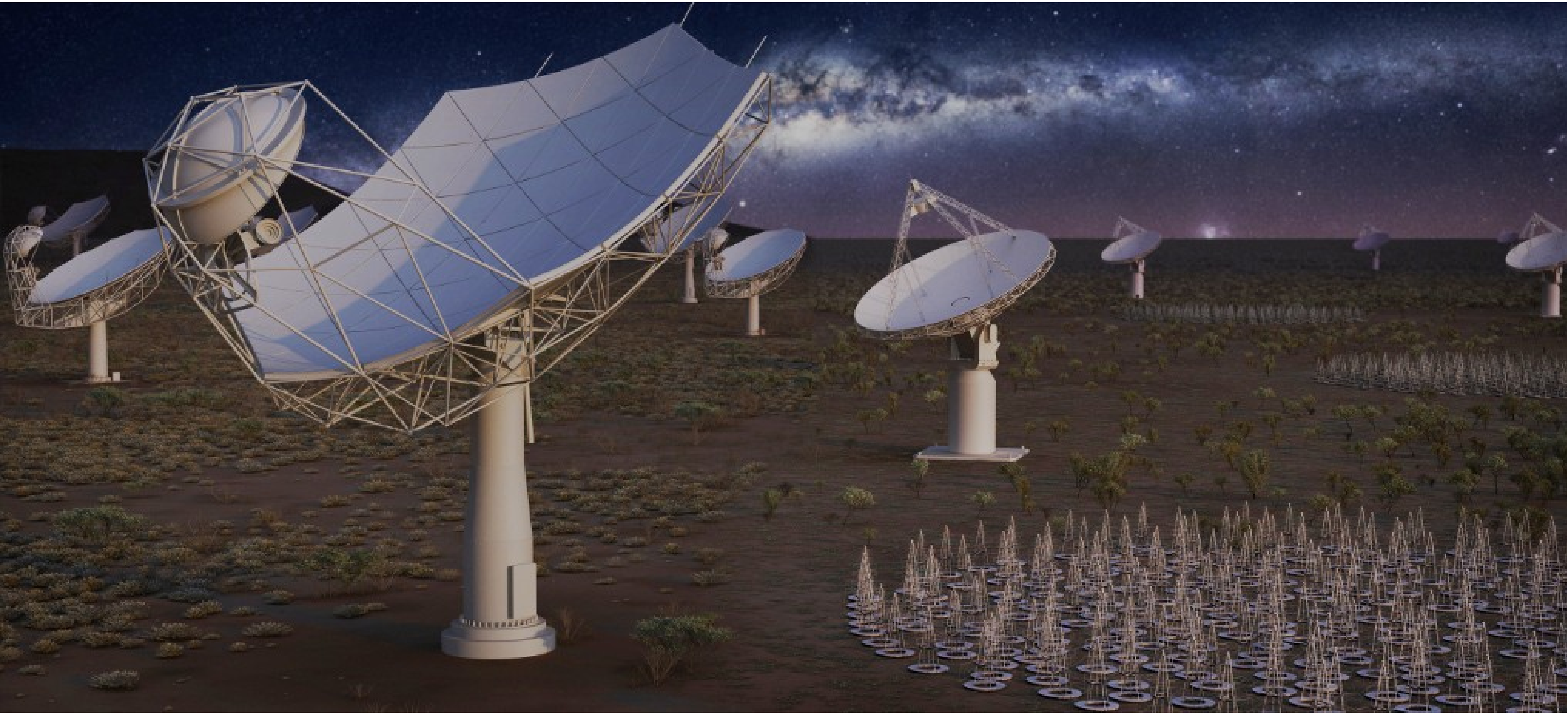
Cosmology with the SKA



Lucchin school 2016
OACN / INAF

Phil Bull
JPL/Caltech
+ SKA Cosmology SWG

Outline

Lecture 1: The sky through a radio telescope

1. Radio astronomy in the SKA era
2. Basics of radio receivers
3. Detecting radio sources
4. Fundamentals of interferometry

Lecture 2: Radio galaxies

1. Physical sources of radio emission in galaxies
2. Aperture synthesis
3. Continuum surveys; 2D correlations and weak lensing
4. HI galaxy redshift surveys; peculiar velocities

Lecture 3: Intensity mapping

1. Intensity mapping
2. Designing an intensity mapping experiment
3. Foreground contamination
4. Open questions and the future of radio cosmology

The era of big surveys

The way we do astronomy is changing!

***Big science*:** Big surveys, big datasets, big teams, big questions, big budgets…

(Big headaches)

The era of big surveys

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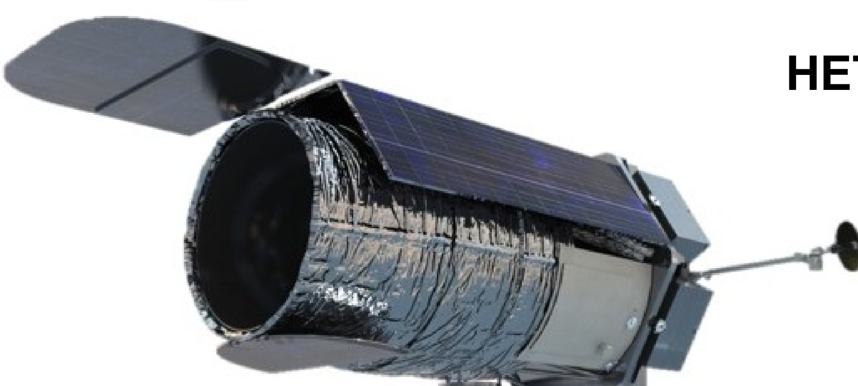
Euclid
(ESA/Astrium)

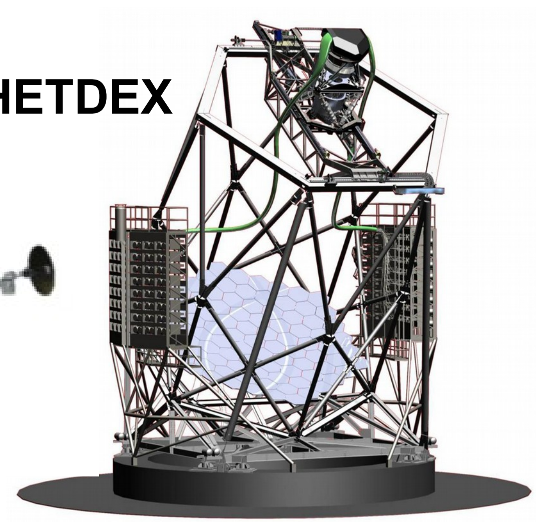
New science!

SKA (SKAO)

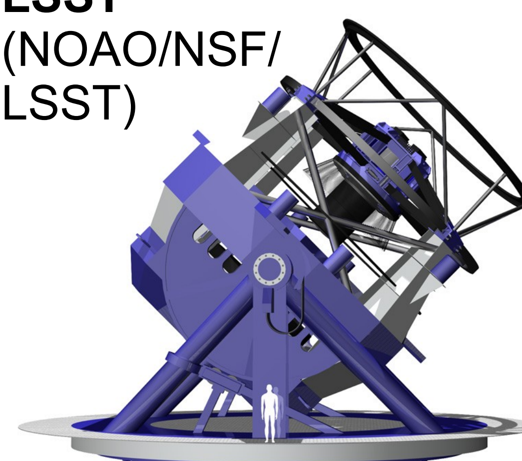


WFIRST (NASA)

HETDEX



LSST
(NOAO/NSF/LSST)



What we want...

Understanding!

- What is dark energy?
- Is inflation real?
- Where does General Relativity break down?
- Are there other particles? Forces? (e.g. dark matter)

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What we need...

Data!

- Map of how matter is distributed throughout space-time
- Information on how structures grow

→ **Observe billions(!) of galaxies across cosmic time**

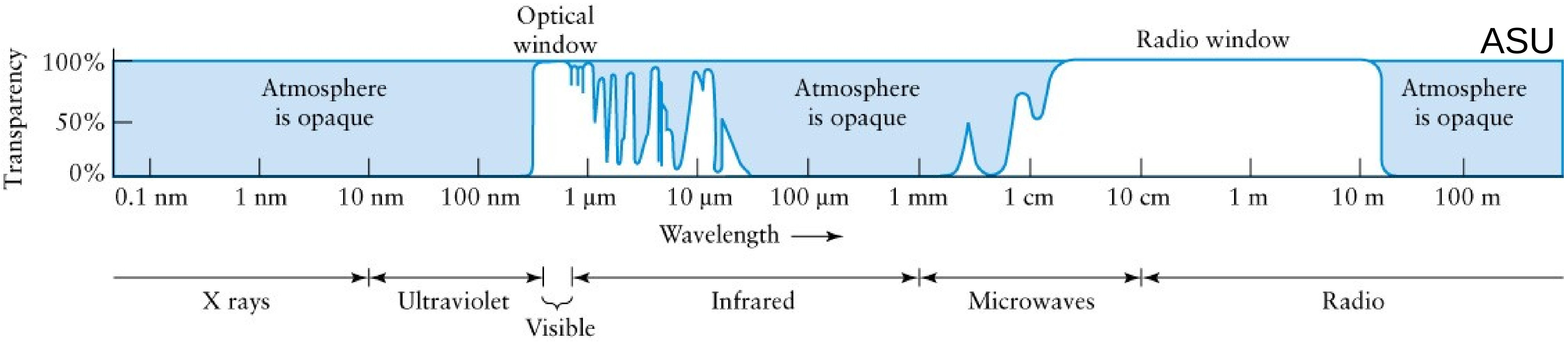
Theory!

- New ideas on how to explain these phenomena
- (See arXiv:1512.05356 for a review...)

Radio cosmology

The radio sky is very different to other wavelengths

ASU



Radio cosmology

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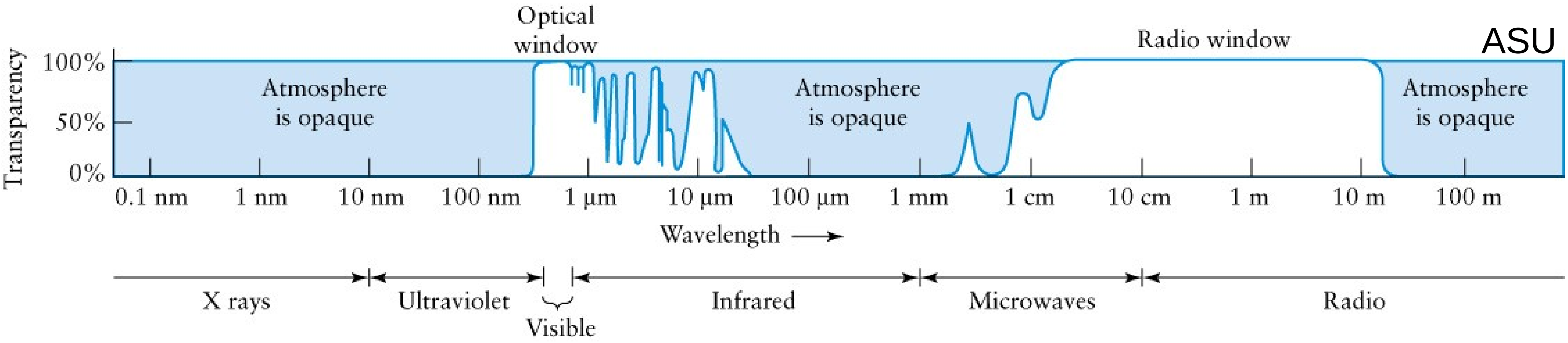


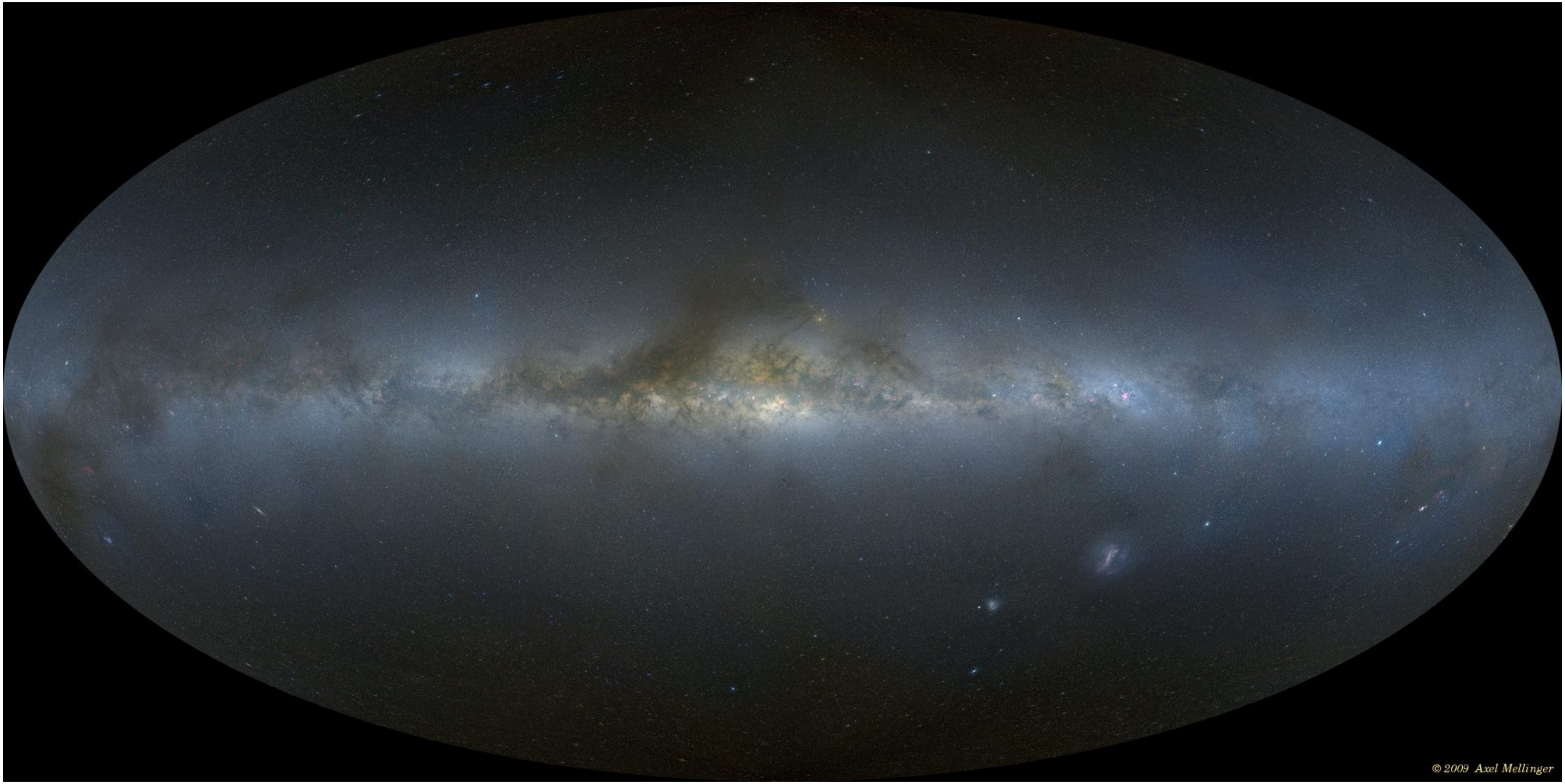
Lots of high-energy physics: Black holes, neutron stars, pulsars, supernovae… Many bright objects to look for

Radio doesn't get absorbed easily: Radio waves emitted by neutral hydrogen pass through dust/gas

Efficient way of seeing 100's of millions of galaxies that trace the large-scale structure of space-time

Radio astronomy in the SKA era

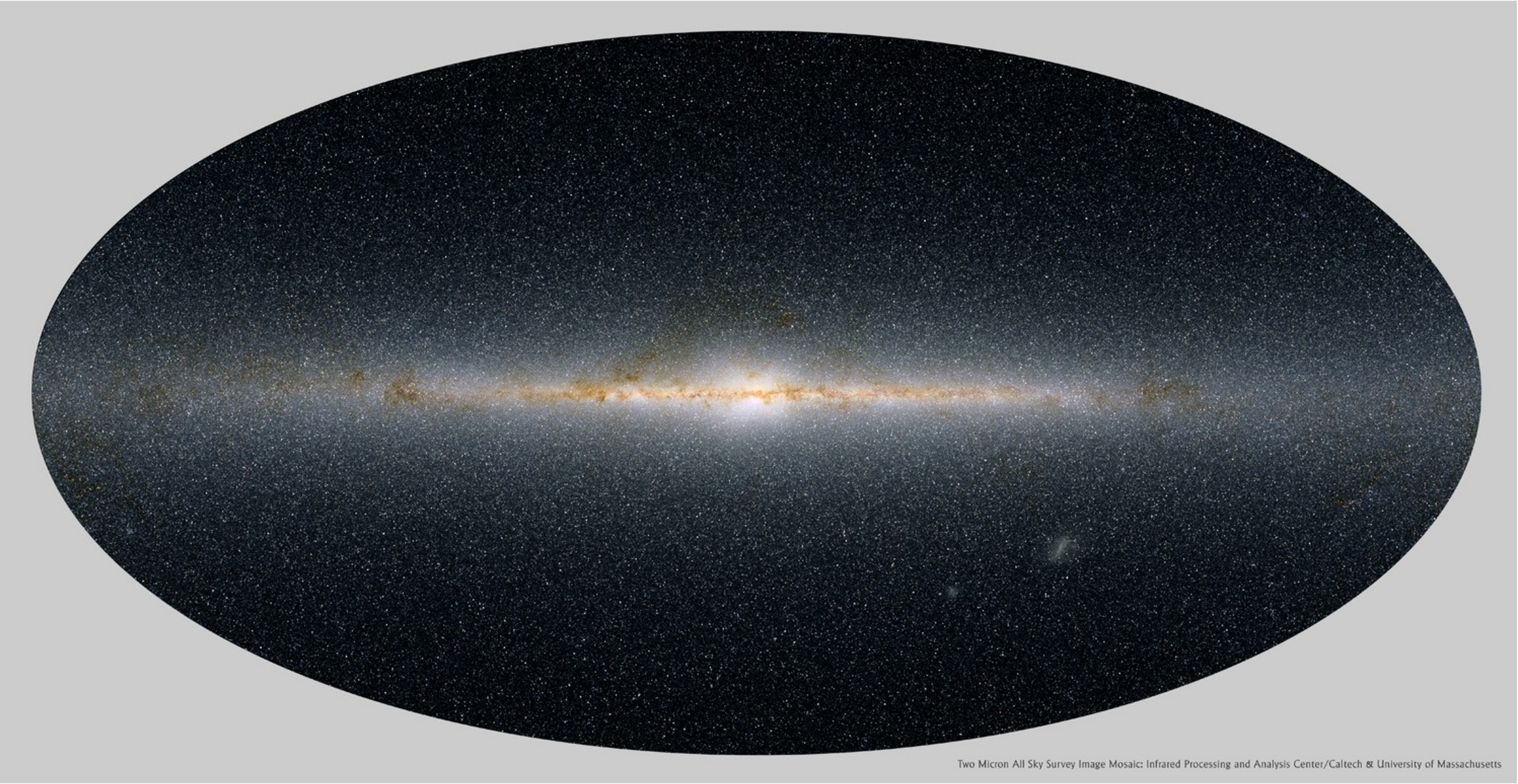
The sky



Optical

Axel Mellinger

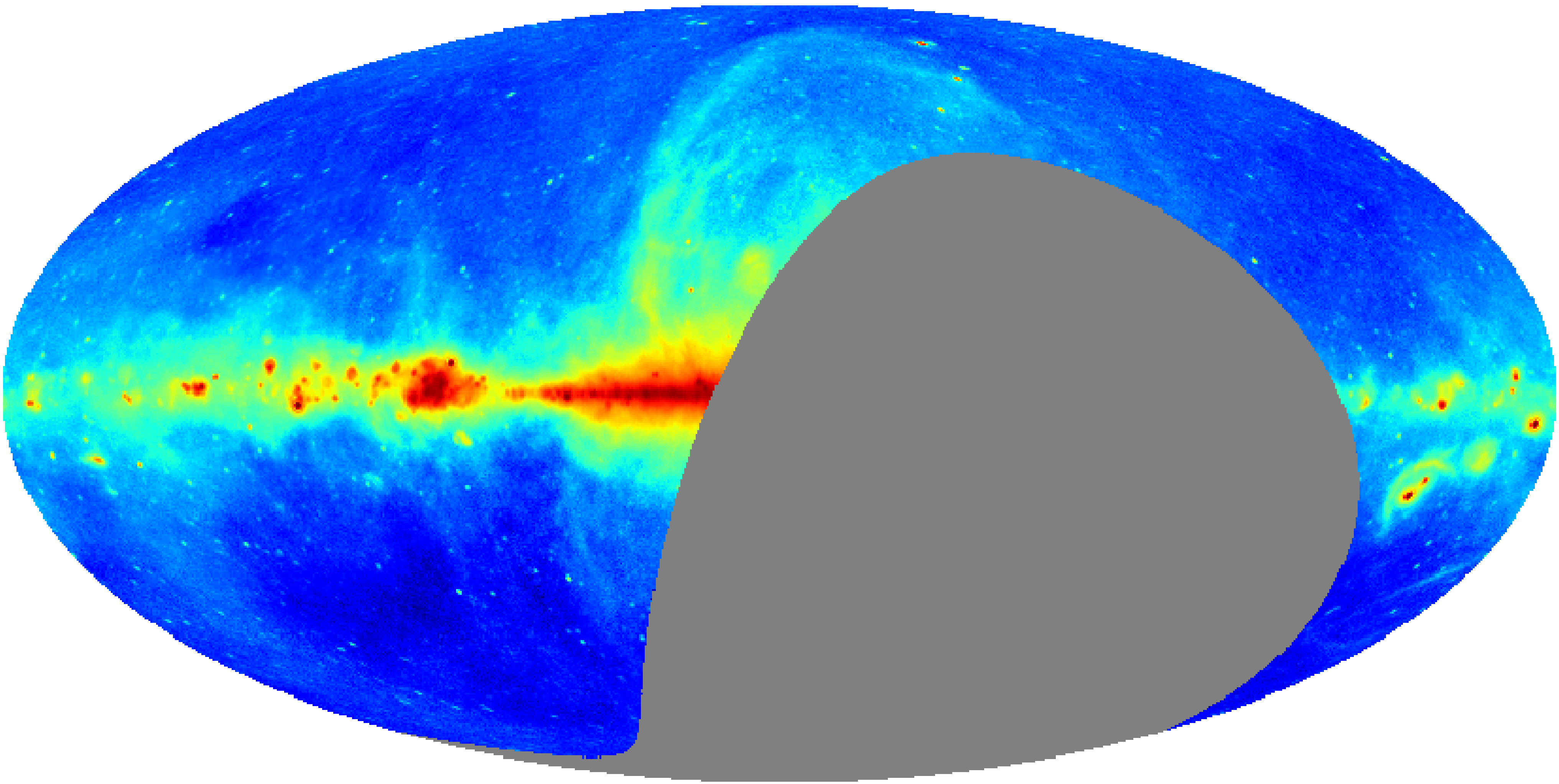
The sky



Infrared

2MASS

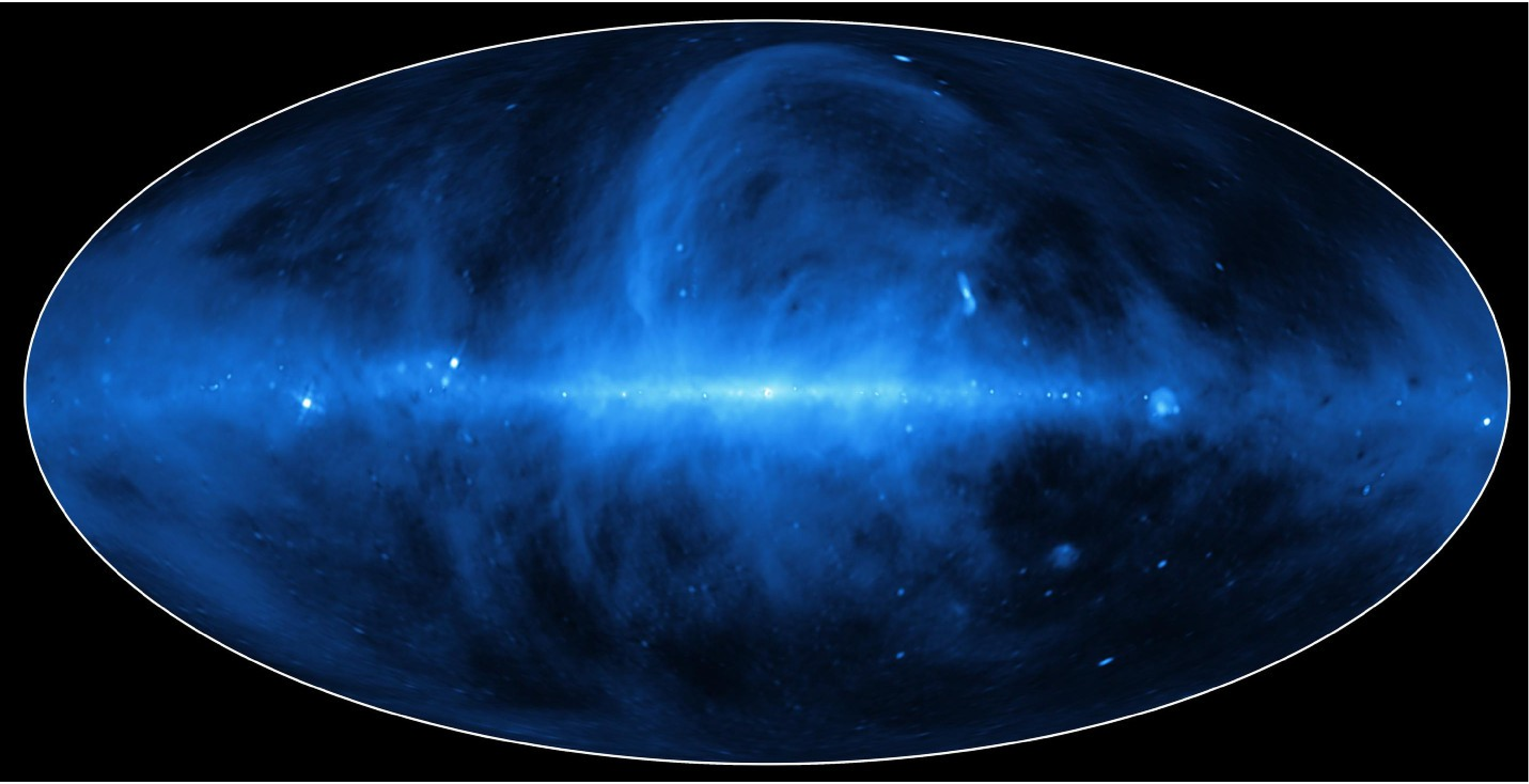
The sky



Radio (5 GHz)

CBASS

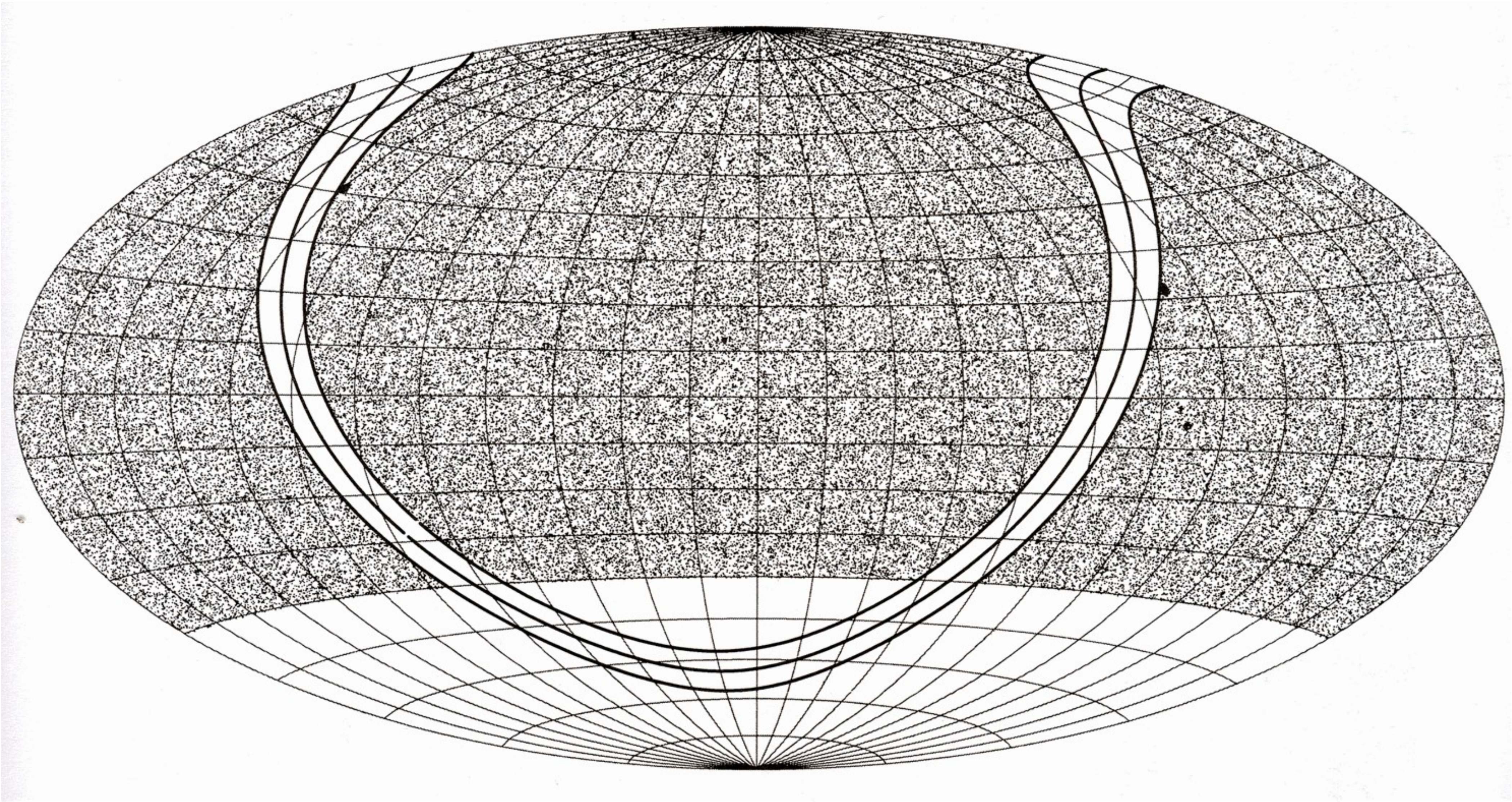
The sky



Radio (1.4 GHz) (rescaled)

Planck

The sky

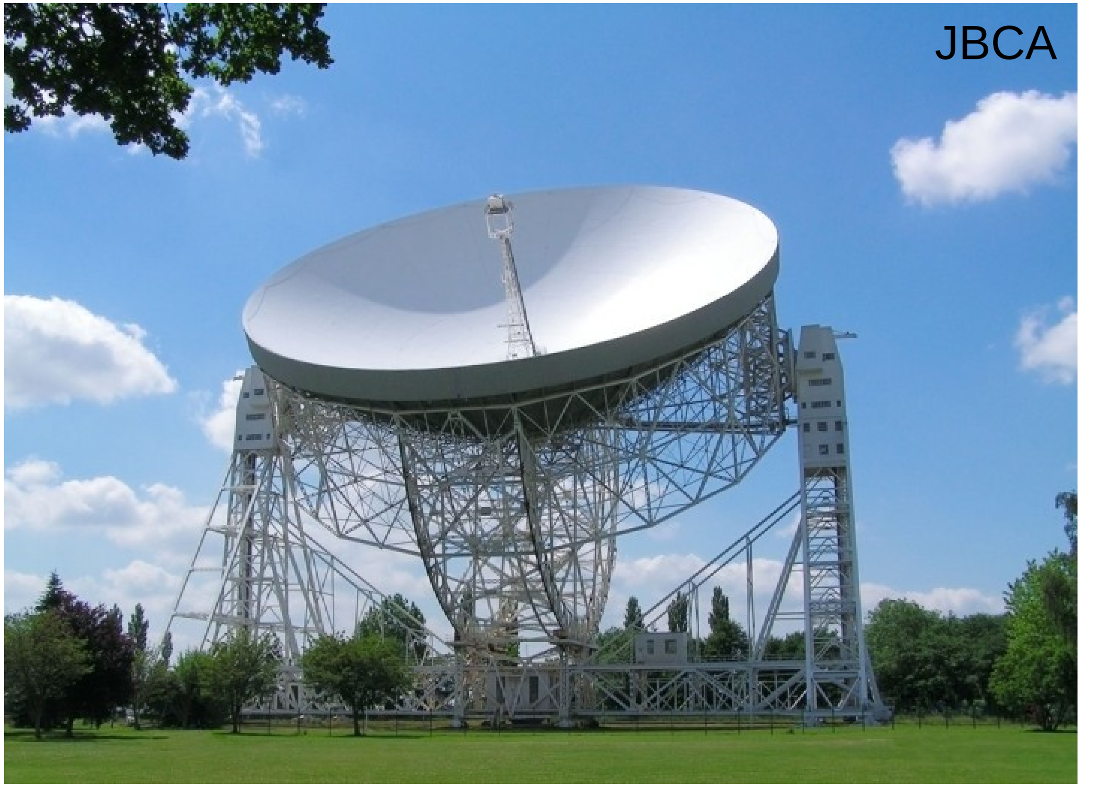


Radio (1.4 GHz) (just galaxies)

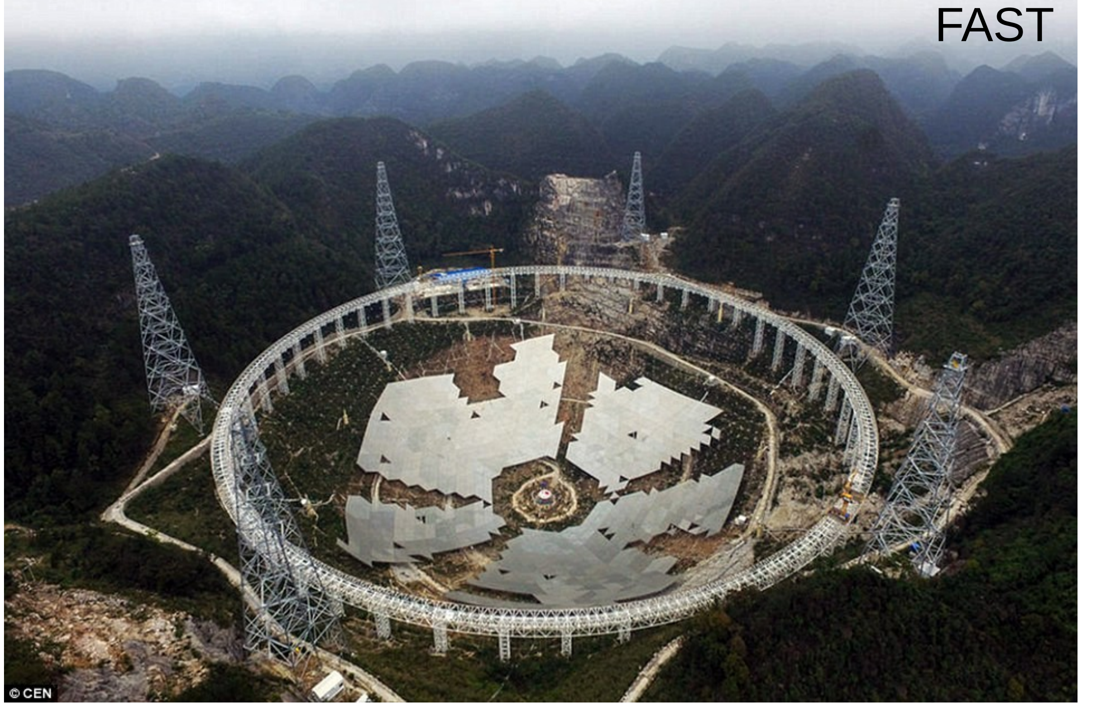
J. Condon / NVSS

Single-dishes

"Classic" single-dish radio telescopes



Arecibo



Radio arrays

VLA / NRAO

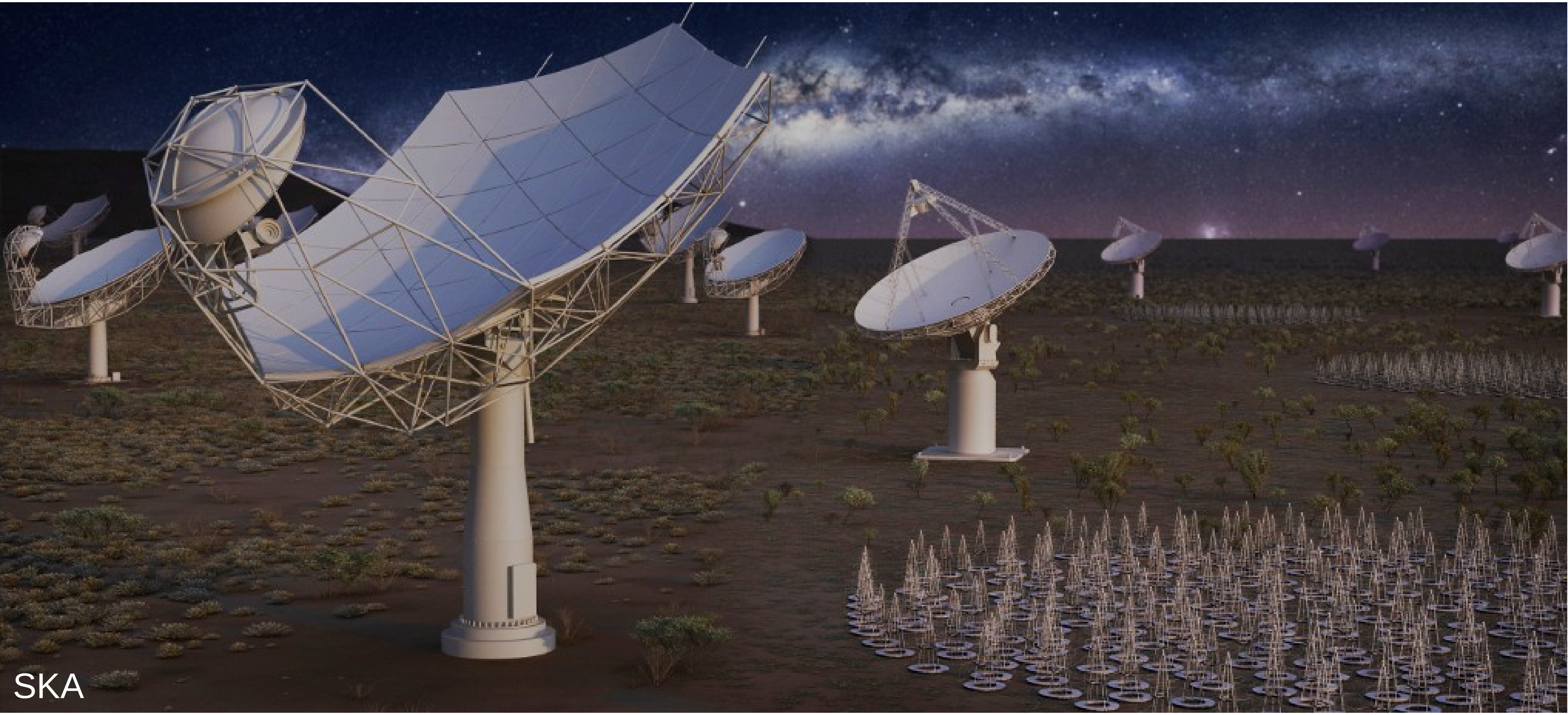
LOFAR / ASTRON

ATCA

Square Kilometre Array

SKA1-MID
(South Africa)

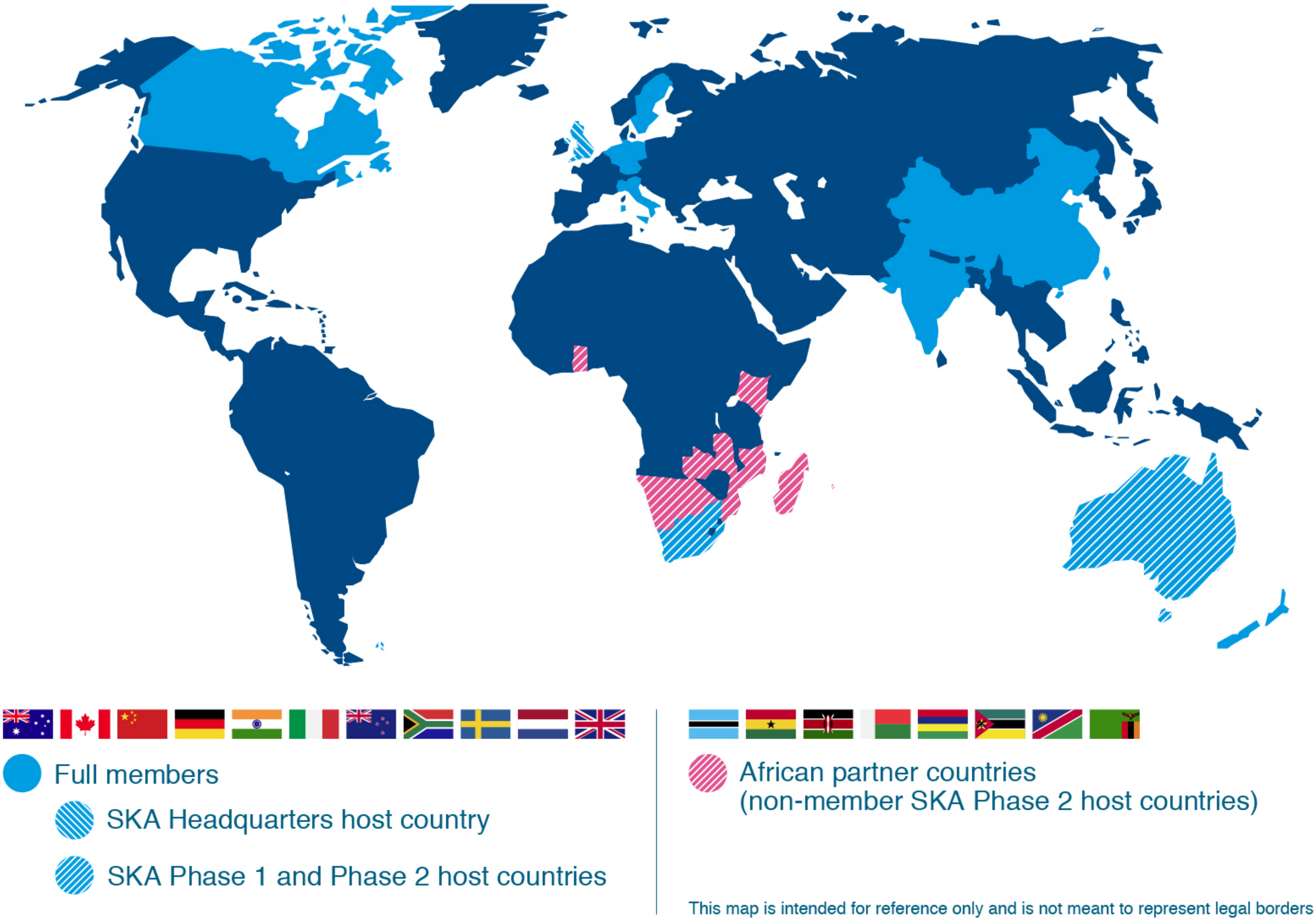
Mid-frequency dish array
350 MHz – 14 GHz (5 bands), 190 dishes



Low-frequency aperture array
50 – 350 MHz, ~500 stations x 90 dipoles

SKA1-LOW
(Australia)

Square Kilometre Array



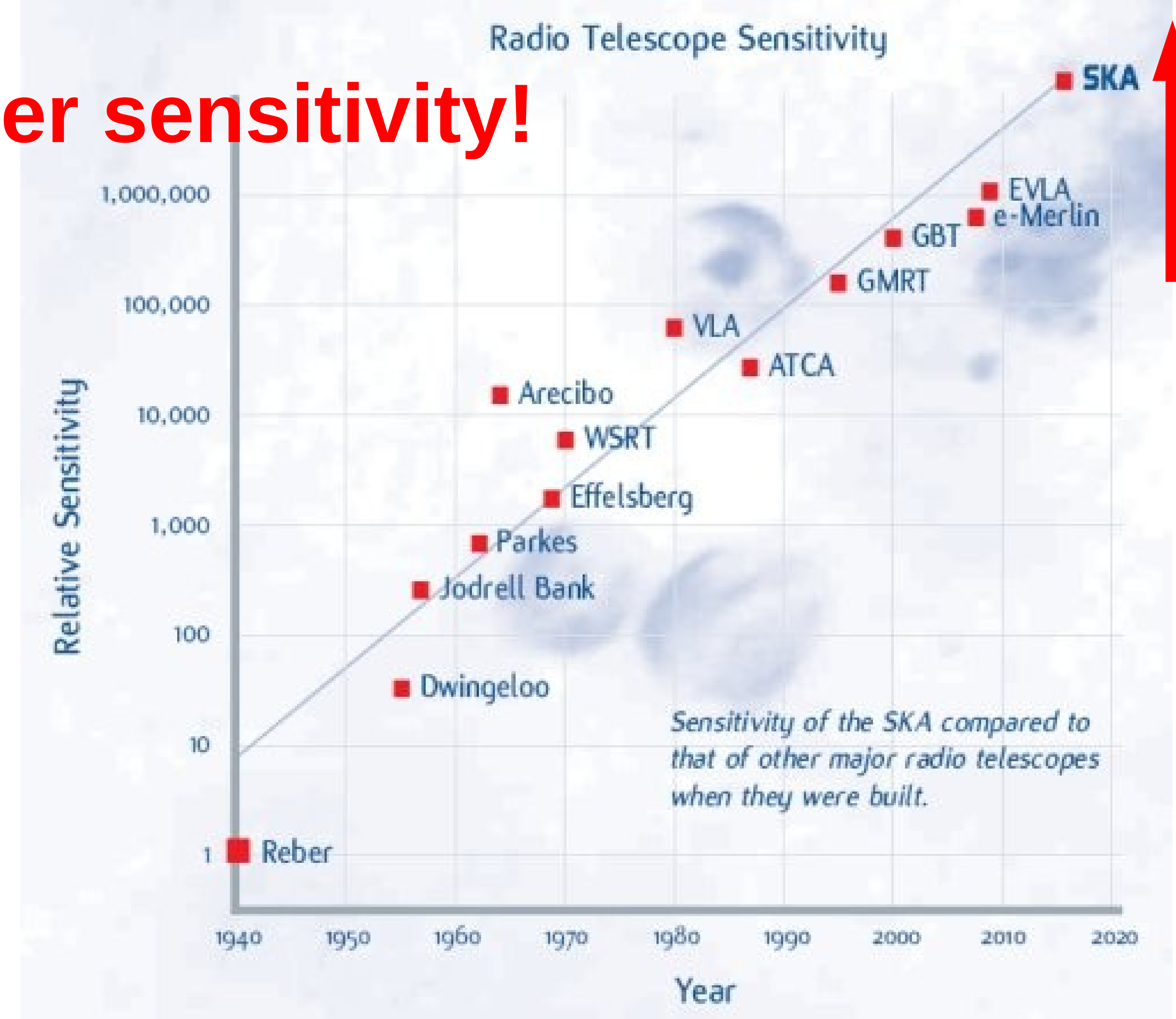
The SKA in context

What does the SKA do that older radio telescopes don’t?

The SKA in context

What does the SKA do that older radio telescopes don't?

Higher sensitivity!



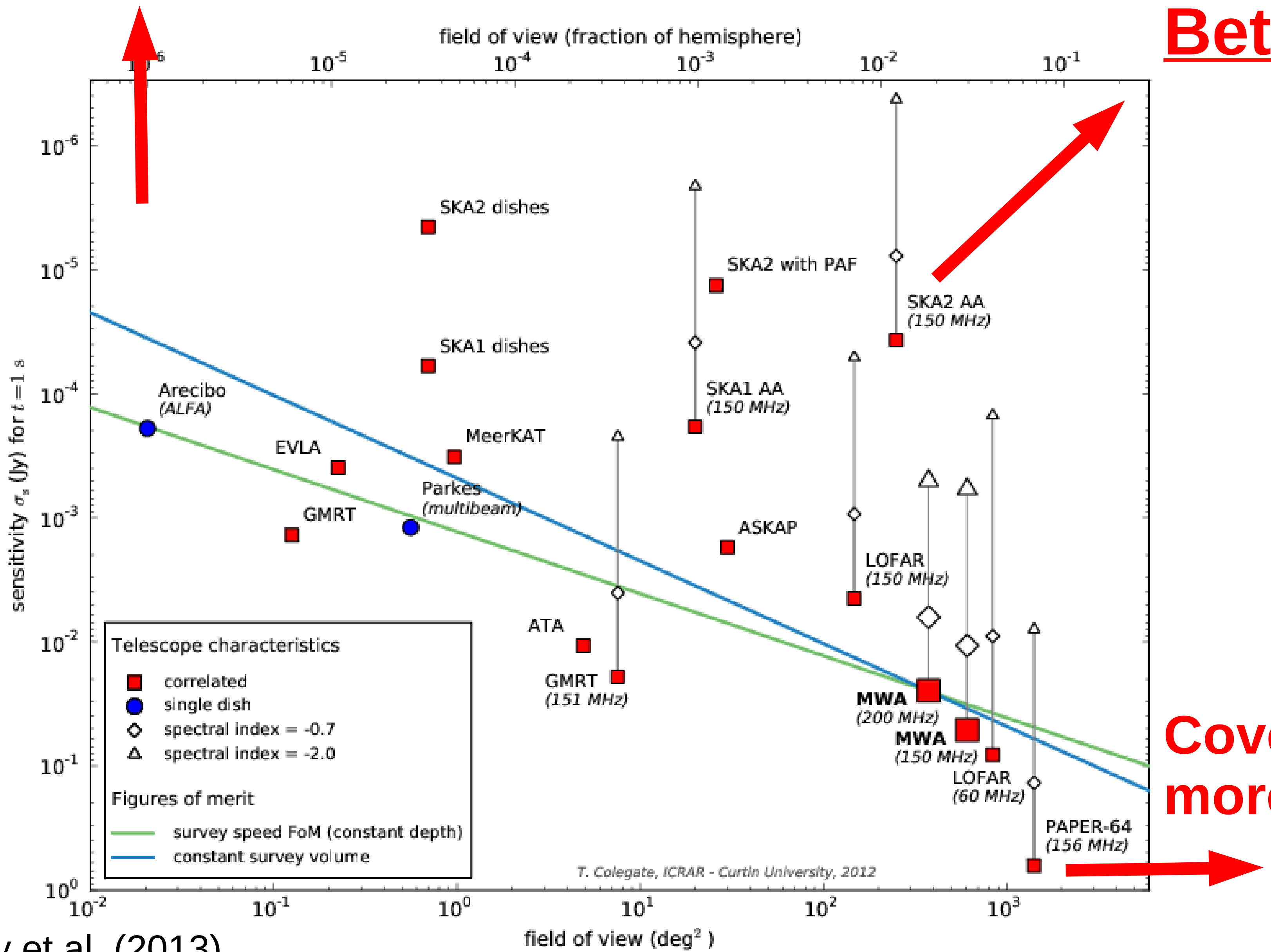
Better!

Sensitivity

Radio window

Less noise

Better!



Covers more sky

Tingay et al. (2013)

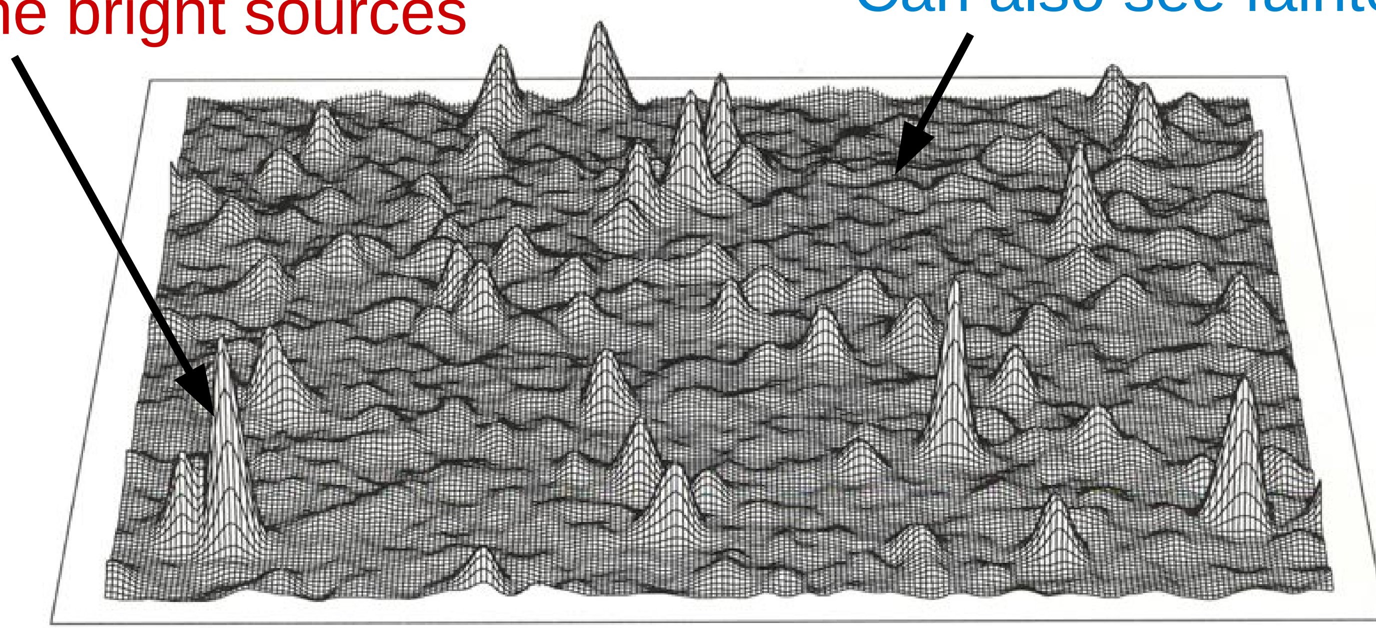
How to improve radio telescopes

Better sensitivity:

- Low-noise receivers (cryogenics, better amplifiers)
- Better location (less radio interference, better weather)
- Bigger dish / more dishes (interferometer)
- Wider bandwidth (collect more photons!)

Low sensitivity = high noise
Only see the bright sources

High sensitivity = low noise
Can also see fainter sources

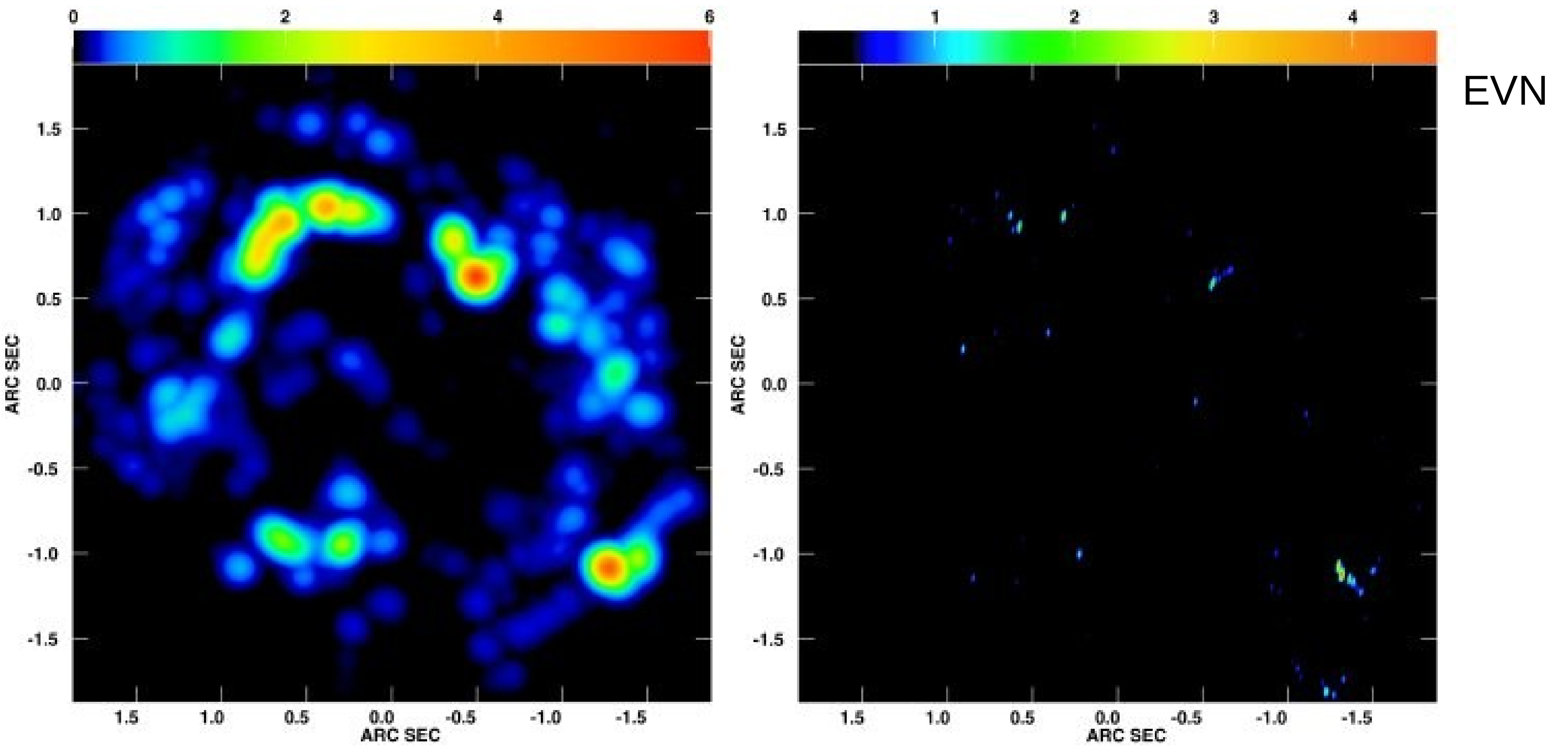


NRAO

How to improve radio telescopes

Better resolution:

- Bigger dish (single-dish)
- More dishes, longer baselines (interferometer)



Short baselines (low resolution) Long baselines (high resolution)

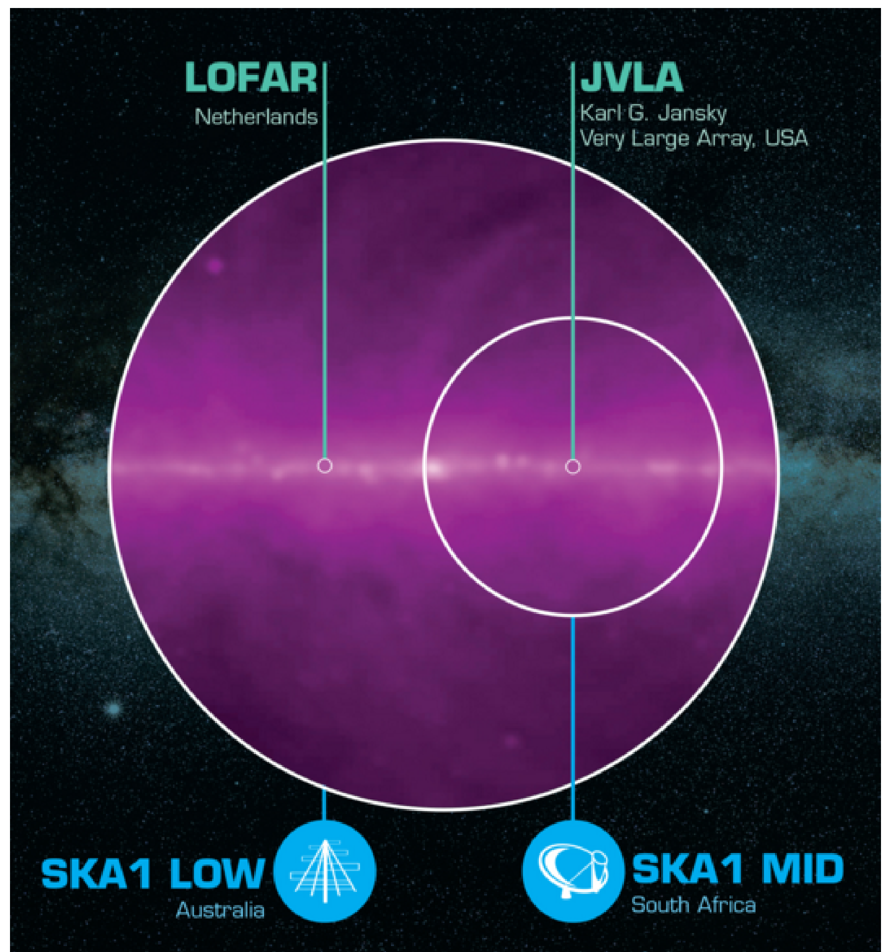
How to improve radio telescopes

Faster surveys:

- Lower noise
- Bigger field of view
- Multi-beam receivers

New science:

- Cover different wavelengths
- Narrow frequency channels
- Faster sampling / processing



The SKA does all these things...

- Better sensitivity (more dishes, low-noise receivers)
- Better resolution (more dishes, more baselines)
- Big bandwidth, many bands, many frequency channels
- Excellent sites (South African and Australian deserts, low RFI)
- Huge field of view (fast surveys)

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Remember what cosmologists need...

Map of how matter is distributed throughout space-time

SKA <u>intensity mapping survey</u>: reconstruct the large-scale matter distribution from $0 < z < 12$

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Observe billions of galaxies across cosmic time

SKA continuum galaxy survey: detect millions of galaxies out to $z \sim 5$; measure lensing and 2D clustering

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Welcome to the era of radio cosmology!

Remember what cosmologists need...

Map of how matter is distributed throughout space-time

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Observe billions of galaxies across cosmic time

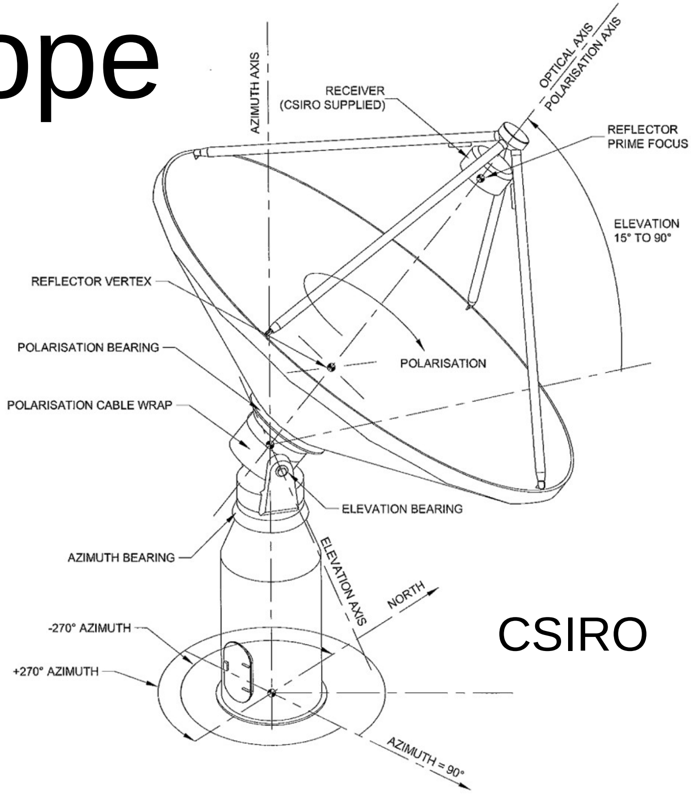
SKA <u>continuum galaxy survey</u>: detect millions of galaxies out to $z \sim 5$; measure lensing and 2D clustering

Basics of radio receivers

Anatomy of a radio telescope

Reflector/ antenna

Focuses and collects radio waves and feeds them into electronics



CSIRO

Anatomy of a radio telescope

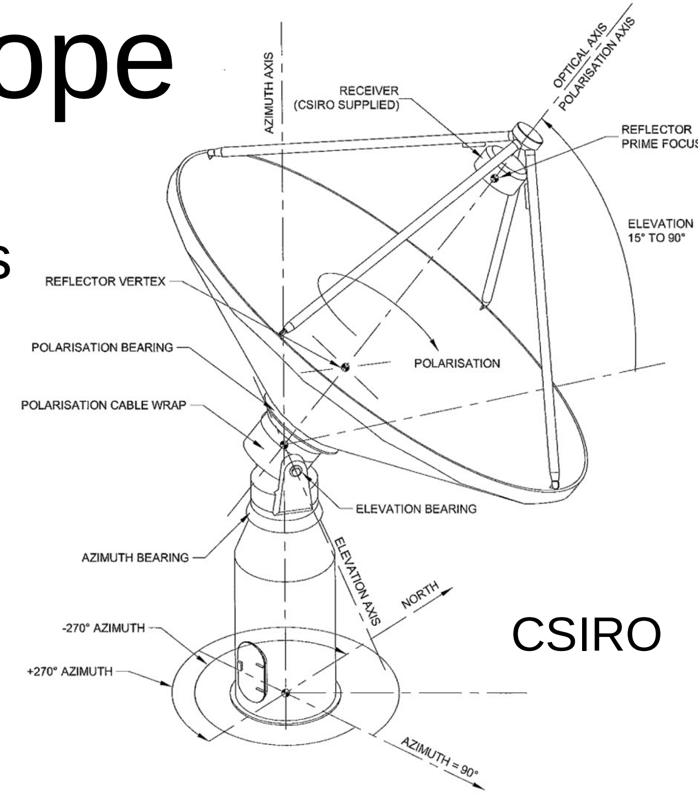
Reflector/ antenna

Focuses and collects radio waves and feeds them into electronics

↓

Mixers / filters

Converts waves into lower-frequency signal and filters out unwanted frequencies



CSIRO

Anatomy of a radio telescope

Reflector/ antenna	Focuses and collects radio waves and feeds them into electronics
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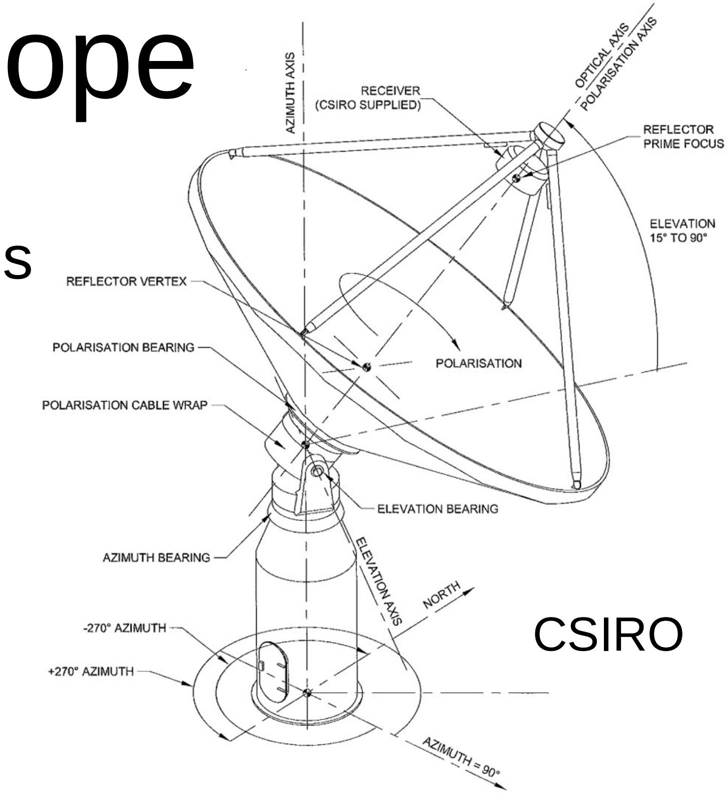
Amplifiers	Boost the amplitude of input signals (without adding too much extra noise!)



CSIRO

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↓

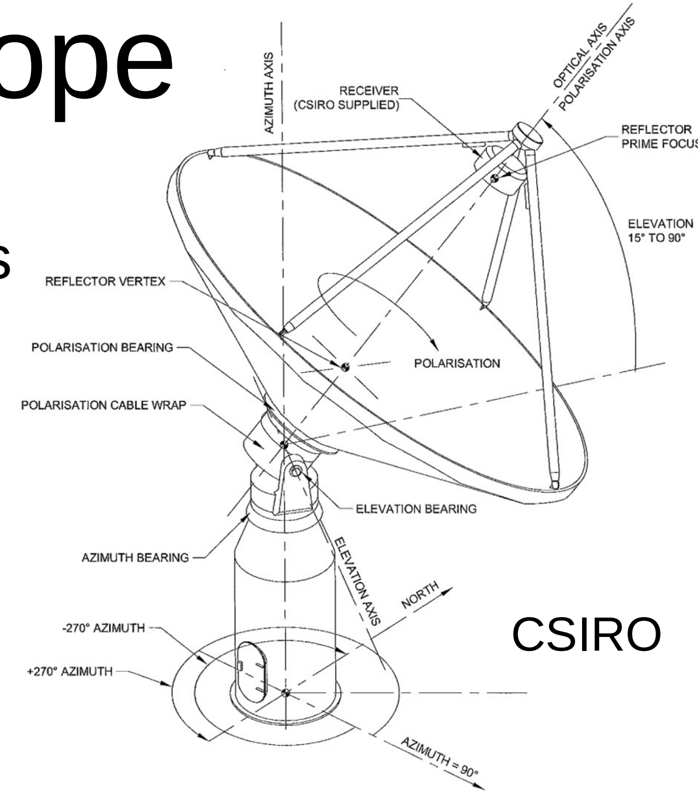
Mixers / filters — Converts waves into lower-frequency signal and filters out unwanted frequencies

↓

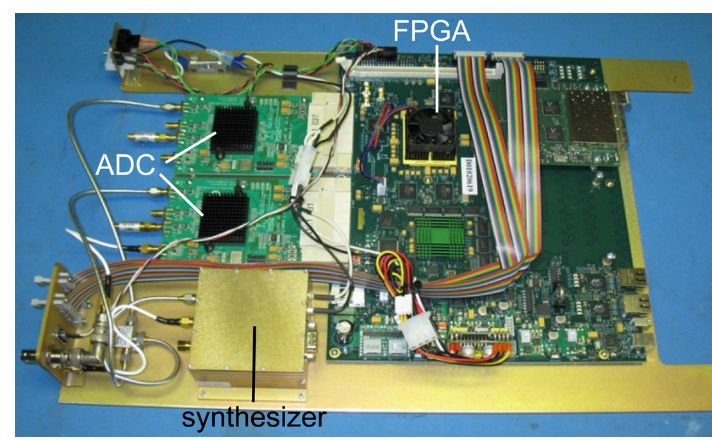
Amplifiers — Boost the amplitude of input signals (without adding too much extra noise!)

↓

Backend — "Detects" and digitises input signals, splits into frequency channels, sends data to PC



CSIRO

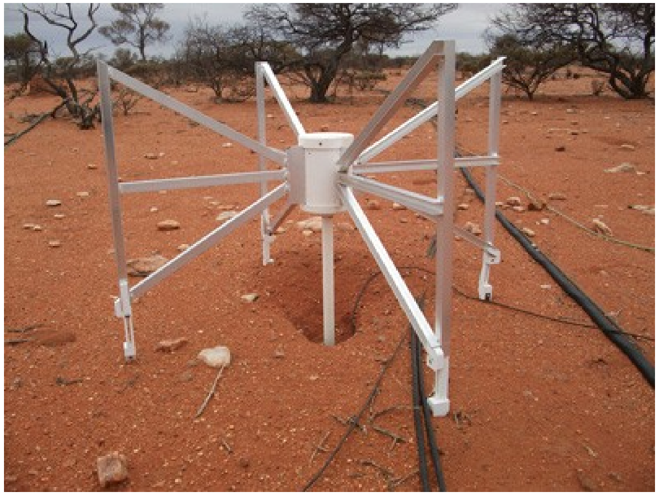


Prestage & Ford 2014

Real systems can be **much** more complicated!

Resolution and collecting area

ICRAR

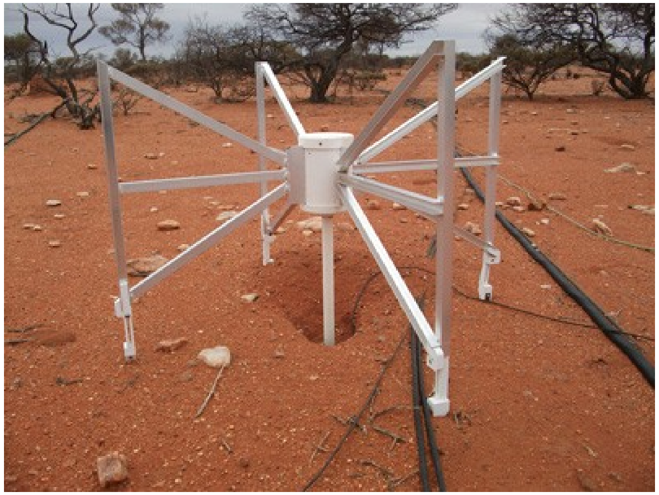


Antenna

- Collects and focuses radio waves
- All you need is a conductive material!
- Dishes focus waves from one direction
- Dipoles collect waves from most of the sky

Resolution and collecting area

ICRAR



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Diffraction / optics

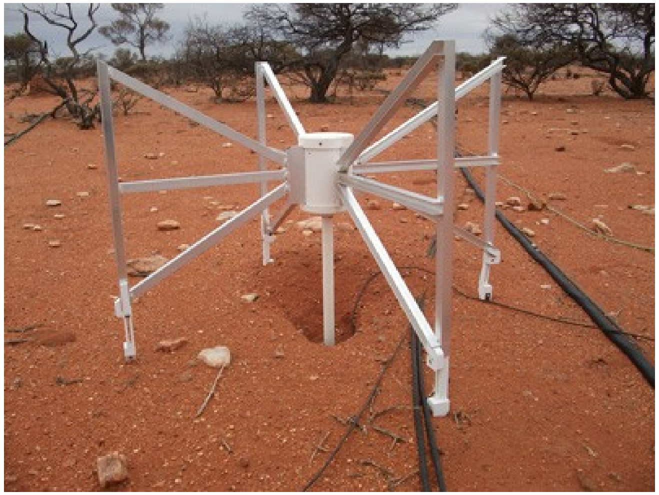
- Shape of antenna and optical path determine how much radiation enters the telescope from each direction → sets the **resolution**
- Area (*aperture*) of antenna sets the total amount of radiation entering the telescope

$$\theta \approx \mathcal{O}(1) \times (\lambda / D_{\mathrm{dish}})$$

$$A_{\mathrm{eff}} \approx 0.7\pi (D_{\mathrm{dish}}/2)^2$$

Resolution and collecting area

ICRAR



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- Trade-off between sensitivity and resolution? → **Interferometry**

Noise and sensitivity

Receiver noise

- Radio receivers measure signal + **thermal noise**
- Noise comes from electronics, the sky, the ground...
- Total noise temperature is the **system temperature**

Reducing noise

- Lower system temperature = less noise
- Can **average the signal** over time – noise averages down
- Can also average the signal over **frequency**;
  wider *bandwidth* = more photons = lower noise

Radiometer equation

$$\sigma_{\mathrm{T}} \approx \frac{T_{\mathrm{sys}}}{\sqrt{\delta\nu\, t_{\mathrm{obs}}}} \approx \frac{\textit{Thermal noise temperature}}{\textit{Number of “samples”}}$$

Typical numbers: SKA1-MID dish (band 1)

Dish diameter:	15 m
System temperature:	23 K
Total bandwidth:	700 MHz
Observing frequency:	350 – 1050 MHz
Frequency channels:	Can choose! (~10 kHz typical)
Observing time:	Can choose! (Let’s try 1 hour)

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Observing time: Can choose! (Let's try 1 hour)

$$\theta \approx \mathcal{O}(1) \times (\lambda / D_{\rm dish})$$

~1.1 degrees @ 1000 MHz

$$A_{\rm eff} \approx 0.7\pi (D_{\rm dish}/2)^2$$

~124 m^2

$$\sigma_{\rm T} \approx \frac{T_{\rm sys}}{\sqrt{\delta\nu\, t_{\rm obs}}}$$

~3.8 mK (10 kHz channel)

Detecting radio sources

Detecting galaxies

What determines whether we can "see" a galaxy with a radio telescope?

(1) How bright is the galaxy?

Flux density: how much power is received from the source?

$$S_\nu = \int_{\text{source}} I_\nu(\theta, \phi) d\Omega \qquad\qquad S = \frac{L}{4\pi d_L^2}$$

$$1\text{Jy} = 10^{-26}\,\text{Wm}^{-2}\text{Hz}^{-1}$$

- Galaxy flux densities are usually ~mJy or µJy
- A mobile phone at 1km has S ~ 1 MJy!

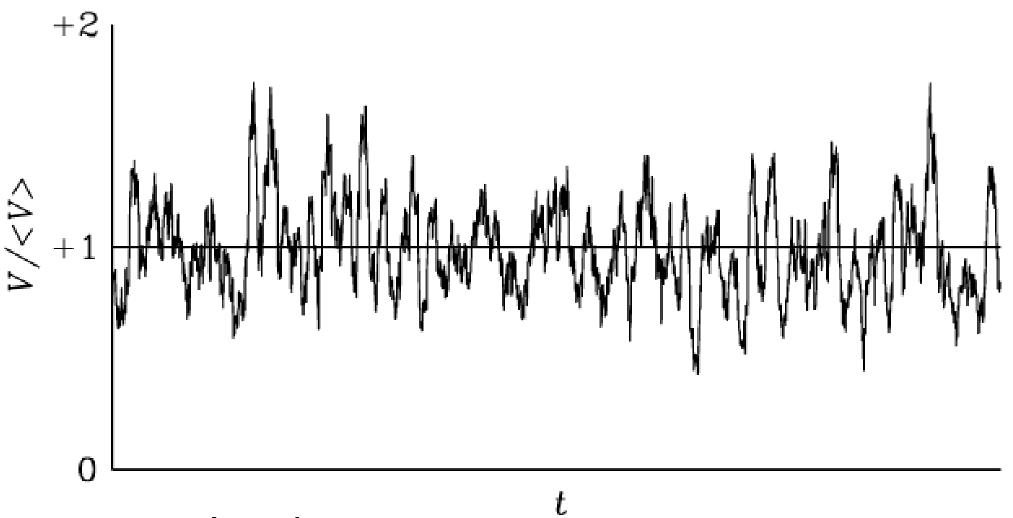
Detecting galaxies

What determines whether we can “see” a galaxy with a radio telescope?

(2) How sensitive is the radio telescope?

- Radio waves cause *voltages* in the receiver electronics
- The voltages are *amplified* to make them measurable

Thermal noise from the sky and inside the receiver electronics gets added to the voltage signal of the source



J. Condon / NRAO

$$\sigma_S \approx \frac{2k_B T_{sys}}{A_{eff}\sqrt{\delta\nu\, t_{obs}}}$$

Radiometer equation

(*flux* sensitivity)

Detecting galaxies

What determines whether we can “see” a galaxy with a radio telescope?

(3) Are other things contaminating the signal?

The telescope measures the **total amount of radiation** coming from the direction it is pointing in

Detecting galaxies

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- What if we're actually seeing >1 galaxies close together?

- Or emission from our own galaxy?

- Or emission from Earth/satellites/mobile phones?

- Or just a random noise fluctuation?

Detecting galaxies

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(3) Are other things contaminating the signal?

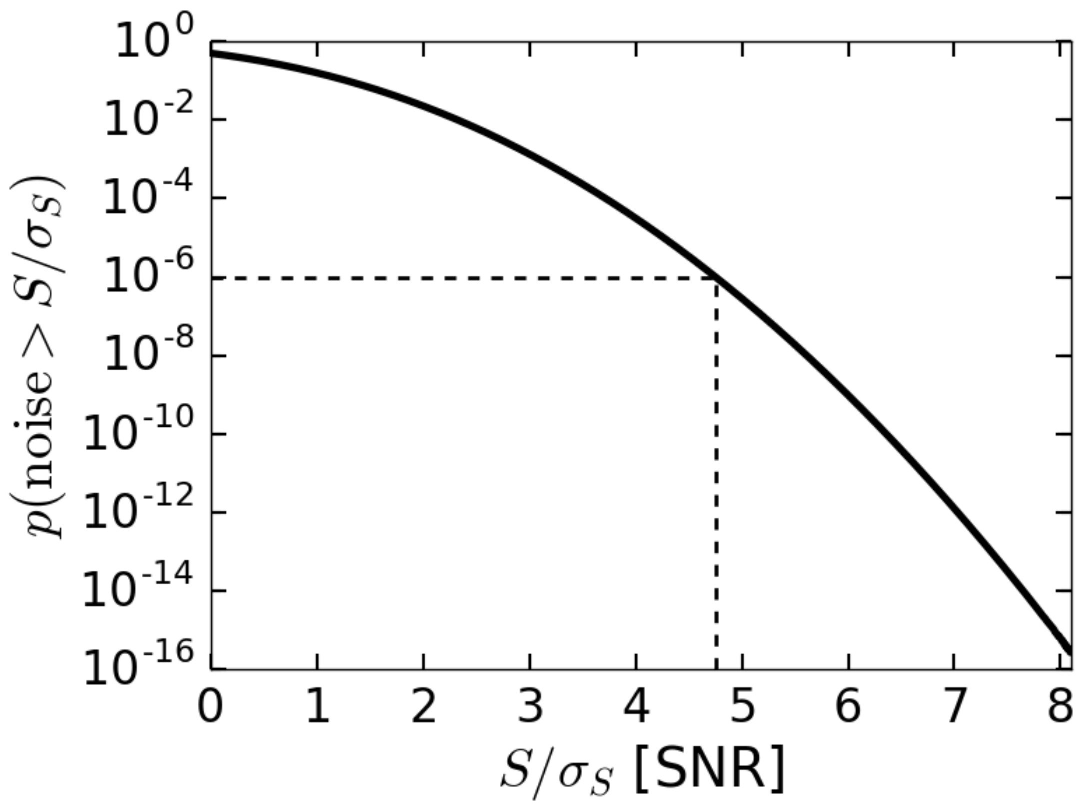
The telescope measures the **total amount of radiation** coming from the direction it is pointing in

- What if we’re actually seeing >1 galaxies close together?
  Confusion
- Or emission from our own galaxy?
  Foregrounds
- Or emission from Earth/satellites/mobile phones?
  Interference / RFI
- Or just a random noise fluctuation?
  Statistical fluctuations

Thresholding

How often will we mistake a noise fluctuation for a galaxy?

→ Can only "keep" candidate galaxies that are several times brighter than the noise level



In a sample of 10^6 galaxies with $S > 4.75\ \sigma_S$:

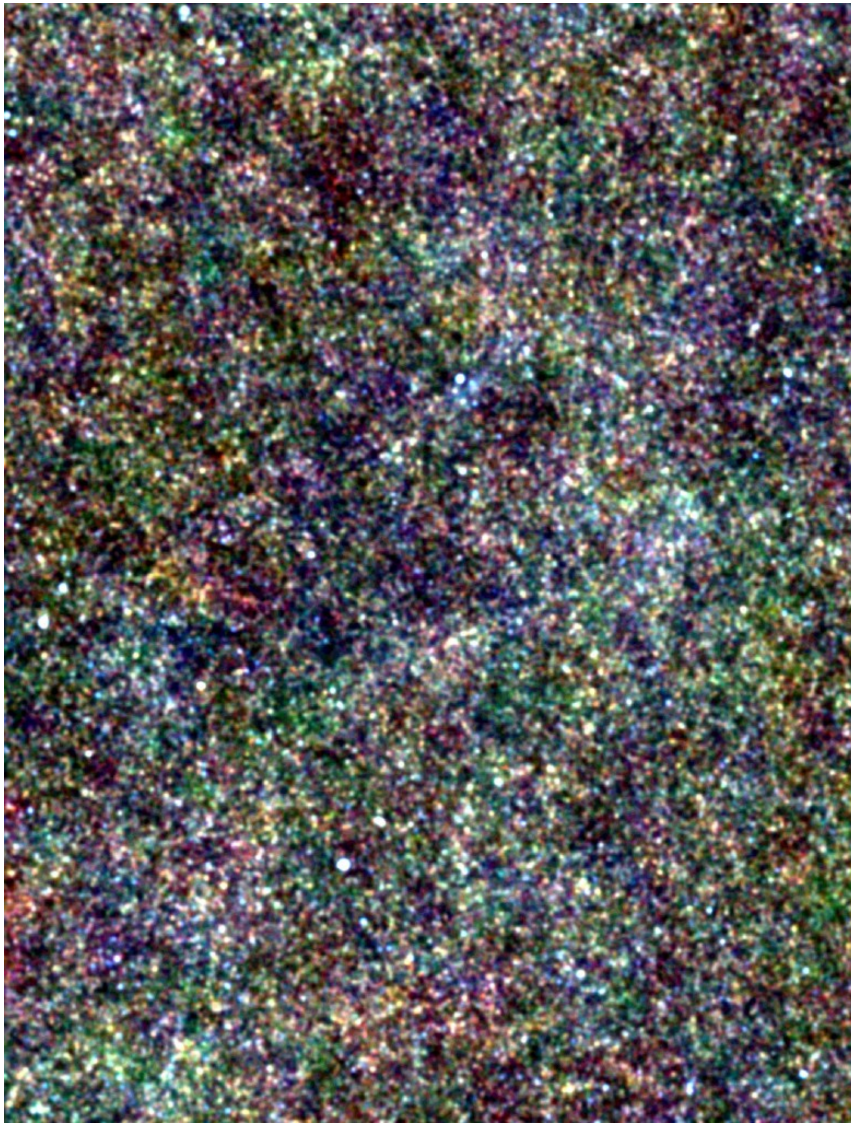
~1 will be a noise fluctuation!

(assumes Gaussian noise)

Thresholding throws away random fluctuations **and** real galaxies that are too faint

Confusion

ESA / Herschel



Objects that appear close together on the sky:

Can the telescope tell if they are separate objects?

If not, the sources are said to be **confused** with each other

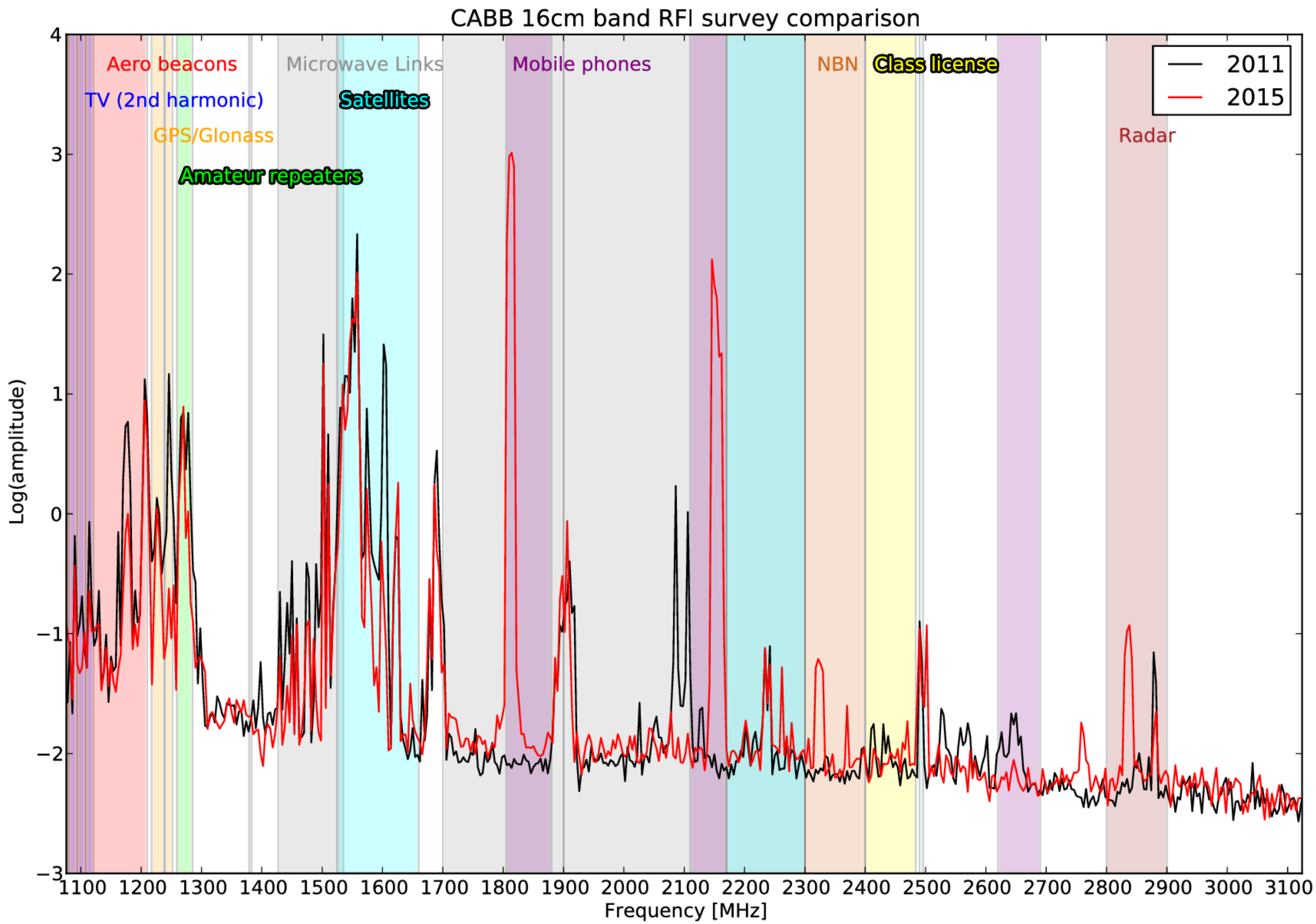
There are typically many more faint sources than bright ones
→ image can be crowded with faint objects

Very sensitive telescopes are limited by confusion rather than noise → need **better resolution**

Radio Frequency Interference (RFI)

Humans cause a lot of pollution at radio frequencies!

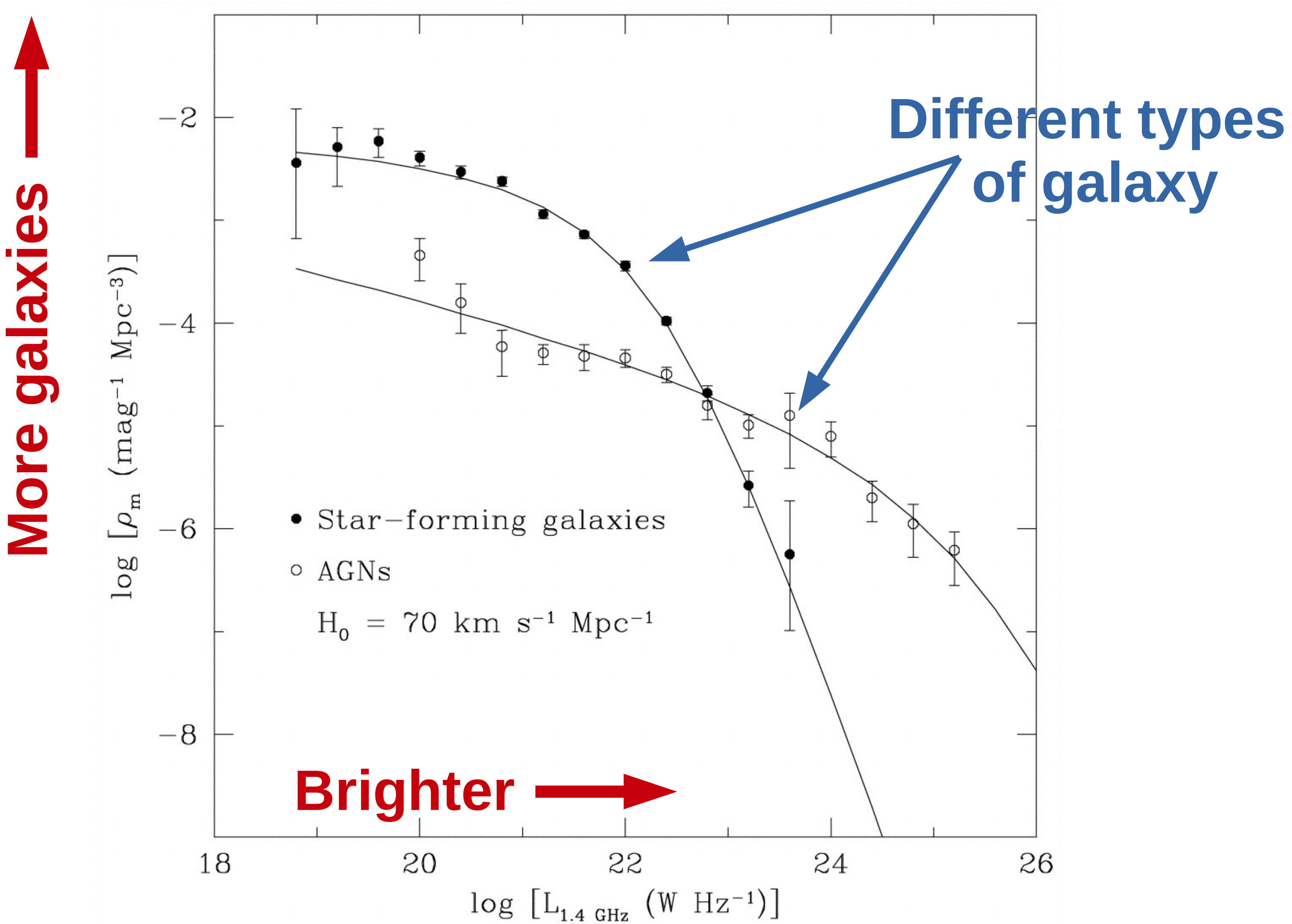
→ Move to a “radio-quiet” site to reduce the RFI



CSIRO

Galaxy number counts

Number of galaxies vs. their intrinsic luminosity

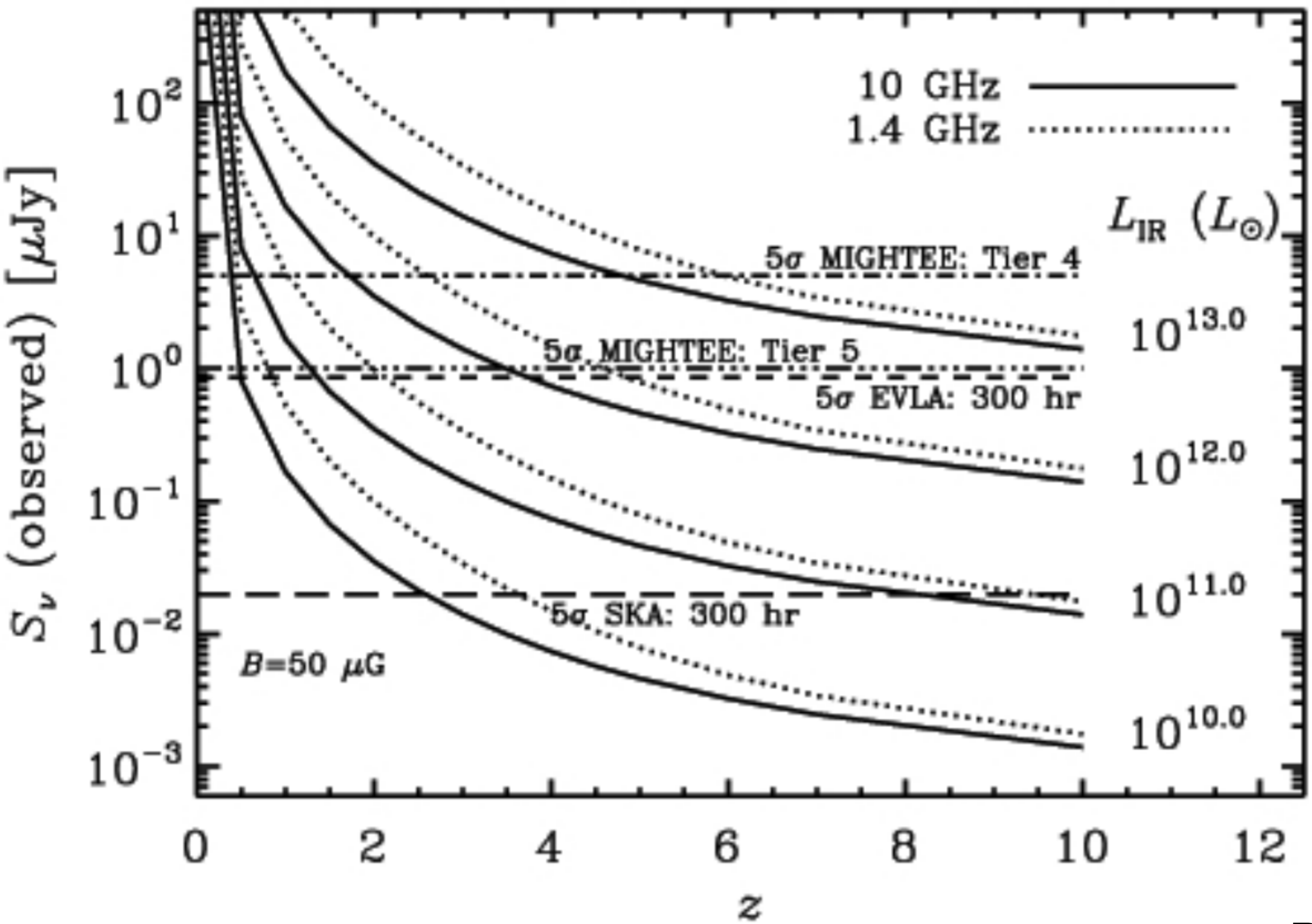


J. Condon / NRAO

Number counts vs. redshift

- Distant sources are fainter
- Source populations evolve with redshift
- Luminosity depends on frequency (redshifted!)

$$S = \frac{L}{4\pi d_L^2}$$



R. Norris et al. 2012

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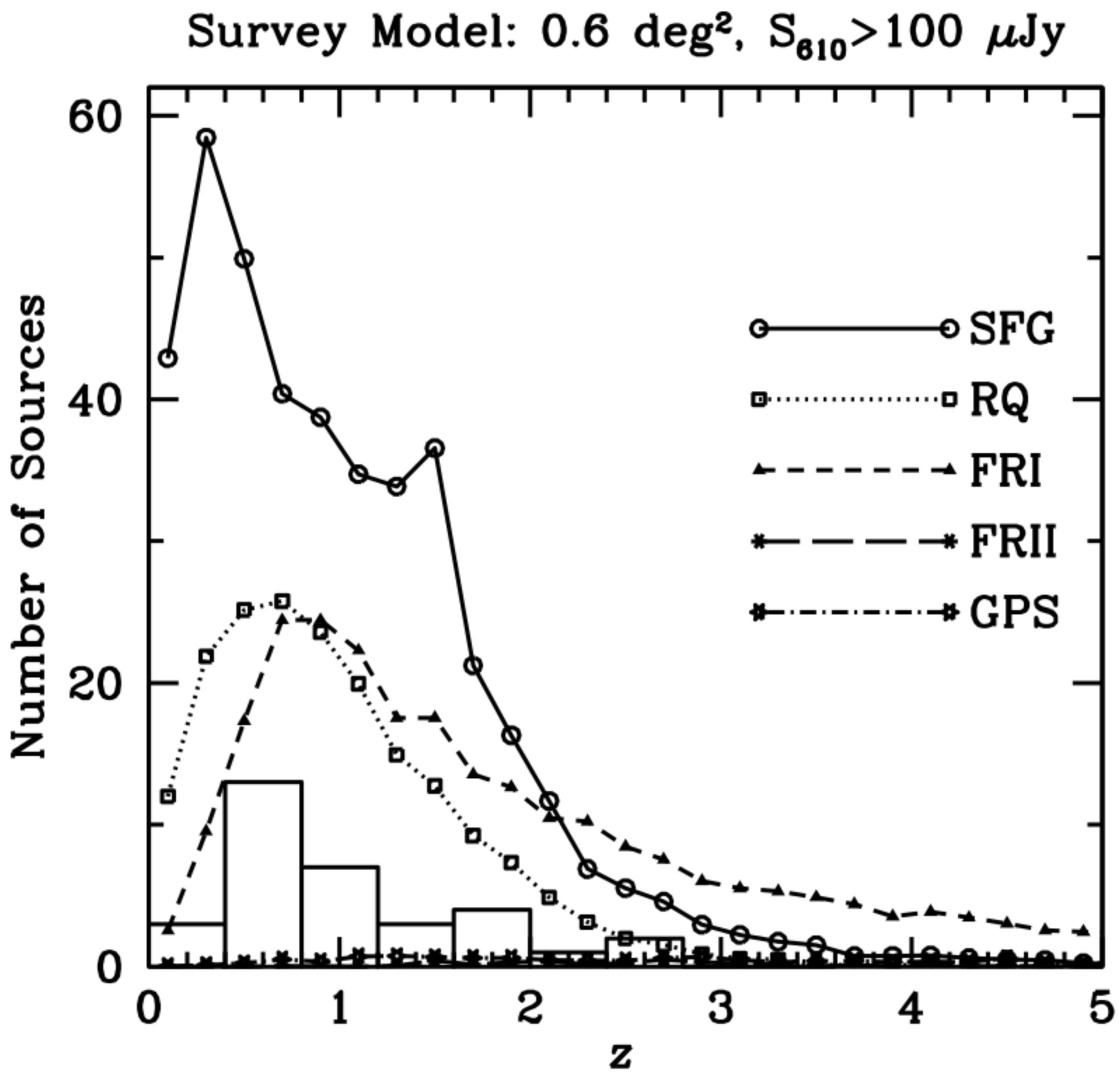


R. Norris et al. 2012

Radio interferometry: Basics

Two-element interferometer

Plane wave enters each receiver *with a phase/delay* that depends on their separation:

Vector of baseline **d** on the ground

$$\Delta\phi = 2\pi \frac{d \sin\theta}{\lambda} = \boldsymbol{u} \cdot \boldsymbol{\theta}$$

Vector of source on the sky

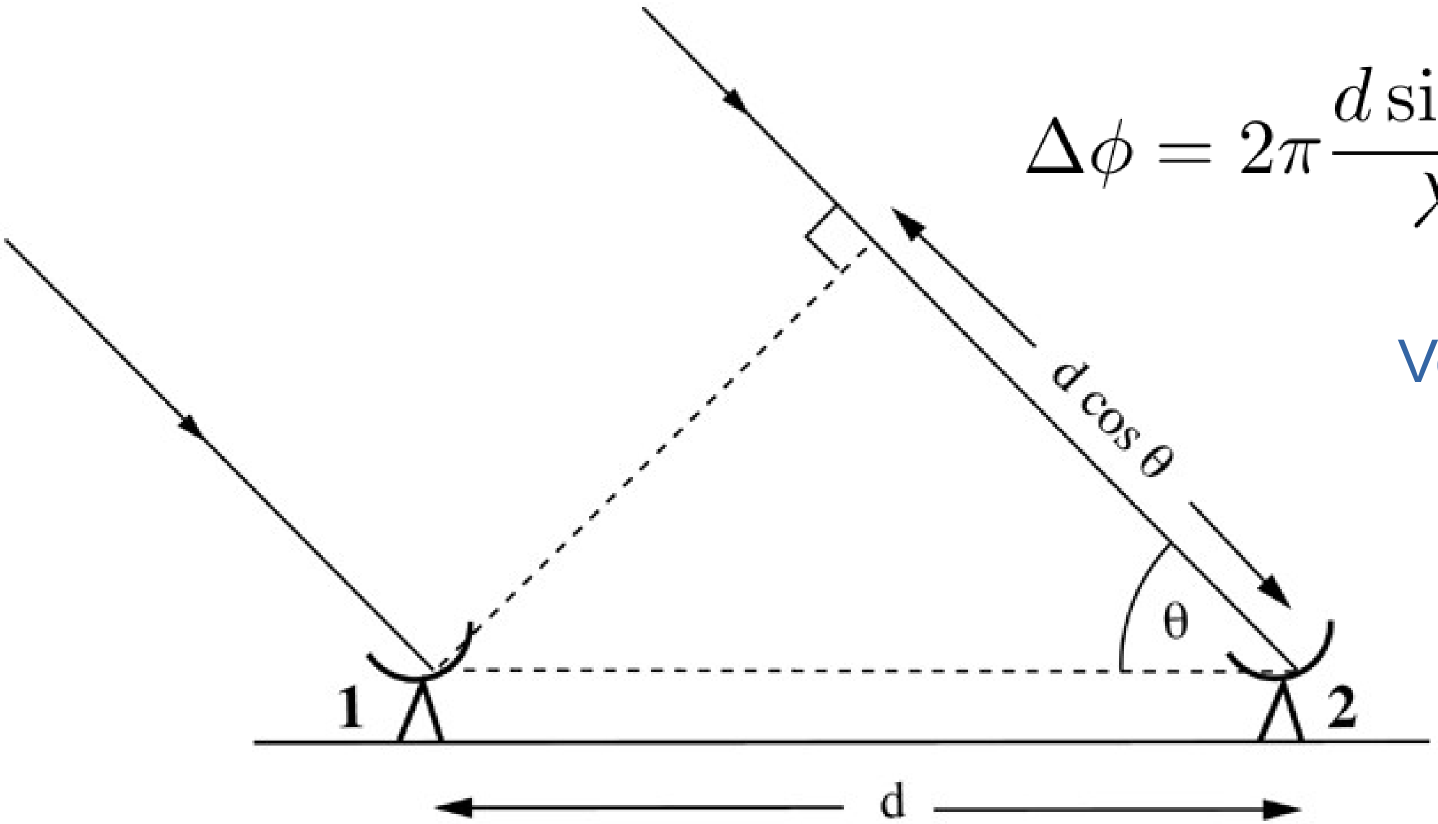


Fig 5.11 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

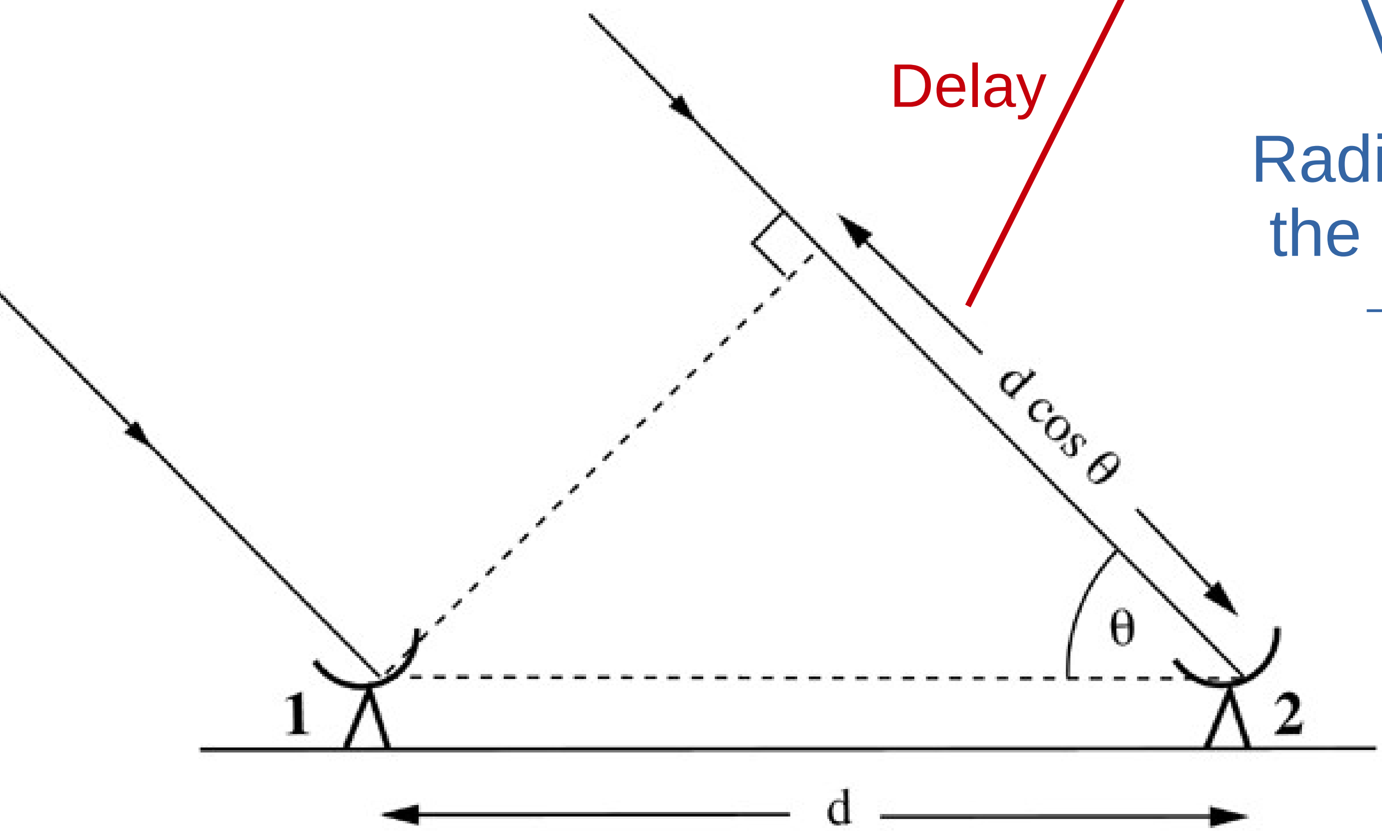
The electric field of the wave, E, *induces a voltage* in the receivers:

$$v_2(t) = \int_{-\pi}^{+\pi} A(\theta)E(\theta)e^{i\omega t}d\theta$$

$$v_1(t) = \int_{-\pi}^{+\pi} A(\theta)E(\theta)e^{i(\omega t+\Delta\phi)}d\theta$$

Delay

Radio waves from all over the sky enter the receiver → **integrate over θ**



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The electric field of the wave, E, *induces a voltage* in the receivers:

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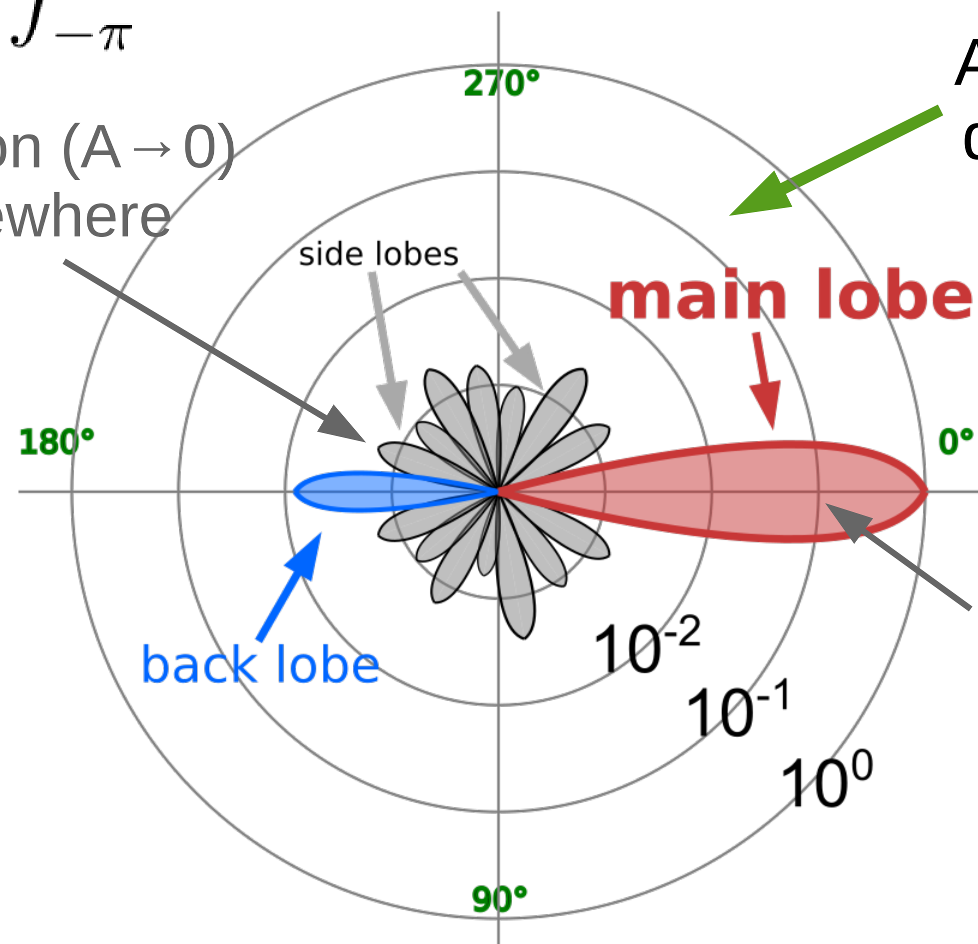
$$v_1(t) = \int_{-\pi}^{+\pi} A(\theta)E(\theta)e^{i(\omega t+\Delta\phi)}\,d\theta$$

The antenna pattern of each receiver, A(θ), *attenuates* the signal

Amount of attenuation depends on direction of the source

More attenuation (A → 0) if source is elsewhere



Less attenuation (A ~ 1) if source is near the centre of the beam

Now multiply (*correlate*) the voltages from the two receivers and measure (*detect*) the resulting signal:

Correlation **multiplies** voltages and **averages** signal over time

<Averaging> – only **coherent** signals do not average-out

$$\langle v_1(t) \cdot v_2^*(t) \rangle \quad = \quad \left\langle \int_{-\pi}^{+\pi} A(\theta)E(\theta)e^{i\omega t}e^{i\boldsymbol{u}\cdot\boldsymbol{\theta}}d\theta \cdot \int_{-\pi}^{+\pi} A^*(\theta')E^*(\theta')e^{-i\omega t}d\theta' \right\rangle$$

Emission from different sources (θ ≠ θ') is incoherent, so **averages to zero**

(Why doesn't the emission from a single incoherent source average out? – *van Cittert-Zernike theorem*)

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$$= \int_{-\pi}^{+\pi} |A(\theta)|^2 |E(\theta)|^2 e^{i\boldsymbol{u}\cdot\boldsymbol{\theta}} d\theta$$

Fourier integral!

Define the **intensity distribution** on the sky and **primary beam**:

$$I(\theta) = |E(\theta)|^2; \qquad B(\theta) = |A(\theta)|^2$$

$$\tilde{I}(\theta) \equiv B(\theta) I(\theta) = \int_{-\infty}^{+\infty} \tilde{I}(\boldsymbol{k})\, e^{i\boldsymbol{k}\cdot\boldsymbol{\theta}} d\boldsymbol{k}$$

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Fourier integral!

$$= \int_{-\pi}^{+\pi} \tilde{I}(\theta)e^{i\boldsymbol{u}\cdot\boldsymbol{\theta}}d\theta$$

Picks out a **single** mode from I(θ), with Fourier wavenumber **u**

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Fourier integral!

Picks out a **single** mode from I(θ), with Fourier wavenumber **u**

→ **Interferometers measure Fourier modes on the sky**

Measured mode depends on baseline length and wavelength,
u = d / λ

Key points: Interferometers

Interferometers measure the *averaged product* of voltages from 2 receivers with *different phase delays*
→ **Phase delay depends on array geometry (baseline length)**

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→ **Interferometers see the whole sky** (weighted by a beam)

Key points: Interferometers

Interferometers measure the *averaged product* of voltages from 2 receivers with *different phase delays*
→ **Phase delay depends on array geometry (baseline length)**

The voltages are a function of the *intensity over the whole sky*, attenuated by an *antenna pattern*
→ **Interferometers see the whole sky** (weighted by a beam)

Fourier modes of the intensity distribution with wavenumber $u = d / \lambda$ (matching the phase delay) interfere *constructively*
→ **Each baseline measures a single Fourier mode** of the (antenna-weighted) intensity on the whole sky

Complications...

Phase delay depends on wavelength

$$\Delta\phi = 2\pi \frac{d \sin\theta}{\lambda}$$

- Interferometer response is *chromatic*
- Measure *different Fourier modes* at different frequencies!
- Averaging over frequency (bandwidth) therefore averages over Fourier modes
- Signal is *smeared out* by averaging

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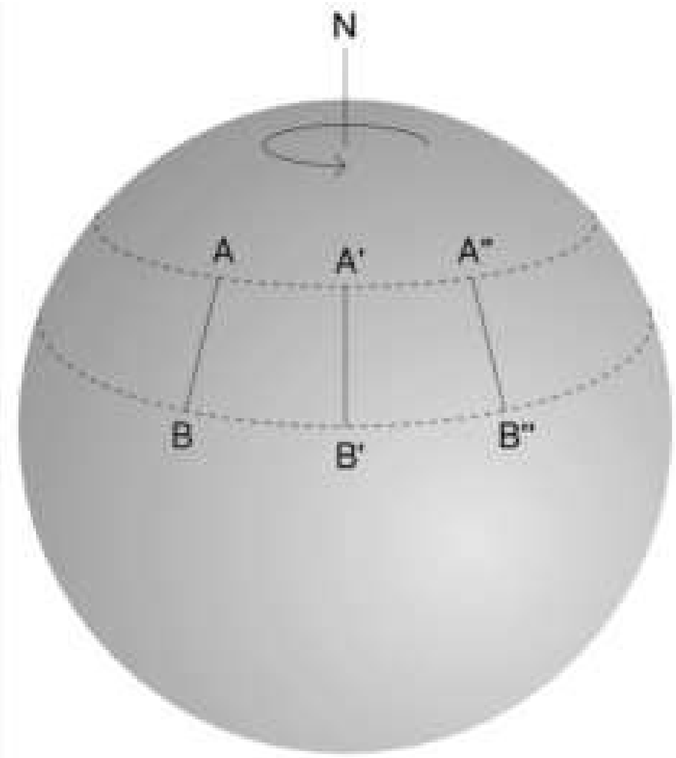
Earth rotation

- Baselines are aligned with different directions on the sky at different times of day
- Measure *different Fourier modes* as the Earth rotates



Complications...

Mode-mixing due to the primary beam

- Interferometers see intensity *modulated by primary beam*
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Sky curvature

- The sky is curved; we should use **spherical harmonic** basis (Fourier basis is not orthonormal on the sky)
- Wide-angle/“horizon” effects arise (see final lecture)

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Further reading (advanced):

- T. Bastian, *Radio interferometry notes* [https://is.gd/PmsBR8]
- Parsons et al. 2012, *Delay transform* [arXiv:1204.4749]
- Shaw et al. 2014, *m-mode analysis* [1401.2095]
- Cornwell, Holdaway & Uson 1993, *Radio interferometric imaging of very large objects*

Aperture synthesis

Two receivers → many receivers

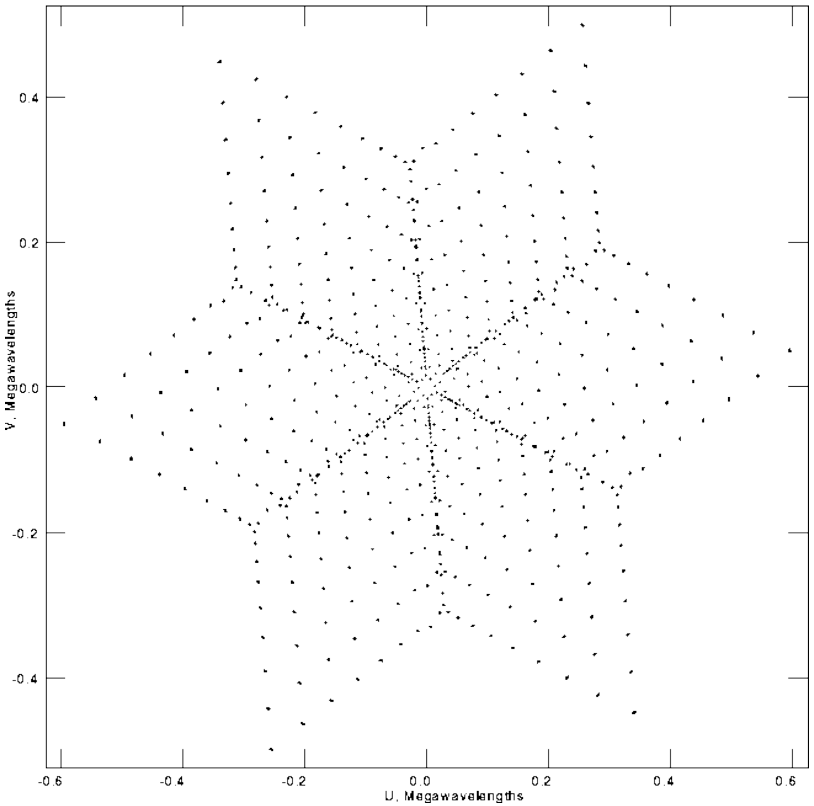
2 receivers = 1 baseline = 1 Fourier mode

N receivers = N(N-1)/2 baselines

Correlate all the receivers → get more Fourier modes in one "snapshot"

Baselines can point in different directions → **2D** Fourier plane

VLA / NRAO



Array layout: placing the receivers

Recall: Length of baseline, d ∝ Fourier wavenumber, **u**

- Short baselines = small **u** = large scales
- Long baselines = high resolution

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Higher density = higher sensitivity per mode

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Recall: Length of baseline, d ∝ Fourier wavenumber, **u**

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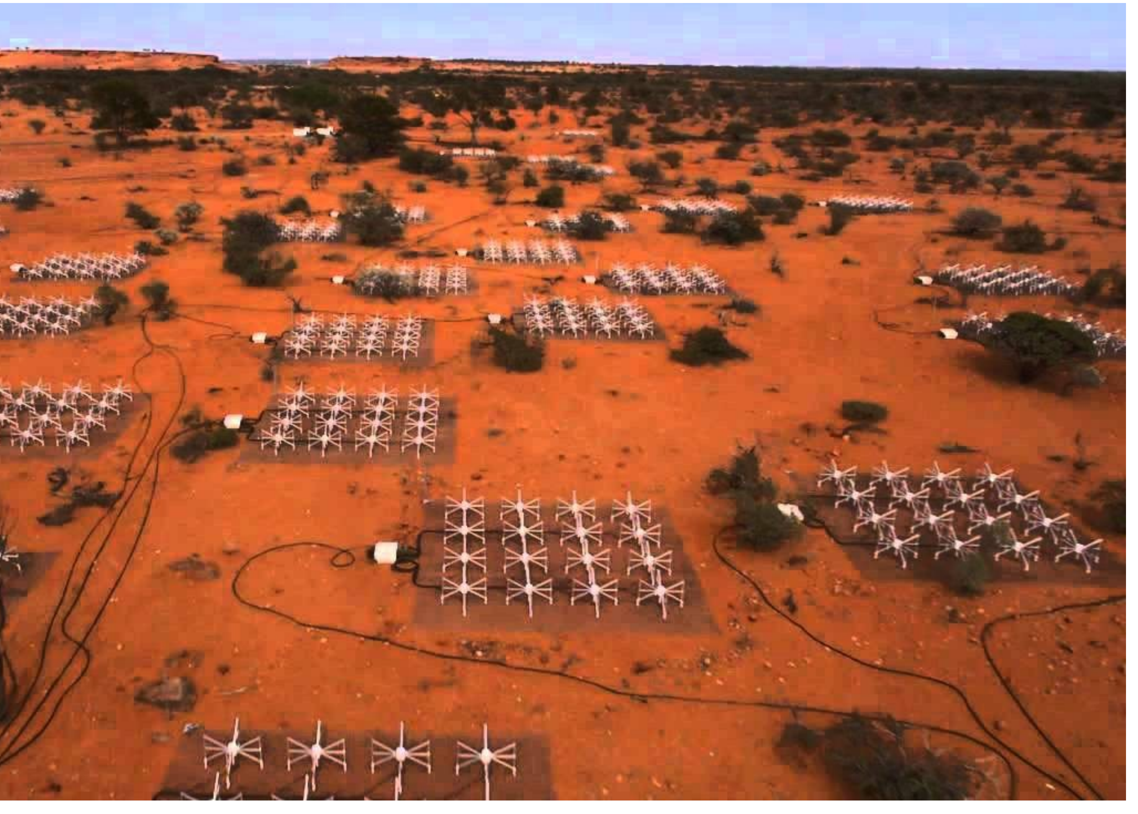
For large arrays: Care about the **number density** of long vs. short baselines.
Higher density = higher sensitivity per mode

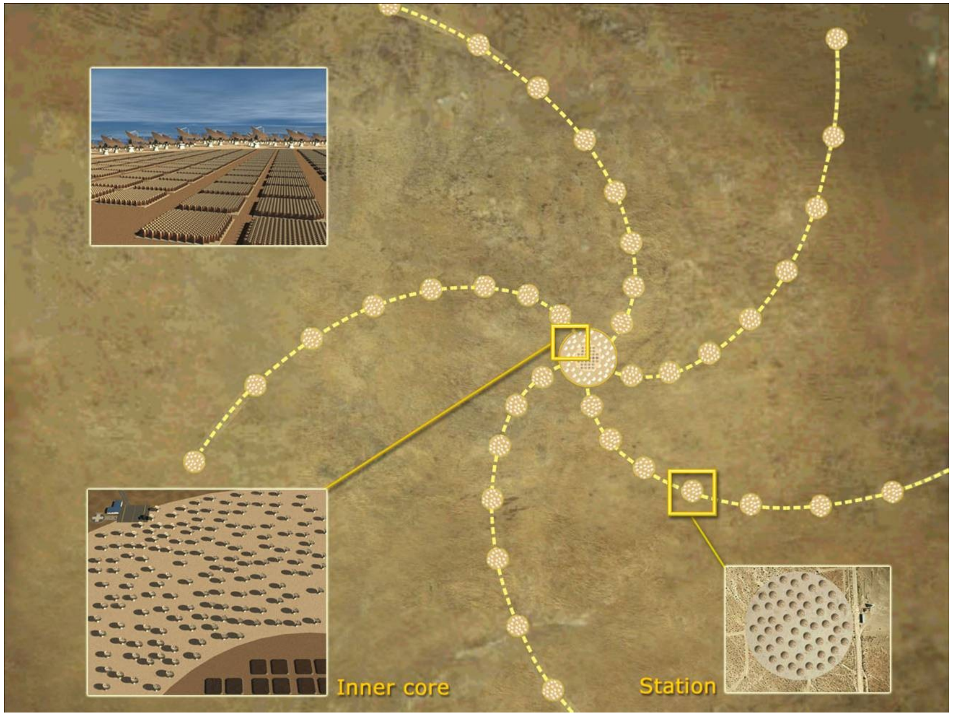
Optimise: Where do you need most sensitivity?

- Small objects (e.g. jets) → more long baselines (sparse array)
- Large scales → more short baselines (dense array)
- Detect galaxies → balanced baseline distribution

Sparse array
e.g. JIVE/EVN

Dense array
e.g. MWA





Balanced array
e.g. SKA-MID

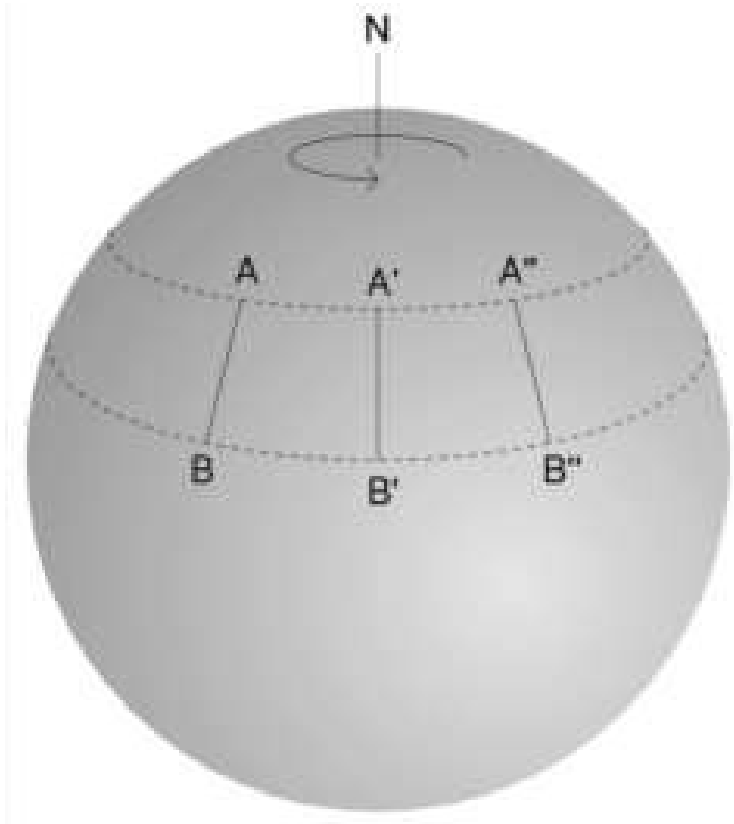
Earth rotation

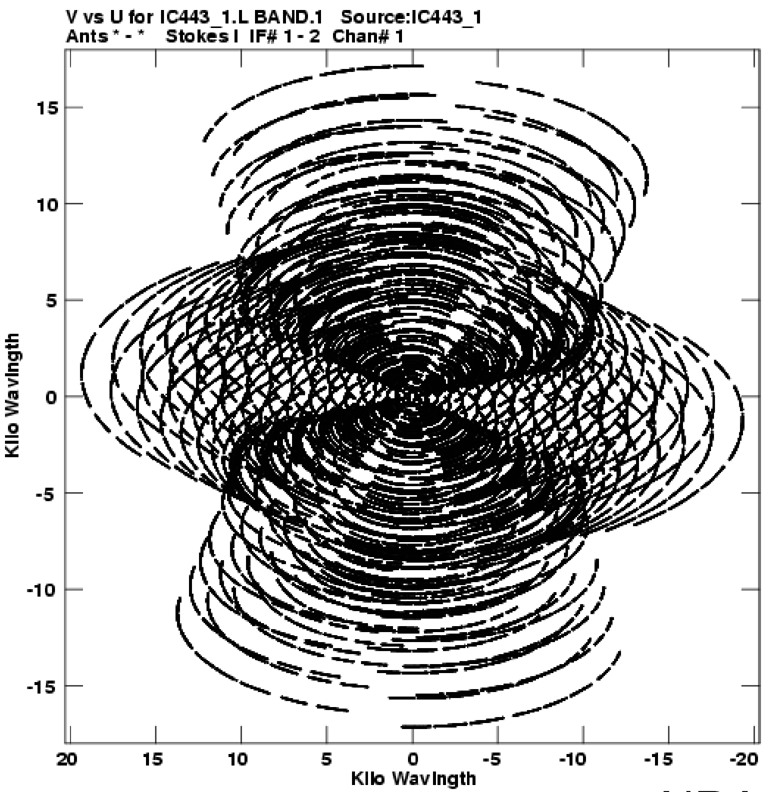
As the Earth rotates, the baseline vectors **rotate** with respect to the sky → sample different Fourier modes at different times

Represent baselines in the **uv** (Fourier) plane

→ Each baseline traces a curve in the uv plane over time

Get more Fourier modes just by waiting...





NRAO / VLA

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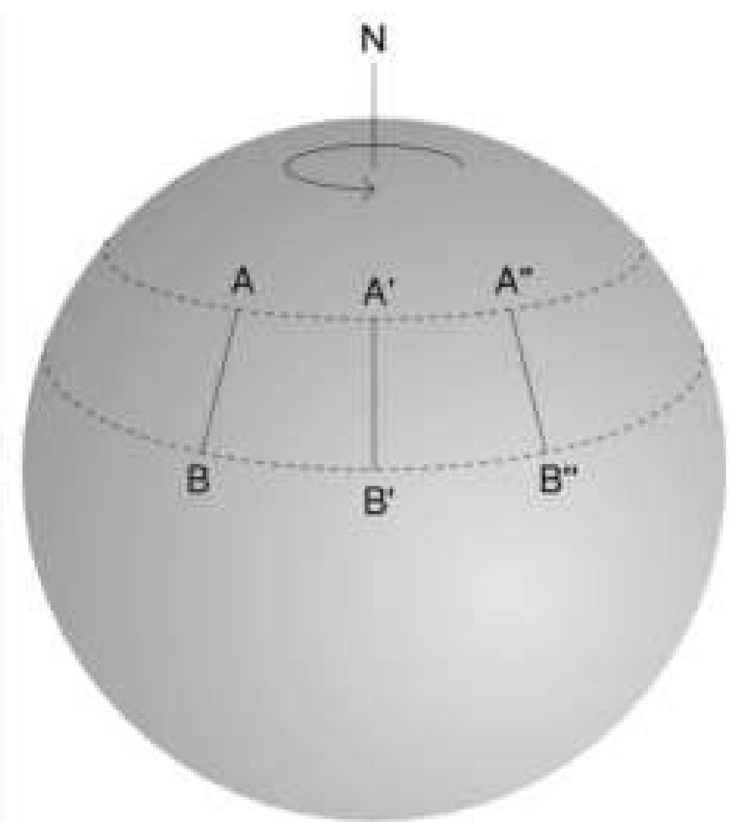
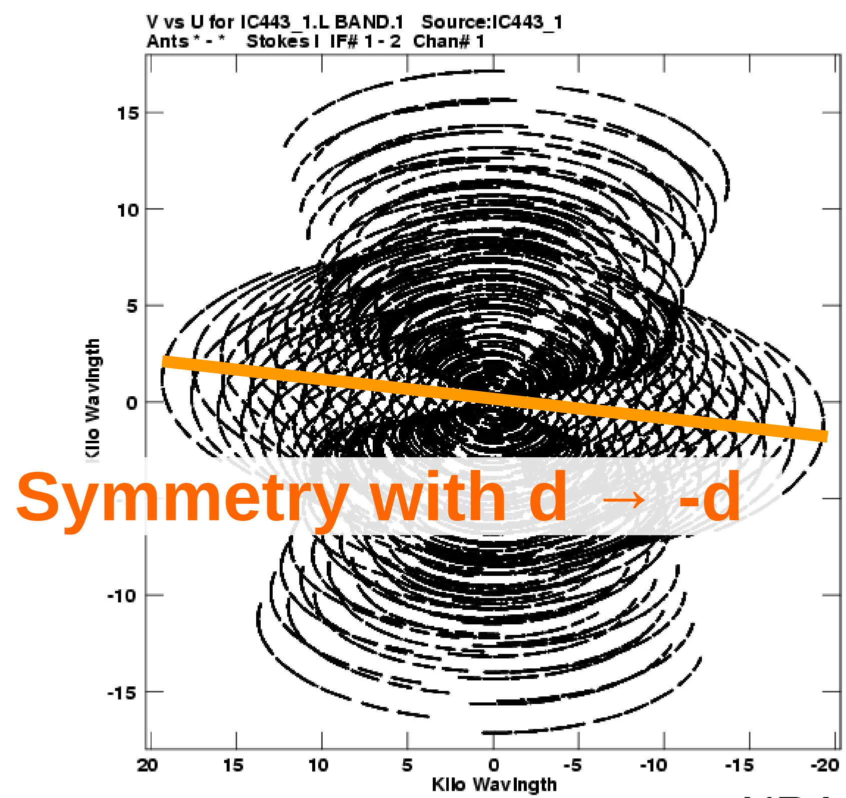


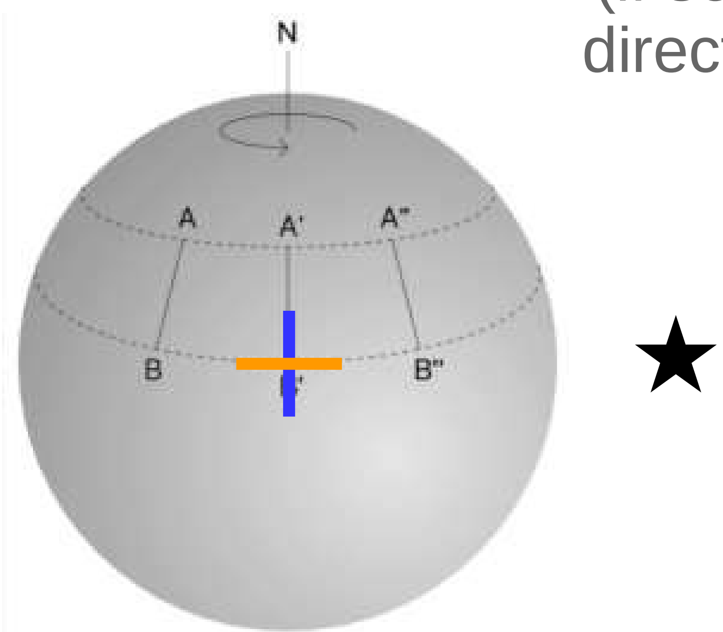


NRAO / VLA

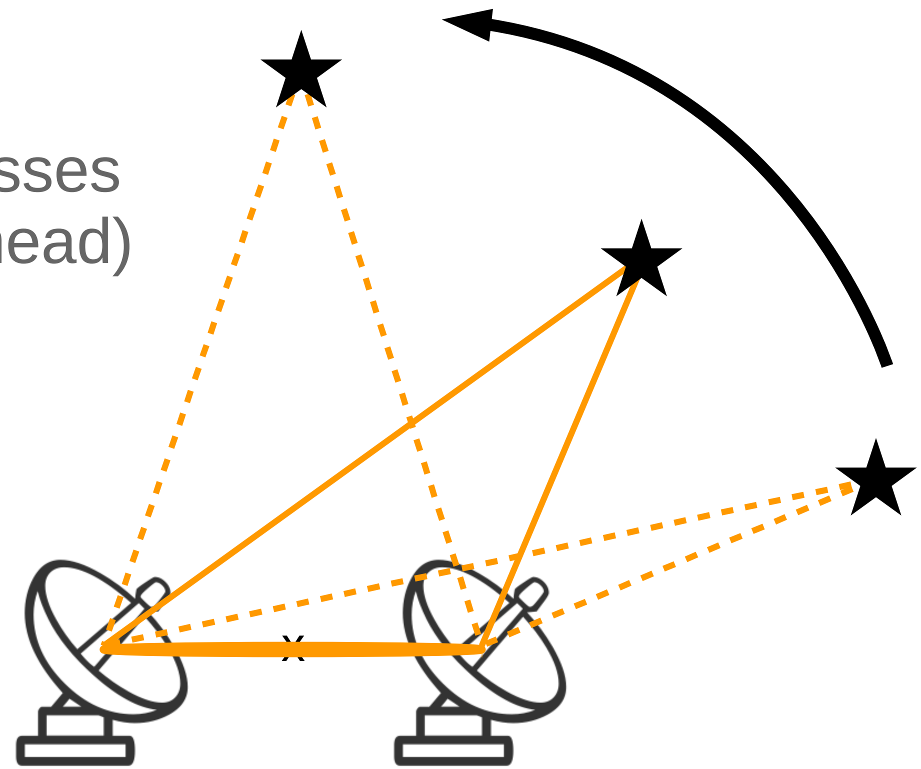
Earth rotation

Also depends on **latitude** of array and angle of source

Baseline along the equator (east-west):
|u| varies but v=0 → **line** in the uv plane



(if source passes directly overhead)



Baseline across the equator (north-south):
→ delay is always the same: u = const.

Earth rotation

Also depends on **latitude** of array and angle of source

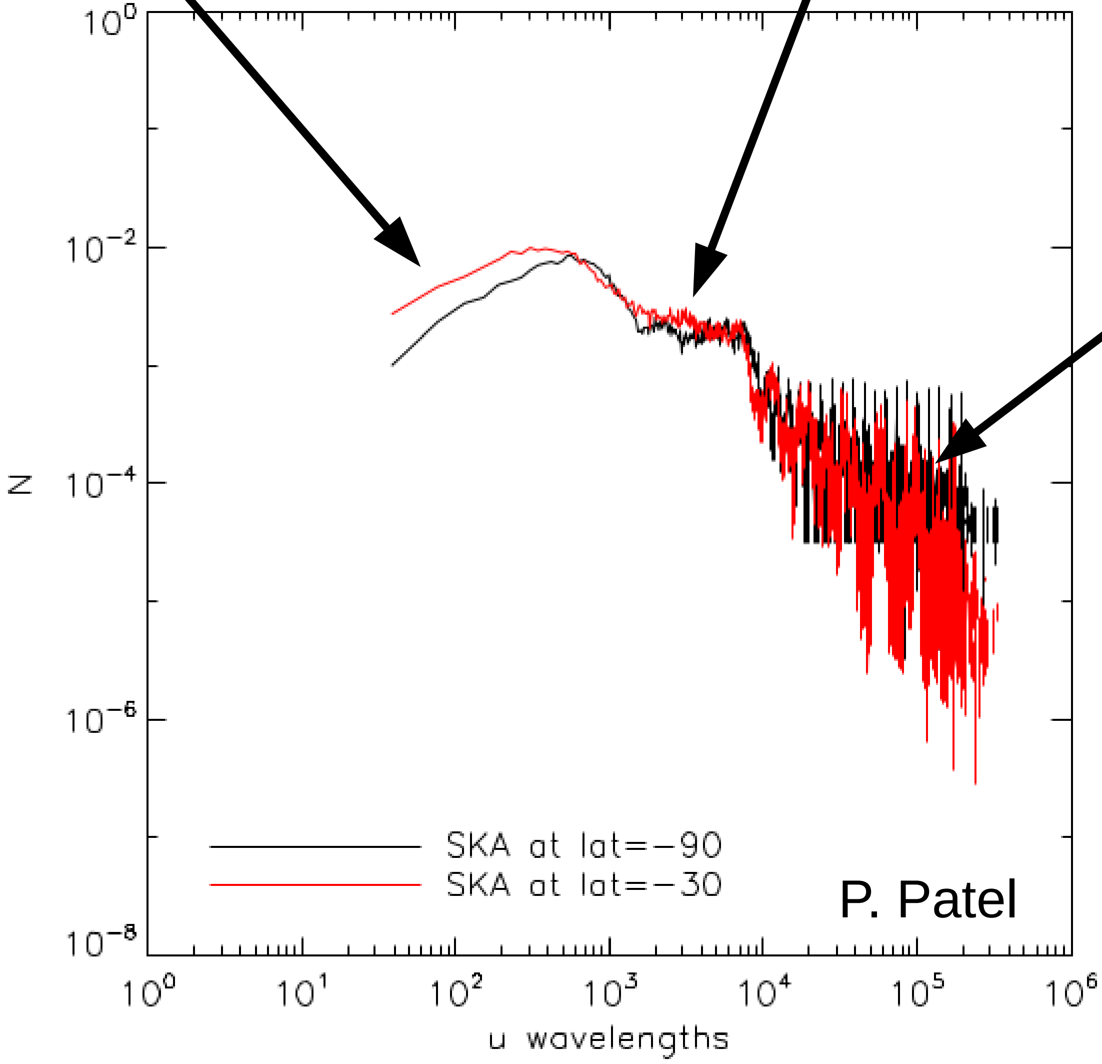
Tenerife (28.3° N)

SKA1-MID *average* baseline density

Many short baselines (dense core)

Plateau of intermediate baselines (“spiral arms”)

“Tail” of long baselines

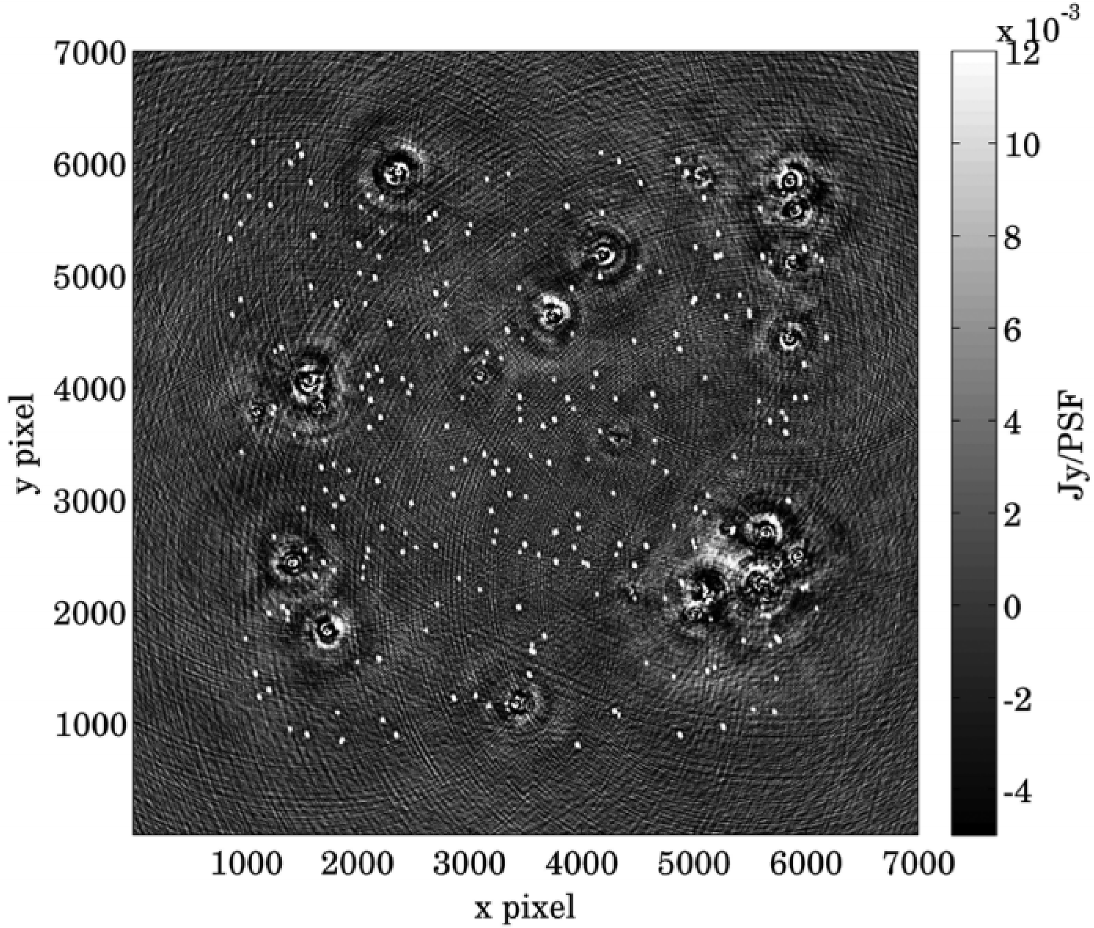


Averaged over rings in **uv**, |u|=const.

Missing baselines and weighting

Measured visibilities = Fourier coefficients

- Inverse FT to reconstruct the intensity distribution, I(θ)
- But some baselines are always missing…



Yatawatta 2015

Missing baselines and weighting

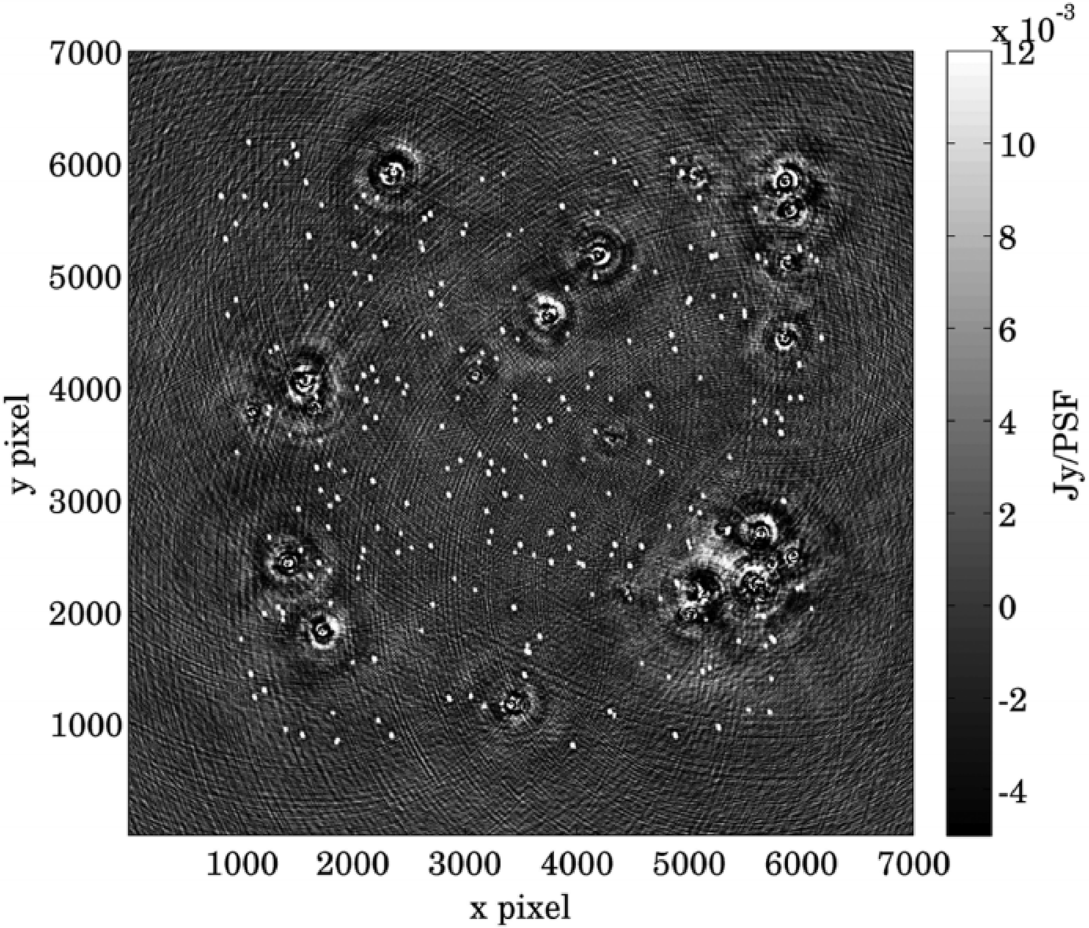
Measured visibilities = Fourier coefficients

- Inverse FT to reconstruct the intensity distribution, I(θ)
- But some baselines are always missing…

Problem when measuring **flux**: when baselines are missing, some flux is not counted!

Some baselines are poorly sampled: high noise

Primary beam sidelobes also add extra structure to image



Yatawatta 2015

Deconvolution

Remove the primary beam by “dividing it out”

$$\langle v_1(t) \cdot v_2^*(t) \rangle \;=\; \int_{-\pi}^{+\pi} |A(\theta)|^2 |E(\theta)|^2 e^{i\boldsymbol{u}\cdot\boldsymbol{\theta}} d\theta$$

Simple “CLEAN” method: for every peak in the image, divide by (scaled) primary beam, then multiply by delta-fn

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Simple “CLEAN” method: for every peak in the image, divide by (scaled) primary beam, then multiply by delta-fn

Bad for diffuse emission! Poorly modelled by delta-fns

(More advanced methods exist to properly weight by the noise etc.)

Do you even need to make an image?
Can do source detection, measure galaxy properties etc. directly, in Fourier (visibility) space

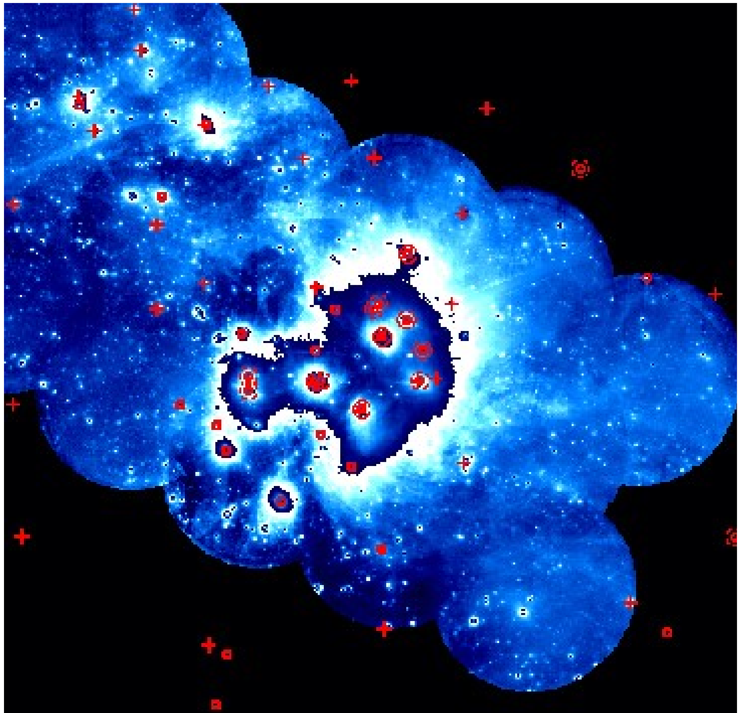
Mosaicing

Each image is restricted to the primary beam field of view
  i.e. a single “pointing”

To make a map, many pointings must be stitched together

Recall: interferometers can’t measure Fourier modes corresponding to scales larger than the **shortest** baseline (and we normally have FOV = $\lambda/D_{dish} > \lambda/D_{min}$)

S. Gibson



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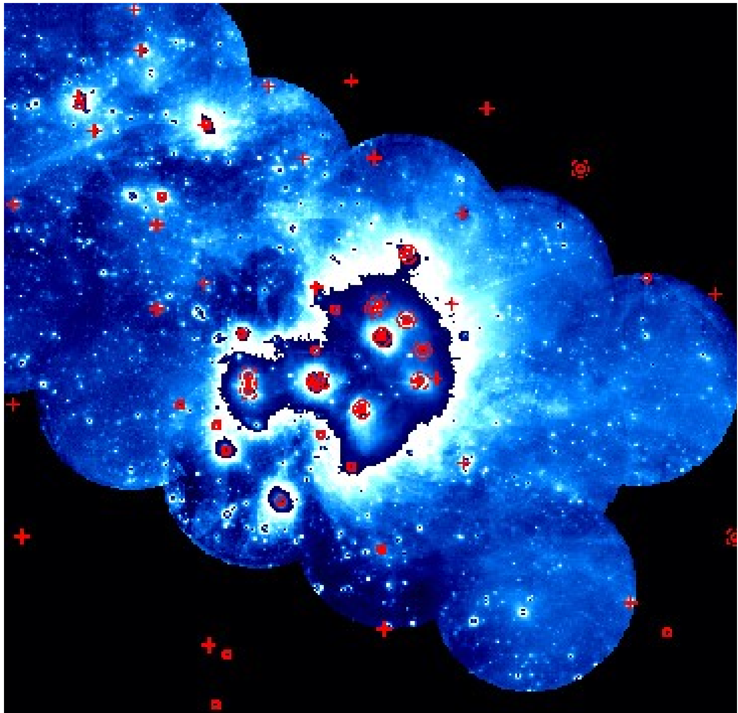
"Maps" are essentially "high-pass" filtered i.e. large scales are removed

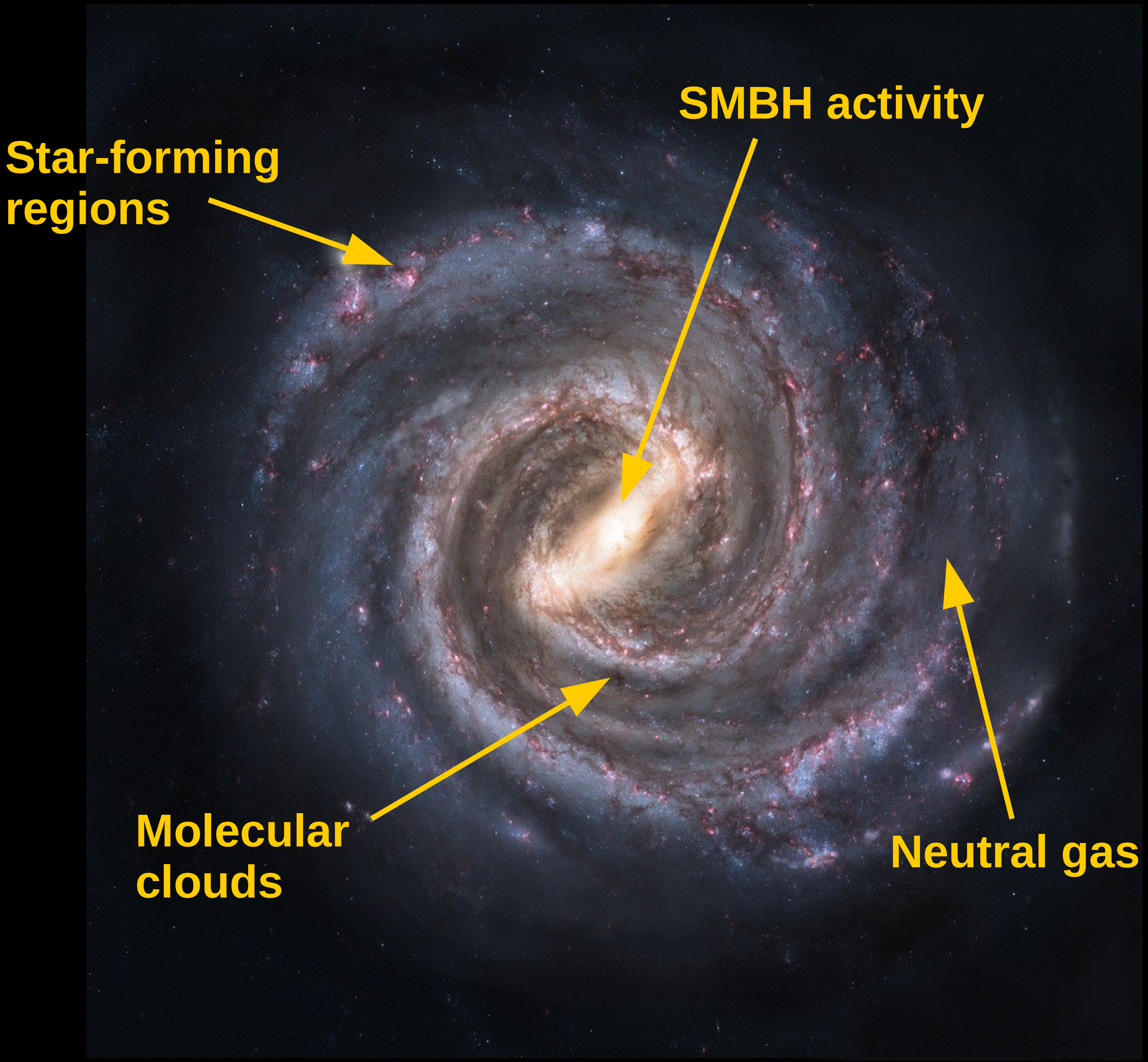
Not a "true" image – **missing information**
- Can add autocorrelation info from single dishes to "fill in" large scales
- Not necessary for galaxy surveys (only care about counting objects)

S. Gibson



Physical sources of radio emission in galaxies

Nick Risinger / NASA (artistic impression)



Nick Risinger / NASA (artistic impression)

Active Galactic Nuclei

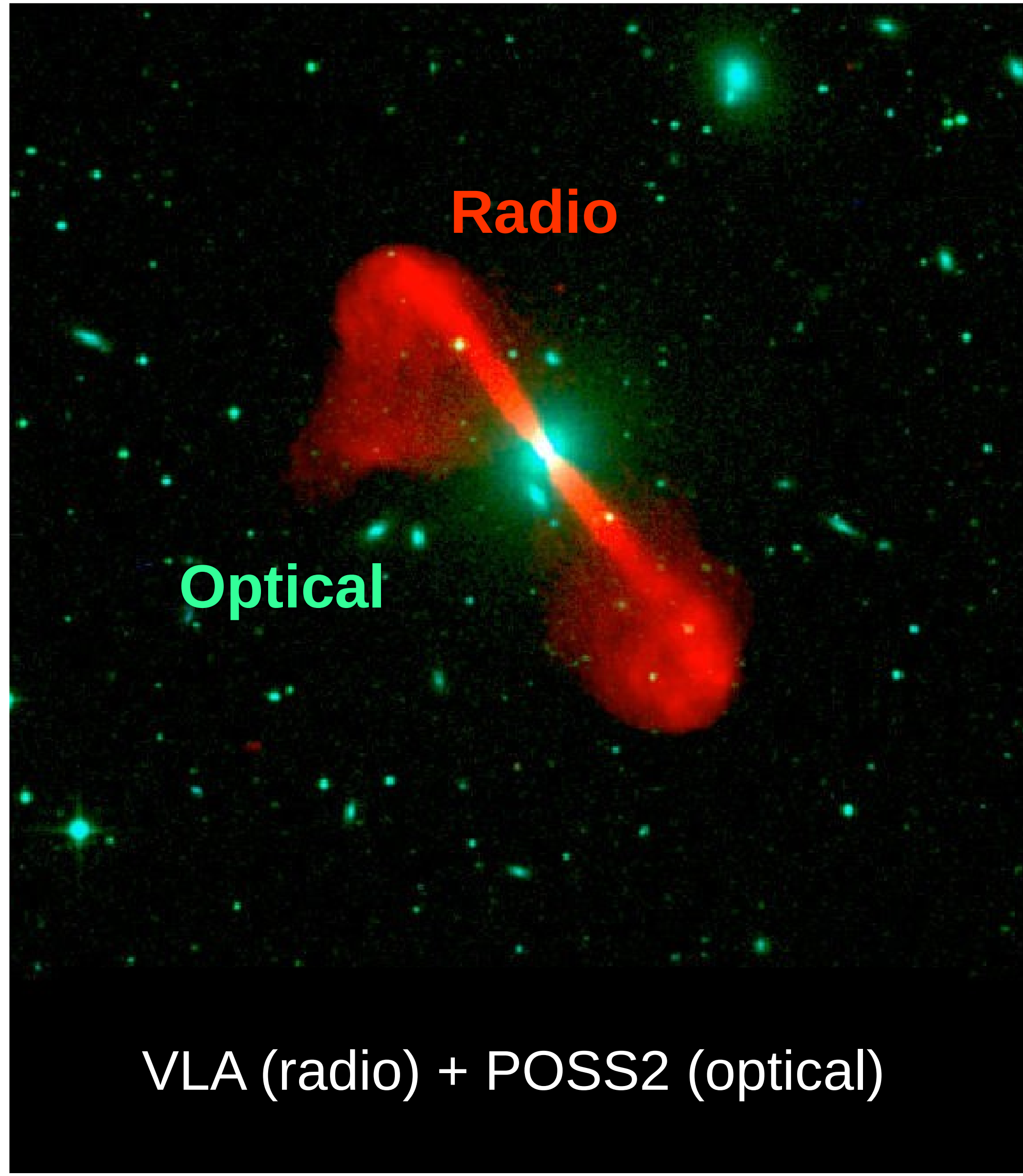
NRAO / AUI

Almost all galaxies have a **super-massive black hole** (SMBH) at the centre

Matter falls into SMBH → **accretion disk** forms outside

Friction releases extreme amounts of energy

Strong magnetic fields form



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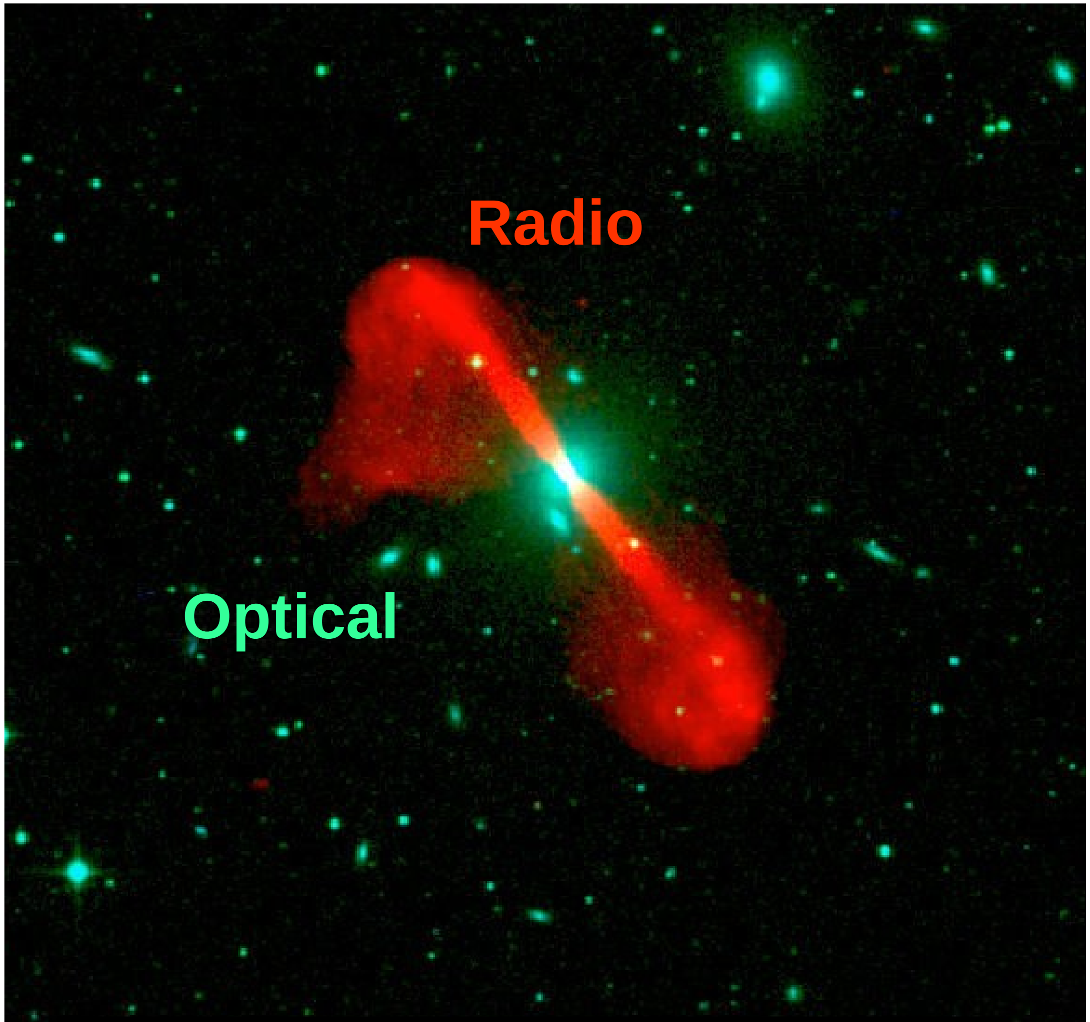

VLA (radio) + POSS2 (optical)

Almost all galaxies have a **super-massive black hole** (SMBH) at the centre

Matter falls into SMBH → **accretion disk** forms outside

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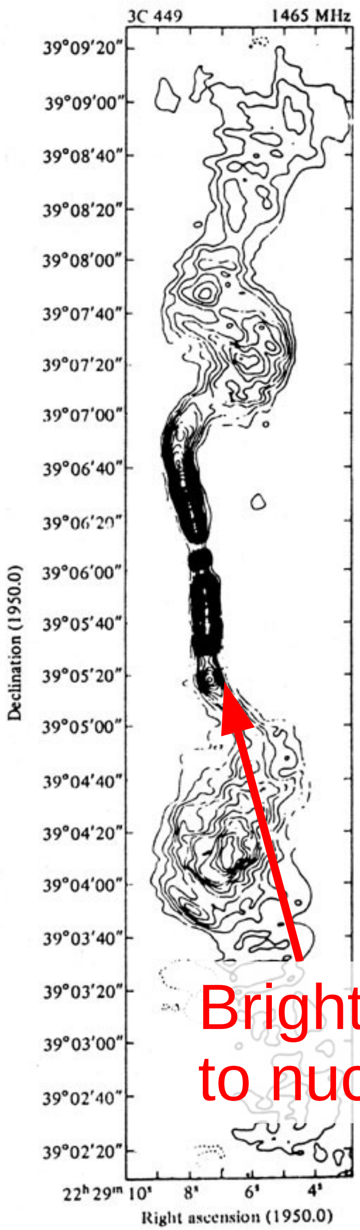
Strong magnetic fields form

Jet of highly-accelerated charged particles is emitted along the SMBH spin axis

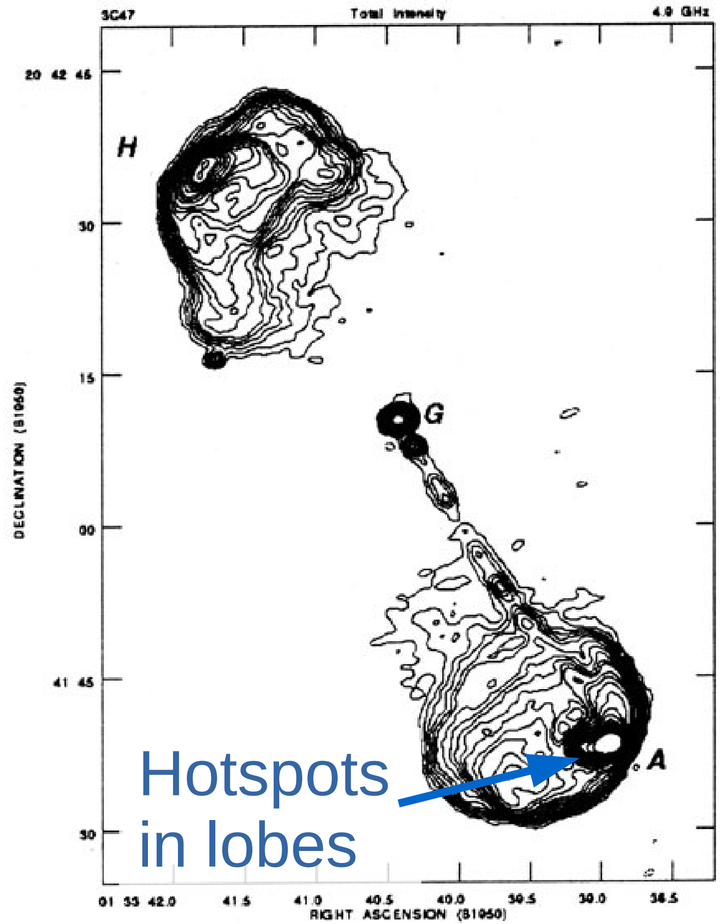
Very bright **synchrotron** emission from the jet

FR-I



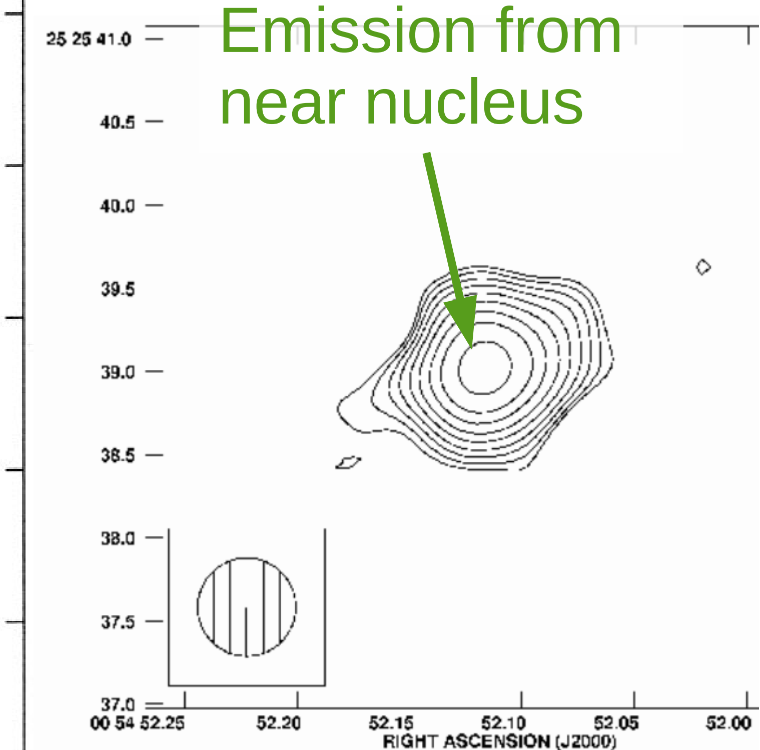
Perley et al. 1979

FR-II



Bridle et al. 1994

RQQ



Leipski et al. 2006

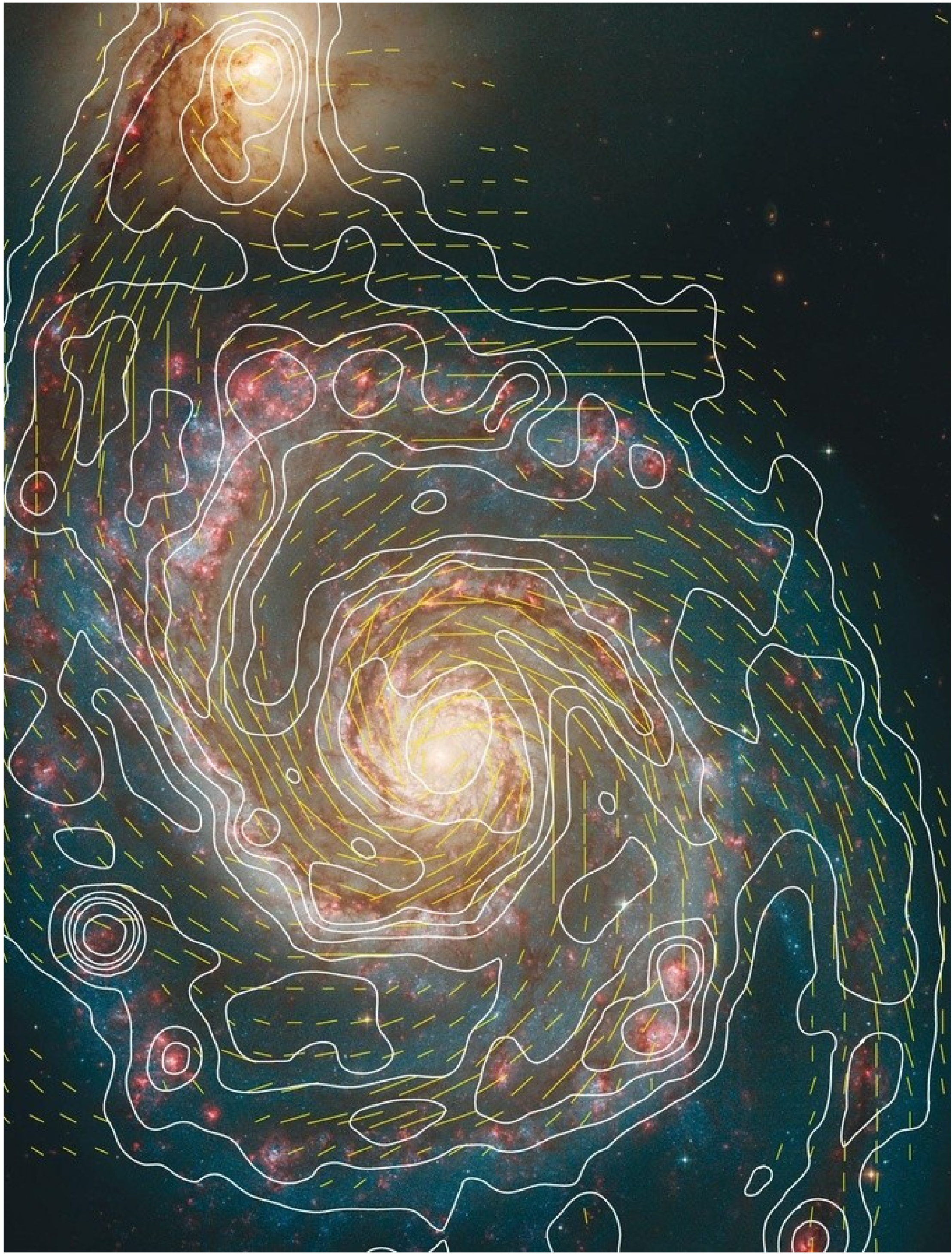
Most AGN are “radio-quiet”
(but still emit in the radio)

Star formation

Stars form when cold gas clouds **collapse** under gravity and heat up

Some fraction of **high-mass** (O,B) stars is formed

These burn fast and bright, ionising surrounding gas



VLA / HST / STScI

Star formation

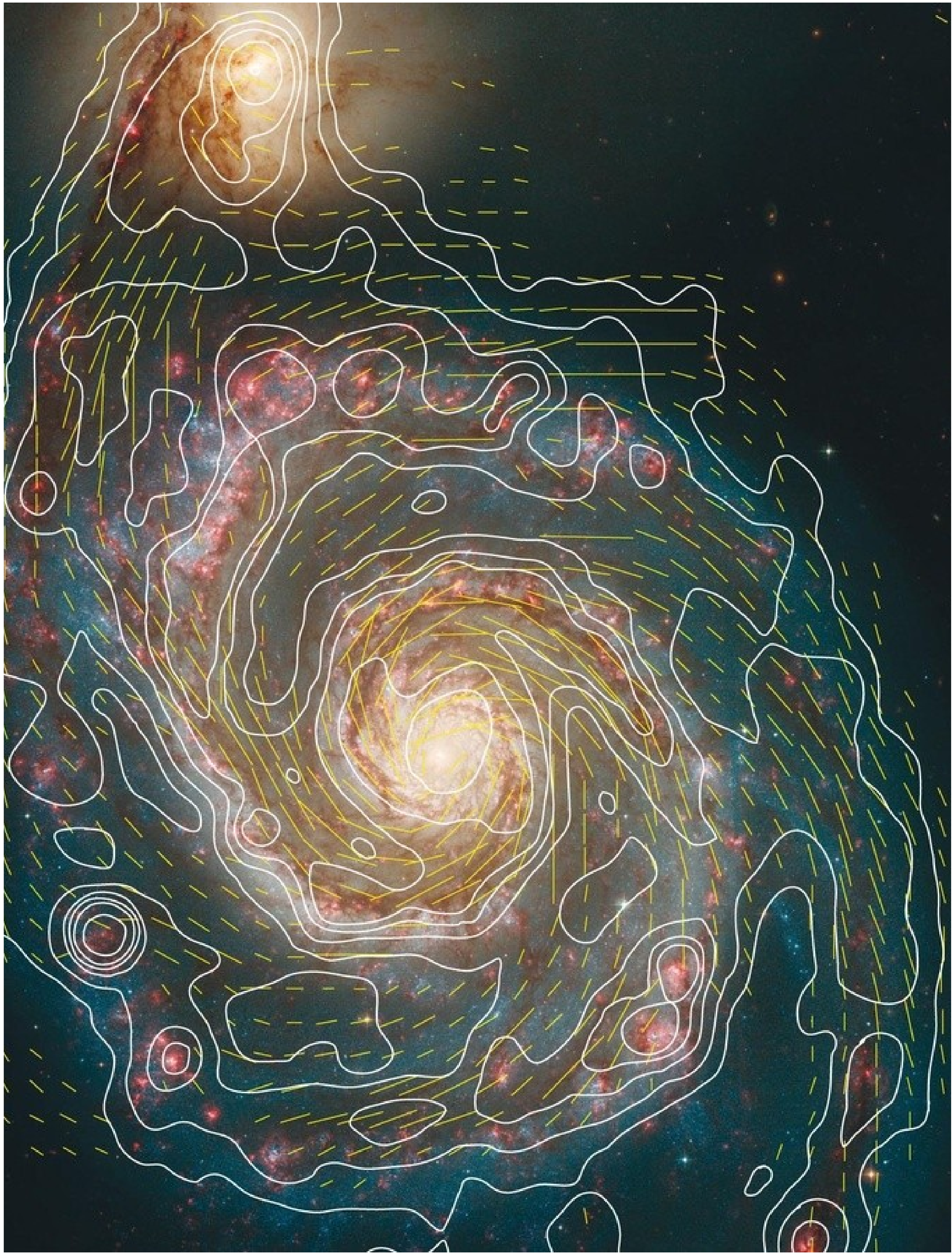
Stars form when cold gas clouds **collapse** under gravity and heat up

Some fraction of **high-mass** (O,B) stars is formed

These burn fast and bright, ionising surrounding gas

They soon run out of fuel and explode → **supernova**

Supernova remnants: free electrons + magnetic fields → *synchrotron radiation*



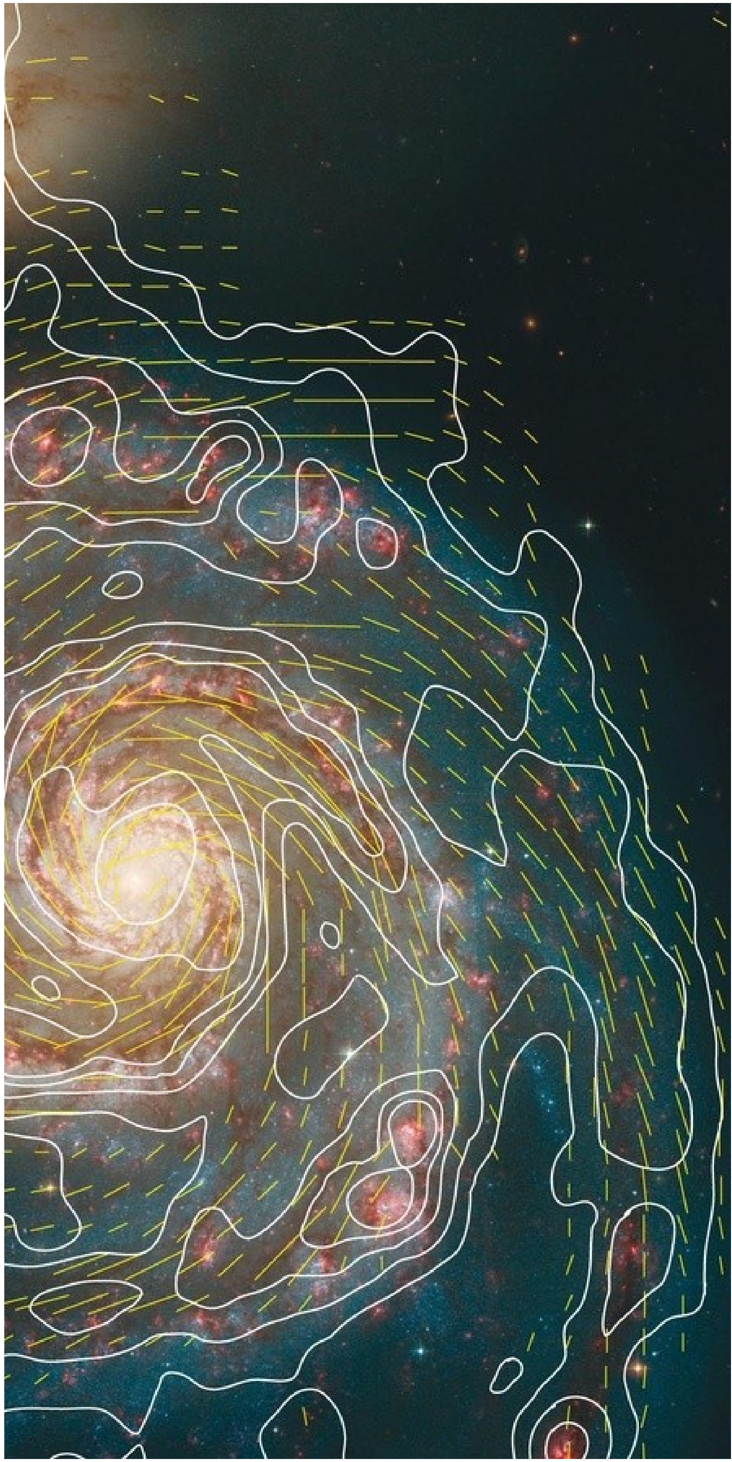
VLA / HST / STScI

Star formation

A strong correlation between radio and IR luminosity is observed
→ both are **tracers of star formation**

$$L_{1.4\,\mathrm{GHz}} = 4.324 \times 10^{29} \mathrm{erg/s}\, \frac{\psi_{\mathrm{SFR}}}{M_\odot\,\mathrm{yr}^{-1}}$$

Rieke et al. 2009



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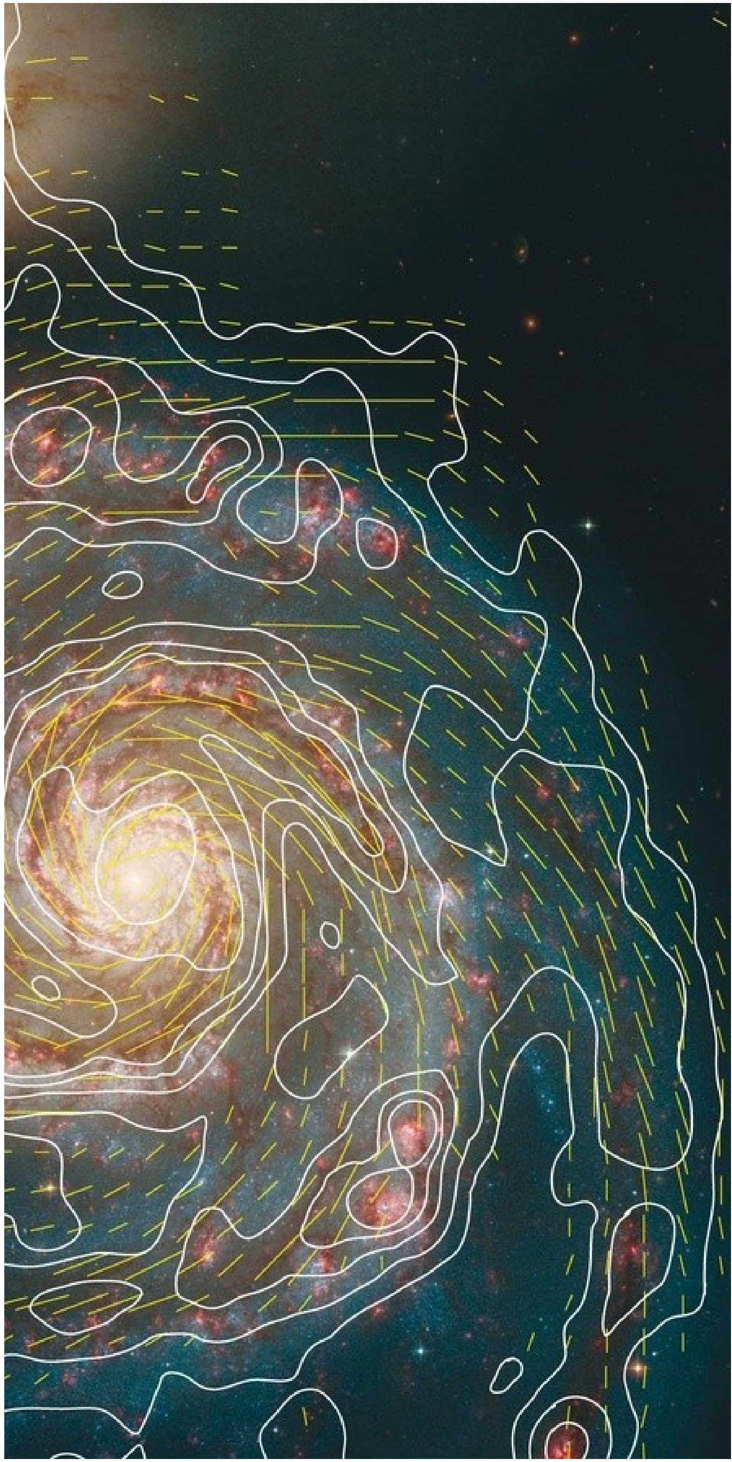
Dust obscuration is a big problem for other SFR indicators – but not radio

(N.B. Small fraction of free-free emission is also present – not pure synchrotron)



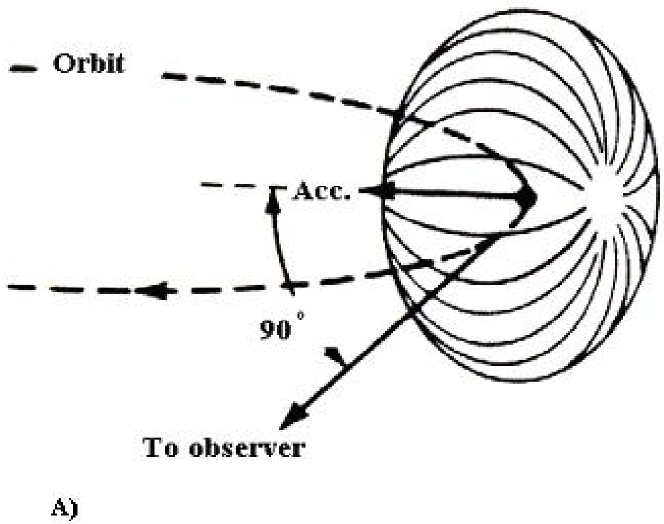
VLA / HST / STScI

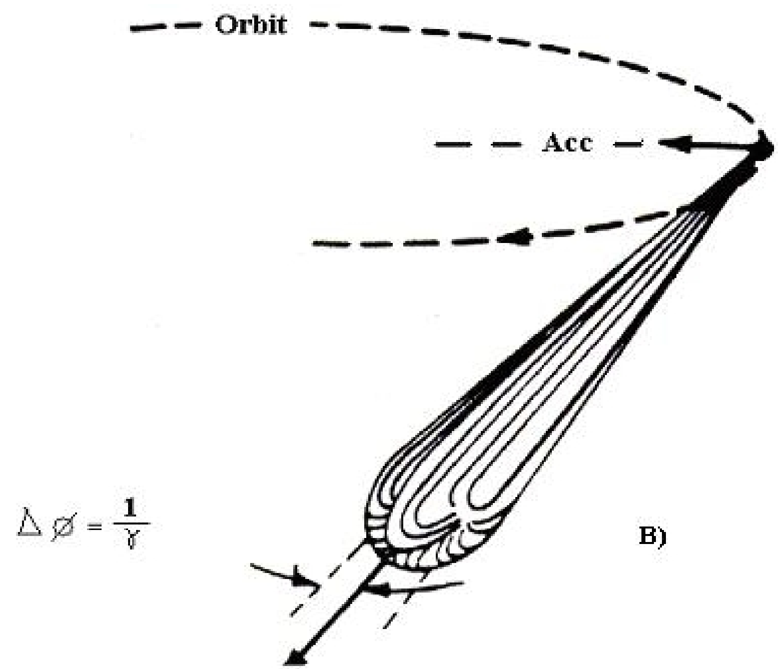
Synchrotron radiation

Charged particles emit radiation when accelerated

Magnetic fields accelerate electrons → *cyclotron* radiation

Emission is **relativistically beamed** for high-energy electrons





Power emitted by a single electron:

$$P = \left\langle \frac{dE}{dt} \right\rangle = \frac{4}{3}\sigma_T \beta^2 \gamma^2 \frac{cB^2}{8\pi}$$

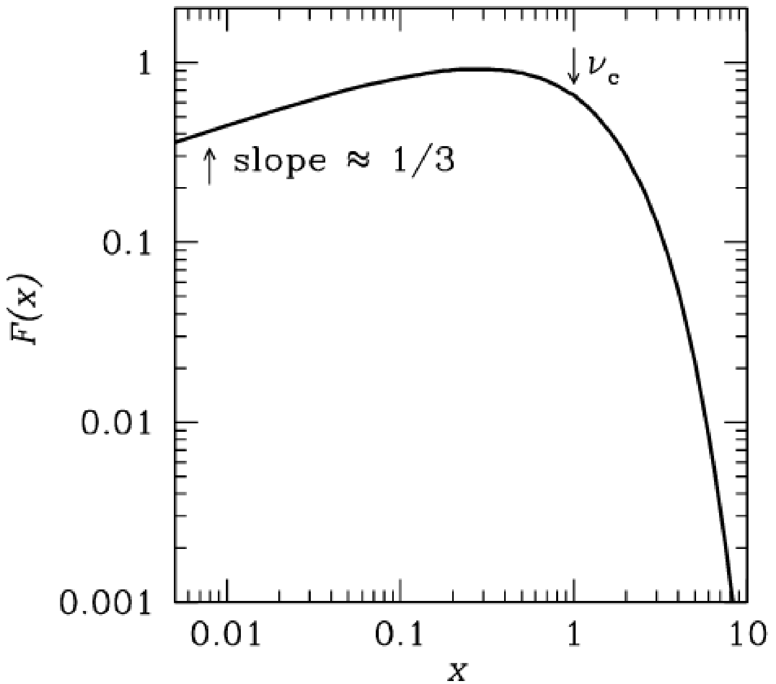
J. Condon / NRAO

Synchrotron radiation

Emission frequency depends on the *boosted* gyro frequency

For a single electron:

J. Condon / NRAO



$$\nu_{\rm crit} \simeq \gamma^2 \nu_g = \frac{\gamma^2}{2\pi}\frac{eB}{m_e c}$$

$$\approx 17.6\,{\rm GHz}\left(\frac{\gamma}{10^4}\right)^2\left(\frac{B}{1\,{\rm nT}}\right)$$

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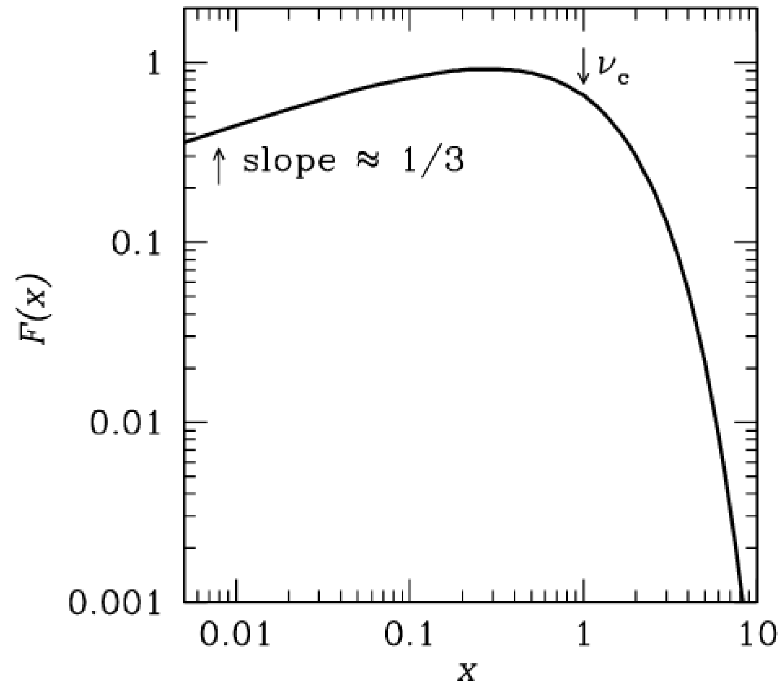


Electron energy distribution

Cosmic rays in the ISM have a power-law energy distribution

$$\frac{dN_e(E)}{dEdV} \propto E^{-\delta} \qquad \delta \approx 2.4$$

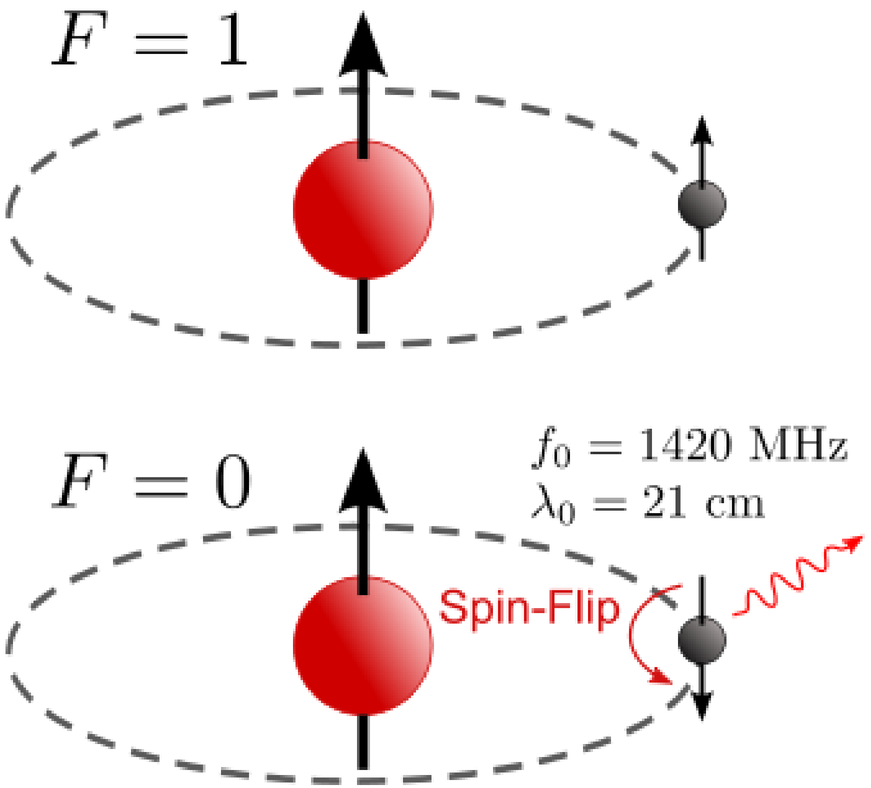
Final emission power is a product of power-laws, to give:

$$\epsilon_\nu \sim \nu^{-0.7}$$

Neutral Hydrogen

Proton-electron spin alignment in Hydrogen ground state

Rare "spin-flip" transition (~10^{-7} yr^{-1}) emits λ=21.1cm line



6 μeV!
(~10^{-24} J)

Wikimedia

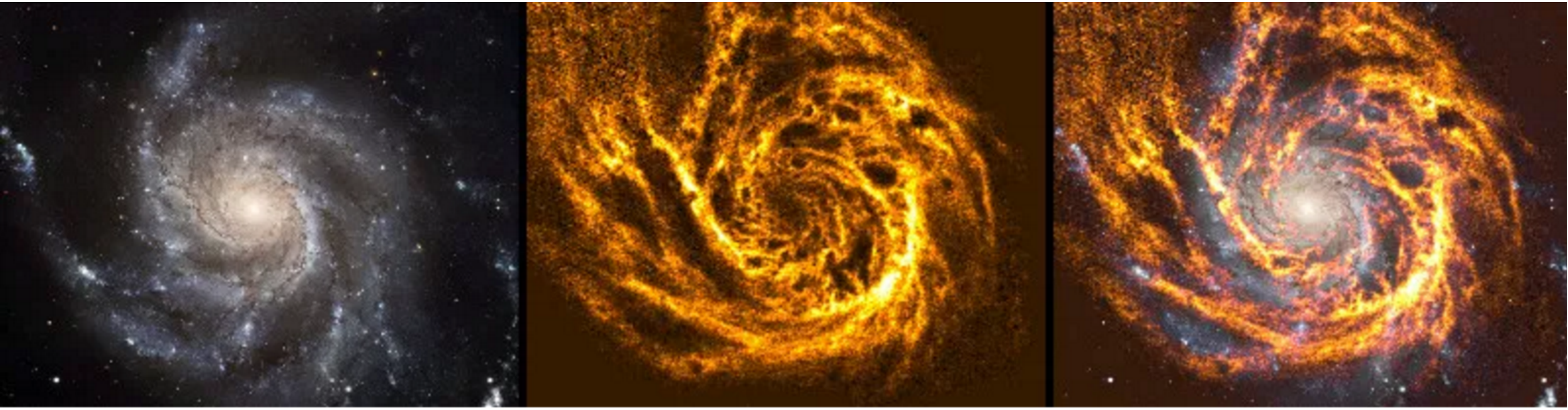
Neutral Hydrogen

Proton-electron spin alignment in Hydrogen ground state

Rare “spin-flip” transition (~10^{-7} yr^{-1}) emits λ=21.1cm line

Neutral Hydrogen (“HI”) is common in the Universe! Can be used to see regions that don’t emit any other light

21cm line is redshifted → observed at λ = 21cm x (1 + z)

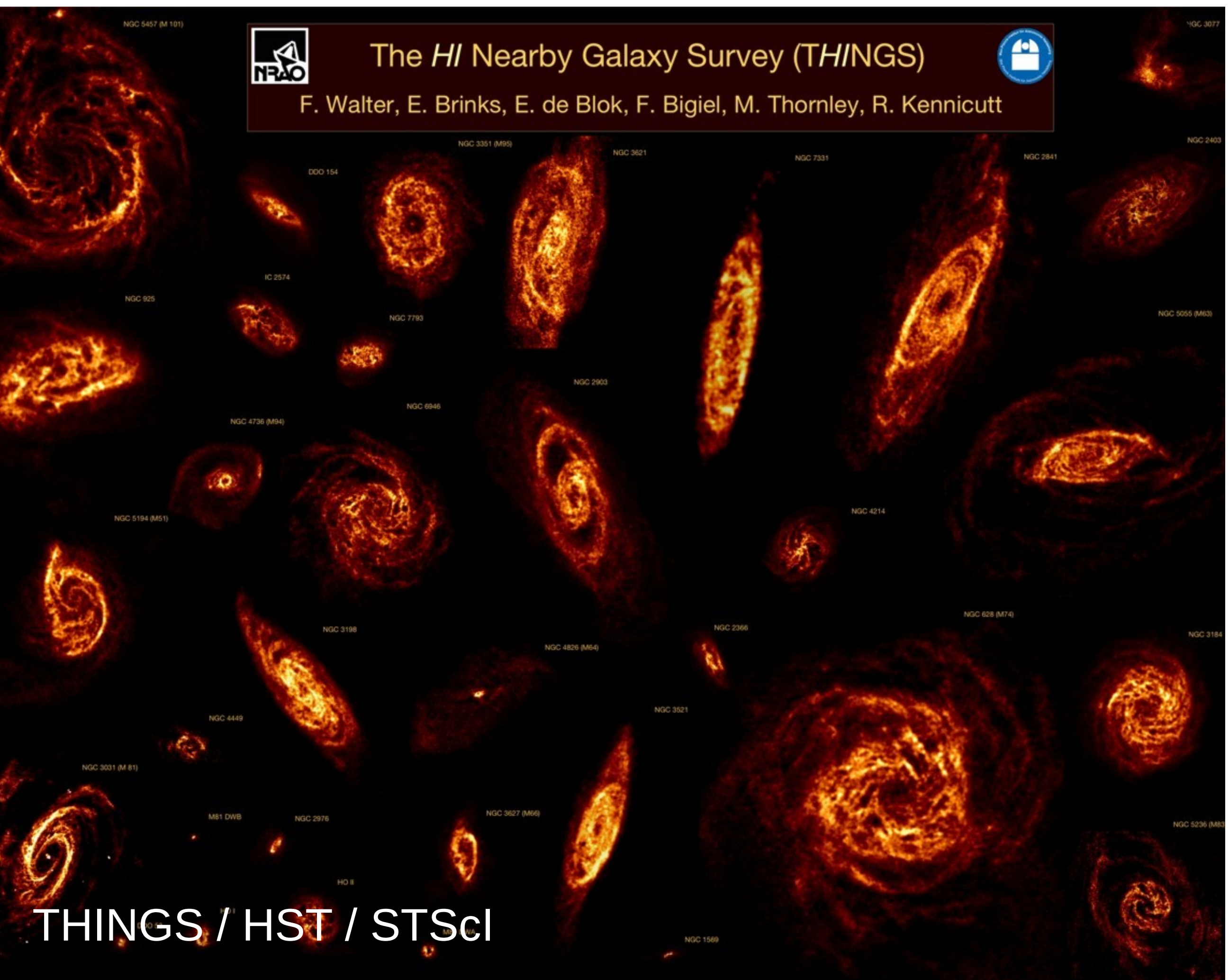


THINGS / HST / STScI

Neutral Hydrogen

It’s easy to destroy HI...

- Photo-ionisation by UV background from stars/galaxies
- Processing of neutral gas into stars (star formation)



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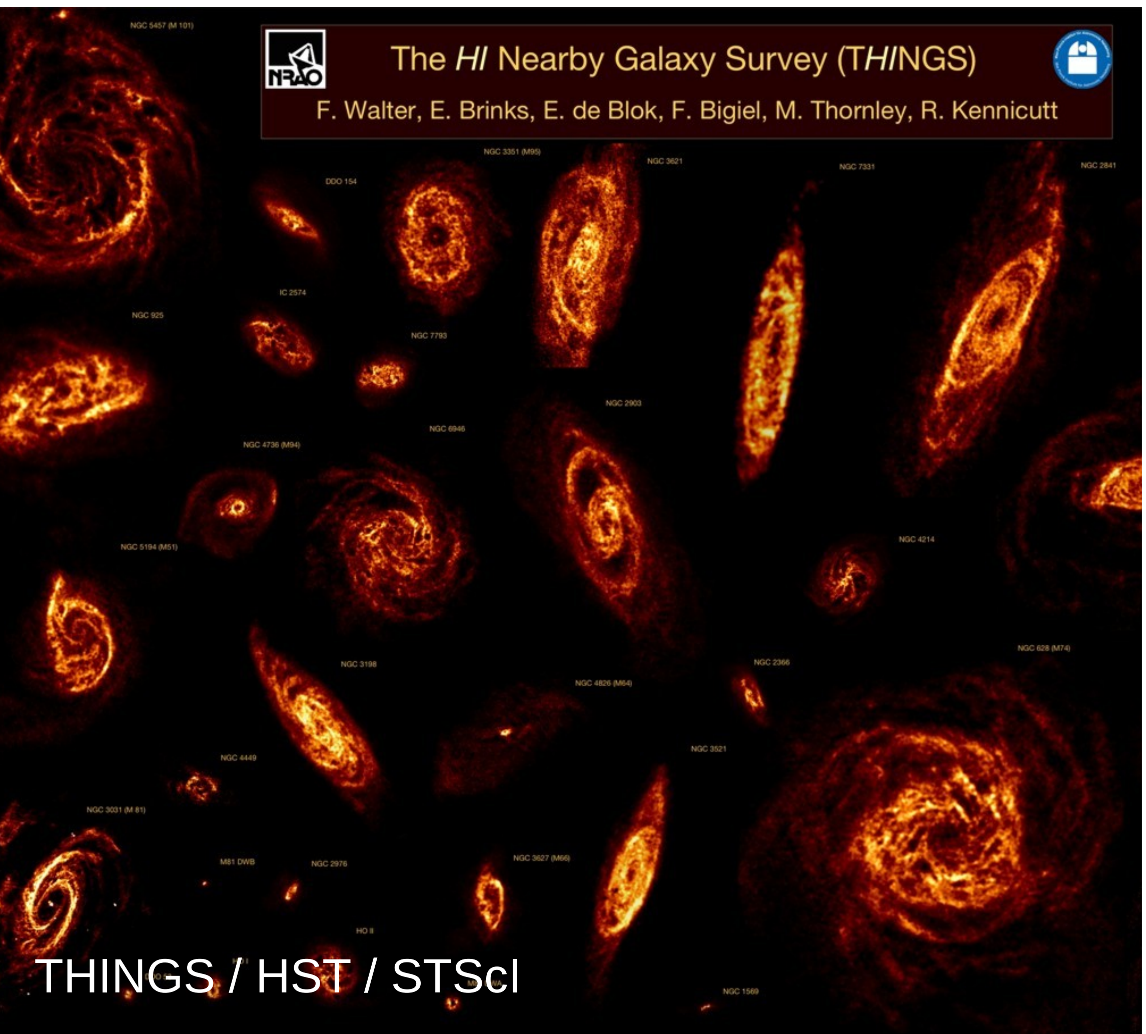

HI gas cycles through *reservoirs* in galaxies

- Ionised gas falls in from IGM and cools → **new HI**
- Gas inside reservoir is **shielded** from UV
- HI falls into galaxy and eventually **forms stars**

Neutral Hydrogen

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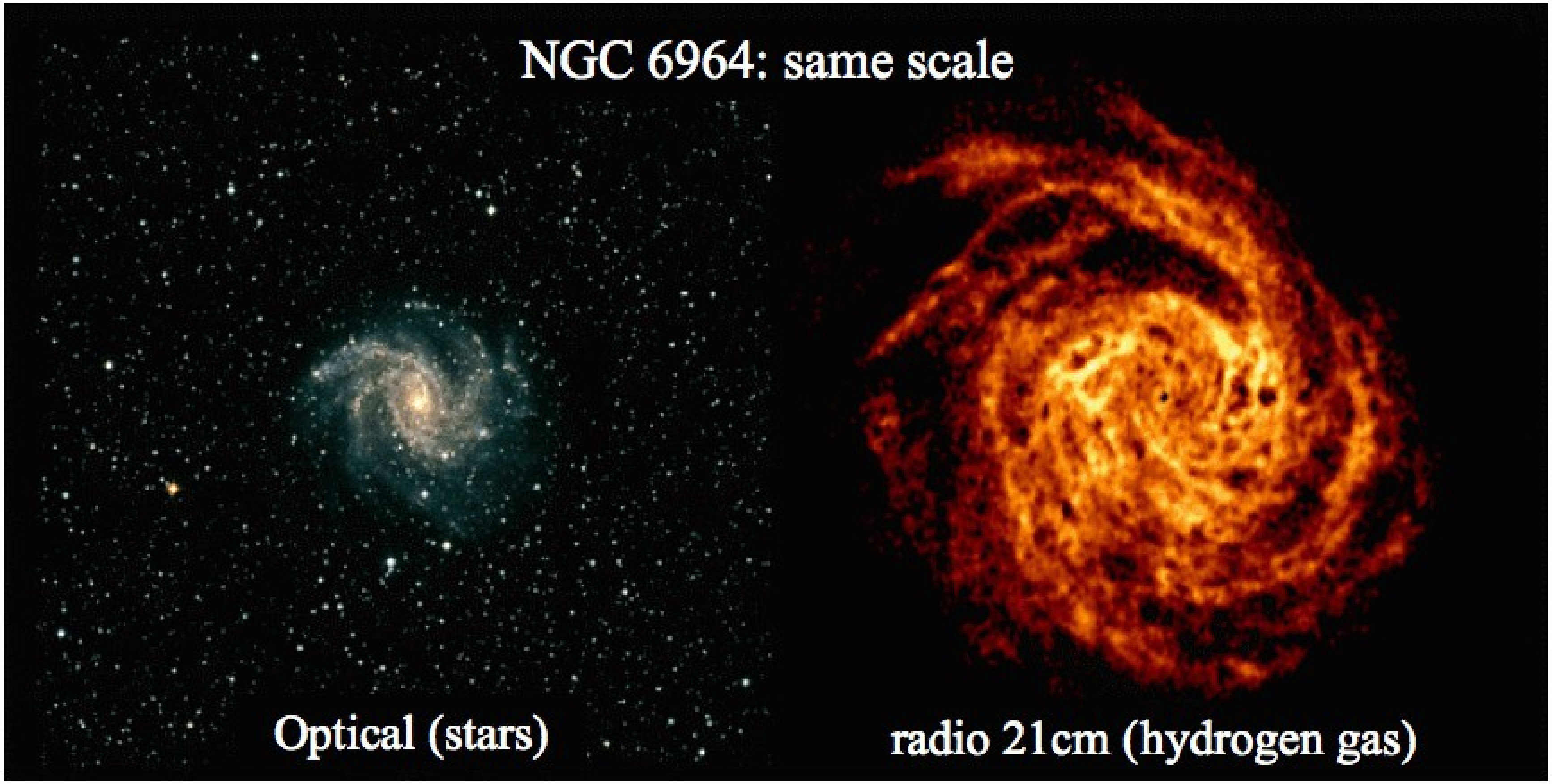


SKA

Continuum galaxy surveys

Detection

(1) Stare at the sky (integrate) until some noise level is reached...

(2) Integrate over full bandwidth to **improve sensitivity**

$$\sigma_{\rm S} \approx \frac{2k_{\rm B}T_{\rm sys}}{A_{\rm eff}\sqrt{\delta\nu\, t_{\rm obs}}}$$

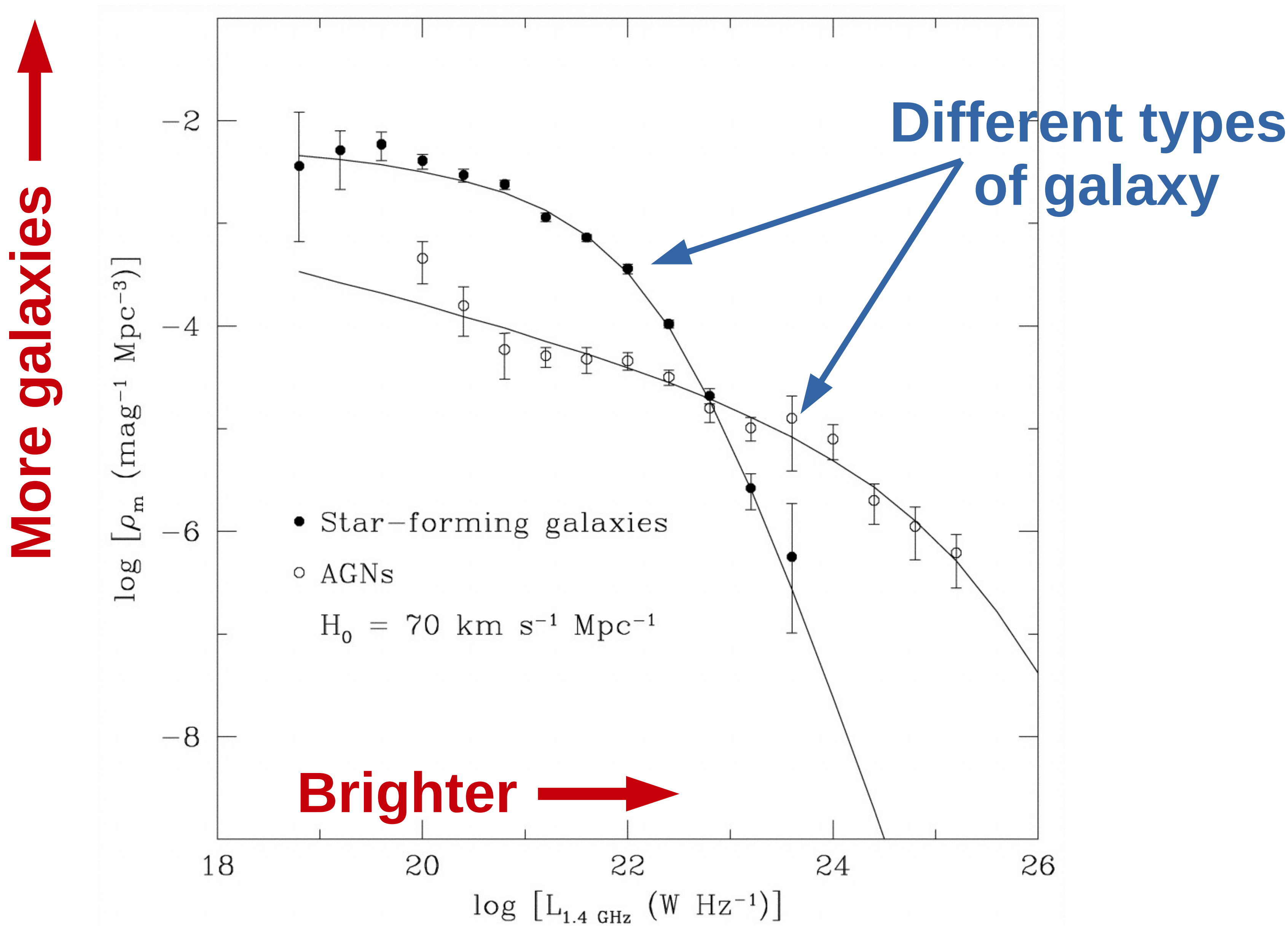
(3) Make image from interferometer snapshots

(4) Keep point sources that are brighter than some threshold
above the noise level

(Recall the issues of confusion, thresholding etc.)

Galaxy number counts

Number of galaxies vs. their intrinsic luminosity

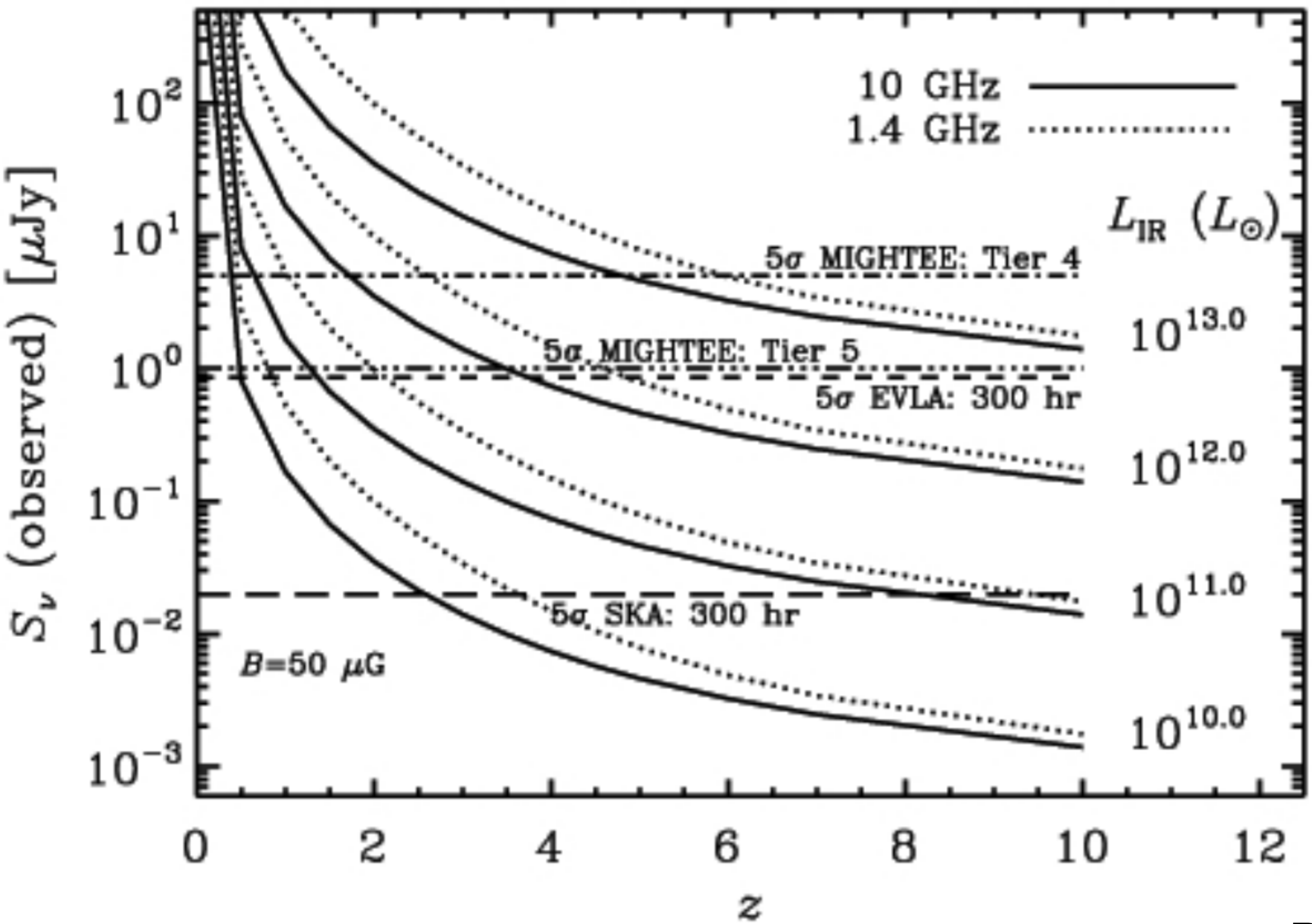


J. Condon / NRAO

Number counts vs. redshift

- Distant sources are fainter
- Source populations evolve with redshift
- Luminosity depends on frequency (redshifted!)

$$S = \frac{L}{4\pi d_L^2}$$



R. Norris et al. 2012

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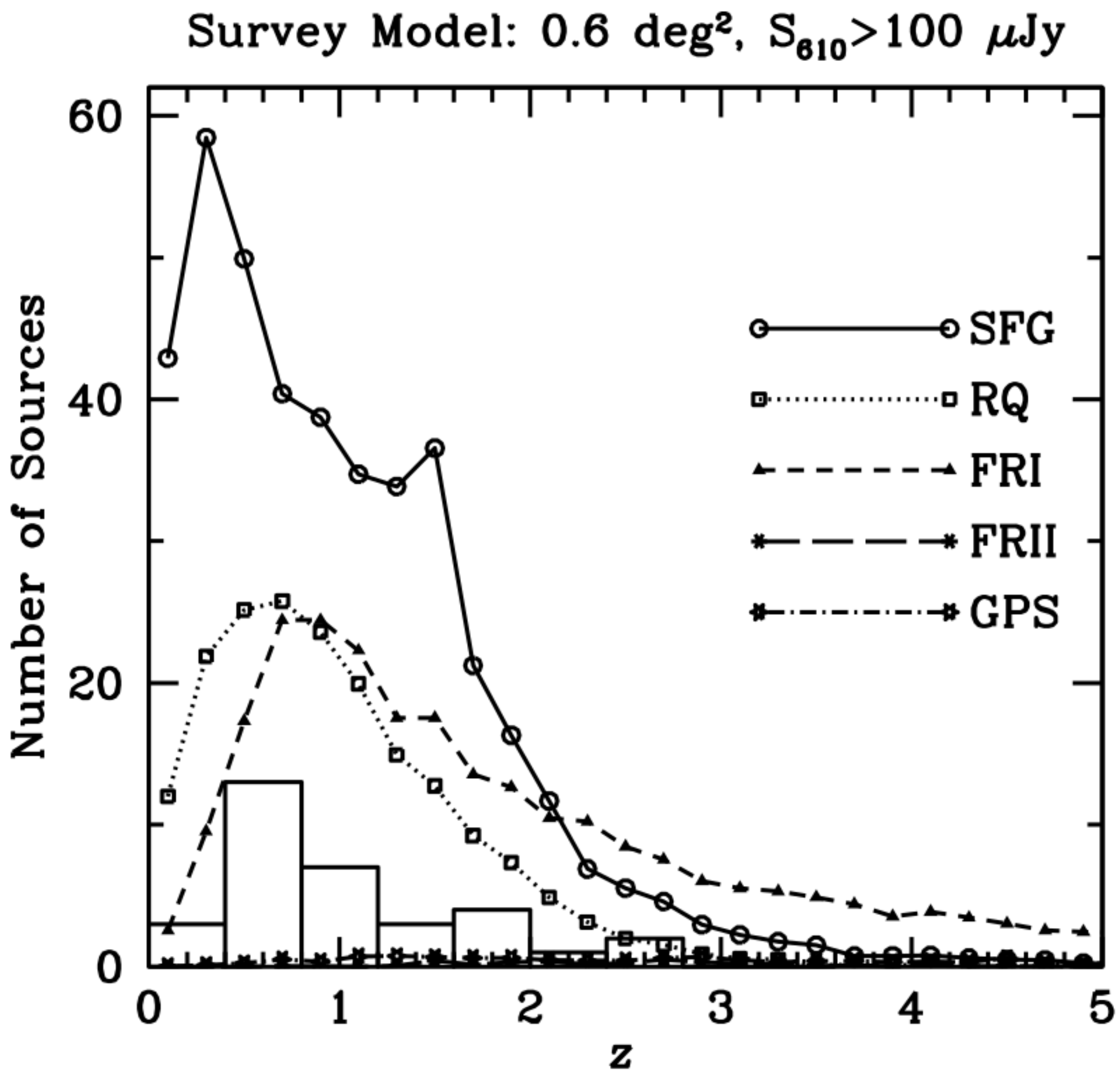

R. Norris et al. 2012

Cosmology with continuum galaxies

No redshift information

- Continuum spectra are smooth → no lines or features
- Can only measure the 2D (angular) coordinates

Cosmology with continuum galaxies

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- Continuum spectra are smooth → no lines or features
- Can only measure the 2D (angular) coordinates

2D clustering

- Much less information than 3D, but still useful
- High number densities: valuable for **lensing**
- Look for **preferred directions** and anisotropies

Classification

- Galaxies can be *classified* by spectra and morphology
- Different types of galaxy live in dark matter halos of different masses

“Value-added” weak lensing

Intrinsic galaxy properties

- Some *intrinsic* properties (i.e. before lensing) can be inferred and compared with (lensed) observations
- Use these to separate lensing from *intrinsic alignments*

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Examples

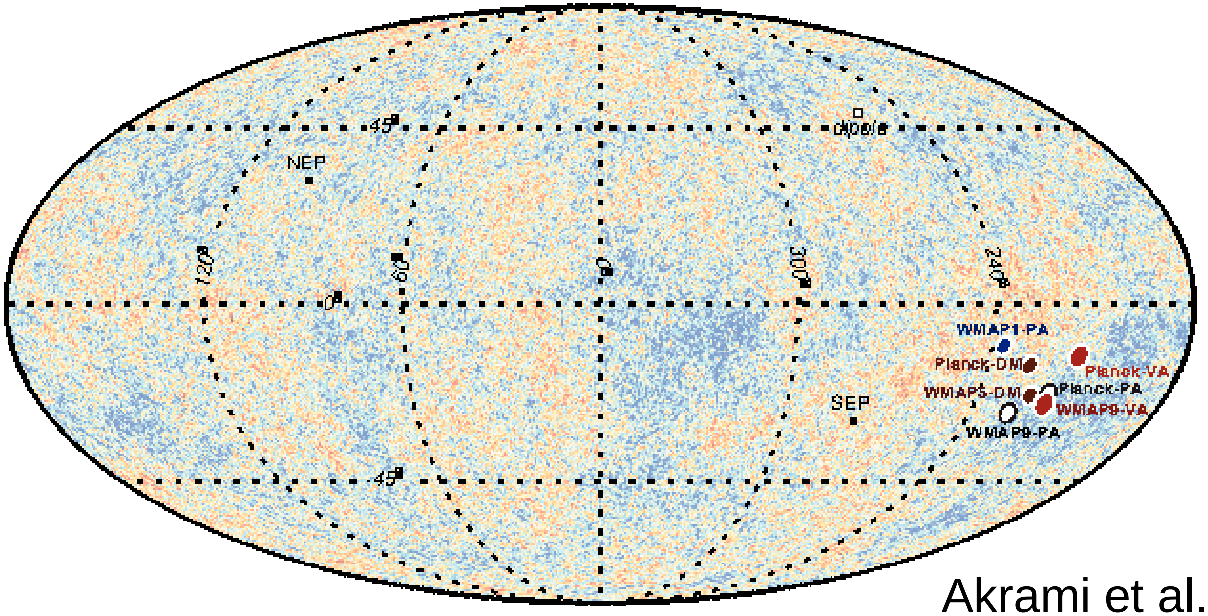
- Rotation velocities (Blain 2002; Morales 2006)
- Polarisation (Brown & Battye 2011)

Problems

- Deconvolution can affect shape measurements…
- Measure ellipticity directly in visibility (Fourier) space?
- See arXiv:1507.06639 for SKA lensing requirements

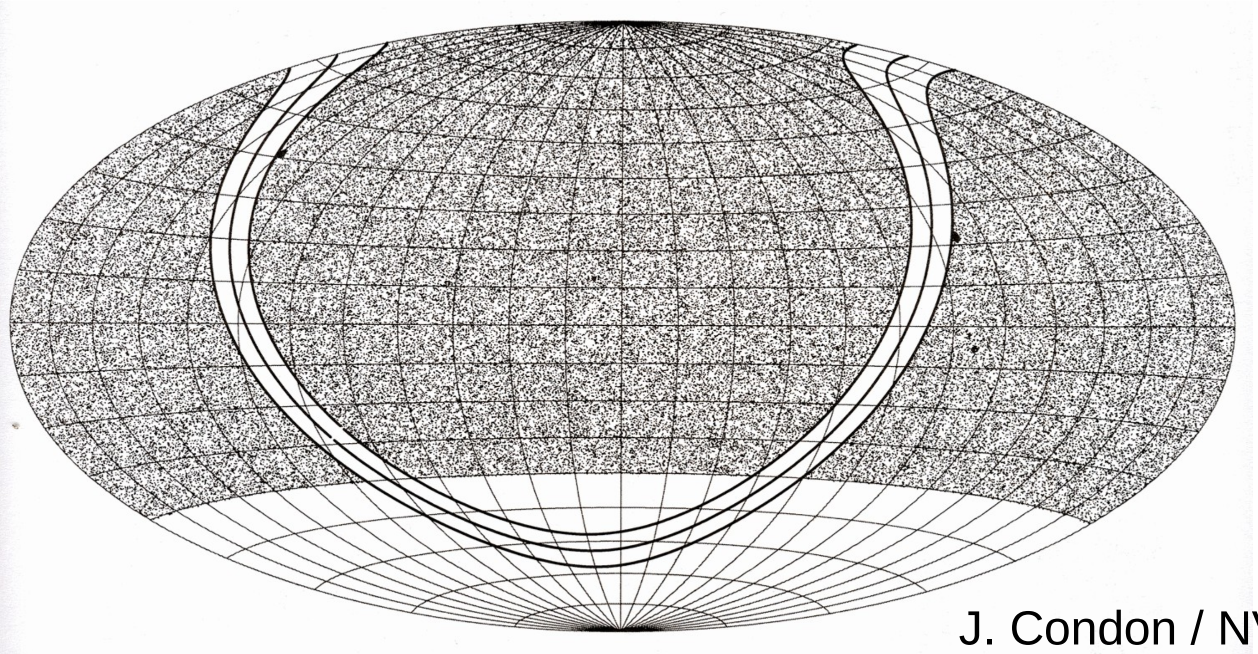
Cosmology with continuum galaxies

Anisotropy / preferred directions?



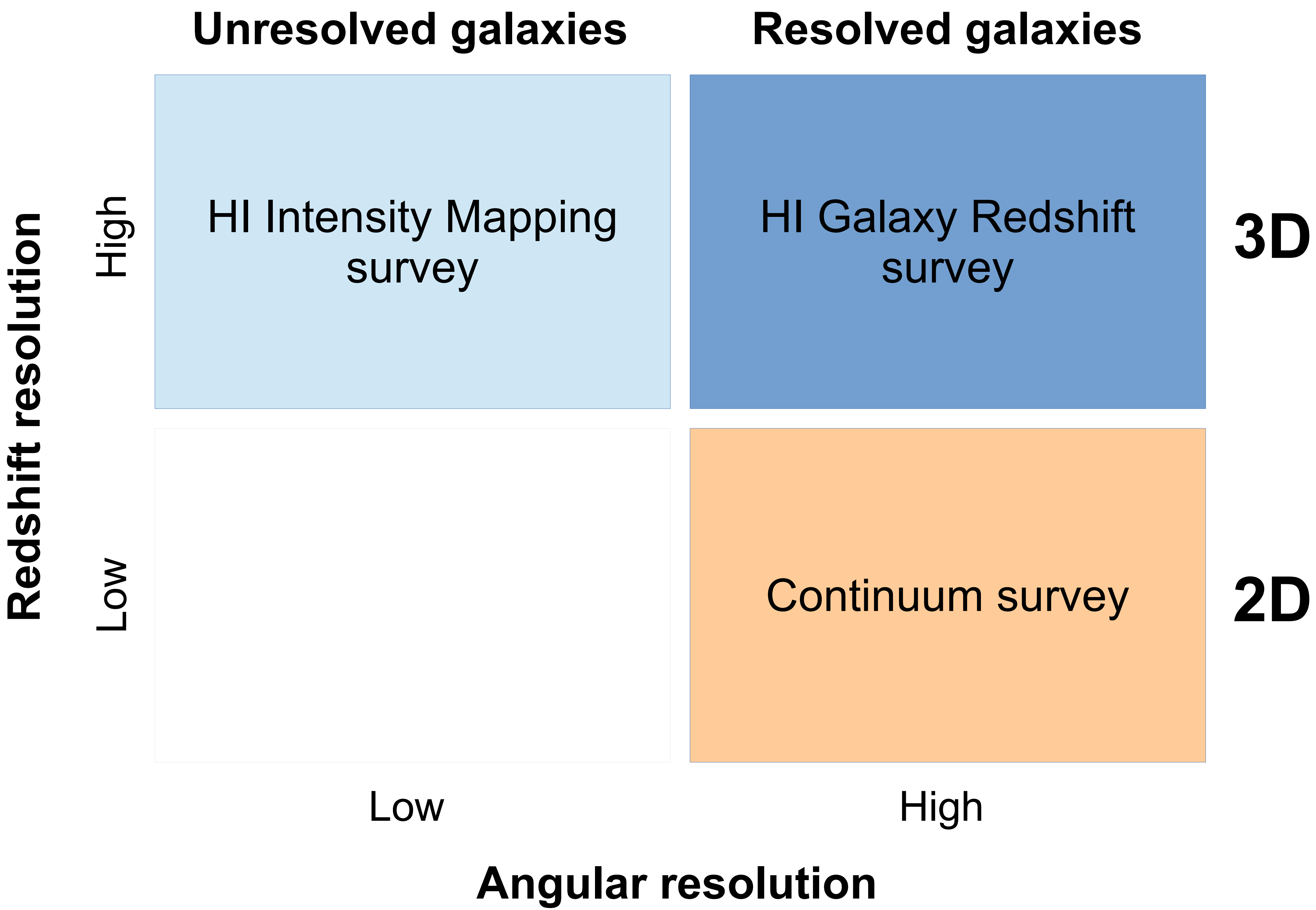
Akrami et al. 2014

Small (~7%) power asymmetry seen in the CMB



J. Condon / NVSS

Is it real? Need to cross-check with galaxy distribution


Unresolved galaxies
Resolved galaxies
HI Intensity Mapping survey
HI Galaxy Redshift survey
3D
Continuum survey
2D
Redshift resolution
High
Low
Low
High
Angular resolution

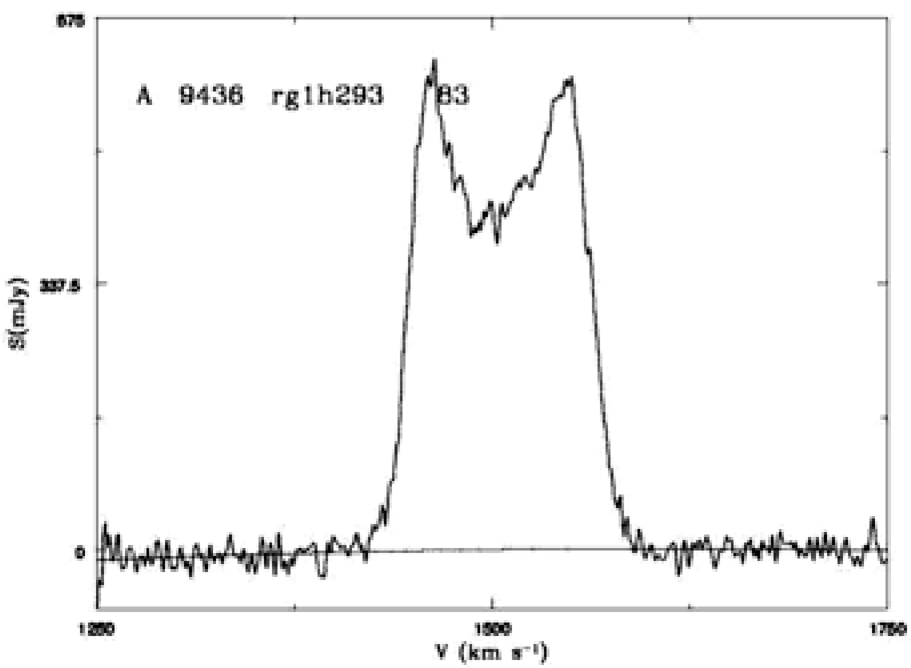
HI galaxy surveys

Neutral Hydrogen

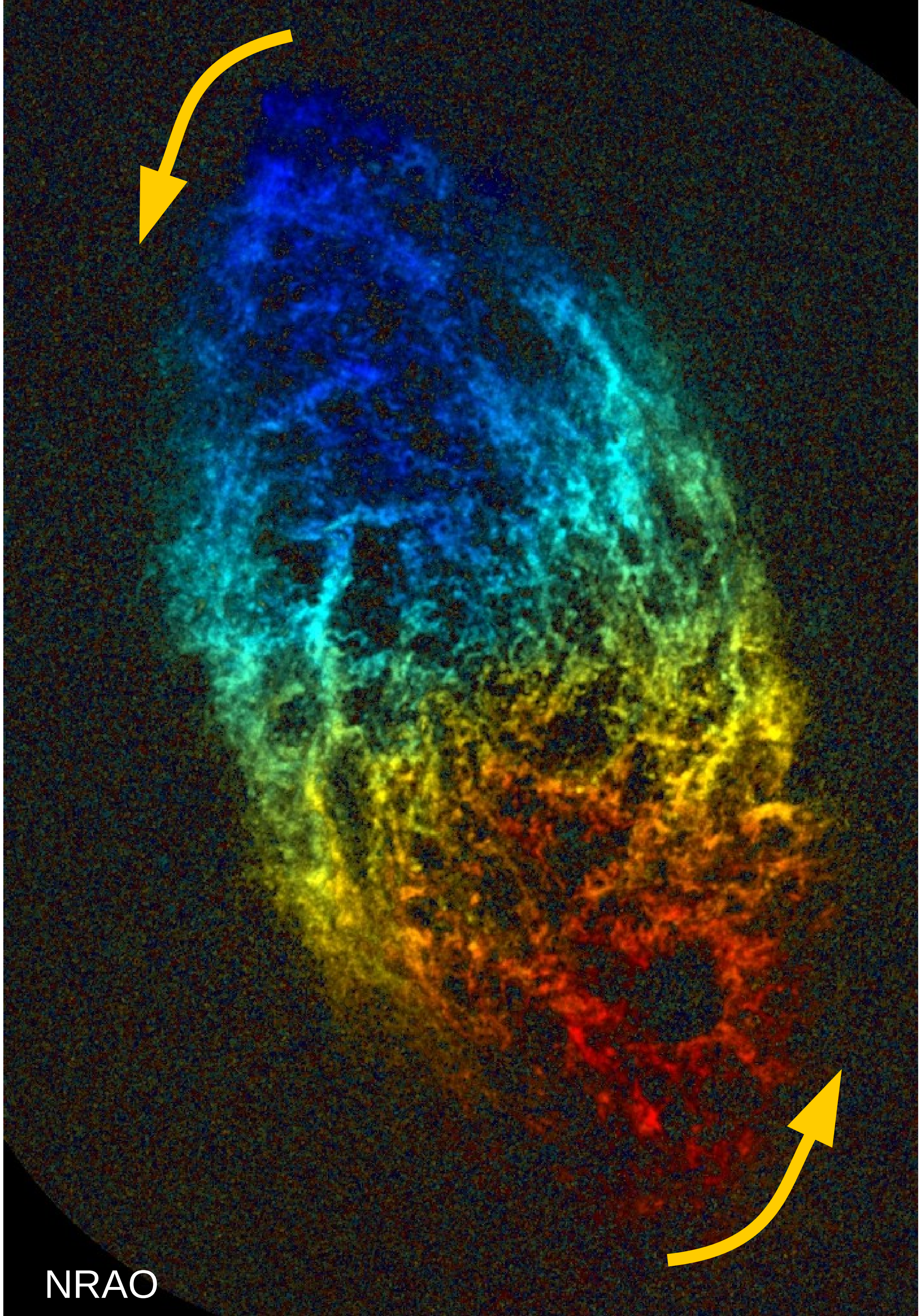
21cm line is Doppler shifted by galaxy rotation

Traces motion of gas in galaxies: “rotation curve”

“Double-peaked” line profile



ALFALFA



Detecting HI galaxies

Need sensitivity in **narrow band** to detect 21cm line

$$\sigma_{\rm S} \approx \frac{2k_{\rm B}T_{\rm sys}}{A_{\rm eff}\sqrt{\delta\nu\, t_{\rm obs}}}$$

~few kHz

Source detection algorithm

- Need to reject “lines” that are just RFI and noise peaks

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~few kHz

Source detection algorithm

- Need to reject "lines" that are just RFI and noise peaks
- If we see a double-peaked line, it's not noise/RFI... but *face-on* galaxies don't have a double peak
- If we choose a larger δν, the noise is smaller… but then we won't see a double peak for *almost* face-on galaxies

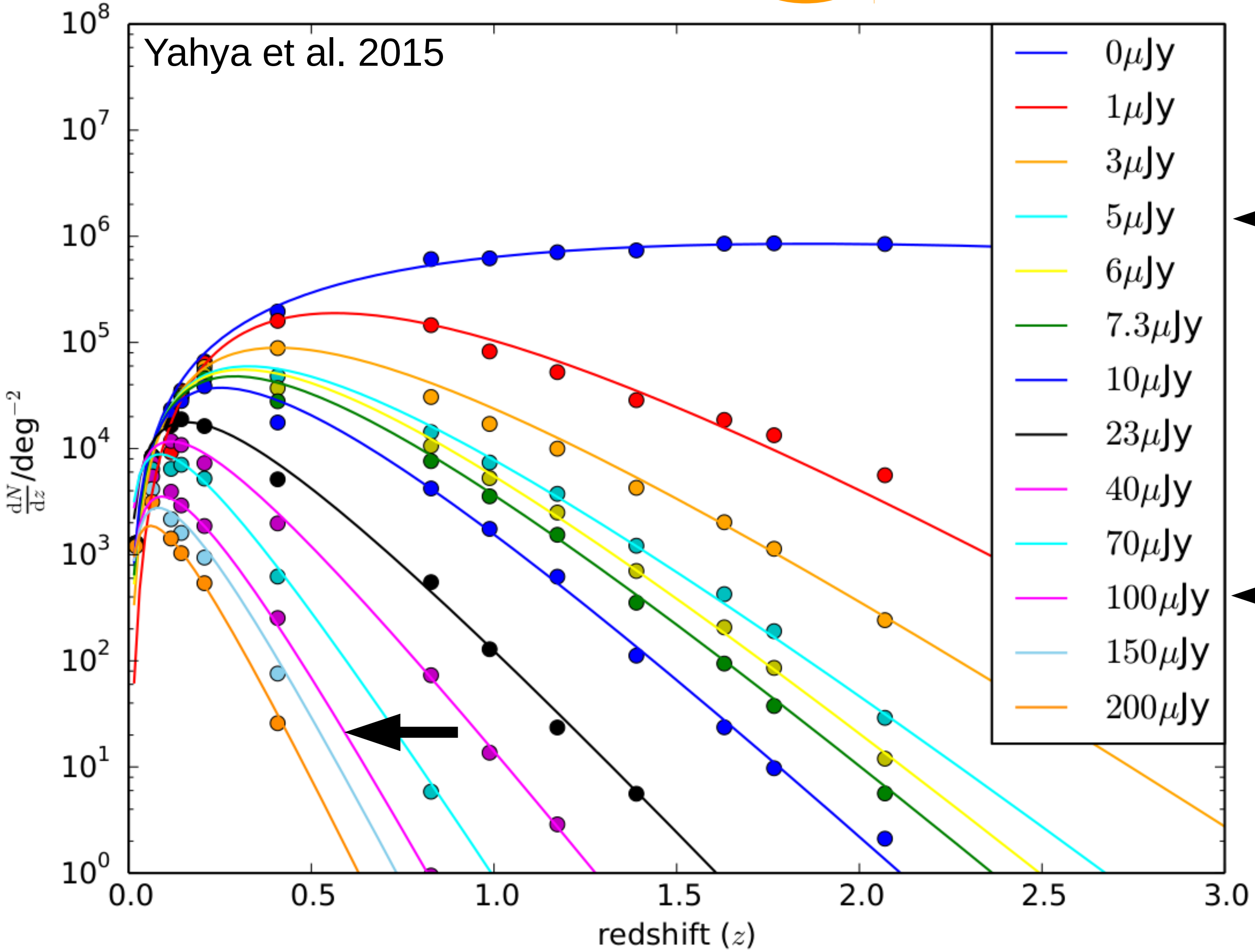
→ Smart algorithms can be designed, but quickly get complicated...

Detecting HI galaxies

Need sensitivity in **narrow band** to detect 21cm line

$$\sigma_S \approx \frac{2k_B T_{sys}}{A_{eff}\sqrt{\delta\nu\, t_{obs}}}$$

Depends on the survey area + total survey time



SKA2
~30k deg^2

SKA1-MID
~5,000 deg^2

Detecting HI galaxies

SKA1-MID: ~few million HI galaxies at $z < 0.4$
SKA2: ~1 billion HI galaxies at $z < 1.5$

All with high-precision **3D positions** (angle + redshift):
→ Measure the *3D galaxy power spectrum*

- Baryon acoustic oscillations → expansion rate
- Redshift-space distortions → growth of structure
- Cross-correlation/tomography → improve lensing etc.

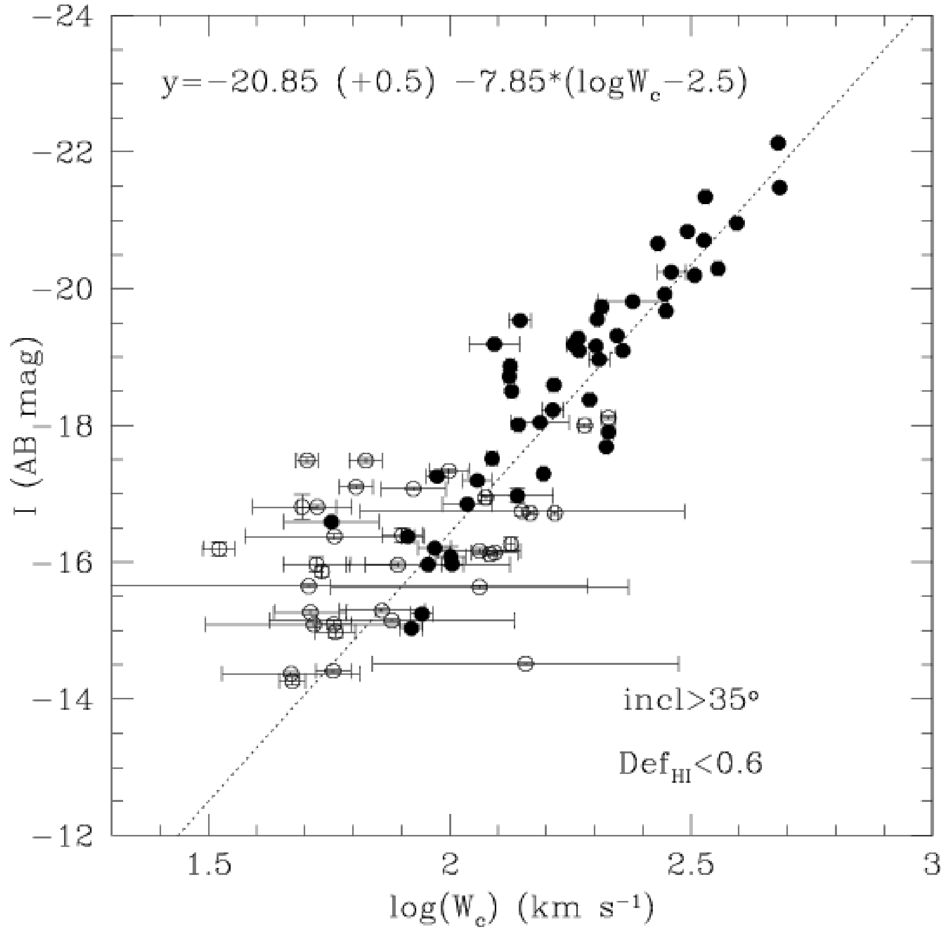
(See lectures by others)

Unique with HI: direct galaxy velocity measurements

Peculiar velocities

Tully-Fisher: Relation between max. *rotation* velocity and luminosity: $L \propto v_{\max}^{\alpha}$

Gavazzi et al. 2008



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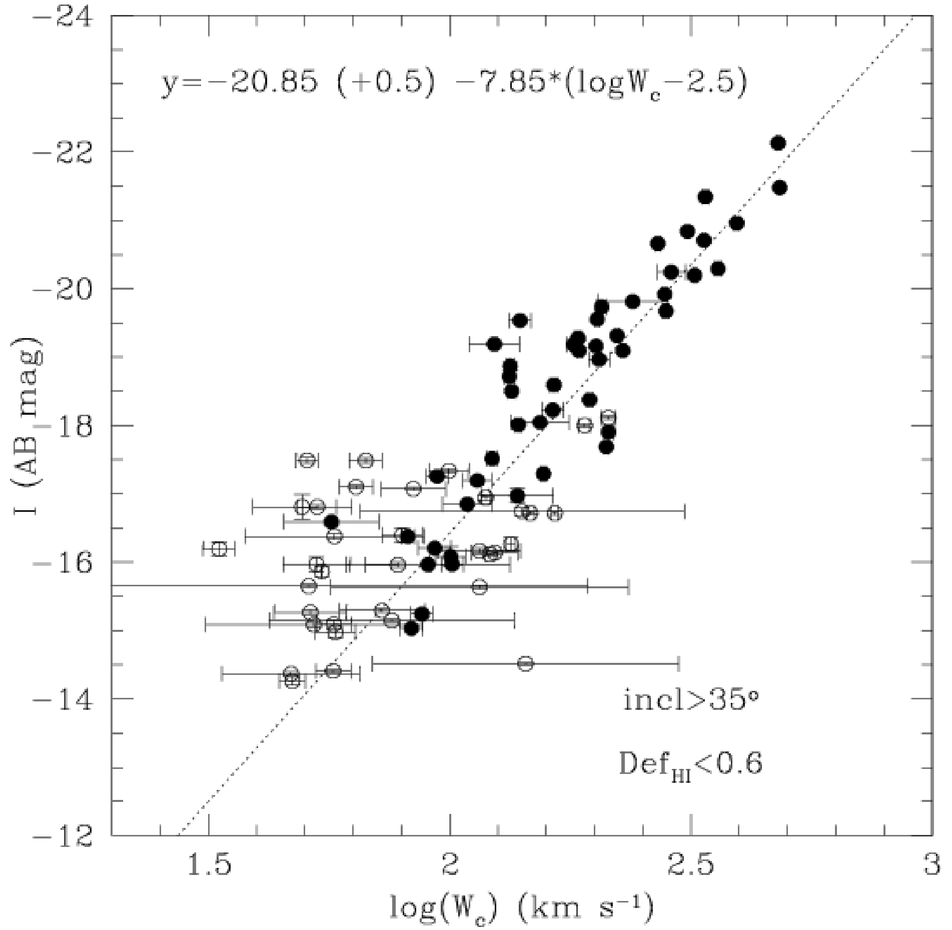

21cm line width related to v_{max}

→ Use measured flux and width as “standard candle”:

$$L = \kappa\, w_{21}^{\alpha} \qquad S = \frac{L}{4\pi d_L^2}$$

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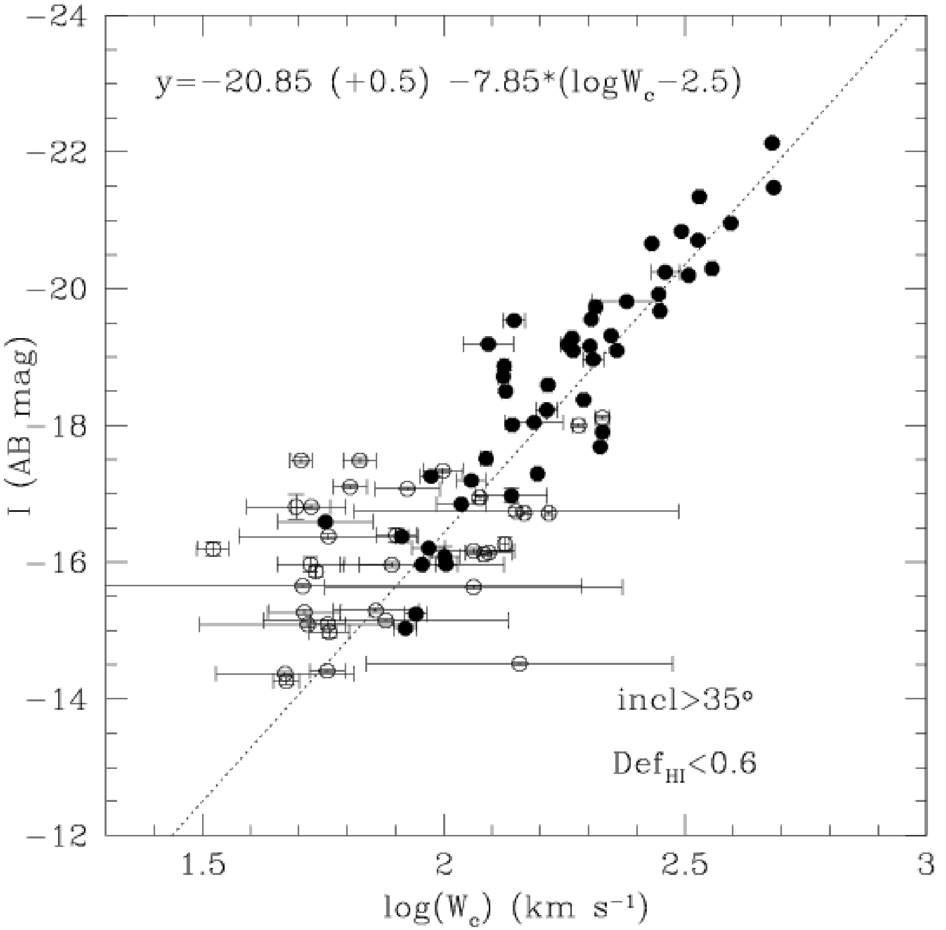


Measured luminosity distance:

$$d_L(z_{\rm true}) = \sqrt{\frac{\kappa\, w_{21}^{\alpha}}{4\pi S}}$$

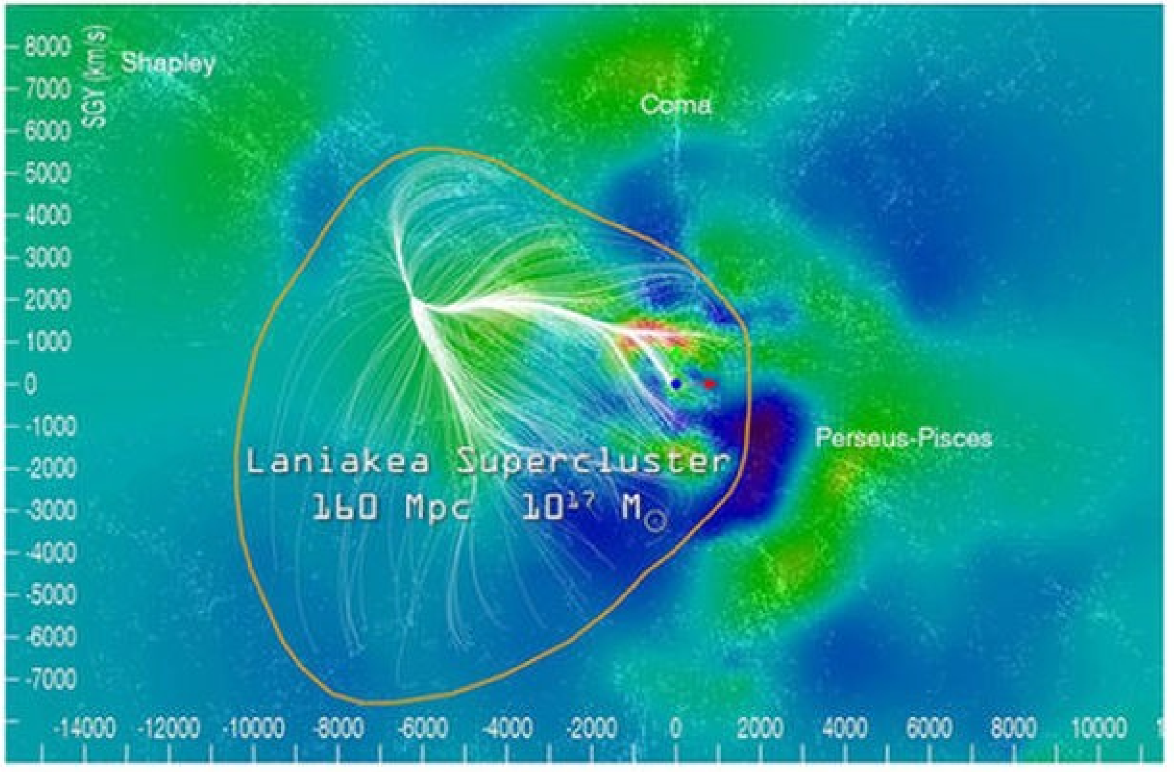
Invert to get true redshift and compare to *observed* redshift:

$$z_{\rm obs} = z_{\rm true} + (\boldsymbol{v}\cdot\hat{n}/c)$$

Peculiar velocities

What can we learn from peculiar velocities?

- Galaxy motions identify objects that are gravitationally **bound**:



DPvision/CEA

- Measures **growth**, f(z), and **expansion rate**, H(z):

$$\mathbf{v}(t, \mathbf{k}) = \frac{H\,f}{a}\,\frac{i\mathbf{k}}{k^2}\delta(t, \mathbf{k})$$

Intensity mapping

Intensity mapping

Why detect individual galaxies?

- If you only care about larger scales...
- High SNR detection of galaxy 'wastes' photons
- Spectroscopic redshifts take a long time

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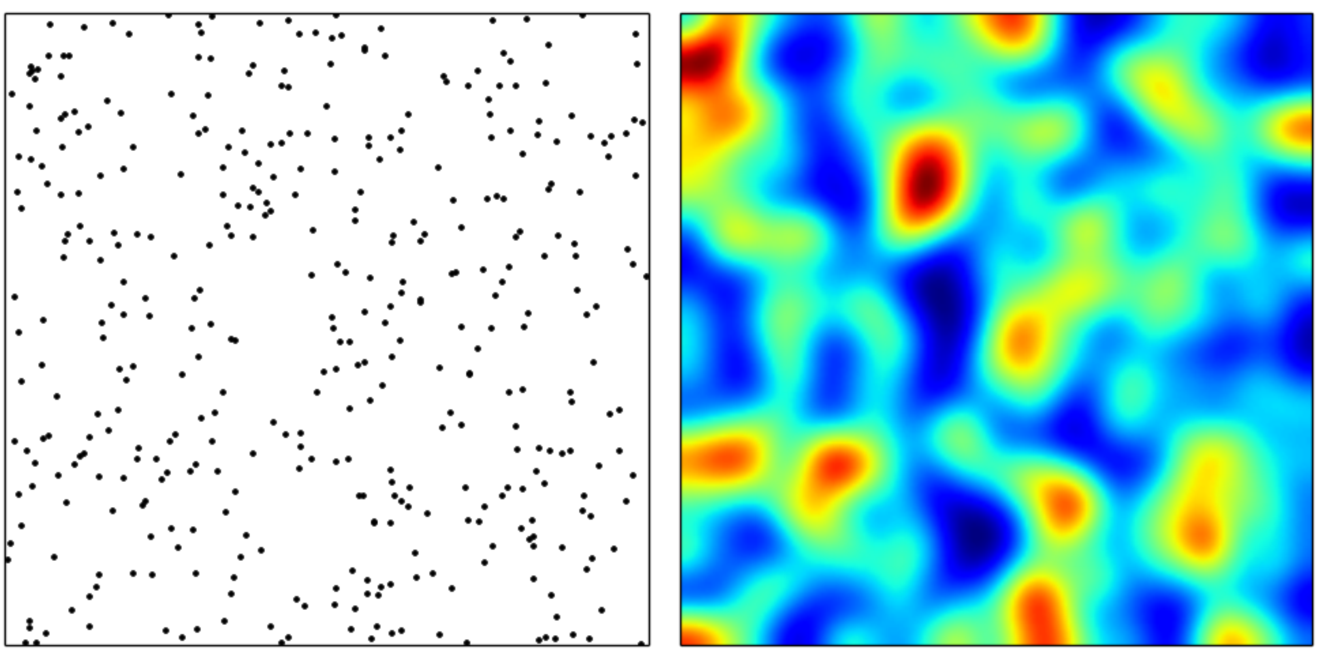
→ **Map out emission integrated over many galaxies**



Intensity mapping

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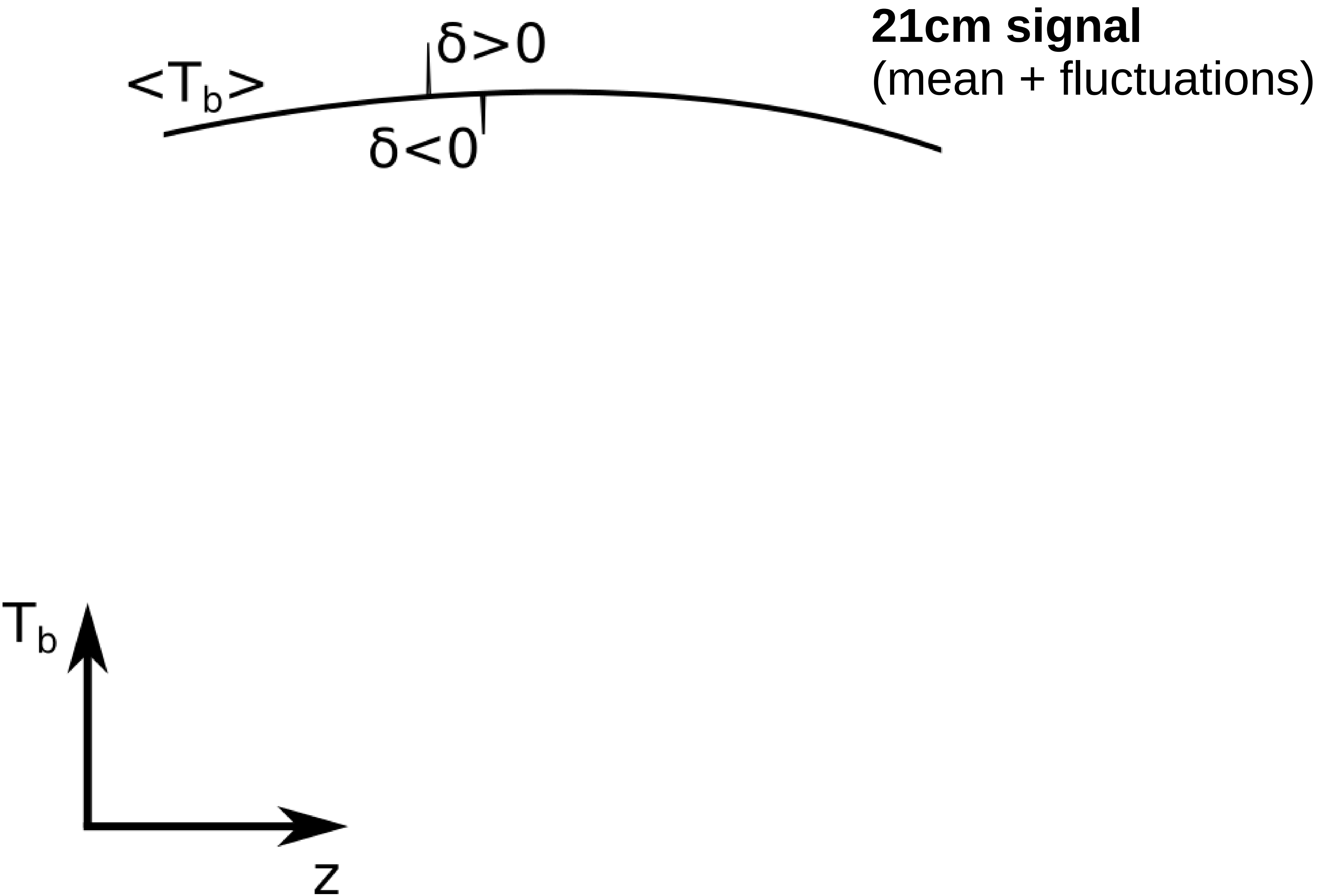
→ **Map out emission integrated over many galaxies**

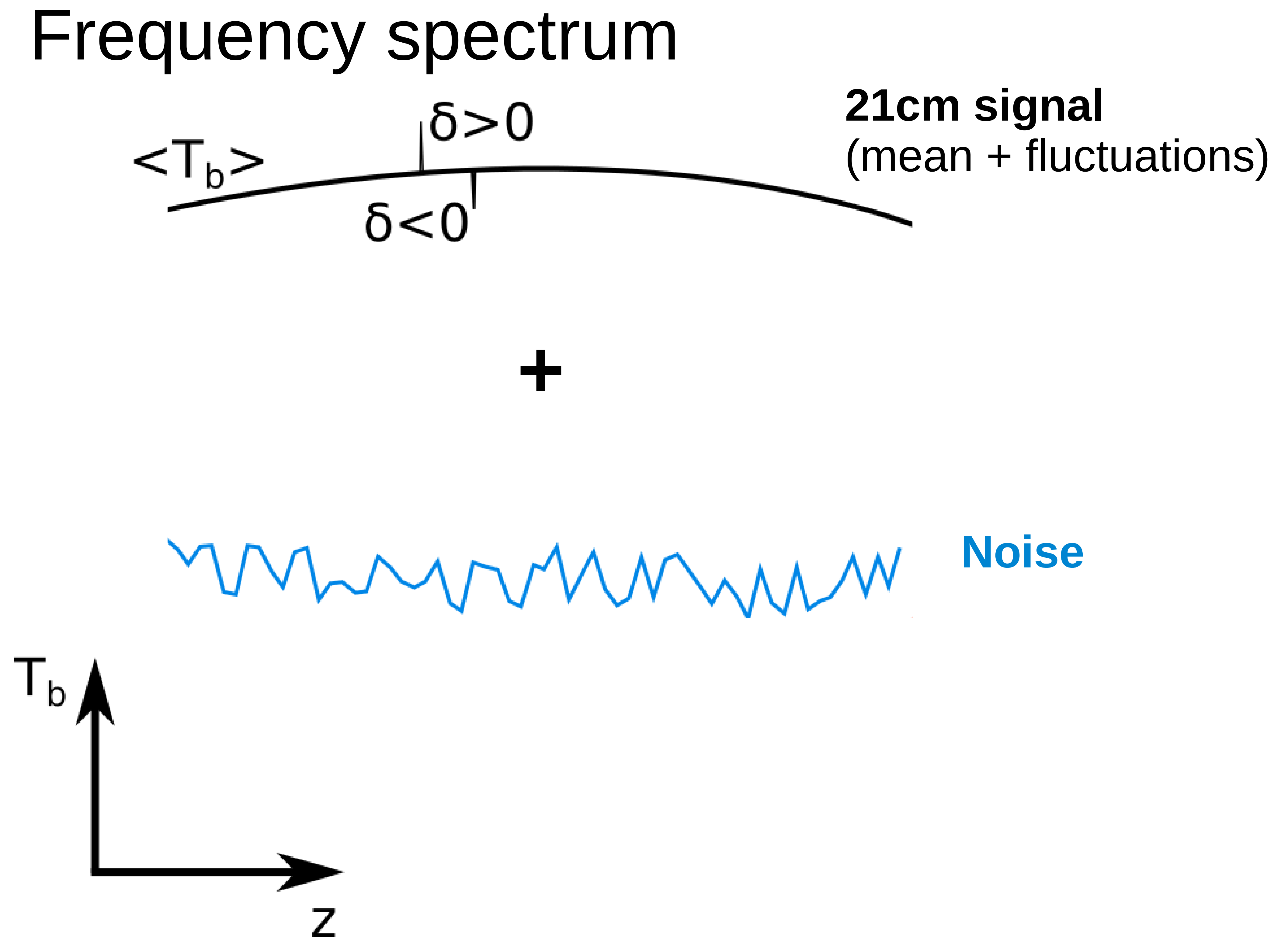
21cm intensity maps

- Low-resolution still preserves large-scales (c.f. CMB)
- Integrated emission is easier to detect / no thresholding
- Detecting an emission line → get redshifts for free

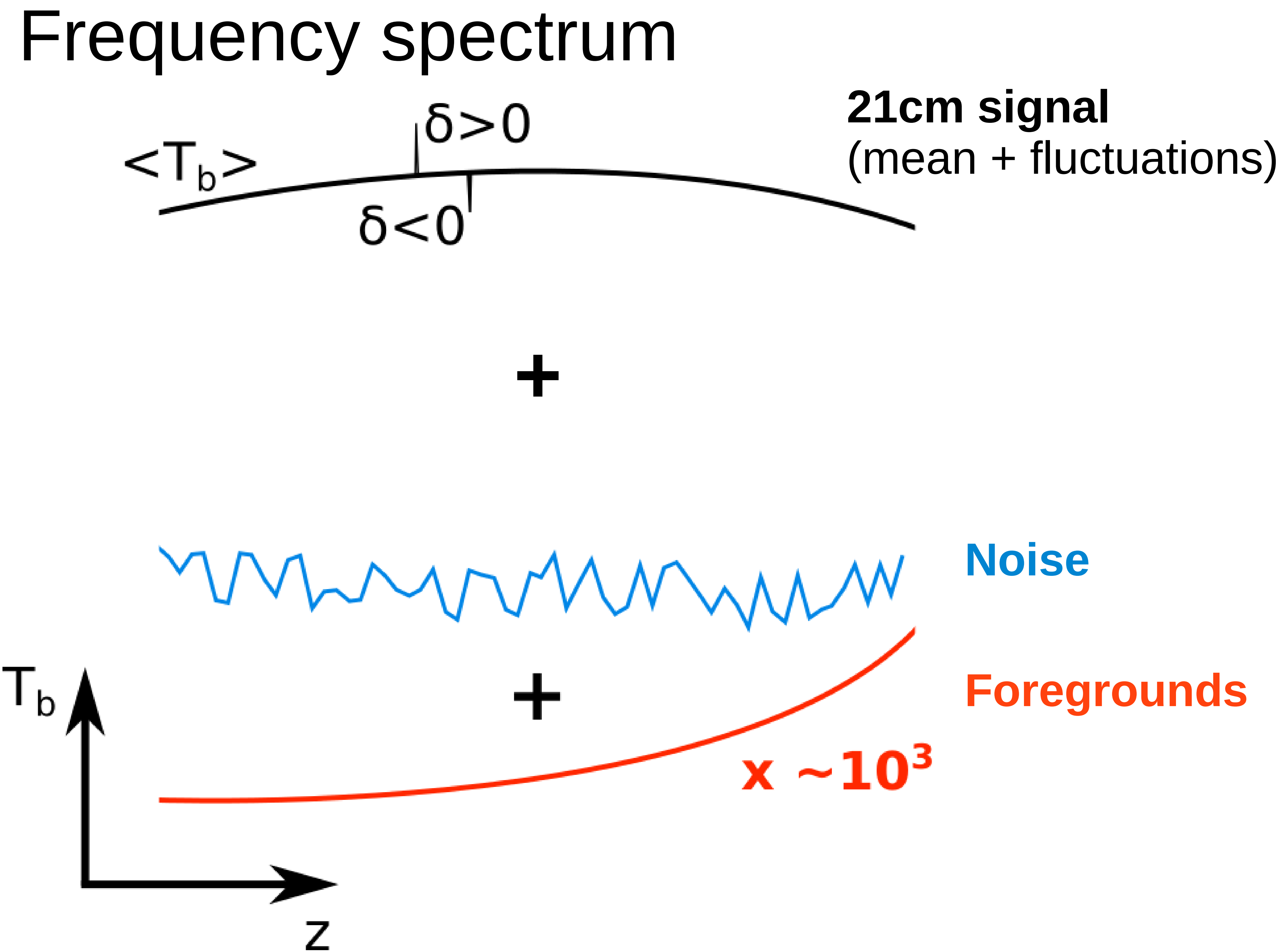
See **Bull** et al. (1405.1452) for a primer

Frequency spectrum





Frequency spectrum
21cm signal
(mean + fluctuations)
<Tb>
δ>0
δ<0
+
Noise
Tb
z



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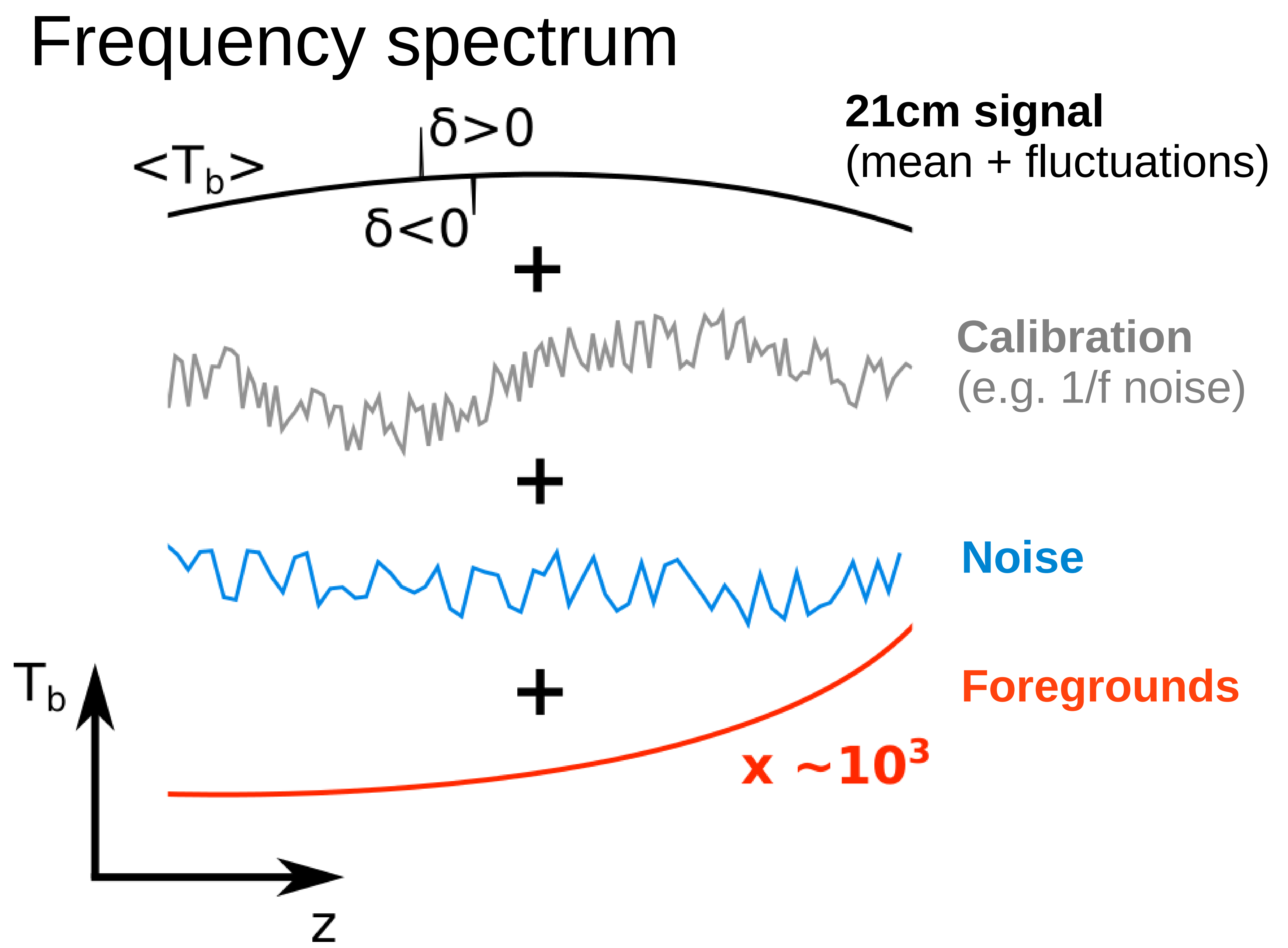
Foregrounds
x ~10³
Tb
z


Frequency spectrum
21cm signal
(mean + fluctuations)
<Tb>
δ>0
δ<0
+
Calibration
(e.g. 1/f noise)
+
Noise
+
Foregrounds
x ~10^3
Tb
z

21cm brightness temperature

Mean temperature of **all the HI** at a given redshift:

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

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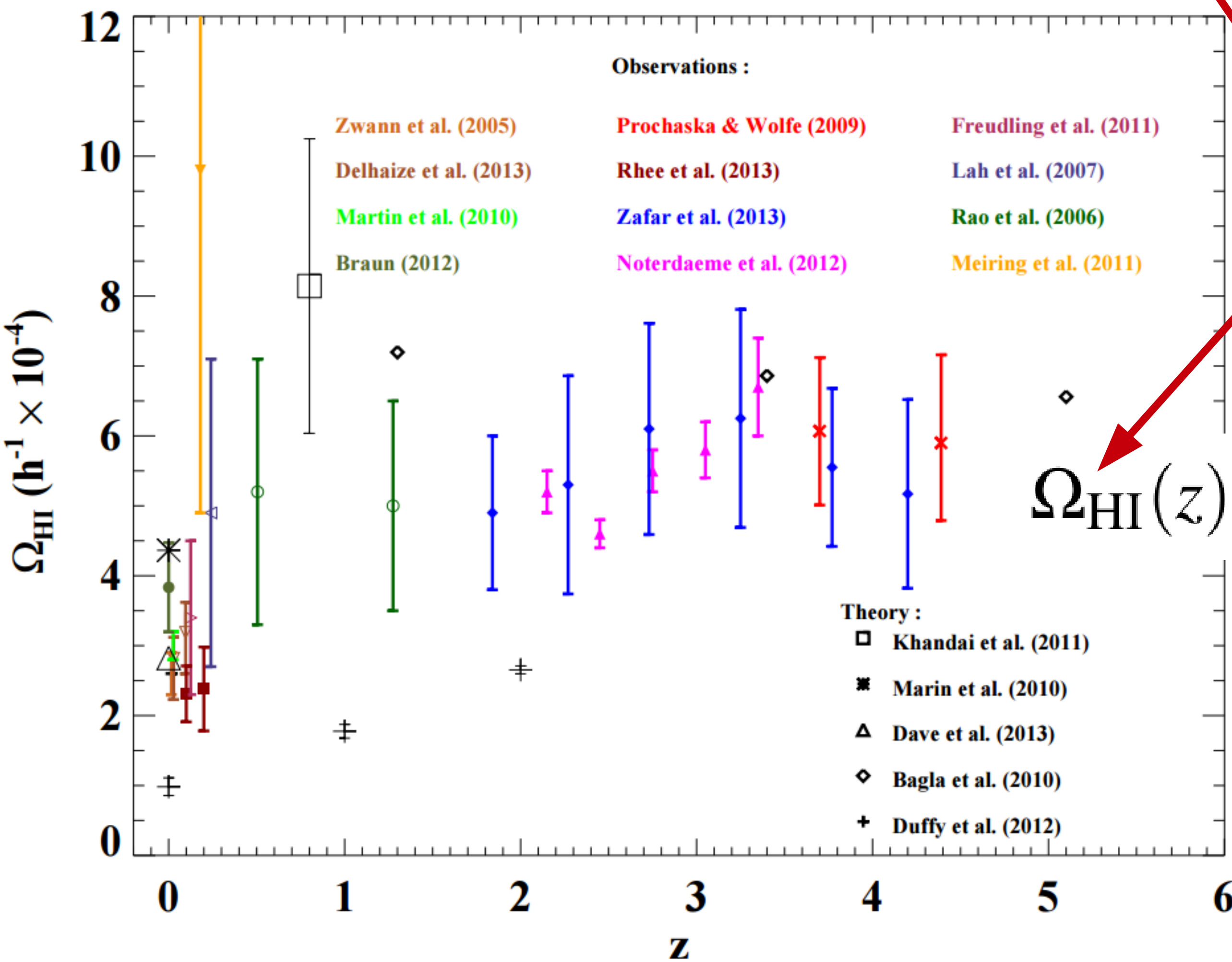

What fraction of the cosmic energy density is in neutral hydrogen?

$$\Omega_{\rm HI}(z) \equiv (1+z)^{-3}\rho_{\rm HI}(z)/\rho_{c,0}$$

H. Padmanabhan et al. 2015

21cm brightness temperature

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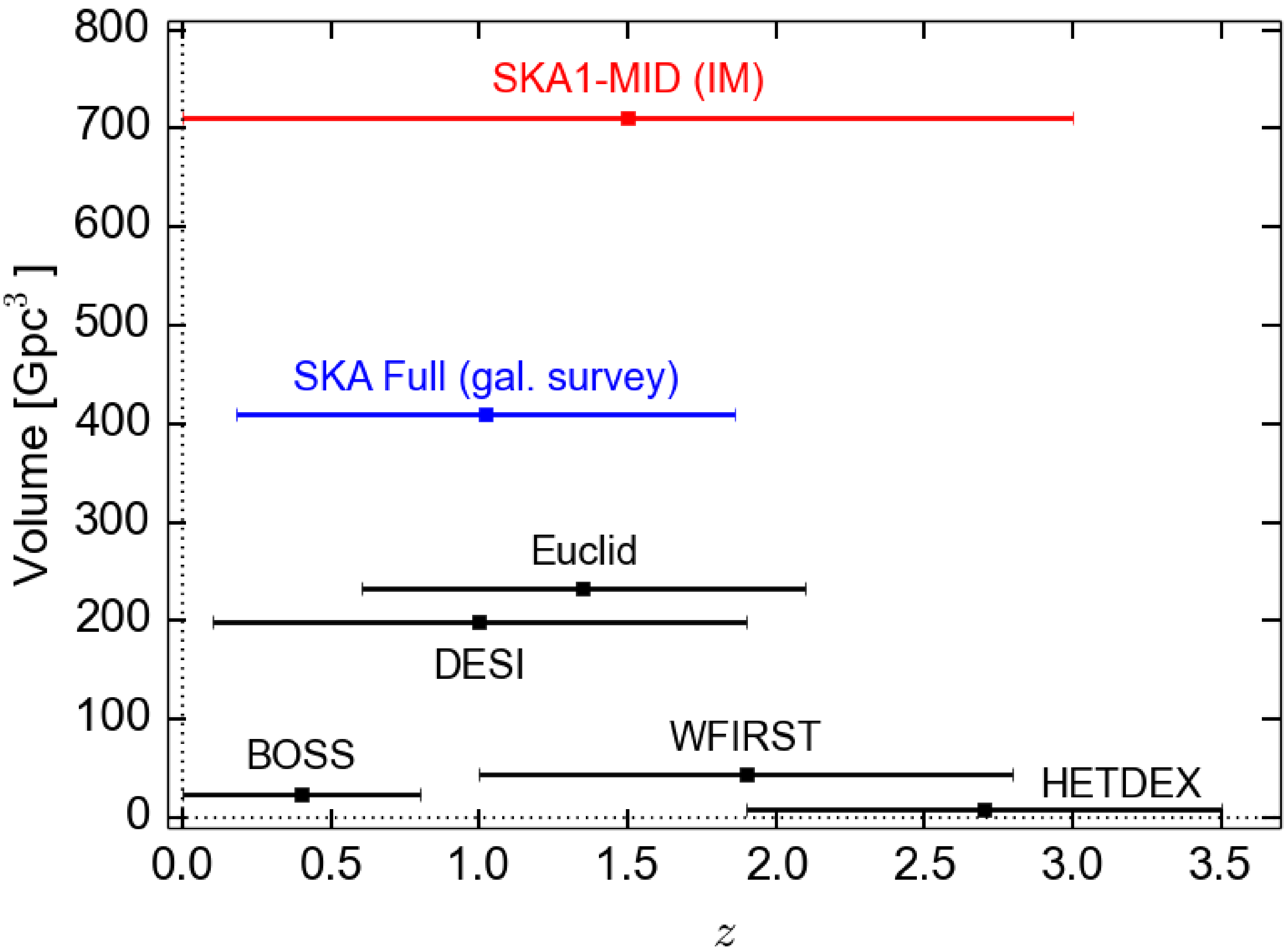
Temperature in a **volume element** at a given frequency/angle:

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

Volume

Intensity mapping is very fast → uses all the photons

Can survey much bigger volumes in the same time

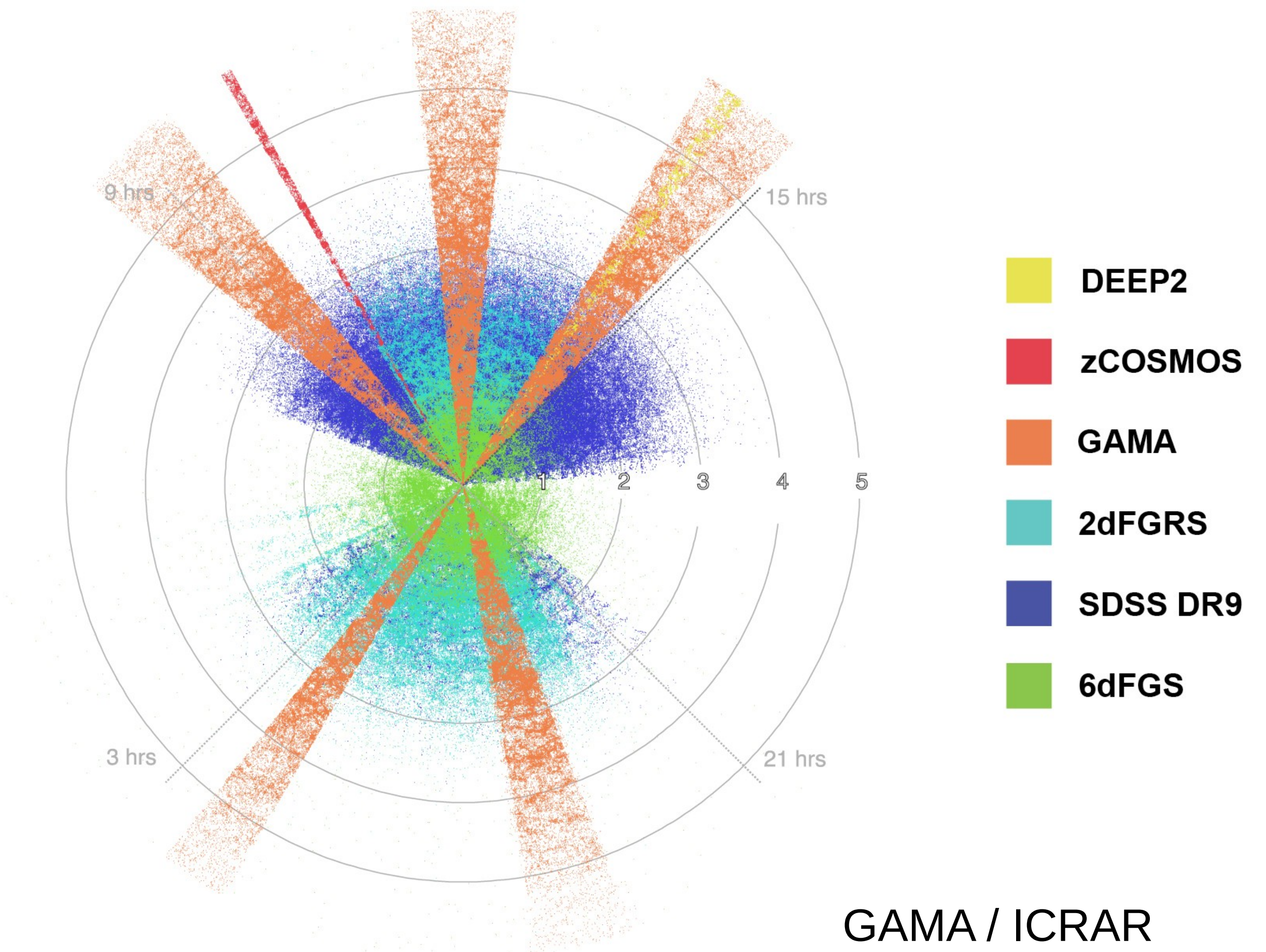


Designing an intensity mapping experiment

Designing an IM experiment

Sensitivity; depth vs. width

- Signal is faint; need high sensitivity to detect it
- Small survey area = greater depth; more time per pointing
- Large survey area = shallower, but can cover larger volume



GAMA / ICRAR

Designing an IM experiment

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- Signal is faint; need high sensitivity to detect it
- Small survey area = greater depth; more time per pointing
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Resolution

- Match the resolution to the scales you care about!
- Big dishes = small field of view. More sensitive but slower surveys
- Interferometers: which Fourier modes? Sparse or dense?

Designing an IM experiment

Frequency range

- Frequency range maps directly to redshift range
- Which redshifts matter for the physics you are targeting?
- Wide bandwidths are possible with radio, but receivers get worse if it’s too wide (need *multi-mode* receivers)

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Systematic effects!

- Foregrounds are much bigger than the signal
- Small instabilities in the receiver / beam / calibration can mix a small fraction of foregrounds into the signal
- Need a very stable receiver, or one that's easy to calibrate!

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$$$

- Radio receivers are (relatively) cheap, but people and electricity are not
- Can you justify spending €1 billion? €100m? €10m?

Single dish or interferometer?

We can use the SKA in single-dish *or* interferometer mode
→ depends on which **angular scales** we care about!

Single-dish (also called autocorrelation)

$$\delta\theta \gtrsim \frac{\lambda}{D_{\rm dish}}$$

(Can see angular scales larger than this size)

Interferometer

$$\frac{\lambda}{D_{\rm min}} \gtrsim \delta\theta \gtrsim \frac{\lambda}{D_{\rm max}}$$

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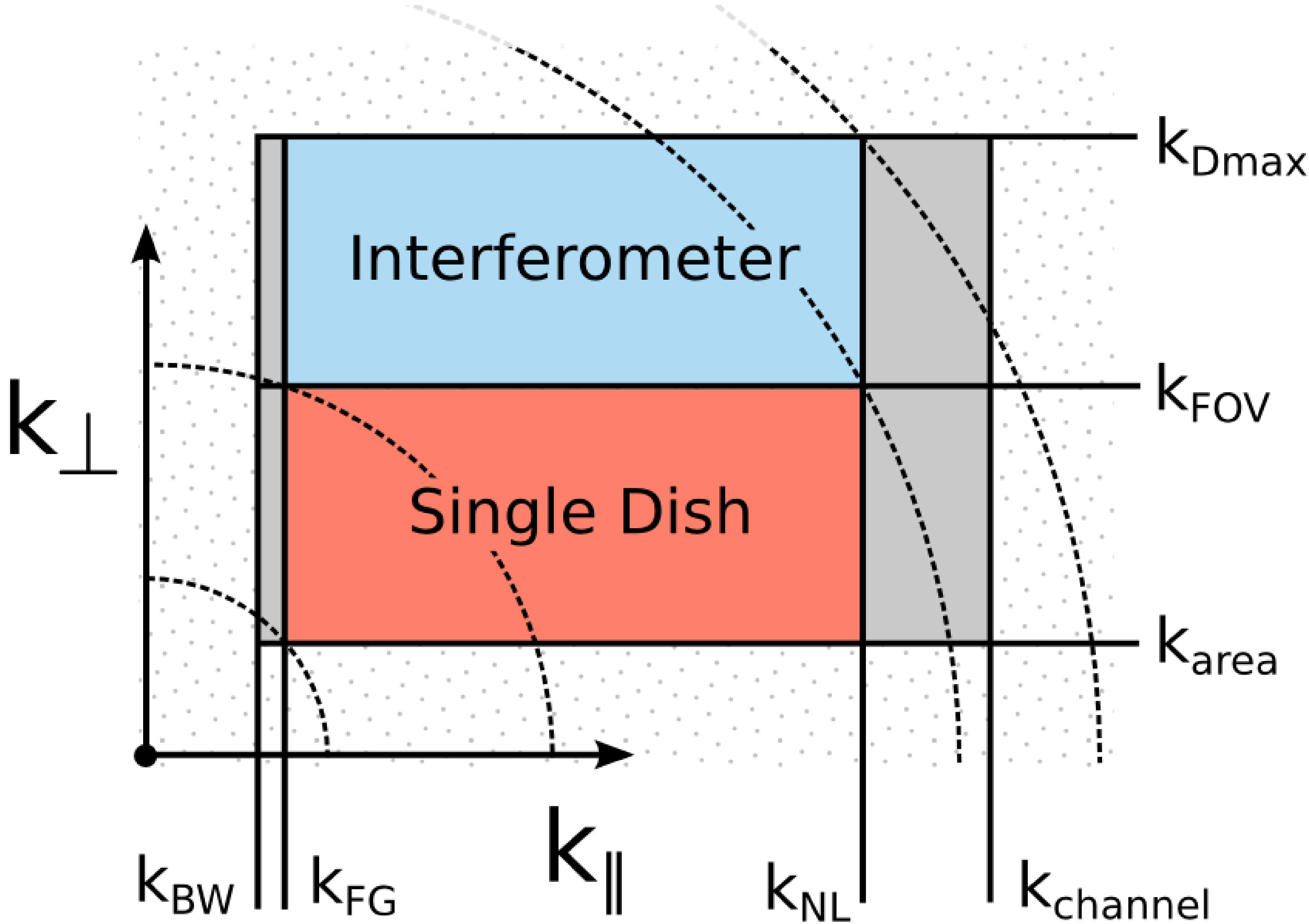
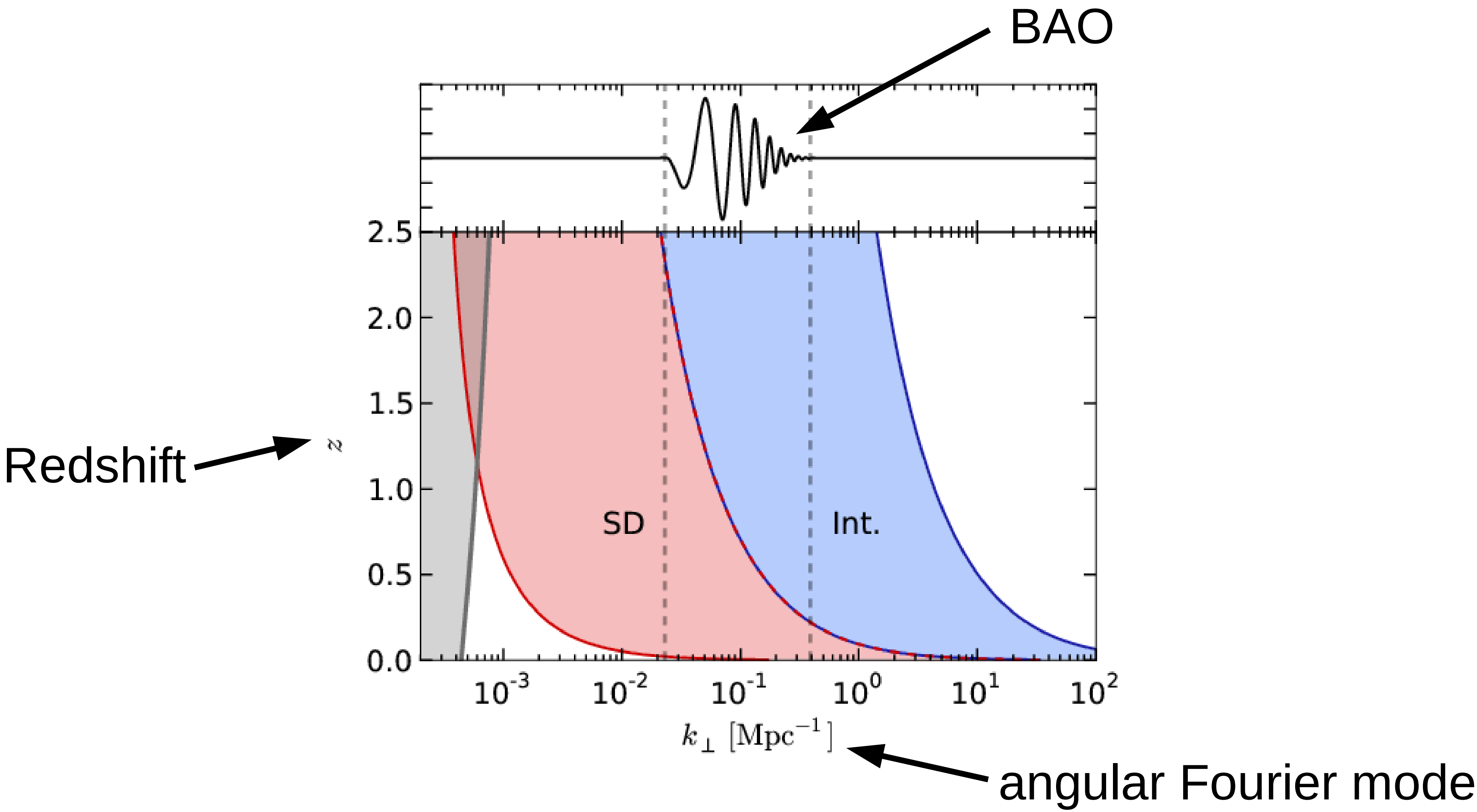


Baryon acoustic oscillations

If we want to measure the BAO with the SKA, which mode is better?

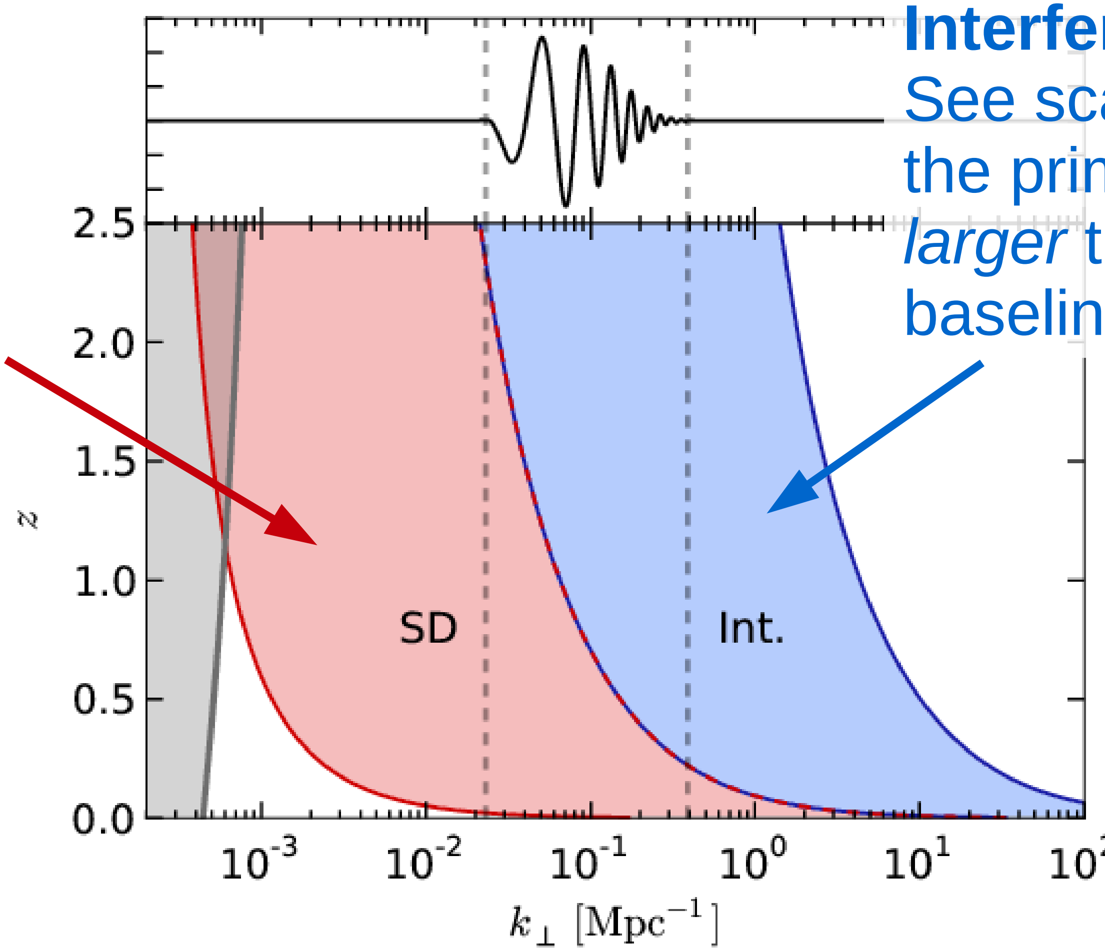


Baryon acoustic oscillations

If we want to measure the BAO with the SKA, which mode is better?

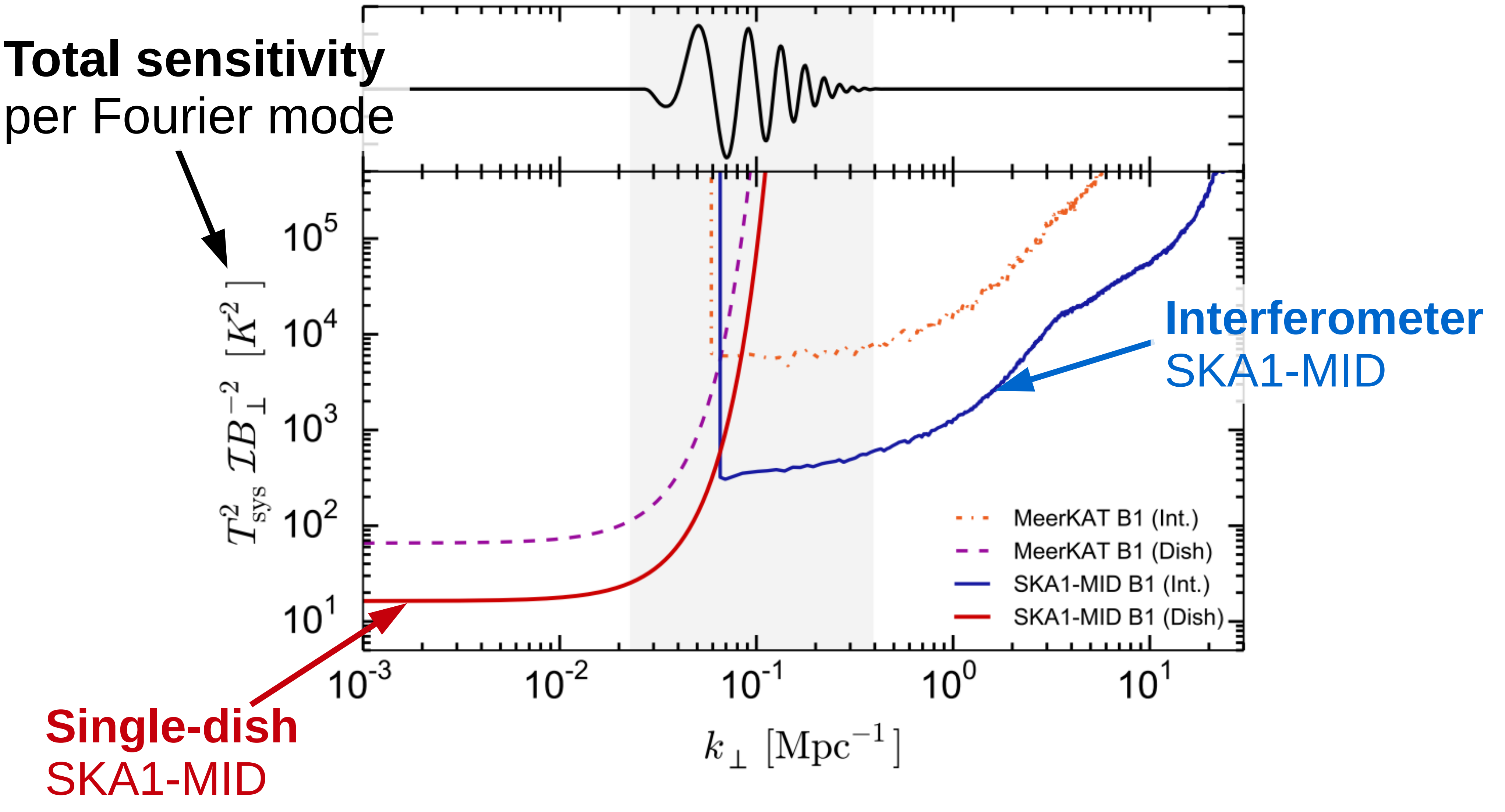
Single-dish
See all scales larger than the beam

Interferometer
See scales *smaller* than the primary beam, but *larger* than the max. baseline



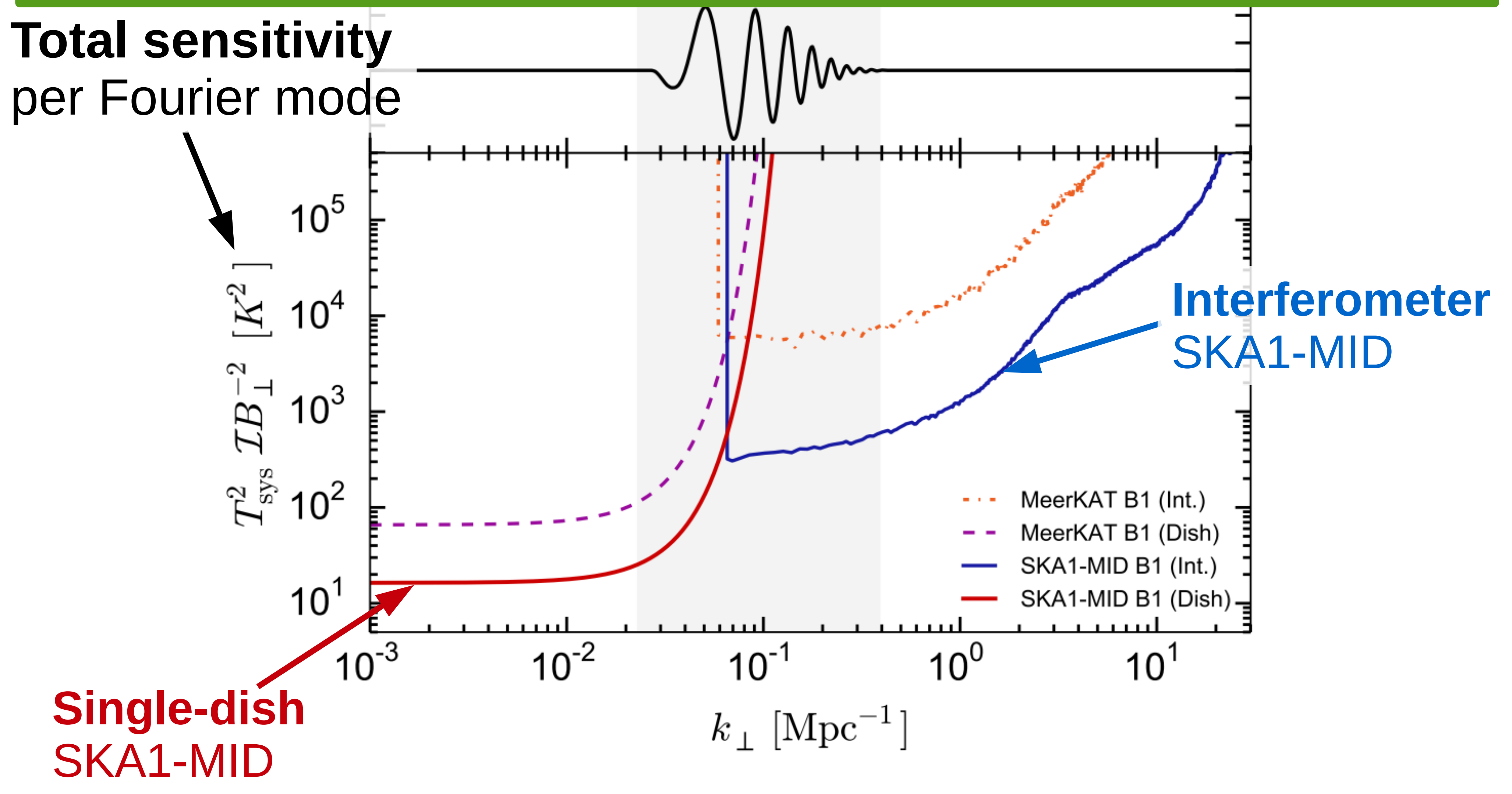
Relative sensitivity

Interferometers are typically less sensitive than single-dish



Relative sensitivity

SKA is too sparse for intensity mapping
In interferometer mode



Single-dish mode is harder to calibrate (1/f noise)

Better to use a **dense interferometer array**

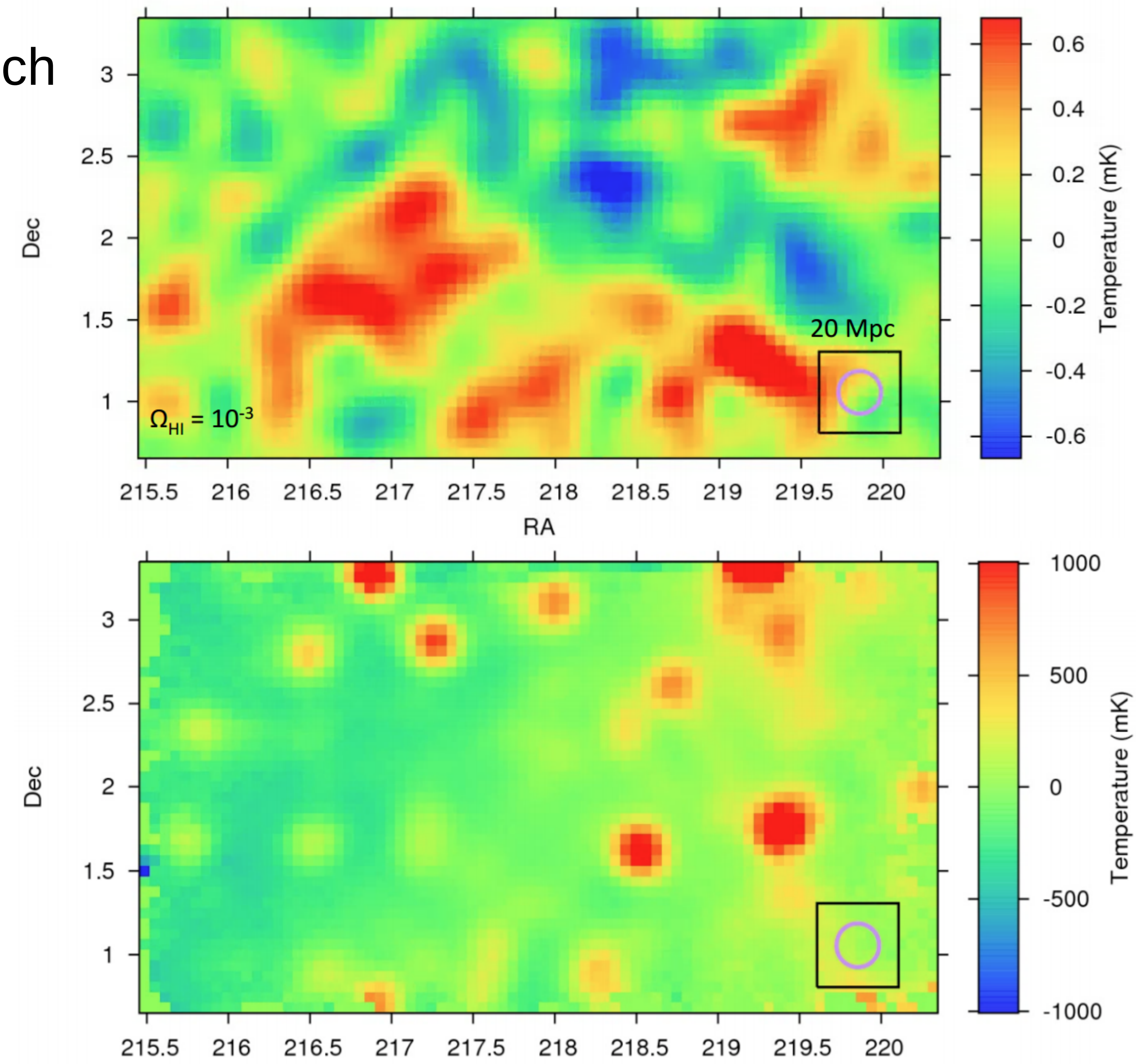
HIRAX / J. Sievers

CHIME

Foreground contamination

Foreground contamination

Our galaxy is much brighter than the 21cm signal



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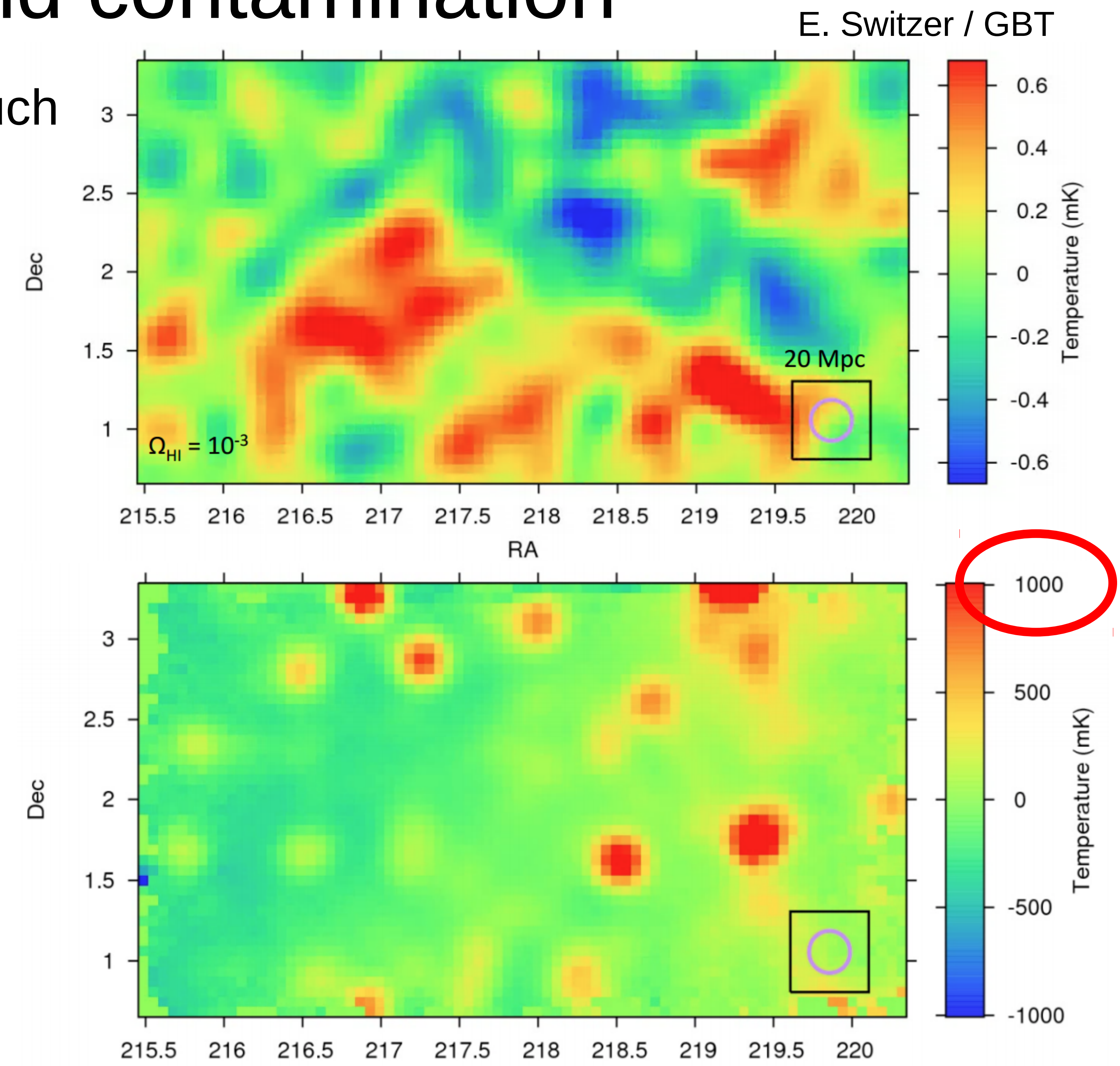
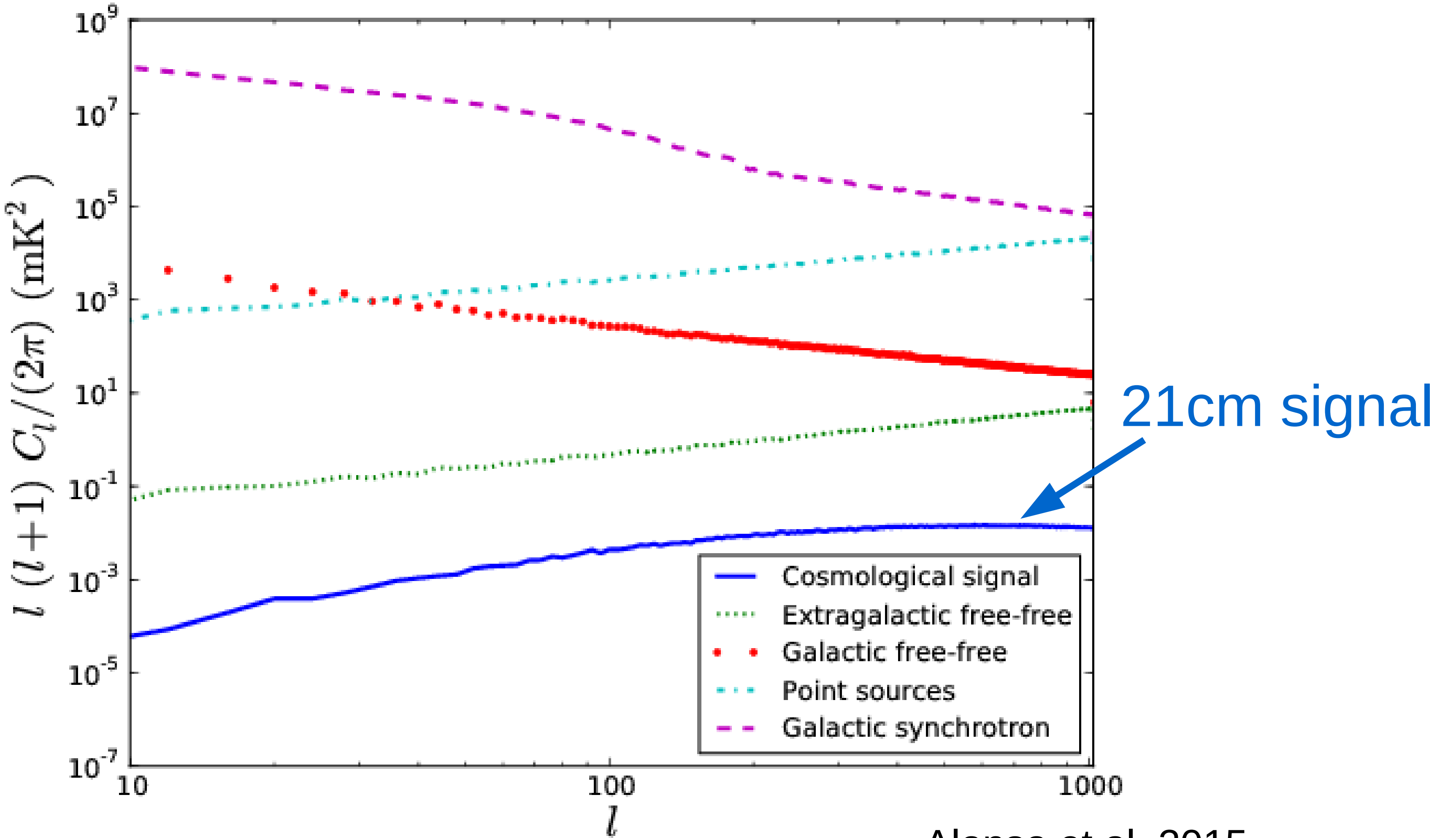


Foreground contamination

Foregrounds dominate, but are **smooth** in frequency/angle?

Example foreground angular power spectra from simulations:



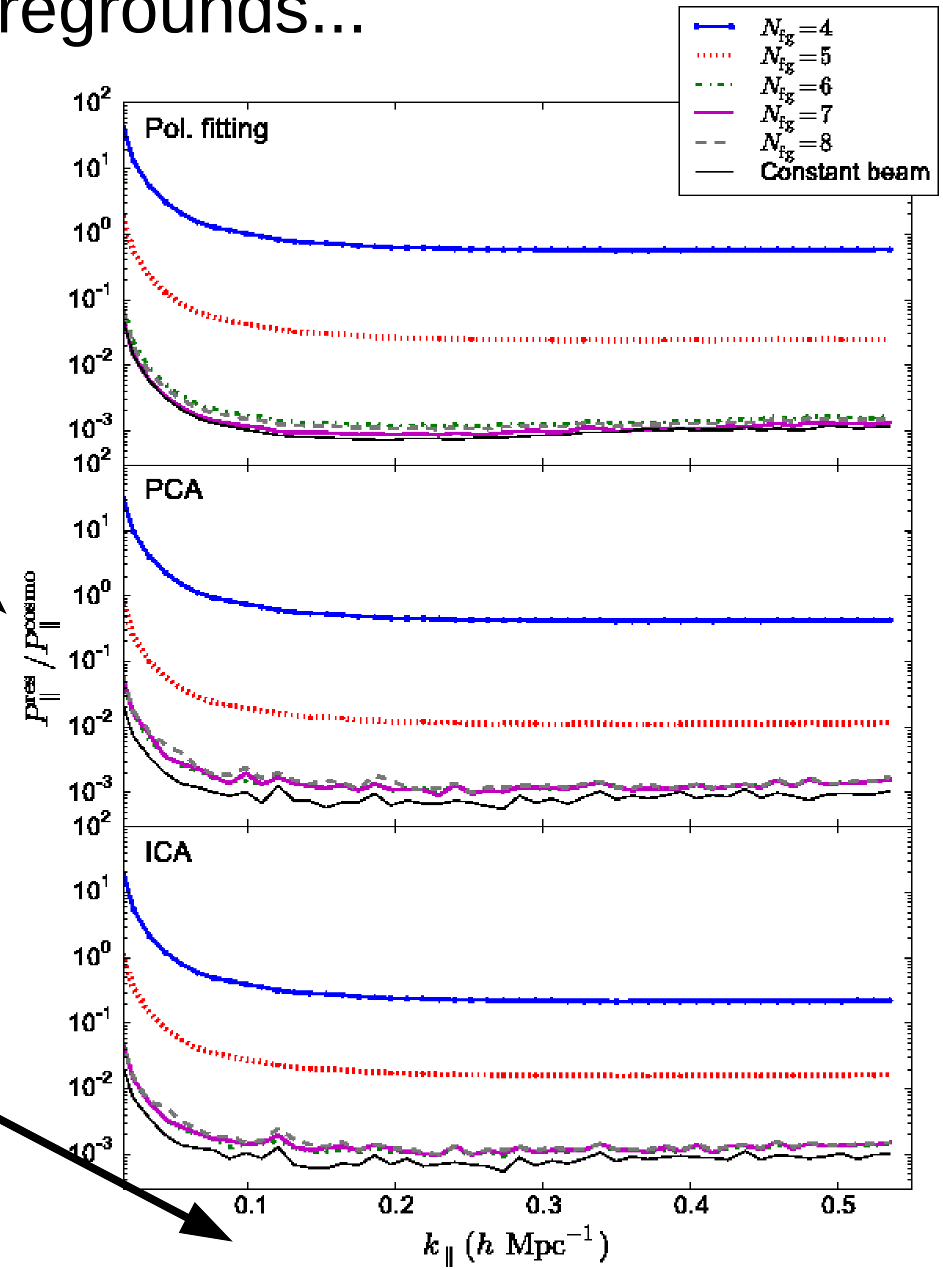
Alonso et al. 2015

Foreground contamination

Subtracting a few smooth (long-wavelength Fourier) modes should subtract most of the foregrounds...

Left-over foregrounds as a fraction of the 21cm signal

Fourier wavenumber in parallel (frequency) direction

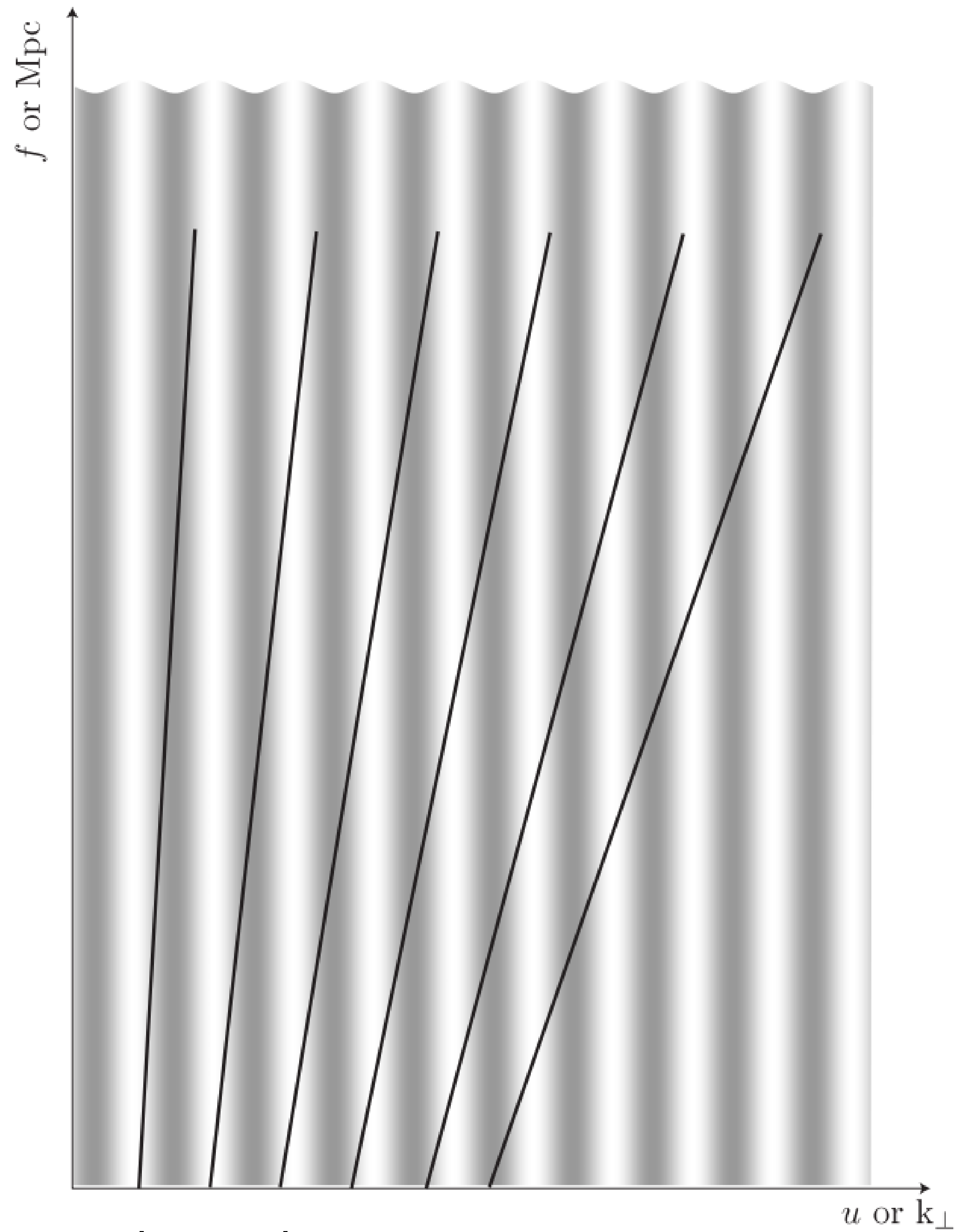


Alonso et al. 2015

Foreground wedge

Interferometers are intrinsically chromatic → sample different Fourier modes at different frequencies

We **pixelise** the Fourier plane (necessary for analysis)



Morales et al. 2012

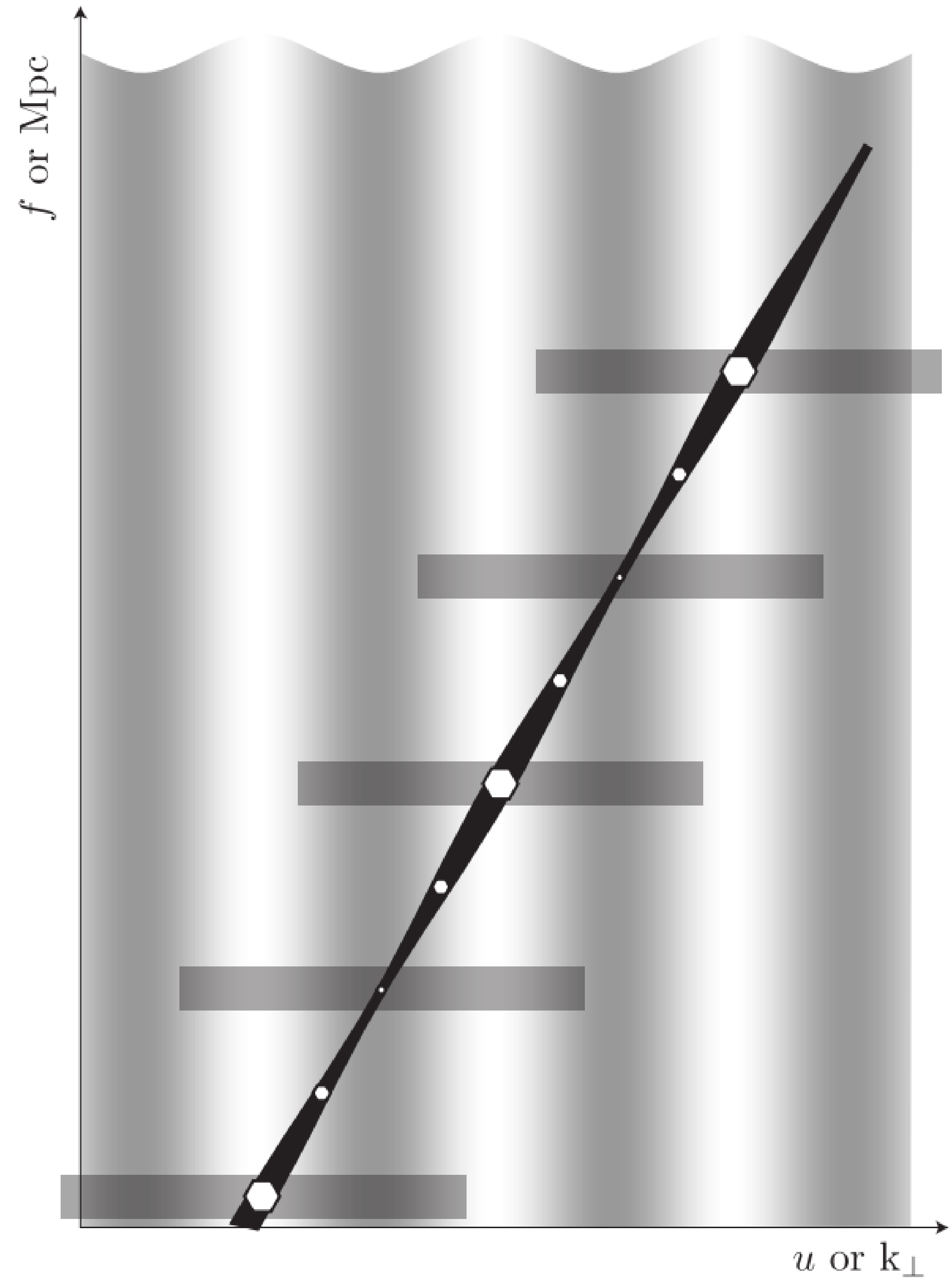
Foreground wedge

Interferometers are intrinsically chromatic → sample different Fourier modes at different frequencies

We **pixelise** the Fourier plane (necessary for analysis)

This loses some information
→ leads to coupling between angular & frequency modes

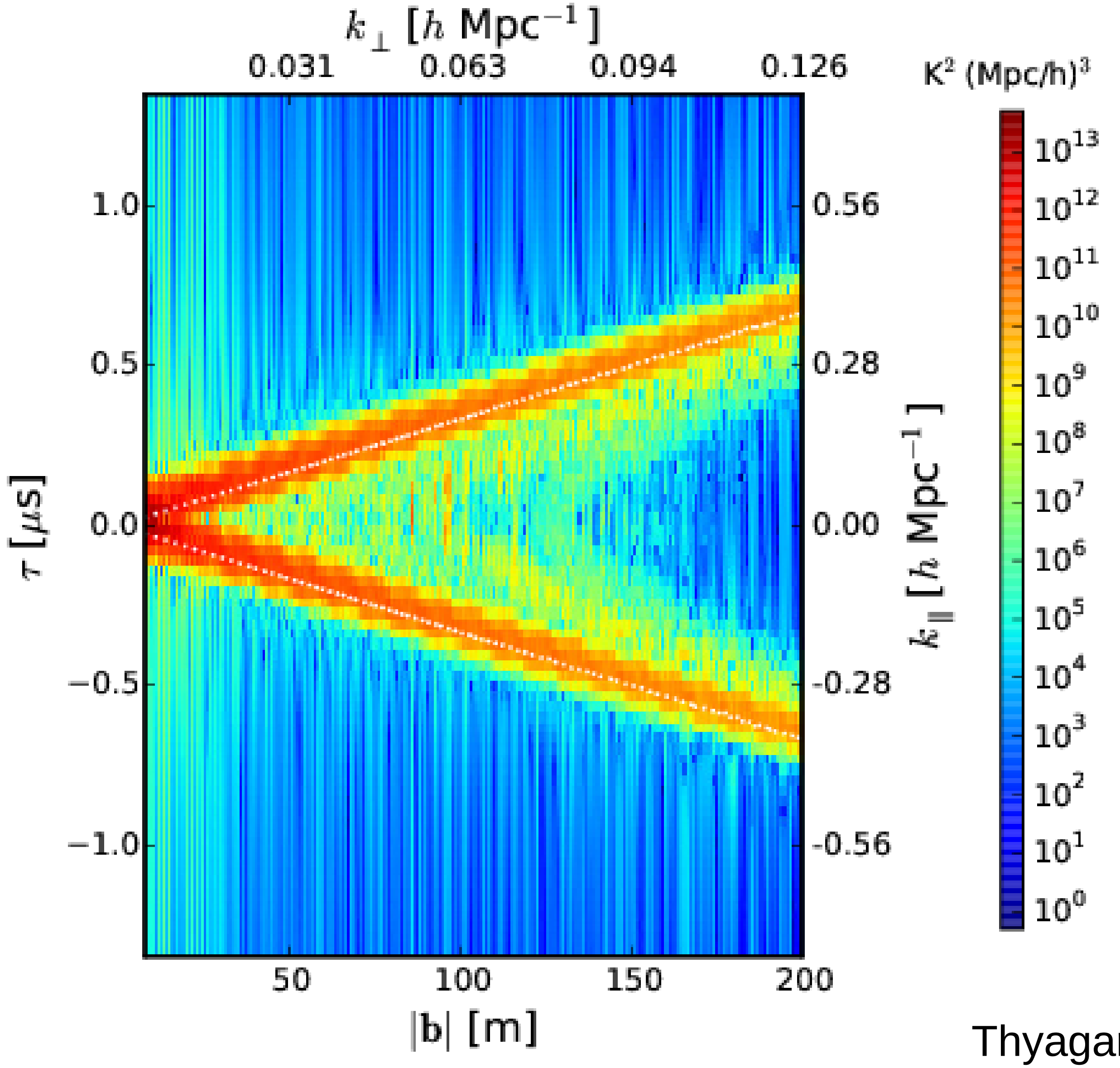
Frequency structure of foregrounds is connected to small-scale angular modes!



Morales et al. 2012

Foreground wedge

Some Fourier modes are completely spoiled by the bright foregrounds

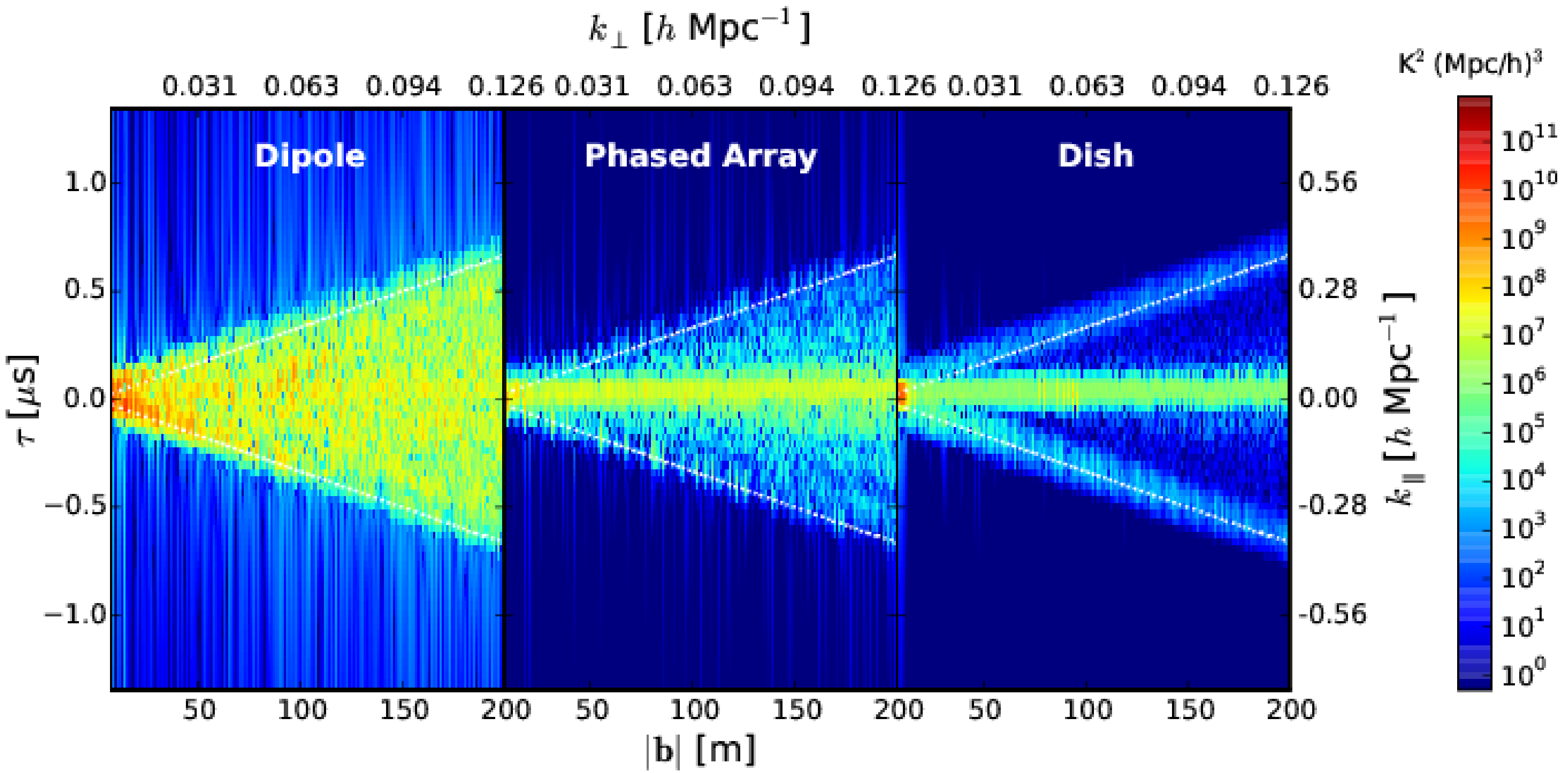


Thyagarajan et al. 2015

Foreground wedge

Some Fourier modes are completely spoiled by the bright foregrounds

Information lost in pixelisation depends in part on the primary beam



Thyagarajan et al. 2015

Polarisation leakage

Polarised emission: angle of polarisation rotates as it passes through ionised gas → **Faraday rotation** effect

$$\alpha = \alpha_0 + \lambda^2 \, \psi(\boldsymbol{r}) \qquad \psi(\boldsymbol{r}) = \frac{e^3}{2\pi (m_e c^2)^2} \int_0^r dr' n_e(\boldsymbol{r}') B_{\parallel}(\boldsymbol{r}')$$

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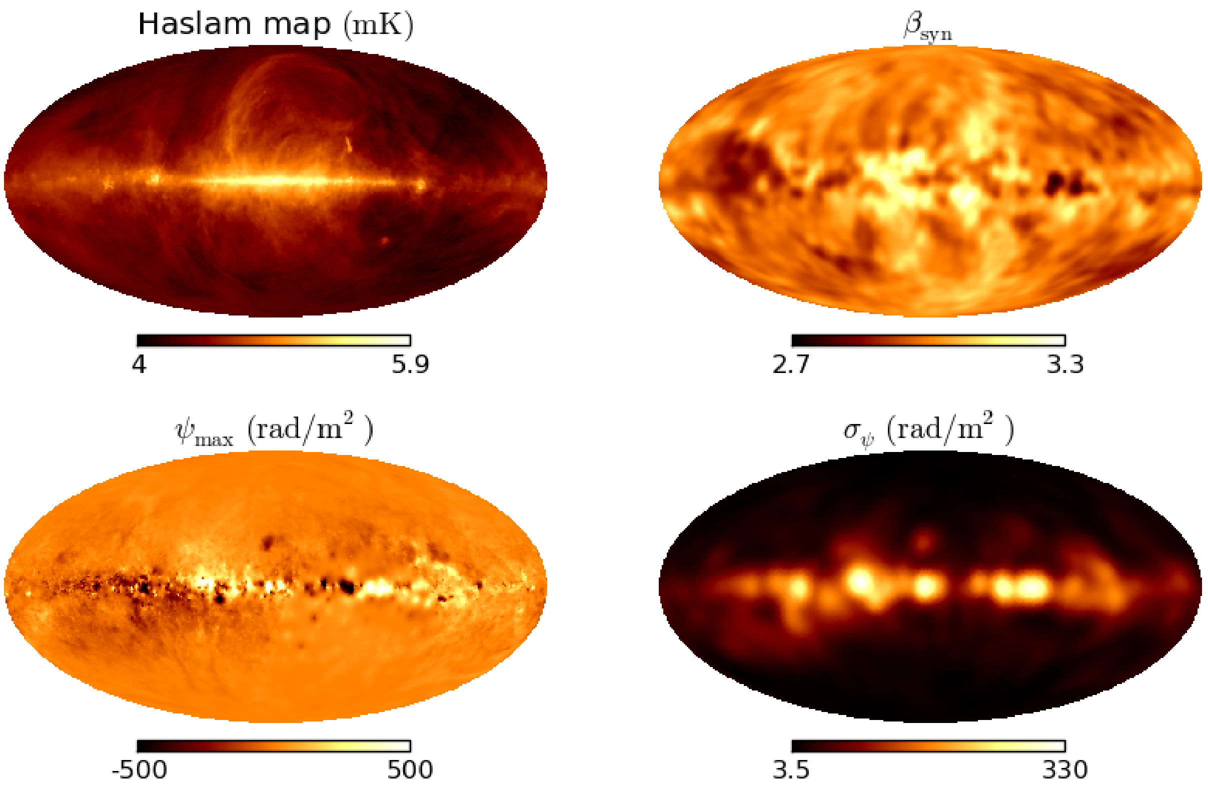
Frequency-dependent: **smooth** spectra gain extra **structure**

Rotation happens faster at longer wavelengths → worse at low freq.

More rotation near the galactic plane



Alonso et al. 2014

Polarisation leakage

Radio telescopes can’t perfectly separate different polarisations

→ Polarised emission **leaks** into observed total intensity signal

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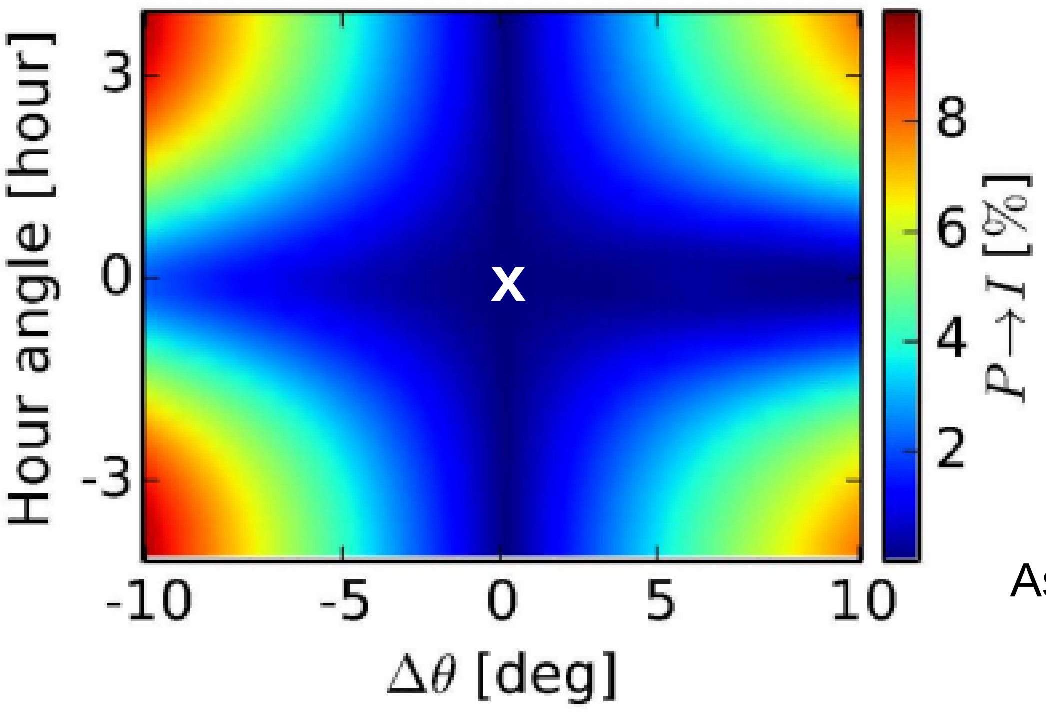
Leakage is worse around the edges of the beam



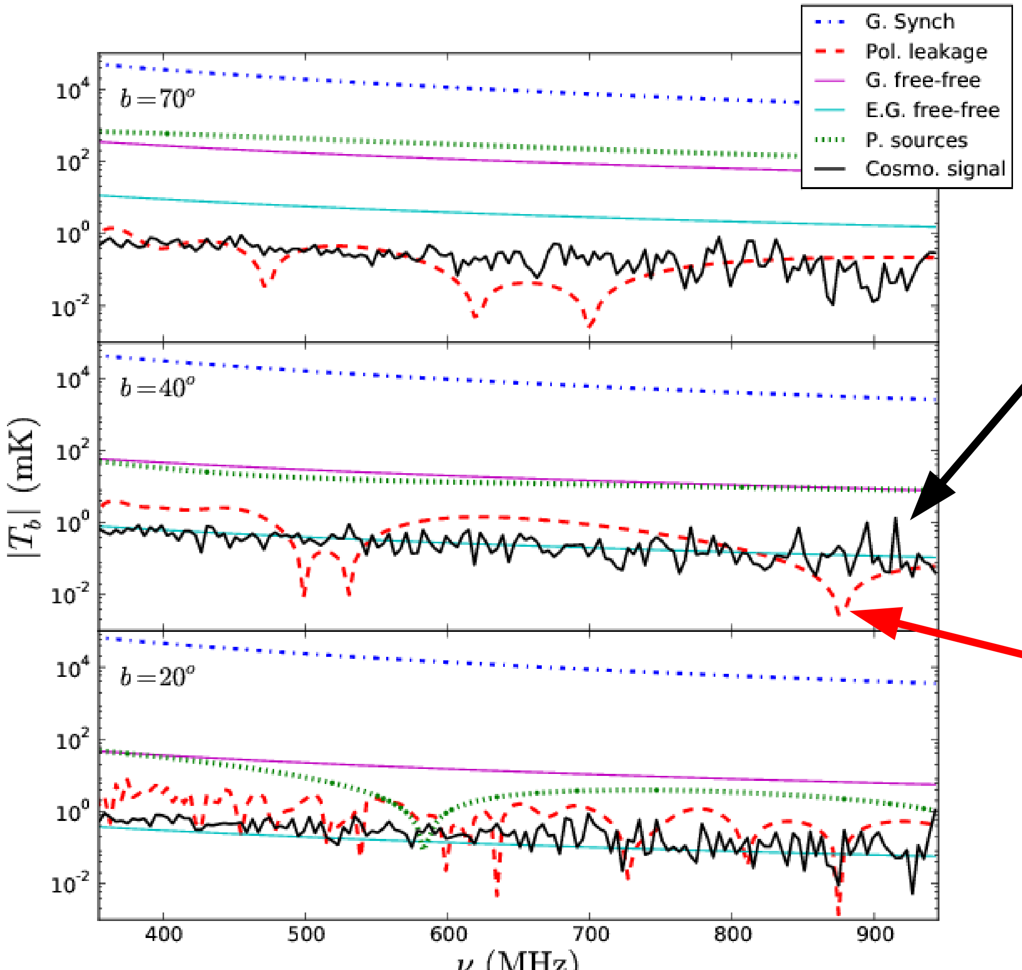
Asad et al. 2015

Complicated signal: Depends on frequency, polarisation angle of source, position on the sky, orientation of the radio receiver...

Polarisation leakage

Polarised foregrounds are fainter than total intensity ones **but** have extra spectral structure due to **Faraday rotation**

Much harder to separate from the cosmological signal!



Cosmological signal

Polarisation leakage

Alonso et al. 2014

Open questions and the future of radio cosmology

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  (intrinsic alignment, deblending, multi-tracer)

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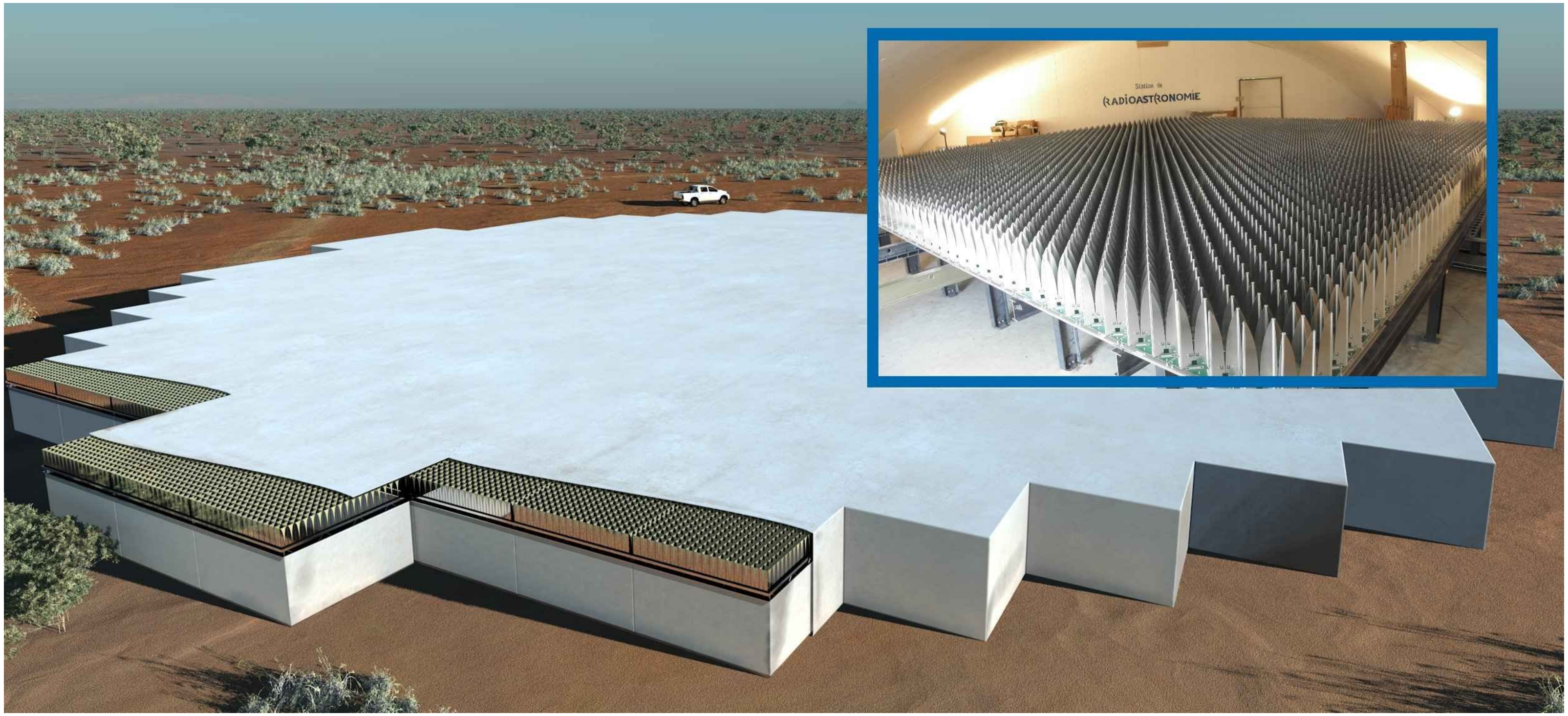
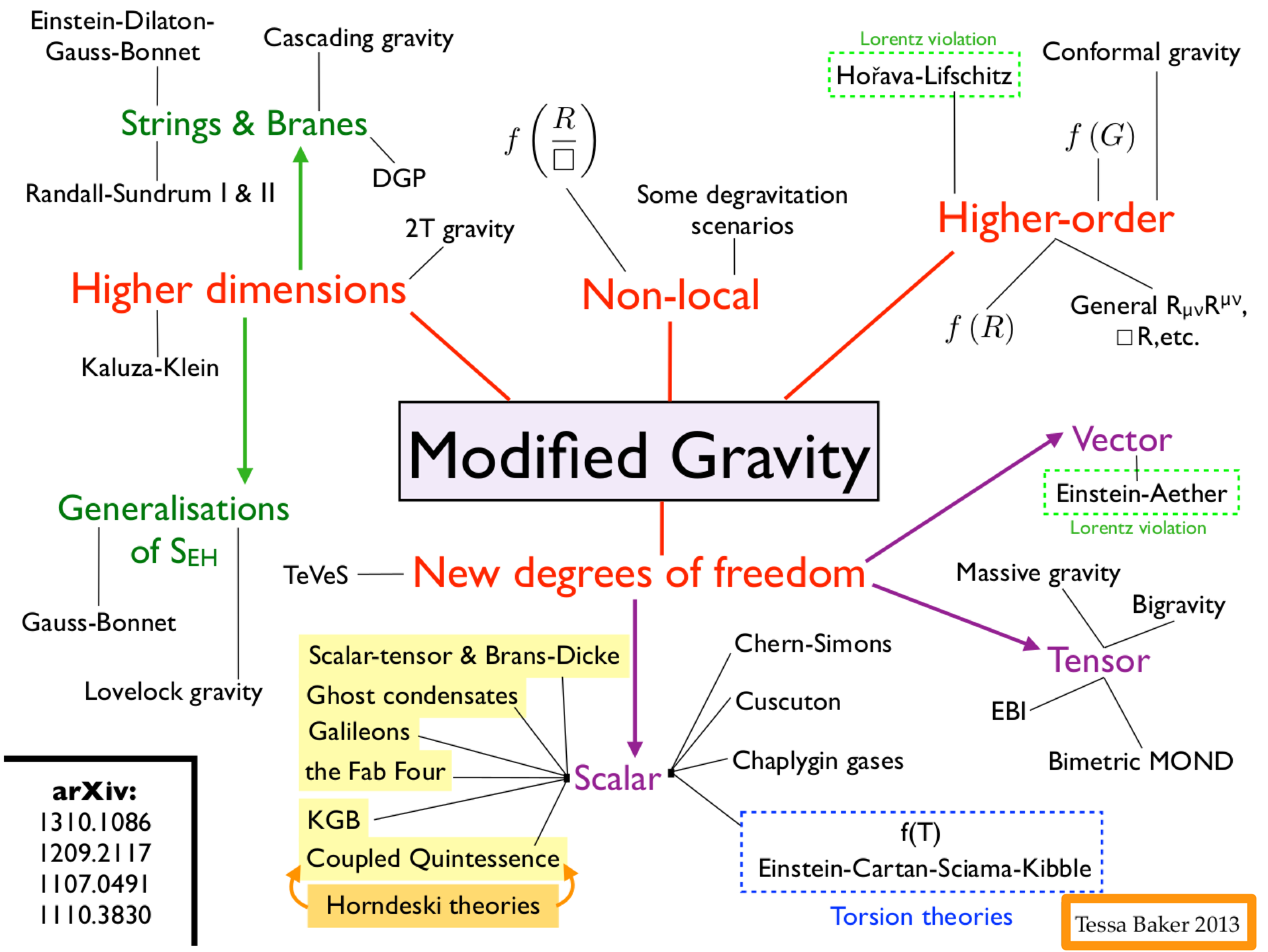
- Can radio + optical/IR surveys work better together? (intrinsic alignment, deblending, multi-tracer)
- Can we handle IM foregrounds well enough?
- What are FRBs?
- Can we trust intensity maps? (cross-correlation)
- What is the most useful thing we can do to solve dark energy / gravity / etc. problems?

The future of radio cosmology

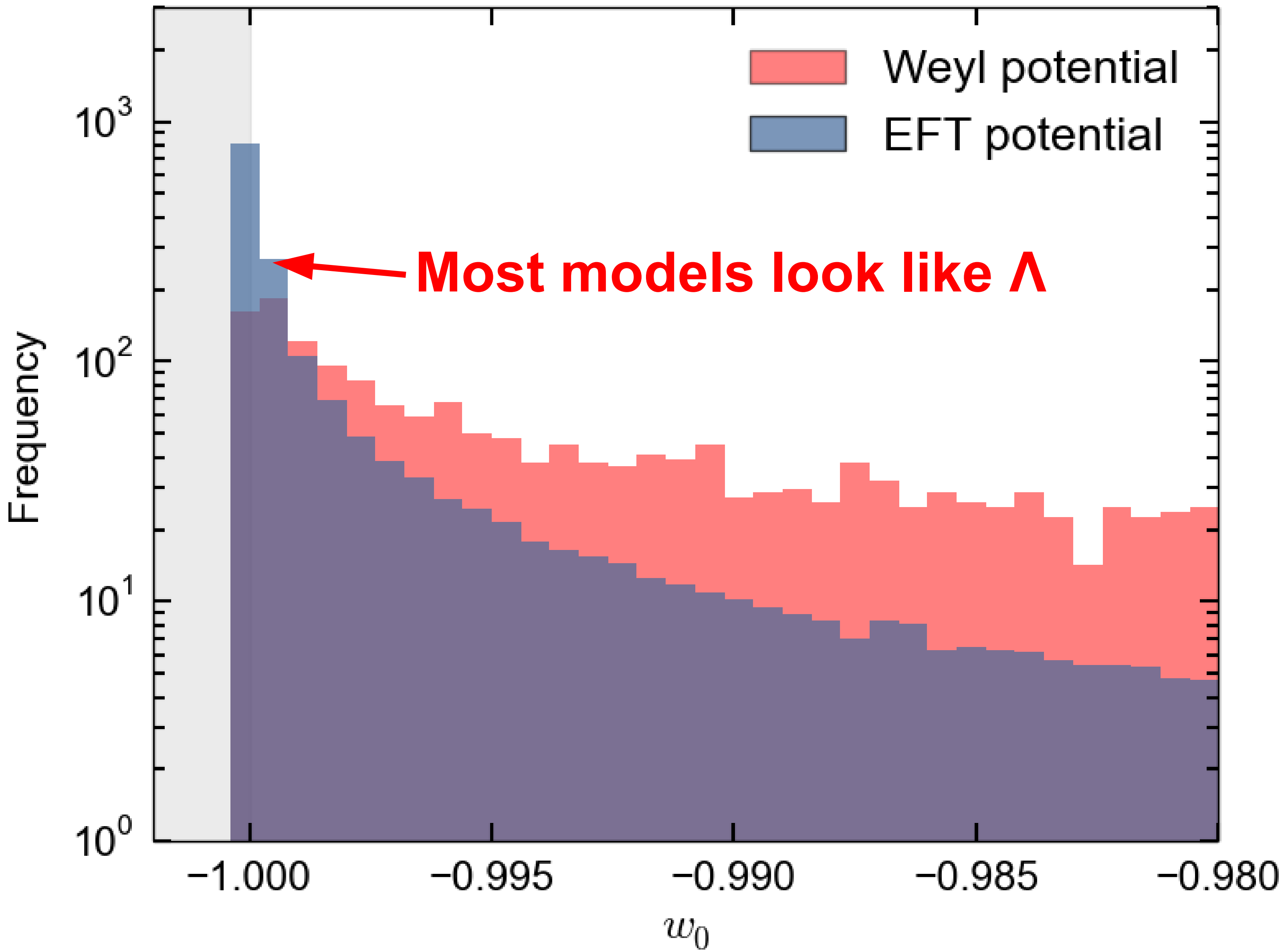
- Epoch of Reionisation / dark ages → go to the Moon!
- Dense aperture arrays (MFAA/SKA2)
- The Cosmic Atlas (21cm map of the entire Universe!)
- Second-order effects (polarised 21cm, IM lensing)



SKA2 / MFAA / EMBRACE


Einstein-Dilaton-Gauss-Bonnet
Cascading gravity
Strings & Branes
DGP
Randall-Sundrum I & II
2T gravity
Higher dimensions
Kaluza-Klein
Generalisations of S_{EH}
Gauss-Bonnet
Lovelock gravity
$f\left(\frac{R}{\Box}\right)$
Some degravitation scenarios
Non-local
Lorentz violation
Hořava-Lifschitz
Conformal gravity
$f(G)$
Higher-order
$f(R)$
General $R_{\mu\nu}R^{\mu\nu}$, $\Box R$, etc.
Modified Gravity
Vector
Einstein-Aether
Lorentz violation
TeVeS
New degrees of freedom
Massive gravity
Bigravity
Tensor
EBI
Bimetric MOND
Scalar-tensor & Brans-Dicke
Ghost condensates
Galileons
the Fab Four
KGB
Coupled Quintessence
Horndeski theories
Scalar
Chern-Simons
Cuscuton
Chaplygin gases
f(T)
Einstein-Cartan-Sciama-Kibble
Torsion theories
arXiv:
1310.1086
1209.2117
1107.0491
1110.3830
Tessa Baker 2013

A priori predictions for **w** from a specific class of theories
(Here: quintessence)



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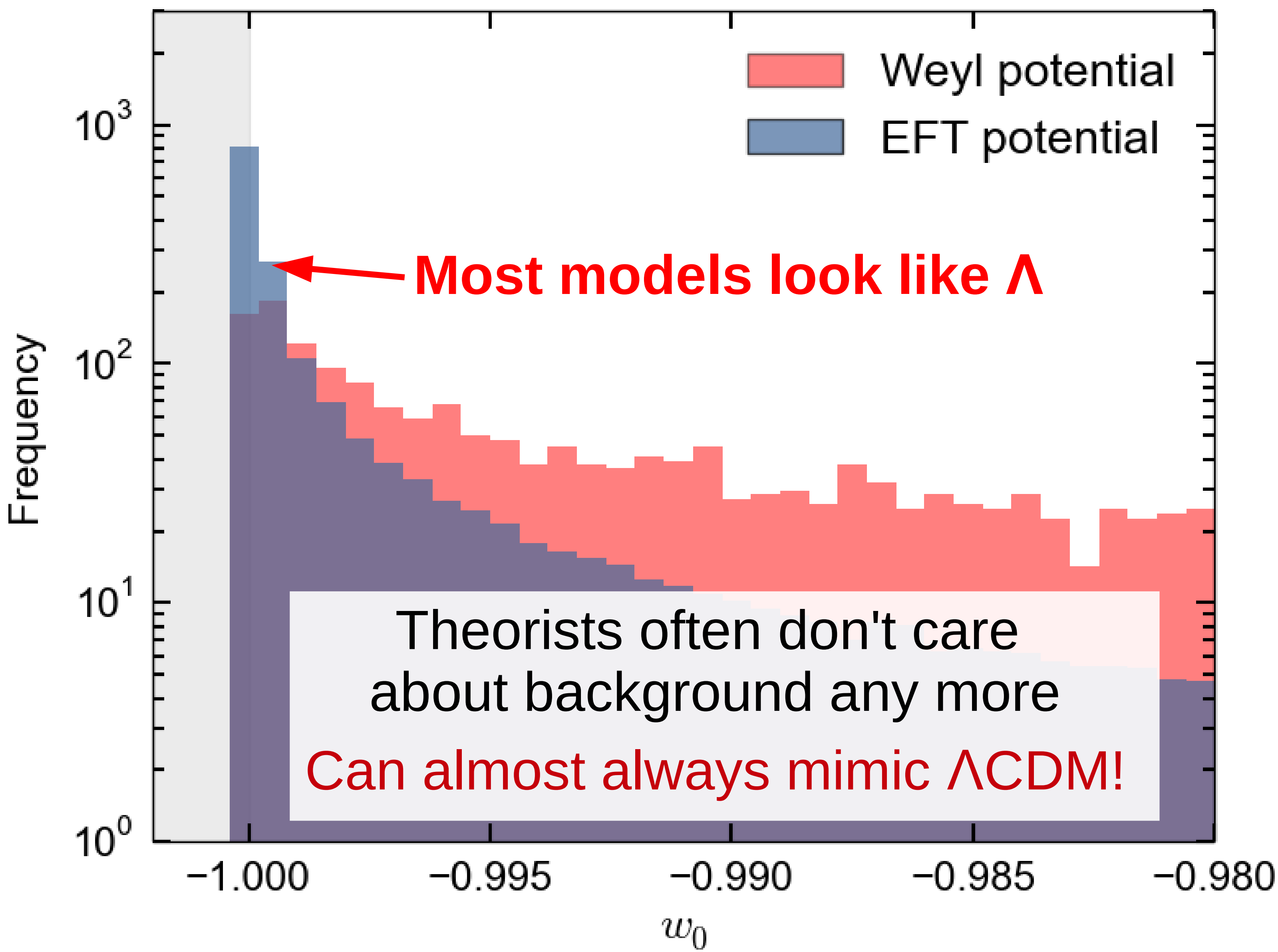
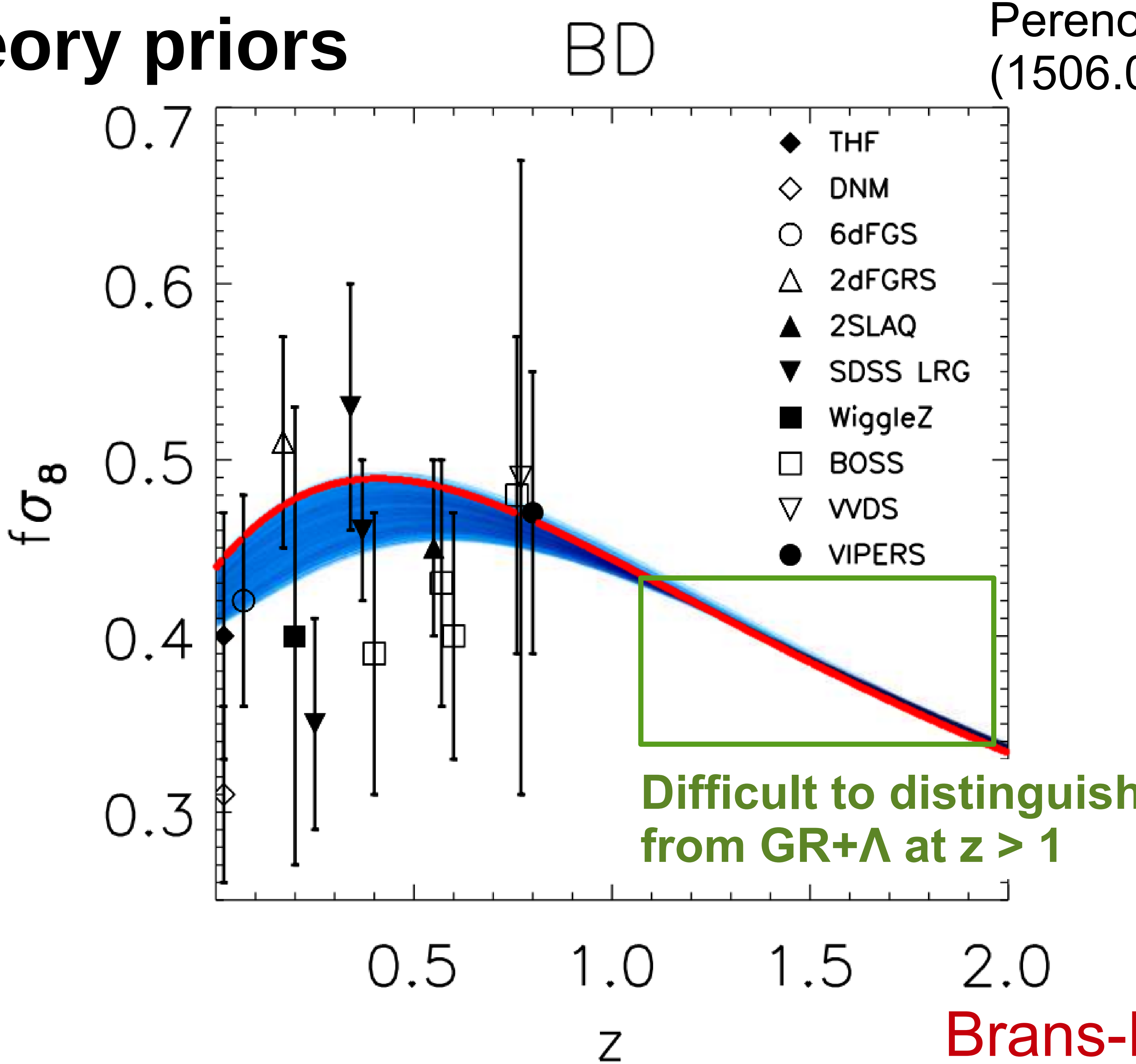


Theory priors

Perenon et al. (1506.03047)



Brans-Dicke

The End

Thanks!

Email: philbull@gmail.com