ALMA CO/^{13}CO/C^{18}O Absorption
Smallest Structures in GMCs in MW

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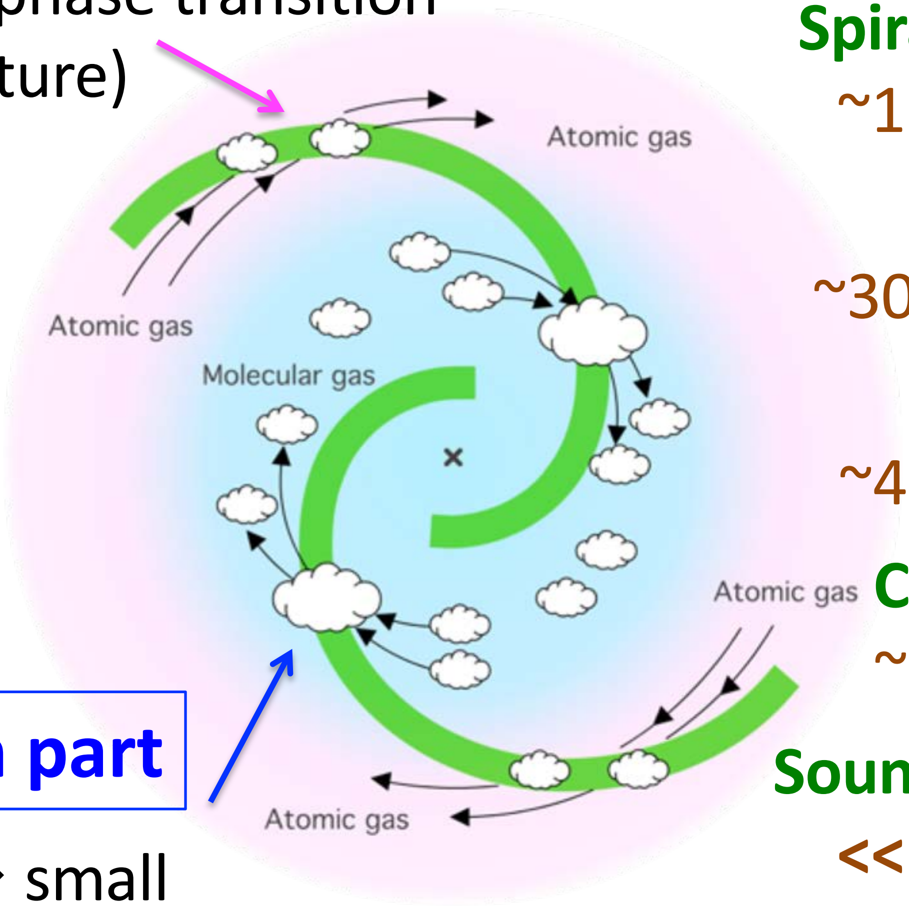
Evolution of Gas Phase in Galaxies

Outer gas-poor part

"HI → H2 → HI" phase transition
(old textbook picture)



Inner gas-rich part

Small→ large → small
molecular clouds
(not in old textbooks)

Energy cascade

Spiral arm gradients
~1kpc; ~20-30km/s

Cloud-cloud
~300pc; ~10km/s

Cloud internal
~40pc; ~4km/s

Clumps w/i cloud
~1pc; ~1km/s

Sound speed at ~10K
<<1pc; ~0.2km/s

Cloud structures at this smallest scale?

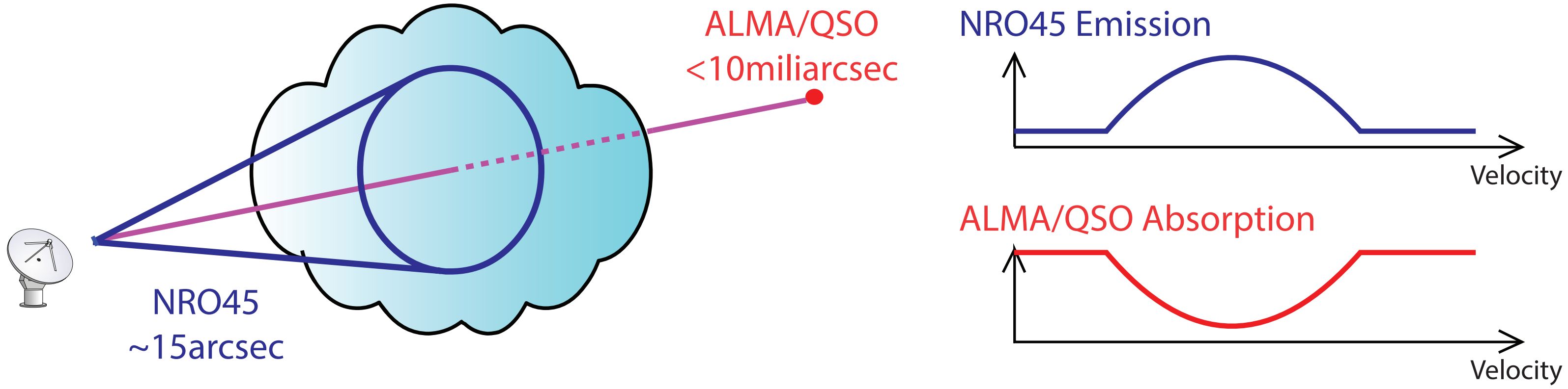
Synthesis of literature work (see Koda et al. 2009; Koda, Scoville & Heyer 2016)

Cloud Structure: Continuous or Droplets?

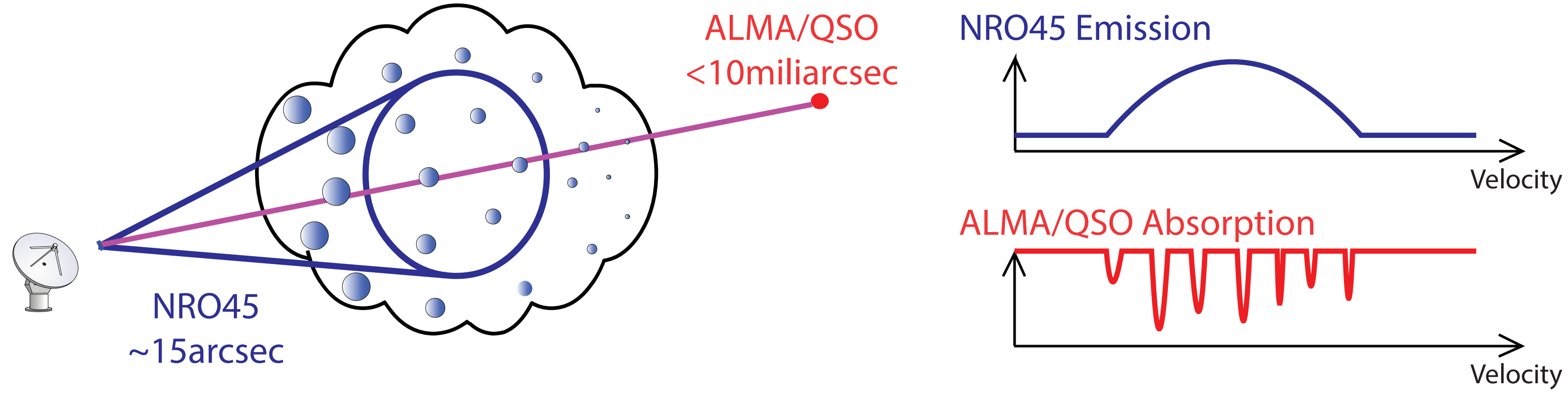
Molecular absorptions toward compact QSOs with ALMA

highest spatial & velocity resolutions

(a) Continuous medium



(b) Clumpy medium



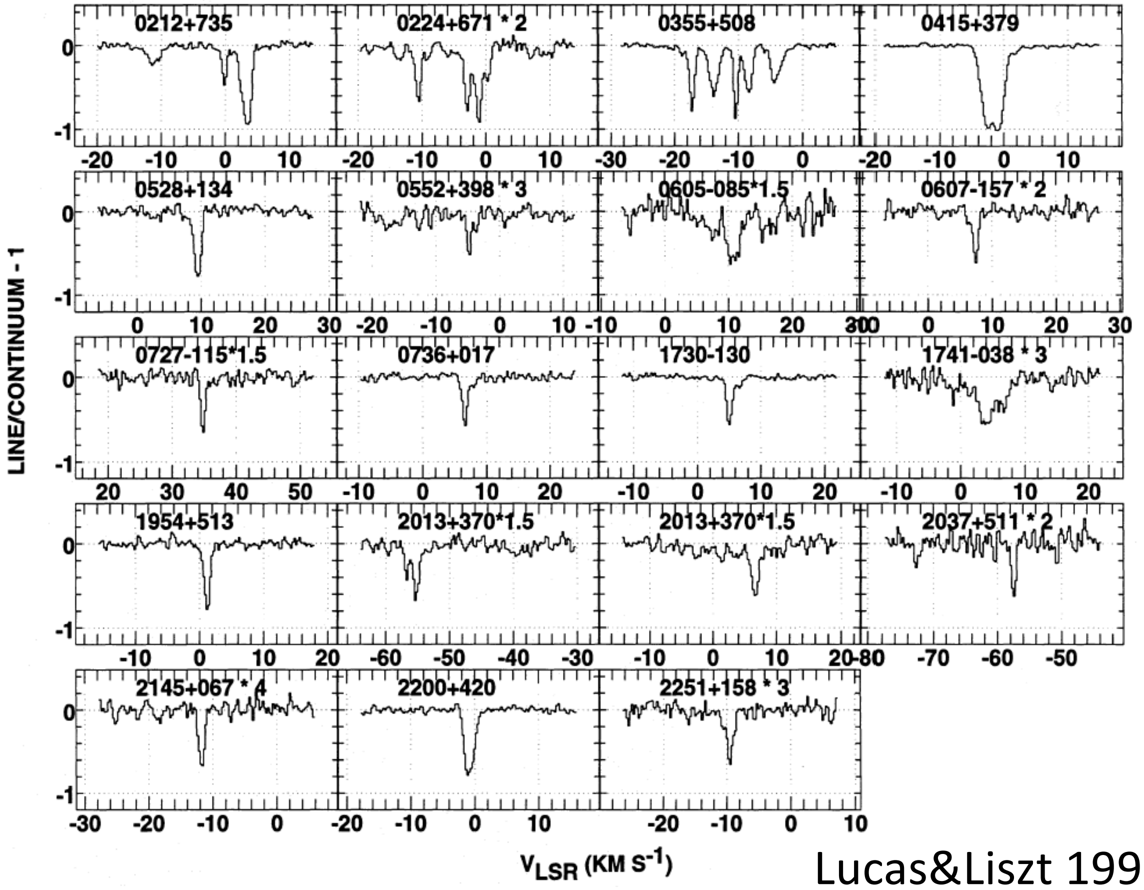
Molecular Absorption at *High* Galactic Latitude

Limited at high latitudes where bright QSOs exist

HCO+(1-0)
Absorption

Narrow line width
(dV~1km/s)

Plateau de Bure Interferometer



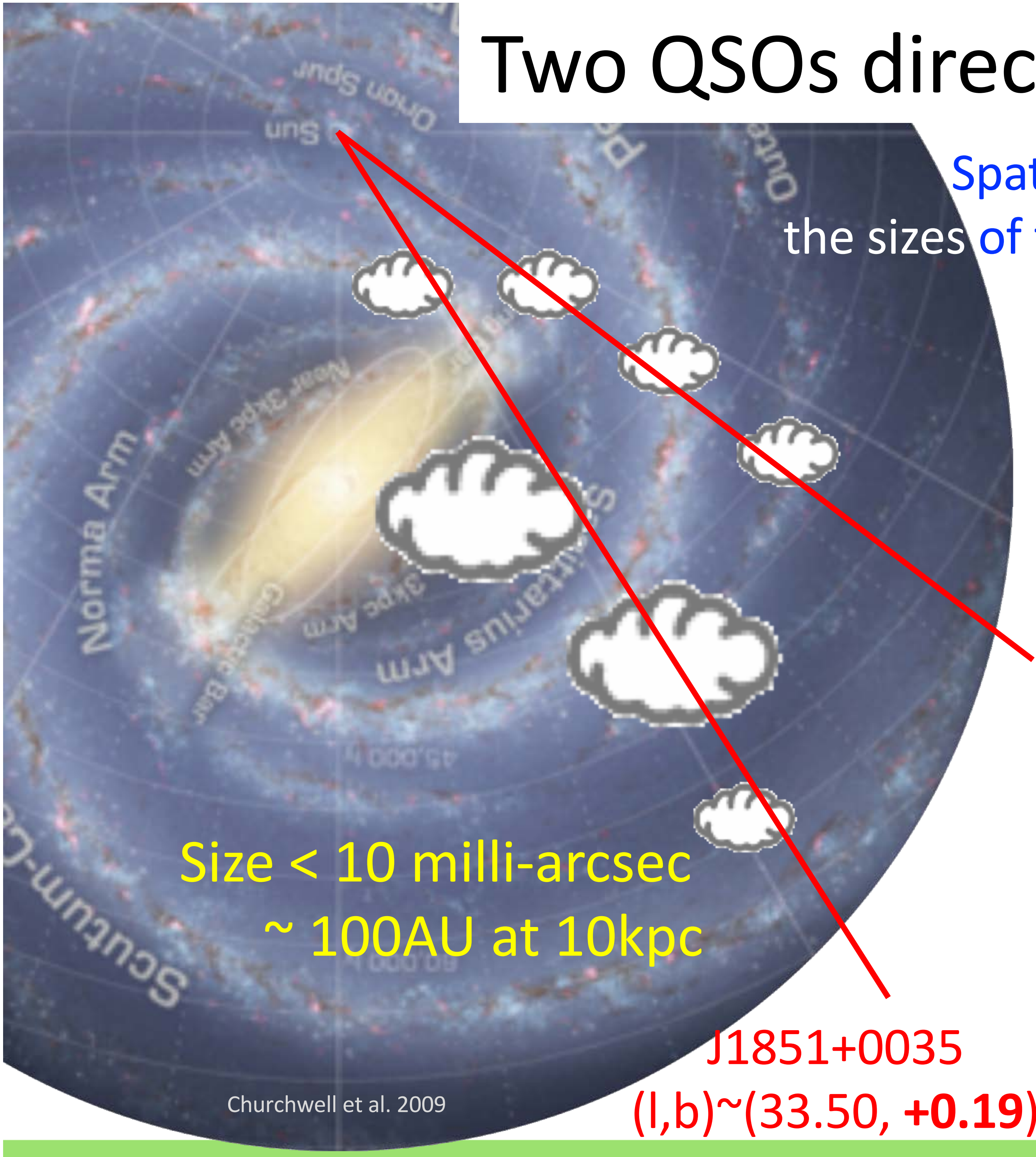
Lucas&Liszt 1996

A series of historic work by Harvey Liszt and his collaborators (1993-2018);

e.g. , Marscher et al. 1991, 1993; Moore & Marscher 1995; Wilkind & Combes 1996, 1997; Ando et al. 2016; many more

Two QSOs directly behind MW

Spatial resolution limited by
the sizes of the QSOs <10milliarcsec

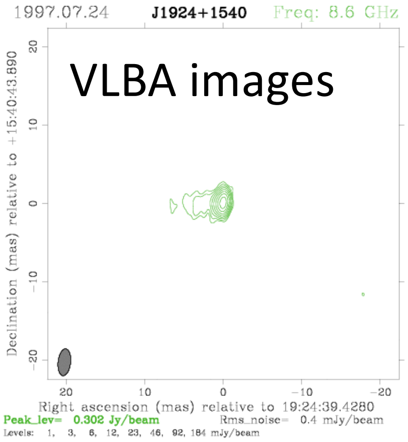


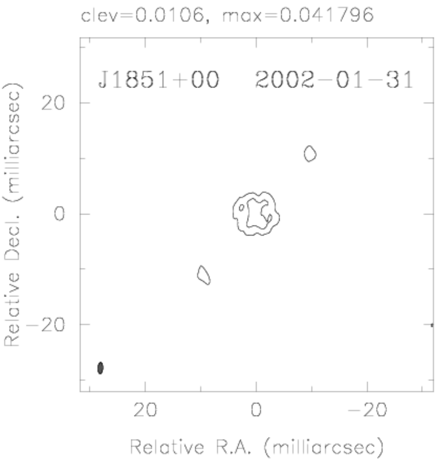
Size < 10 milli-arcsec
~ 100AU at 10kpc

Churchwell et al. 2009

J1924+1540
(l,b)~(50.63, **-0.03**)

VLBA images



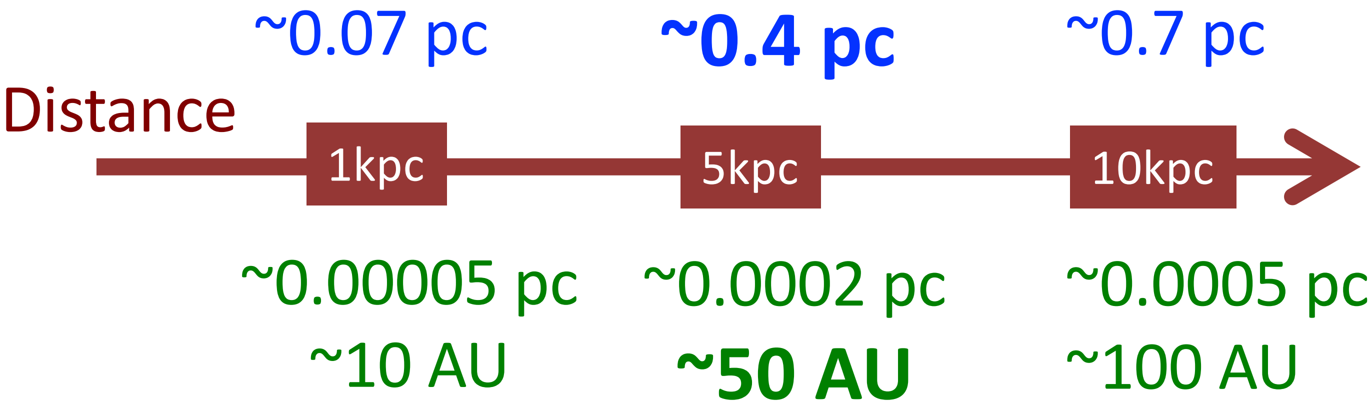


J1851+0035
(l,b)~(33.50, **+0.19**)

Observation Parameters

	Molecles	Transition	Resolution	
NRO45 Emission	CO, 13CO, C18O	J=1-0	15“	0.34 km/s
ALMA Absorption	CO, 13CO, C18O	J=1-0 & 2-1	**<10milliarcsec**	**~0.04 km/s**

Nobeyama 45m telescope (NRO45): **~15 arcsec beam**



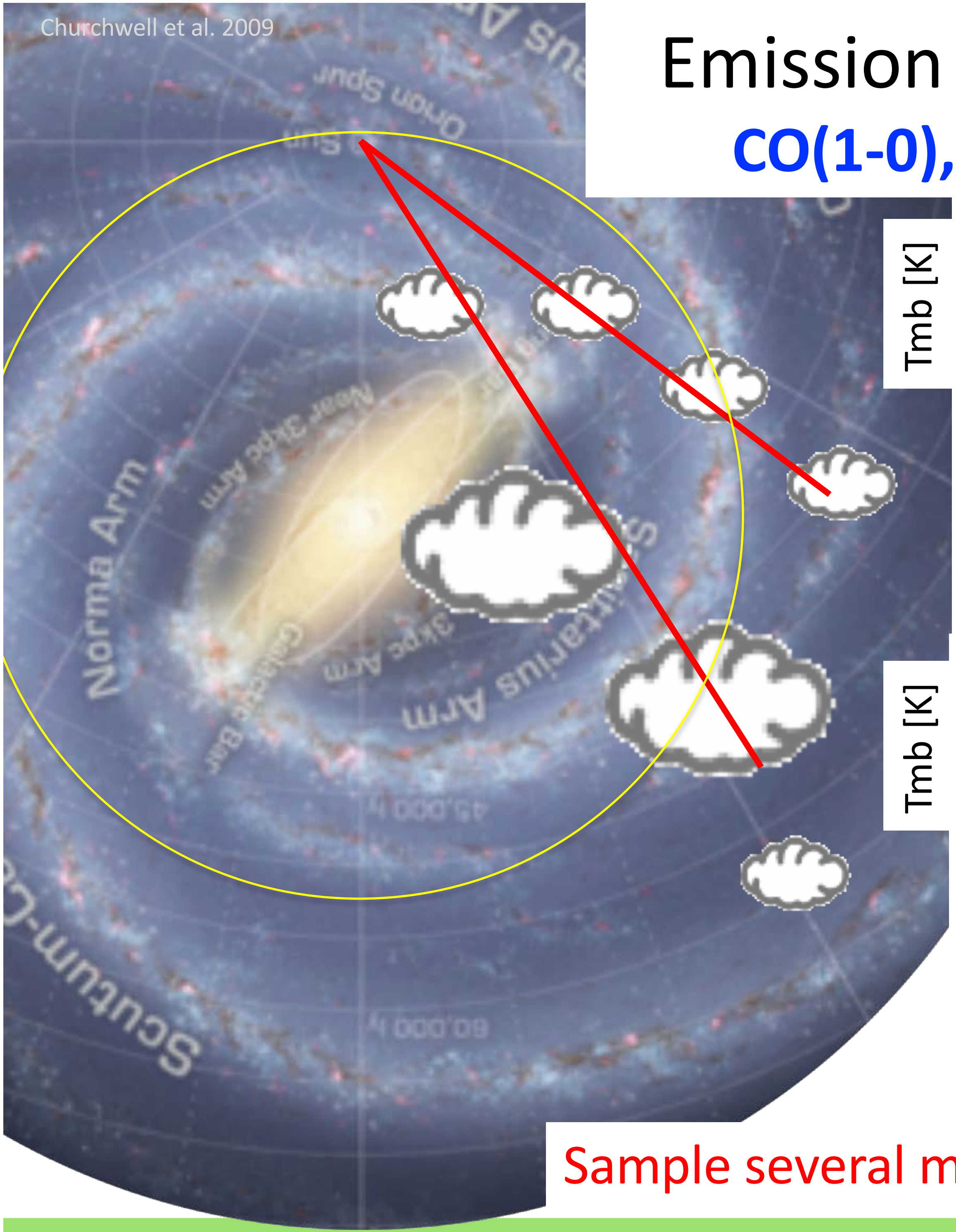
ALMA+QSO: **<~ 10 mili-arcsec**

Velocity Resolution **Resolve sound speed of ~10K gas (~0.2km/s)**

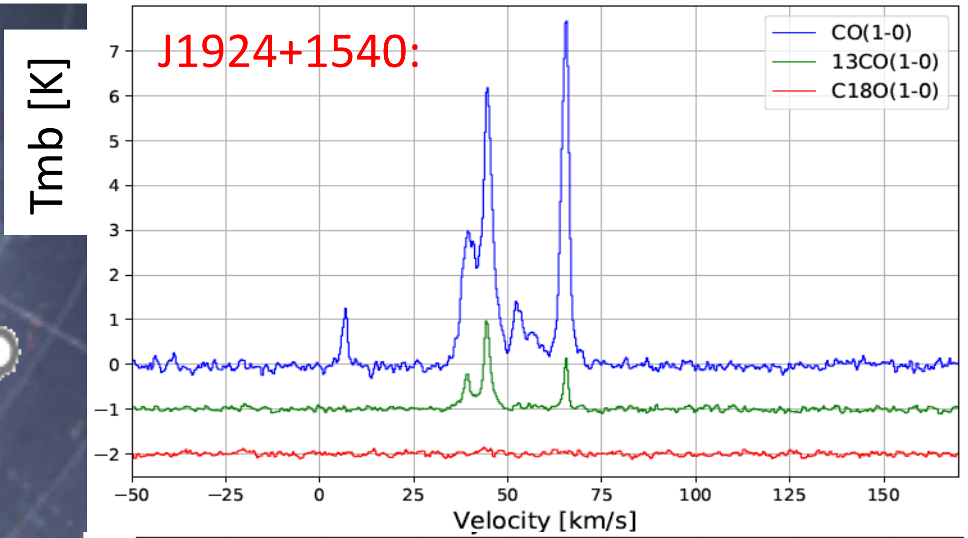
Spatial Resolution **Trace ~10-100 AU scale structures**

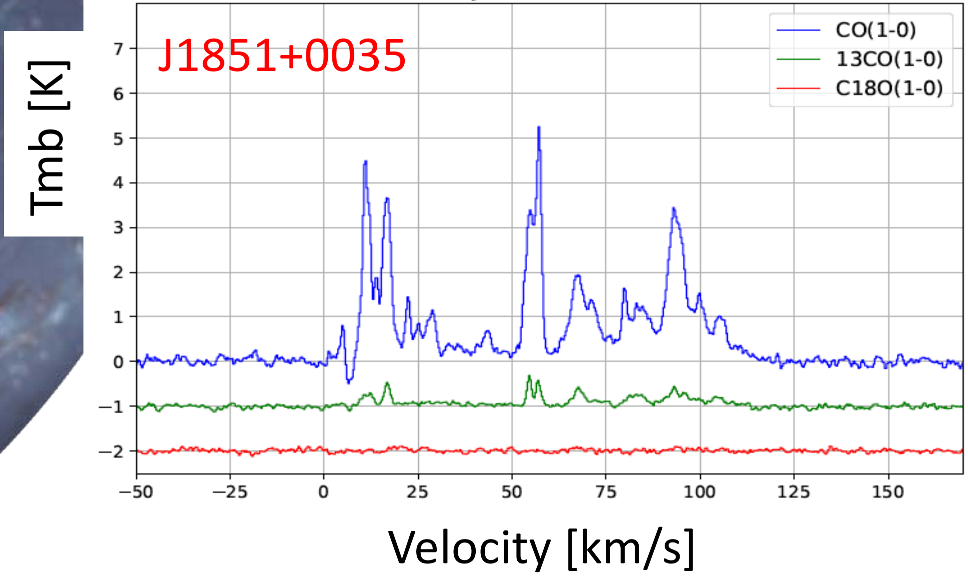
Emission Profiles from NRO45

CO(1-0), 13CO(1-0), C18O(1-0)



Churchwell et al. 2009





Sample several molecular clouds along velocity

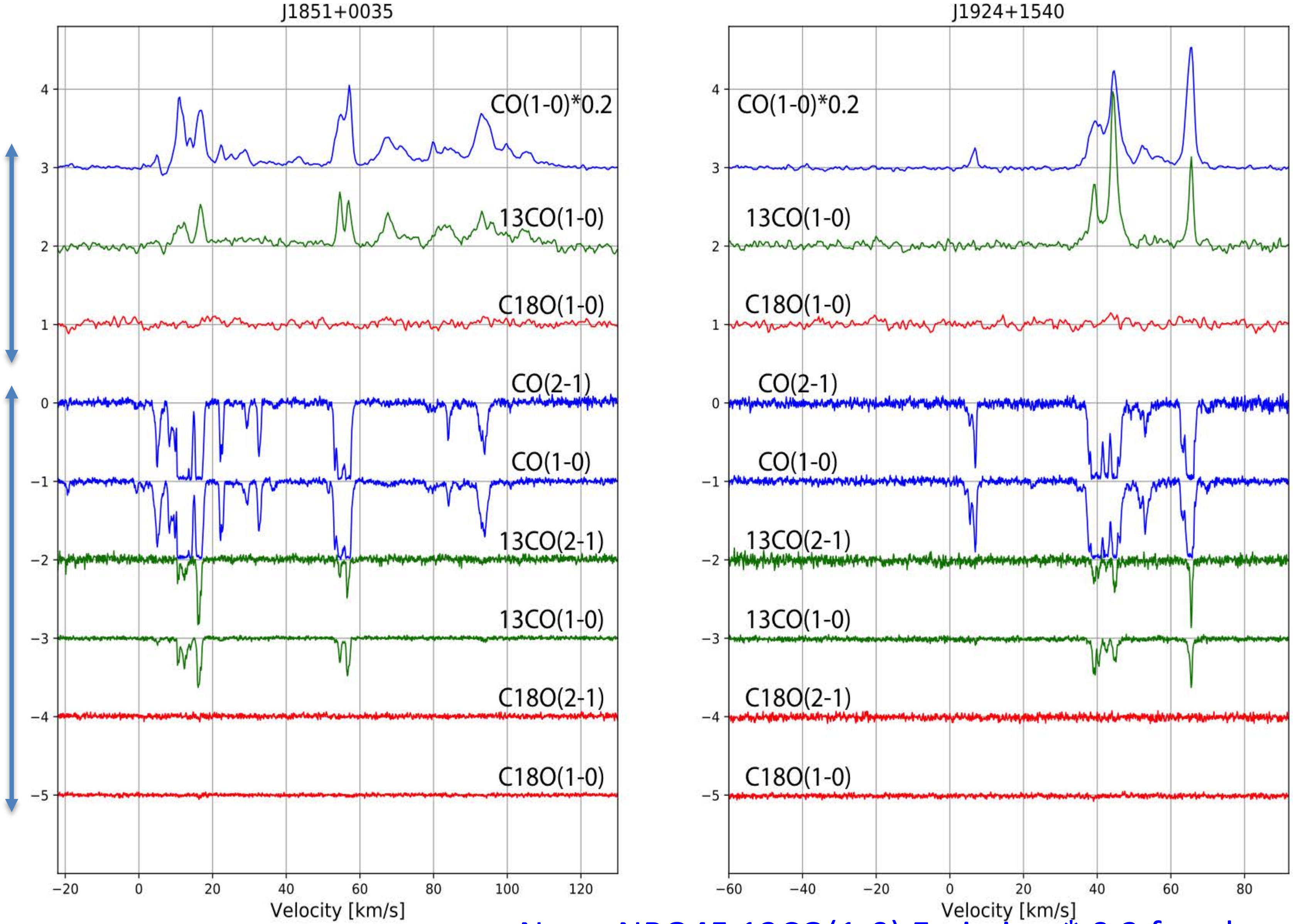
NRO45 Emission & ALMA Absorption

Emission
(NRO45)
~15arcsec

T_{mb} [K]

Absorption
(ALMA)
<~10mas

Exp(-τ)

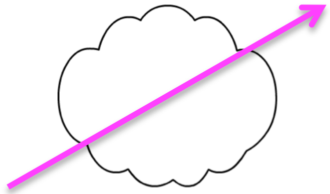


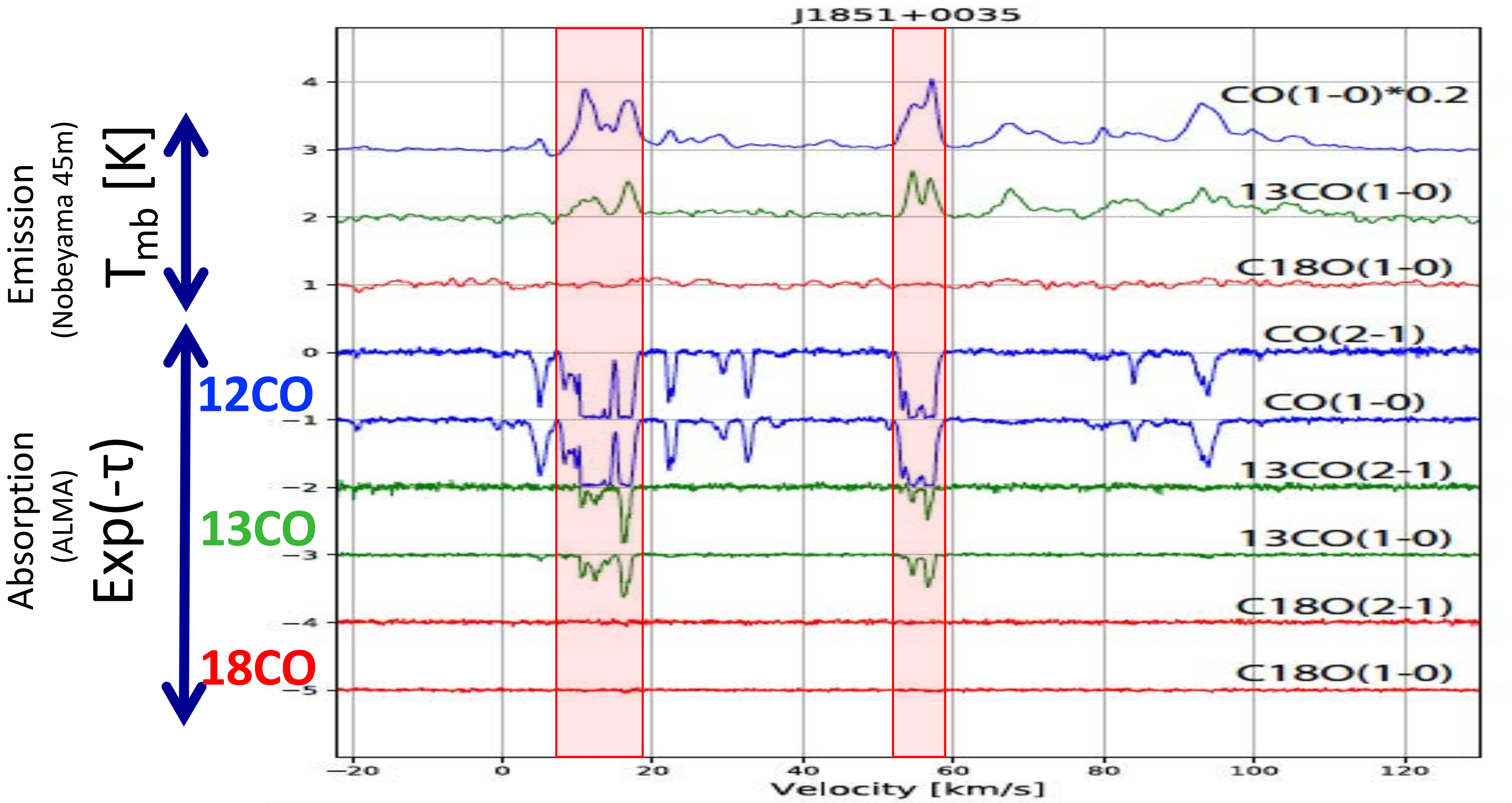
Note: NRO45 12CO(1-0) Emission * 0.2 for plots

Case A: $\tau_{12CO(1-0)}$>>1

Case	$\tau_{12CO(1-0)}$	13CO Absorption	12CO&13CO Emission
A	>>1	Present	Present

Heart of cloud?

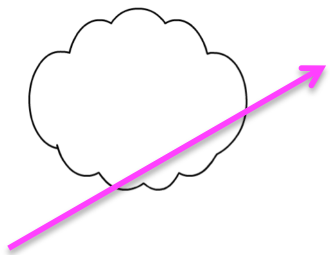


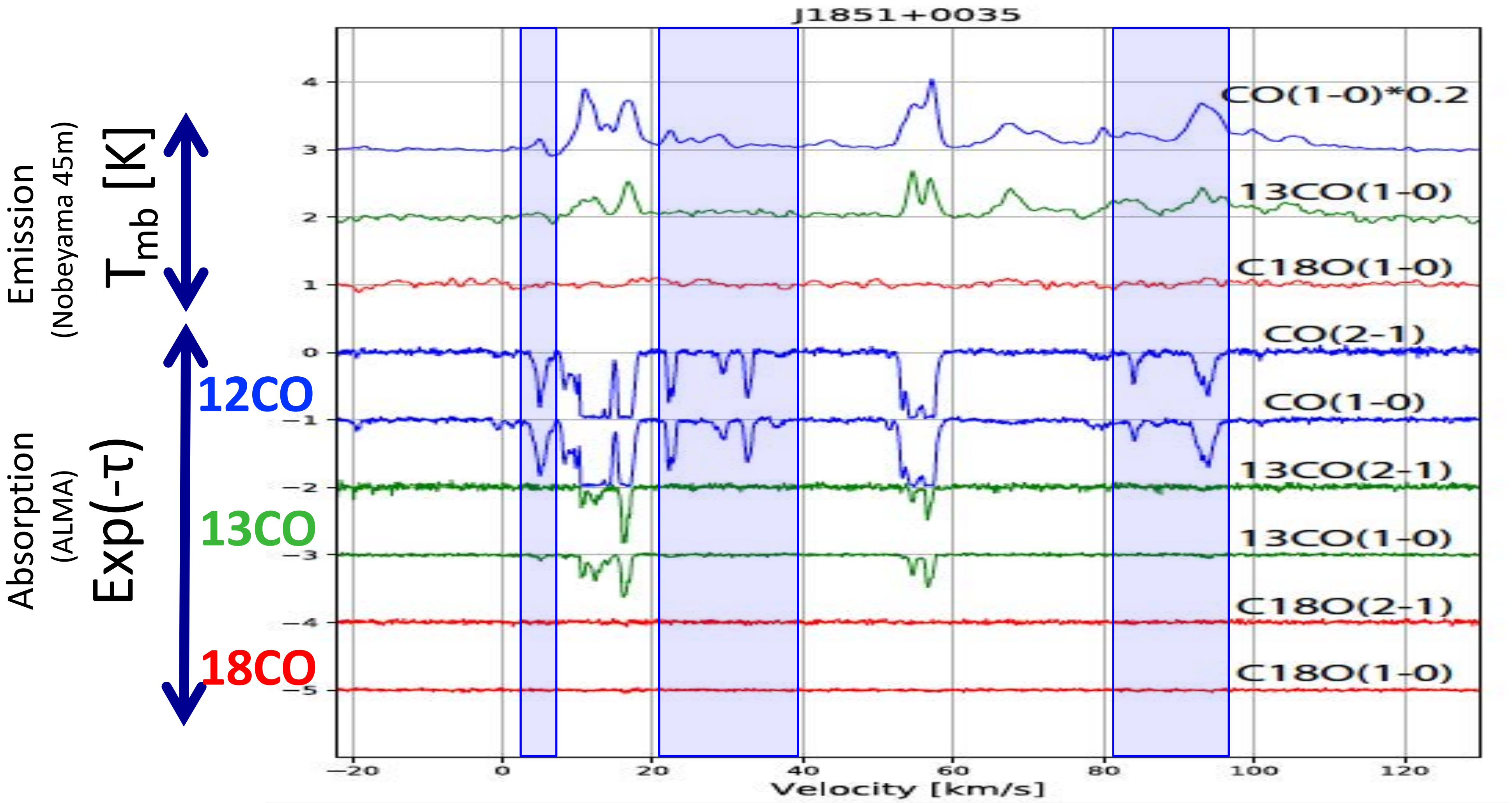


Case B: $\tau_{12CO(1-0)}$~1

Case	$\tau_{12CO(1-0)}$	13CO Absorption	12CO&13CO Emission
B	~1	Absent	Present

Cloud edge?

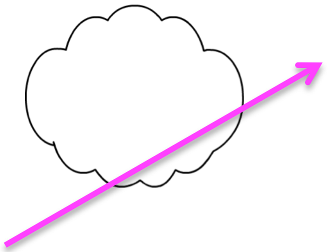


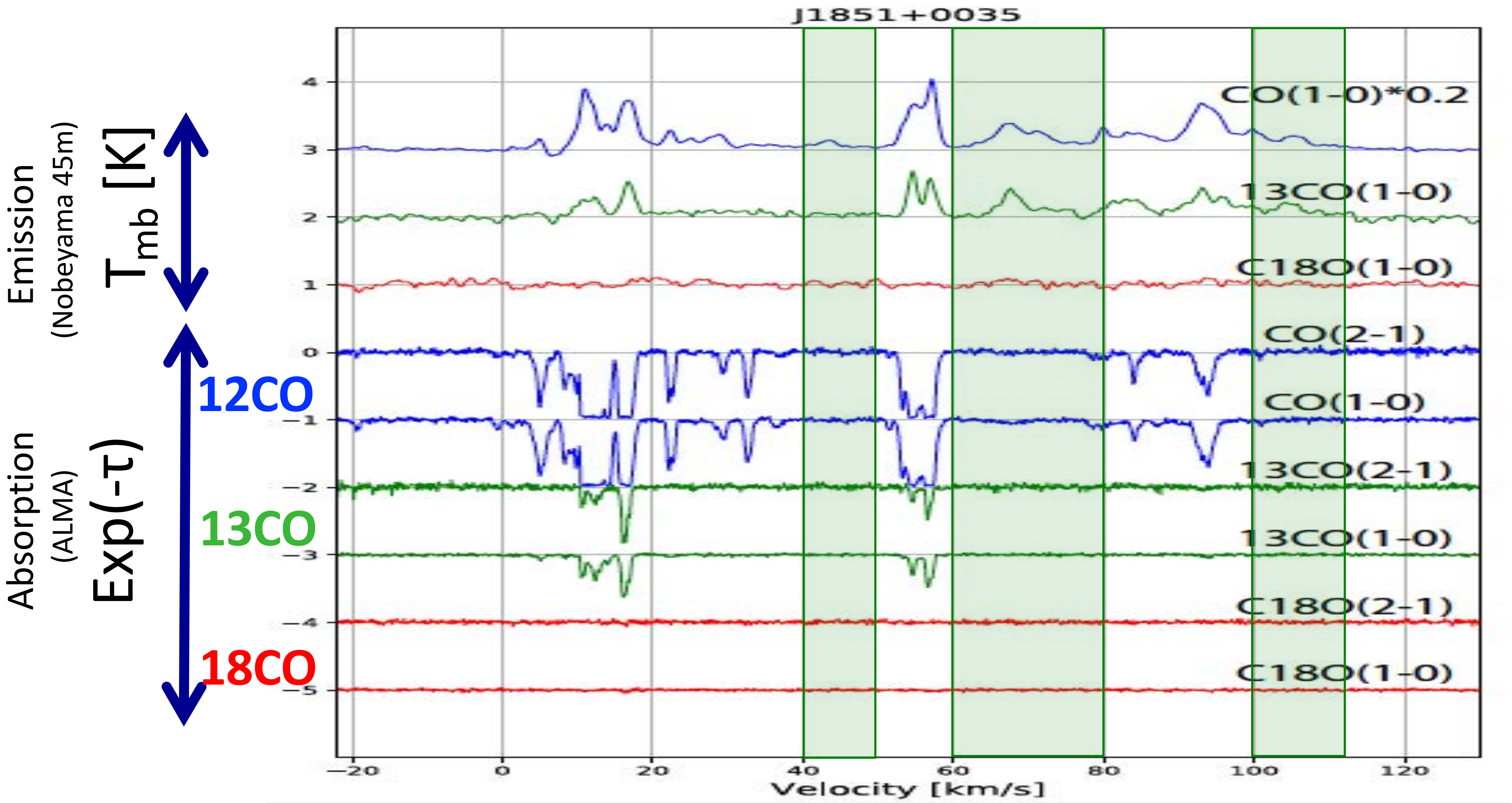


Case C: $\tau_{12CO(1-0)}$~0

Case	$\tau_{12CO(1-0)}$	13CO Absorption	12CO&13CO Emission
C	~0	Absent	Present

Cloud edge?



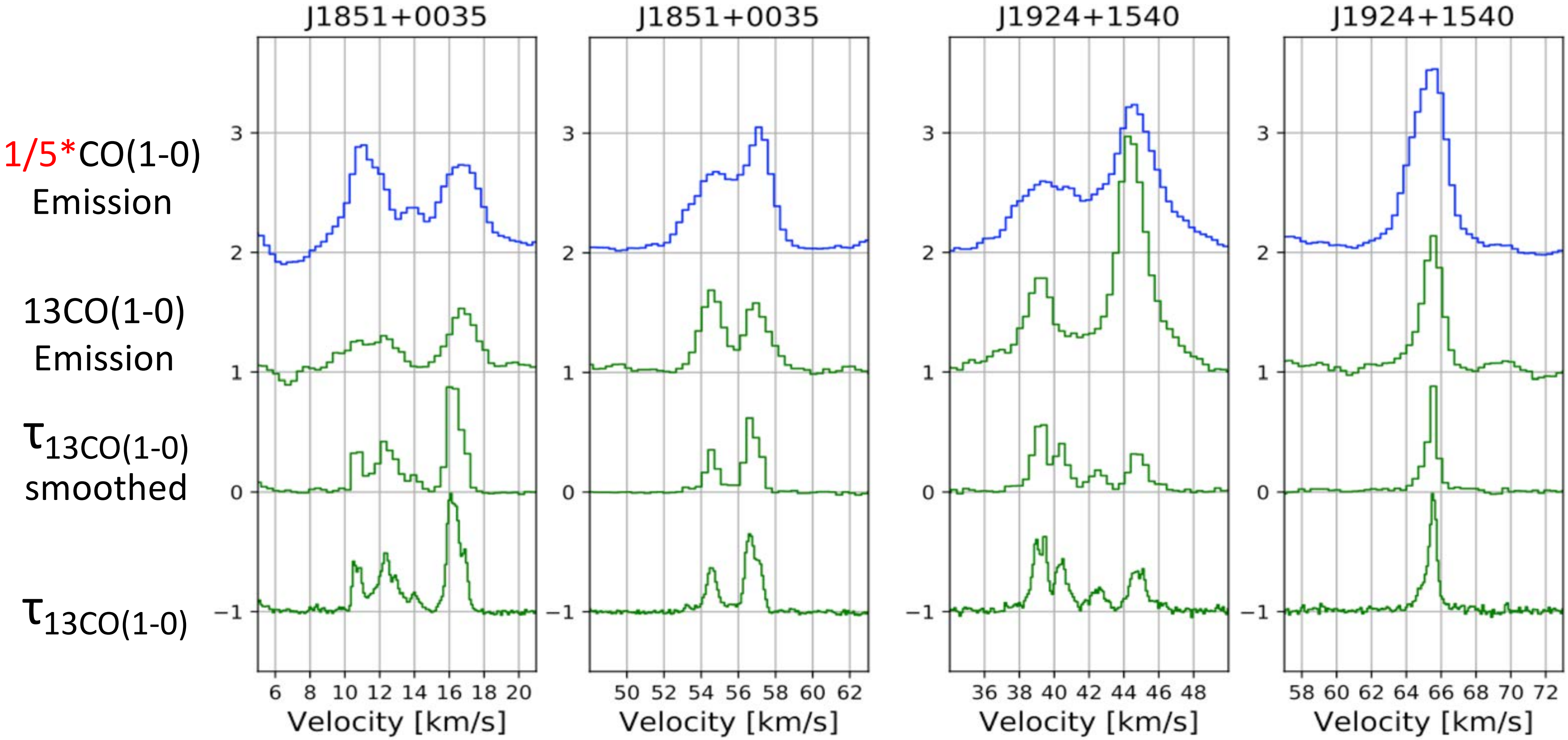


Case A: $\tau_{CO(1-0)}$>>1

CO Saturated, but Multiple Droplets in 13CO

13CO emission & τ_{13CO} profiles different→ Spatial variations w/i NRO45 beam

CO saturated ($\tau_{12CO(1-0)}$>>1) → molecular gas between droplets as well

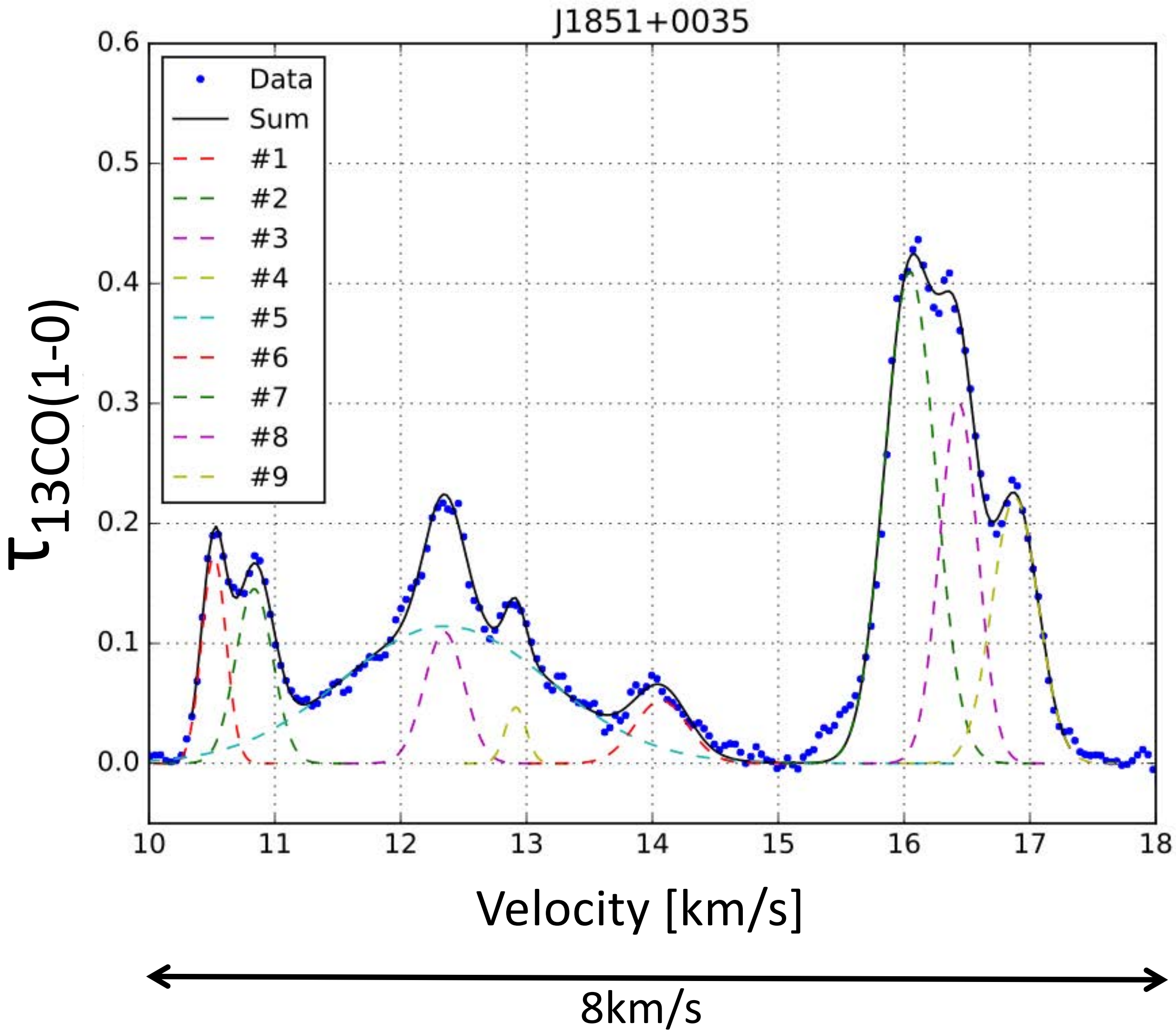


Case A: $\tau_{CO(1-0)}$>>1

Multi-component Gaussian Fit

Velocity dispersion ~ Sound speed

→ Droplets supported ***by thermal pressure***, not by turbulent pressure



	τ0	v0 [km/s]	dv [km/s]
# 1	0.17	10.52	0.10
# 2	0.15	10.84	0.15
# 3	0.11	12.35	0.16
# 4	0.05	12.91	0.08
# 5	0.11	12.35	0.82
# 6	0.05	14.07	0.21
# 7	0.41	16.05	0.20
# 8	0.30	16.43	0.15
# 9	0.22	16.88	0.18

Native ~0.04km/s resolution

Excitation Temperature (T_{ex}) from τ_{21}/τ_{10}

The uncertainty of beam filling factor is NOT a problem.

10-100 AU resolution justifies **One-zone** approx. & **LTE** assumption

Absorption Coefficient

$$\alpha_{\nu_{J+1,J}}\, d\nu_{J+1,J} = \frac{h\nu_{J+1,J}}{4\pi}\left(n_J B_{J,J+1} - n_{J+1} B_{J+1,J}\right) \overset{\substack{\textbf{LTE}\\ \downarrow}}{=} \frac{c^2}{8\pi\nu_{J+1,J}^{2}}\,\underline{n_J}\,\frac{g_{J+1}}{g_J}A_{J+1,J}\left[1-\exp\left(-\frac{h\nu_{J+1,J}}{k\underline{T_{ex}}}\right)\right]$$

$$\frac{\tau_{21}}{\tau_{10}} = \frac{\int \alpha_{21}\, ds}{\int \alpha_{10}\, ds} \longrightarrow \boxed{\frac{\tau_{21}}{\tau_{10}} = 2\exp\left(-\frac{h\nu_{10}/k}{T_{ex}}\right)\left[1+\exp\left(-\frac{h\nu_{10}/k}{T_{ex}}\right)\right]}$$

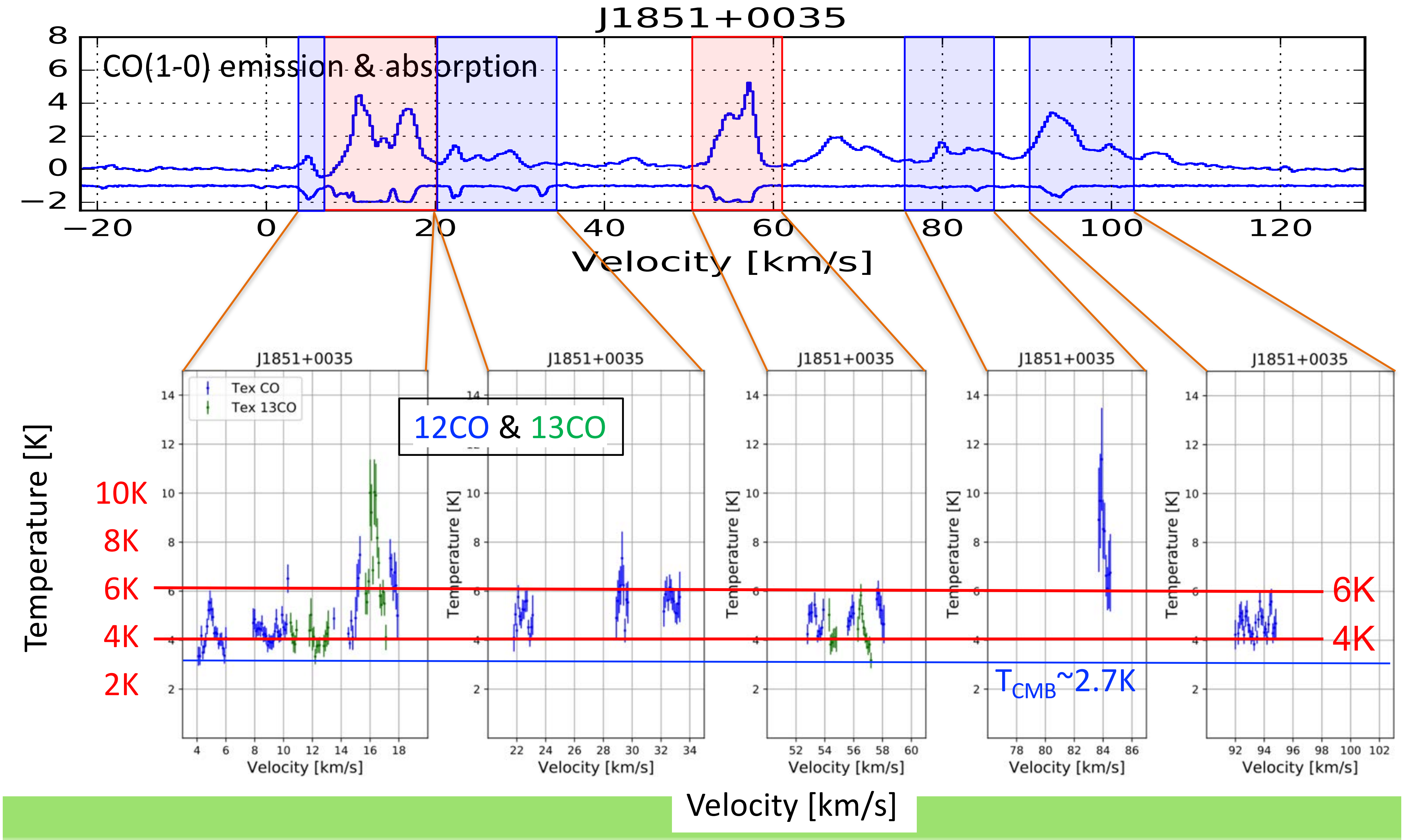
$$\boxed{\begin{gathered} A_{J+1,J} \propto \nu_{J+1,J}^{3}\frac{J+1}{g_{J+1}} \\ g_J = 2J+1 \\ \frac{n_{J+1}}{n_J} = \frac{g_{J+1}}{g_J}\exp\left[-\frac{h\nu_{J+1,J}}{kT_{ex}}\right] \end{gathered}}$$

$$\longrightarrow \boxed{T_{ex} = \frac{-h\nu_{10}/k}{\ln\left[\left(\sqrt{2\tau_{21}/\tau_{10}+1}-1\right)/2\right]}}$$

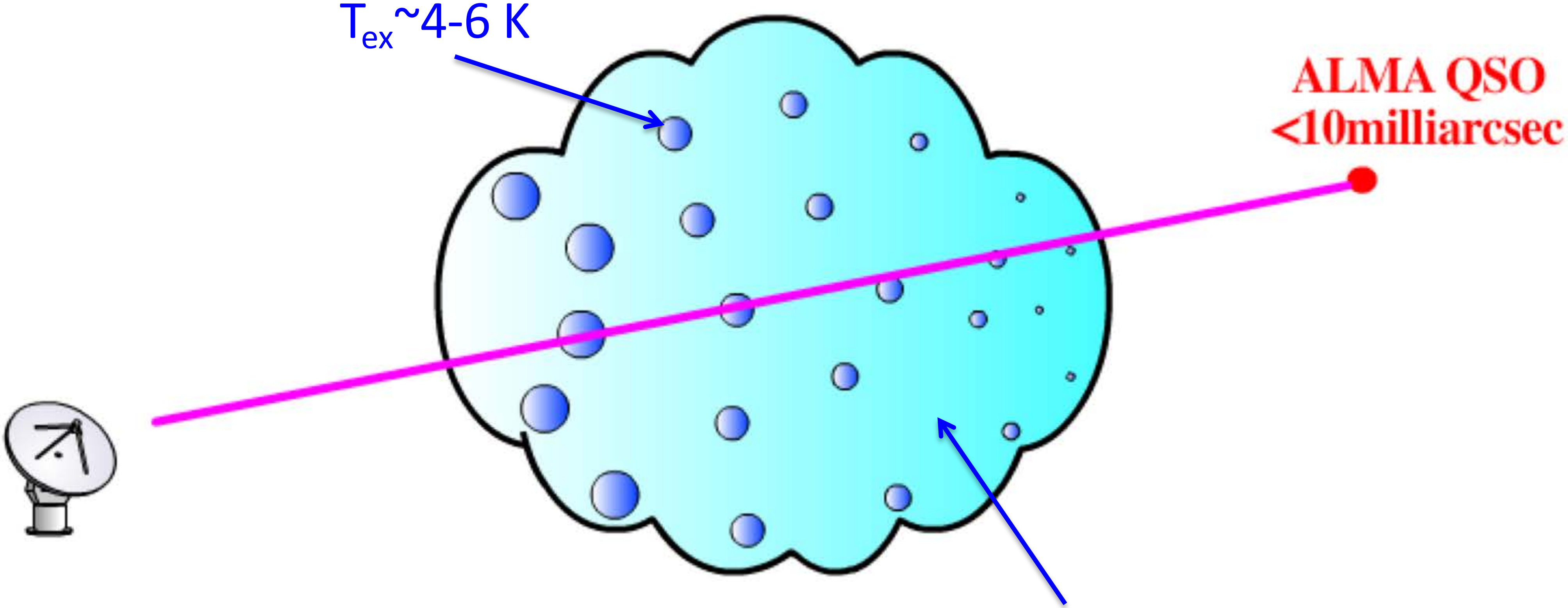
Case A: $\tau_{CO(1-0)}>>1$ **Case B: $\tau_{CO(1-0)}\sim1$**

Excitation Temperature from Absorption

Temperature ~4-6K – colder than typically assumed ~10-15K



Case A: $\tau_{CO(1-0)} >> 1$



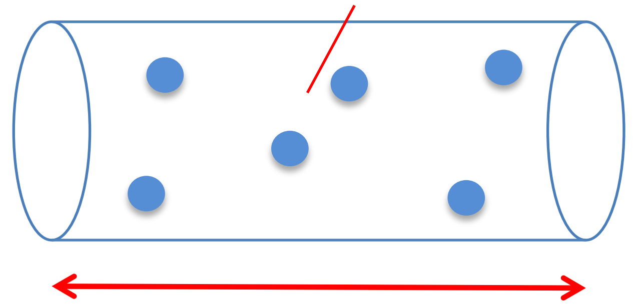
Sound-speed droplets seen
in 13CO absorption
T_{ex}~4-6 K

Extended component
between droplets see in 12CO

An idea – comment welcome!

Size of Droplet: From Observed Numbers

Single-dish beam

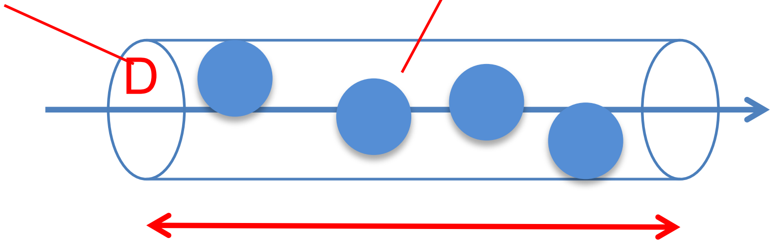


N_{emi} = # of droplets in emission in this volume

Single-dish beam area $=\pi b^2$

l = depth of molecular cloud

Absorption measurements



diameter of droplet

D

N_{abs} = # of droplets in absorption

l = depth of molecular cloud

Droplet density

$$n_{droplet} = \frac{N_{emi}}{\pi b^2 l}$$

# of droplets in absorption

$$N_{abs} = \left(\pi D^2 l\right) n_{droplet}$$

➡ $$D = \left(\frac{N_{abs}}{(\pi l) n_{droplet}}\right)^{1/2} = b\left(\frac{N_{abs}}{N_{emi}}\right)^{1/2}$$

➡ *Size of droplet:* $R_d = D/2 \approx 0.03\ \text{pc}$

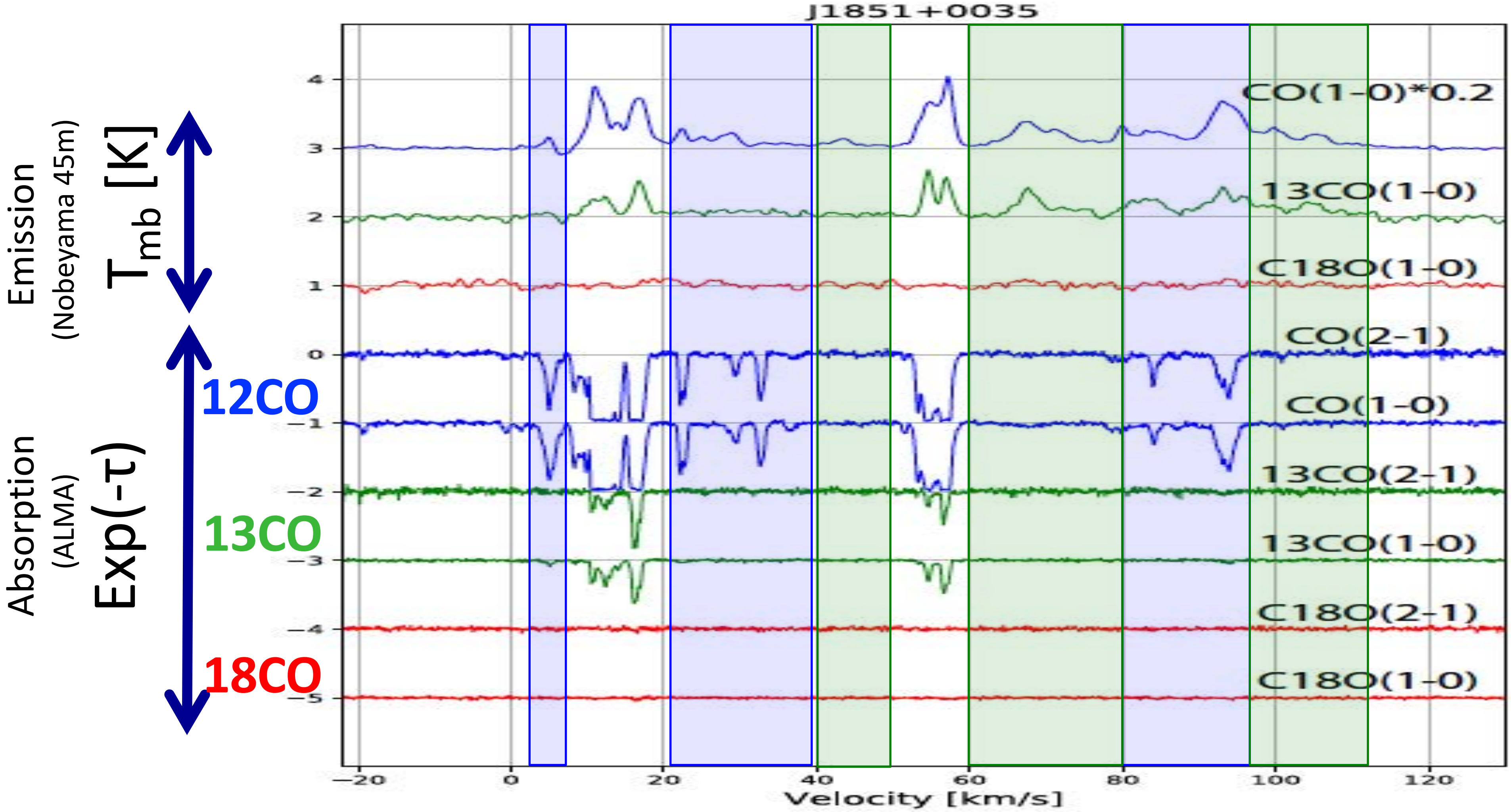
N_{abs}/N_{emi}~1/10 –because absorption lumpy, emission smooth.

b = 0.2pc – our fiducial NRO45 beam size at 5kpc

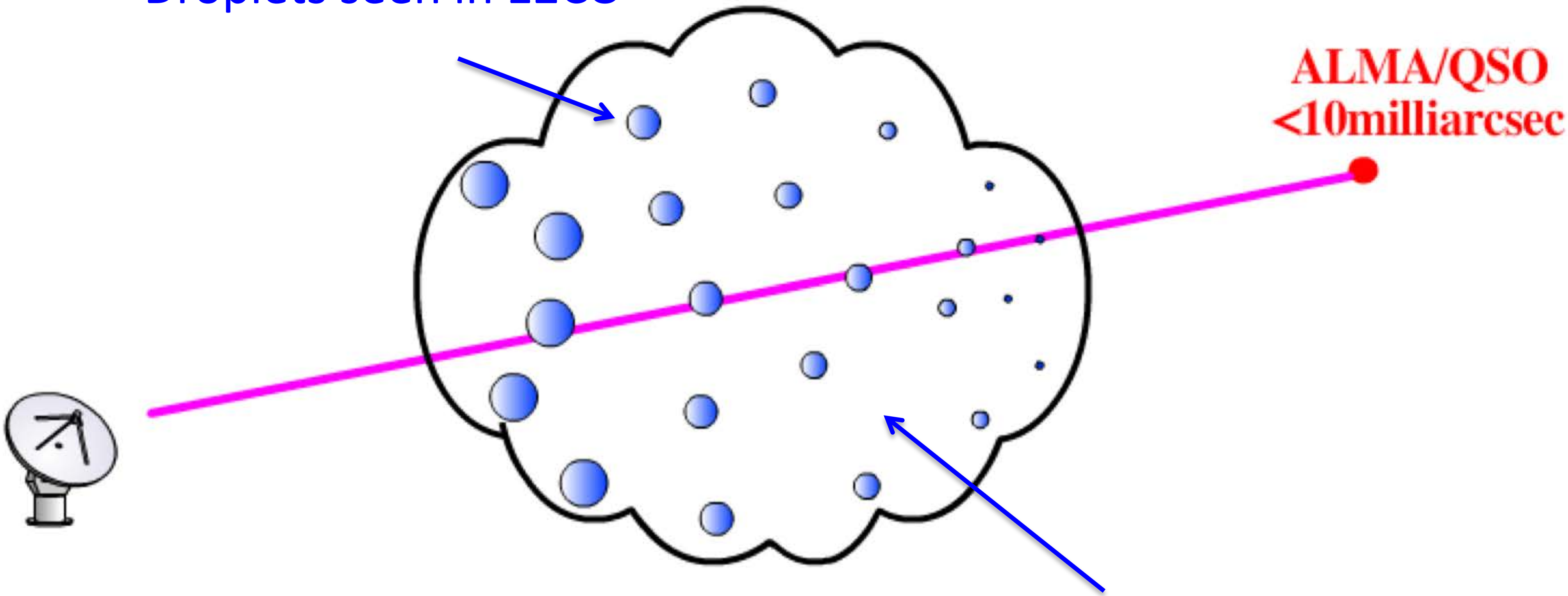
Case B: $\tau_{12CO(1-0)}$~1, Case C: $\tau_{12CO(1-0)}$~0

Similar analysis

→Droplets exist in CO absorption; ambient gas at very low level



Case B ($\tau_{12CO(2-1)}$~1) & Case C (~0)

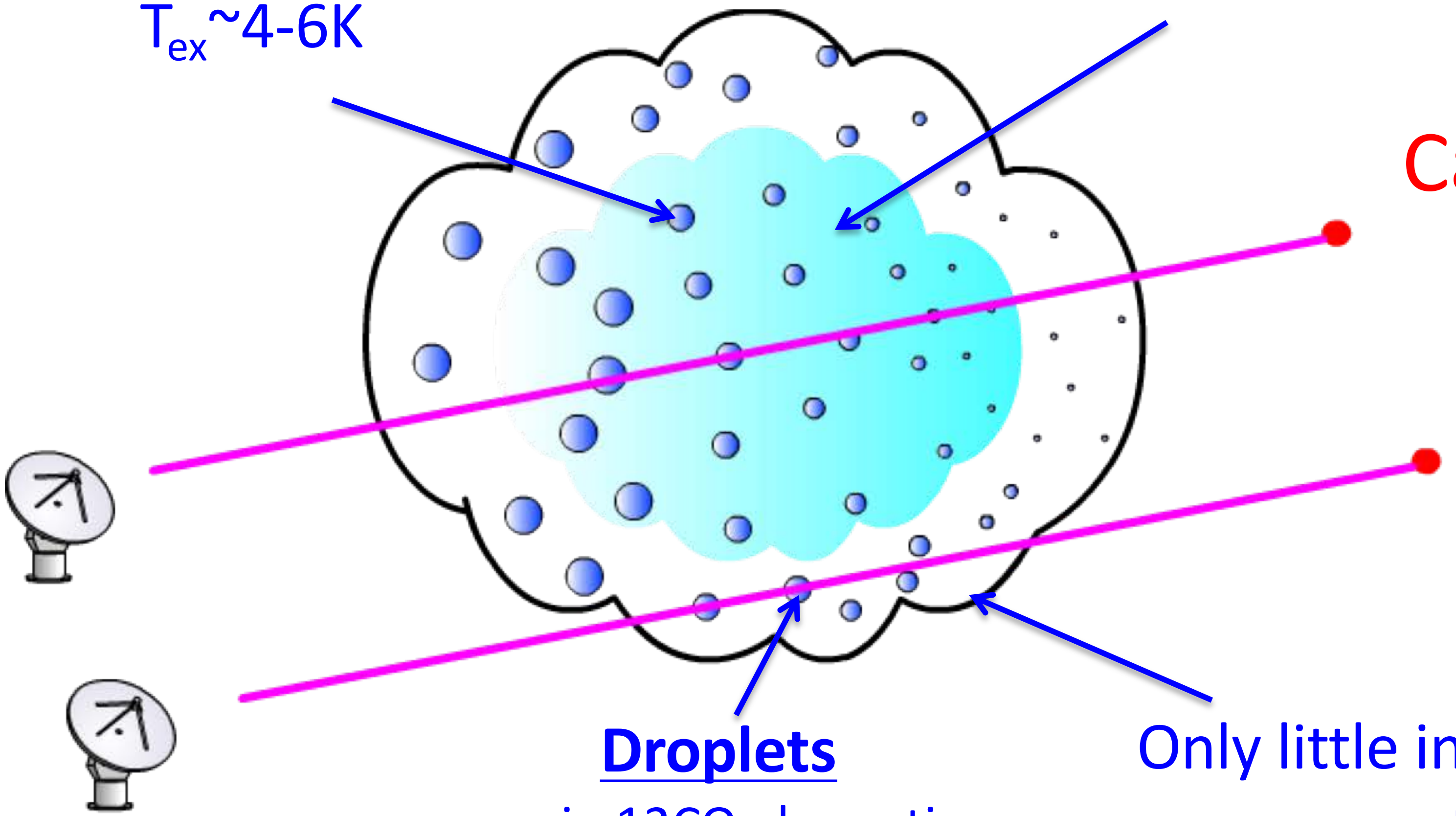


Droplets seen in 12CO

Only little inter-droplet
gas near the edge

Synthesis as Summary

Geometry could be spheres (droplets), filaments, or sheets



Sound-speed droplets

seen in 13CO absorption

T_{ex}~4-6K

Extended gas between droplets

seen in 12CO absorption

Case A

Case B

Case C

Droplets

seen in 12CO absorption

Only little inter-droplet gas near the edge

Random parts of GMCs, not the areas around SF parts