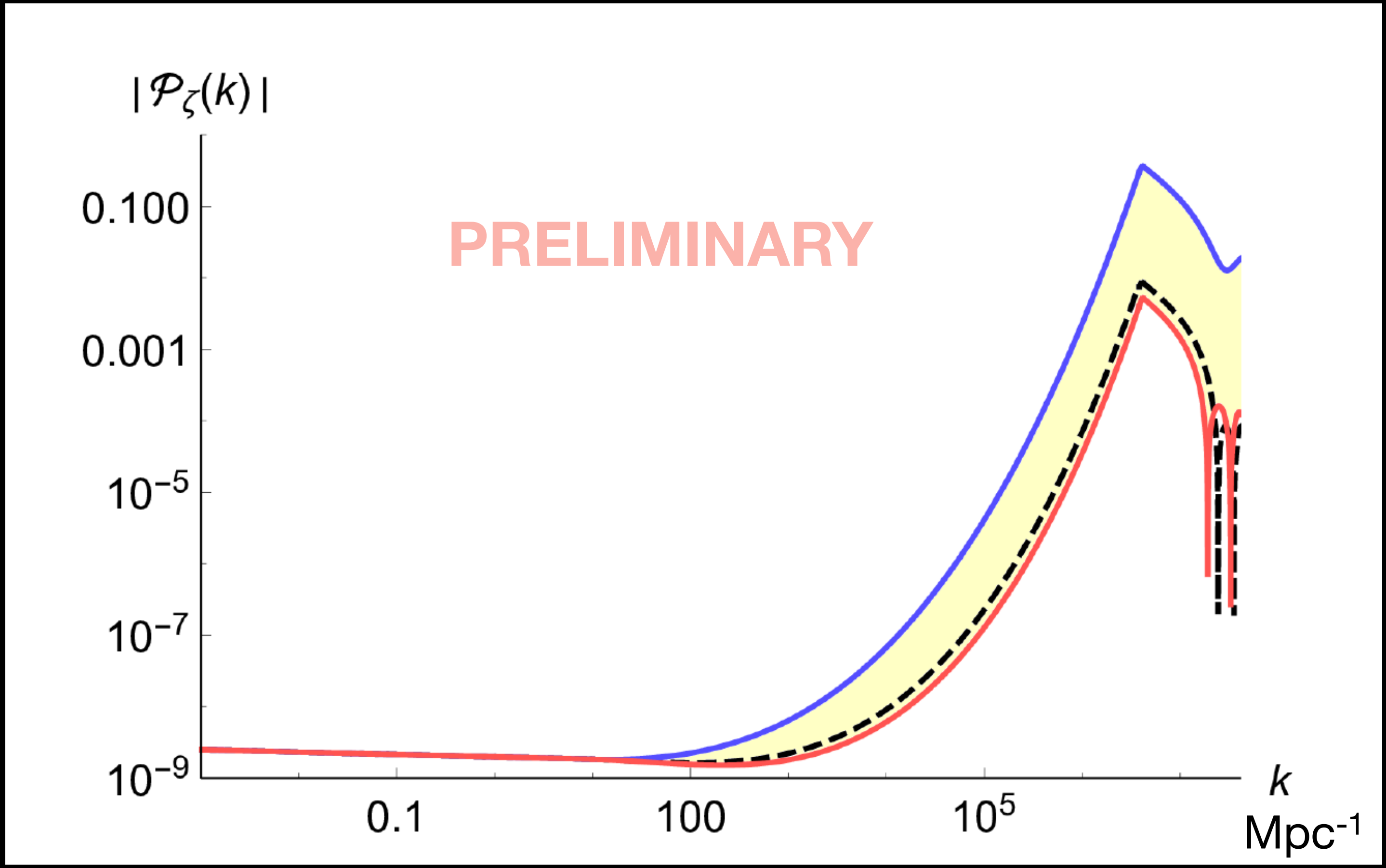
Large scales towards small scales:

P(k) grows to reach an amplitude such that PBH can be formed with $f_{PBH}$=obs. limit

Small scales :

Peaks profile → $\xi_{\mathbf{s}}$ → $P_s(k)$

# Connection to P(k)




$\alpha = 30$

$\alpha = 1.$

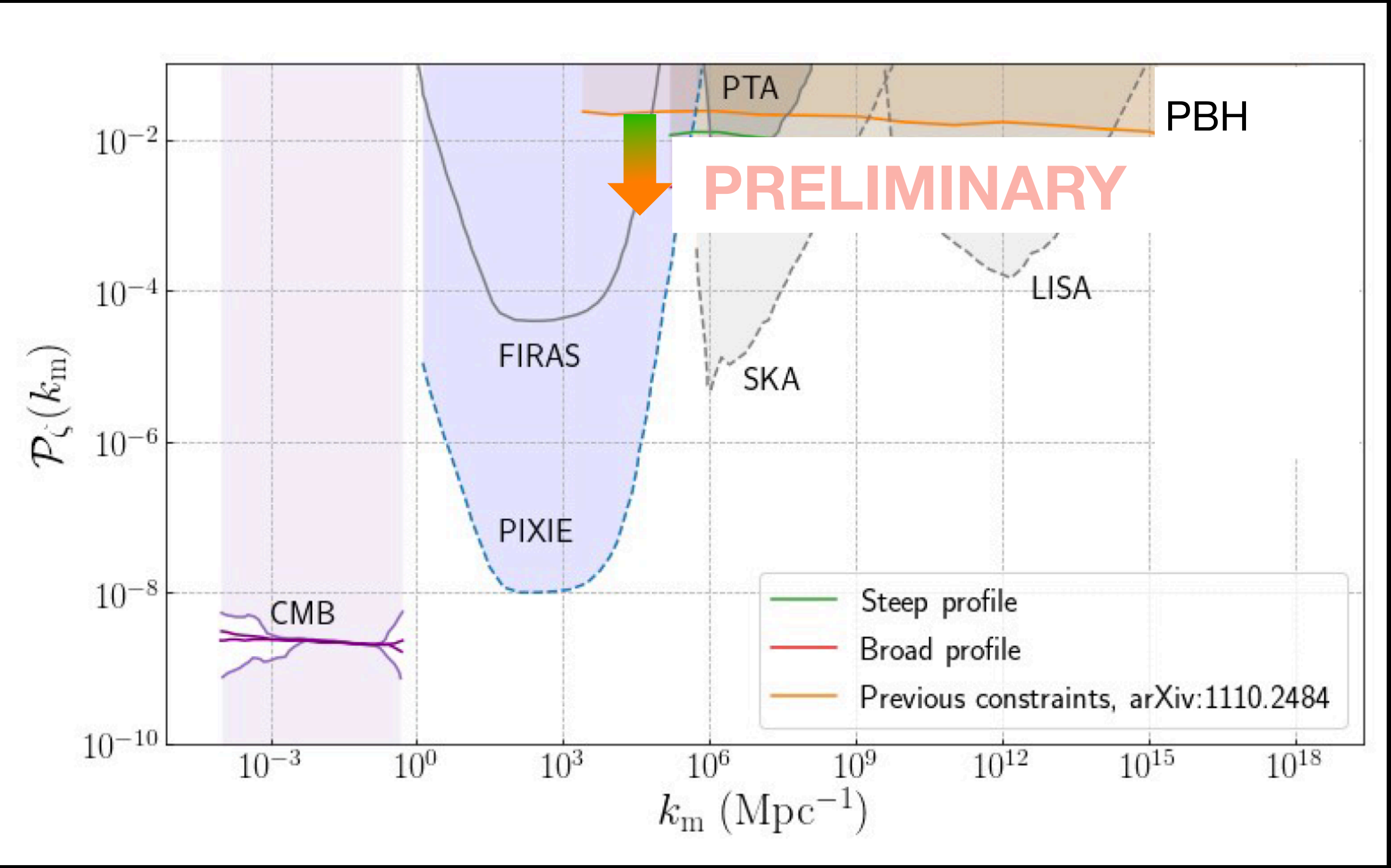
$\alpha = 0.2$

$$M_{PBH} = 1 M_\odot$$

Assume P(k) grows ~$k^4$ (Byrnes )

# RESULTS

## From f $_{PBH}$




**“Ceiling” to a possible P(k) “spike” amplitude, point by point for a MMD of PBH**

# Conclusions

Multi-messengers  cosmology: an example
X-correlation GW-Galaxies → progenitors of BBH mergers

Conversion PBH constraints from MMD to EMD

Connecting PBH abundance to the (primordial)
power spectrum → inflation

# References

- Chasing the progenitors of merging binary black holes, 2018
  Giulio Scelfo, Nicola Bellomo, A. Raccanelli, S. Matarrese, LV

- Primordial Black holes as dark matter: Converting constraints from monochromatic to extended mass distributions , 2017
  Nicola Bellomo, Jose Luis Bernal, A. Raccanelli, LV

➡ Connecting Primordial Black Holes abundance to the primordial power spectrum,
  Alba Kalaja, Nicola Bellomo, et al. in prep.

END