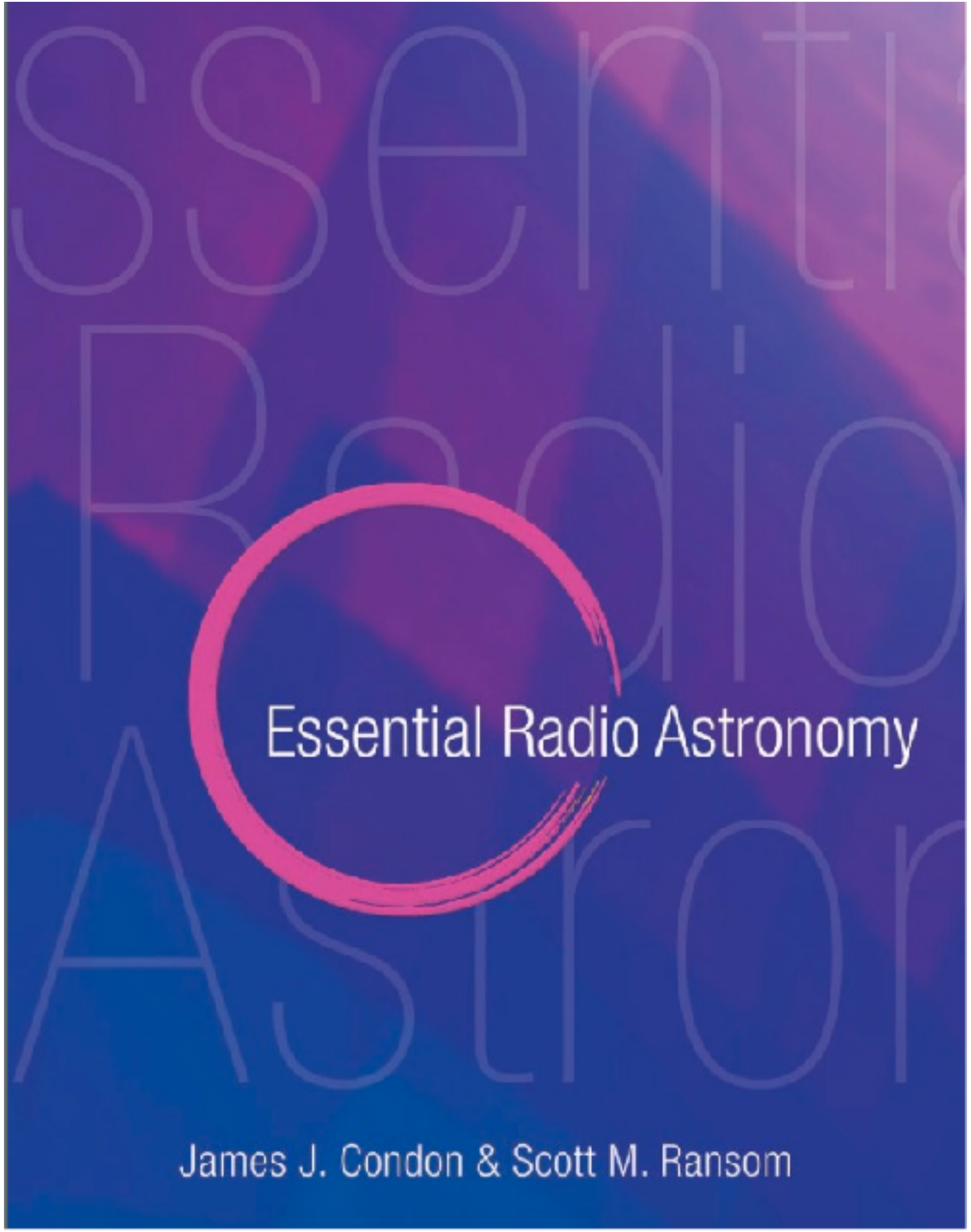
Basics of Radio Astronomy

Lisa Young (NMT)

Sixteenth Synthesis Imaging Workshop

16-23 May 2018

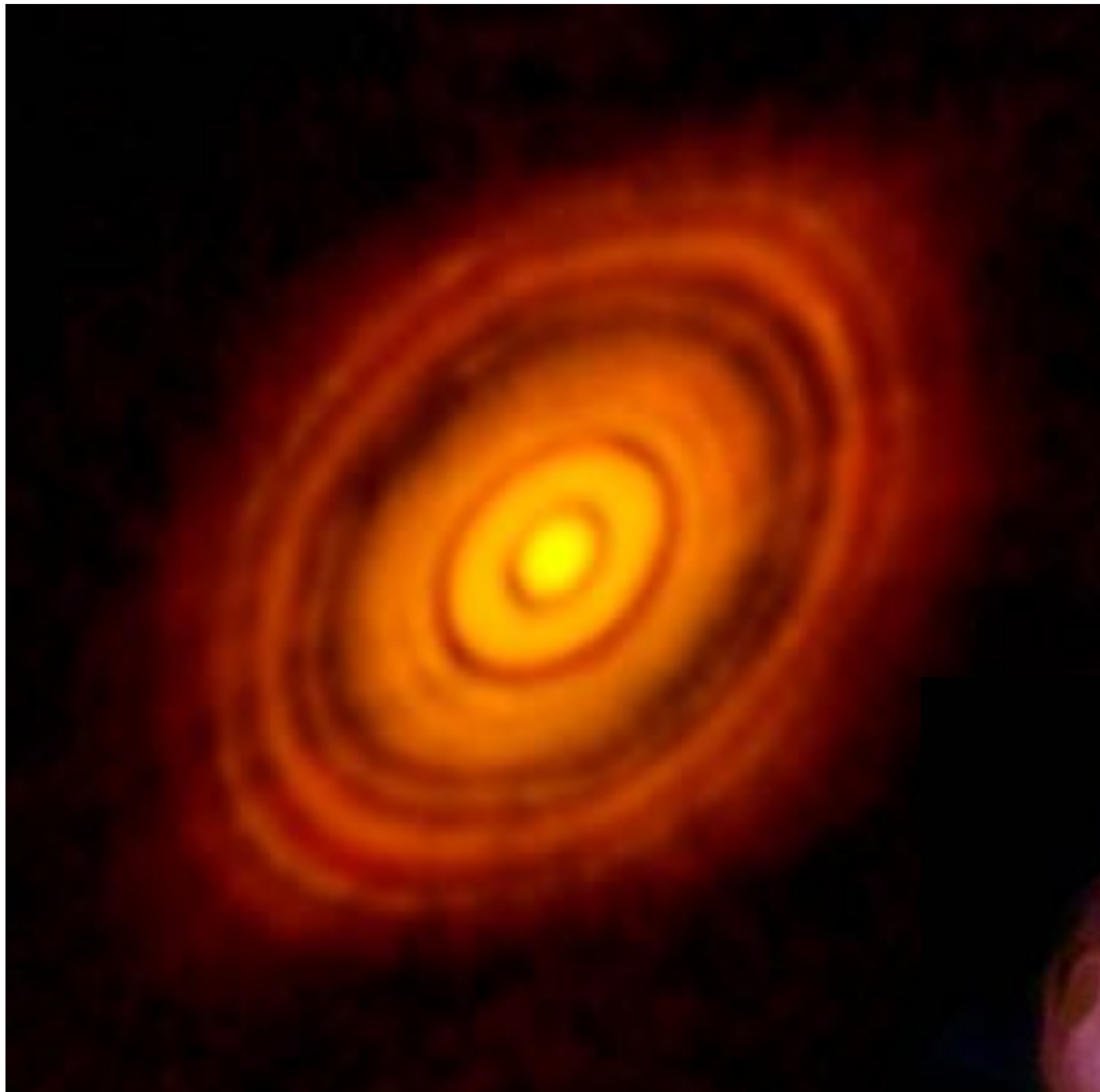

DON'T PANIC



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)

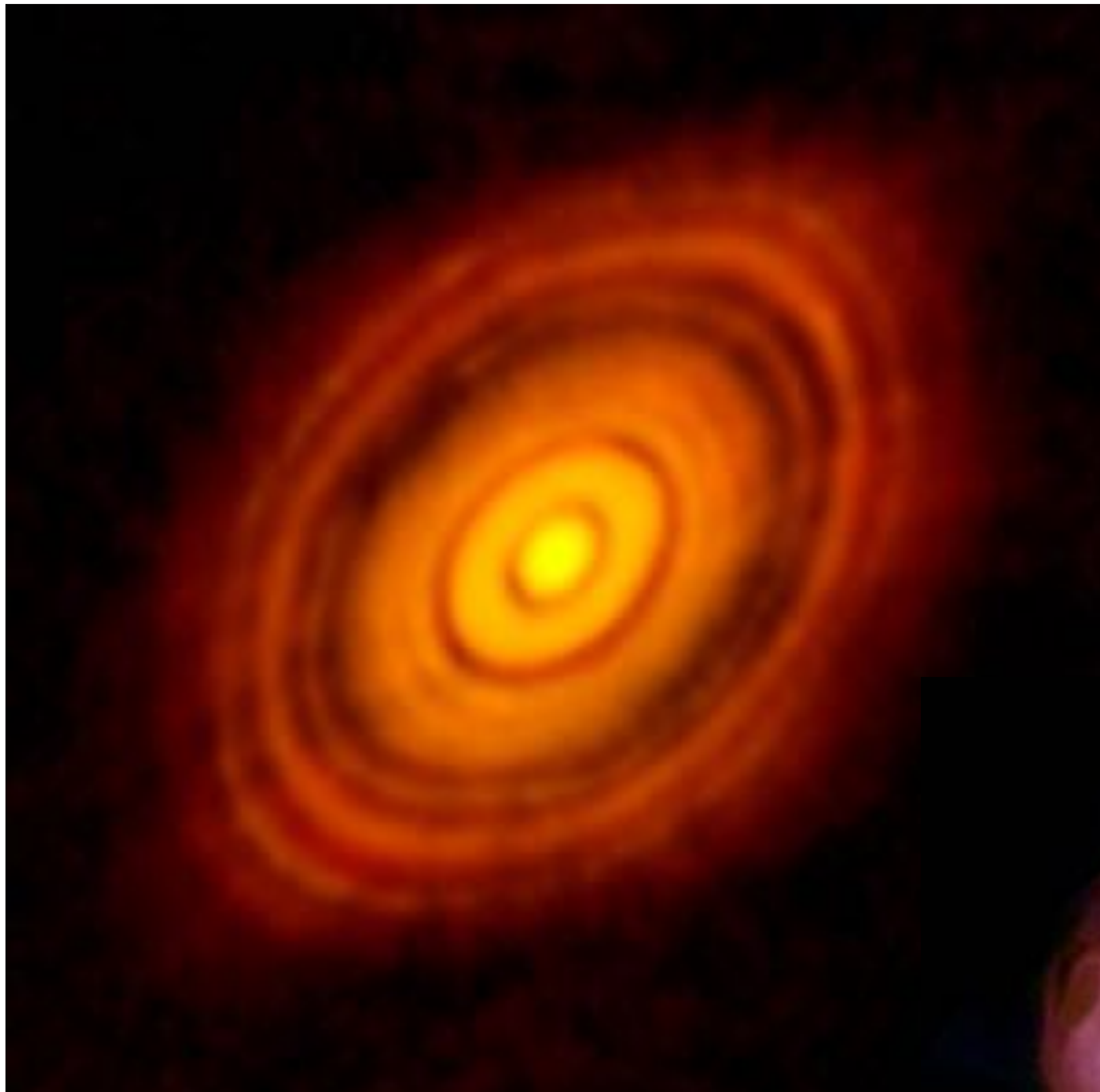
Q1. What are we looking at?

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



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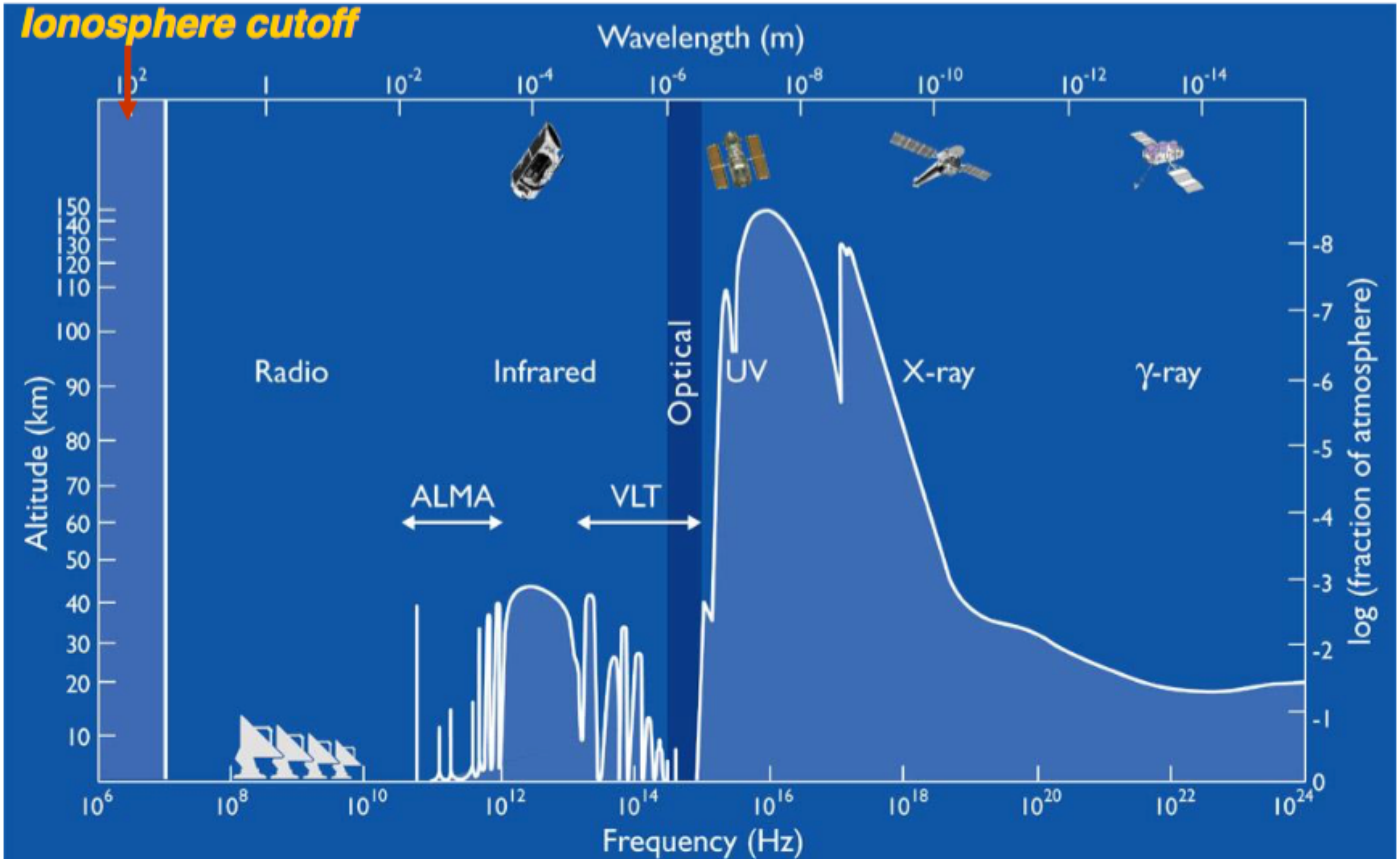
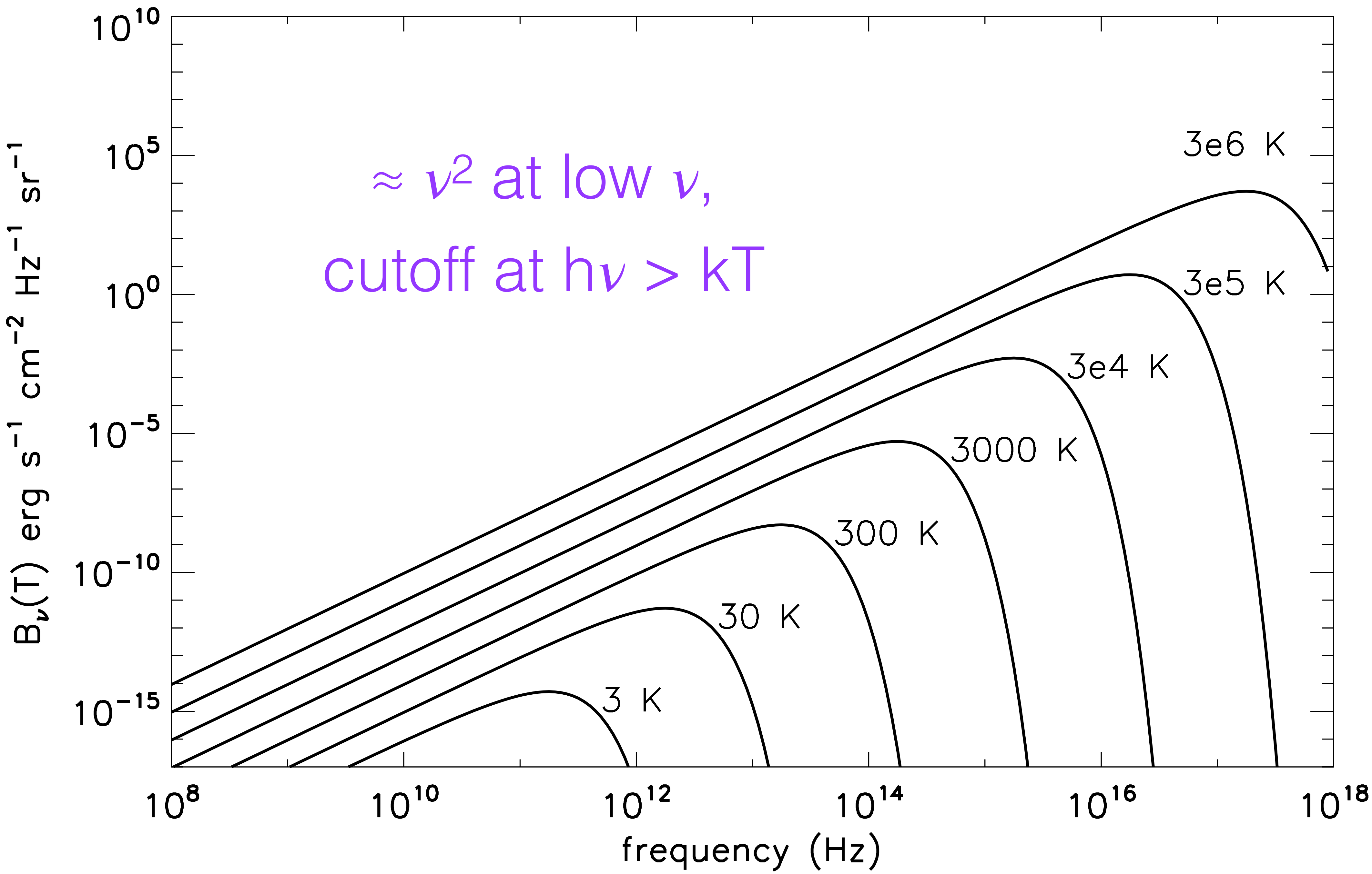
Opacity of the Atmosphere (solid line is altitude at which transmission is reduced by factor of 2)



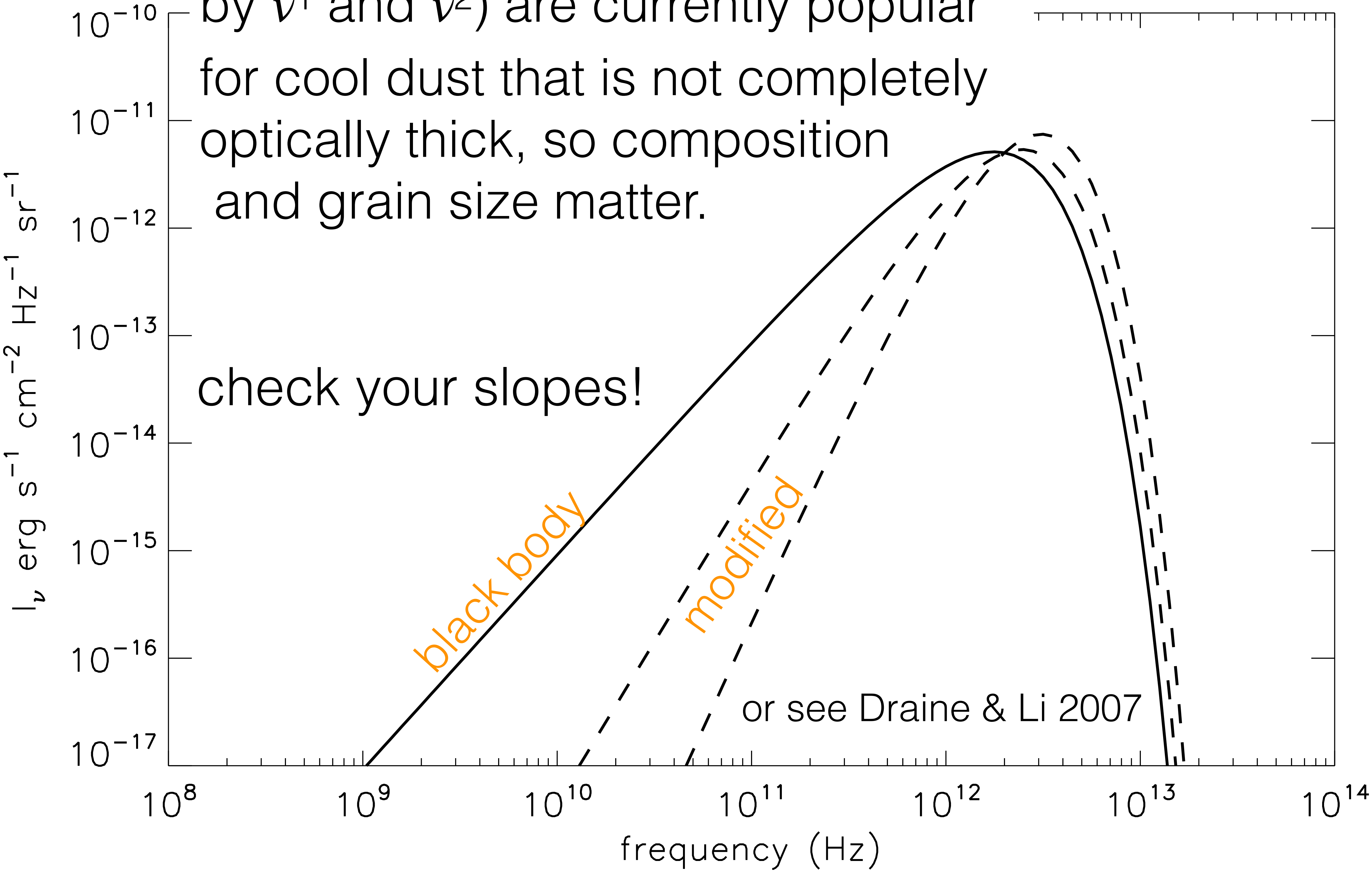
mm and sub-mm range

Black body emission has a characteristic shape.

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

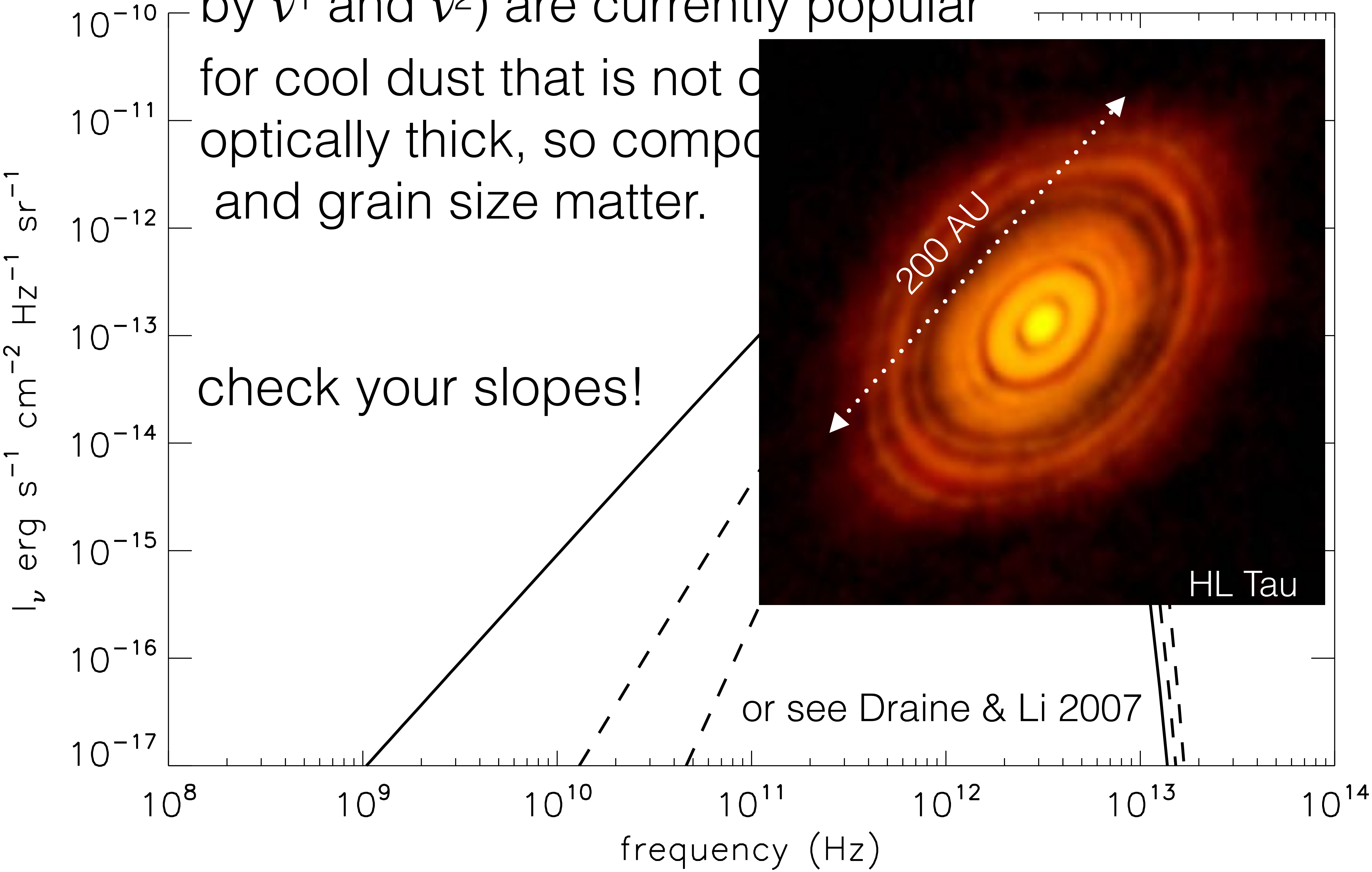


Modified black bodies (here scaled by ν^1 and ν^2) are currently popular for cool dust that is not completely optically thick, so composition and grain size matter.



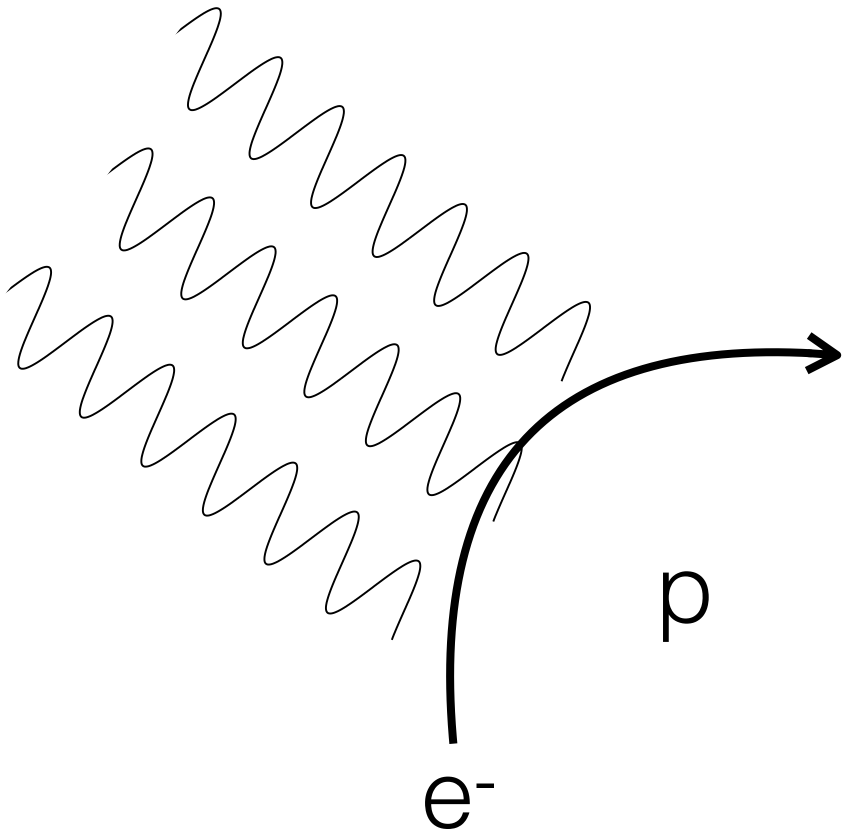
Modified black bodies (here scaled by ν^1 and ν^2) are currently popular for cool dust that is not o[...] optically thick, so compo[...] and grain size matter.

check your slopes!



or see Draine & Li 2007

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



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

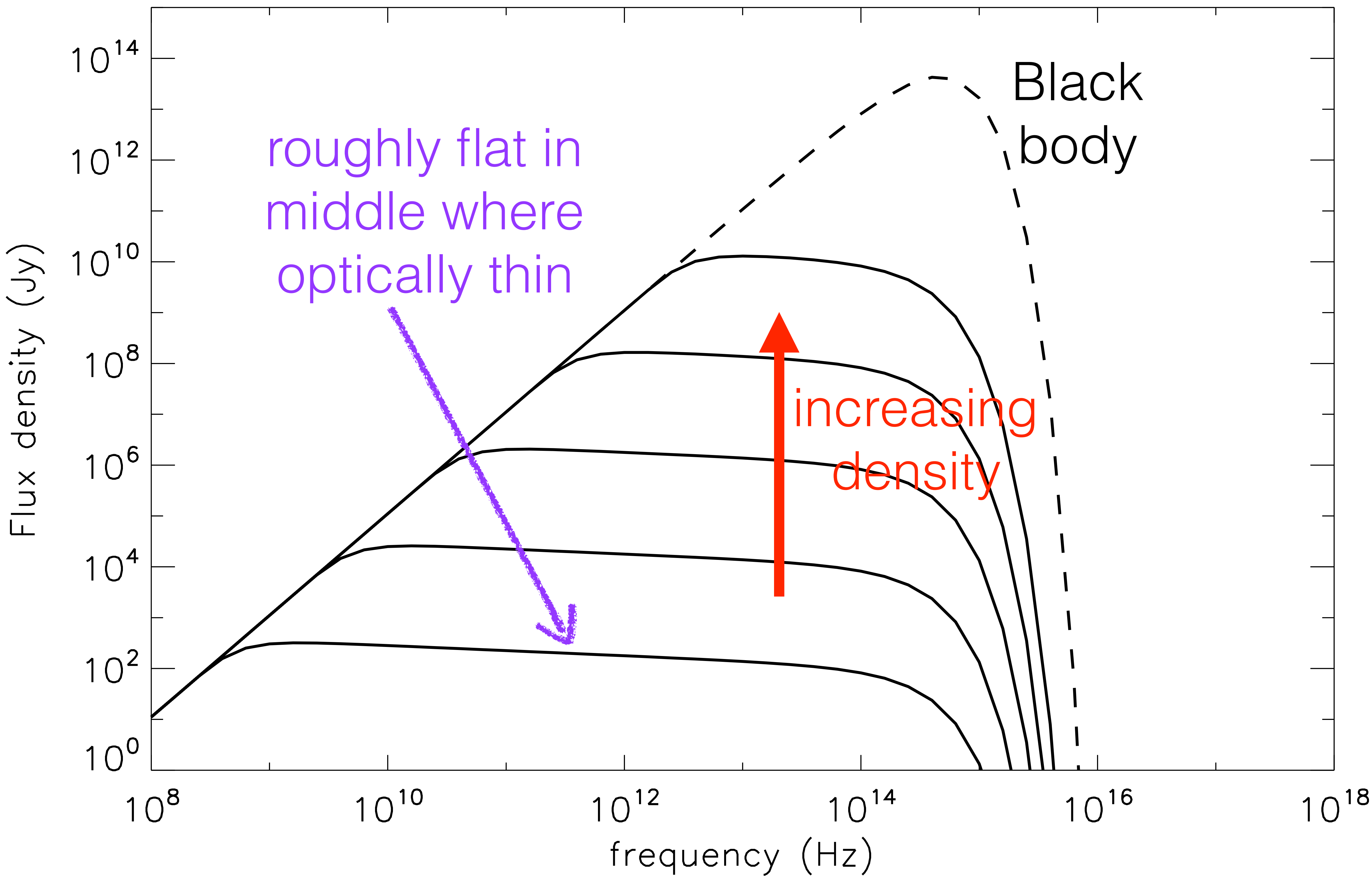
good for estimating density & temperature of ionized gas

- counting ionizing photons
- inferring star formation rate

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

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

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



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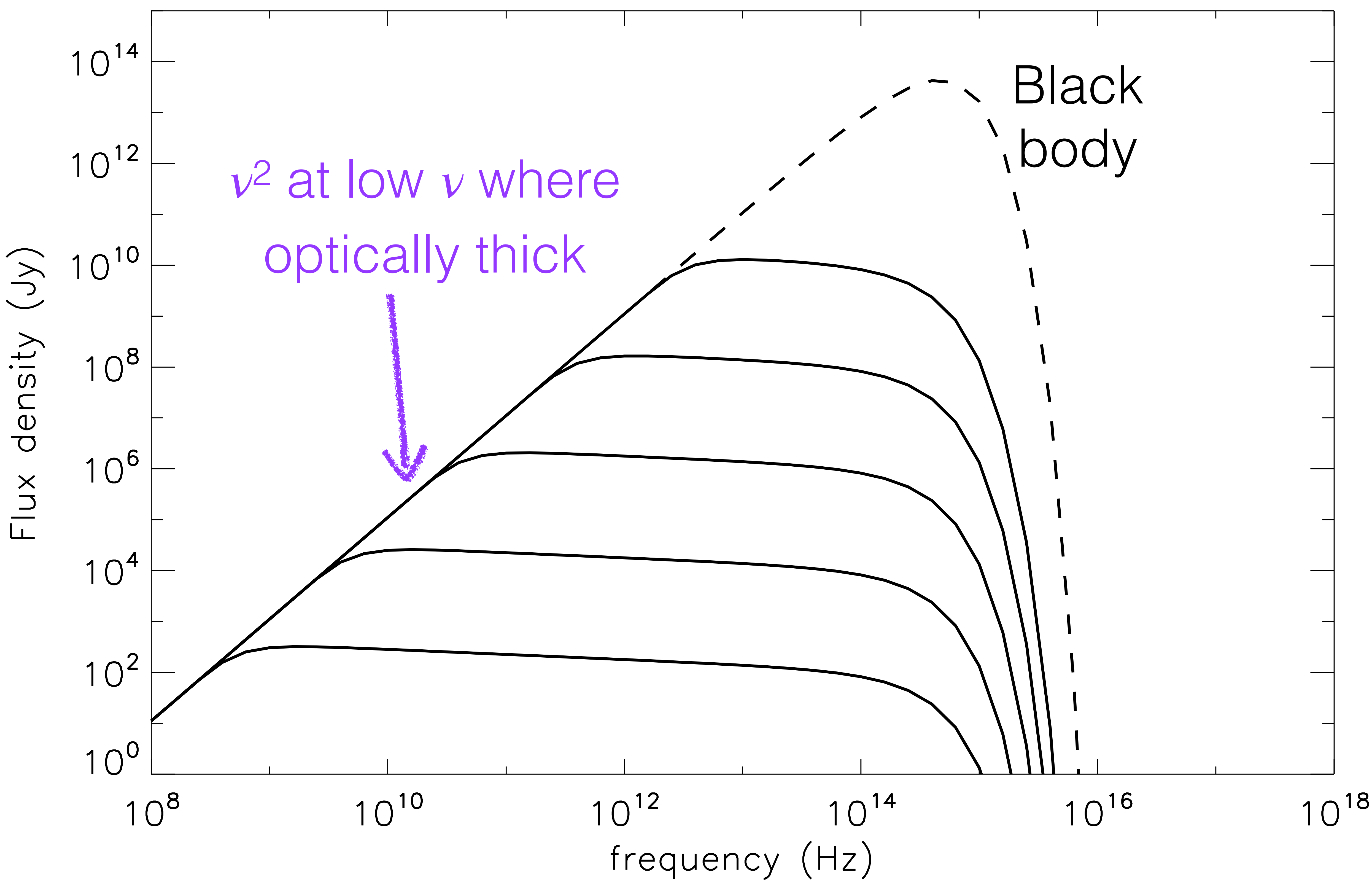
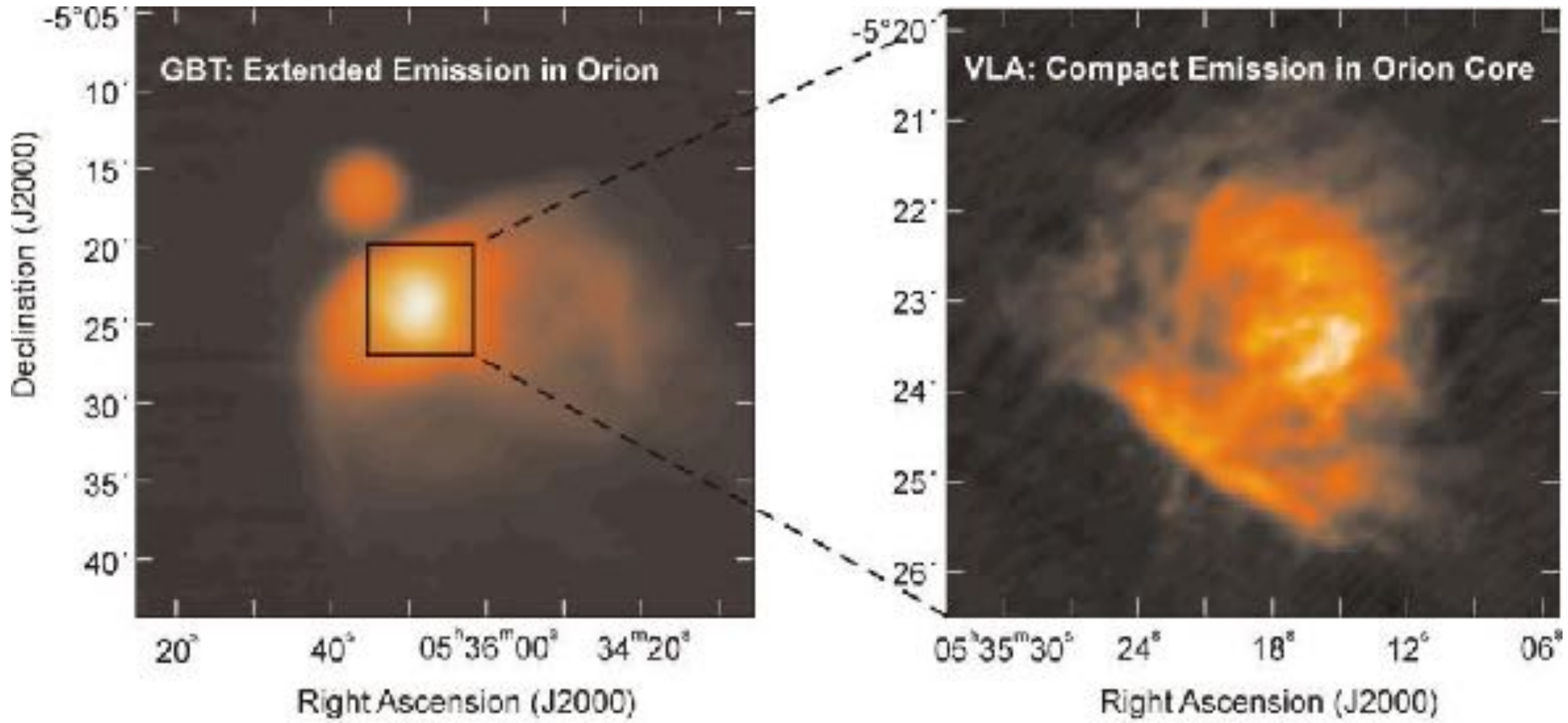
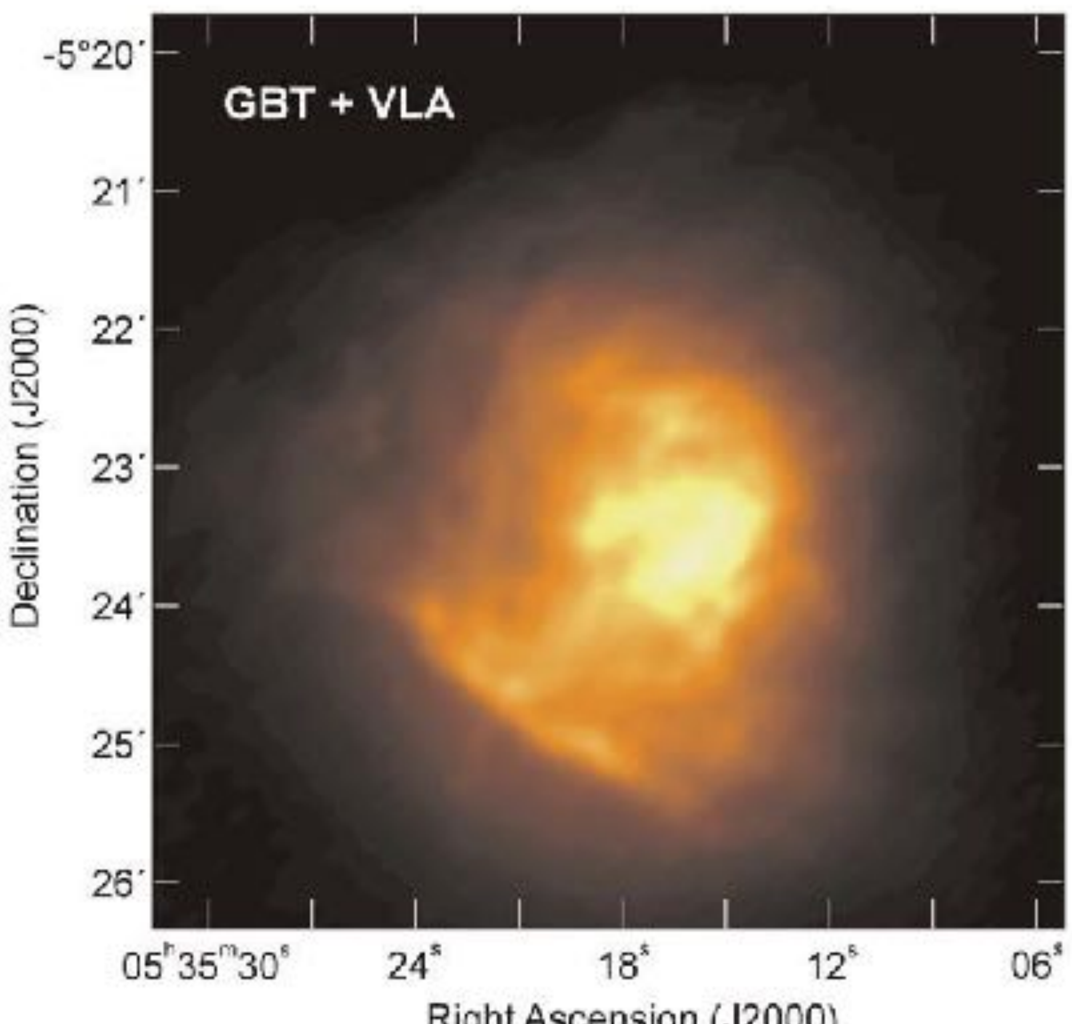




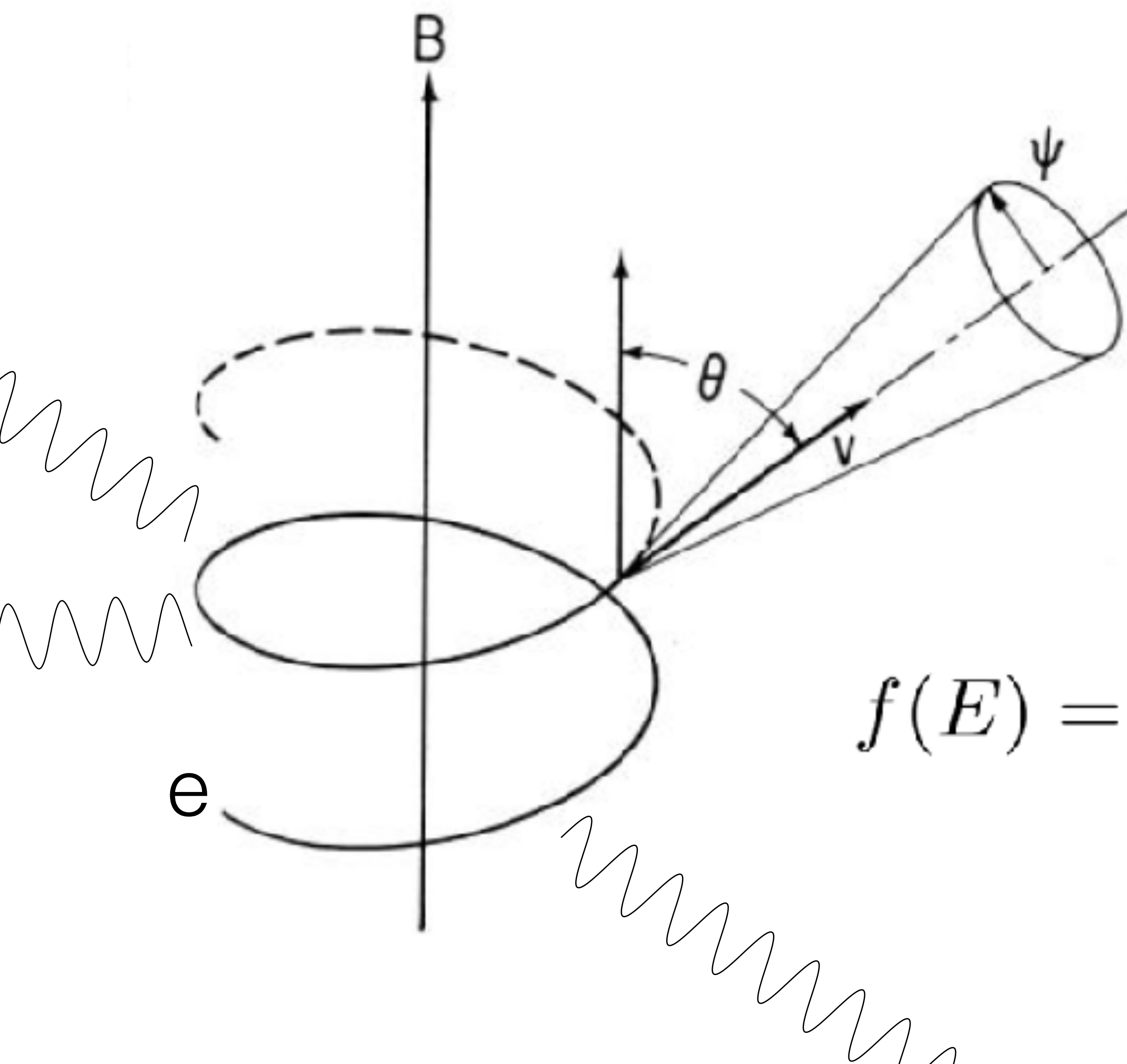
Orion Nebula
8.4 GHz
Dicker et al 2009



HST
optical

Synchrotron emission

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



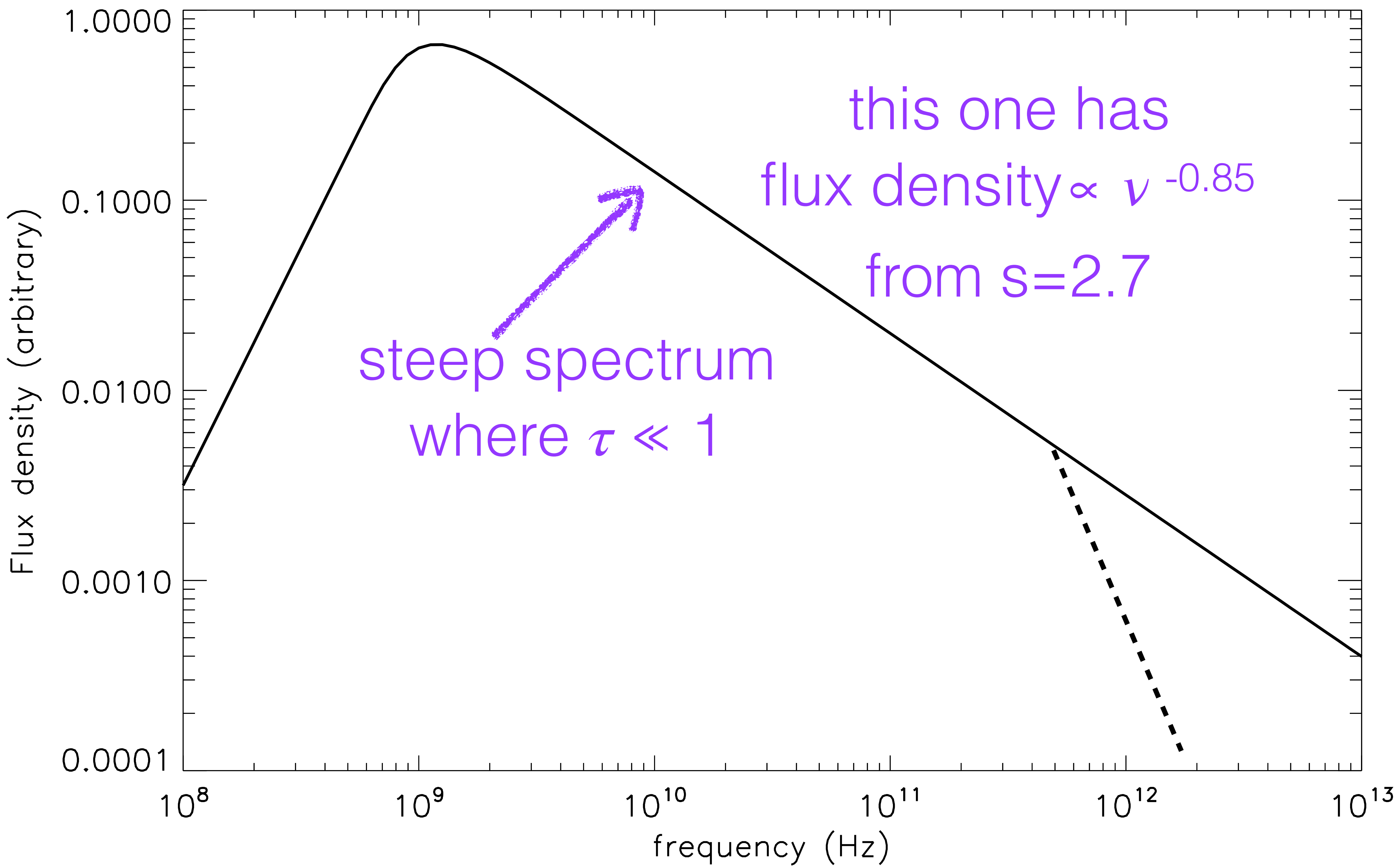
$$\nu_c = \frac{3}{4\pi}\gamma^2 \frac{eB}{mc}\sin\theta$$

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

$$j_{sy}(\nu) \propto P_o\, B^{(s+1)/2}\, f_o\, \nu^{-(s-1)/2}$$ + radiative transfer



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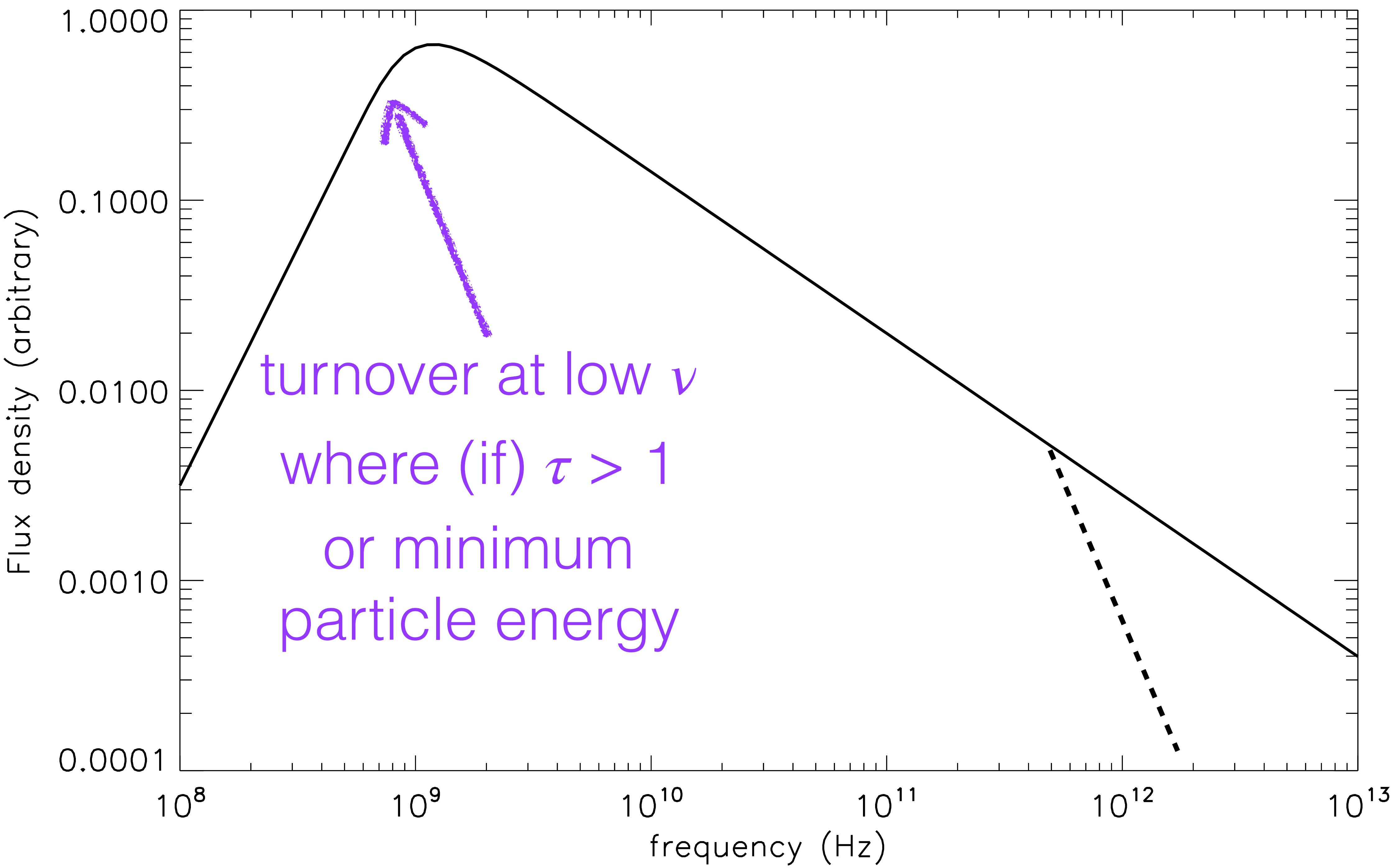

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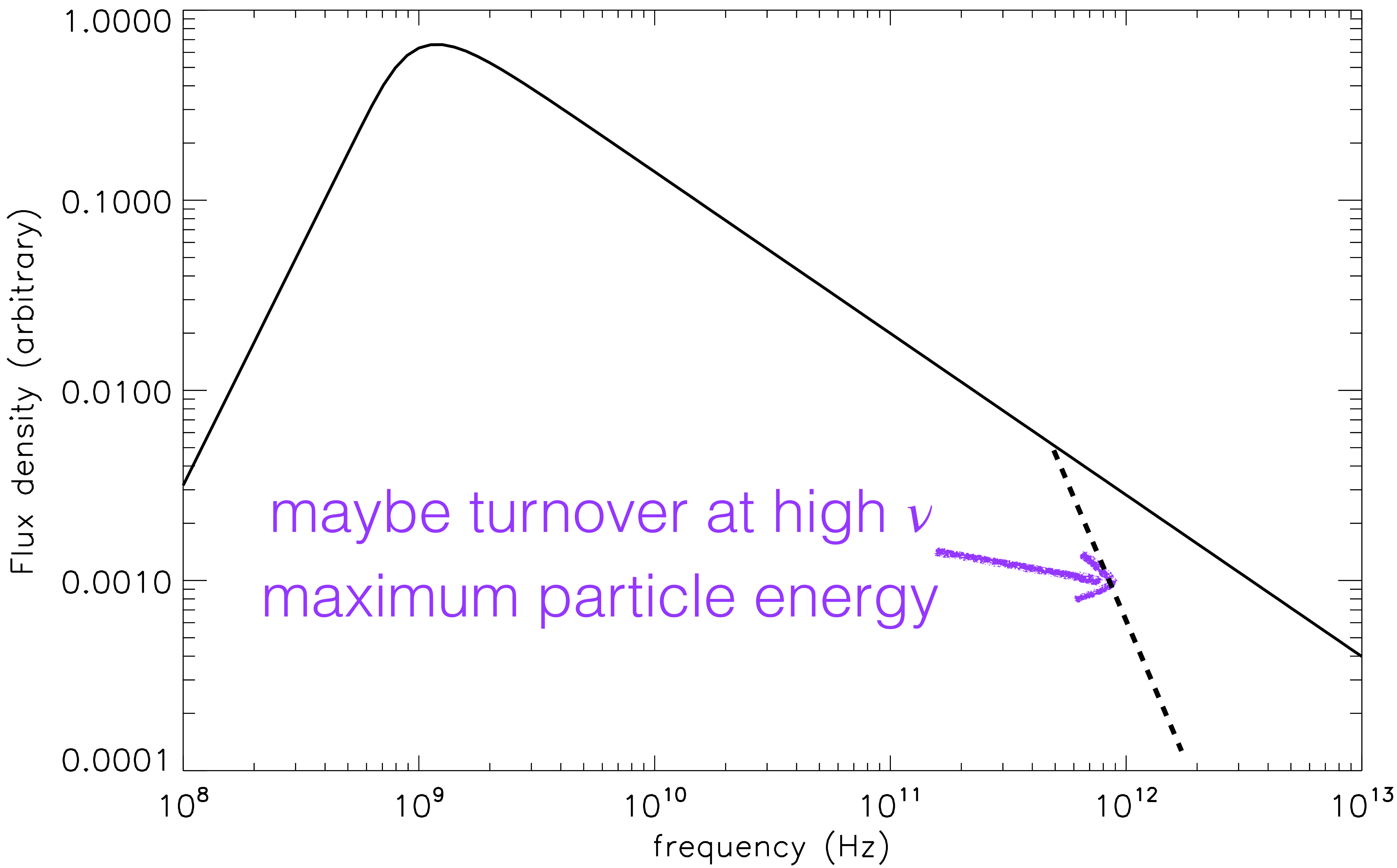
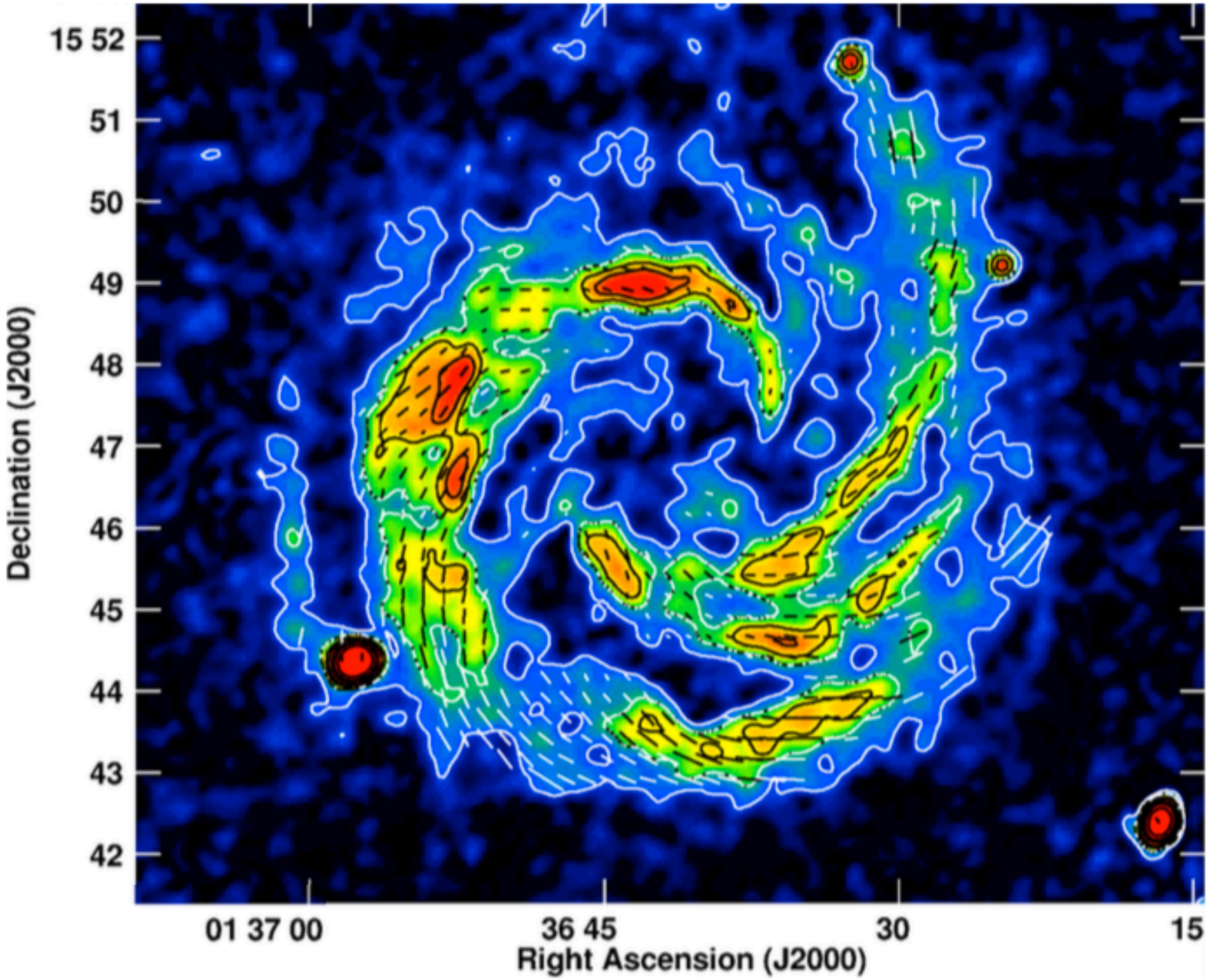


synchrotron from active galaxy Her A, $\nu \sim 6.5$ GHz

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

Synchrotron emission is polarized! Gives info on B field.

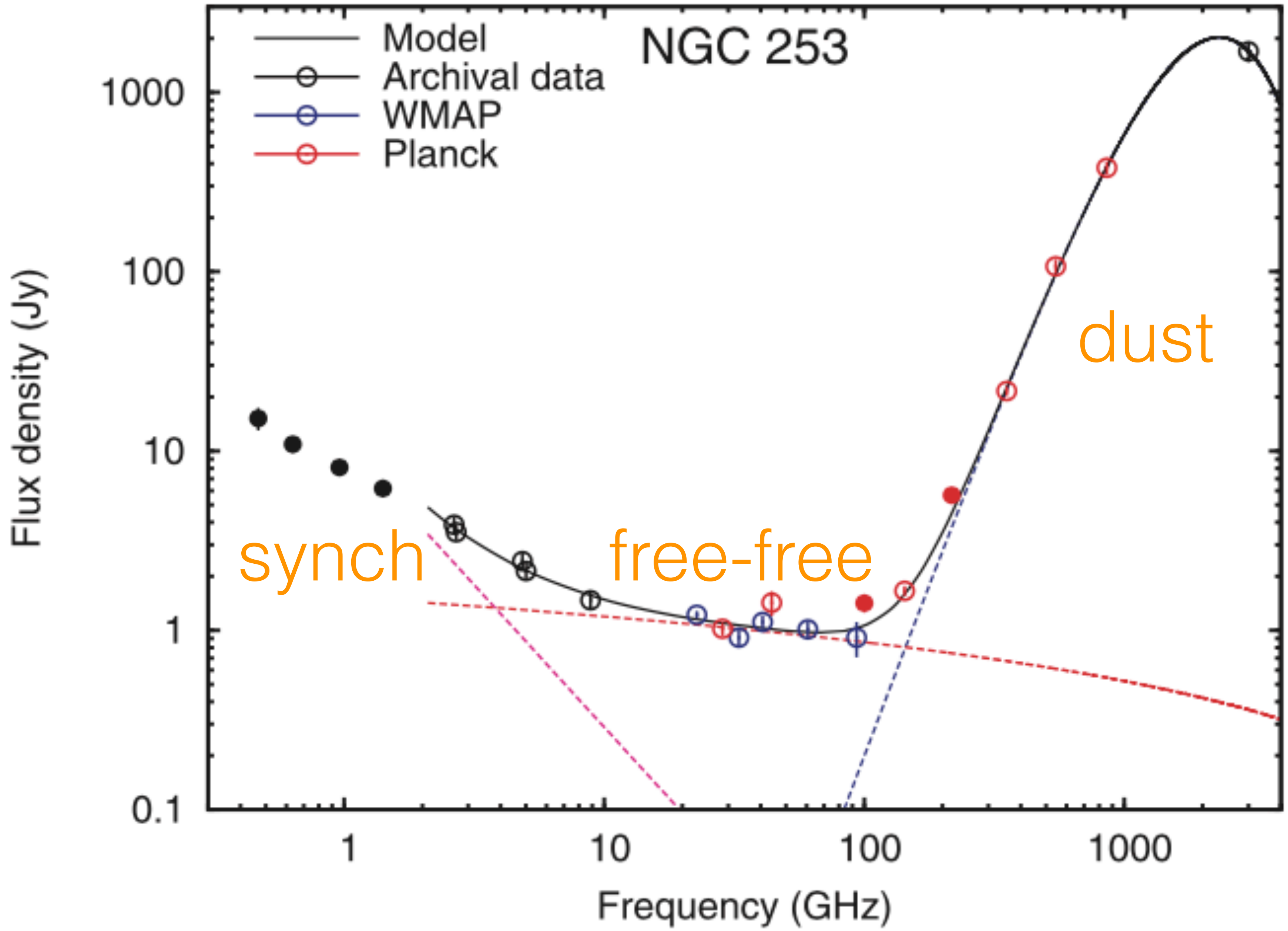


Mulcahy et al 2017; NGC 628, VLA @ 3 GHz

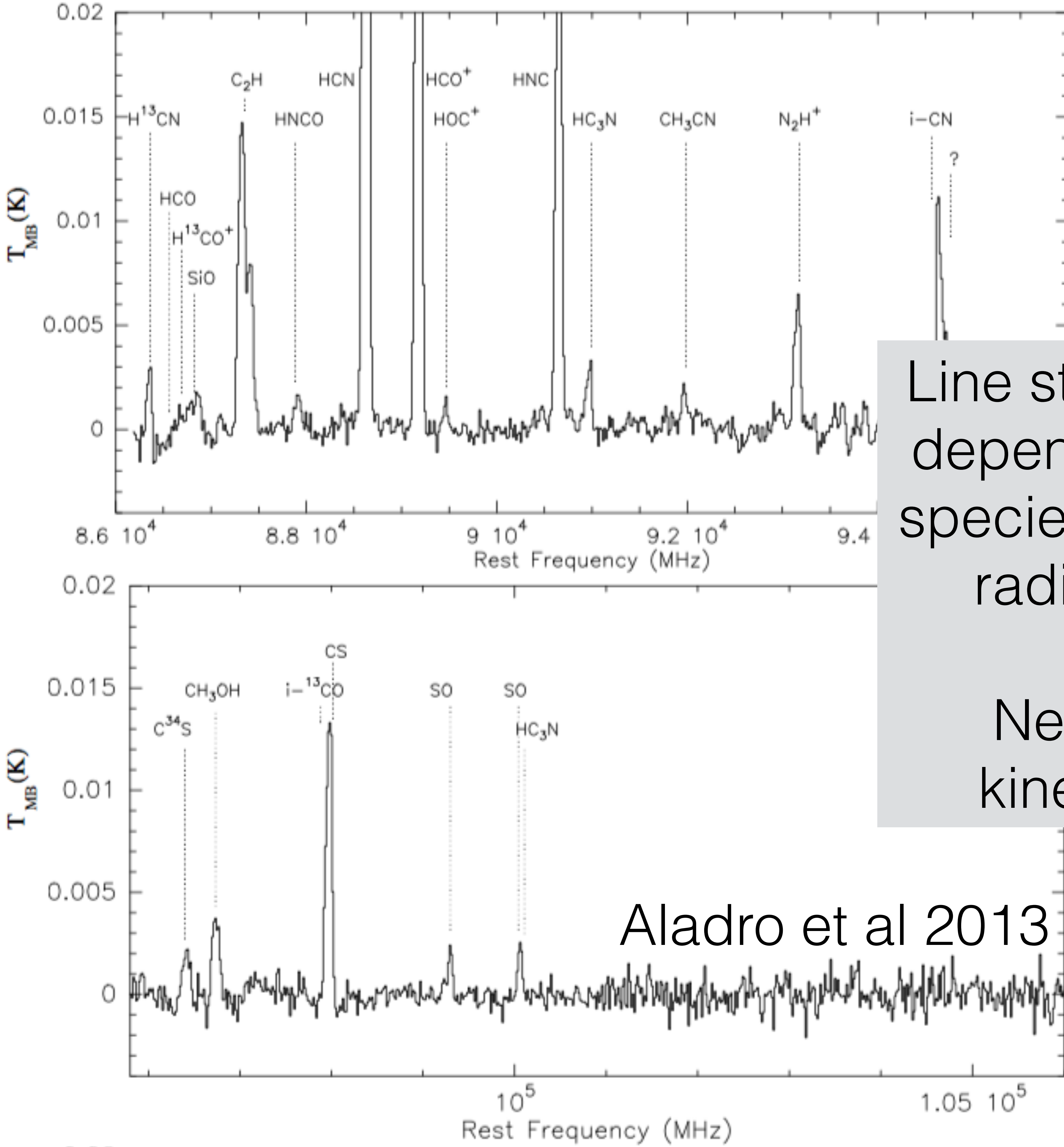
5 GHz

mostly synchrotron from moderate-z active galaxies

Real objects often have a combination of many kinds of emission.



Peel et al 2011



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

Need lines to get kinematics of gas.

(Friday)

Aladro et al 2013

Digression - some definitions that we think are important

Too Many Kinds of Temperature

physical T

excitation T_{ex}

receiver T_{rec}

system T_{sys}

antenna T_A

brightness T_B

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

Planck function

Maxwell-Boltzmann velocity dist.

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

Too Many Kinds of Temperature

physical T

excitation T_{ex}

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brightness T_B

$$n_2/n_1 = (g_2/g_1)e^{-h\nu_o/KT_{ex}}$$

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}

receiver T_{rec}

system T_{sys}

antenna T_A

brightness T_B

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

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

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

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

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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

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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}

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brightness T_B

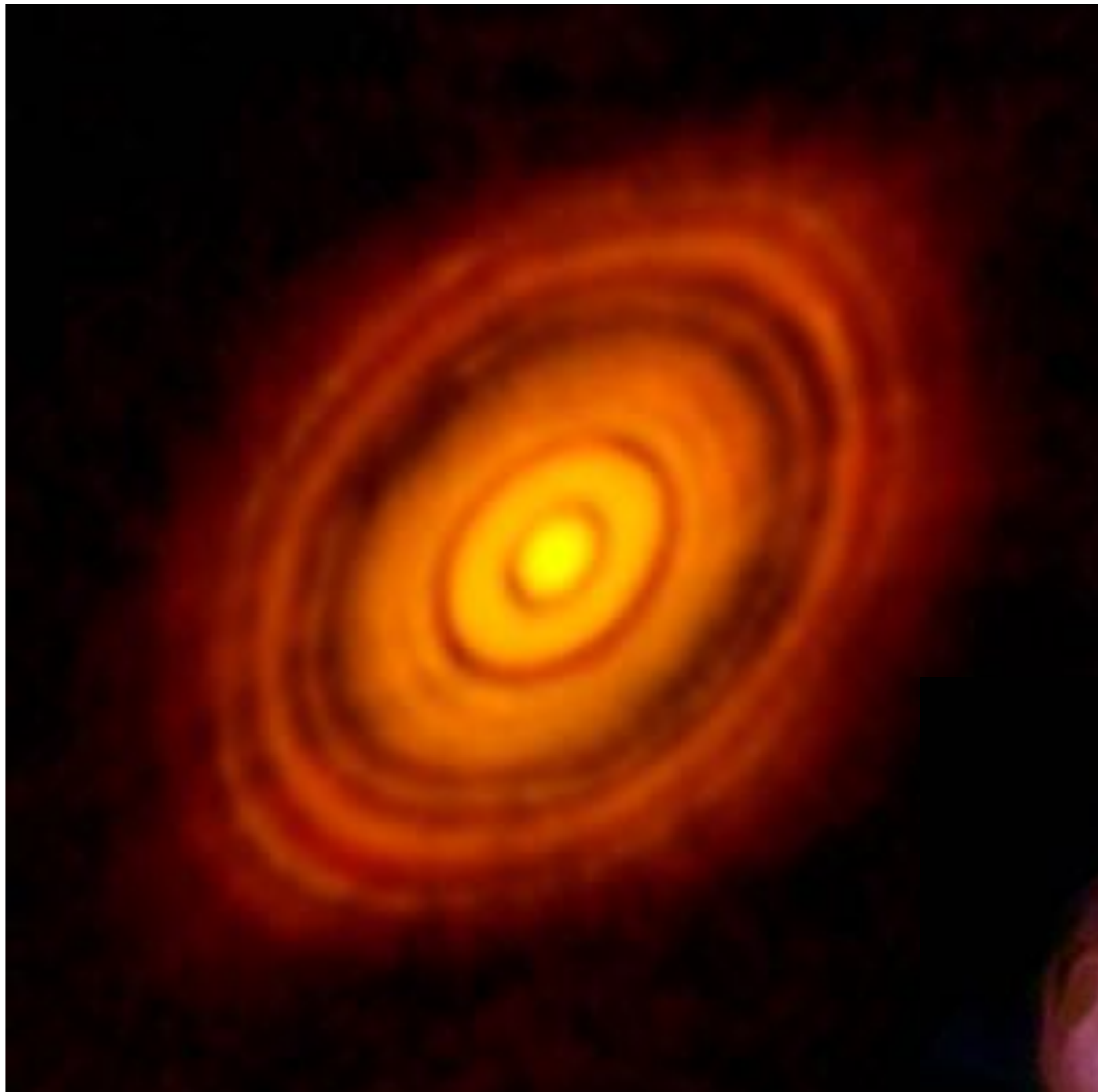
system temperature is particularly important because

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

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

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

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



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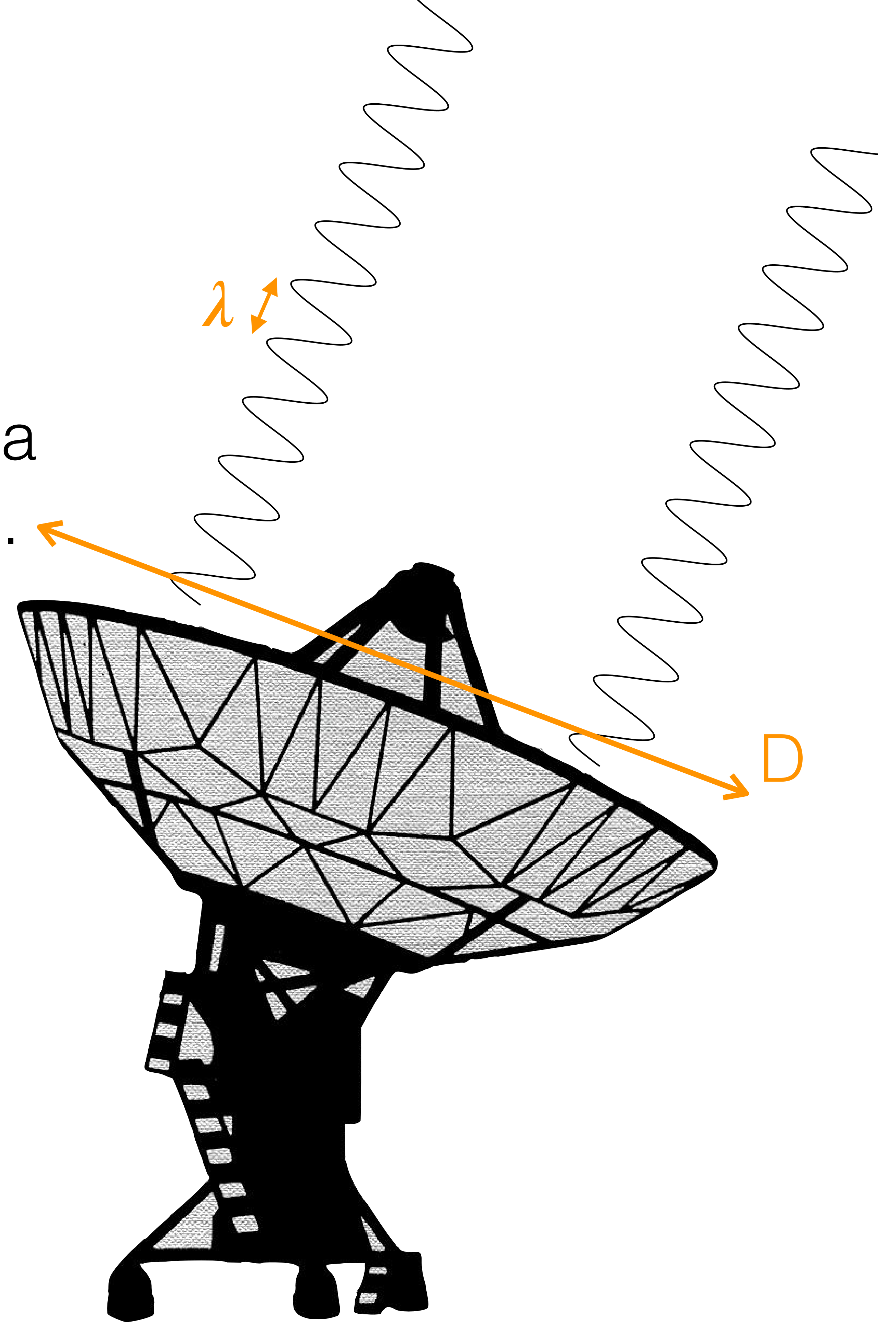
Her A, ν ~ 6.5 GHz, λ ~ 5 cm, resolution ~ 0.5”

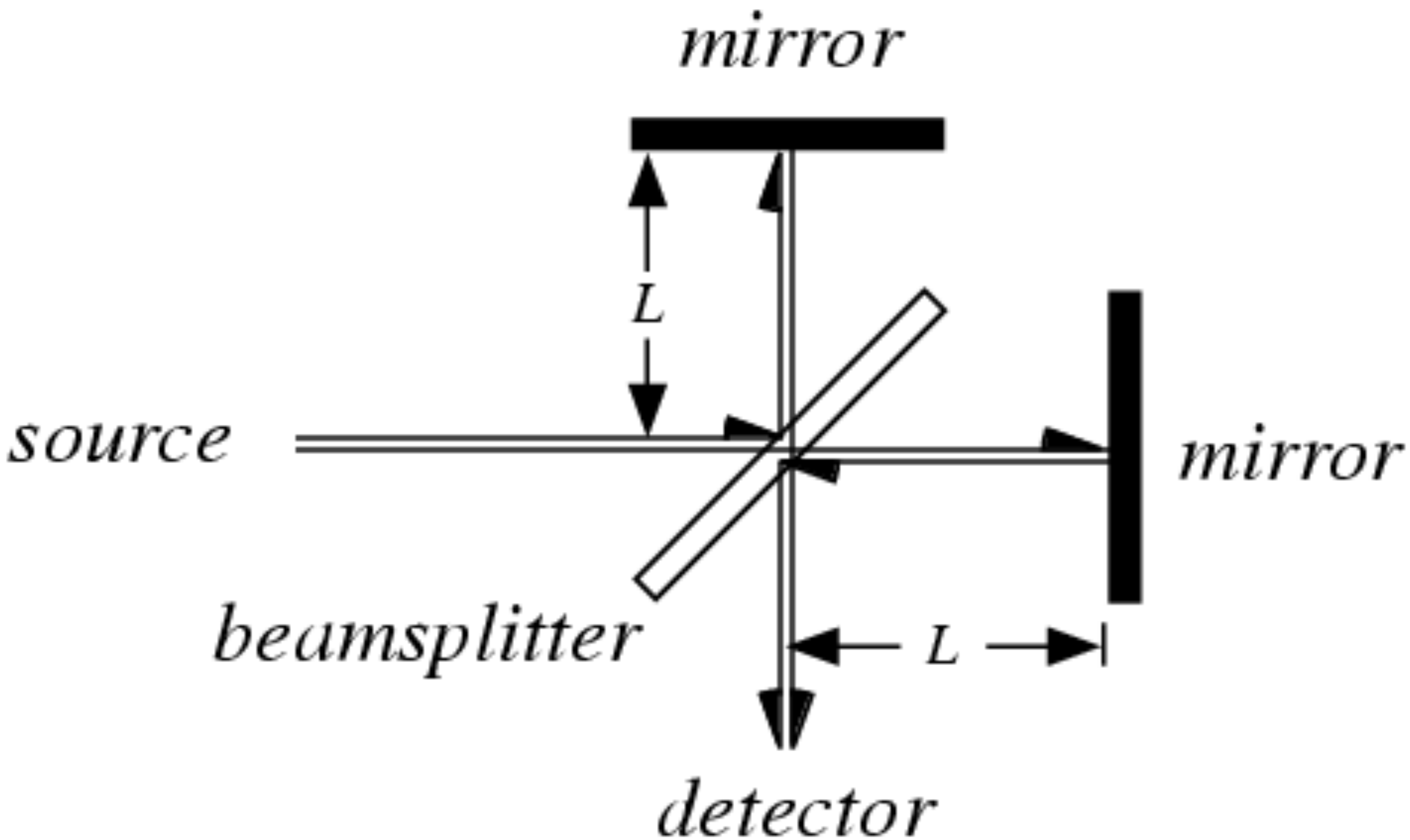
Diffraction theory: this telescope (by itself) has a resolution ~ λ/D radians.

How can we do better than that?

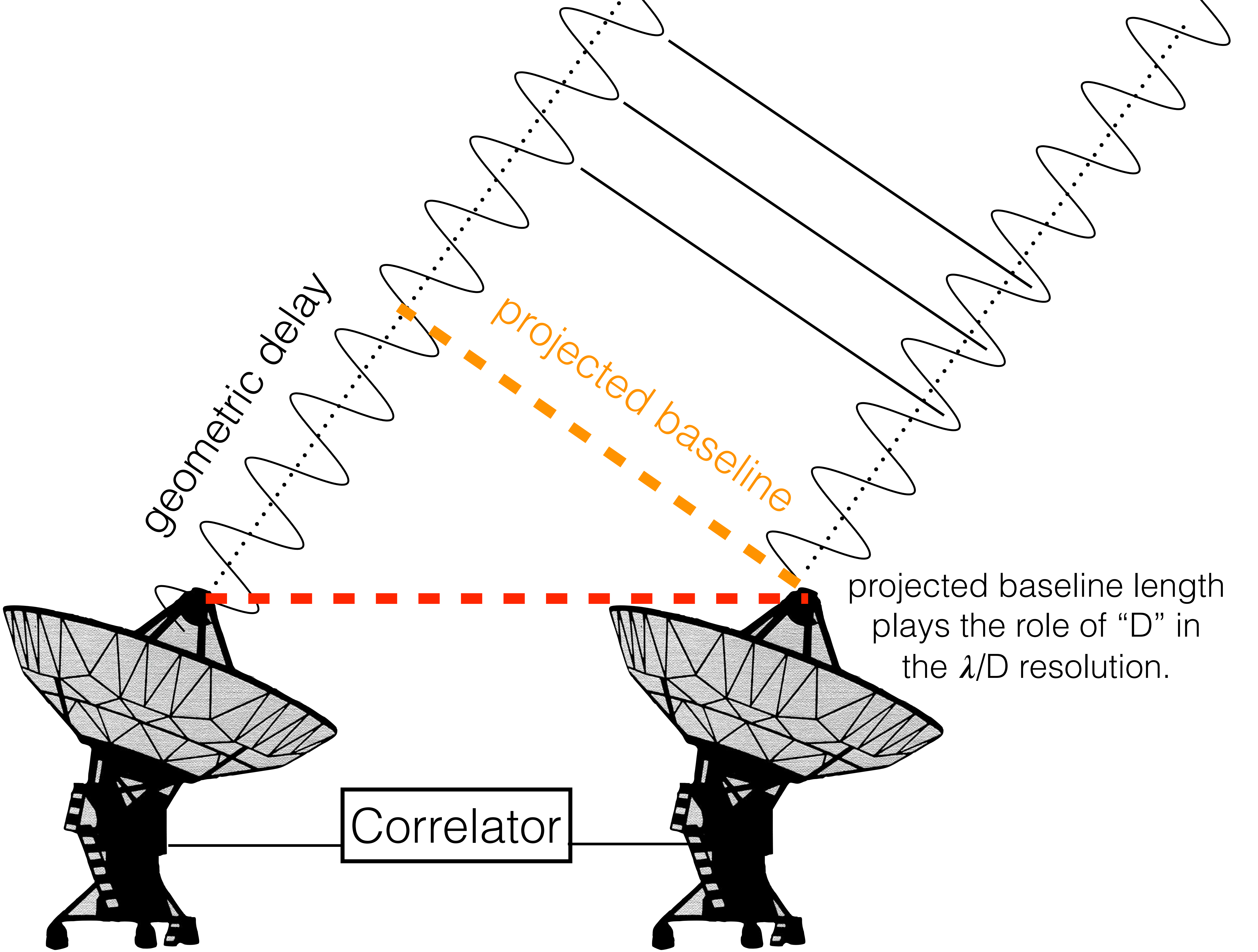
with an interferometer.



an adding interferometer (e.g. Michelson-Morley expt)

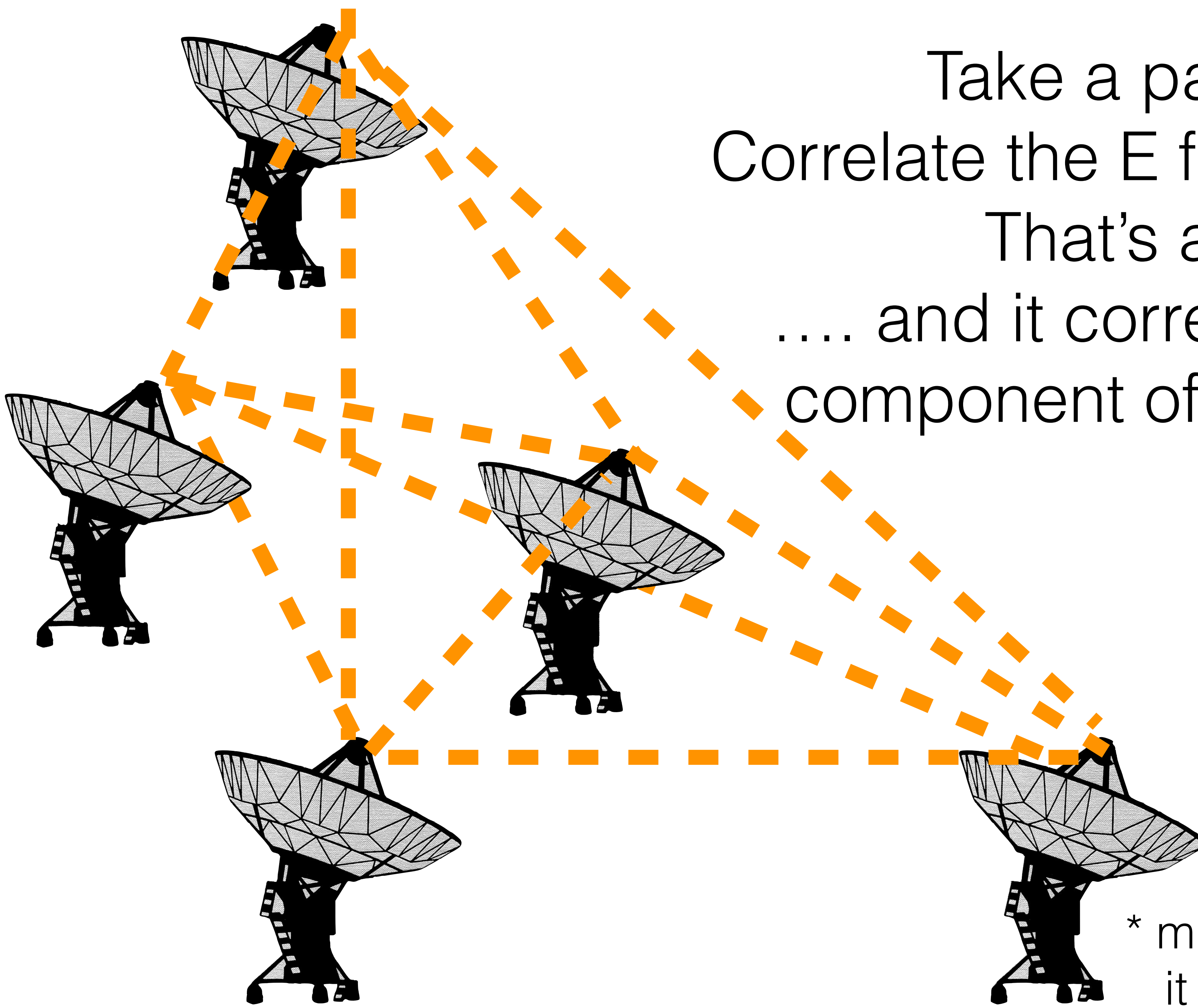


Leonardo Motta, scienceworld.wolfram.com


geometric delay
projected baseline
projected baseline length
plays the role of “D” in
the λ/D resolution.
Correlator

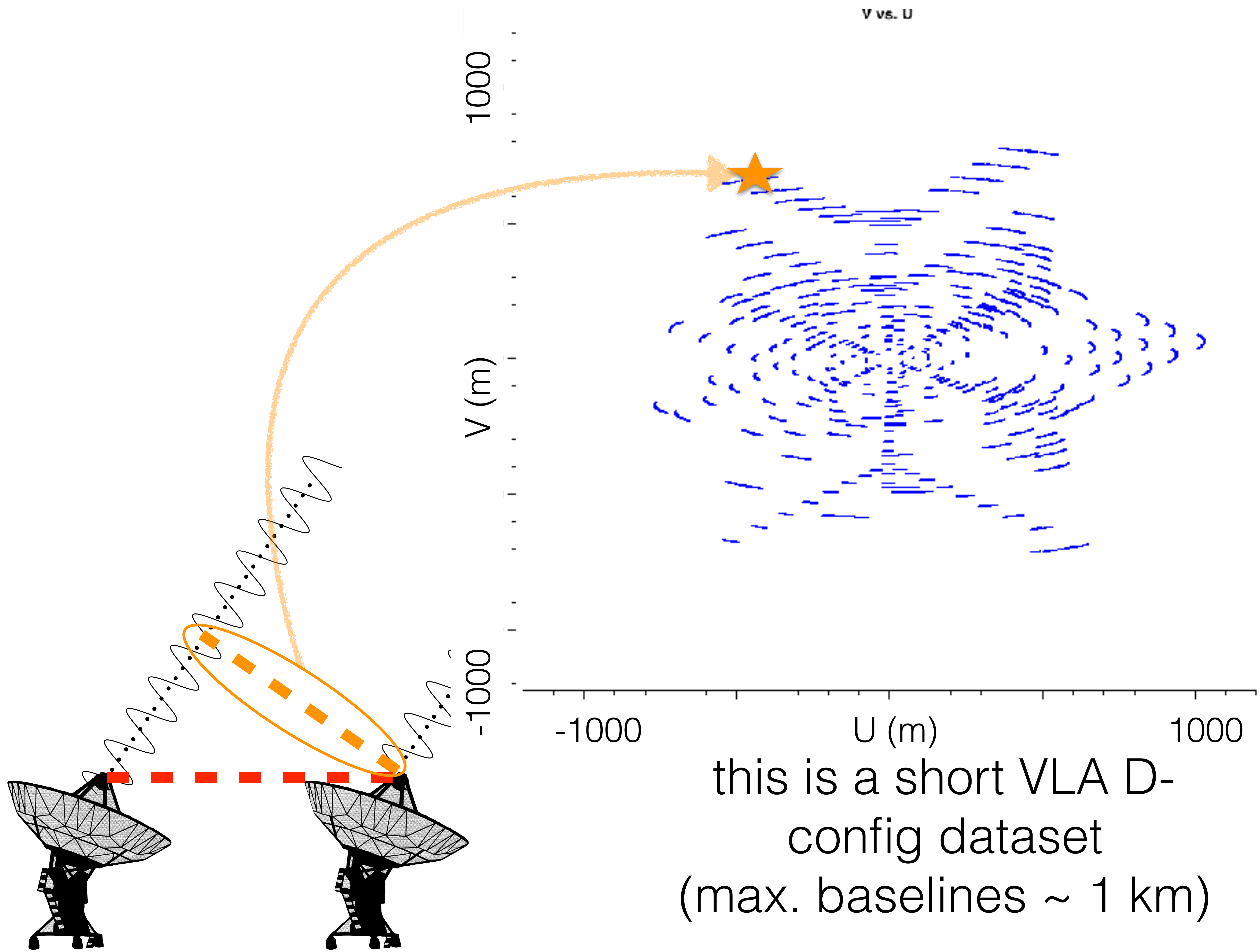
Interferometer theory, very loosely.

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

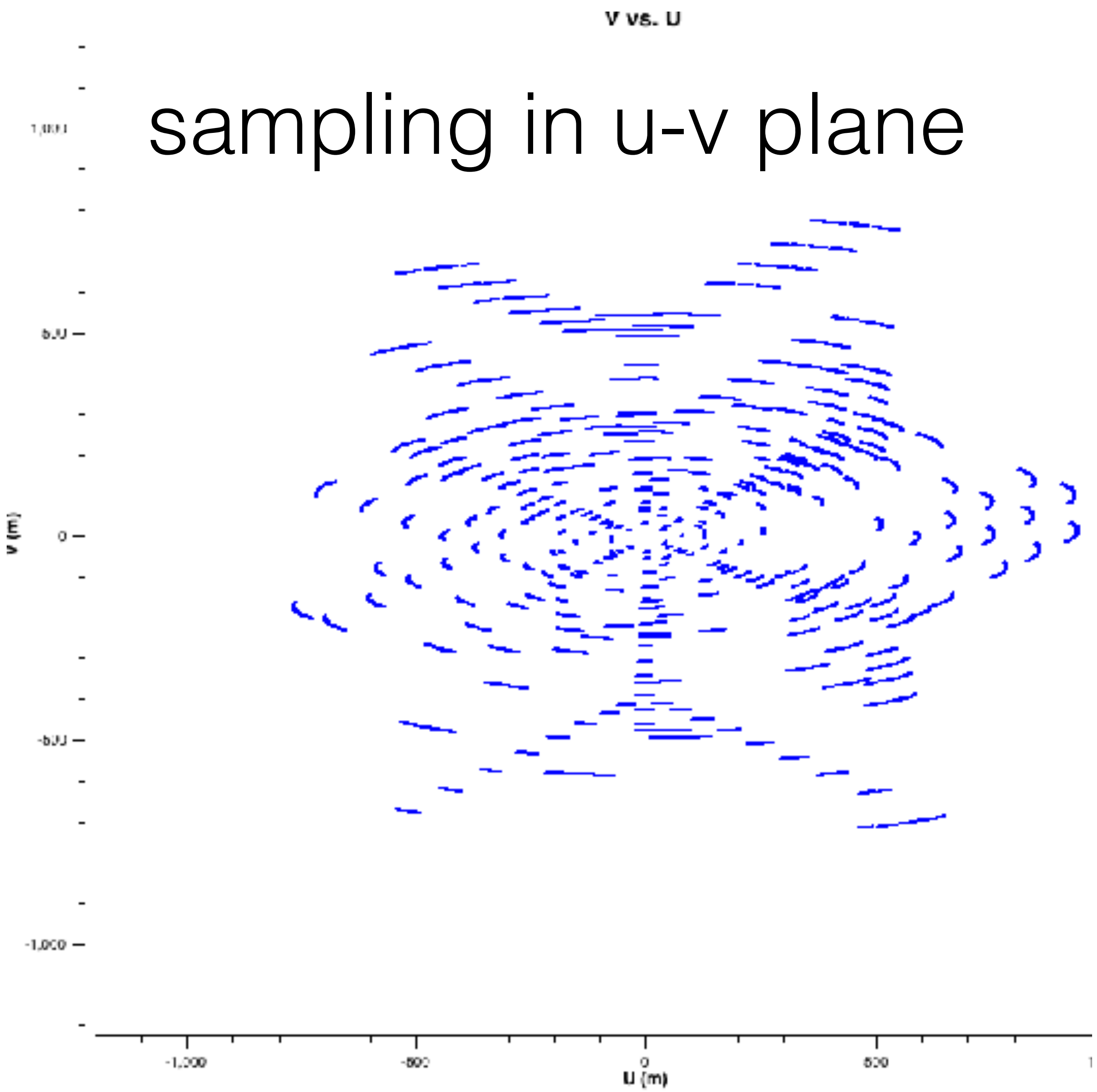


Take a pair of antennas.
Correlate the E fields at each antenna.
That's a "visibility"…
…. and it corresponds to a Fourier component of the sky brightness.

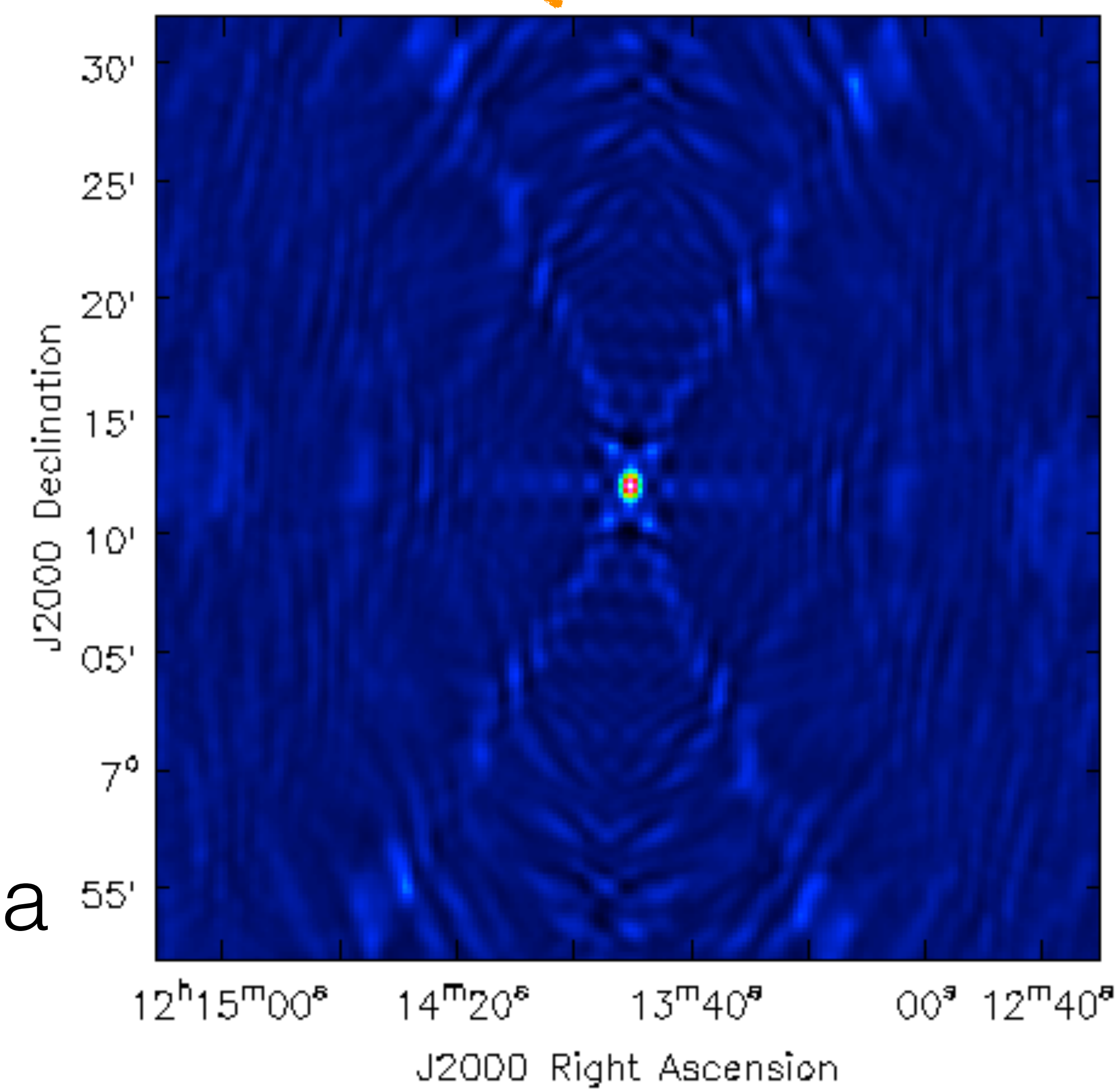
* mutual coherence function, but it looks a lot like a correlation



this is a short VLA D-config dataset (max. baselines ~ 1 km) sampling in u-v plane

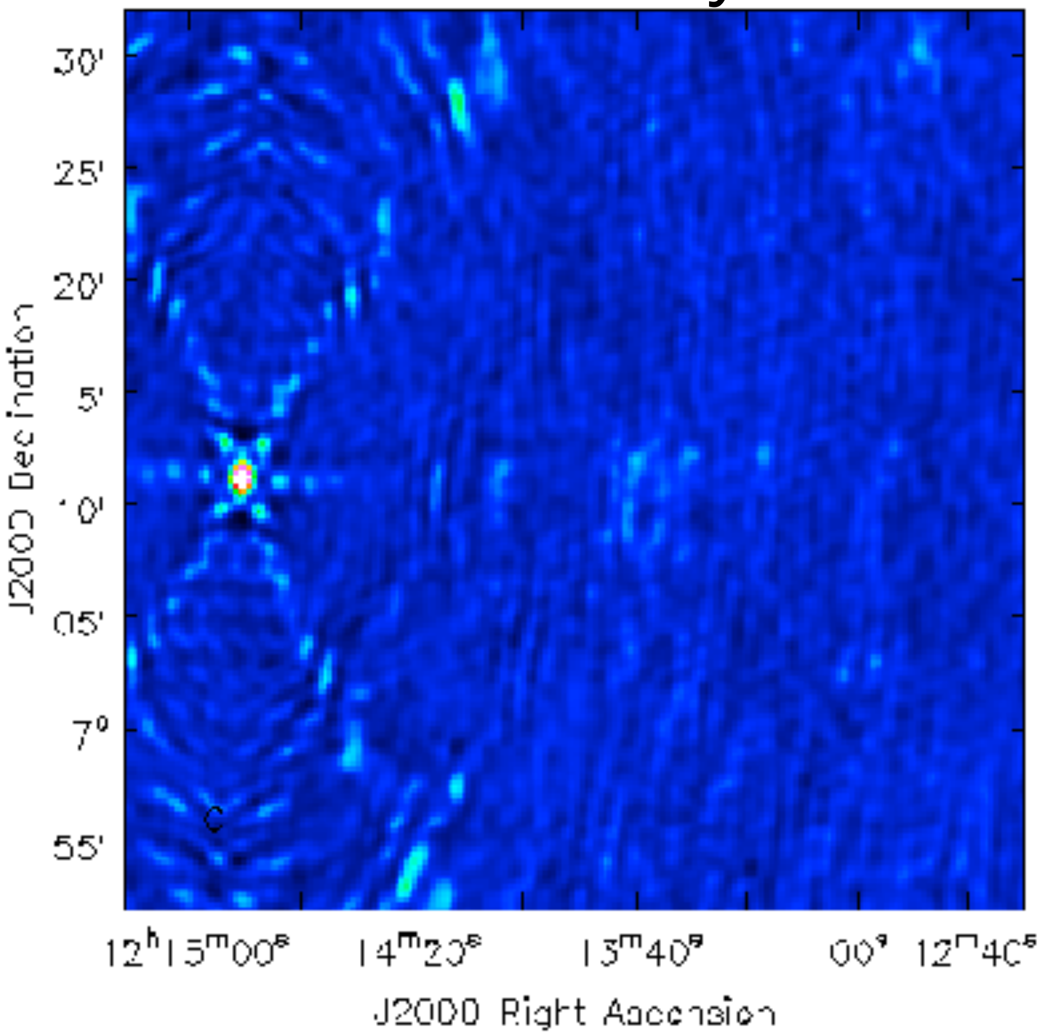


Fourier Transform



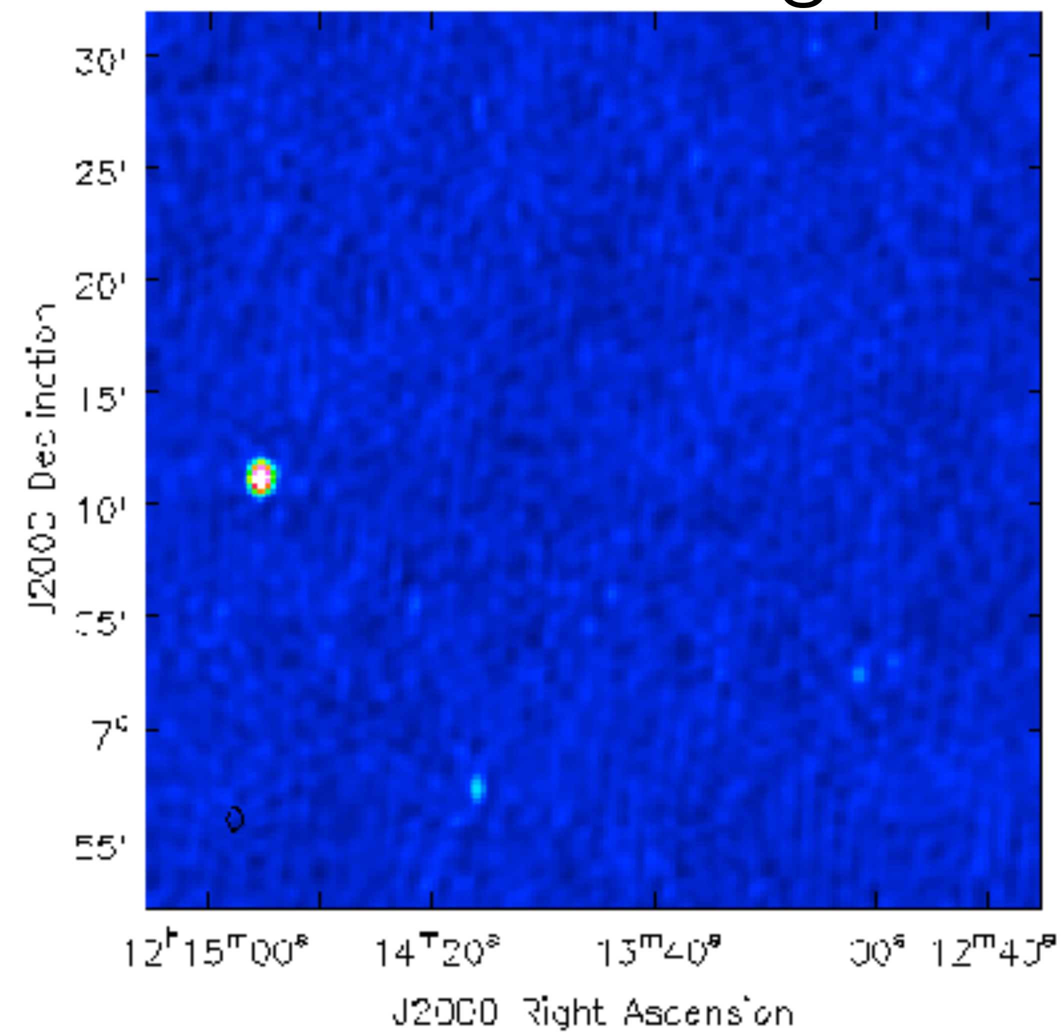
“dirty beam” (PSF) = response of the system to a point source

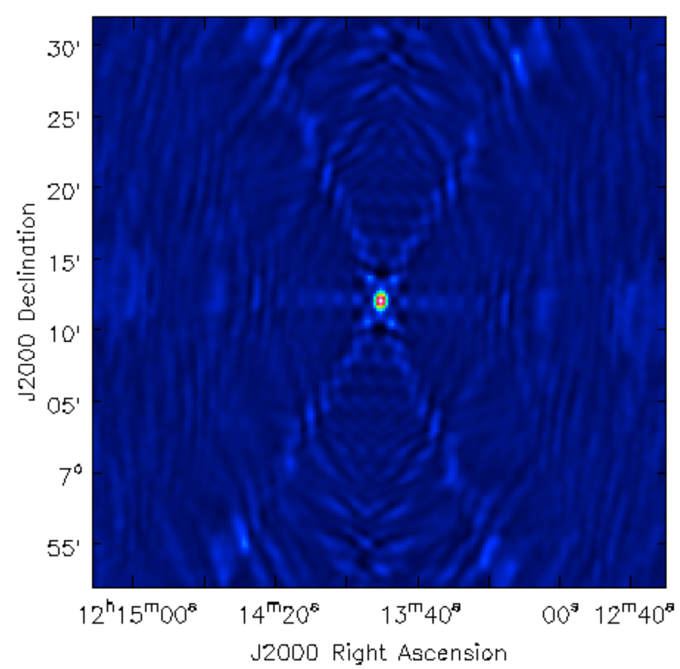
FT of visibility data



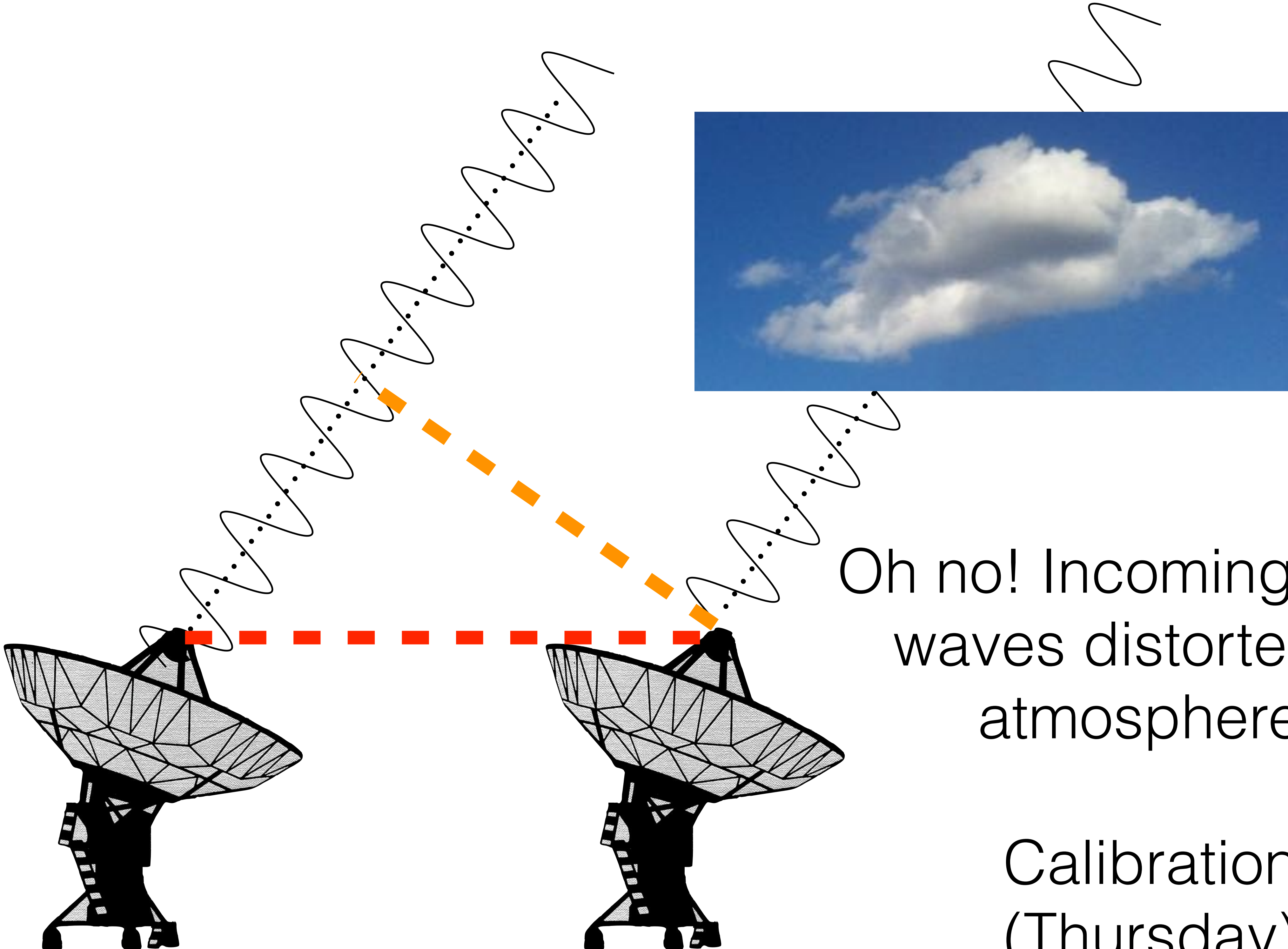
Deconvolution (cleaning)

cleaned image



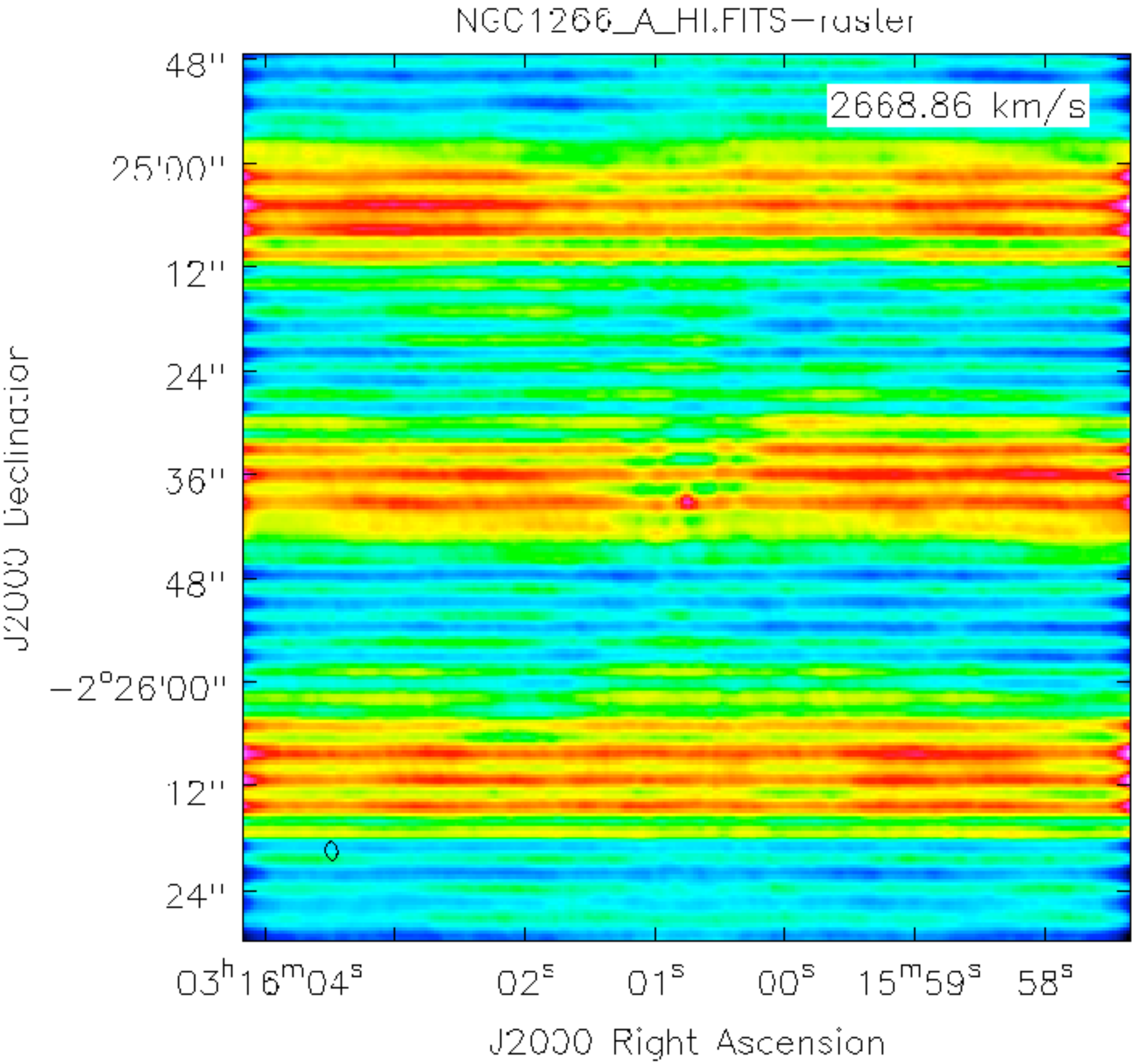


recall this is what point sources look like



Oh no! Incoming plane waves distorted by atmosphere!

Calibration (Thursday)



AAAAAAAA!!!
What happened to my image?

Error Recognition (Tuesday)

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 EXTRAORDINAIRÉ, 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!
WATERSON
MAN, THIS CLASS LASTS FOREVER!
SO WE CARRY THE THREE INTO THE TENS COLUMN....