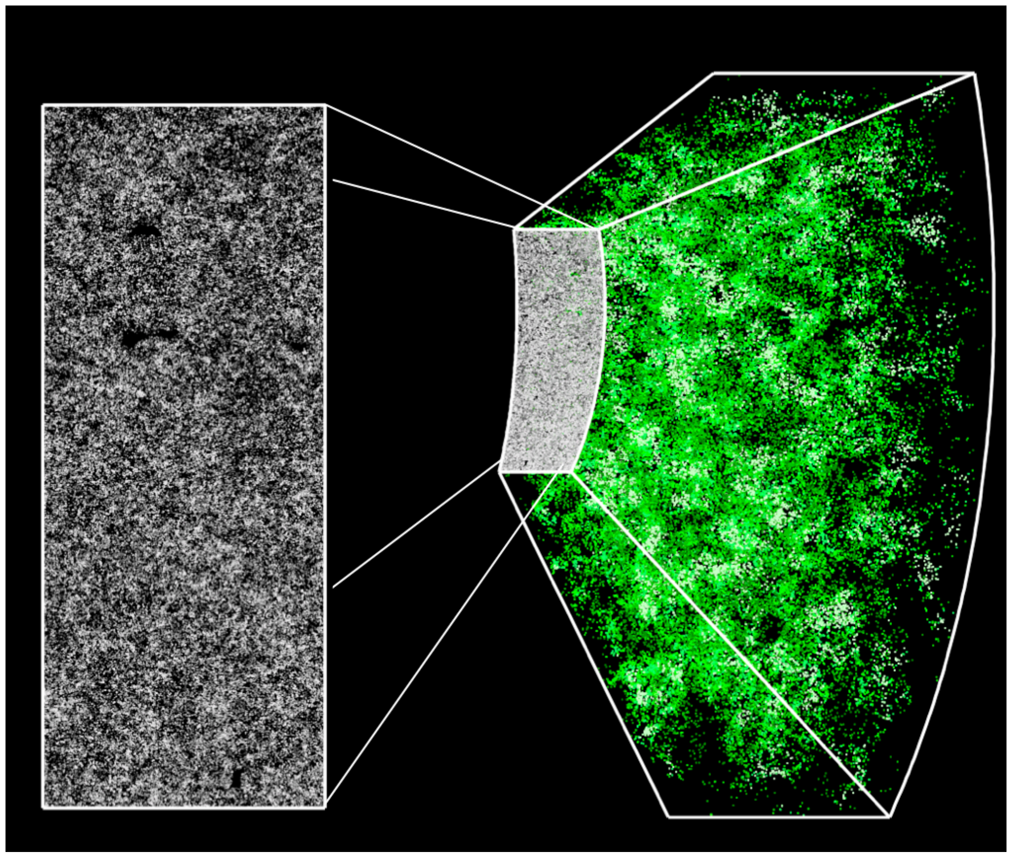
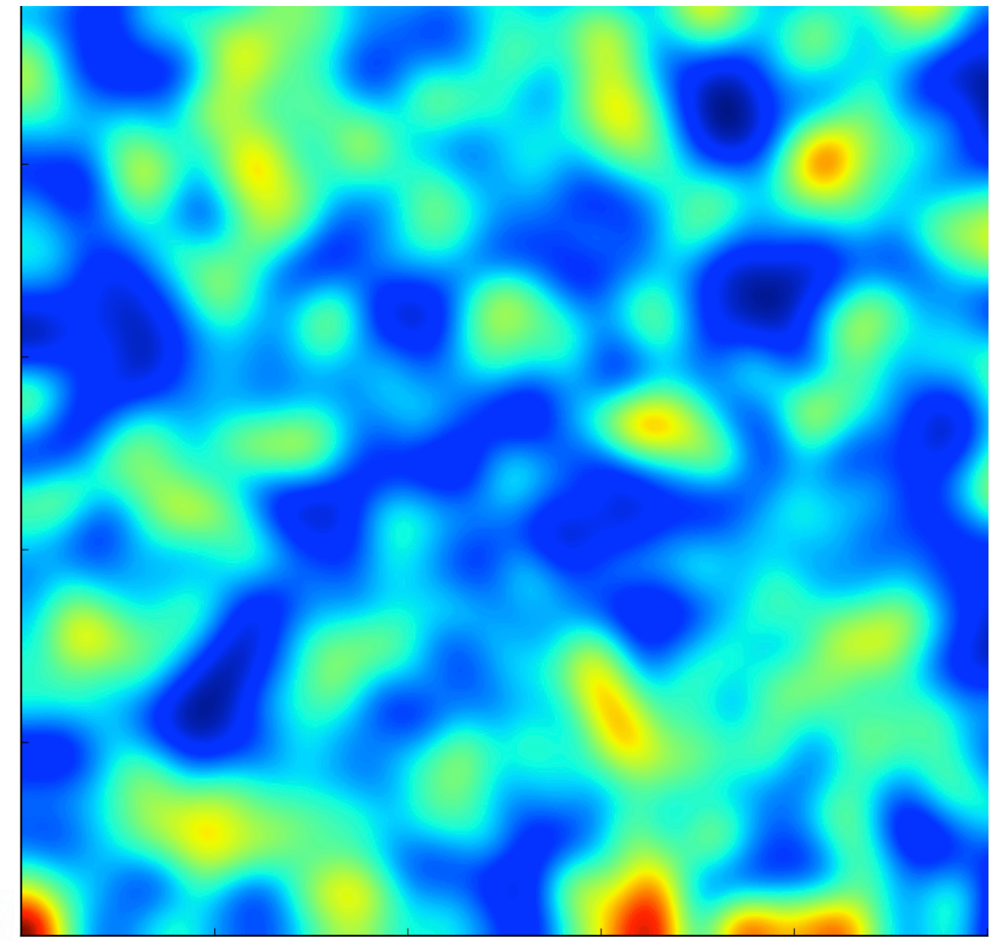
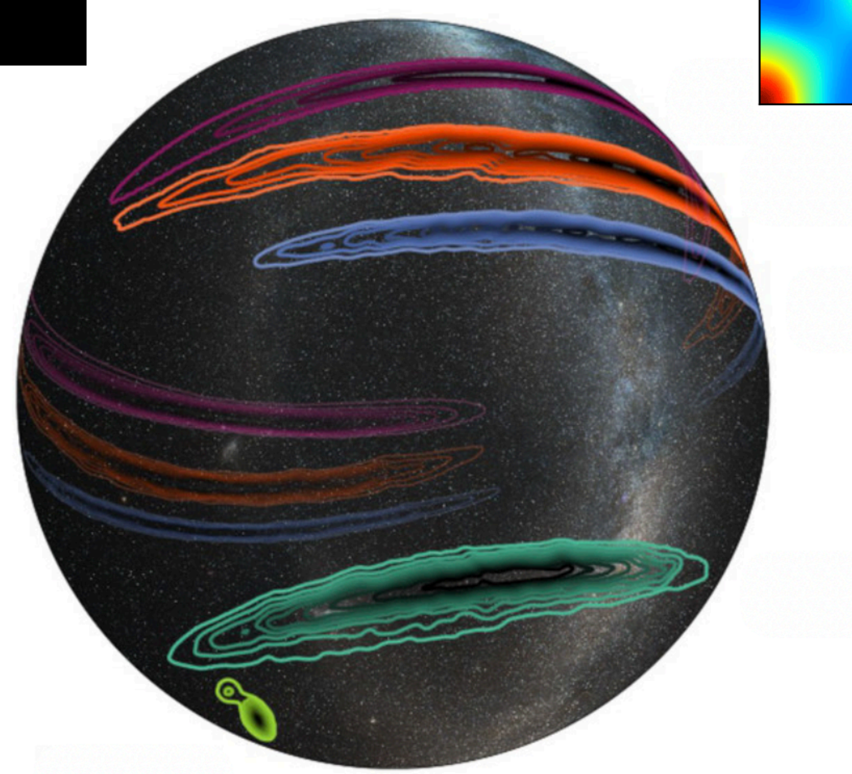
Fundamental physics with multi-messenger cosmology

Alvise Raccanelli

Multi-messenger cosmology

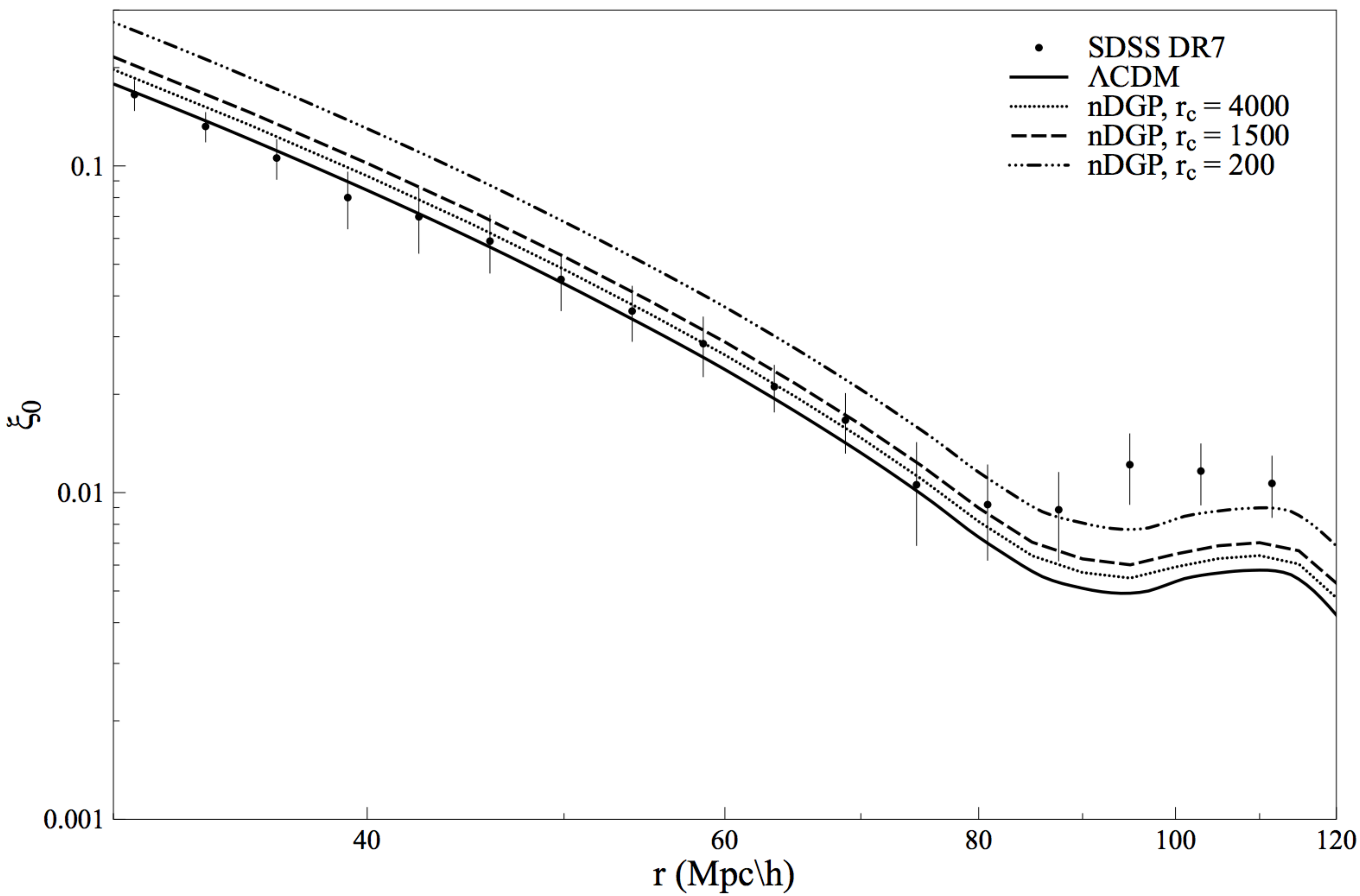






Galaxy correlations

Galaxy correlation function



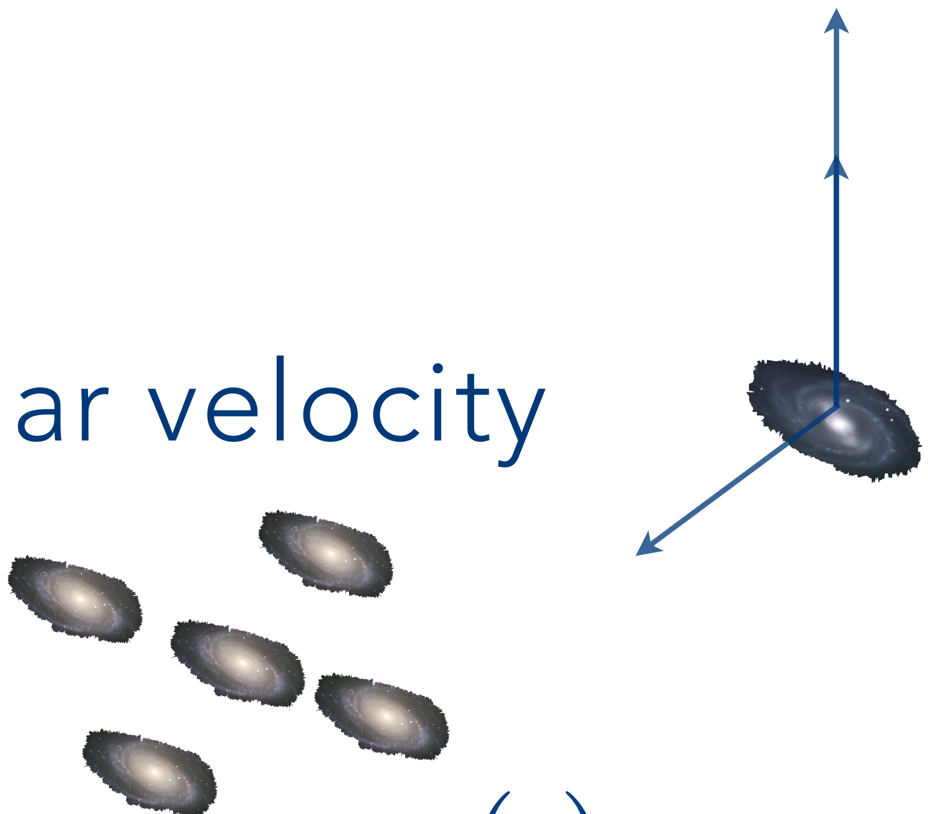
Tests of gravity

Real and Redshift Space

Hubble expansion

peculiar velocity

+ peculiar velocity



$$\boldsymbol{s}(\boldsymbol{r}) = \boldsymbol{r} - \boldsymbol{v}_r(\boldsymbol{r})\hat{\boldsymbol{r}}$$

s = z-space

r = real-space

Redshift-Space power spectrum

$$P^{s}(k) = \left(1 + \beta\mu^{2}\right)^{2} P^{r}(k)$$

Redshift-Space power spectrum

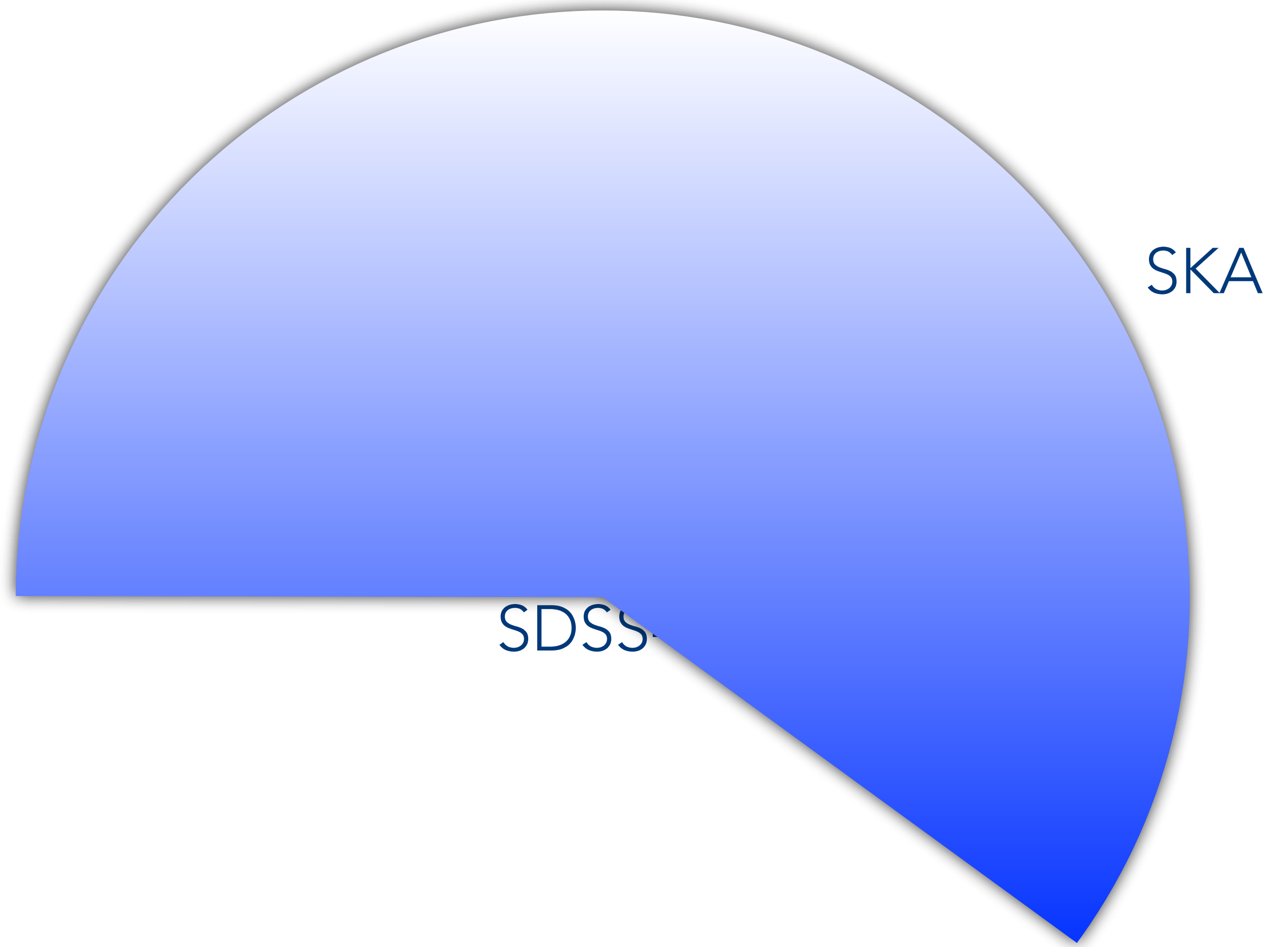
$$\beta = \frac{f}{b} \qquad f = \frac{d \ln D}{d \ln a}$$

D is the growth factor

Measuring f

we can test cosmological models

Large scale galaxy clustering

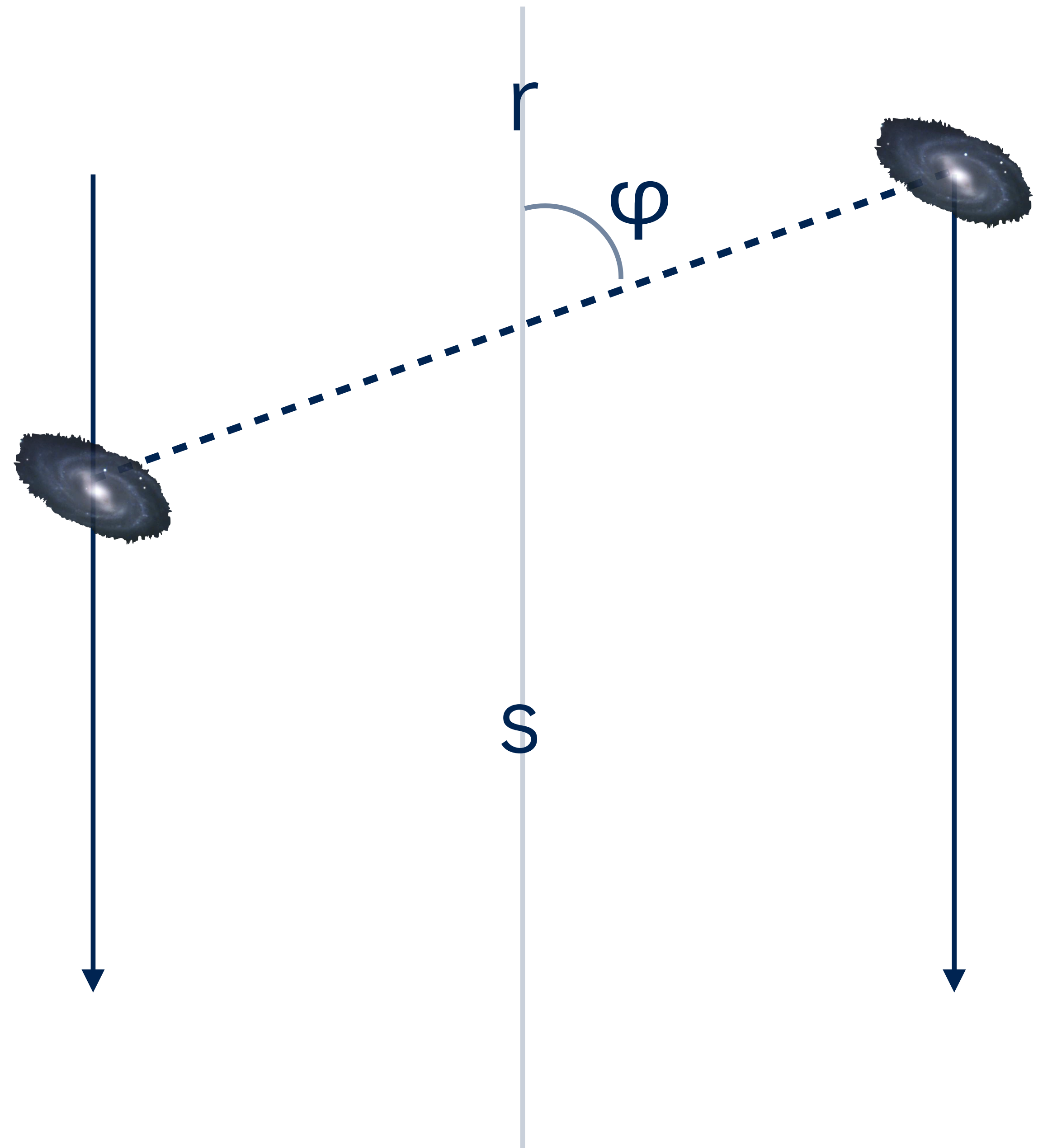


We are going to probe much larger volumes in the next few years

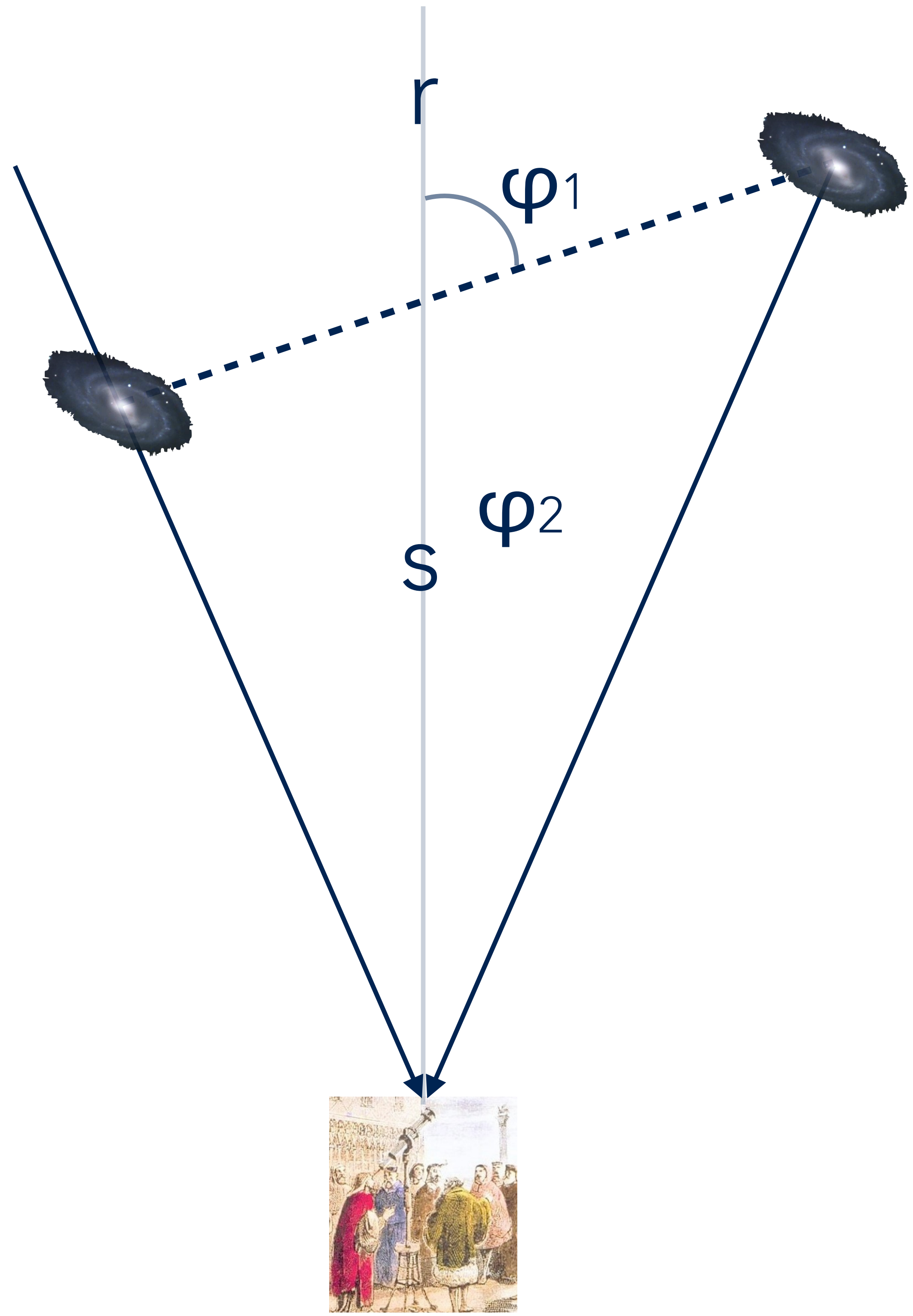
When looking at very large scales the plane-parallel, Newtonian description is not anymore accurate.

We need to include wide angle and general relativistic corrections

Wide-angle clustering



Wide-angle clustering



Wide-angle clustering

Doppler term in the galaxy two-point correlation function: wide-angle, velocity, Doppler lensing and cosmic acceleration effects

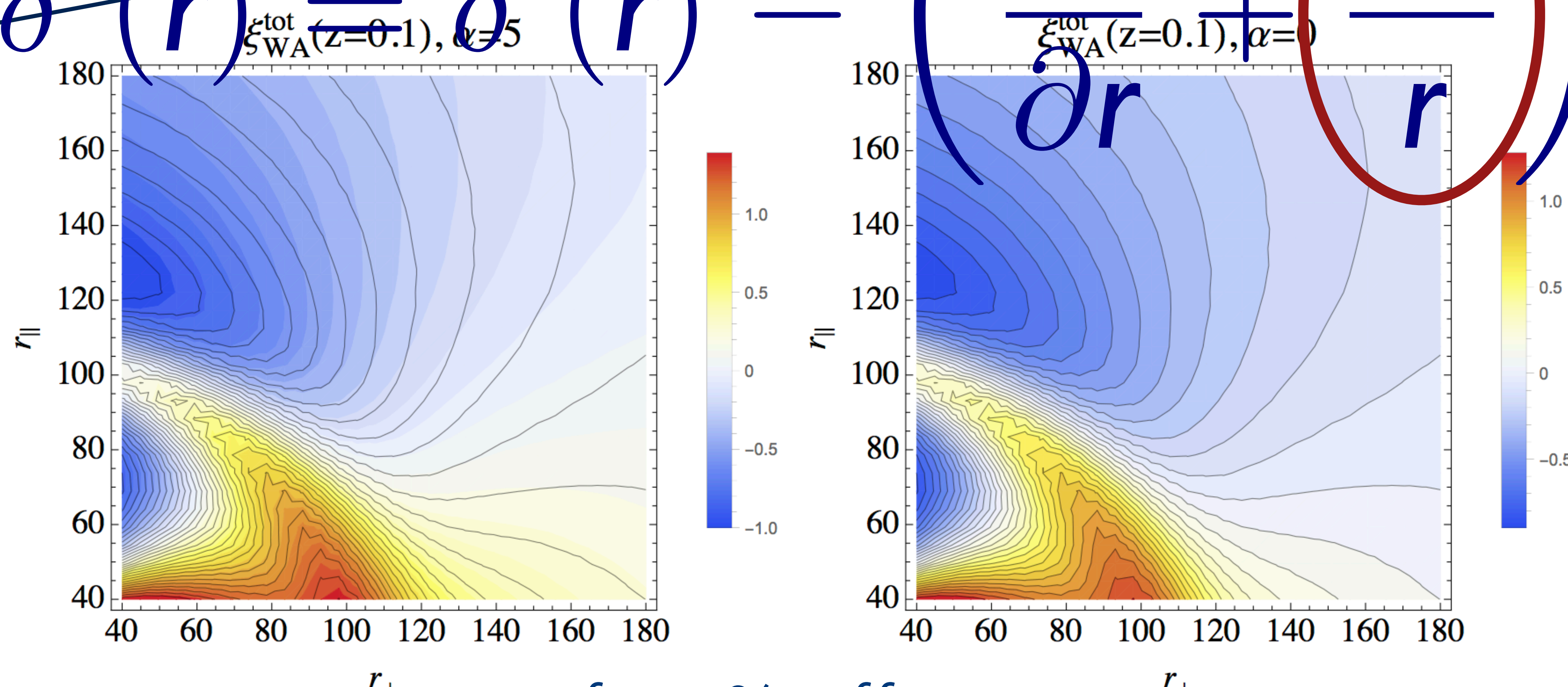
Alvise Raccanelli,[1] Daniele Bertacca,[2] Donghui Jeong,[3,4] Mark C. Neyrinck,[1] and Alexander S. Szalay[1]

Incl α

We study the parity-odd part (that we shall call *Doppler term*) of the *linear* galaxy two-point correlation function that arises from wide-angle, velocity, Doppler lensing and cosmic acceleration effects. As it is important at low redshift and at large angular separations, the Doppler term is usually neglected in the current generation of galaxy surveys. For future wide-angle galaxy surveys, however, we show that the Doppler term must be included. The effect of these terms is dominated by the magnification due to relativistic aberration effects and the slope of the galaxy redshift distribution and it generally mimics the effect of the local type primordial non-Gaussianity with the effective nonlinearity parameter $f_{\rm NL}^{\rm eff}$ of a few; we show that this would affect forecasts on measurements of $f_{\rm NL}$ at low-redshift. Our results show that a survey at low redshift with large number density over a wide area of the sky could detect the Doppler term with a signal-to-noise ratio of $\sim 1-20$, depending on survey specifications.

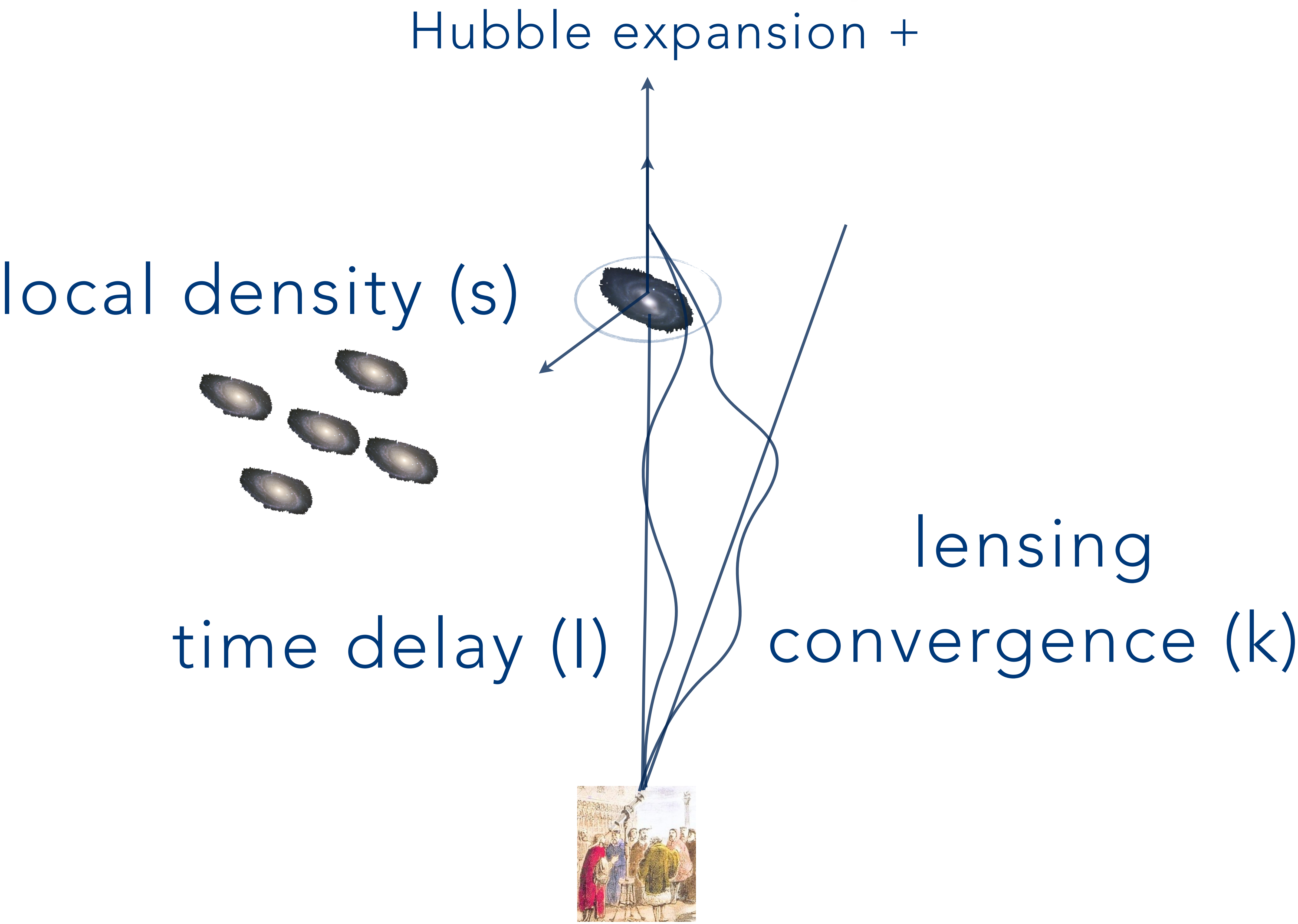
$$\delta^s(r) = \delta^r(r) - \left(\frac{\partial v}{\partial r} + \frac{\alpha v}{r}\right)$$

no α



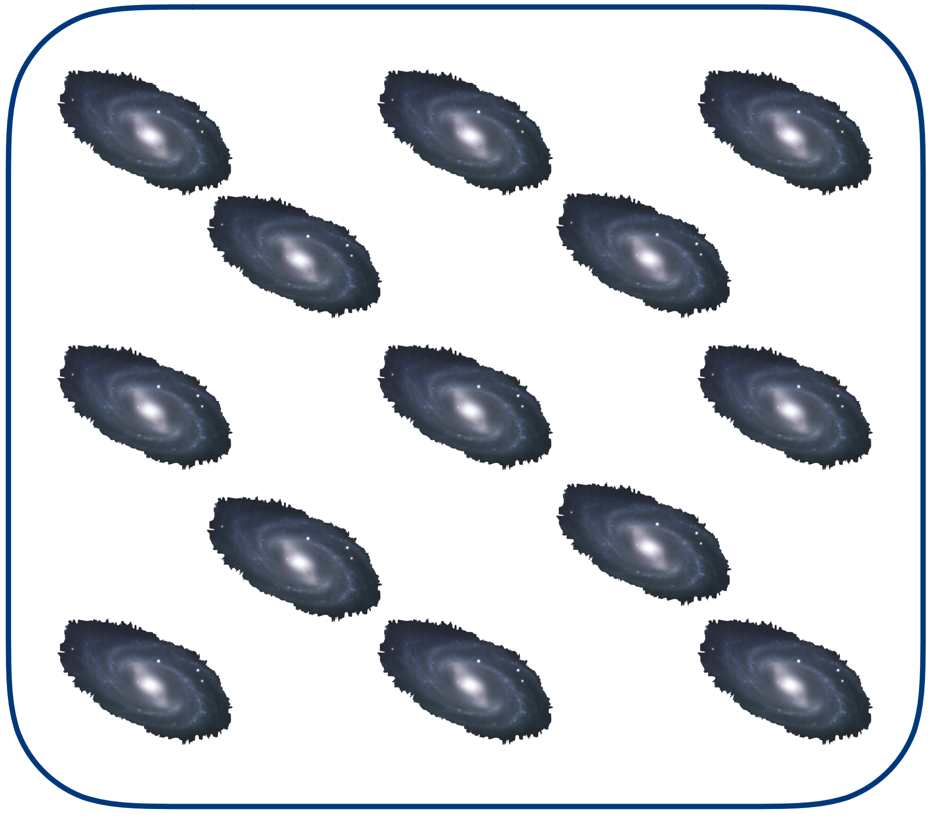
few % effect

Real and Redshift Space in GR



Radial Correlations

Cosmic magnification

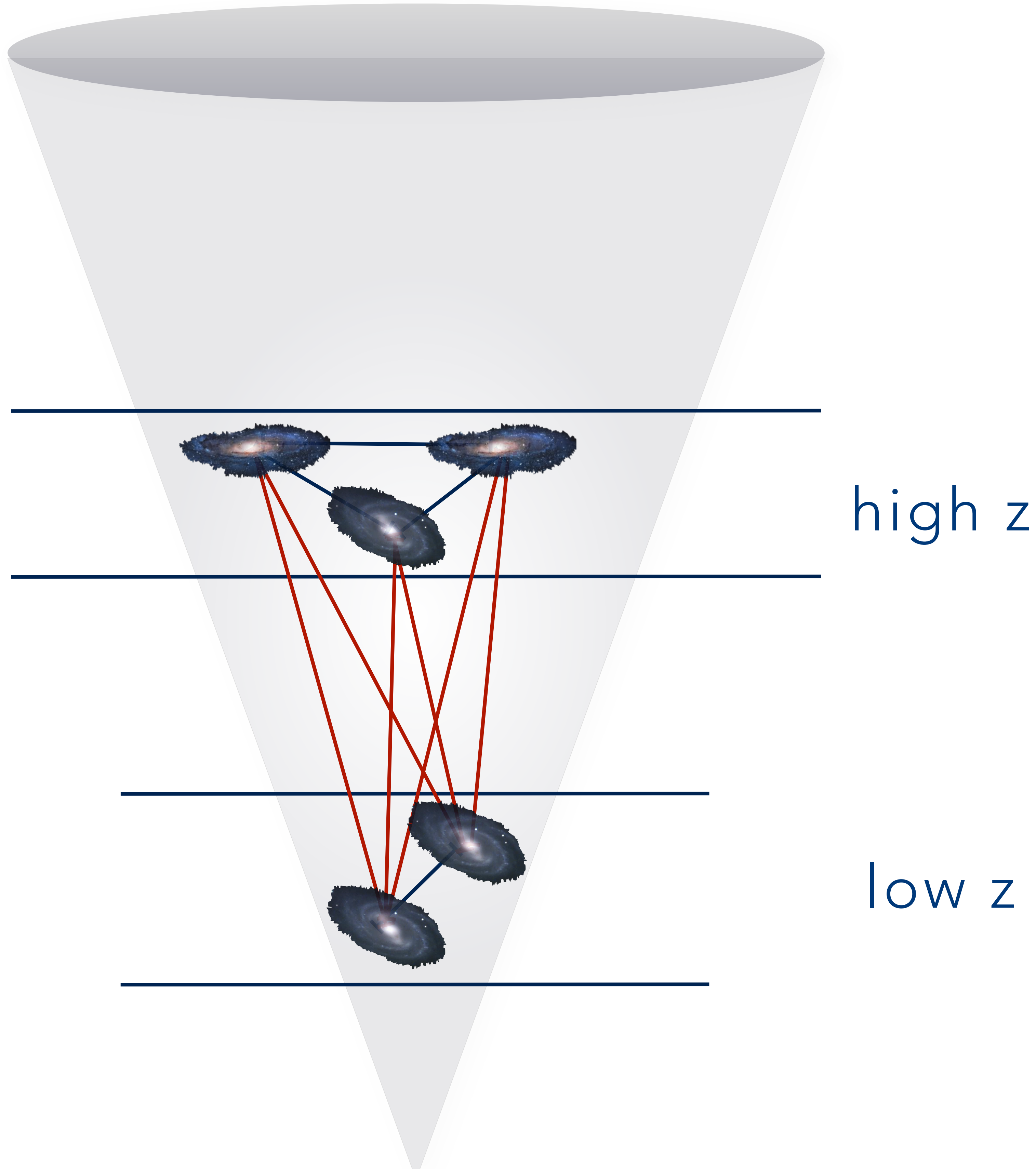


Induces correlations on radial direction

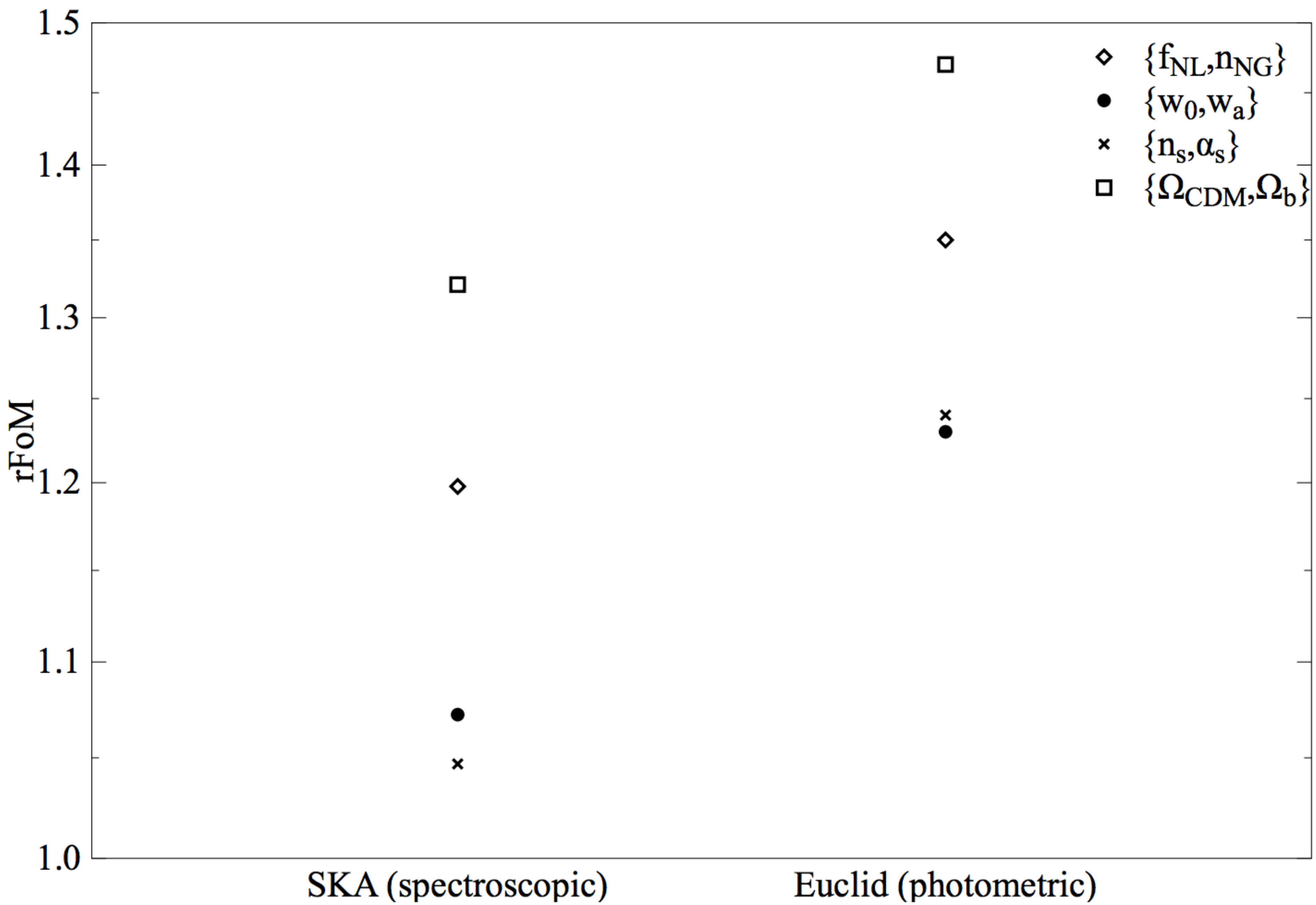
Radial Correlations

More information

Specifically important for PFS & WFIRST!



Large scale galaxy clustering future



Ratio of FoM when including relativistic corrections

ULSS clustering

$$\xi(z_2,\theta,\varphi) = b(z_1)b(z_2)\sum_{\tilde{L},\tilde{\ell}} \Psi_{\tilde{L}\tilde{\ell}}(z_2,\theta,\varphi)\,\mathcal{P}_{\tilde{L}}(\cos\varphi)\,\mathcal{P}_{\tilde{\ell}}(\cos\theta)$$

$$\begin{aligned}
\Psi_{00} &= \left(1+\frac{\beta_1}{3}+\frac{\beta_2}{3}+\frac{29}{225}\beta_1\beta_2\right)\xi_0^0 - \left(\gamma_1+\gamma_2+\frac{1}{3}\beta_1\gamma_2+\frac{1}{3}\gamma_1\beta_2+\frac{1}{9}\beta_1\beta_2\frac{\alpha_1}{\chi_1}\frac{\alpha_2}{\chi_2}\right)\xi_0^2 + \\
&\quad +\gamma_1\gamma_2\xi_0^4 + \sin(\varphi)\sin(\theta)\left[\left(1+\frac{1}{3}\beta_1\right)\beta_2\frac{\alpha_2}{\chi_2}+\left(1+\frac{1}{3}\beta_2\right)\beta_1\frac{\alpha_1}{\chi_1}\right]\xi_1^1 + \\
&\quad -\sin(\varphi)\sin(\theta)\left(\gamma_1\beta_2\frac{\alpha_2}{\chi_2}+\beta_1\frac{\alpha_1}{\chi_1}\gamma_2\right)\xi_1^3 - \left(\frac{2}{9}\beta_1+\frac{2}{9}\beta_2+\frac{44}{315}\beta_1\beta_2\right)\xi_2^0 + \\
&\quad +\frac{2}{9}\left(\beta_1\beta_2\frac{\alpha_1}{\chi_1}\frac{\alpha_2}{\chi_2}+\gamma_1\beta_2+\beta_1\gamma_2\right)\xi_2^2 + \frac{32}{1575}\beta_1\beta_2\xi_4^0\,, \\
\Psi_{11} &= \left[-\left(1+\frac{7}{25}\beta_1\right)\beta_2\frac{\alpha_2}{\chi_2}+\left(1+\frac{7}{25}\beta_2\right)\beta_1\frac{\alpha_1}{\chi_1}\right]\xi_1^1 + \left(\gamma_1\beta_2\frac{\alpha_2}{\chi_2}-\beta_1\frac{\alpha_1}{\chi_1}\gamma_2\right)\xi_1^3 + \\
&\quad +2\sin(\varphi)\sin(\theta)\left(\beta_2-\beta_1\right)\xi_2^0 + 2\sin(\varphi)\sin(\theta)\left(\beta_1\gamma_2-\gamma_1\beta_2\right)\xi_2^2 + \\
&\quad +\frac{2}{25}\left(\beta_1\frac{\alpha_1}{\chi_1}\beta_2-\beta_1\beta_2\frac{\alpha_2}{\chi_2}\right)\xi_3^1\,, \\
\Psi_{02} &= -\frac{16}{315}\beta_1\beta_2\xi_0^0 + \frac{4}{9}\beta_1\beta_2\frac{\alpha_1}{\chi_1}\frac{\alpha_2}{\chi_2}\xi_0^2 - \frac{8}{15}\sin(\varphi)\sin(\theta)\beta_1\beta_2\left(\frac{\alpha_1}{\chi_1}+\frac{\alpha_2}{\chi_2}\right)\xi_1^1 + \\
&\quad +\left(\frac{2}{9}\beta_1+\frac{2}{9}\beta_2+\frac{100}{441}\beta_1\beta_2\right)\xi_2^0 - \frac{2}{9}\left(\beta_1\beta_2\frac{\alpha_1}{\chi_1}\frac{\alpha_2}{\chi_2}+\gamma_1\beta_2+\beta_1\gamma_2\right)\xi_2^2 + \\
&\quad +\frac{2}{15}\sin(\varphi)\sin(\theta)\beta_1\beta_2\left(\frac{\alpha_1}{\chi_1}+\frac{\alpha_2}{\chi_2}\right)\xi_3^1 - \frac{88}{2205}\beta_1\beta_2\xi_4^0\,, \\
\Psi_{20} &= \left(\frac{2}{9}\beta_1+\frac{2}{9}\beta_2+\frac{4}{21}\beta_1\beta_2\right)\xi_2^0 - \frac{2}{9}\left(3\beta_1\beta_2\frac{\alpha_1}{\chi_1}\frac{\alpha_2}{\chi_2}+\gamma_1\beta_2+\beta_1\gamma_2\right)\xi_2^2 + \\
&\quad +\frac{2}{3}\sin(\varphi)\sin(\theta)\beta_1\beta_2\left(\frac{\alpha_1}{\chi_1}+\frac{\alpha_2}{\chi_2}\right)\xi_3^1 - \frac{8}{63}\beta_1\beta_2\xi_4^0\,, \\
\Psi_{22} &= -\left(\frac{8}{9}\beta_1+\frac{8}{9}\beta_2+\frac{16}{21}\beta_1\beta_2\right)\xi_2^0 + \frac{8}{9}\left(\gamma_1\beta_2+\beta_1\gamma_2\right)\xi_2^2 + \\
&\quad +\frac{8}{63}\beta_1\beta_2\xi_4^0\,, \\
\Psi_{13} &= \frac{8}{25}\beta_1\beta_2\left(\frac{\alpha_1}{\chi_1}-\frac{\alpha_2}{\chi_2}\right)\xi_1^1 - \frac{2}{25}\beta_1\beta_2\left(\frac{\alpha_1}{\chi_1}-\frac{\alpha_2}{\chi_2}\right)\xi_3^1\,, \\
\Psi_{31} &= -\frac{2}{5}\beta_1\beta_2\left(\frac{\alpha_1}{\chi_1}-\frac{\alpha_2}{\chi_2}\right)\xi_3^1\,, \\
\Psi_{04} &= \frac{64}{525}\beta_1\beta_2\xi_0^0 - \frac{64}{735}\beta_1\beta_2\xi_2^0 + \frac{24}{1225}\beta_1\beta_2\xi_4^0\,, \\
\Psi_{40} &= \frac{8}{35}\beta_1\beta_2\xi_4^0\,,
\end{aligned}$$

ULSS Clustering

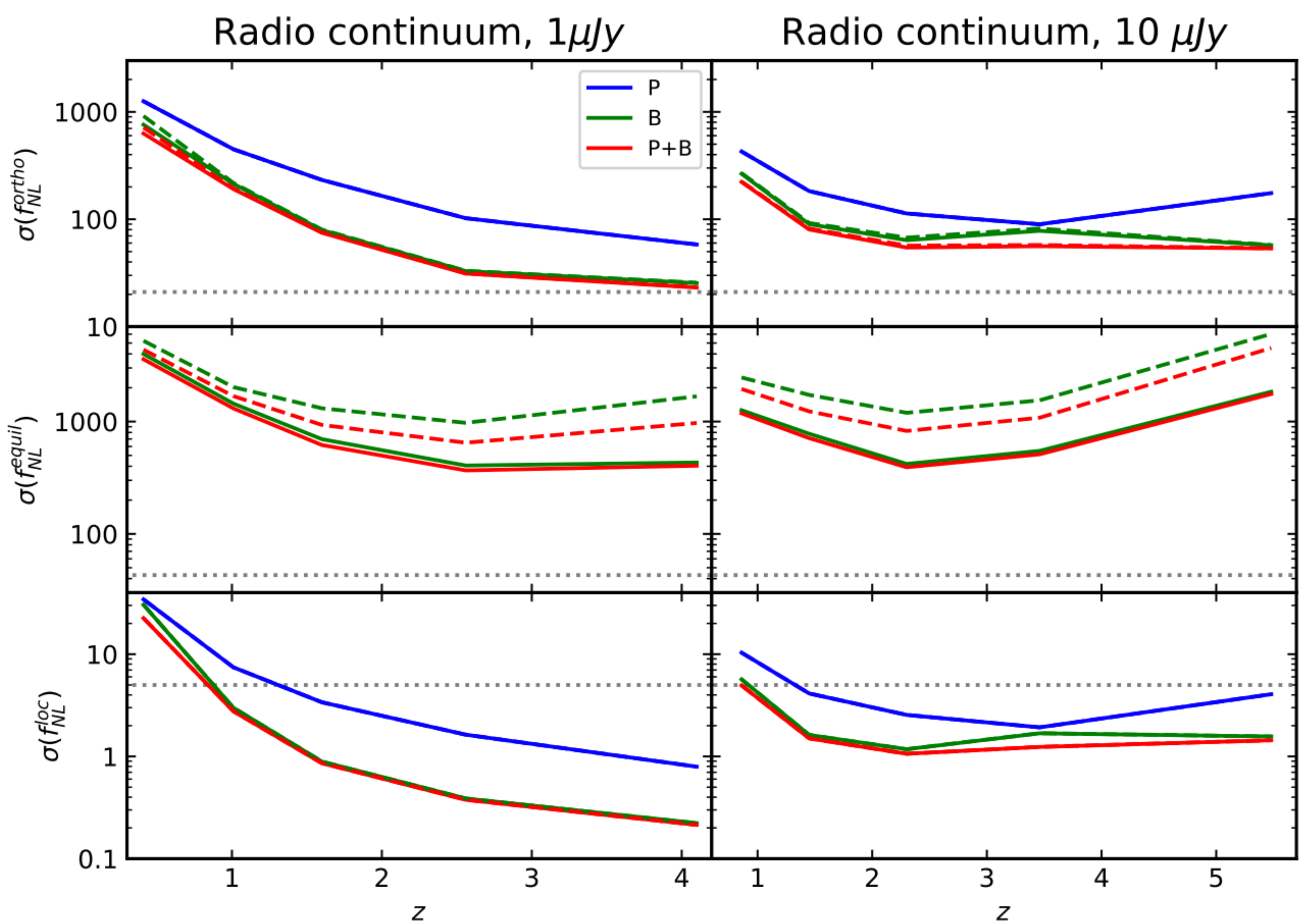
Proper estimators and efficient data analysis still needs to be developed

(Just started, work in progress)

First attempts in Euclid, but still approximated
(e.g., moving line of sight, but not 2 los)

Large scale galaxy clustering future

bispectrum, galaxy bias



non-Gaussianity from galaxy bispectrum with radio arrays

(not including relativistic effects)

Large scale galaxy clustering

bispectrum

$$B_{\ell_1\ell_2\ell_3}(k_1,k_2,k_3) = \sum_{abc}\sqrt{\frac{(2\ell_1+1)(2\ell_2+1)(2\ell_3+1)}{4\pi}}\sum_{\ell_{\mathbf{p}_1}\ell_{\mathbf{q}_1}\bar{\ell}_1}(-1)^{-(\bar{\ell}_1+\ell_{\mathbf{q}_1}+\ell_{\mathbf{p}_1})}\frac{(2\bar{\ell}_1+1)(2\ell_{\mathbf{q}_1}+1)(2\ell_{\mathbf{p}_1}+1}{4\pi}$$

$$\times\begin{pmatrix} \ell_{\mathbf{q}_1} & \ell_1 & \ell_{\mathbf{p}_1} \\ 0 & 0 & 0 \end{pmatrix}\begin{pmatrix} \ell_{\mathbf{p}_1} & \ell_2 & \bar{\ell}_1 \\ 0 & 0 & 0 \end{pmatrix}\begin{pmatrix} \bar{\ell}_1 & \ell_3 & \ell_{\mathbf{q}_1} \\ 0 & 0 & 0 \end{pmatrix}\begin{Bmatrix} \ell_1 & \ell_2 & \ell_3 \\ \bar{\ell}_1 & \ell_{\mathbf{q}_1} & \ell_{\mathbf{p}_1} \end{Bmatrix}$$

$$\times(-1)^{\ell_2+\ell_3}\int\frac{q_2^2\mathrm{d}q_2}{(2\pi)^3}\frac{q_3^2\mathrm{d}q_3}{(2\pi)^3}\left[\mathcal{K}^{a(2)}_{\ell_1\ell_{\mathbf{p}_1}\ell_{\mathbf{q}_1}\bar{\ell}_1}(k_1;q_2,q_3)\,\mathcal{M}^{b(1)}_{\ell_2}(k_2,q_2)\,\mathcal{M}^{c(1)}_{\ell_3}(k_3,q_3)\right]P_\Phi(q_2)P_\Phi(q_3)$$

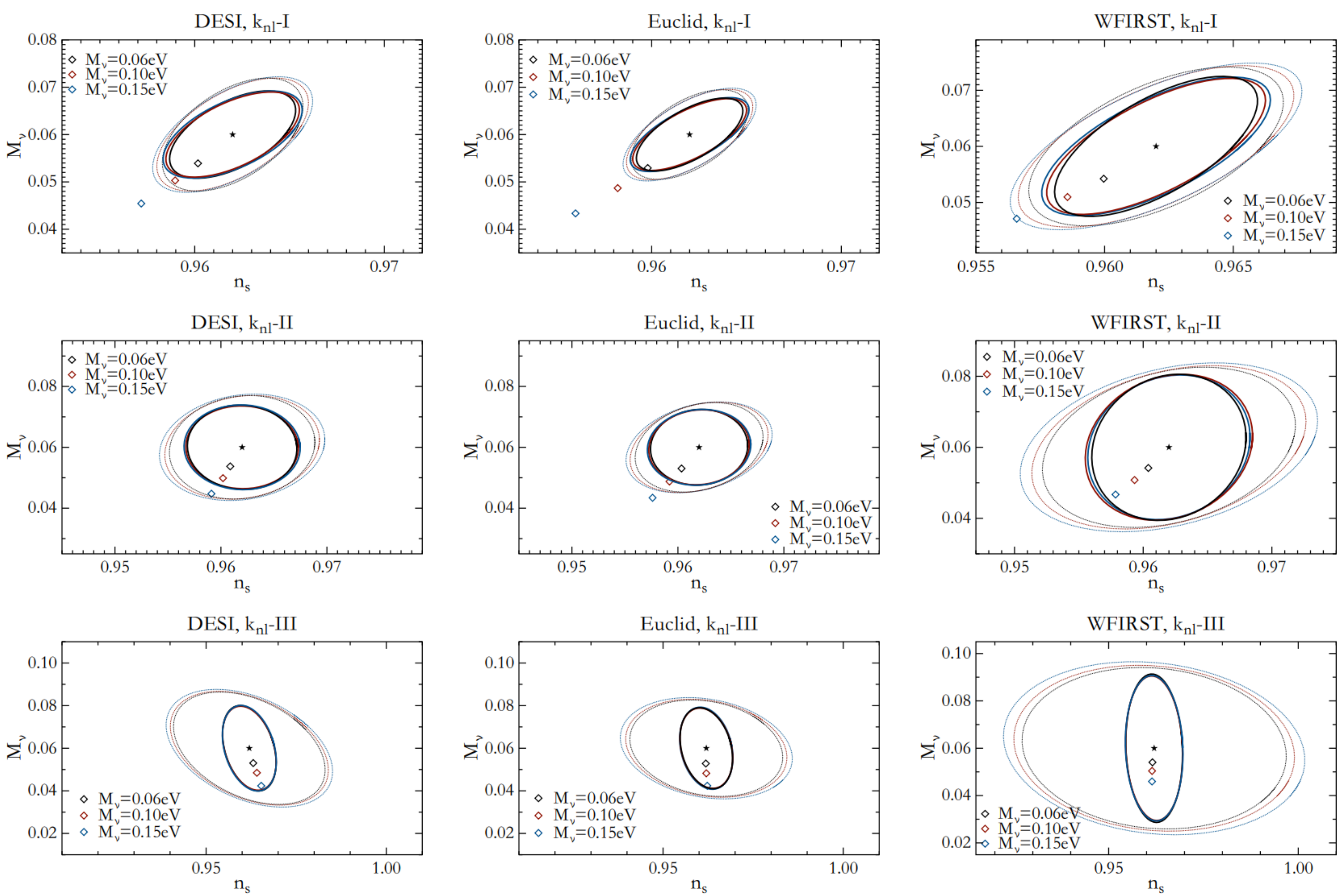
$$\mathcal{M}^{\delta_g^{(2)}(2)}_{\ell m\ell_{\mathbf{p}}m_{\mathbf{p}}\ell_{\mathbf{q}}m_{\mathbf{q}}\bar{\ell}\bar{m}}(k;p,q) = (4\pi)^3\aleph^*_\ell(k)(-1)^m i^{\ell_{\mathbf{p}}+\ell_{\mathbf{q}}}(2\bar{\ell}+1)^{-1}\mathcal{G}^{\ell\ell_{\mathbf{p}}\ell_{\mathbf{q}}}_{-mm_{\mathbf{p}}m_{\mathbf{q}}}\times$$

$$\times\int\mathrm{d}\bar{\chi}\;\bar{\chi}^2\mathcal{W}(\bar{\chi})\left[\frac{1}{2}F^{\delta_g(2)}_{\bar{\ell}}(p,q;\eta)j_{\ell_{\mathbf{p}}}(p\bar{\chi})j_{\ell_{\mathbf{q}}}(q\bar{\chi})\mathcal{T}^\Phi(\mathbf{p},\eta)\mathcal{T}^\Phi(\mathbf{q},\eta)\right]j_\ell(k\bar{\chi})$$

Formalism including relativistic effects

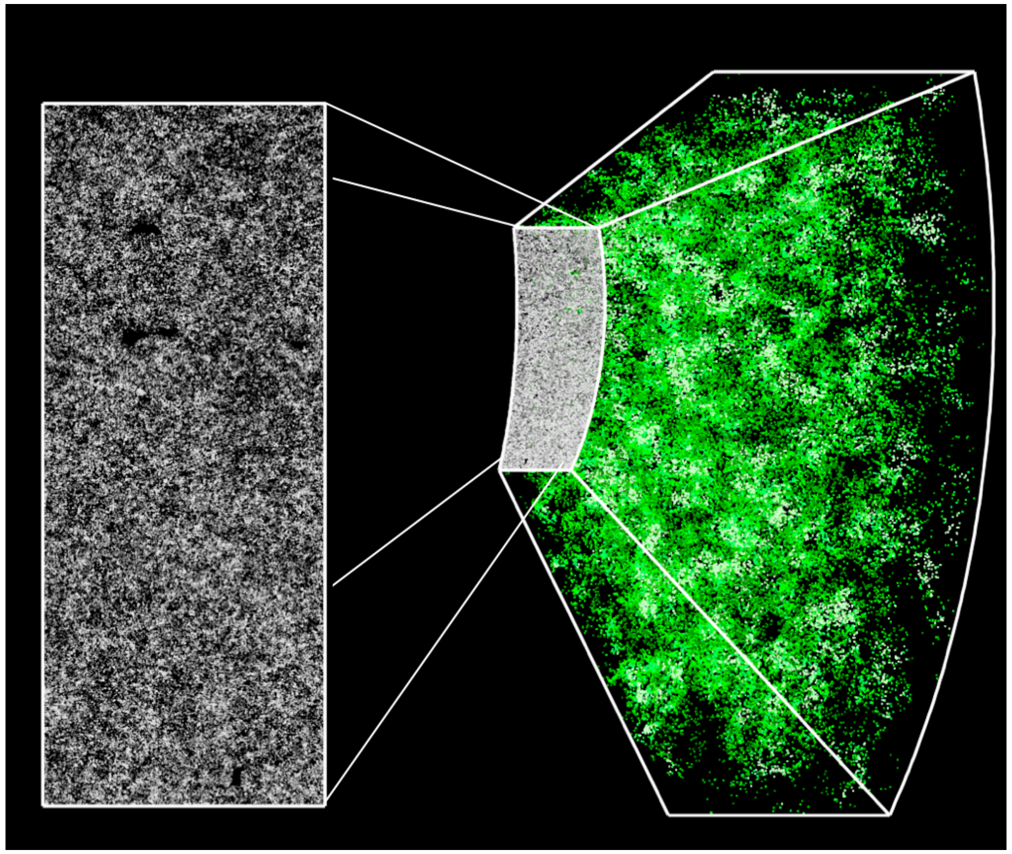
Large scale galaxy clustering

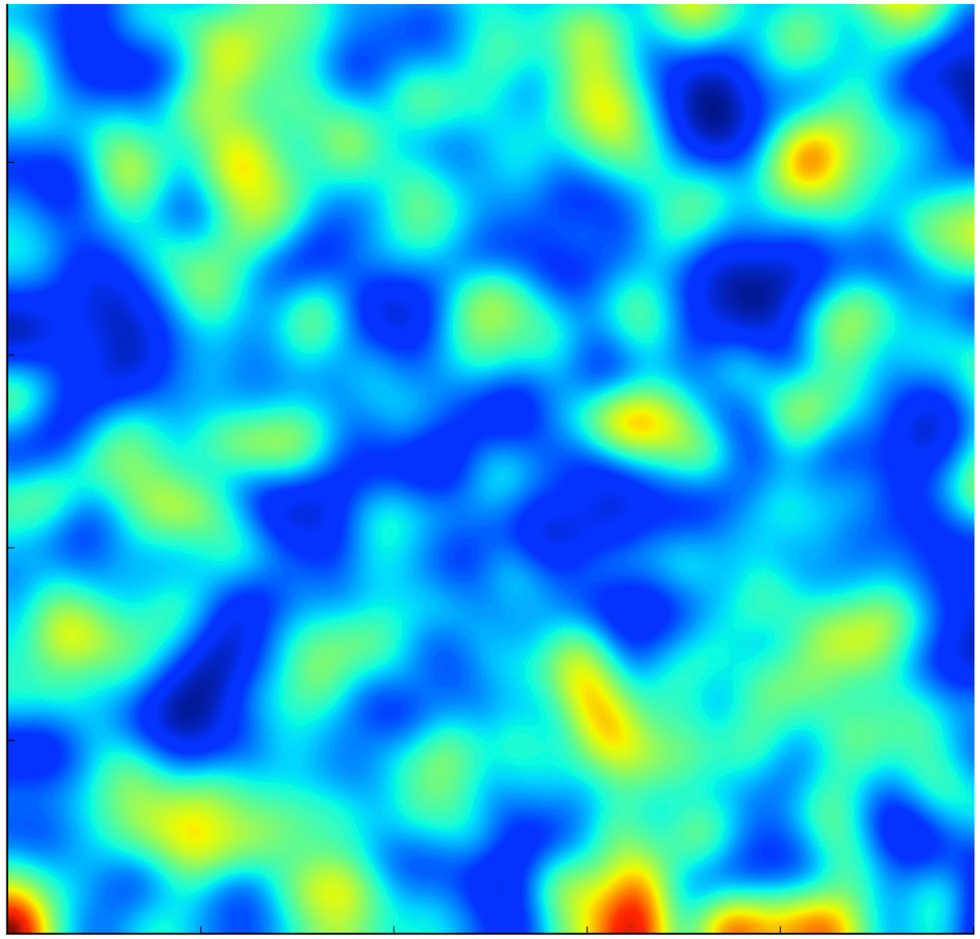
Neutrino mass effects

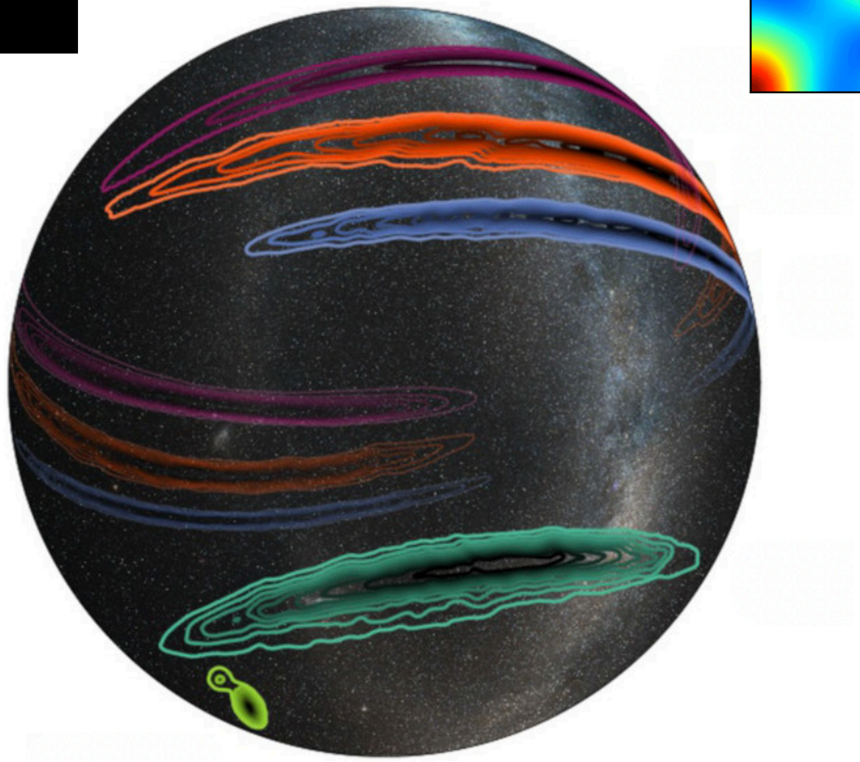


Effects of neutrino mass on galaxy bias

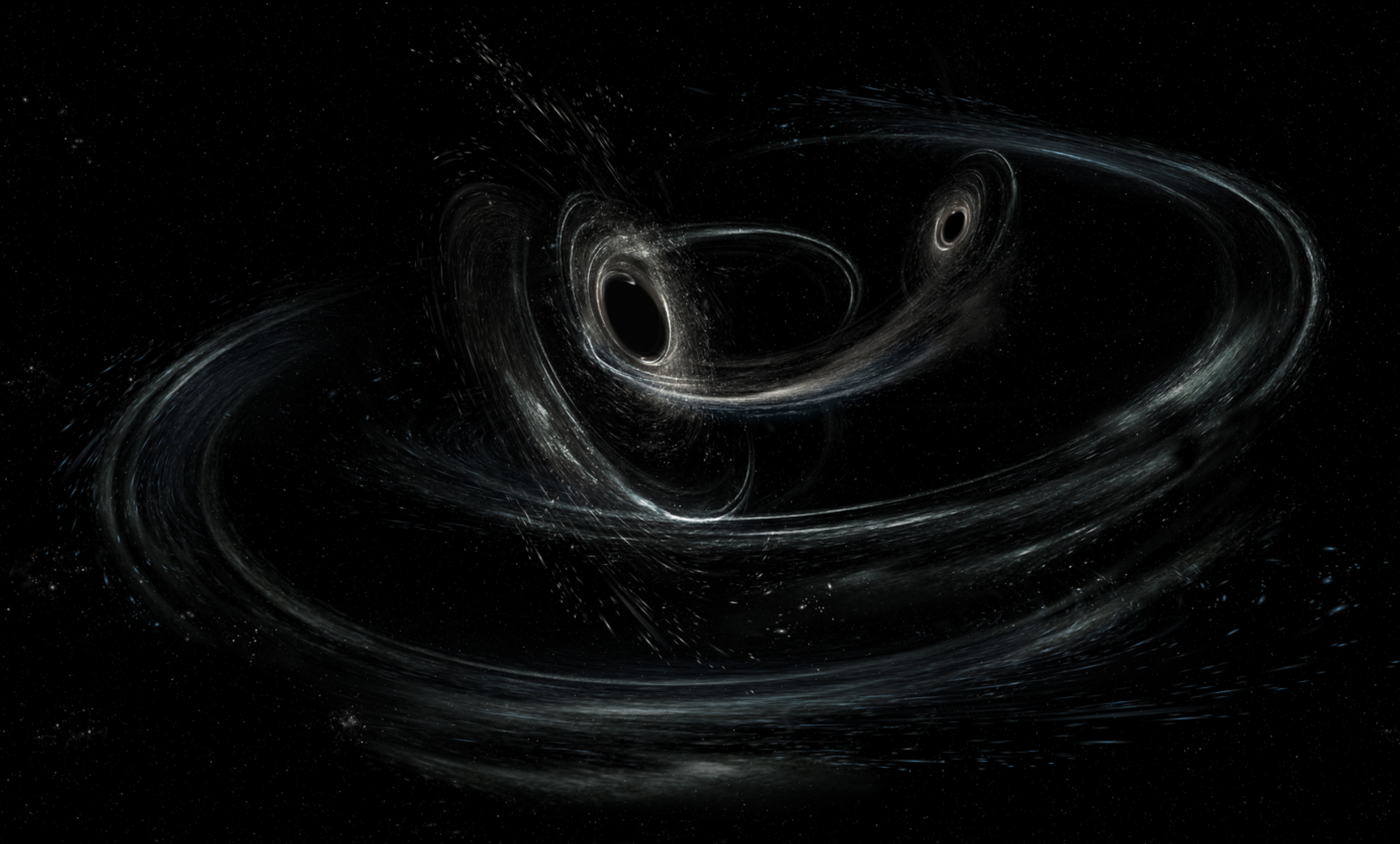
Multi-messenger cosmology



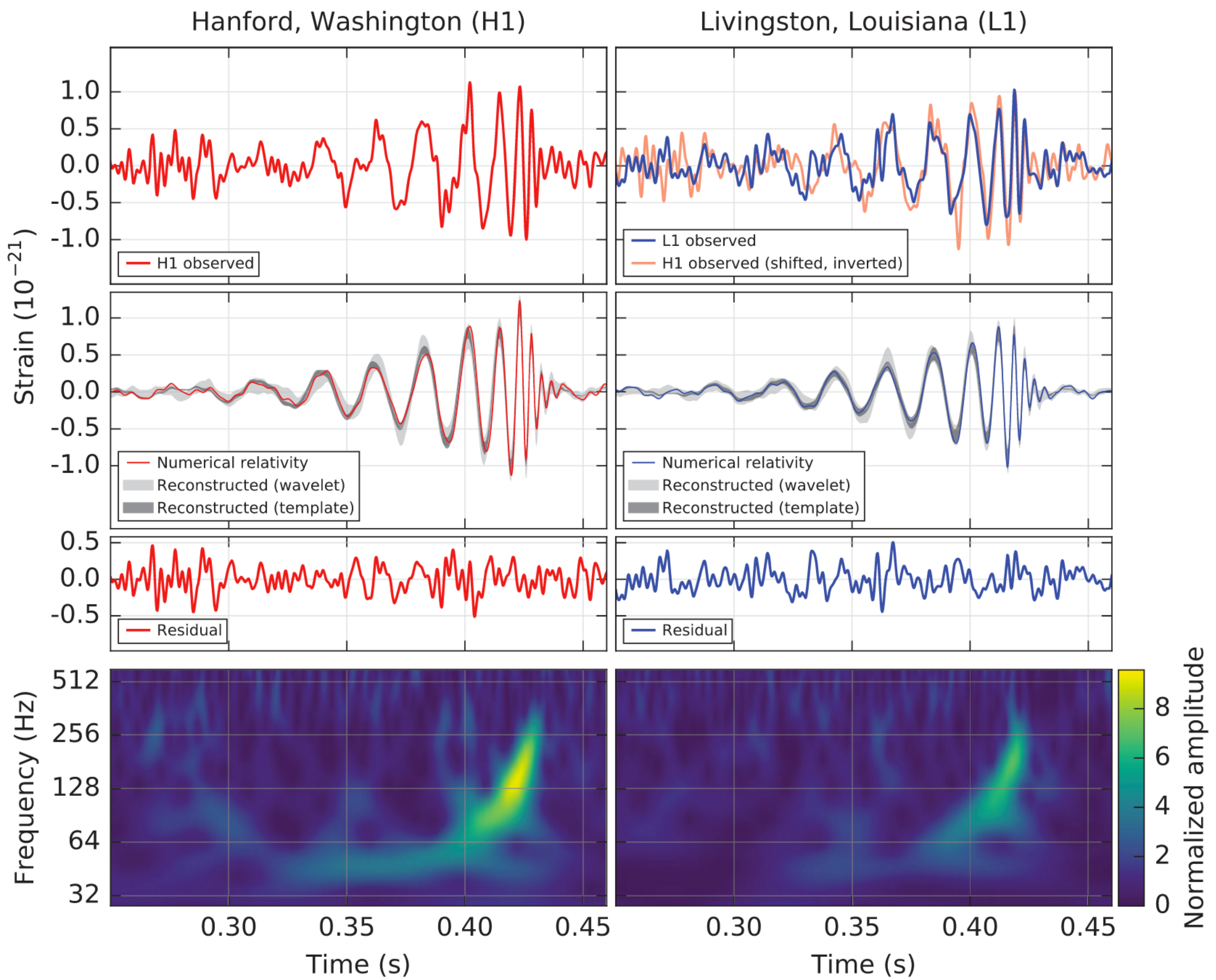




A long time ago in a galaxy far, far away....



On planet Earth, 14/09/15

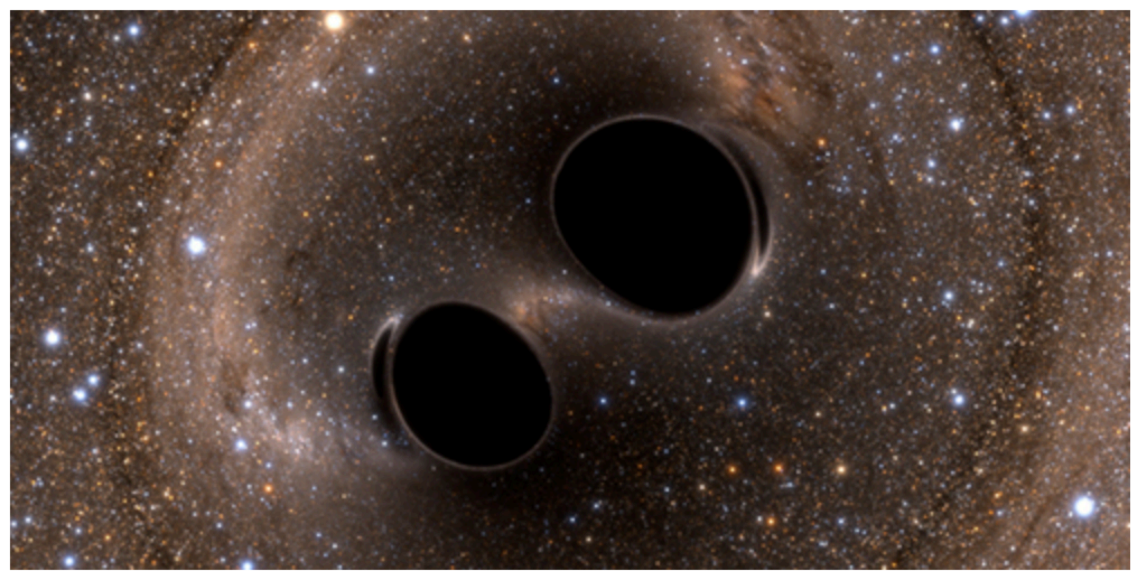


Are PBHs the DM?

Synopsis: Gravitational Waves May Hold Dark Matter Secret

May 19, 2016

A theoretical analysis examines the possibility that the black holes detected by LIGO serve as dark matter.



Simulating eXtreme Spacetimes

Featured in Physics

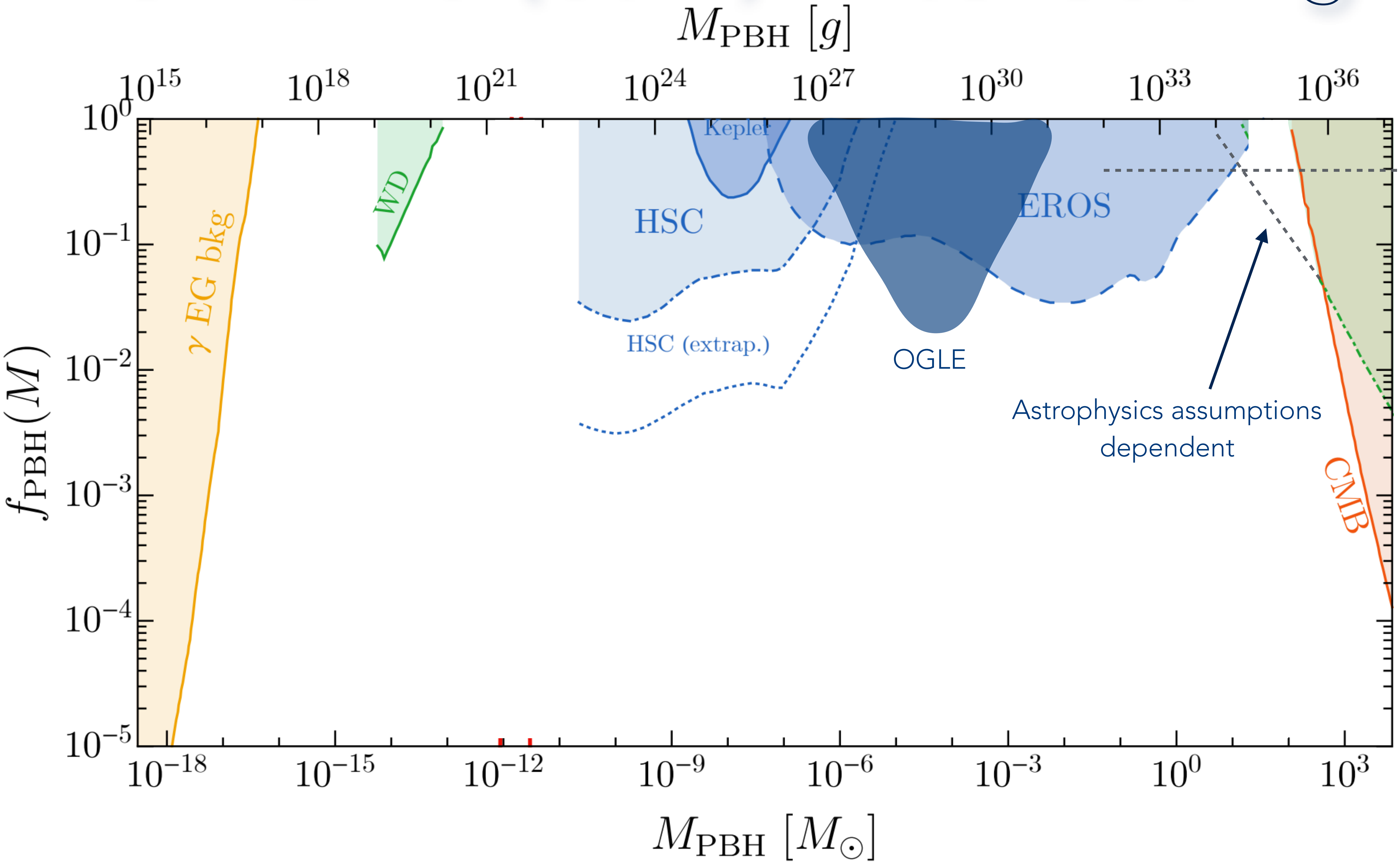
Did LIGO Detect Dark Matter?

Simeon Bird, Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, and Adam G. Riess

Phys. Rev. Lett. **116**, 201301 – Published 19 May 2016

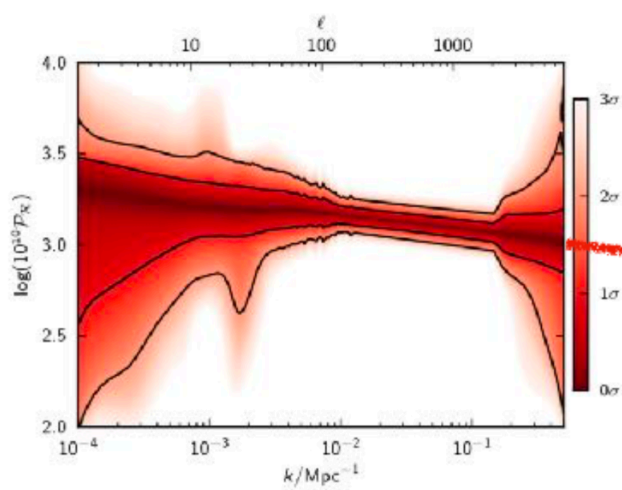
Physics See Synopsis: Gravitational Waves May Hold Dark Matter Secret

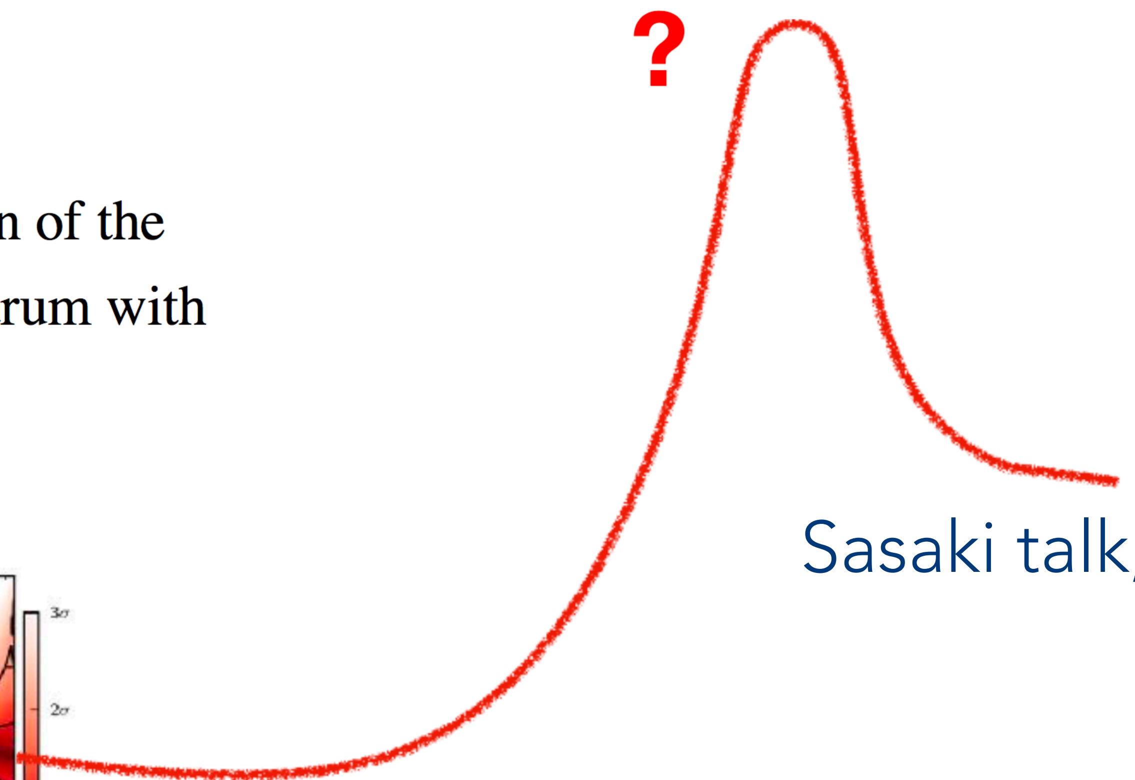
Are PBHs (still) interesting?



Early Universe physics with PBHs

Bayesian reconstruction of the primordial power spectrum with l<2300. (Planck 2015)





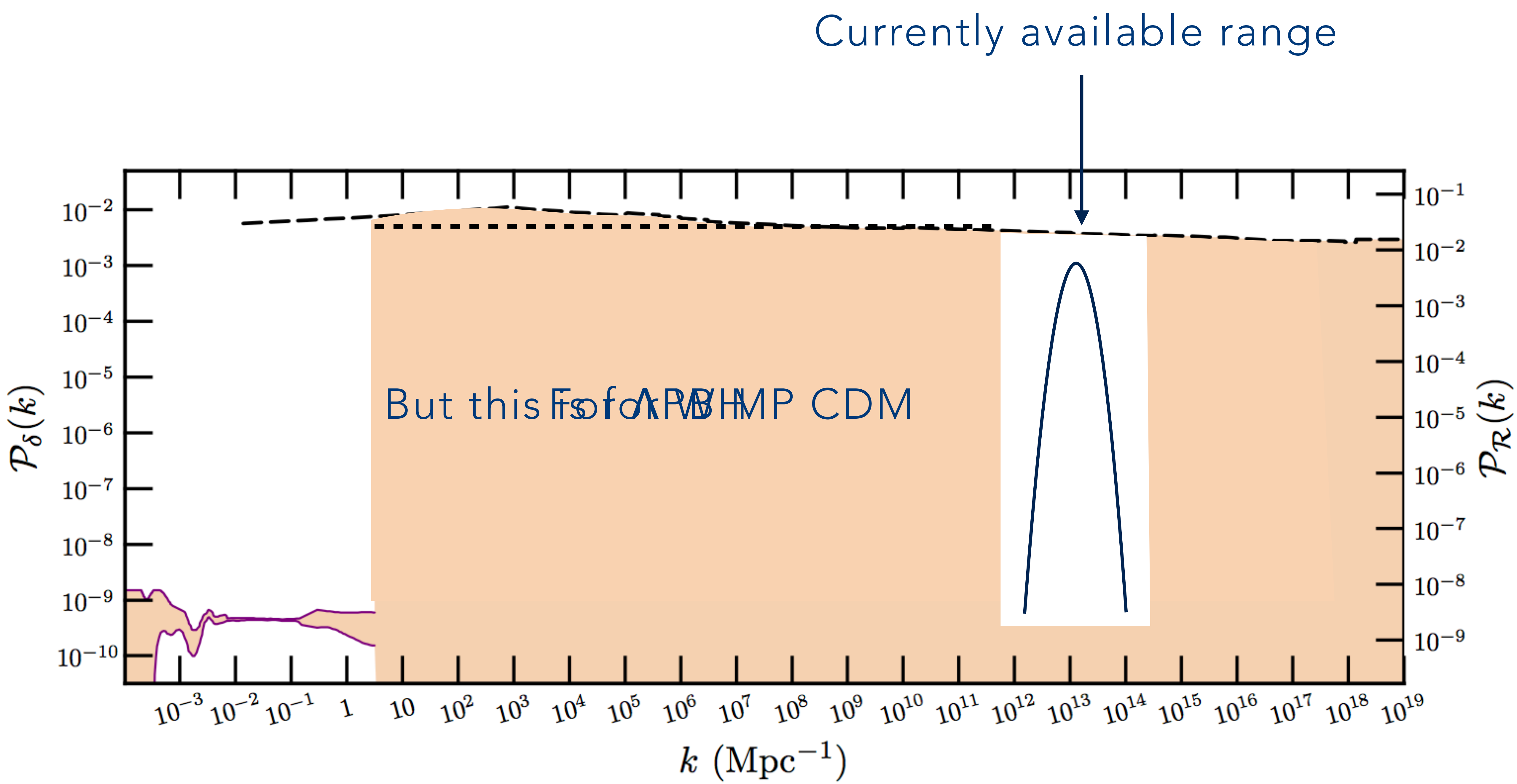
Sasaki talk, CERN

The resolution is lacking to say anything precise about higher k.

PBH formation requires (in "standard" scenarios) a peak in the power spectrum

We can use their existence (or lack of) to probe very small scale power spectrum

Early Universe physics with PBHs



AR, R. Brustein, in preparation

GW with radio surveys

Gravitational wave astronomy with radio galaxy surveys

Alvise Raccanelli

ABSTRACT

In the next decade, new astrophysical instruments will deliver the first large-scale maps of gravitational waves and radio sources. Therefore, it is timely to investigate the possibility to combine them to provide new and complementary ways to study the Universe. Using simulated catalogues appropriate to the planned surveys, it is possible to predict measurements of the cross-correlation between radio sources and GW maps and the effects of a stochastic gravitational wave background on galaxy maps. Effects of GWs on the large scale structure of the Universe can be used to investigate the nature of the progenitors of merging BHs, the validity of Einstein's General Relativity, models for dark energy, and detect a stochastic background of GW. The results obtained show that the galaxy-GW cross-correlation can provide useful information in the near future, while the detection of tensor perturbation effects on the LSS will require instruments with capabilities beyond the currently planned next generation of radio arrays. Nevertheless, any information from the combination of galaxy surveys with GW maps will help provide additional information for the newly born gravitational wave astronomy.

SKA GW working group

ask me to join if interested!

Tensor perturbations
Clustering

volume

$$\tilde{\delta}_{gT} = f_{\tilde{\chi}} h_{\|} + f'_{\tilde{\chi}} h'_{\|} + f \int \frac{d\chi}{\chi} h_{\|} + \tilde{f} \int \frac{d\chi}{\tilde{\chi}} h_{\|}$$
$$+ f' \int d\chi \, h'_{\|} + f_{\kappa} \nabla^2_{\Omega} \int d\chi \frac{\tilde{\chi} - \chi}{\chi \tilde{\chi}} h_{\|} + f_o \, h_{\|o}.$$

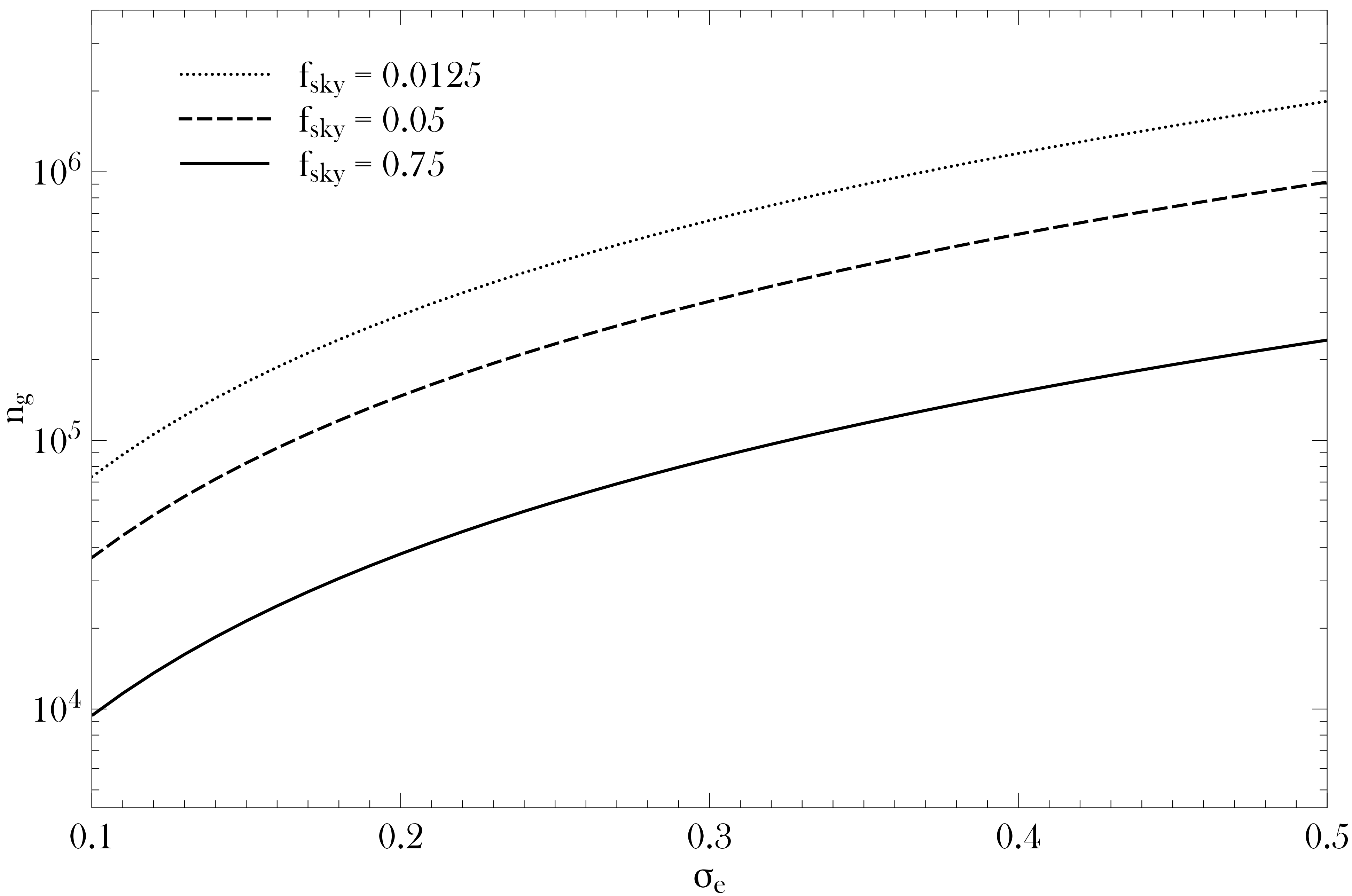
magnification

Tensor perturbations
Lensing

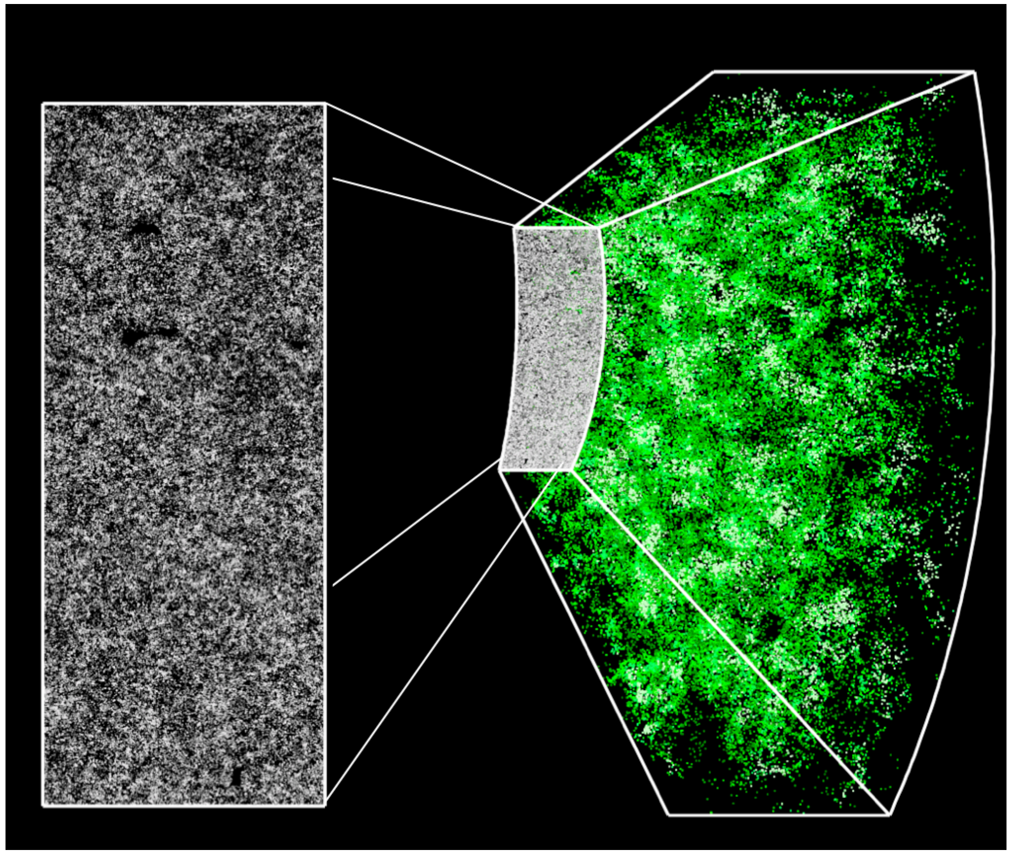
Tensor perturbations contribute to B-modes

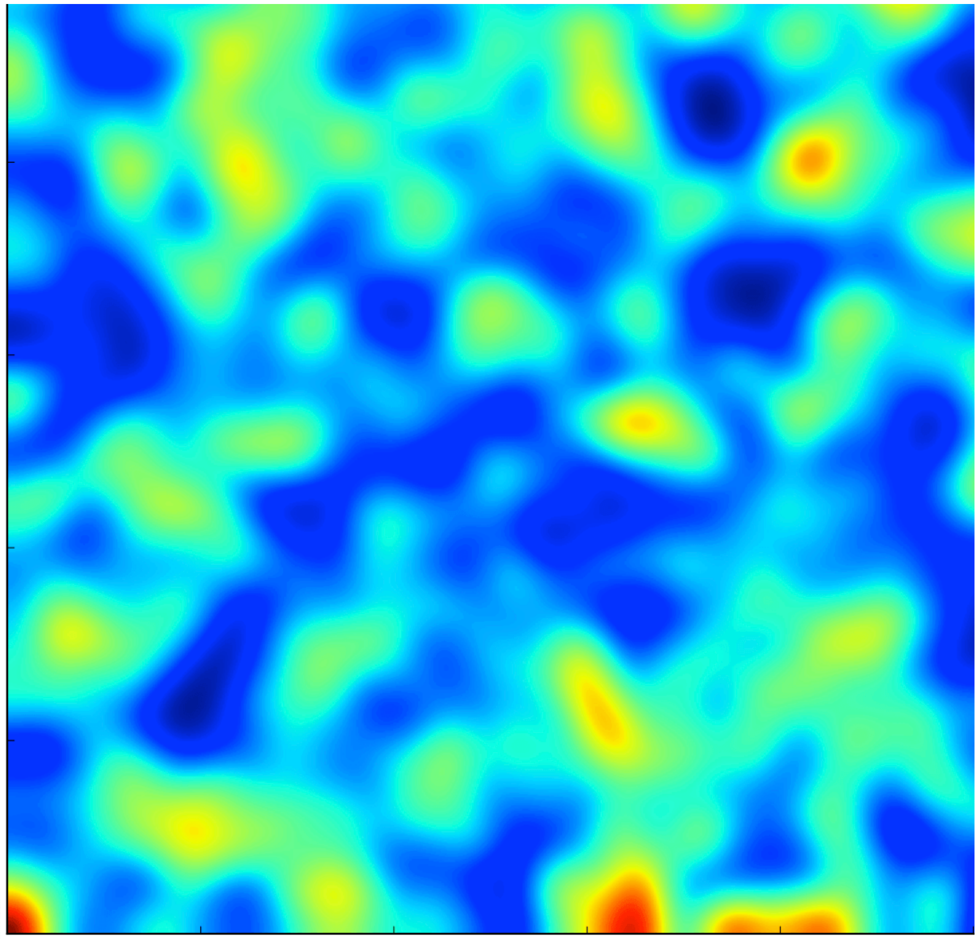
the curl-mode of the correlation of galaxy ellipticities can be used to detect a SGWB

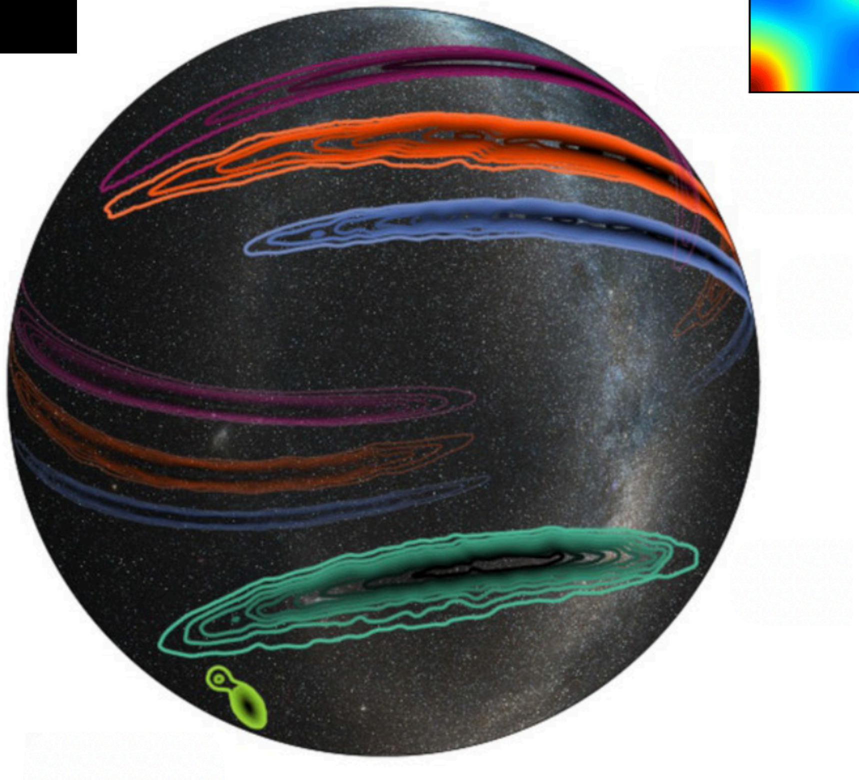
Tensor perturbations
Lensing



Multi-messenger cosmology

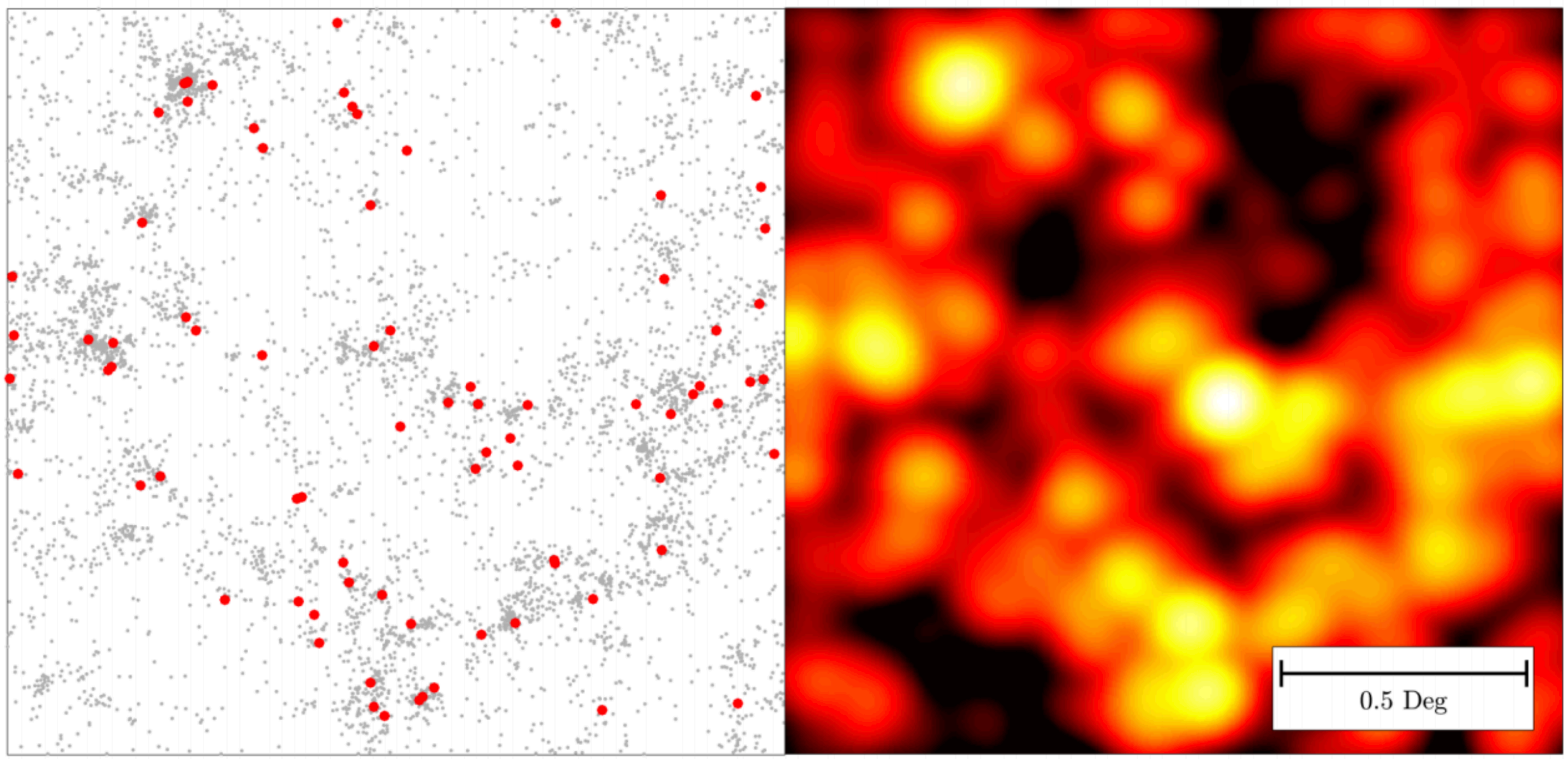






The future: intensity mapping

Galaxy surveys give detailed properties of brightest galaxies
Intensity maps give statistical properties of all galaxies



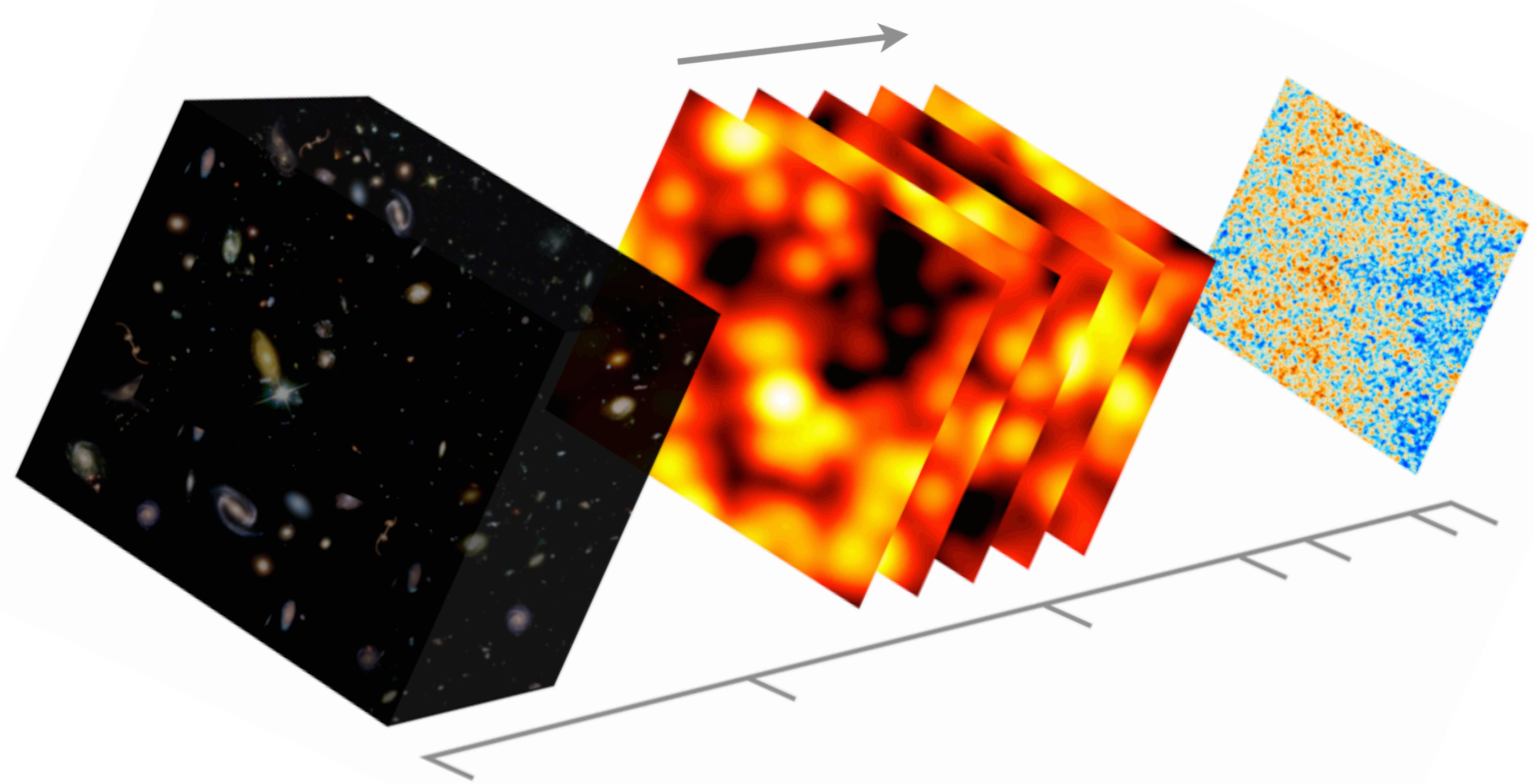
credit: Ely Kovetz

The future: intensity mapping

Large scales fast, small scales precisely

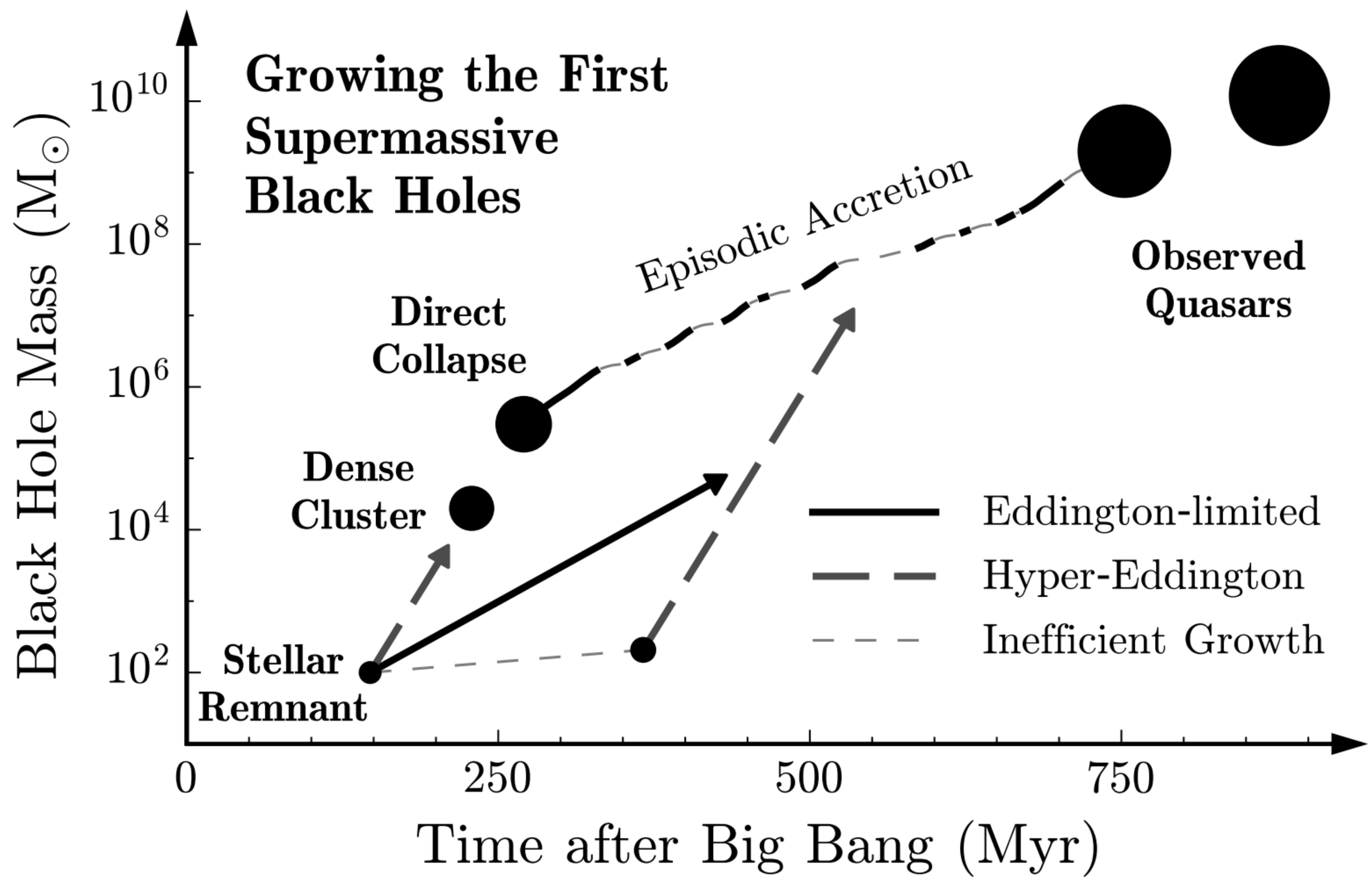
Potentially to extreme high redshift

Tomography



SMBH seeds

Too massive QSOs at high-z (observed)



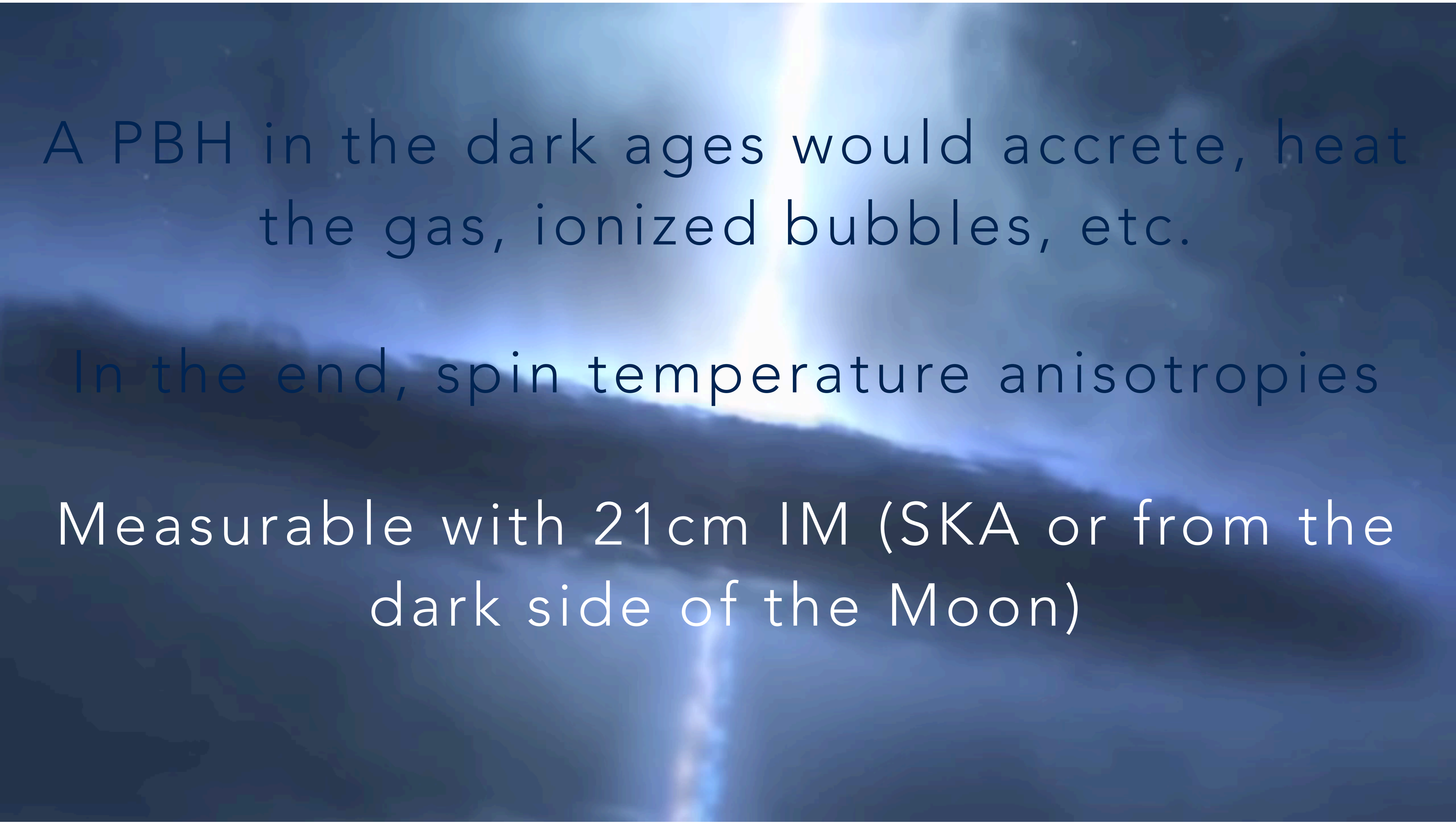
SMBH seeds

PBHs could be the explanation

A small (ΩPBH~1e-8) population of sufficiently massive PBHs (~1e3 — 1e4 Msun) Could provide seeds for SMBHs

But how to test it?

SMBH seeds

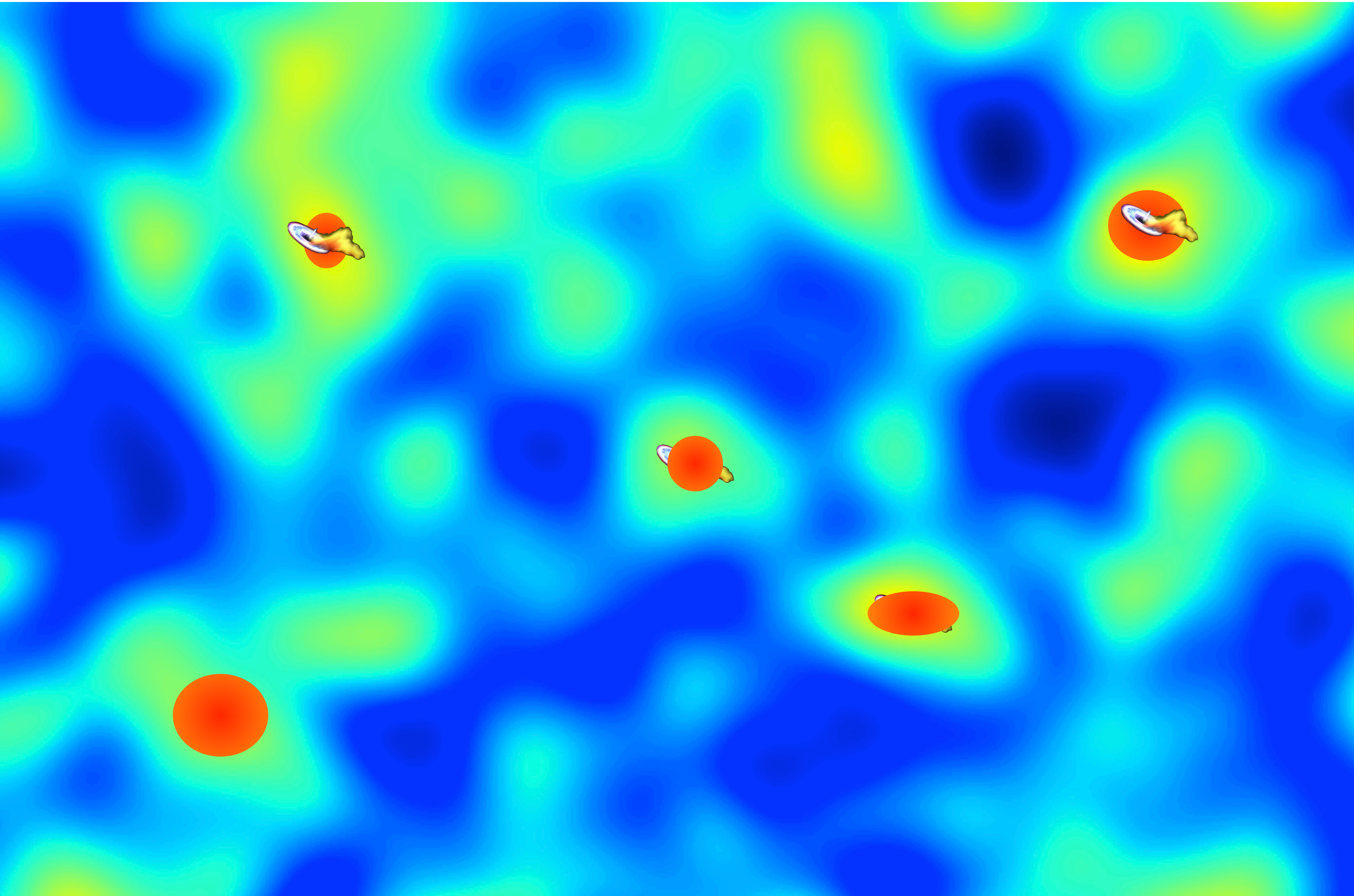


A PBH in the dark ages would accrete, heat the gas, ionized bubbles, etc.

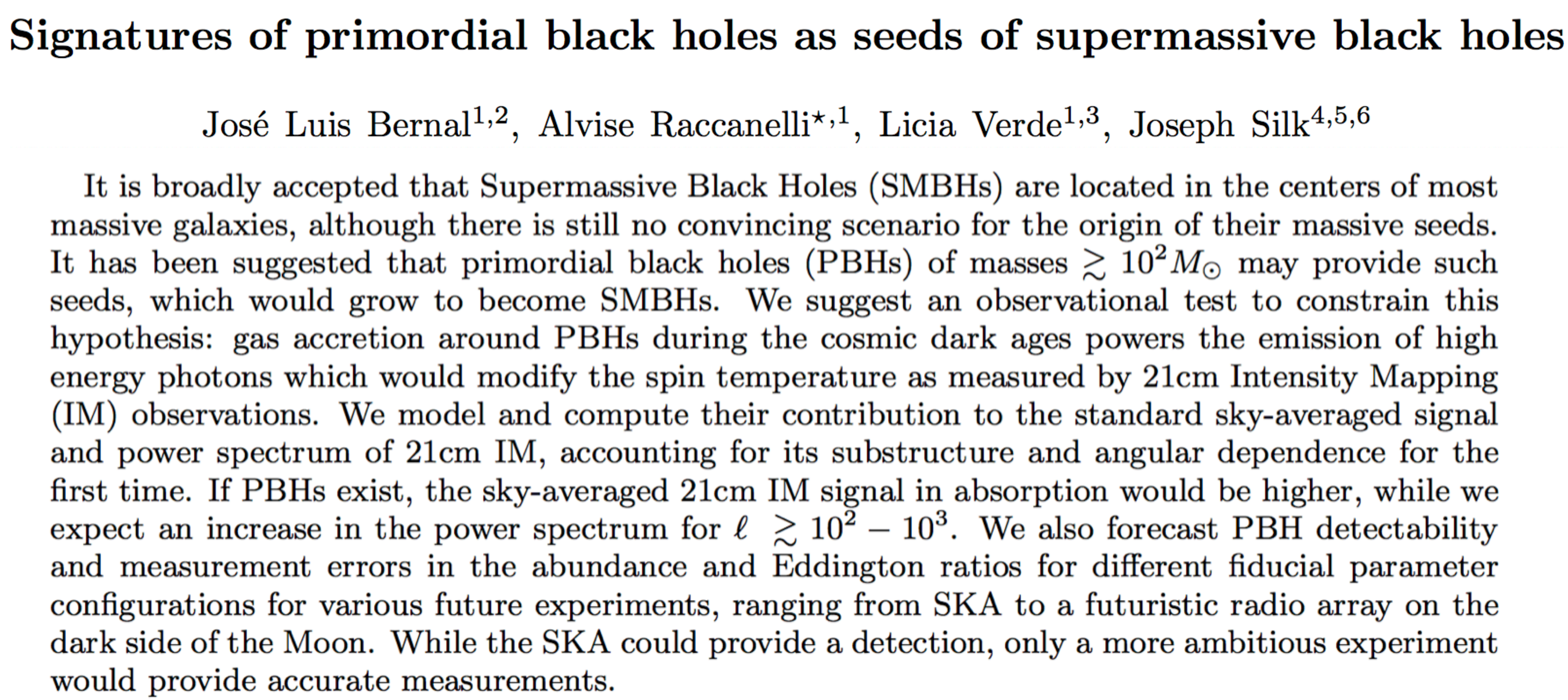
In the end, spin temperature anisotropies

Measurable with 21cm IM (SKA or from the dark side of the Moon)

SMBH seeds



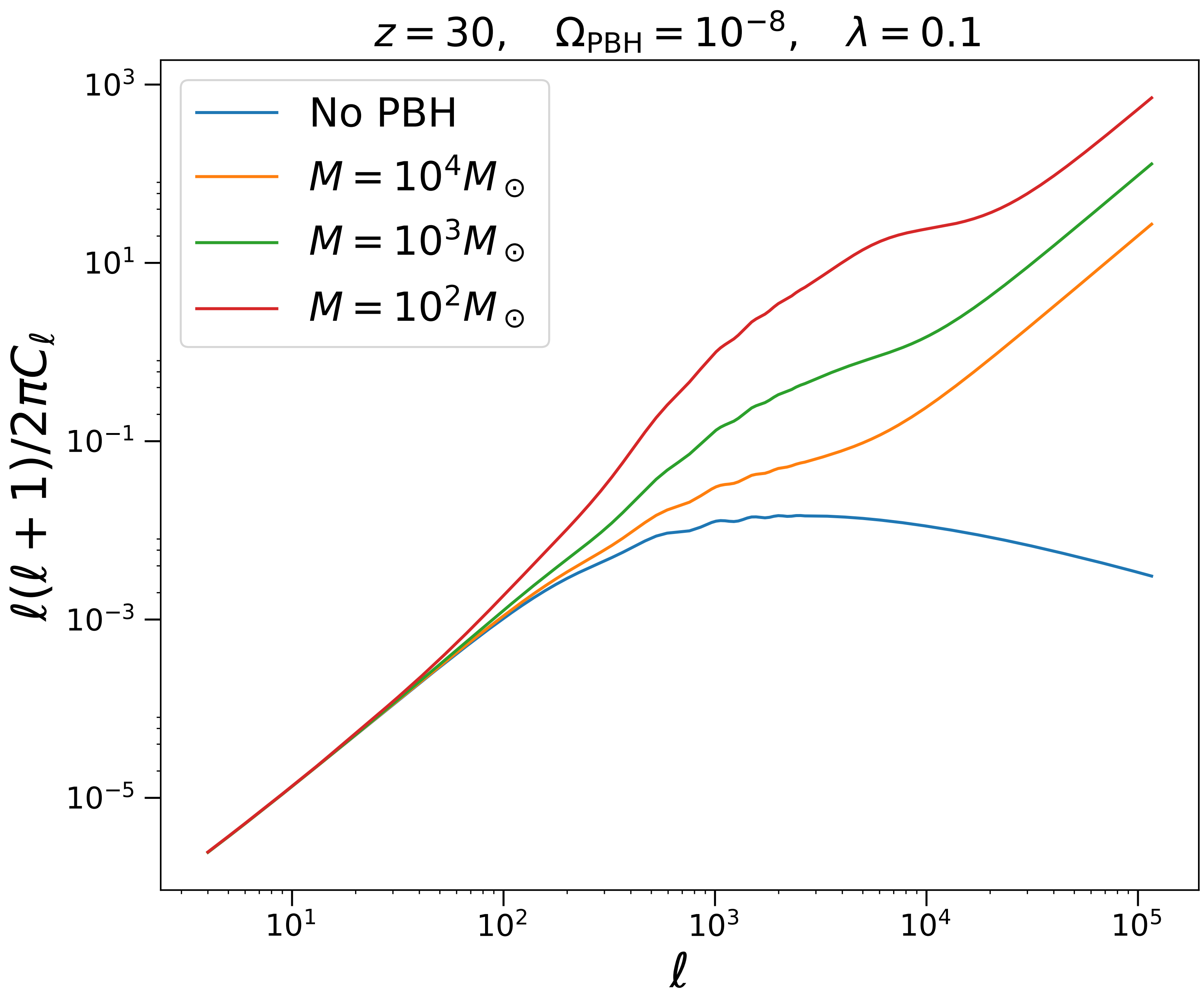
SMBH seeds


Signatures of primordial black holes as seeds of supermassive black holes

José Luis Bernal[1,2], Alvise Raccanelli[⋆,1], Licia Verde[1,3], Joseph Silk[4,5,6]

It is broadly accepted that Supermassive Black Holes (SMBHs) are located in the centers of most massive galaxies, although there is still no convincing scenario for the origin of their massive seeds. It has been suggested that primordial black holes (PBHs) of masses $\gtrsim 10^2 M_\odot$ may provide such seeds, which would grow to become SMBHs. We suggest an observational test to constrain this hypothesis: gas accretion around PBHs during the cosmic dark ages powers the emission of high energy photons which would modify the spin temperature as measured by 21cm Intensity Mapping (IM) observations. We model and compute their contribution to the standard sky-averaged signal and power spectrum of 21cm IM, accounting for its substructure and angular dependence for the first time. If PBHs exist, the sky-averaged 21cm IM signal in absorption would be higher, while we expect an increase in the power spectrum for $\ell \gtrsim 10^2 - 10^3$. We also forecast PBH detectability and measurement errors in the abundance and Eddington ratios for different fiducial parameter configurations for various future experiments, ranging from SKA to a futuristic radio array on the dark side of the Moon. While the SKA could provide a detection, only a more ambitious experiment would provide accurate measurements.

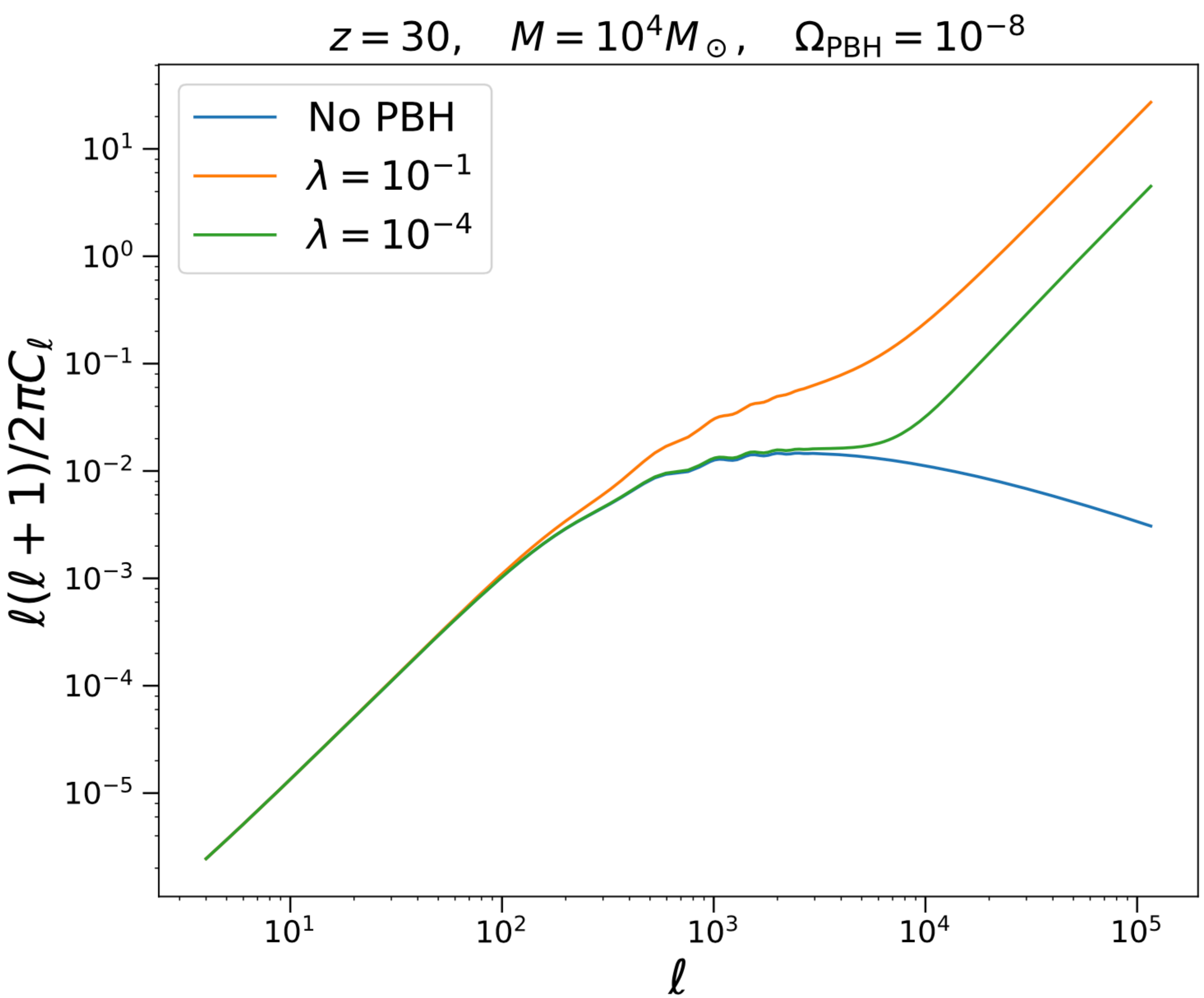
SMBH seeds



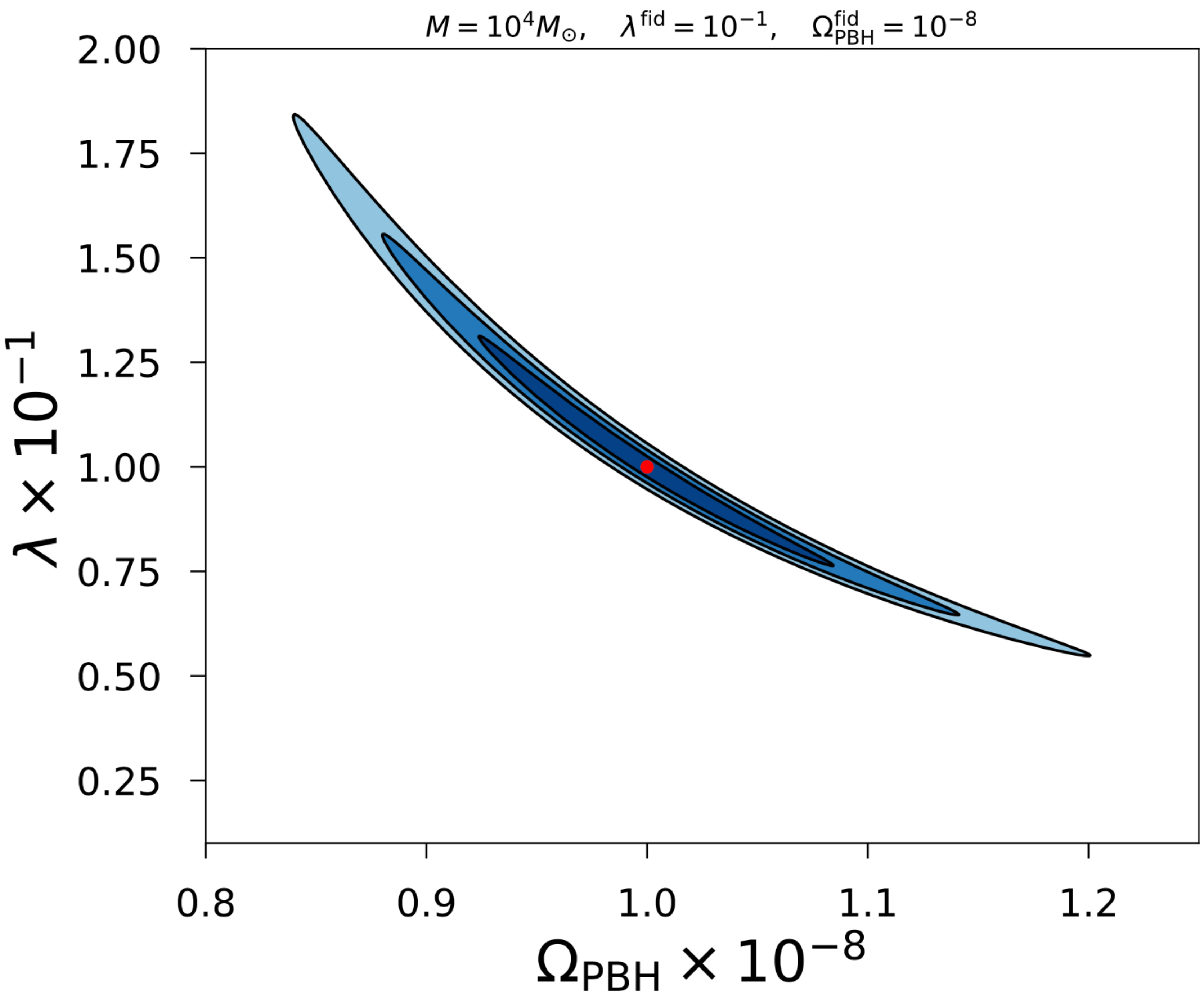
$z = 30, \quad \Omega_{\rm PBH} = 10^{-8}, \quad \lambda = 0.1$
No PBH
$M = 10^4 M_\odot$
$M = 10^3 M_\odot$
$M = 10^2 M_\odot$
$\ell(\ell+1)/2\pi C_\ell$
10^3
10^1
10^{-1}
10^{-3}
10^{-5}
10^1
10^2
10^3
10^4
10^5
ℓ

BH accretion

We can study accretion mechanisms and efficiency



SMBH seeds


$M = 10^4 M_\odot, \quad \lambda^{\rm fid} = 10^{-1}, \quad \Omega_{\rm PBH}^{\rm fid} = 10^{-8}$
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
$\lambda \times 10^{-1}$
0.8
0.9
1.0
1.1
1.2
$\Omega_{\rm PBH} \times 10^{-8}$

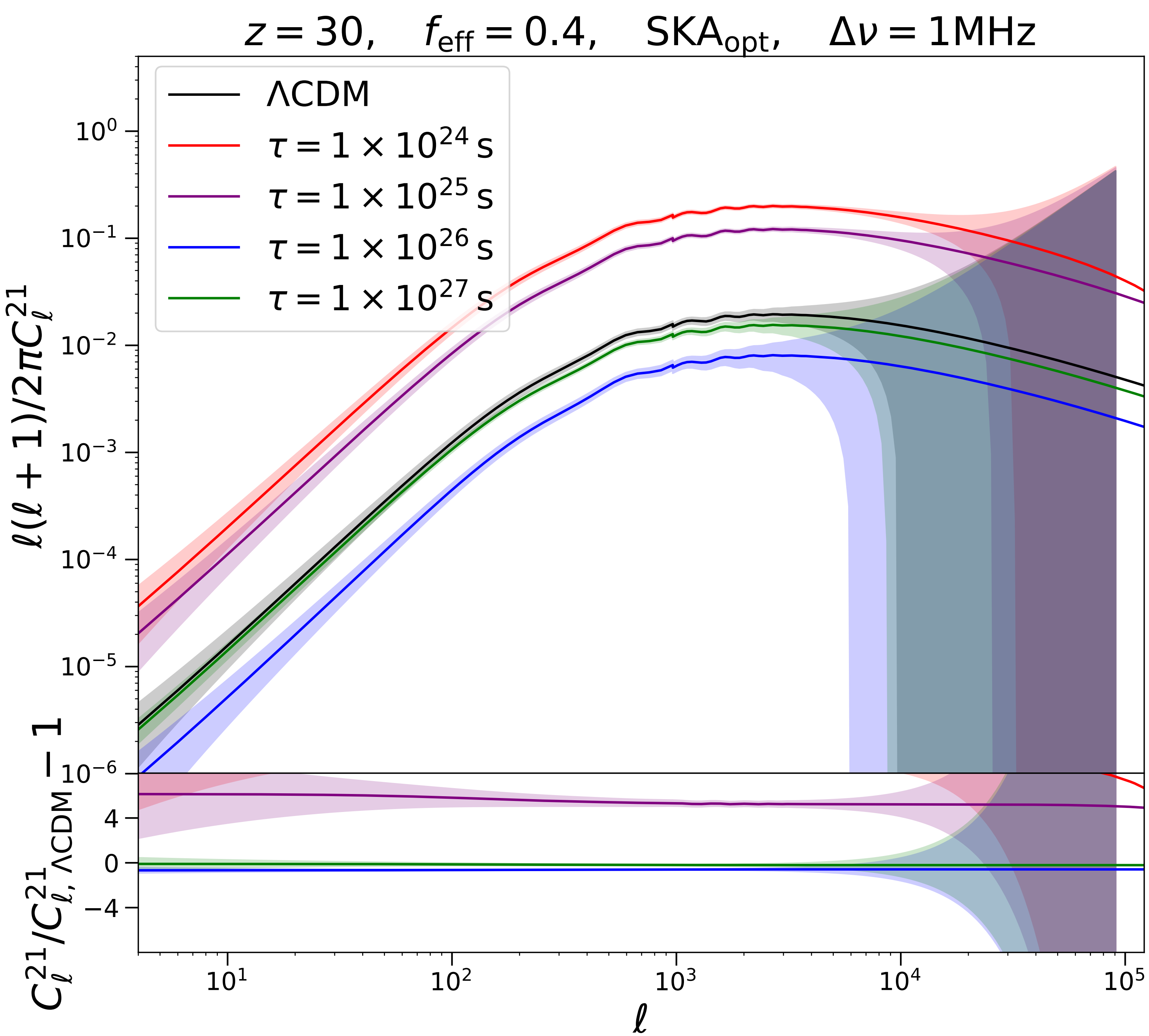
Multi-messenger

In the dark ages

If they are not BHs

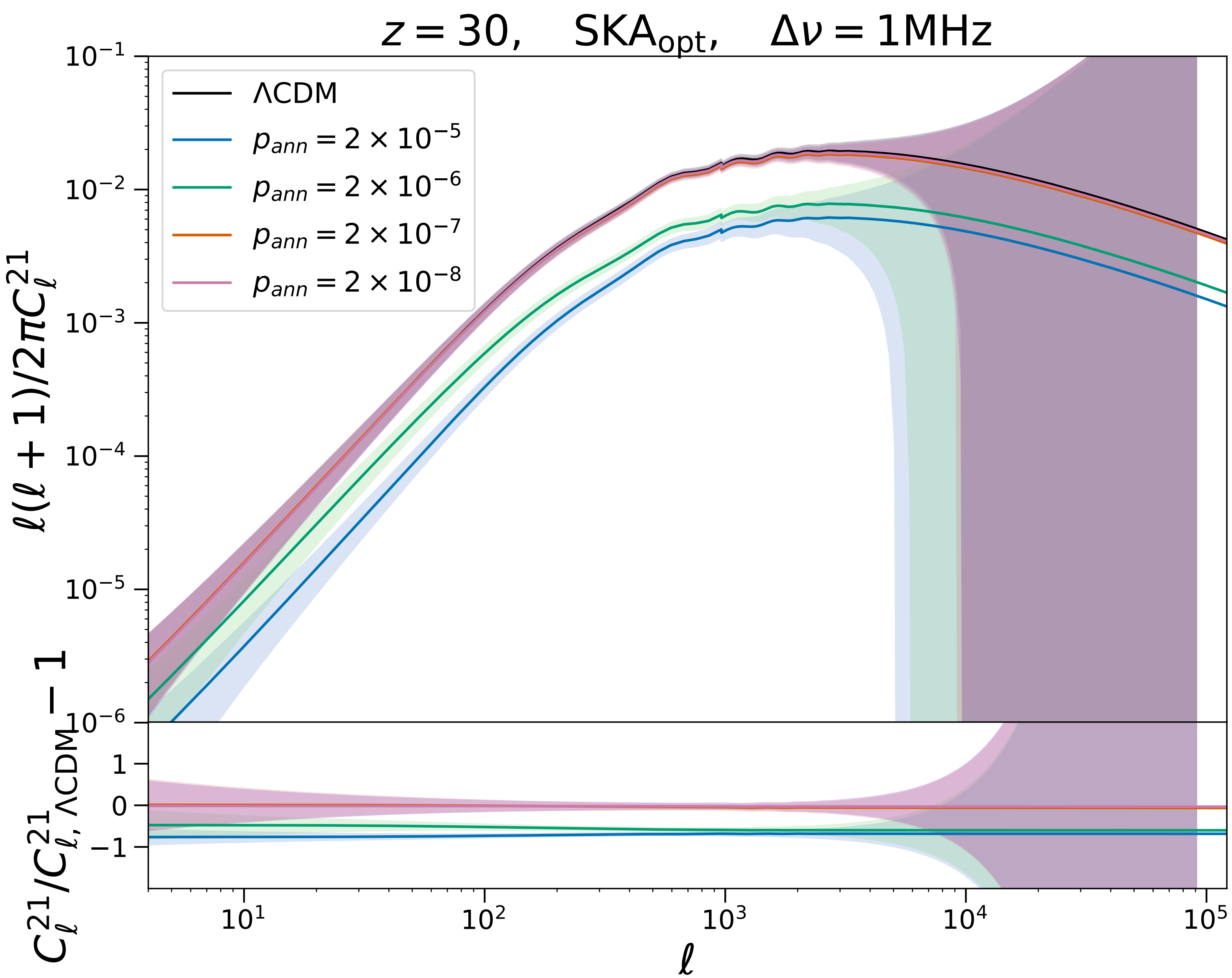
(no gravitational waves detected,
PBHs ruled out from other tests, ...)

Multi-messenger: DM decay



It could be dark matter decay

Multi-messenger: DM ann



or annihilation

Multi-messenger: DM decay

Dark matter in the dark ages

Katie Short[a,b] **José Luis Bernal**[a,b] **Alvise Raccanelli**[a] **Jens Chluba**[d] **Licia Verde**[a,c]

soon...

Multi-Messenger

What can we do if we pair

Multi-messenger future: GW x LSS

Determining the progenitors of merging black hole binaries

Alvise Raccanelli, Simeon Bird, Ilias Cholis, Ely D. Kovetz, and Julian B. Muñoz
Department of Physics & Astronomy,
Johns Hopkins University, 3400 N. Charles St.,
Baltimore, MD 21218, USA

We propose a method for determining the progenitors of black hole (BH) mergers observed via their gravitational wave (GW) signal. We argue that measurements of the cross-correlation of the GW events with overlapping galaxy catalogs can determine if BH mergers trace the stellar mass of the Universe, as would be expected from mergers of the endpoints of stellar evolution. If on the other hand the BHs are of primordial origin, as has been recently suggested, their merging would be preferentially hosted by lower biased objects, and thus have a lower cross-correlation with star-forming galaxies. Here we forecast the expected precision of the cross-correlation measurement for current and future GW detectors such as LIGO and the Einstein Telescope. We then predict how well these instruments can distinguish the model that identifies high-mass BH-BH mergers as the merger of primordial black holes that constitute the dark matter in the Universe from more traditional astrophysical sources.

GW×LSS: Chasing the Progenitors of Merging Binary Black Holes

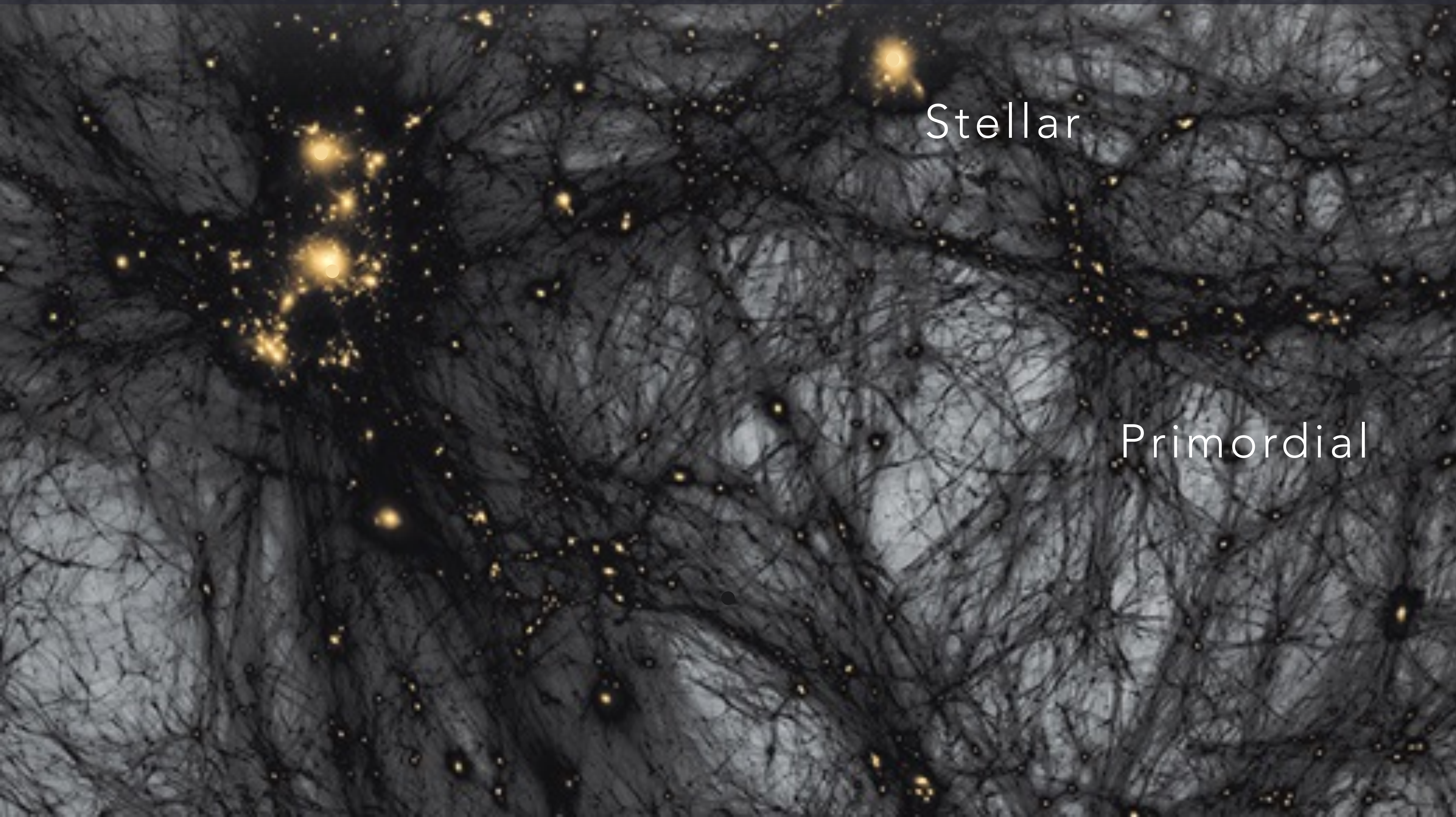
Giulio Scelfo[a,b] Nicola Bellomo[b,c] Alvise Raccanelli[b] Sabino Matarrese[a,d,e,f] Licia Verde[b,g]

Abstract. Are the stellar-mass merging binary black holes, recently detected by their gravitational wave signal, of stellar or primordial origin? Answering this question will have profound implications for our understanding of the Universe, including the nature of dark matter, the early Universe and stellar evolution. We build on the idea that the clustering properties of merging binary black holes can provide information about binary formation mechanisms and origin. The cross-correlation of galaxy with gravitational wave catalogues carries information about whether black hole mergers trace more closely the distribution of dark matter – indicative of primordial origin – or that of stars harboured in luminous and massive galaxies – indicative of a stellar origin. We forecast the detectability of such signal for several forthcoming and future gravitational wave interferometers and galaxy surveys, including, for the first time in such analyses, an accurate modelling for the different merger rates, lensing magnification and other general relativistic effects. Our results show that forthcoming experiments could allow us to test most of the parameter space of the still viable models investigated, and shed more light on the issue of binary black hole origin and evolution.

Binary formation, evolution, and merging

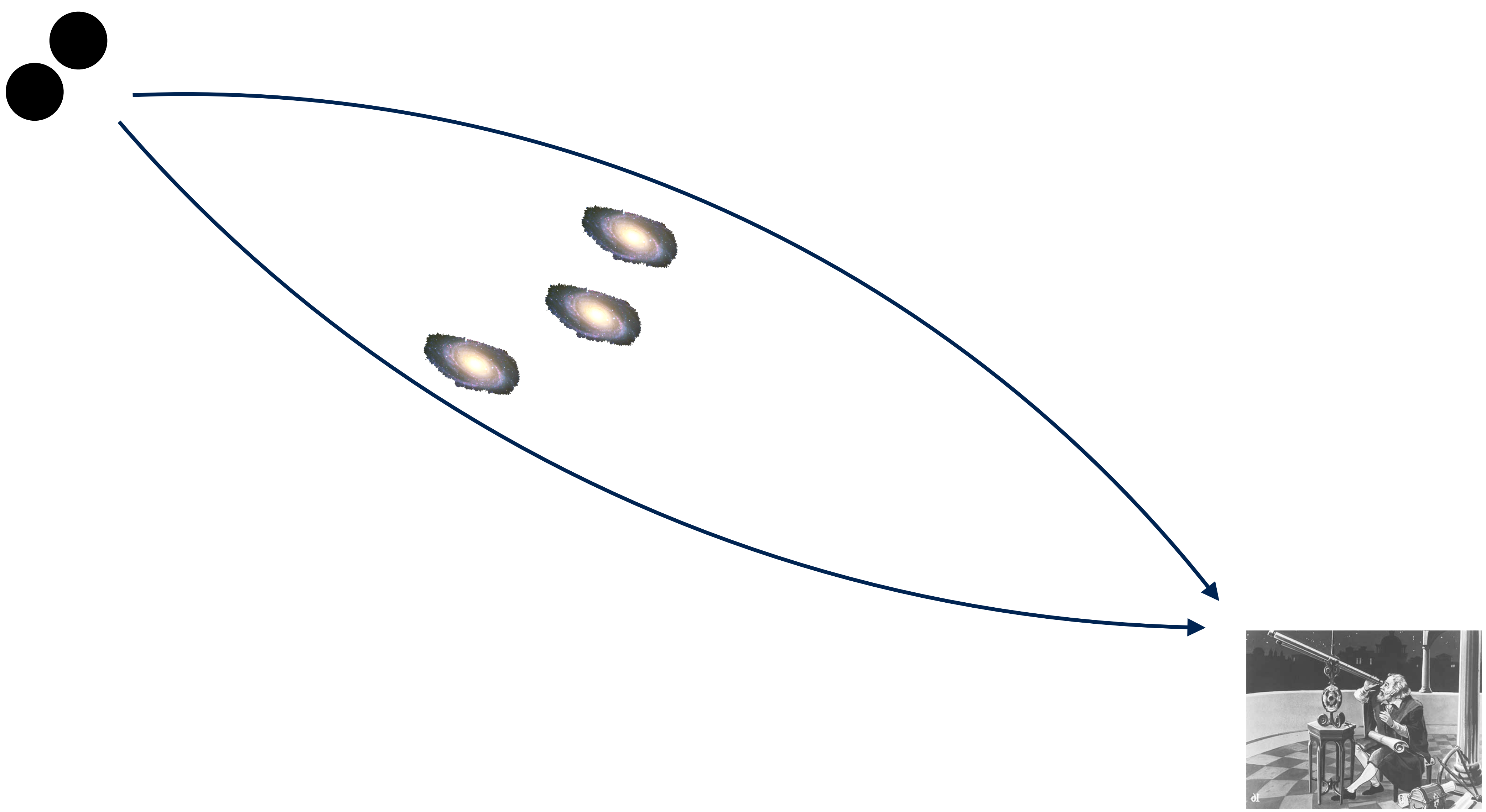
(open debate, simulations needed)

Binary black hole merger locations

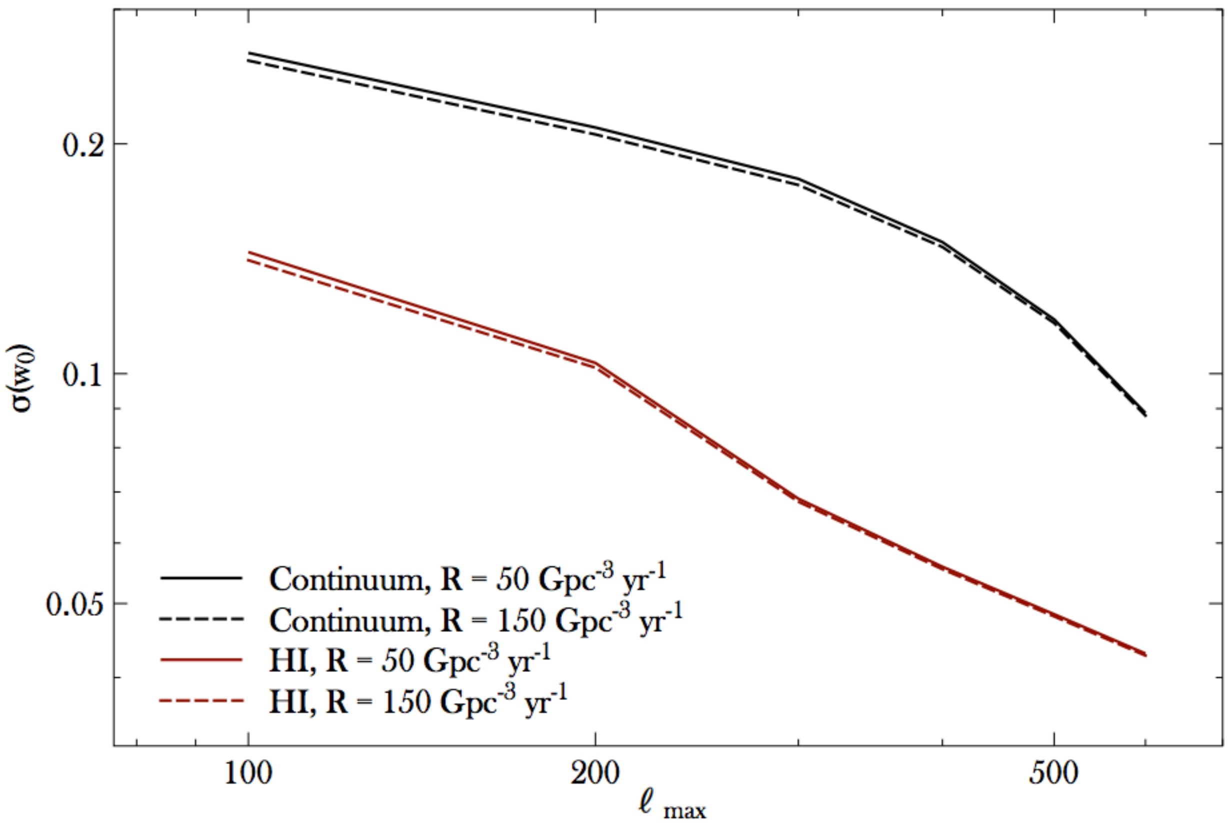


Multi-Messenger: GW x LSS

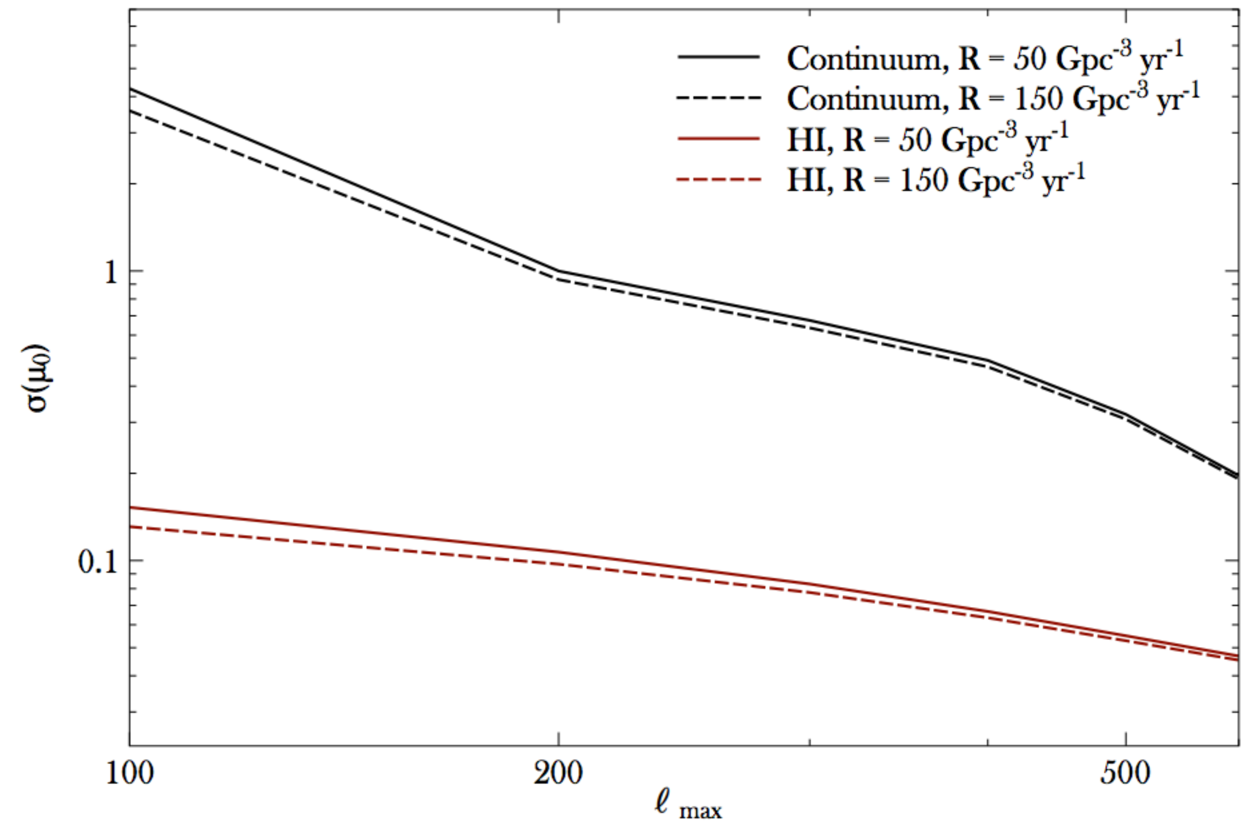
Lensing of GWs



Multi-Messenger: GW x LSS



Tests of dark energy parameters



Tests of modified gravity parameters

Could do better than BOSS+Planck! + different systematics

One more thing

Radio astronomy from the Moon

Lunar Radio Array

Can access the cosmic dark ages

No astrophysical complications

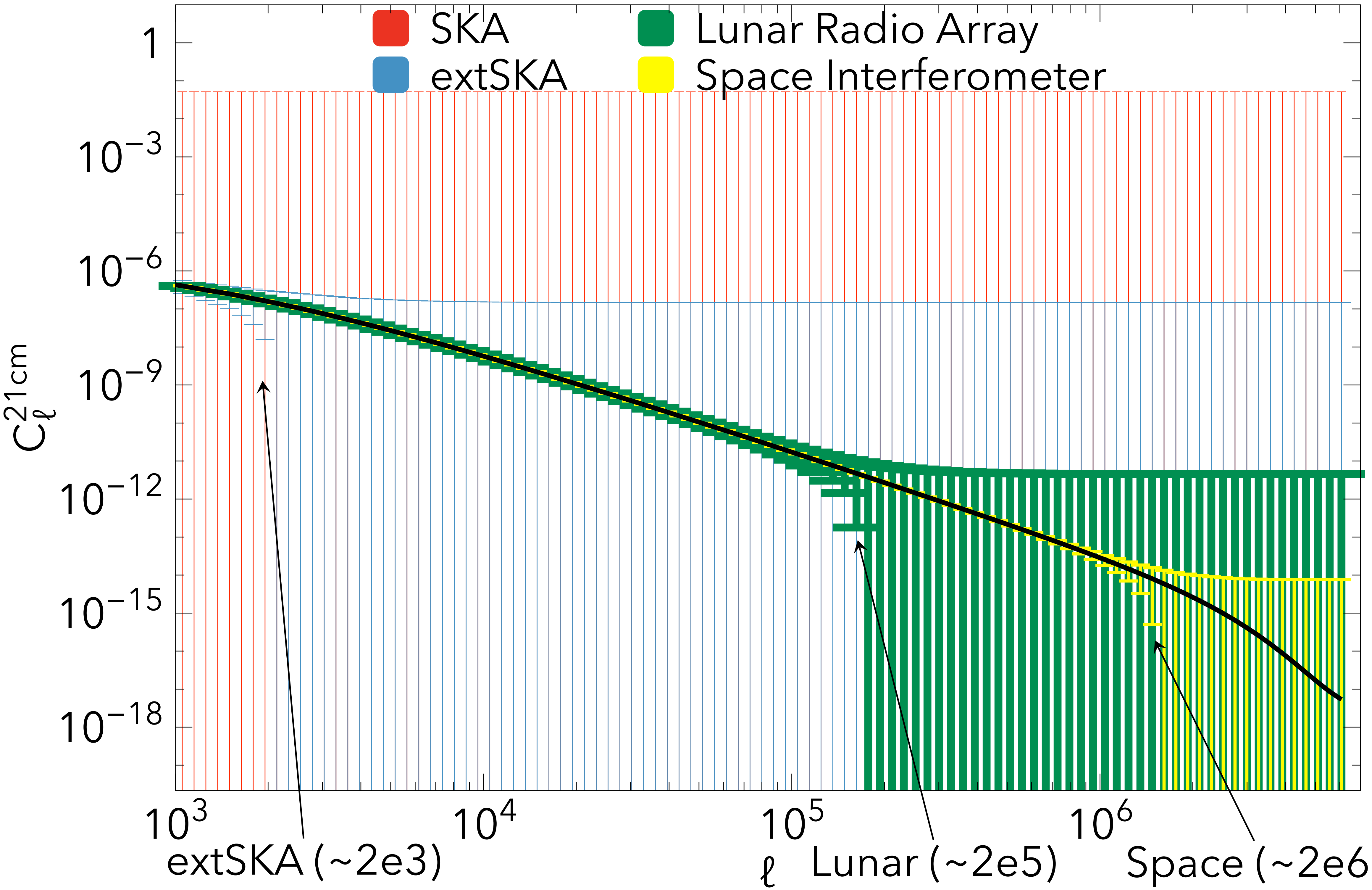
Linear physics

No Silk damping

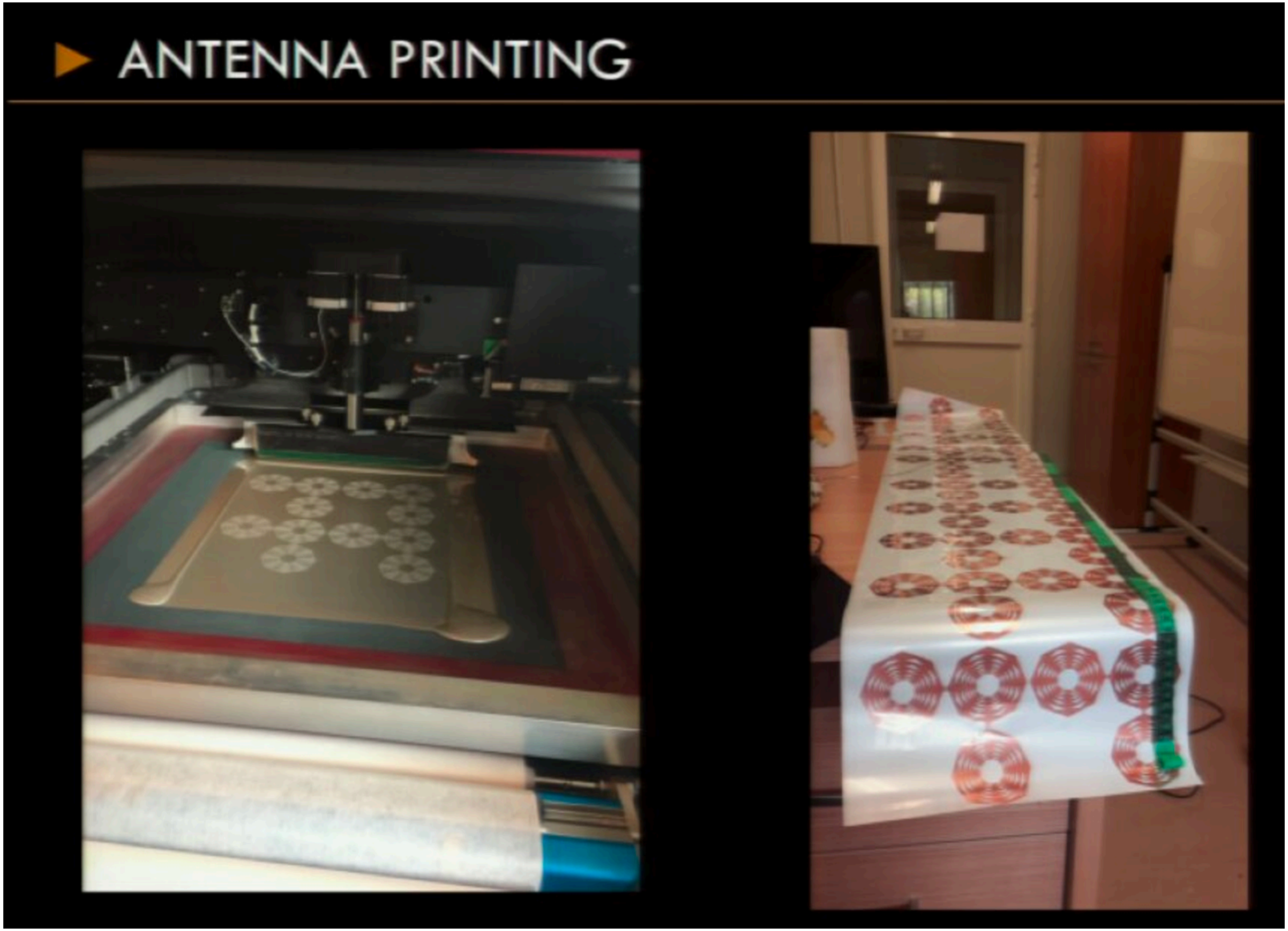
Hence: can probe extremely low scales

(i.e., test DM models, inflationary features)

Matter power spectrum



Moon telescope



Moon telescope

SOME CHALLENGES

- How do we power a large number of antennas on the far-side of the moon?
  - Currently the low-frequency aperture array in SKA is projected to consume ~1.6MW just to collect the data
- How do we transmit the data rates back to earth for processing or do we process the antenna data on the moon?
  - Currently each antenna is producing ≈20Gbit/s so some sort of processing is required in order to decrease the data rate beamed back to earth, but again power is another limiting factor in SKA (so much so, that it is no longer planned to happen on site)


esa
NVM
Moon
KICT
Brew

Perspectives

What can we do with multi-messenger?

21cm: N(z) — SMBH seeds - BH accretion
Galaxy surveys: MG — Clustering — QG
Radio continuum: SGWB
CTA: Decaying processes

ありがとうございます

Thank you