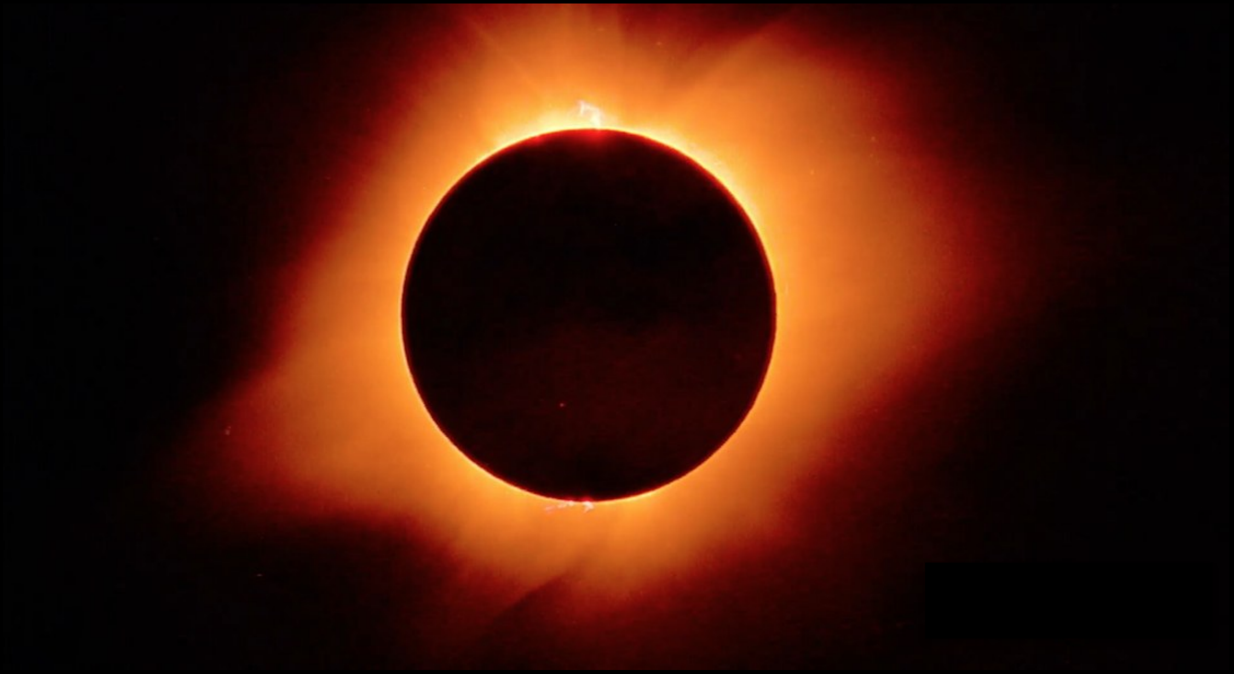
Measuring the dark universe



Luca Amendola
University of Heidelberg

In search of the dark

Searching with new probes

Searching in new domains

Or: a short overview of what
I have been doing in the last couple
years beside Euclid…

In search of the dark

Searching with new probes

21cm

GWs

Searching in new domains

PBH

Searching with new probes

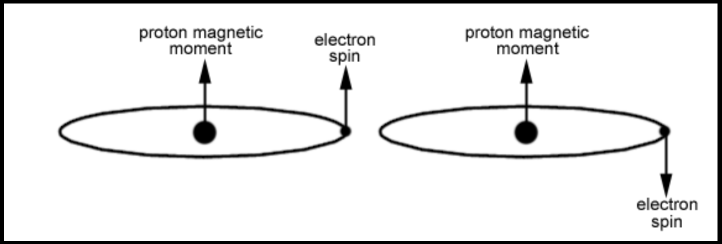
- So far, cosmology has been essentially CMB+LSS+WL+SNIa+Clusters
- Insufficient to break all the degeneracies and probe intermediate redshifts
- New probes: 21cm, GWs, polarization in CMB, new distance indicators, redshift drift,…

Observing Hydrogen

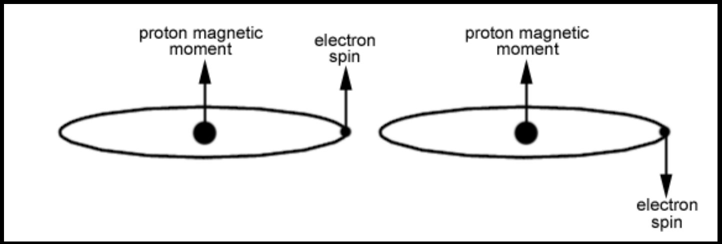
H_2 (molecular hydrogen) difficult to observe (no optical/radio lines, no dipole, etc)

HII (ionized hydrogen) free-free (Bremsstrahlung) + free-bound (recombination)

HI (atomic hydrogen) hyperfine spin-flip at 21cm



Observing HI



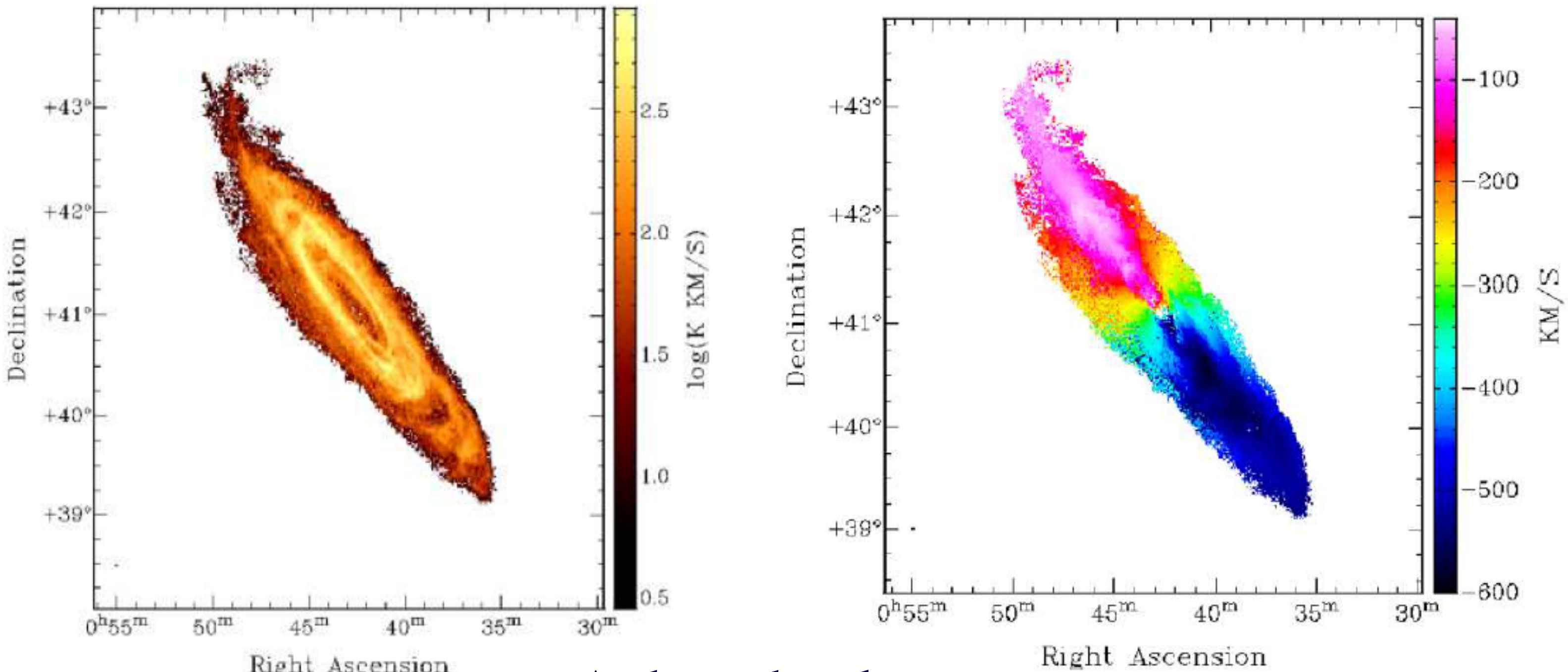
HI hyperfine spin-flip at 21cm, not absorbed by dust:
we can measure redshift in galaxies and before/during reionization!

redshift	frequency (CMB=160 MHz)
0	1420 MHz
10	130 MHz
20	70Mhz

Observing HI

HI hyperfine spin-flip at 21cm + not absorbed by dust

we can measure galaxy Doppler redshift!



Andromeda galaxy

Chemin et al. 2009

Intensity Mapping

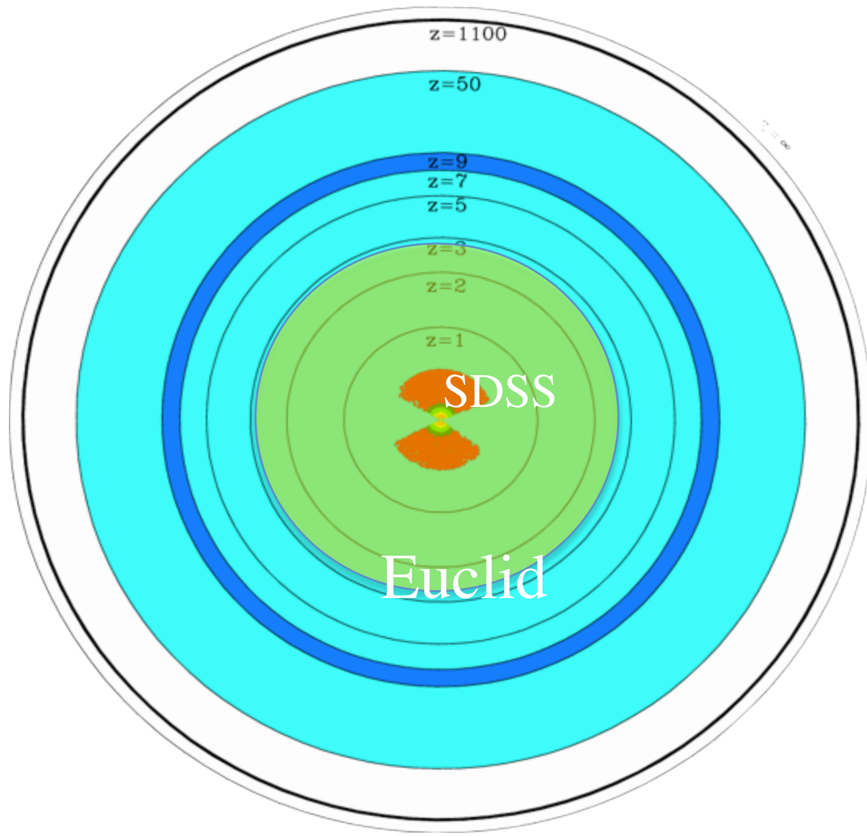
HI hyperfine spin-flip at 21cm + not absorbed by dust
we can measure redshift before reionization!

Intensity Mapping
(Chang et al 2008,
Wyithe & Loeb 2008):
HI from large-scale structure
rather than galaxies

up to z=50:
Epoch of Reionization z=6-10

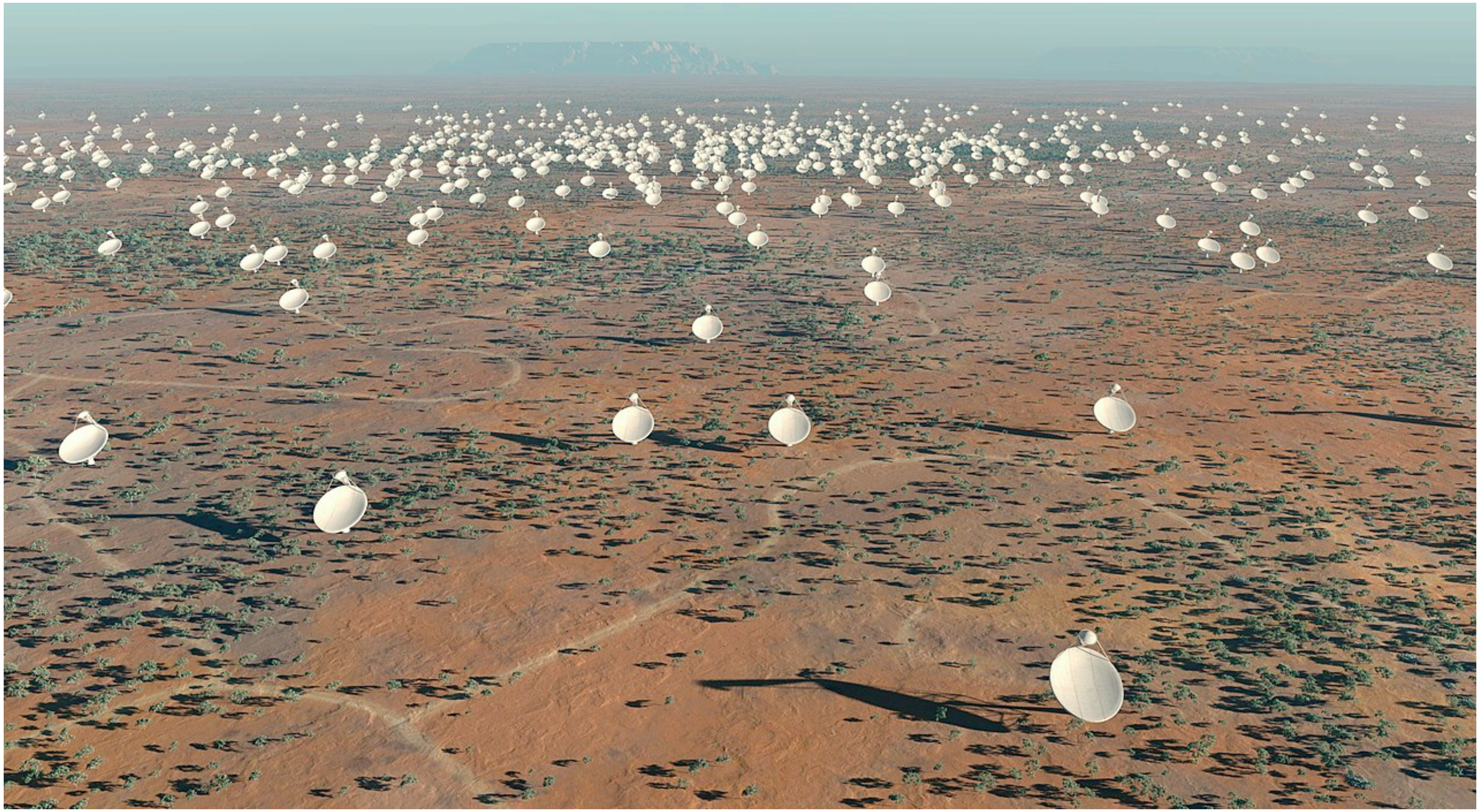
Experiments: GMRT, LOFAR, MWA, PAPER, 21CMA, GBT, CRT, CHIME

Just like CMB, but in 3D!



Tegmark & Zaldarriaga 2008

Square Kilometer Array



1 sq. km area radio-telescope

Intensity Mapping

Estimate of the expected 21cm flux (21cmFAST*)

- Linear perturbations are evolved with Zeldovich approx at z>>1
- regions above a certain threshold are "ionized" (so no HI)
- 21cm emission from HI relative to CMB photons

spin - CMB temperature

$$\delta T_{\mathrm{b}}(\mathbf{x}, z) = \frac{T_{\mathrm{S}} - T_{\gamma}}{1+z}\left(1 - e^{-\tau_{\nu 0}}\right)$$

reionization parameters:

$$R_{\mathrm{mfp}} = 20\,\mathrm{Mpc},\ T_{\mathrm{vir}} = 3 \times 10^4\,\mathrm{K},\ \zeta = 20,$$

mean free path, halo virial temperature, ionization efficiency

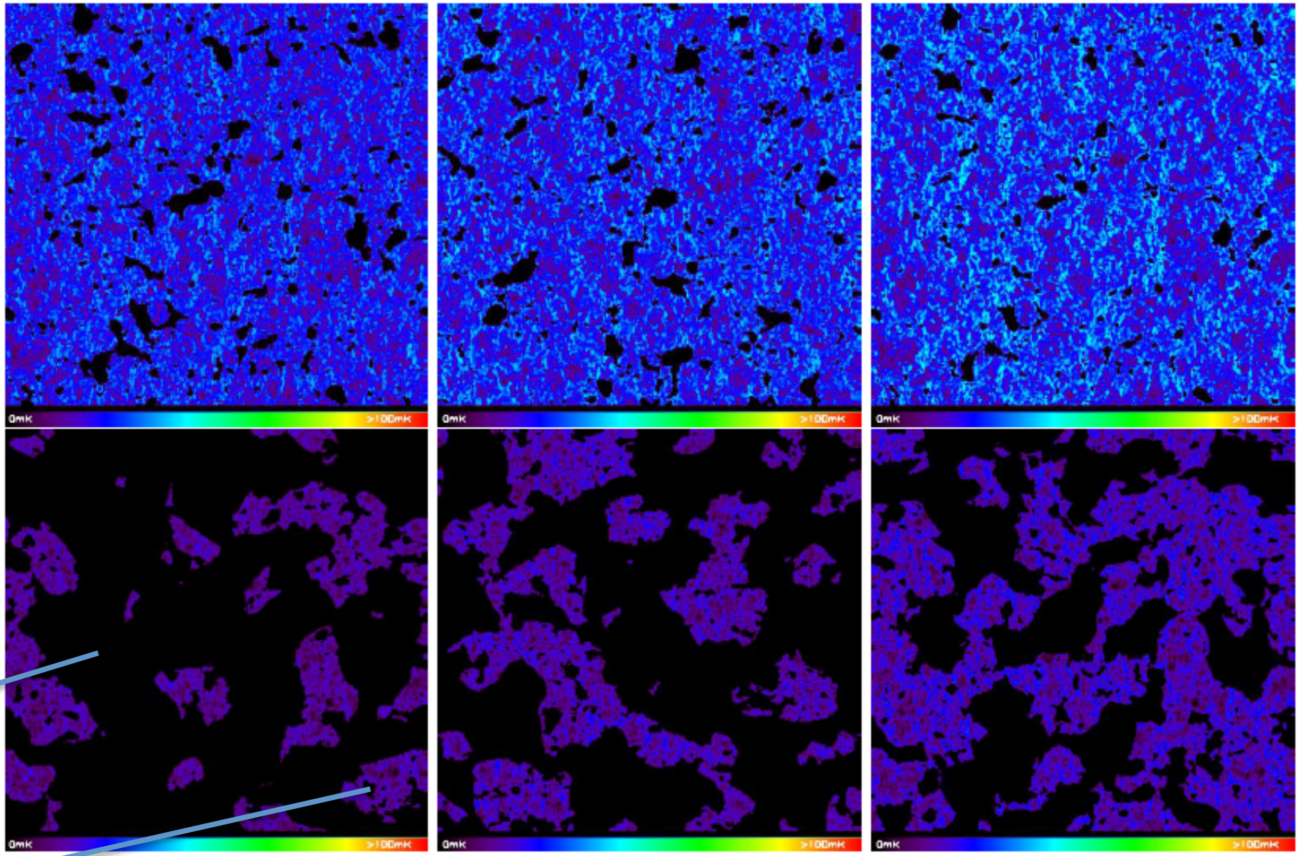
* github.com/andreimesinger/21cmFAST

Intensity Mapping

Y = 1.01 Y = 1 Y = 0.99

z=10

z=7



ionized

21cm

Heneka and L.A. 2018 1805.03629

Intensity Mapping

We consider wCDM plus a
modified gravity parameter **Y**
assumed constant within the relevant epochs

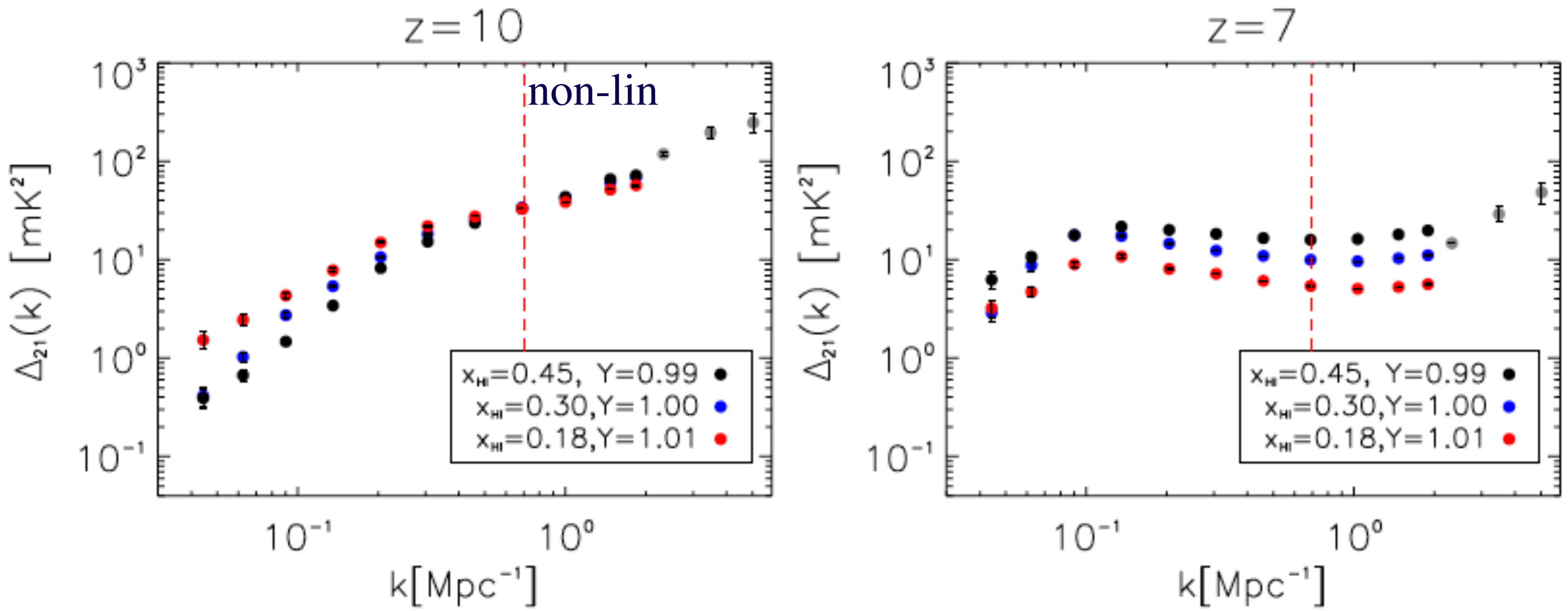
$$Y\left(z,k\right)=-\frac{2k^{2}\Psi}{3\left(aH\right)^{2}\Omega_{\mathrm{m}}\delta_{\mathrm{m}}}.$$

This affects the linear matter perturbation equation

$$\delta_{\mathrm{m}}''+\left(2+\frac{E'}{E}\right)\delta_{\mathrm{m}}'=\frac{3}{2}\frac{\delta_{\mathrm{m}}}{a^{3}E^{2}}\Omega_{\mathrm{m}}Y,$$

21cm power spectrum

Forecasts for SKA 1



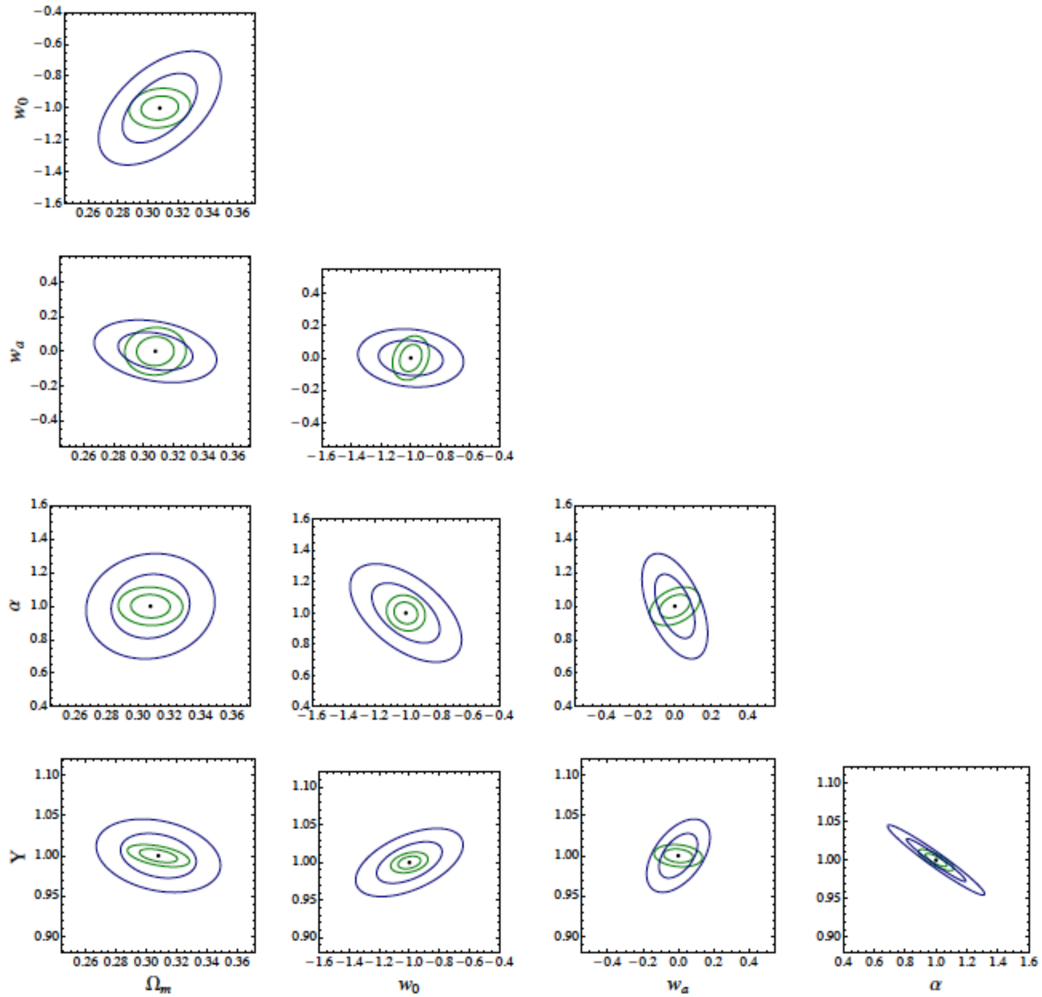
21cm forecasts

Forecasts for SKA 1,
z=6 to z=11

Parameters

$$\Omega_{\mathrm{m},0}, w_0, w_{\mathrm{a}}, Y, \alpha$$

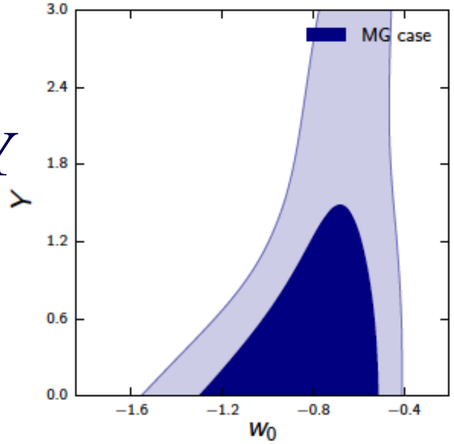
$$\alpha = \delta'_{in}/\delta_{in}$$



21cm forecasts

Current data, z=0 to z=1

Y



Taddei, Martinelli, L.A. et al. 1610.01059

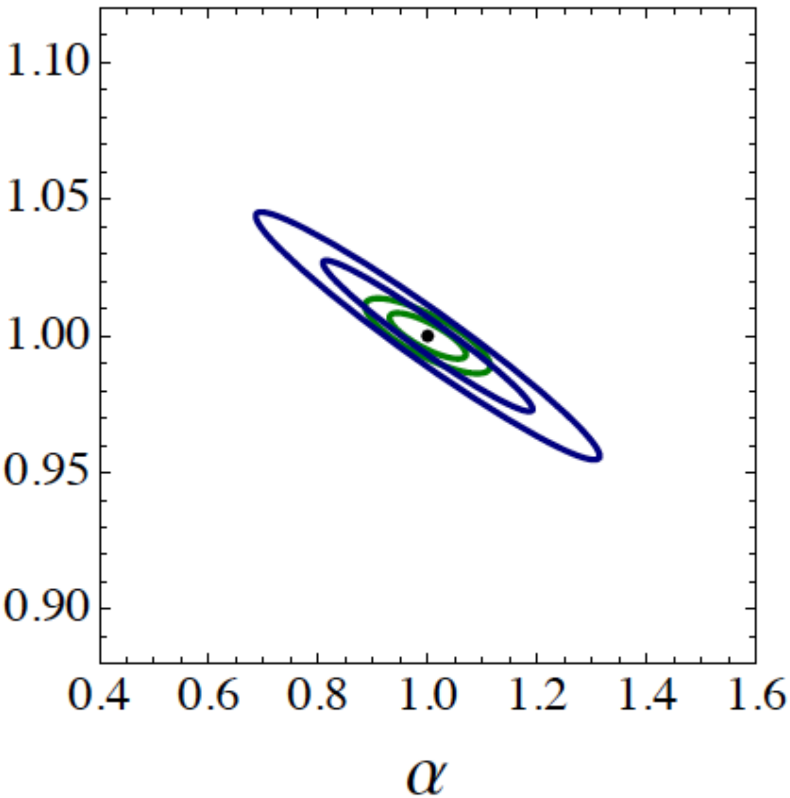
Parameters

$$\Omega_{\mathrm{m},0}, w_0, w_{\mathrm{a}}, Y, \alpha$$

$$\alpha = \delta'_{in}/\delta_{in}$$

Forecasts for SKA 1, z=6 to z=11

Y



Heneka and L.A. 2018 1805.03629

21cm forecasts

	$\Omega_{\mathrm{m},0}$	w_0	w_{a}	Y	α	R_{mfp} [Mpc]	T_{vir} [K]	ζ
fiducial	0.308	-1.0	0.0	1.0	1.0	20	3×10^4	20
1σ error	0.008	0.05	0.06	0.006	0.06	-	-	-
1σ error +'w'	0.016	0.144	0.072	0.018	0.126	-	-	-
1σ error	0.022	0.023	0.024	0.013	0.119	2.0	31.7	2.8
1σ error +'w'	0.015	0.202	0.297	0.016	0.103	1.3	31.8	2.6
1σ error + k_{shot}	0.075	0.260	0.443	0.039	0.341	-	-	-
1σ error + k_{lin}	0.307	0.841	0.548	0.116	0.879	-	-	-

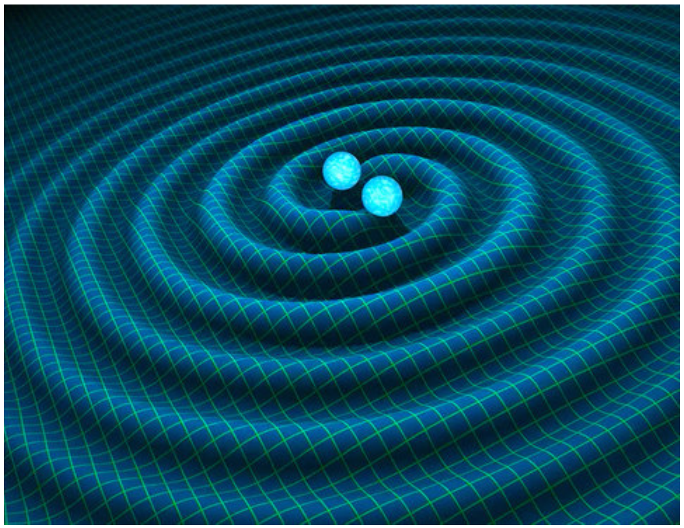
21cm forecasts

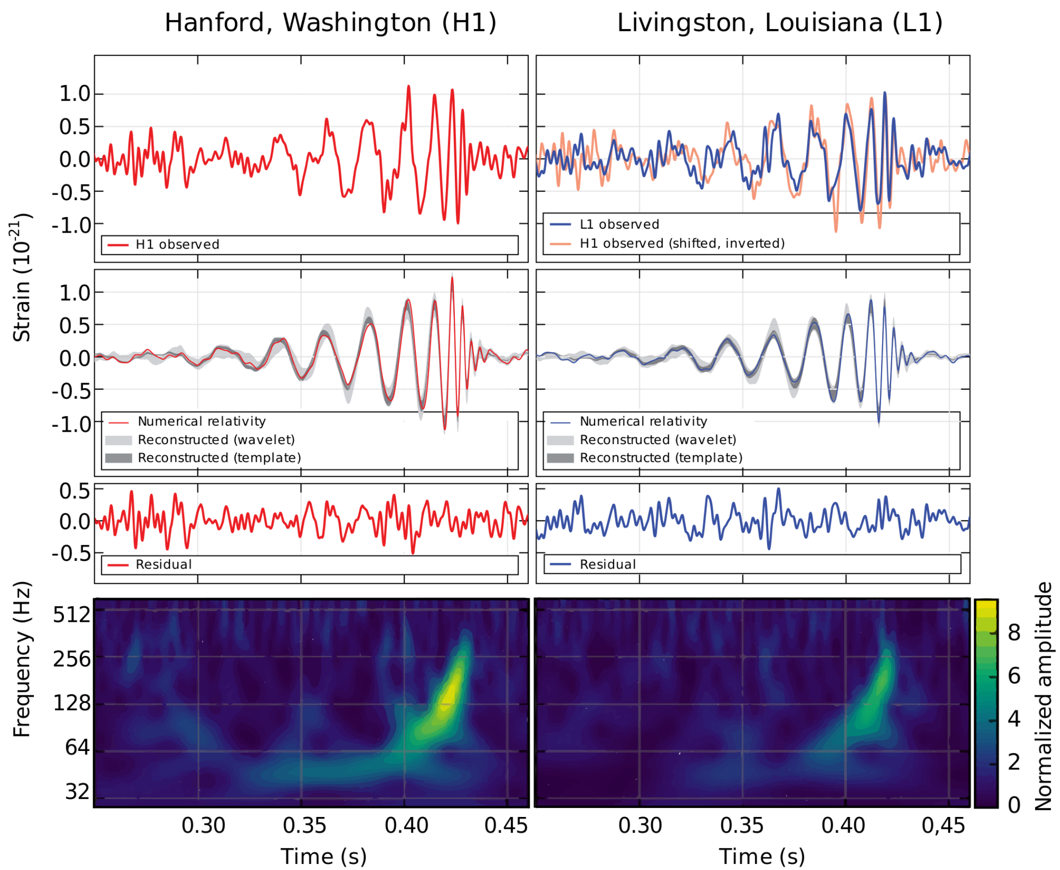
21cm: unique probe of the Universe at high redshift

highly sensitive to the linear growth

strong constraints on Y at redshifts much larger than with SNIa or galaxy clustering/weak lensing

GW as standard sirens





GW as standard sirens

Amplitude of GW

$$h_\times = \frac{4}{d_L(z)} \left(\frac{G\mathcal{M}_c(z)}{c^2} \right)^{5/3} \left(\frac{\pi f}{c} \right)^{2/3} \cos\iota \sin[\Phi(f)]\,,$$

measure luminosity distance with GW chirps

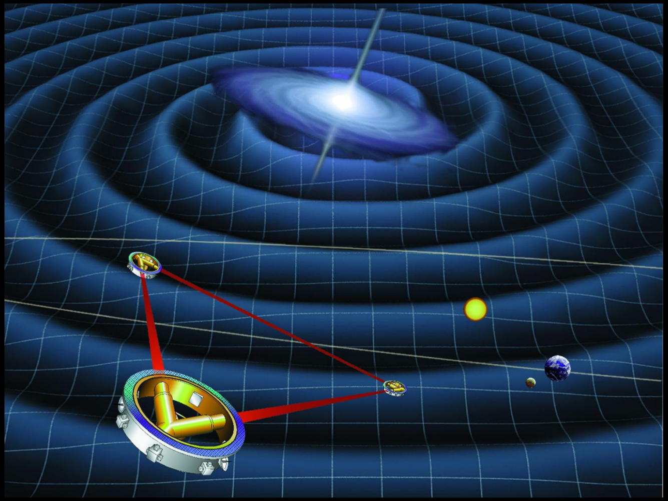
measure redshift with optical counterparts

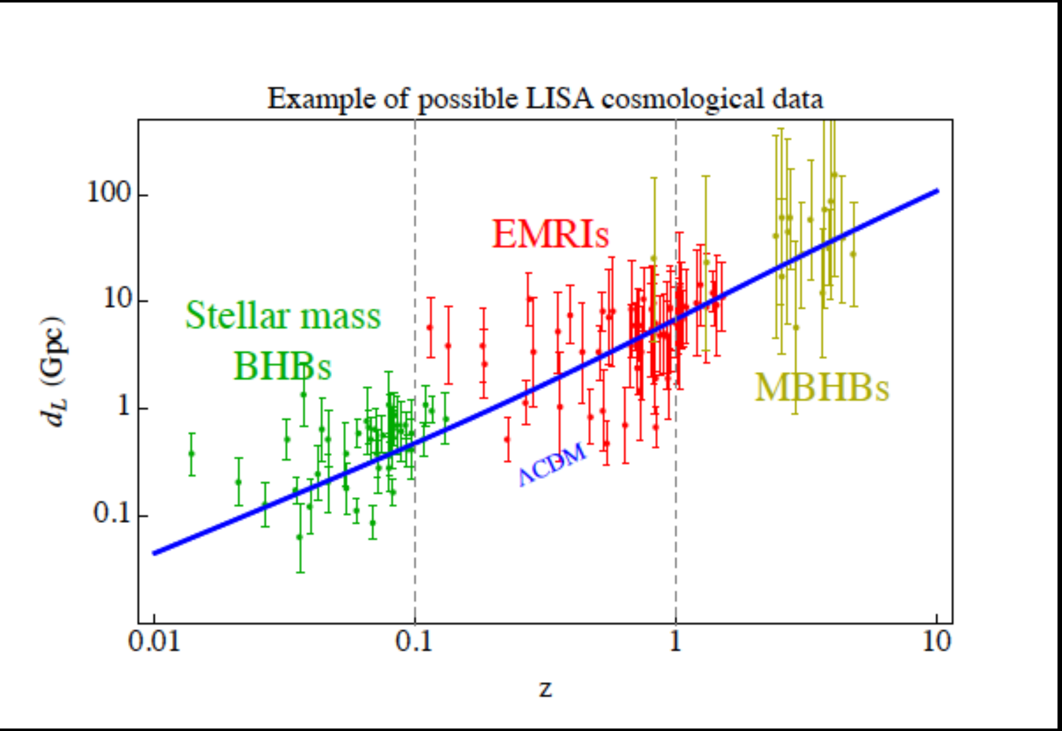
GW as standard sirens

Amplitude of GW

$$h_\times = \frac{4}{d_L(z)} \left(\frac{G\mathcal{M}_c(z)}{c^2}\right)^{5/3} \left(\frac{\pi f}{c}\right)^{2/3} \cos\iota \sin[\Phi(f)]\,,$$

Distribution of GW events with LISA





Tamanini 2017

GWs in non-standard gravity

$$\ddot{h} + 3H(1+\alpha_M)\dot{h} + (1+\cancel{\alpha})k^2 h = 0$$

$$\alpha_M = \mathcal{H}^{-1}\frac{d\ln M_*^2}{dt}$$

$$h_a = \left(\frac{M_{*,\mathrm{em}}}{M_{*,\mathrm{obs}}}\right) \times h_s\,,$$

$$h_\times = \frac{4}{d_L(z)}\left(\frac{G\mathcal{M}_c(z)}{c^2}\right)^{5/3}\left(\frac{\pi f}{c}\right)^{2/3}\cos\iota\sin[\Phi(f)]\,,$$

$$d_{\mathrm{GW}} = (1+z)^{\frac{\alpha_M}{2}} d_L.$$

GW-distance

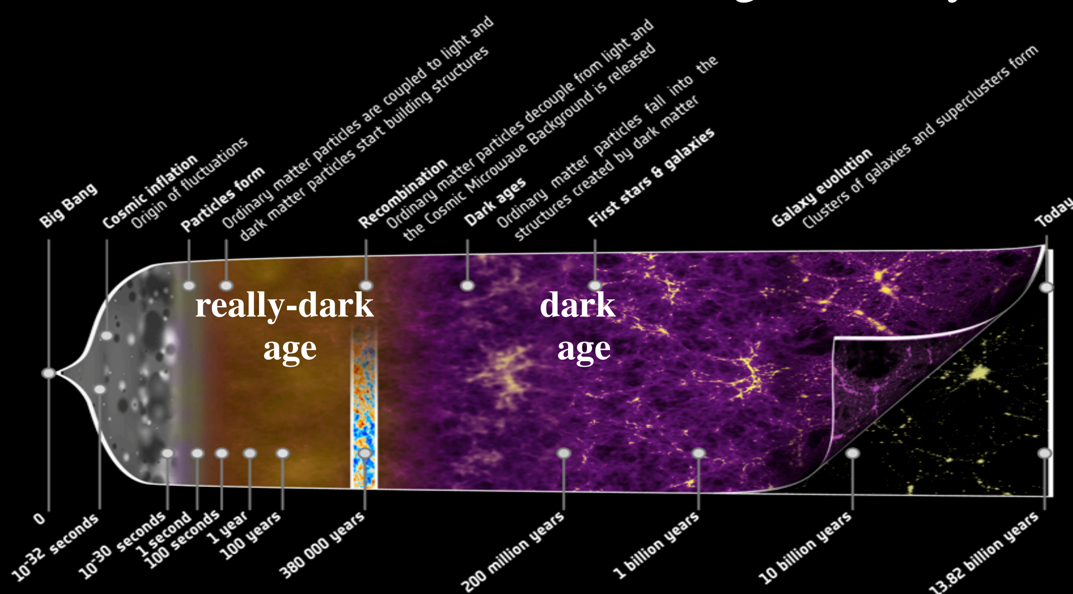
L.A. et al. 1712.08623

More from GWs

Lensing of GWs
ISW of GWs
Power spectra of GWs
GW backgrounds
…

Searching in new domains

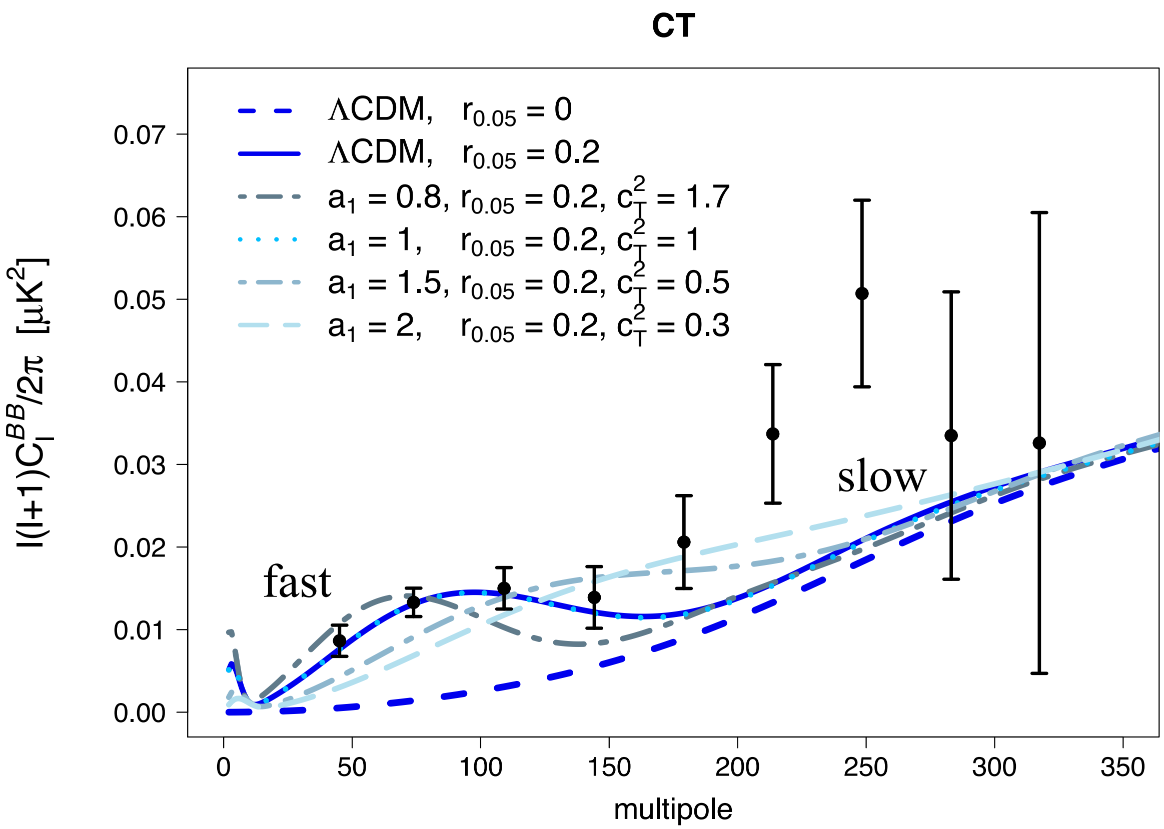
- Dark matter and dark energy are not dark but transparent
- The evolution of the Universe before decoupling is however really dark!
- Only two almost direct probes so far: BBN and CMB BB spectrum
- What else: B-modes, PBHs, non-gaussianity…?



Gravitational wave speed

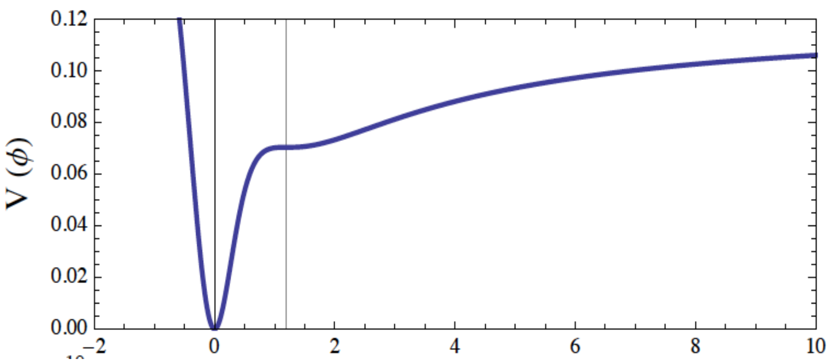
varying

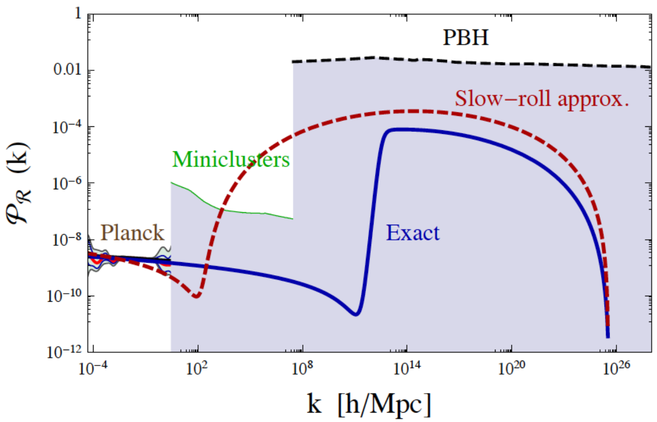
$$c_T^2 = 1 + \alpha_T$$



L.A., G. Ballesteros, V. Pettorino, 2014
See also Raveri, Silvestri and Zhou, 2014

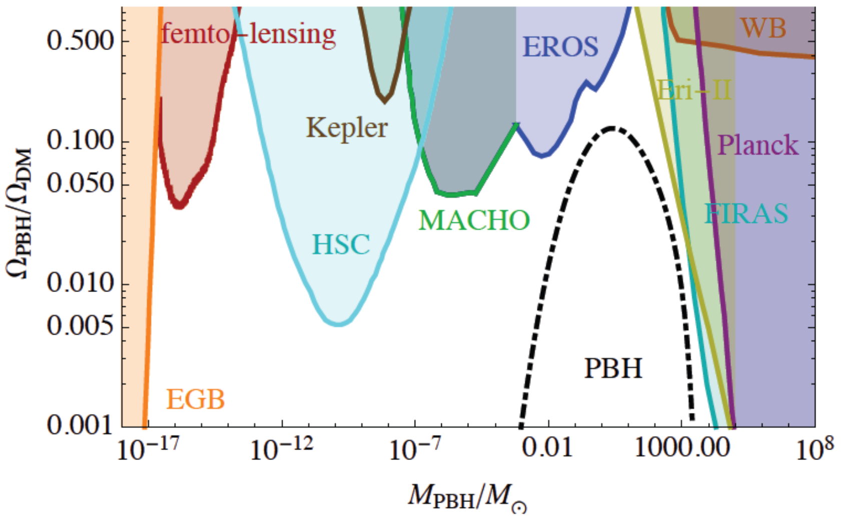
PBH after inflation





PBH are normally assumed to form from spectral peaks due to features in slow-rolling inflation
Eg inflection in the potential

$$P \sim \frac{H^2}{\varepsilon}$$



Garcia-Bellido & Ruiz Morales 2017, 1702.03901

Growth during radiation era?

Matter growth equations

$$\delta_m'' + \left(1 + \frac{H'}{H}\right)\delta_m' - \frac{3}{2}\left(\Omega_m \delta_m + \Omega_r \delta_r\right) = 0$$

Perturbation do not grow because

$$\Omega_m \approx 0$$
$$\delta_r \approx 0$$

interacting fields

Interacting fields ψ (heavy) and ϕ (light)

$$S = \int d^4x\sqrt{-g}\left[\frac{M_P^2}{2}R + \mathcal{L}_R + \mathcal{L}(\phi) + \mathcal{L}(\phi,\psi)\right] ,$$

$$\mathcal{L}(\phi,\psi) = i\bar{\psi}\left(\gamma^\mu\nabla_\mu - m(\phi)\right)\psi \, ,$$

coupling $$\beta(\phi) = -M_P\frac{\partial \ln m(\phi)}{\partial\phi} \, .$$

EOM

$$\dot{\rho}_\phi + 3H(\rho_\phi + p_\phi) = \frac{\beta}{M_P}(\rho_\psi - 3p_\psi)\,\dot{\phi} \, ,$$

$$\dot{\rho}_\psi + 3H\left(\rho_\psi + p_\psi\right) = -\frac{\beta}{M_P}\left(\rho_\psi - 3p_\psi\right)\dot{\phi} \, ,$$

interacting fields

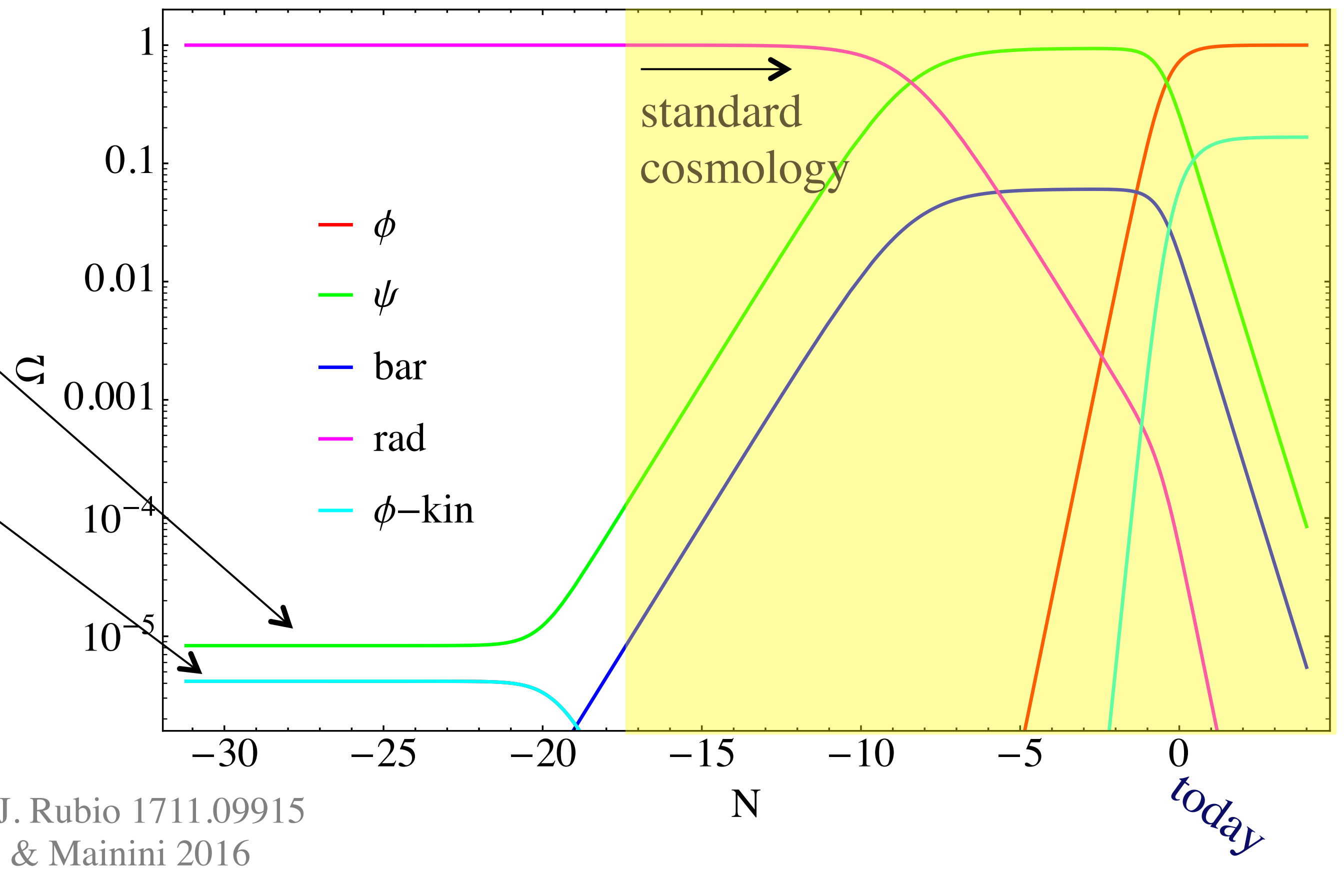
EOM

$$\dot{\rho}_\phi + 3H(\rho_\phi + p_\phi) = \frac{\beta}{M_P}(\rho_\psi - 3p_\psi)\,\dot{\phi}\,,$$

$$\dot{\rho}_\psi + 3H\,(\rho_\psi + p_\psi) = -\,\frac{\beta}{M_P}(\rho_\psi - 3p_\psi)\,\dot{\phi}\,,$$

$$\Omega_\psi = \frac{1}{3\beta^2}$$

$$\Omega_\phi = \frac{1}{6\beta^2}$$



L.A., C. Wetterich and J. Rubio 1711.09915
see also Bonometto & Mainini 2016

Growth during radiation era!

$$\delta_m'' + \left(1+\frac{H'}{H}\right)\delta_m' - \frac{3}{2}(\Omega_m\delta_m + \Omega_r\delta_r) = 0$$

$$\delta_\psi'' + \left(1 + \frac{\mathcal{H}'}{\mathcal{H}} - \frac{\beta\phi'}{M_P}\right)\delta_\psi' - \frac{3}{2}(Y\Omega_\psi\delta_\psi + \Omega_R\delta_R) = 0.$$

$Y = 1+\beta^2$

If a particle ψ strongly interacts with coupling $\beta >> 1$ with a field ϕ, perhaps dark energy, then there are two consequences:

1) The effective gravitational force is large ($Y = 1+\beta^2 >> 1$)
2) The amount of ψ during radiation is larger ($\Omega_r >> \Omega_\chi >> \Omega_{bar}$)

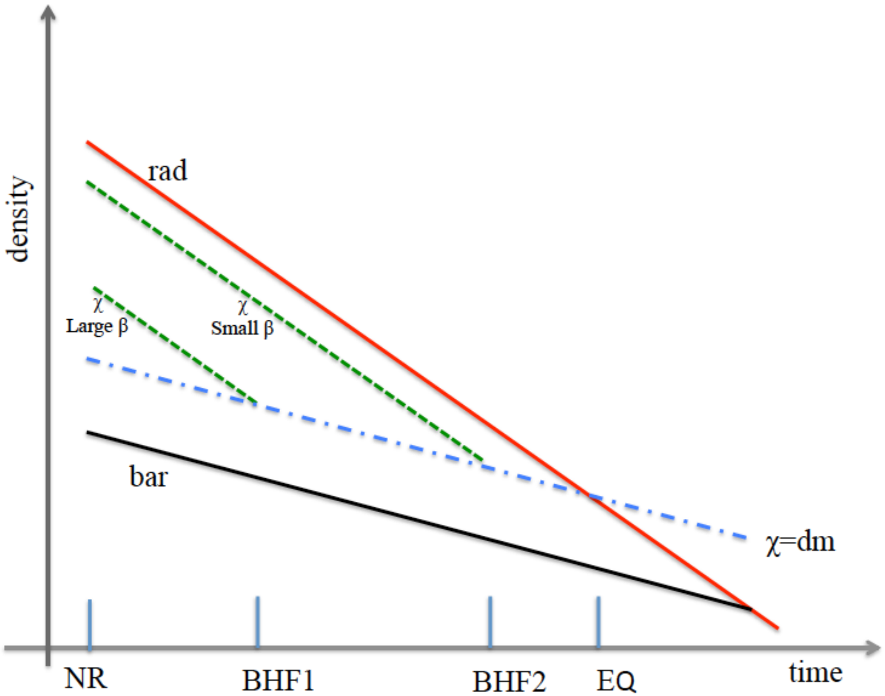
$$\delta_\psi'' - \delta_\psi' - \delta_\psi = 0\,.$$

Growth during radiation era

Growth as $\delta_\chi \sim a^{1.6}$ after horizon reenter during radiation: formation of BHs or DM-balls

Simple relation between BH mass and coupling parameter β

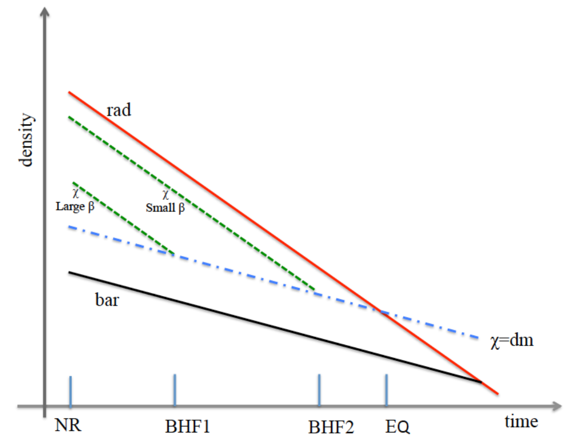
$$|\beta_c| = 585 \left(\frac{M_{\mathrm{BH}}}{M_\odot}\right)^{-1/6}$$

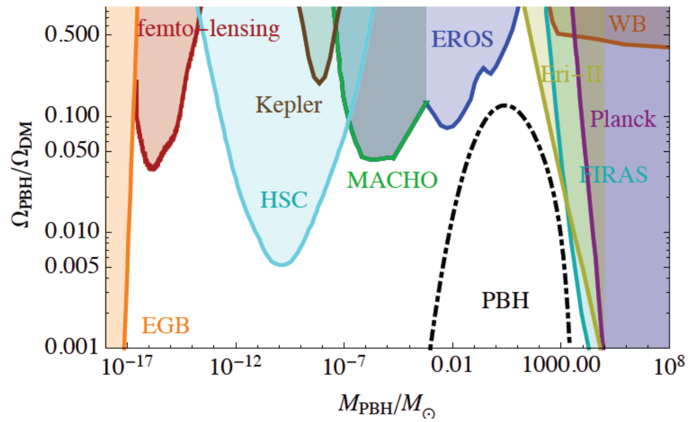


L.A., C. Wetterich and J. Rubio 1711.09915

Growth during radiation era

- No need of special features on the inflationary spectrum
- Do these objects become BHs or do they virialize into DM-balls?
  - Is the coupling fully screened?
- If DM-balls, they escape the strong constraints on PBHs
- Dark matter ψ remains confined into these structures





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Conclusions

there's more darkness to discover
out there!

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