Constraining modifications of gravity with synergies between radio and optical surveys

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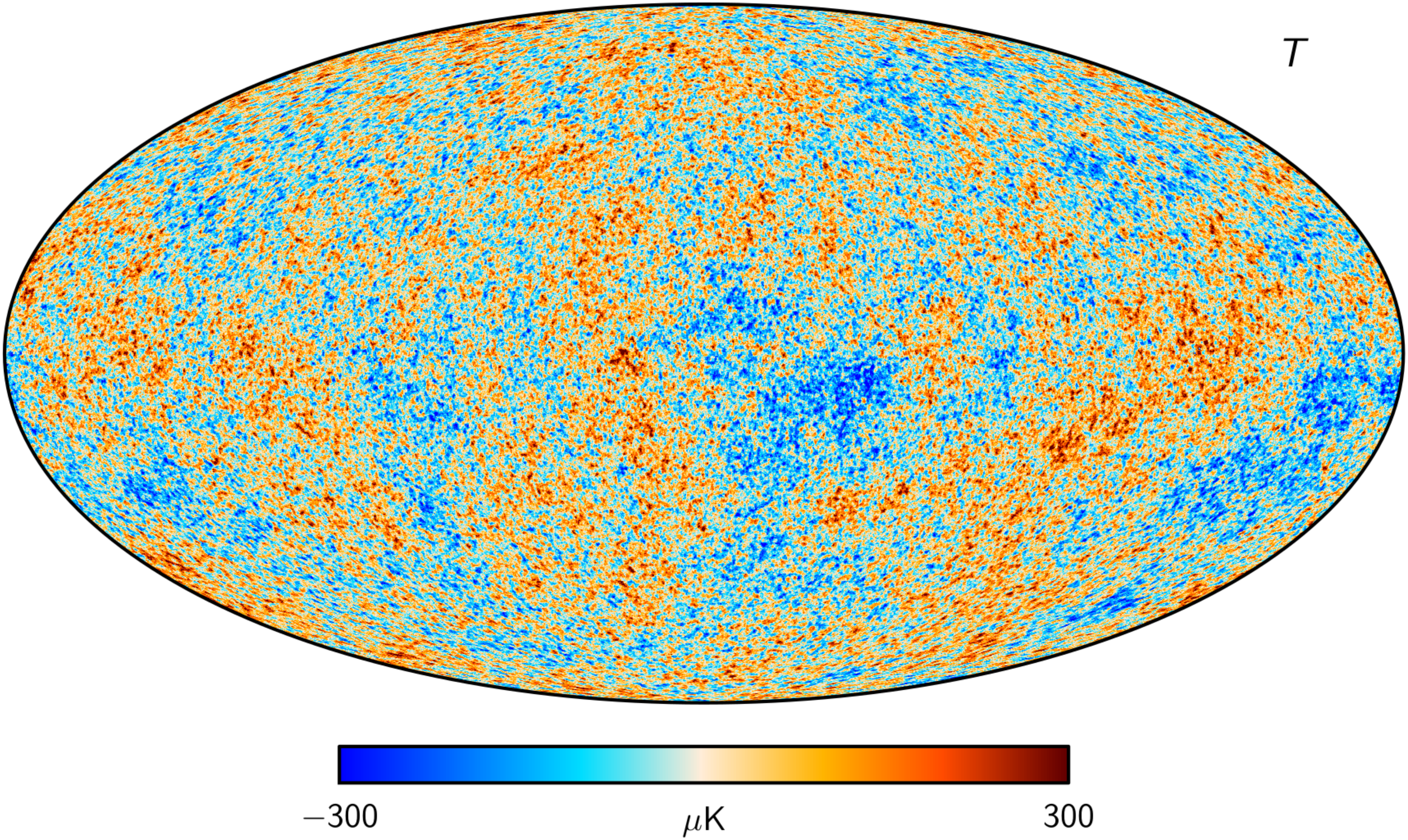
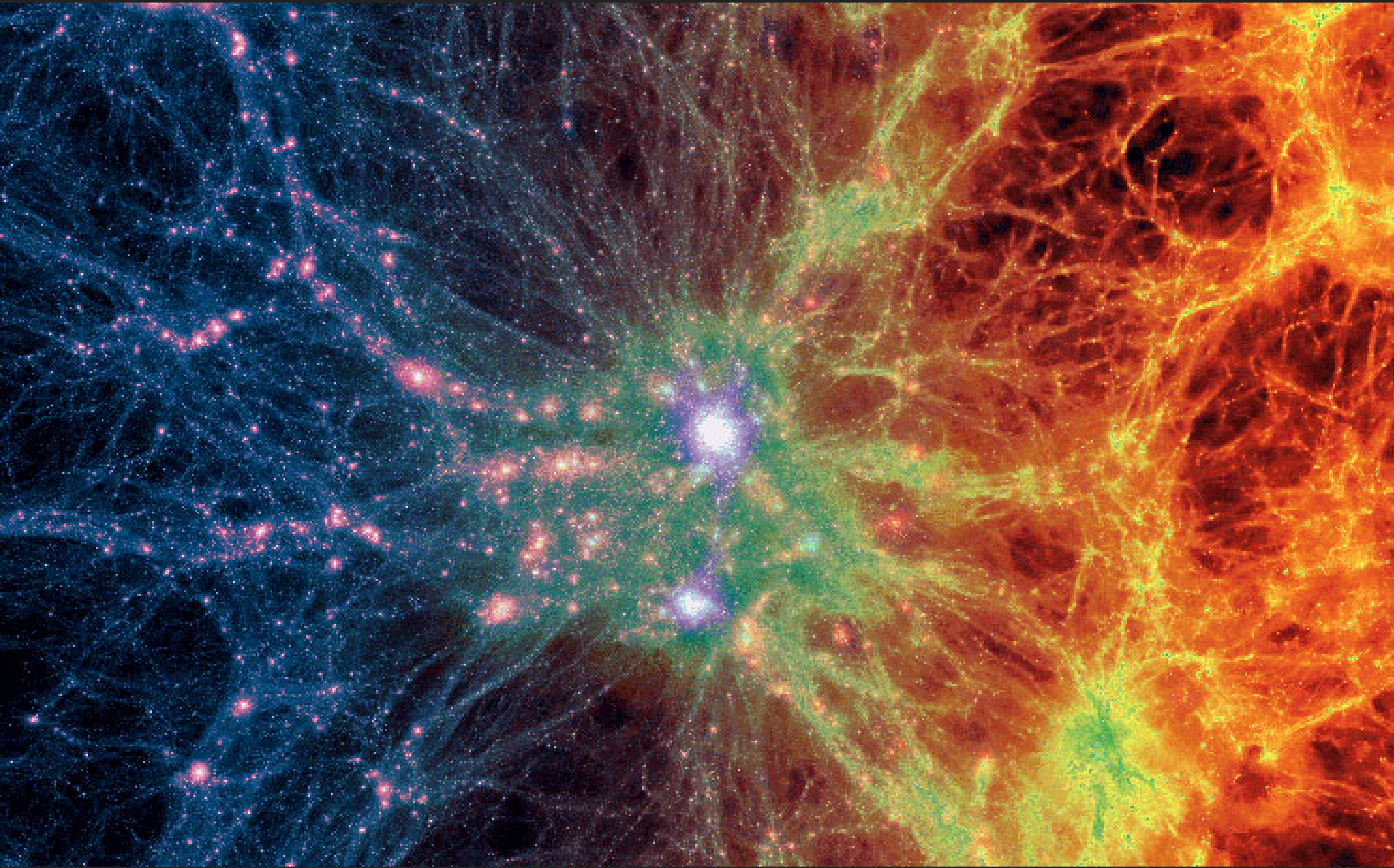
arXiv:2210.05705 published in Phys. Dark Univ.

Cosmic Microwave Background



Planck 2018 CMB Temperature map (Commander) . wiki.cosmos.esa.int/planck-legacy-archive/index.php/CMB_maps

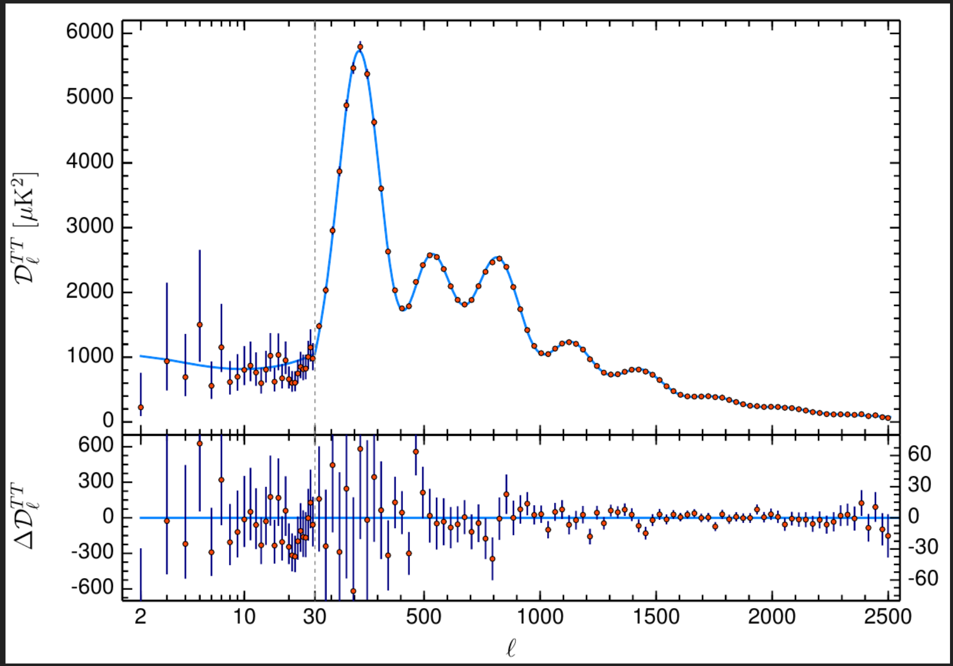
Large Scale Structure



Illustris Simulation: www.nature.com/articles/nature13316

The Standard ΛCDM model

- ΛCDM is still best fit to observations.
- Predictive model with few free parameters.



$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Concordance Cosmology:

- Lensing
- CMB
- Clustering
- Supernovae
- Clusters

The Standard ΛCDM model

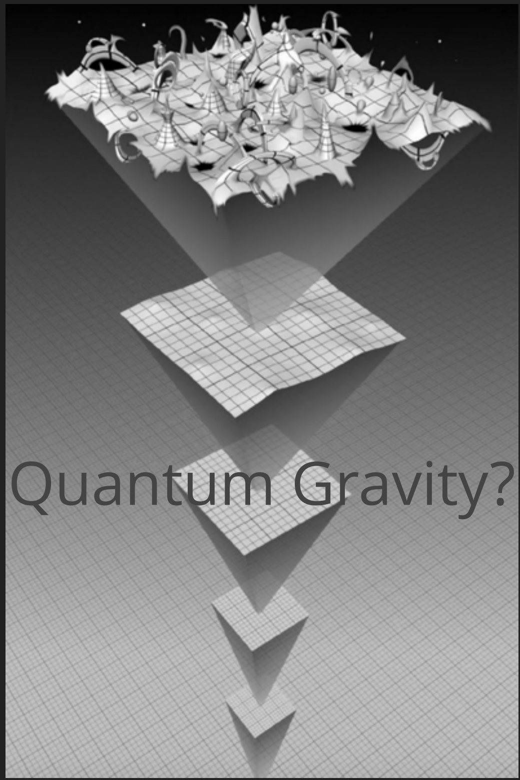
$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

- ΛCDM is still best fit to observations.
- Some questions remain:
- Λ and CDM.
- Cosmological Constant Problem:

O(100) orders of magnitude wrong

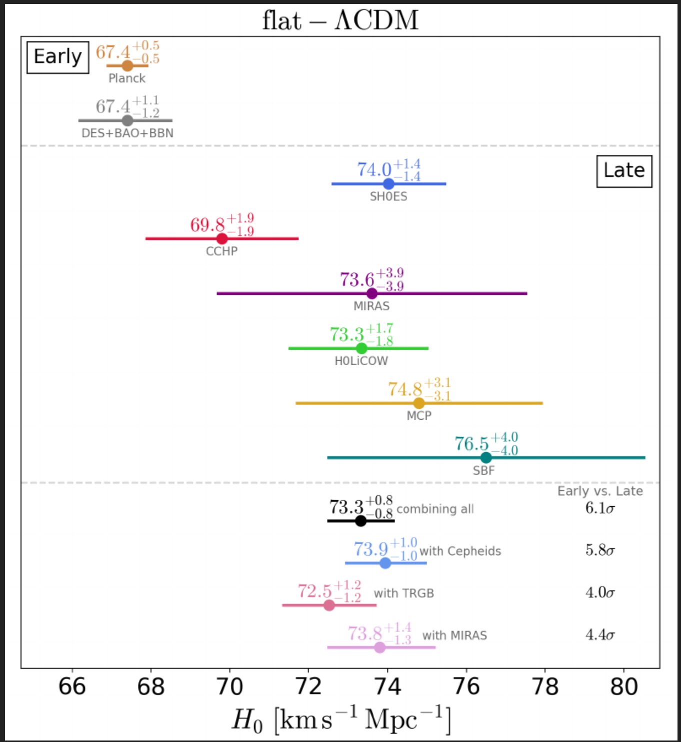
(Zeldovich 1967, Weinberg 1989, Martin 2012).

Composed of naturalness and coincidence sub-problems, among others.

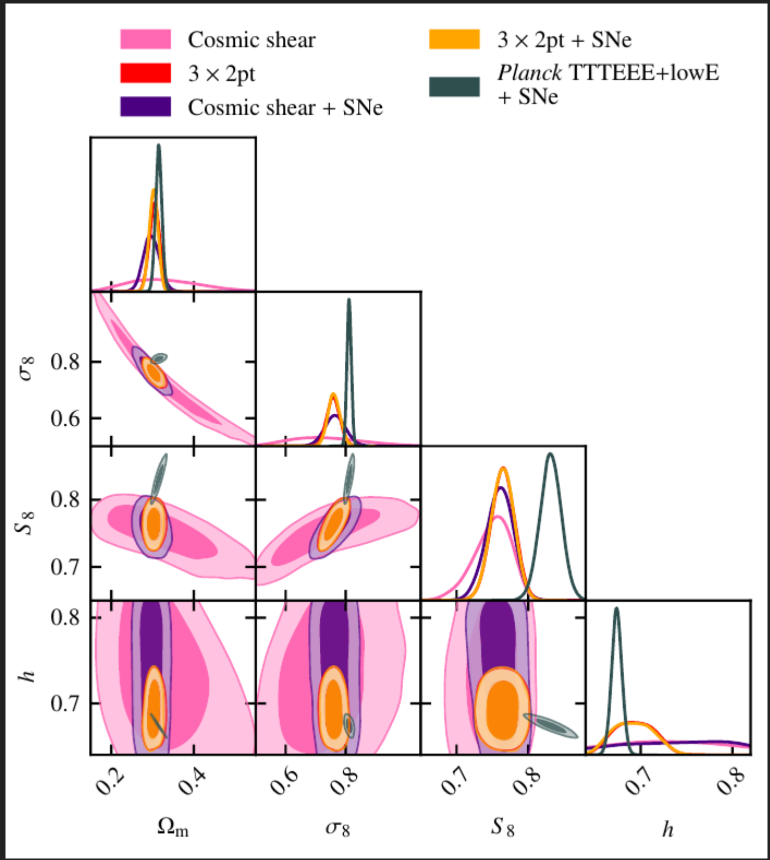


Tensions in the ΛCDM model

- ΛCDM is still best fit to observations.
- Some questions remain:
- H0 tension, now ~5σ



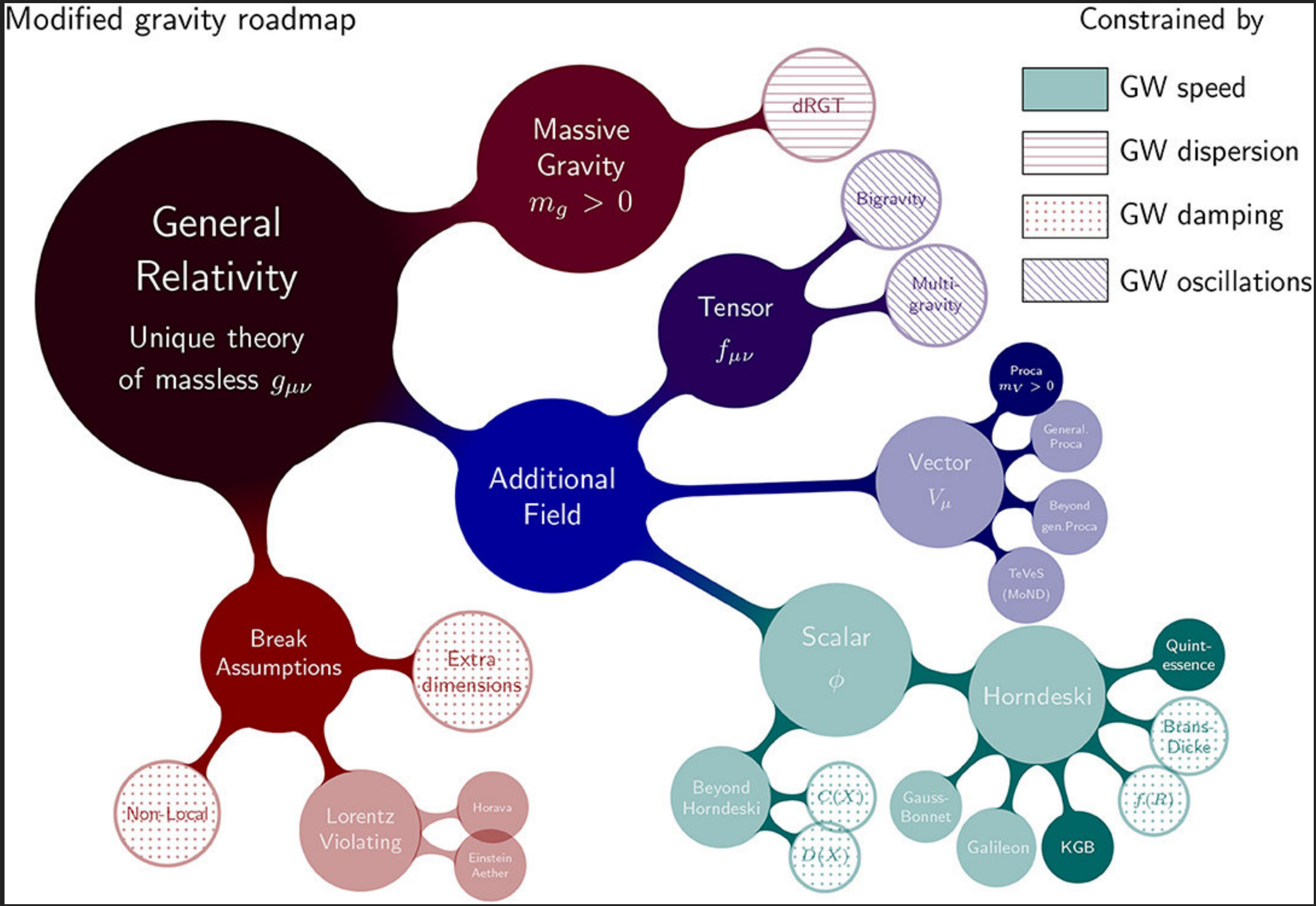
L.Verde, et al 2019. arXiv:1907.10625



Planck, Clusters and Lensing tension on clustering amplitude σ_8

KiDS 1000 Cosmology, arXiv:2010:16416

Alternatives to ΛCDM



Ezquiaga, Zumalacárregui, Front. Astron. Space Sci., 2018

Parametrized modified gravity

In ΛCDM the two linear gravitational potentials Ψ and Φ are equal to each other

$$\mathrm{ds}^2 = -(1+2\Psi)\mathrm{dt}^2 + \mathrm{a}^2(1-2\Phi)\mathrm{dx}^2$$

We can describe general modifications of gravity (of the metric) at the linear level with 2 functions of scale (k) and time (a)

$$-k^2(\Phi(a,k)+\Psi(a,k)) \equiv 8\pi G a^2 \Sigma(a,k)\rho(a)\delta(a,k)$$

$$-k^2\Psi(a,k) \equiv 4\pi G a^2 \mu(a,k)\rho(a)\Delta(a,k)$$

$$\eta(a,k) \equiv \Phi(a,k)/\Psi(a,k) \quad .$$

Lensing ($\Sigma(a,k)$)

Clustering ($\mu(a,k)$)

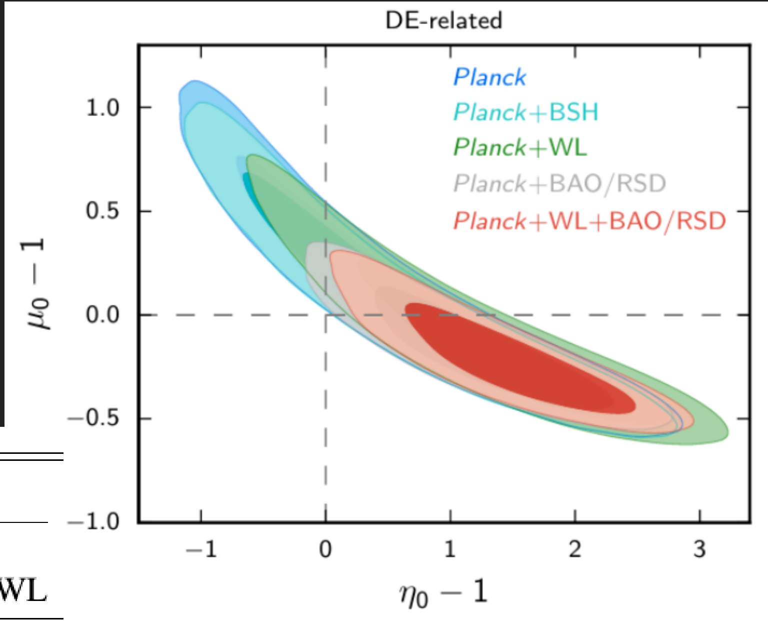
$$\Sigma(a,k) = \frac{1}{2}\mu(a,k)(1+\eta(a,k))$$

Only two independent functions

Late-time parametrization: Planck constraints

- Using Planck satellite data in 2015 and 2018, constraints were obtained on these two functions μ and η.
- Late-time parametrization: dependent on Dark Energy fraction

$$\mu(a,k) \equiv 1 + E_{11}\Omega_{\mathrm{DE}}(a)$$
$$\eta(a,k) \equiv 1 + E_{22}\Omega_{\mathrm{DE}}(a)$$



Planck 2018 results VI, arXiv:1807.06209

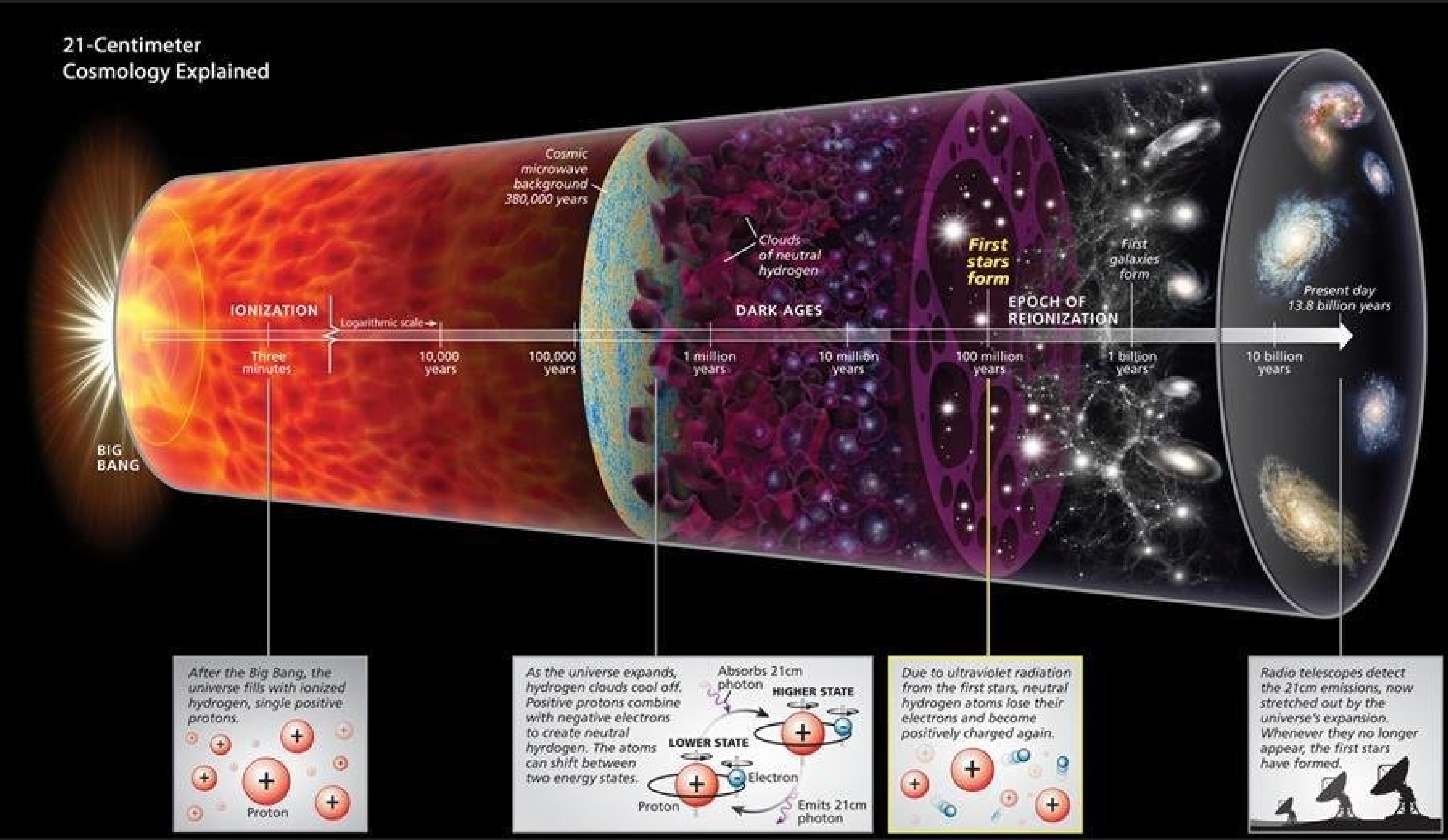
Parameter	With CMB lensing: *Planck*	*Planck* +SNe+BAO	*Planck* +BAO/RSD+WL
$\mu_0 - 1$	$0.10^{+0.30}_{-0.42}$	$0.05^{+0.26}_{-0.39}$	$-0.07^{+0.19}_{-0.32}$
$\eta_0 - 1$	$0.22^{+0.55}_{-1.0}$	$0.32^{+0.63}_{-0.89}$	$0.32^{+0.63}_{-0.89}$
$\Sigma_0 - 1$	0.100 ± 0.093	0.106 ± 0.086	$0.018^{+0.059}_{-0.048}$

Planck 2015 results XIV, arXiv:1502.01590

Forecasts for Stage-IV surveys in:

Casas et al (2017), arXiv:1703.01271

The Evolution of the Universe and the Dark Ages



Complementarity of probes

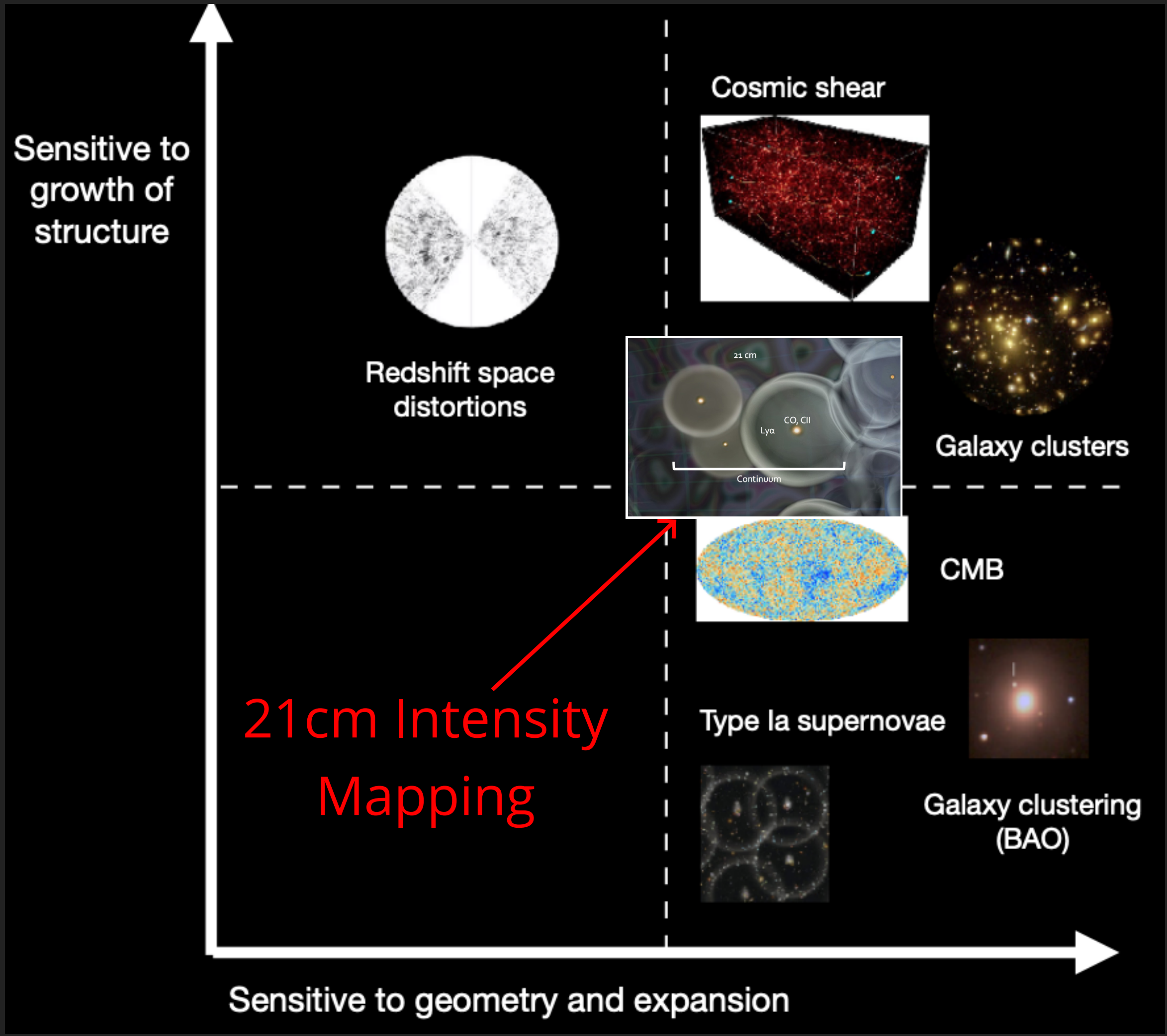
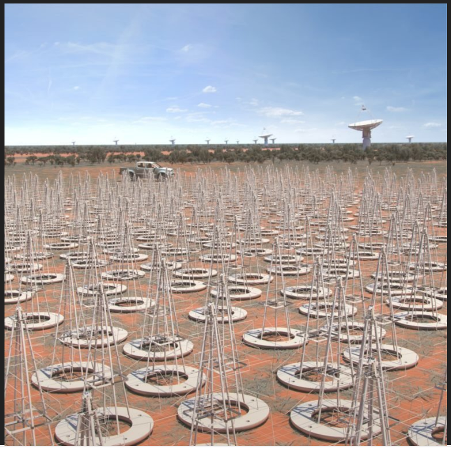


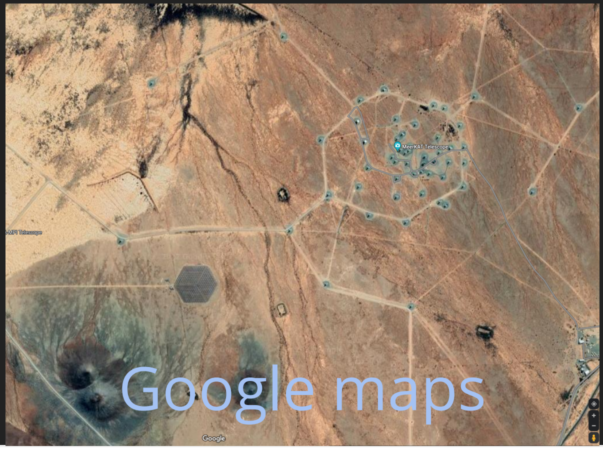
Image credit: Sunayana Bhargava

The Square Kilometer Array Obs. (SKAO)

SKAO

- SKA Phase 1: SKA1-Low and SKA1-Mid
- SKA1-Low: 130,000 dipole antennas, 65km max. baseline (Australia)
- SKA1-Mid: ~200 dishes of ~15m diameter, max. baseline 150km (South Africa)
- Precursors: ASKAP, MEERKAT, HERA...



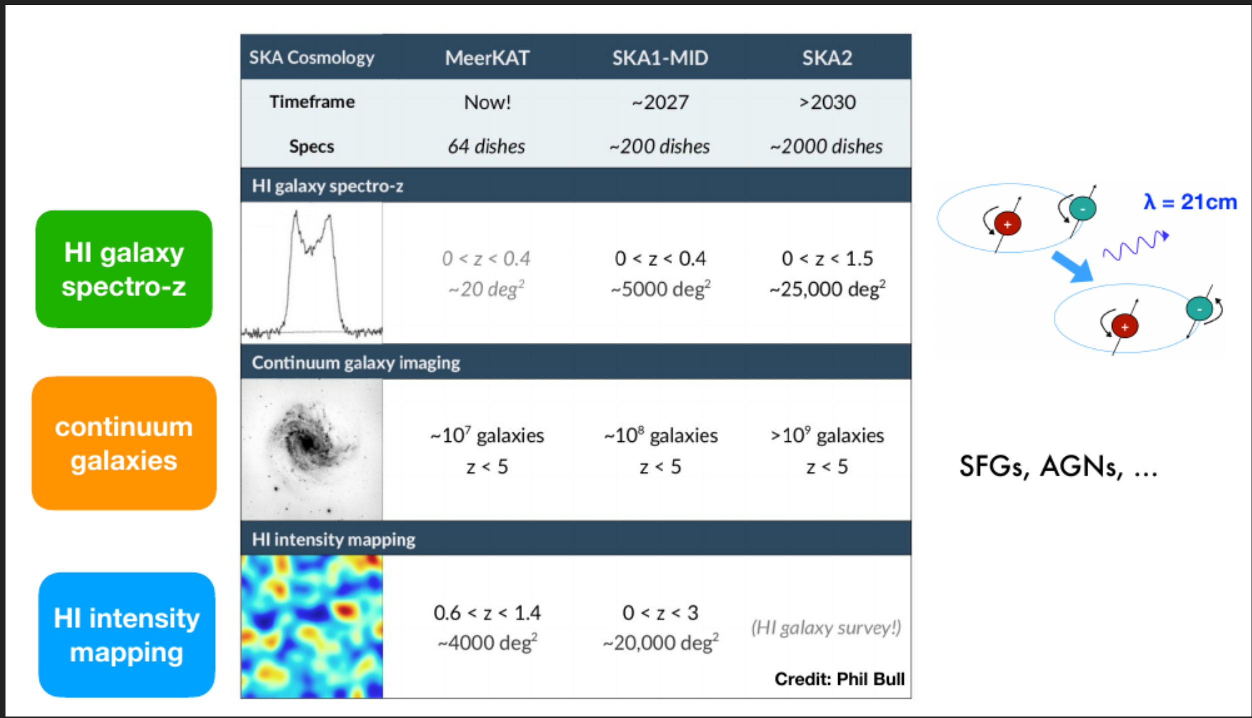


SKAO Probes

- Continuum emission: Allows detection of position and shapes of galaxies.
- Line emission of neutral Hydrogen (HI, 21cm):

1. Using redshifted HI line -> spectroscopic galaxy survey

Image credit: Isabella Carucci



SKA Cosmology	MeerKAT	SKA1-MID	SKA2
Timeframe	Now!	~2027	>2030
Specs	*64 dishes*	*~200 dishes*	*~2000 dishes*
HI galaxy spectro-z			
	$0 < z < 0.4$ ~20 deg^2	$0 < z < 0.4$ ~5000 deg^2	$0 < z < 1.5$ ~25,000 deg^2
Continuum galaxy imaging			
	~10^7 galaxies $z < 5$	~10^8 galaxies $z < 5$	>10^9 galaxies $z < 5$
HI intensity mapping			
	$0.6 < z < 1.4$ ~4000 deg^2	$0 < z < 3$ ~20,000 deg^2	*(HI galaxy survey!)*

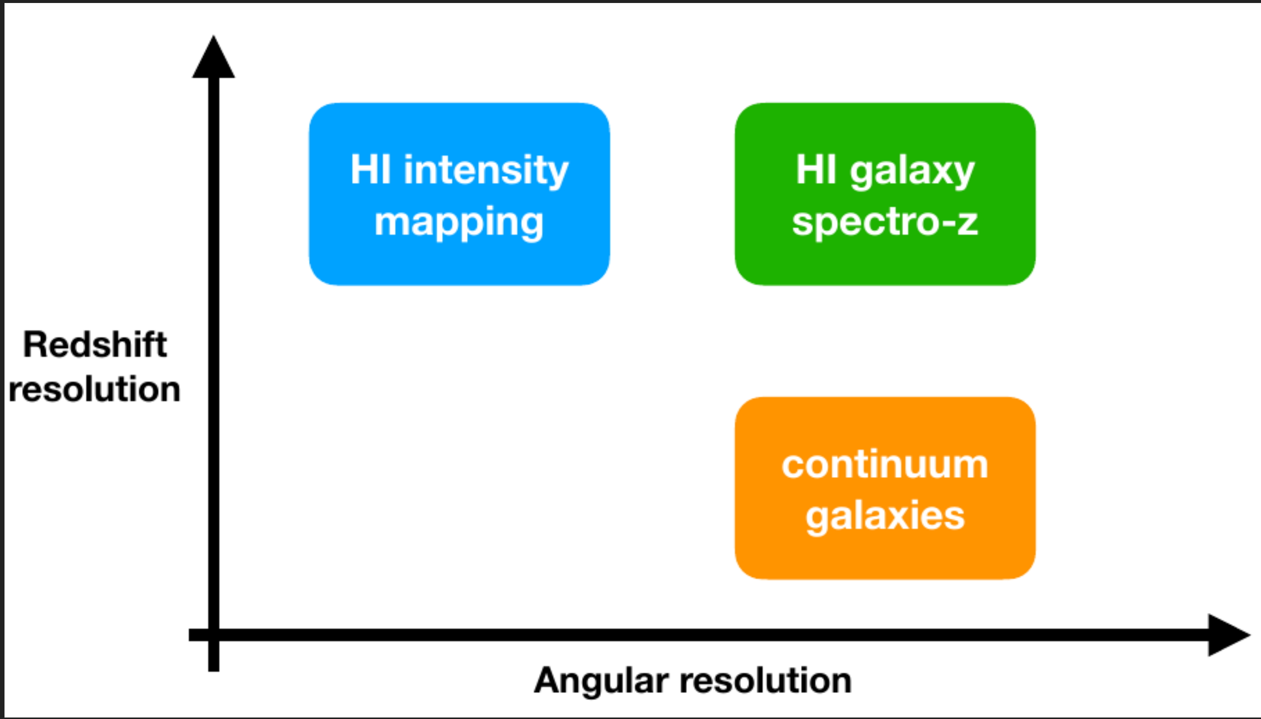
2. Intensity Mapping: Large scale correlations in HI brightness temperature -> very good redshift resolution, good probe of structures

SKAO Probes

- Continuum emission: Allows detection of position and shapes of galaxies.
- Line emission of neutral Hydrogen (HI, 21cm):

1. Using redshifted HI line -> spectroscopic galaxy survey

Image credit: Isabella Carucci



2. Intensity Mapping: Large scale correlations in HI brightness temperature -> very good redshift resolution, good probe of structures

SKAO GC Surveys

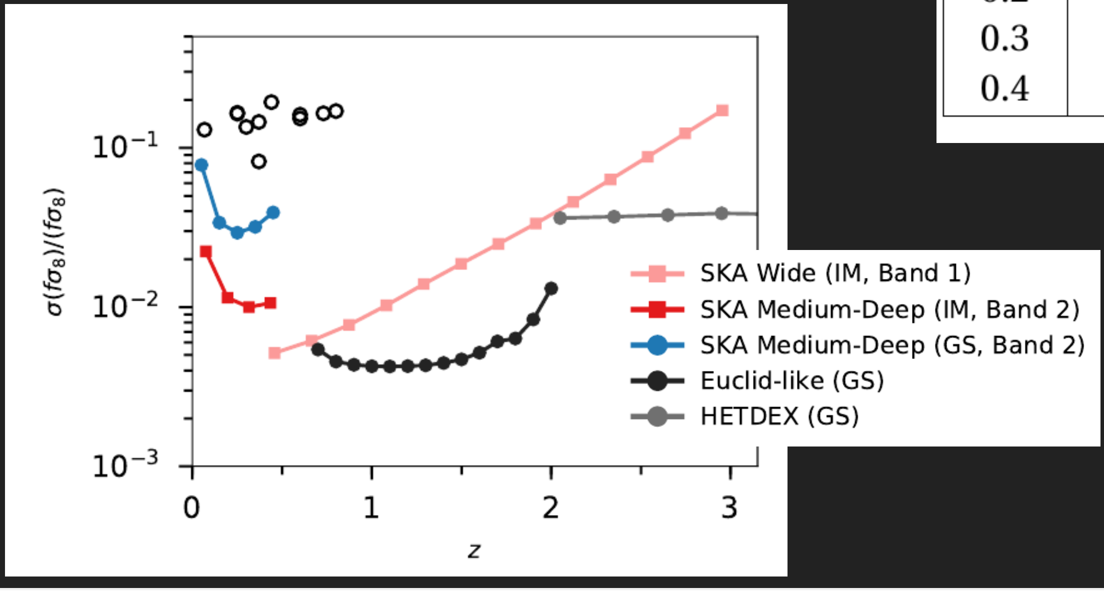
SKA1 Medium Deep Band 2: $5000\,\mathrm{deg}^2$

1. GCsp: HI galaxy spec. redshift survey: $0.0 < z < 0.5$ probes 3D matter power spectrum in Fourier space.

HI galaxies spectroscopic survey

$z_{\rm min}$	$z_{\rm max}$	$n(z)$ [Mpc^{-3}]	$b(z)$	$S_{\rm rms}$ [μJy]
0.0	0.1	2.73×10^{-2}	0.657	117.9
0.1	0.2	4.93×10^{-3}	0.714	109.6
0.2	0.3	9.49×10^{-4}	0.789	102.9
0.3	0.4	2.23×10^{-4}	0.876	97.5
0.4	0.5	6.44×10^{-5}	0.966	93.1

SKA1 Redbook 2018, arXiv:1811.02743



SKAO Angular Surveys

SKA1 Medium Deep Band 2: $5000\,\mathrm{deg}^2$

1. GCsp: HI galaxy spec. redshift survey: $0.0 < z < 0.5$ probes 3D matter power spectrum in Fourier space
2. GCco + WL + XCco (Continuum): $0.0 < z < 3.0$ probes angular clustering of galaxies, Weak Lensing (Weyl potential) and galaxy-galaxy-lensing. Angular number density: $n \approx 3.2 \mathrm{arcmin}^{-2}$

Continuum galaxy survey

Bin	$z_{\rm min}$	$z_{\rm max}$	$N/10^6$	bias	$\alpha_{\rm mag}$
Medium-Deep Band 2 Survey					
1	0.0	0.3	4.14	0.86	0.76
2	0.3	0.6	6.25	0.86	1.04
3	0.6	0.9	8.06	0.90	1.05
4	0.9	1.2	7.78	1.21	1.19
5	1.2	1.5	7.85	1.52	1.30
6	1.5	1.8	5.77	1.58	1.22
7	1.8	2.1	4.54	2.09	1.46
8	2.1	3.0	7.90	2.39	1.25
9	3.0	6.0	6.12	2.85	1.25
Total			58.41		

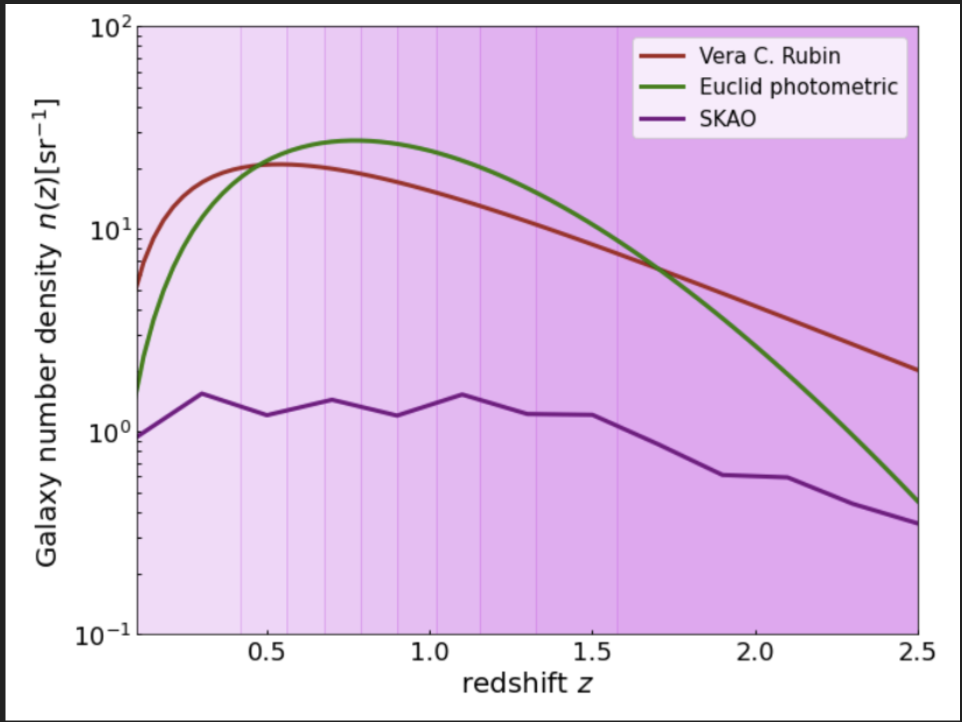
SKA1 Redbook 2018, arXiv:1811.02743

SKAO Angular Surveys

SKA1 Medium Deep Band 2: $5000\,\mathrm{deg}^2$

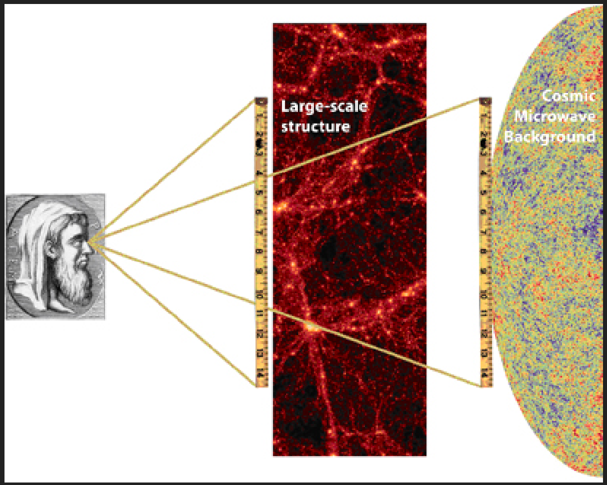
1. GCsp: HI galaxy spec. redshift survey: $0.0 < z < 0.5$ probes 3D matter power spectrum in Fourier space
2. GCco + WL + XCco (Continuum): $0.0 < z < 3.0$ probes angular clustering of galaxies, Weak Lensing (Weyl potential) and galaxy-galaxy-lensing. Angular number density: $n \approx 3.2\mathrm{arcmin}^{-2}$
3. For comparison: Stage-IV: $n \approx 30\mathrm{arcmin}^{-2}$

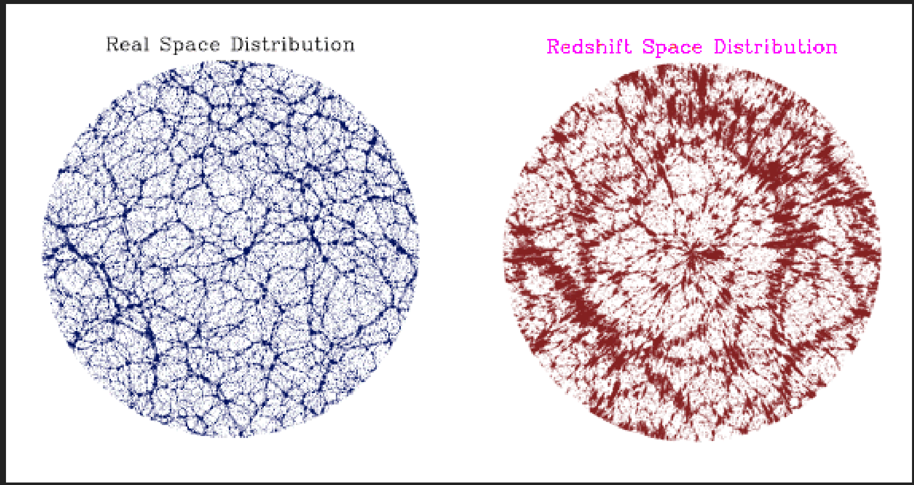
Continuum galaxy survey



*kindly provided by Stefano Camera

Galaxy Clustering Recipe





BAO

Clustering

RSD

Spec-z

$$P_{\rm obs}(k_{\rm ref},\mu_{\rm ref};z) = \frac{1}{q_\perp^2 q_\parallel}\left\{\frac{\left[b\sigma_8(z)+f\sigma_8(z)\mu^2\right]^2}{1+\left[f(z)k\mu\sigma_{\rm p}(z)\right]^2}\right\}\frac{P_{\rm dw}(k,\mu;z)}{\sigma_8^2(z)}F_{\rm z}(k,\mu;z)+P_{\rm s}(z)$$

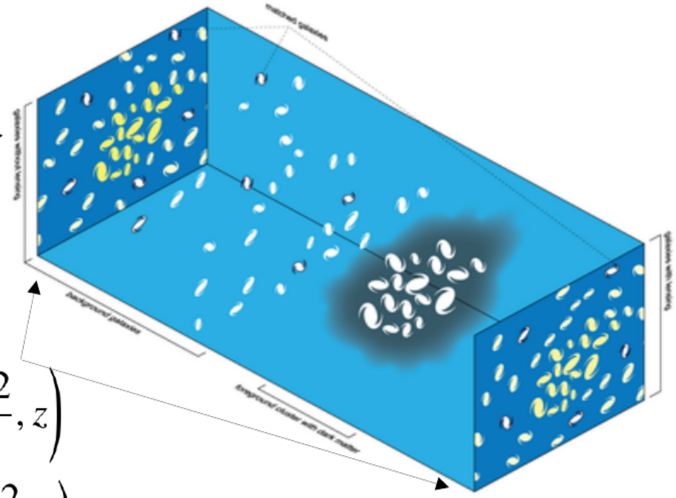
Euclid Collaboration, IST:Forecasts, arXiv: 1910.09273

3x2pt recipe

Shear-Shear, Galaxy-Galaxy, Galaxy-Lensing **correlations**

Shear-Shear — Intrinsic Alignments

$$\mathcal{W}_i^{\mathrm{L}} = W_i^{\gamma}(z) - \frac{\mathcal{A}_{\mathrm{IA}} C_{\mathrm{IA}} \Omega_{\mathrm{m}} \mathcal{F}_{\mathrm{IA}}(z)}{D(z)} W_i^{\mathrm{IA}}(z)$$



XC

$$C_{ij}^{\mathrm{GL}}(\ell) = \int \frac{dz}{H(z) r^2(z)} \mathcal{W}_i^{\mathrm{G}}(z) \mathcal{W}_j^{\mathrm{L}}(z) P_{\delta\delta}\left(\frac{\ell + 1/2}{r(z)}, z\right)$$

$$C_{ij}^{\mathrm{GG}}(\ell) = \int \frac{dz}{H(z) r^2(z)} \mathcal{W}_i^{\mathrm{G}}(z) \mathcal{W}_j^{\mathrm{G}}(z) P_{\delta\delta}\left(\frac{\ell + 1/2}{r(z)}, z\right)$$

GCph

WL

$$C_{ij}^{\mathrm{LL}}(\ell) = \int_{z_{\min}}^{z_{\max}} \frac{dz}{H(z) r^2(z)} \mathcal{W}_i^{\mathrm{L}}(z) \mathcal{W}_j^{\mathrm{L}}(z) P_{\delta\delta}\left(\frac{\ell + 1/2}{r(z)}, z\right)$$

Directly constrains MG function Σ through Weyl potential

$$-k^2(\Phi(a,k) + \Psi(a,k)) \equiv 8\pi G a^2 \Sigma(a,k) \rho(a) \delta(a,k)$$

$$P_{\delta\delta} \rightarrow \Sigma^2 P_m$$

Euclid preparation: VII. Forecast validation for Euclid cosmological probes. arXiv:1910.09273

SKAO IM Surveys

SKA1 Medium Deep Band 1: $20000\,\mathrm{deg}^2$

- IM: Intensity mapping survey

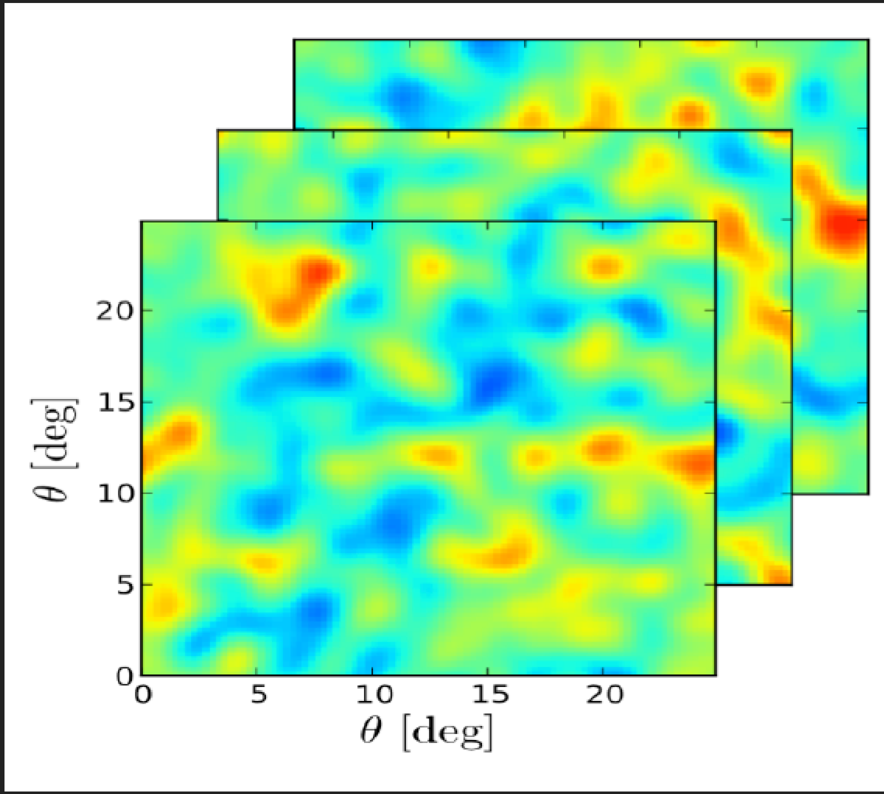
  $0.4 < z < 2.5$
- Very good redshift resolution: $\Delta z \approx \mathcal{O}(10^{-3})$
- We use: 11 redshift bins
- Single dish mode:

  $N_d = 197$

  $t_{obs} = 10000\,\mathrm{hr}$

  We limit to the scales

  $0.001 < k < 0.25\,[h/\mathrm{Mpc}]$



Intensity Mapping

- IM probes the underlying matter power spectrum.
- Density bias given by the HI mass contained in dark matter halos.
- 21cm brightness temperature depends on cosmological background & the energy fraction of neutral Hydrogen in the Universe Ω_{HI}.
- $P_{\delta\delta,zs}(z,k)$ is the redshift space matter power spectrum

$$P^{\rm IM}(z,k) = \bar{T}_{IM}(z)^2 \mathrm{AP(z)K^2_{rsd}(z,\mu;b_{HI})}$$
$$FoG(z,k,\mu_\theta)$$
$$\times P_{\delta\delta,dw}(z,k)$$

$$K_{\rm rsd}(z,\mu;b_{\rm HI}) = [b_{\rm HI}(z)^2 + f(z)\mu^2]$$

$$b_{\rm HI}(z) = 0.3(1+z) + 0.6$$

$$\bar{T}_{\rm IM}(z) = 189h\frac{(1+z)^2 H_0}{H(z)}\Omega_{HI}(z)\ \mathrm{mK}$$

$$\Omega_{HI} = 4(1+z)^{0.6}\times 10^{-4}$$

Carucci et al (2020) arXiv:2006.05996

Jolicoeur et al (2020) arXiv:2009.06197

Intensity Mapping x GCsp

- Cross correlation combines one term of brightness T with one K term for each "redshift sample".
- Same underlying matter power spectrum for both probes.
- A combined z-error (damping along the line of sight), where "sp" dominates, since the IM resolution is 1-2 orders of magnitude better.

$$
\begin{aligned}
P^{\mathrm{IM}\times\mathrm{g}}(z,k) = \\
\bar{T}_{\mathrm{IM}}(z)\mathrm{AP}(z)r_{\mathrm{IM,opt}}\; K_{\mathrm{rsd}}(z,\mu;b_{\mathrm{HI}}) \\
\times K_{\mathrm{rsd}}(z,\mu;b_{\mathrm{g}})FoG(z,k,\mu_\theta)P_{\delta\delta,dw}(z,k) \\
\times\exp[-\tfrac{1}{2}k^2\mu^2(\sigma_{\mathrm{IM}}(z)^2+\sigma_{\mathrm{sp}}(z)^2)]
\end{aligned}
$$

$$\sigma_i(z) = \tfrac{c}{H(z)}(1+z)\delta_z$$

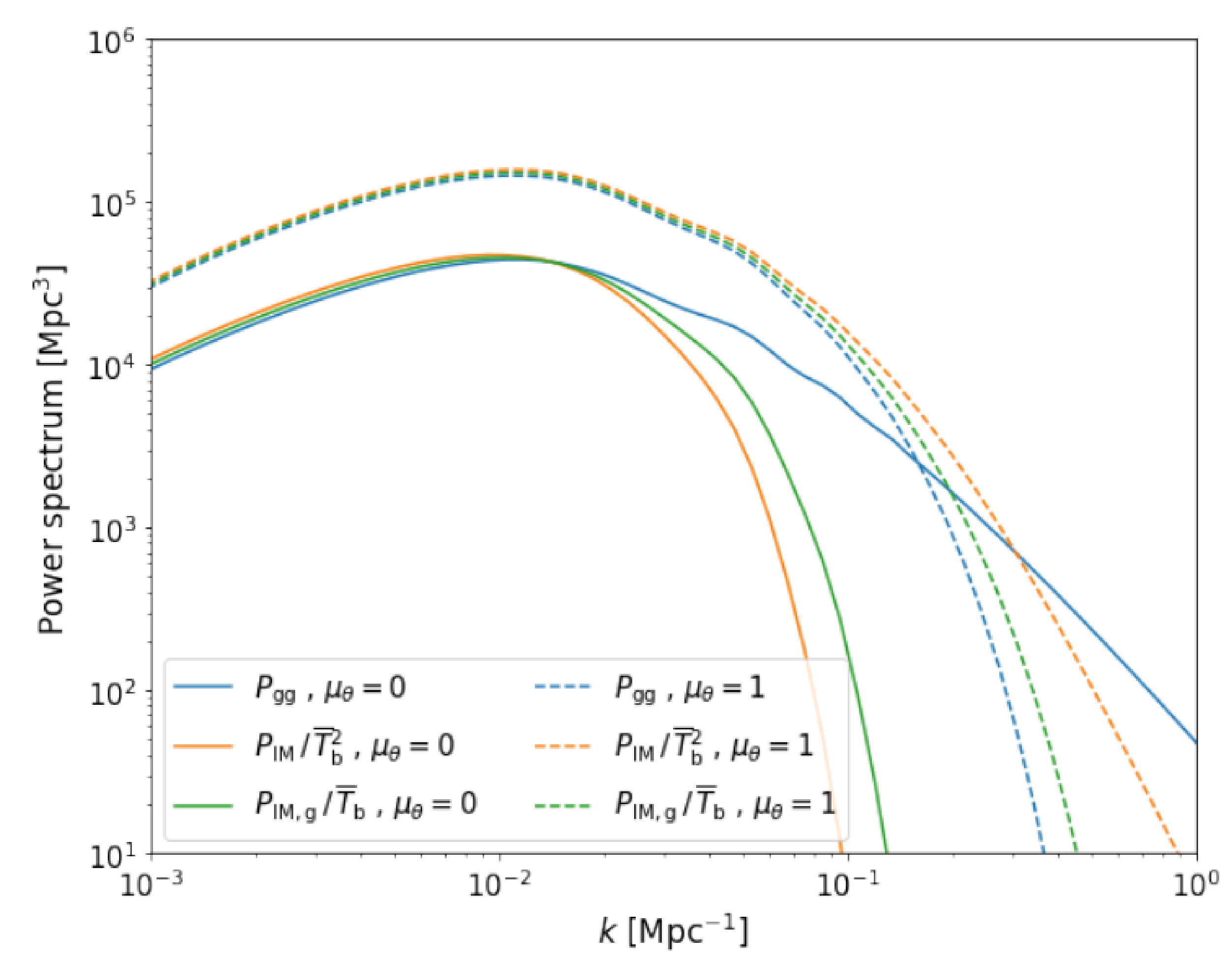
$b_{\mathrm{g}}(z) =$ fit to simulations for given galaxy sample

Wolz et al (2021) arXiv:2102.04946

Jolicoeur et al (2020) arXiv:2009.06197

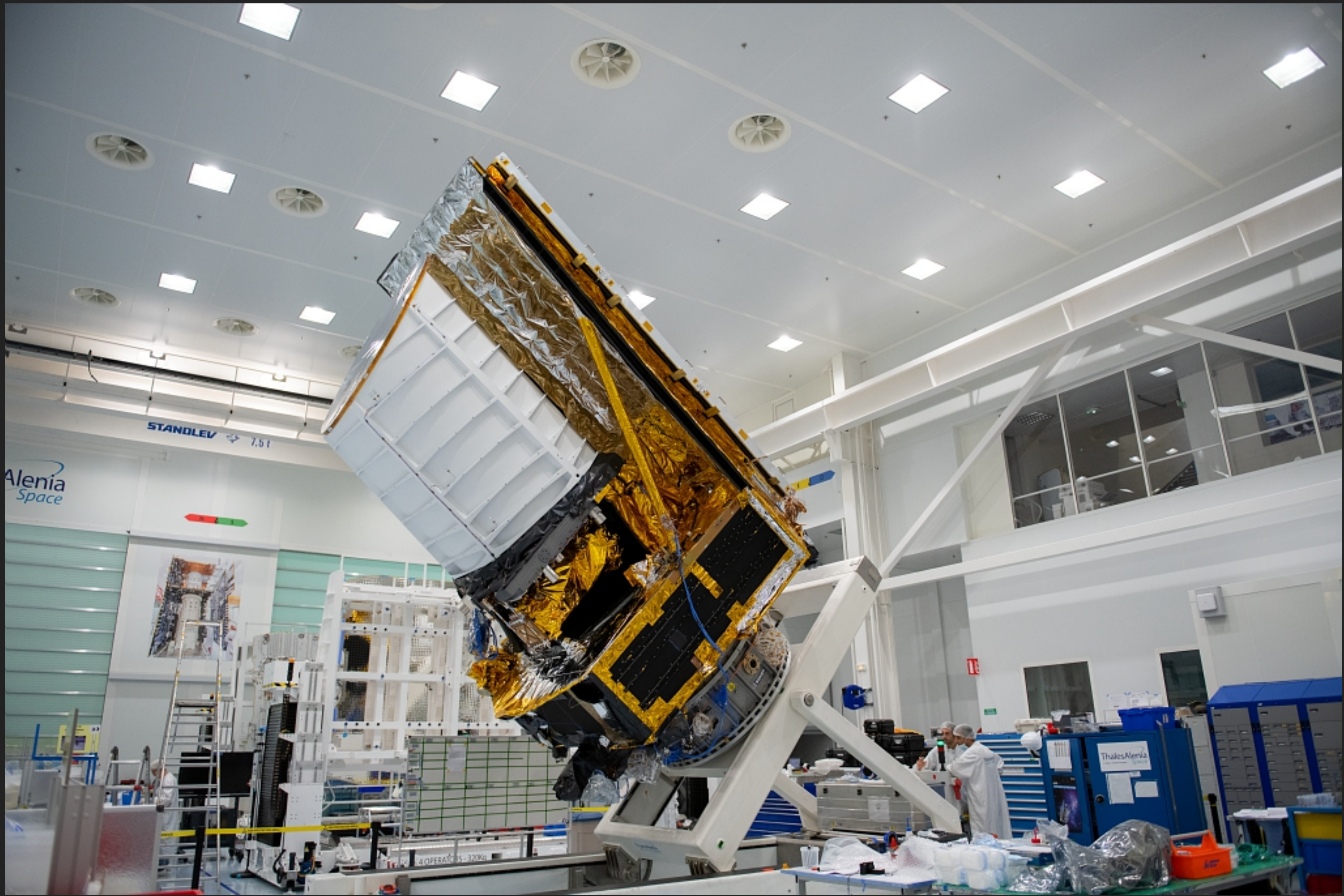
Intensity Mapping

- P_{gg} underlying galaxy power spectrum.
- P_{IM}/T_b^2: IM power spectrum.
- $P_{IM,g}/T_b^2$ cross-spectrum.
- Angle-dependent beam effect is in the signal*, damps accross the l.o.s.
- Along the l.o.s. damping due to FoG, but higher amplitude due to Kaiser.



* Beam term in appendix

Stage-IV surveys



Euclid space satellite, now waiting in Cannes

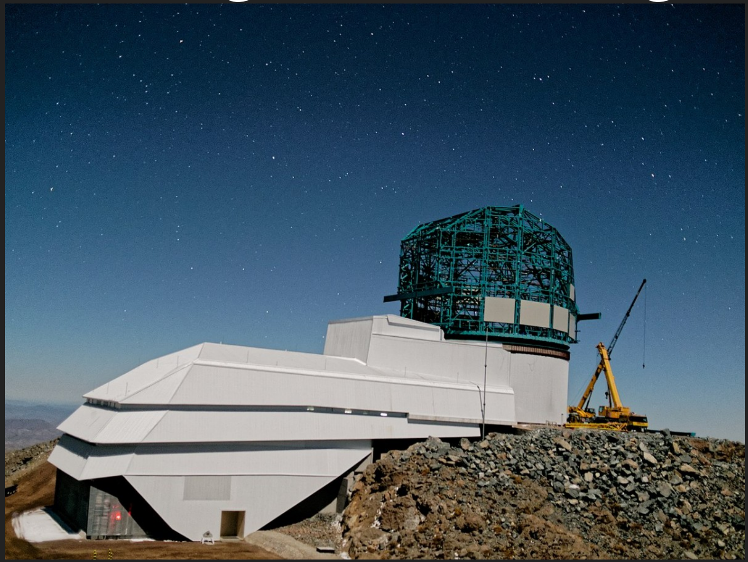
DESI telescope

Specialized in Galaxy Clustering

- 14 000 square degrees in the sky
- 30 million accurate galaxy spectra
- Redshifts: 0 < z < 2
- Quasars up to z~3.5
- 5 years of observation

Vera Rubin Observatory

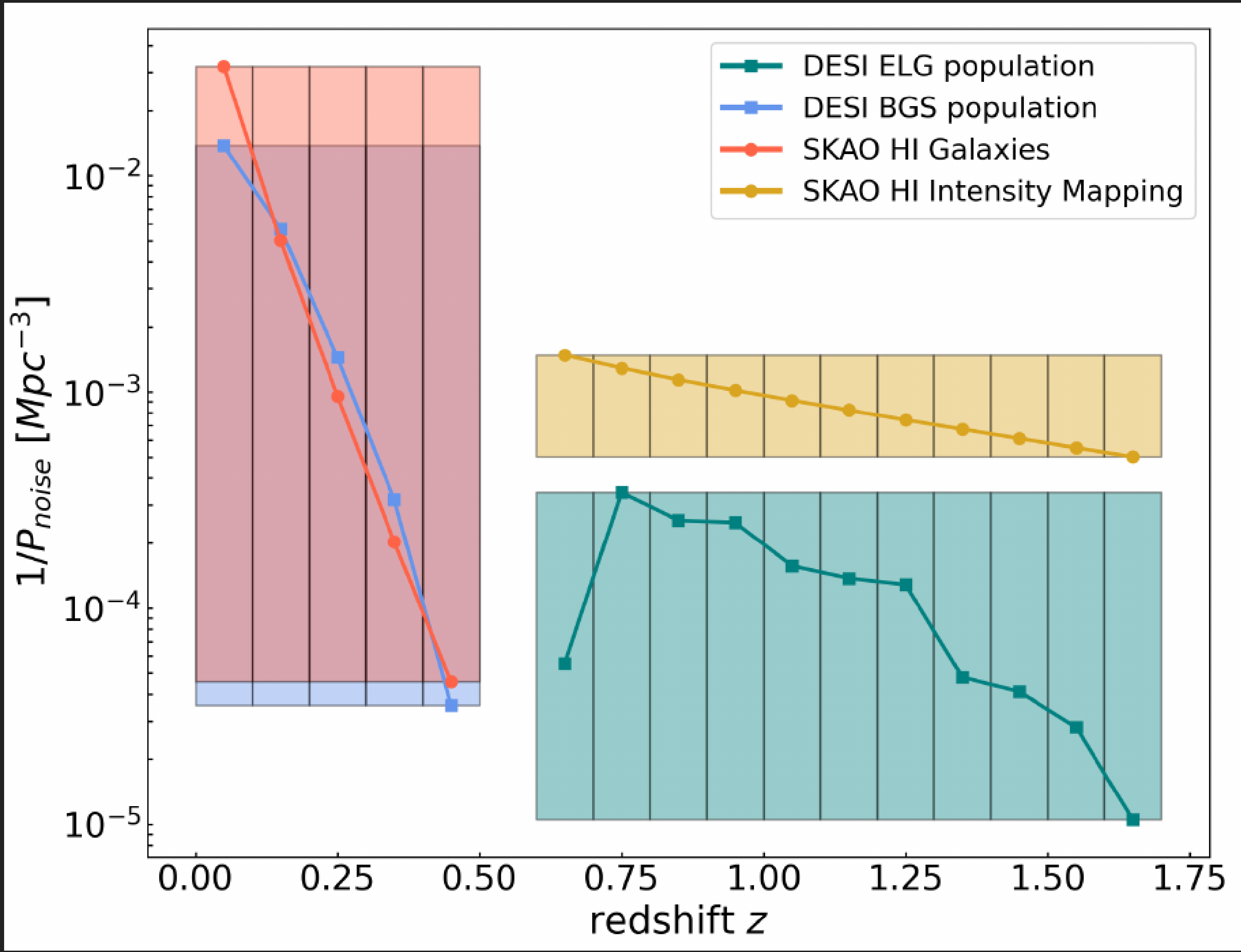
Specialized in Photometric Angular Probes:
Lensing and Clustering



- Located in Chile, 8.4m telescope
- 20 billion galaxies
- Redshifts: $0 < z \sim< 3$
- 18,000 square degrees
- 11 years of observation

Galaxy Clustering - IM Synergies

- GCsp-IM Cross-correlation in overlapping bins
- Addition in disjoint bins
- No GCsp-GCsp cross-correlation



Fisher Matrix forecasts

Given a likelihood function L, representing the probability of the data d, given the model parameters Θ , the Fisher matrix is defined as the Hessian of the L:

$$F_{\alpha\beta} = - \left. \frac{\partial^2 \ln L(\boldsymbol{\Theta})}{\partial \Theta_\alpha \, \partial \Theta_\beta} \right|_{\rm fid}$$

Assuming that L is a multivariate Gaussian distribution with a covariance matrix C independent of Θ :

$$F_{\alpha\beta} = \frac{\partial \boldsymbol{t}^{\mathsf{T}}}{\partial \Theta_\alpha} \, \mathsf{C}^{-1} \, \frac{\partial \boldsymbol{t}}{\partial \Theta_\beta}$$

The explicit form of F, depends on the given observational probe and the physical model assumption, for example for GCsp:

$$F_{\alpha\beta}^{AB} = \sum_{m,n=1}^{N_{\rm b}} \sum_{a,b,c,d,n} \frac{\partial P_{AB}(\bar{z}_m, k_a, \mu_b)}{\partial \Theta_\alpha} \times \frac{\partial P_{AB}(\bar{z}_n, k_c, \mu_d)}{\partial \Theta_\beta} \left[\mathsf{C}^{AB}(\bar{z}_m, \bar{z}_n) \right]^{-1}_{abcd}$$

Fisher Matrix forecasts

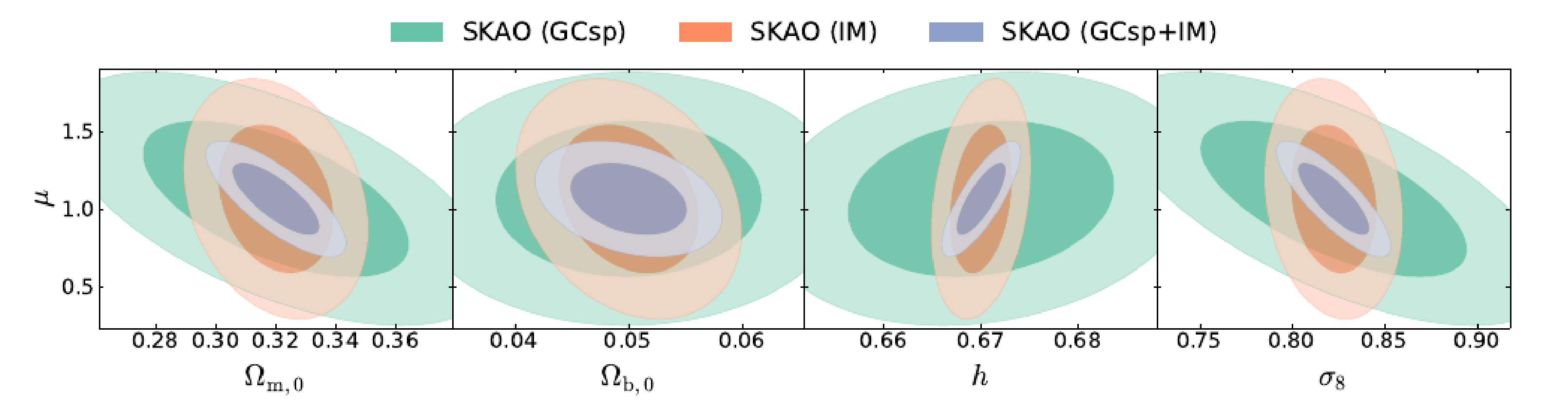
What do we expect from the forecasts before doing them, just by looking at the formulas and the specs?

- SKAO (Phase1) has more independent probes but less statistical power (n(z) and area) -> less constraining power than Stage-IV
- WL and 3x2pt better at constraining Σ
- GCsp and IM better at constraining μ
- GCsp x IM cross-corr. improves constraints on parameters?

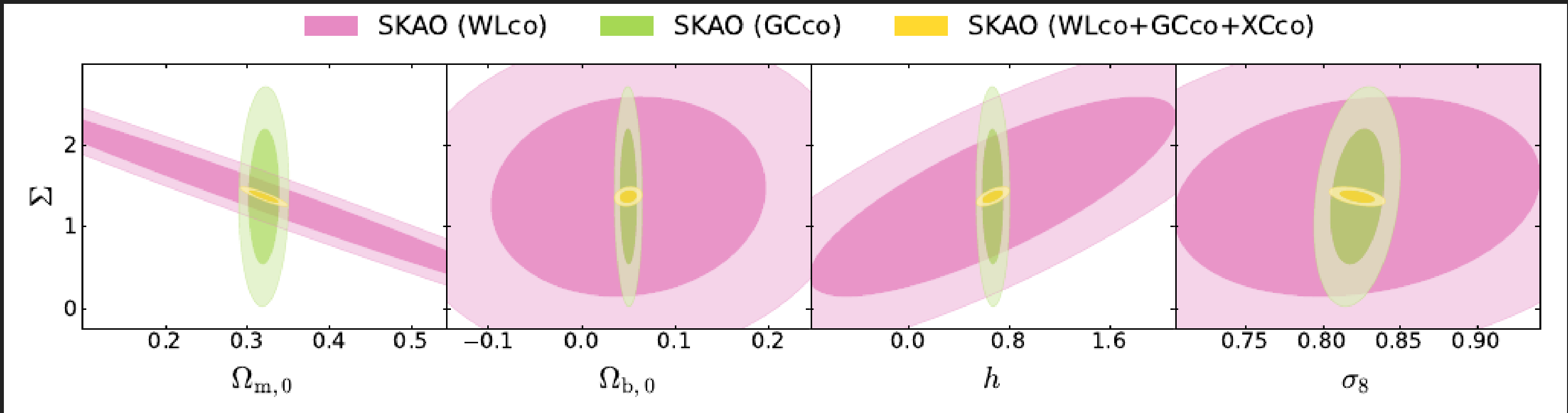
Let's see the results !

SKAO Results

- GC-IM probes measure μ at small z, where μ becomes important.

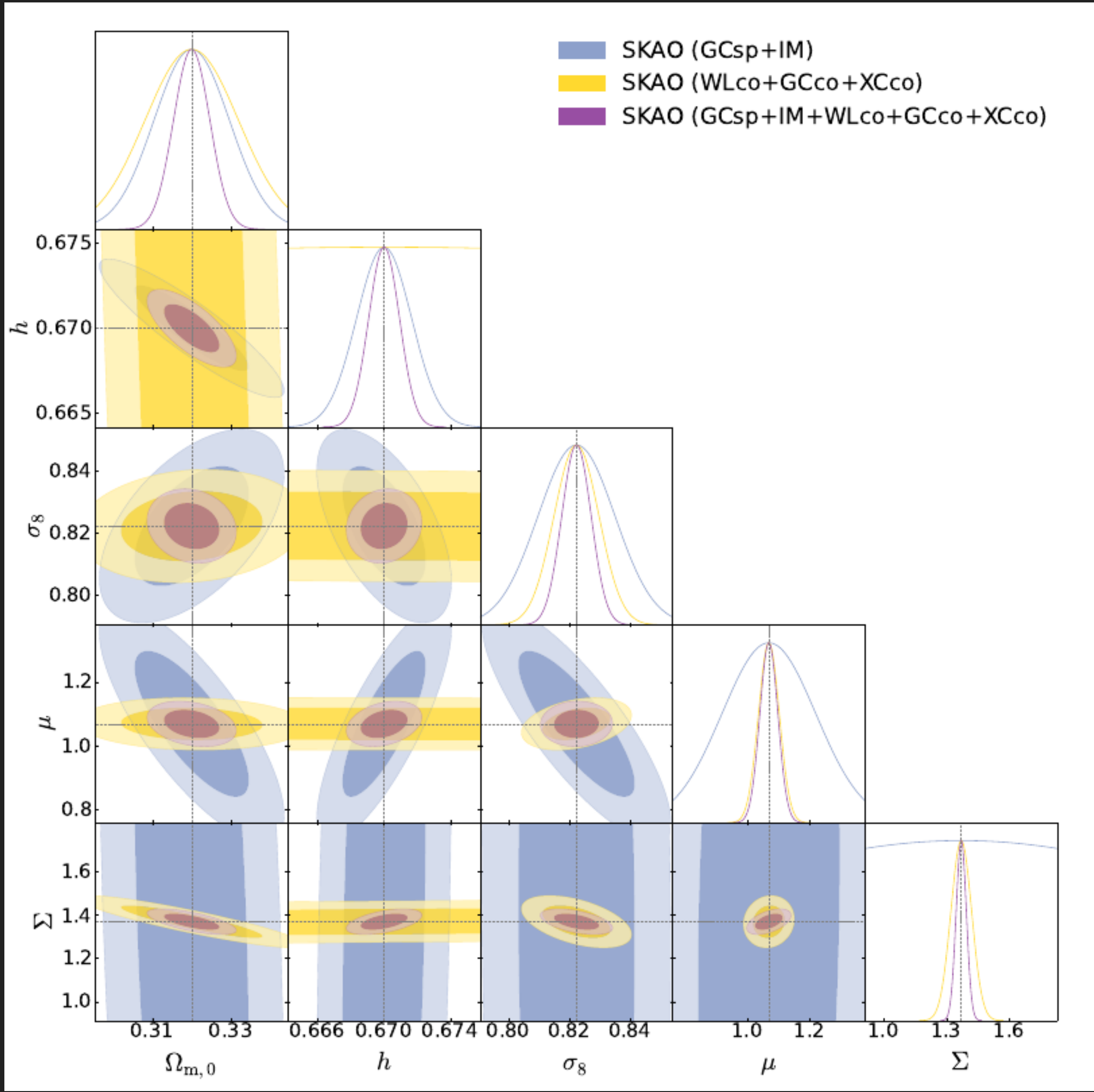


- Continuum probes measure better Σ ; Weyl potential is important.

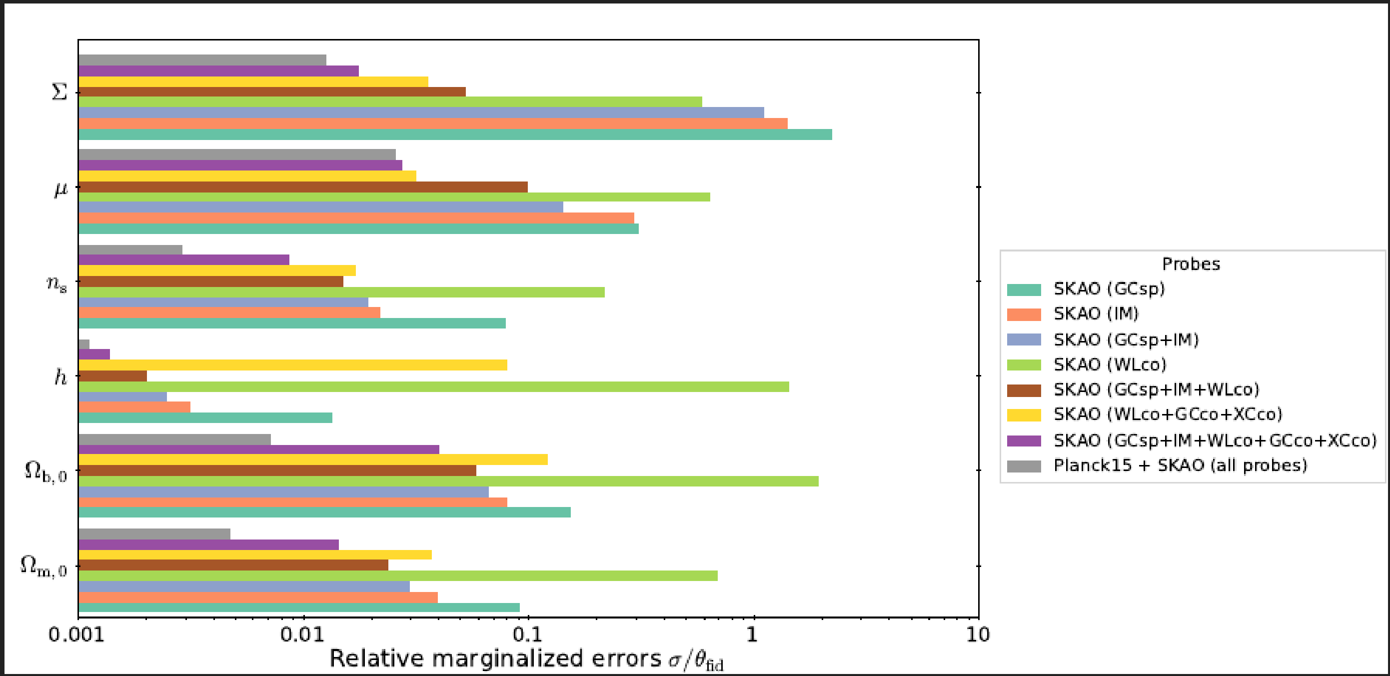


SKAO Results

- Blue: Combined GCsp+IM (3D)
- Yellow: Combined continuum probes (2D: angular)
- Purple: Combination of 3D and angular probes
- Constraints on μ are good in angular, due to the XC contribution from GCco clustering.



SKAO Results

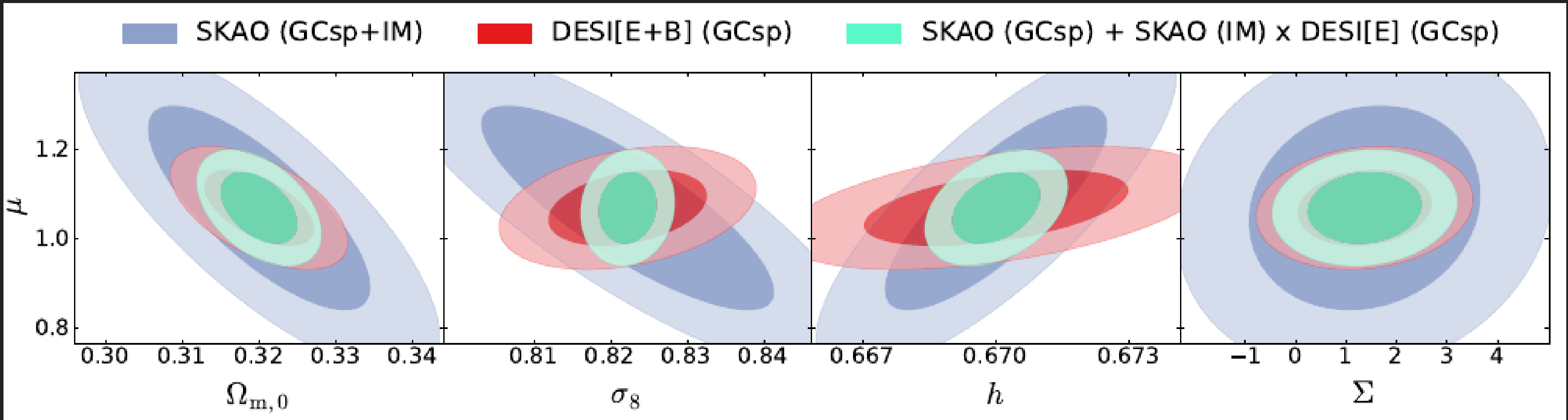


- Combining all SKAO probes (optimistic), 2-3% errors on μ and Σ.
- Minor improvement from Planck, mainly through ISW and CMB lensing.

SKAO	$\Omega_{m,0}$	$\Omega_{b,0}$	h	n_s	μ	Σ
Fiducial	0.32	0.05	0.67	0.96	1.07	1.37
GCsp	9.2%	15.5%	1.4%	7.9%	31.0%	224%
IM	3.9%	8.1%	0.3%	2.2%	29%	141%
GCsp+IM	3.0%	6.7%	0.2%	1.9%	14%	111%
WLco	69.4%	194%	144%	22%	63%	59%
GCsp+IM+WLco	2.4%	5.9%	0.2%	1.5%	10%	5.2%
WLco+GCco+XCco	3.7%	12.2%	8.0%	1.7%	3.2%	3.6%
SKAO_{all}	1.4%	4.0%	0.1%	0.9%	2.7%	1.8%
SKAO_{all}+Planck15	0.5%	0.7%	0.1%	0.3%	2.6%	1.3%

SKAO x DESI cross-correlation

- GCxIM probes do not improve constraints on MG parameters, but improvement on h and σ_8



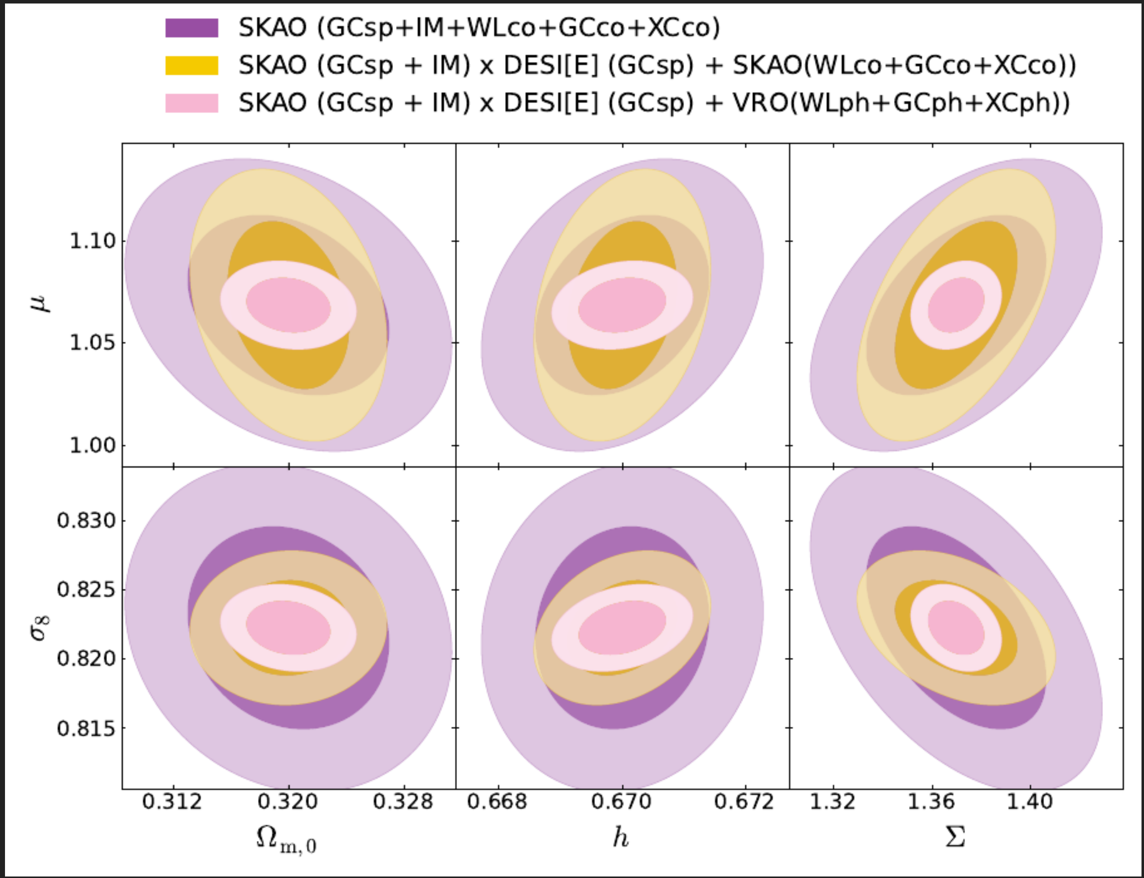
DESI_E : high-z Emission Line Galaxies

DESI_B: low-z Bright Galaxy Sample

SKAO GCsp: low-z HI Galaxies

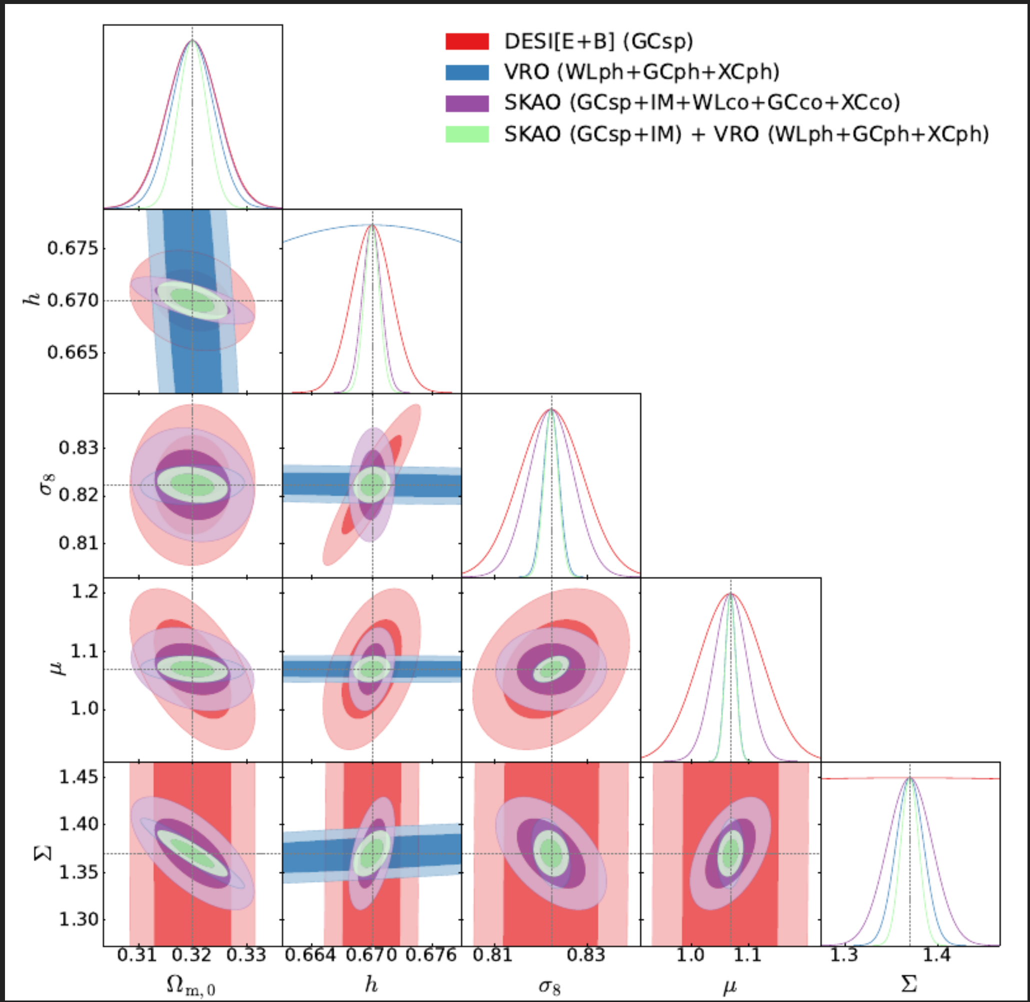
SKAO x DESI cross-correlation

- However, when combined with angular probes, there is a larger gain.



SKAO + optical

- SKAO + one Stage-IV survey is as competitive as two Stage-IV surveys together
- SKAO(all) better than DESI at constraining μ and especially Σ
- SKAO(all) better than VRO at constraining h
- SKAO(spectro) + VRO, as good as DESI+VRO
- SKAO(spectro) x DESI + VRO has the maximum constraining power



SKAO + optical

- SKAO + one Stage-IV survey is as competitive as two Stage-IV surveys

	$\Omega_{m,0}$	$\Omega_{b,0}$	h	n_s	μ	Σ
	0.32	0.05	0.67	0.96	1.07	1.37
$DESI_{E+B}$ (GCsp) + VRO (angular)	0.64%	1.69%	0.11%	0.23%	0.84%	0.59%
SKAO(angular) + SKAO (GCsp) + SKAO x $DESI_E$	0.87%	1.91%	0.09%	0.57%	2.55%	1.2%
SKAO (GCsp+IM) + VRO (angular) + SKAO x $DESI_E$	0.6%	1.51%	0.07%	0.23%	0.83%	0.55%

SKAO	$\Omega_{m,0}$	$\Omega_{b,0}$	h	n_s	μ	Σ
Fiducial	0.32	0.05	0.67	0.96	1.07	1.37
$SKAO_{all}$	1.4%	4.0%	0.1%	0.9%	2.7%	1.8%
$DESI_{E+B}$ (GCsp) + SKAO (angular)	1.1%	2.2%	0.2%	0.7%	2.6%	1.6%
SKAO (GCsp+IM) + VRO (angular)	0.8%	2.2%	0.1%	0.2%	0.9%	0.7%
$DESI_{E+B}$ (GCsp) + VRO (angular)	0.6%	1.7%	0.1%	0.2%	0.8%	0.6%

Conclusions

- ΛCDM is still the best fit to observations, however certain theoretical uncertainties and tensions in data are still of concern.
- Constraining modifications of gravity at the level of perturbations -> hints for alternative models.
- SKAO will be able to probe weak lensing and matter density perturbations in novel and independent ways compared to optical surveys.
- This will place constraints on deviations of standard gravity at yet unexplored redshifts.
- Synergies with optical surveys, like Euclid, DESI and Rubin, including cross-correlations are promising to remove systematics and break degeneracies.
- Using the good z-resolution of SKAO HI IM could place tight constraints on redshift-binned parametrizations.

Backup slide

SKA1 vs Euclid

SKA1:

GC+WL+XC (Continuum) + IM (HI 21cm) + GCsp(HI)

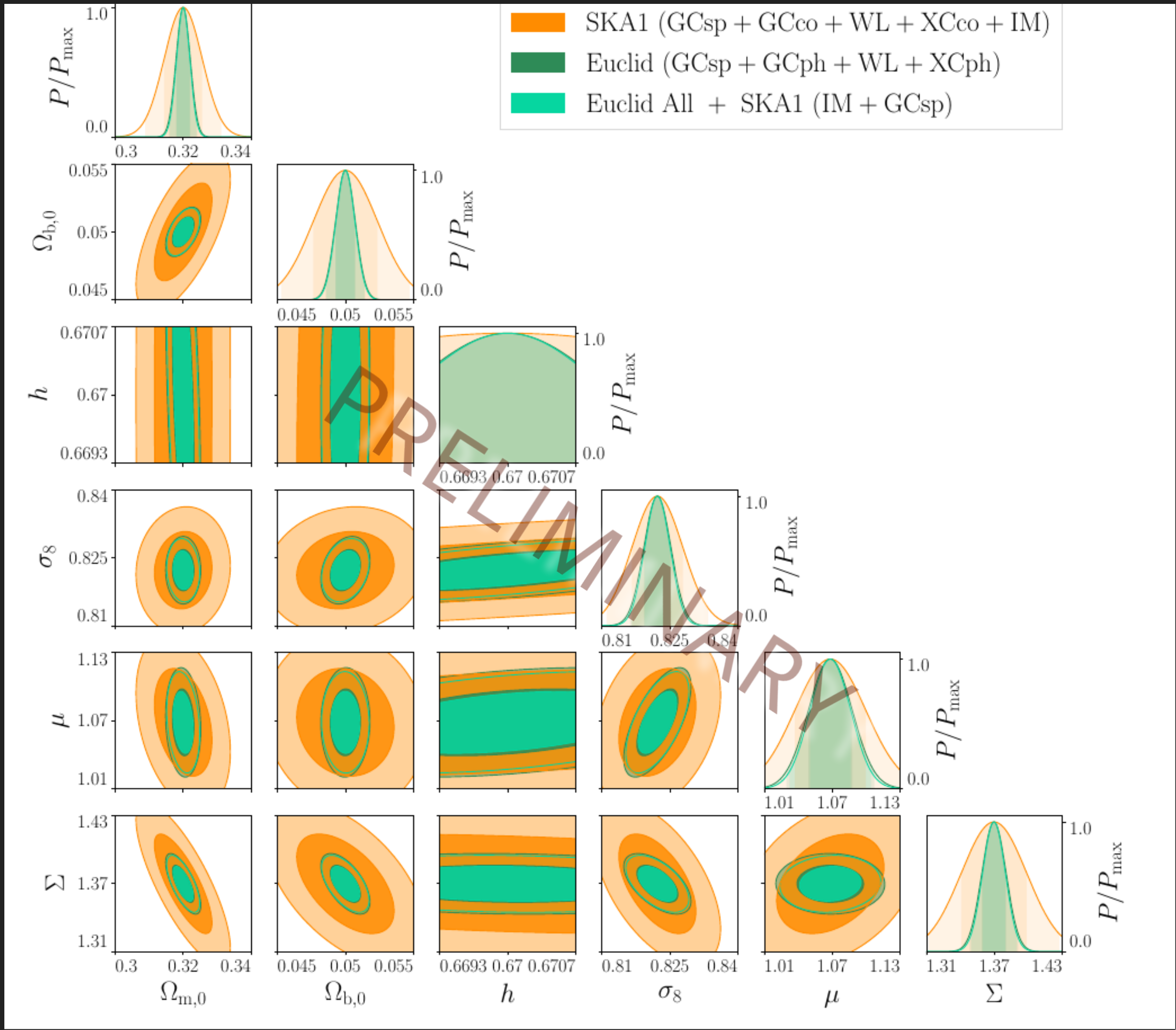
vs

Euclid (Gcsp+GCph+WL+XCph)

vs

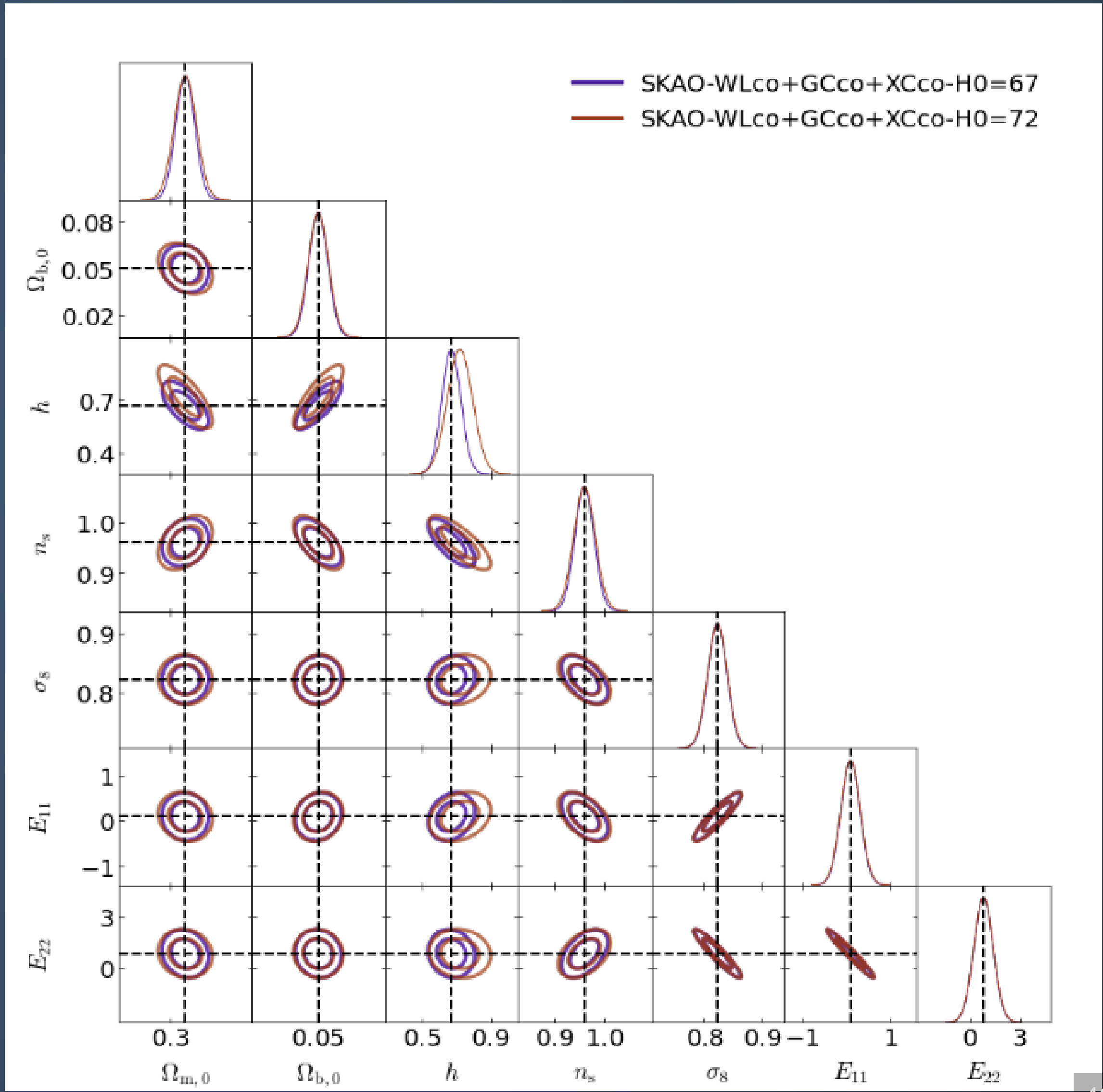
Euclid (Gcsp+GCph+WL+XCph) +SKA1 Pk-probes.

Unfortunately, the μ constraints from Euclid alone dominate over the improvement that SKA1 "Pk-probes" add



Backup slide

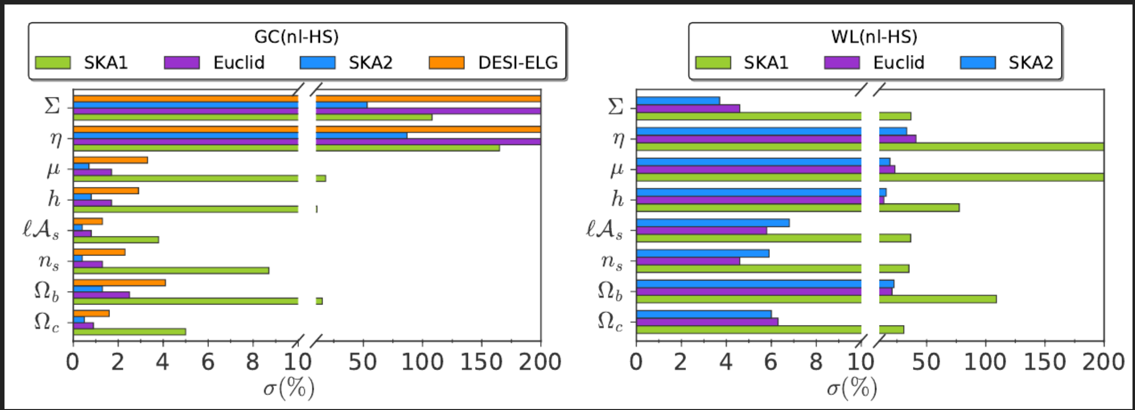
Testing at higher H0 value



Late-time: Old SKA1, Euclid forecasts

- Old SKA1 forecasts contain only WL continuum and GCsp from HI galaxies
- Linear GCsp formalism and no IA params in WL

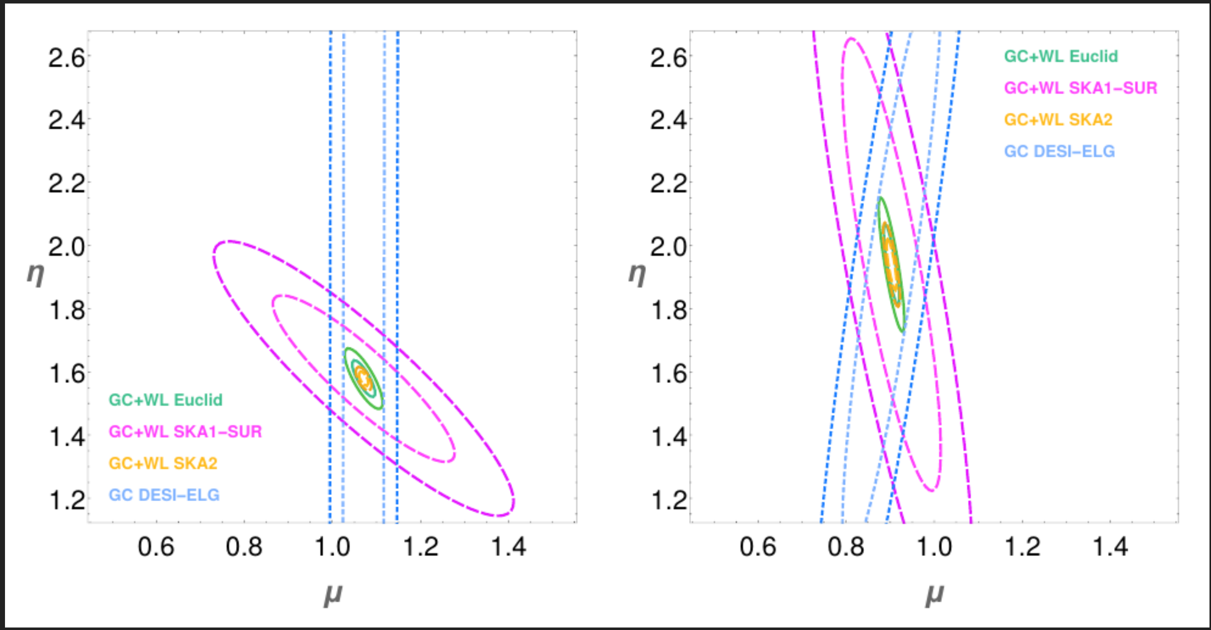
	Ω_c	Ω_b	n_s	$\ell\mathcal{A}_s$	h	μ	η	Σ	MG FoM
Fiducial	0.254	0.048	0.969	3.060	0.682	1.042	1.719	1.416	relative
GC(nl-HS)									
Euclid	0.9%	2.5%	1.3%	0.8%	1.7%	1.7%	475%	291%	2.9
SKA1-SUR	5%	15.3%	8.7%	3.8%	10.8%	18.1%	165%	108%	1.7
SKA2	0.5%	1.3%	0.4%	0.4%	0.8%	0.7%	86.8%	53.2%	5.5
DESI-ELG	1.6%	4.1%	2.3%	1.3%	2.9%	3.3%	899%	552%	1.8
WL(nl-HS)									
Euclid	6.3%	20.7%	4.6%	5.8%	13.8%	23.3%	40.9%	4.6%	4.5
SKA1	30.8%	109%	35%	36.5%	77.6%	220%	405%	36.8%	0.5
SKA2	6%	22.5%	5.9%	6.8%	15.9%	19%	33.2%	3.7%	4.9
GC+WL(lin)									
Euclid	1.8%	5.9%	2.8%	2.3%	4.2%	7.1%	10.6%	2%	6.6
SKA1	10.1%	47.6%	25.4%	21.7%	40.4%	26.4%	28.8%	13.6%	3.7
SKA2	1.2%	4.5%	2.2%	1.9%	3.3%	4.1%	5.5%	1.6%	7.5

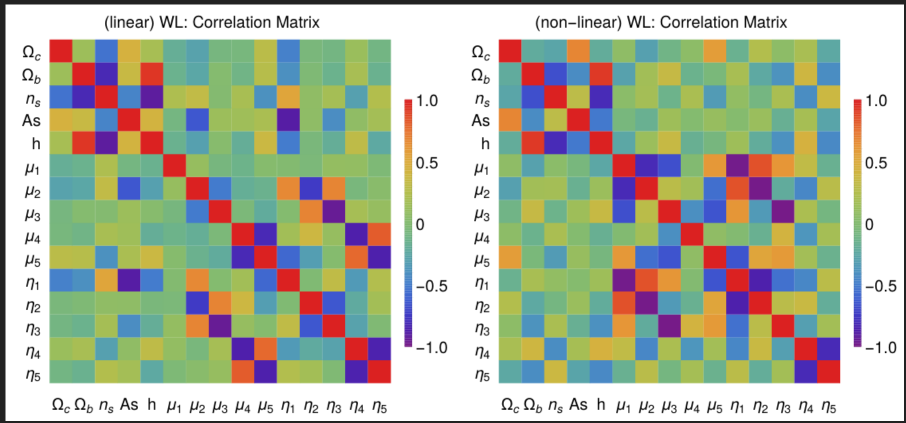


Casas et al (2017), arXiv:1703.01271

Late-time: Old SKA1, Euclid forecasts

- However, we do roughly recover the same contour orientations and constraints with the new WL SKA1 forecasts.
- Deeply non-linear Pk recipe is the same, using an interpolation to recover GR at small scales.





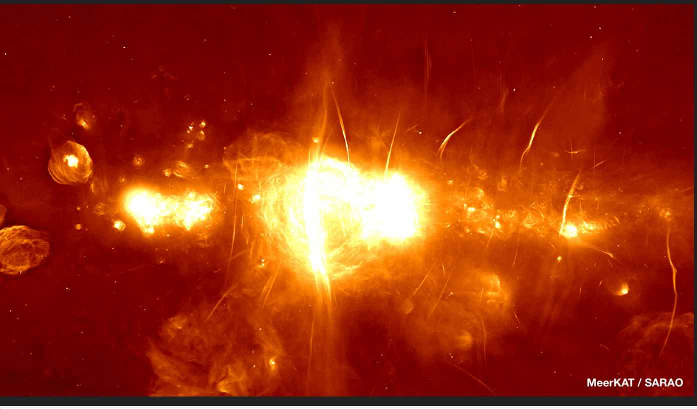
Casas et al (2017), arXiv:1703.01271

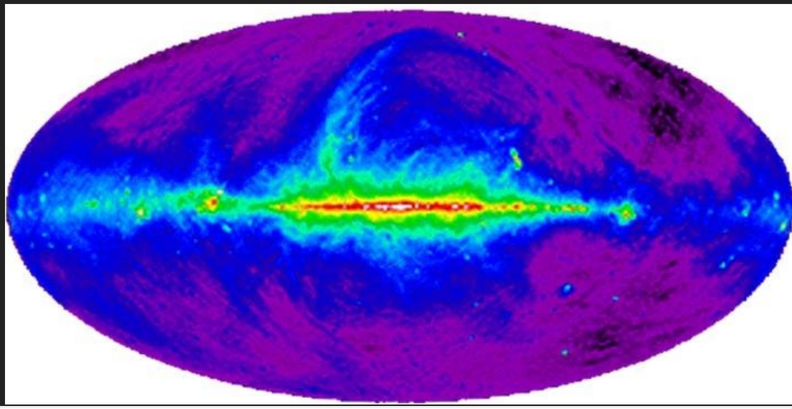
The Square Kilometer Array Obs. (SKAO)

- Next-generation Radioastronomy observatory
- Largest radiotelescope in the world: eventually 1km^2 area.
- 15 countries + partners
- Australia + South Africa installations
- ~2 billion Euros up to 2030.
- 5Tbps data rate and 250 Pflops needed for computation

The Square Kilometer Array Obs. (SKAO)

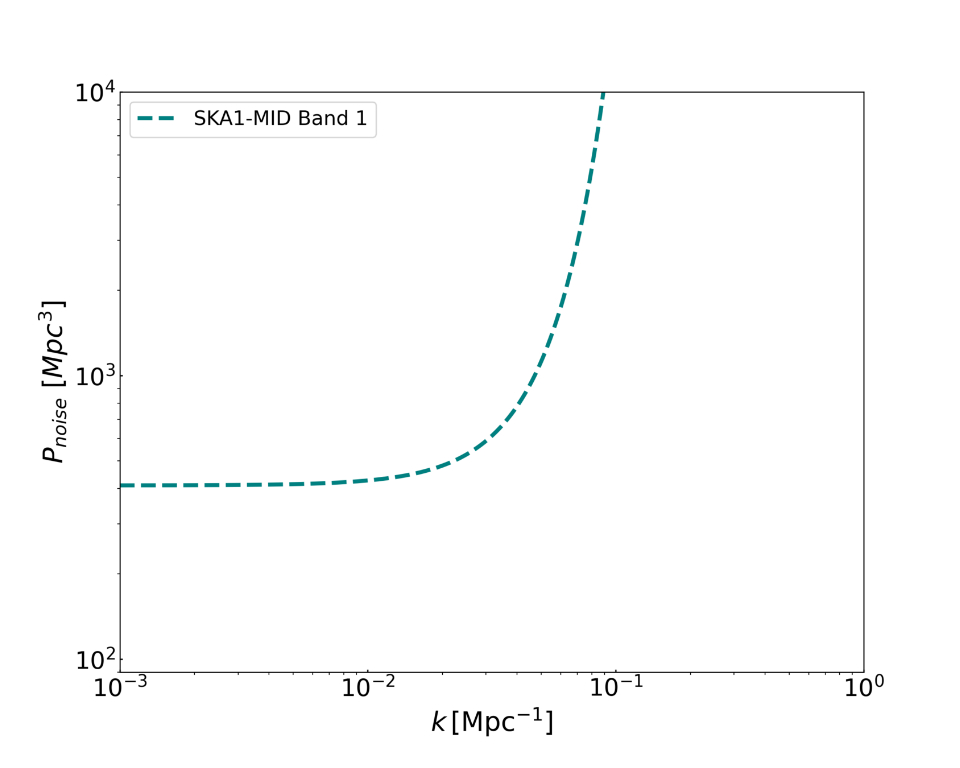
- 15,000-20,000 square degrees in the sky
- Precursors: 10^7, SKA-phase1: 10^8, SKA-phase2: 10^9 galaxies
- SKA1-MID: 0 < z < 3
- SKA1-Low: 3 < z < ~ 20
- Cosmology is just one small area, Exoplanets, Craddle of Life, Reionization, Cosmic Magnetism....





Intensity Mapping Noise Terms

$$P_{\rm noise}(z) = \frac{2\pi f_{\rm sky}}{\nu_{21} t_{\rm tot}} \frac{(1+z)r(z)^2}{\mathcal{H}(z)} \left[\frac{T_{\rm sys}(z)}{\bar{T}_{\rm HI}(z)}\right]^2 \frac{\alpha(z,k_\perp)}{\beta(z,k_\perp)^2} \quad h^{-3}{\rm Mpc}^3$$



Number of dishes

$$\alpha_{SD} = \frac{1}{N_d}$$

Effective beam

$$\beta_{SD} = \exp\left[-\frac{k_\perp r(z)^2 \theta_b(z)^2}{8\ln 2}\right]$$

Jolicoeur et al (2020) arXiv:2009.06197

Backup slide

Backup slide

Backup slide

Backup slide

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## Parameter bounds
****
SKA1 (GCsp)
Omegam    Omegab    h    ns    sigma8    mu    Sigma
0.3200    0.0500    0.6700    0.9600    0.8222    1.0685    1.3697
0.0265    0.0069    0.0090    0.0720    0.0469    0.3173    3.2427
8.2829%    13.8606%    1.3448%    7.5051%    5.7076%    29.6927%    236.7406%
****
****
SKA1 (IM)
Omegam    Omegab    h    ns    sigma8    mu    Sigma
0.3200    0.0500    0.6700    0.9600    0.8222    1.0685    1.3697
0.0170    0.0057    0.0216    0.0565    0.0214    0.2498    1.9288
5.3020%    11.3062%    3.2188%    5.8894%    2.6055%    23.3790%    140.8123%
****
****
SKA1 (WL)
Omegam    Omegab    h    ns    sigma8    mu    Sigma
0.3200    0.0500    0.6700    0.9600    0.8222    1.0685    1.3697
0.2221    0.0975    0.9668    0.2110    0.0788    0.6818    0.8108
69.4198%    194.9278%    144.2922%    21.9805%    9.5874%    63.8066%    59.1968%
****
****
SKA1 (GCco+WL)
Omegam    Omegab    h    ns    sigma8    mu    Sigma
0.3200    0.0500    0.6700    0.9600    0.8222    1.0685    1.3697
0.0121    0.0061    0.0549    0.0186    0.0095    0.0351    0.0544
3.7726%    12.2405%    8.1985%    1.9403%    1.1535%    3.2890%    3.9708%
****
****
SKA1 (GCco+WL+XCco)
Omegam    Omegab    h    ns    sigma8    mu    Sigma
0.3200    0.0500    0.6700    0.9600    0.8222    1.0685    1.3697
0.0119    0.0061    0.0539    0.0164    0.0074    0.0337    0.0493
3.7129%    12.1608%    8.0383%    1.7040%    0.9005%    3.1501%    3.6000%
****
****
SKA1 (GCsp+GCco+WL+XCco+IM)
Omegam    Omegab    h    ns    sigma8    mu    Sigma
0.3200    0.0500    0.6700    0.9600    0.8222    1.0685    1.3697
0.0056    0.0024    0.0031    0.0100    0.0056    0.0314    0.0289
1.7506%    4.7395%    0.4583%    1.0451%    0.6844%    2.9344%    2.1134%
****
```