

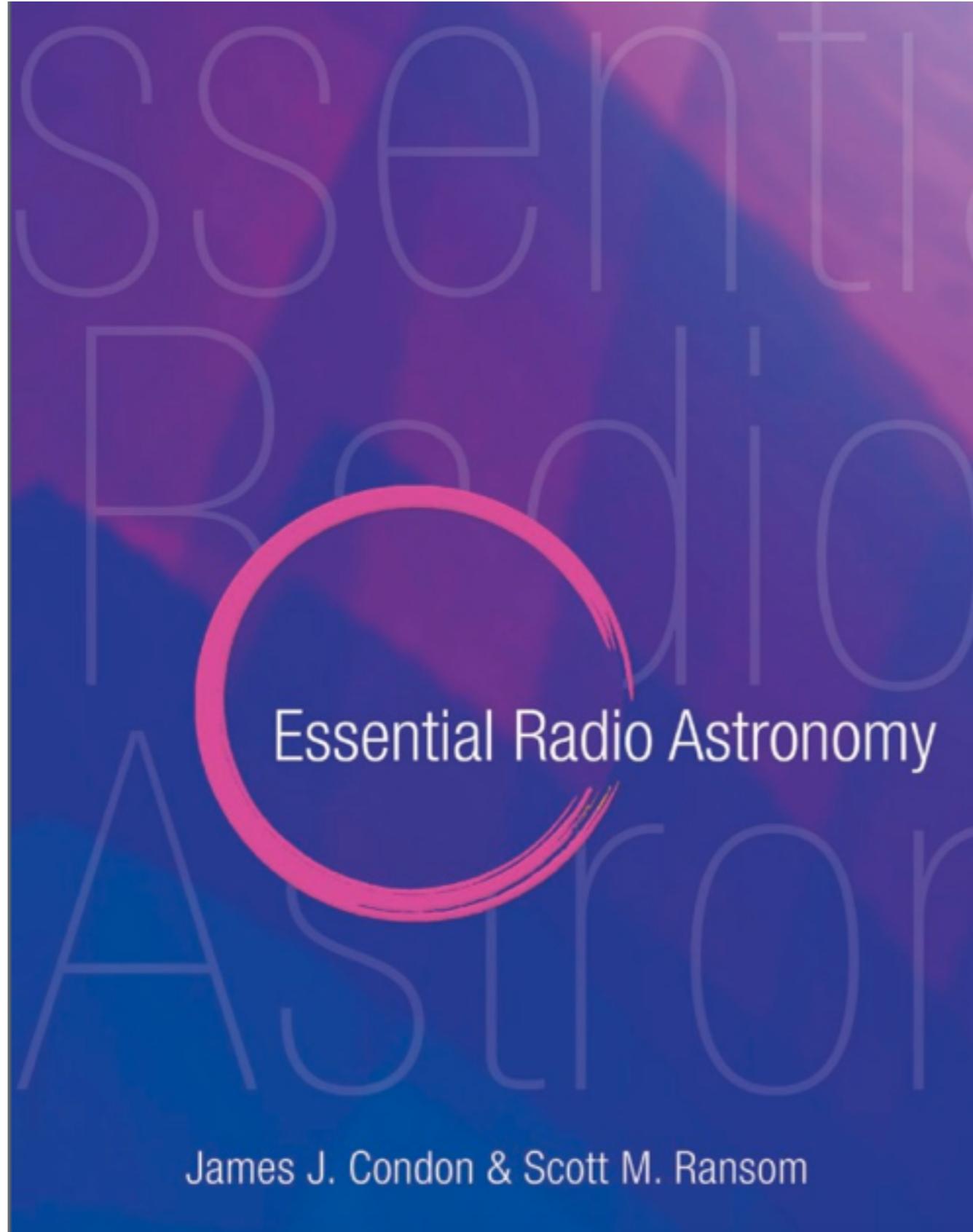
Basics of Radio Astronomy

With emphasis on synthesis imaging

Lisa Young, NMT
June 2016

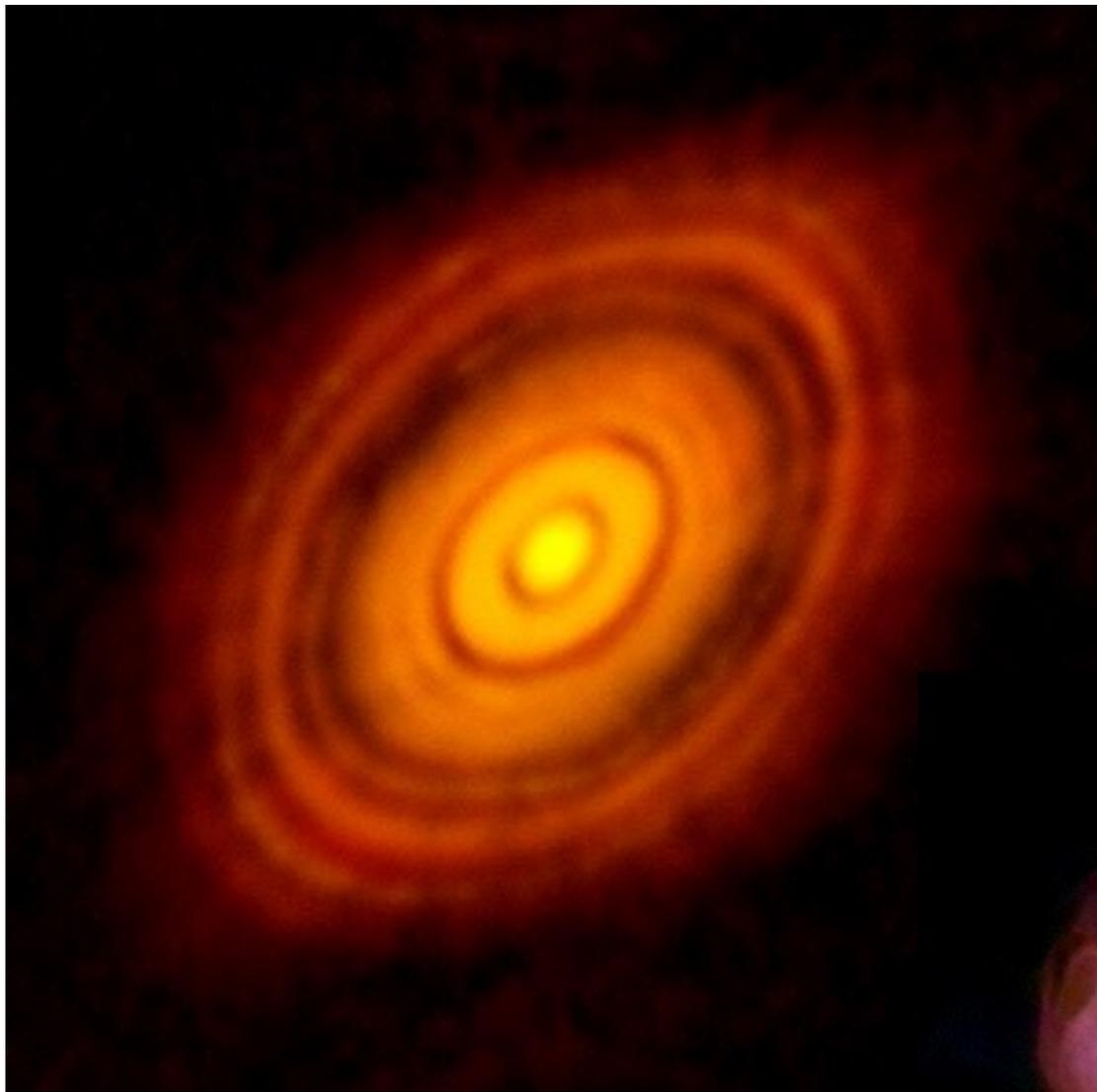


DON'T PANIC



*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?

Intensity and Flux

Specific intensity (surface brightness) is the energy passing through some surface in some direction, per unit time, (detector) area, frequency interval & solid angle.

$$dE = I_\nu dA dt d\nu d\Omega.$$

erg s⁻¹ cm⁻² Hz⁻¹ sterad⁻¹ or W m⁻² Hz⁻¹ sterad⁻¹

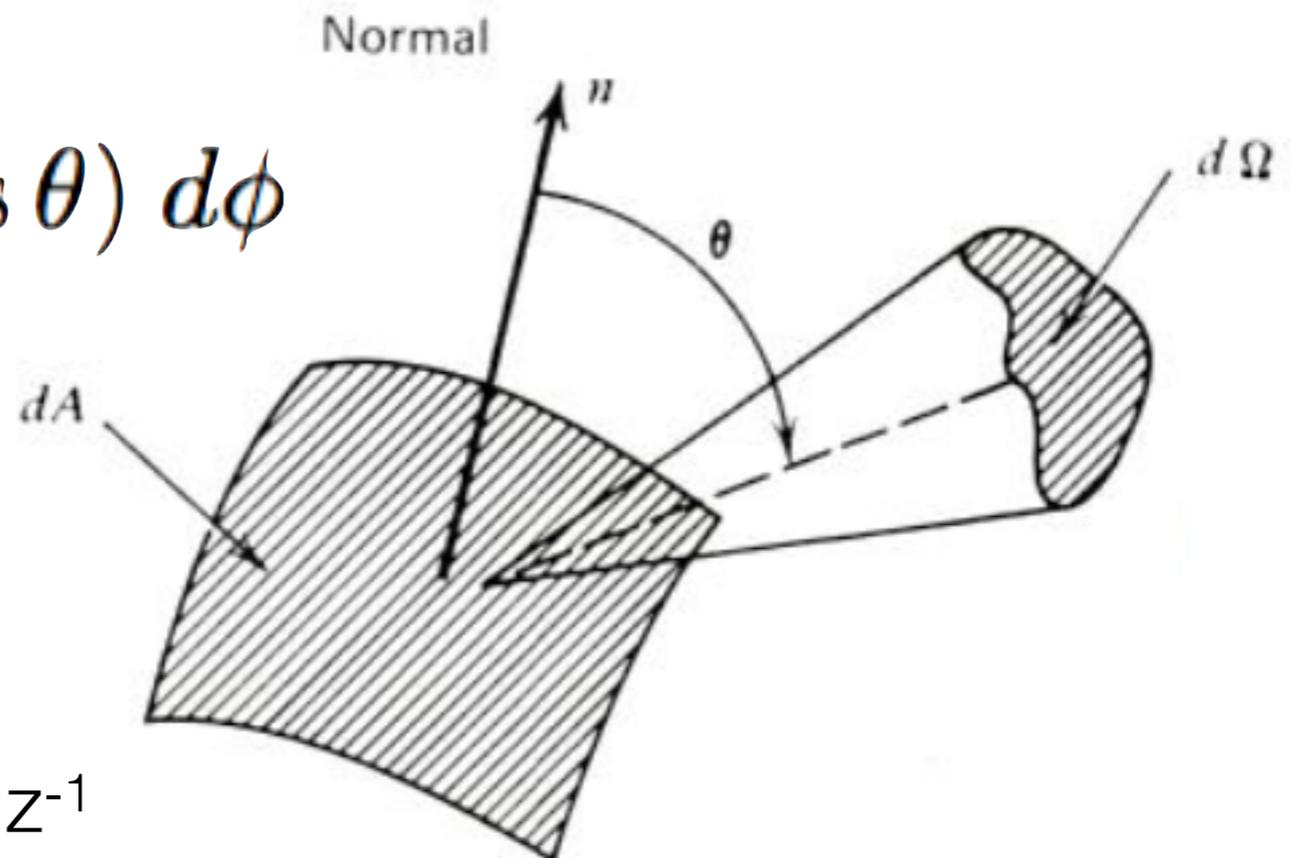
Flux density is specific intensity, integrated over angle.

$$F_\nu = \int I_\nu \cos \theta d(\cos \theta) d\phi$$

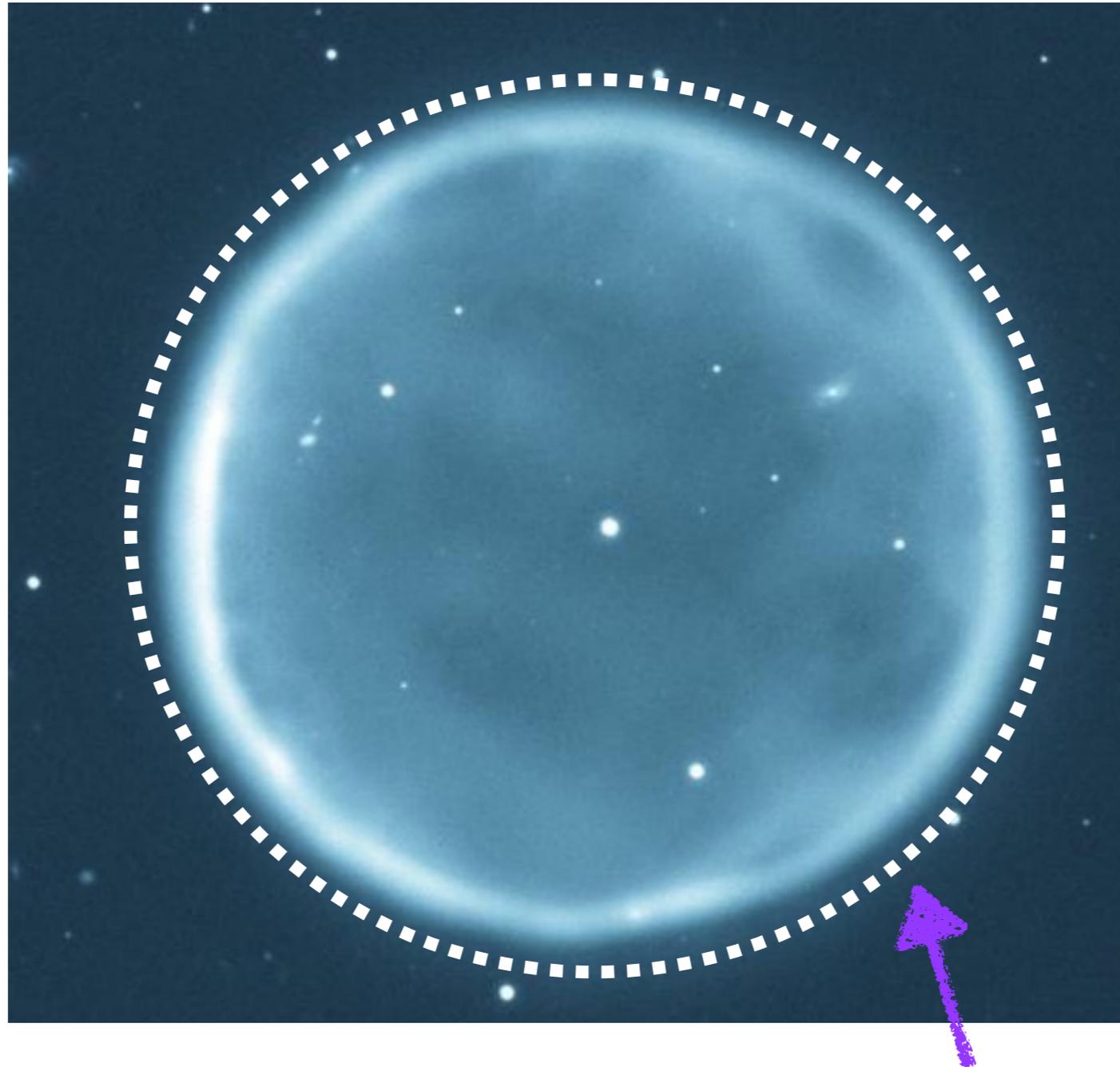
or if your source is small and simple:

$$F_\nu = I_\nu d\Omega.$$

erg s⁻¹ cm⁻² Hz⁻¹ or W m⁻² Hz⁻¹

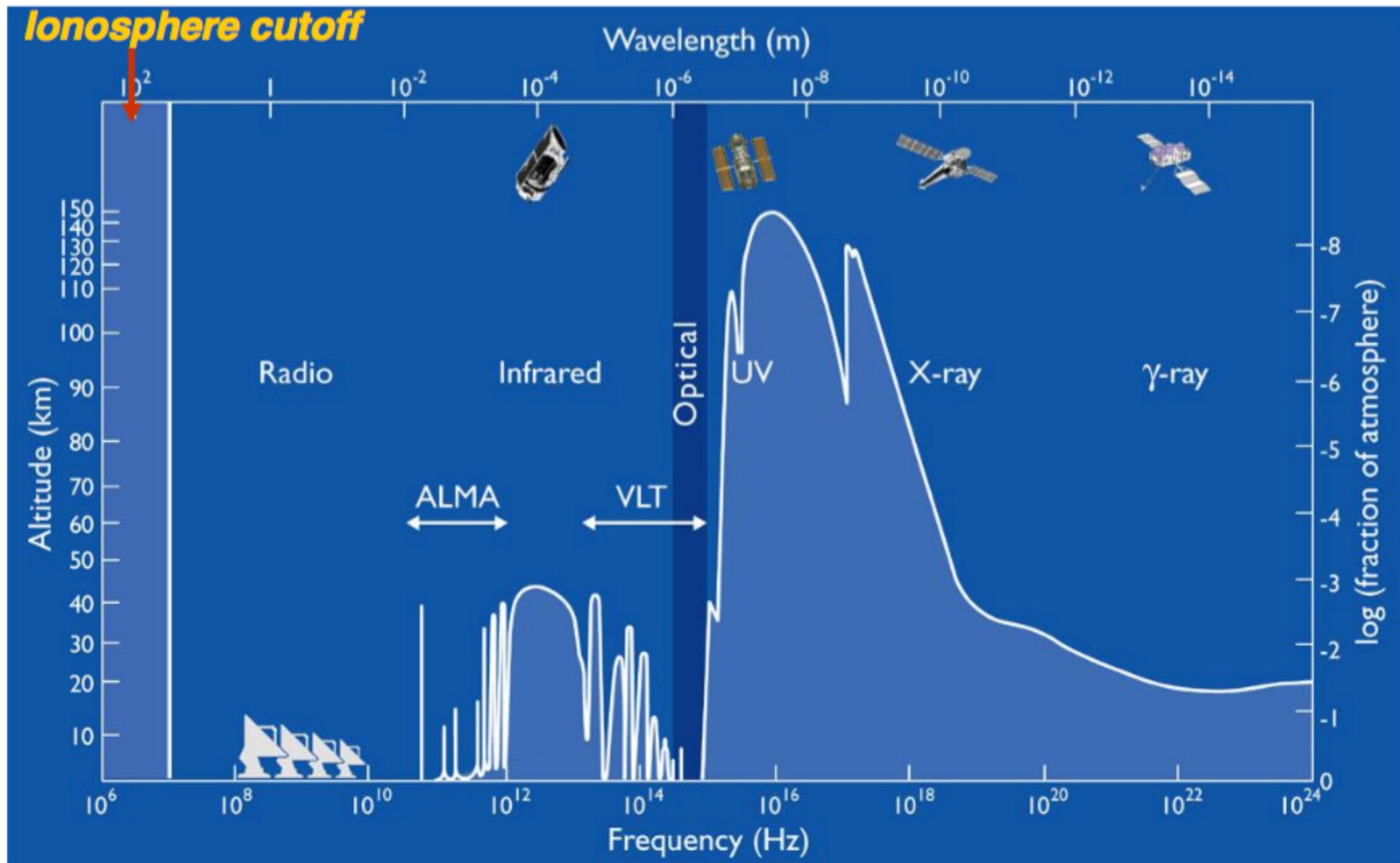


Color indicates the intensity (surface brightness) at each position.



Flux is what you get if you integrate over solid angle.

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



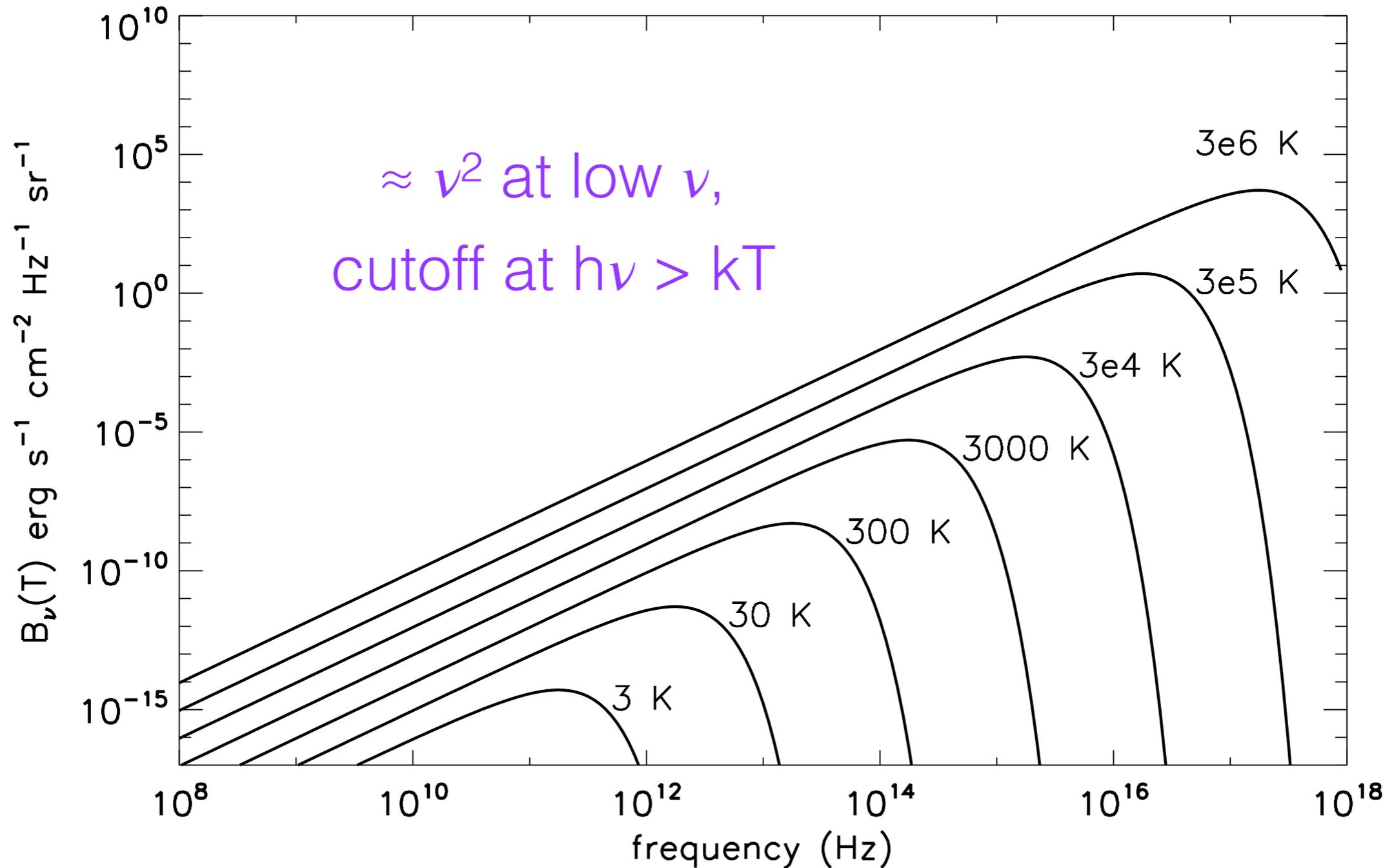
mm and sub-mm range

NRAO Synthesis Workshop 2014

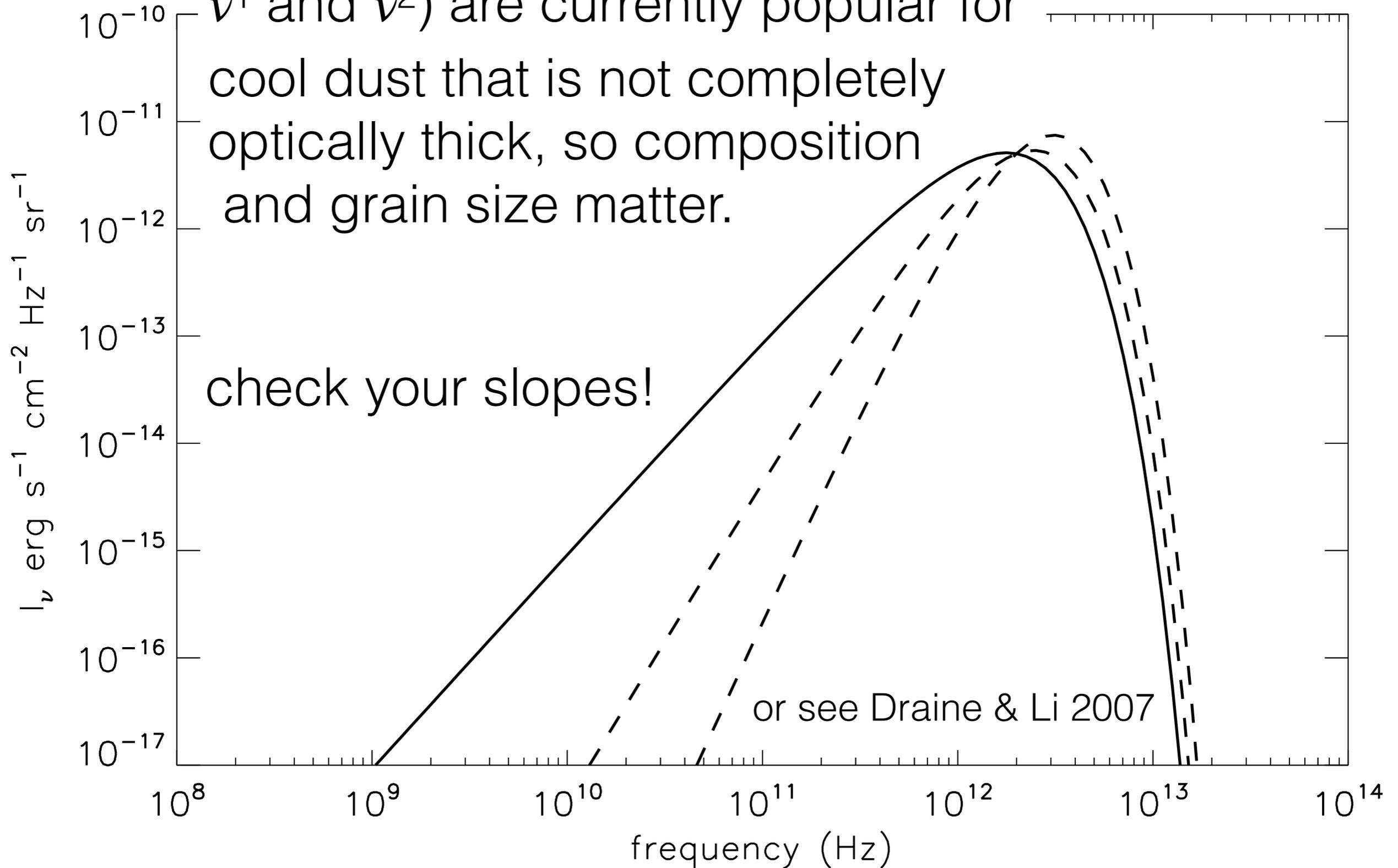
Black body emission

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

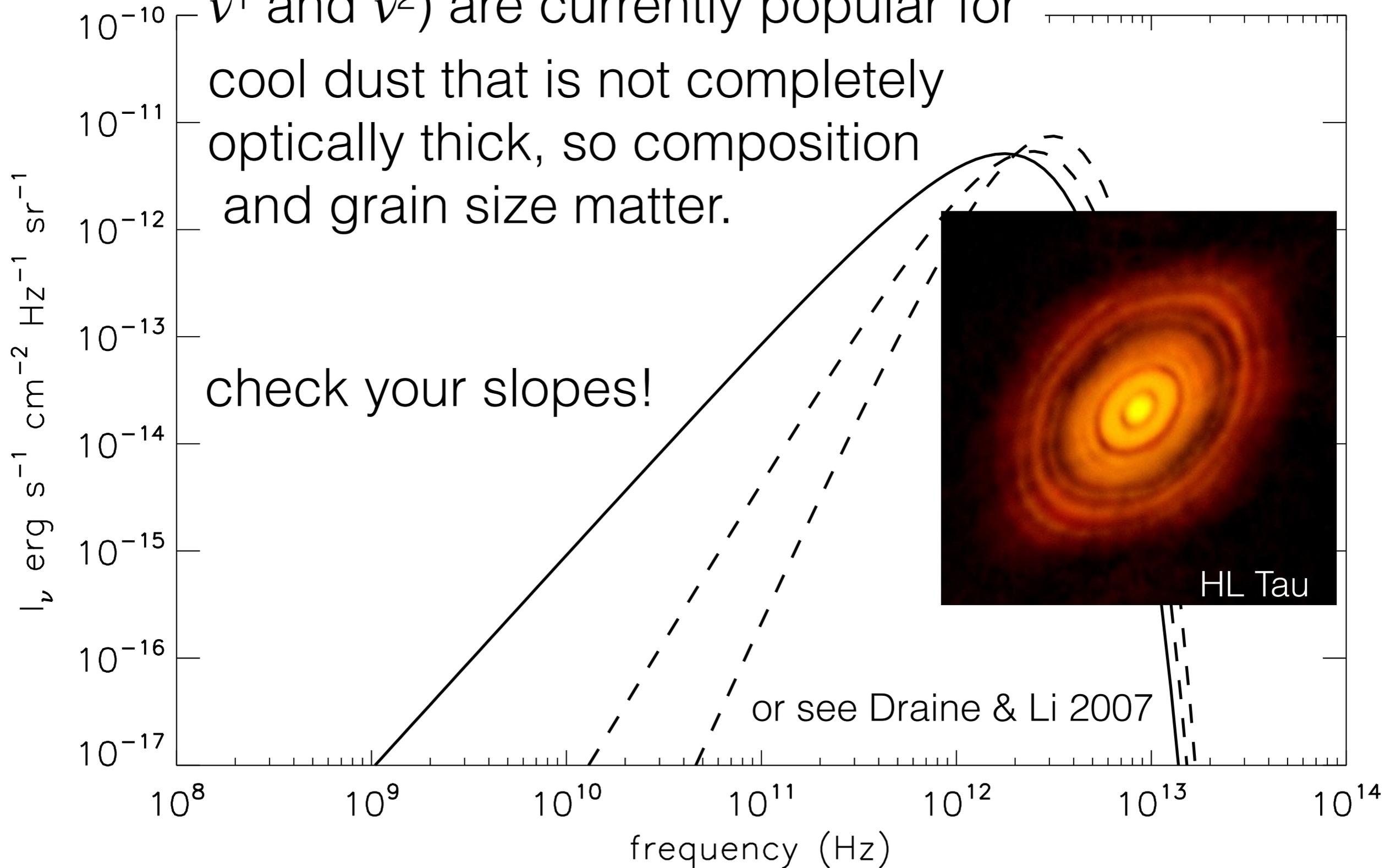
this is specific intensity



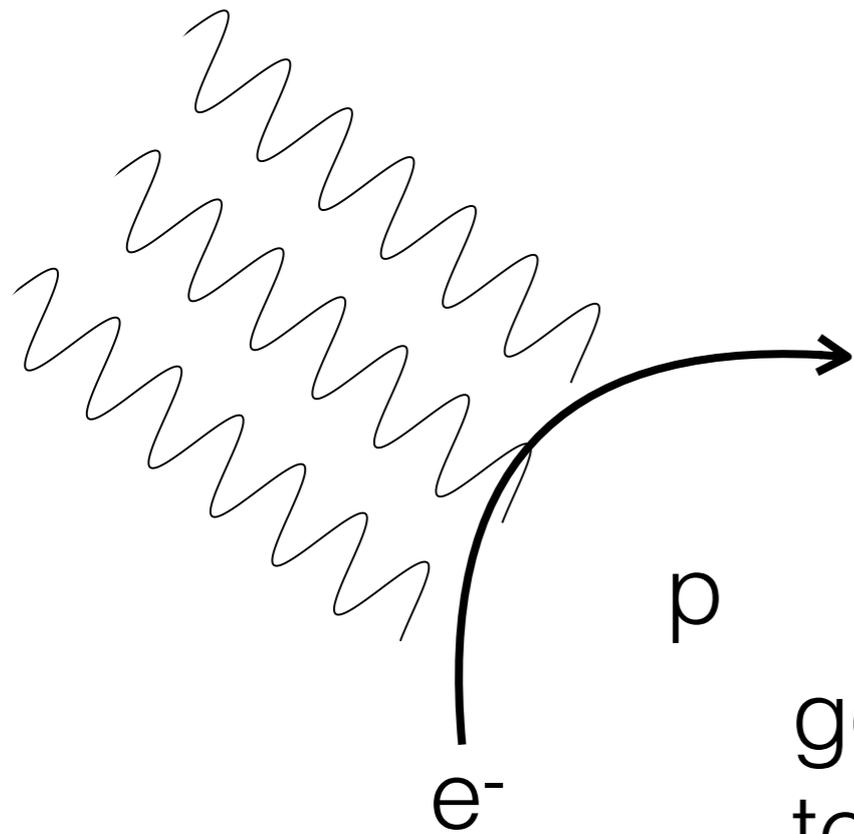
Modified black bodies (here scaled by ν^1 and ν^2) are currently popular for cool dust that is not completely optically thick, so composition and grain size matter.



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



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

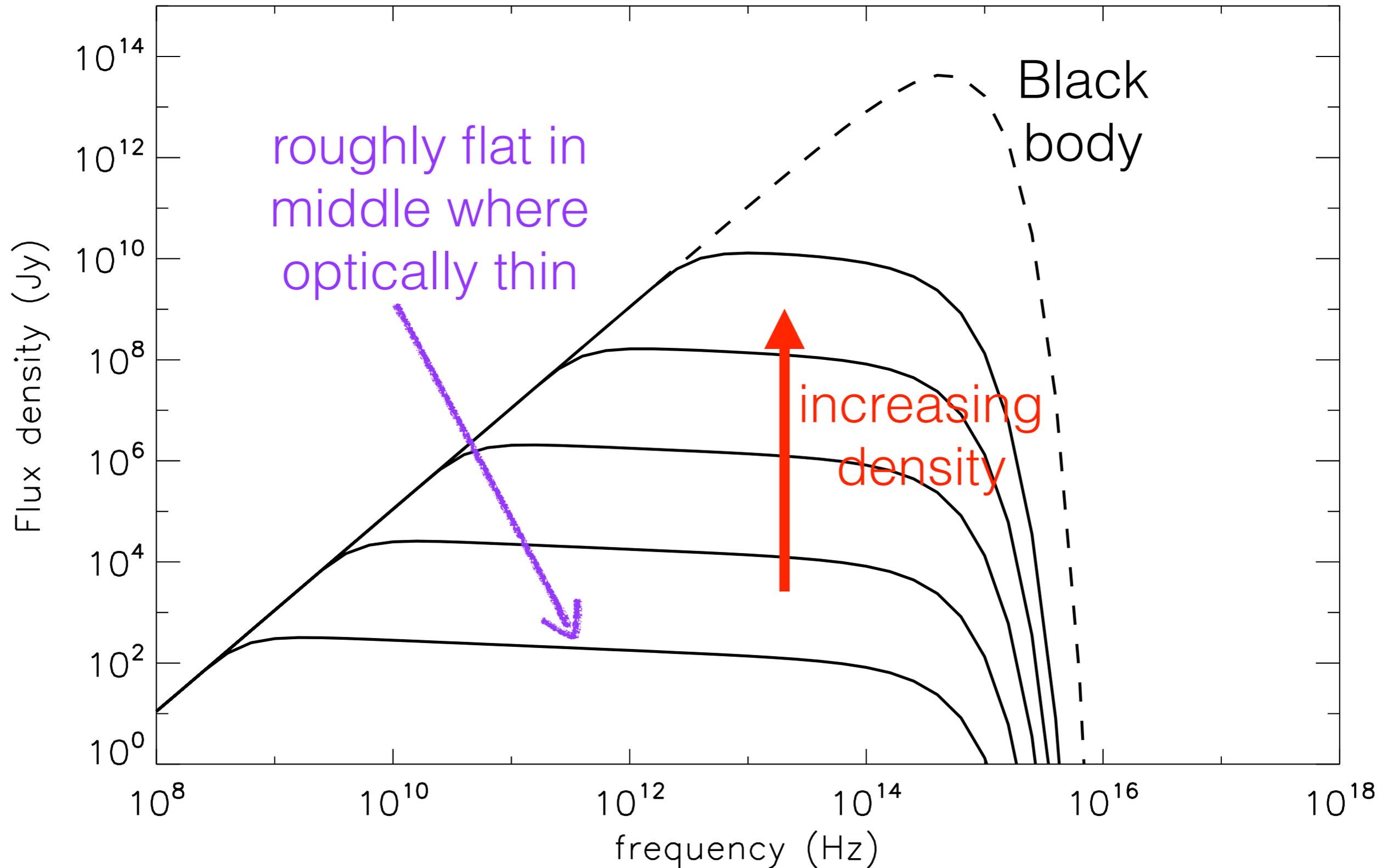
good for estimating density &
temperature of ionized gas

- counting ionizing photons
- inferring star formation rate

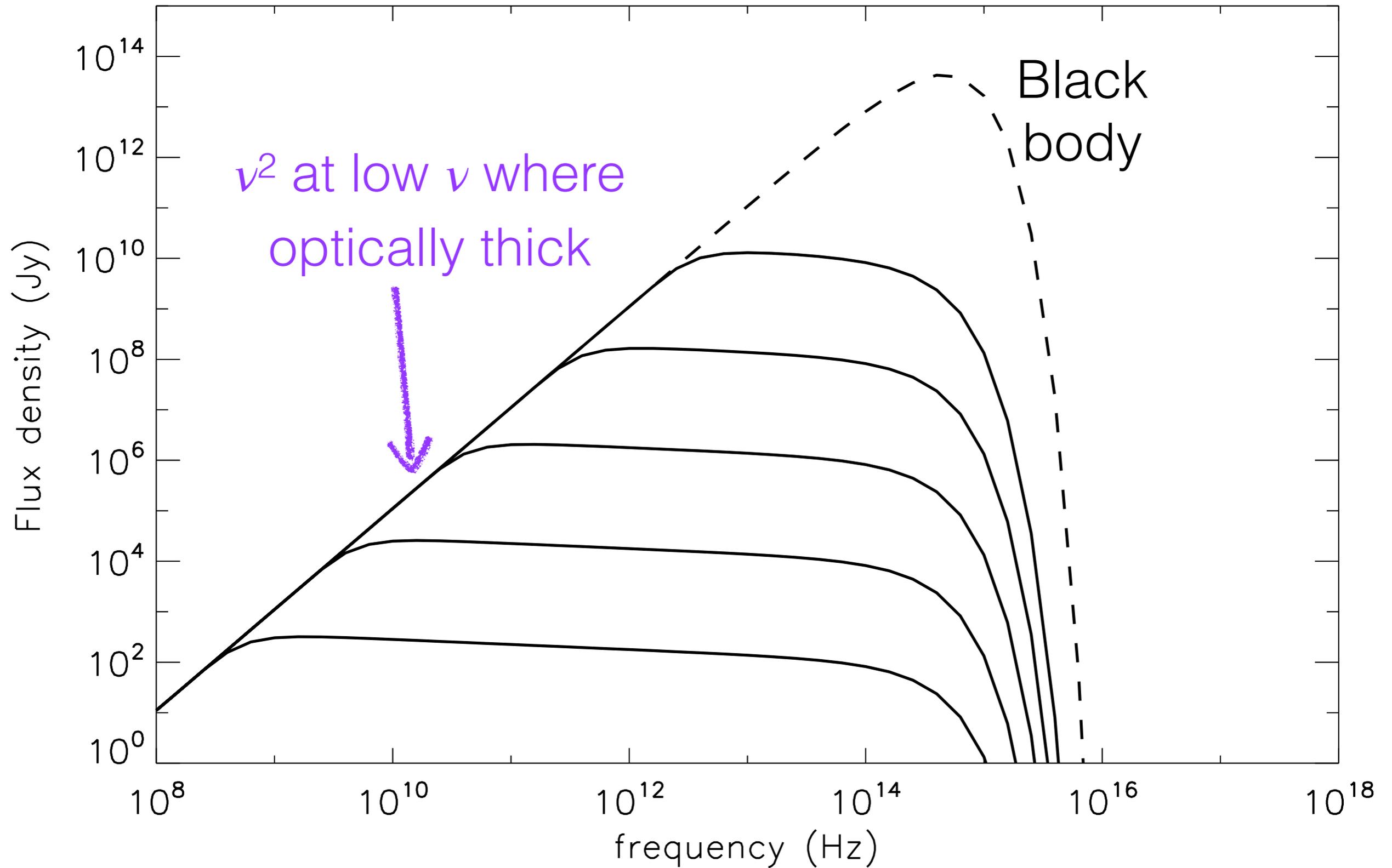
$$j_{\text{ff}}(\nu) = \frac{8}{3} \left(\frac{2\pi}{3} \right)^{1/2} \frac{e^6}{m_e^{3/2} c^3} \frac{n_e n_i}{(k_B T)^{1/2}} g_{\text{ff}}(\nu, T) e^{-h\nu/k_B T}$$

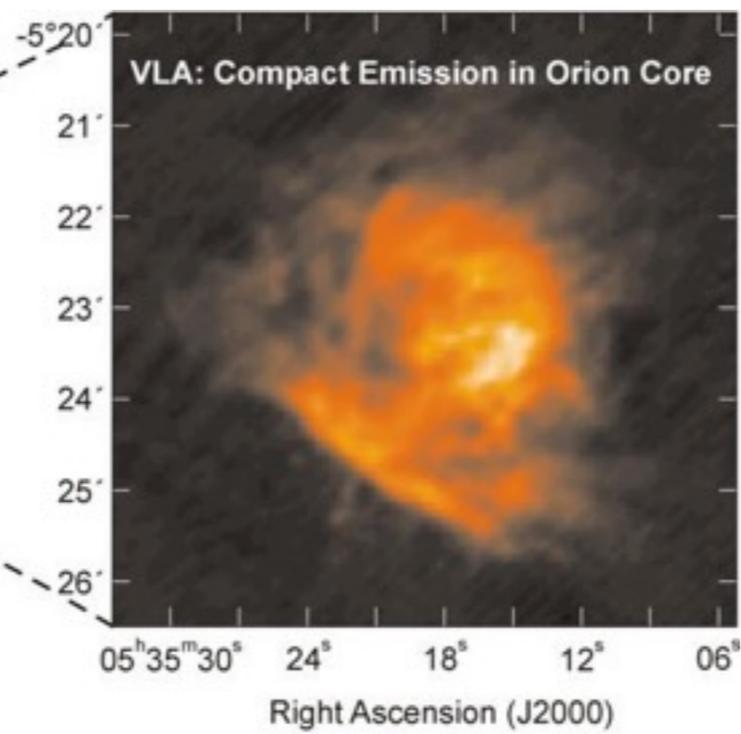
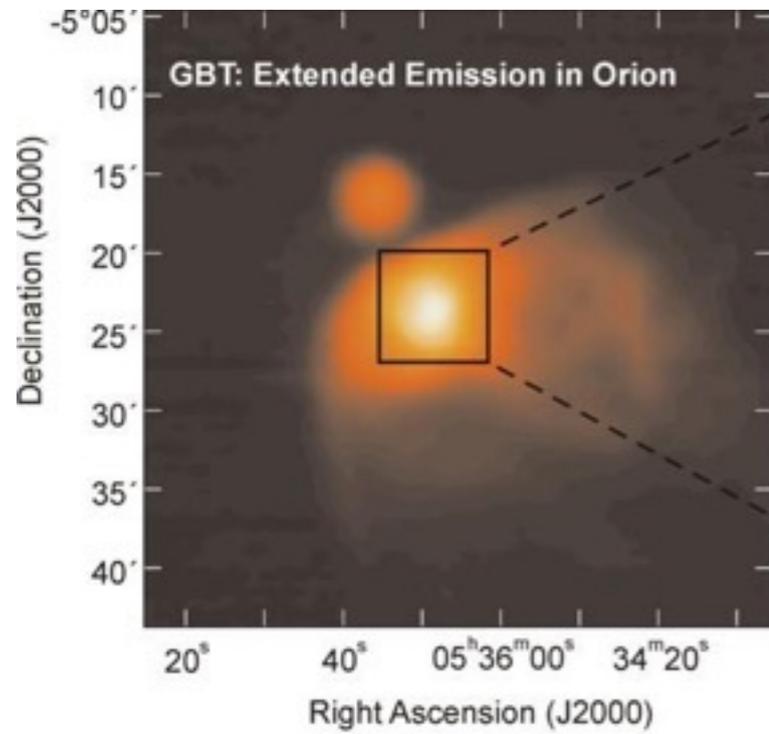
emission coefficient (e.g. erg s⁻¹ cm⁻³ Hz⁻¹ ster⁻¹)

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

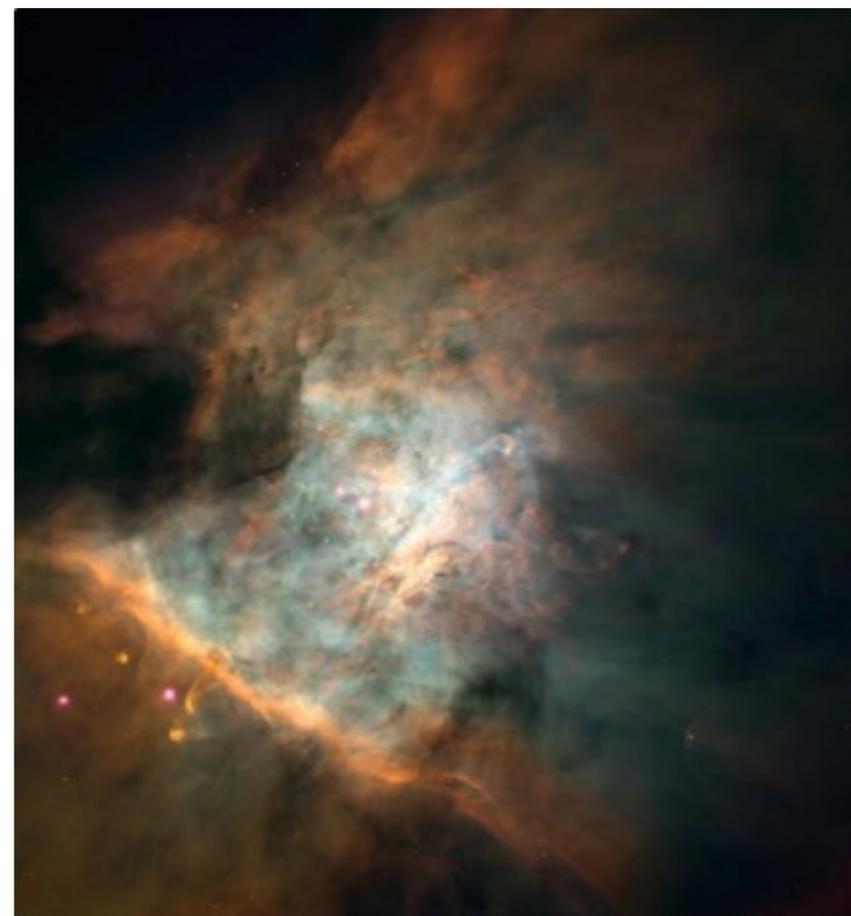
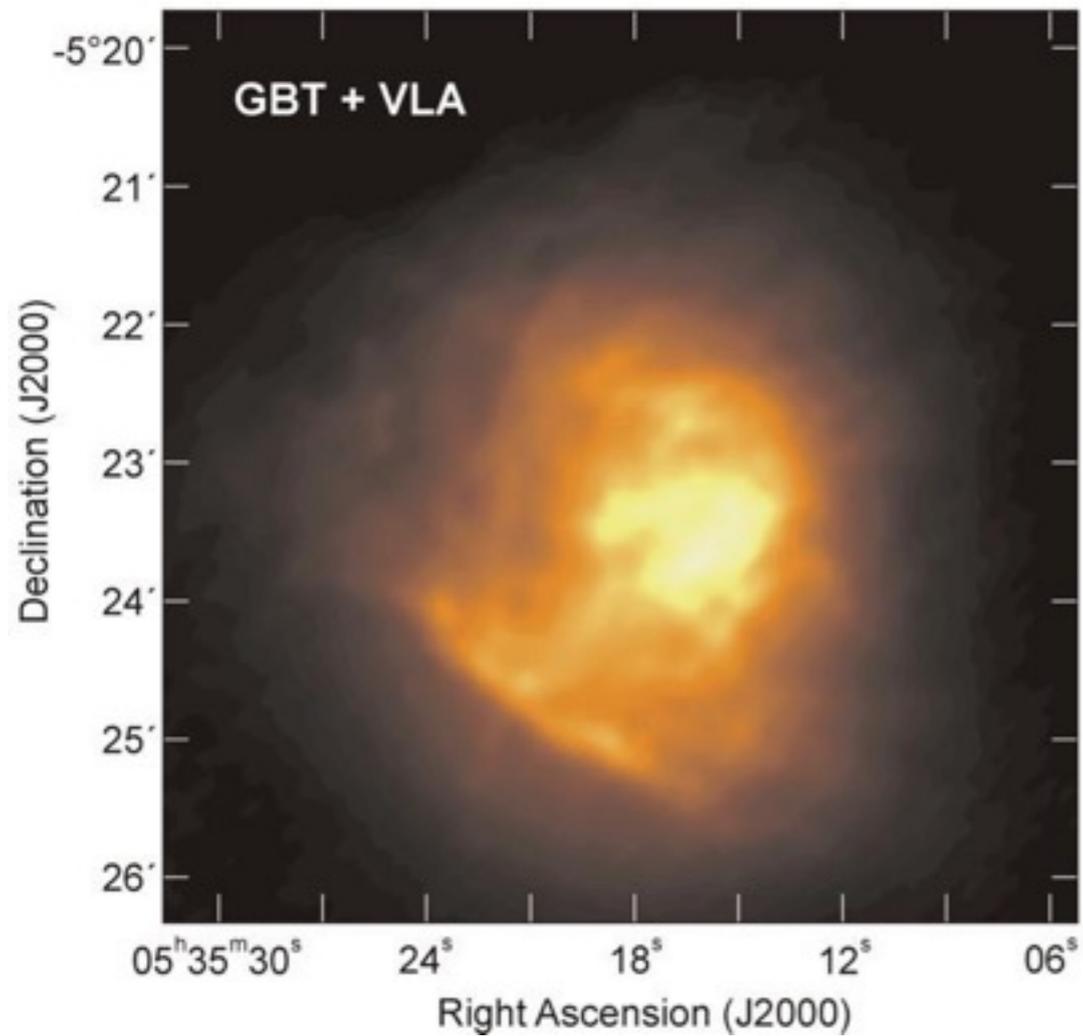


$$j_{ff}(\nu) = \frac{8}{3} \left(\frac{2\pi}{3} \right)^{1/2} \frac{e^6}{m_e^{3/2} c^3} \frac{n_e n_i}{(k_B T)^{1/2}} g_{ff}(\nu, T) e^{-h\nu/k_B T} + \text{radiative transfer}$$





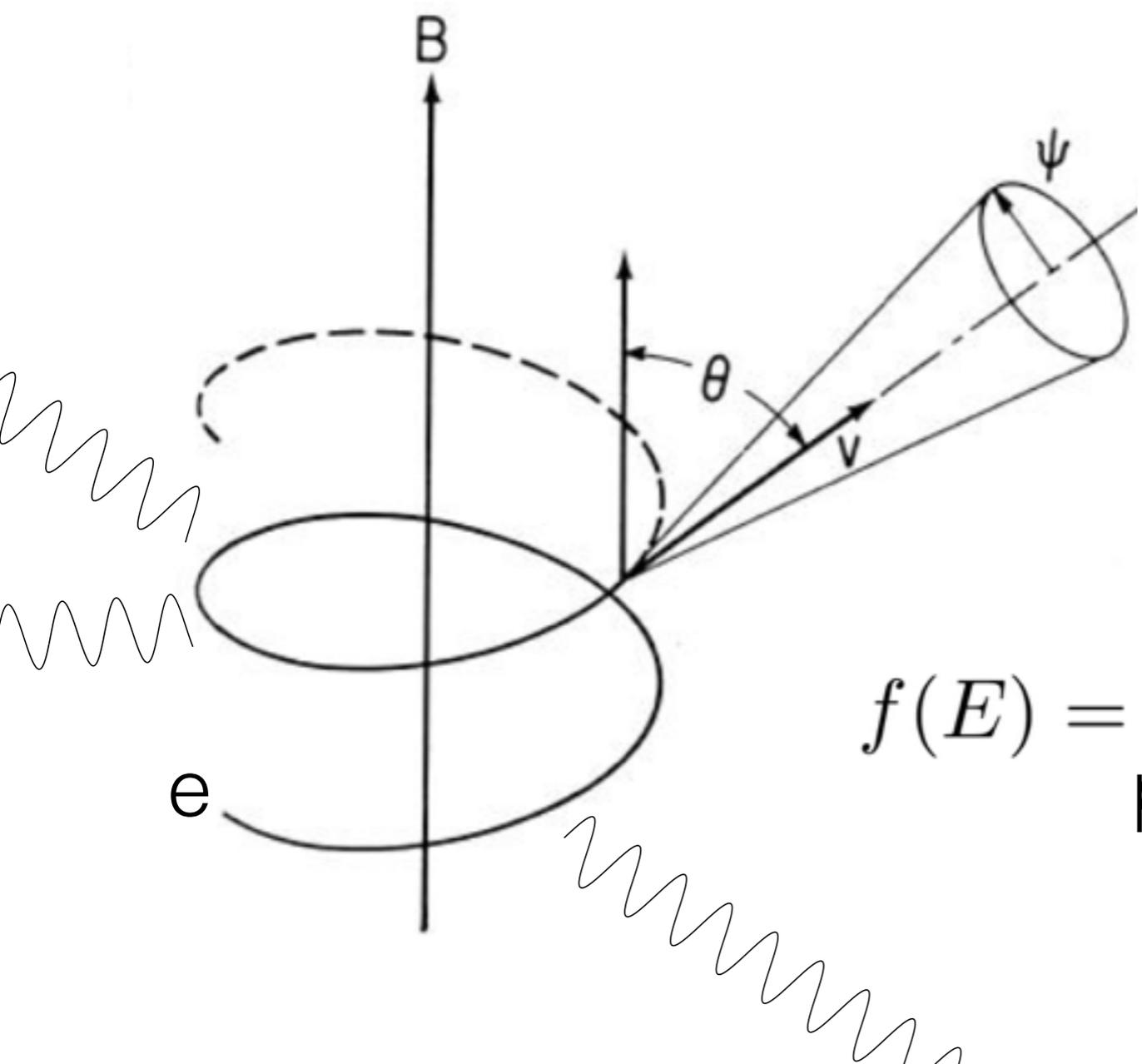
Orion Nebula
8.4 GHz
Dicker et al 2009



Synchrotron emission

nonthermal (usu: relativistic) electrons in a B field
polarized emission!

can get particle energies, n and B



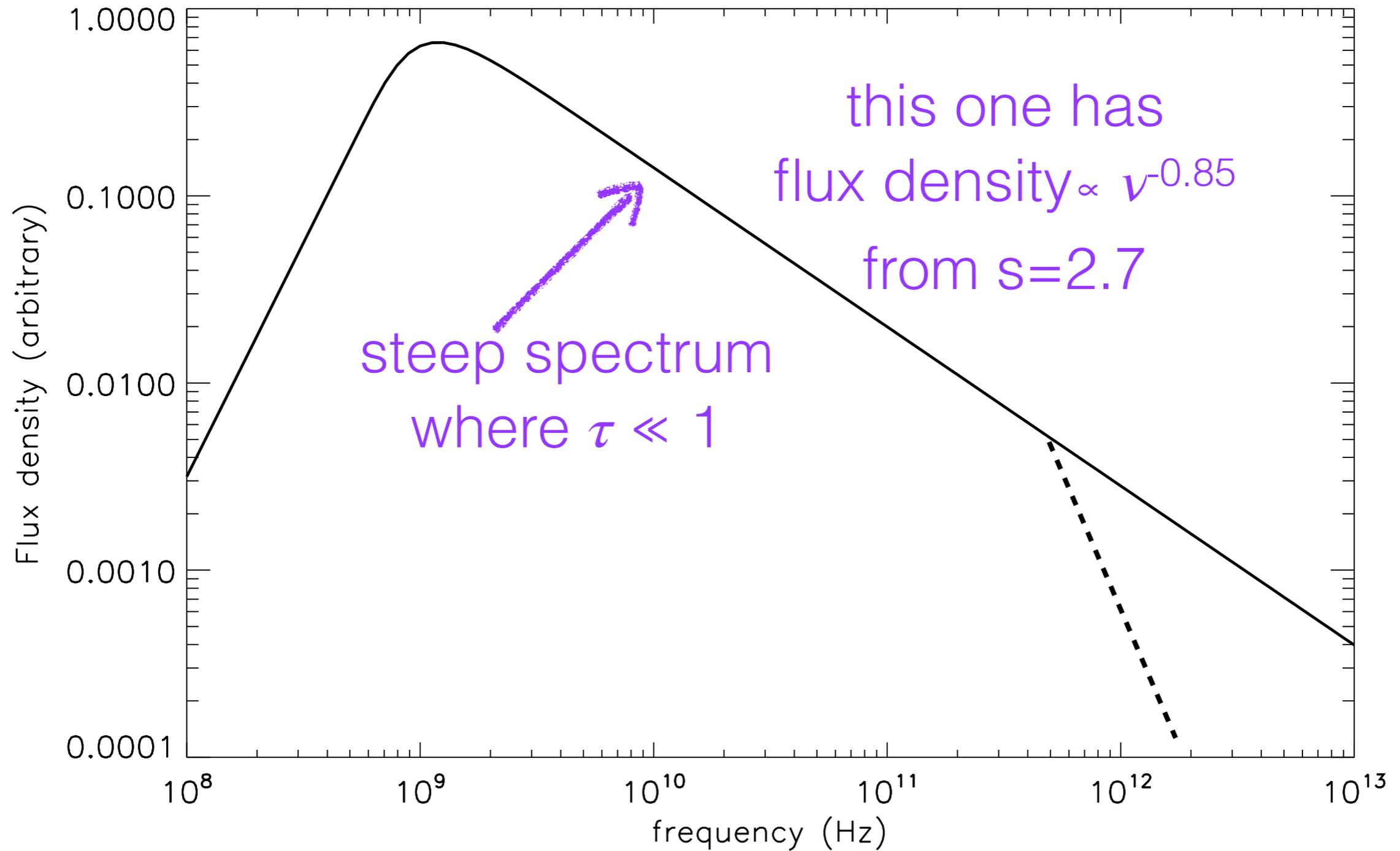
$$\nu_c = \frac{3}{4\pi} \gamma^2 \frac{eB}{mc} \sin \theta$$

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

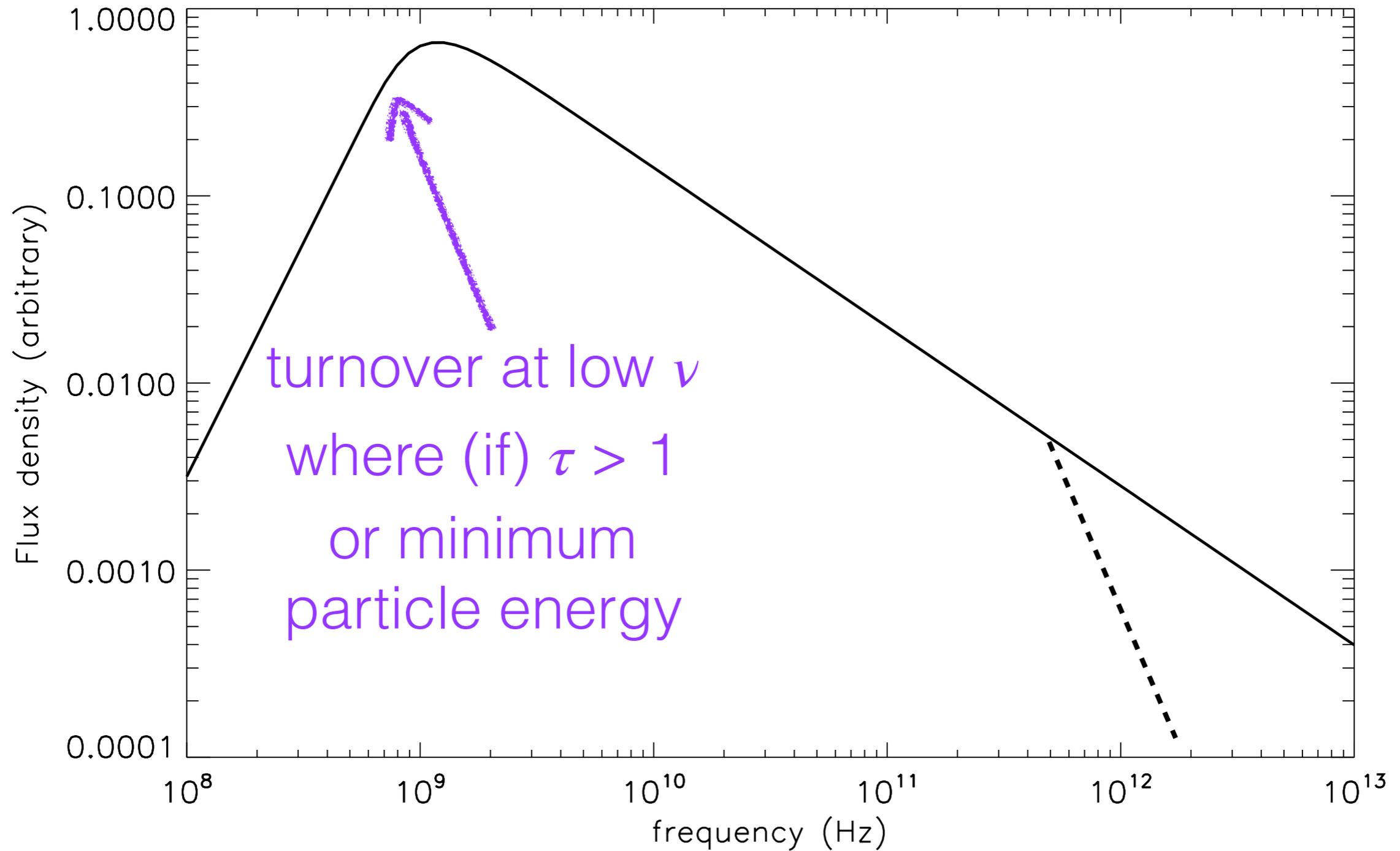
$$f(E) = f_0 E^{-s}$$

power law distribution of
electron energies

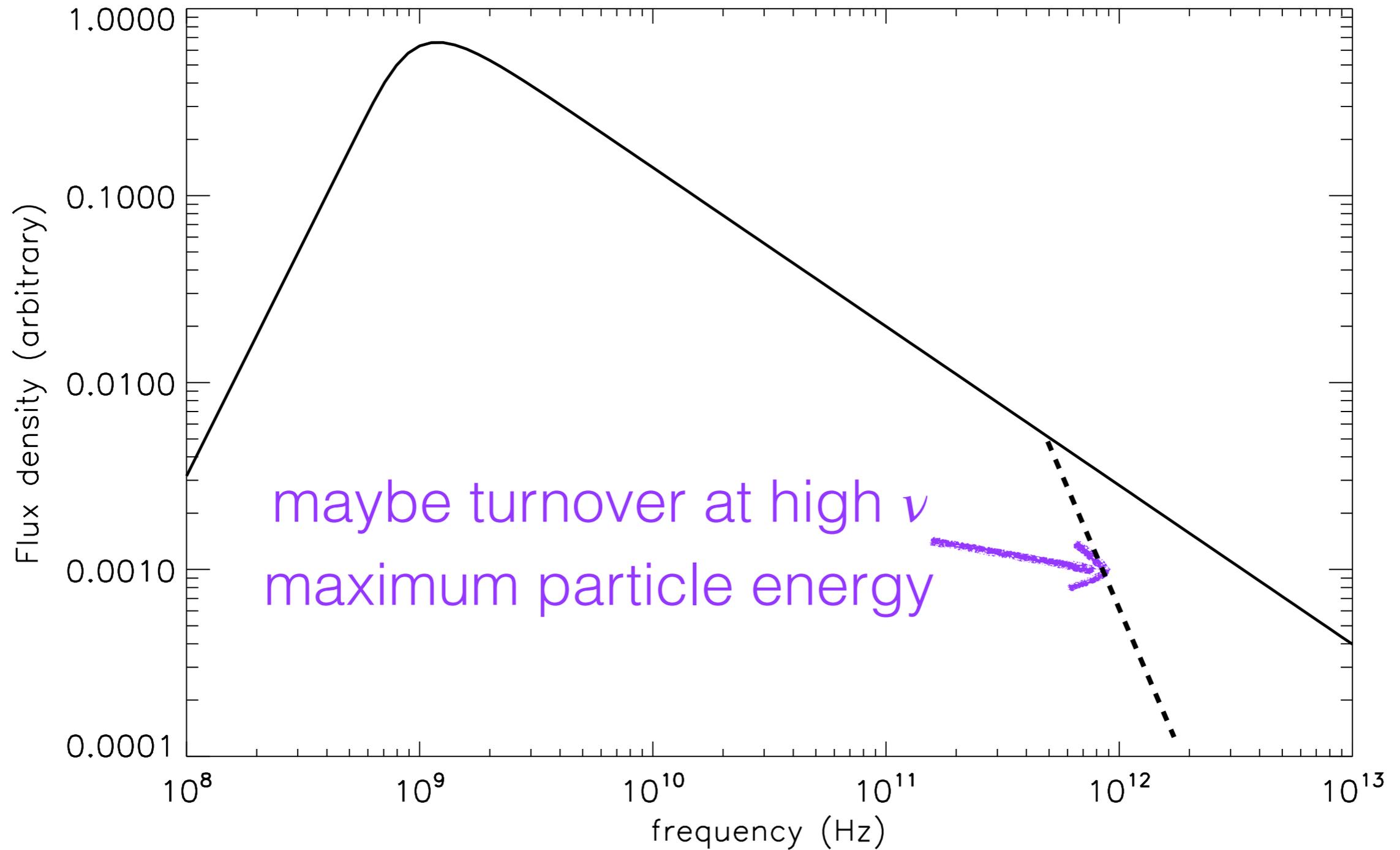
$$j_{sy}(\nu) \propto P_o B^{(s+1)/2} f_o \nu^{-(s-1)/2} + \text{radiative transfer}$$



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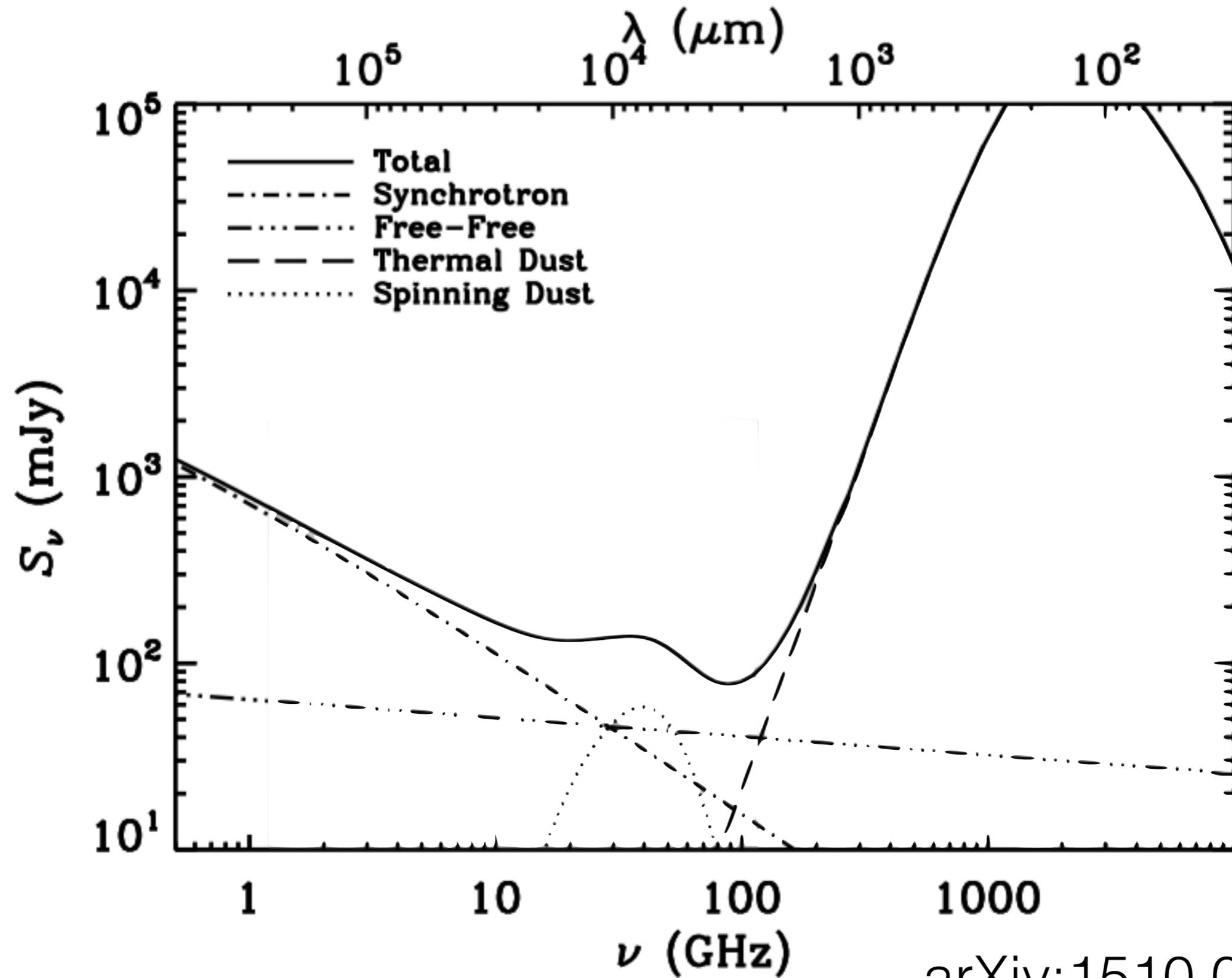
synchrotron from active galaxy Her A, $\nu \sim 6.5$ GHz



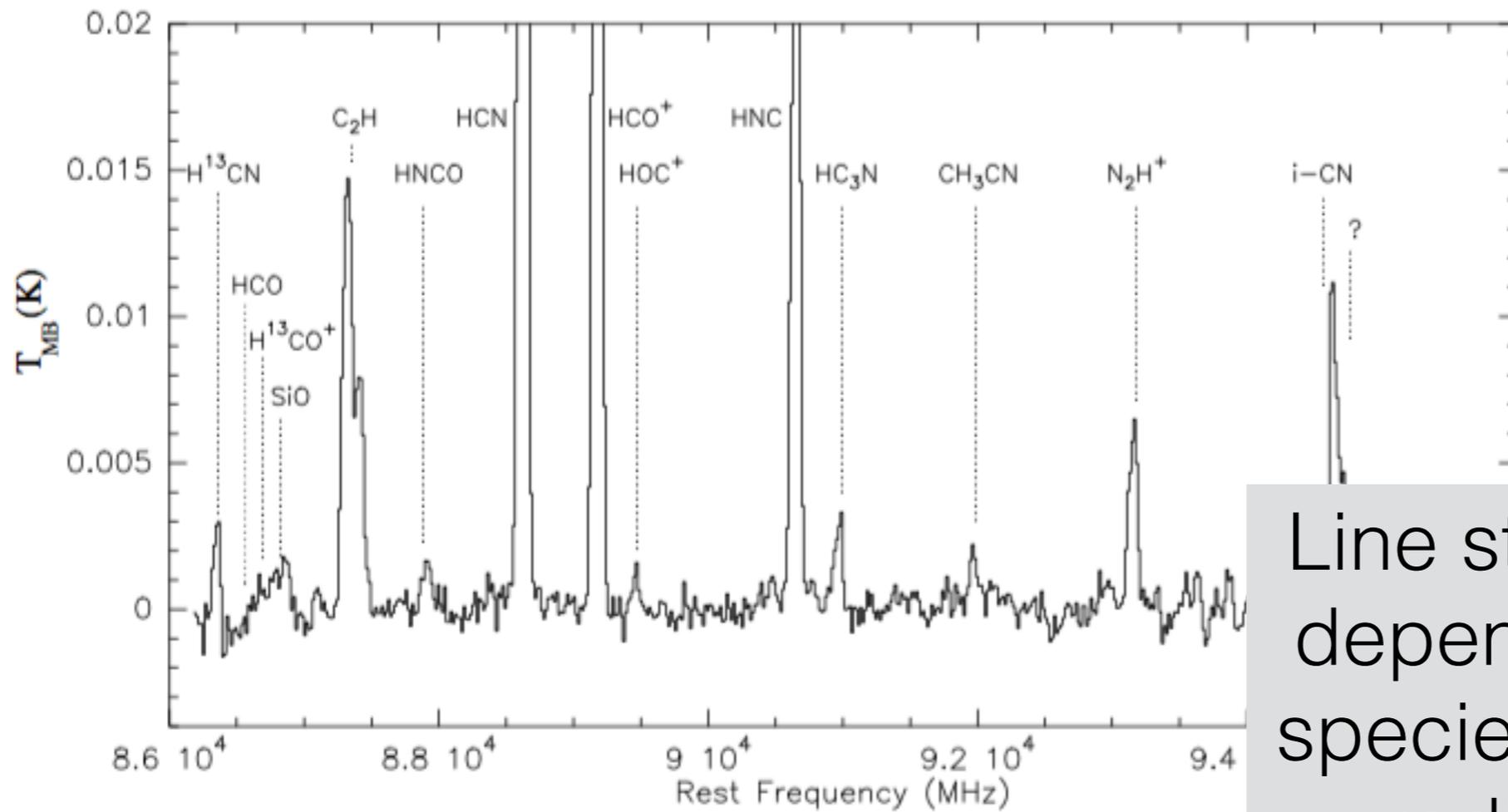
5 GHz

mostly
synchrotron
from
moderate- z
active
galaxies

model composite radio spectrum of a galaxy

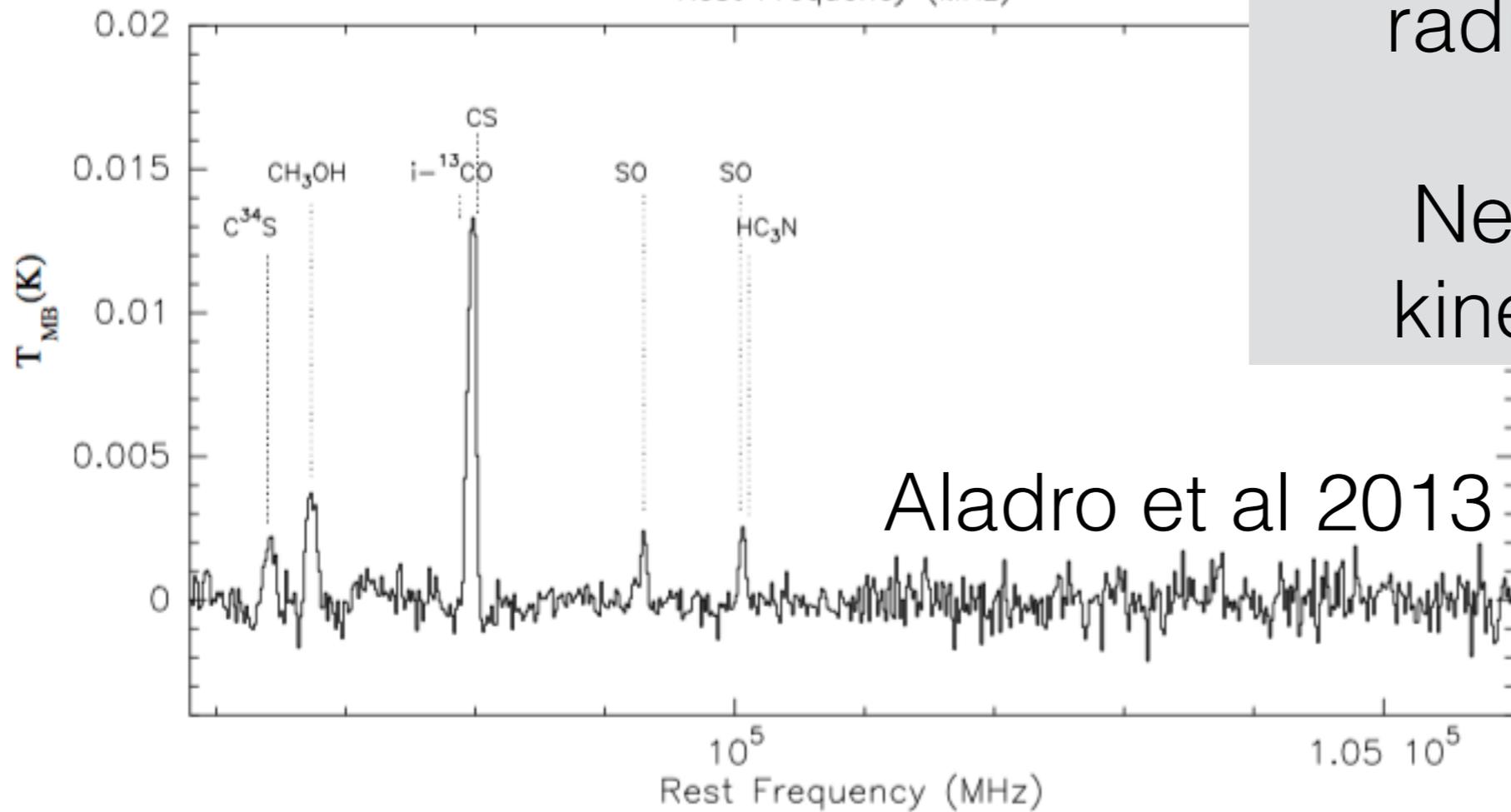


arXiv:1510.06431



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

Need lines to get kinematics of gas.



Aladro et al 2013

Too Many Kinds of Temperature

physical T

excitation T_{ex}

receiver T_{rec}

system T_{sys}

antenna T_A

brightness T_B

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

Planck function

Maxwell-Boltzmann velocity dist.

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

Too Many Kinds of Temperature

physical T

excitation T_{ex}

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brightness T_B

$$n_2/n_1 = (g_2/g_1)e^{-h\nu_0/KT_{\text{ex}}}$$

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

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

excitation T_{ex}

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

receiver T_{rec}

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

system T_{sys}

antenna T_A

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

brightness T_B

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

Too Many Kinds of Temperature

physical T

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brightness T_B

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.

$$J = W \text{ Hz}^{-1}$$

$$\text{erg} = \text{erg s}^{-1} \text{ Hz}^{-1}$$

Too Many Kinds of Temperature

physical T

excitation T_{ex}

receiver T_{rec}

system T_{sys}

antenna T_A

brightness T_B

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}

receiver T_{rec}

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antenna T_A

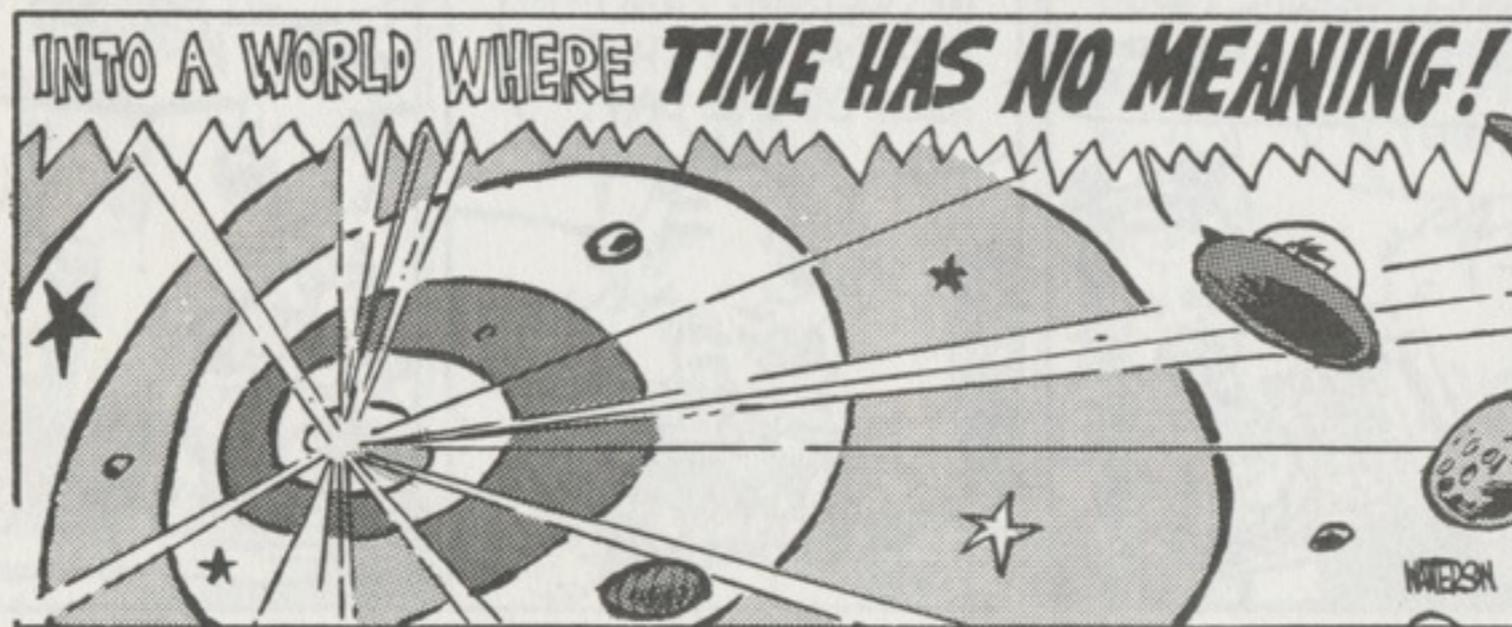
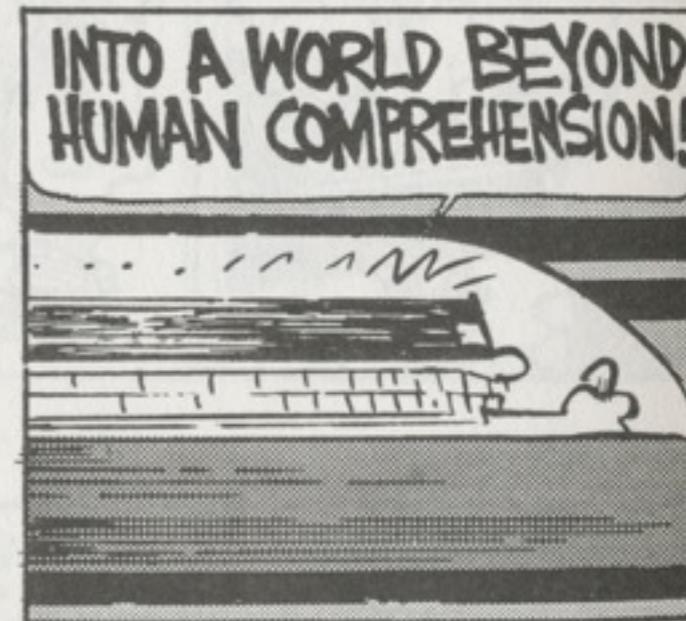
brightness T_B

system temperature is particularly important because

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

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

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



HL Tau, $\nu \sim 290$ GHz, $\lambda \sim 1$ mm,
resolution $\sim 0.03''$

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



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

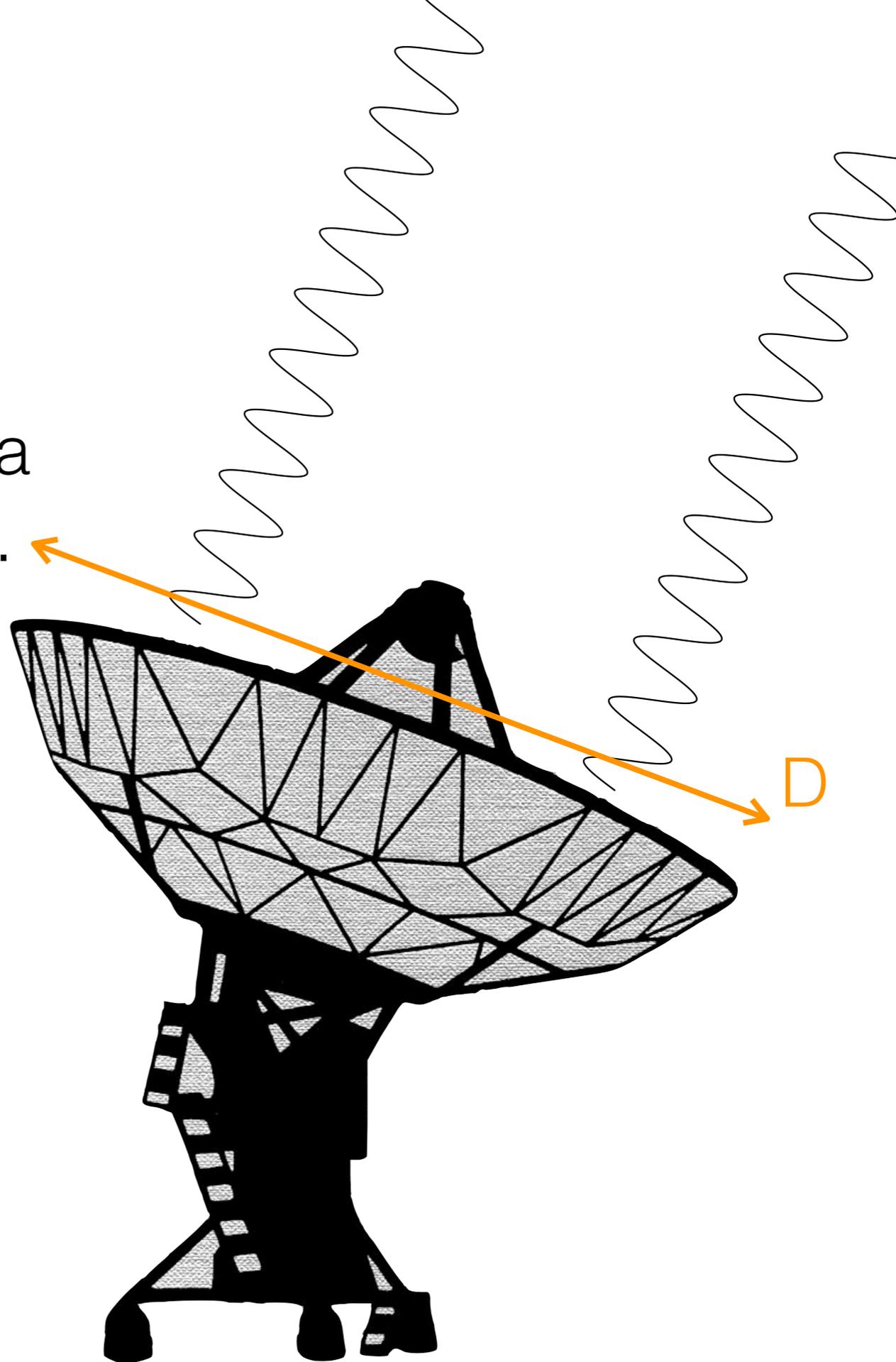


Her A, $\nu \sim 6.5$ GHz, $\lambda \sim$
5 cm, resolution $\sim 0.5''$

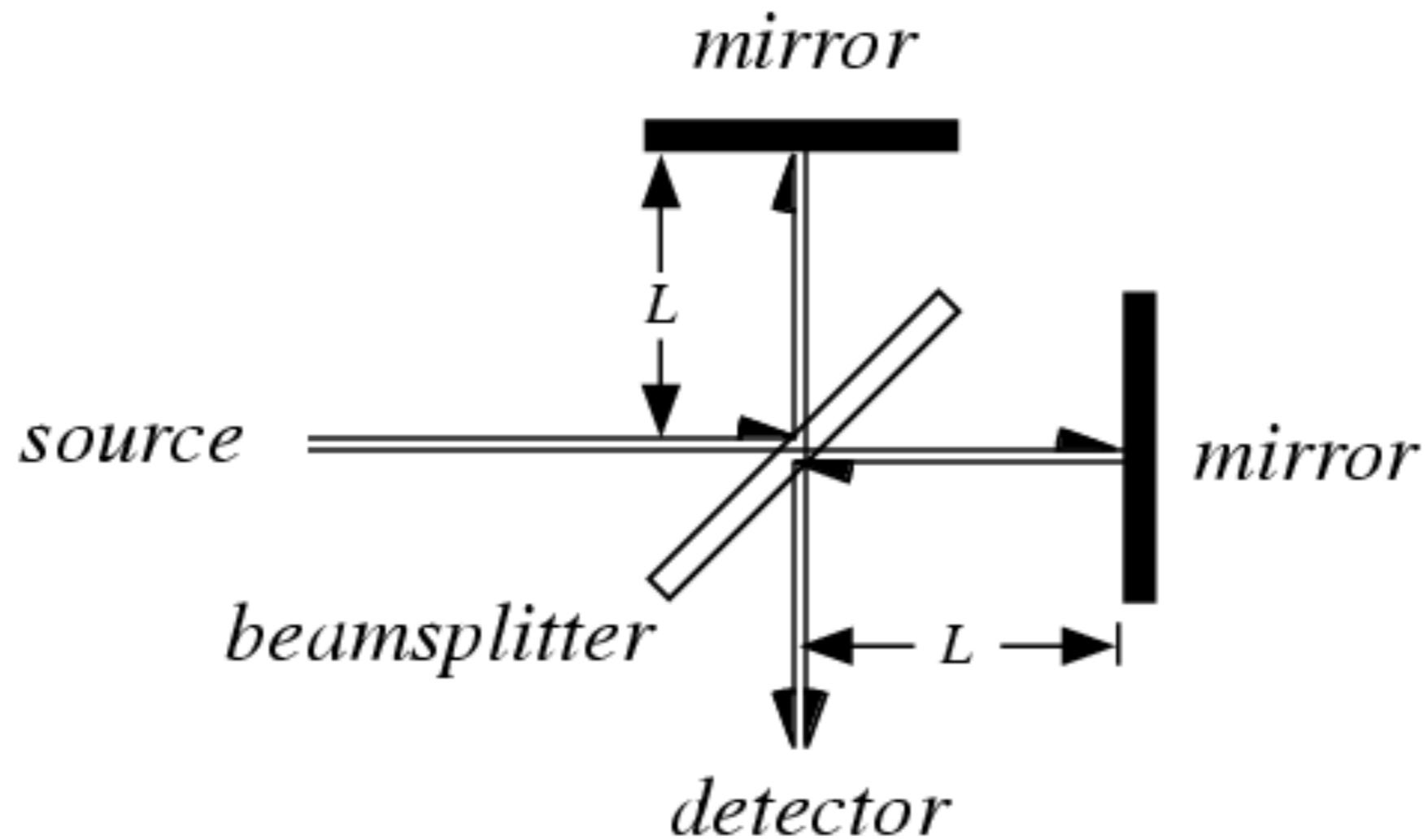
Diffraction theory: this telescope (by itself) has a resolution $\sim \lambda/D$ radians.

How can we do better than that?

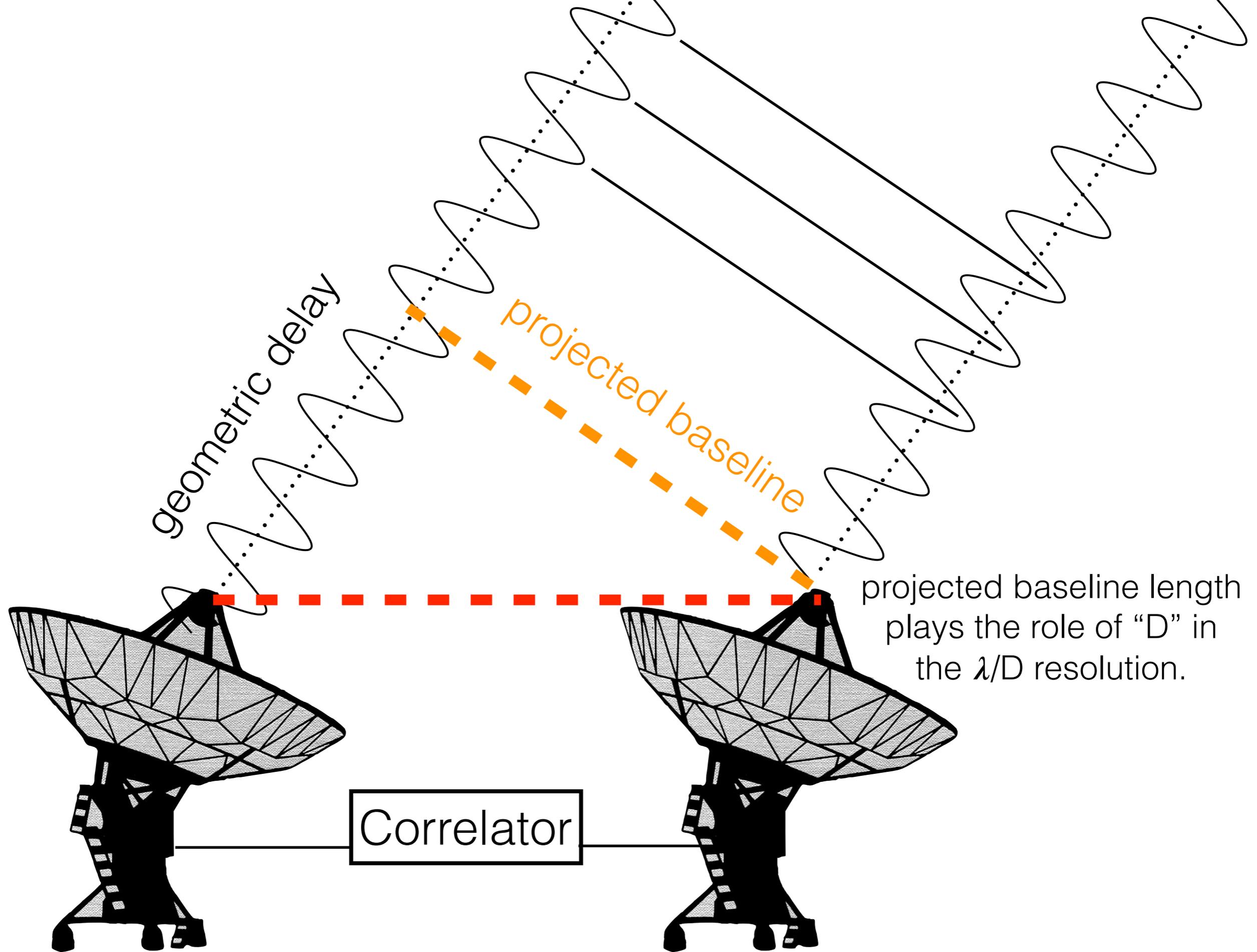
with an interferometer.



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

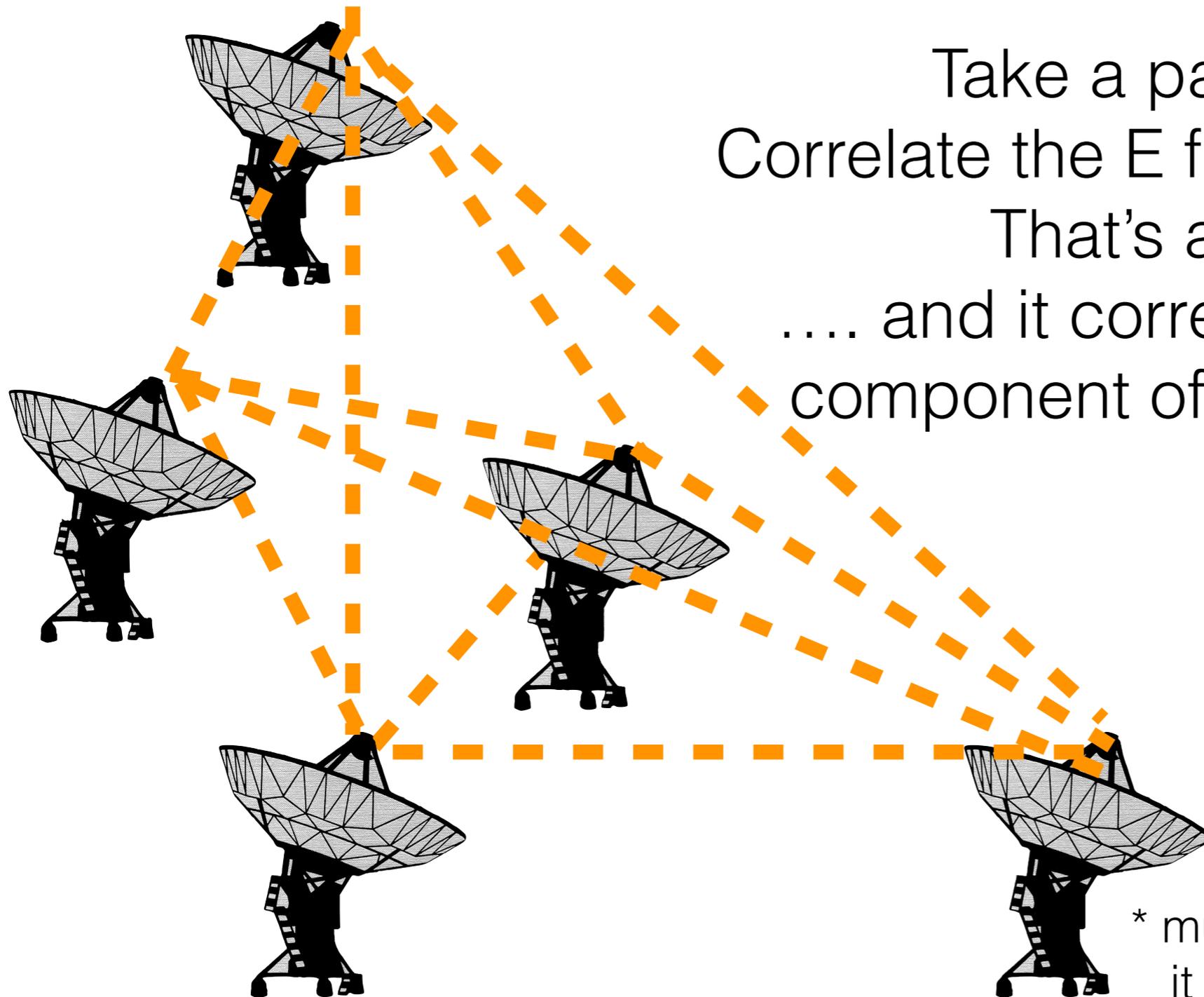


Leonardo Motta, scienceworld.wolfram.com



Interferometer theory, very loosely.

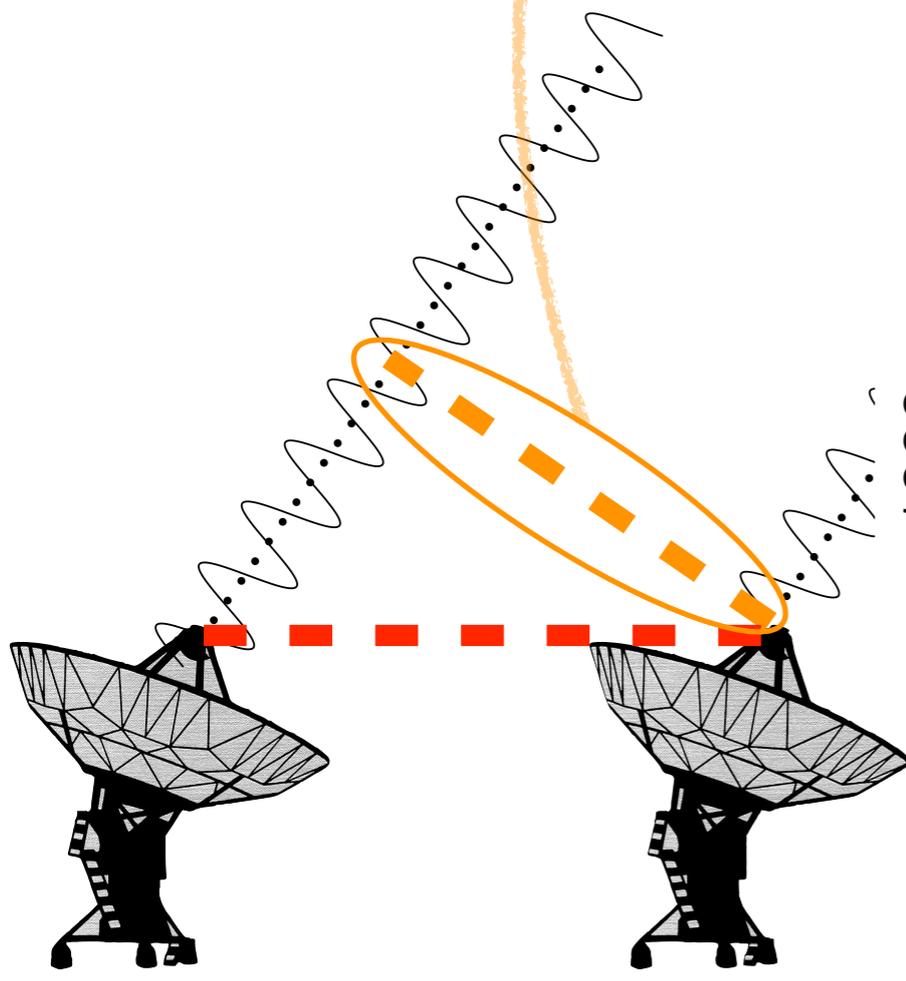
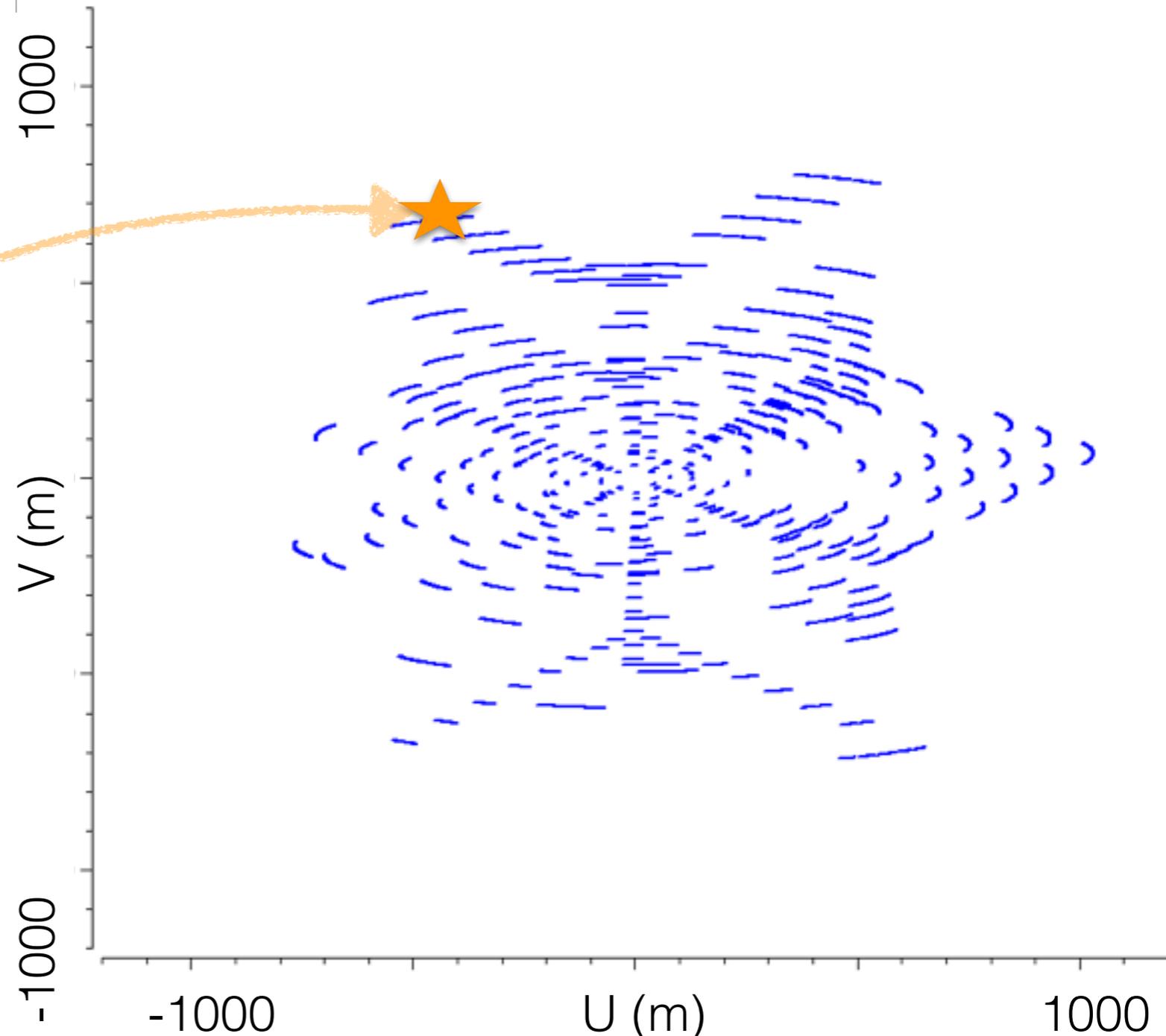
correlation* of E field at Earth = FT of brightness distribution of the sky.



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

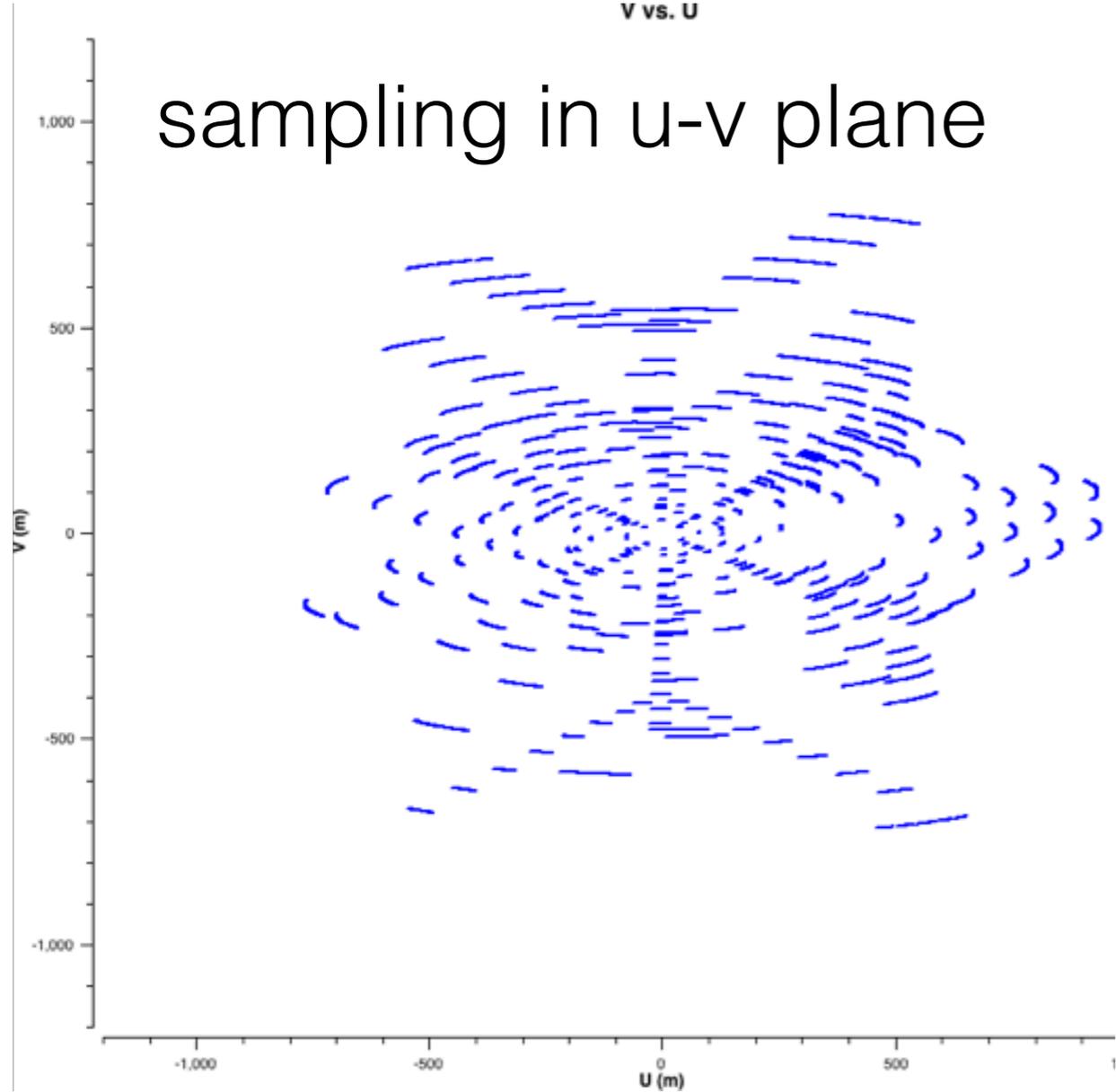
V vs. U



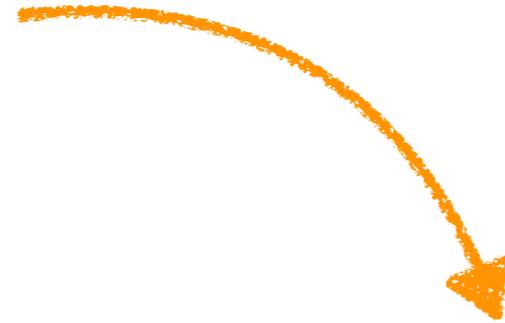
this is a short VLA D-
config dataset
(max. baselines ~ 1 km)

V vs. U

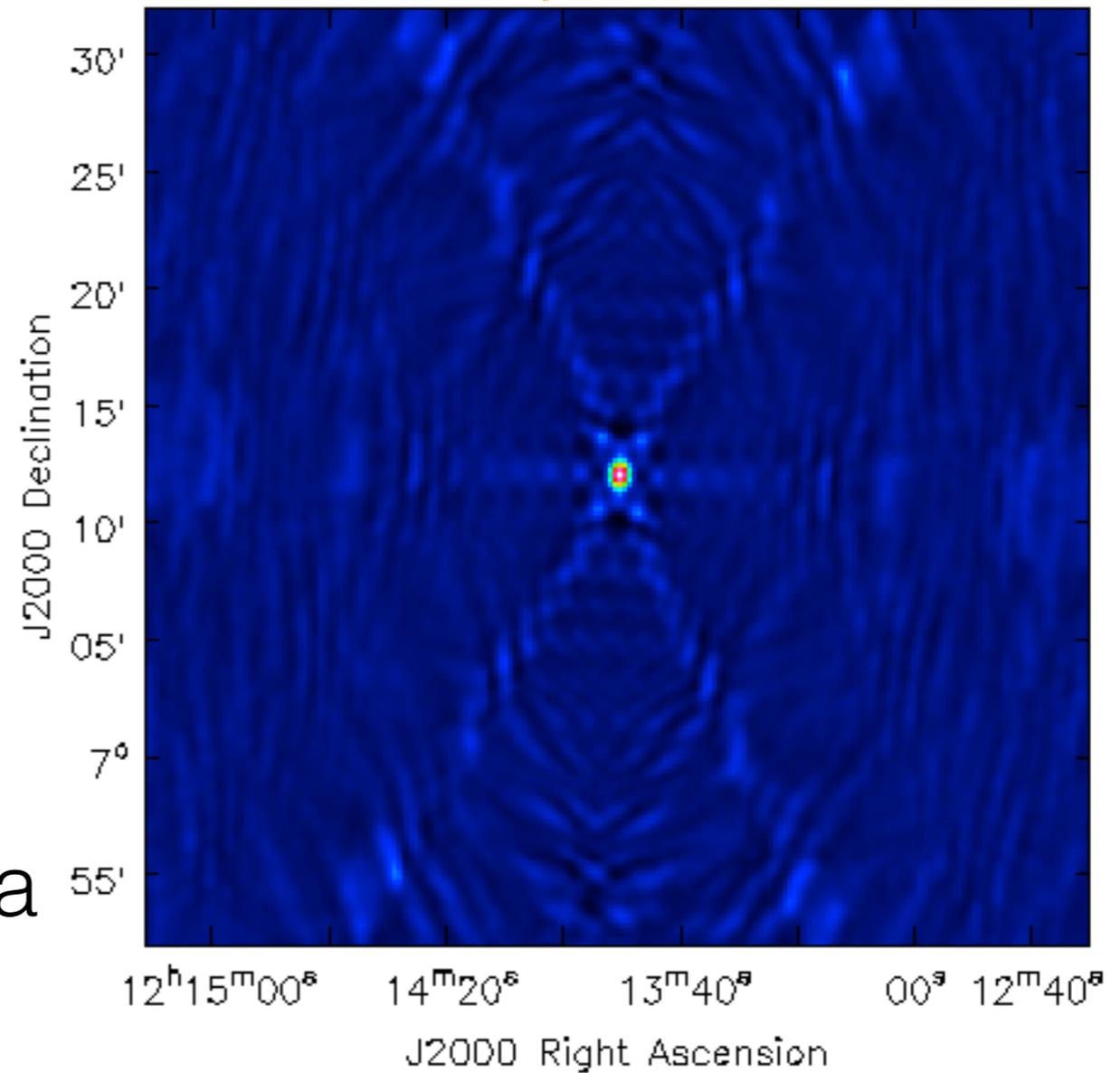
sampling in u-v plane



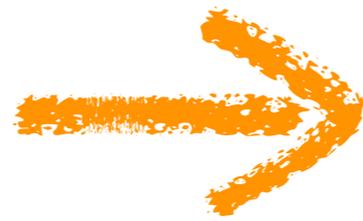
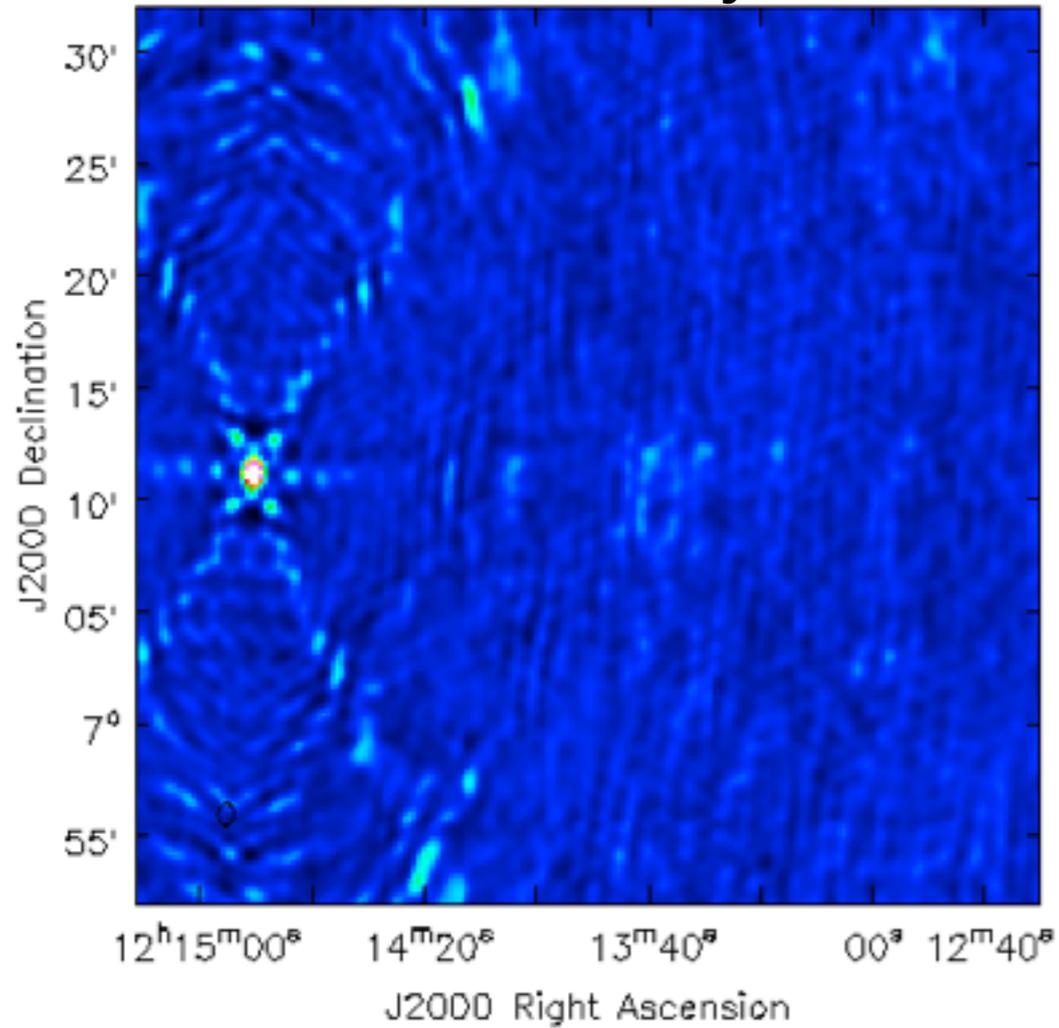
Fourier Transform



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

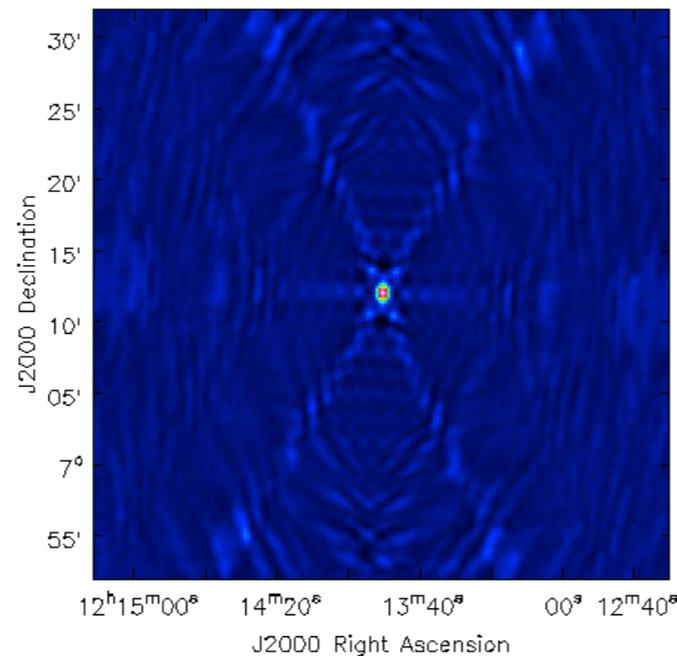
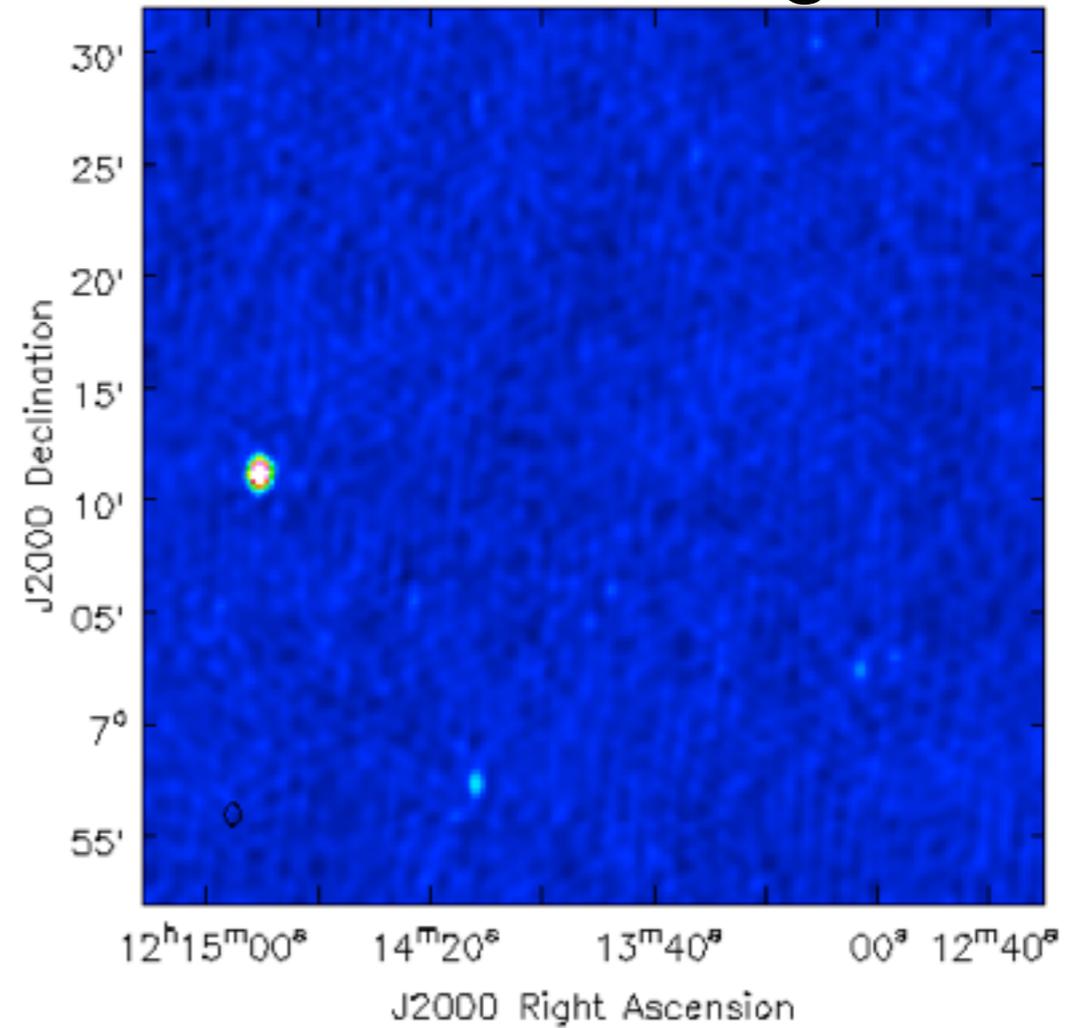


FT of visibility data

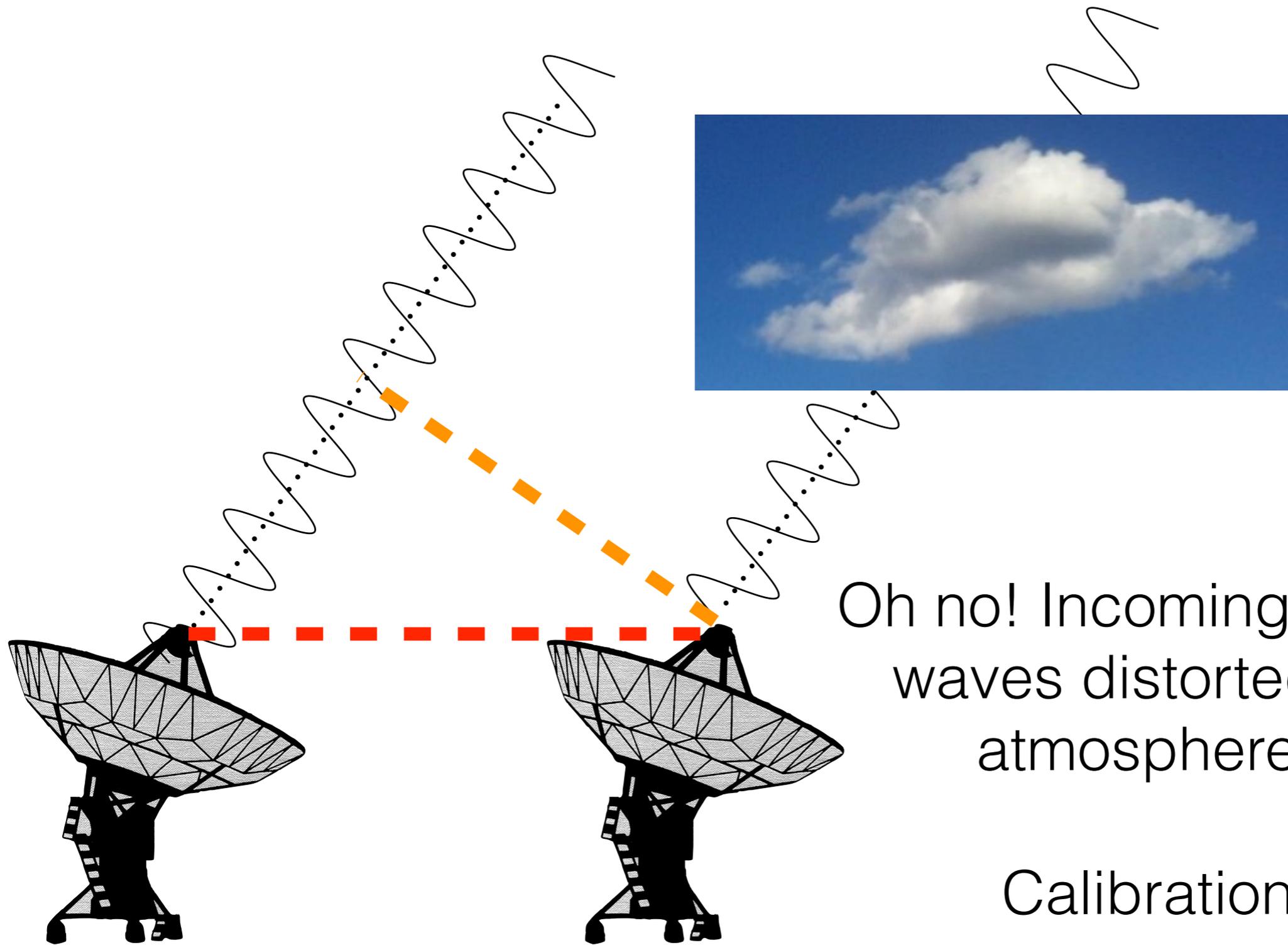


Deconvolution
(cleaning)

cleaned image



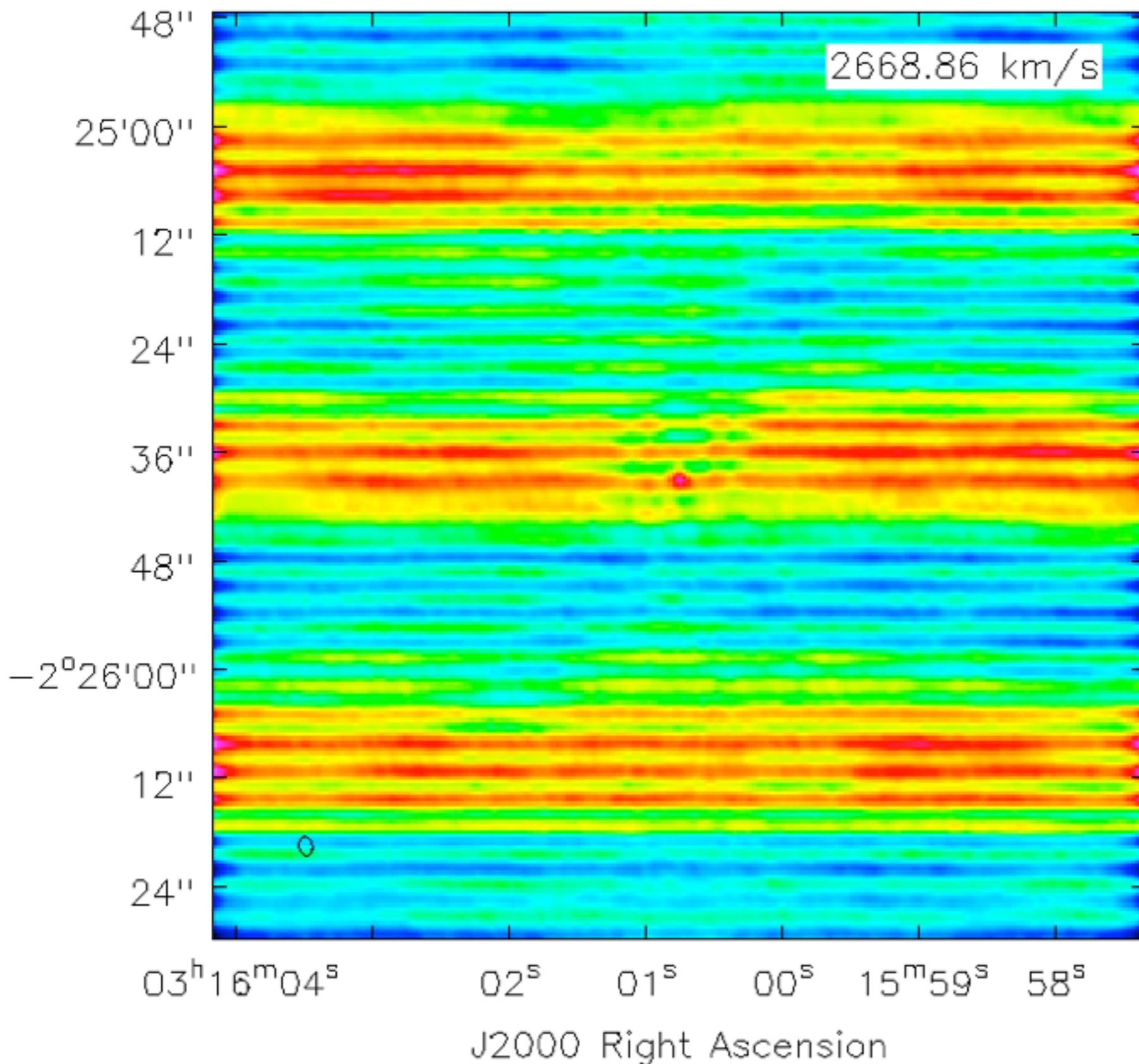
recall this is
what point
sources look like



Oh no! Incoming plane waves distorted by atmosphere!

Calibration

NGC1266_A_HI.FITS-raster



AAAAAAAAA!!!
What happened
to my image?

Error Recognition
& Error Analysis

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*

