High Resolution Spectroscopy with CCAT

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remark:

KOSMA together with
Radioastronomy group at the Argelander Institut für Astronomie (AifA)
Frank Bertoldi, Universität Bonn

aim at CCAT participation at 10% level, supported by universities and local federal state (Nordrhein-Westfalen, NRW)

High Resolution Spectroscopy with CCAT

- science needs for high spectral resolution
- instrumentation and sensitivities
- CCAT in comparison to other observatories
- examples of science areas
  - resolve high density, high UV PDR structure
  - ISM structure traced through PDR surfaces
  - line surveys in warm, dense cores
  - absorption studies against dust continuum background sources
  - plus many more, covered in other talks ...

science needs for high spectral resolution: line widths

- **ISM line widths**
  - **ISM clouds:**
    - turbulent line widths (suprathermal, but subalfvenic)
$\Delta v \lesssim 0.1$ km/s (thermal width /cold cloud / no turbulence) to
$\Delta v = 10$ km/s (turbulent width in warm cloud core)
  - **star formation cores (gravity dominates)**
    - virial line widths (high mass / low mass) $\Delta v =$ a few km/s to 10 km/s
  - **proto-planetary systems**
    - Keplerian velocities: $\Delta v \approx 100$ km/s (inner disk) to $\Delta v \approx 1$ km/s (Kuiper belt)

- **Milky Way & Galaxies: rotation curve**
  - **Galactic Center / nuclei: $\Delta v \approx 200 - 300$ km/s**
  - **galactic disks: edge on / face on: $\Delta v \approx 20 - 300$ km/s**

science need for high spectral resolution: science goal

integrated intensities provide

- info on energy balance (heating/cooling)
- abundances of species

often sufficient for first analysis

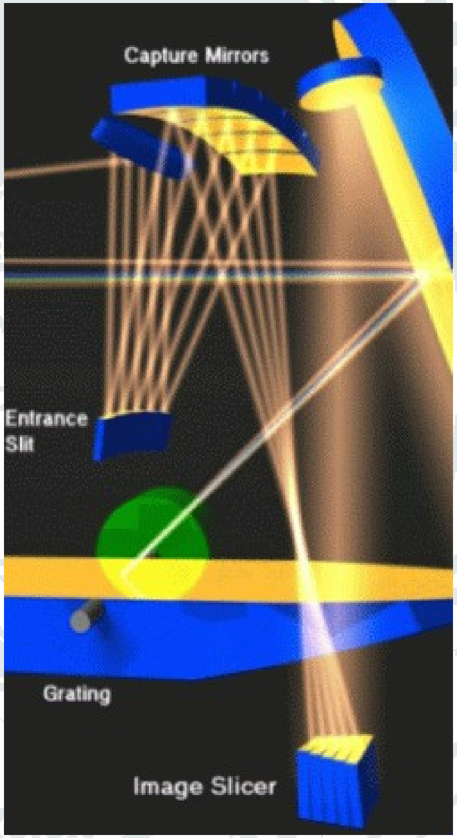
resolved line profiles

- allow study of kinematics and dynamics
  - outflows, rotation, accretion/expansion
- are essential to overcome spatial and spectral crowding
  - sources spatially not resolved:
    kinematic information can separate spatially overlapping components
    - “clump identification”, turbulent structure (spatial structure at all scales)
    - external galaxies: disk/core
    - proto-planetary systems: inner/outer disk
  - dense and warm cores: spectral confusion limit (“weed”-lines)
- give best sensitivity for line detection with continuum and/or background noise

heterodyne vs. direct detection spectroscopy: trade-off

- resolution vs. integration time:
  fair compromise: 10-30 resolution elements across line profile
- direct detection spectrometers (grating spect. / image slicer)
  - large format 2D-arrays
  - complex image slicing optics

  example: PACS/HIFI: 16 spectral channels on 5x5 spatial pixels



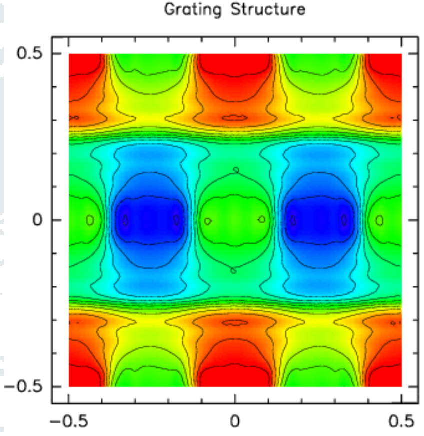
- heterodyne spectrometer arrays
  - resolution and bandwidth can be covered at affordable cost with DFT spectrometer technology
  - SIS-mixer technology (up to 1.5 THz ?) allows very wide instantaneous bandwidth
  - advanced opto-mechanical designs and waveguide micro-machining technology allow compact configurations
  - advances in LO power and Fourier-optics allow LO-distribution onto many mixers

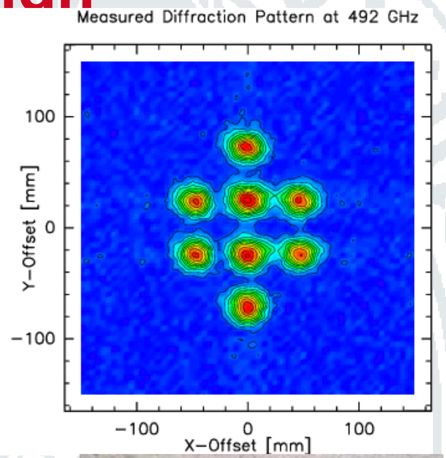
  examples:

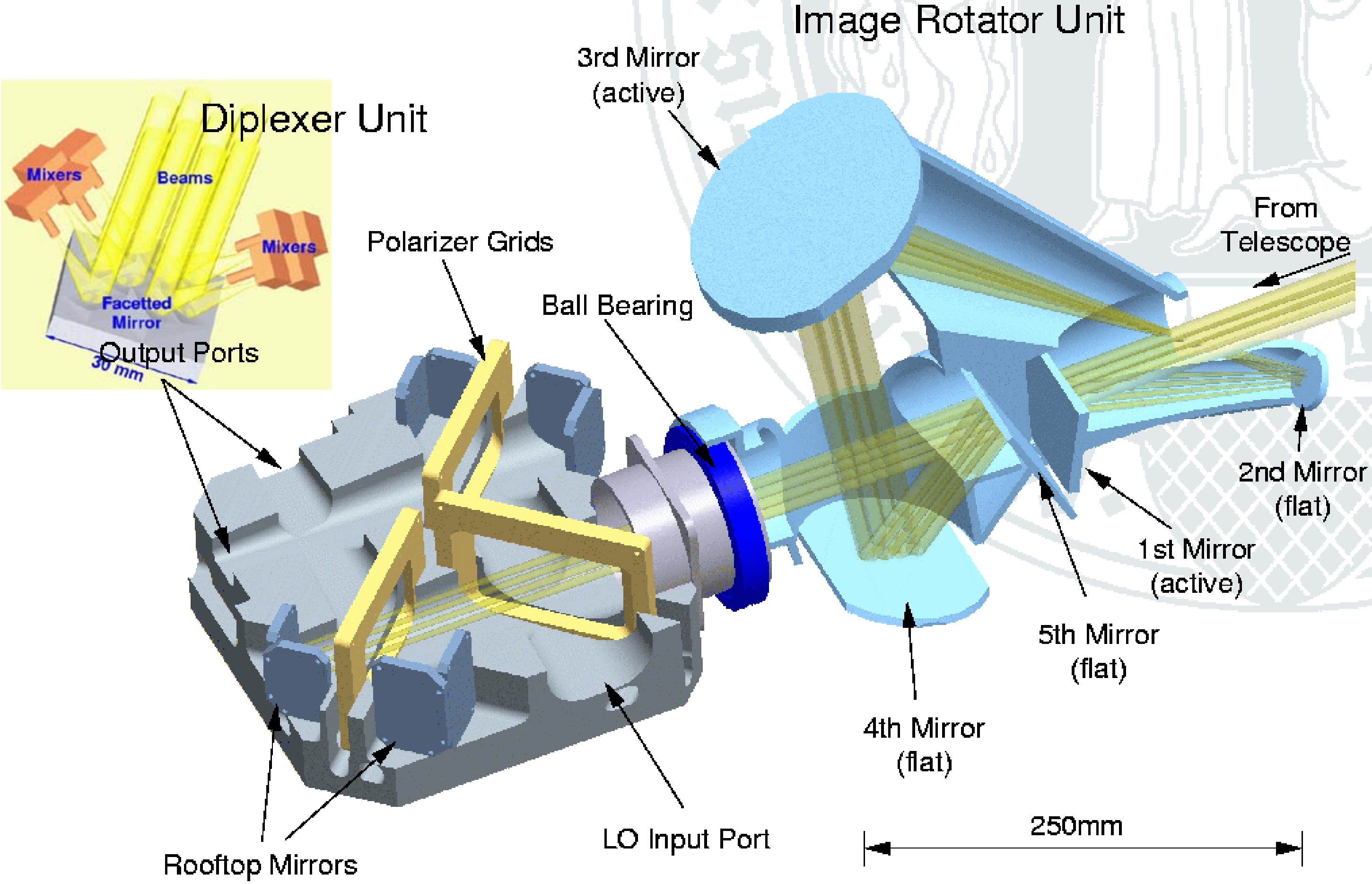
  CHAMP/APEX: 2 frequencies (650, 850 GHz), times 7 pixels
  SMART/NANTEN2: 2 frequencies (460, 810 GHz) times 8 pixels
  SuperCam/HHT: single frequency band (345 GHz), 64 pixels

heterodyne array: example: SOFIA STAR 1.9 THz design

- **integrated optics**
- **Fourier-grating LO distribution**







heterodyne vs. direct detection spectroscopy: trade-off

both instrument technologies:

- **similar capability in spatial and spectral multiplexing**
- **progress towards larger size of 3D cubes coming**

thus: single pixel sensitivity is what matters:

note: SIS performance (3 times QL) expected up to at least 1500 GHz

real system: given NEP_{coh} and T_{rec}

correspondence:

$$NEP \Leftrightarrow 2kT_{rec}\sqrt{\Delta\nu} = 2.8\times10^{-17}\,\mathrm{W\,Hz}^{-1/2}\;T_{rec}/1000\,\mathrm{K}\sqrt{\Delta\nu_{MHz}}$$

$$\downarrow$$

crossover resolution:

$$R_{cross} = \frac{\nu}{\Delta\nu_{cross}} = 4\nu\left(\frac{kT_{rec}}{NEP_I}\right)^2$$

crossover line width:

$$\Delta\nu_{cross} = \frac{c}{R_{cross}} = \frac{\lambda}{4}\left(\frac{NEP_I}{kT_{rec}}\right)^2$$

ν [GHz]	T_{rec}[K]	NEP[W $Hz^{-1/2}$]	R_{cross}	v_{cross}[km/s]
820	400	2×10^{-16}	2500	120

CCAT in comparison to other observatories

size / angular resolution:

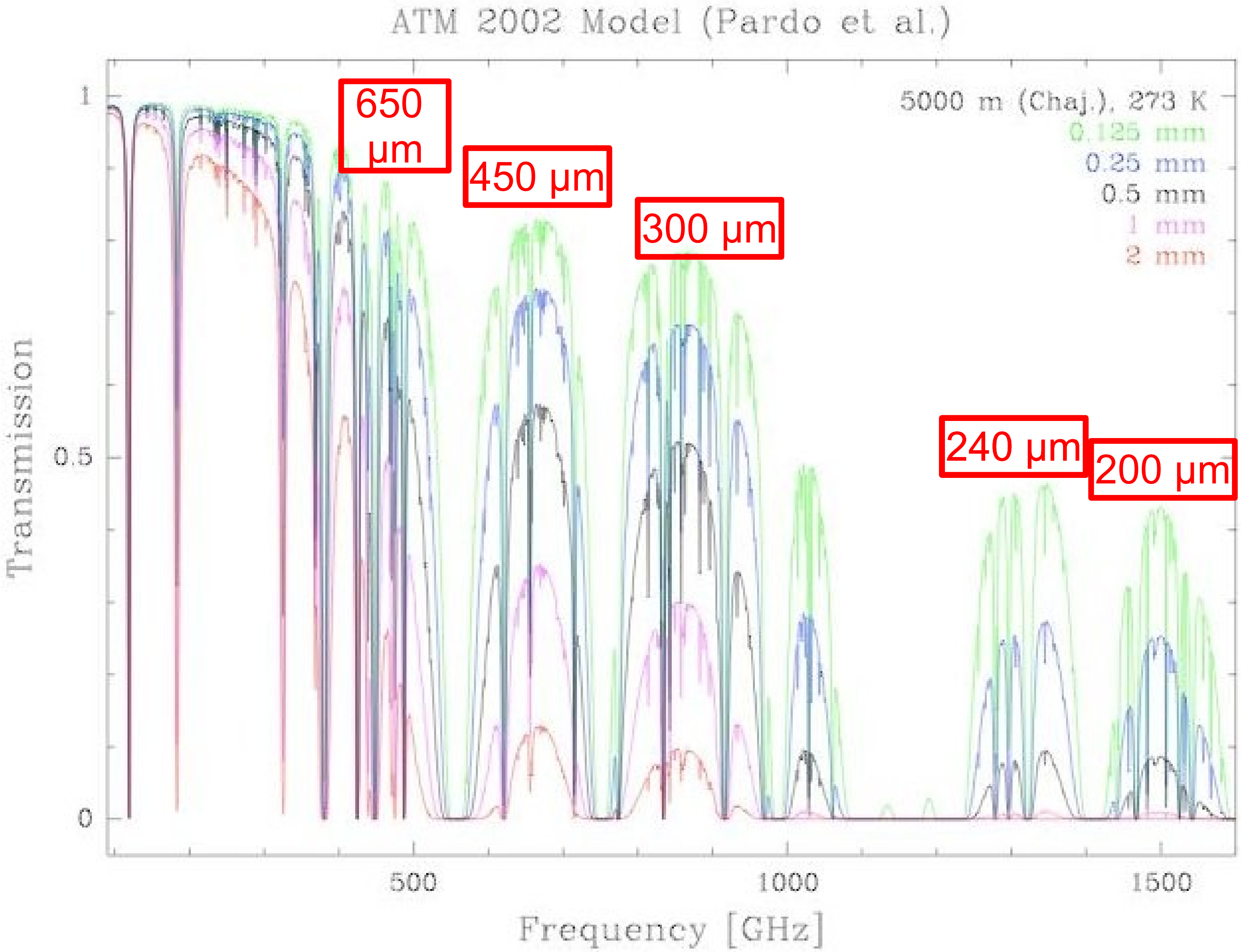
- APEX (diameter 12m; rms 16 µm; limited day time ops), λ ≤ 350 µm
  - @350 µm: 5.3 times less effective area than CCAT (25m, rms 10 µm)
  - 2 times larger beam size
- LMT 50m, IRAM 30m (λ ≤ 1.3 mm), MOPRA 22m (λ = 3 mm)
  - valuable complementarity at lower frequencies
  - 2 to 3 times larger beam
    [8 times larger for MOPRA, but only southern telescope]
- ALMA (50 x 12m plus compact array)
  - primary beam 2 times larger than CCAT
  - no spatial arrays: slow mosaicking
  - schedule for higher bands will take some time (350 µm)

CCAT with heterodyne arrays (64 – 128 pxs) will be very important pathfinder (& zero spacing for ALMA)

NANTEN2-4m, ASTE-10m, APEX-12m, CCAT-25m
provide a complementary range of angular resolution

CCAT in comparison to other observatories

CCAT site: Cerro Chajnantor: superb atmospheric conditions



CCAT in comparison to other observatories: atmosphere

comparison between Chajnantor plateau (APEX, ALMA) and Cerro Chajnantor (CCAT):

- median τ@350 μm for May to October
  - ALMA plateau: $\tau \approx 1.5$
  - Cerro Chajnantor: $\tau \approx 1.0$
- average source elevation 60°, i.e. Airmass 1.24
- Ruze-factor for η_b

signal ~ $\eta_b \exp(-\tau/\mathrm{Airmass})$

- results in 5.2 faster observing time for same S/N (times beam-size/filling advantage)

- even more at lower elevation angles, higher frequencies

High Resolution Spectroscopy with CCAT

- examples of science areas
  - resolve PDR structure in high density, high UV regions
  - ISM structure of fractal cloud
  - high mass star forming regions: line surveys/mapping
  - absorption studies
- not repeated here:
  - ALMA complement:
    - fill-in of zero spacing
    - spatial multiplexing advantage with array rx
  - low-mass star forming cores (→ Jaffe's talk)
  - nearby galaxies and Galactic Center (→ Goldsmith's talk)
  - solar system science topics (→ Brogan's talk)
  - astrochemistry (→ Lis's talk)

CCAT: resolve PDR structure in high UV, high density sources

- probe relevant spatial scales in PDR layered structure
  - high densities
  - efficient gas heating
  - excitation of mid-J CO lines
  - [CI] 1-0 and 2-1 from narrow transition layer
  - PDR-layer: $A_v \approx 2$ to 4 mag

3.5" CCAT beam @350 µm resolves A_v=2.6 mag for density of 10^5 cm^{-3} and a source at 500 pc (Orion)

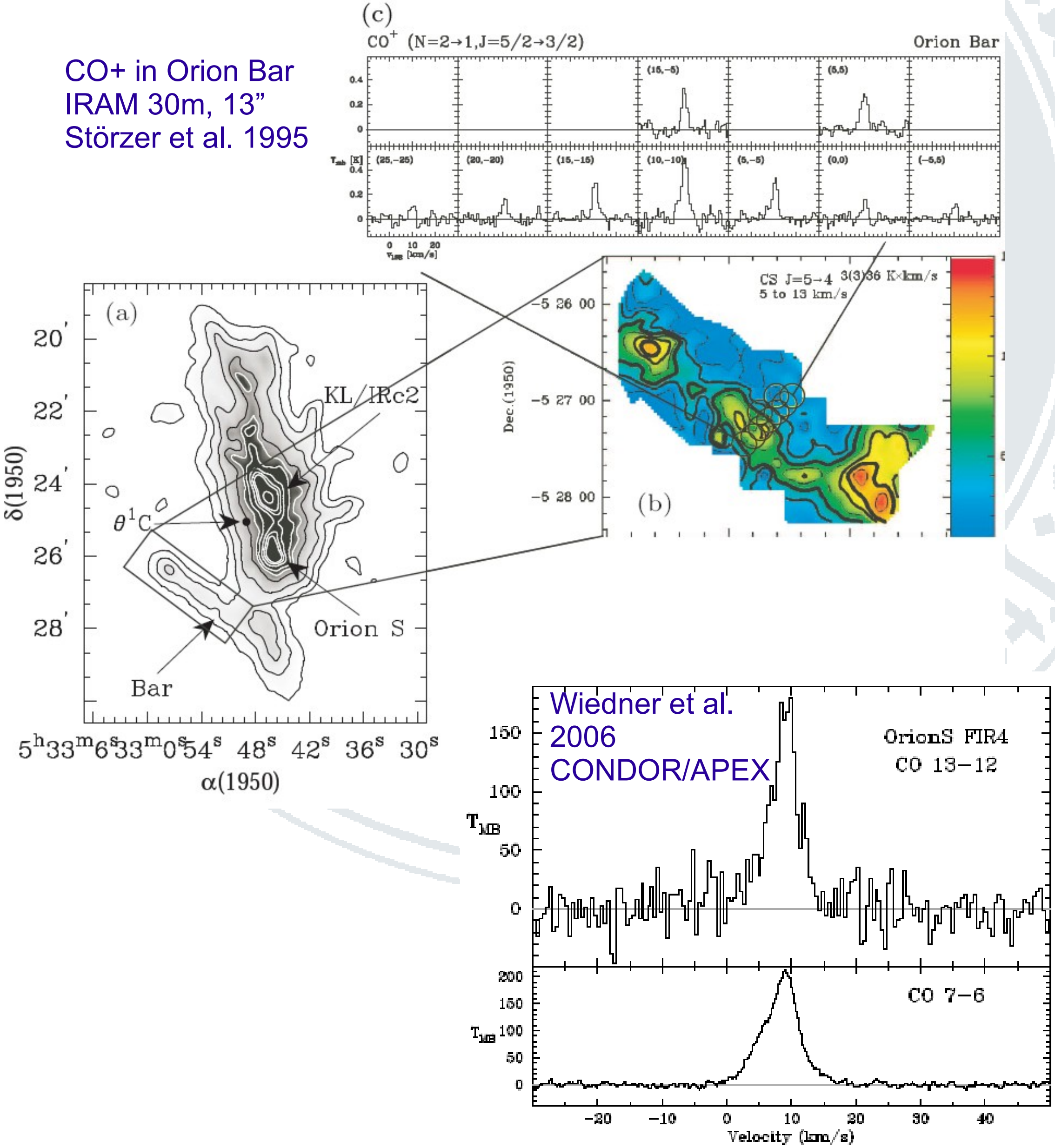
lines:

^{12}CO, ^{13}CO mid-J and high-J

[CI] 1-0 and 2-1

[NII] 205 µm

CO$^+$, HDO, CN, CS, ...



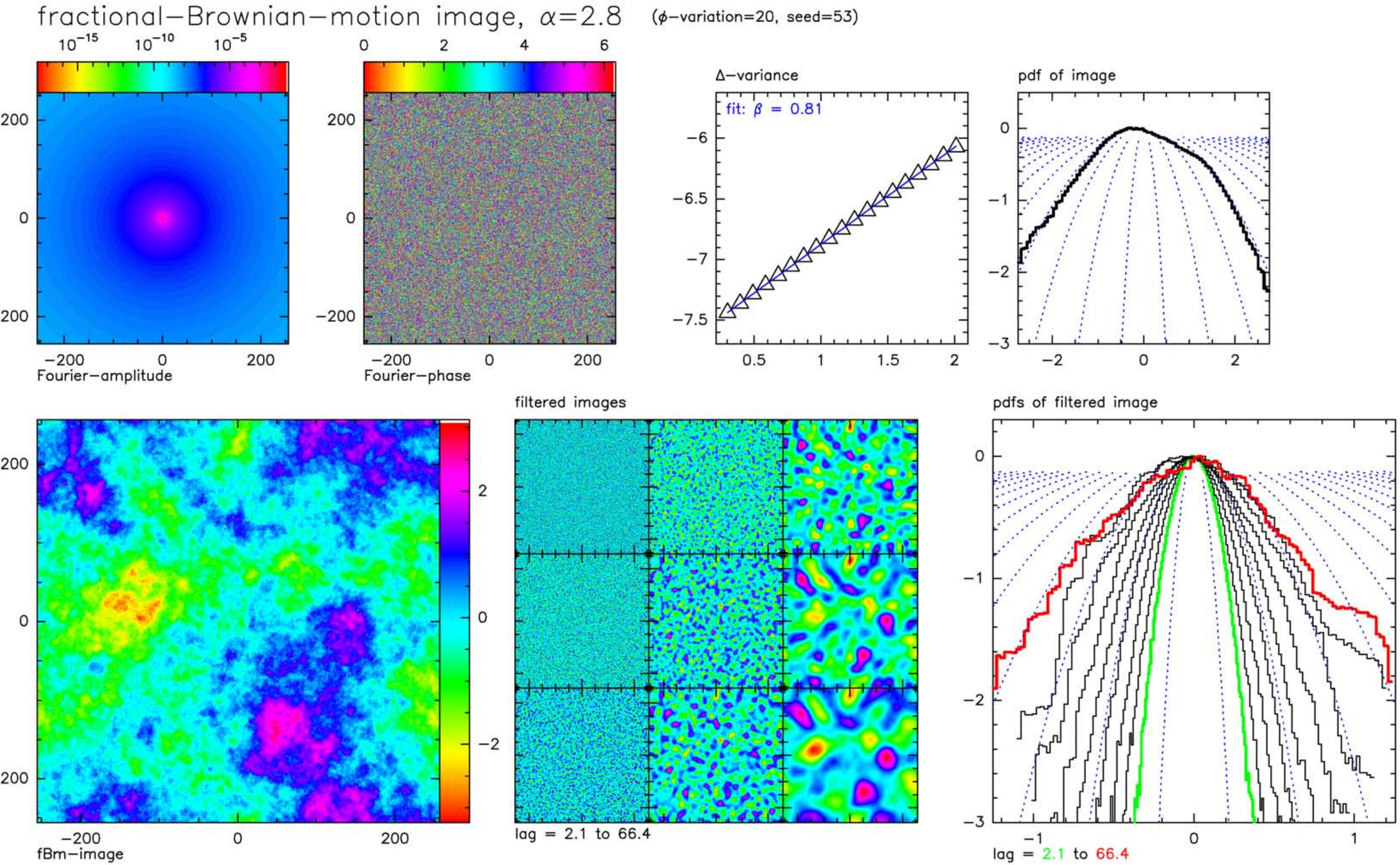
CO+ in Orion Bar
IRAM 30m, 13"
Störzer et al. 1995

Wiedner et al. 2006
CONDOR/APEX

CCAT: ISM structure traced by PDR emission from fractal clouds

- **ISM clouds show a turbulent, fractal structure down to well below sub-solar mass fragments**
  - **turbulent support controls SF-efficiency**
  - **may determine IMF**
  - **affects feed-back/self-regulation of star-formation**
- **UV radiation from young stars creates photon-dominated regions on cloud surfaces**
- **characteristic PDR-emission includes [CII]- and [CI]- fine-structure lines, CO and ^{13}CO rotational lines plus FIR continuum**

CCAT: probe small spatial scales in high excitation lines
(in combination with ALMA)



fBm structure (power low power spectrum, random phases) provides good model for ISM (HI and CO)

- reproduces power spectra and Δ -variance of observed maps
- reproduces non-Gaussian wings on difference-pdfs at large lags

observations of structural characteristics: clump decomposition

clump decomposition methods

- Gaussian decomposition (Stutzki & Güsten 1988; Kramer et al. 1998)
- clump-find-algorithm (Williams et al. 1994)

yield

- clump statistics: mass-spectra, size-spectra, shape/orientation
- correlations between clump properties: e.g. mass-size relation

- connection to power spectrum/ fBm
  - mass-size-relation
  - mass-spectrum
  - randomly positioned clumps
  - → fBm intensity map

$$\boxed{\begin{array}{c} M \propto r^{\gamma} \\ dN/dM \propto M^{-\alpha} \\ \downarrow \\ P(k) \propto k^{-\beta} \quad with \quad \beta = \gamma\,(3-\alpha) \end{array}}$$

- velocity structure helps to tell individual clumps apart

fractal clump distribution: properties

power law mass spectrum $dN/dM \propto M^{-\alpha}, \alpha = 1.8$
power law mass size relation $M \propto r^{-\gamma}, \gamma = 2.3$

gives

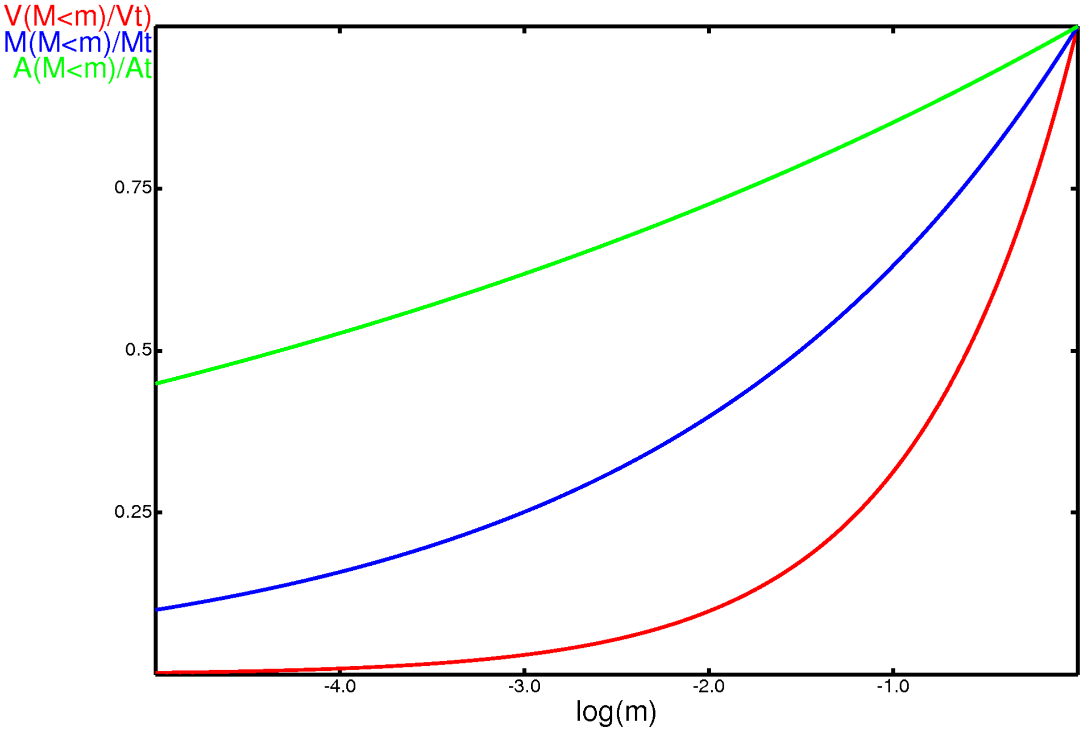
- an ever increasing number of smaller and smaller clumps

with (normalized to most massive clump)

- increasing density: $\rho/\rho_1 = (M/M_1)^{(\gamma-3)/\gamma} = (M/M_1)^{-0.304}$
- almost constant column density: $N/N_1 = (M/M_1)^{(\gamma-2)/\gamma} = (M/M_1)^{0.13}$
- a cumul. mass function $M(\mu < m)/M_{tot} = (m/M_1)^{(2-\alpha)} = (m/M_1)^{0.2}$
- a cumul. volume function $V(\mu < m)/V_{tot} = (m/M_1)^{\frac{3}{\gamma} - \alpha + 1} = (m/M_1)^{0.504}$
- a cumul. area function $A(\mu < m)/A_{tot} = (m/M_1)^{\frac{2}{\gamma} - \alpha + 1} = (m/M_1)^{0.07}$

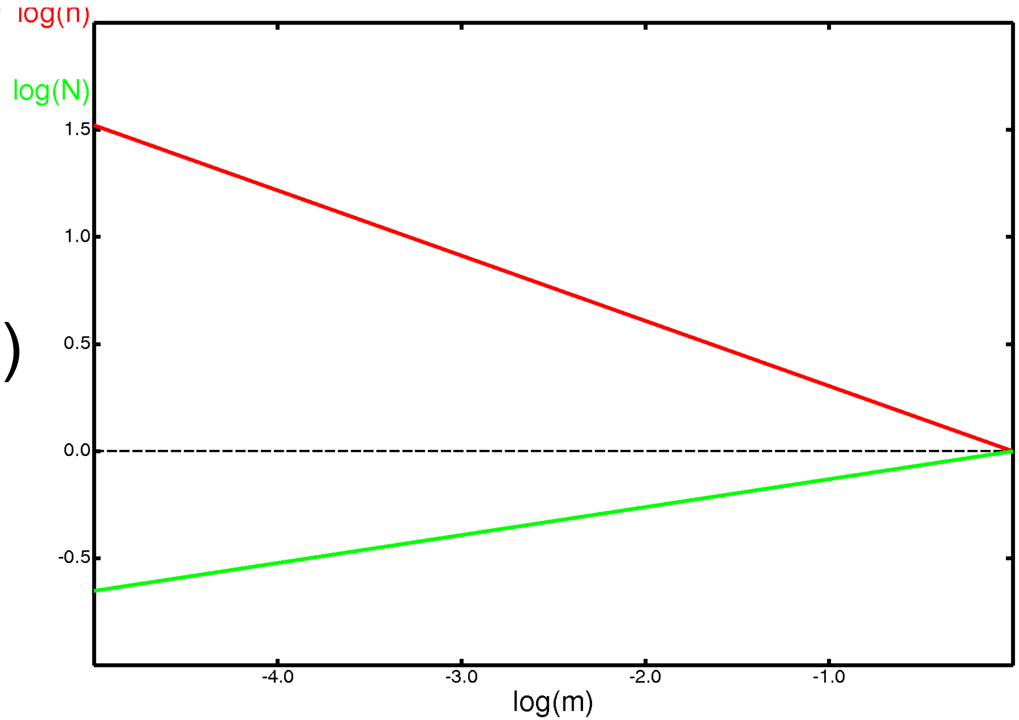
clump ensemble

cumulative distribution of
- volume
- mass
- area



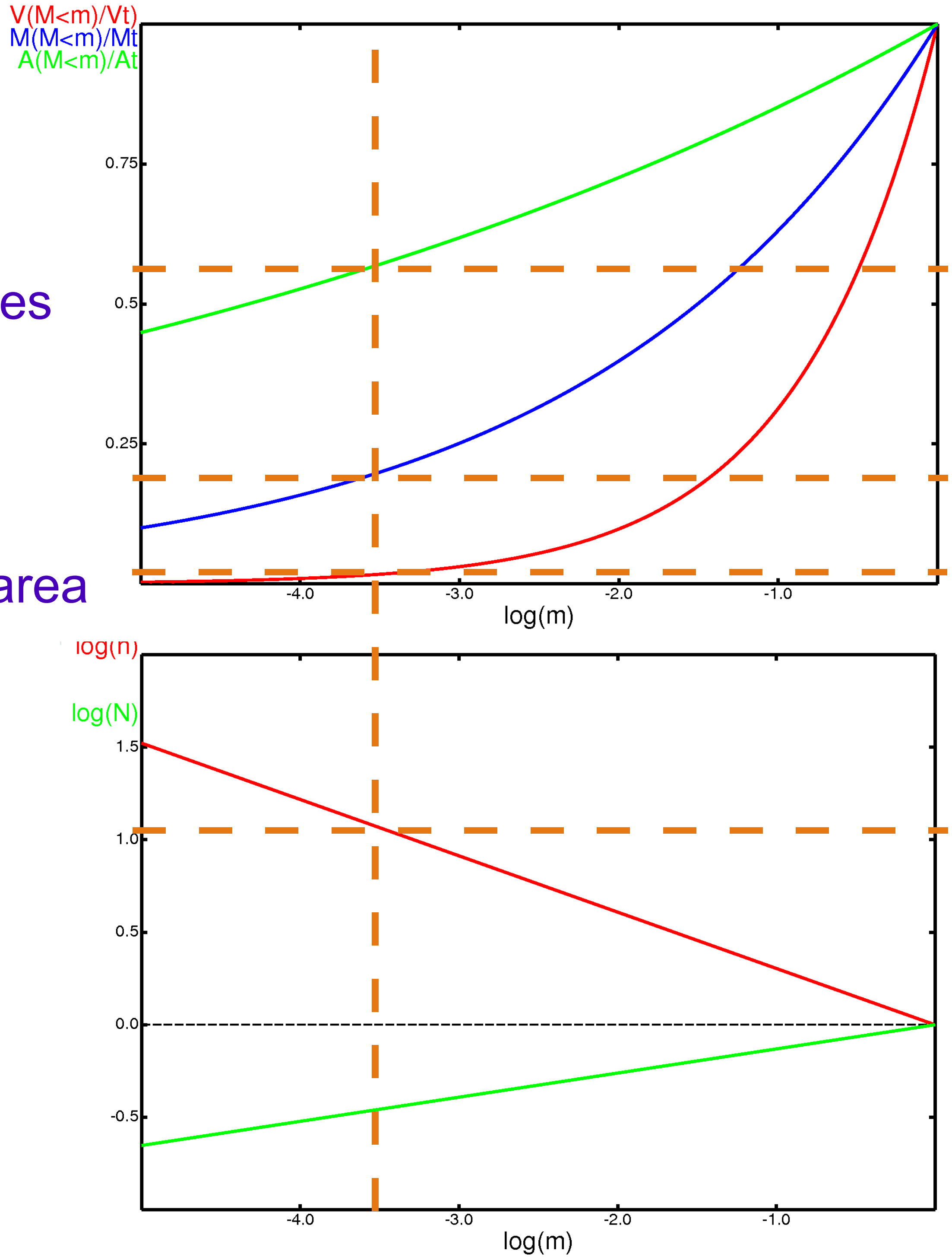
variation of
- clump density
- clump column density

(normalized to largest clump)



example:
clumps with a
density enhancements > 10 times
largest clump

- occupy 2% of the volume
- include 21% of the mass
- provide 58% of the projected area

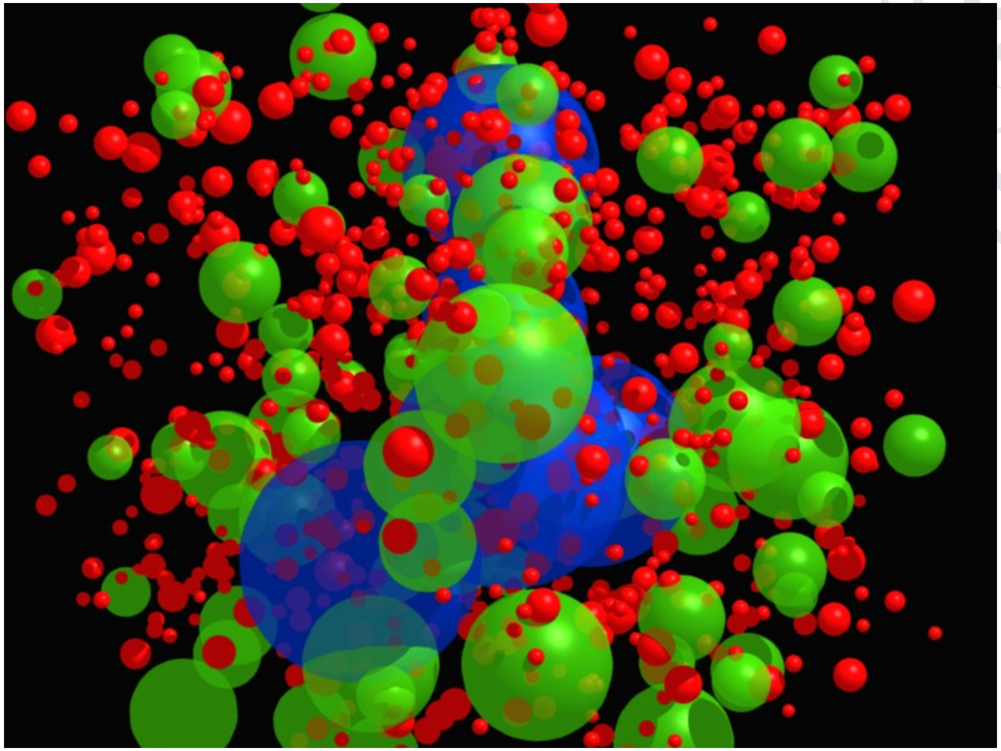


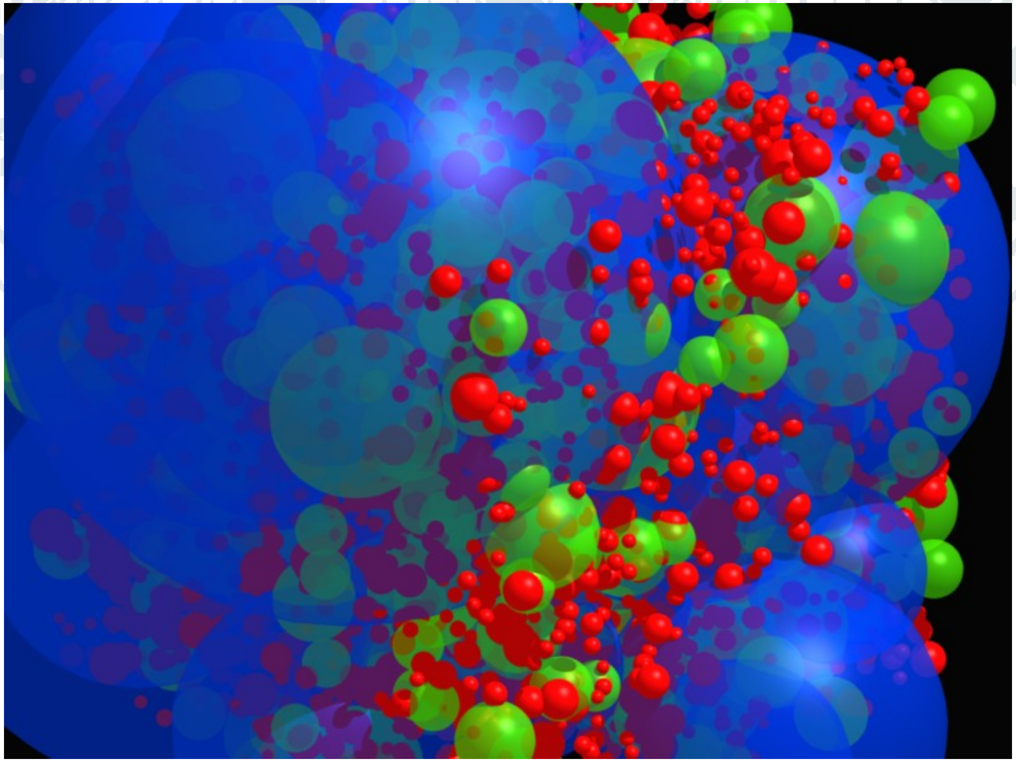
fractal clump distribution: examples

- fBm distribution: random positioning of clumps
- different volumes: volume filling factor η_V

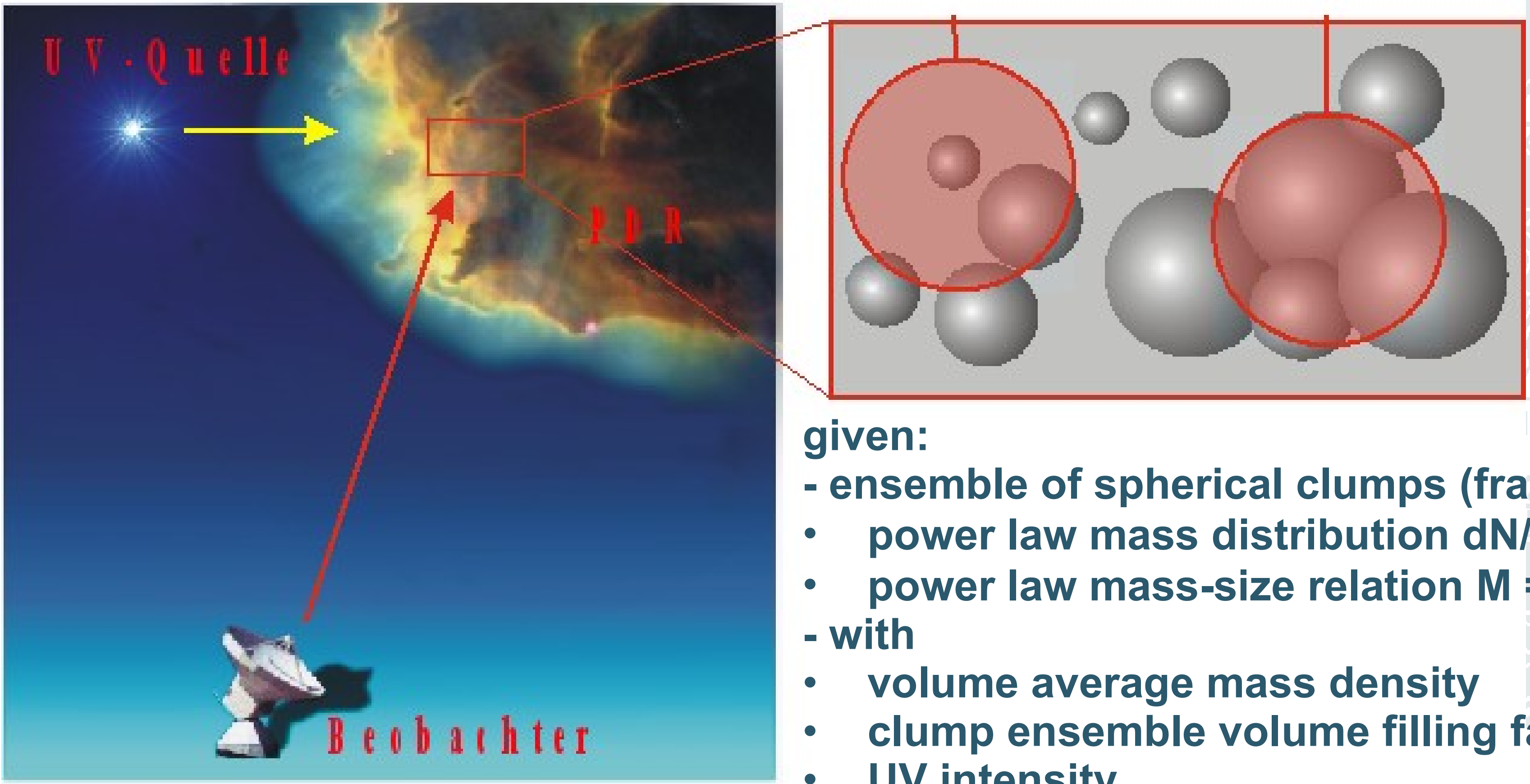
(note: turbulence: high density, small clumps should be inside low density regions → spatial correlation in clump distribution)

$\eta_V \approx 0.1$ high/medium/low density $\eta_V \approx 1.0$





clumpy cloud PDR model:
PDR emission of fractal structure



given:

- ensemble of spherical clumps (fractal structure)
  - power law mass distribution $dN/dM = A\,M^{-\alpha}$
  - power law mass-size relation $M = B\,r^{-\gamma}$
- with
  - volume average mass density
  - clump ensemble volume filling factor
  - UV intensity
  - metallicity

calculate

- volume emissivity in PDR lines & continuum
- fold with source distribution
  (mass density, UV intensity, filling factor, ...)

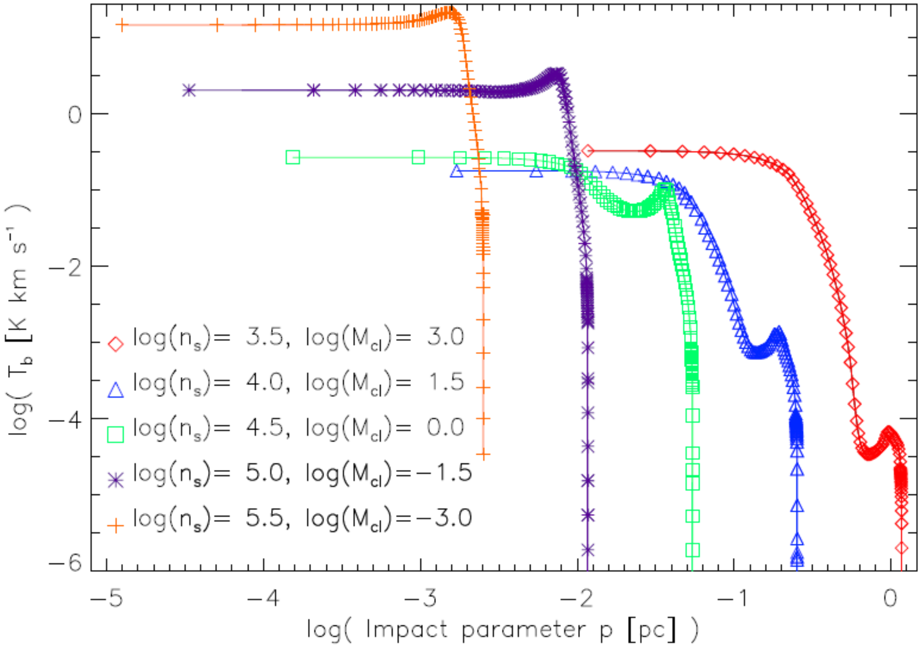
result

- observable line intensities

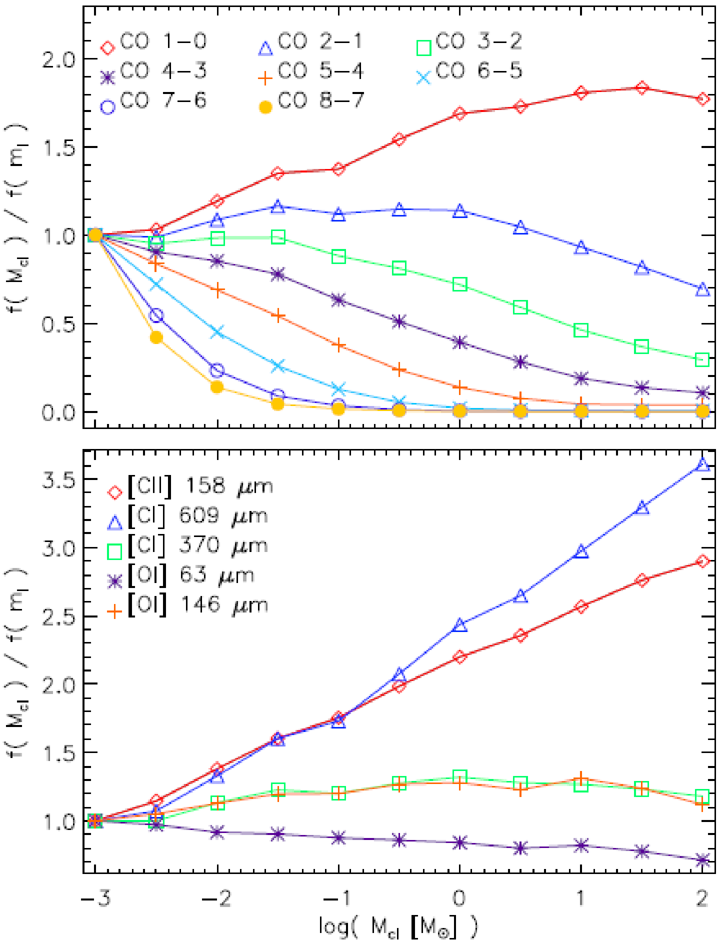
variation of clump density and line characteristics (critical density, temperature)

give distinct variations in the clump intrinsic brightnesses emissivity of clump ensemble

CO 7-6 clump brightness profile



clump mass specific emissivity of clump ensemble



note:

this is for average Galactic emssion

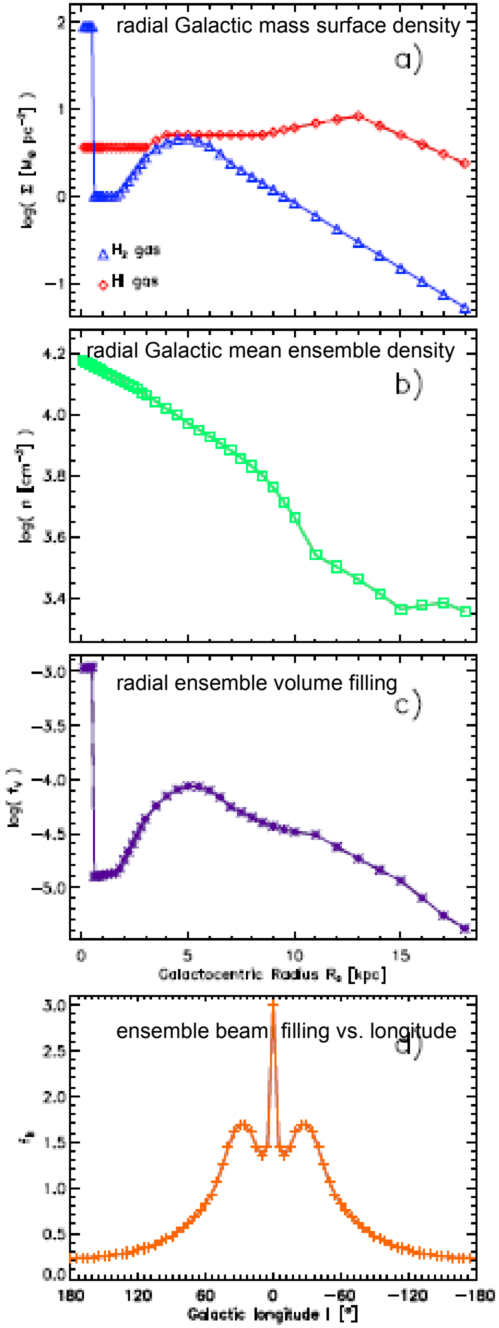
with

clump ensemble average density $10^{3.5}$ cm^{-3}

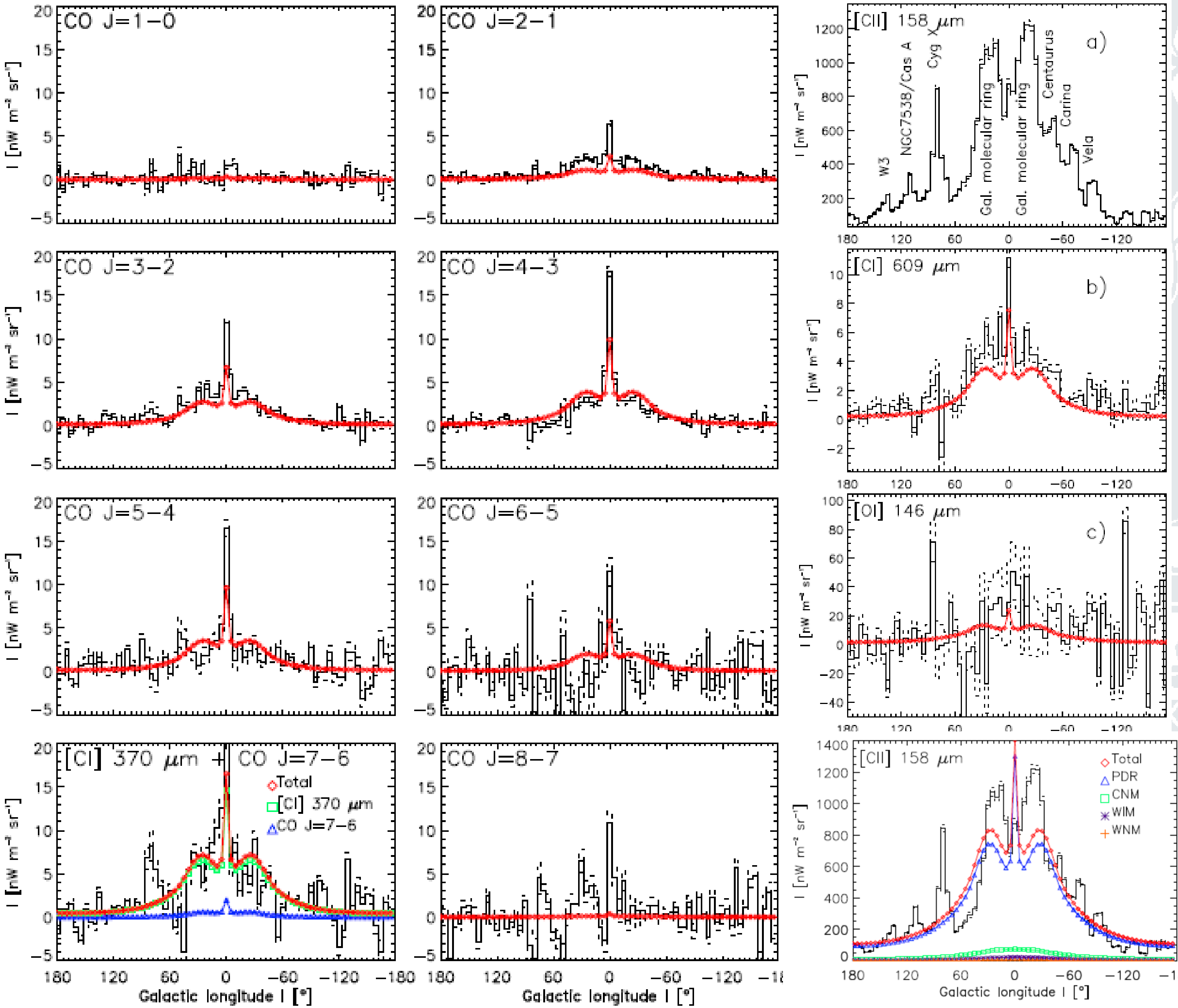
UV-intensity G_0=150

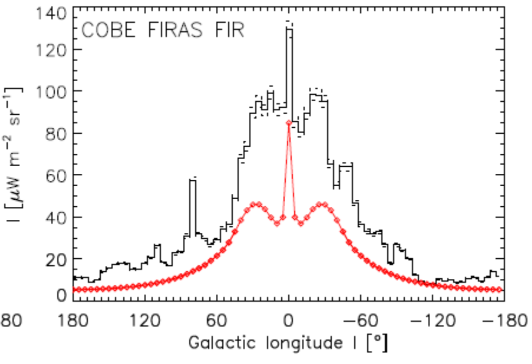
but trend is the same for high density, high UV

Large scale emission of the Milky Way / longitudinal distribution



- **simple cylindrically symmetrical MW model (fixed height, radial variation of physical parameters)**
- **mass surface density → mass volume density**
  (Clemens et al. 1985, Bronfman et al. 2000)
- **mean molecular cloud intrinsic volume density (Wolfire et al. 2003)**
- **UV field from distribution of OB associations (McKee & Williams, 1997)**
  plus typical average distance OB cluster -- molecular cloud
- **α, γ from fractal characteristics**
  (Heithausen et al. 1998)





A&A submitted

Cubick, Stutzki,
Ossenkopf,
Kramer & Röllig

clumpy PDR model
(no fitting!)
reproduces all
observed lines
within factor of 2

ISM structure:

above was for large scale MW (G_0≈150, n≈$10^{3.5}$ cm^{-2}), but holds equivalenty for denser/higher-UV regions

different lines trace different densities, and hence spatial scales

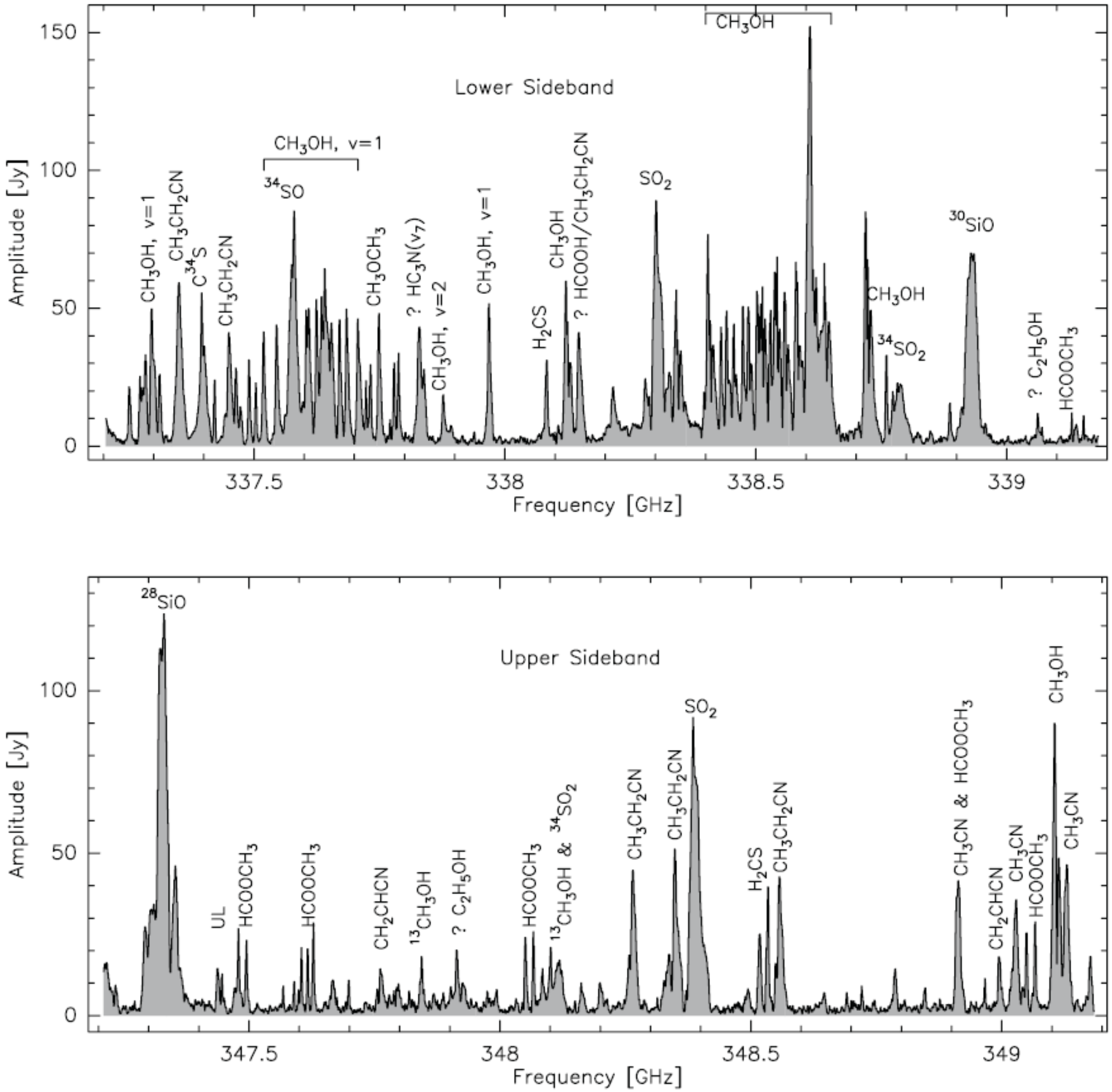
- [CII], [CI] 1-0: large clumps
- [CI] 2-1, mid-J CO: small scale structure
-

What determines the smallest clumps size? (UV evaporation?)

CCAT and ALMA are ideal complement
example: mid-J CO, [CI] in 609 and 350 µm window

- ALMA interferometry in a series of individual pointings
  - directly measures spatial power spectrum index
  - covers angular scales: 10” down to < 0.1”
- CCAT array-receiver (64 pxs)
  - individual pointings provide zero-spacing for ALMA observations
  - OTF maps cover angular scales from >100” to 5”

CCAT: line surveys of warm, dense star forming cores

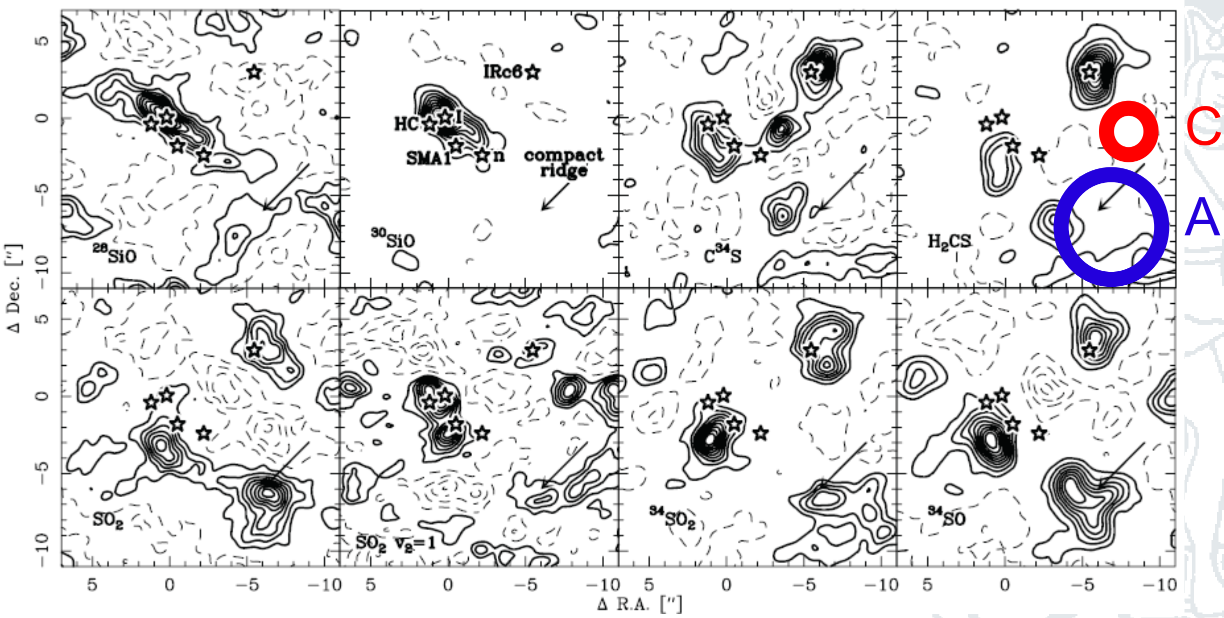


examples in the following from

Beuther et al. 2005
345 GHz SMA “line survey”

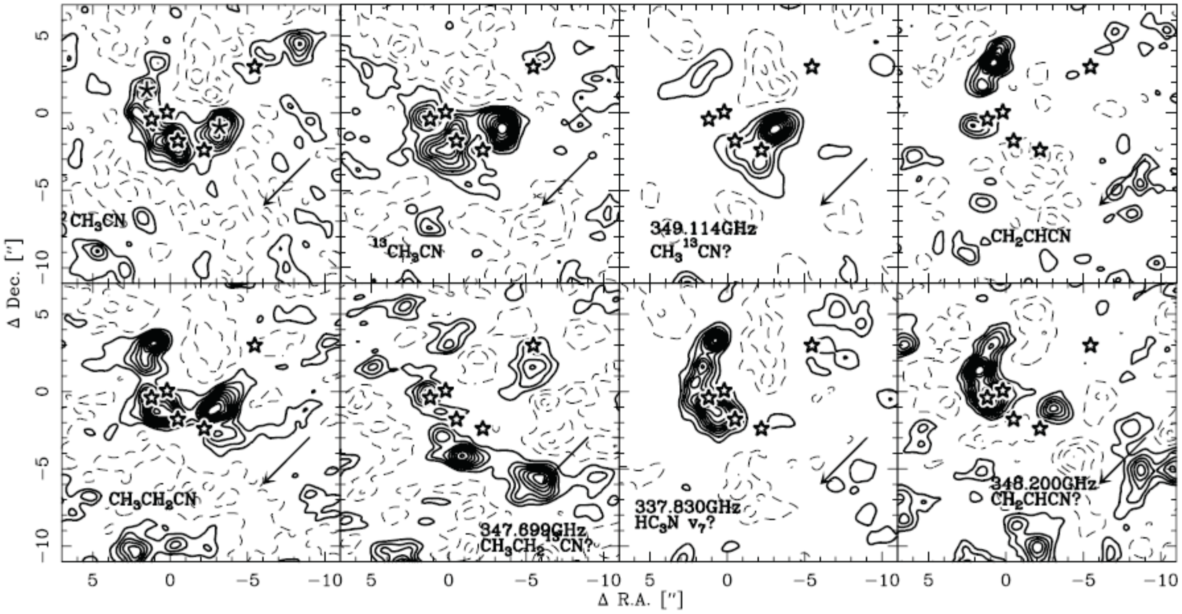
2 GHz each from lsb, usb

145 lines from
13 species
6 isotopologues
5 vibrationally excited states



CCAT beam 350 µm

ALMA primary beam 350 µm



complex spatial distribution:

ALMA
  single pointings with high angular resolution within primary beam

CCAT array rx (64 pxs)
  efficient mapping over 30x30” array footprint

Important:
  large instantaneous bandwidth of > 8 GHz, sideband separation

CCAT: Absorption studies against thermal dust emission

- use dust continuum at 450, 350 and 200 µm
- reaches from a few K up to ≈10 K in many massive star forming cores in inner galaxy
- even a few outer galaxy sources with close to 1 K dust continuum in 15” beam
- continuum from background star-burst galaxies in Galactic plane (?)

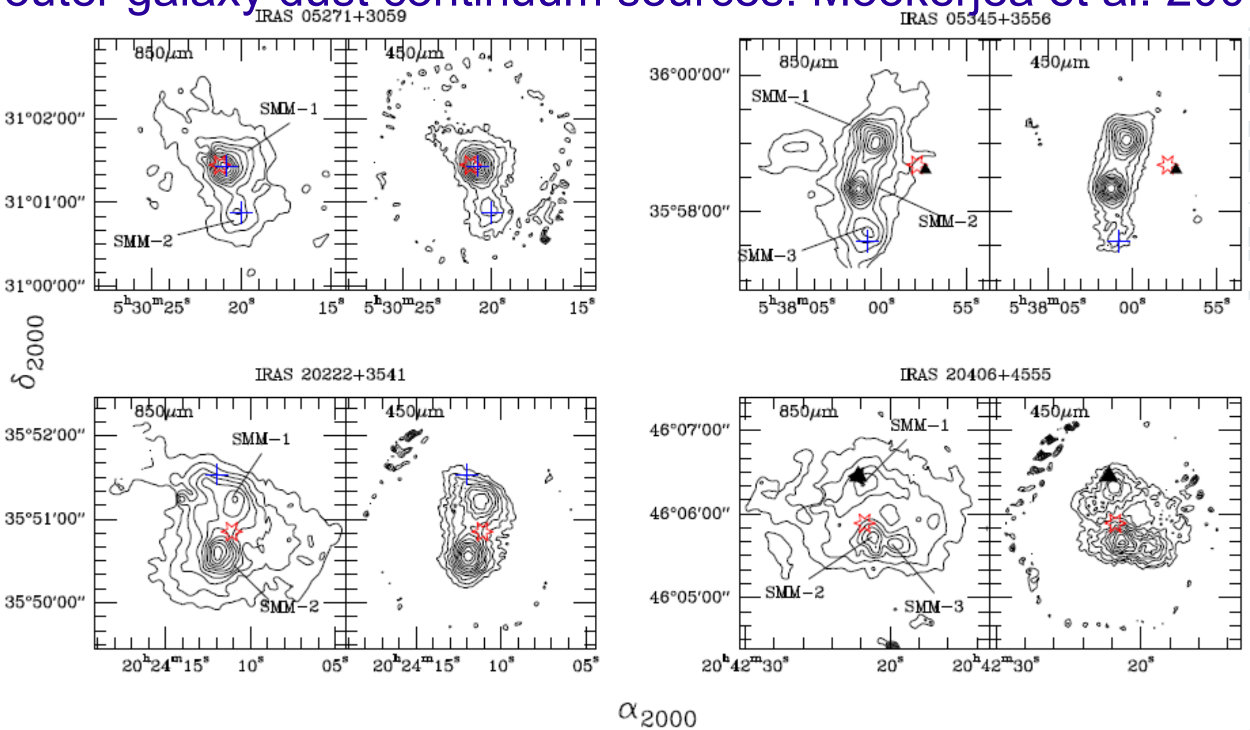
ΔT (1σ, 1hr)=40 mK with T_{rec}=240 K (810 GHz) in Δv=1 km/s

ground state lines

- [CI] 492 GHz
- HCl 626 GHz
- H_2O_2 670 GHz
- DF 651 GHz
- CH^+ 835 GHz
- HNCO 923 GHz
- H_2D+ 1370 GHz

→ Lis's talk

outer galaxy dust continuum sources: Mookerjea et al. 2007



Summary: CCAT high resolution spectroscopy

- coherent vs. incoherent detector/instrument technology: crossover resolution matches border between integrated/resolved line profiles
- better site and better surface of CCAT give a speed advantage of typically >5 @ 350 µm for CCAT vs. e.g. APEX (times the additional point-source advantage of the larger collecting area, day-time observing, wind protection due to dome)
- CCAT 25m covers a completely unexplored regime of angular resolution in perfect complement to ALMA
- many exciting and unique science areas
- science calls for a multi-color heterodyne array receiver
    - modular/interchangeable detector arrays to cover 600, 450, 350 and 200 µm
    - flexible IF processing/DFT spectrometers:
        - 4 GHz each for spatial multiplexed observations
        - very large instantaneous bandwidth for spectral surveys
    - no fundamental technology limits, but demanding complexity