Mid-J CO Diagnostics of Turbulent Dissipation in Molecular Clouds

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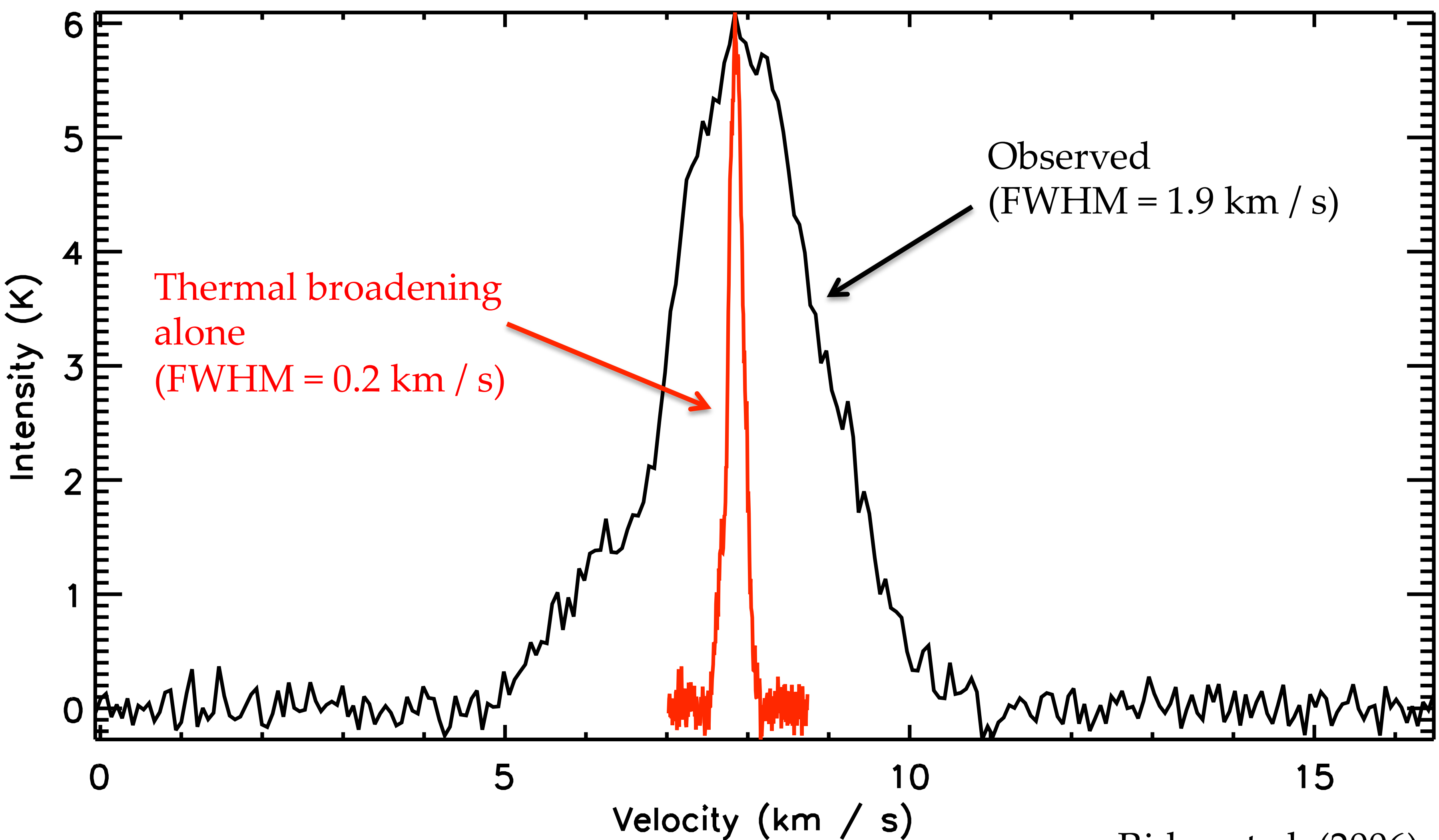
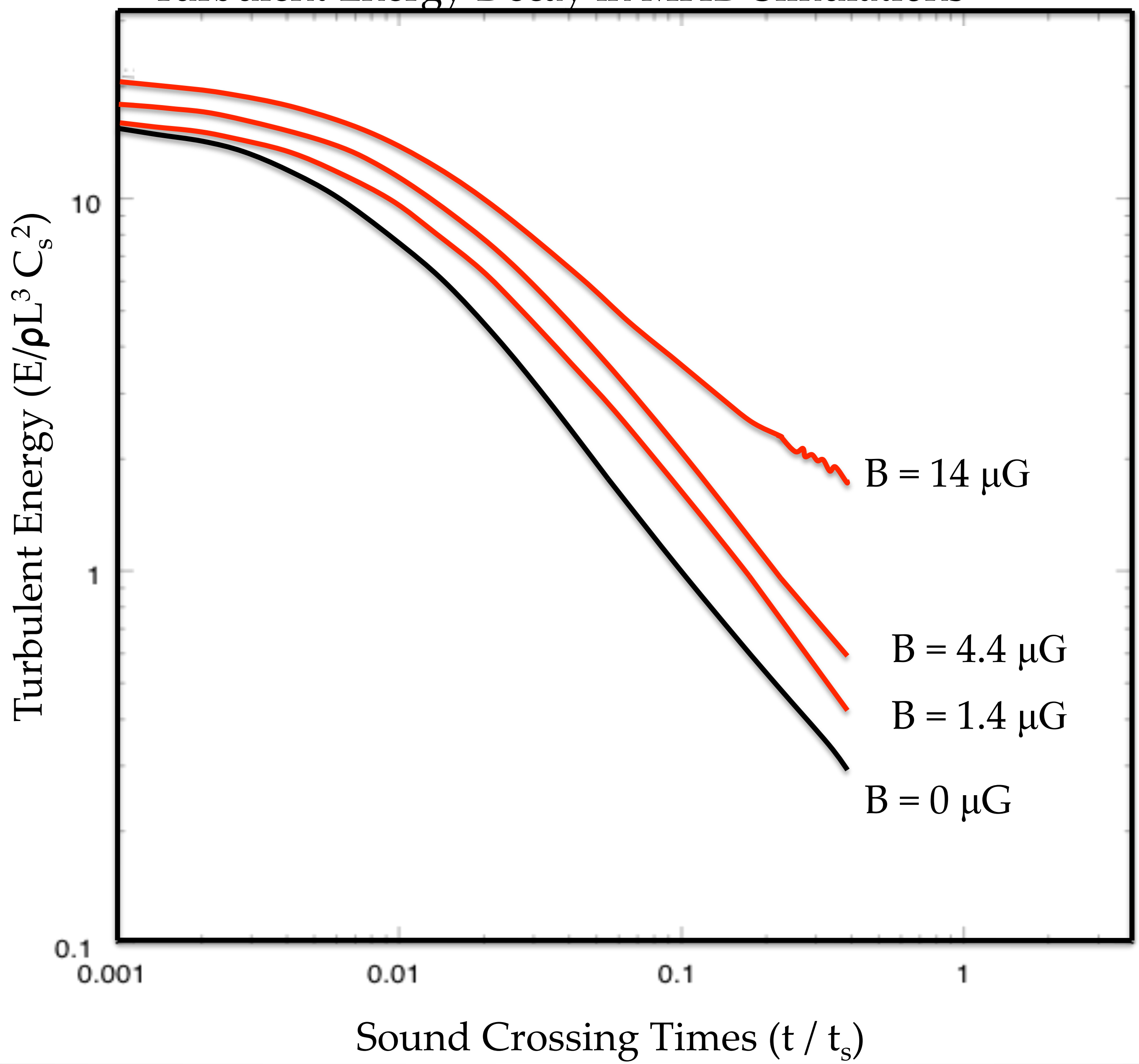
GMCs Contain Supersonic Turbulence

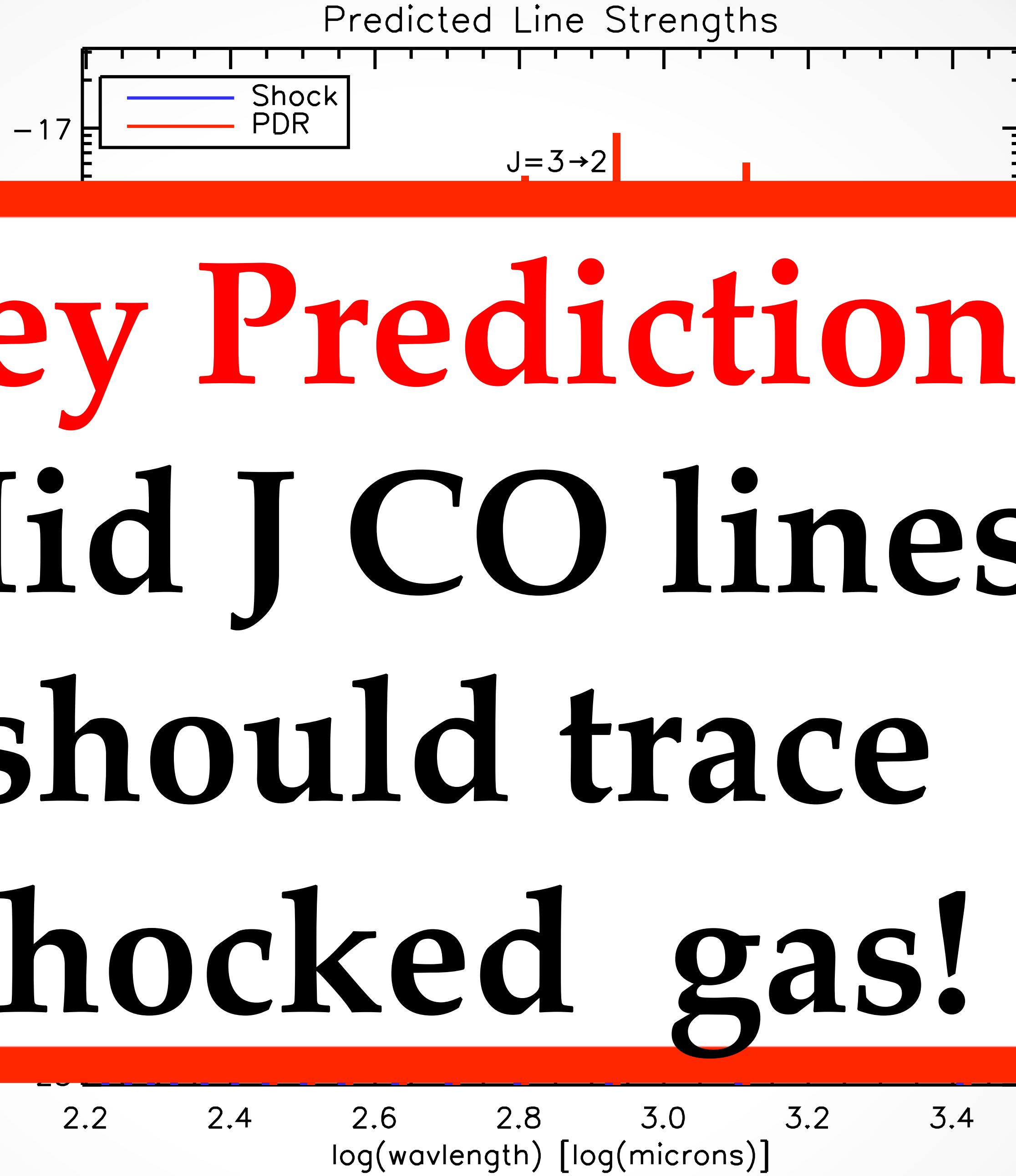


Ridge et al. (2006)

Turbulent Energy Decay in MHD Simulations

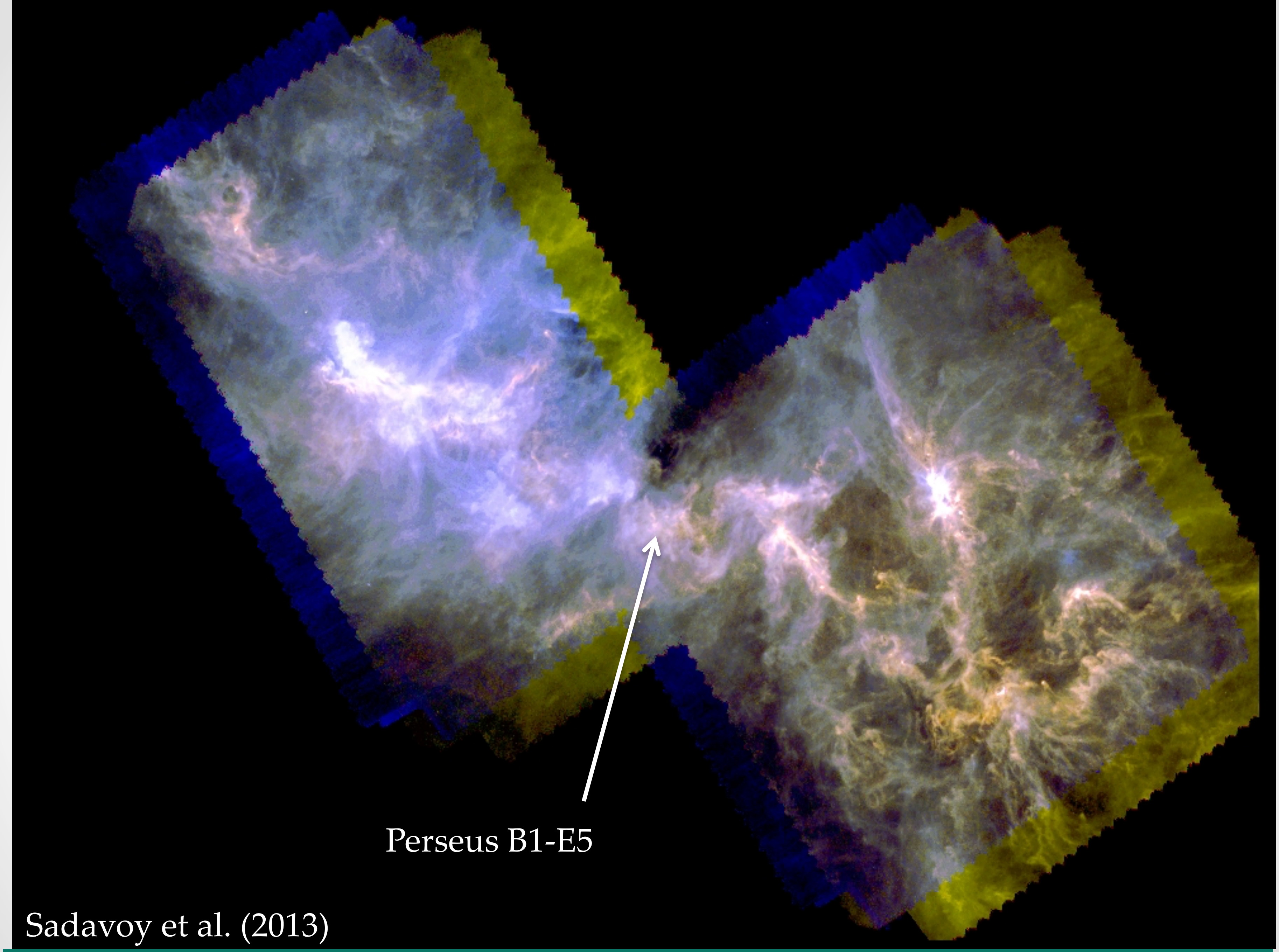


Stone et al. (1998)

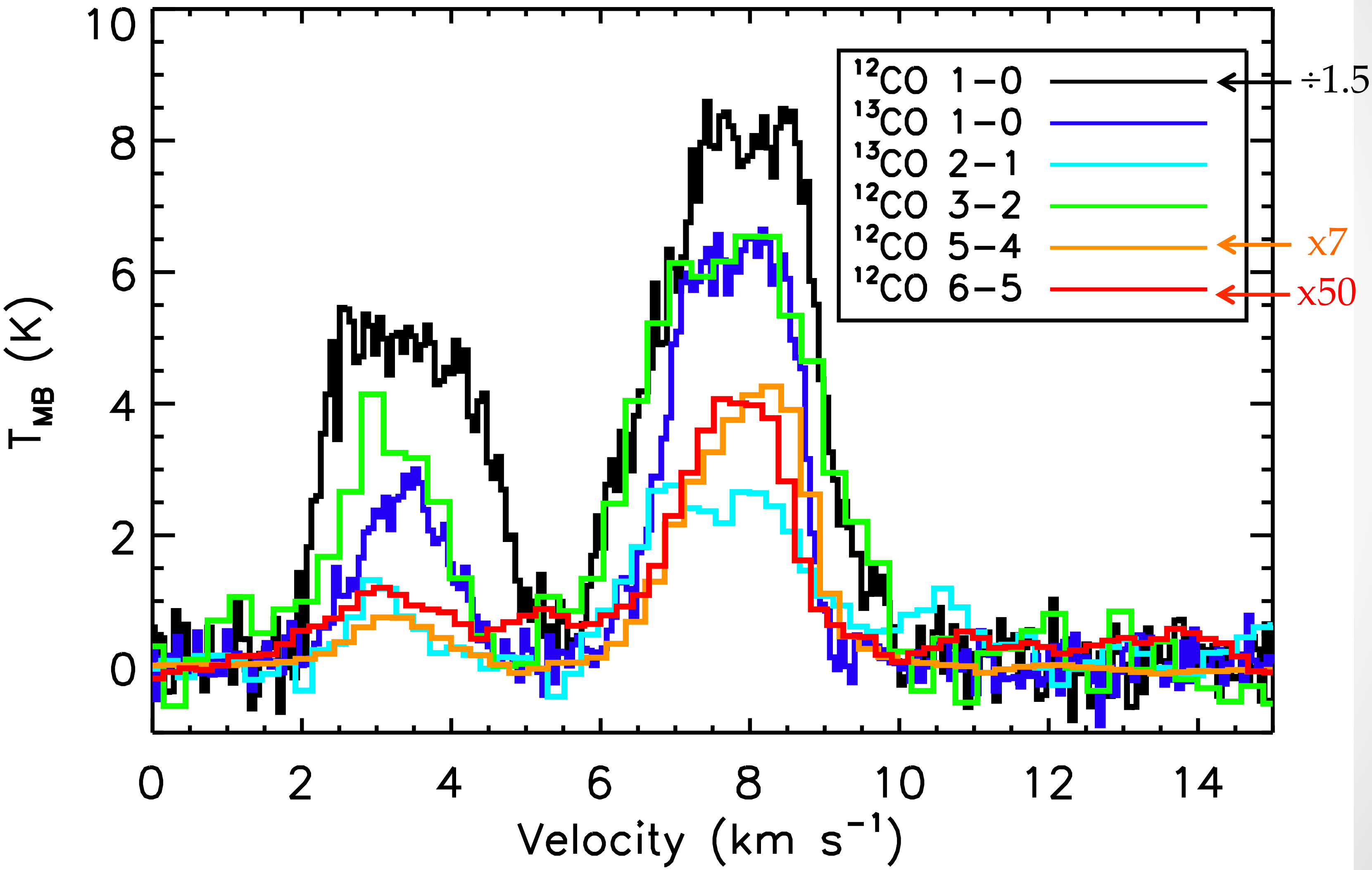


Key Prediction:

Mid J CO lines should trace shocked gas!


Perseus B1-E5
Sadavoy et al. (2013)

CO Observations



CO SED

Key Observation:

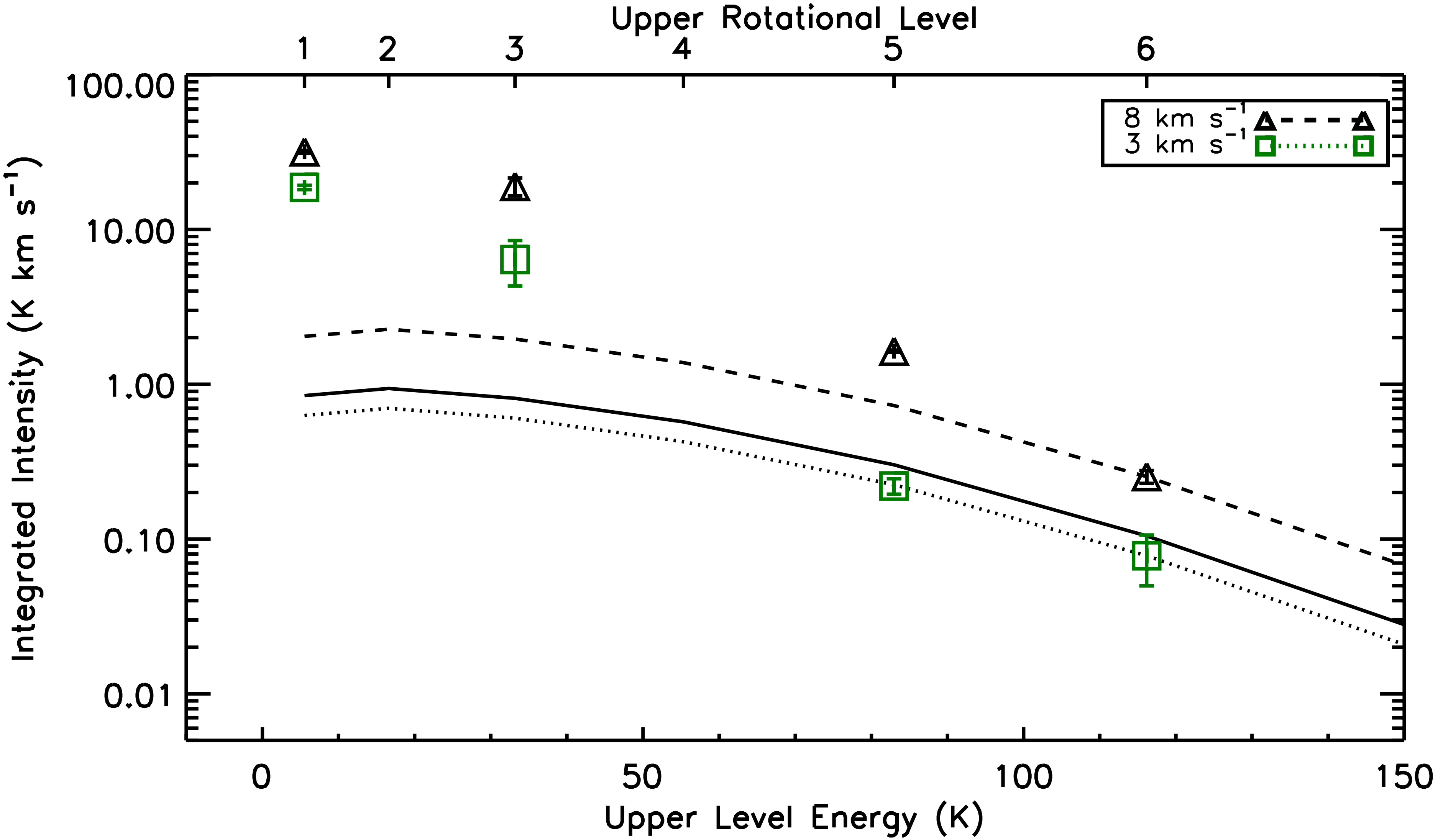
CO 6-5 line is too bright for PDR models!

Ratio to ^{12}CO 3 to 2 Integrated Intensity

0 50 100 150

Upper Level Energy (K)

Consistent with Shock Models



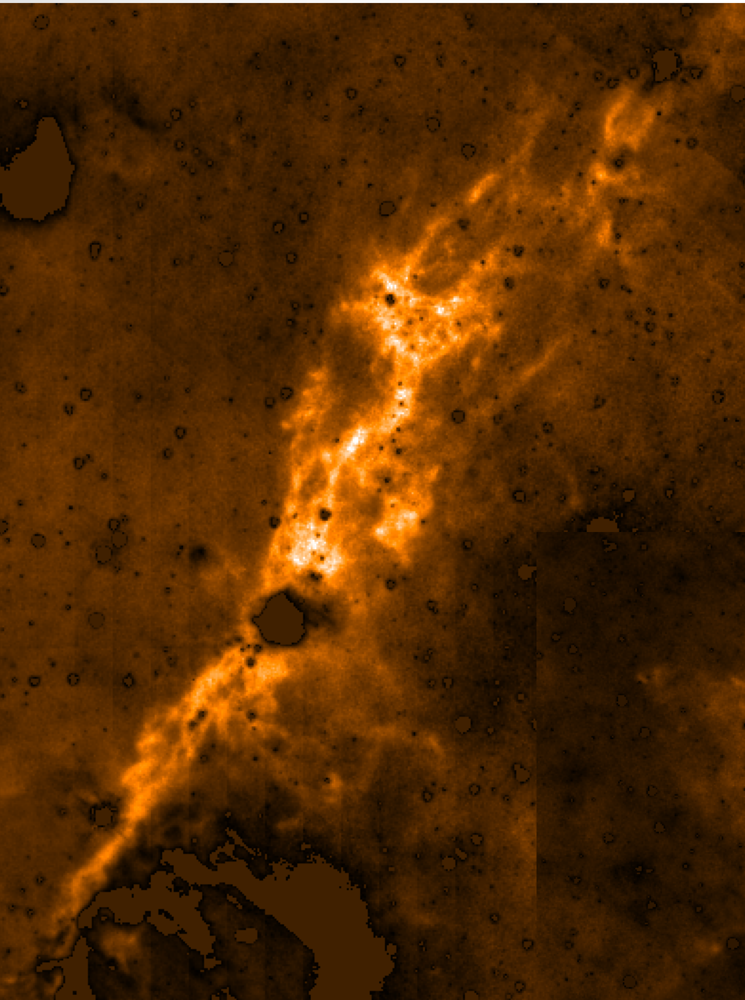
Shock Properties

- Volume filling factor of the shocked gas is 0.15%.
- Turbulent energy dissipation rate is 3.5×10^{32} ergs s^{-1}.
- Turbulent energy dissipation timescale is three times smaller than the flow crossing timescale.

Archival Value

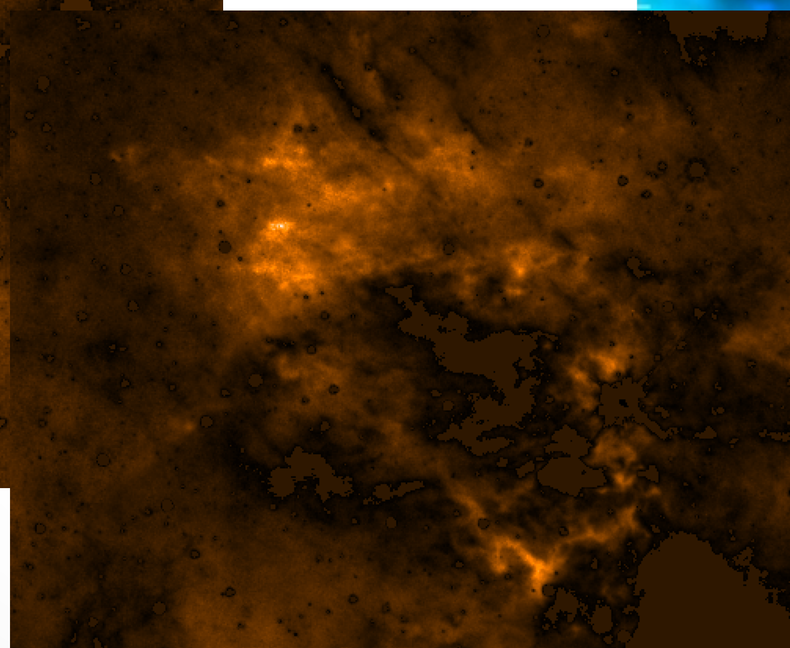
- This shock emission should be ubiquitous. It should be present towards any molecular cloud, if one looks deep enough and away from other heating sources.
- SPIRE has sensitivity to these mid-J lines.
- SPIRE has an array of 19 pixels for the 6-5 to 8-7 lines.
- Is there anything in your ‘uninteresting’ off-source pixels?

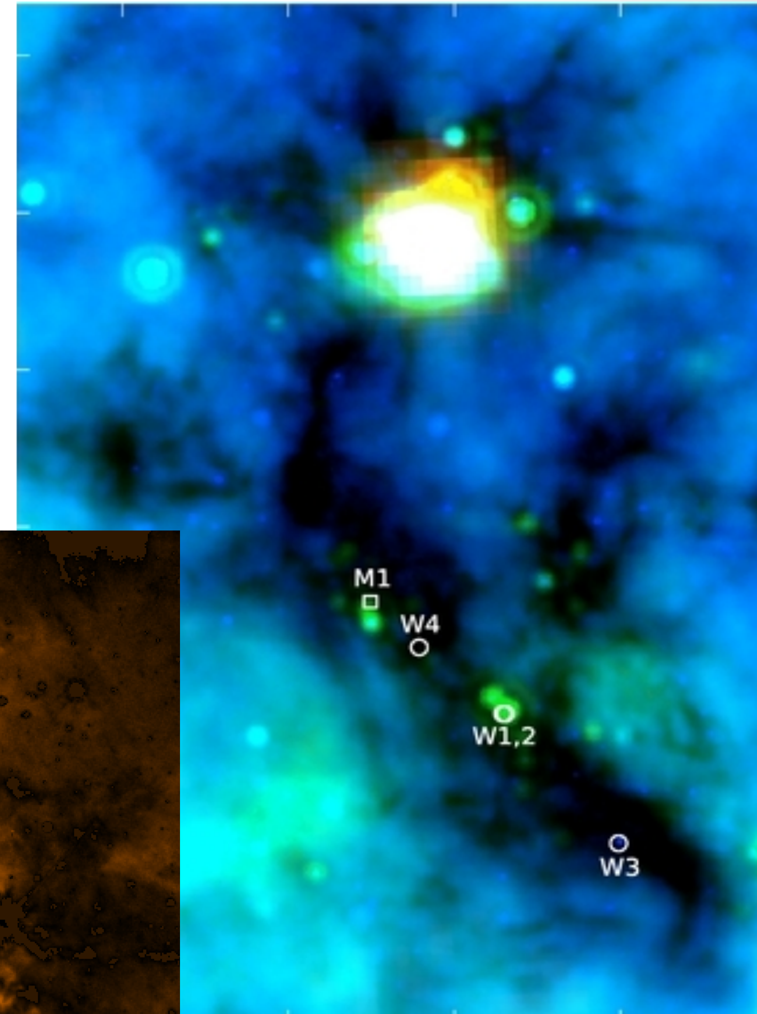
IRDCs



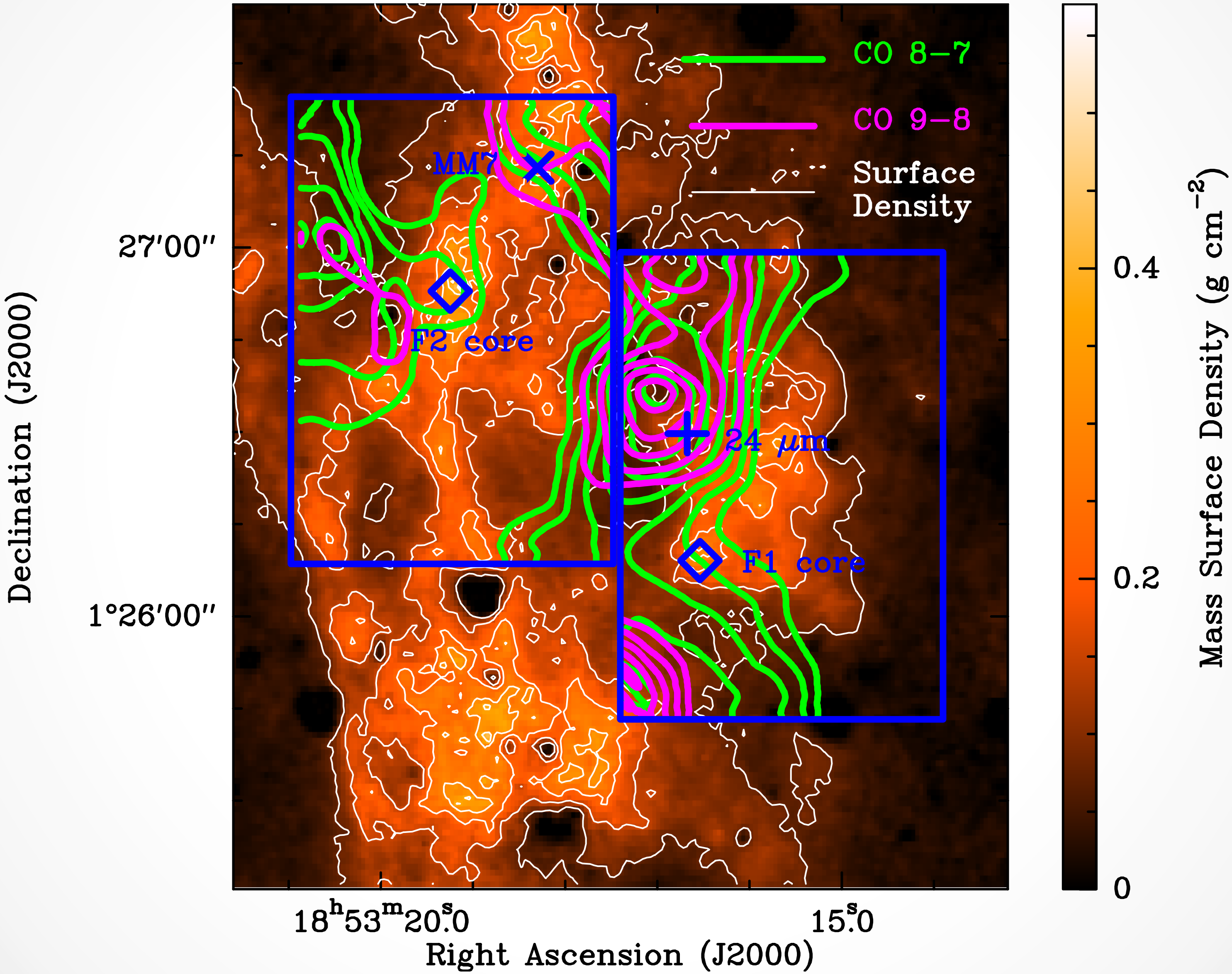
Butler & Tan (2012)

Wang et al. (2012)

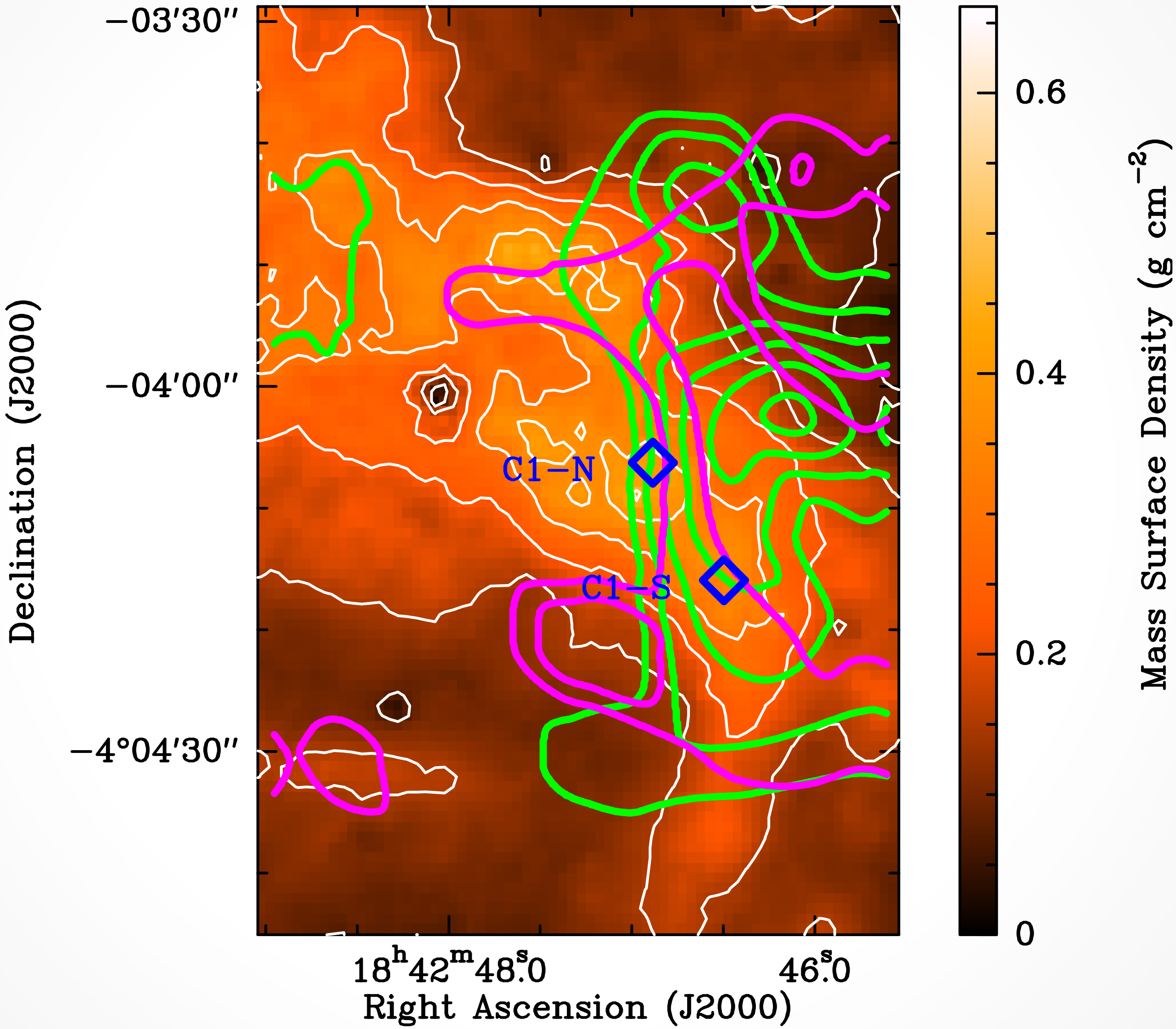




IRDC F

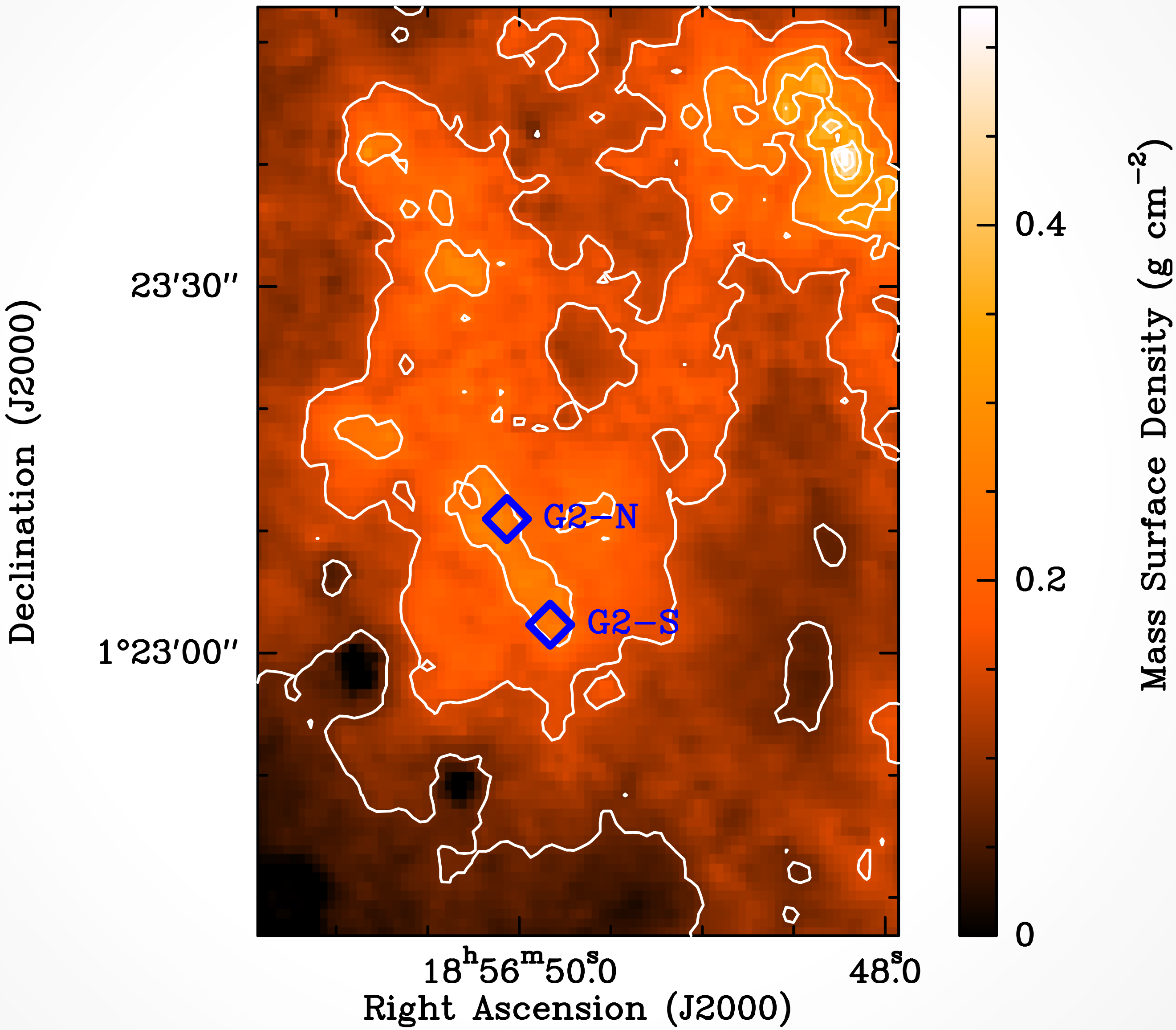

CO 8−7
CO 9−8
Surface Density
MM7
F2 core
24 μm
F1 core
27′00″
1°26′00″
Declination (J2000)
18h53m20.s0
15.s0
Right Ascension (J2000)
0.4
0.2
0
Mass Surface Density (g cm−2)

IRDC C

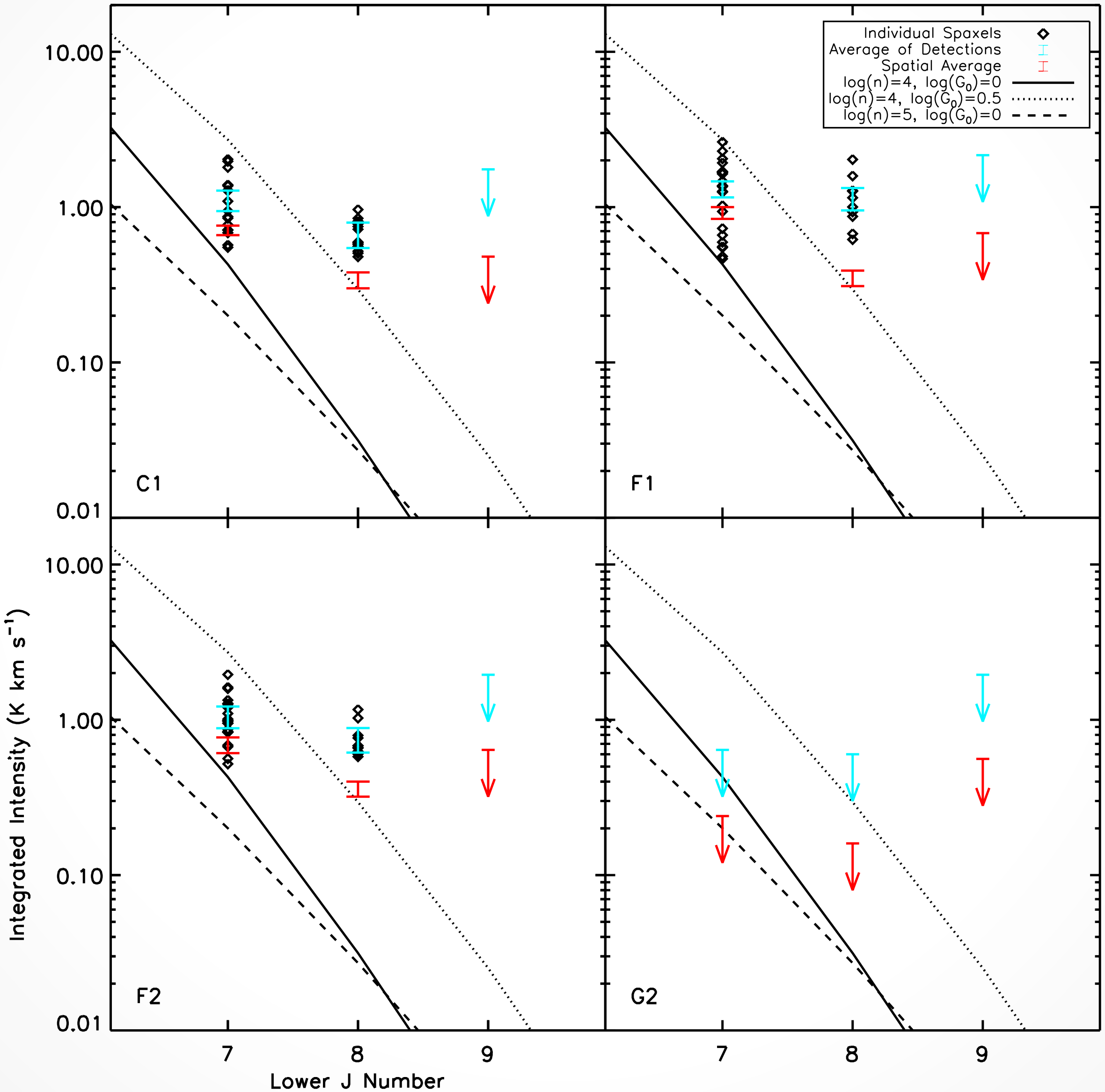


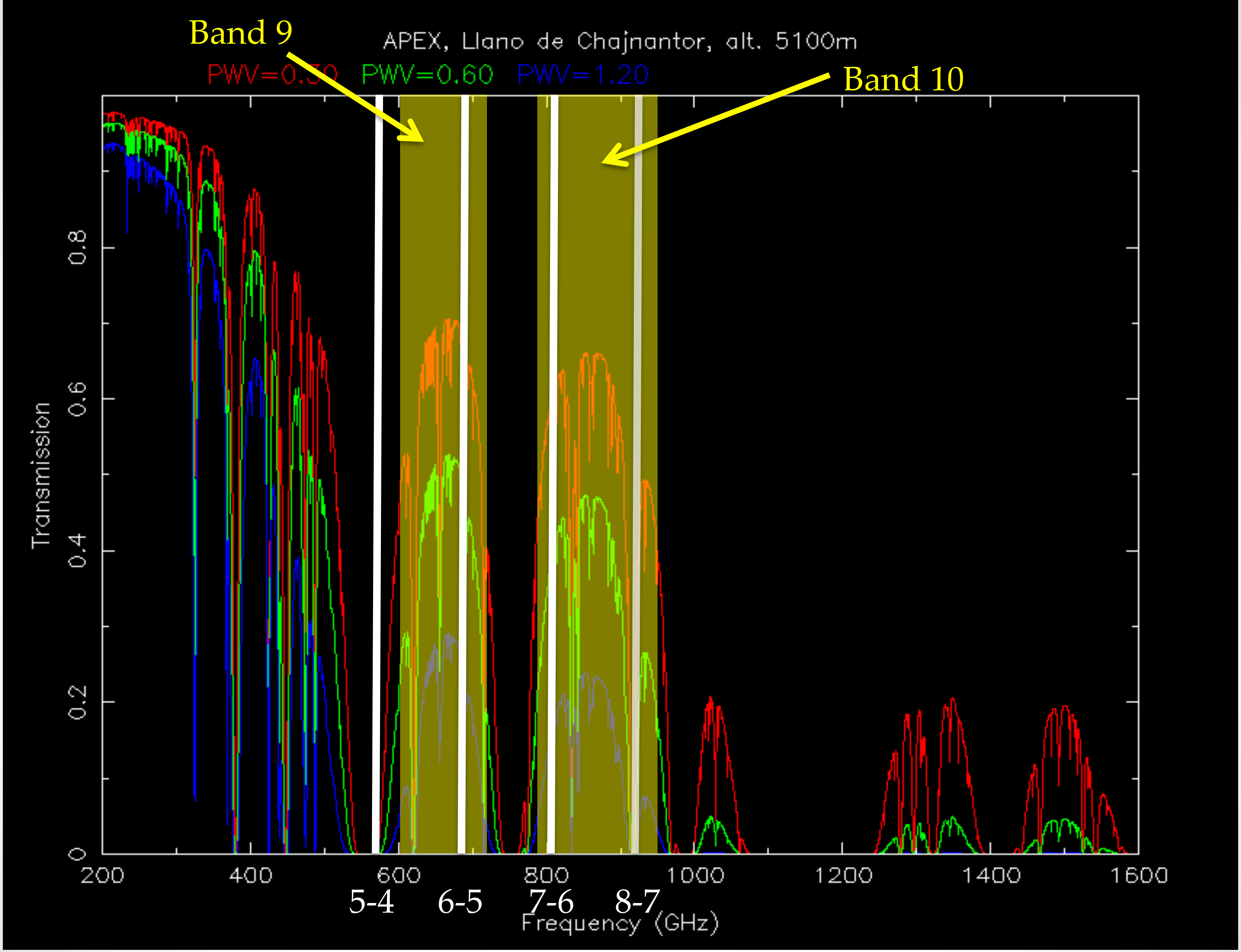
−03′30″
−04′00″
−4°04′30″
Declination (J2000)
18h42m48.s0
46.s0
Right Ascension (J2000)
C1−N
C1−S
0.6
0.4
0.2
0
Mass Surface Density (g cm−2)

IRDC G


G2−N
G2−S
23′30″
1°23′00″
Declination (J2000)
18h56m50.s0
48.s0
Right Ascension (J2000)
0.4
0.2
0
Mass Surface Density (g cm−2)

IRDCs


Individual Spaxels
Average of Detections
Spatial Average
log(n)=4, log(G0)=0
log(n)=4, log(G0)=0.5
log(n)=5, log(G0)=0
C1
F1
F2
G2
10.00
1.00
0.10
0.01
7
8
9
Integrated Intensity (K km s-1)
Lower J Number



Band 9
APEX, Llano de Chajnantor, alt. 5100m
PWV=0.30 PWV=0.60 PWV=1.20
Band 10
Transmission
0 0.2 0.4 0.6 0.8
200 400 600 800 1000 1200 1400 1600
5-4 6-5 7-6 8-7
Frequency (GHz)

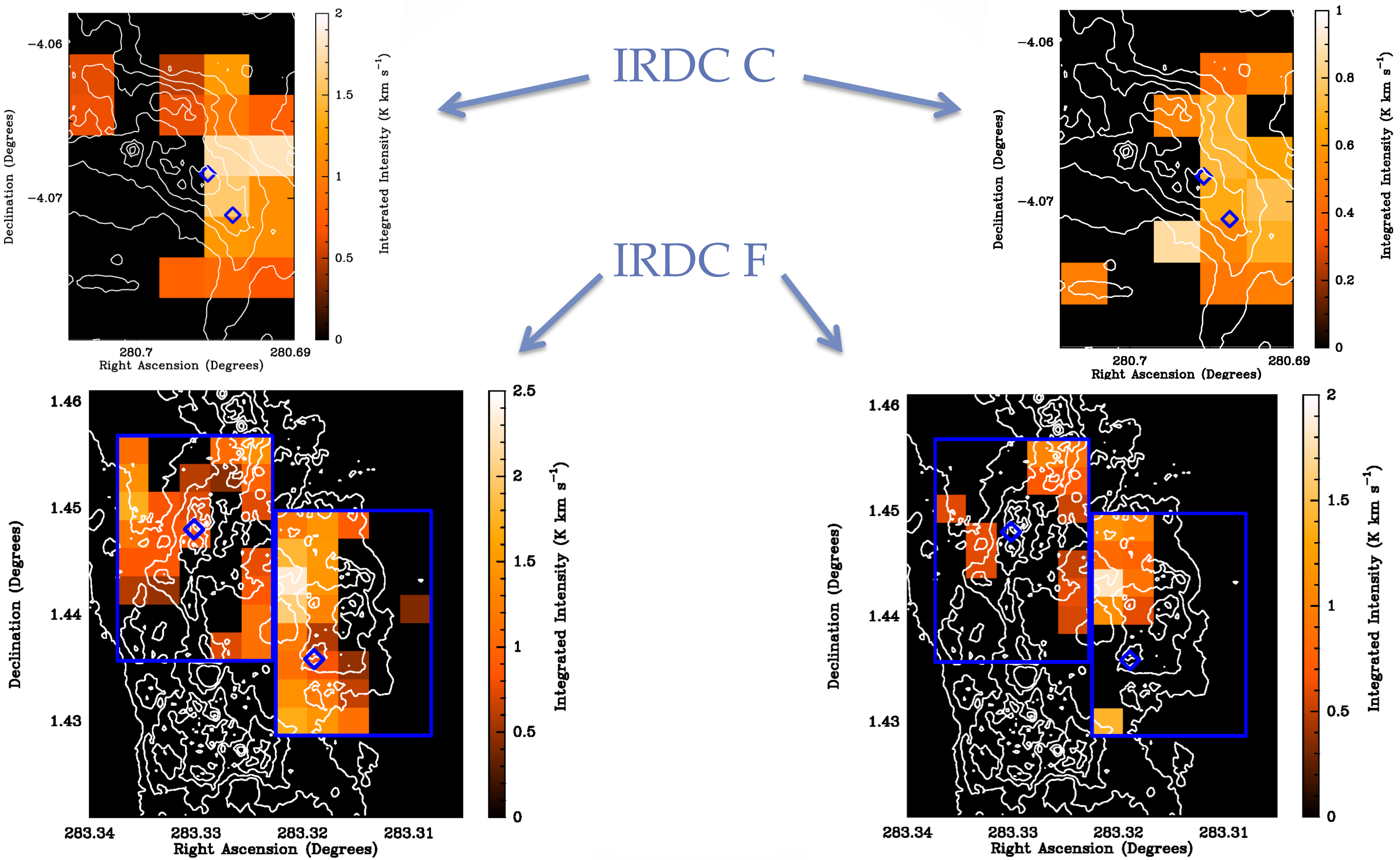
Why ALMA?

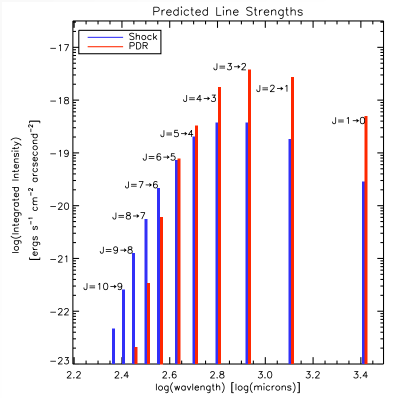
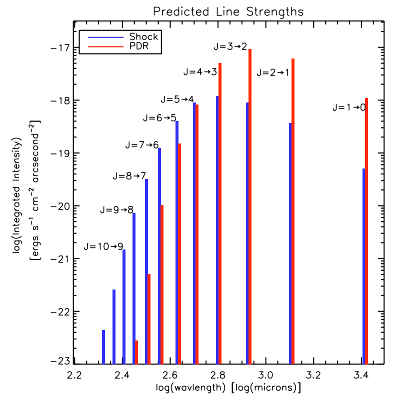
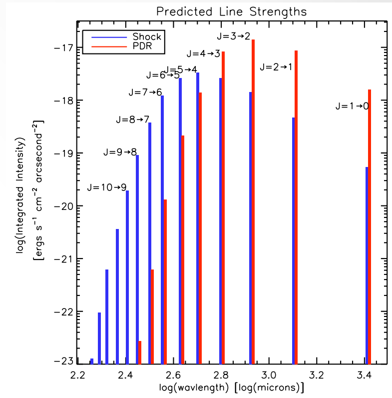
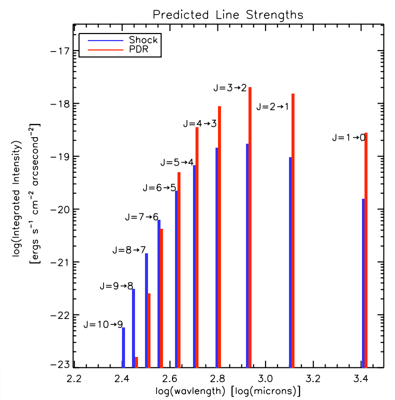
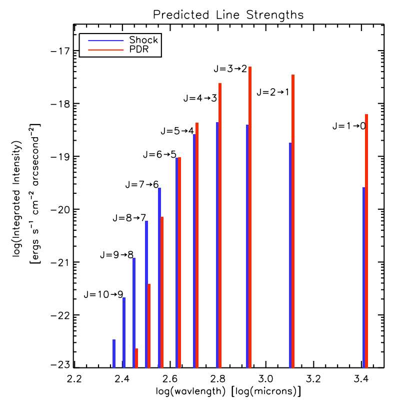
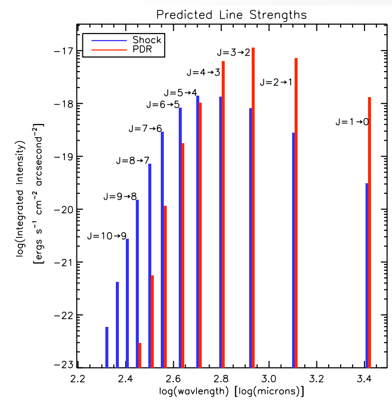
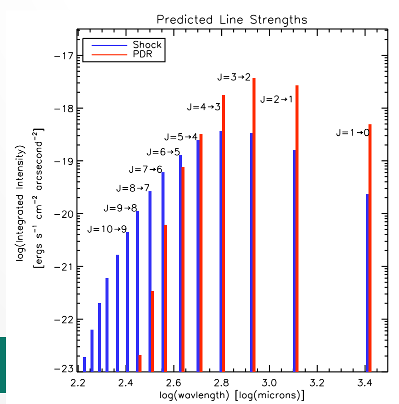
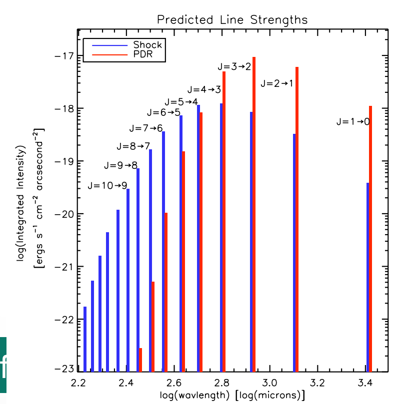
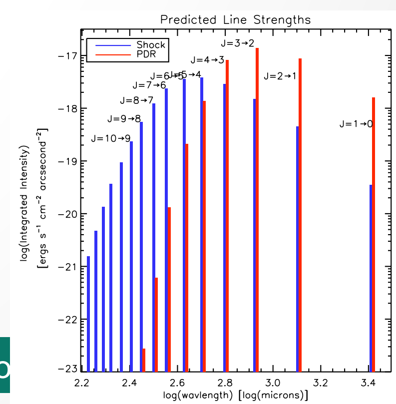
- Key difference between shock heating and cosmic ray or ISRF heating is that shocks are intermittent.
  - Shock heated gas should be highly spatially variable such that this emission will not be filtered out by ALMA.
  - The shocks should also be somewhat randomly distributed, rather than well collimated as in protostellar outflows.
- ALMA should reveal the spatial distribution of shocks
  - The locations of shocks may hold clues to the formation mechanisms of GMCs
  - ALMA should benefit from much larger beam filling factors

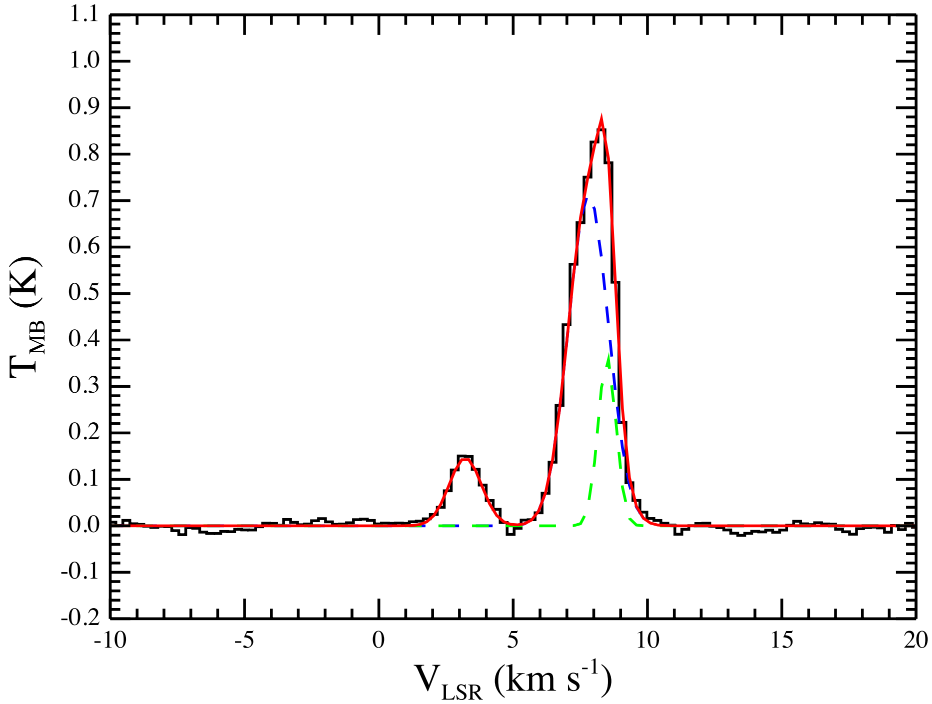
Summary

- Molecular clouds contain supersonic turbulence and this turbulence should decay relatively rapidly.
- Most of this turbulent energy is dissipated via CO lines.
- Mid to high J CO lines trace shock emission and are observable!
- Perseus B1-E5 has emission in mid J CO lines above that predicted by PDR models, as expected for shock emission.
- IRDCs show regions with enhanced mid J CO emission, inconsistent with PDR models
- ALMA provides the capability to resolve individual shock structures

8 to 7 IRDC Observations 9 to 8

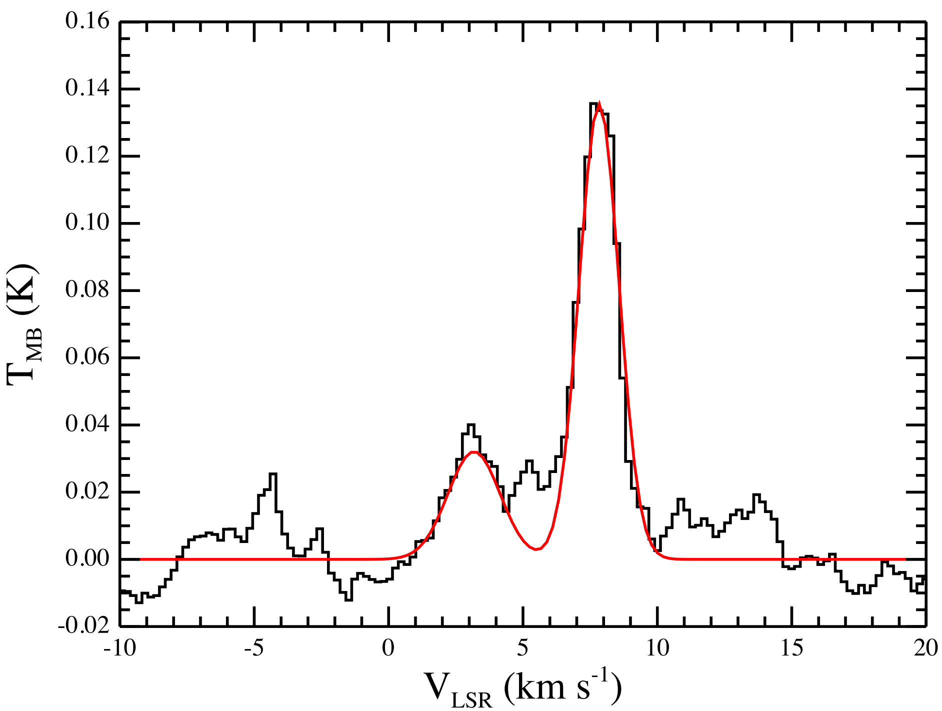


	$n = 10^{2.5}$ cm^{-3}	$n = 10^{3}$ cm^{-3}	$n = 10^{3.5}$ cm^{-3}
$v = 3$ km s^{-1}, $b = 0.3$			
$v = 2$ km s^{-1}, $b = 0.1$			
$v = 3$ km s^{-1}, $b = 0.1$			

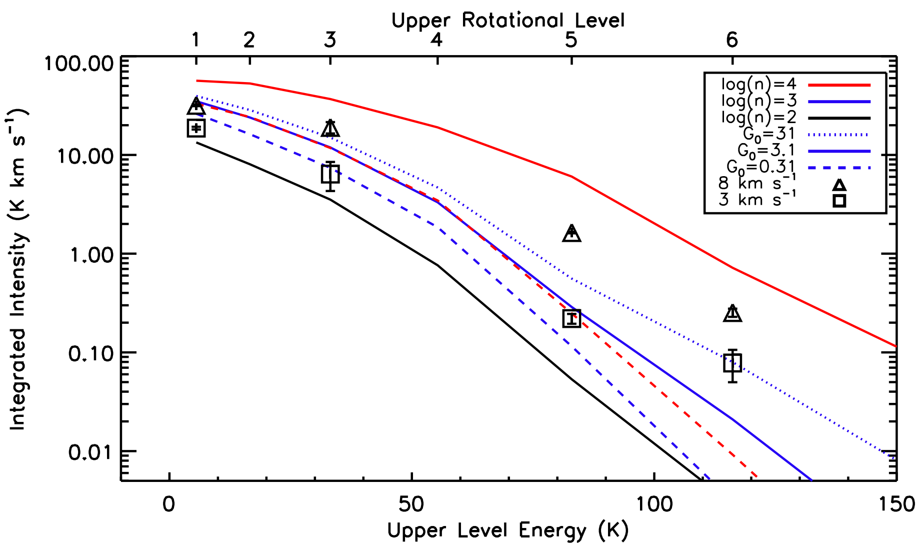


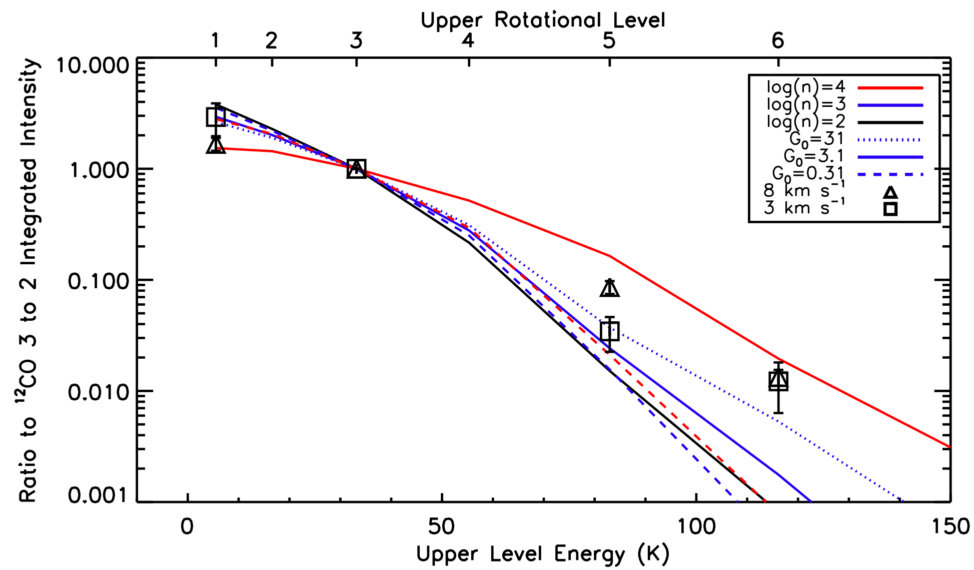
CO 5 - 4

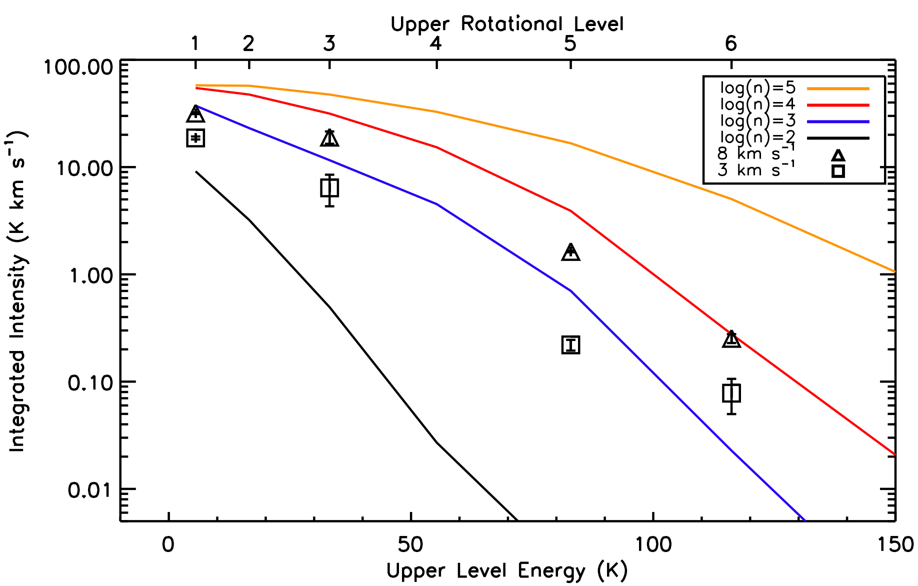
CO 6 - 5

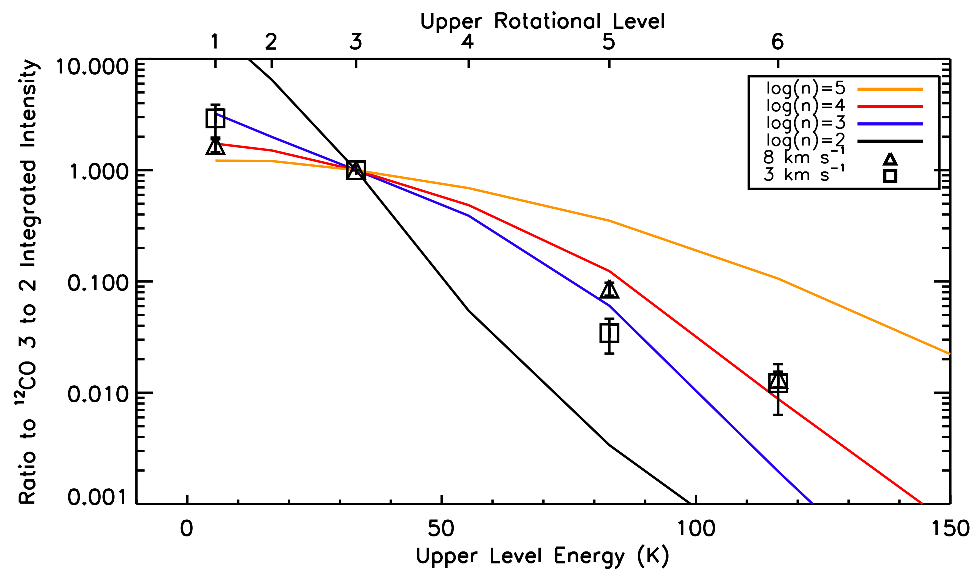


CO SED


Upper Rotational Level
1 2 3 4 5 6
100.00
10.00
1.00
0.10
0.01
Integrated Intensity (K km s^{-1})
0 50 100 150
Upper Level Energy (K)
log(n)=4
log(n)=3
log(n)=2
G_0=31
G_0=3.1
G_0=0.31
8 km s^{-1}
3 km s^{-1}


Upper Rotational Level
1 2 3 4 5 6
10.000
1.000
0.100
0.010
0.001
Ratio to ^{12}CO 3 to 2 Integrated Intensity
0 50 100 150
Upper Level Energy (K)
log(n)=4
log(n)=3
log(n)=2
G_0=31
G_0=3.1
G_0=0.31
8 km s^{-1}
3 km s^{-1}


Upper Rotational Level
1 2 3 4 5 6
100.00
10.00
1.00
0.10
0.01
Integrated Intensity (K km s^{-1})
0 50 100 150
Upper Level Energy (K)
log(n)=5
log(n)=4
log(n)=3
log(n)=2
8 km s^{-1}
3 km s^{-1}


Upper Rotational Level
1 2 3 4 5 6
10.000
1.000
0.100
0.010
0.001
Ratio to ^{12}CO 3 to 2 Integrated Intensity
0 50 100 150
Upper Level Energy (K)
log(n)=5
log(n)=4
log(n)=3
log(n)=2
8 km s^{-1}
3 km s^{-1}