Cosmology with SKA : intensity mapping

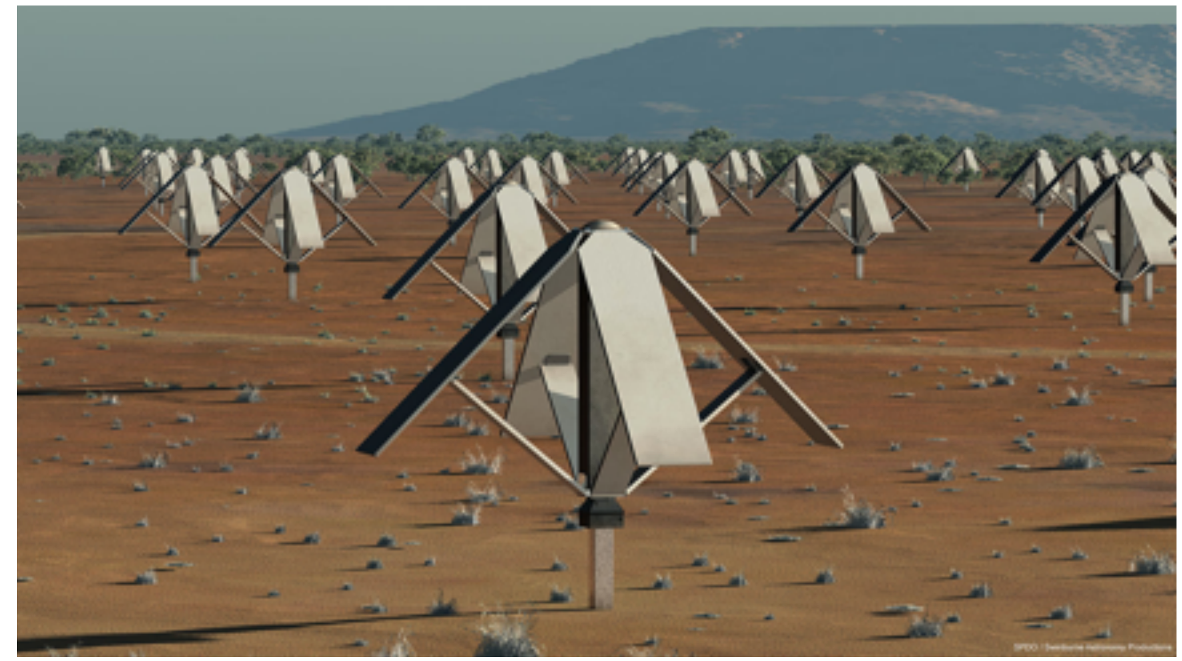
- SKA telescope
- Review of main cosmology goals
- Focus on intensity mapping : « best prospect for doing transformative cosmology with Phase 1 of the SKA »

proceedings from « Advancing astrophysics with SKA », 06/2014

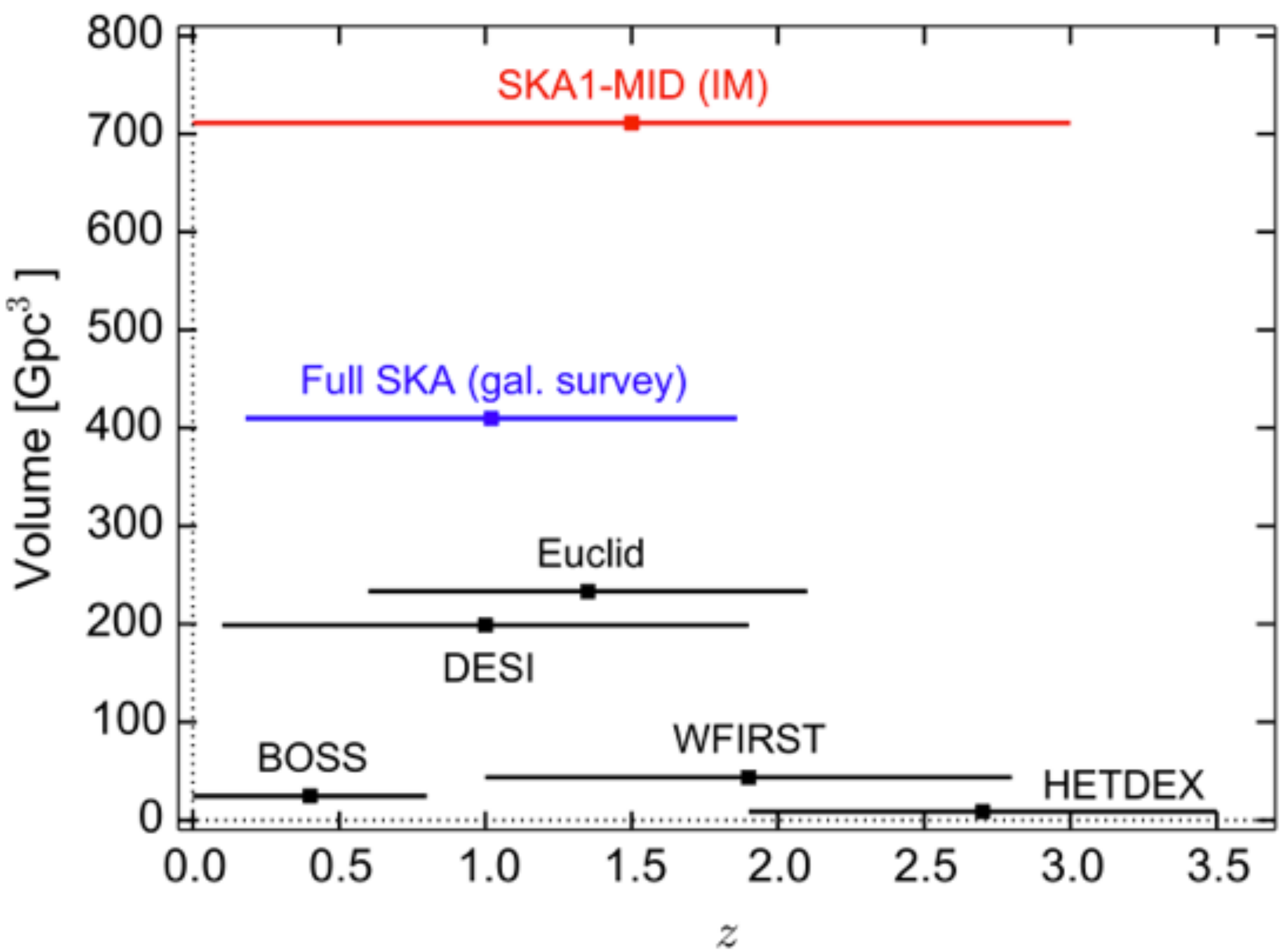
Cosmo-club 17/03/2015
E. Armengaud

SKA

- Major radio observatory of this century…
- SKA1 (2020) : low, mid, survey
  - low : 250k antennas; 50-350 MHz ; 21cm@EoR
  - mid : 64+190 dishes; 350-3050 MHz
  - survey : 36+60 dishes ; 650-1670 MHz
- SKA2 (2025)



Advantage of surveys with SKA : huge volumes



SKA2 HI galaxy survey : 30 kdeg2, out to z~2

SKA1 HI IM : 30 kdeg2, out to z~3

HI galaxy redshift survey

- HI = principally dense regions inside galaxies (shielded from UV bg)
- 1420/(1+z) MHz

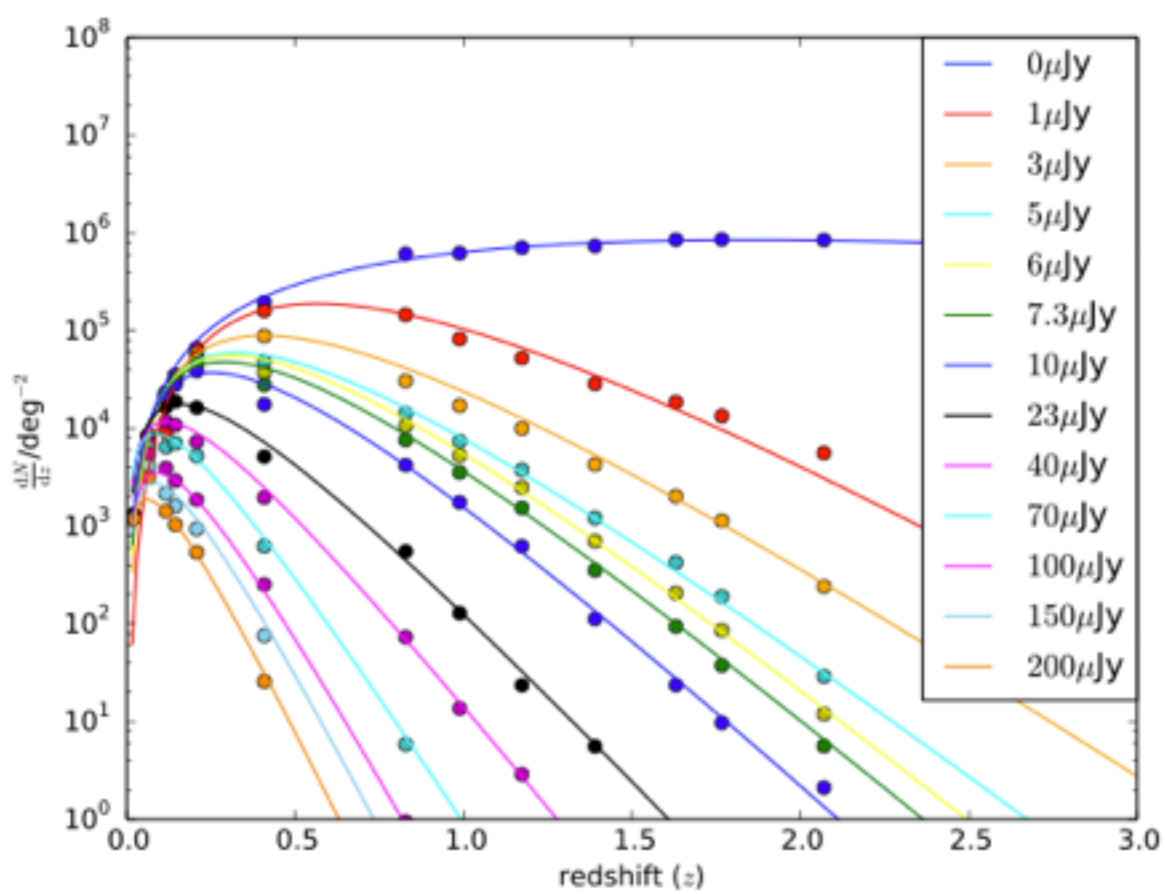
- Systematics/bias different from optical
- No star contamination; but galactic synchrotron complicate angular selection fct

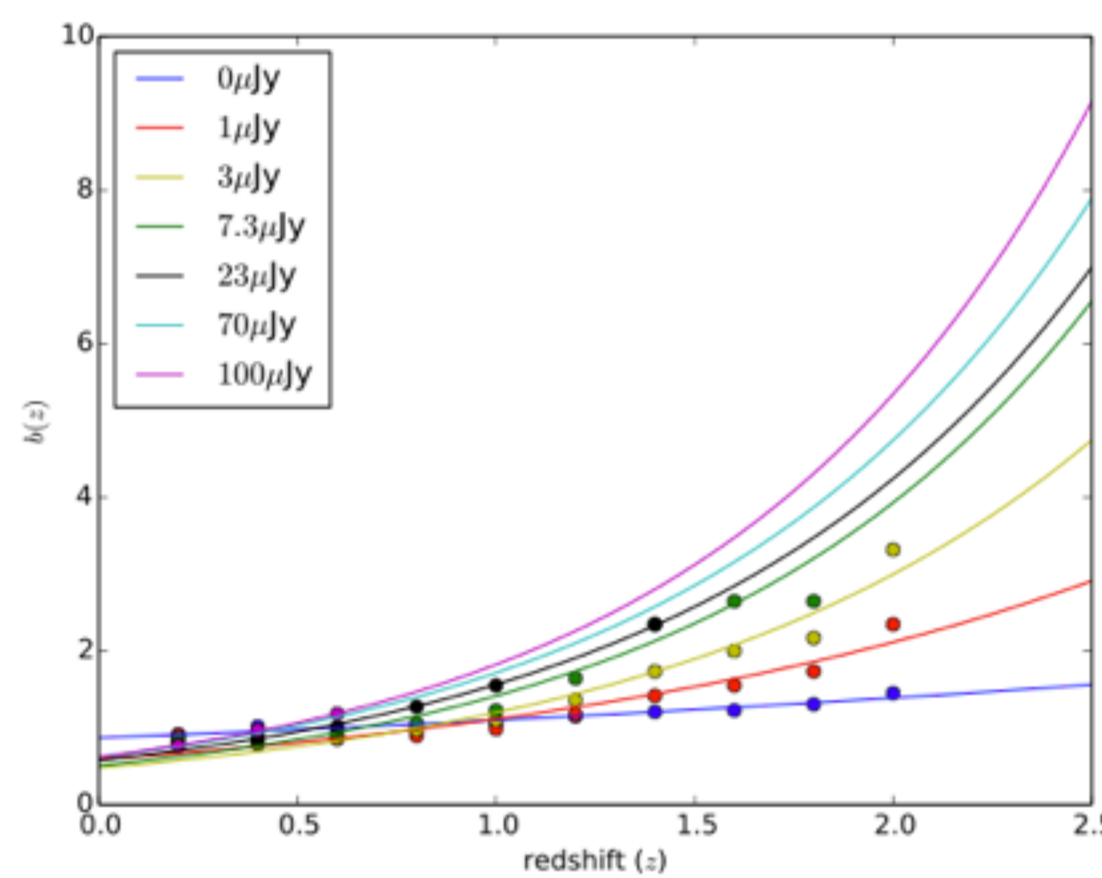
- So far, only few galaxies up to z~0.2 detected
  - Weak emission : for (z=1.5, M_HI = 10^9 Msol) yields 1 muJy

- SKA1 « not transformational » : 5x10^6 galaxies out to z=0.5
- SKA2 « competitive with Euclid » : 30 kdeg2, 10^9 HI galaxies 0.2<z<1.8

HI galaxy redshift survey : signal from individual galaxies

- SAX-sky simu : Millennium simulation + galaxies + HI (+CO..).
  - Derive gaz for each galaxy « based on properties of nearby regular spirals »
- Find analytic model for dn/dz and b(z)
- Derive ~one billion HI galaxies for SKA2





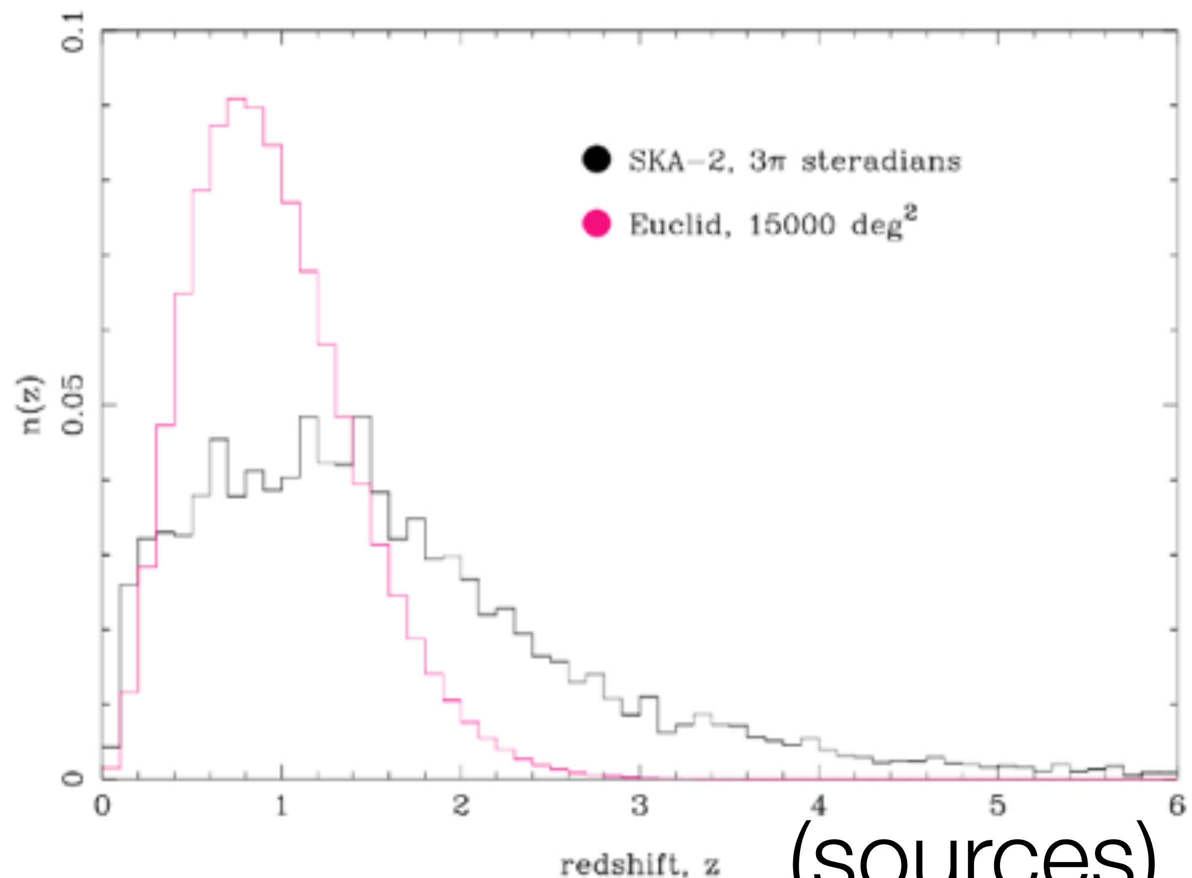
Continuum survey

- Already used for ISW detection (large sky volume)
- No z but if good resolution can separate different source populations with different biases

  ==> use multitracer technique for bias-related measurement: eg. prospect sigma(f_NL)=2.2 for SKA2
- Sources have optical emission lines : follow-up spectroscopy
- Dipole in LSS :
  - Current constraint : NVSS survey.
  - SKA2 all-sky continuum : expect measurement of dipole similar to Planck: 1 degree position, few % amplitude.

Lensing with continuum survey

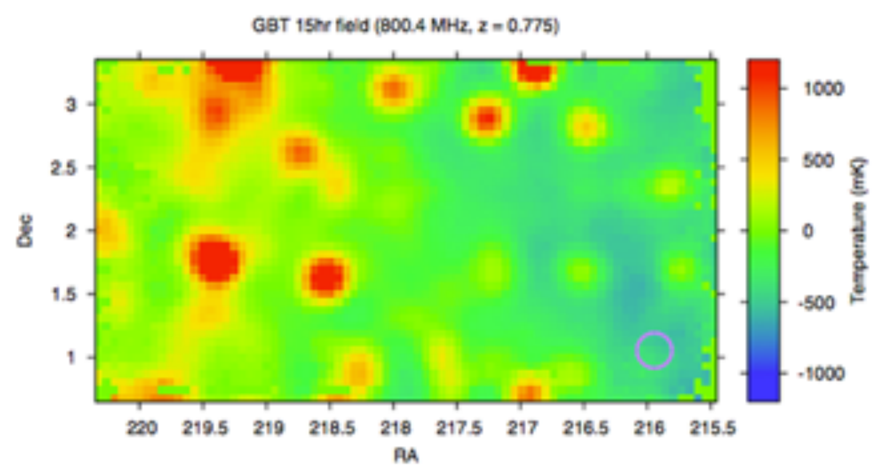
- Complementary to optical surveys: different systematics (beam)
- Scan larger z range
- May use polarized emission : yield intrinsic (unlensed) shape of galaxies
    - if polarization signal strong enough + low scatter in polarization angle vs galaxy angle…
- SKA1 : medium-deep survey, 5000 deg2, 1 muJy
- SKA 2 : 3pi survey, 75 sources/arcmin?? (100 nJy)

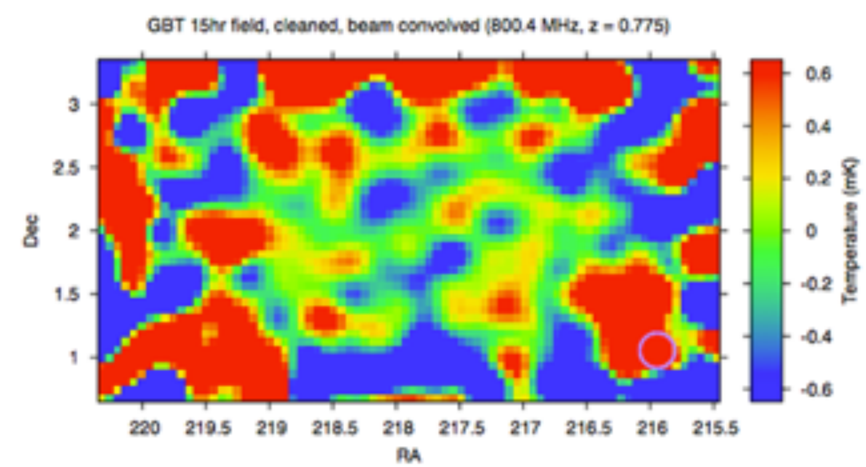


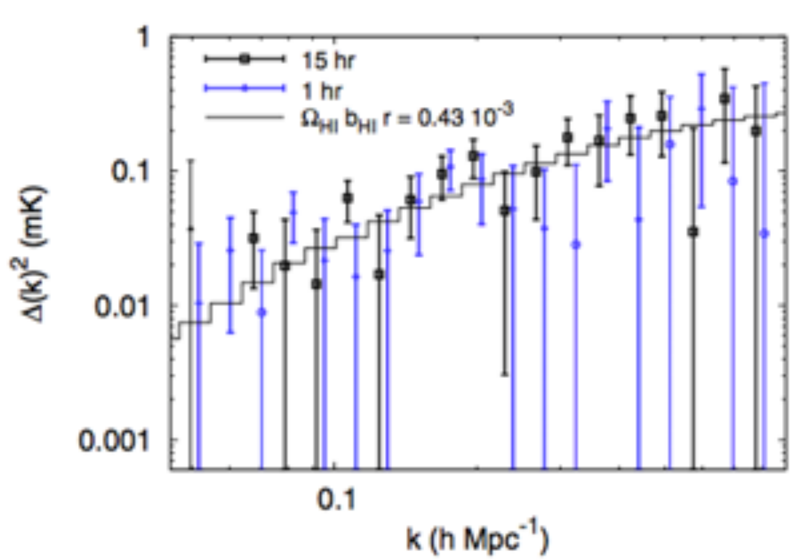
(sources)

(Late-time) Intensity Mapping

- Do not resolve galaxies
  - Information = datacube (ra,dec,z)
- Foregrounds and systematics



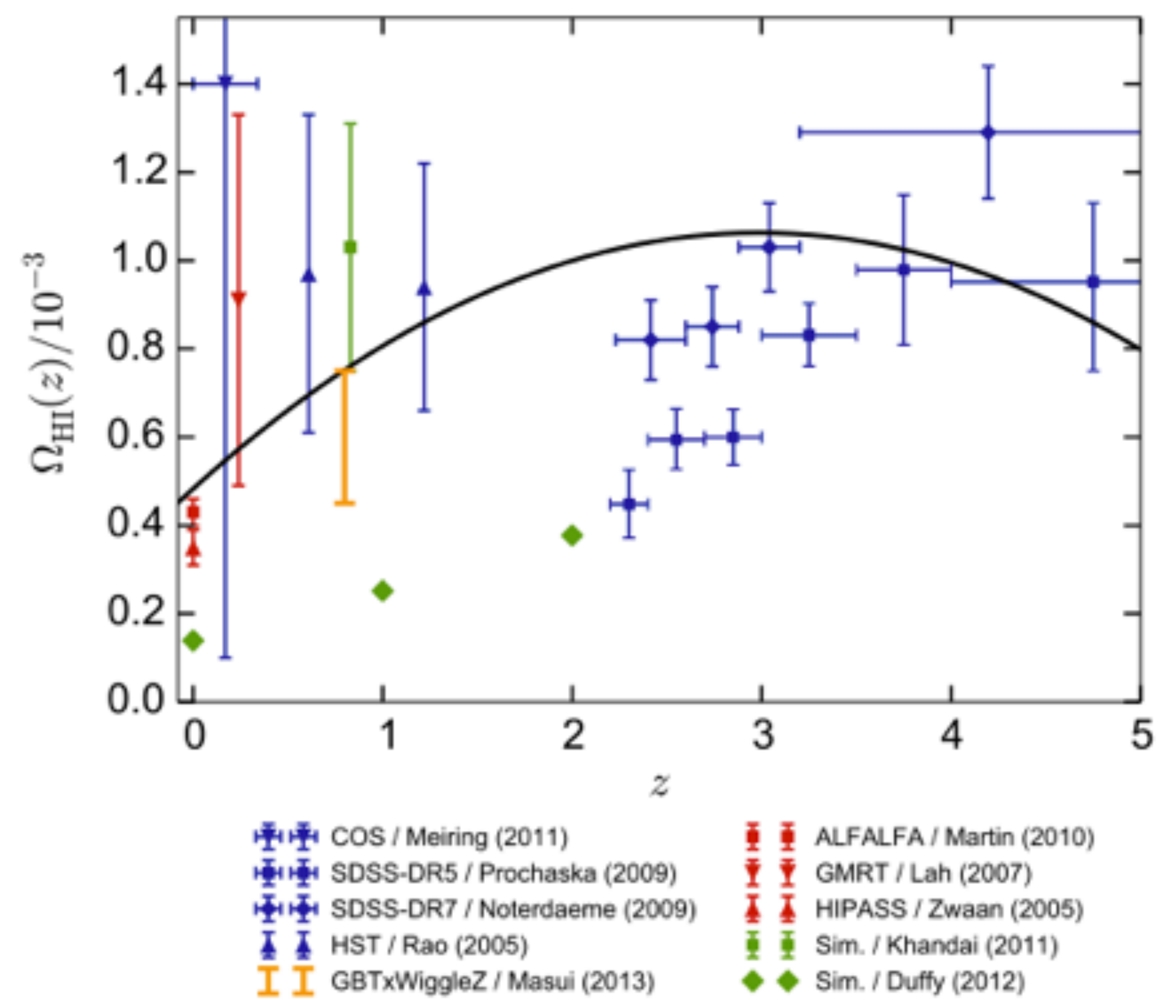




IM signal

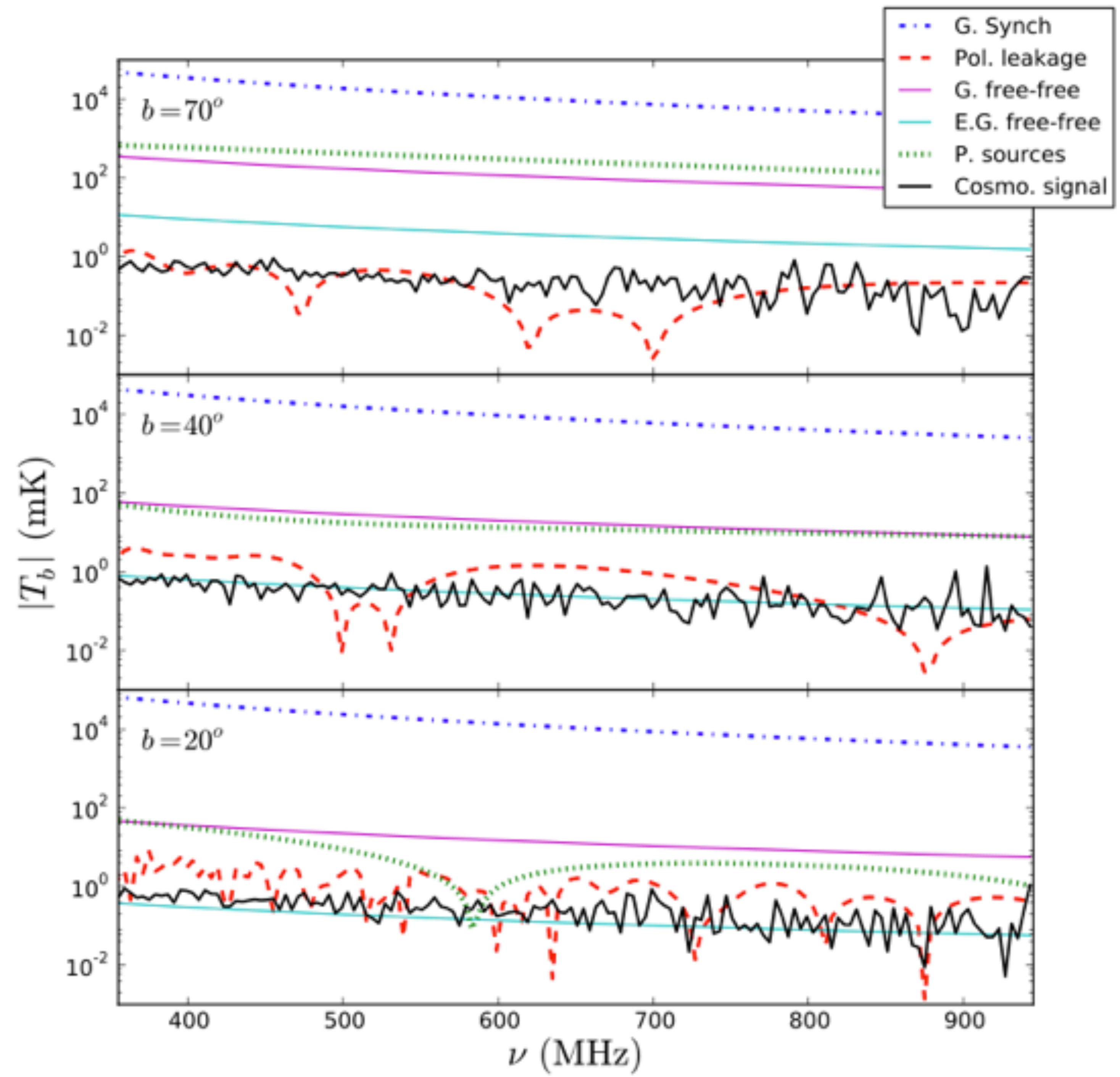
$$\overline{T}_b(z) \approx 566h \left(\frac{H_0}{H(z)}\right) \left(\frac{\Omega_{HI}(z)}{0.003}\right) (1+z)^2 \,\mu K$$

- Omega_HI : from 21cm observations from galaxies at low z ; Damped Ly-alpha systems at high z
- Brightness fluctuations: need to know the bias b_HI
- For predictions : simple model where bias obtained from link between amount of HI in a dark matter halo of mass M : M(HI) = AM^a
- Huge uncertainties. Font-Ribera et al. (2012) : DLA ==> HI hosted in high mass halos ==> factor 2 on bias



Foregrounds/systes

- Dominant : GSE; power law freq (index varies with latitude)
- Extragalactic sources : Poisson noise
- Polarized signal from GSE (strong frequency dependance due to Faraday rotation) + leakage to unpolarized measurement
  - Most problematic (for current measurements?)
- Atmosphere ; RFI
- 1/f noise : fast scan speed

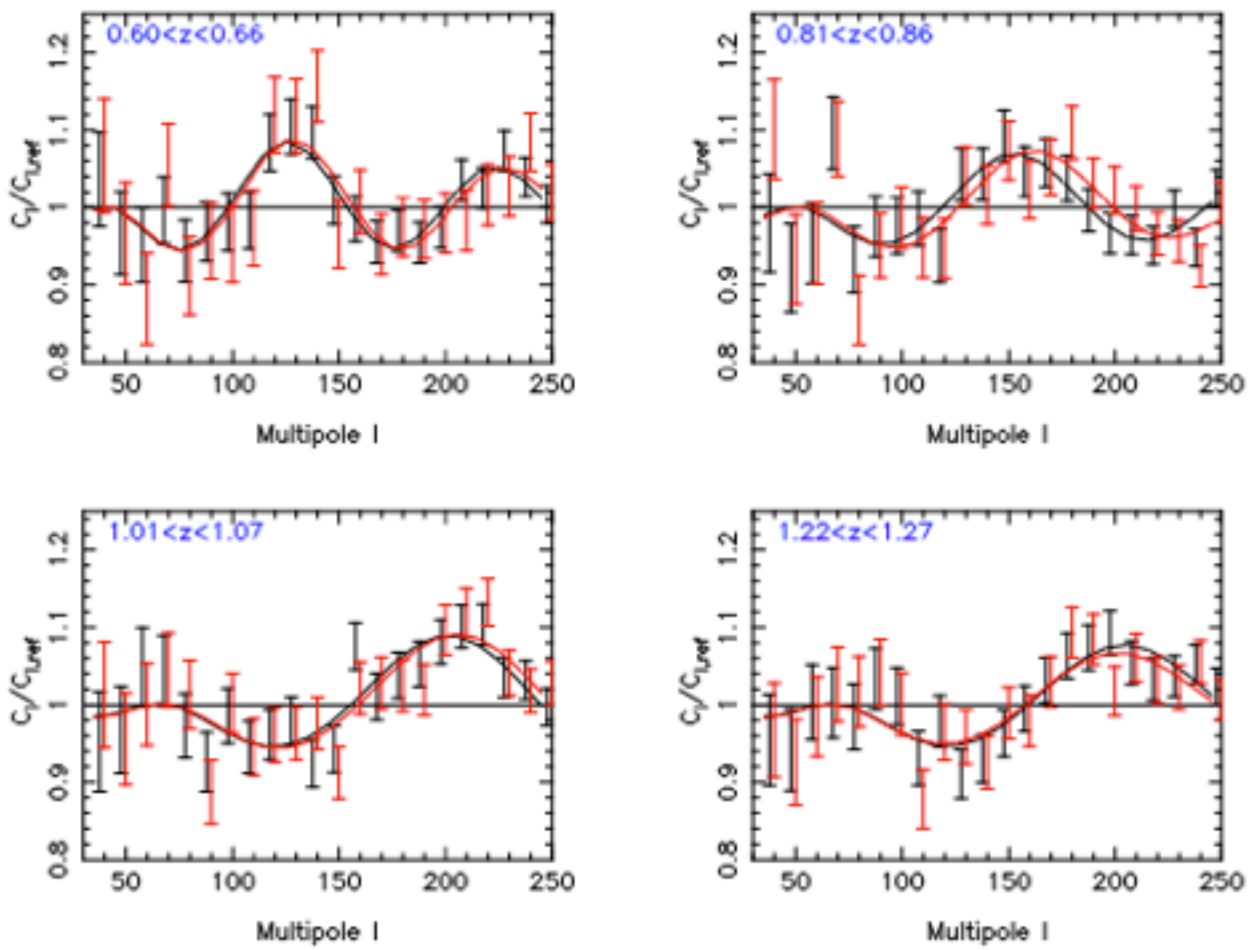


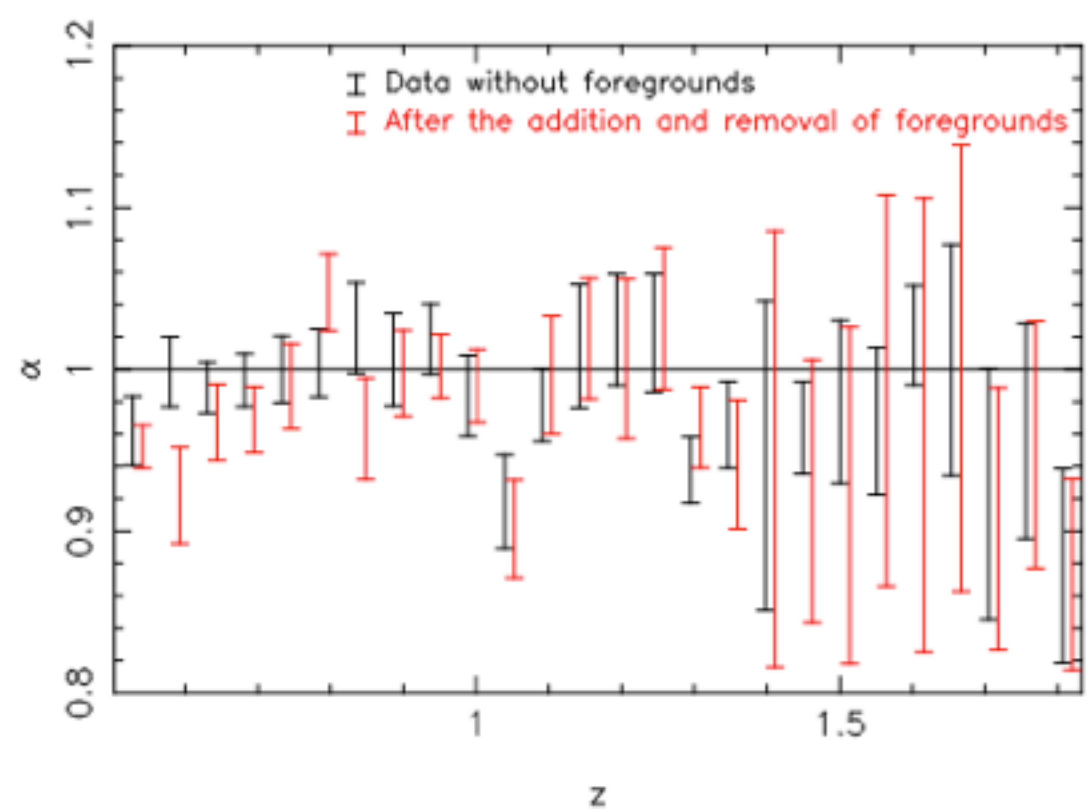
Foreground cleaning

- « Not unreasonable to hope that they can be successfully subtracted ».
  - Mostly thanks to frequency structure (smoothness)
  - Several algorithms (« blind » vs « non-blind »)
- Ok for « robust » features like BAO
- Residual bias on large scales ?? « can be successful over a wide range of scales provided foregrounds are sufficiently smooth »
- Instrumental errors (beam, calibration) can significantly impact foreground removal

Foreground cleaning example

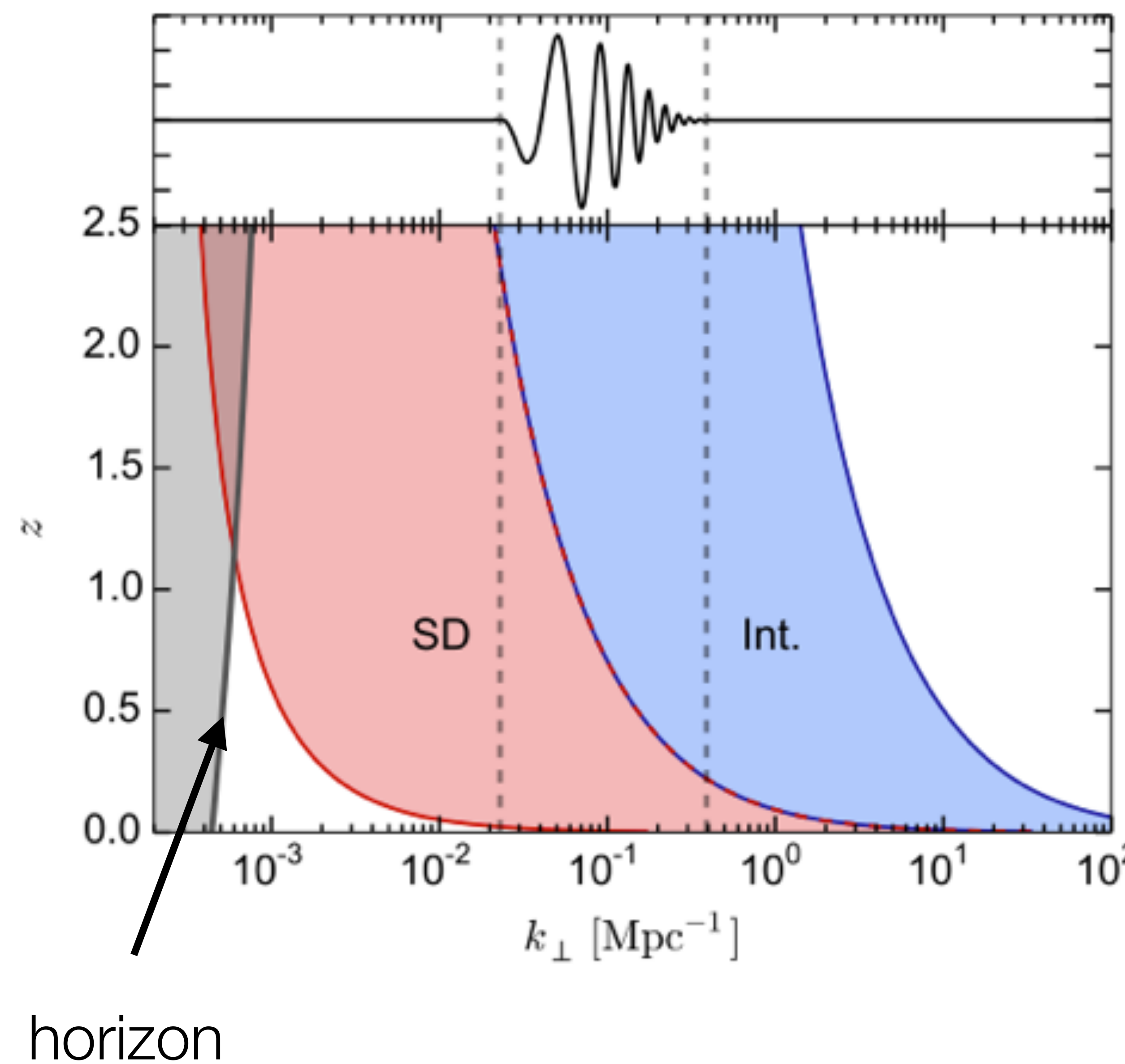
- Free-free + GSE (only). For GSE, extrapolate 408MHz Haslam map with direction-dependant spectral index (Planck)
- No polarization leakage, calib error, RFI…
- Independant component analysis (« blind »)
- SKA1-MID, band 1, beam=1.6 deg2





Single dish vs interfermometry

- SD: mosaic of pointing.
  - Pixel size = resolution = beam of dish.
  - Largest scale = survey area ;
- Int : better resolution but cannot make mosaic of different pointings
  - Largest scale driven by min baselines.
- SKA1 configuration : small density of short baseline
  - ==> single dish always wins for z<1.5.
  - SKA2 dense aperture array : better suited for interferometric IM

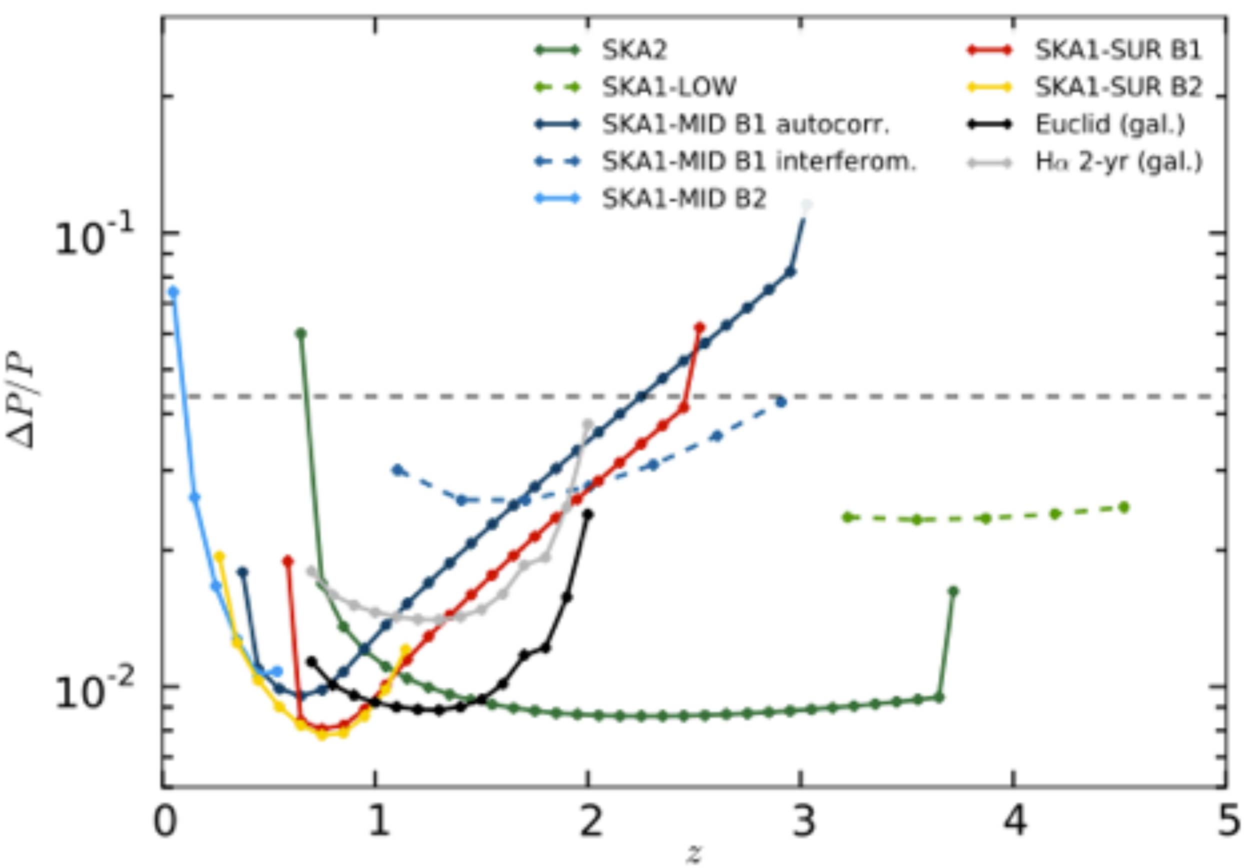


IM plans

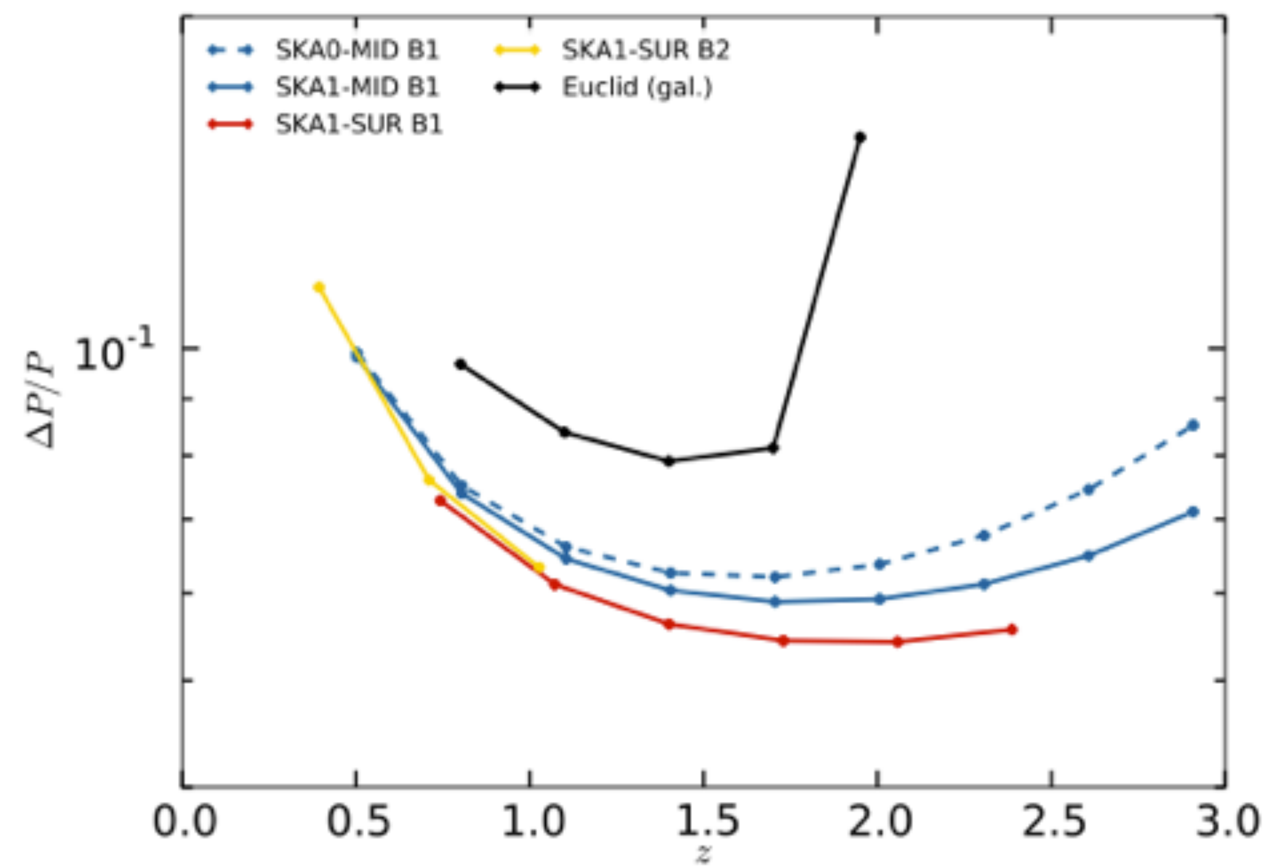
- Current :
  - GBT single dish : first tentative detection (cross-corr wigglez)
  - BINGO single dish (detect HI @ z=0.3)
  - Dedicated short-baseline interferometers : CHIME (cylinders), Tianlai
- SKA-I : prefer single dish mode, either MID or SUR (+low for z>3)
  - Challenge : calibrate single dish.

Telescope [a]	Band [MHz] [b]	z	Target freq.	T_{inst} [K]	N_d	D [m] [c]	A_{eff} [m^2] [d]	θ_B^2 [deg^2] [e]	N_b
SKA0-MID	900 - 1760	(0) - 0.58	1310 [MHz]	20	127	15	140	0.51	1
SKA0-SUR [f]	650 - 1800 [g]	(0) - 1.19	1300	30	48	15	140	0.51	36 [h]
SKA1-MID	350 - 1050	0.35 - 3.06	700	28	254	15	140	1.78	1
SKA1-MID	900 - 1760	(0) - 0.58	1310	20	254	15	140	0.51	1
SKA1-SUR	350 - 900 [g]	0.58 - 3.06	710	50	60	15	140	1.71	36 [h]
SKA1-SUR [f]	650 - 1800 [g]	(0) - 1.19	1300	30	96	15	140	0.51	36 [h]
SKA1-LOW	50 - 350 [i]	3.06 - 27	110	40	911	35	925 [j]	28	3 [k]
SKA2 [l]	300 - 1000	0.42 - 3.73	500	15	4000	10	63	8.0	10

BAO scale



k=0.01 Mpc-1

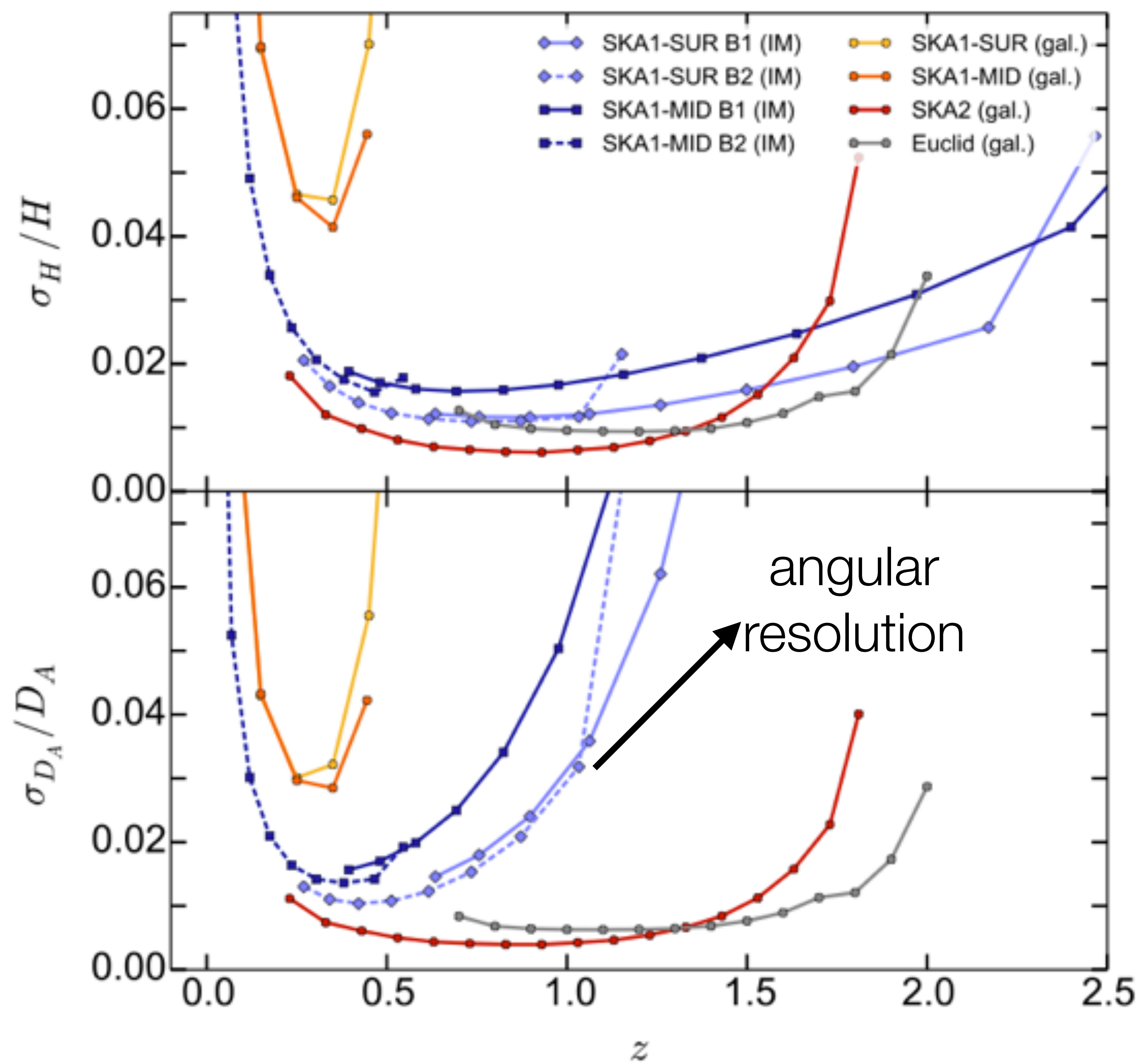


No effect of foregrounds/systes…

IM science : BAO

- 25 kdeg2
- No effect of fg subtraction…
- Bias = free param in each z bin
- SKA1 IM: « low z dataset of choice »

- Constrain OmegaK<10^-3 (Planck 10^-2)

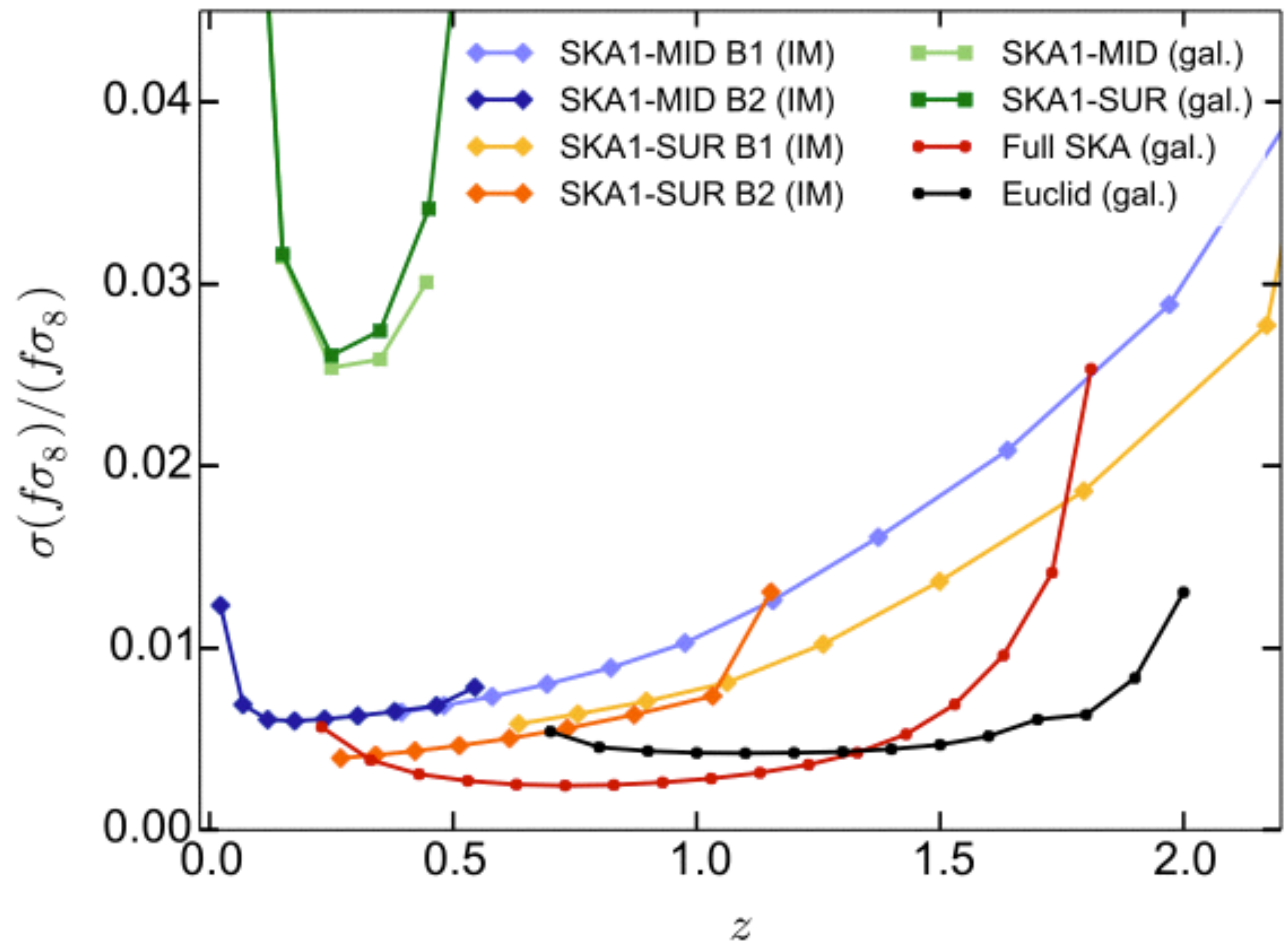


IM science : RSD

$$f(a) \equiv \frac{d\ln\delta_M(a)}{d\ln a},$$

$$f' + q(x)\,f + f^2 = \tfrac{3}{2}\Omega_M\xi\,,$$

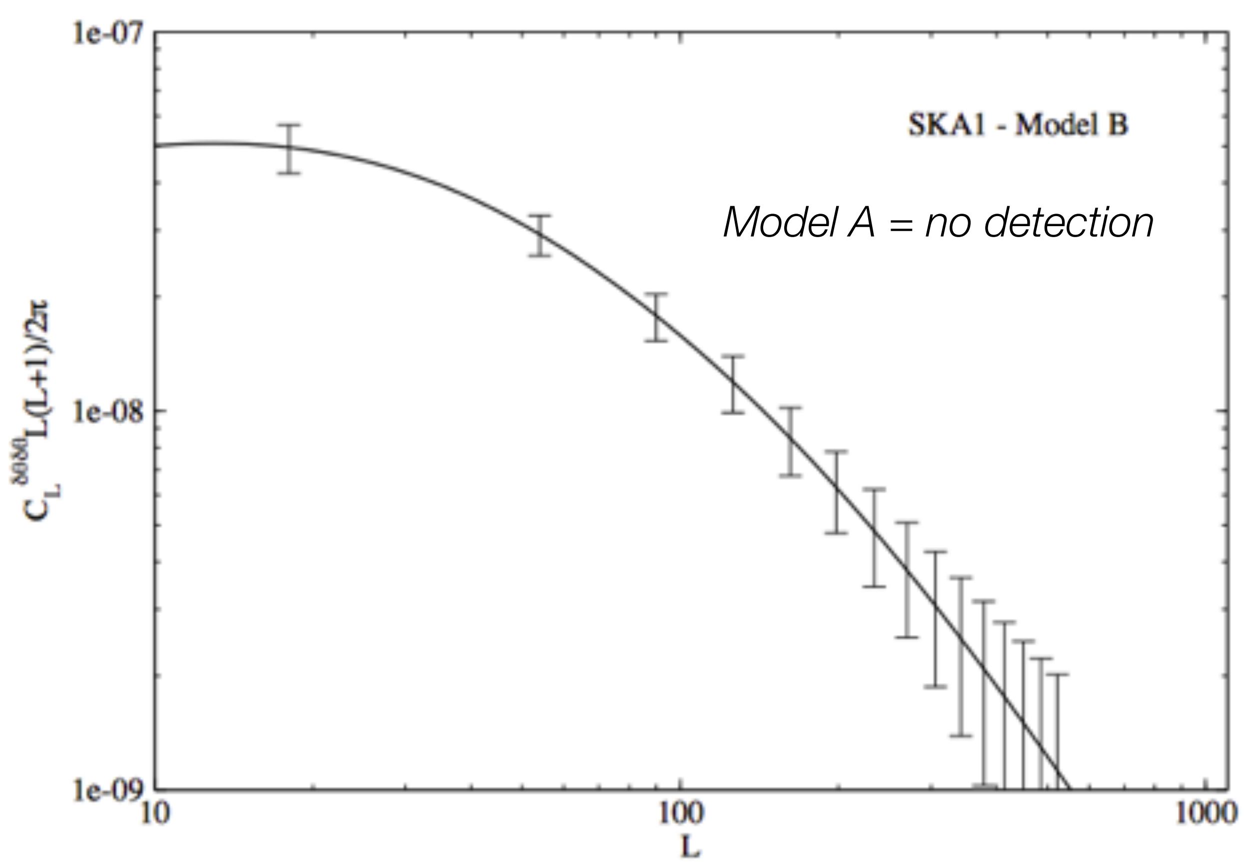
$$P_g^s(k,\mu,z) = \left[b(z) + f(z)\mu^2\right]^2 P_m^r(k,z) + P_{shot}(z)\,,$$



- No systematics…

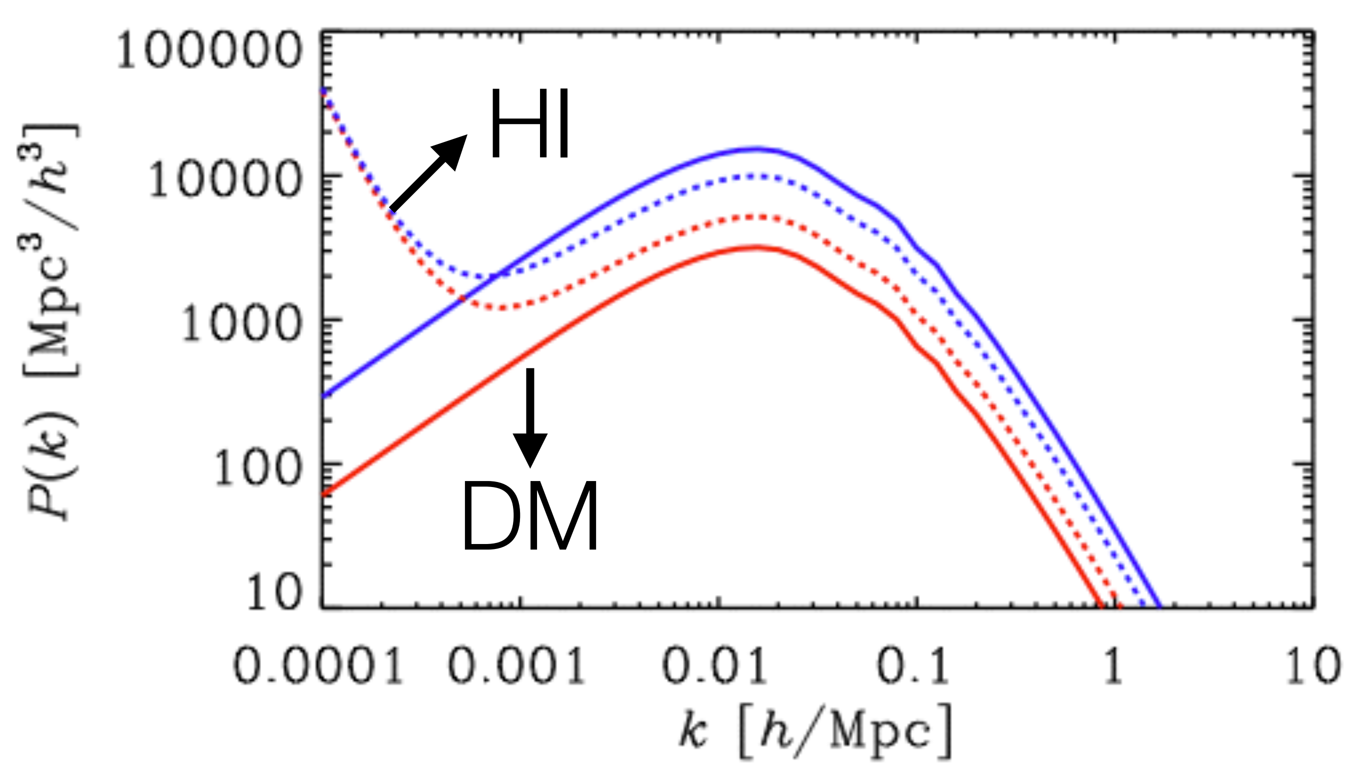
Lensing with HI IM

- Effect on clustering properties of galaxies that is coherent over a large range in z.
- Similar to CMB lensing : use « Fourier space quadratic estimator », ie the 2pt statistics of displacement field « dtheta »
- Reach higher z than other lensing surveys
- Feasability depends on Omega_HI @ z~2-3
- No systematics/foregrounds…



Also with SKA1-IM : Very large scales ?

- Measure turnaround in power spectrum @ k~0.01 Mpc-1
  - > 10 deg (z~1)
- Probe super-horizon modes
- Primordial non-gaussianities:
  - Effect on LSS spectrum : bias correction ~ f_NL x k^-2
  - Expect f_NL~-2.2 due to non-linear GR correction



$$P_N = \sigma_T^2 V_{\mathrm{pix}}$$

$$\frac{T_{\mathrm{sys}}}{\sqrt{2\delta\nu\, t_p}}$$

$$V_{\mathrm{pix}} = (r\theta_{\mathrm{B}})^2 \times (y\delta\nu)$$

$$\lambda/D)$$

HI signal calculation

$$T_b(\nu,\Omega) \approx \overline{T}_b(z)\left[1 + b_{\rm HI}\delta_m(z) - \frac{1}{H(z)}\frac{dv}{ds}\right].$$

$$\rho_{\rm HI}(z) = \int_{M_{\rm min}}^{M_{\rm max}} dM \frac{dn}{dM}(M,z)\, M_{\rm HI}(M,z),$$

$$b_{\rm HI}(z) = \rho_{\rm HI}^{-1} \int_{M_{\rm min}}^{M_{\rm max}} dM \frac{dn}{dM}(M,z)\, M_{\rm HI}(M,z)\, b(z,M),$$

Polarization leakage

- $V^{pp} = g_p (I+Q)$
- $V_{qq} = g_q (I-Q)$
- Derive $I = V_{pp} + V_{qq}$
- But g —> g+dg , so $V_{pp}+V_{qq}$ = I + correction with part of the correction ~ Q x (dg_p-dg_q) : leakage
- Fear mostly off-axis leakage
- Issue : Faraday rotation makes polarized emission non smooth

Table xxx: Parameters for Comparable Telescopes															
		eMERLIN	JVLA	GBT	GMRT	Parkes MB	LOFAR	FAST	MeerKAT	WSRT	Arecibo	ASKAP	SKA1-survey	SKA1-low	SKA-mid
A_{eff}/T_{sys}	m^2/K	60	265	276	250	100	61	1250	321	124	1150	65	391	1000	1630
FoV	deg^2	0.25	0.25	0.015	0.13	0.65	14	0.0017	0.86	0.25	0.003	30	18	27	0.49
Receptor Size	m	25	25	101	45	64	39	300	13.5	25	225	12	15	35	15
Fiducial frequency	GHz	1.4	1.4	1.4	1.4	1.4	0.12	1.4	1.4	1.4	1.4	1.4	1.67	0.11	1.67
Survey Speed FoM	$deg^2\ m^4\ K^{-2}$	9.00×10^2	1.76×10^4	1.14×10^3	8.13×10^3	6.50×10^3	5.21×10^4	2.66×10^3	8.86×10^4	3.84×10^3	3.97×10^3	1.27×10^5	2.75×10^6	2.70×10^7	1.30×10^6
Resolution	arcsec	$10\text{-}150 \times 10^{-3}$	1.4 - 44	420	2	660	5	88	11	16	192	7	0.9	11	0.22
Baseline or Size	km	217	1 - 35	0.1	27	0.064	100	0.5	4	2.7	225	6	50	50	200
Frequency Range	GHz	1.3-1.8, 4-8, 22-24	1 - 50	0.2 - 50+	0.15, 0.23, 0.33, 0.61, 1.4	0.44 to 24	0.03 – 0.22	0.1 – 3	0.7 - 2.5, 0.7 - 10	0.3 – 8.6	0.3 - 10	0.7-1.8	0.65-1.67	0.050 – 0.350	0.35-14
Bandwidth	MHz	400	1000	400	450	400	4	800	1000	160	1000	300	500	250	770
Cont. Sensitivity	$\mu Jy\text{-}hr^{-1/2}$	27.11	3.88	5.89	6.13	16.26	266.61	0.92	3.20	20.74	0.89	28.89	3.72	2.06	0.72
Sensitivity, 100 kHz	$\mu Jy\text{-}hr^{-1/2}$	1714	388	373	411	1029	1686	82	320	830	89	1582	263	103	63
SEFD	Jy	46.0	10.4	10.0	11.0	27.6	45.2	2.2	8.6	22.3	2.4	42.5	7.1	2.8	1.7