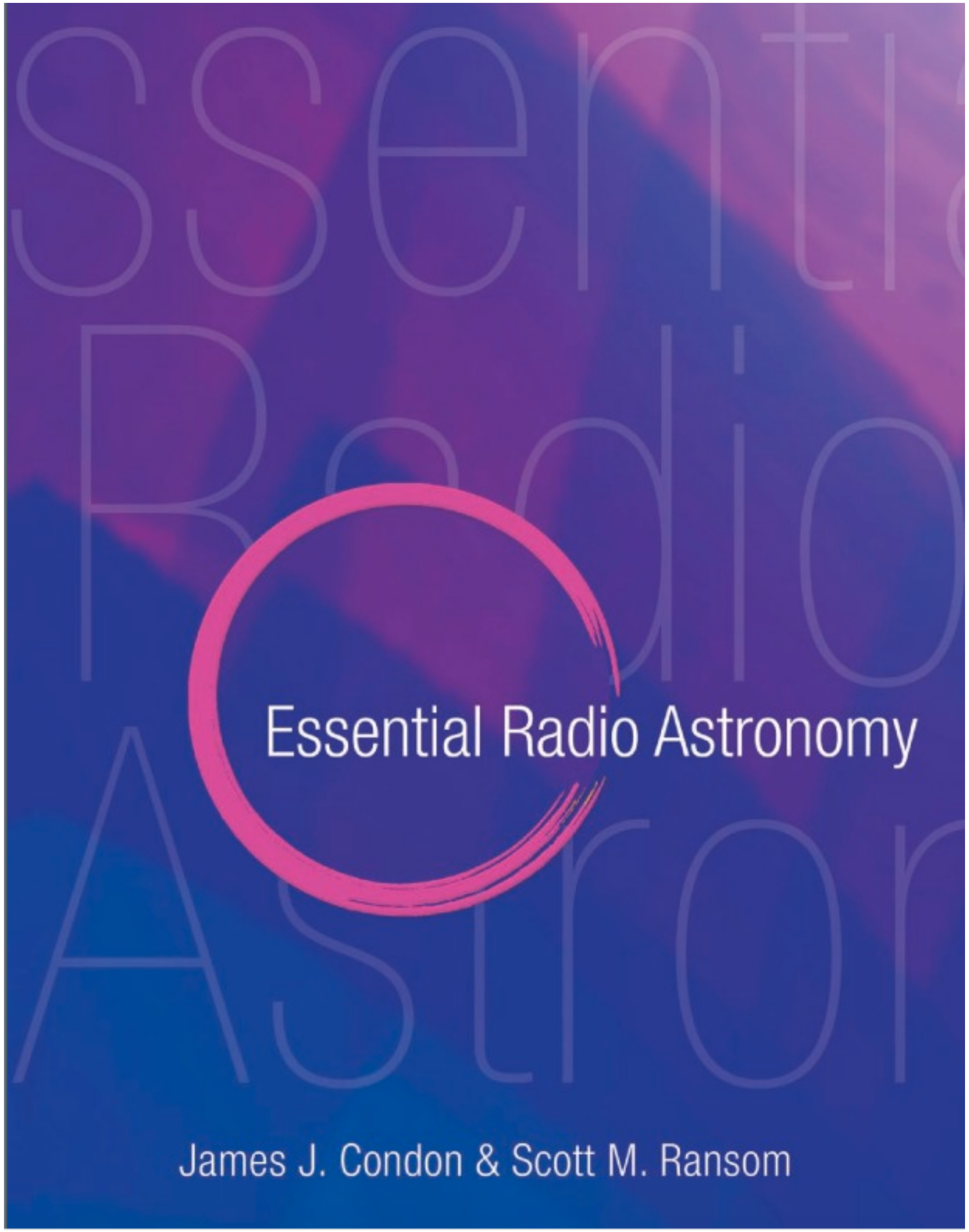
Basics of Radio Astronomy

Lisa Young (NMT)

18th Synthesis Imaging Workshop

18-25 May 2022

Watch the lectures as many times as it takes!



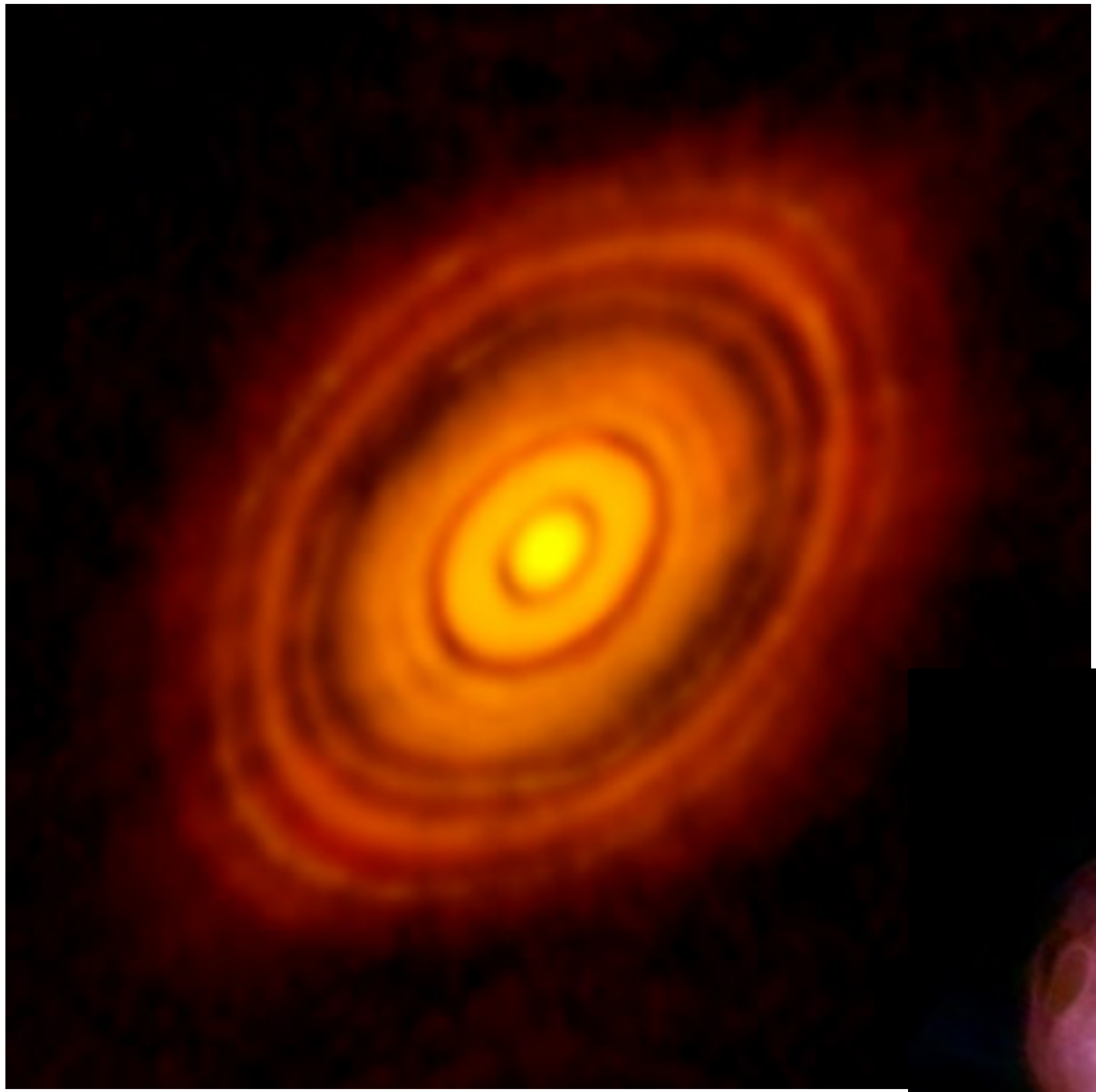
Essential Radio Astronomy

James J. Condon & Scott M. Ransom

Essential Radio Astronomy
Condon & Ransom

Princeton University
Press, 2016

https://science.nrao.edu/opportunities/courses/era/



ALMA (NRAO/ESO/NAOJ); C. Brogan, B. Saxton (NRAO/AUI/NSF)

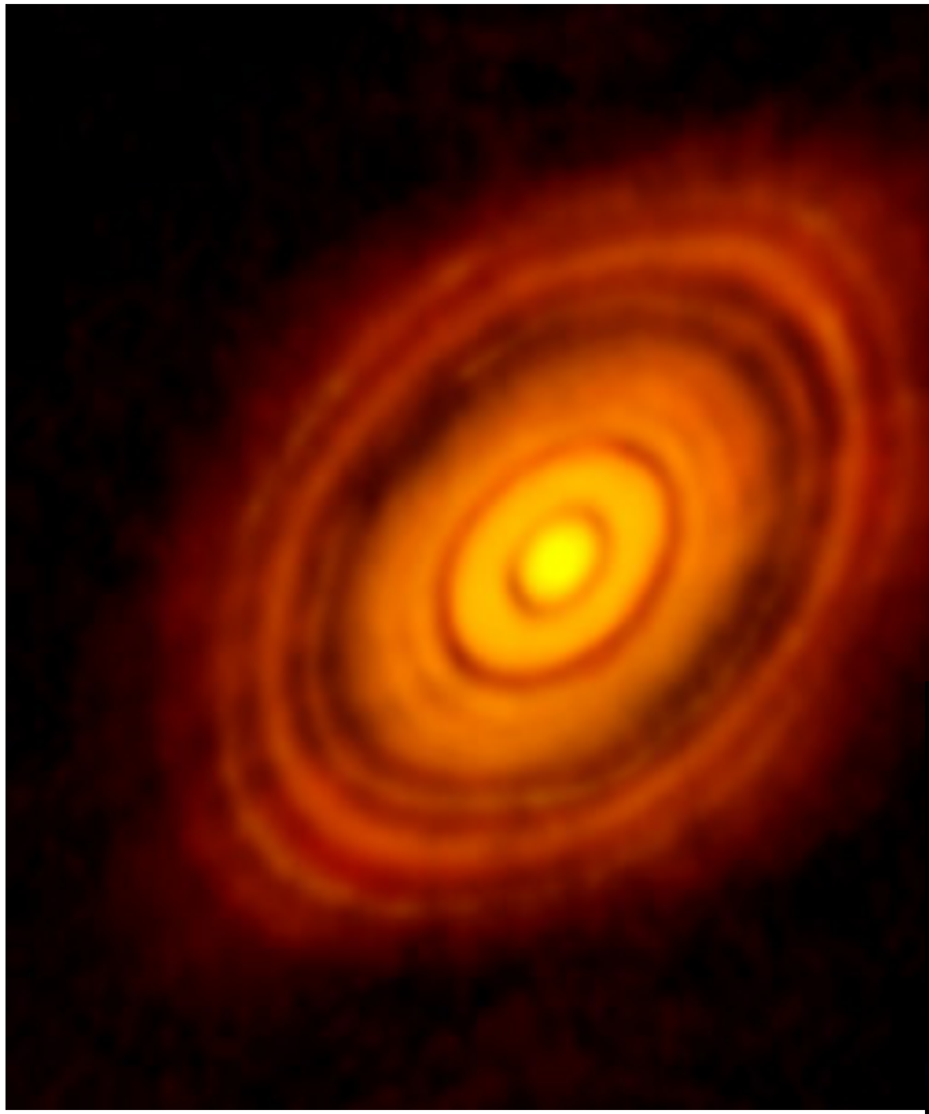
Q1. What are we looking at?

B. Saxton, W. Cotton and R. Perley (NRAO/AUI/NSF)

Q2. How did you make these images?

Q1. What are we looking at?

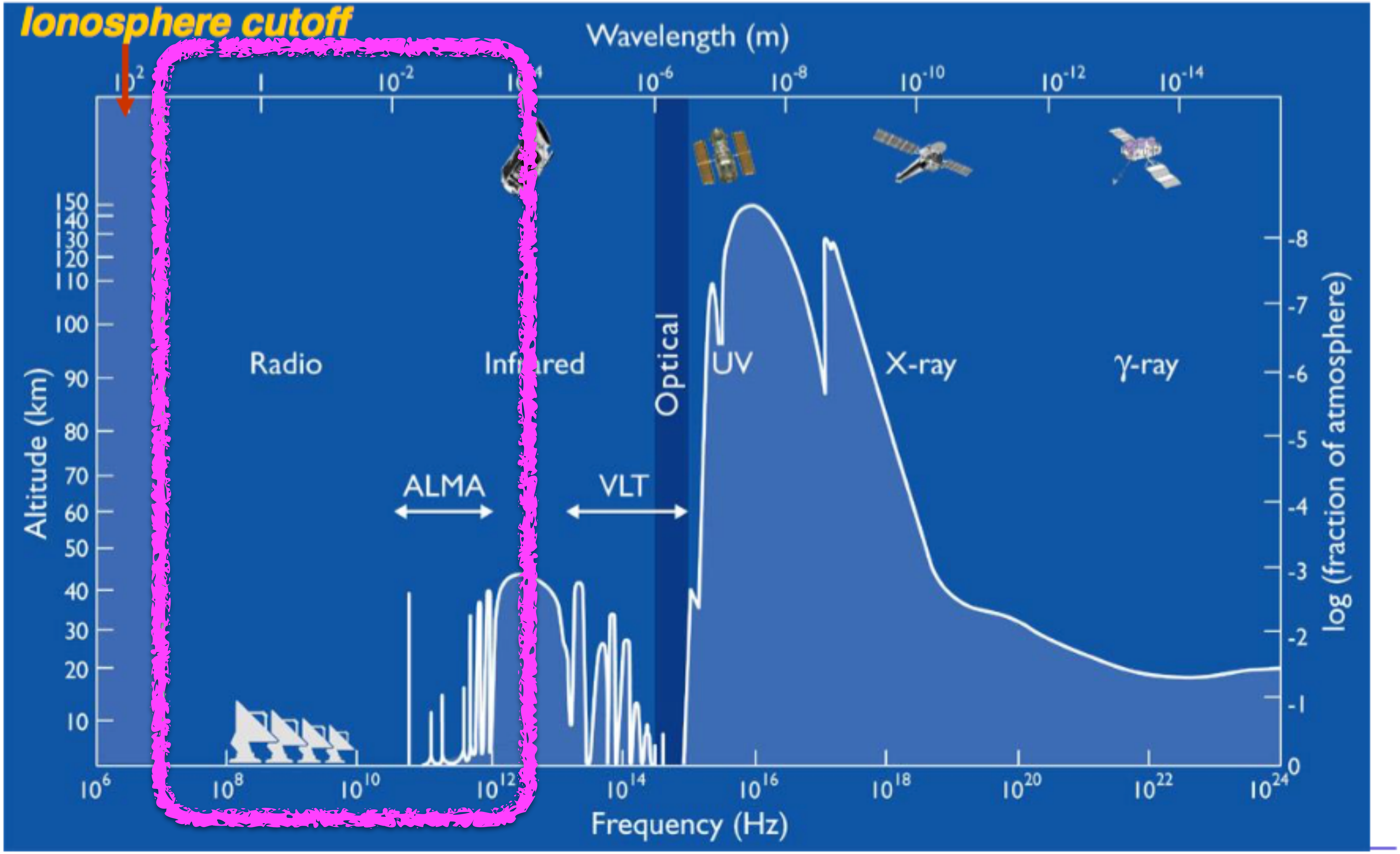
check the spectrum



ALMA (NRAO/ESO/NAOJ); C. Brogan, B. Saxton (NRAO/AUI/NSF)

B. Saxton, W. Cotton and R. Perley (NRAO/AUI/NSF)

Opacity of the Atmosphere (solid line is altitude at which transmission is reduced by factor of 2)

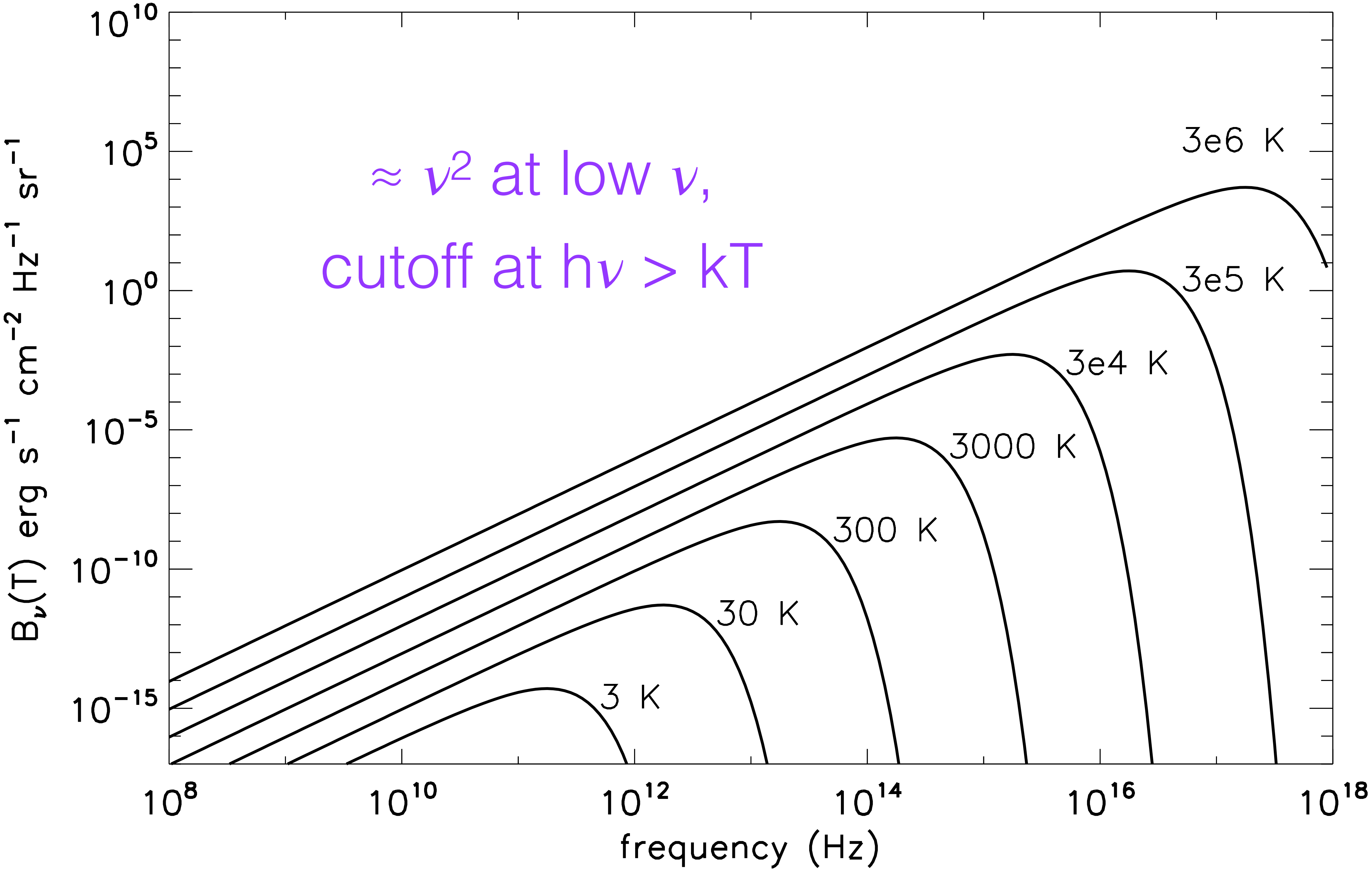


NRAO Synthesis Workshop 2014

mm and sub-mm range

Black body emission has a characteristic shape.

$$B(\nu, T) = B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/k_B T} - 1}$$

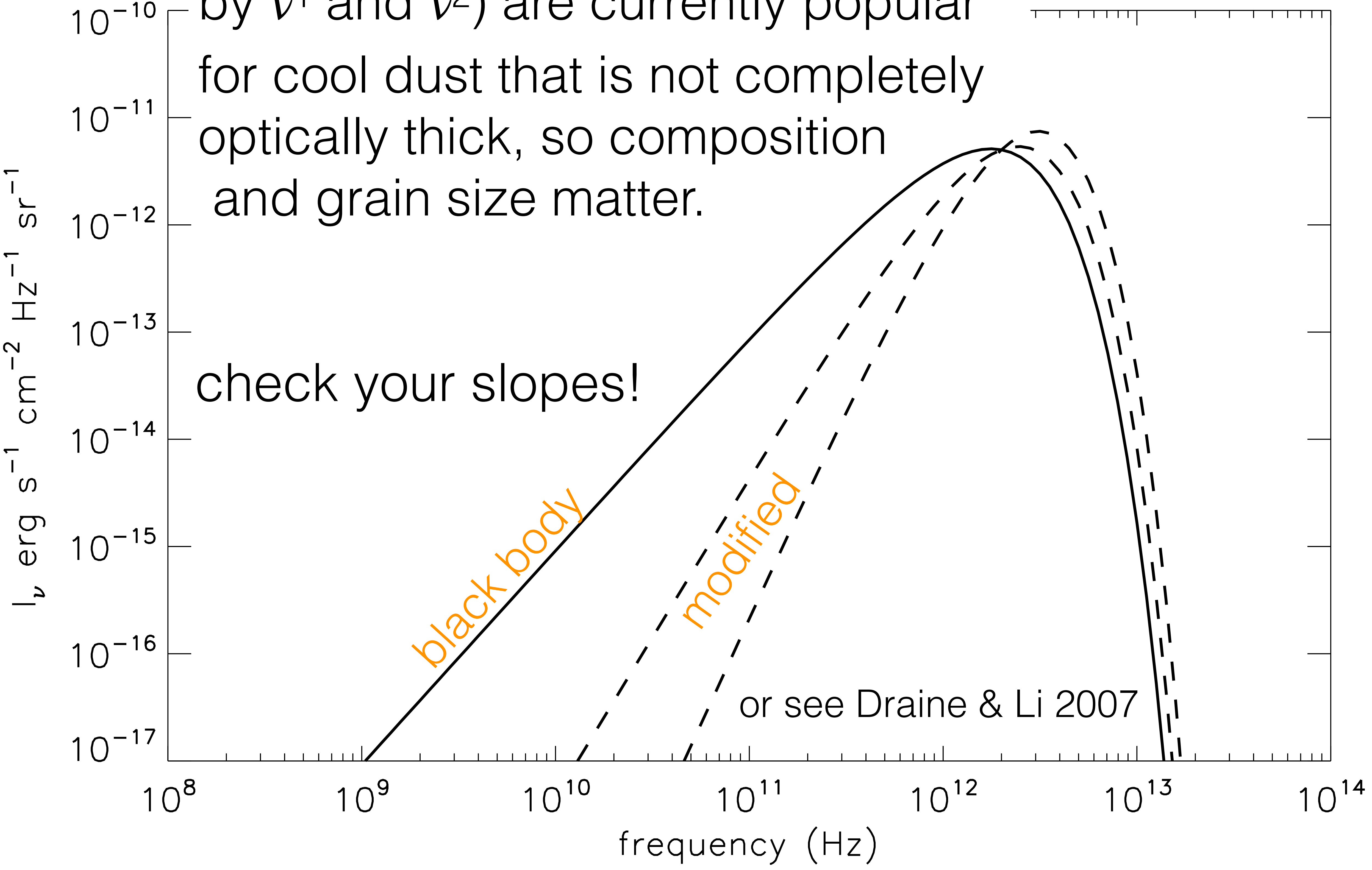


$\approx \nu^2$ at low ν,

cutoff at $h\nu > kT$

Modified black bodies (here scaled by ν^1 and ν^2) are currently popular for cool dust that is not completely optically thick, so composition and grain size matter.

check your slopes!



or see Draine & Li 2007

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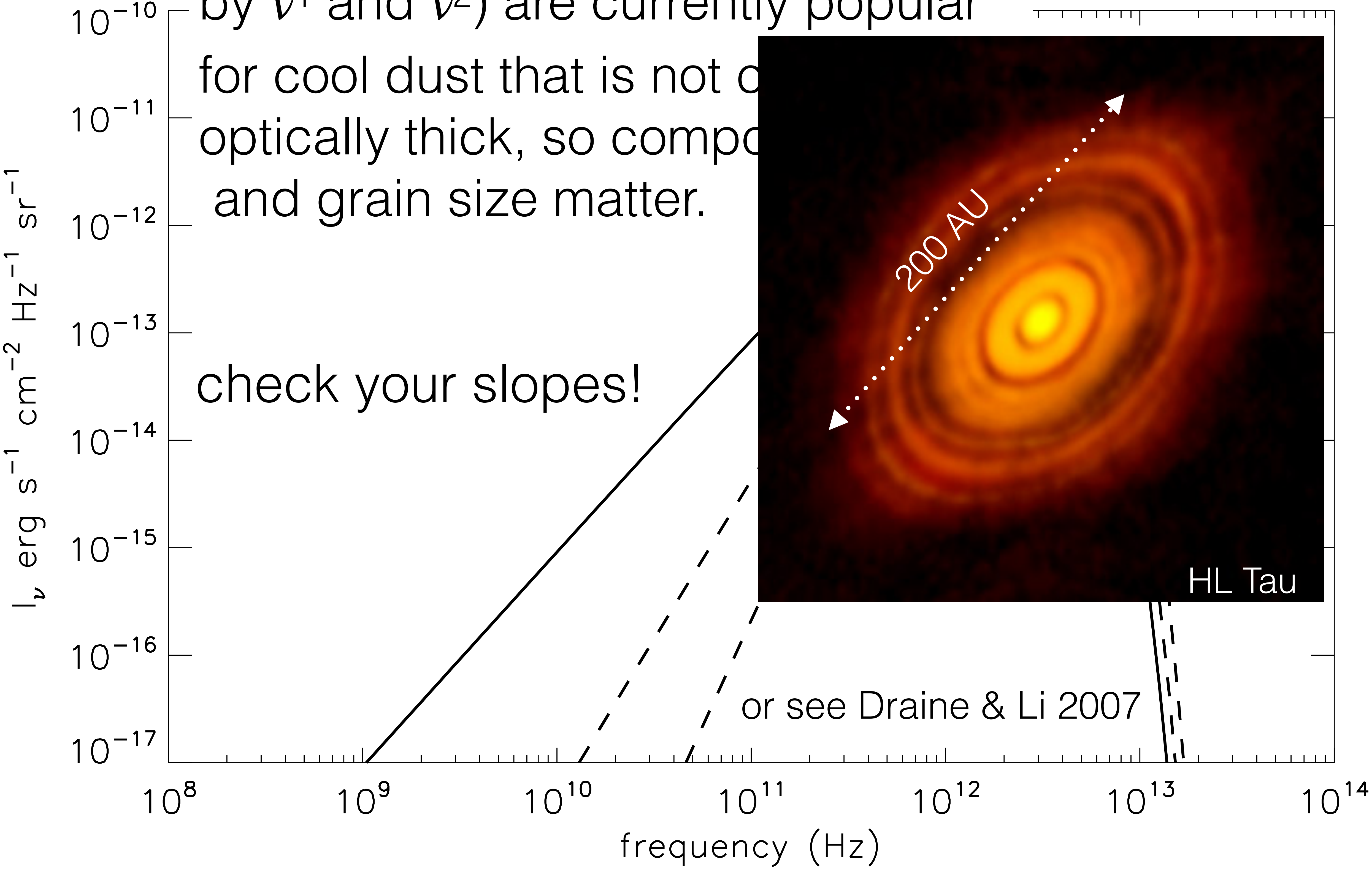
optically thick, so compo

and grain size matter.

check your slopes!



or see Draine & Li 2007

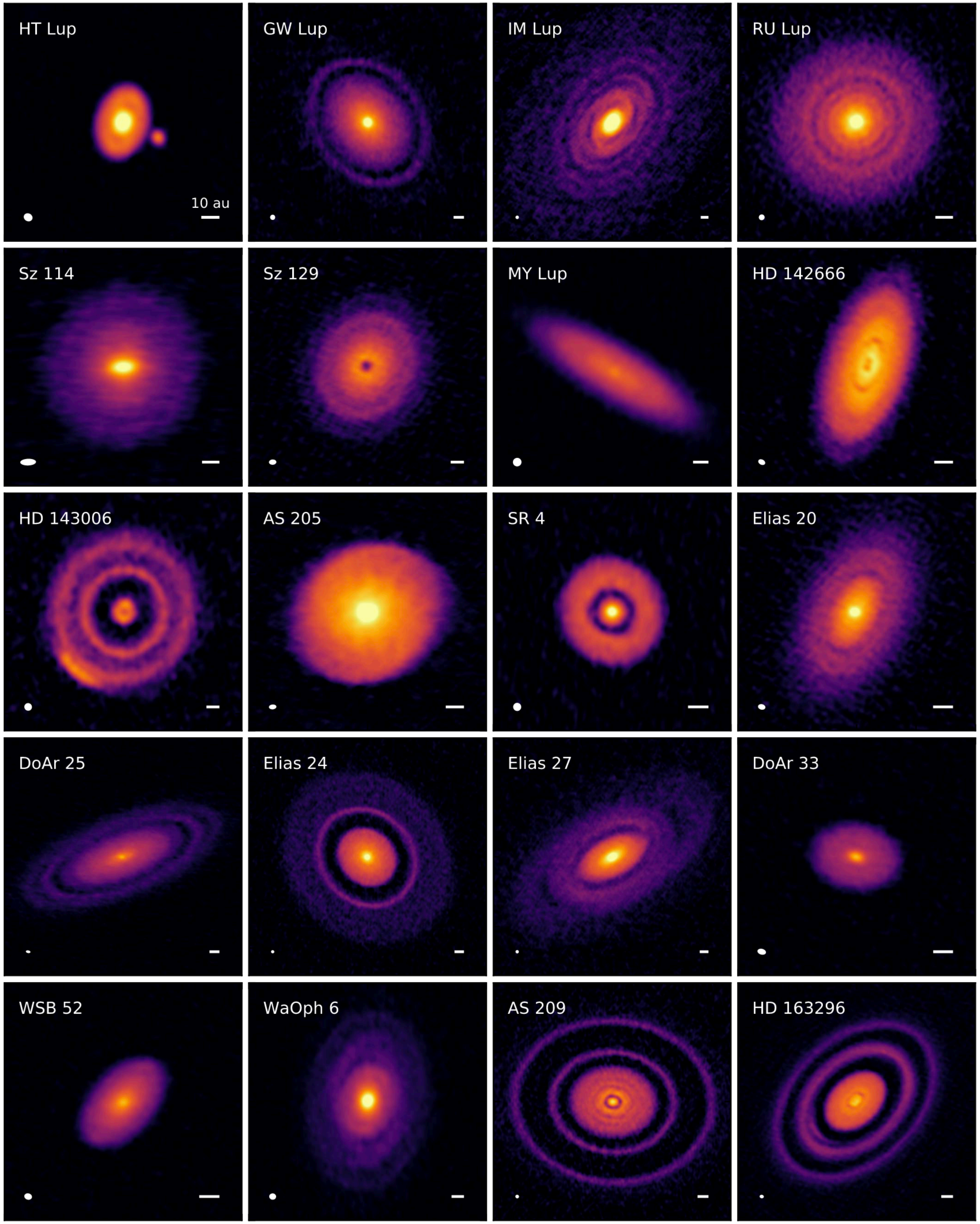
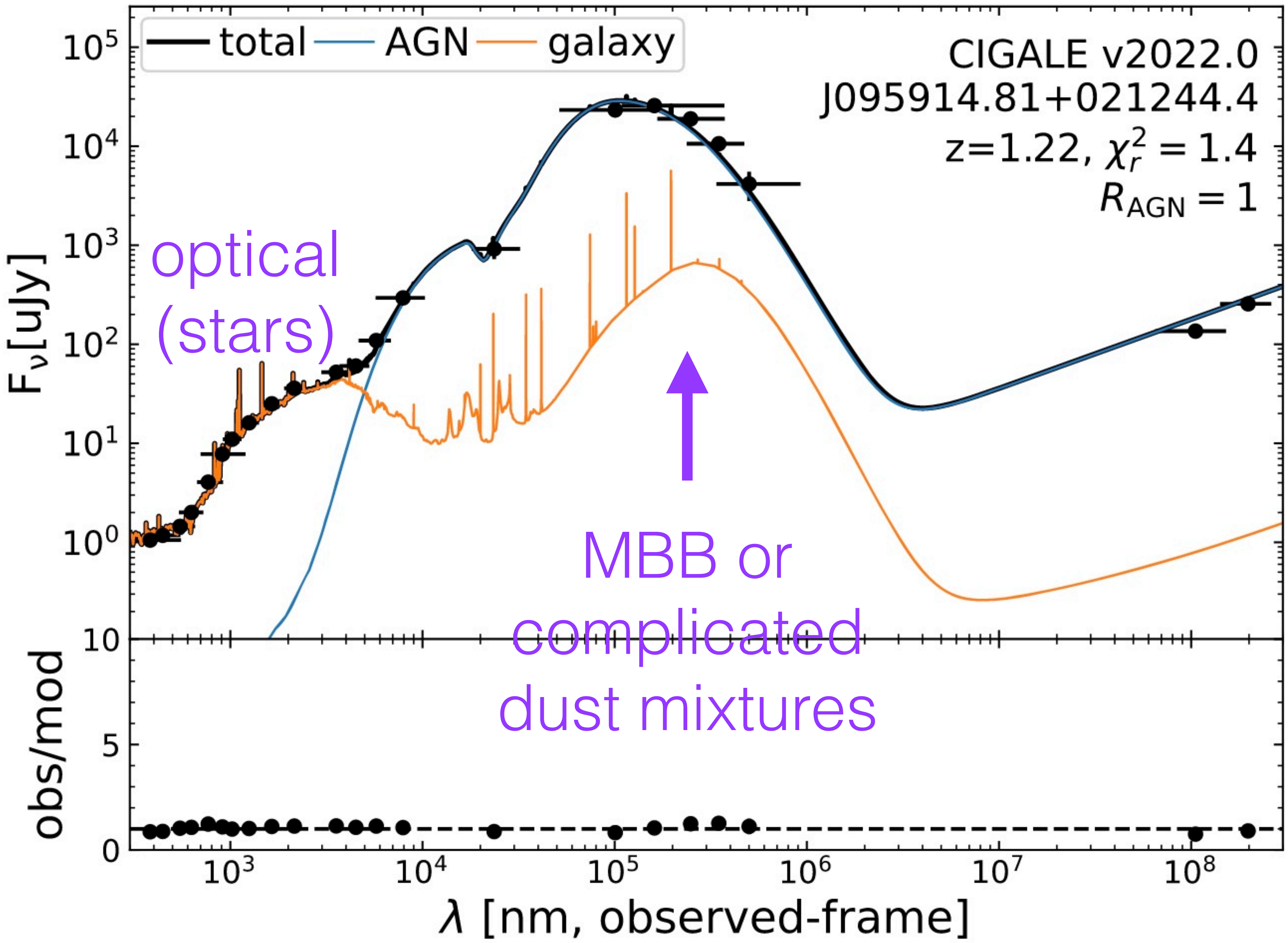


Figure 3. Gallery of 240 GHz (1.25 mm) continuum emission images for the disks in the DSHARP sample. Beam sizes and 10 au scalebars are shown in the lower left and right corners of each panel, respectively. All images are shown with an asinh stretch to reduce the dynamic range (accentuate fainter details without over-saturating the bright emission peaks). For more quantitative details regarding the image dimensions and intensity scales, see Huang et al. (2018a) and Kurtovic et al. (2018).

Lots more!
DSHARP
Andrews et al 2018
ALMA 240 GHz

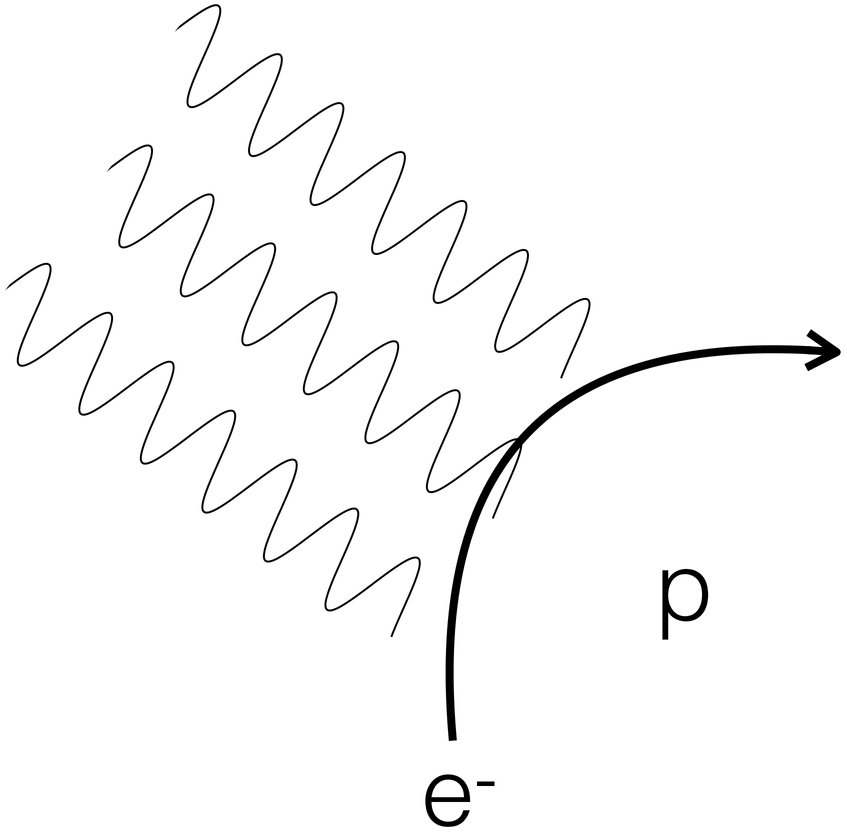


optical (stars)

MBB or complicated dust mixtures

Galaxy SED and template from CIGALE (Yang et al 2022)

Bremsstrahlung (a.k.a. free-free) emission



optically thin, thermal emission
from ionized gas : HII regions etc.

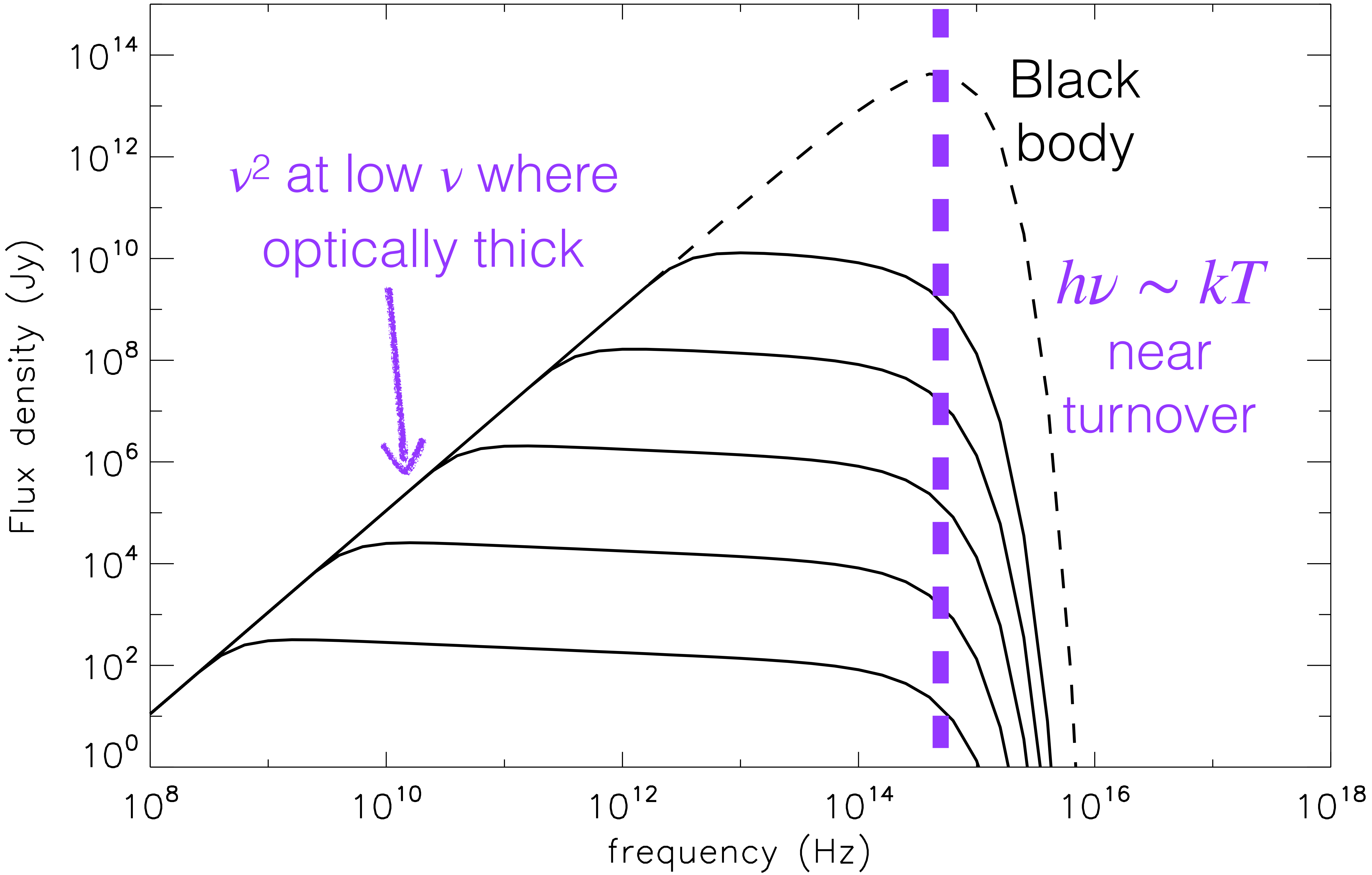
good for estimating density & temperature of ionized gas

- counting ionizing photons
- inferring star formation rate

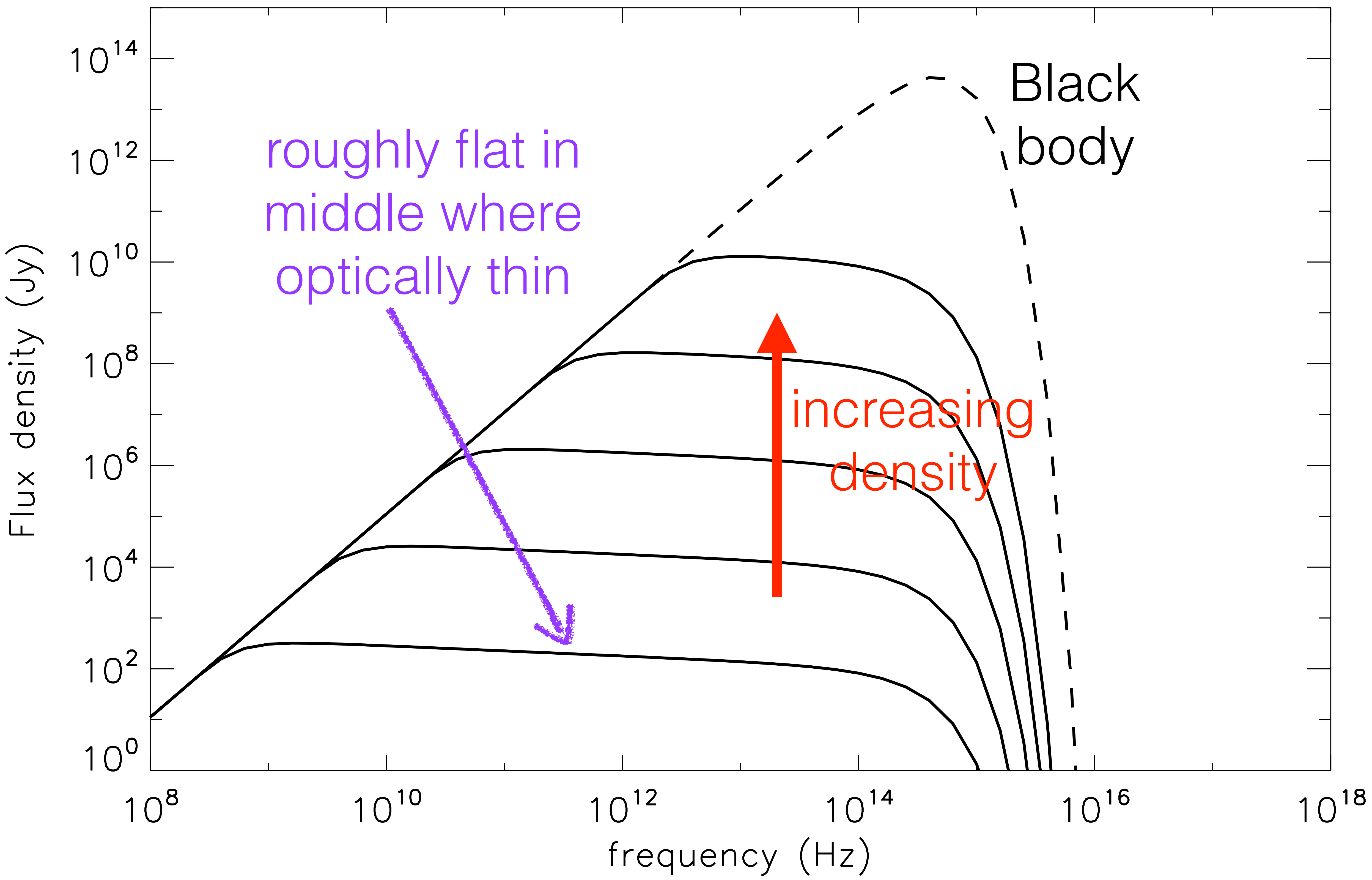
$$j_{ff}(\nu) = \frac{8}{3}\left(\frac{2\pi}{3}\right)^{1/2} \frac{e^6}{m_e^{3/2} c^3} \boxed{\frac{n_e n_i}{(k_B T)^{1/2}}} g_{ff}(\nu, T) e^{-h\nu/k_B T}$$

emission coefficient (e.g. erg s^{-1} cm^{-3} Hz^{-1} ster^{-1})

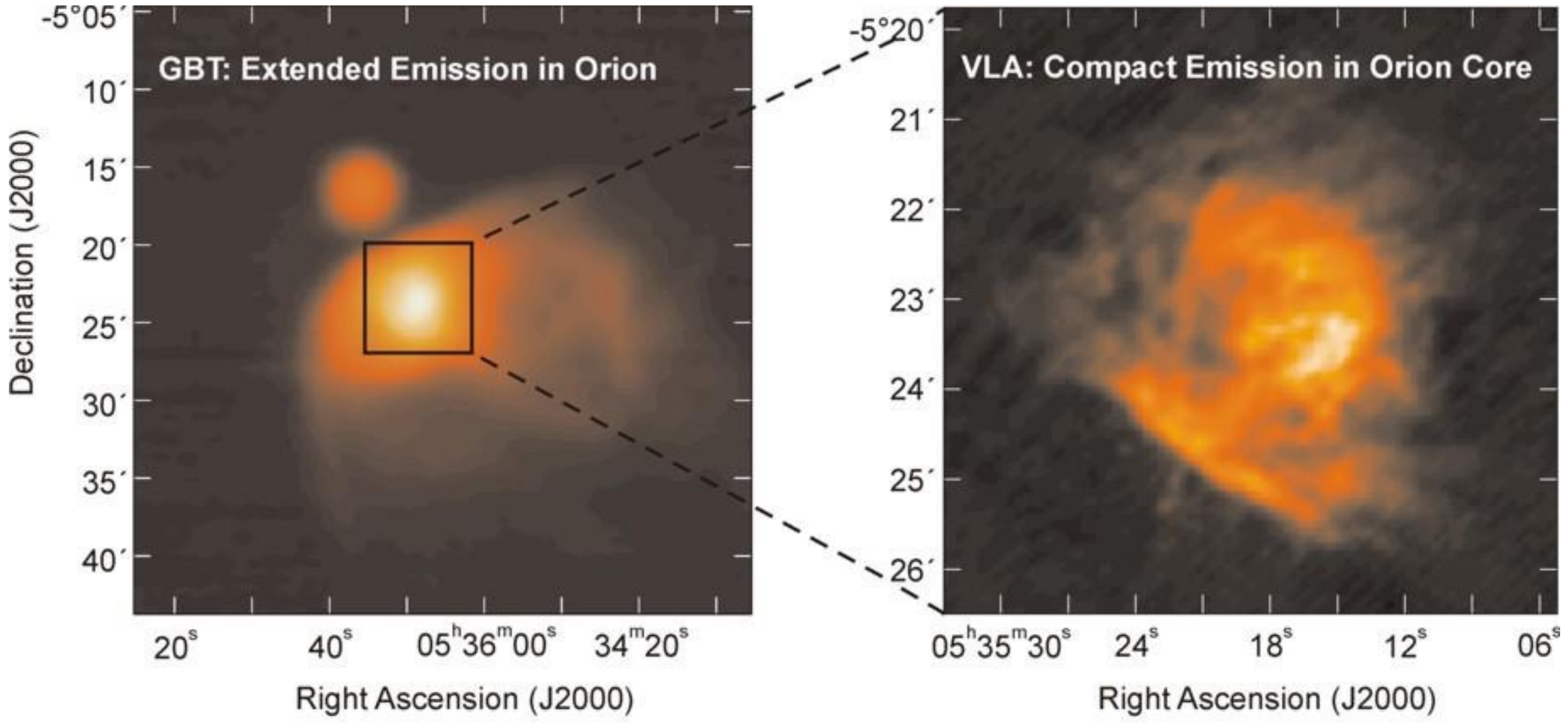
Bremsstrahlung spectra



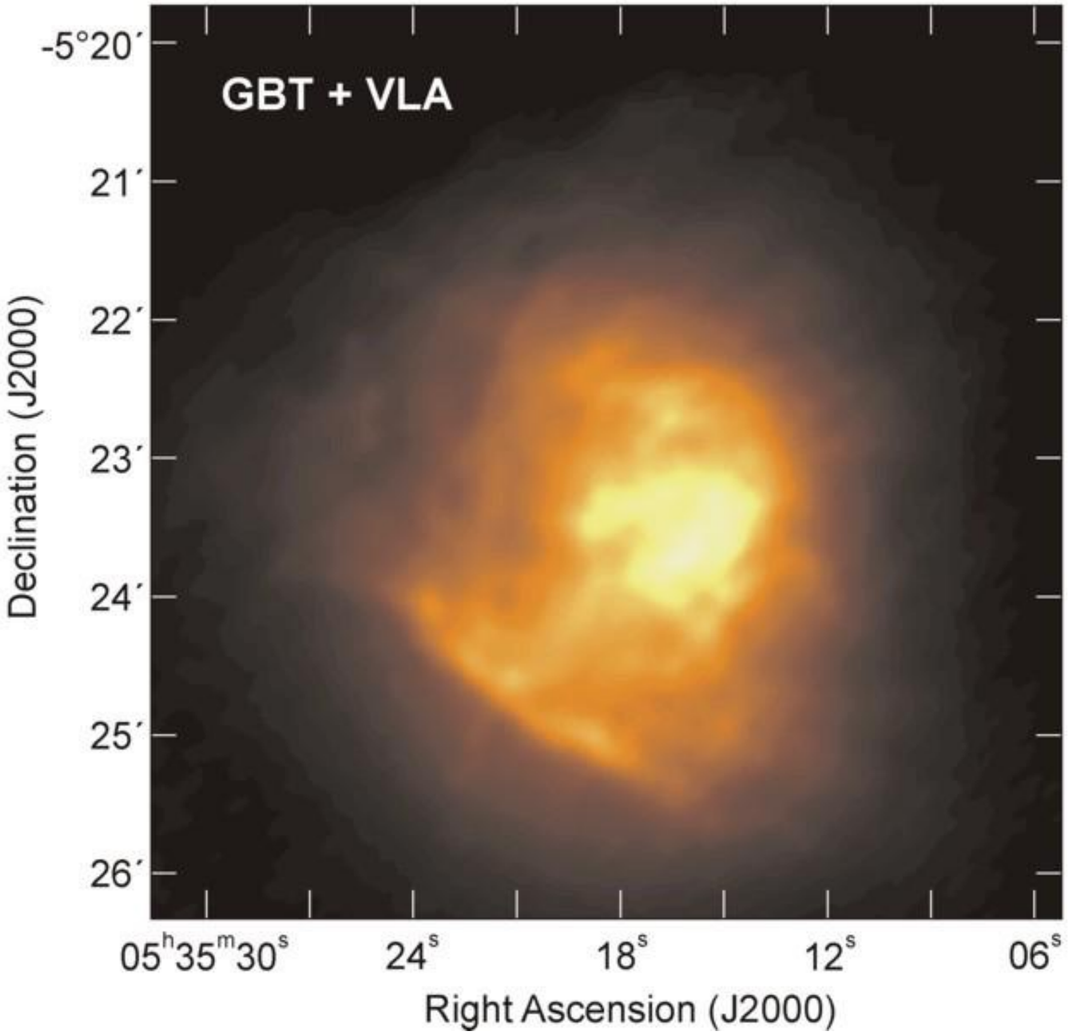
Bremsstrahlung spectra

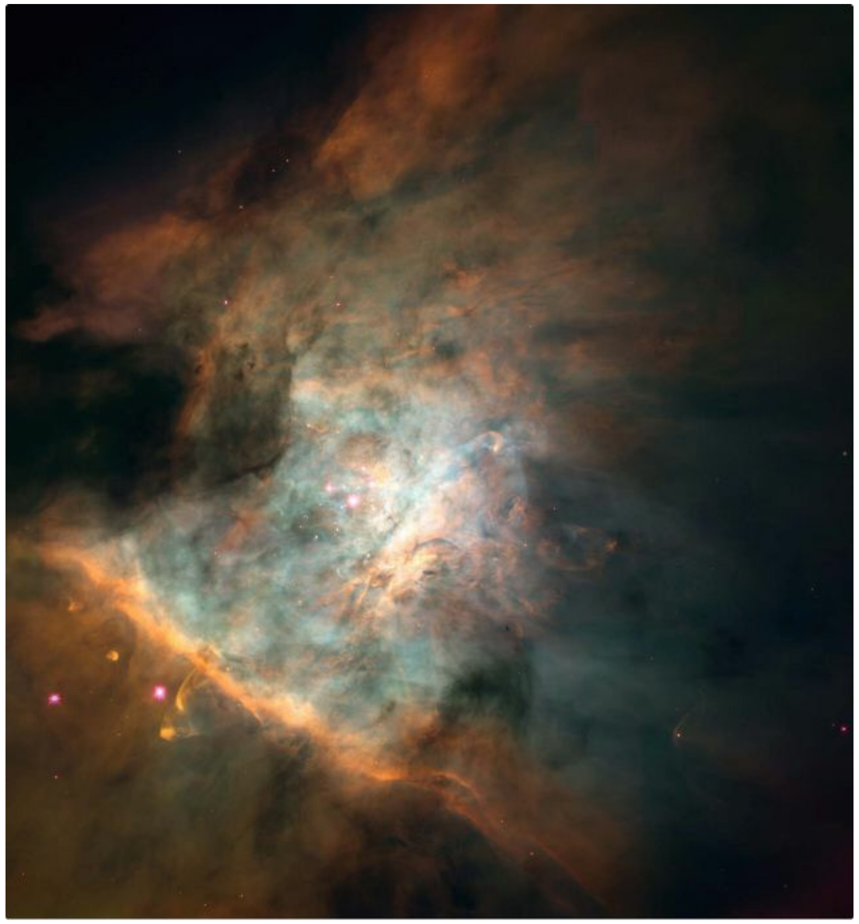


roughly flat in middle where optically thin



Orion Nebula
8.4 GHz
Dicker et al 2009

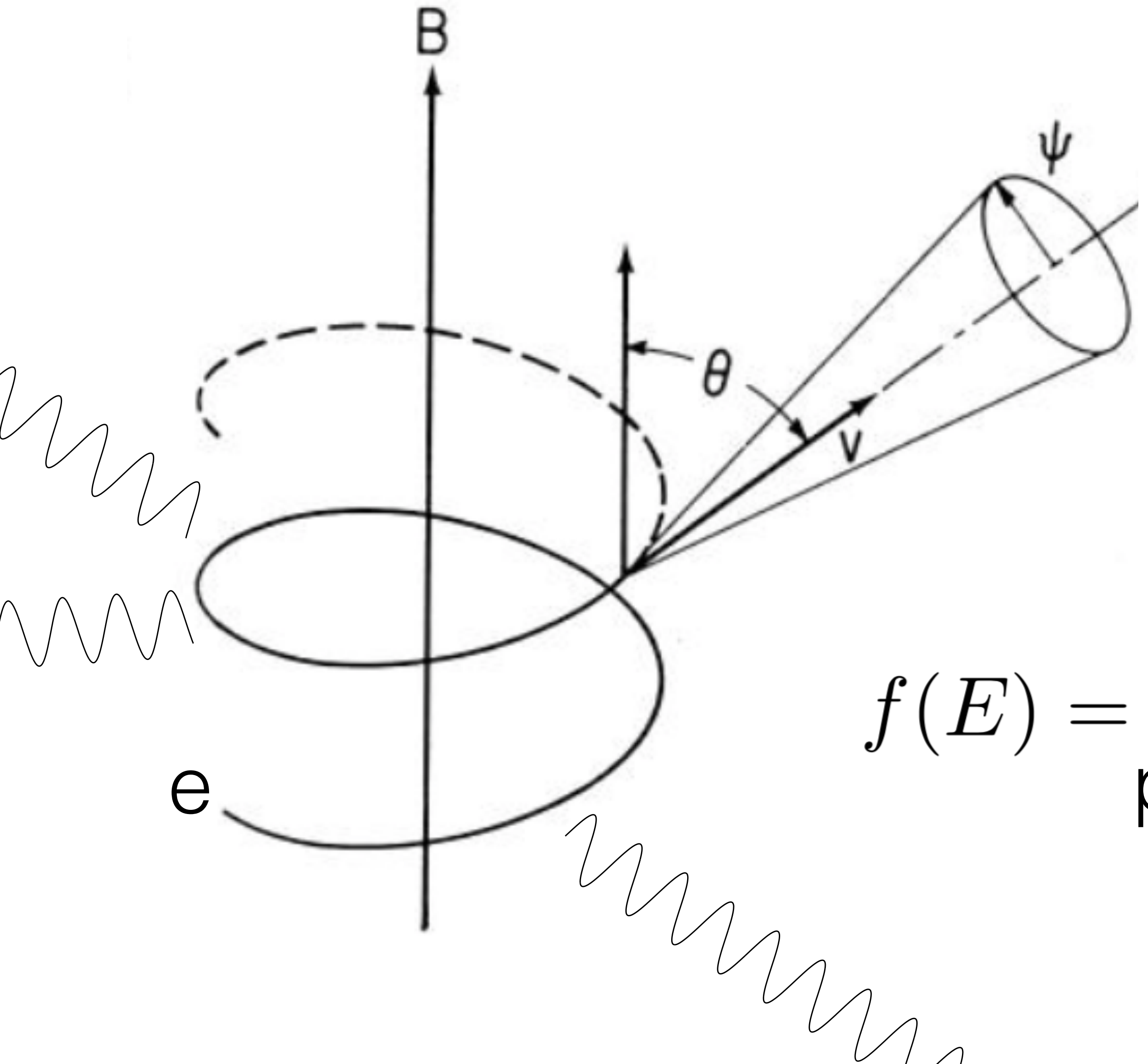




HST
optical

Synchrotron emission

nonthermal (usu: relativistic) electrons in a B field
can get particle energies, n and B



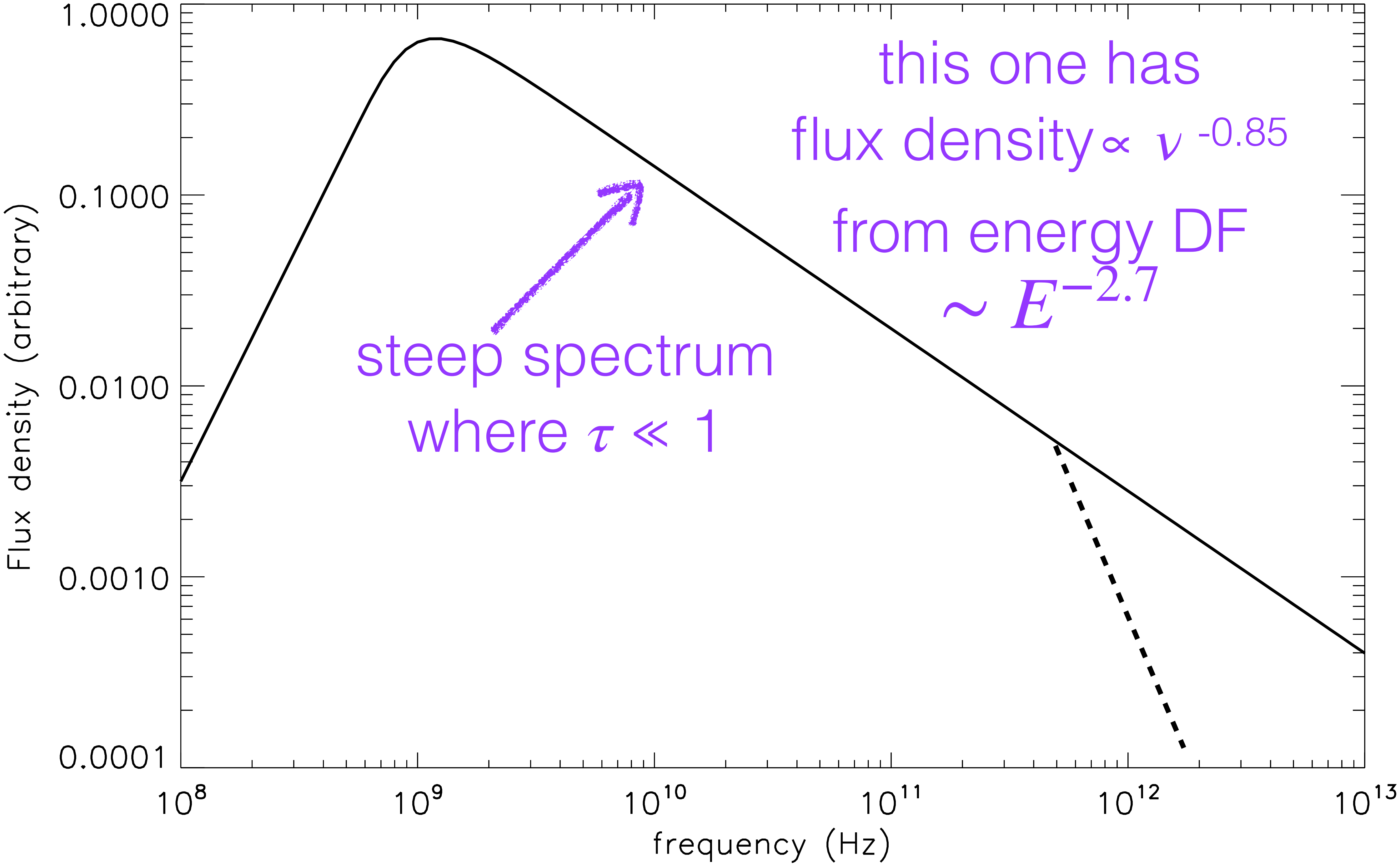
$$\nu_c = \frac{3}{4\pi}\boxed{\gamma^2}\frac{e\boxed{B}}{mc}\sin\theta$$

An electron of energy γ
($E = \gamma mc^2$) radiates at
this frequency.

$$f(E) = f_o E^{-s}$$

power law distribution of
electron energies

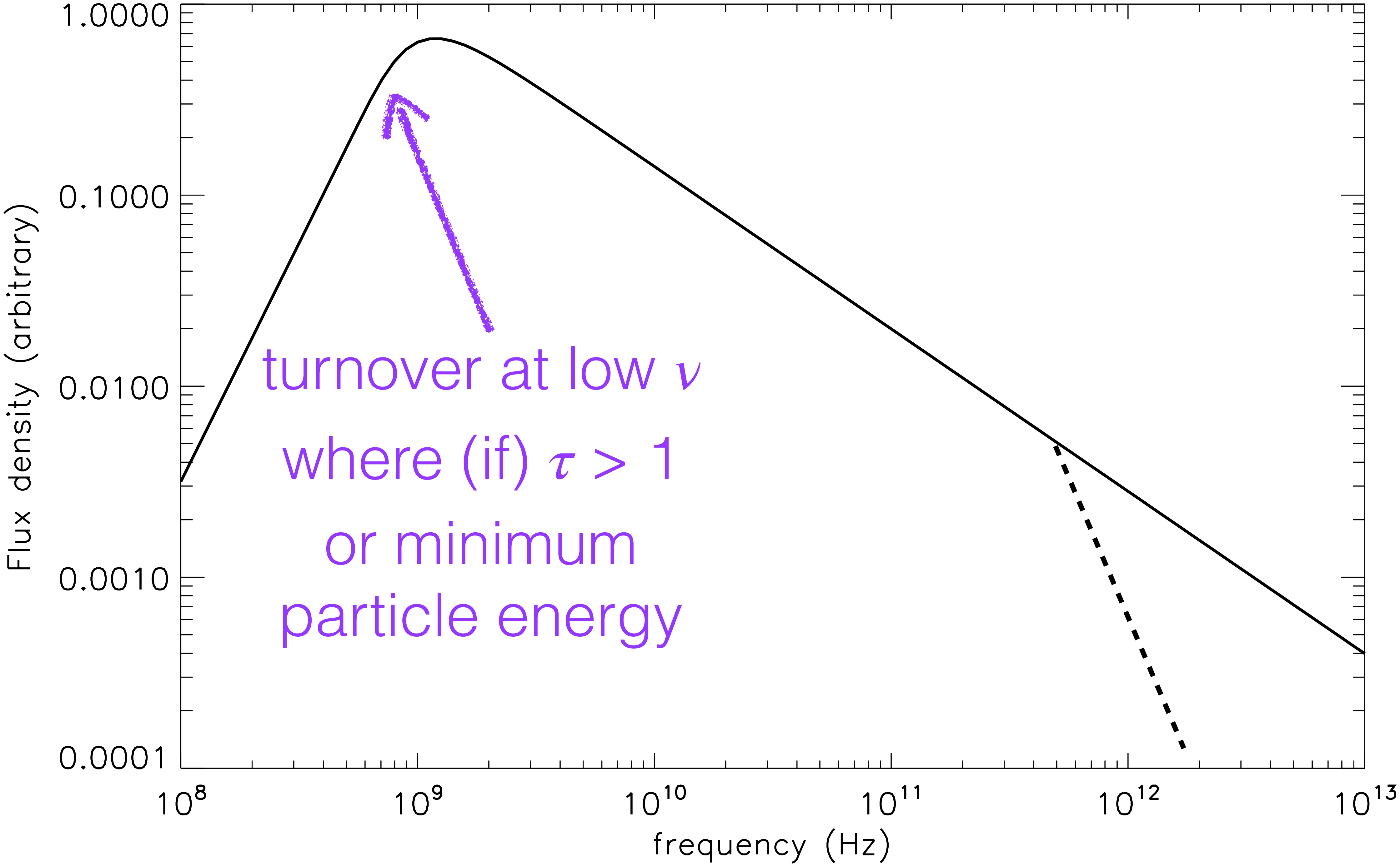
Nonthermal synchrotron spectrum



this one has
flux density $\propto \nu^{-0.85}$
from energy DF
$\sim E^{-2.7}$

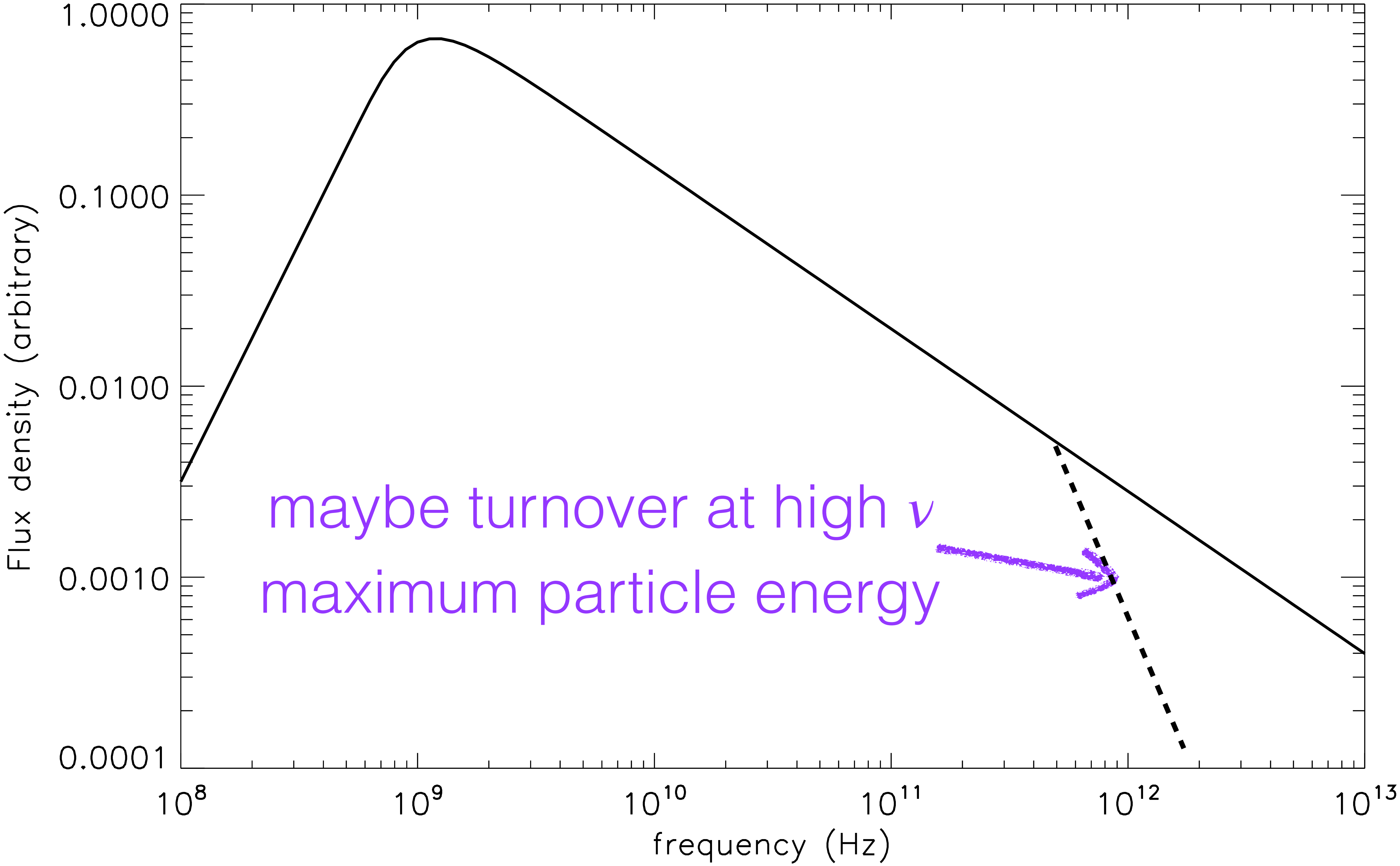
steep spectrum
where $\tau \ll 1$

Nonthermal synchrotron spectrum



turnover at low ν
where (if) $\tau > 1$
or minimum
particle energy

Nonthermal synchrotron spectrum



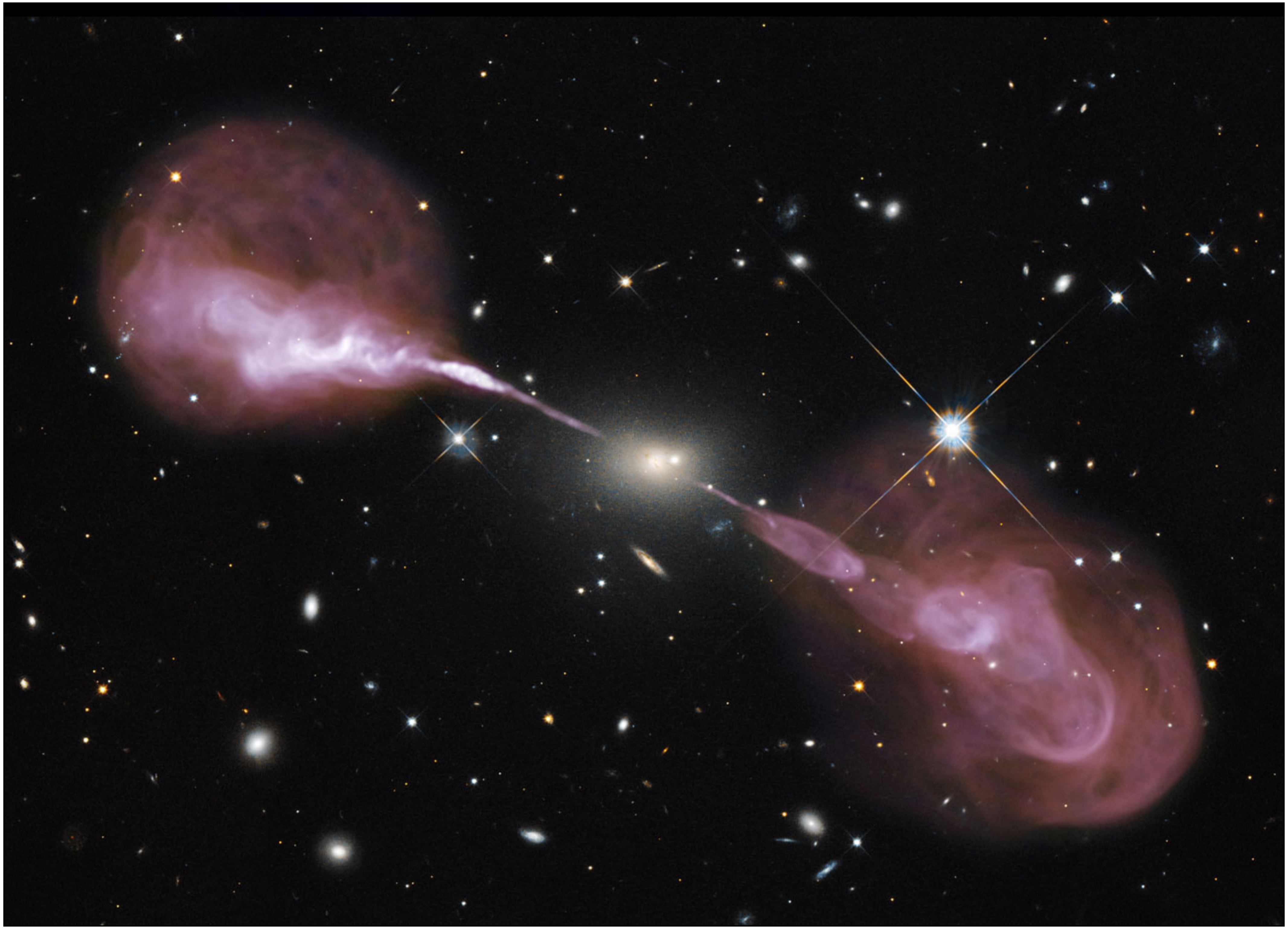
maybe turnover at high ν

maximum particle energy

synchrotron from active galaxy Her A, $\boldsymbol{\nu} \sim 6.5$ GHz

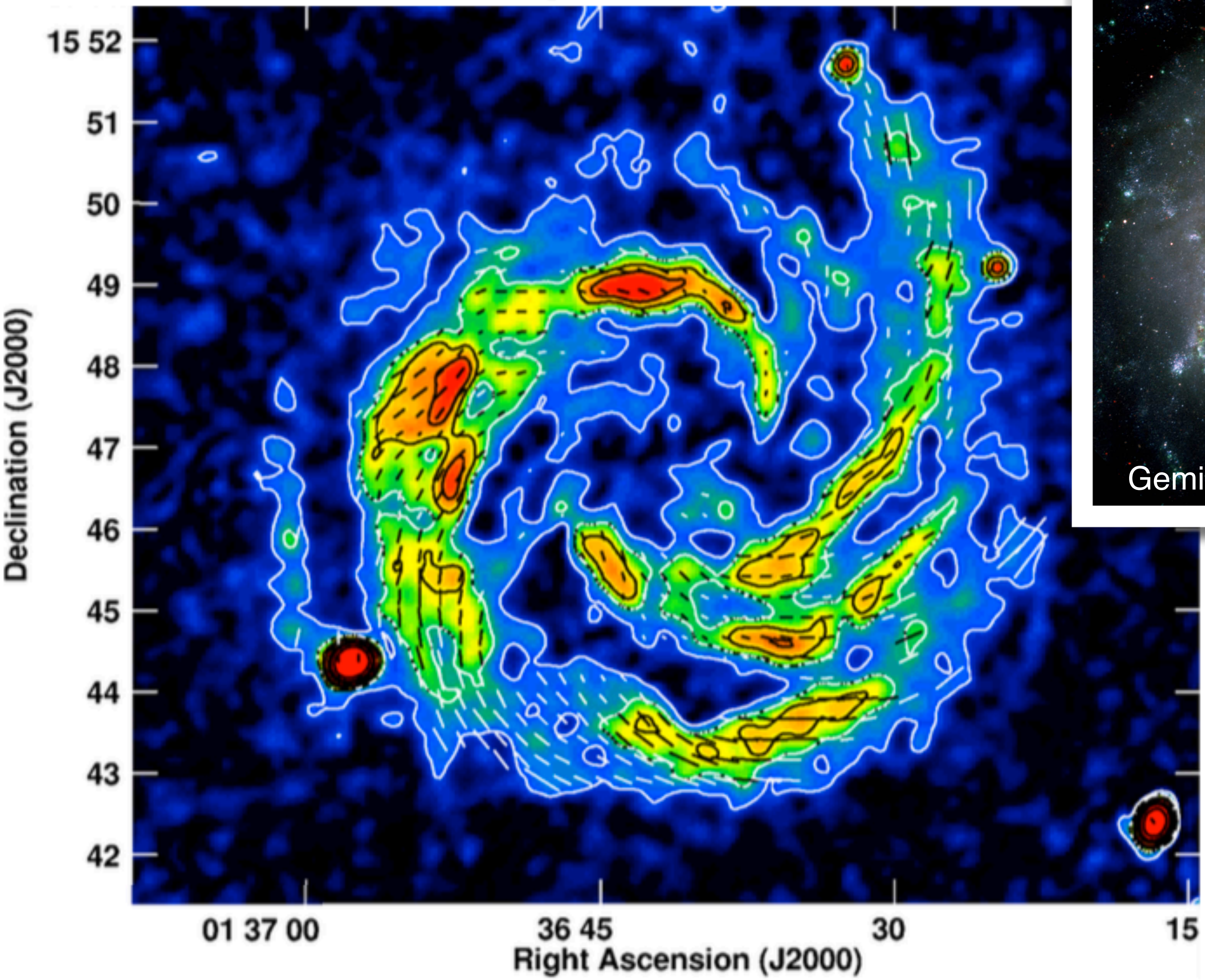
B. Saxton, W. Cotton and R. Perley (NRAO/AUI/NSF)

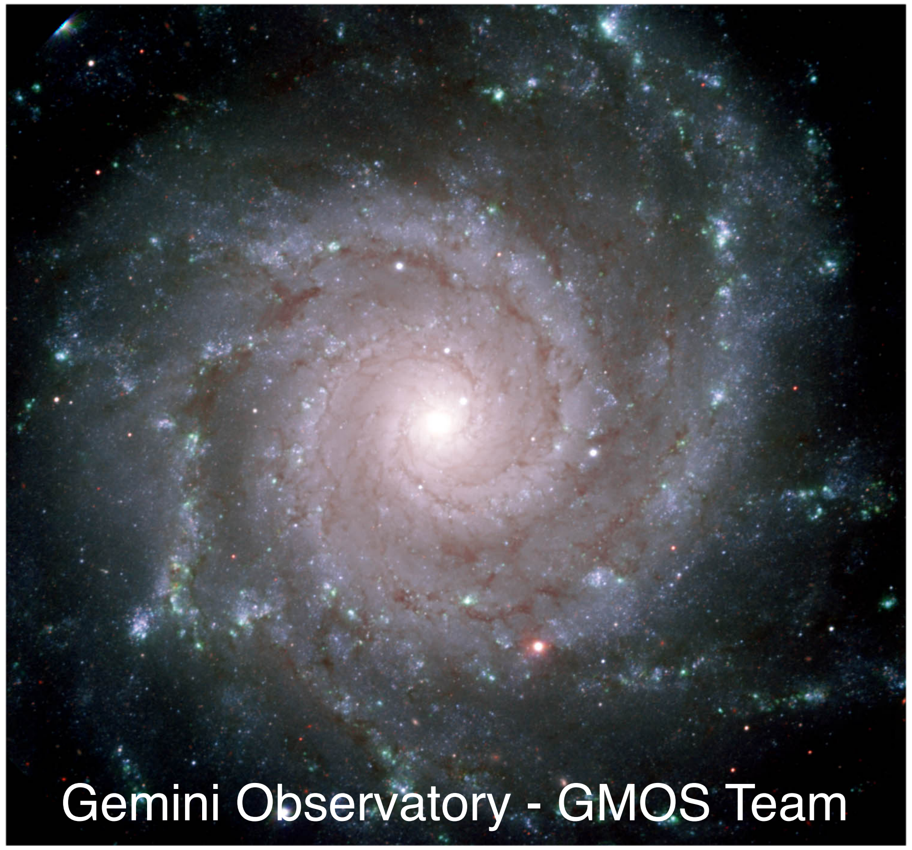
synchrotron from active galaxy Her A, $\nu \sim 6.5$ GHz



B. Saxton, W. Cotton and R. Perley (NRAO/AUI/NSF)

Synchrotron emission is polarized! Gives info on B field.

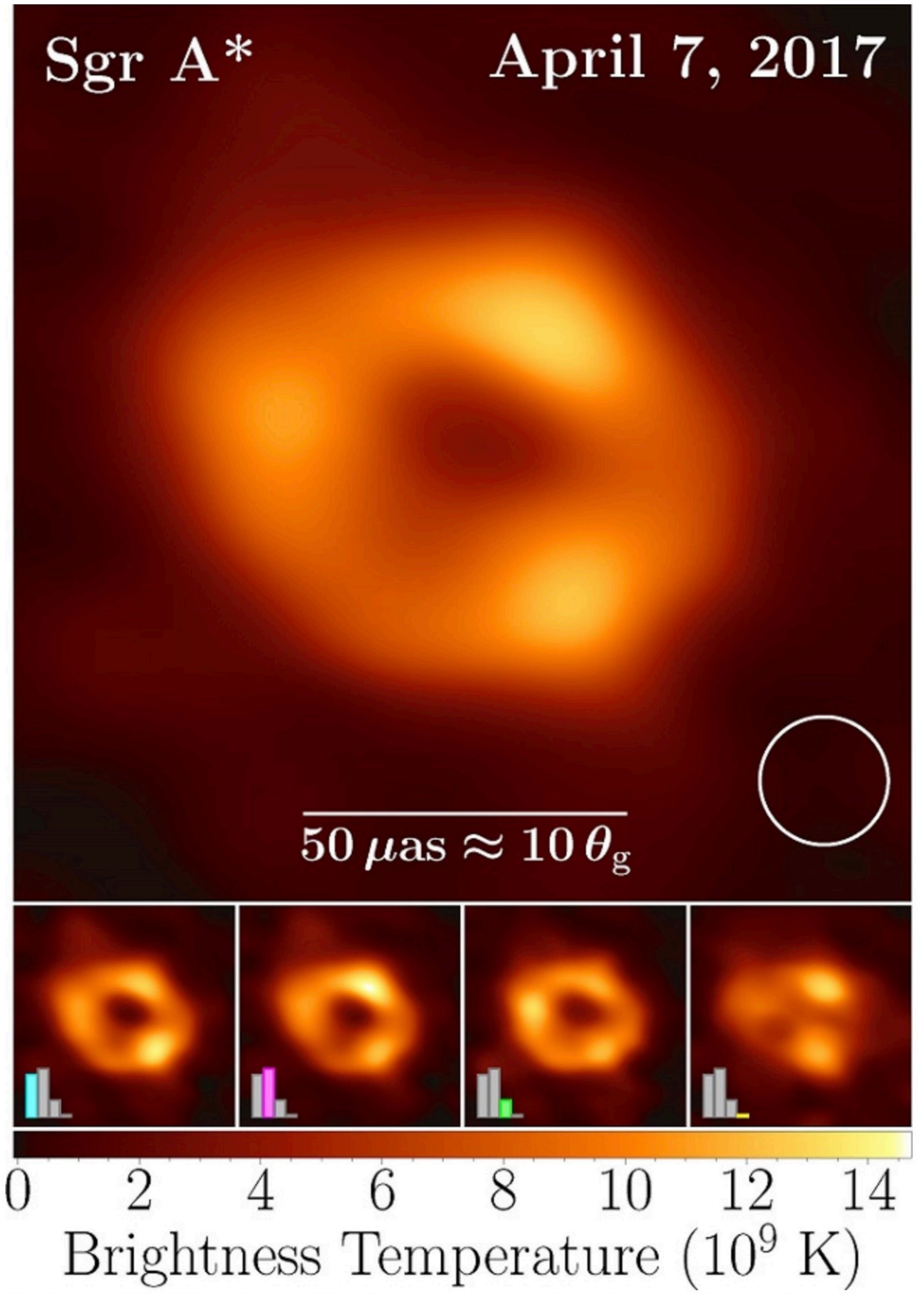




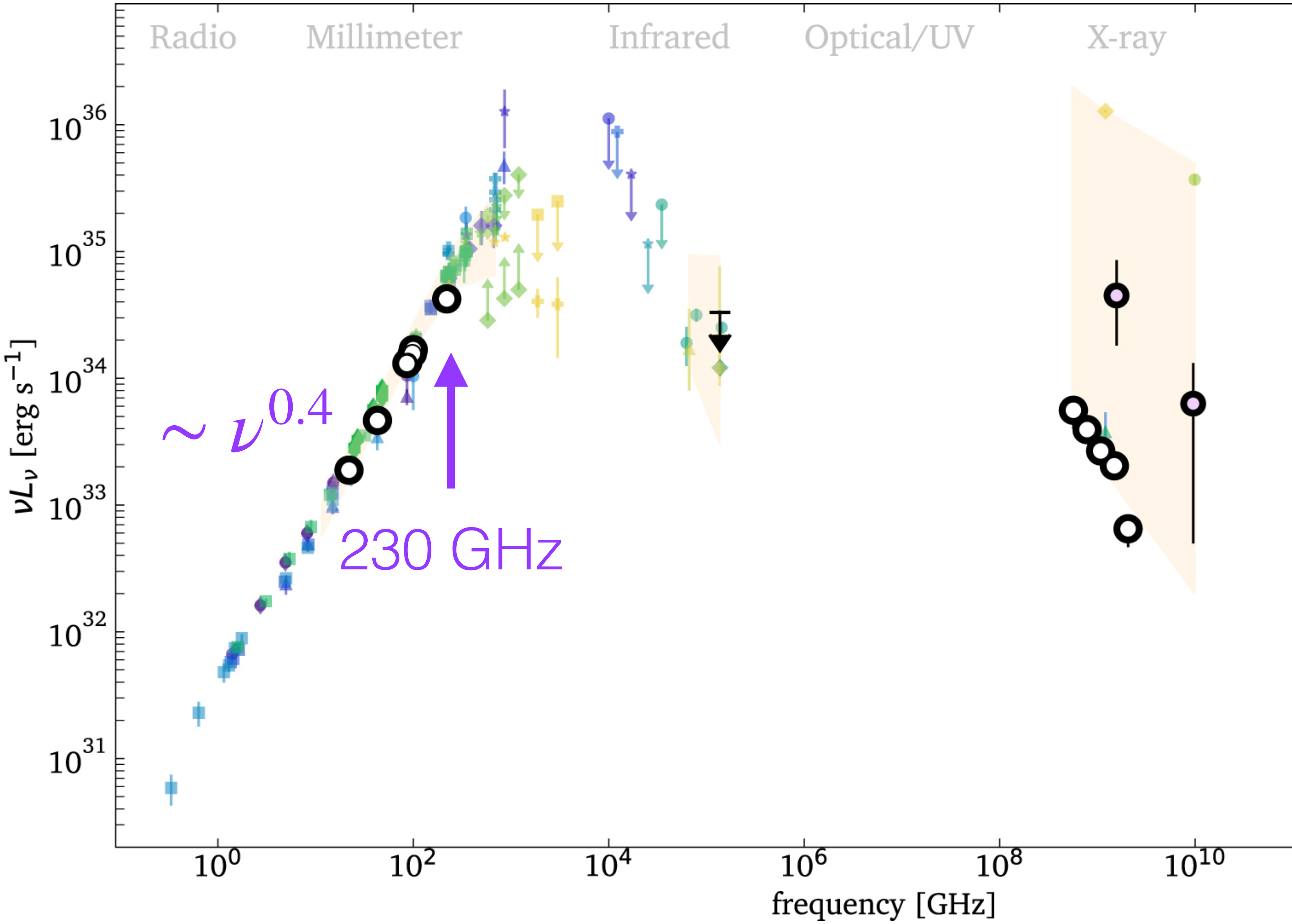
Mulcahy et al 2017; NGC 628, VLA @ 3 GHz

What about this stuff?

EHT Collab. 2022
papers 1 and 2



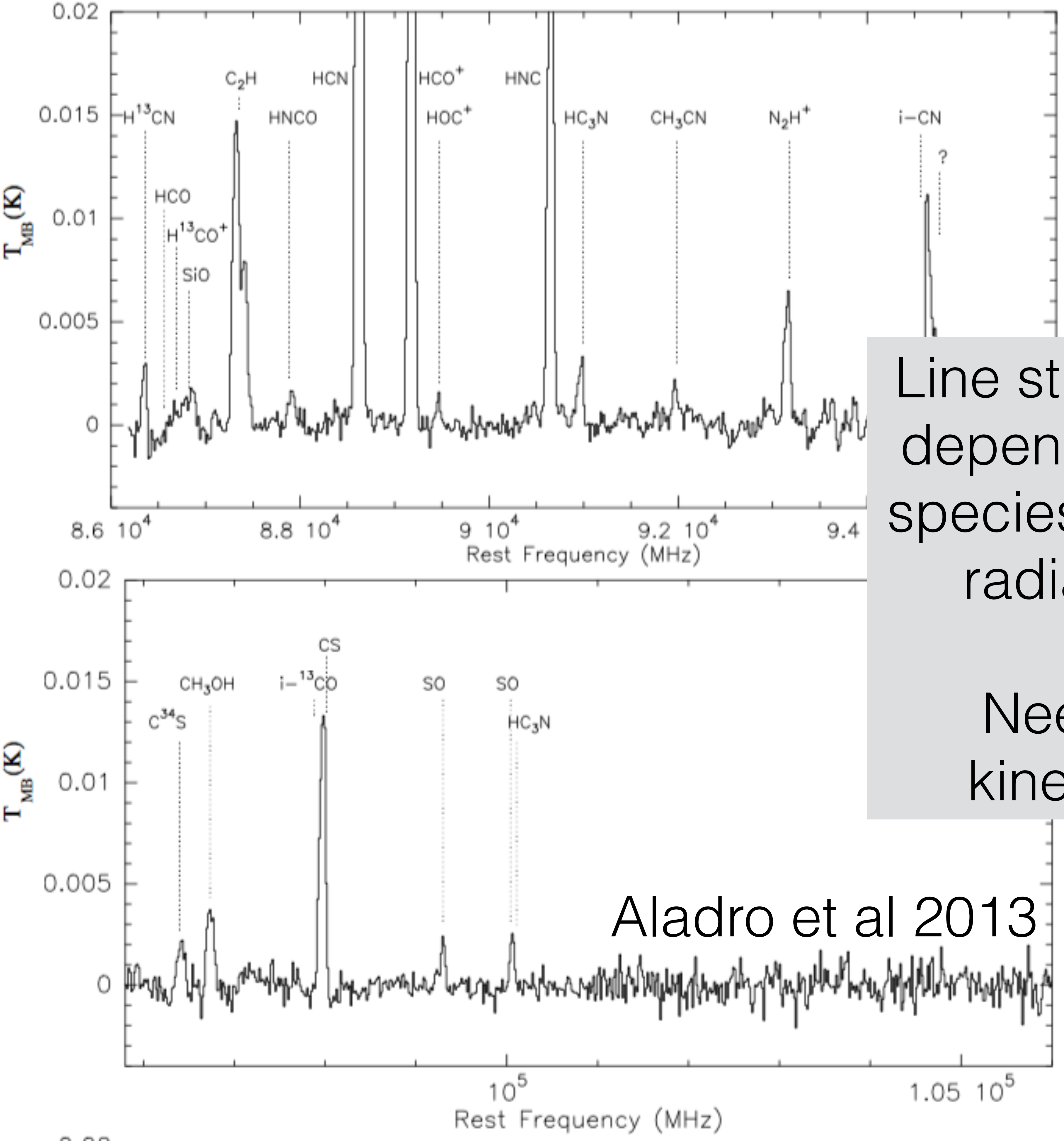
EHT image of Sgr A* (top; Paper I). Ring-like images dominate the wide range of images obtained across multiple methods, however, variability and sparse visibility domain coverage make selection of a single image impossible (Paper III). The inset images represent different imaging solutions and their associated frequency (histograms).



synchrotron from thermal
(HOT!) electrons

see also Bower et al 2015

Spectral lines

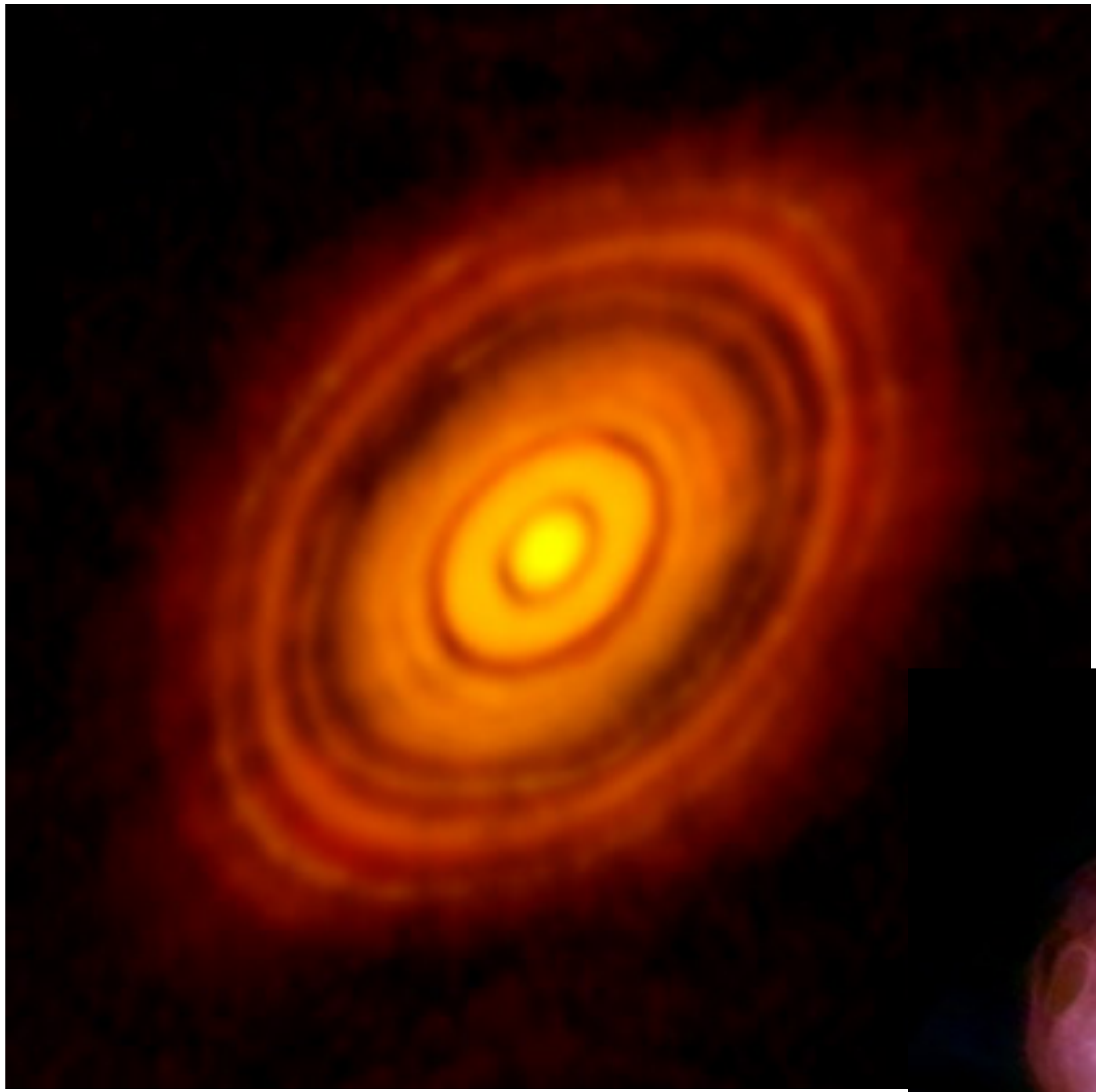


Aladro et al 2013

Line strengths generally depend on gas density, species abundance, T_{ex}, radiation field, etc.

Need lines to get kinematics of gas.

(Tuesday 24th)



HL Tau, ν ~ 290 GHz, λ ~ 1mm, resolution ~ 0.03”
thermal dust

ALMA (NRAO/ESO/NAOJ); C. Brogan, B. Saxton (NRAO/AUI/NSF)

B. Saxton, W. Cotton and R. Perley (NRAO/AUI/NSF)

Her A, ν ~ 6.5 GHz, λ ~ 5 cm, resolution ~ 0.5”
nonthermal synchrotron

Digression - some definitions that might cause confusion

Too Many Kinds of Temperature

physical T

excitation T_{ex}

brightness T_B

antenna T_A

receiver T_{rec}

system T_{sys}

$$B(\nu, T) = B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/k_B \boxed{T}} - 1}$$

Planck function

Maxwell-Boltzmann velocity dist.

$$f(v) = 4\pi n \left(\frac{m}{2\pi k_B \boxed{T}}\right)^{3/2} v^2 e^{-mv^2/2k_B \boxed{T}}$$

kinetic temperature

Too Many Kinds of Temperature

physical T

excitation T_{ex}

brightness T_B

antenna T_A

receiver T_{rec}

system T_{sys}

$$n_2/n_1 = (g_2/g_1)e^{-h\nu_o/K\boxed{T_{\text{ex}}}}$$

This one describes the relative populations of two energy levels, in a collection of atoms/molecules/ions.

T_{ex} may or may not be equal to T, depending on how well-behaved your particles are.

Too Many Kinds of Temperature

- physical T
- excitation T_{ex}
- **brightness T_B**
- antenna T_A
- receiver T_{rec}
- system T_{sys}

$$B_\nu(T) \simeq \frac{2\nu^2}{c^2} k_B T \quad \text{when} \quad h\nu \ll k_B T$$

Thus: we define T_B as a scaled version of the specific intensity.

$$I_\nu = 2\frac{\nu^2}{c^2} k_B \boxed{T_B}$$

for thermal rad, $\tau < 1$, low ν: $T_B < T$

nonthermal rad: T_B can do whatever it wants since T is not meaningful

Too Many Kinds of Temperature

physical T

excitation T_{ex}

brightness T_B

antenna T_A

receiver T_{rec}

system T_{sys}

kT_A is the power delivered by a thermal source at the input of the receiver (e.g. if you replaced the whole antenna/dish with a resistor).

So T_A is a measure of how bright your source is & how it couples to your telescope beam. $T_A < T_B$ because of efficiency of telescope.

tricky units note: J = W Hz^{-1}
erg = erg s^{-1} Hz^{-1}

Too Many Kinds of Temperature

physical T

excitation T_{ex}

brightness T_B

antenna T_A

receiver T_{rec}

system T_{sys}

These quantify the noise that will be contributed to your measurement by emission from the receiver, dish, atmosphere, etc.

Generally want them to be as small as possible.

At high frequencies T_{sys} is strongly weather-dependent.

Too Many Kinds of Temperature

physical T

excitation T_{ex}

brightness T_B

antenna T_A

receiver T_{rec}

system T_{sys}

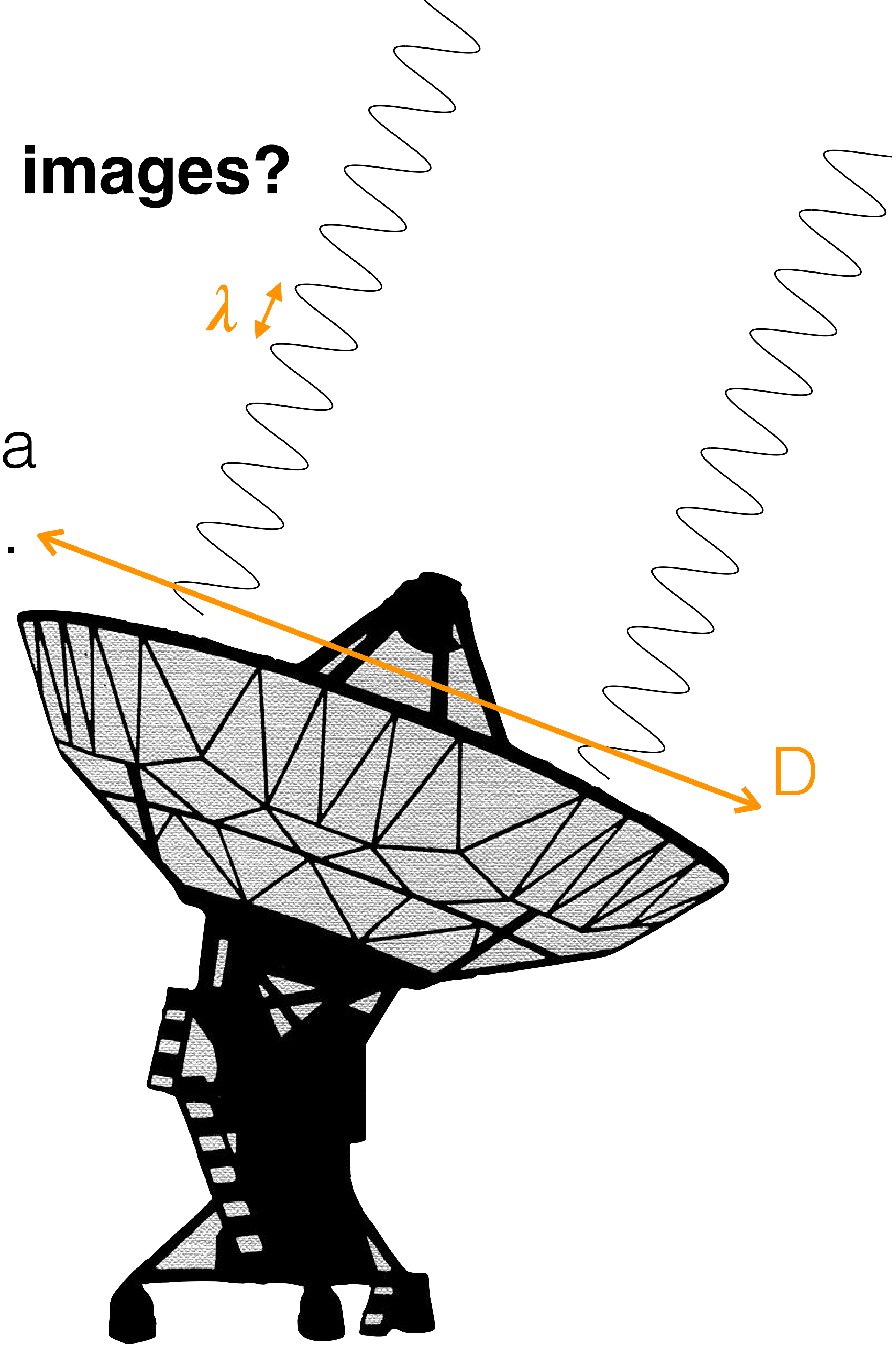
system temperature is particularly important because

$$\Delta T_{\mathrm{RMS}} = \frac{T_{\mathrm{sys}}}{\sqrt{\Delta\nu\,\tau}}$$

rms temperature fluctuations in your measurement scale with T_{sys}.

Increasing bandwidth ($\boldsymbol{\Delta\nu}$) and integration time (τ) helps.

How did we make those images?



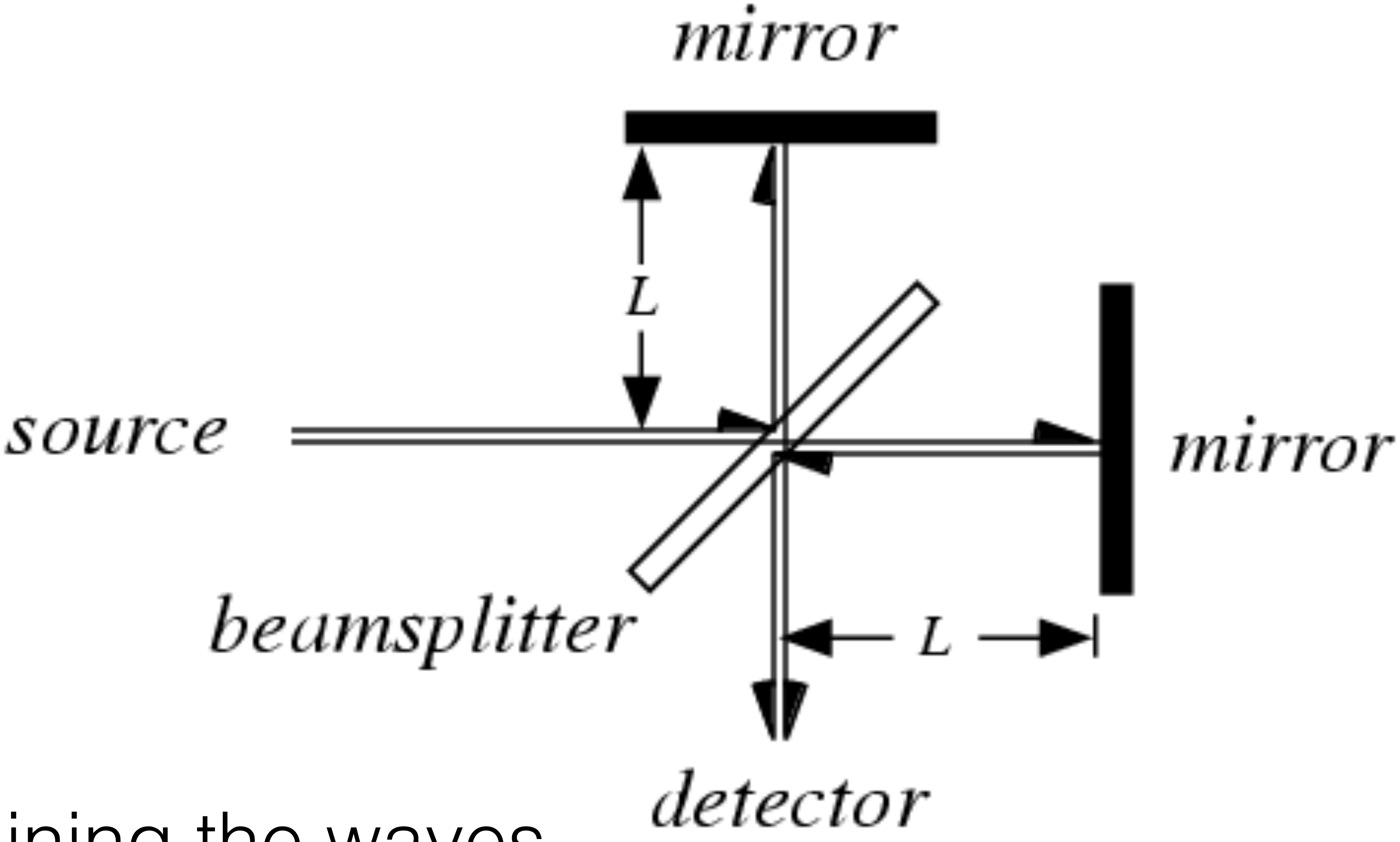
Diffraction theory: this telescope (by itself) has a resolution ~ λ/D radians.

How can we do better than that?

with an interferometer.

An adding interferometer

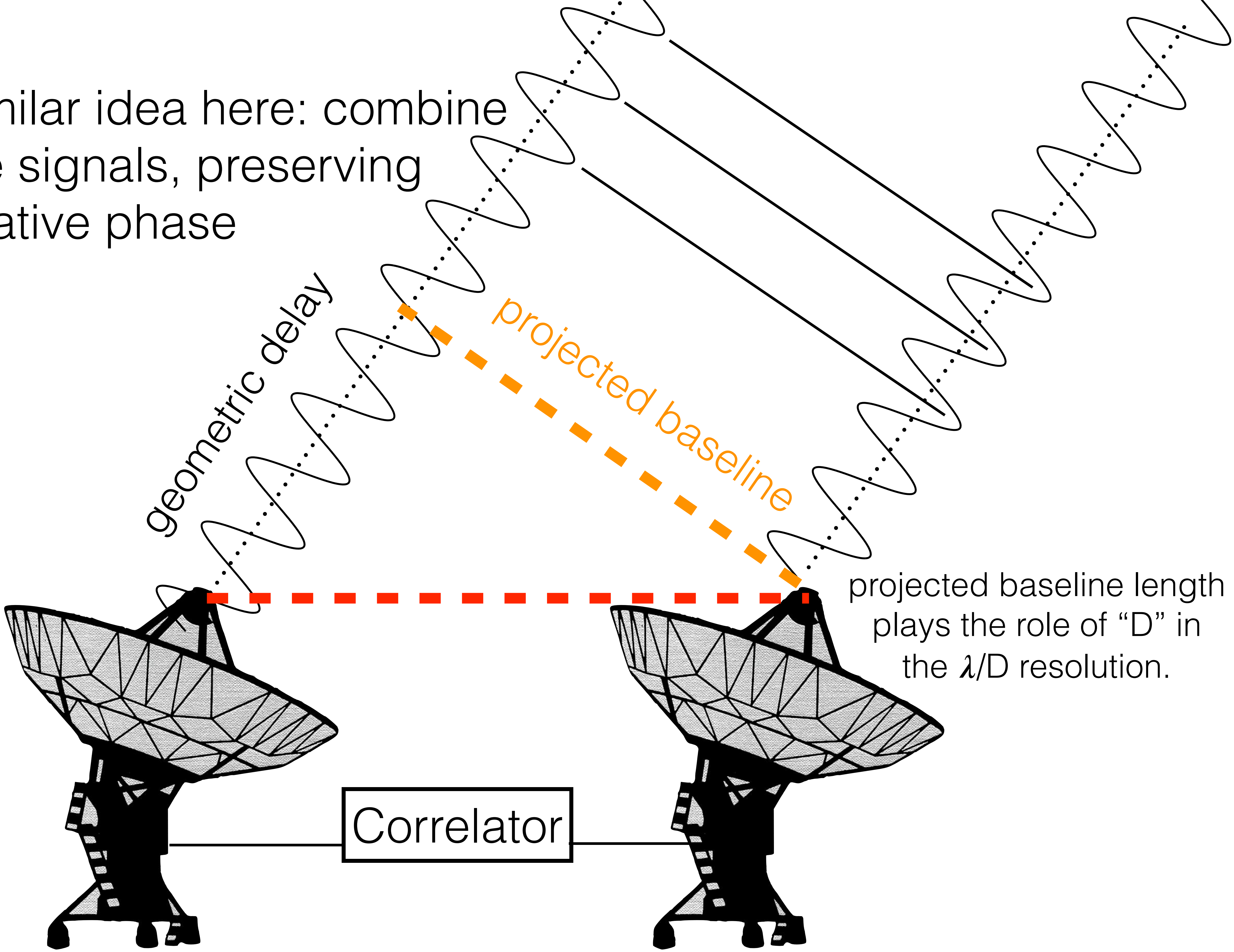
(e.g. Michelson-Morley experiment; LIGO)



Leonardo Motta, scienceworld.wolfram.com

Combining the waves gives exquisite sensitivity to path length differences.

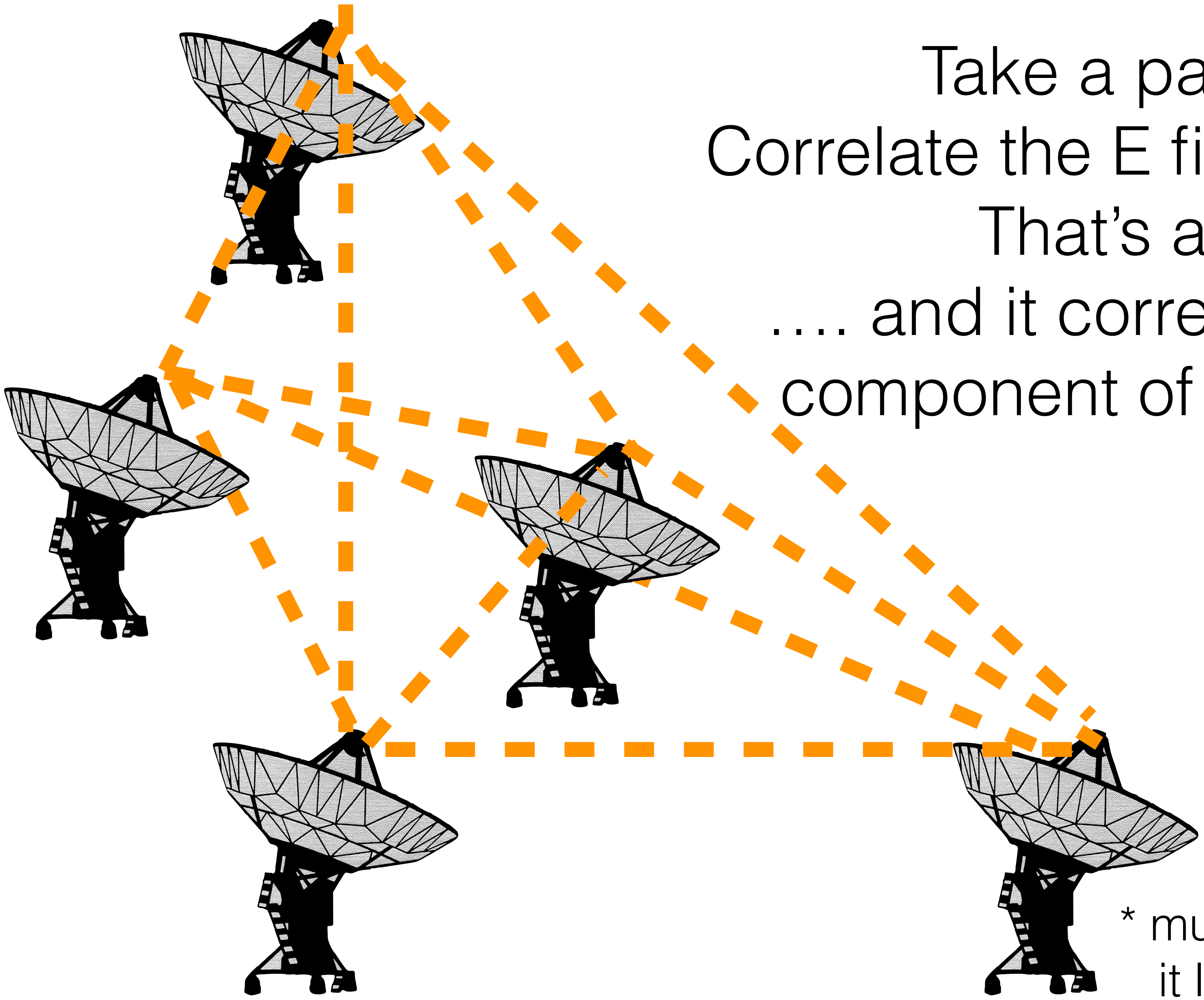
Similar idea here: combine the signals, preserving relative phase



projected baseline length plays the role of "D" in the λ/D resolution.

Interferometer theory, very loosely.

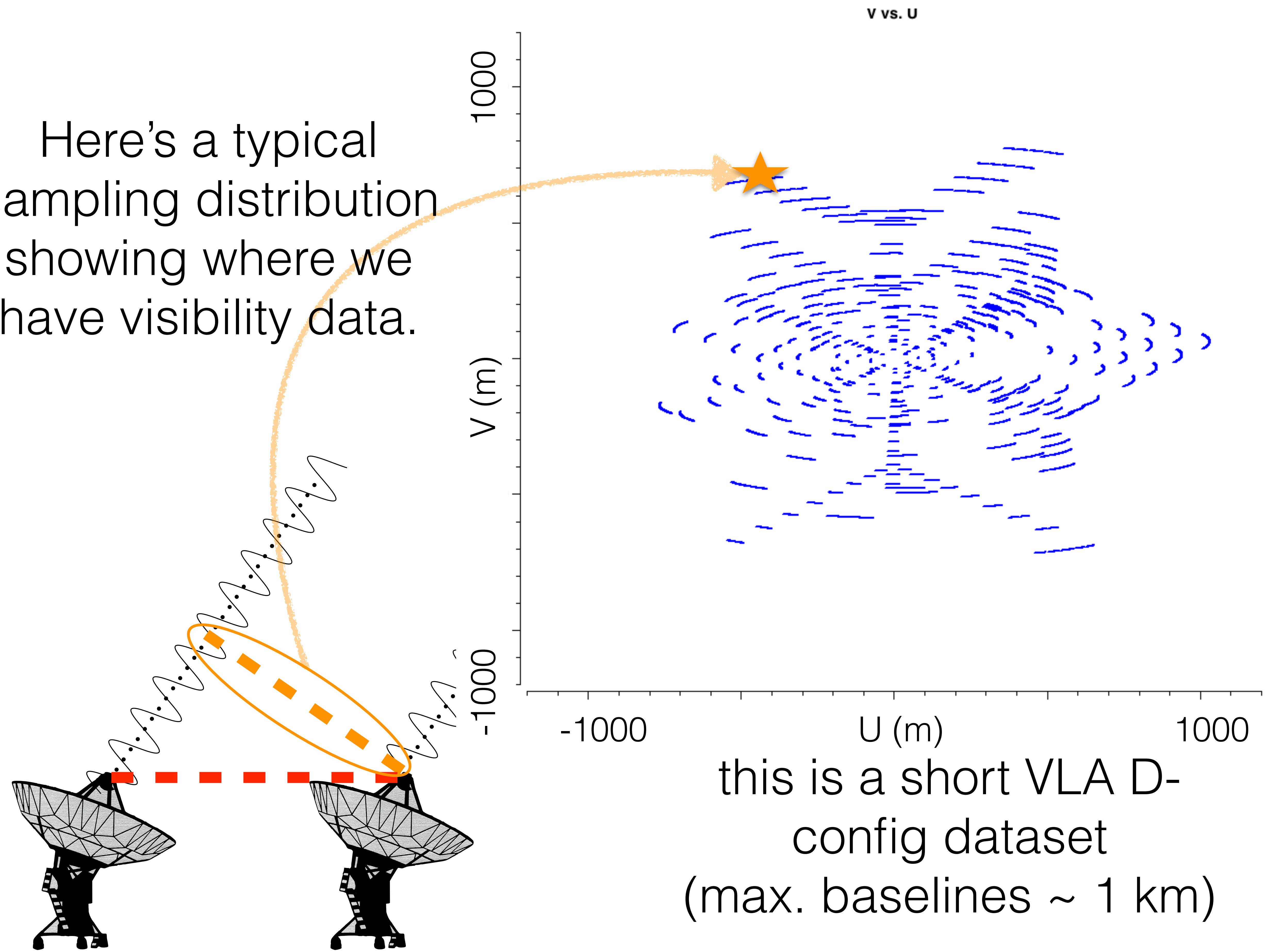
correlation* of E field at Earth = FT of brightness distribution of the sky.



Take a pair of antennas.
Correlate the E fields at each antenna.
That's a "visibility"…
…. and it corresponds to a Fourier component of the sky brightness.

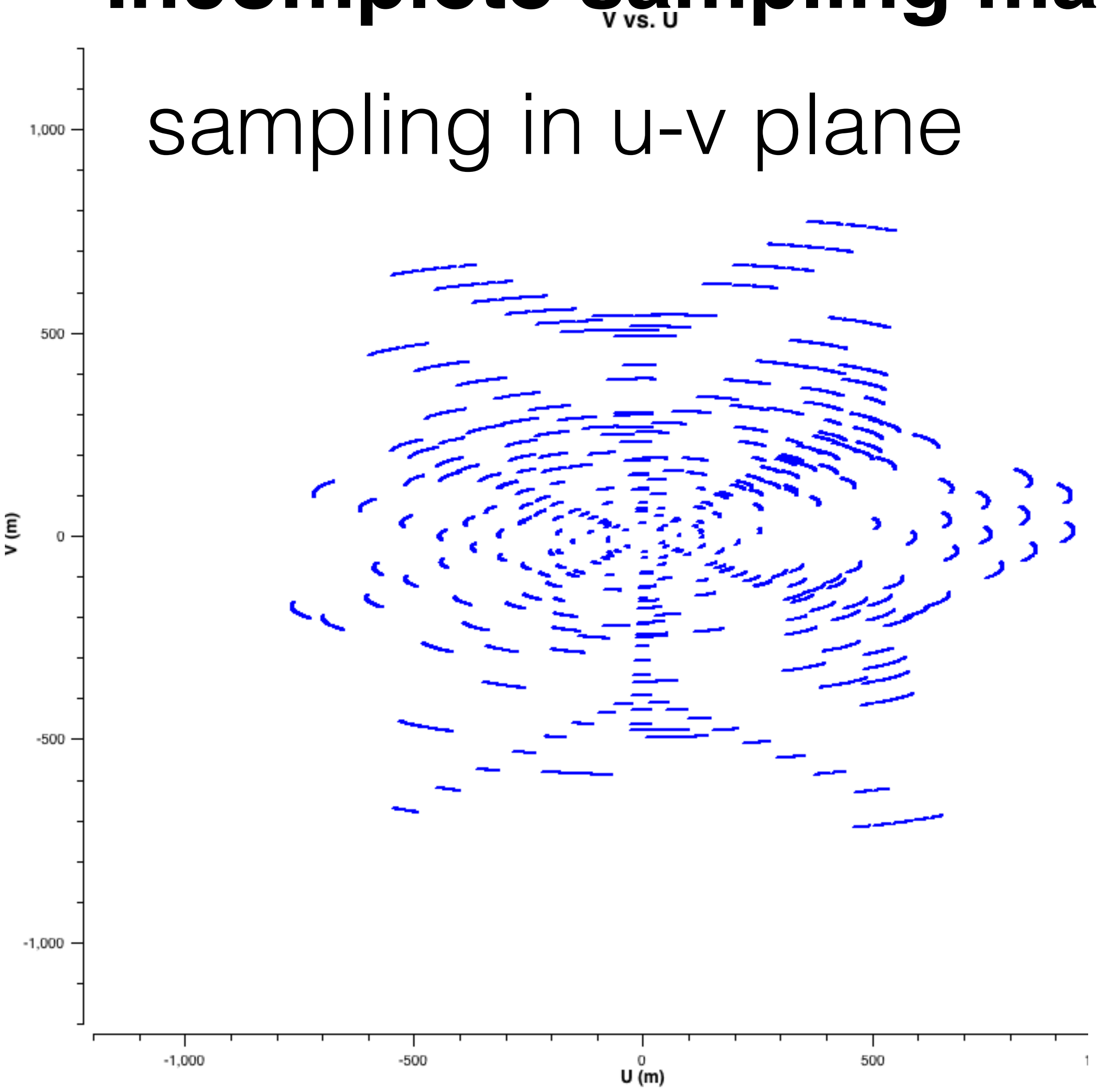
* mutual coherence function, but it looks a lot like a correlation

Here’s a typical sampling distribution showing where we have visibility data.



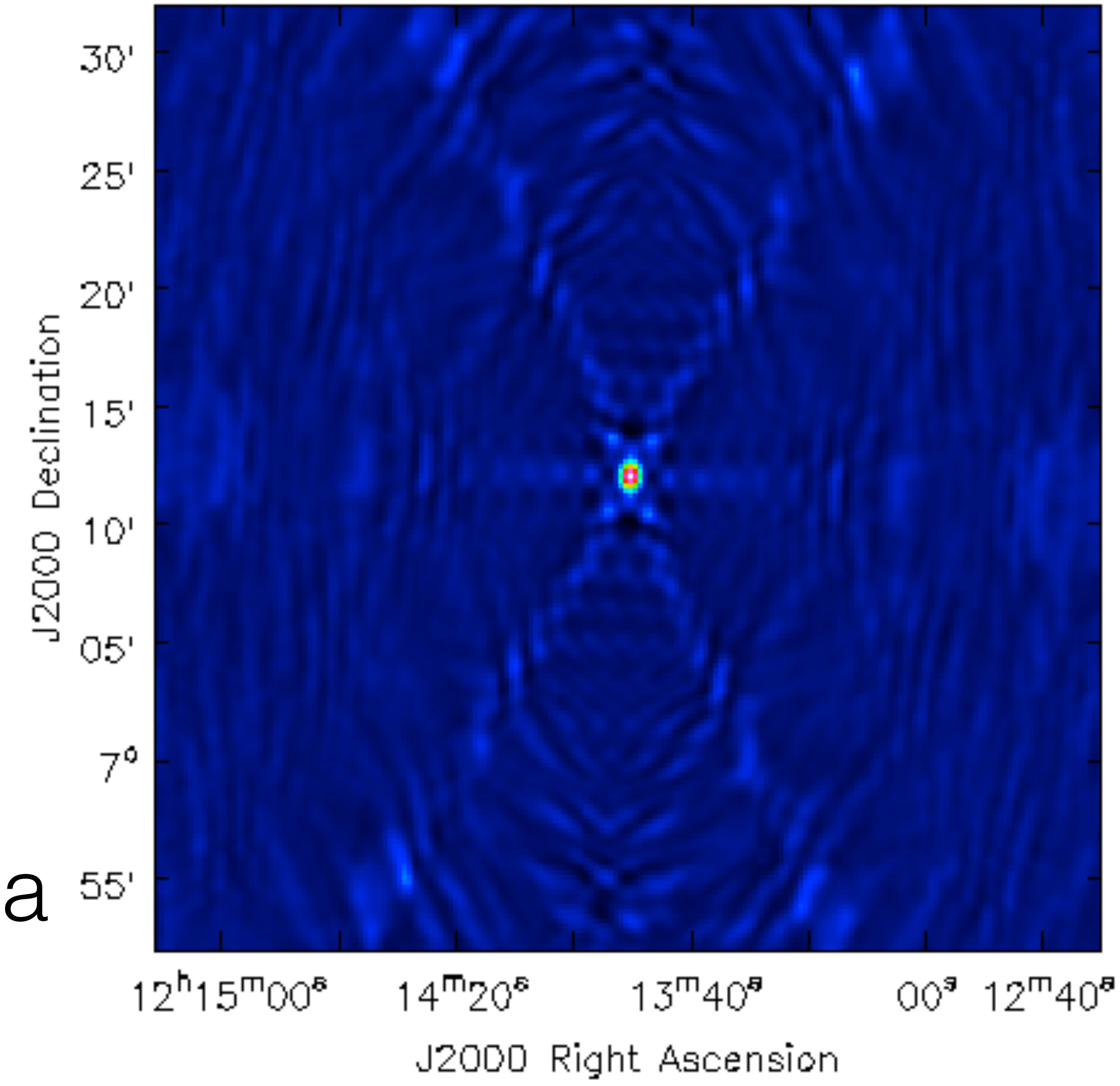
this is a short VLA D-config dataset (max. baselines ~ 1 km)

Incomplete sampling makes artifacts in our images.



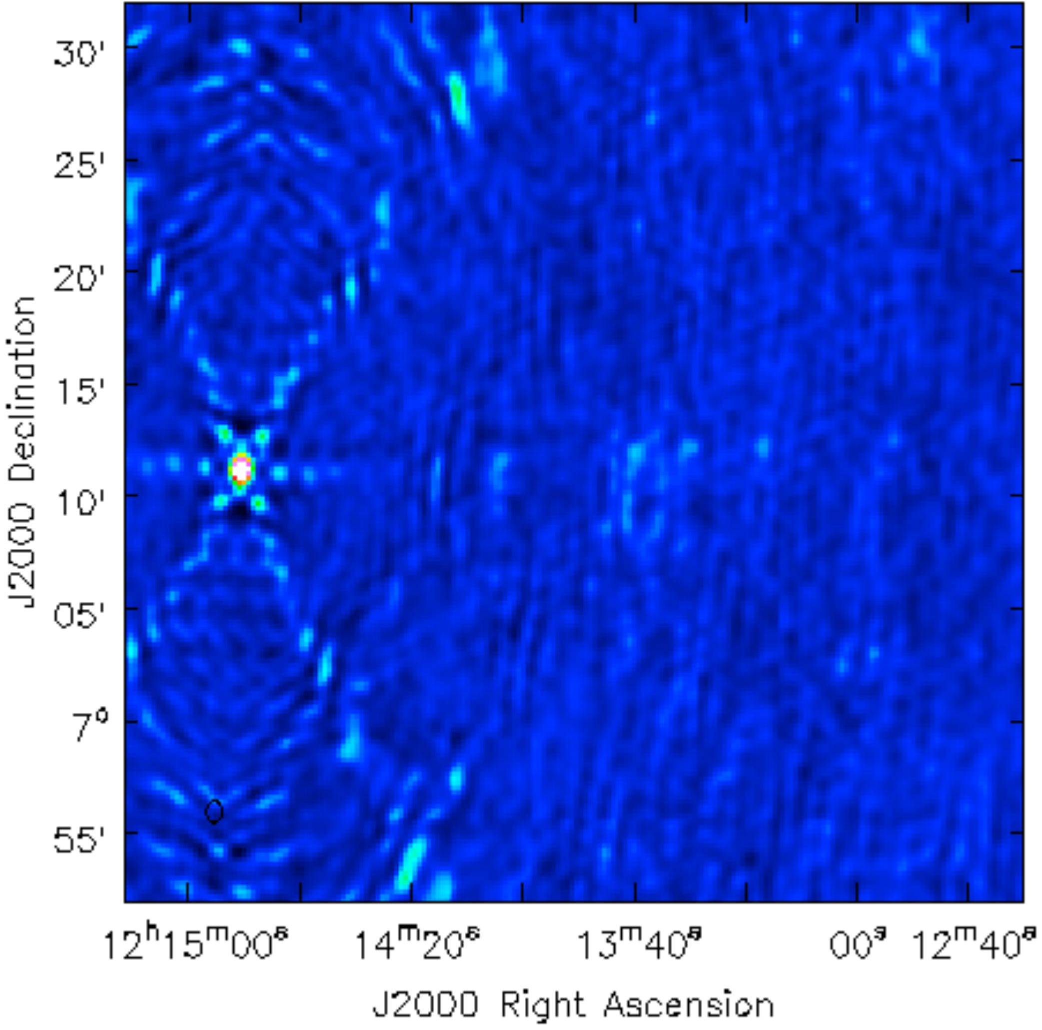
sampling in u-v plane

Fourier Transform



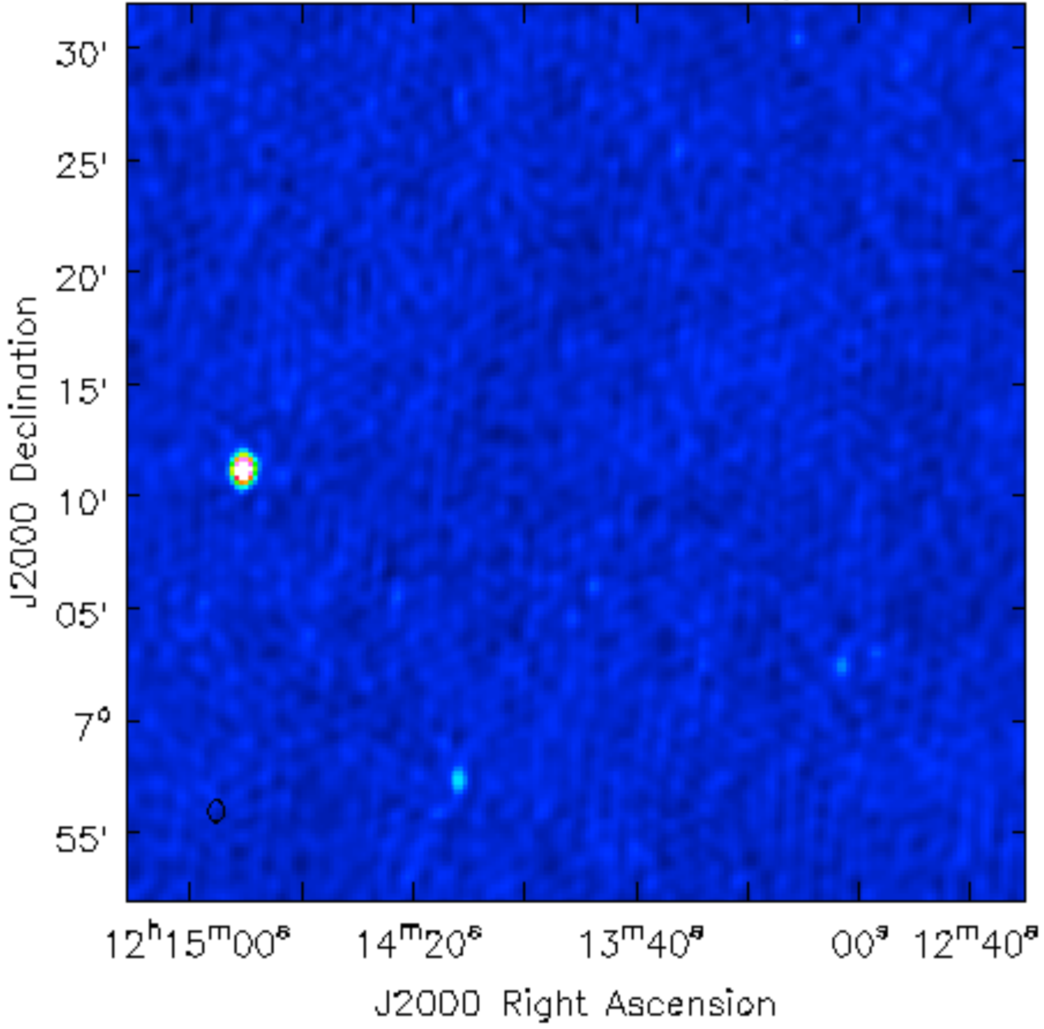
“dirty beam” (PSF) = response of the system to a point source

FT of visibility data

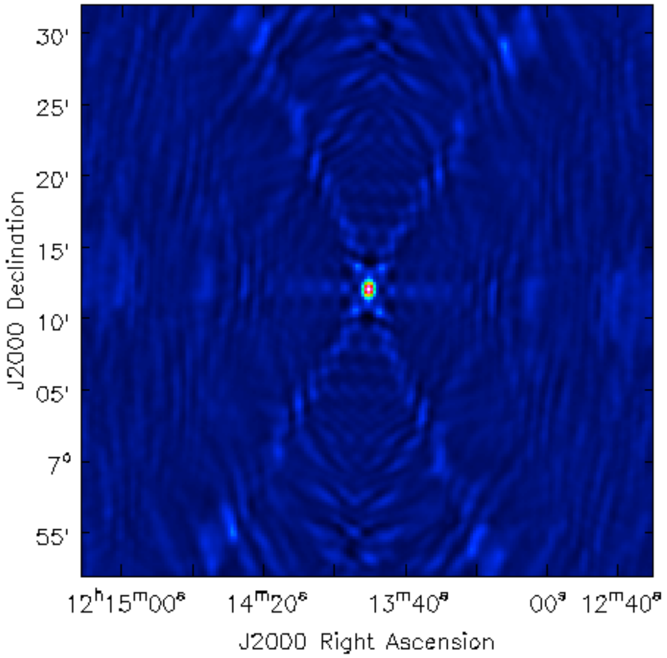


Deconvolution (cleaning)

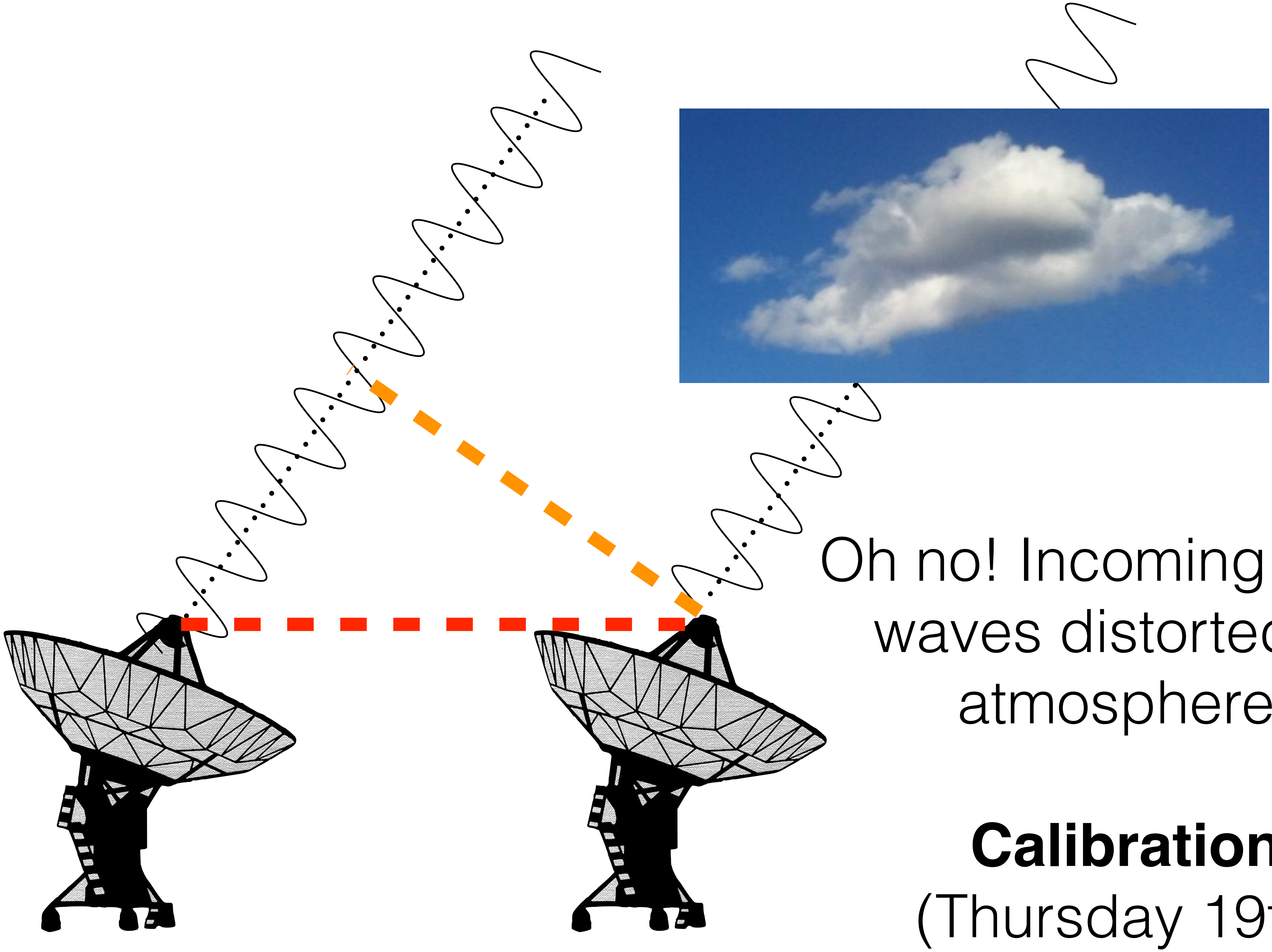
cleaned image



Cleaning up the artifacts

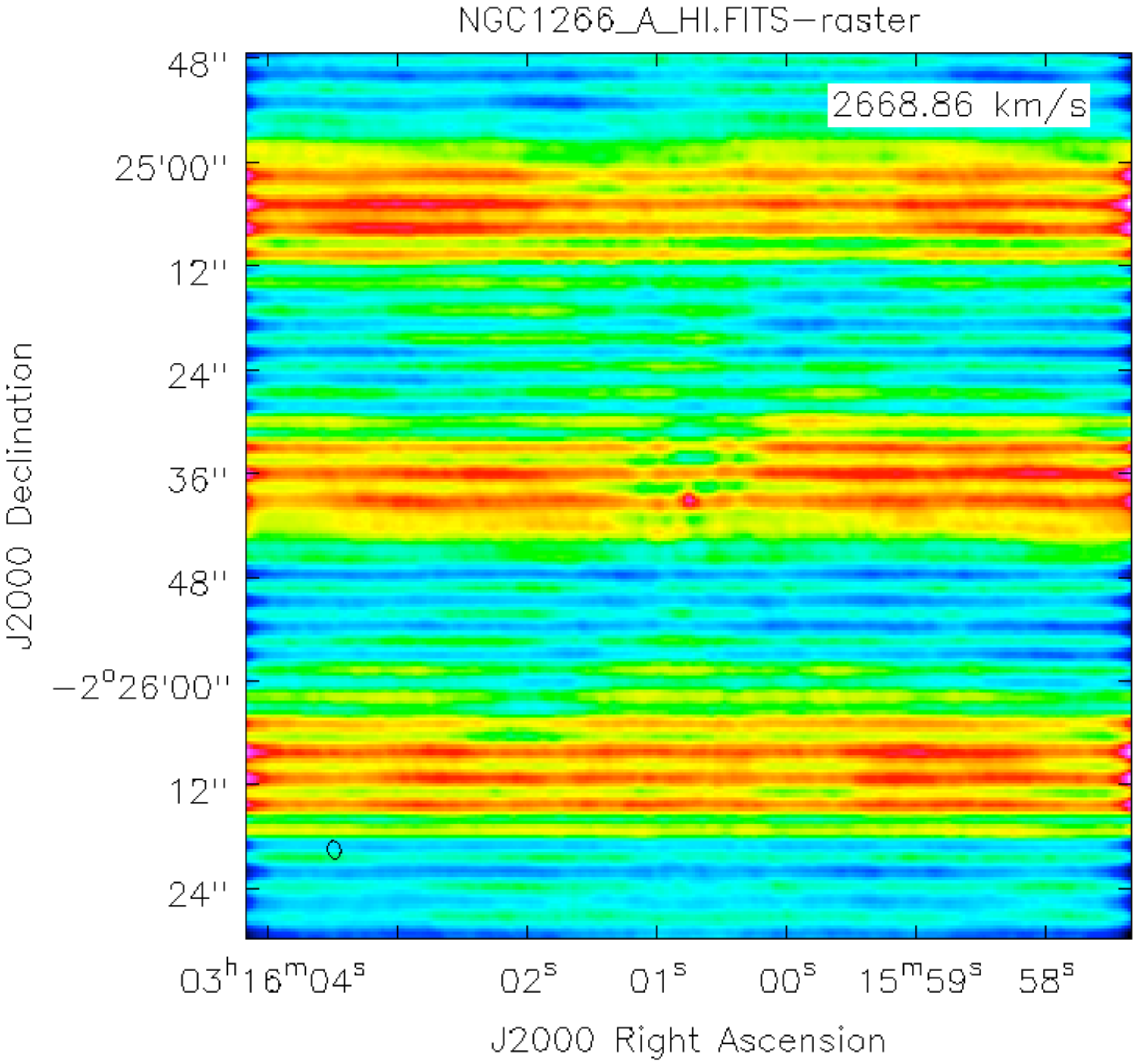


recall this is what point sources look like



Oh no! Incoming plane waves distorted by atmosphere!

Calibration
(Thursday 19th)



AAAAAAAA!!!
What happened
to my image?

Error Recognition
(Monday 23rd)

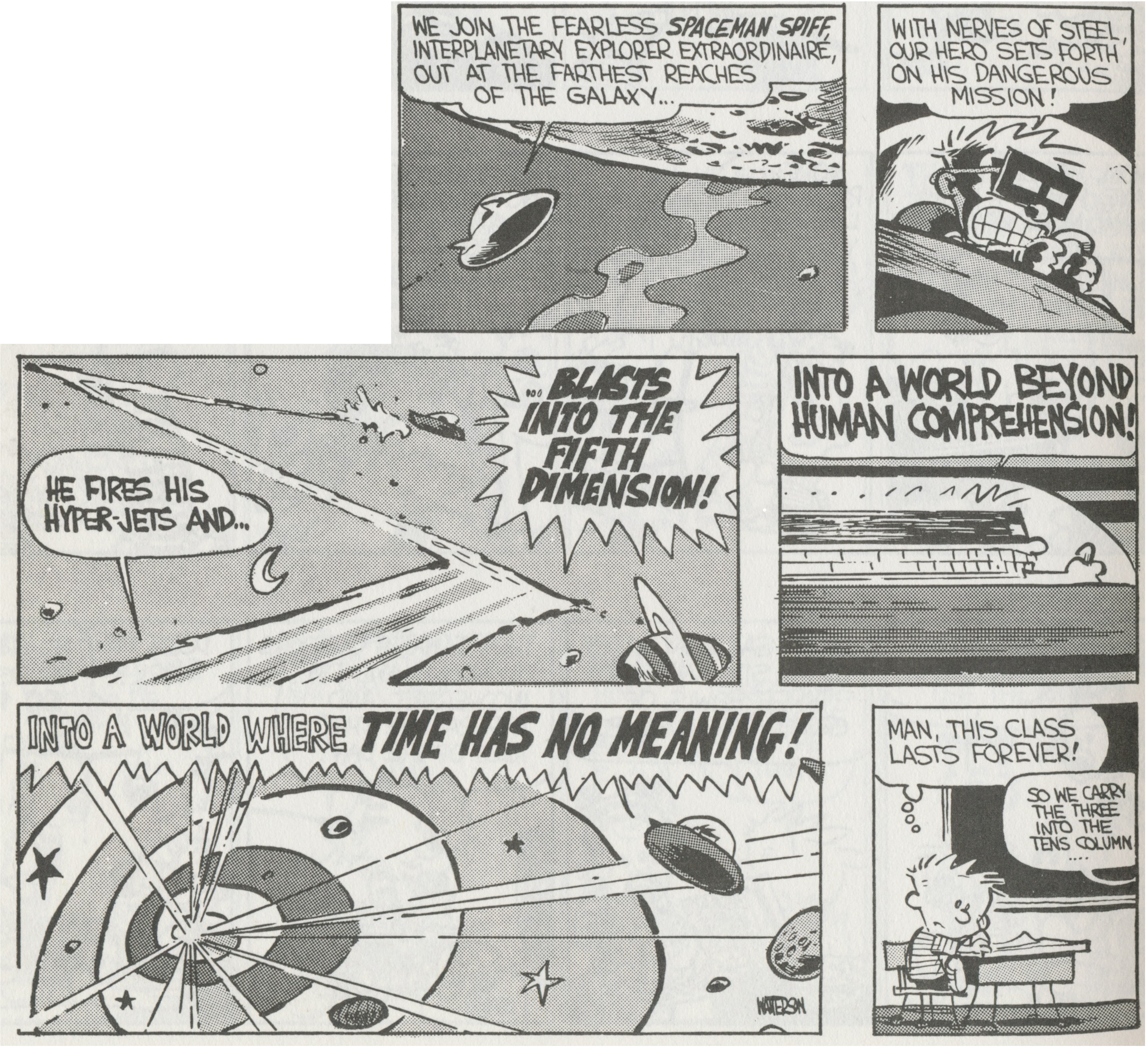
Other good books

“What am I looking at?”

Rybicki & Lightman *Radiative Processes in Astrophysics*
Longair *High Energy Astrophysics*

“How did you make those images?”

Rohlfs & Wilson *Tools of Radio Astronomy*
Thompson, Moran & Swenson *Interferometry & Synthesis in Radio Astronomy*


WE JOIN THE FEARLESS SPACEMAN SPIFF, INTERPLANETARY EXPLORER EXTRAORDINAIRE, OUT AT THE FARTHEST REACHES OF THE GALAXY...
WITH NERVES OF STEEL, OUR HERO SETS FORTH ON HIS DANGEROUS MISSION!
HE FIRES HIS HYPER-JETS AND...
...BLASTS INTO THE FIFTH DIMENSION!
INTO A WORLD BEYOND HUMAN COMPREHENSION!
INTO A WORLD WHERE TIME HAS NO MEANING!
WATTERSON
MAN, THIS CLASS LASTS FOREVER!
SO WE CARRY THE THREE INTO THE TENS COLUMN....