Interferometric observations of the 21 cm line: overview, challenges and current status

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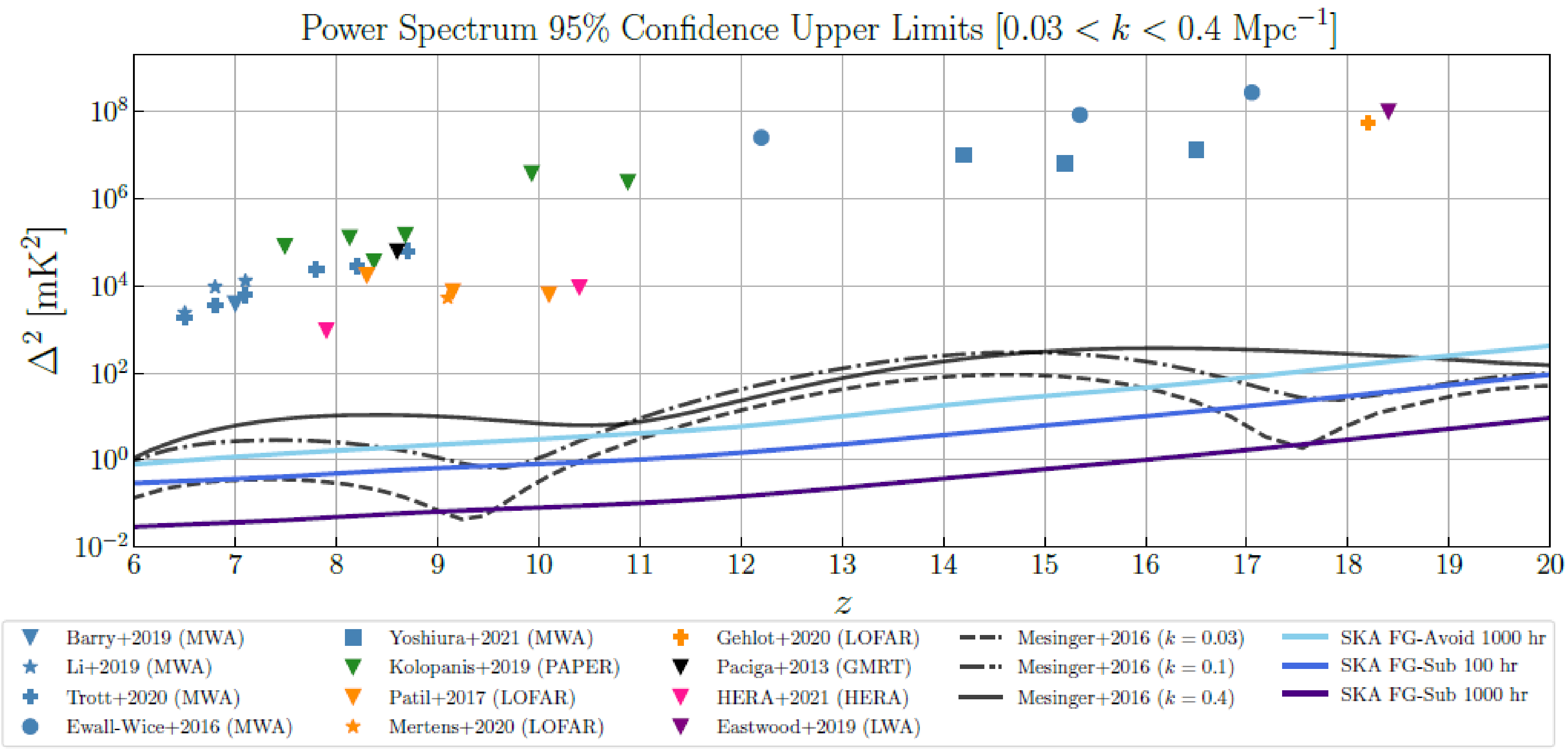
INAF-IRA

“21 cm cosmology”, Trieste, September 11-15, 2023

State of the art of the field

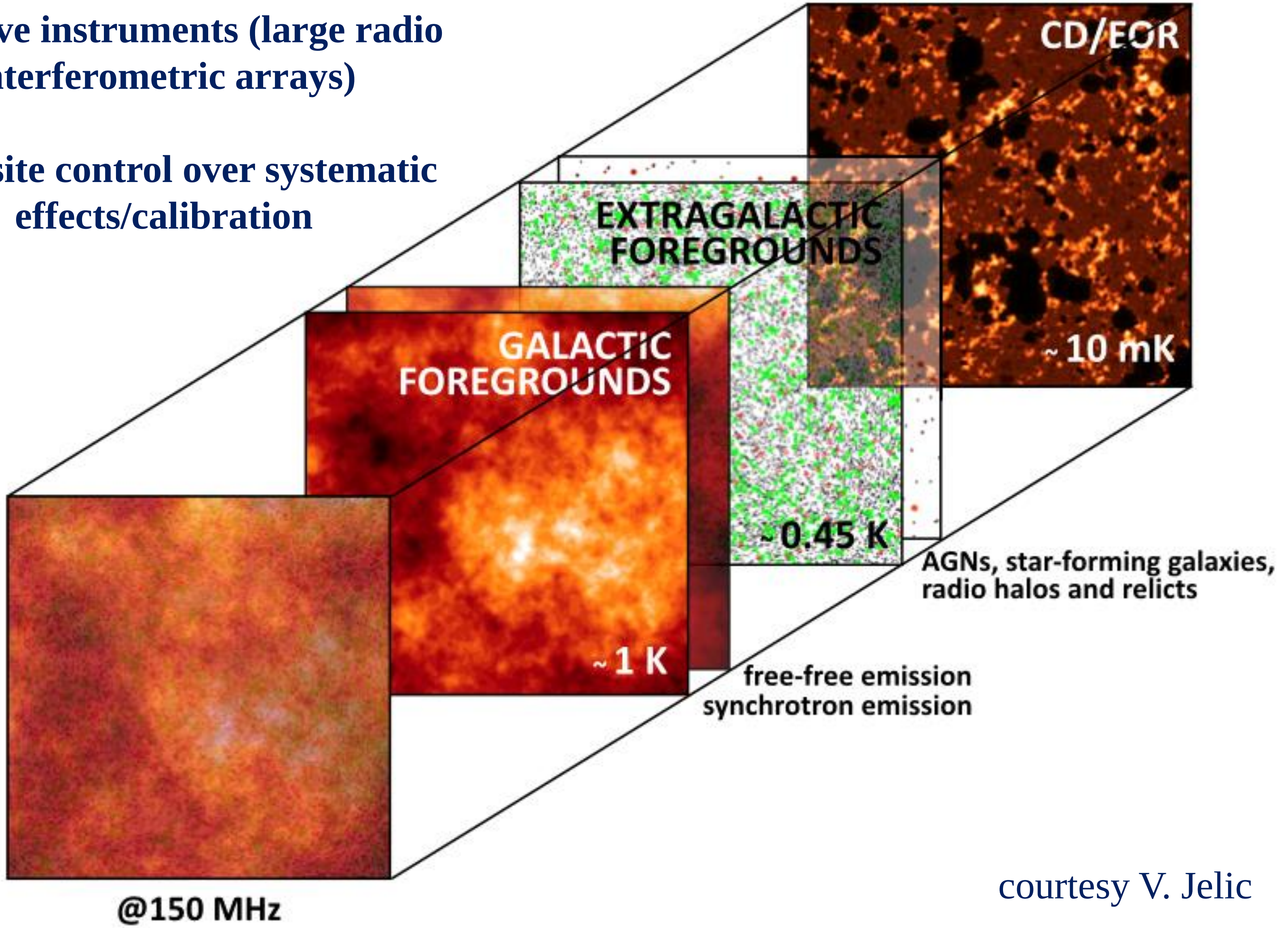


Barry et al. (2022)

21 cm interferometric observations are (still) challenging

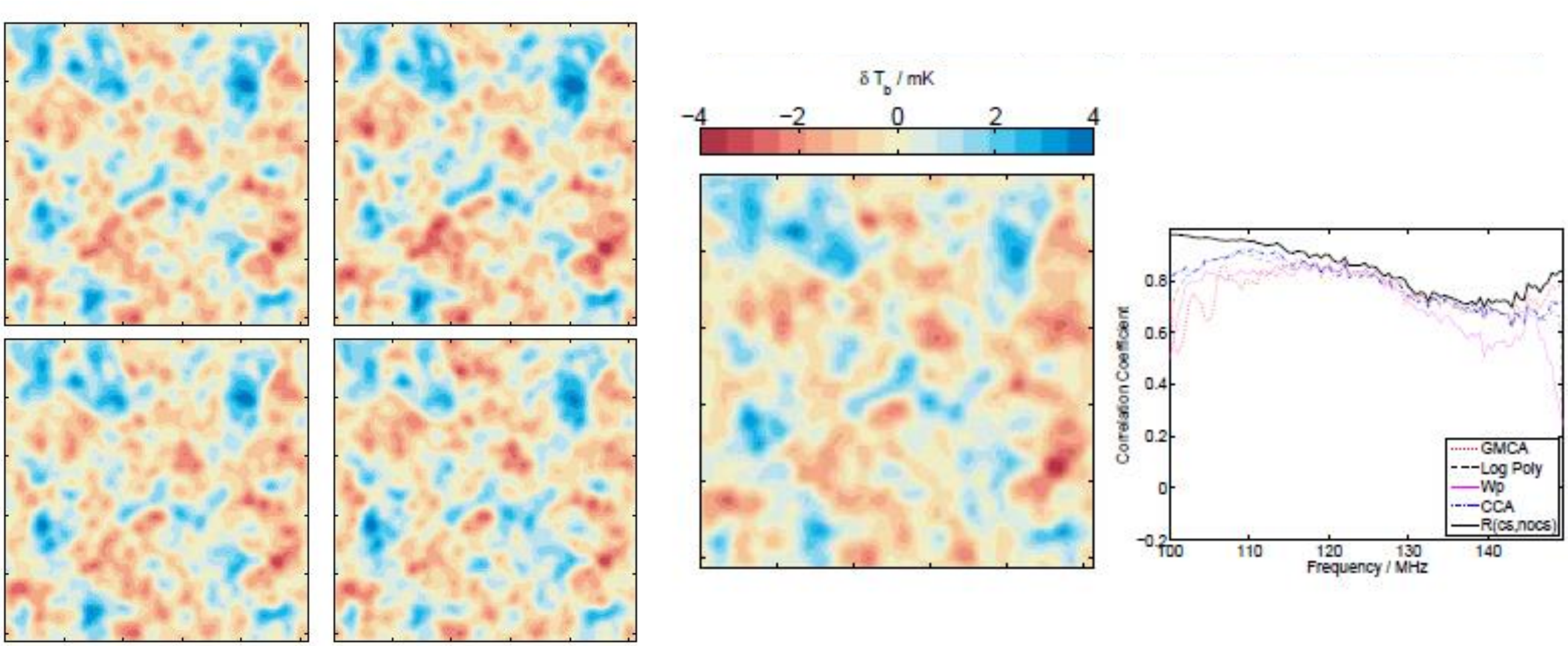
- **Sensitive instruments (large radio interferometric arrays)**

- **Exquisite control over systematic effects/calibration**



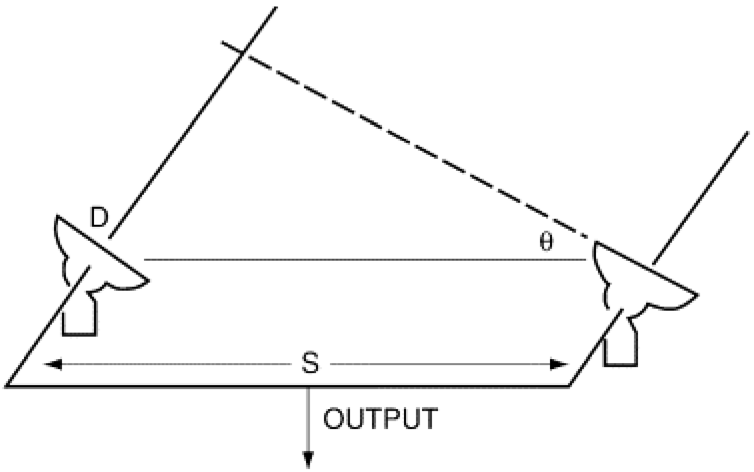
courtesy V. Jelic

Foreground separation ALWAYS works in simulations



Chapman et al. (2015)

What does an interferometer measure?



$$V_{ij}(\nu) = \int_{\Omega} A(\nu) I(\nu) e^{2\pi i\, \hat{b}\cdot\hat{s}}\, ds$$

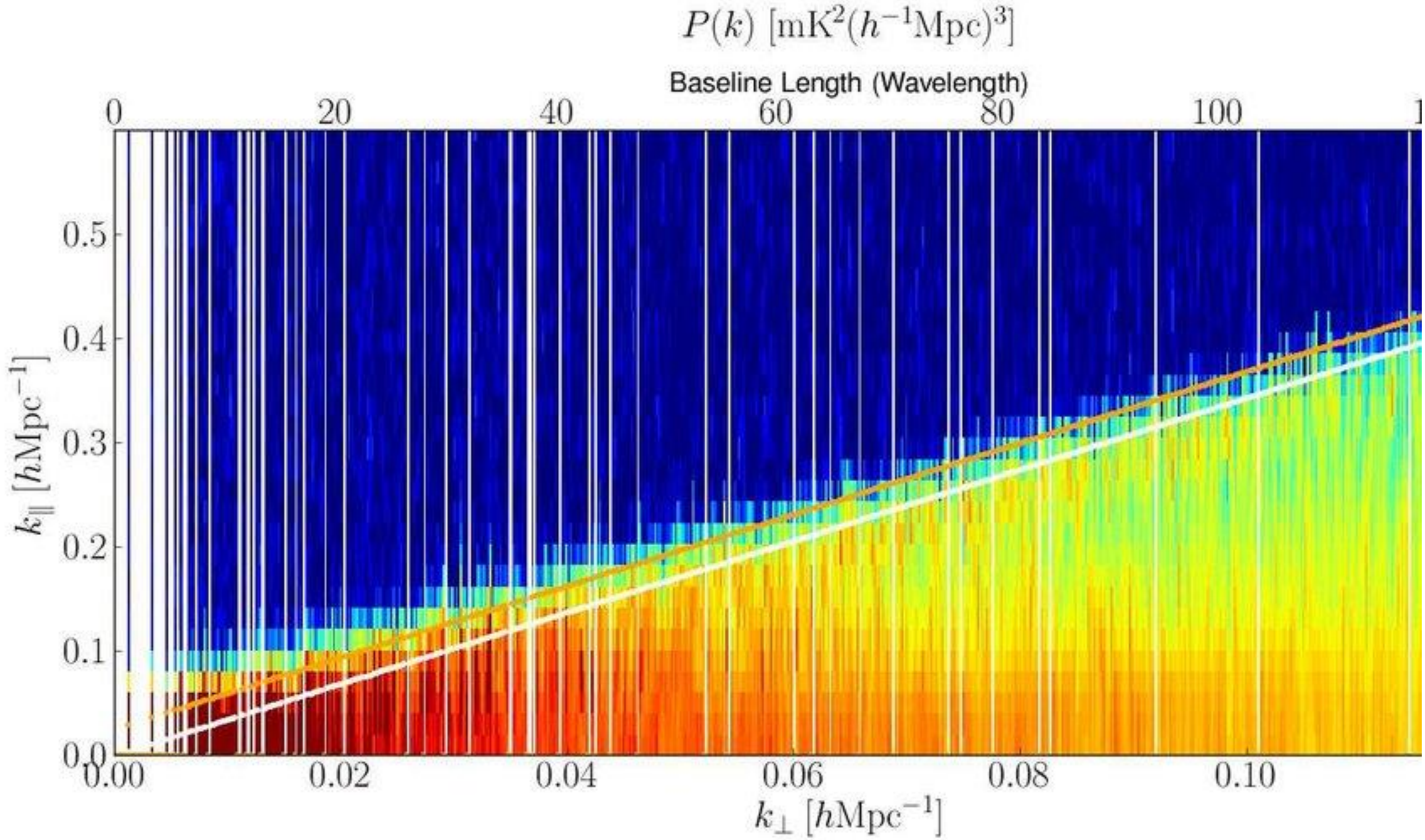
$$\tilde{V}_{ij}(\tau) = \int_{B} V_{ij}(\nu) e^{2\pi i \nu \tau}\, d\nu$$

$$power\ spectrum \propto \tilde{V}_{ij}(\nu)\, \tilde{V}_{ij}^{*}(\nu)$$

$$k_{\perp} \propto 2\pi u$$

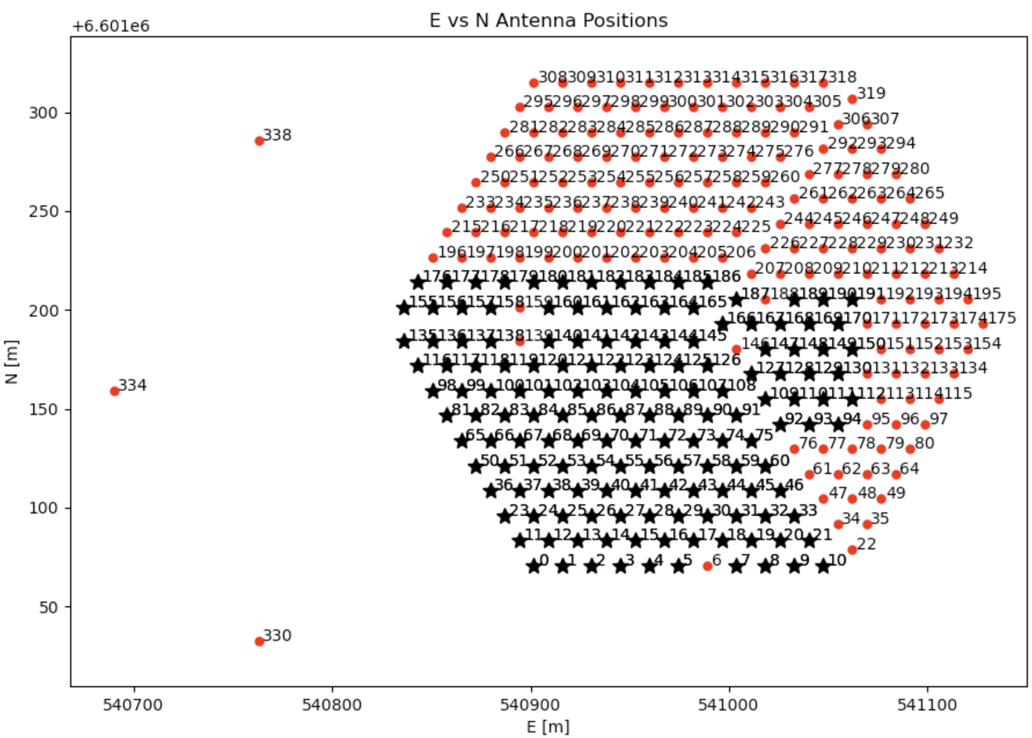
$$k_{\parallel} \propto \frac{2\pi}{\Delta \upsilon}$$

The wedge paradigm

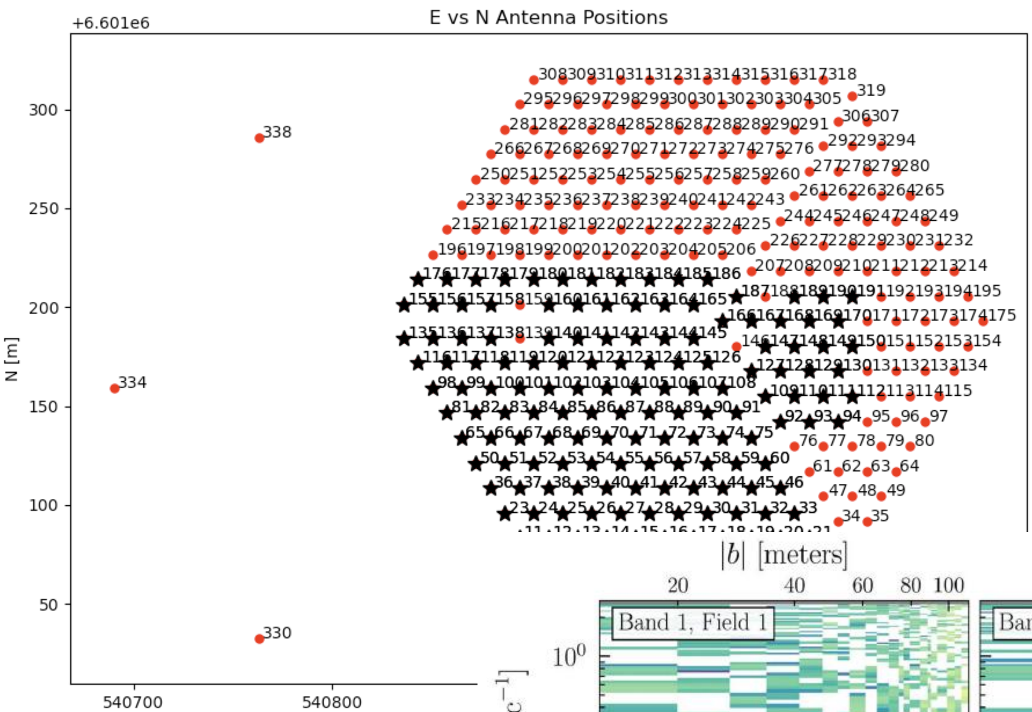


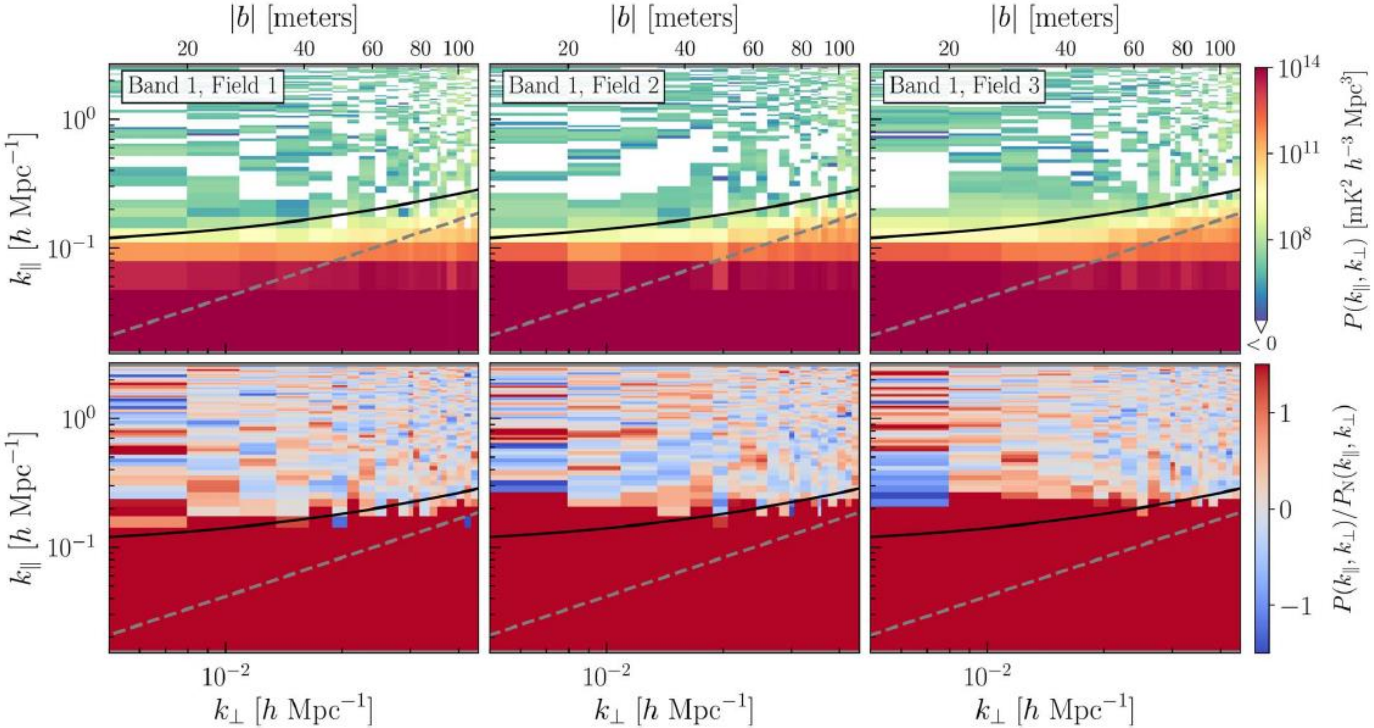
Pober et al. (2013)

HERA


E vs N Antenna Positions
+6.601e6
N [m]
E [m]
300
250
200
150
100
50
540700
540800
540900
541000
541100
334
338
330
319

HERA



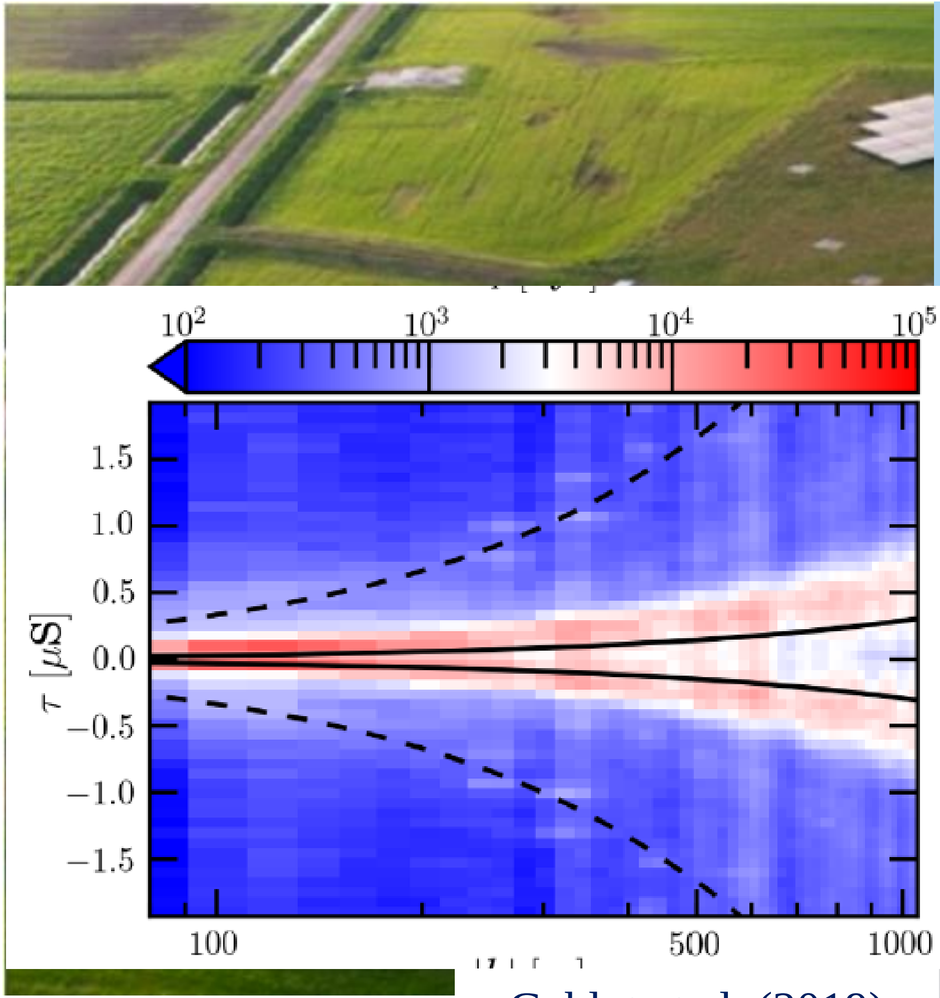


The HERA collaboration (2012)

LOFAR

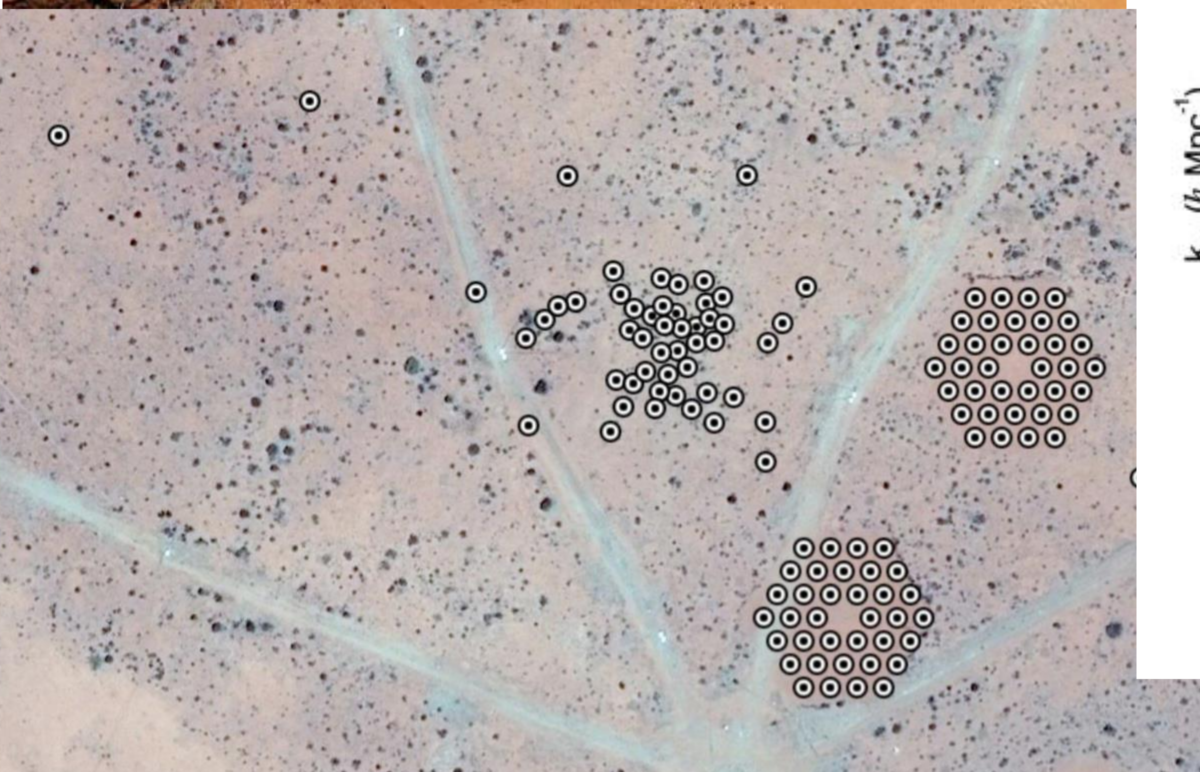

Onsala
Irbene
Birr
Dutch stations
Chilbolton
Norderstedt
Bałdy
Potsdam
Borówiec
Jülich
Effelsberg
Tautenburg
Łazy
Nançay
Unterweilenbach
Medicina

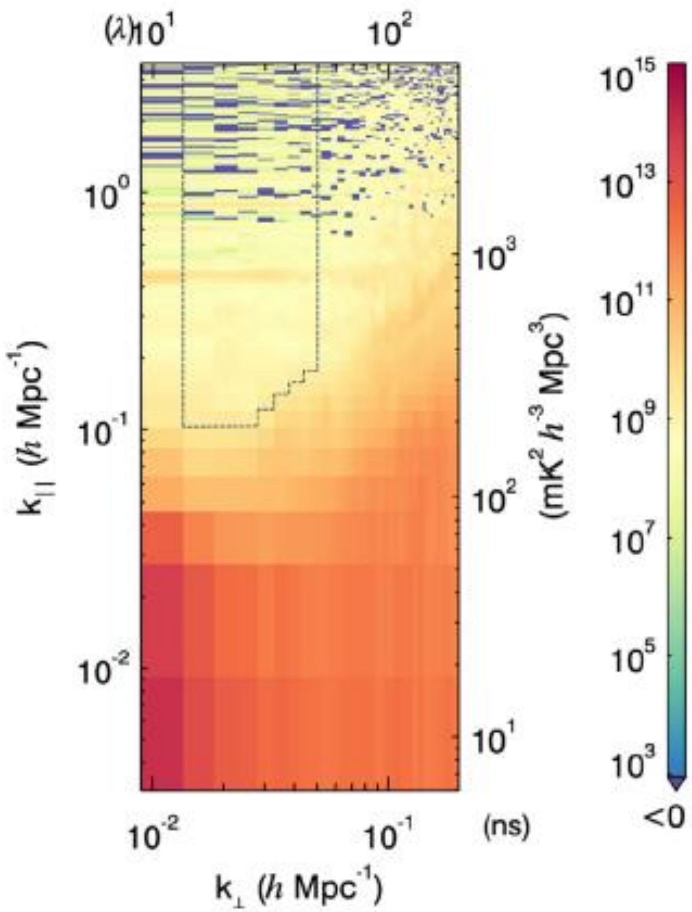
LOFAR



Gehlot et al. (2019)

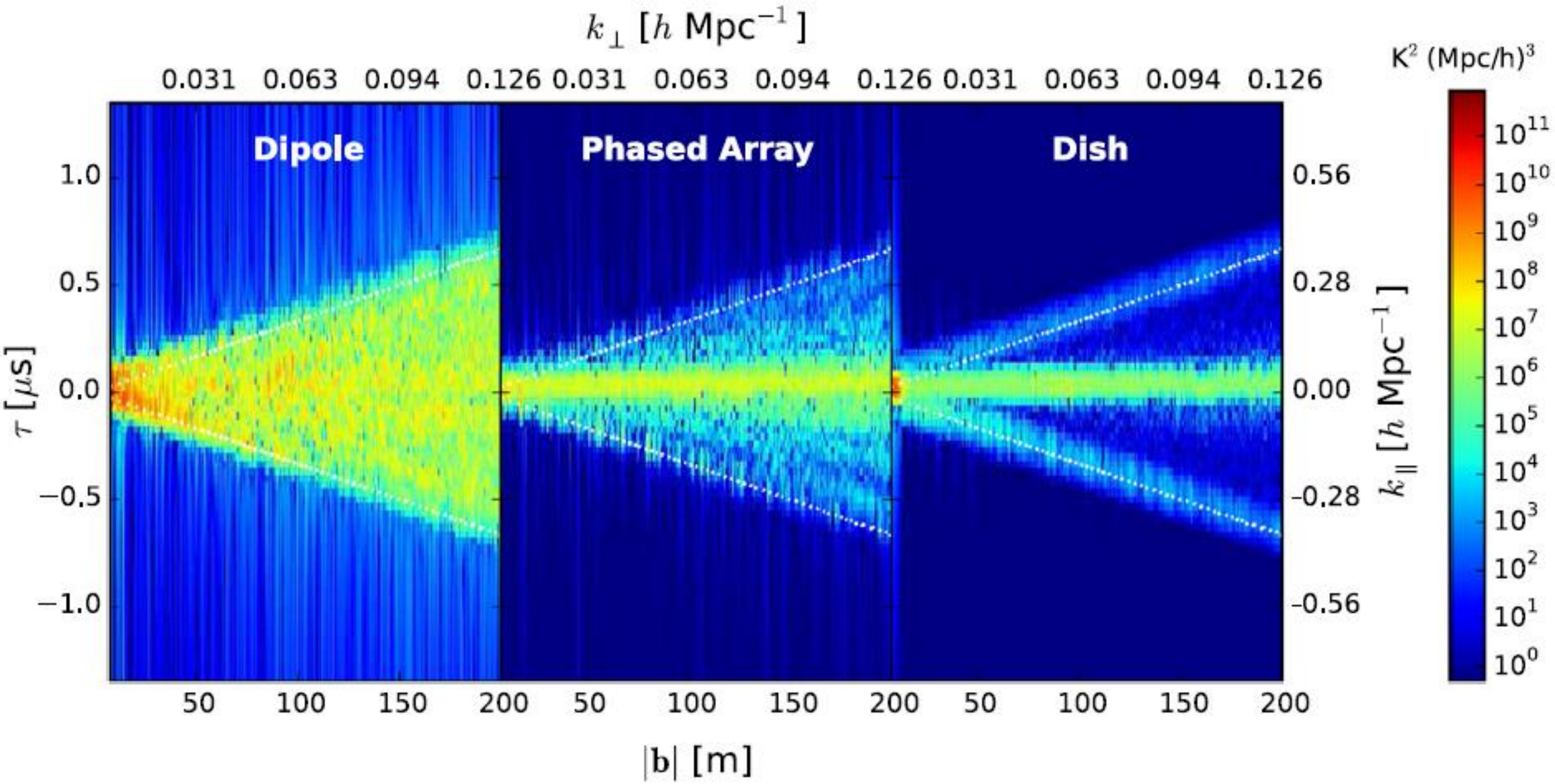
MWA





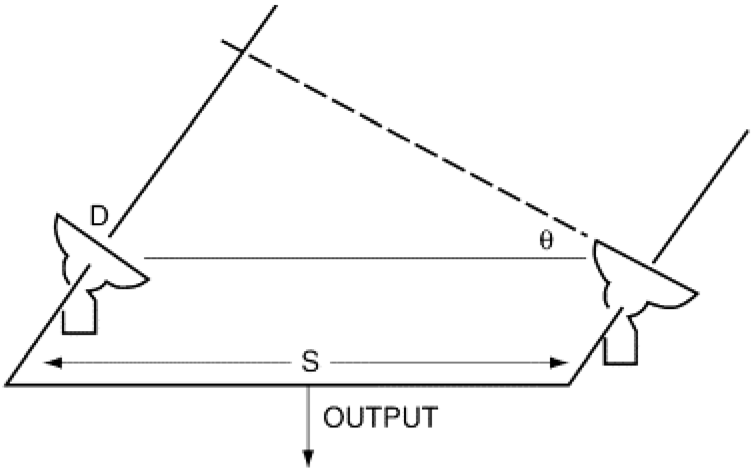
Rahimi et al. (2021)

Also the receiving element matters



Thyagarajan et al. (2015)

What does an interferometer measure? (aka, a walk through calibration)



What we measure

Calibration parameters

We assume we know it

We assume we know it (at some level)

$$V_{ij}(\nu) = g_i(\nu)\, g_j^{\,*}(\nu) \int_{\Omega} A(\nu) I(\nu) e^{2\pi i\, \hat{b}\cdot\hat{s}}\, ds$$

continue walking…

$$\tilde{g}_i(\nu) = g_i(\nu) + \varepsilon_j(\nu) \qquad \tilde{g}_j(\nu) = g_j(\nu) + \varepsilon_j(\nu)$$

$$V^m{}_{ij}(\nu) = \left(g_i(\nu) + \varepsilon_i(\nu)\right)^{-1} \left(g^*{}_j(\nu) + \varepsilon^*{}_j(\nu)\right)^{-1} V^o{}_{ij}(\nu) =$$

$$\approx V^T{}_{ij}(\nu) - \left(\varepsilon_i(\nu) + \varepsilon^*{}_j(\nu)\right) V^T{}_{ij}(\nu) = V^T{}_{ij}(\nu) + \Delta(\nu)\ V^T{}_{ij}(\nu)$$

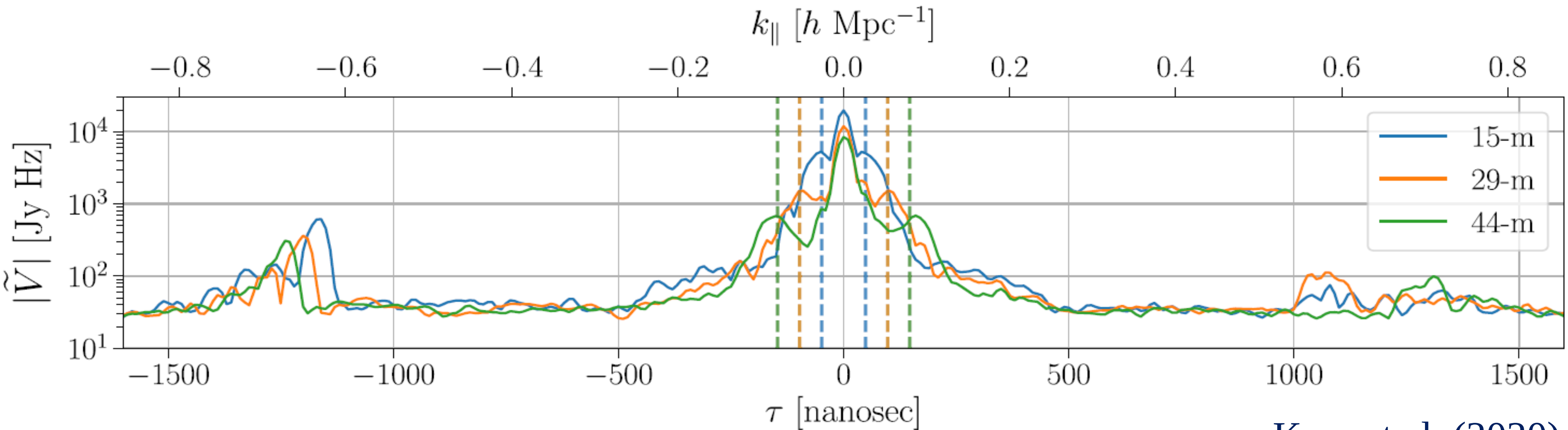
$$\approx V^F{}_{ij}(\nu) + V^{EoR}{}_{ij}(\nu) + \Delta(\nu)\ V^F{}_{ij}(\nu)$$

We think we can separate

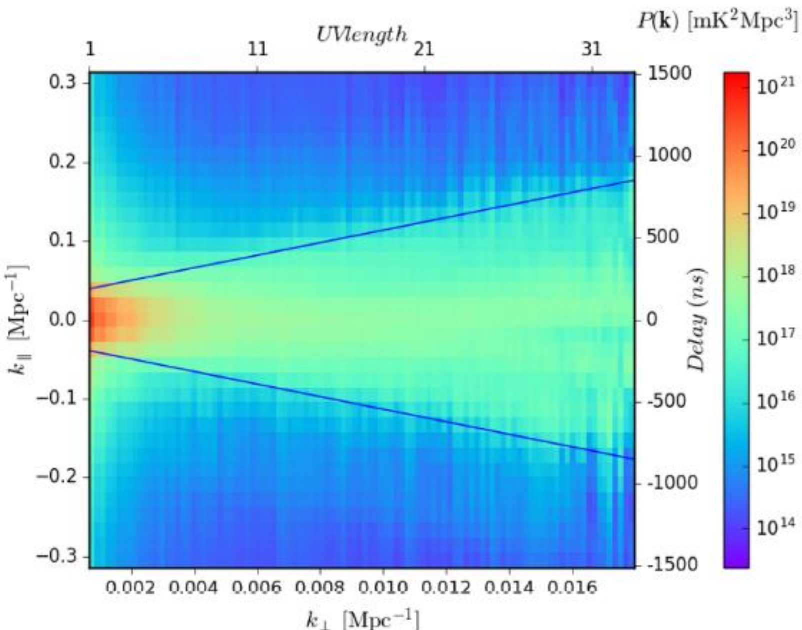
The EoR signal we want to measure

Contamination term that can easily jeopardize the EoR

What does the wedge look like in real life?

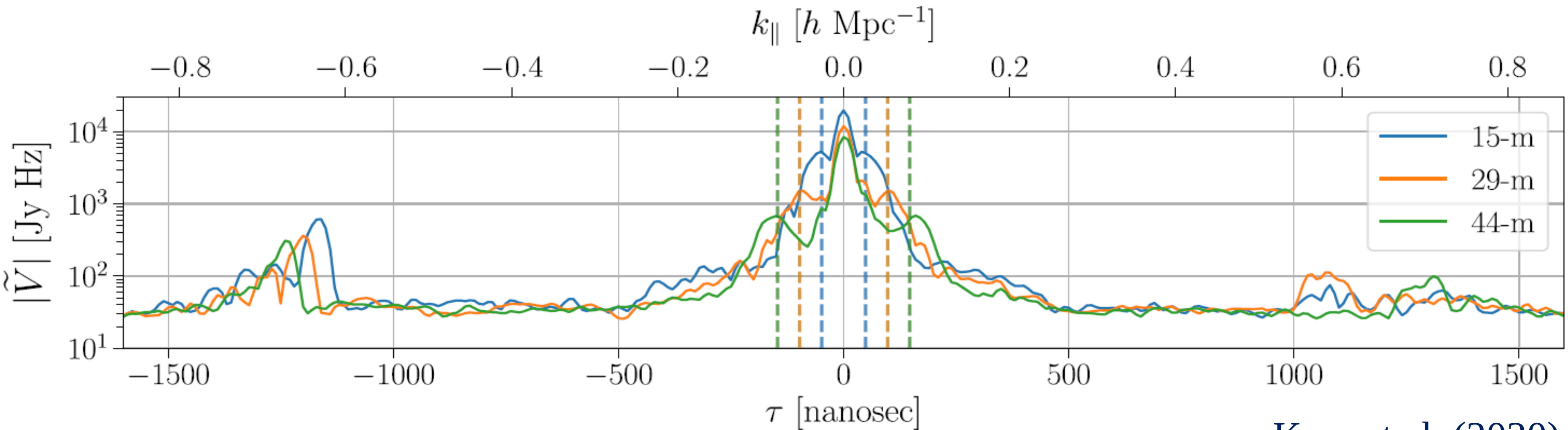


Kern et al. (2020)

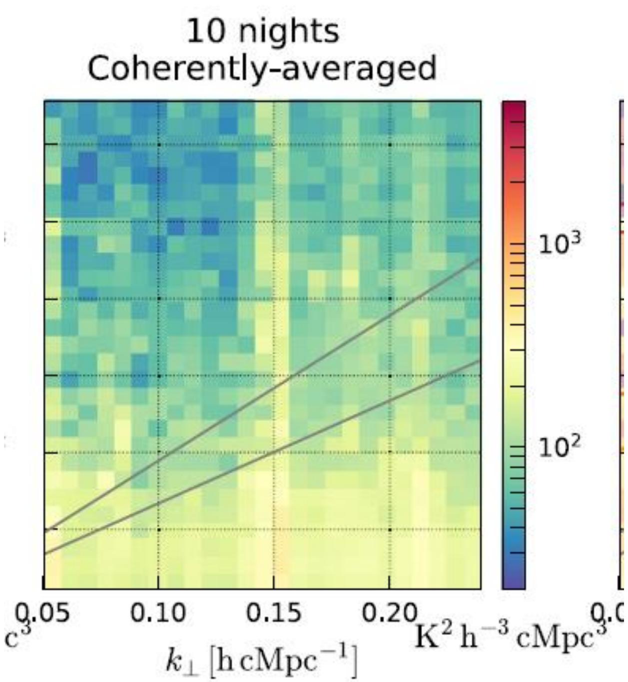


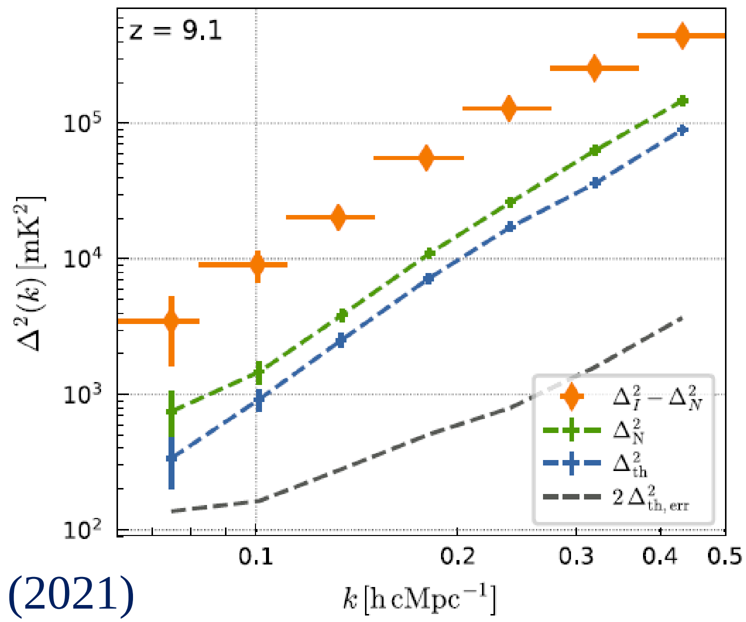
Garsden et al. (2021)

What does the wedge look like in real life?



Kern et al. (2020)





Mertens et al. (2021)

Do we know what corrupts our “wedge ideal picture”?

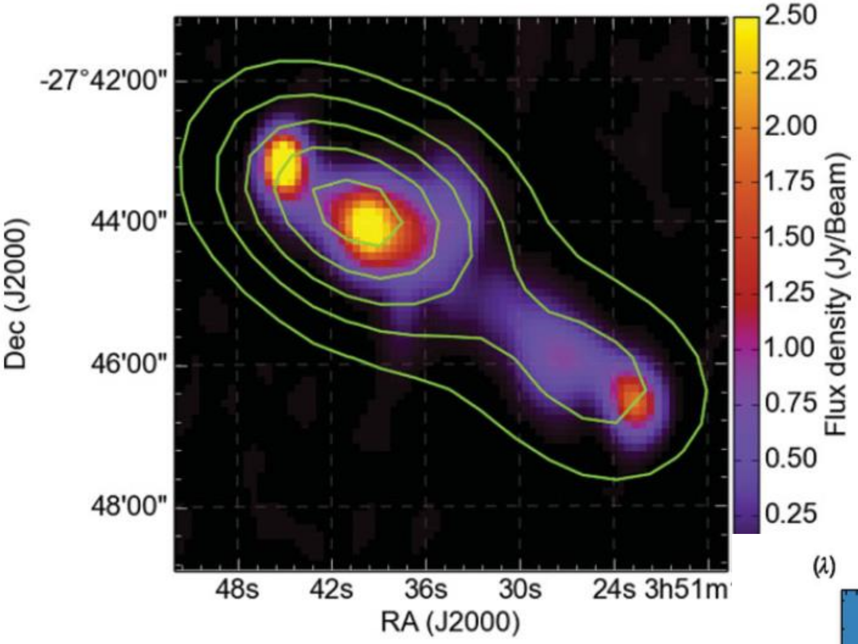
Sometimes yes, sometimes no…

1) Know thy sky

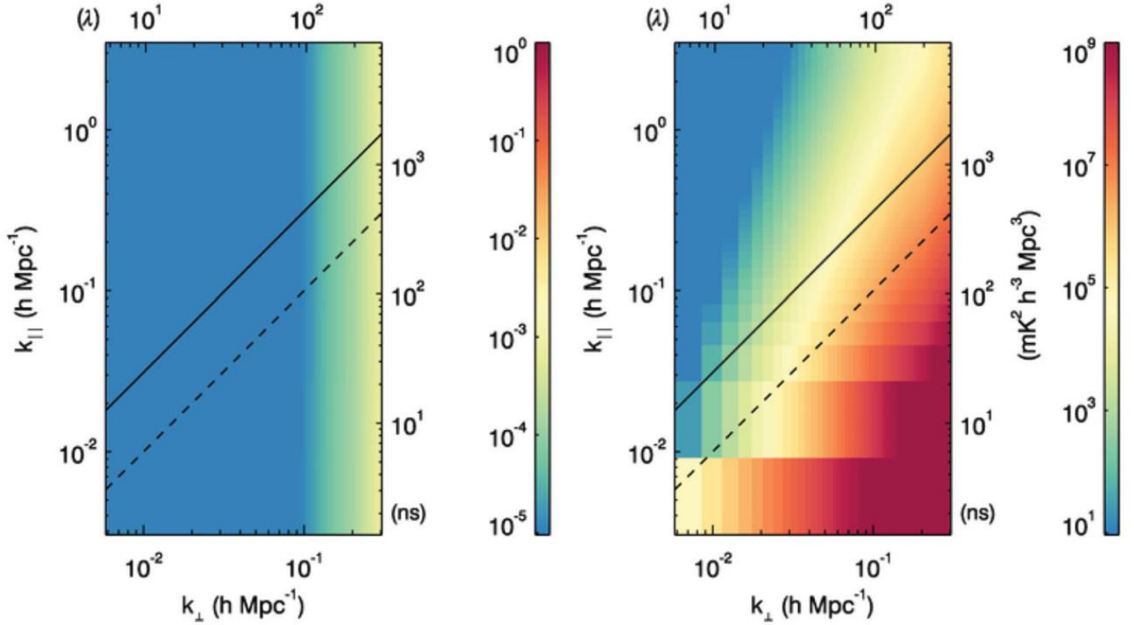
$$V_{12}(u,v) = G_1(t)B_1(\nu)\left[\int_{\Omega} E_1(l,m,\nu)Z_1(t)I(l,m,\nu)Z_2^H(t)E_2^H(l,m,\nu)e^{-2\pi i(ul+vm)}dldm\right]B_2^H(\nu)G_2^H(t)$$

Offringa et al. (2016)

1) Know thy sky



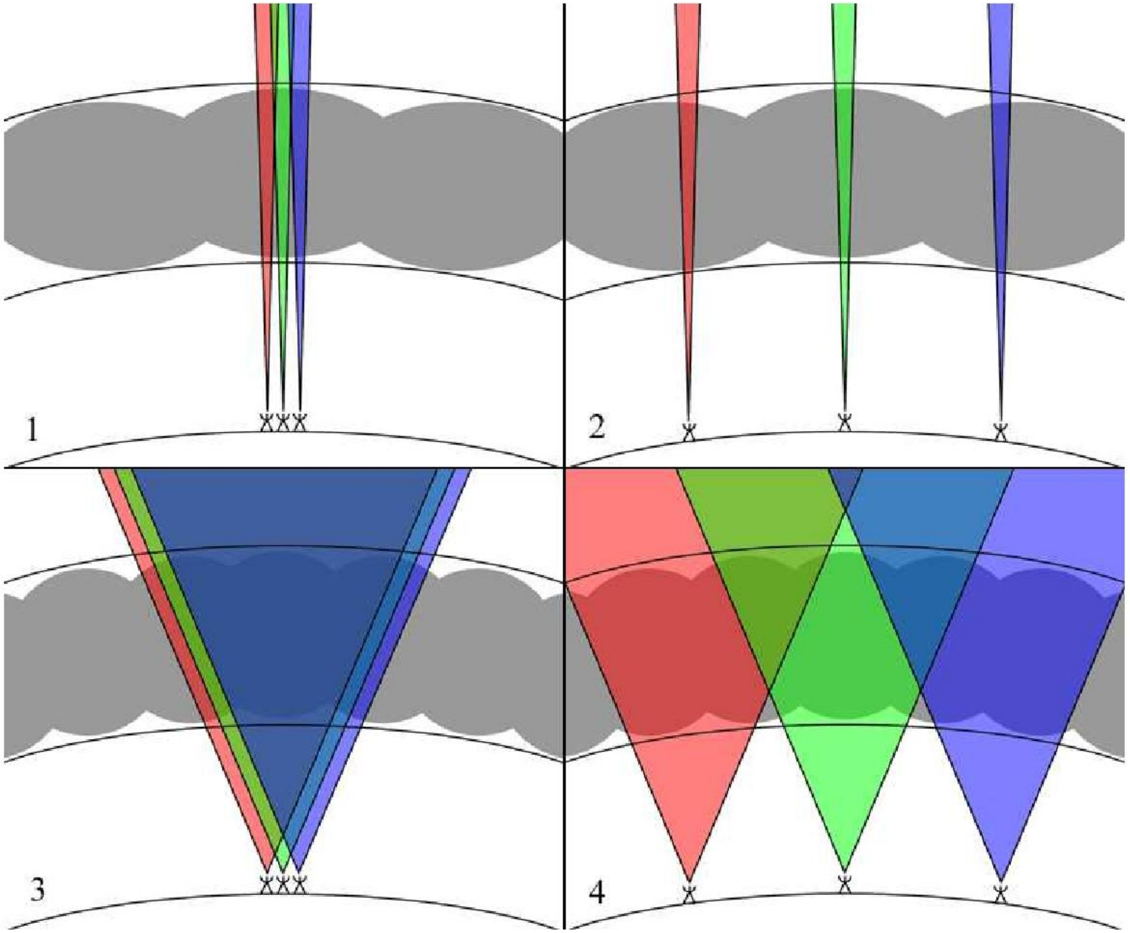
- incomplete sky models bias calibration;
- limited angular resolution prevents detailed source modeling…
- good uv-coverage allows modeling of complex extended structures…



Procopio et al. (2017)

2) Ionosphere

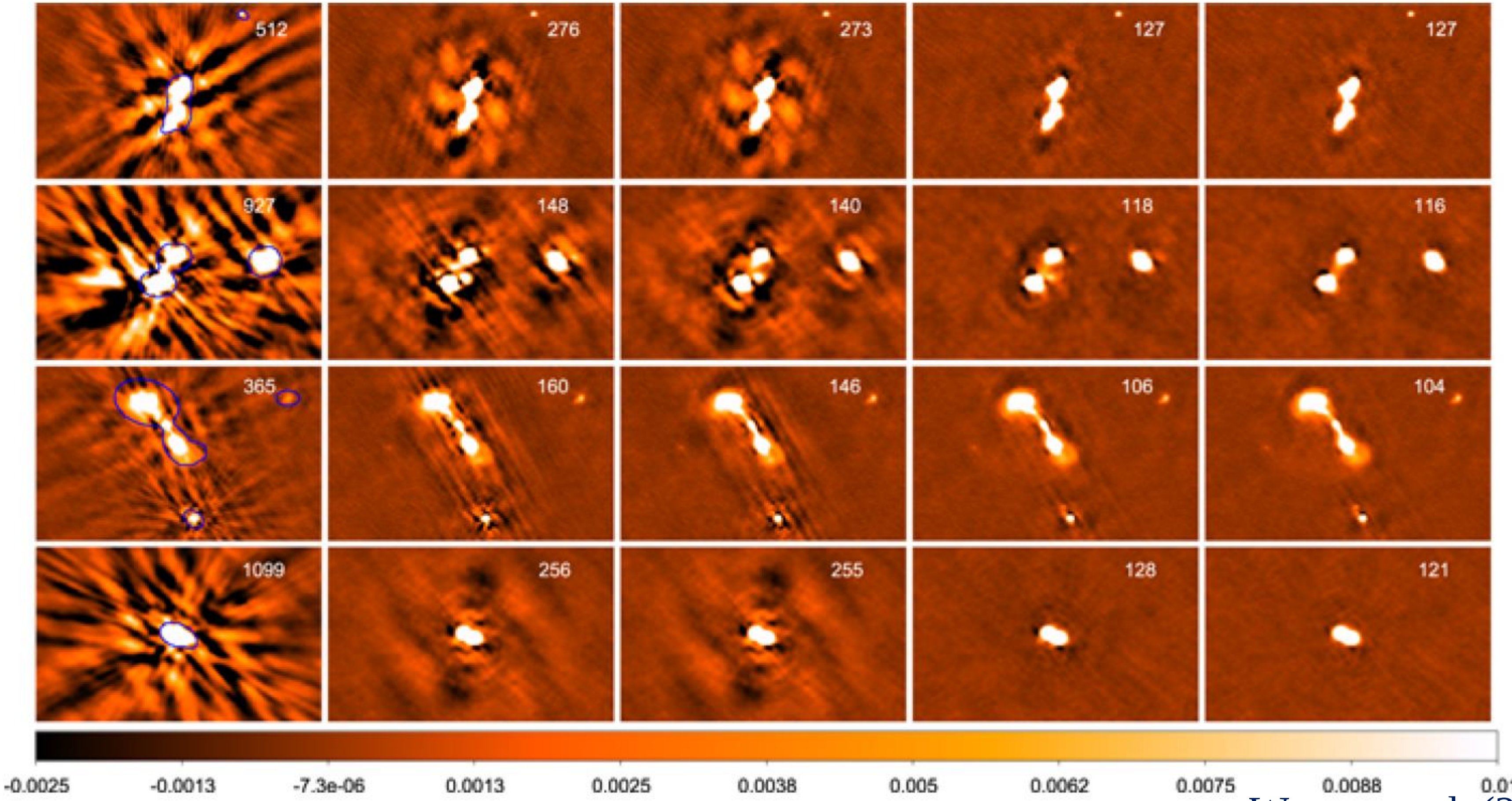
$$V_{12}(u,v) = G_1(t)B_1(\nu)\left[\int_\Omega E_1(l,m,\nu)\, Z_1(t)\, I(l,m,\nu)\, Z_2^H(t)\, E_2^H(l,m,\nu)e^{-2\pi i(ul+vm)}dldm\right]B_2^H(\nu)G_2^H(t)$$



Lonsdale et al. (2004)

2) Ionosphere

$$V_{12}(u,v) = G_1(t)B_1(\nu)\left[\int_\Omega E_1(l,m,\nu)\, Z_1(t)\, I(l,m,\nu)\, Z_2^H(t)\, E_2^H(l,m,\nu)e^{-2\pi i(ul+vm)}dldm\right]B_2^H(\nu)G_2^H(t)$$

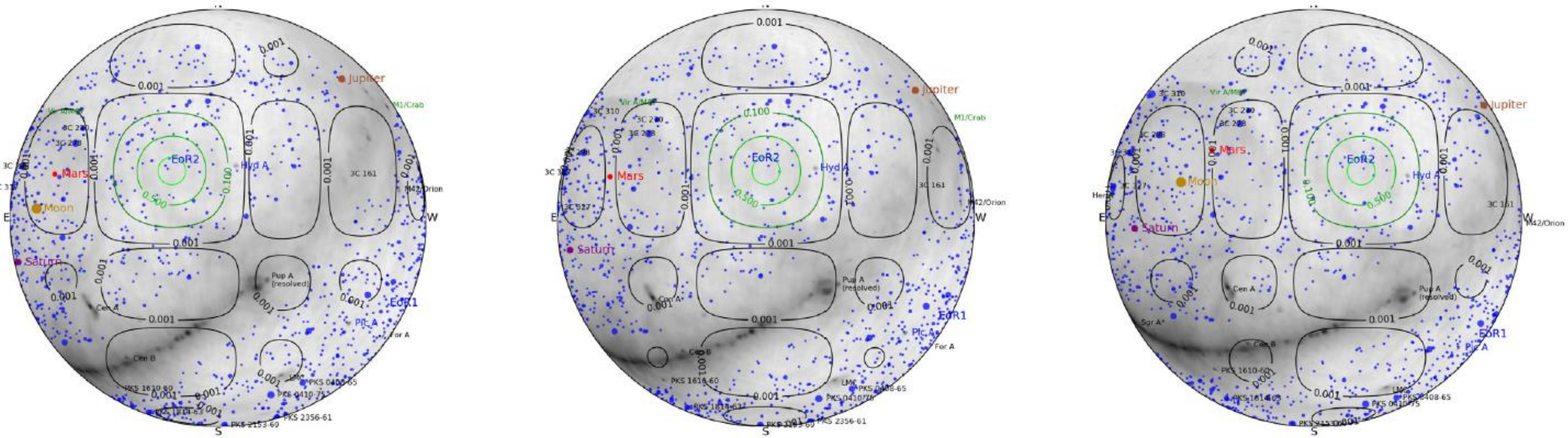


van Weeren et al. (2016)

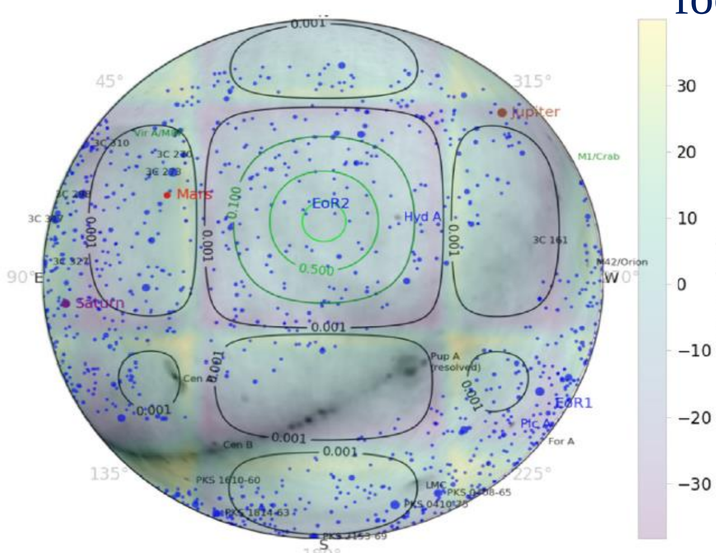
3) Know thy primary beams

$$V_{12}(u,v) = G_1(t)B_1(\nu)\left[\int_\Omega E_1(l,m,\nu)\, Z_1(t)I(l,m,\nu)Z_2^H(t)\, E_2^H(l,m,\nu)\, e^{-2\pi i(ul+vm)}dldm\right]B_2^H(\nu)G_2^H(t)$$

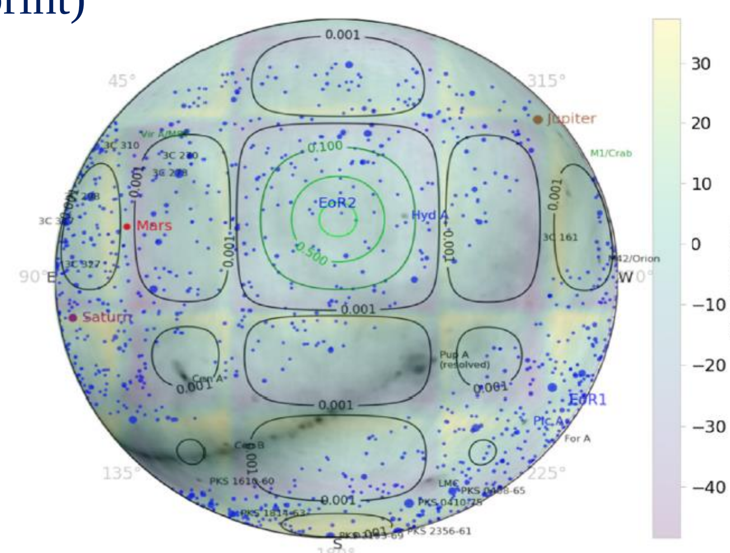
3) Know thy primary beams



Beams are time variable (larger stations/dishes have good sidelobe rejection/bad power spectrum footprint)

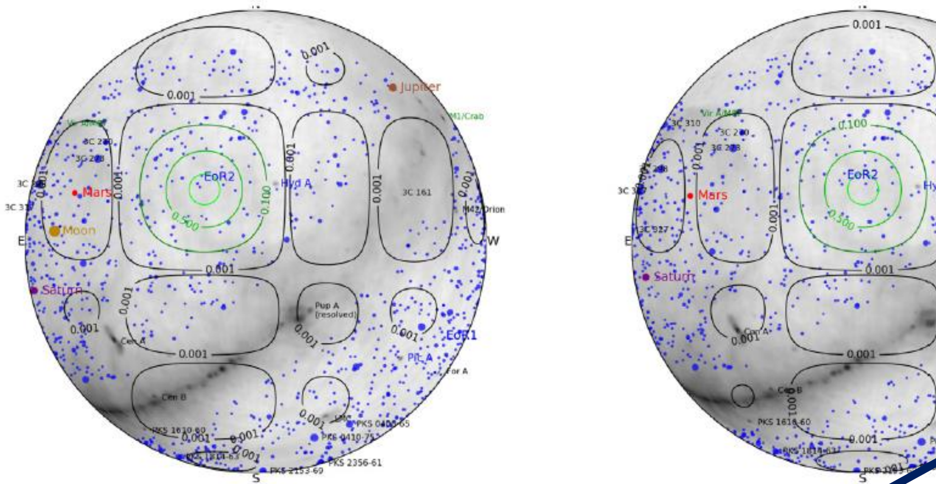


Beams are frequency variable!



Trott et al. (2020)

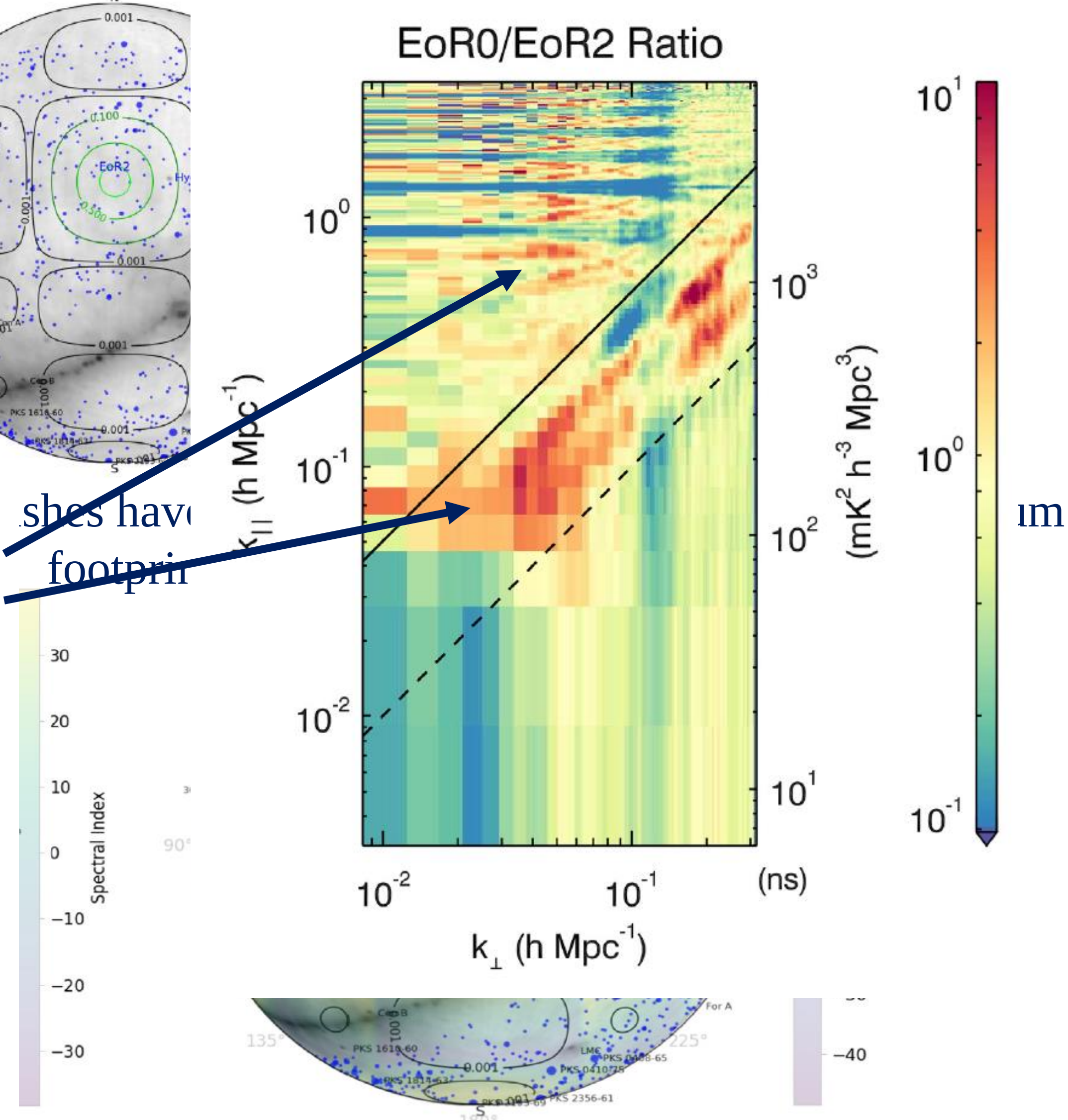
3) Know thy primary beams



- **time and frequency beam structure couples with foregrounds and leaks power in the EoR window;**
- **keep beams steady (if possible);**
- **model beams and sky accurately – not easy as they are degenerate;**
- **redundancy does not help much here…**

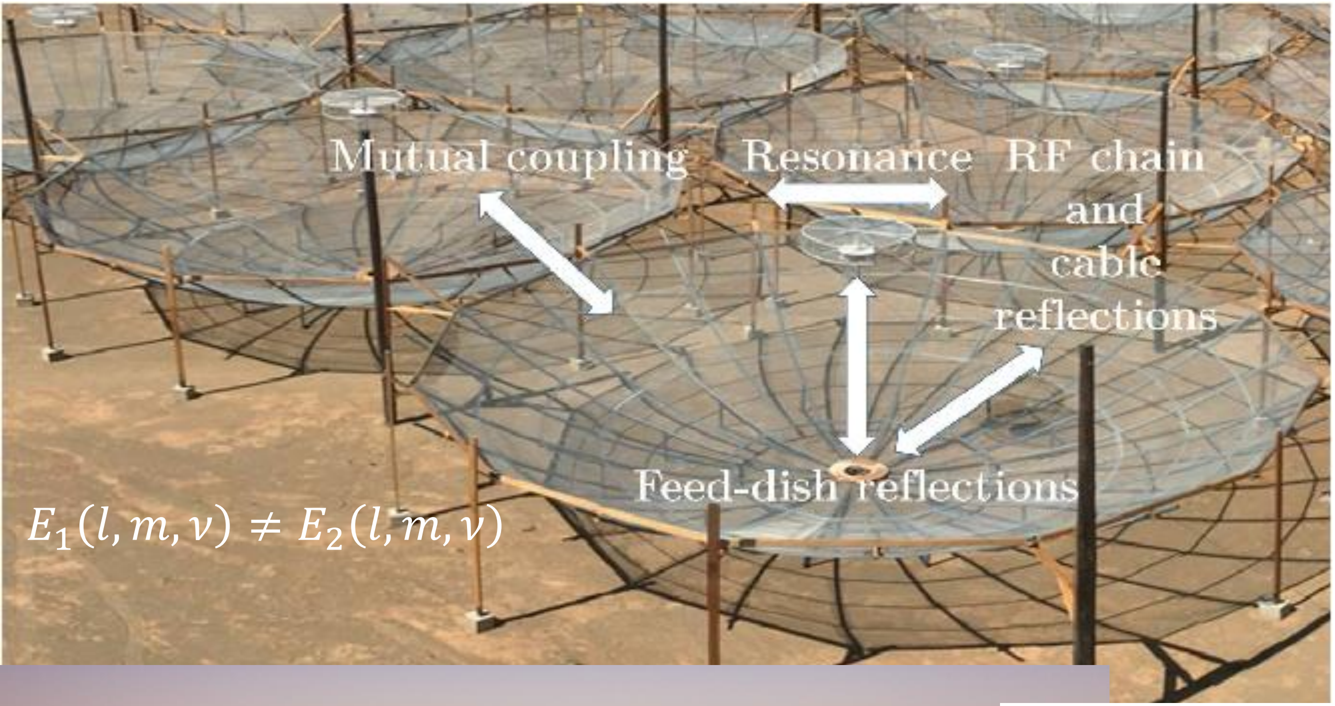
shes have
footprin
um

Beams are frequency variable!



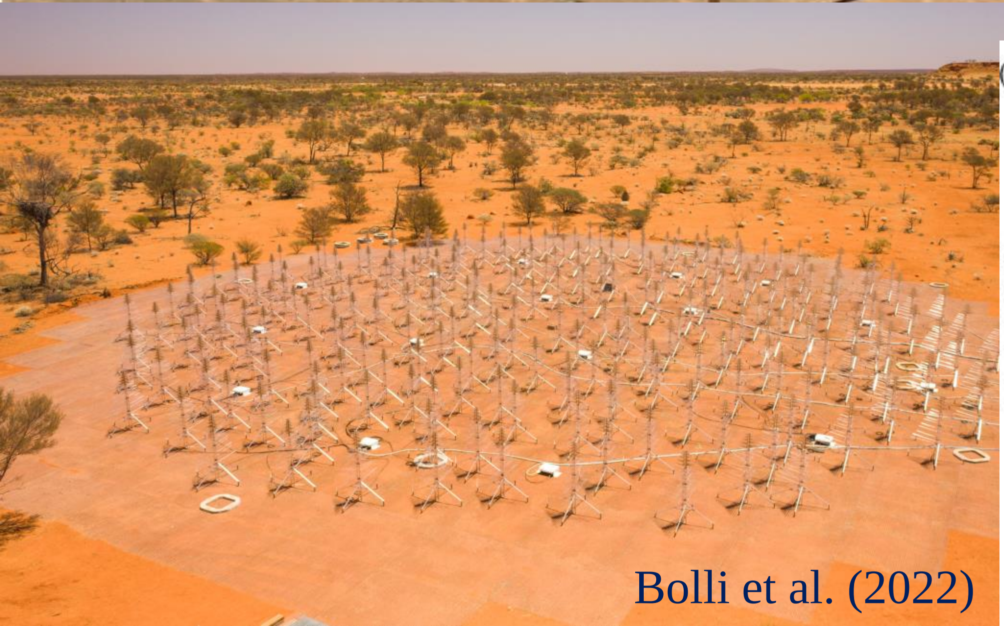
Trott et al. (2020)

3) Know thy primary beams (better)

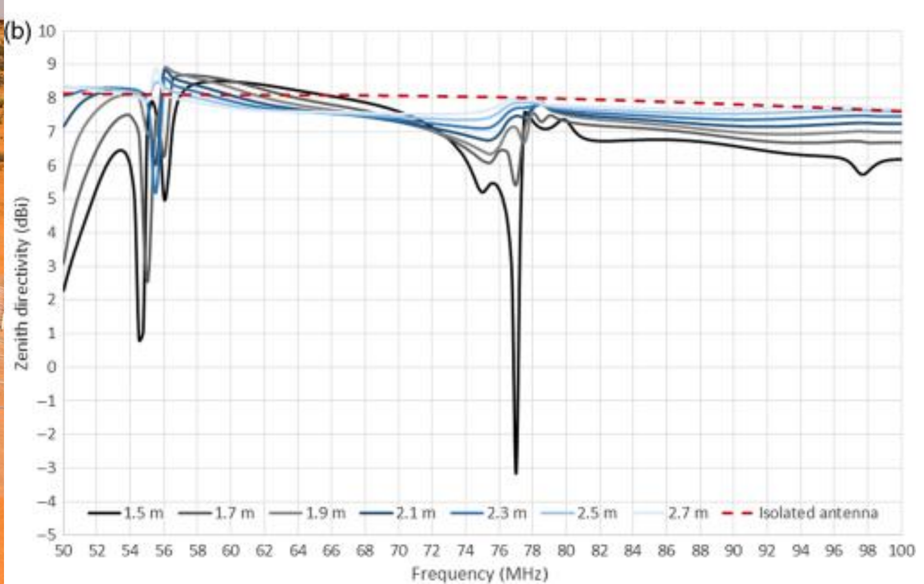


Particularly "bad" as it invalidates redundancy

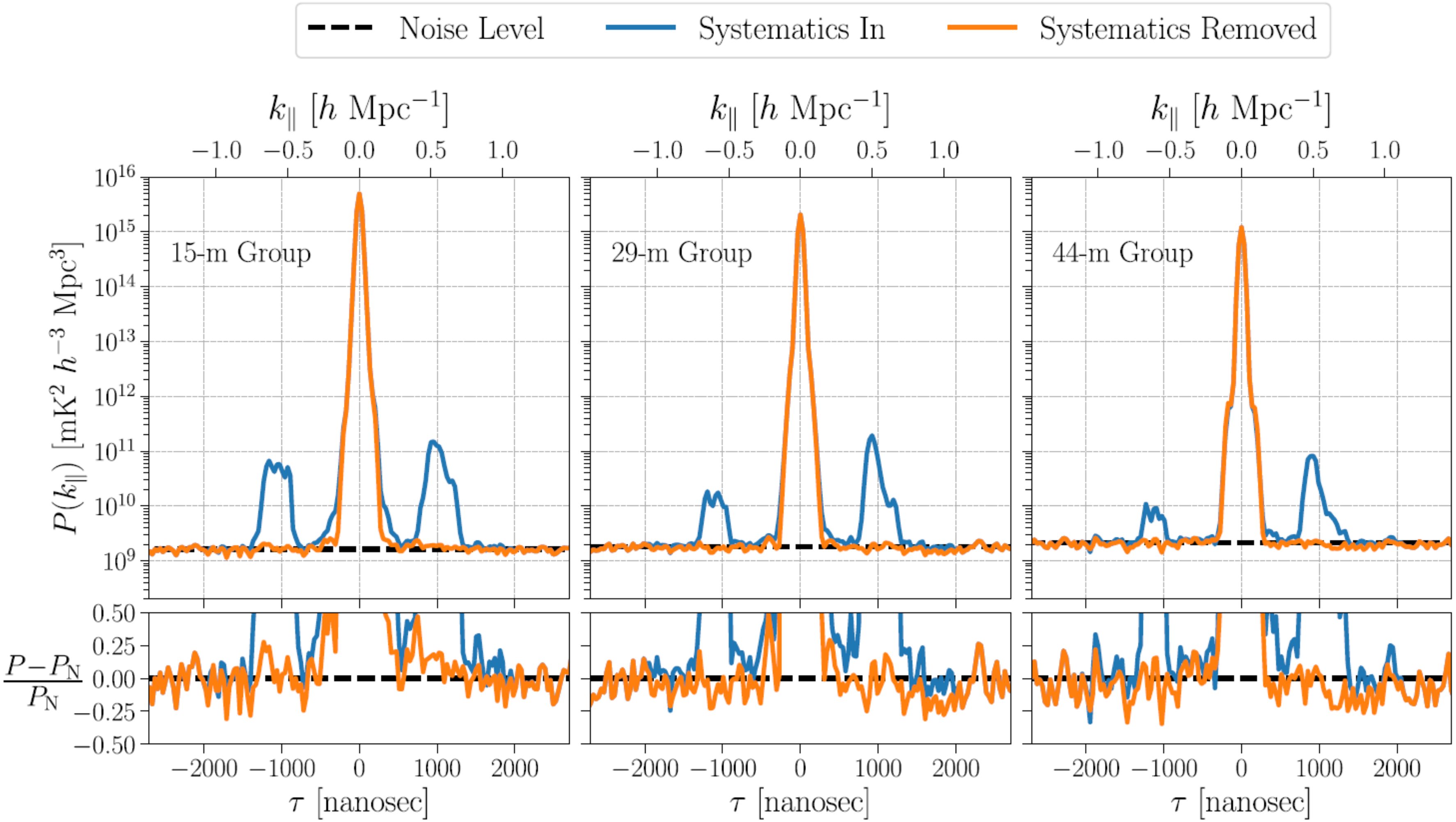
Fagnoni et al. (2021)



Bolli et al. (2022)

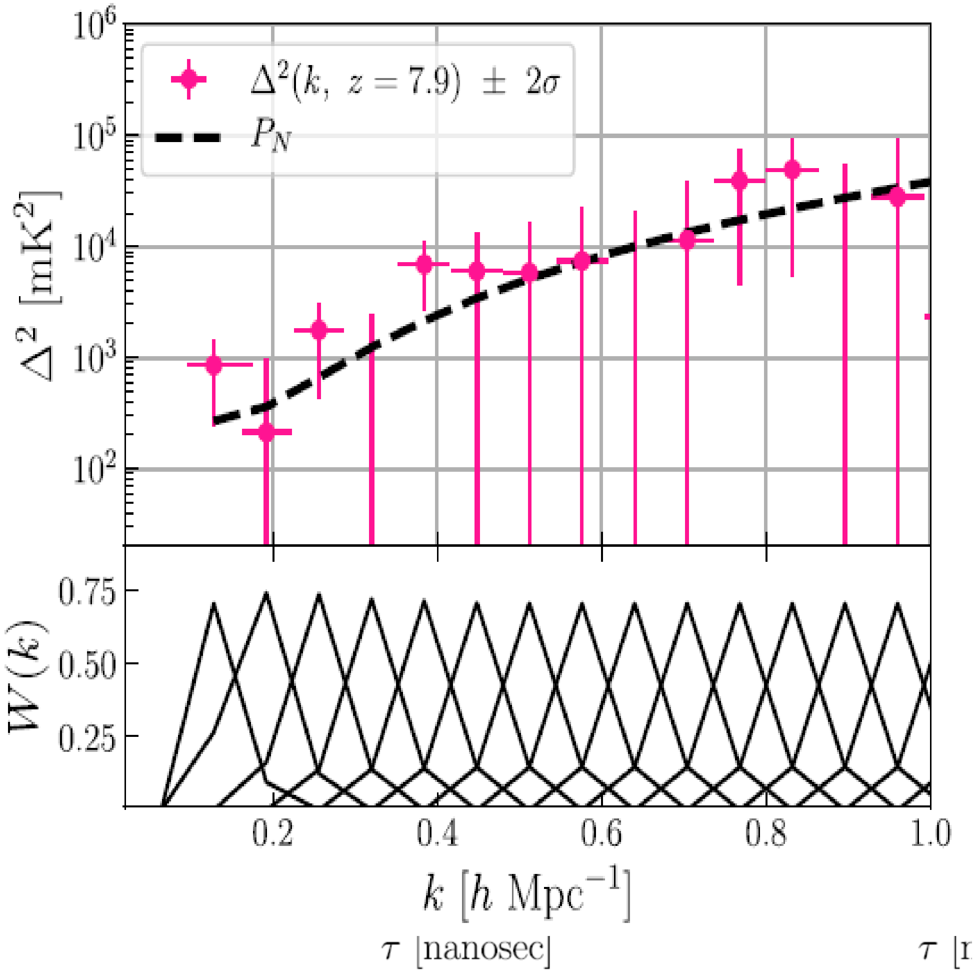


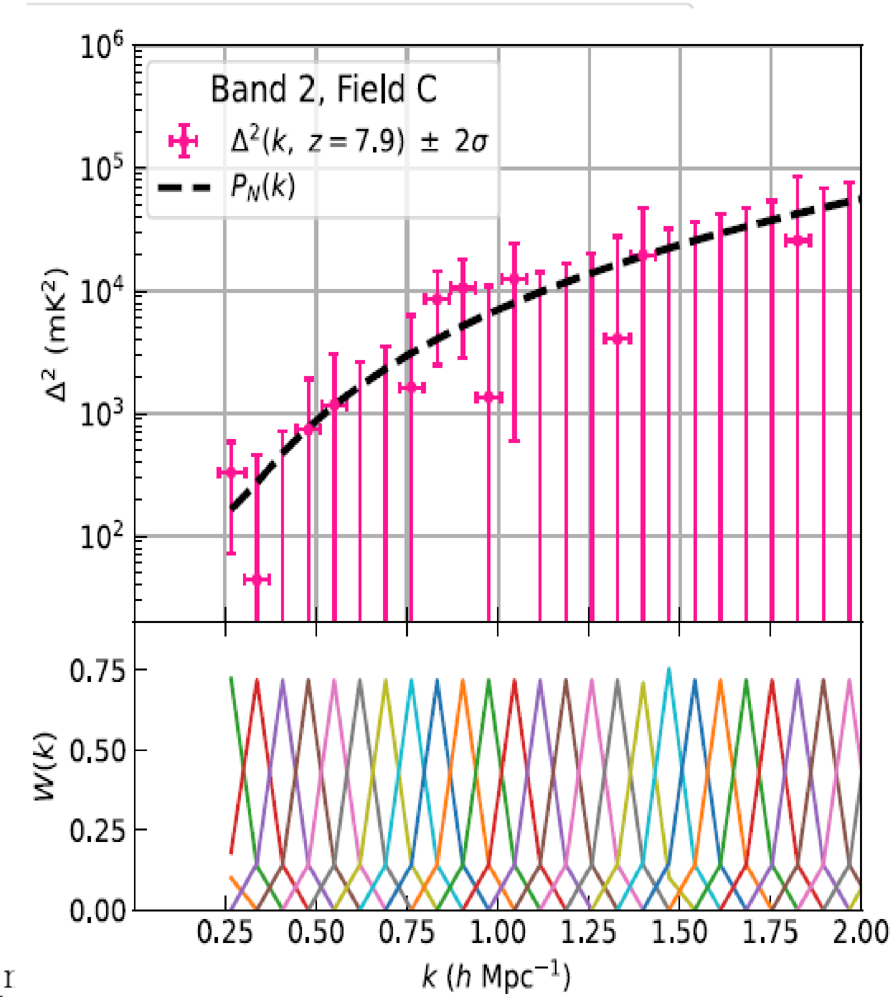
4) Mitigating systematics



Kern et al. (2020)

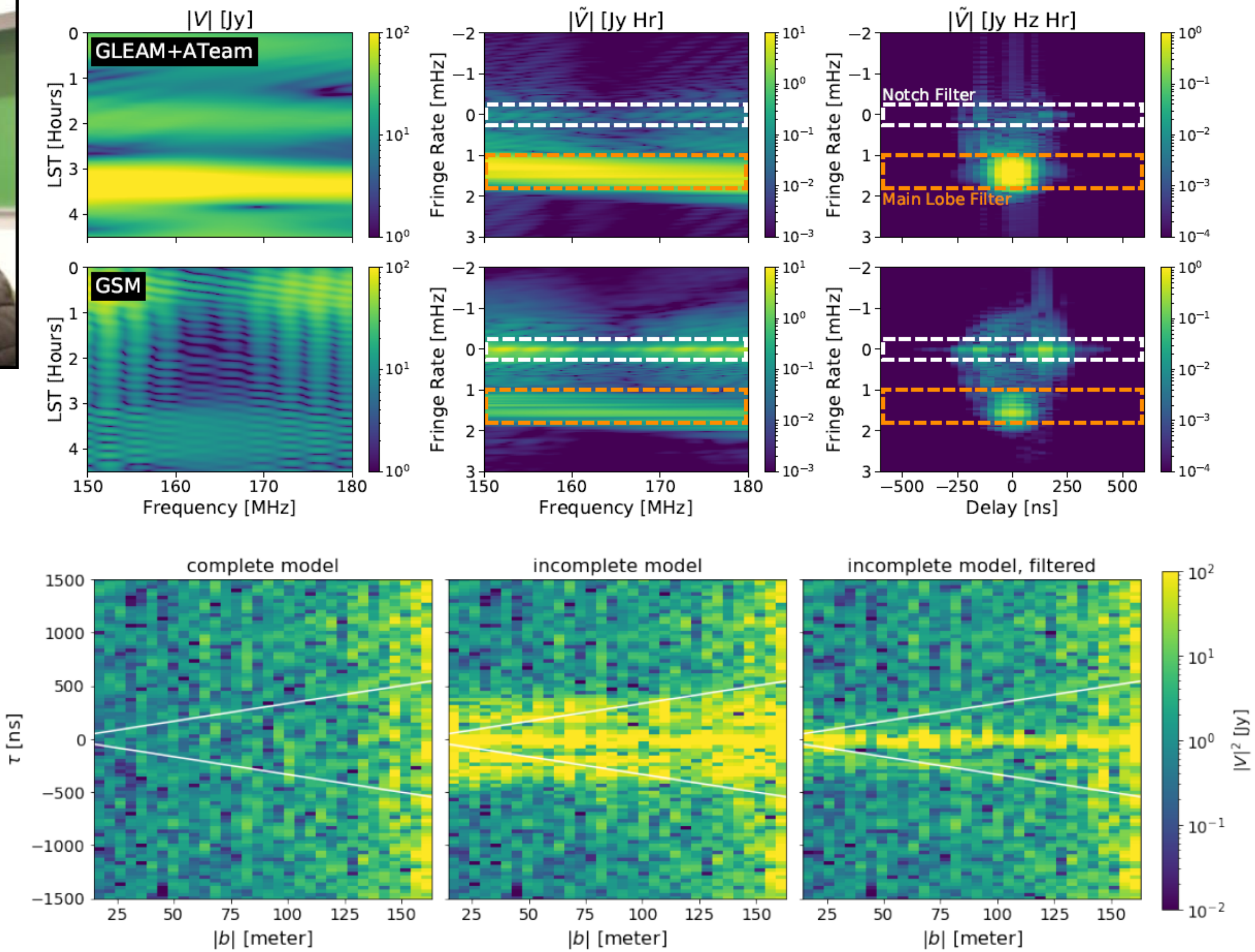
4) It has worked well so far in some cases…





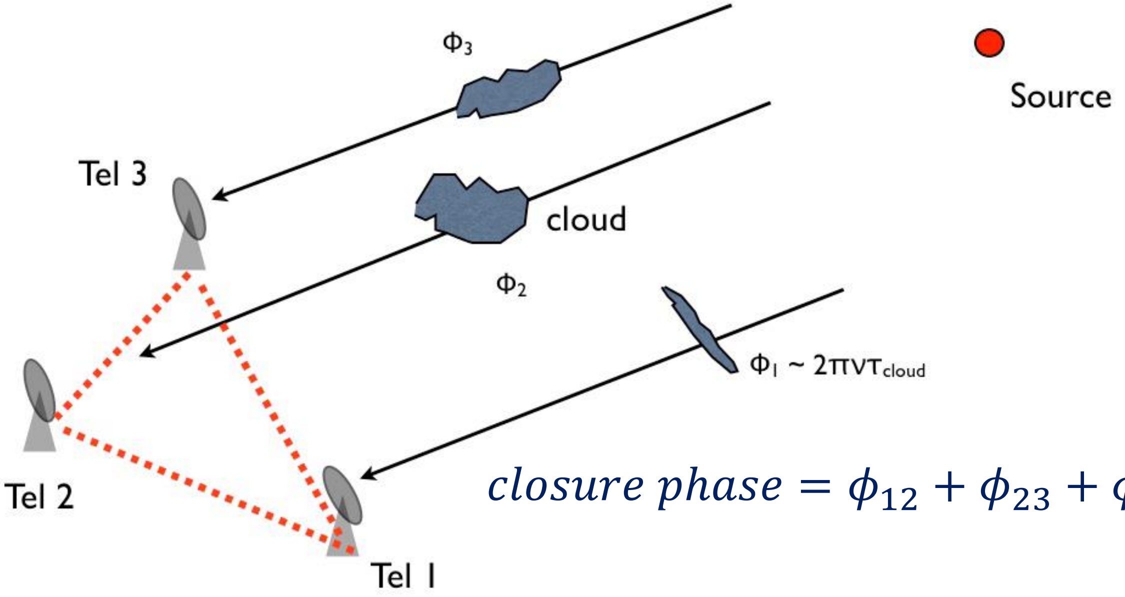
The HERA collaboration (2023, 2022), Aguirre et al. (2021), Kern et al. (2020a, b)

5) Mitigating systematics: fringe rate filters

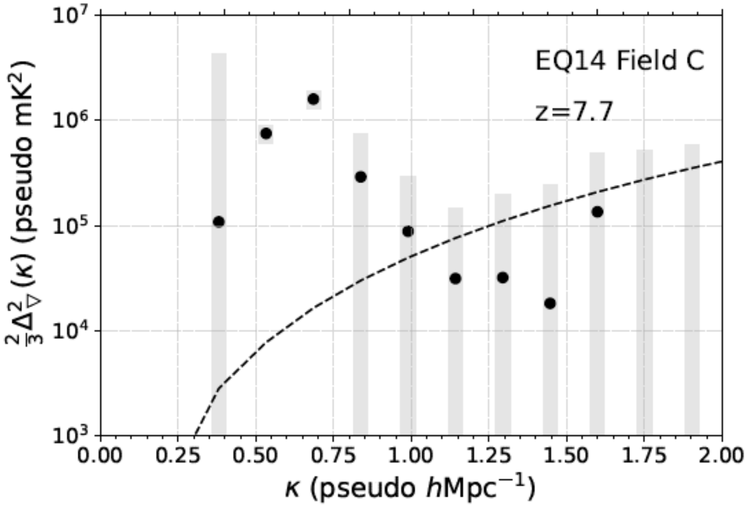


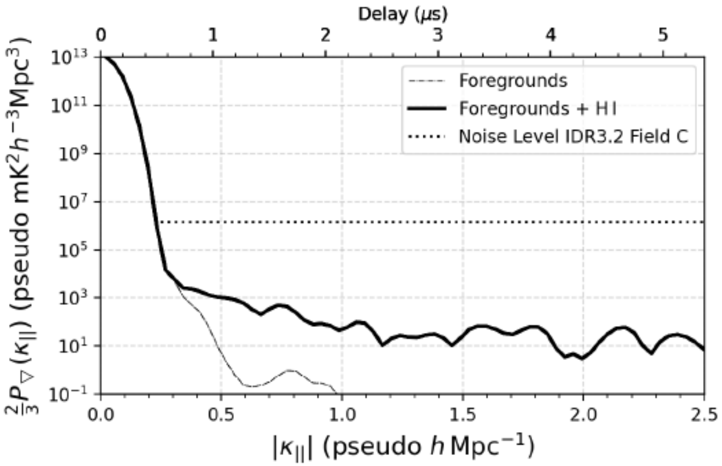
Charles et al. (2023)

6) Mitigating systematics: closure phase



$$closure\ phase = \phi_{12} + \phi_{23} + \phi_{31}$$

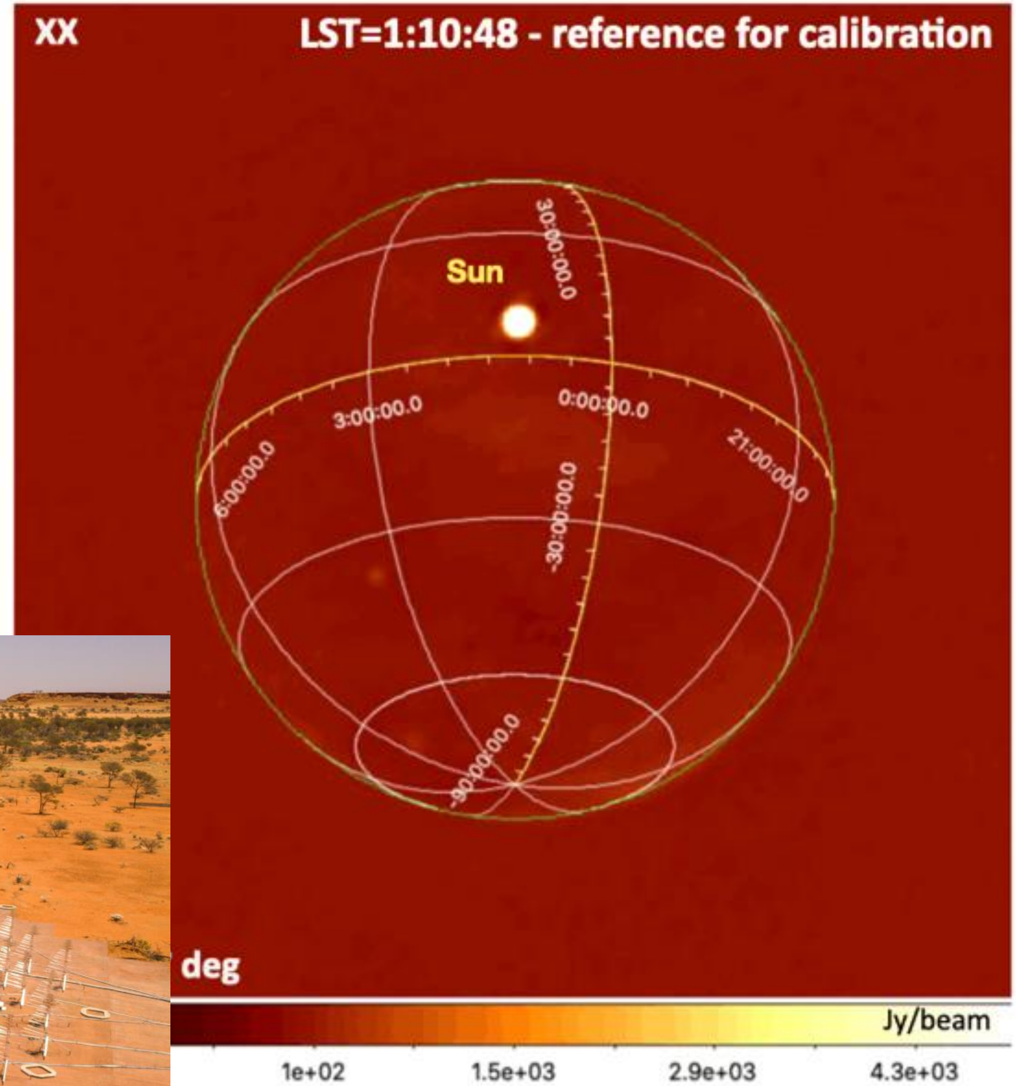


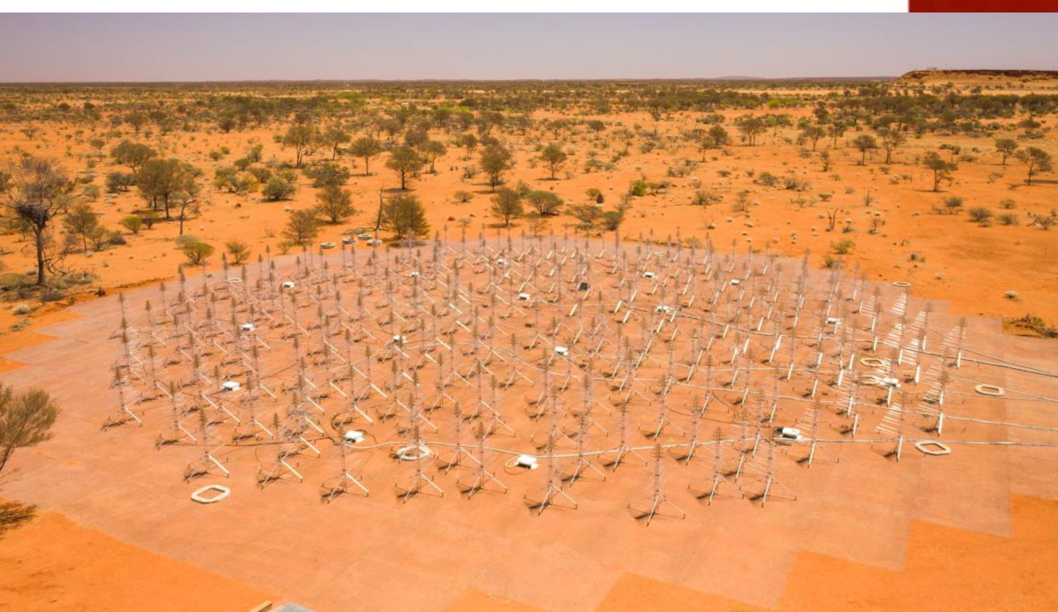


Keller et al. (2023)

The SKA is no longer so far in the future

THANK YOU





Macario et al. (2022)