Galactic foreground emission

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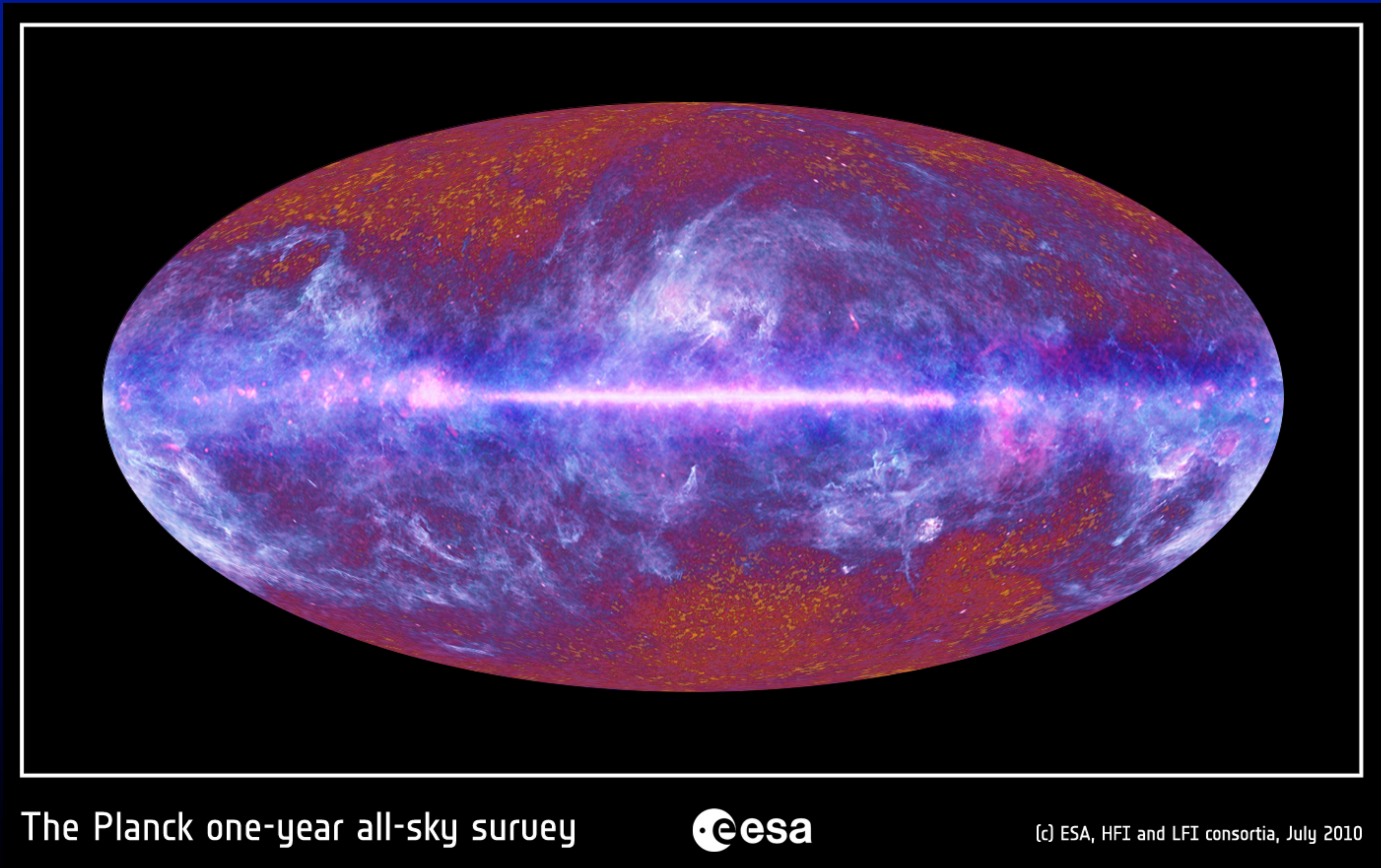
Astrophysics from the radio to the submillimetre, Bologna, 13 Feb 2012

All-sky view, many foregrounds



Plan

Decomposition:

Galactic

foreground

emission

What can emit?

Hydrogen, in various forms

Dust, in various forms

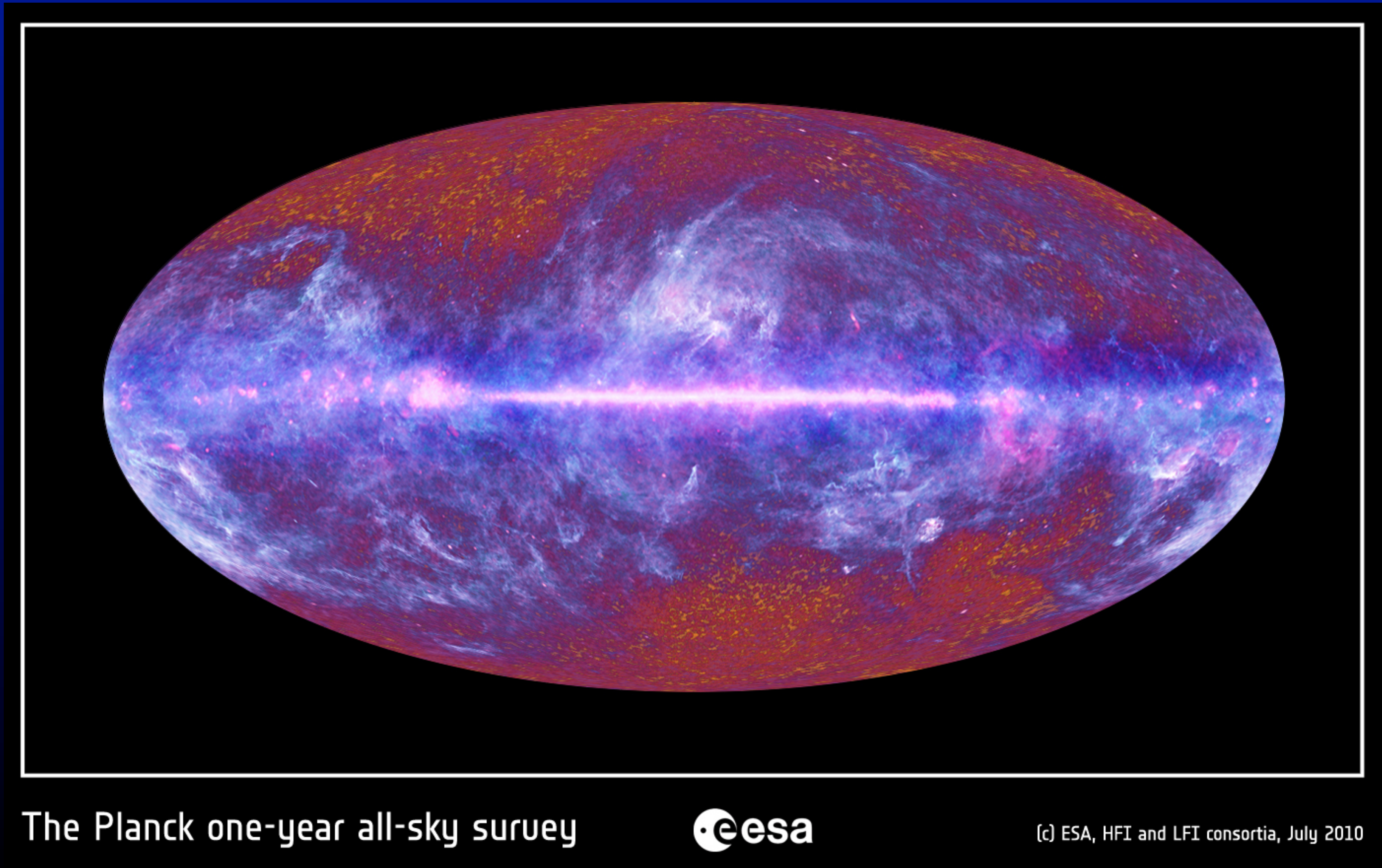
Focusing the plan

Hydrogen, in various forms

Atomic: H I emission line at 21 cm (0.001420 GHz).
Fairly optically thin at low column densities, and so traces how much material there is, as a function of velocity.

Molecular: hard to measure directly; also related to high column density → bright foreground. Used to study this phase of the ISM but harder to remove as a foreground. Avoid here.

Where H I and H_2 ~ blue and white



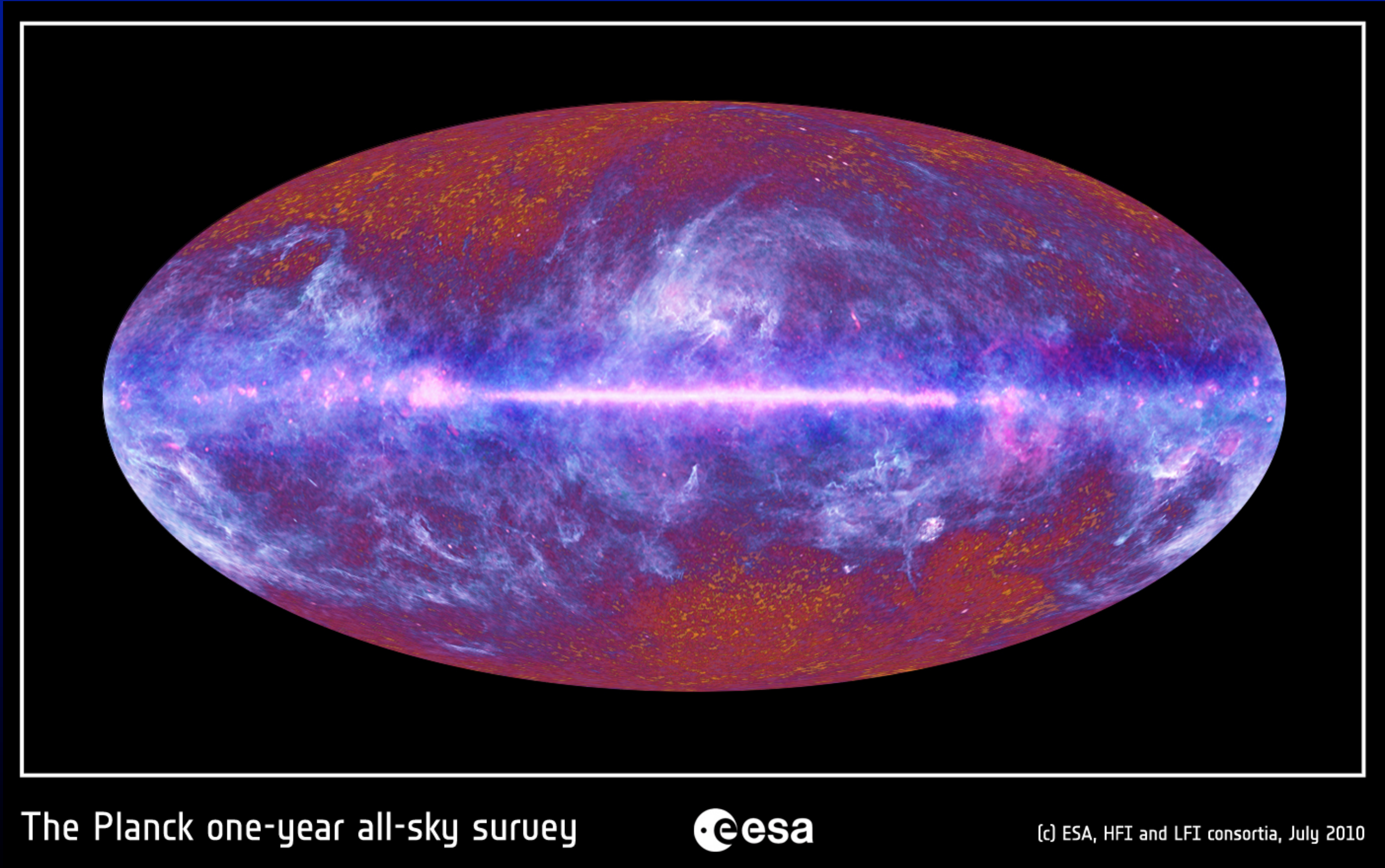
Focusing the plan to higher ν

Hydrogen in a plasma

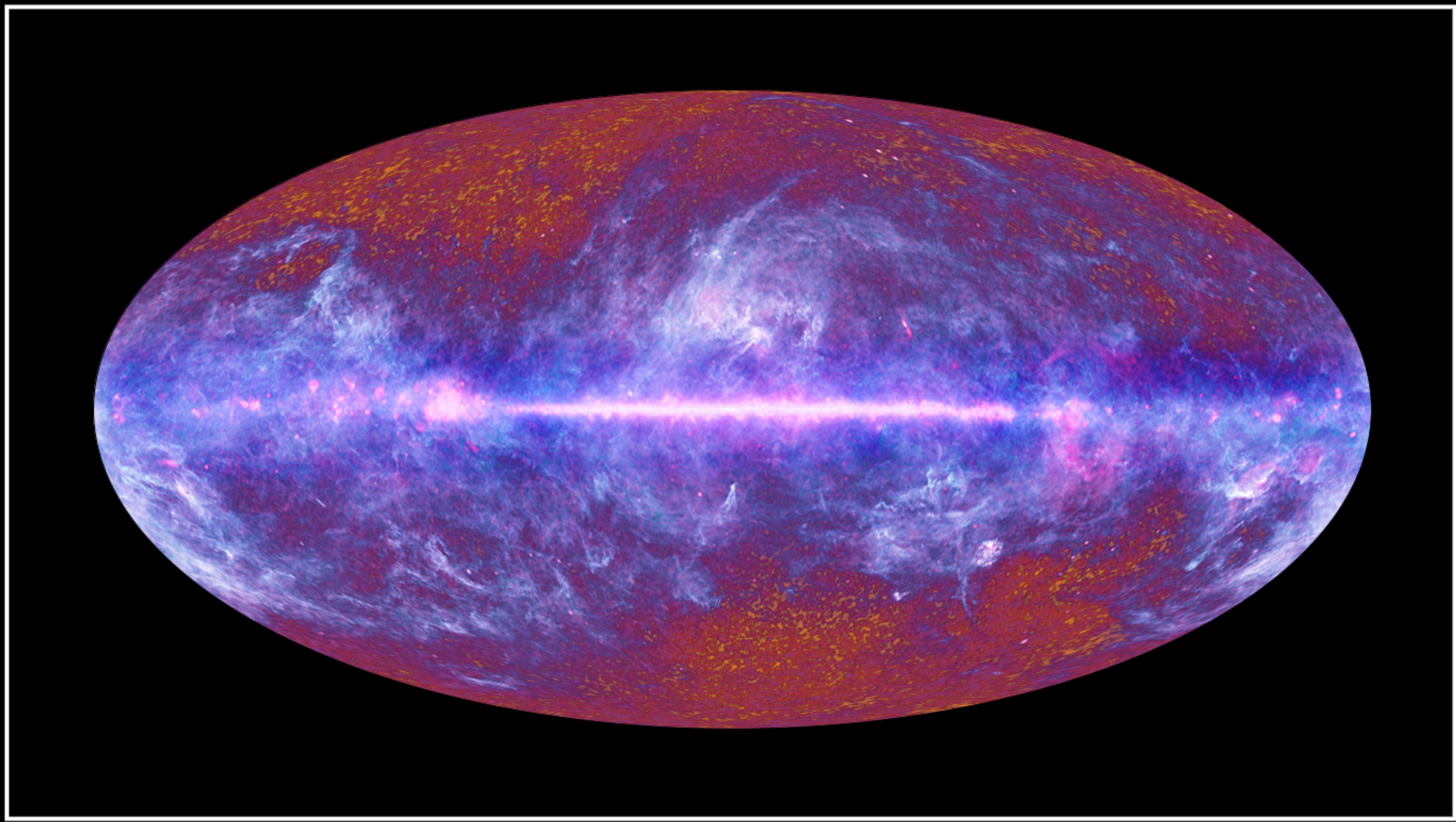
Thermal: free-free emission from radio to higher frequencies. I_ν spectrum fairly flat (cutoff eventually, depending on kinetic temperature).

Relativistic: electrons → synchrotron emission, with falling spectrum.

H II regions and synchrotron – pink



Where H I ~ blue, but dust emission



The Planck one-year all-sky survey

esa

What we are looking at (dust)

These slides try to capture what underlies the thermal dust emission seen by Planck, how Planck improves our ability to study dust, *e.g.*, in measuring the SED and finding T, and to introduce some terminology like the observable called “emissivity”: how much emission there is per H nucleon.

The slides illustrate the SED of dust in the diffuse atomic phase, but the ideas pass over into the molecular phase too.

Dust temperature

The larger (aka “big”) dust particles are in thermal equilibrium with the interstellar radiation field (ISRF).

- Different dust components can have different temperatures T even in the same ISRF.
- T can vary along the line of sight (different velocity components, parcels of gas).

Also, for small particles there is non-equilibrium emission, peaking beyond the Planck bands.

Dust emission

Dust emission is optically thin (at frequencies of interest here):

$$I_\nu = \tau_\nu B_\nu(T).$$

Rising spectrum from the Planck function *and* from the frequency dependence of the opacity, or here, the optical depth τ_ν.

Dust emission and mass

$I_\nu = \tau_\nu B_\nu(T)$.

$I_\nu = \kappa_\nu M_{dust} B_\nu(T)$.

Dust emission measures the mass column density of dust, M_{dust}, modulated non-linearly by dust temperature T.

The largest, thermally-emitting, dust grains dominate the mass and hence the sub-mm emission.

At the outset, κ_ν and T are not known.

Spectral dependence of opacity

$I_\nu = \tau_\nu B_\nu(T).$

$I_\nu = \kappa_\nu M_{dust} B_\nu(T).$

The opacity κ_ν is frequency dependent, ν^β.

β ~ 1.8, but it might be frequency dependent (goal).

Different dust components (size and/or composition) can have different frequency dependence of κ_ν, thus affecting the relative contributions to the sub-mm emission as a function of frequency.

Dust emissivity

$$I_\nu = \tau_\nu B_\nu(T).$$

$$I_\nu = \kappa_\nu M_{dust} B_\nu(T).$$

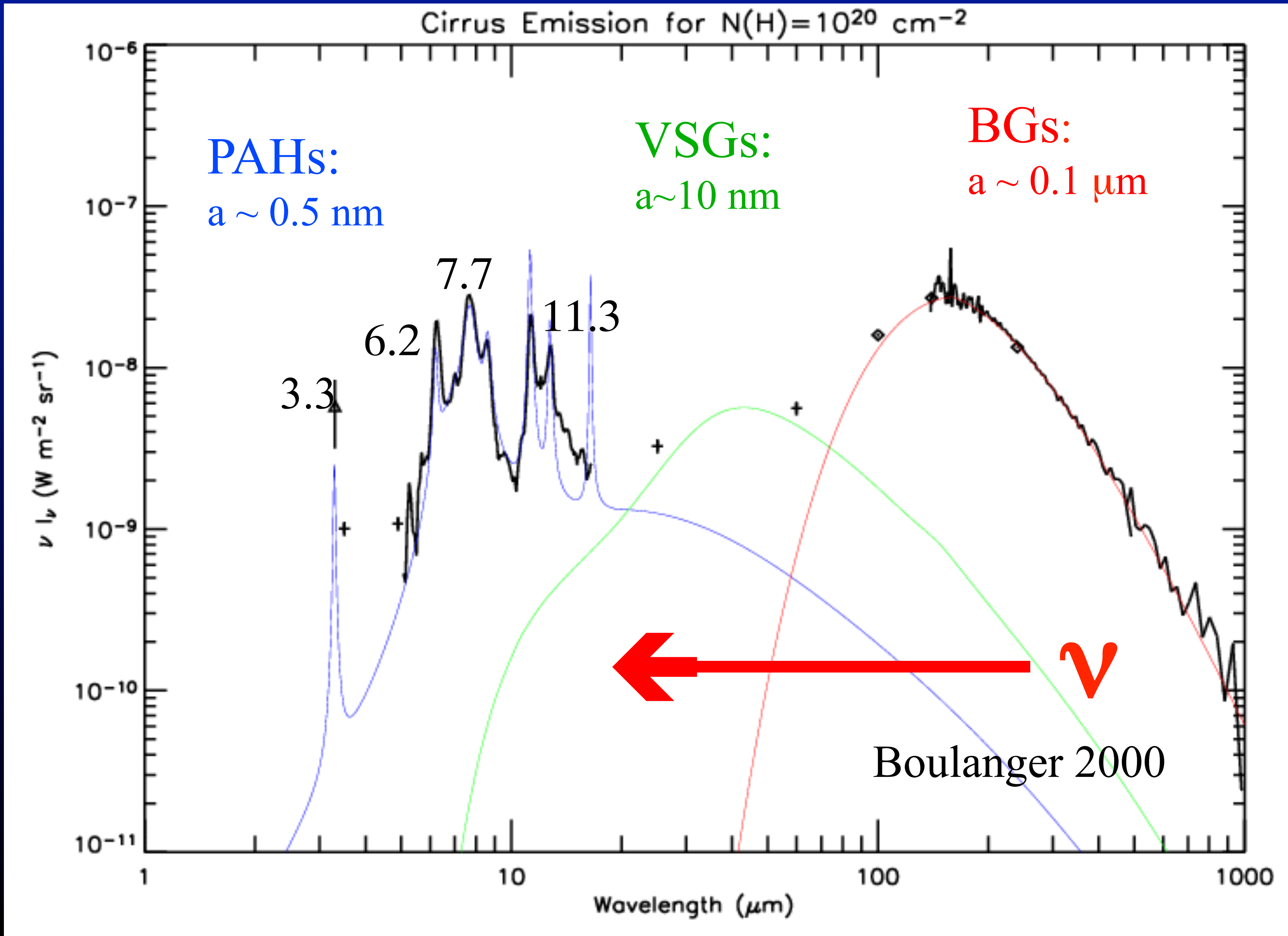
Dust emission is proportional to H column density (properties of dust constant):

$$I_\nu = \kappa_\nu B_\nu(T)\ \mathrm{Dust/Gas}\ \mu m_H N_H.$$

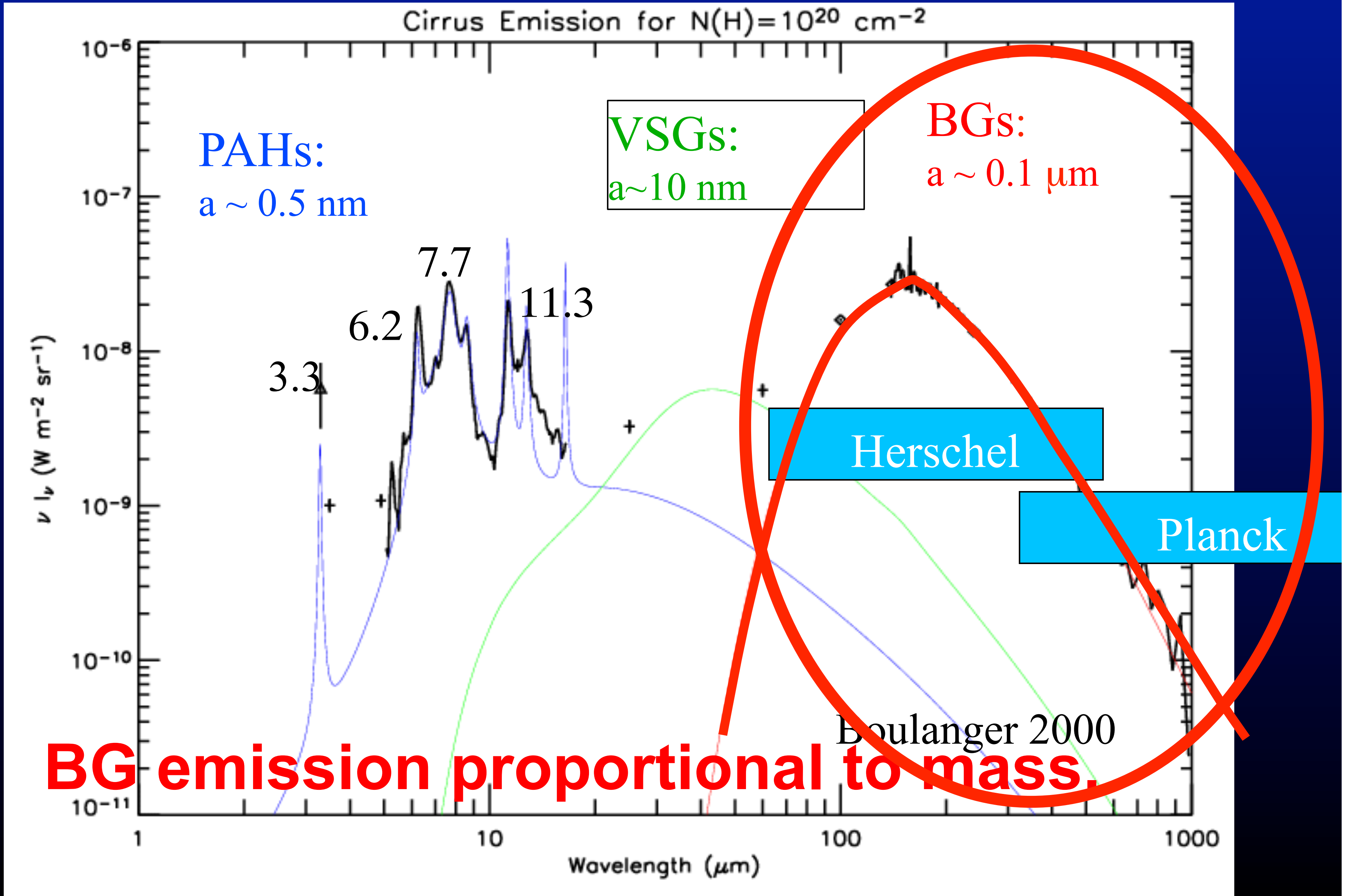
$I_\nu = \varepsilon_\nu N_H$. (→ defines the emissivity: observable)

Dust emission ← → gas emission (see correlation later)

Dust emission components

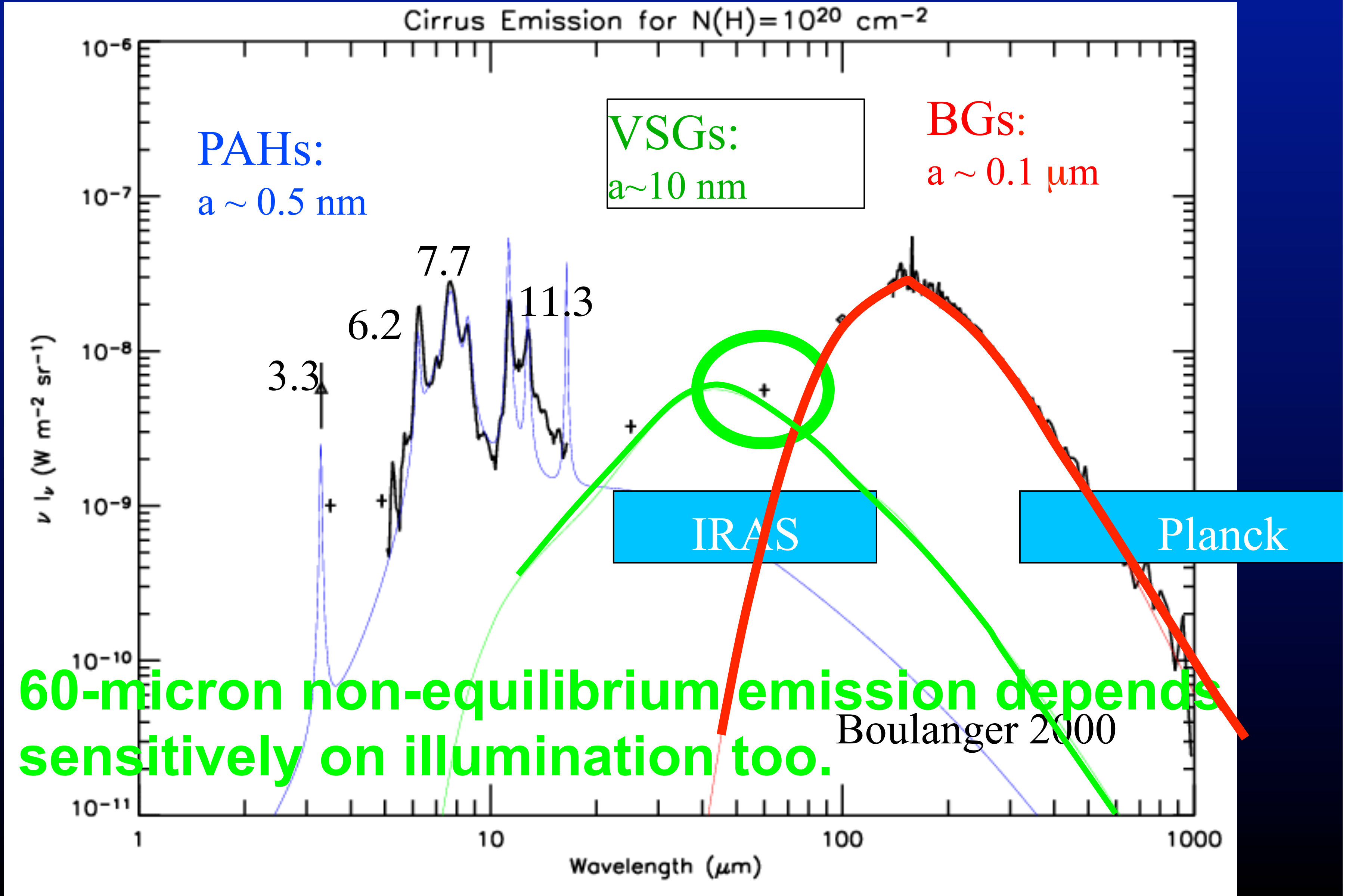


IRAS/Akari/Herschel/Planck: SED into sub-mm
Good definition of BGs relative to others



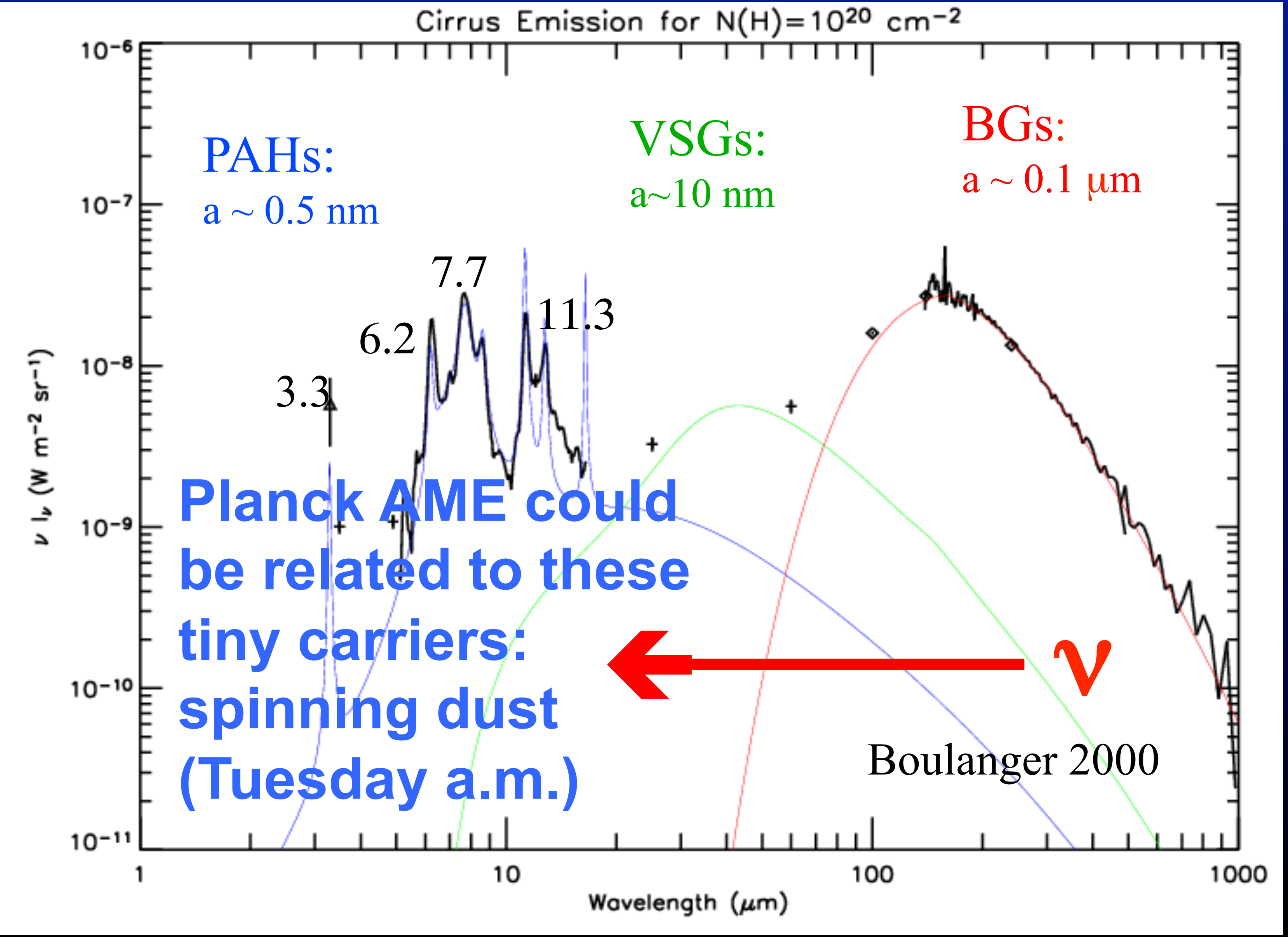
BG emission proportional to mass.

Mass of dust producing short wavelength non-equilibrium emission is less.



60-micron non-equilibrium emission depends sensitively on illumination too.

Dust emission components



Complexity

One of the over-arching themes is that the interstellar medium (ISM) is complex. Therefore, ab initio calculations, definitive predictions, etc., are more an exception than a rule. Thus, the field has been to a large extent observationally driven, but theoretical “understanding” often has not lagged far behind because of the rich suite of ideas on dust physics that have been explored over the past decades.

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Dust models:
More than a fairy tale?

These slides introduce dust models. These depend on a number of constraints on size, composition, etc. There are reasons for introducing the different dust components, though the solution is not entirely unique.

Dust models in the diffuse atomic phase have a rich set of observational constraints, many that are not available for dust in the molecular phase. However, by understanding dust in the atomic phase, we do get constraints on how dust might evolve in the molecular phase (and on the return cycle).

Dust models including emission

Draine and Anderson 1985

Desert, Boulanger, Puget 1990

Draine, Li, Weingartner (various) 2000s

Compiegne, Verstraete, Jones et al. 2011 DUSTEM

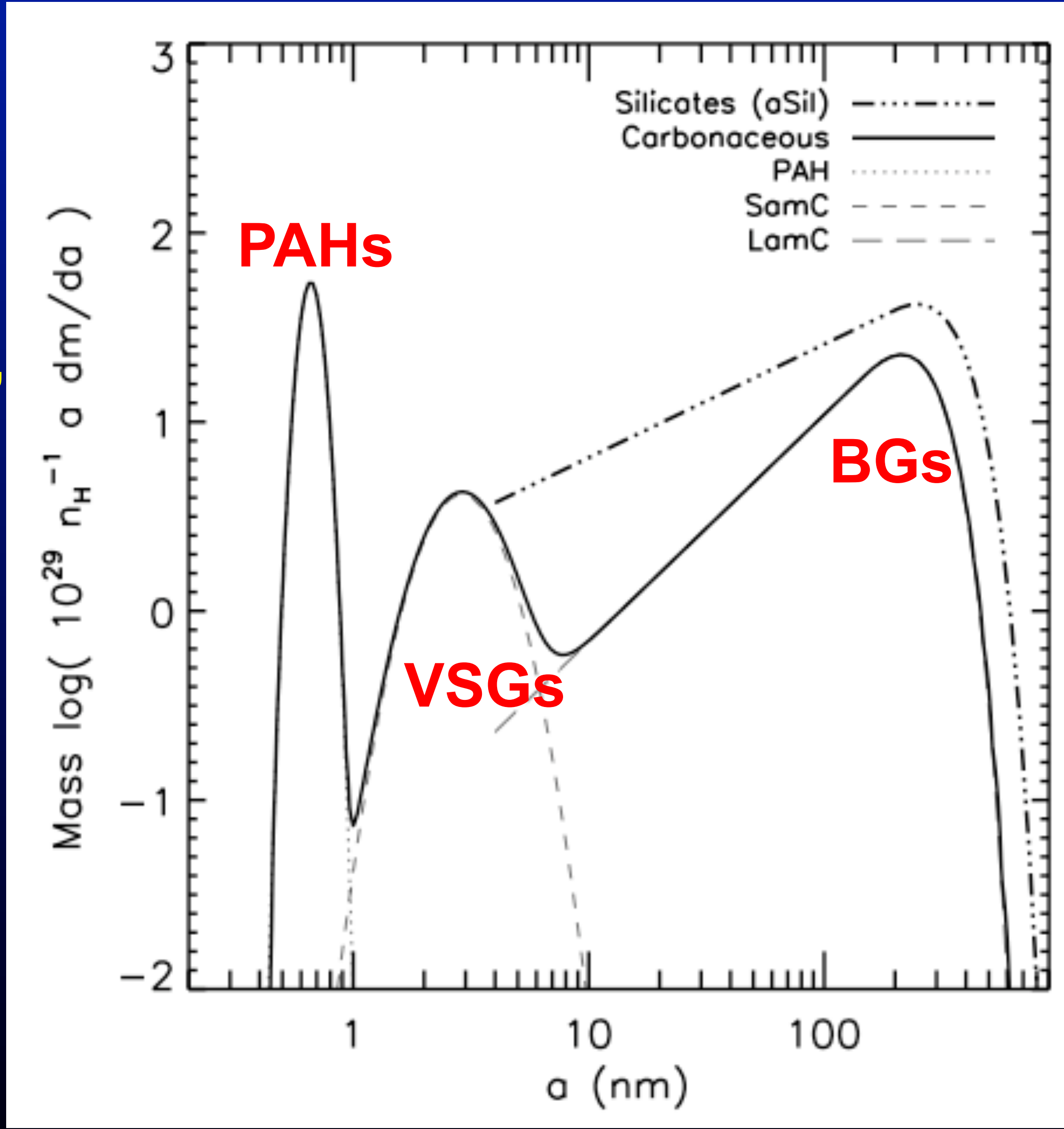
Fischera 2011

Not unique but many areas of agreement, constrained by observations.

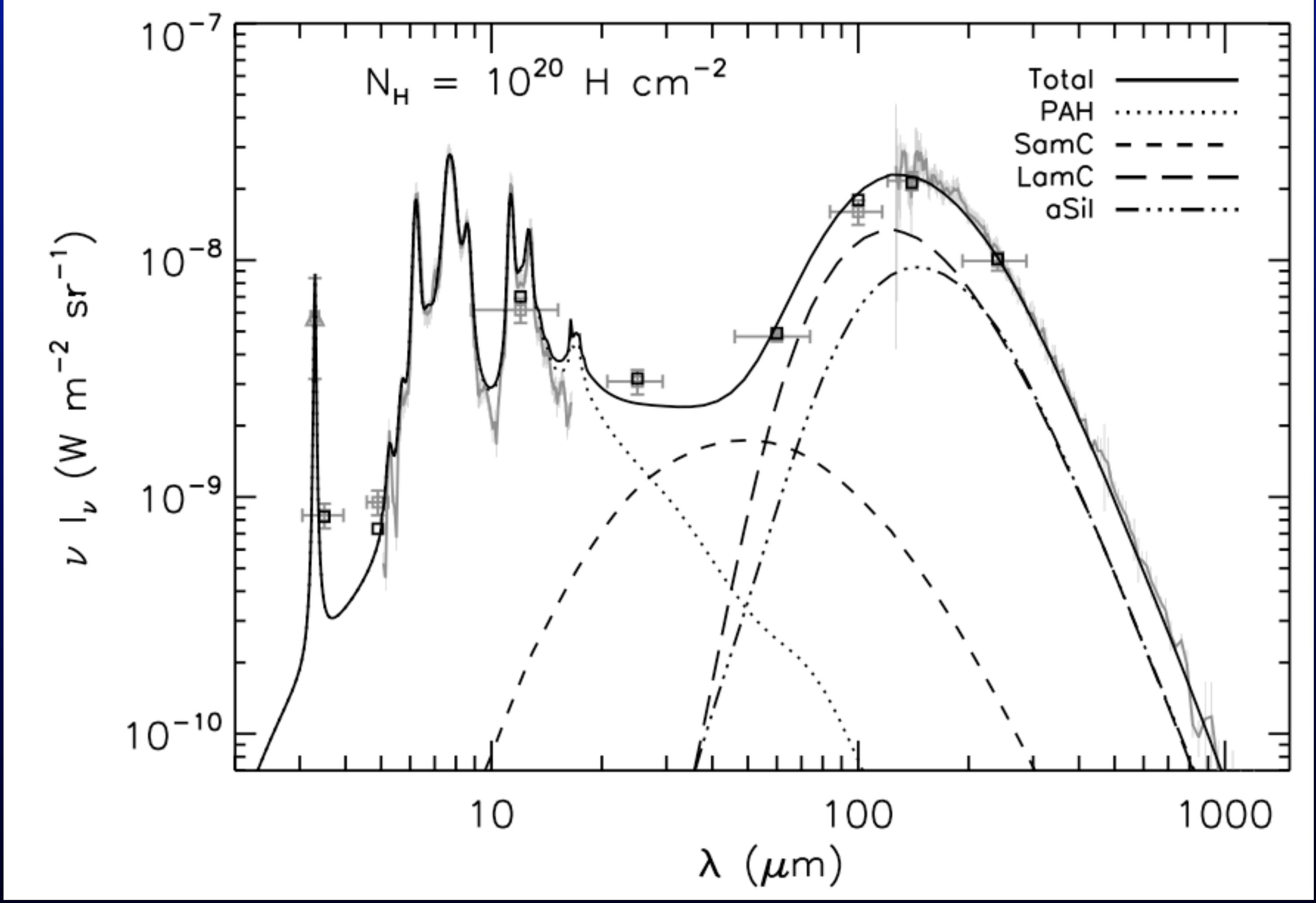
Dust sizes (radius)

"Big" grains:
1000 Å, 100 nm, 0.1 μm,
small bacterium,
large virus,
10^{-23} light year.
(cf. fine hair: 10 μm)

PAH:
7 Å, 0.7 nm
(large molecules)



(self-consistent) Emission



What happens at Planck frequencies with changes in grain components? Spectrum? Polarization?

Dust Evolution

Dust evolution in the cycle:

Diffuse atomic ISM → molecular clouds → star formation → diffuse ISM

Amount of dust mass per H

Size distribution

Dust temperature

We have a diverse set of observational constraints on dust in the diffuse interstellar medium. Therefore concentrate on that atomic phase as the basis.

Gas-correlated dust emission

These slides introduce a major mode of analysis, correlating dust emission with *gas* tracers, in particular our surveys of H I.

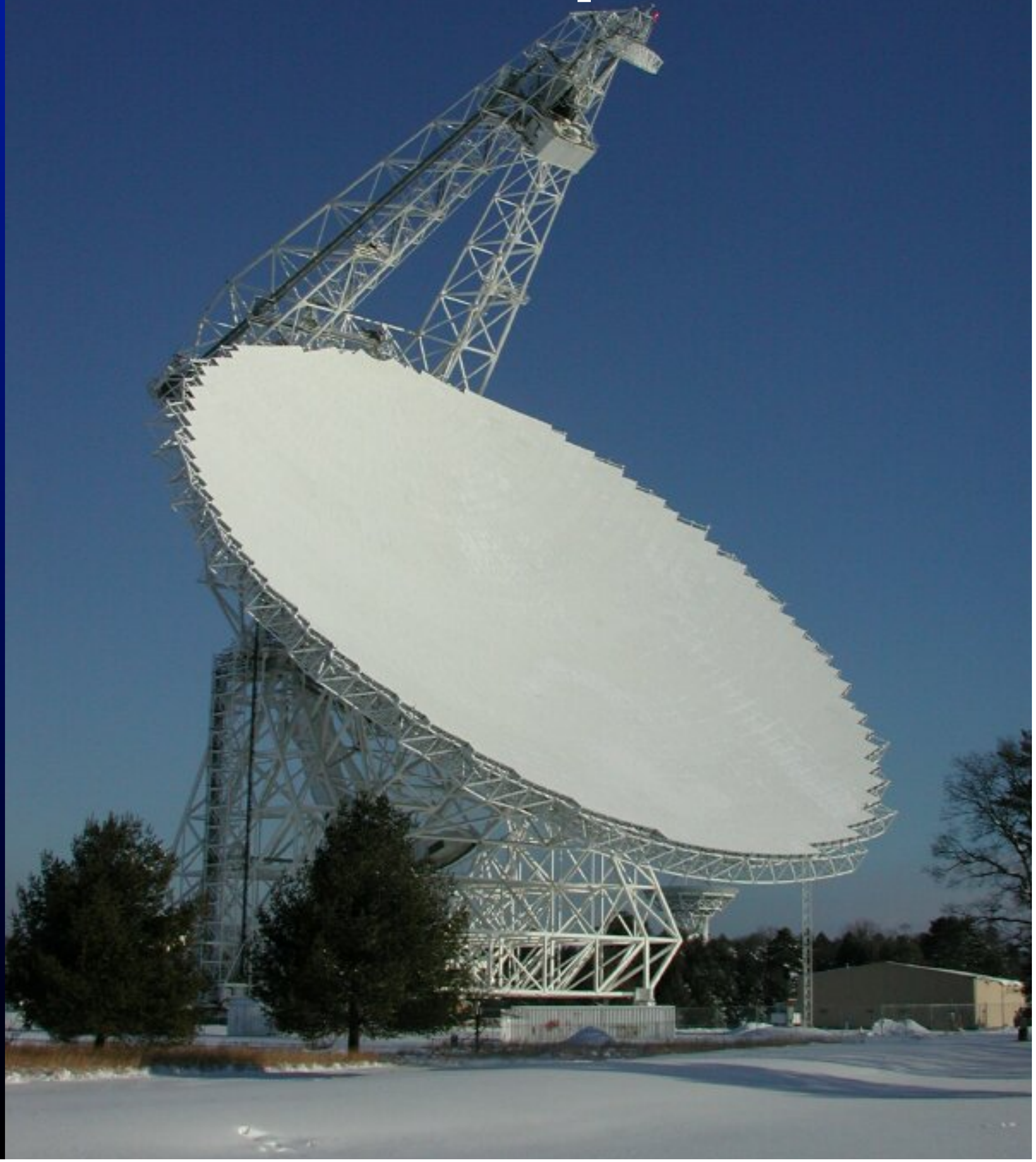
Again, it is productive to work with the atomic diffuse phase, which covers a lot of the high-latitude sky and is very relevant to the foreground for the CMB and the CIBA.

GBT 100-m radio telescope

Used for atomic hydrogen measurements at high Galactic latitude.

Over 800 square degrees. 9’ beam.

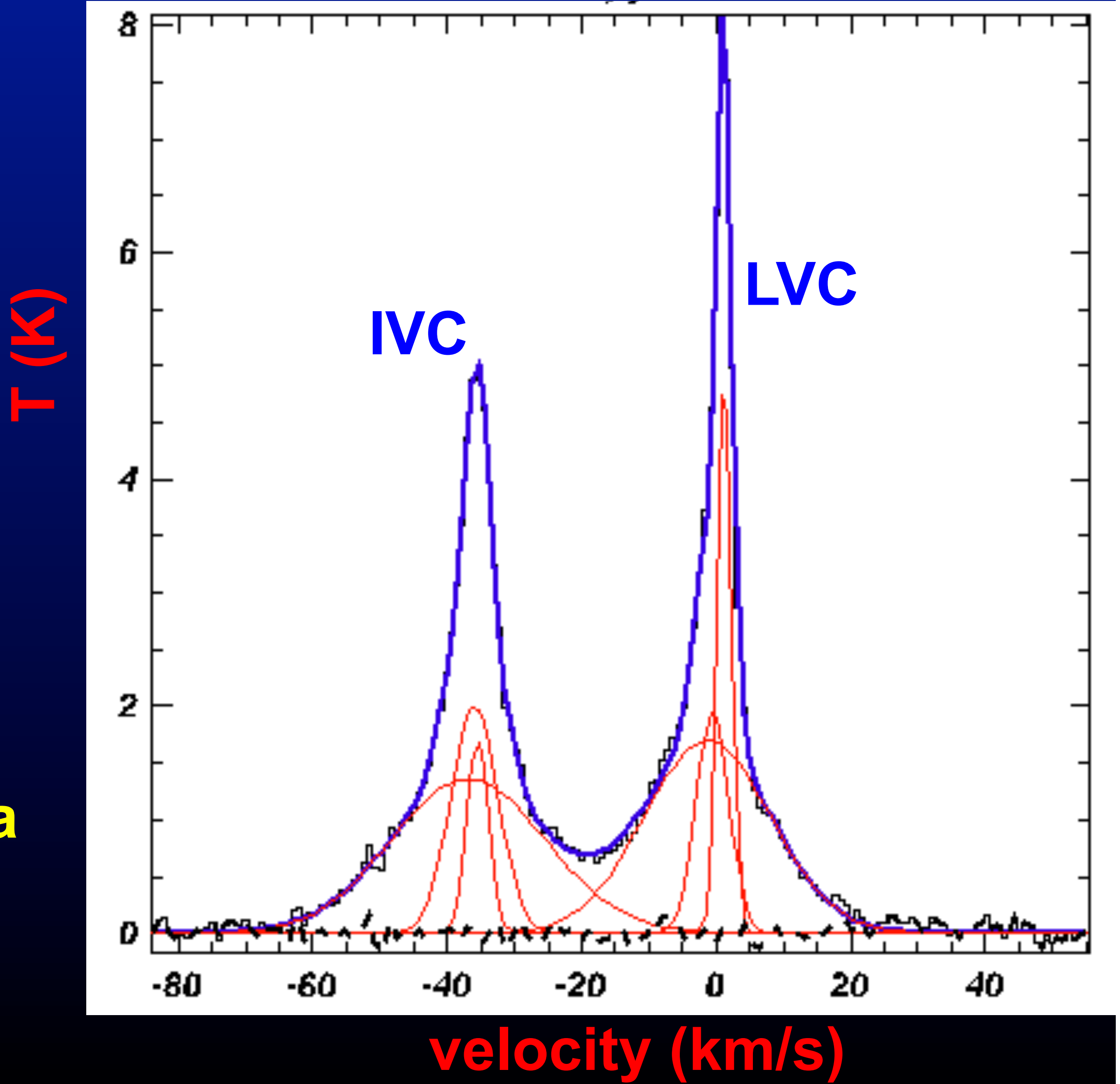
Noise smaller than corresponding noise in dust emission.



Spectrum: T(H I) vs. velocity

H I spectra:
Study physical conditions (density, dust correlations), dynamics.

Spectra are combined into a "data cube."



Two main H I components

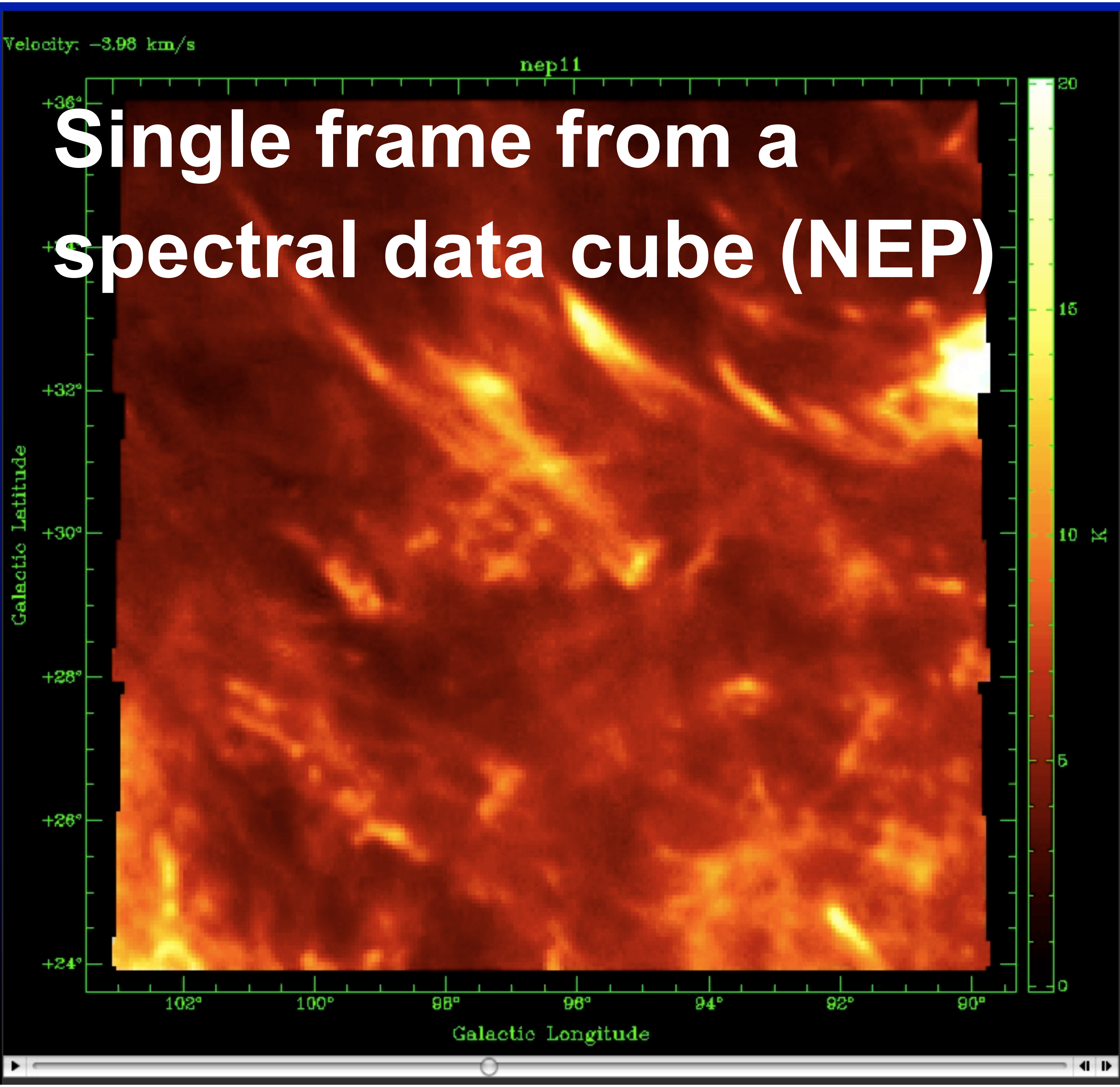
LVC: local gas with velocity near zero.

IVC: more distant gas (100s of pc) with negative velocity, part of “Galactic fountain” falling back into the Galactic plane.

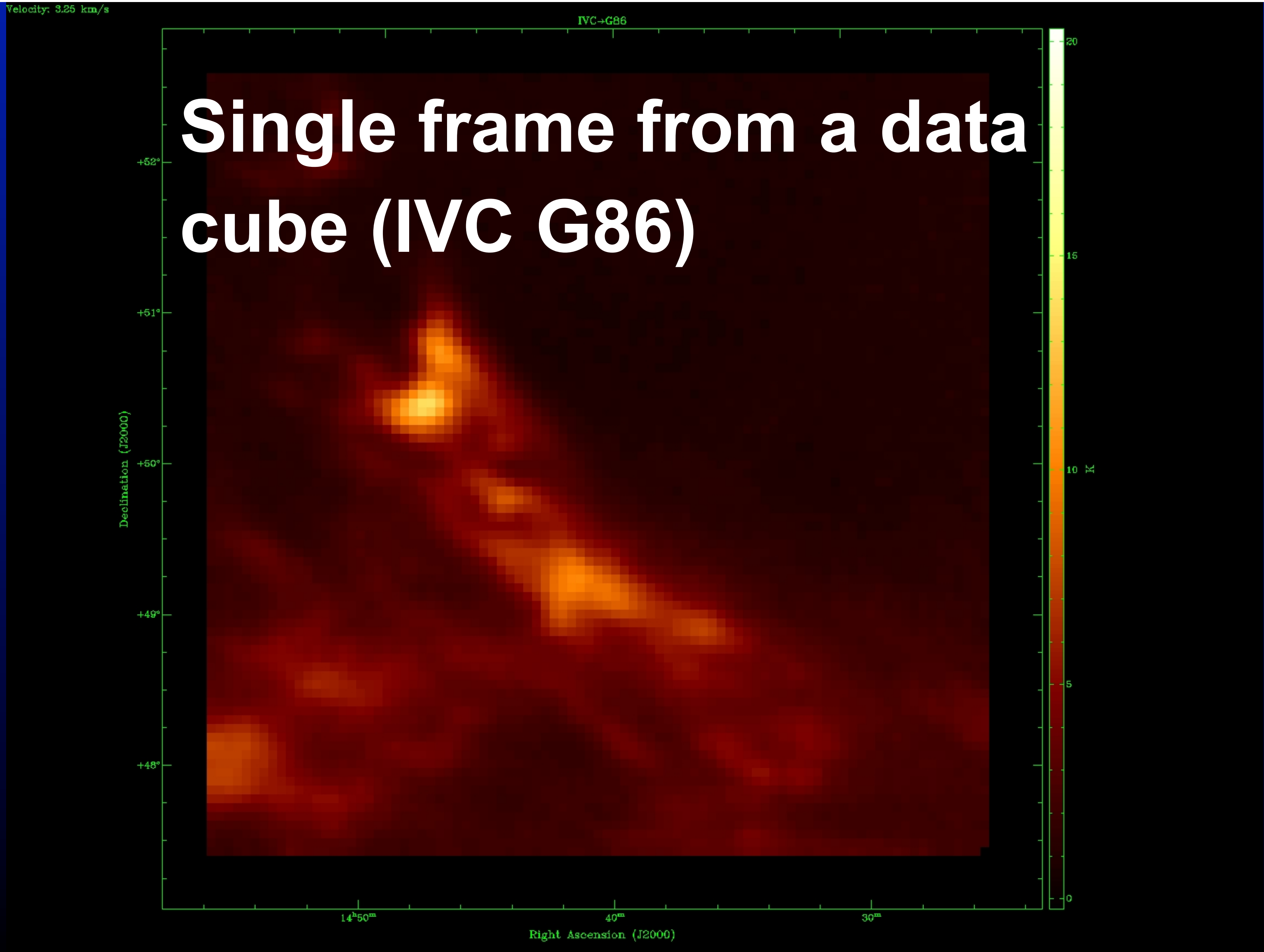
T(H I) image at one velocity

Plane in a “data cube.”

Single frame from a spectral data cube (NEP)



Single frame from a data cube (IVC G86)



T(H I) vs. velocity in movie

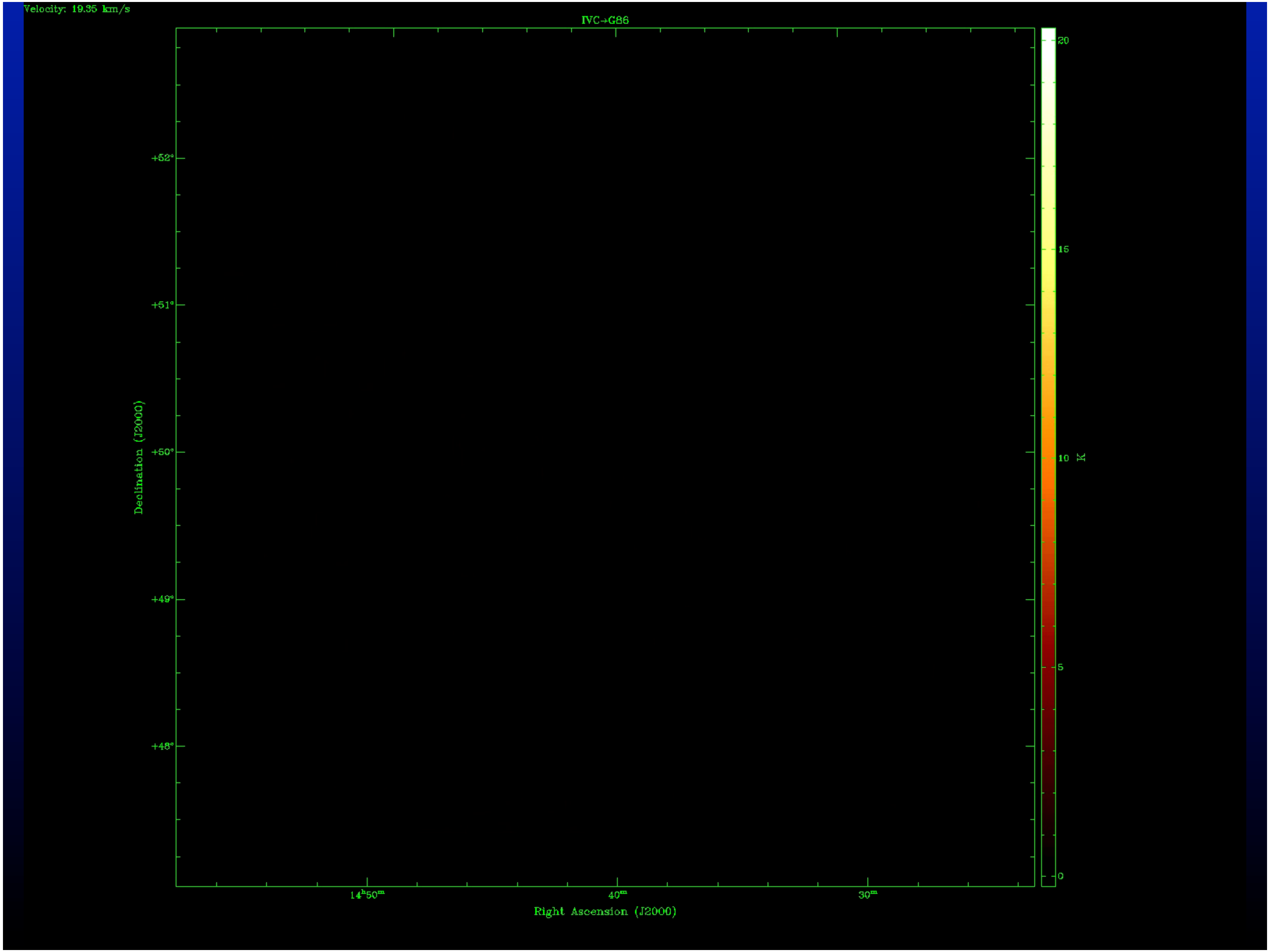
Example: IVC G86, a 5 by 5 degree field being analysed with

Kevin Blagrave

Daniela Pinheiro Goncalves and

Marc-Antoine Miville-Deschenes.

A movie of the IVC G86 spectral data cube is shown here: images of the H I emission channel by channel (every 0.8 km/s) over the range +20 km/s through local gas and then IVC gas to -60 km/s.



Velocity: 19.35 km/s
IVC-G86
+52°
+51°
+50°
+49°
+48°
Declination (J2000)
14h50m
40m
30m
Right Ascension (J2000)
20
15
10
5
0
K

Movie

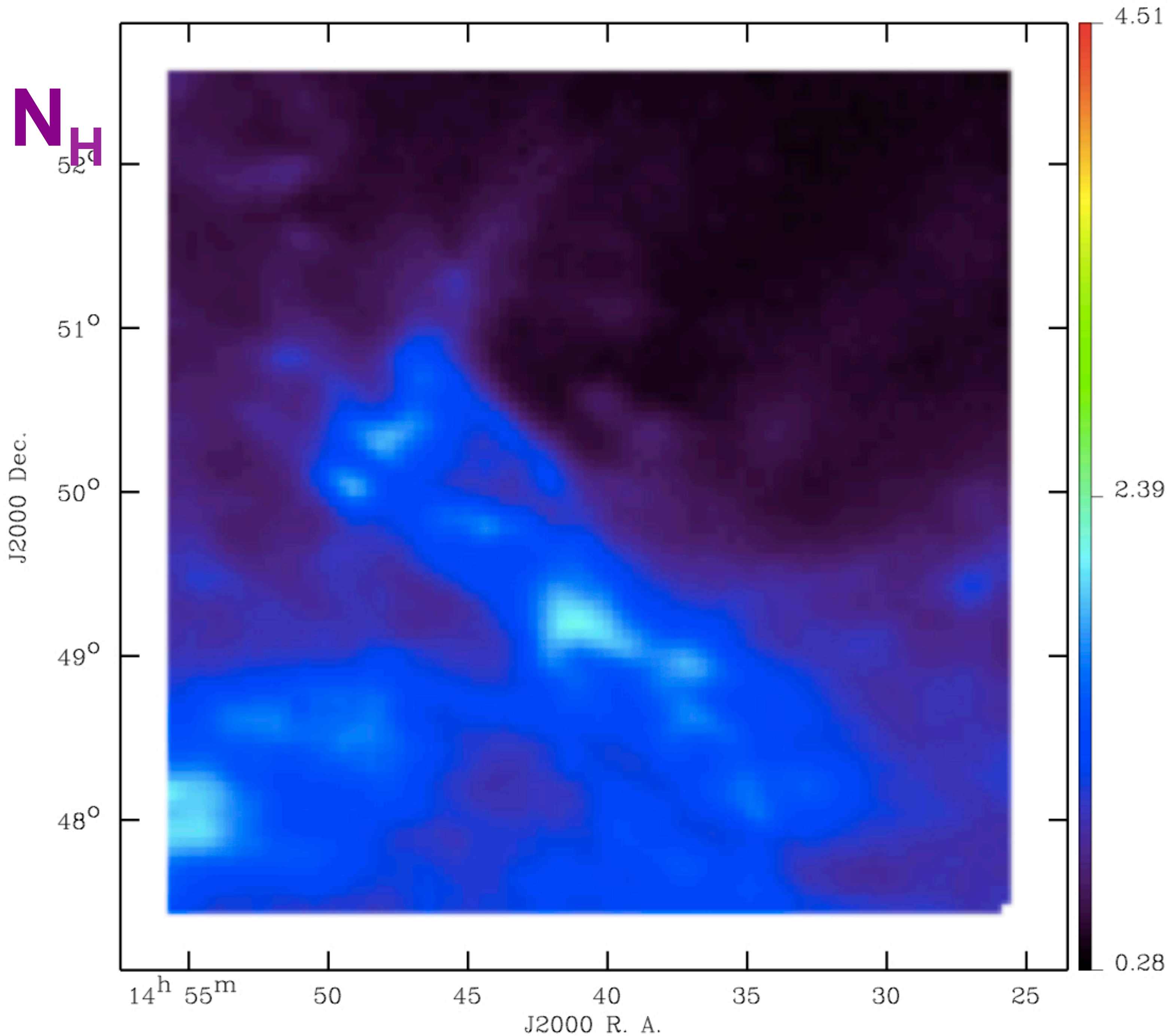
This and other illustrative H I movies can be seen via my website:

www.cita.utoronto.ca/~pgmartin/himovie

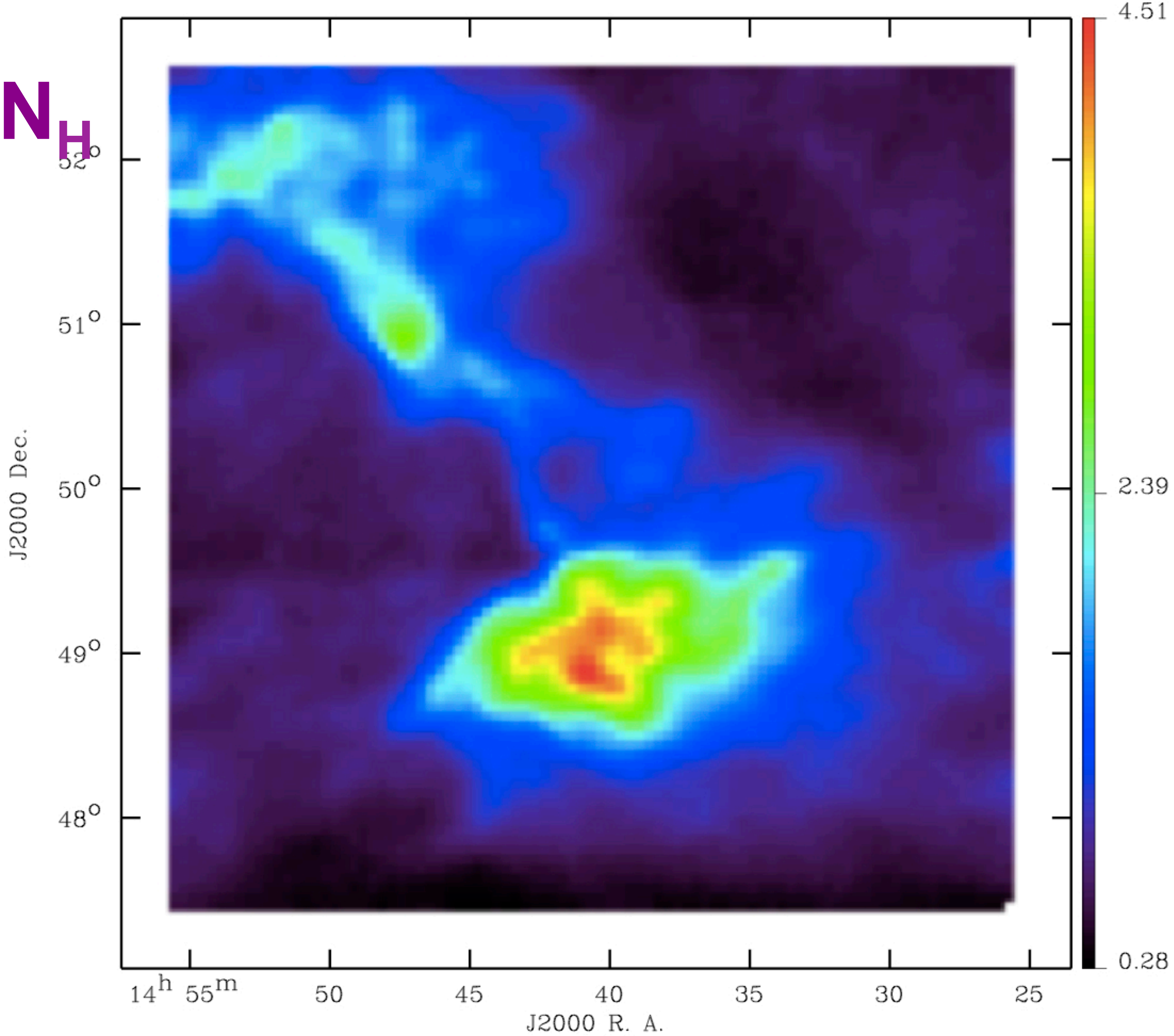
Column density in velocity range

Integrate T(H I) over a range of velocities → N_H

LVC N_H


4.51
2.39
0.28
52°
51°
50°
49°
48°
J2000 Dec.
14h 55m
50
45
40
35
30
25
J2000 R. A.

IVC N_H



4.51
2.39
0.28
52°
51°
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49°
48°
J2000 Dec.
14h 55m
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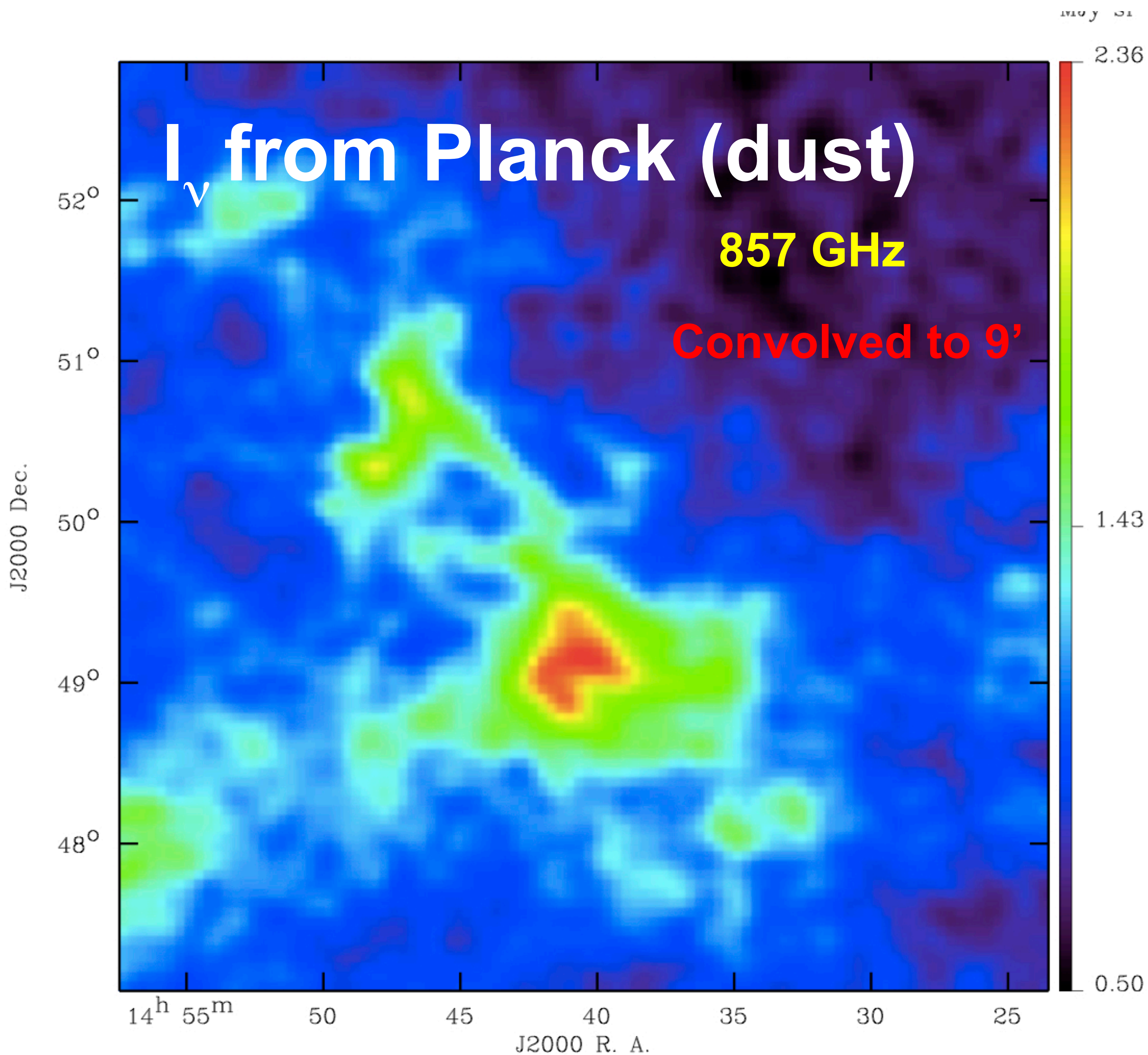
J2000 R. A.



I_ν from Planck (dust)
857 GHz
Convolved to 9'
MJy sr
2.36
1.43
0.50
52°
51°
50°
49°
48°
J2000 Dec.
14h 55m
50
45
40
35
30
25
J2000 R. A.

Model

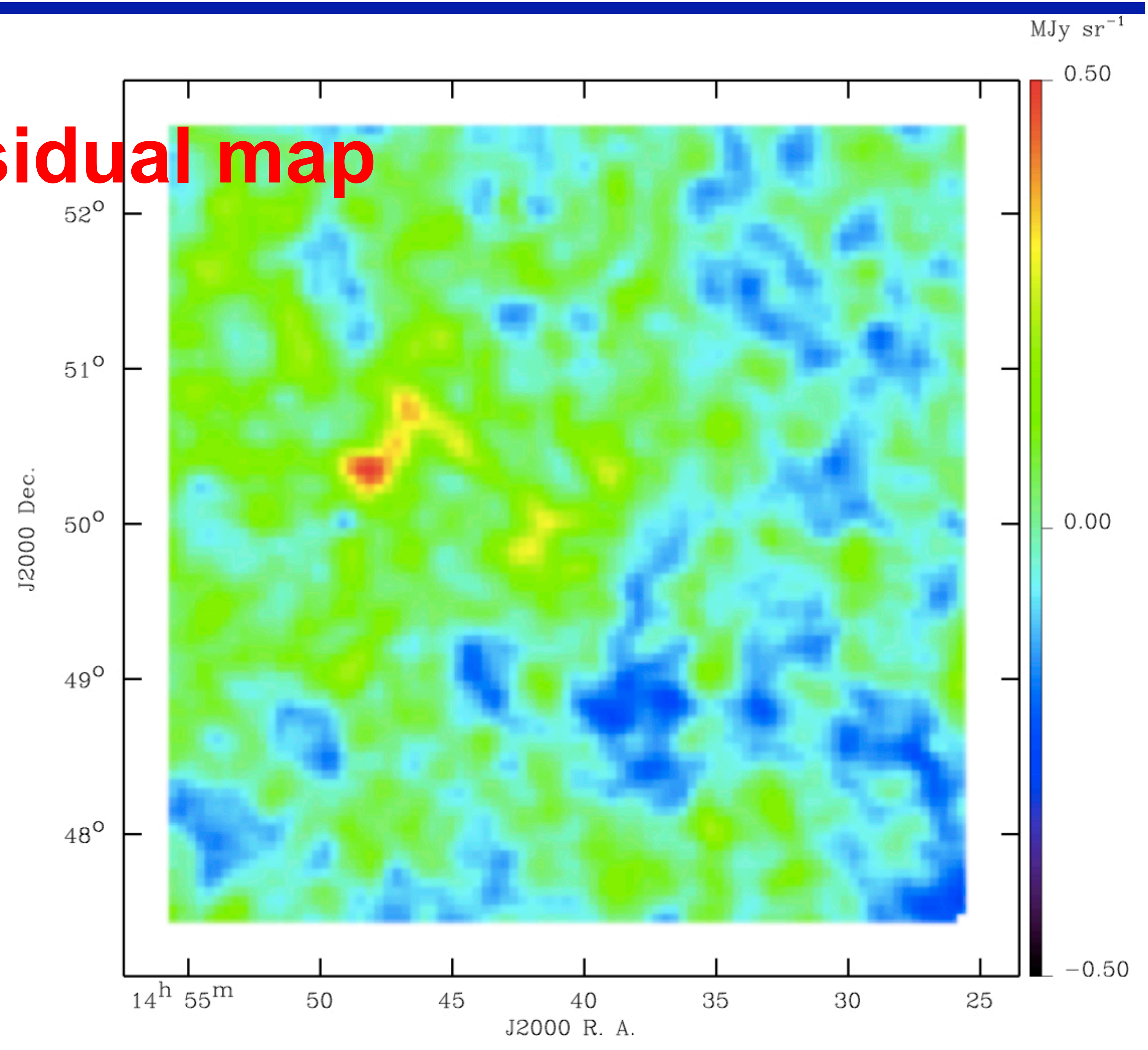
$I_\nu = \kappa_\nu B_\nu(T)$ Dust/Gas $\mu m_H N_H$.

$I_\nu = \varepsilon_\nu N_H$.

Allow for 2 emissivities (LVC, IVC).

Allow for CIB (constant + CIBA).

Residual map



Model results (Planck XXIV)

$I_\nu = \varepsilon_\nu N_H + \text{CIB}.$

Allow for 2 emissivities (LVC, IVC):

0.45 +/- 0.02

0.24 +/- 0.013 (in appropriate units)

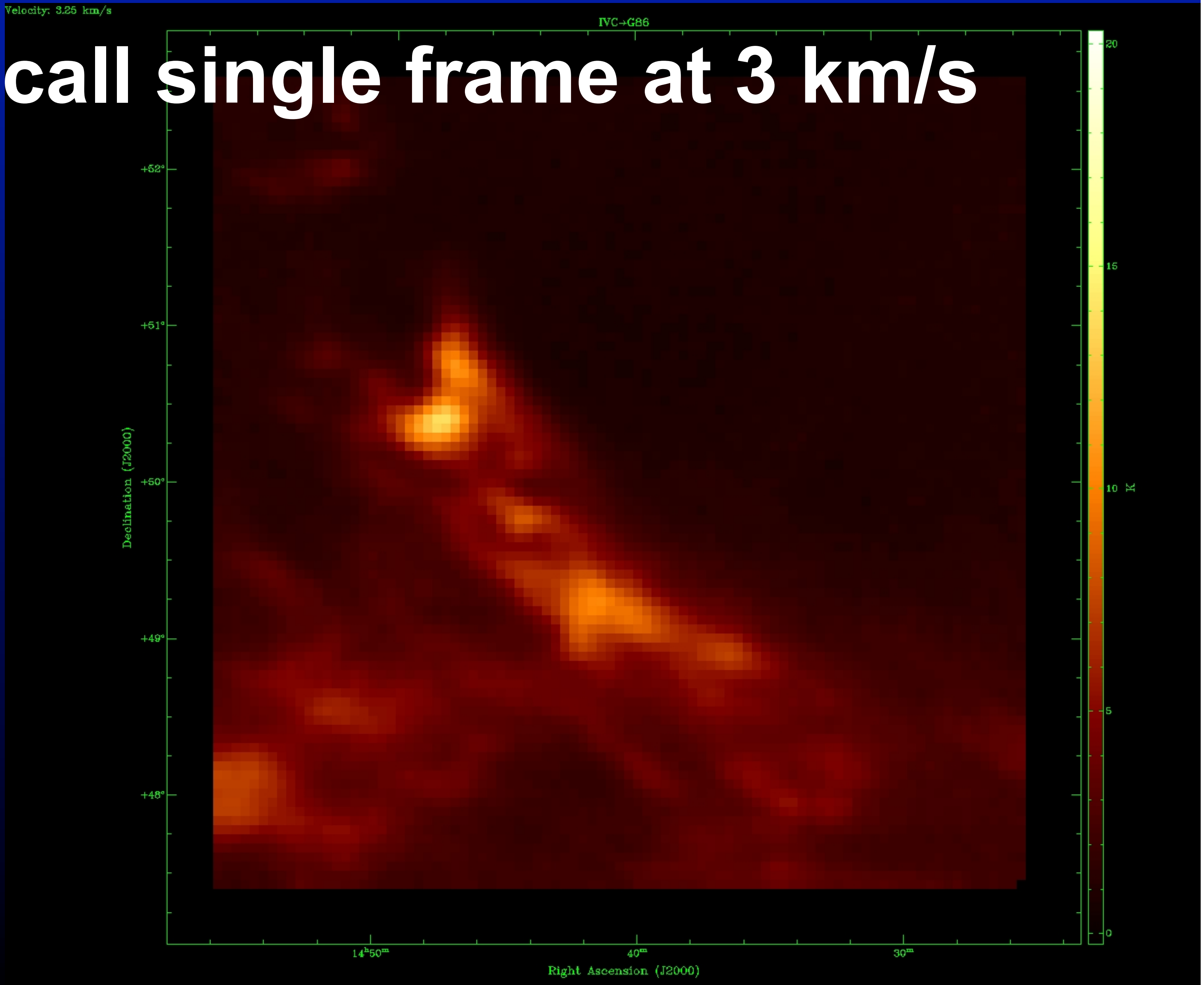
→ Different.

Allow for CIB (constant + CIBA):

constant offset = 0.4 MJy/sr

sigma of CIBA = 0.09 MJy/sr

Recall single frame at 3 km/s



Model

$I_\nu = \varepsilon_\nu N_H + CIB.$

Work in progress…

Allow for 3 emissivities (2 LVC, IVC):

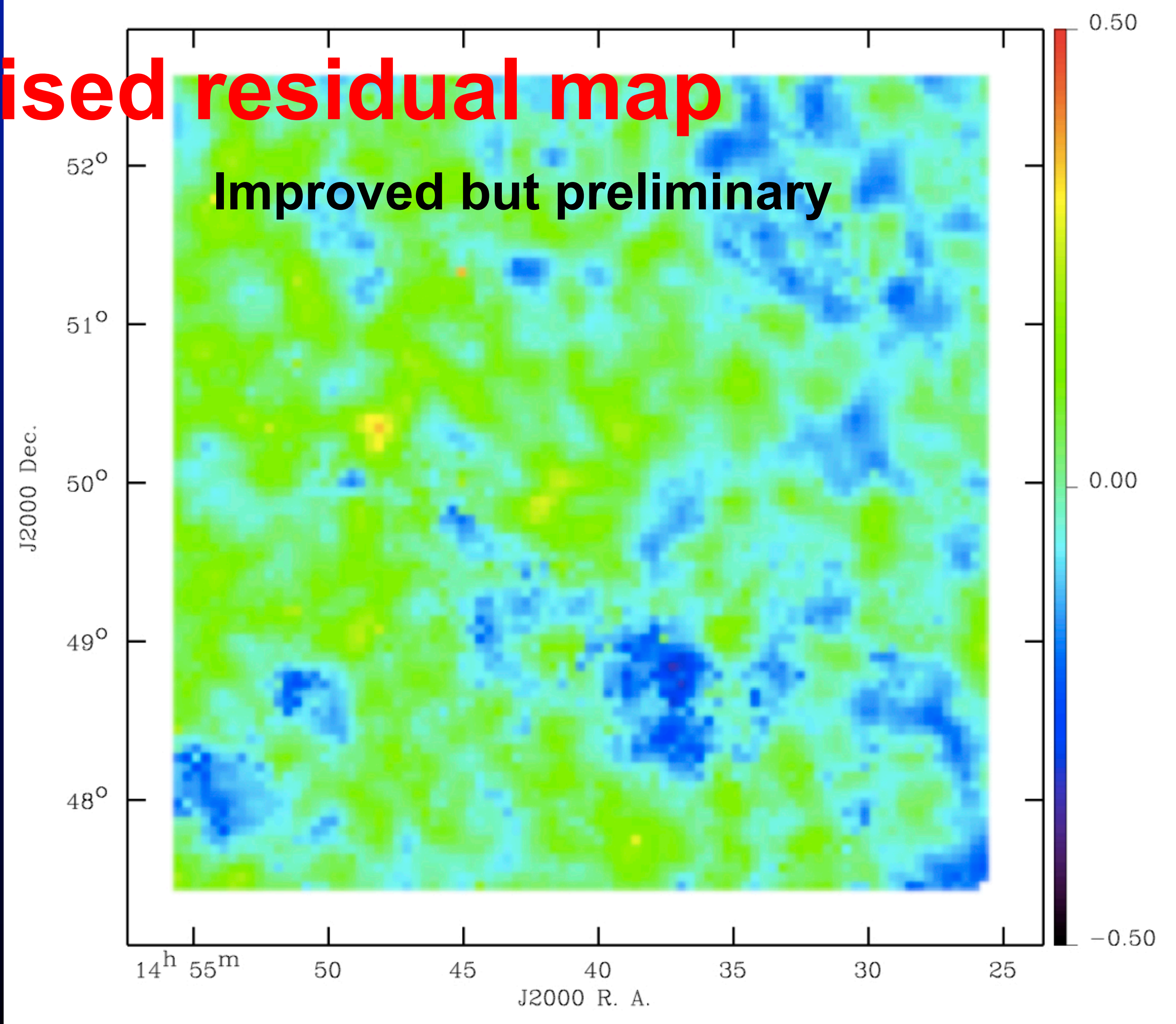
0.45 → 0.67 and 0.36

0.24 unchanged

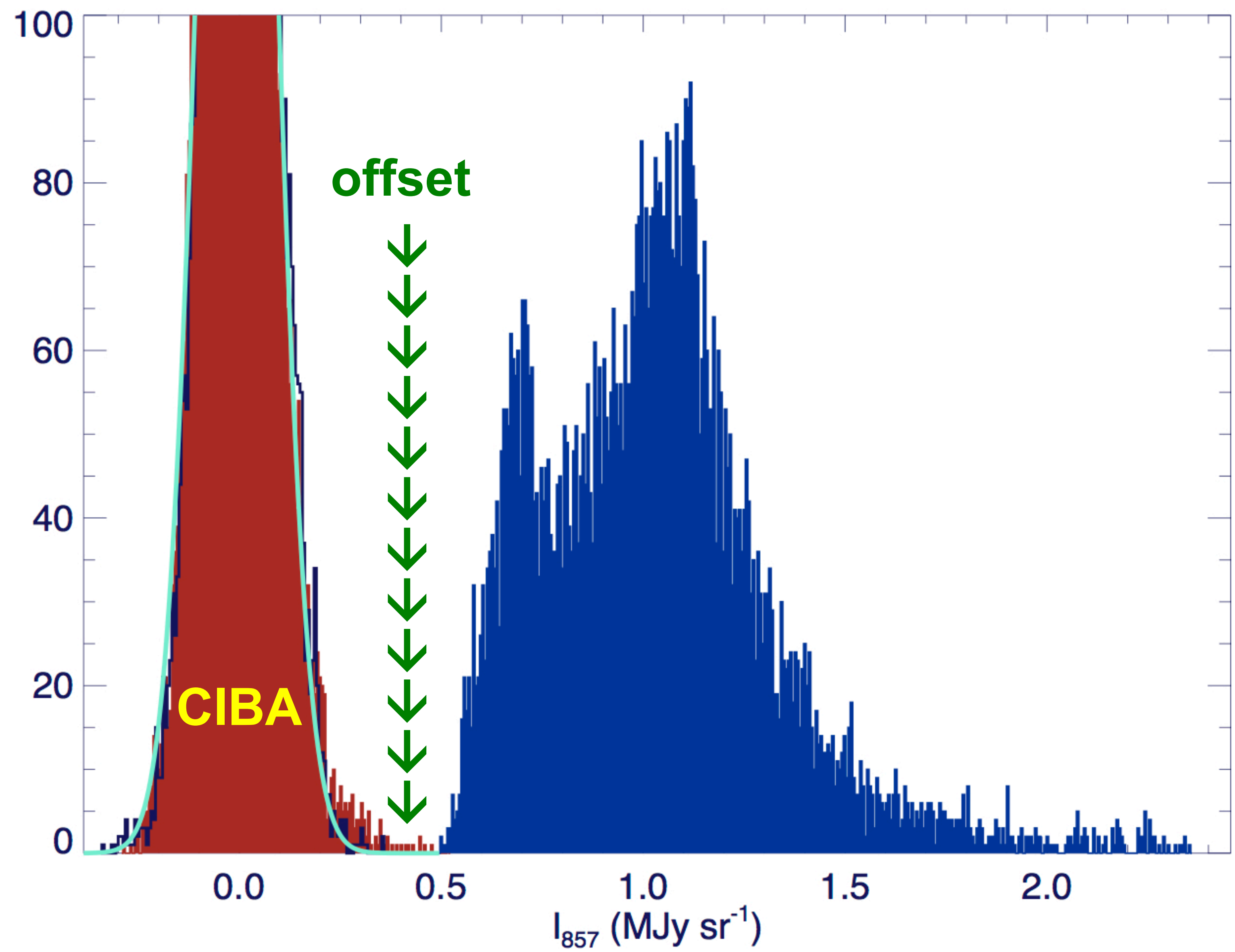
CIB and CIBA (unchanged)

Revised residual map

Improved but preliminary



Histogram of map and residual



CIRB/CIBA

The spatially fluctuating cosmic infrared background radiation is a significant contamination in Galactic faint fields, well detected by Planck (and Herschel).

See presentations on Thursday afternoon.

Amazing correlation

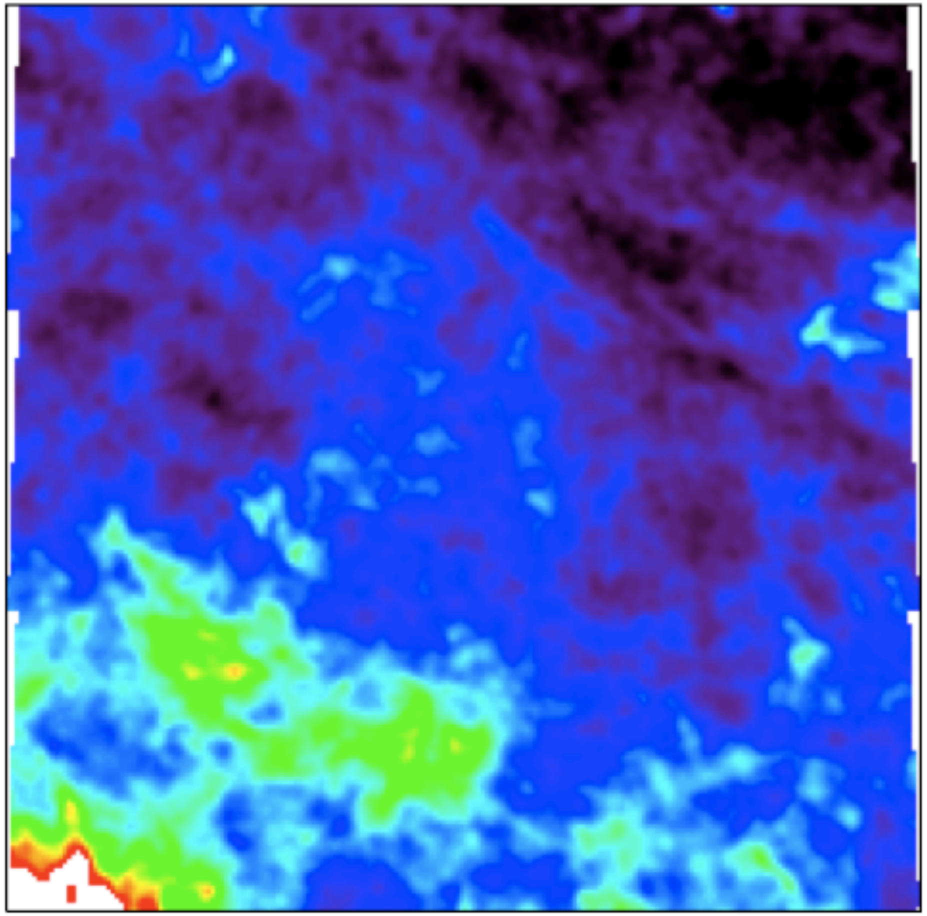
Dust is apparently well mixed with the gas and has similar but not identical properties in the different parcels.

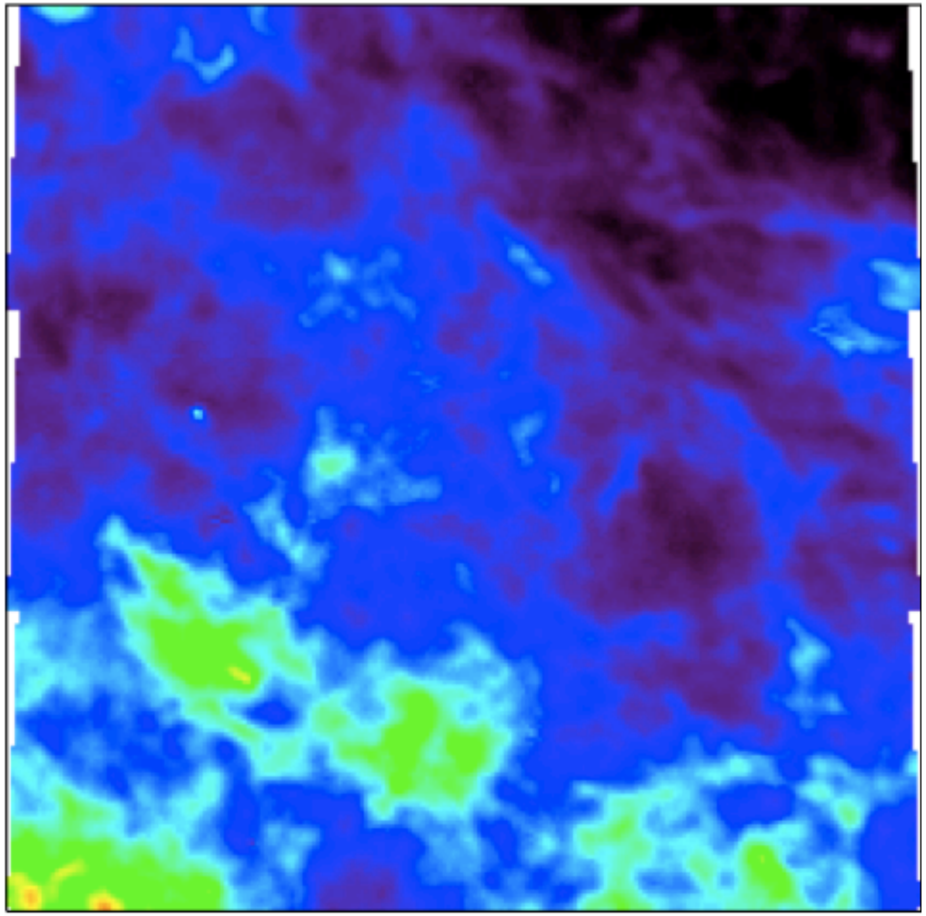
Despite the very complex turbulent gas structure, the associated dust emission over a field this size can be predicted by just “one” number, the emissivity: how much emission there is per H atom. (Actually we got more “sophisticated” and used two emissivities, one for local gas and one for IVC gas.)

This is illustrated for emphasis again in a “test.”

Correlation of dust emission with H I column density

Which is the Planck 857 GHz map (smoothed to 9ʼ) and which is predicted from the GBT H I column density?

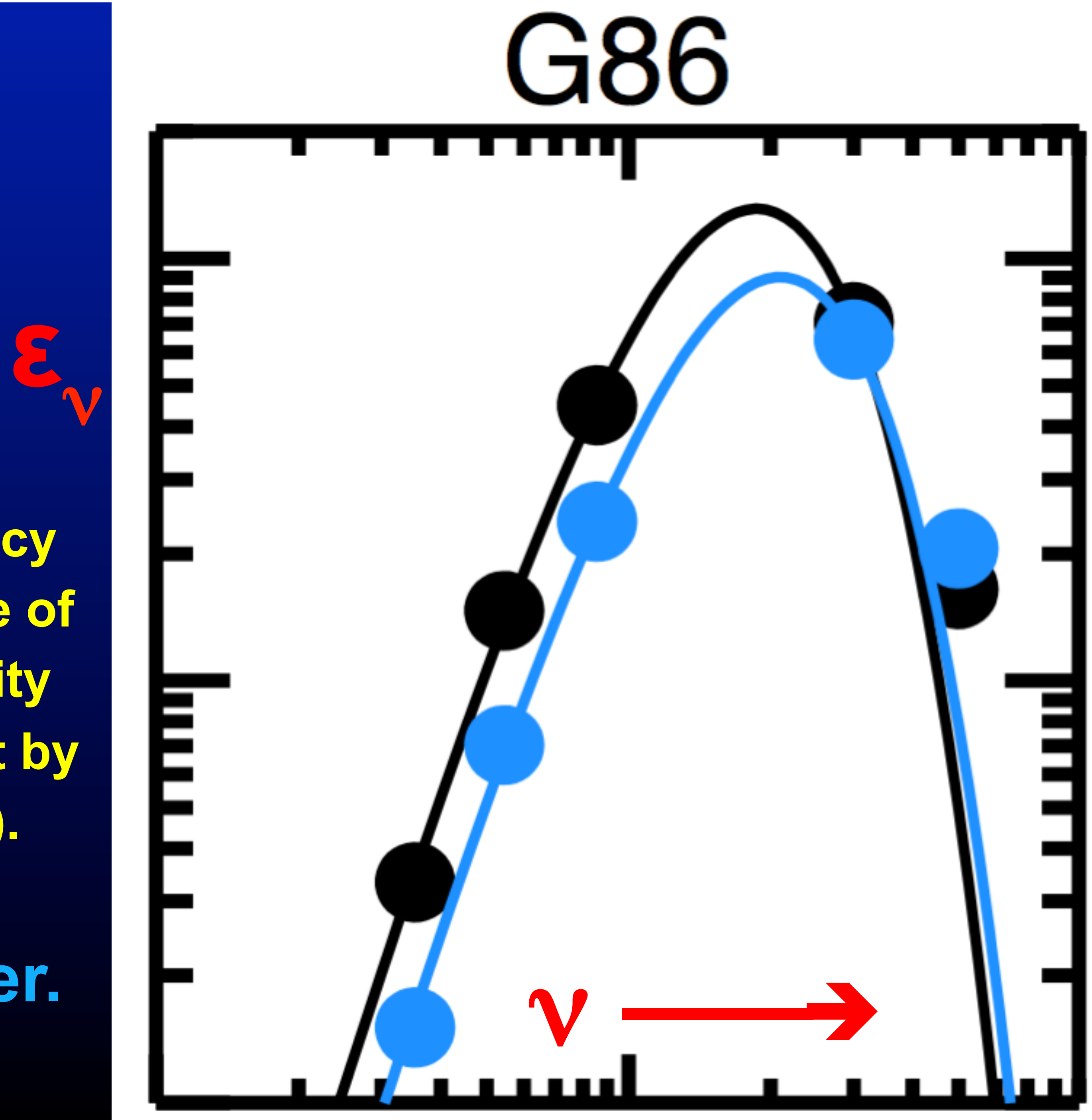




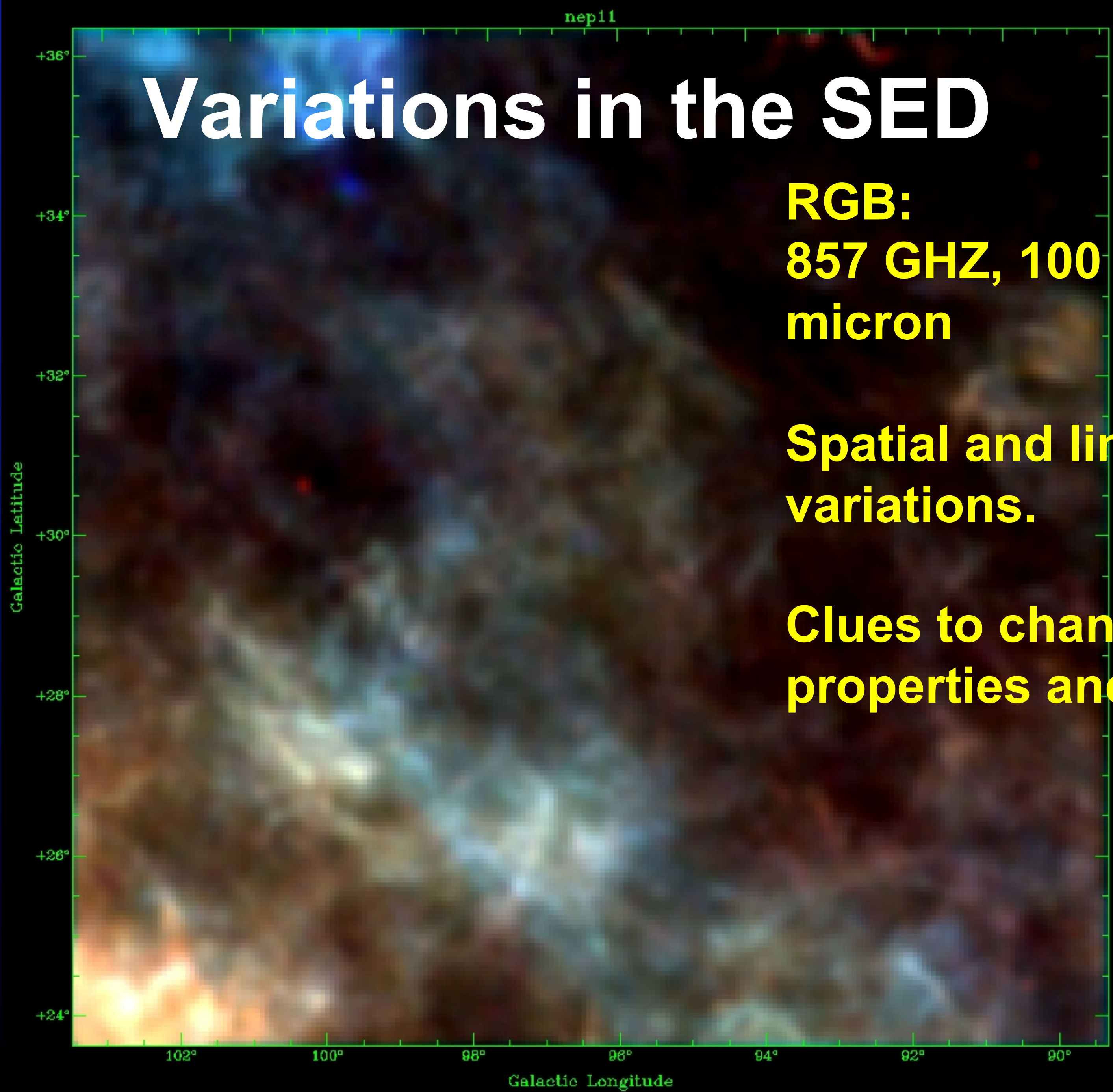
SED

The frequency dependence of the emissivity (component by component).

IVC hotter.



Variations in the SED



RGB:
857 GHZ, 100 micron, 60 micron

Spatial and line of sight variations.

Clues to changes of dust properties and illumination.

Dust properties

$I_\nu = \varepsilon_\nu N_H.$

$I_\nu = \kappa_\nu B_\nu(T)$ Dust/Gas $\mu m_H N_H.$

RECIPE

Measure emissivity as a function of frequency.

Make an SED from these emissivities.

Fit with modified blackbody. Learn about T.

Extract a combination of dust abundance (dust to gas mass ratio) and opacity κ_ν (including β) .

Call this an opacity too →

Dust opacity

$I_\nu = \tau_\nu B_\nu(T)$.

$I_\nu = \kappa_\nu B_\nu(T)$ Dust/Gas $\mu m_H N_H$.

<u>RECIPE (continued)</u>

Define another opacity, in different units.

$$\sigma_\nu = \kappa_\nu \text{ Dust/Gas } \mu m_H = \tau_\nu / N_H.$$

Property of the dust+gas mixture.

Power

RECIPE (continued)

$\sigma_\nu = \kappa_\nu$ **Dust/Gas** $\mu m_H = \tau_\nu / N_H$.

Integrate the SED.

$P = \int 4\pi \sigma_\nu B_\nu(T)\, d\nu$.

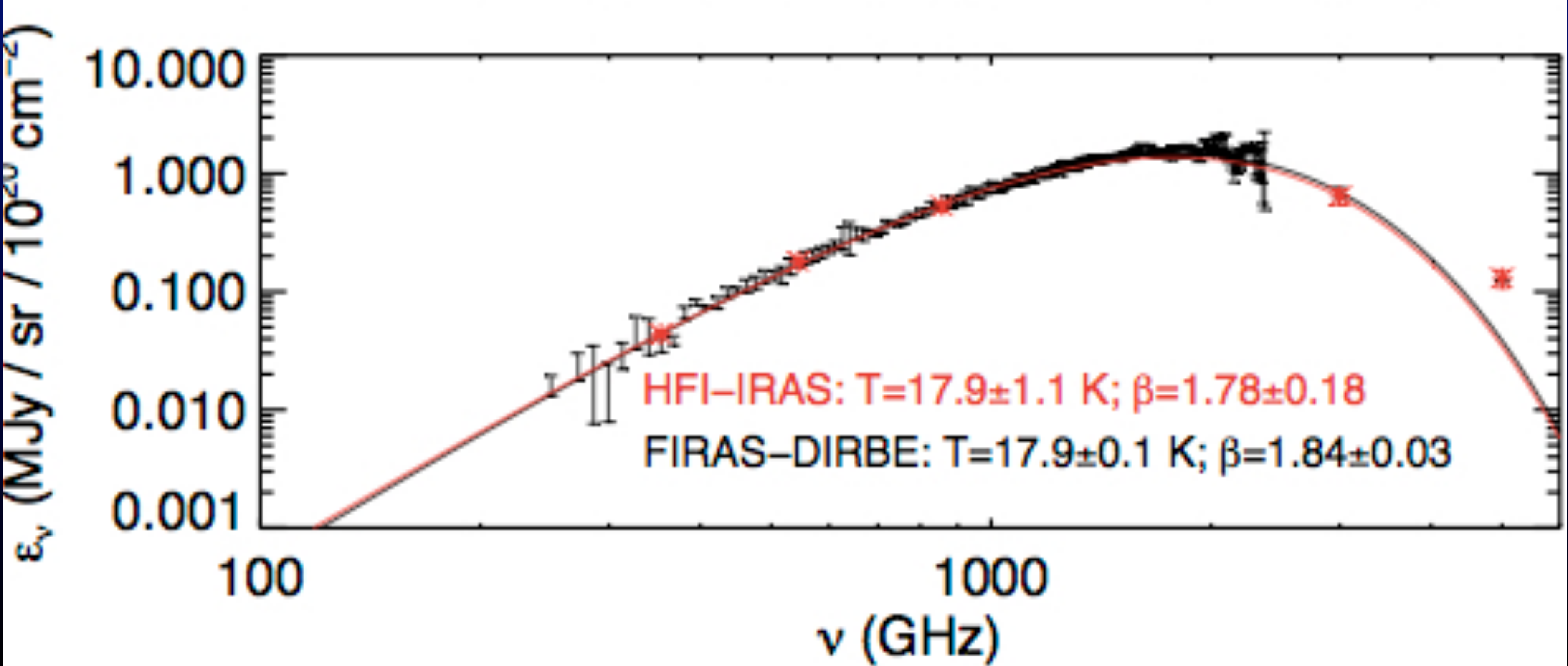
Power emitted per H

== power absorbed per H.

Opacity, T, and P: whole sky

T = 18 K, β = 1.8, σ_ν = 1.0 x 10^{-25} cm^2

Power = 0.38 10^{-30} W/m^2/H [~ 1 $L_\odot/M_\odot$]



Opacity, T, and P:
many regions studied by the GBT

We find changes from region to region and velocity to velocity (Planck XXIV).

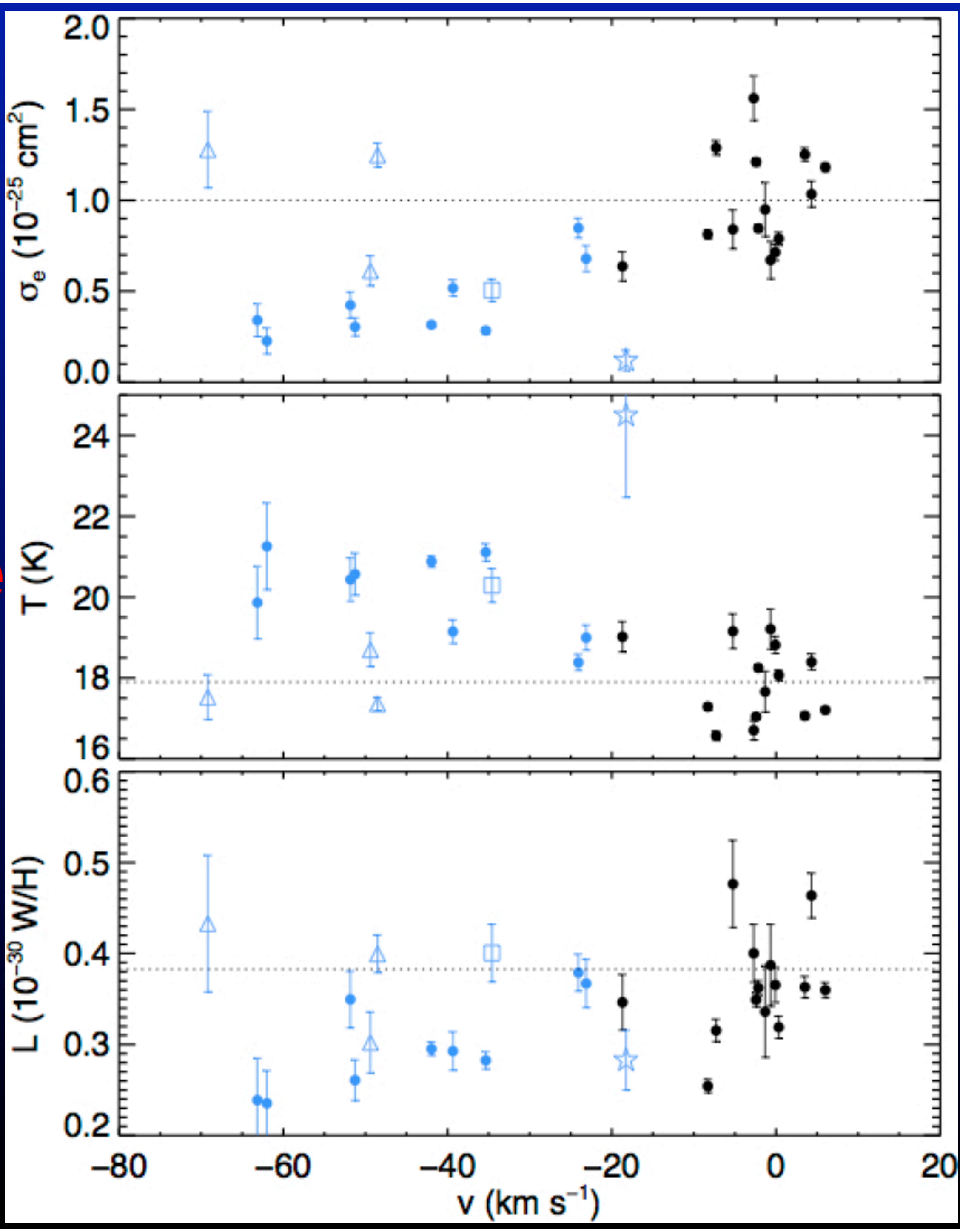
Opacity

Not all the same

→

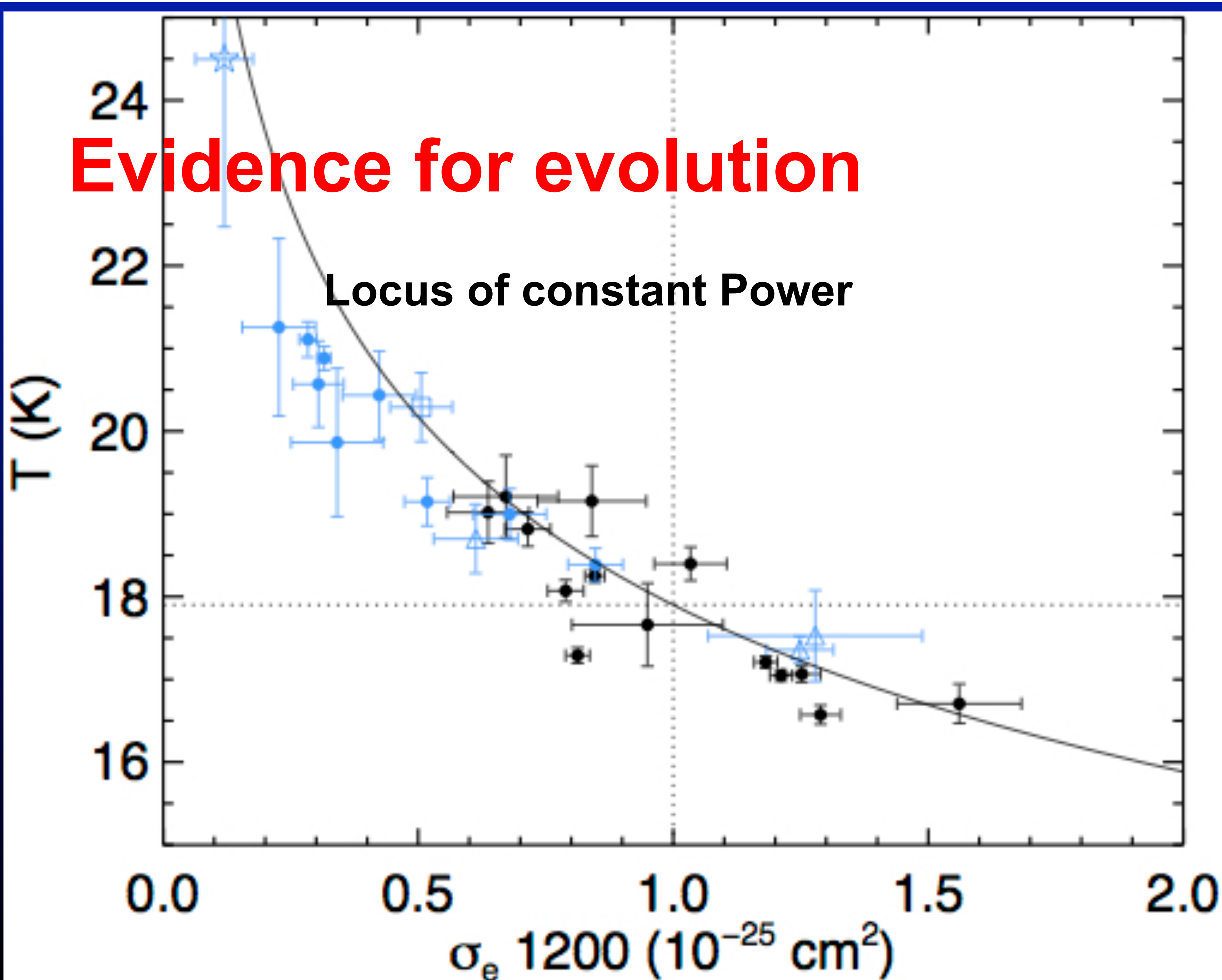
Dust evolution

Temperature

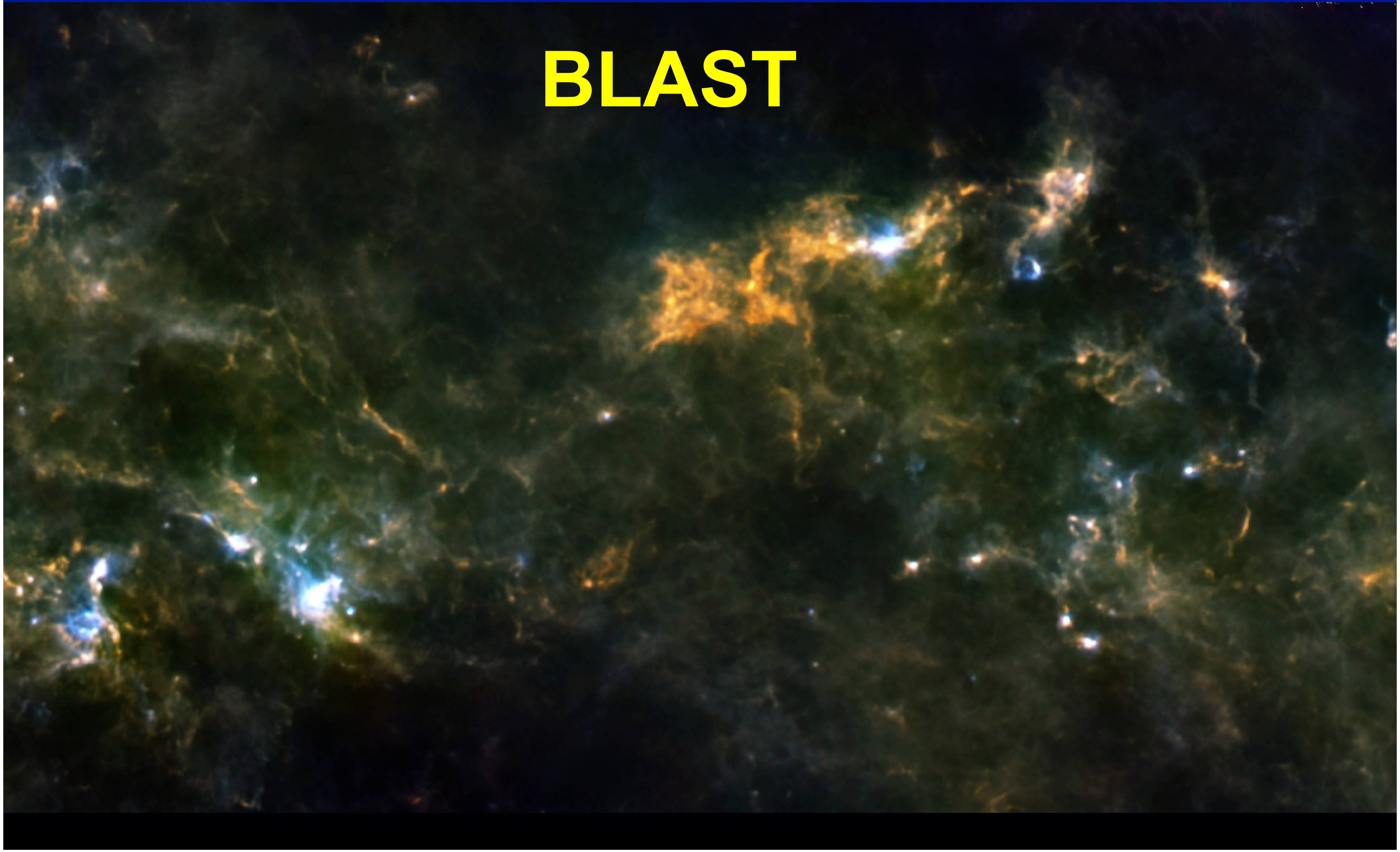


Power

Evidence for evolution



Higher column densities



Use near-infrared colour excess to assess column density

Excess from 2MASS analysis (Bontemps)

Good correlation.

Slope is like ε_ν .

Repeat the whole recipe (Martin et al. 2012).

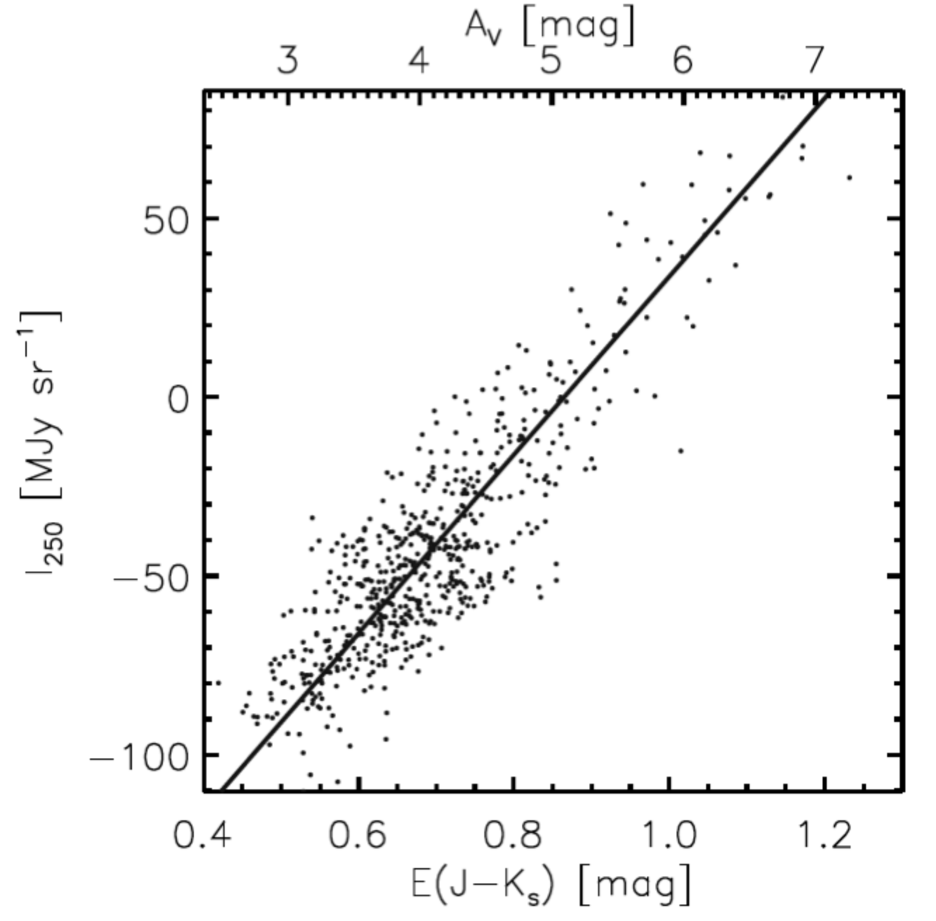
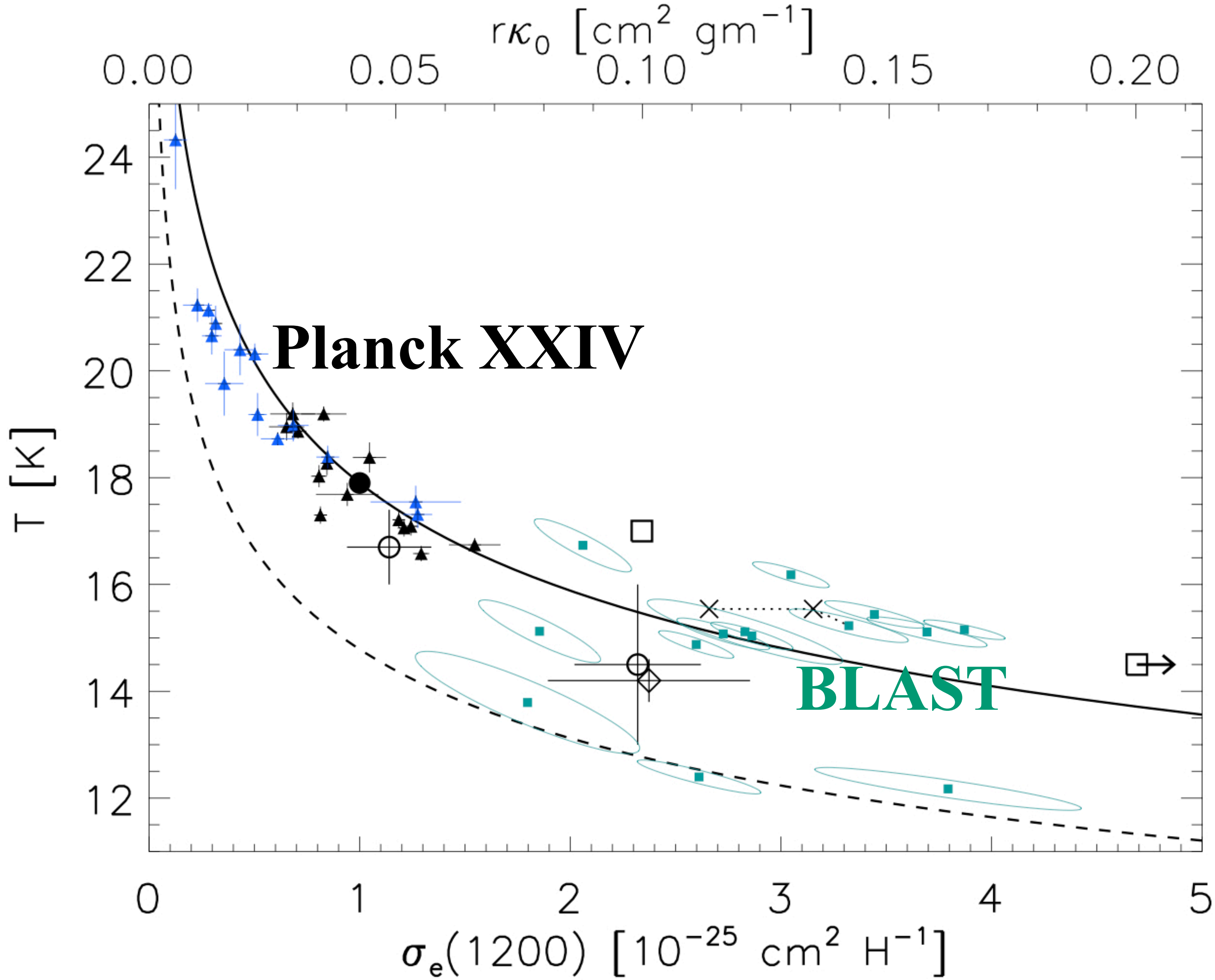


FIG. 4.— Pixel-pixel correlation of 250 μm BLAST emission with the color excess $E(J - K_s)$, in rectangle 7. The solid line has a best-fit slope $\epsilon_c(1200) = 249.0 \pm 5.0$ MJy sr^{-1} mag^{-1}. The A_V scale along the top is only approximate, but is provided for context.


$r\kappa_0$ [cm^2 gm^{-1}]
0.00
0.05
0.10
0.15
0.20
24
22
20
18
16
14
12
T [K]
Planck XXIV
BLAST
0
1
2
3
4
5
$\sigma_e(1200)$ [10^{-25} cm^2 H^{-1}]

Dust evolution

A major goal of work with Planck and Herschel (Abergel) is to follow the evolution of dust in the cycling between diffuse and more dense phases.

Ultimately, we would like to understand how this connects with star formation (presentations by Bally, Molinari, Juvela) and planet formation, but understanding dust in the molecular phase (presentation by Bernard) is challenging enough.

Evolution

Dust evolution in the cycle:

Diffuse ISM → molecular clouds → star formation → diffuse ISM

Mantles. **Limited by available gas. Gas phase C locked in CO, with excess O left for water ice formed on grain surfaces. Complex ice mantles.**

Aggregation **(and in reverse) sublimation, sputtering, fragmentation, vaporization.**

Where does dust evolution begin?

In the dense molecular phase of the ISM.
- Inferred changes in size distribution.
- Complex ice mantles. Evidence for mantles? Yes, NIR spectroscopy.

In molecular clouds we do not have all the optical, UV probes of dust properties that we have for the atomic phase.

Where does evolution begin?

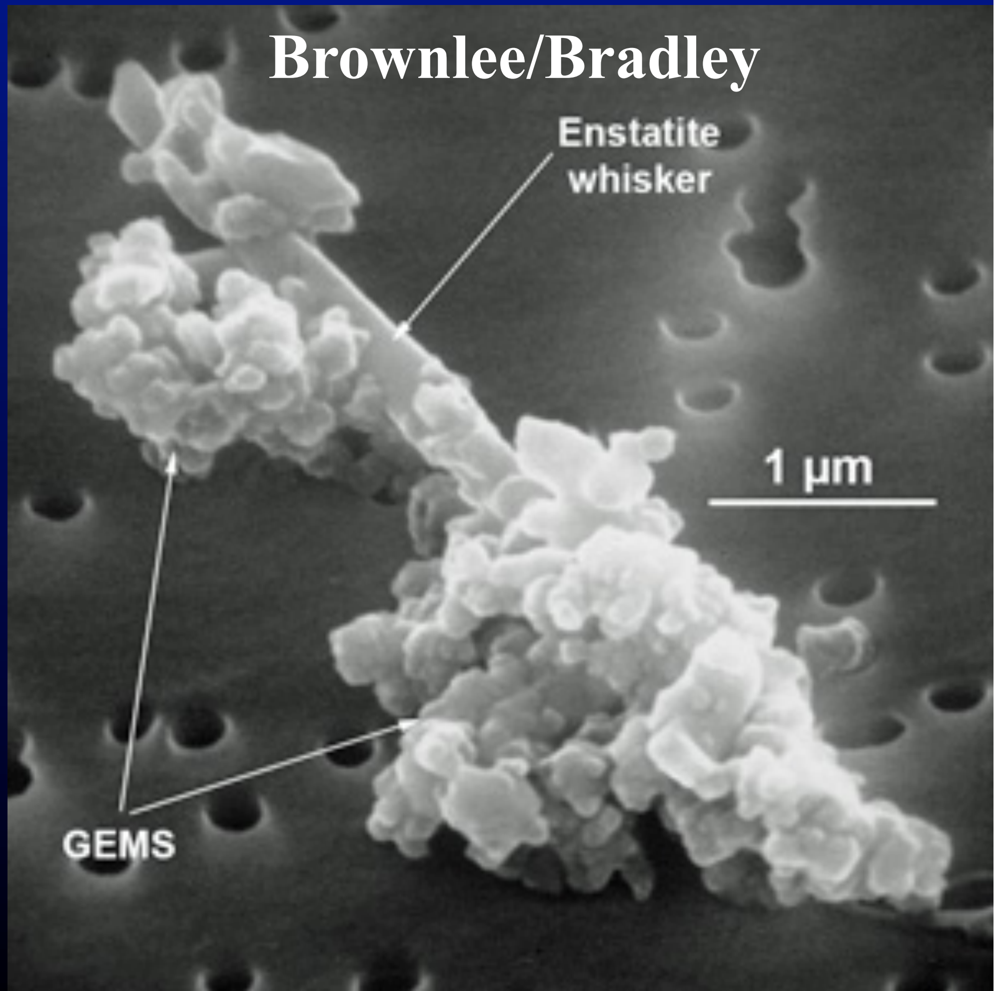
Alternatively, in the atomic medium, starting with
what emerges from the dense molecular phase.

We do see evolution even in the atomic phase.

IVCs show evidence of grain destruction.
"Metals" returned to the gas phase (depletion undone).

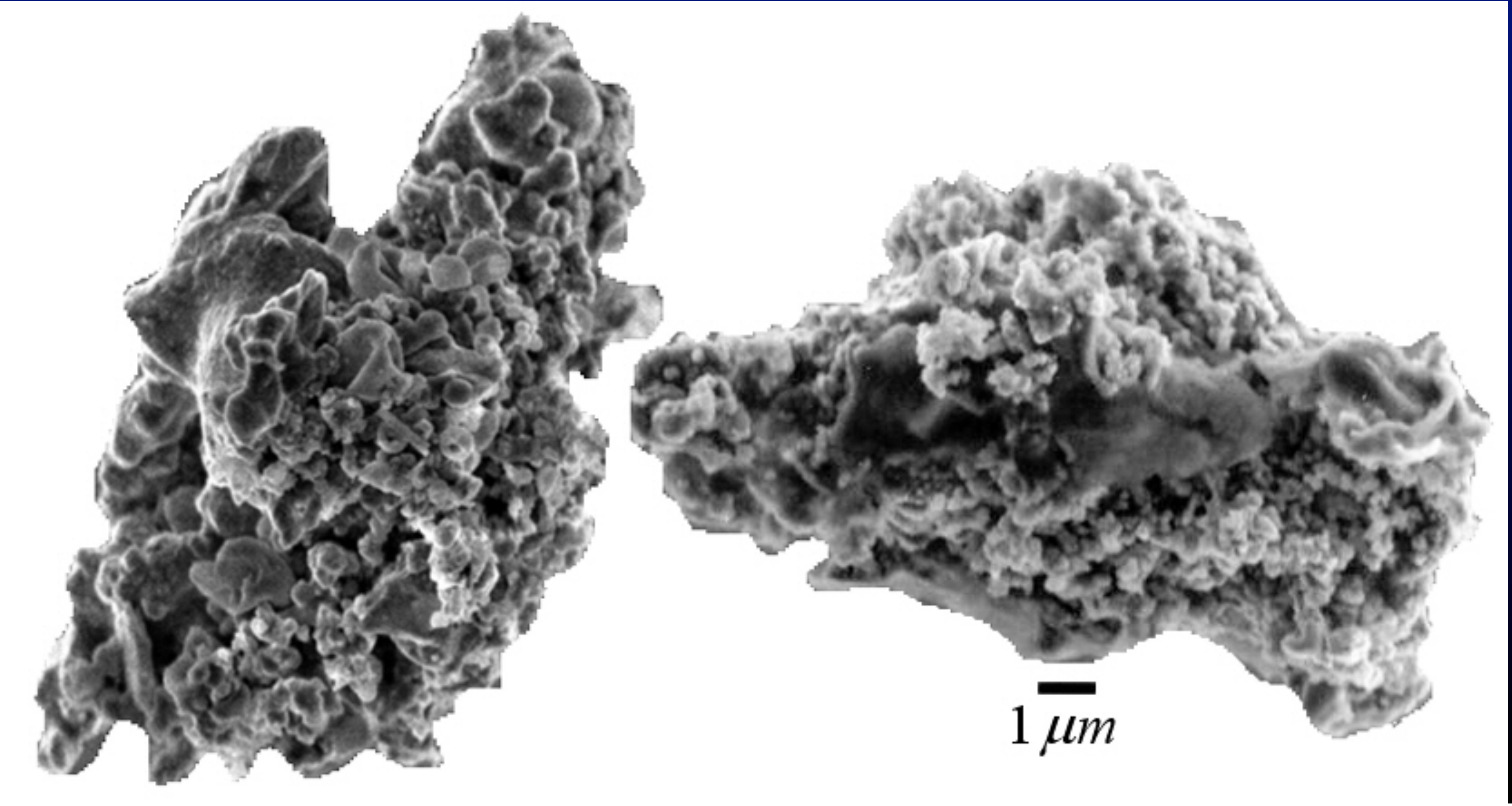
Interplanetary dust particles

- Captured in upper atmosphere.
- Isotopic anomalies, clues to history.
- GEMS: like interstellar silicates (composition, size, shape).
- Residue of C in matrix (even primitive meteorites, the “carbonaceous” chondrites, are carbon poor).



Interplanetary dust particles

Note that these are much larger than interstellar dust particles. They have an aggregate structure.



It is complicated

Nothing is really simple in interpreting dust emission!

There is a lot of structure in the ISM, and phases in which dust can have different properties (size, composition).

The dust temperature reflects an equilibrium between energy radiated in dust emission and energy absorbed from the interstellar radiation field, which changes with environment (radiative transfer and attenuation through the structures; Galactic position).

Disentangling the integrated emission through the Galactic plane is obviously challenging.

Dust Polarization

In this talk we are not discussing results on polarization, but this is a major design focus for Planck, both for the study of dust and removal of the polarized dust foreground to the polarized CMB.

So this is worth one slide! Polarization is inevitable. Read some details in my 2006 article "*On predicting the Polarization of Low Frequency Emission by Diffuse Interstellar Dust.*"

www.cita.utoronto.ca/~pgmartin/himovie/submmpolEDS.pdf

Dust polarization is inevitable

There is good evidence that (some) dust particles are *aspherical* and *aligned*, with respect to the interstellar magnetic field.

Differential extinction: NIR, optical, and UV → *Interstellar polarization* which is well (best) studied in diffuse ISM →

Origin: Large silicates (part of BGs). NOT small dust.

Same grains produce polarized thermal emission.

Predictions based on optical polarization are consistent with observations of diffuse submm polarization (direction, amount), e.g., Archeops.

Planck should be definitive, again driving theory.

On-going research with Planck

Low frequency behaviour (σ_{ν}, β). Deal with "contamination" by CMB, CIBA, CO.

Polarization. Only large grains produce optical polarization. Best bet: silicates.
Degree of polarization (diluted by non-polarizing grains).
Spectrum of polarized flux.
Other experiments: BLASTpol, PILOT, …

Hopefully leads to a better understanding of this dusty **foreground** to the CMB and CIBA.


Complemented by higher resolution H I from DRAO and by Herschel

END

Thanks to the Planck team for the fantastic data and to the Canadian Space Agency for supporting my participation in this grand venture.