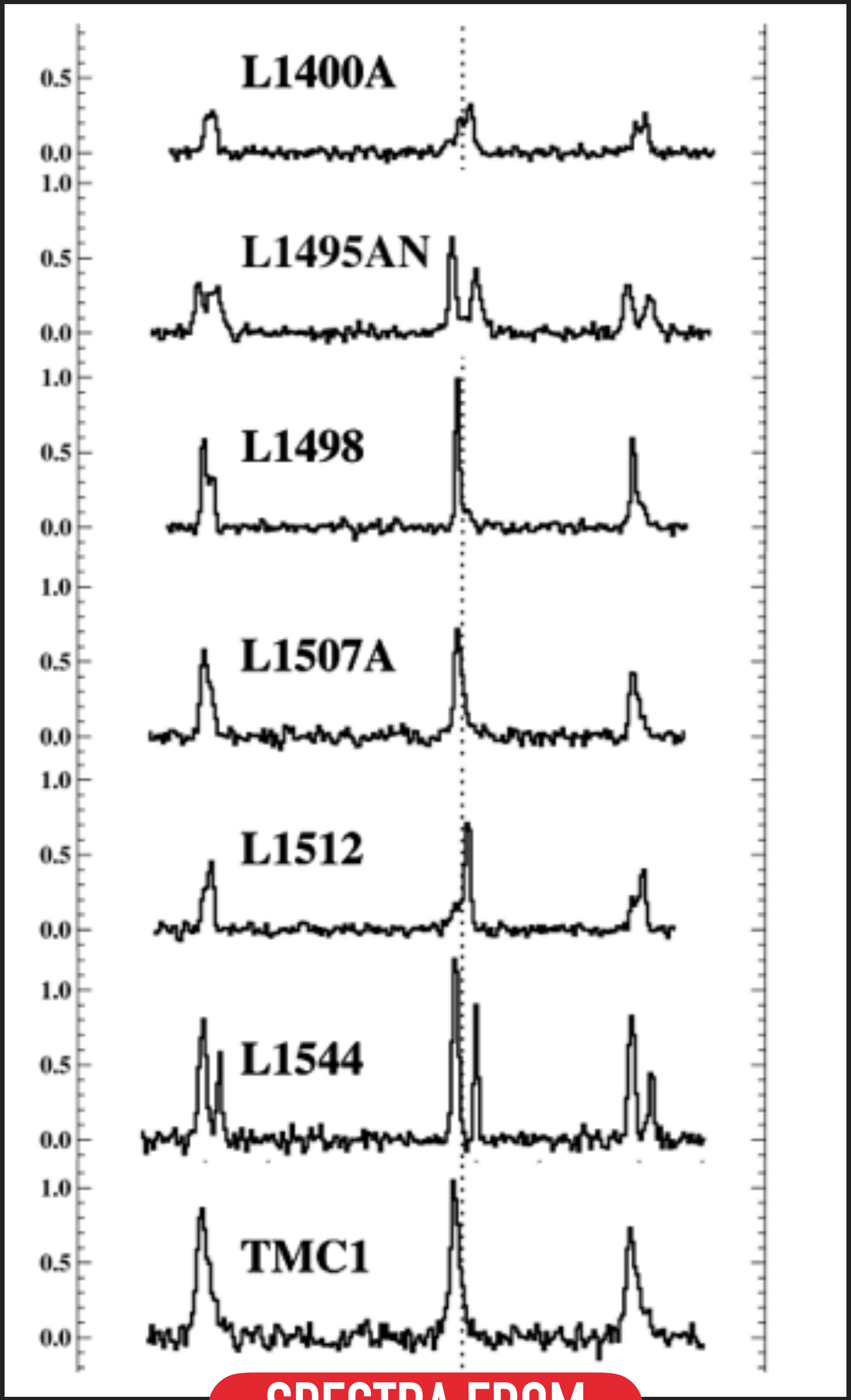
VICTOR S. MAGALHÃES*, PIERRE HILY-BLANT, ALEXANDRE FAURE, FRANÇOIS LIQUE, C. M. WALMSLEY, FABIEN DANIEL

STUDY OF HYPERFINE ANOMALIES AND CARBON FRACTIONATION IN HCN

WHY HCN?

- Goal: understand N heritage from the Protosolar Nebula.
- Tool: Isotopic ratios.
- Molecule of choice: HCN
    - Abundant, easy to detect, formation is understood.
- Problem: τ(HCN) >> 1 in usual ISM conditions.



SPECTRA FROM SOHN ET AL. 2007

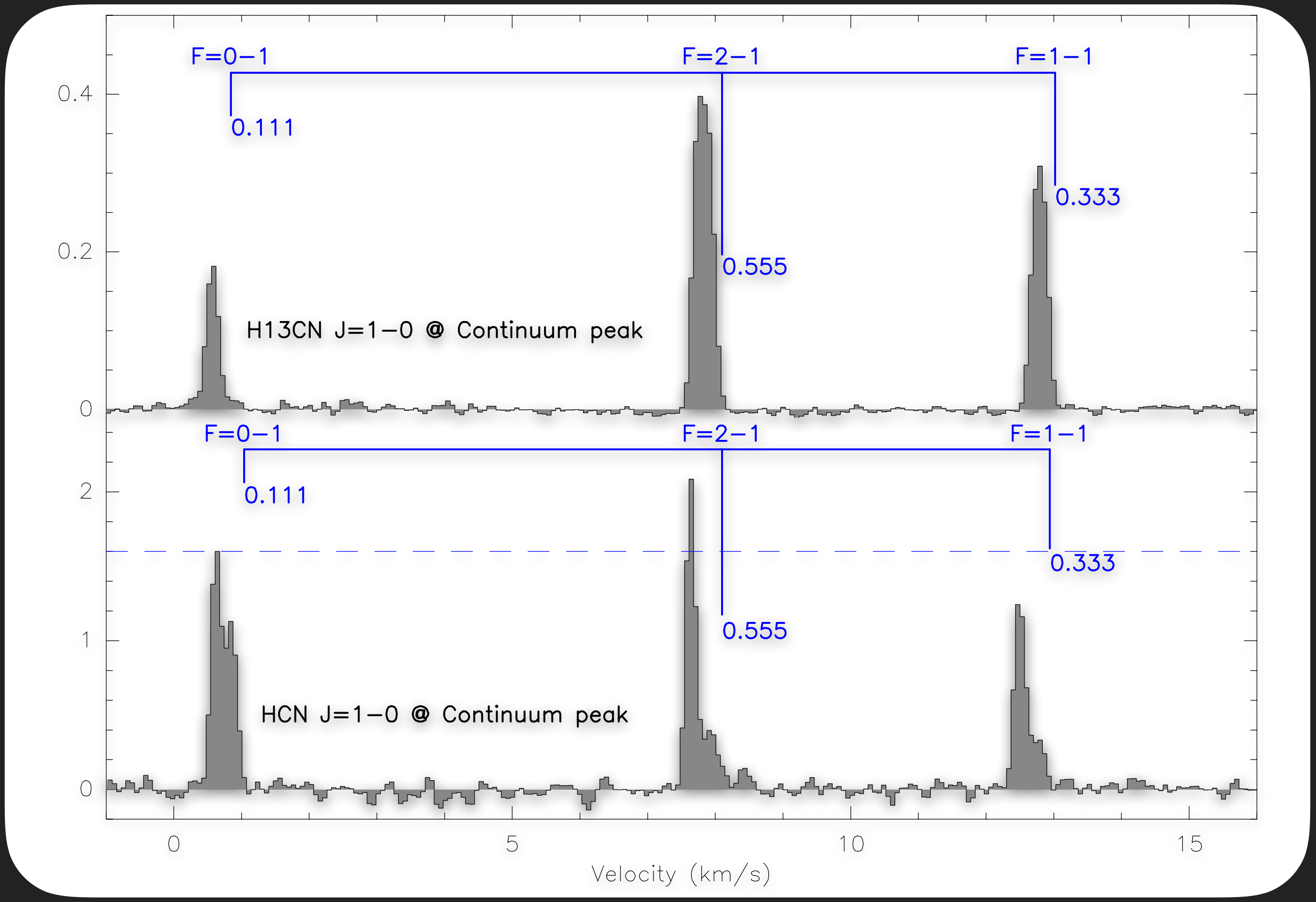
THE DOUBLE ISOTOPOLOGUE METHOD

$$\frac{\mathrm{HCN}}{\mathrm{HC^{15}N}} \approx \frac{\mathrm{H^{13}CN}}{\mathrm{HC^{15}N}} \times \frac{^{12}\mathrm{C}}{^{13}\mathrm{C}}\ , \ \text{with}\ \frac{^{12}\mathrm{C}}{^{13}\mathrm{C}} = 70$$

e.g. Hily-Blant et al. 2013

- Caveat: Chemical fractionation plays a role?
  - From chemical modelling: $H^{12}CN/H^{13}CN$ = 93 - 168 (e.g. Roueff. et al. 2015).
- Solution: Measure N(HCN) directly.
  - how: Use the information contained in the HyperFine Anomalies (HFA) of HCN rotational transitions.

WHAT IS AN HCN HF ANOMALY



- HF components line ratios inconsistent with a single excitation temperature (T_{ex}).
- HFA are a long standing problem in millimetre astronomy (Kwan & Scoville 1974).

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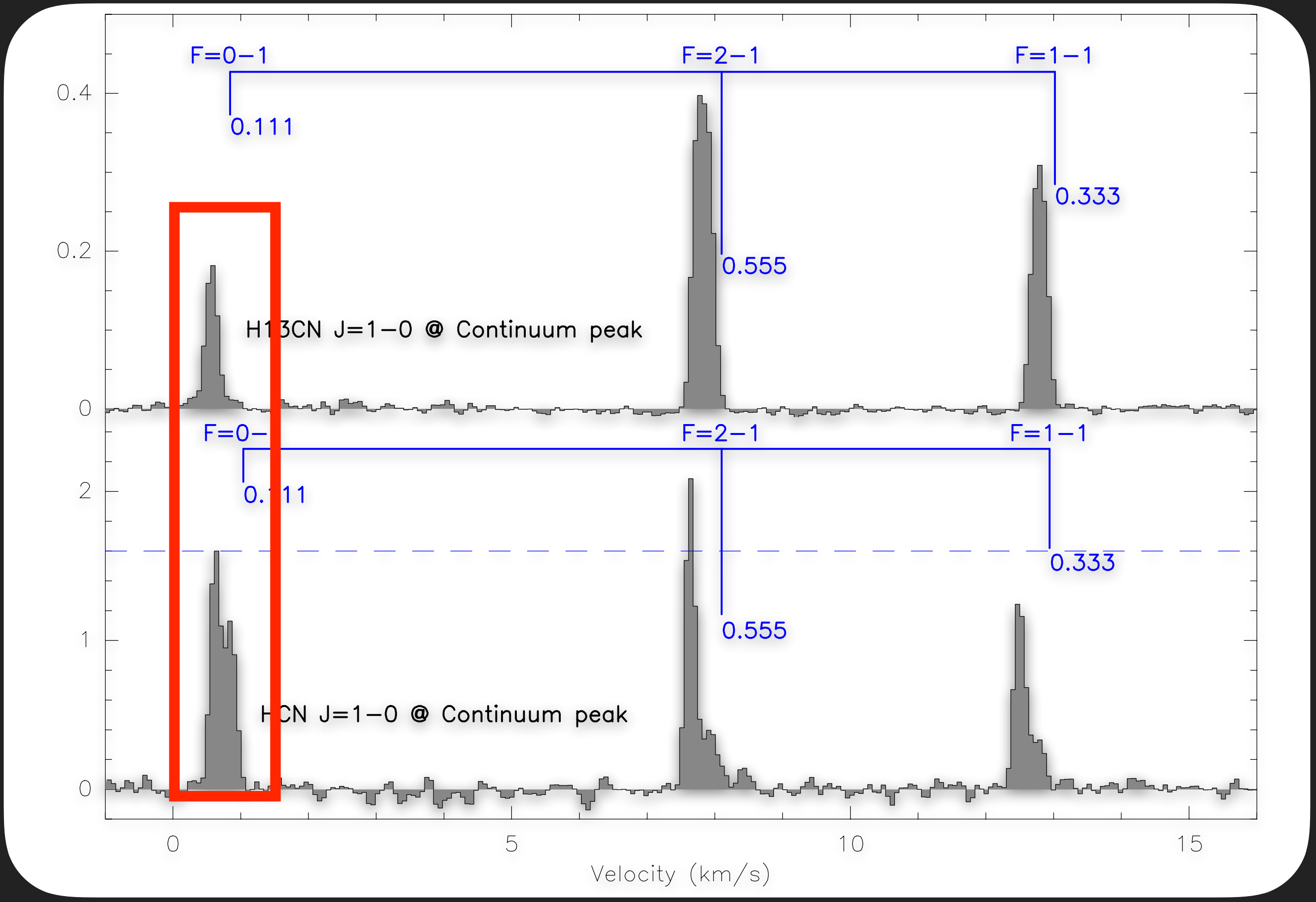

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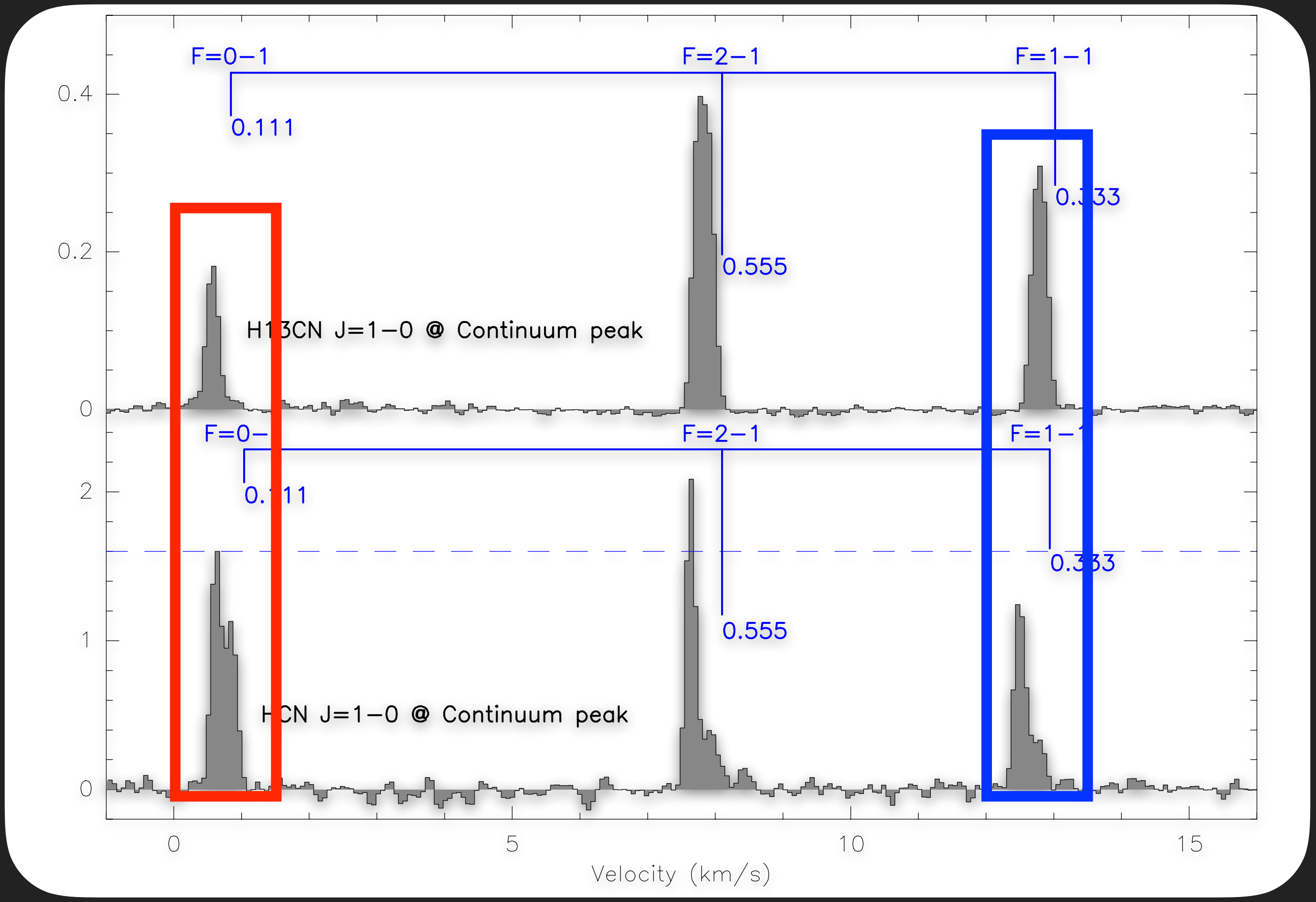

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WHAT WAS KNOWN ABOUT HCN HFA

- Where:
  - Dense cores (e.g. Sohn et al. 2007), HII regions (e.g. Gottlieb et al. 1975).
- Early theories:
  - Self-absorption creates HFA (Langer et al. 1978, Walmsley et al. 1982, Cernicharo et al. 1984)
  - HF Overlap for transitions with $J_{up} \geq 2$ (Guilloteau & Baudry et al. 1981)
  - Collisional selection of HF levels + physical and kinematic structure (Gottlieb et al. 1975)

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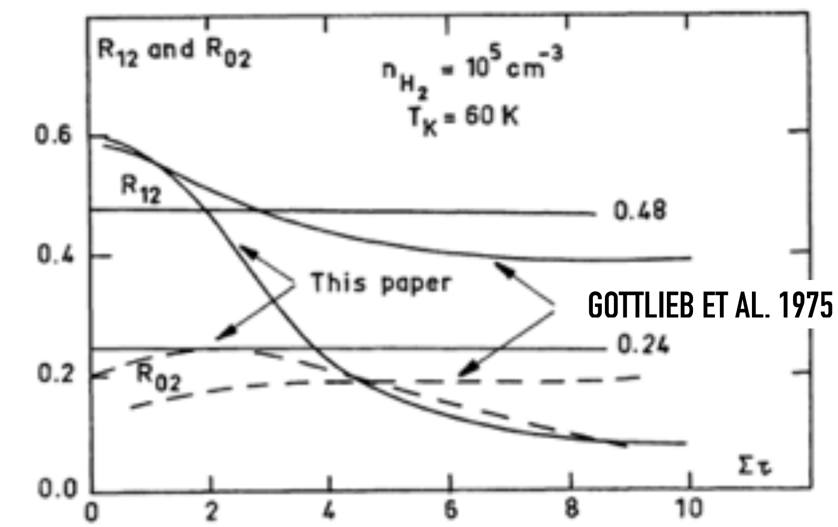
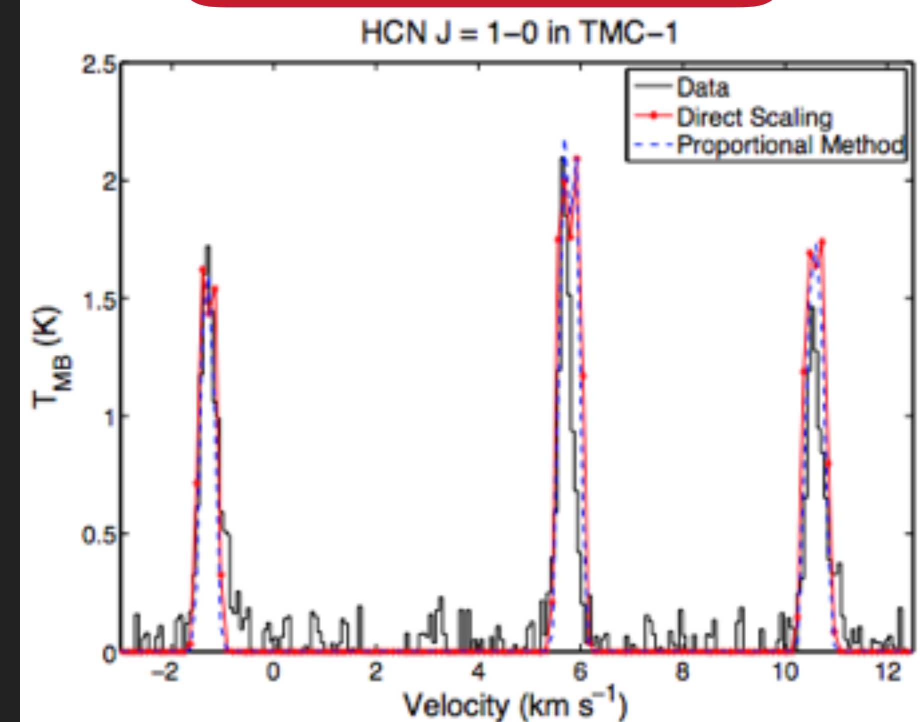
WHAT WAS KNOWN ABOUT HCN HFA

- Qualitatively understood by:
  - Gottlieb et al. 1975
  - Guilloteau & Baudry 1981
- Recent work by Mullins et al. 2016:
  - No source structure.
  - Approximated collisional coefficients.
  - Fit to TMC-1 spectra:
    not satisfactory



GULLOTEAU & BAUDRY 1981



MULLINS ET AL. 2016

WHAT WAS KNOWN ABOUT HCN HFA

COMPLEMENTARY APPROACHES

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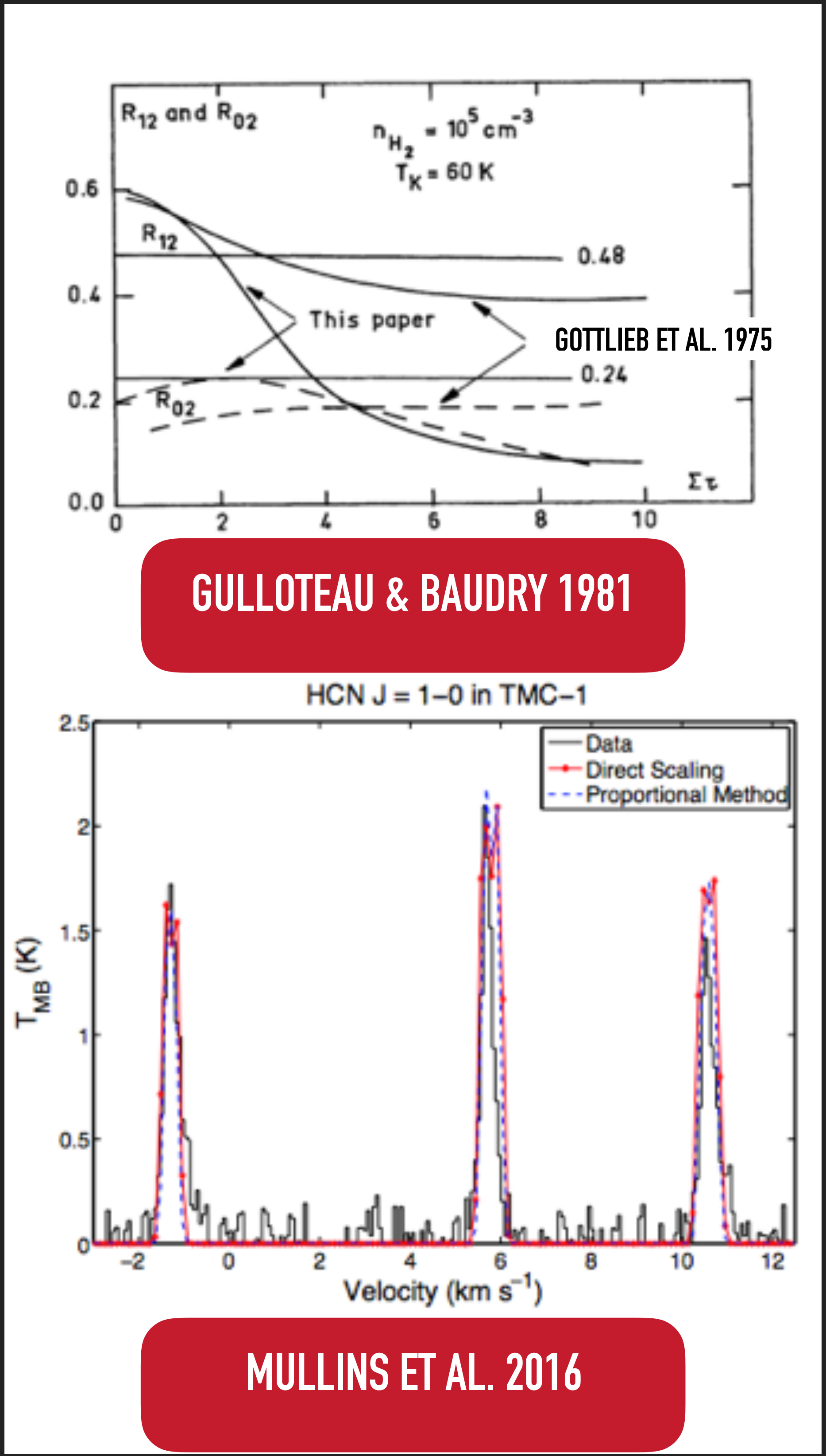
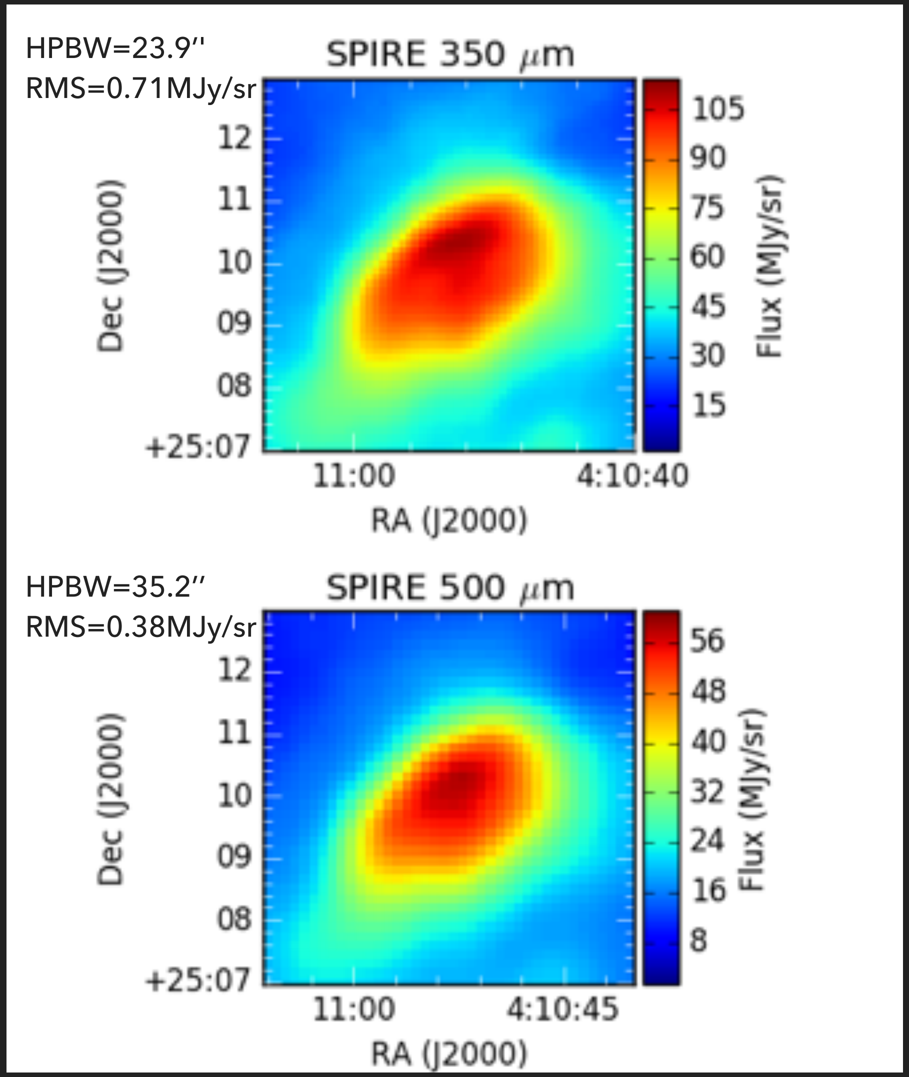


HOW TO RECREATE HFA?

- Target: L1498 well studied PreStellar Core (e.g. Tafalla et al. 2004, Tafalla et al. 2006, Padovani et al. 2011)
- Tool: State of the art 1-D radiative transfer code (Daniel & Cernicharo 2008) Handling:
    - Collisional coefficients that treat HF levels independently.
        - Latest ab initio HCN HF collisional rates (Lique et al. 2016 in prep.).
    - Hyperfine overlap.
    - Complex physical structure, ($T_k(r)$, $n(r)$, $V(r)$, $\sigma(r)$, $X_{species}(r)$)

L1498 PHYSICAL STRUCTURE

- T_k = 10 K (Tafalla et al. 2006).
- σ(r=∞) = 0.265 km/s (Tafalla et al. 2006)
- n(r): Fitting of Herschel/SPIRE @350 & 500 μm.
- Velocity + σ(r=0): $H^{13}CN$ + $HC^{15}N$ spectra.
- σ(r) transition: HCN with fixed abundance.



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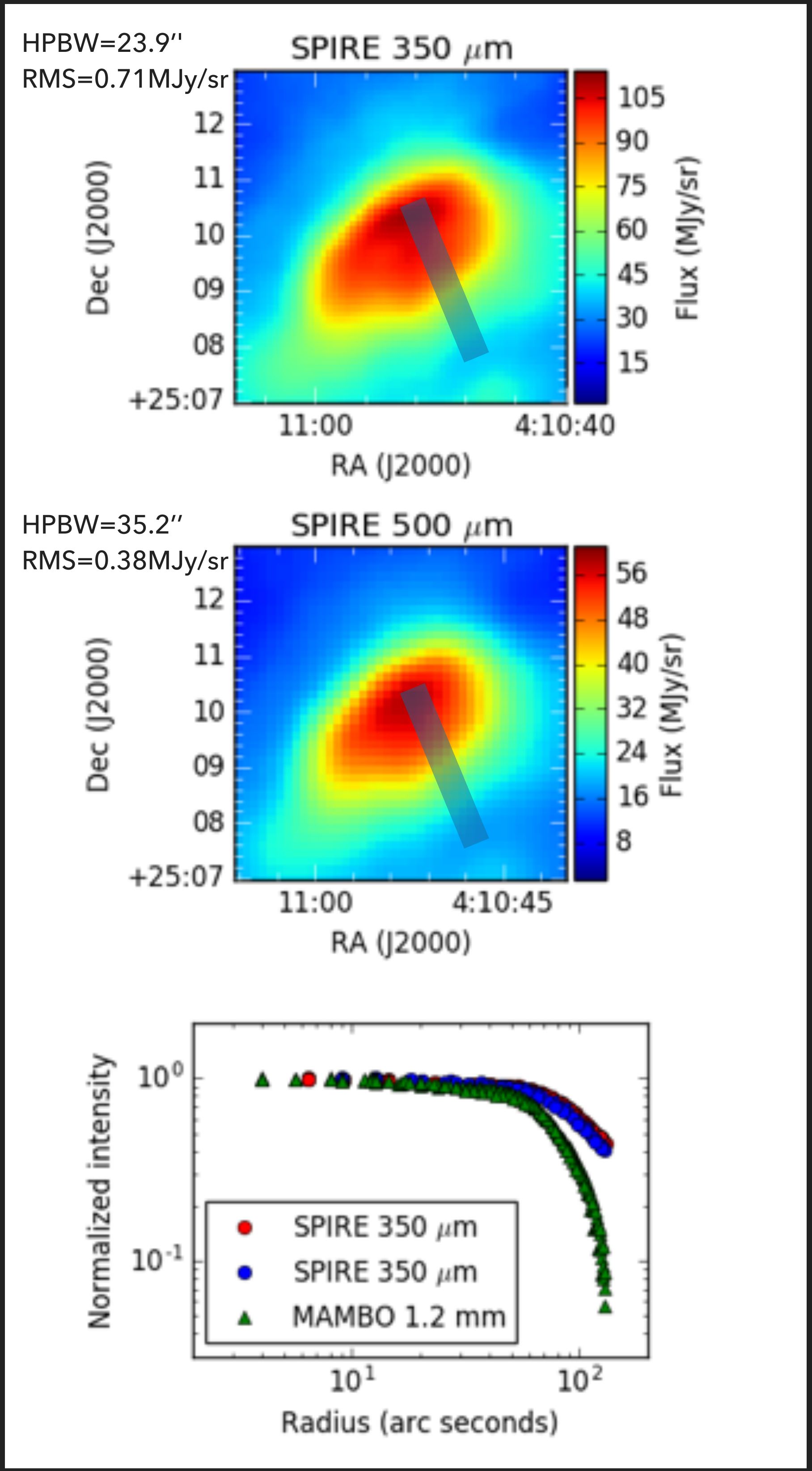

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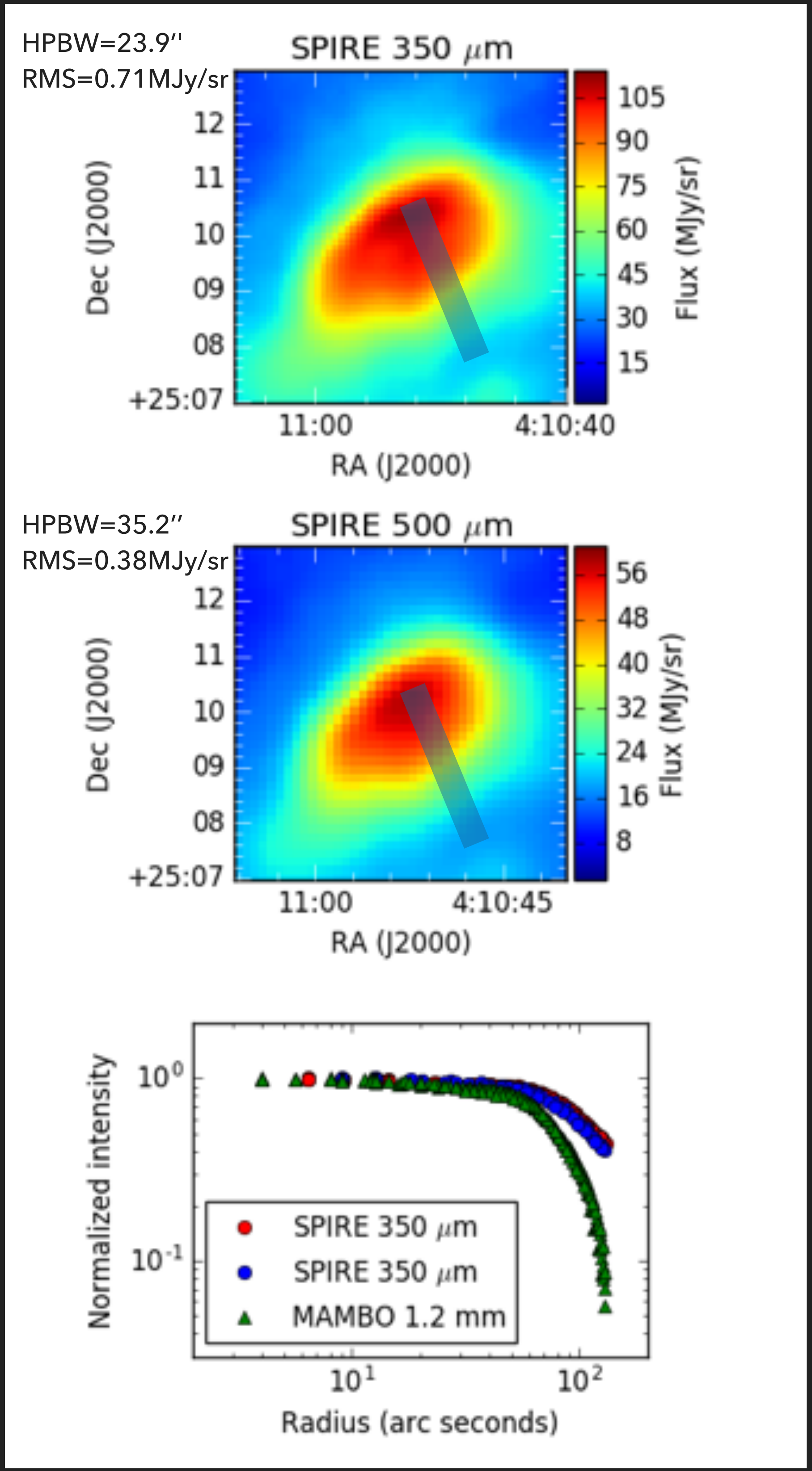

L1498 PHYSICAL STRUCTURE

$$\frac{N(r)}{N_{max}} = 2 \times \frac{\int \left(\frac{1}{1+\frac{r}{r_0}^{\alpha}} + \frac{n_0}{n_{ext}} \right) dr}{\int \left(\frac{1}{1+\frac{r}{r_0}^{\alpha}} + \frac{n_0}{n_{ext}} \right) dr|_{r=0}}$$

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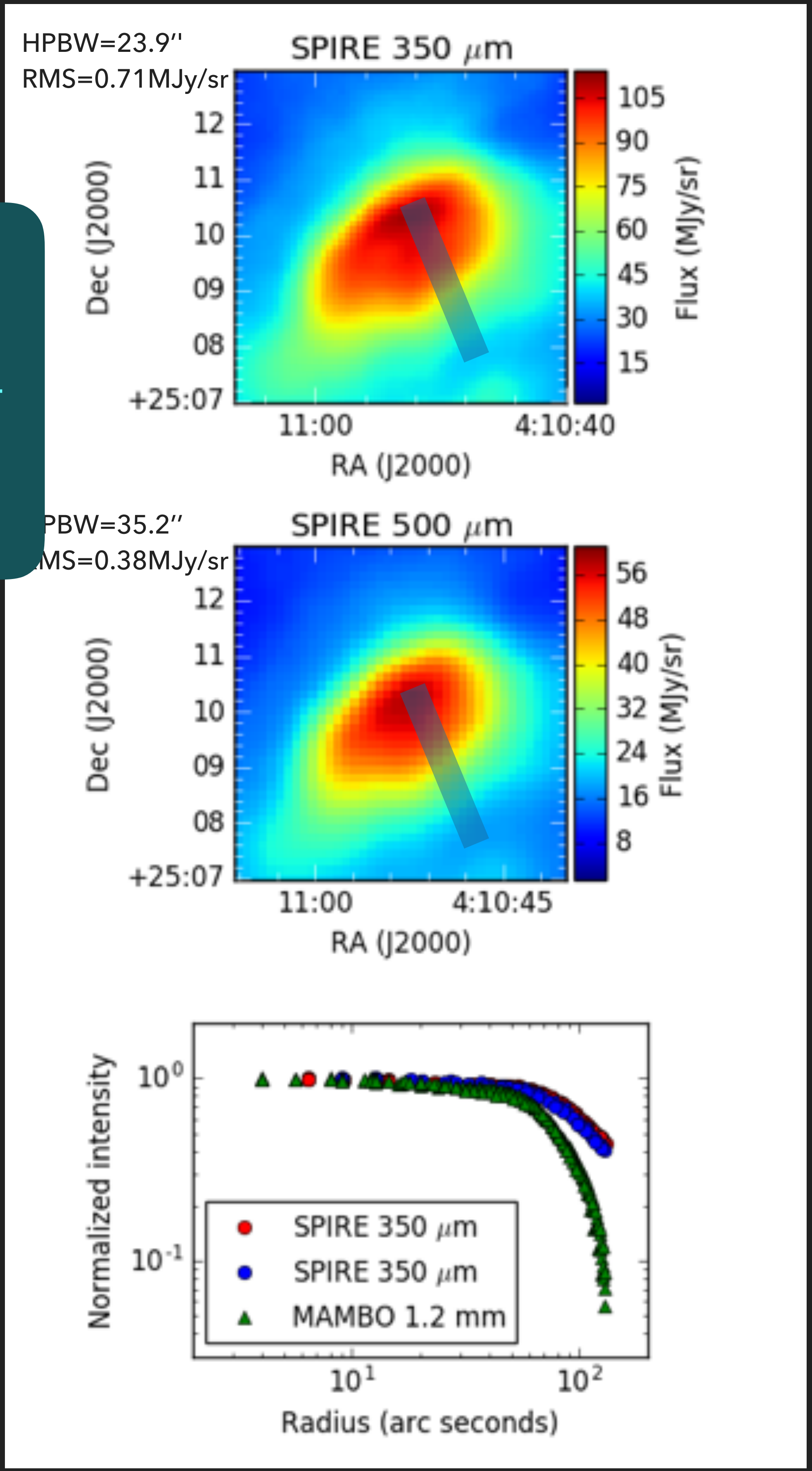

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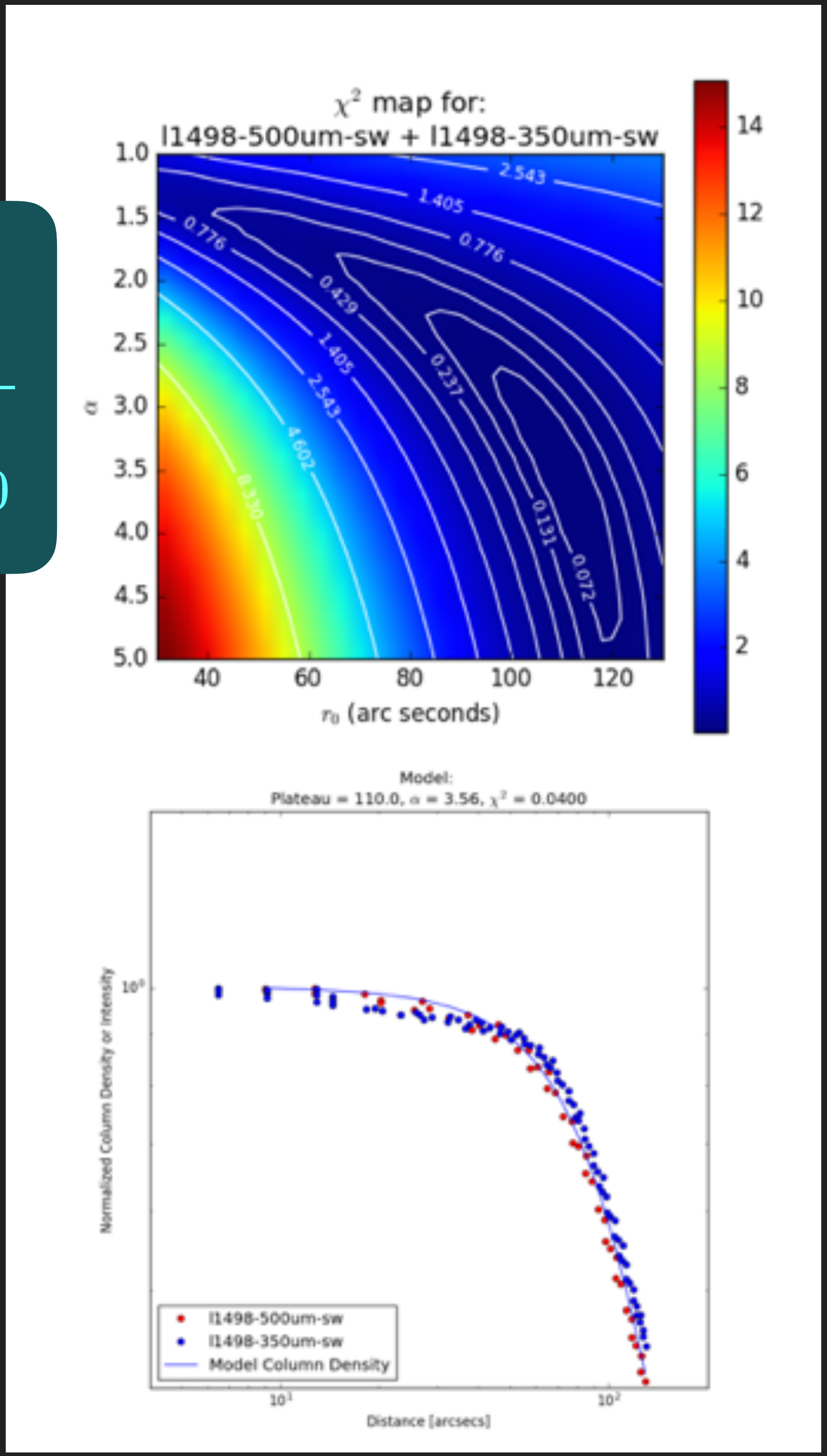

Parameter	This work	Tafalla et al. 2004
$n_0(H_2)$	$6.5 \times 10^{-4} cm^{-3}$	$9.4 \times 10^{-4} cm^{-3}$
r_0	110''	75''
α	3.8	3.5
$N(H_2)$	$3.4 \times 10^{22} cm^{-2}$	$3.4 \times 10^{22} cm^{-2}$

L1498 PHYSICAL STRUCTURE

- T_k = 10 K (Tafalla et al. 2006).
- $\sigma(r=\infty)$ = 0.265 km/s (Tafalla et al. 2006)
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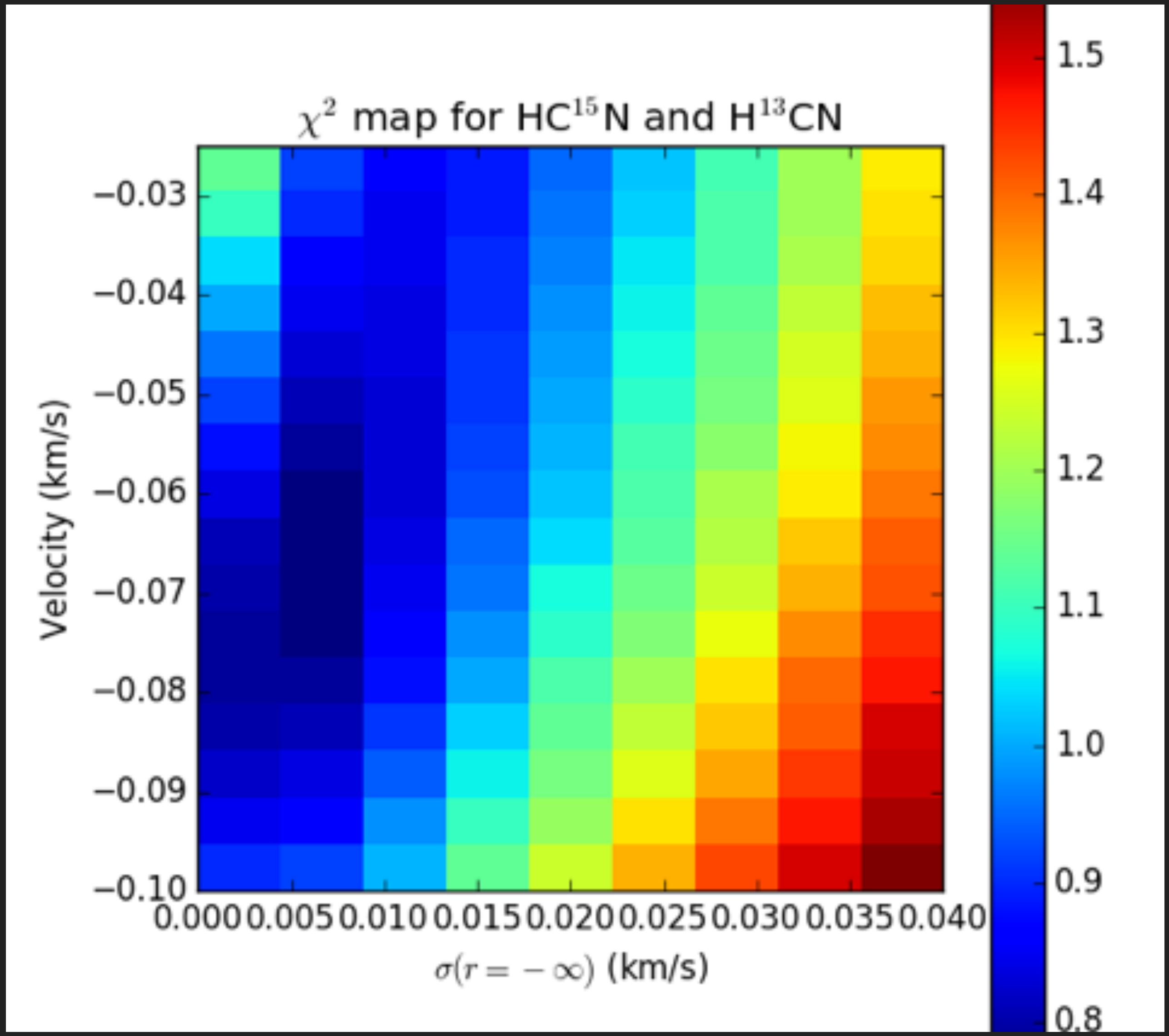

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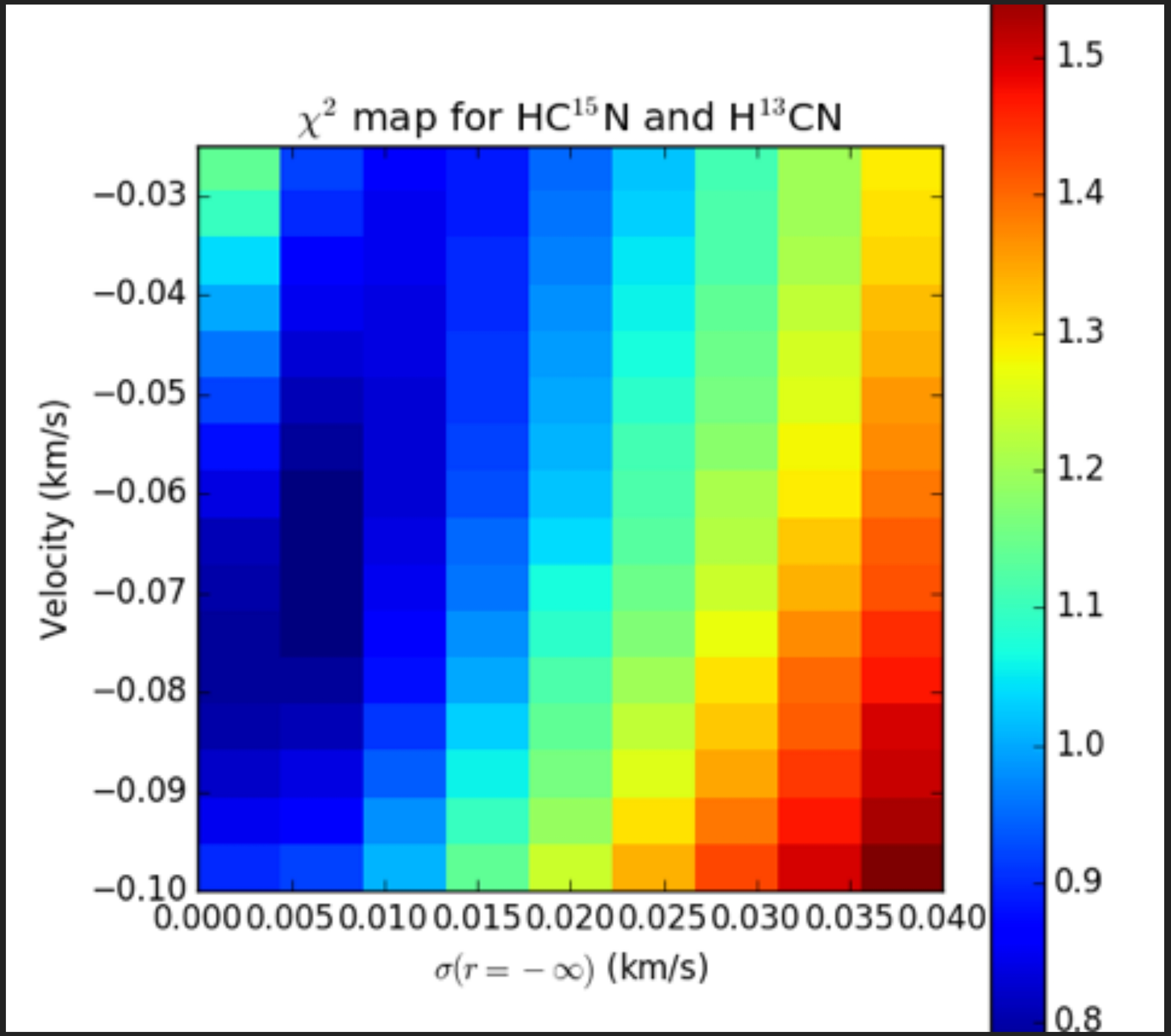
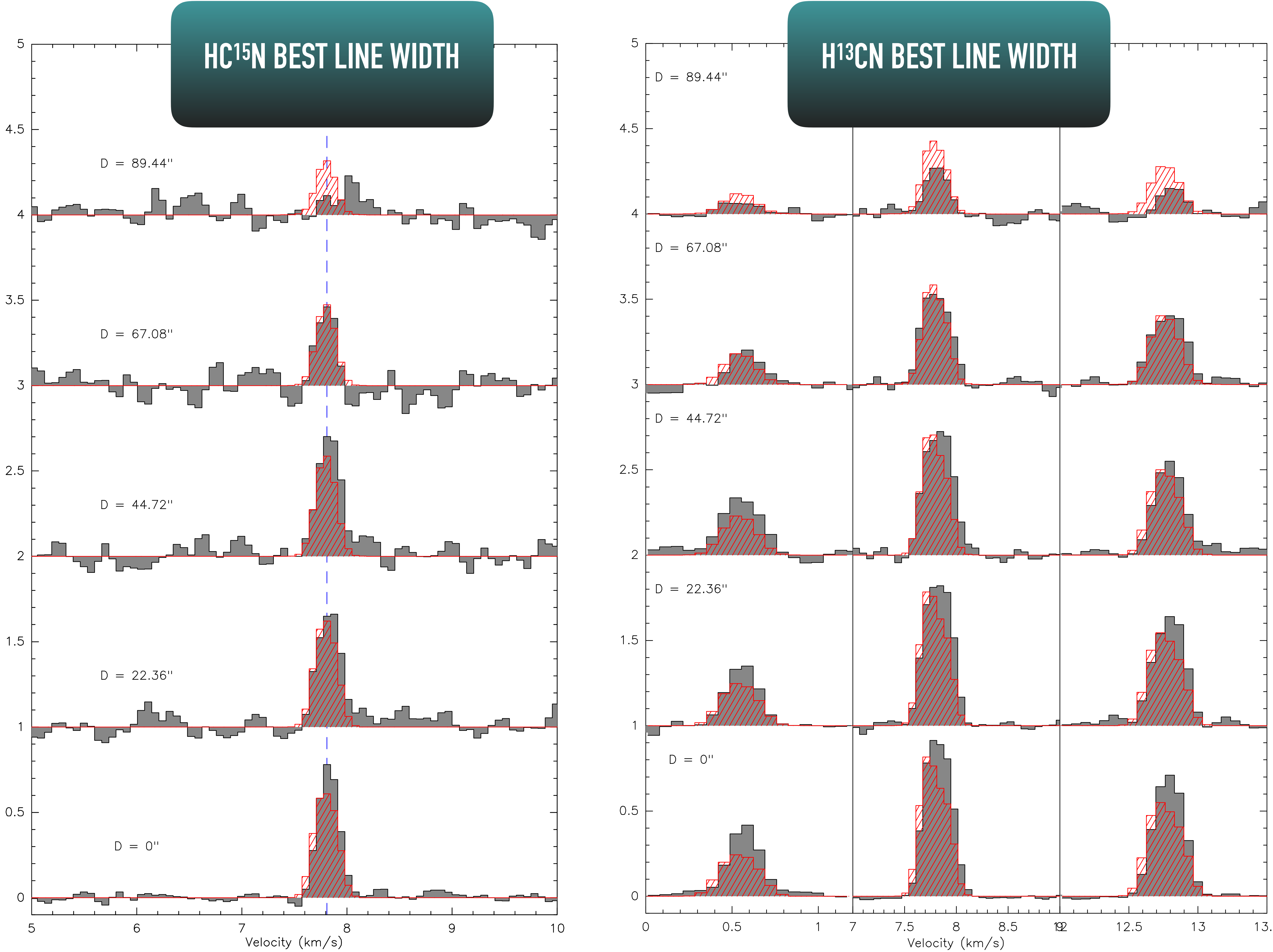
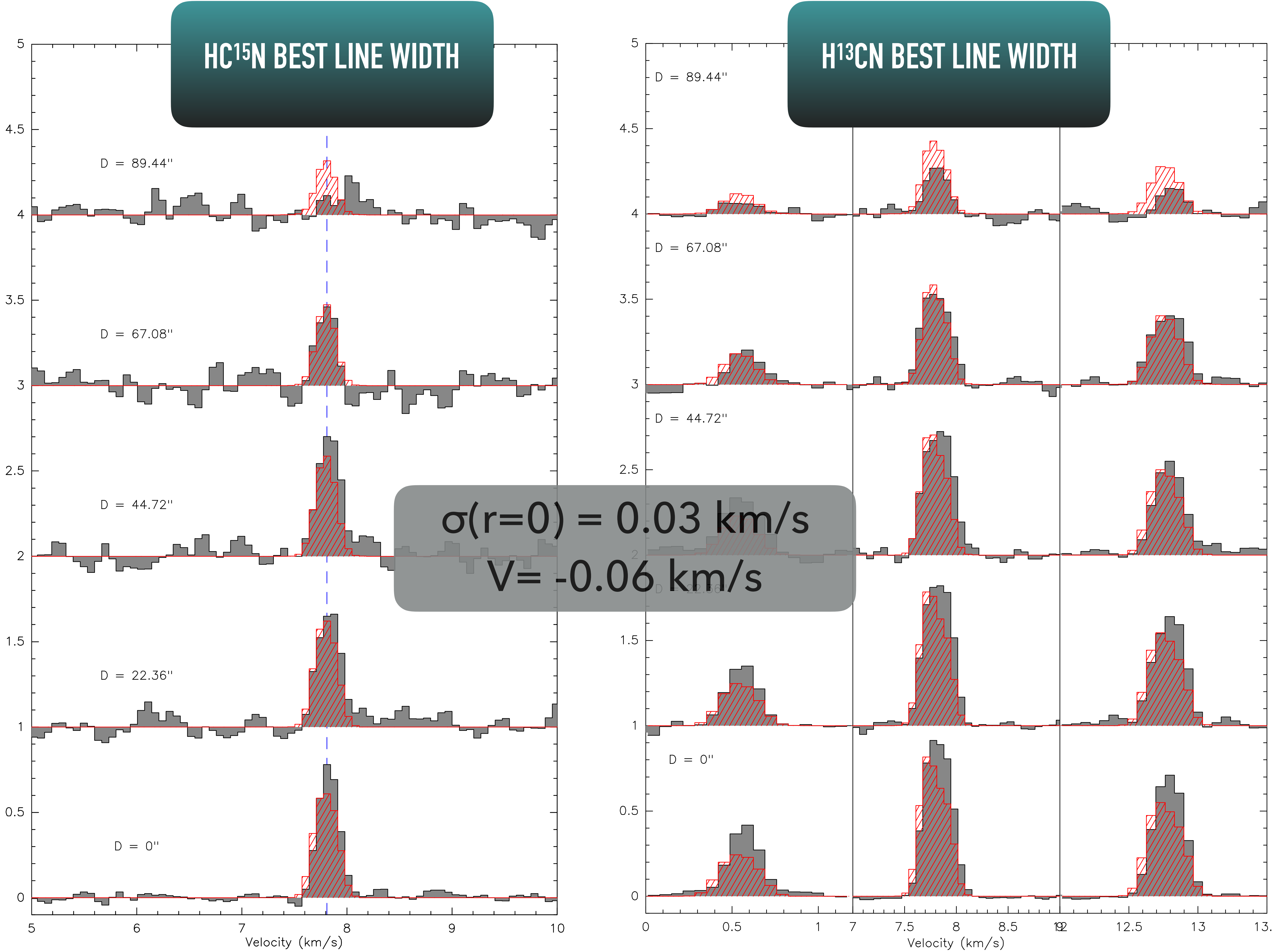




HC15N BEST LINE WIDTH
H13CN BEST LINE WIDTH
D = 89.44''
D = 67.08''
D = 44.72''
D = 22.36''
D = 0''
Velocity (km/s)
Velocity (km/s)



HC15N BEST LINE WIDTH
H13CN BEST LINE WIDTH
σ(r=0) = 0.03 km/s
V= -0.06 km/s
D = 89.44''
D = 67.08''
D = 44.72''
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D = 0''
Velocity (km/s)

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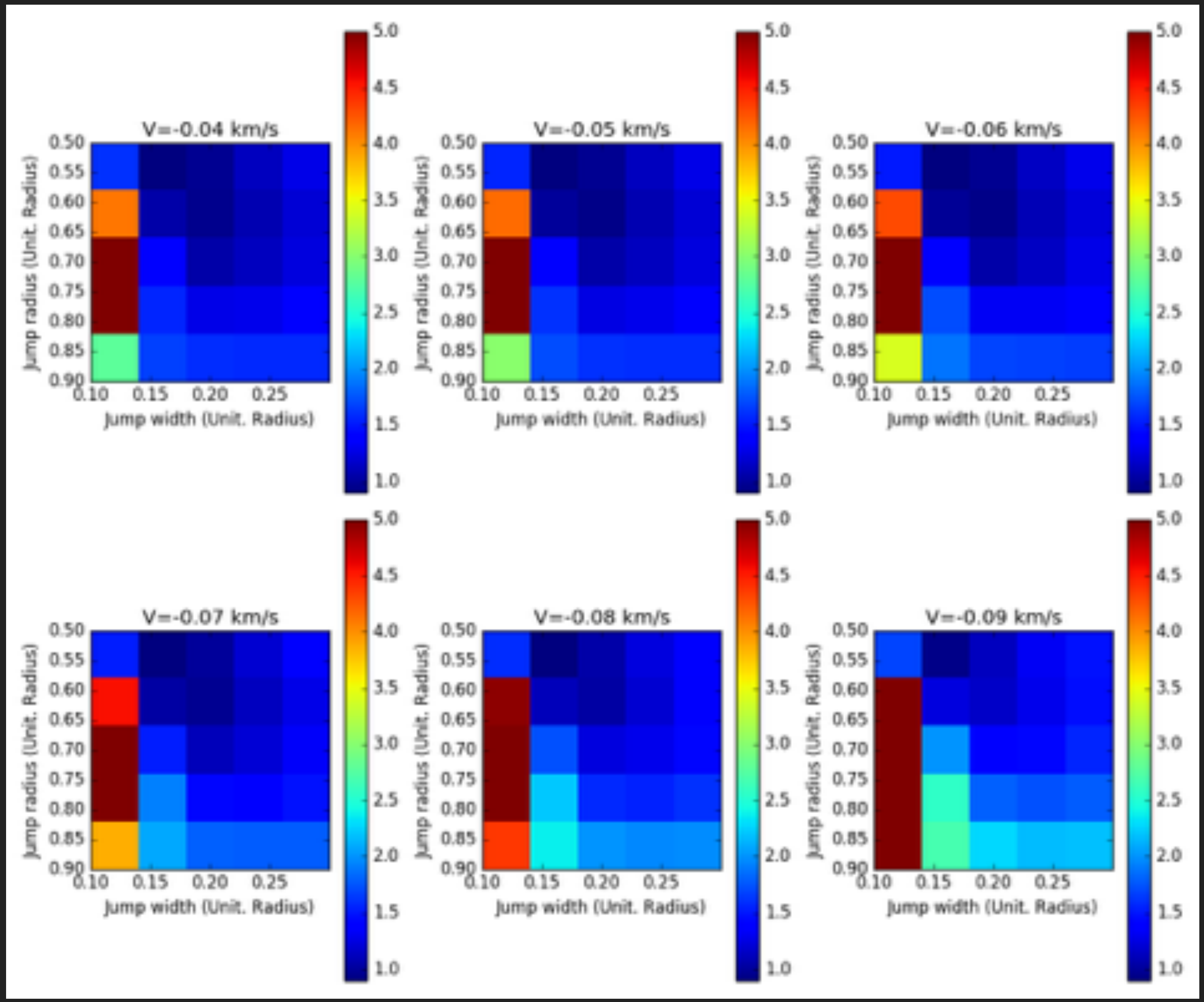
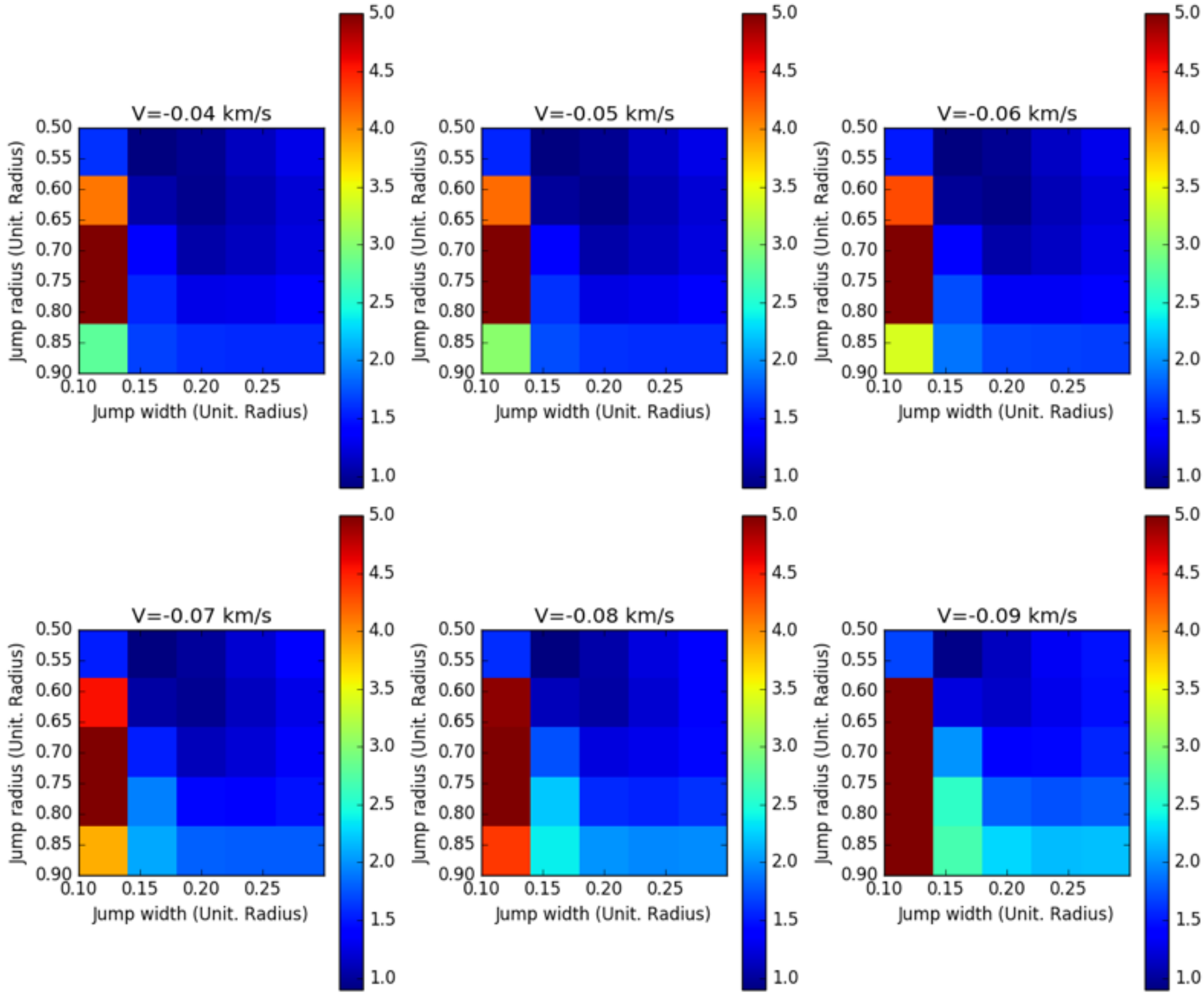
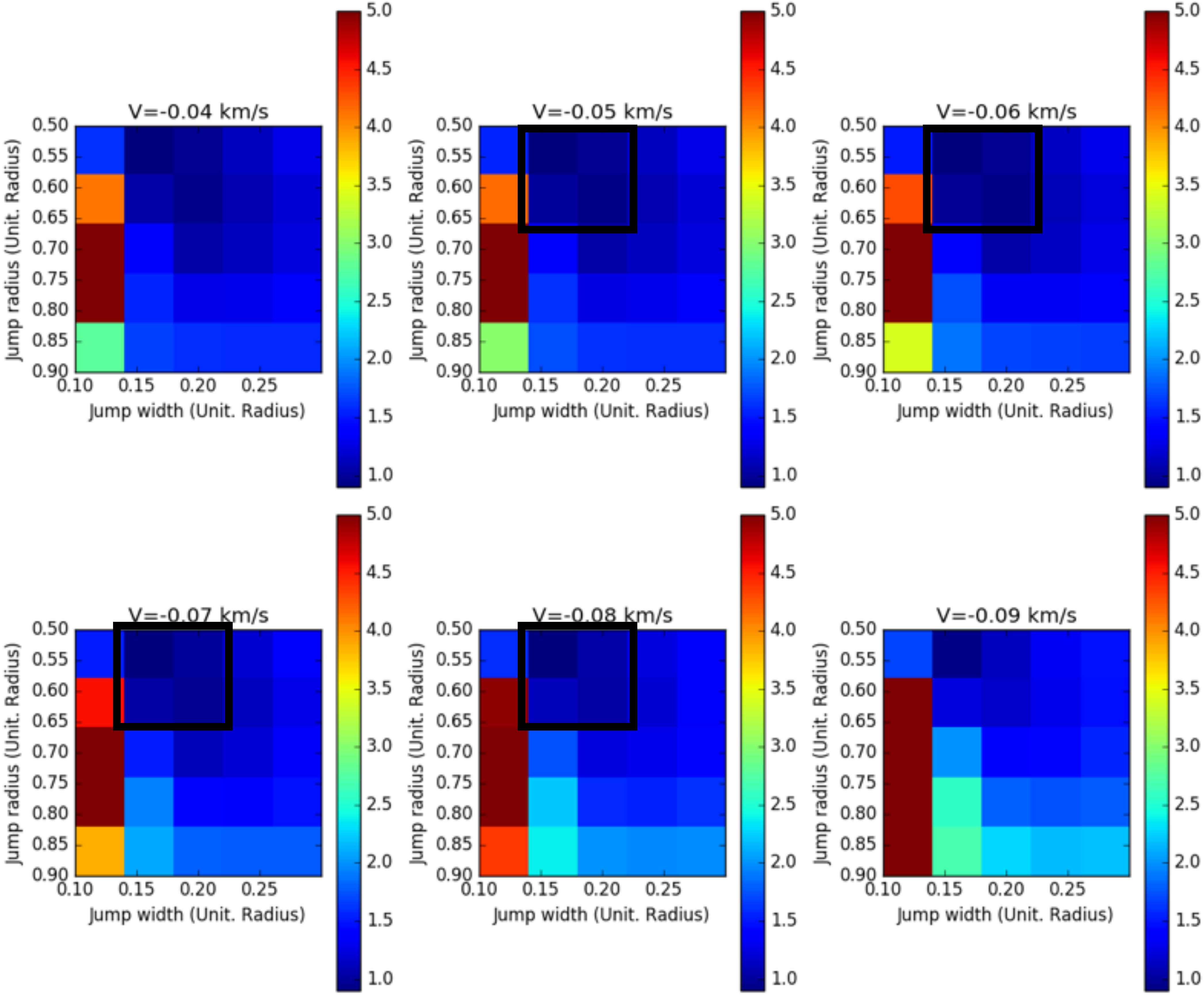



V=-0.04 km/s
V=-0.05 km/s
V=-0.06 km/s
V=-0.07 km/s
V=-0.08 km/s
V=-0.09 km/s
Jump radius (Unit. Radius)
Jump width (Unit. Radius)
0.50
0.55
0.60
0.65
0.70
0.75
0.80
0.85
0.90
0.10
0.15
0.20
0.25
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0



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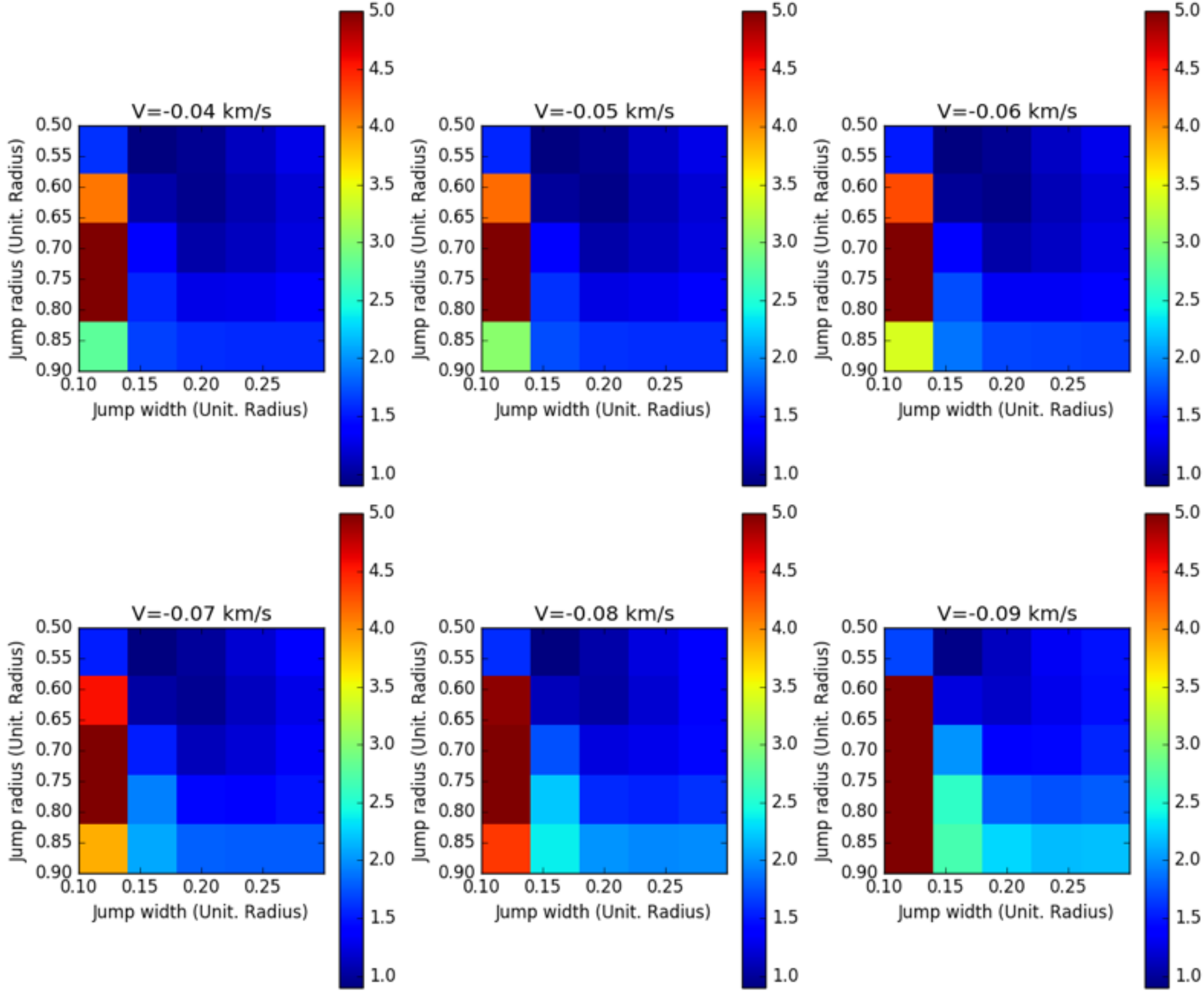
1.0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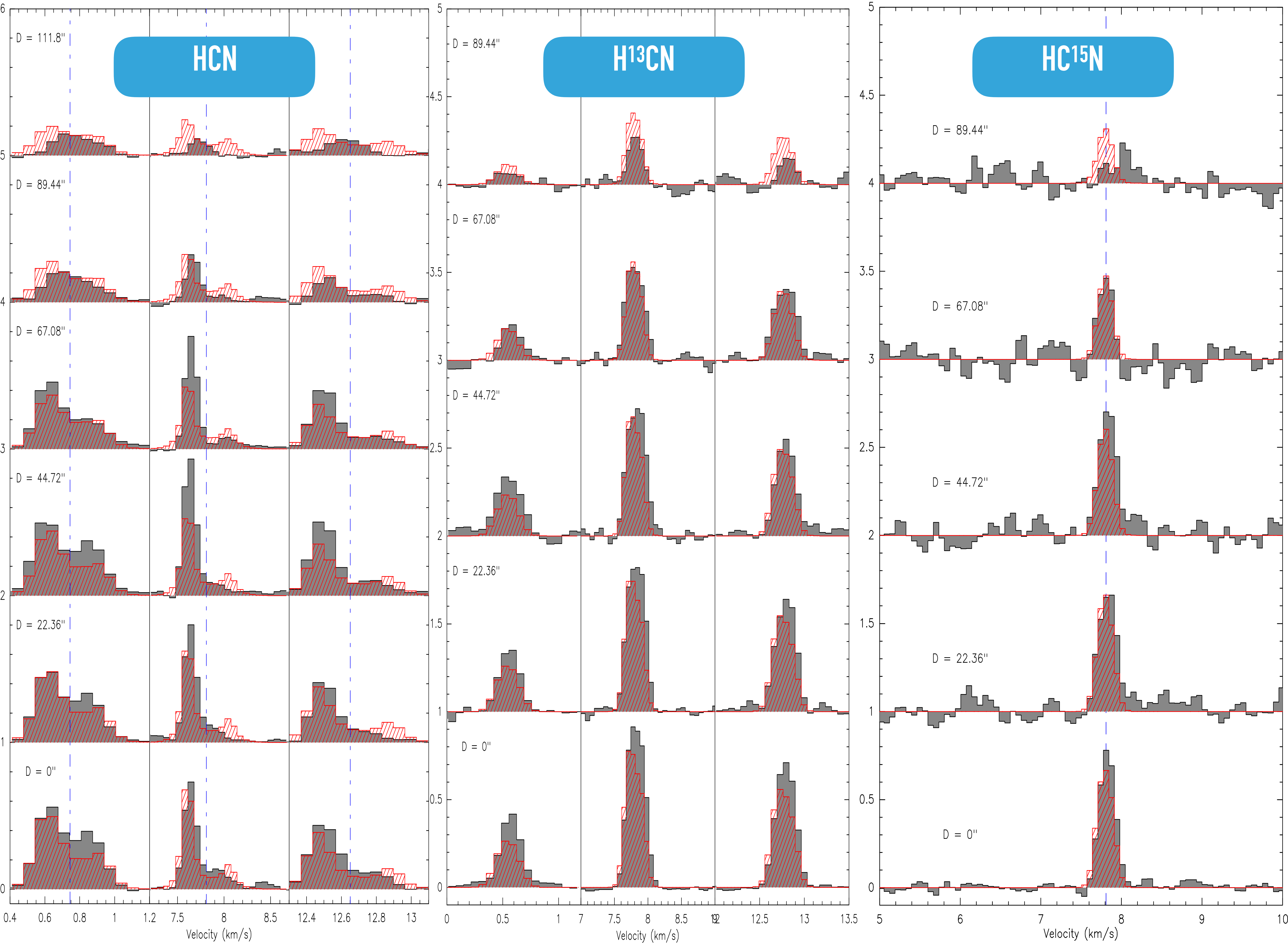

HCN
H13CN
HC15N
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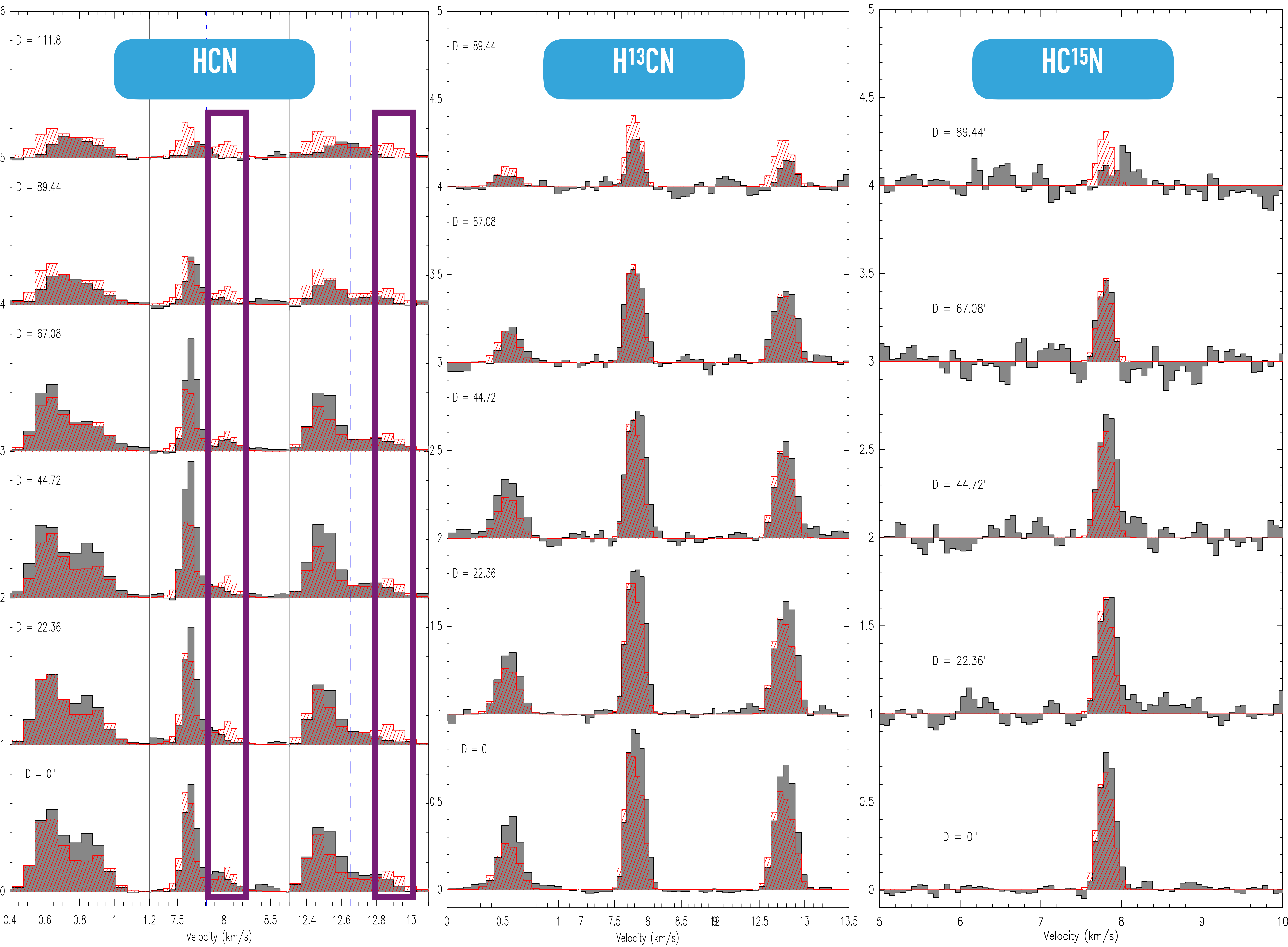
Velocity (km/s)
Velocity (km/s)
Velocity (km/s)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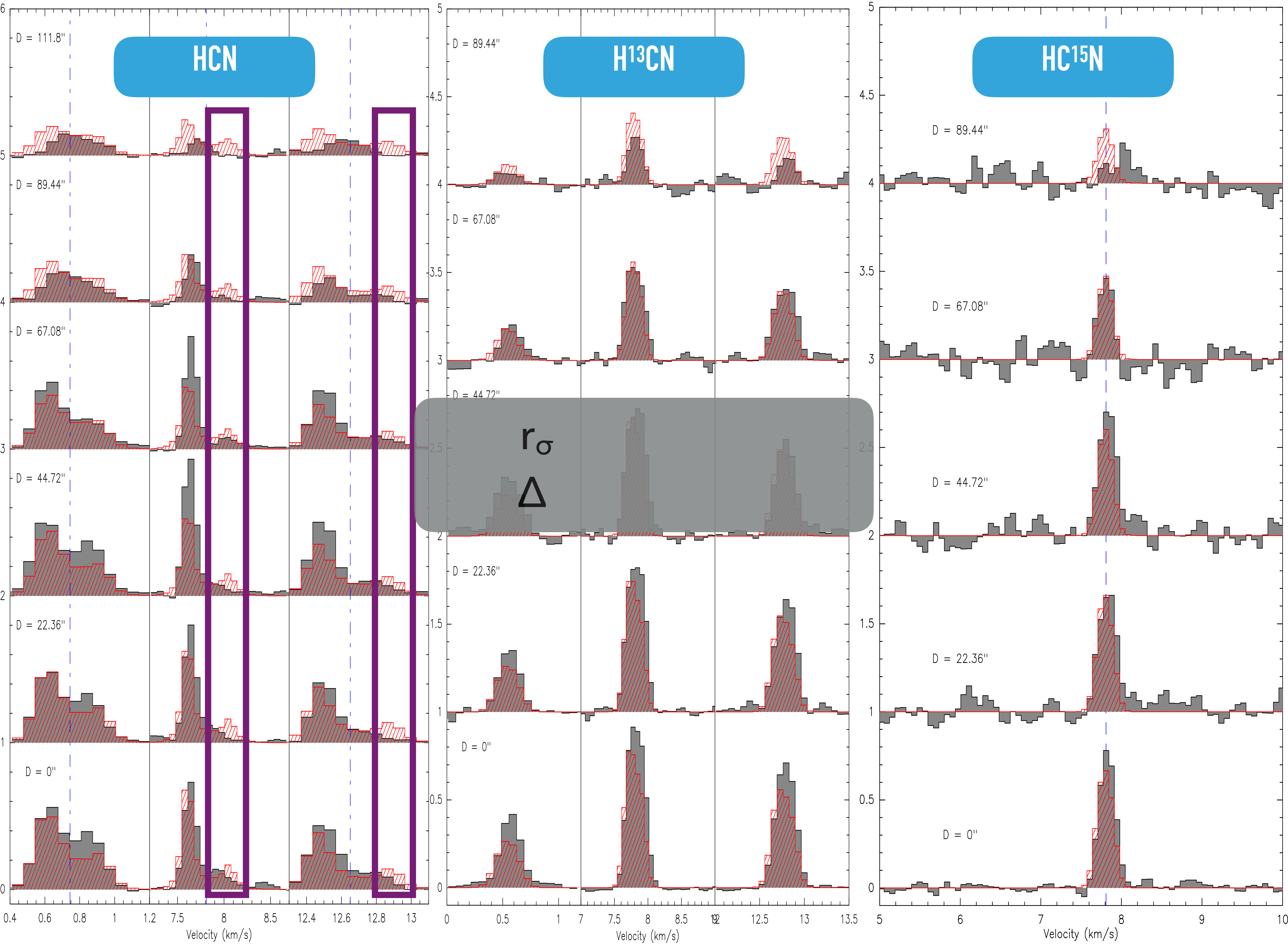
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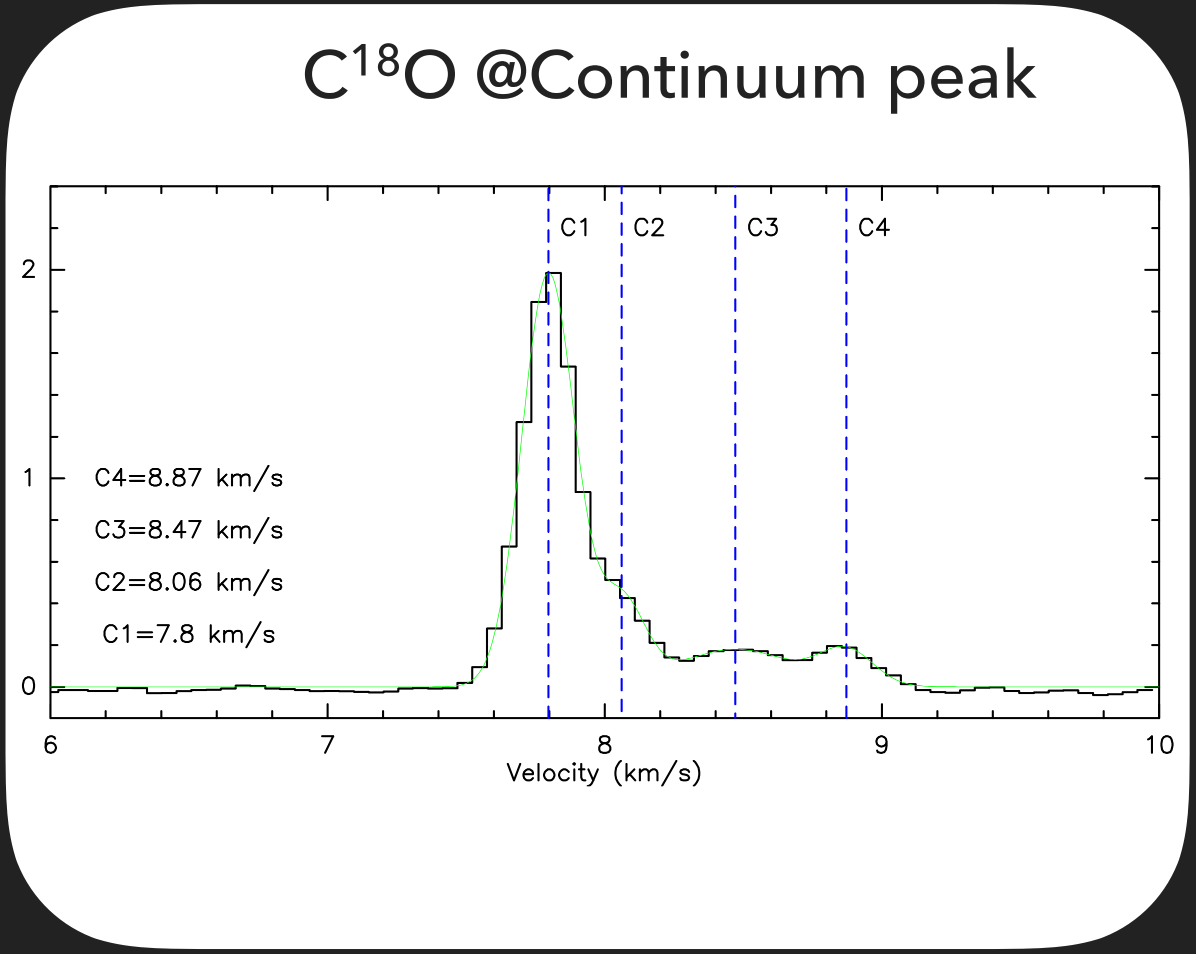
FOREGROUND LAYER

- Tafalla et al. 2006:
  ^{13}CO component to the SW @ ~8.2 km/s.
- Also seen in our $C^{18}O$ spectra @ 8.1 km/s.
- HCN in diffuse medium?
  - Liszt & Lucas 2001
  - Very low T_{ex}



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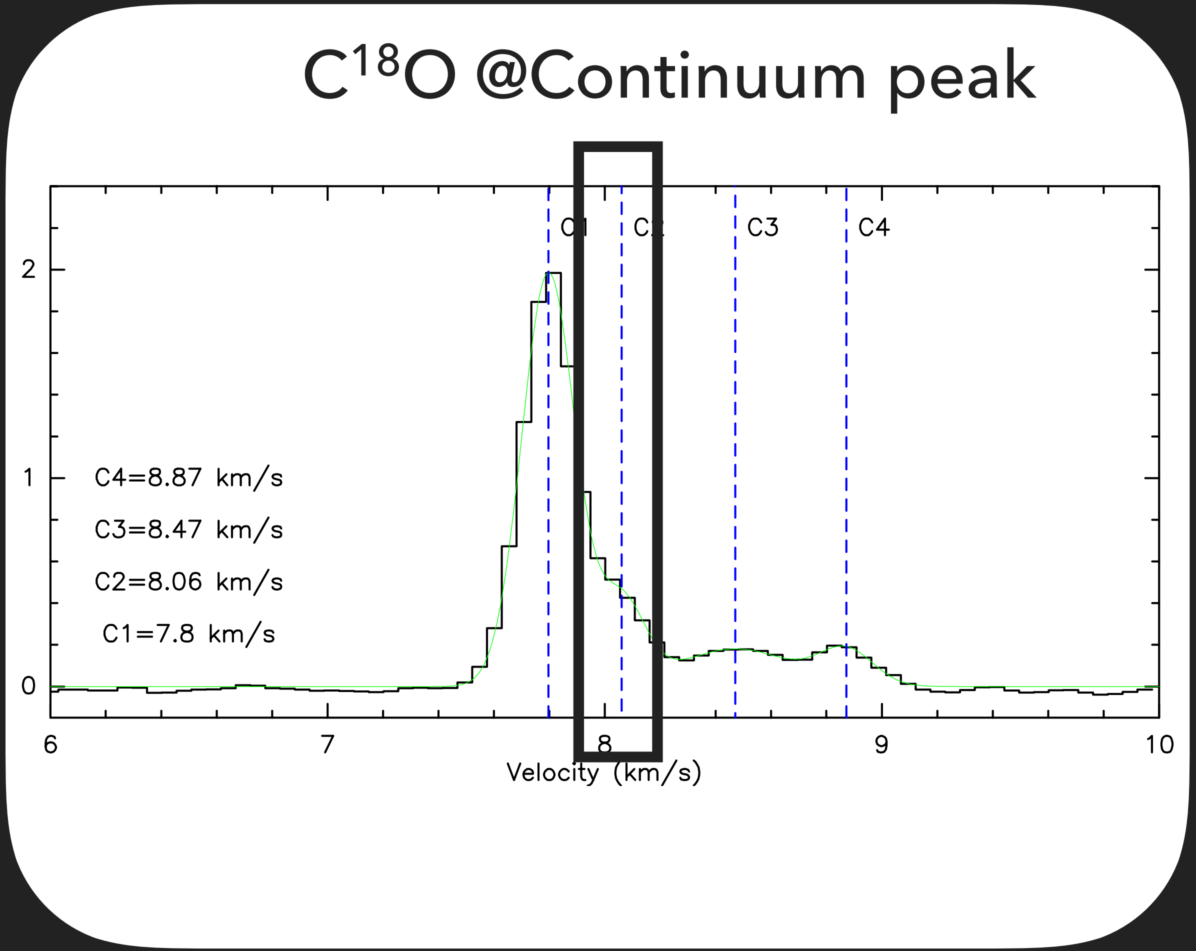
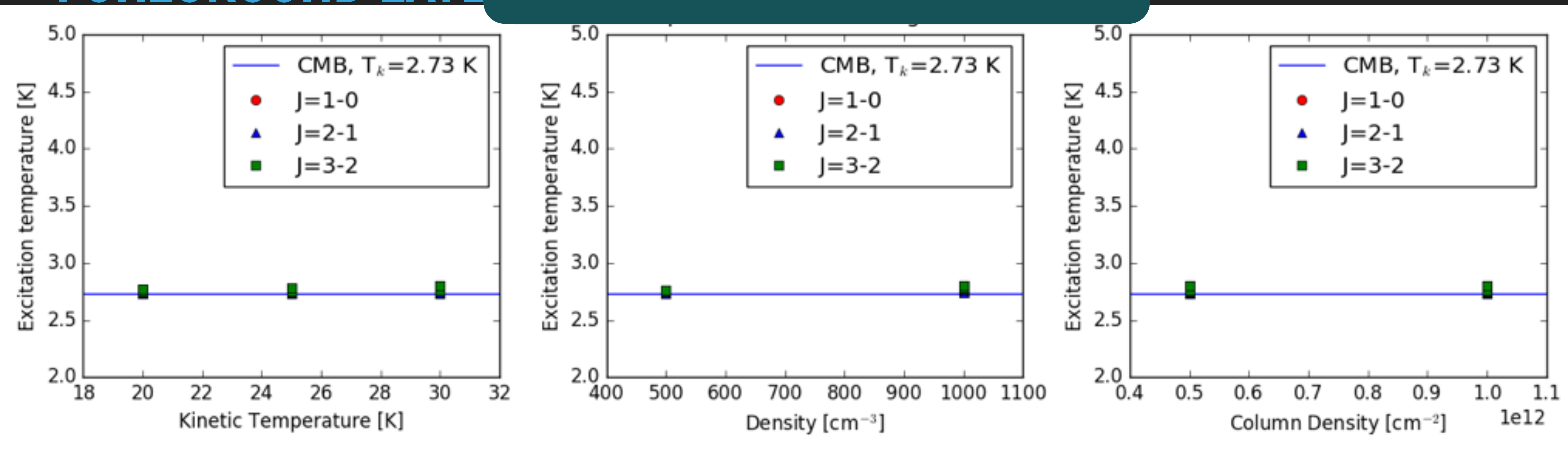


FOREGROUND LAYE

RADEX SIMULATION OF A FOREGROUND LAYER



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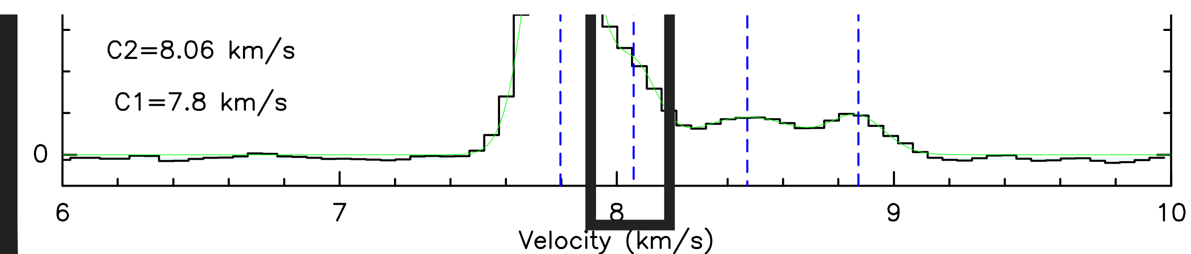

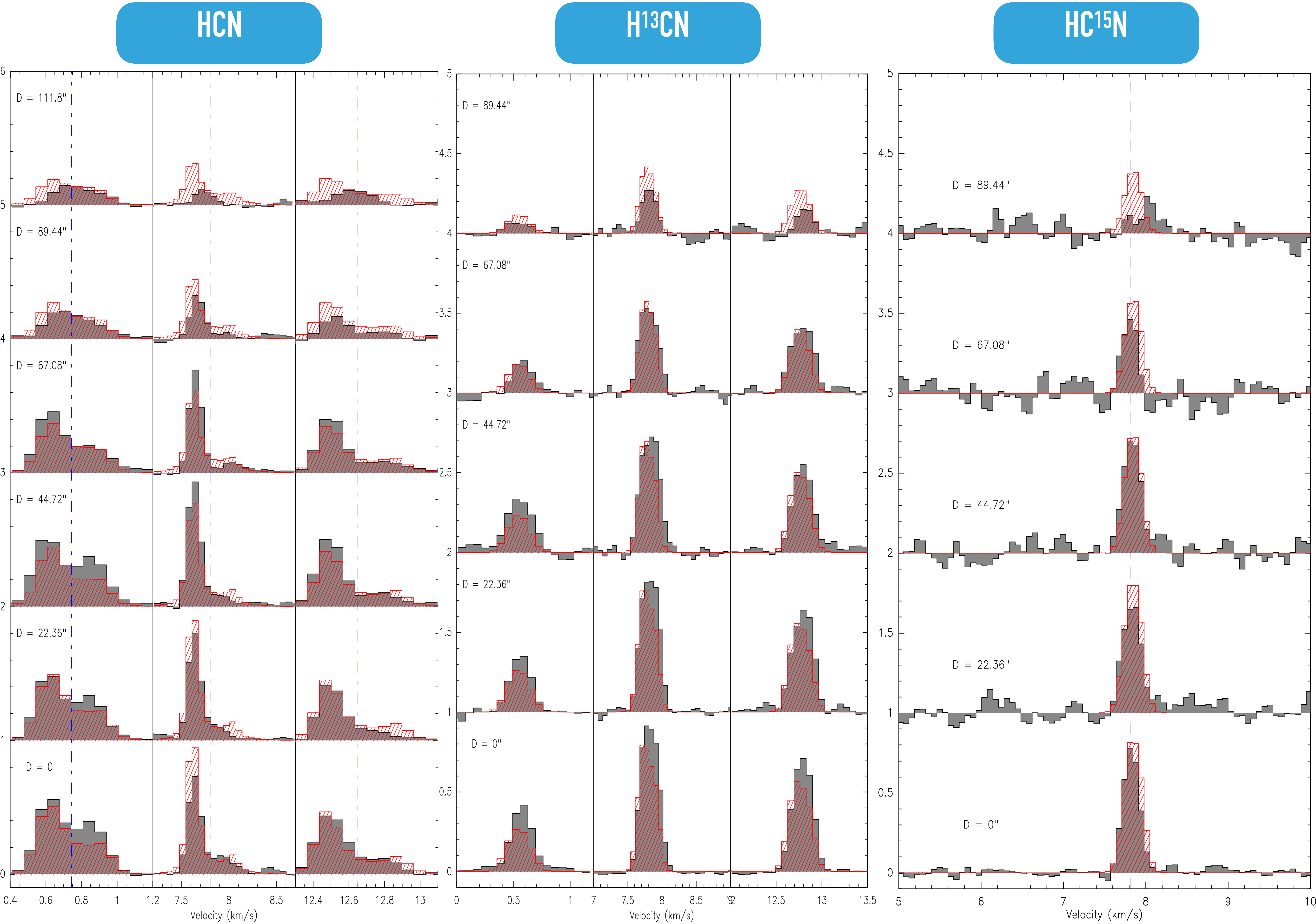
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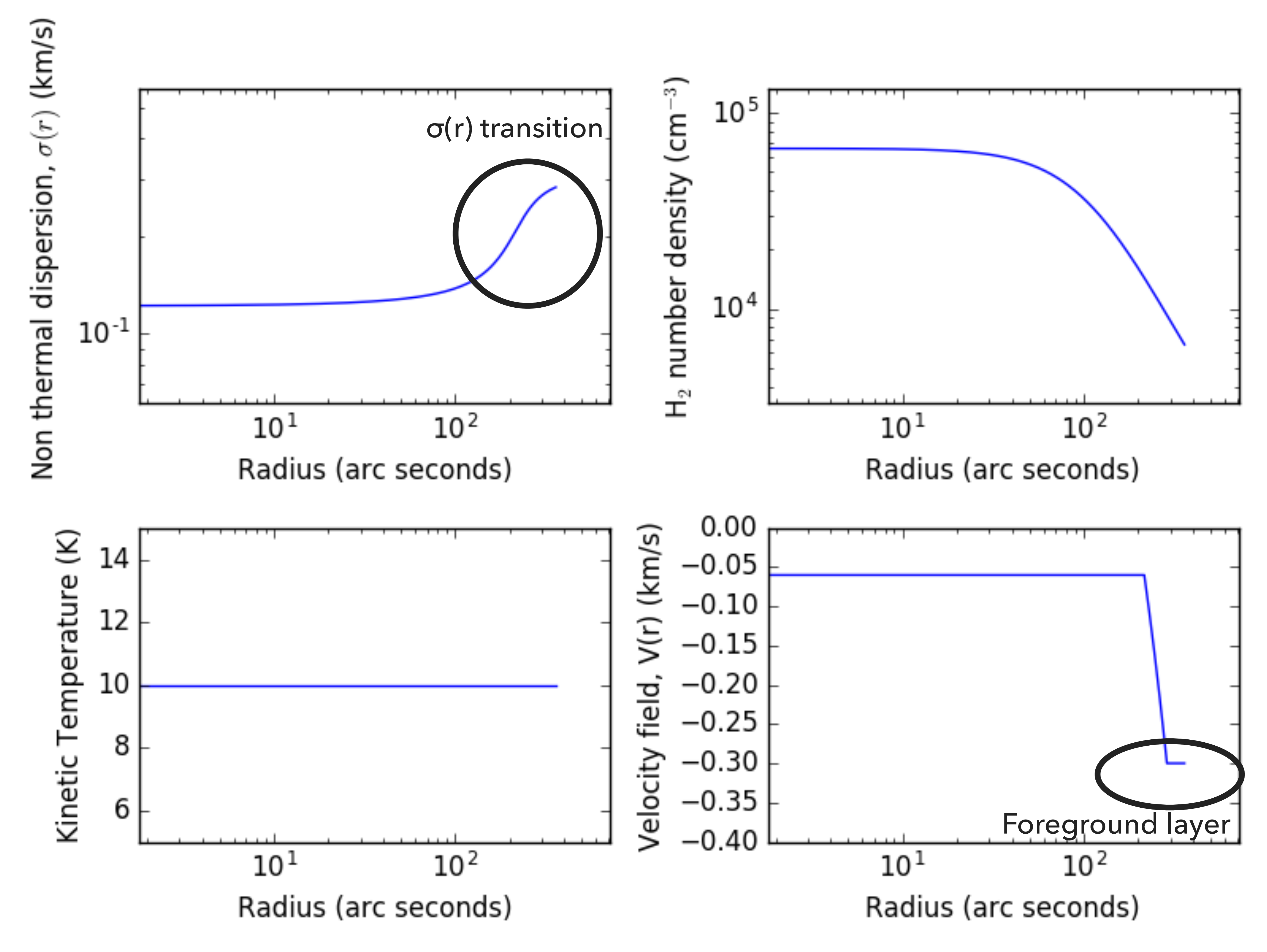
Modelled Physical Structure for L1498



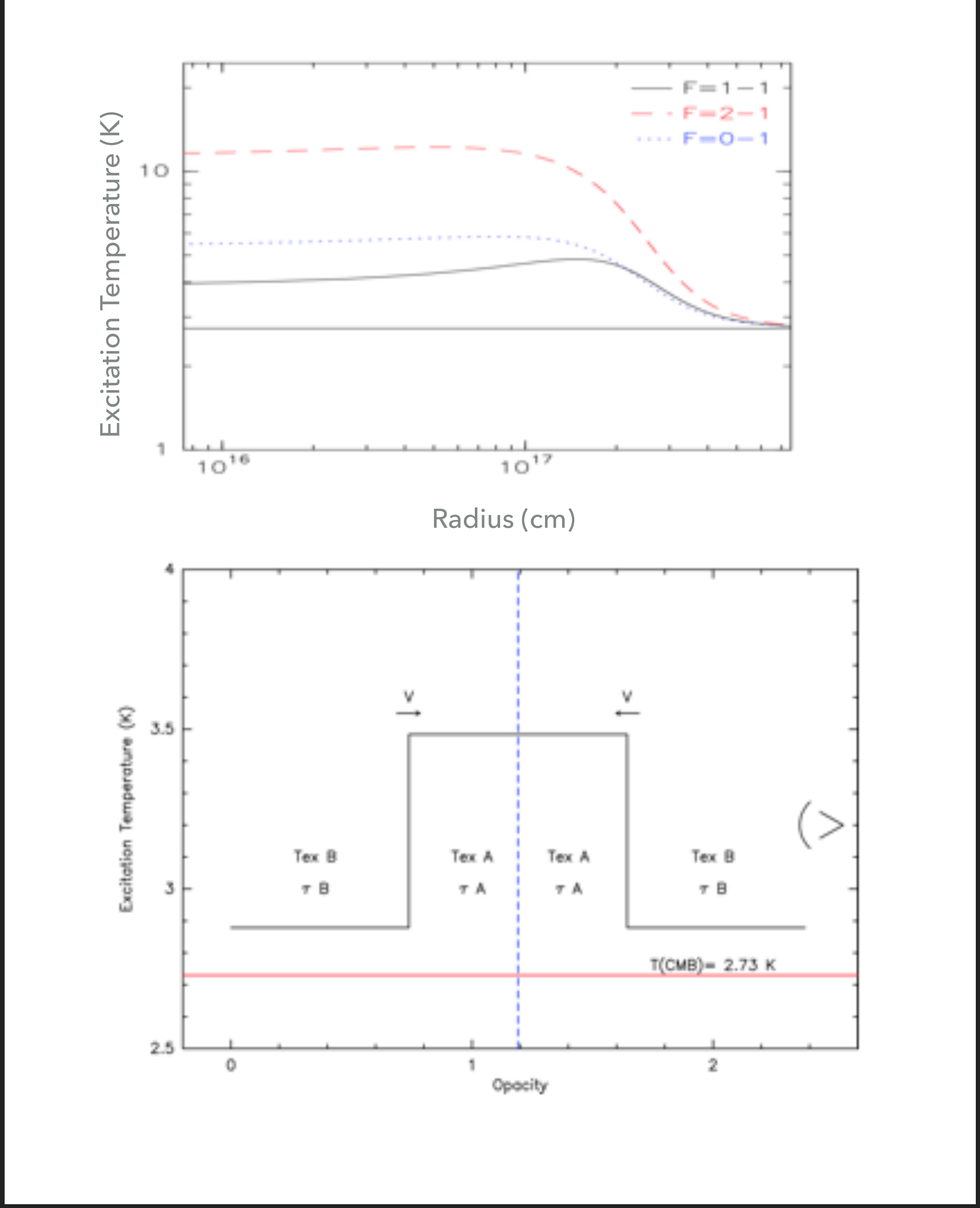
Species	Abundance ($/H_2$) This work	Column density (cm^{-2}) This work	Abundance ($/H_2$) Padovani (2011)	Column density (cm^{-2}) Padovani (2011)
HCN	$2.5 \pm 1.0 \times 10^{-9}$	$8.5 \pm 3.4 \times 10^{13}$	$3.92 \pm 0.96 \times 10^{-9}$	$1.24 \pm 0.18 \times 10^{14}$
$H^{13}CN$	1.0×10^{-10}	3.4×10^{12}	$5.76 \pm 1.41 \times 10^{-11}$	$1.82 \pm 0.26 \times 10^{12}$
$HC^{15}N$	1.5×10^{-11}	5.1×10^{11}		

Radius (arc seconds)

Radius (arc seconds)

UNDERSTANDING THE EMERGING SPECTRA

- Modelled T_{ex} profiles analogous to a two slab model.
- Toy model to understand the emerging spectra:
  - two slabs colliding with two other slabs with the same T_{ex} and τ structure (Similar to: de Vries et al. 2005).



ANALYTICAL REASONING FOR THE ANOMALIES

- From toy model:

$$\frac{\Delta T_b^{01}}{\Delta T_b^{11}} \approx \frac{J_\nu(T_{ex,B}^{01}) + (J_\nu(T_{ex,A}^{01}) - J_\nu(T_{ex,B}^{01}))e^{-\tau_B^{01}} - J_\nu(T_{CMB})}{J_\nu(T_{ex,B}^{11}) - J_\nu(T_{CMB})}$$

- From the radiative pumping: $T_{ex,A}^{01} > T_{ex,B}^{01} > T_{ex,B}^{11}$.
- Thus: $\Delta T_b^{01} > \Delta T_b^{11}$ if:
    - $T_{ex}^{11} < T_{ex}^{01}$

ANALYTICAL REASONING FOR THE ANOMALIES

- From toy model:

Self-absorption in J,F =1,1-0,1 revealing the HFA

$$\frac{\Delta T_b^{01}}{\Delta T_b^{11}} \approx \frac{J_\nu(T^{01}_{ex,B}) + (J_\nu(T^{01}_{ex,A}) - J_\nu(T^{01}_{ex,B}))e^{-\tau_B^{01}} - J_\nu(T_{CMB})}{J_\nu(T^{11}_{ex,B}) - J_\nu(T_{CMB})}$$

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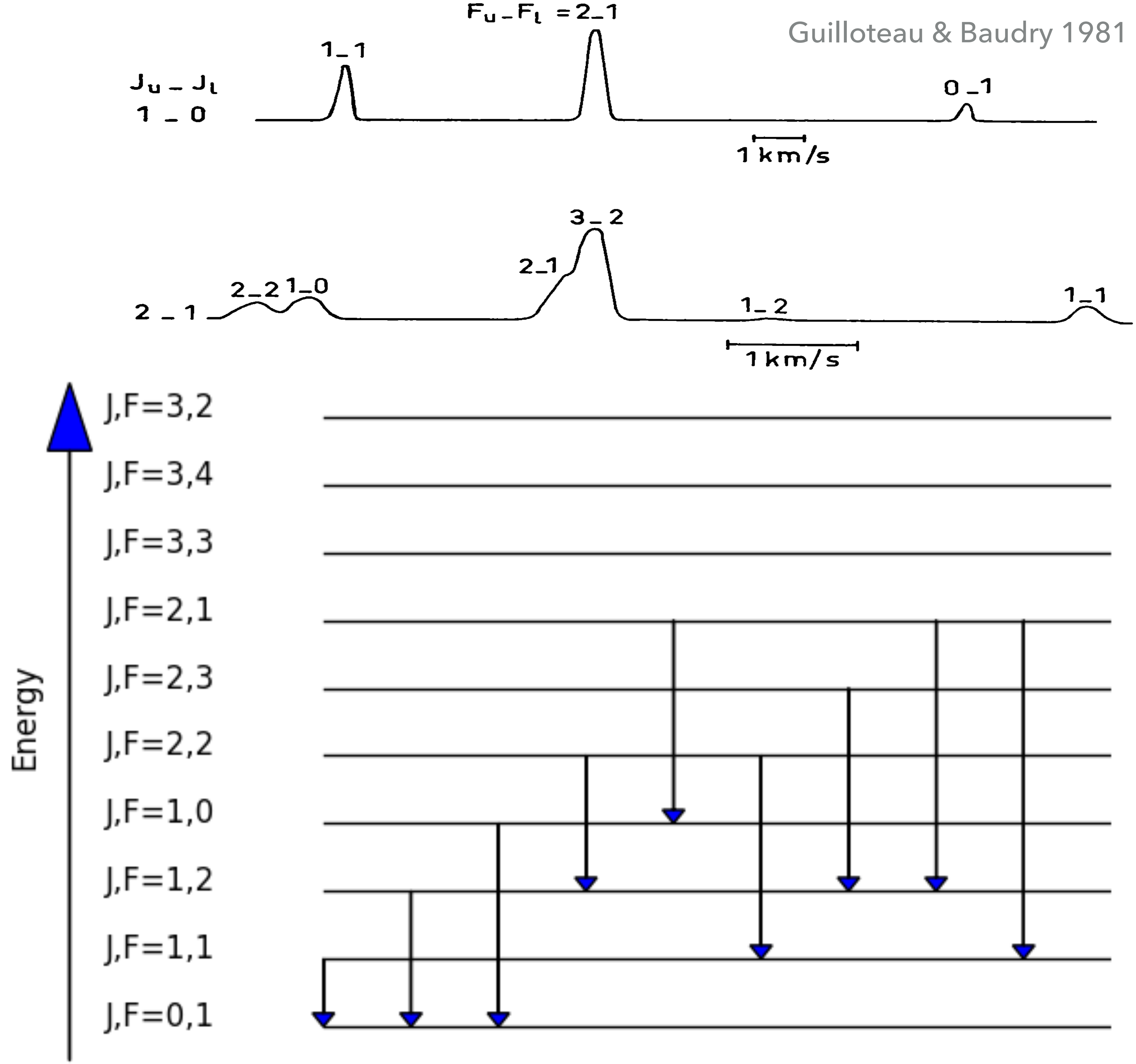
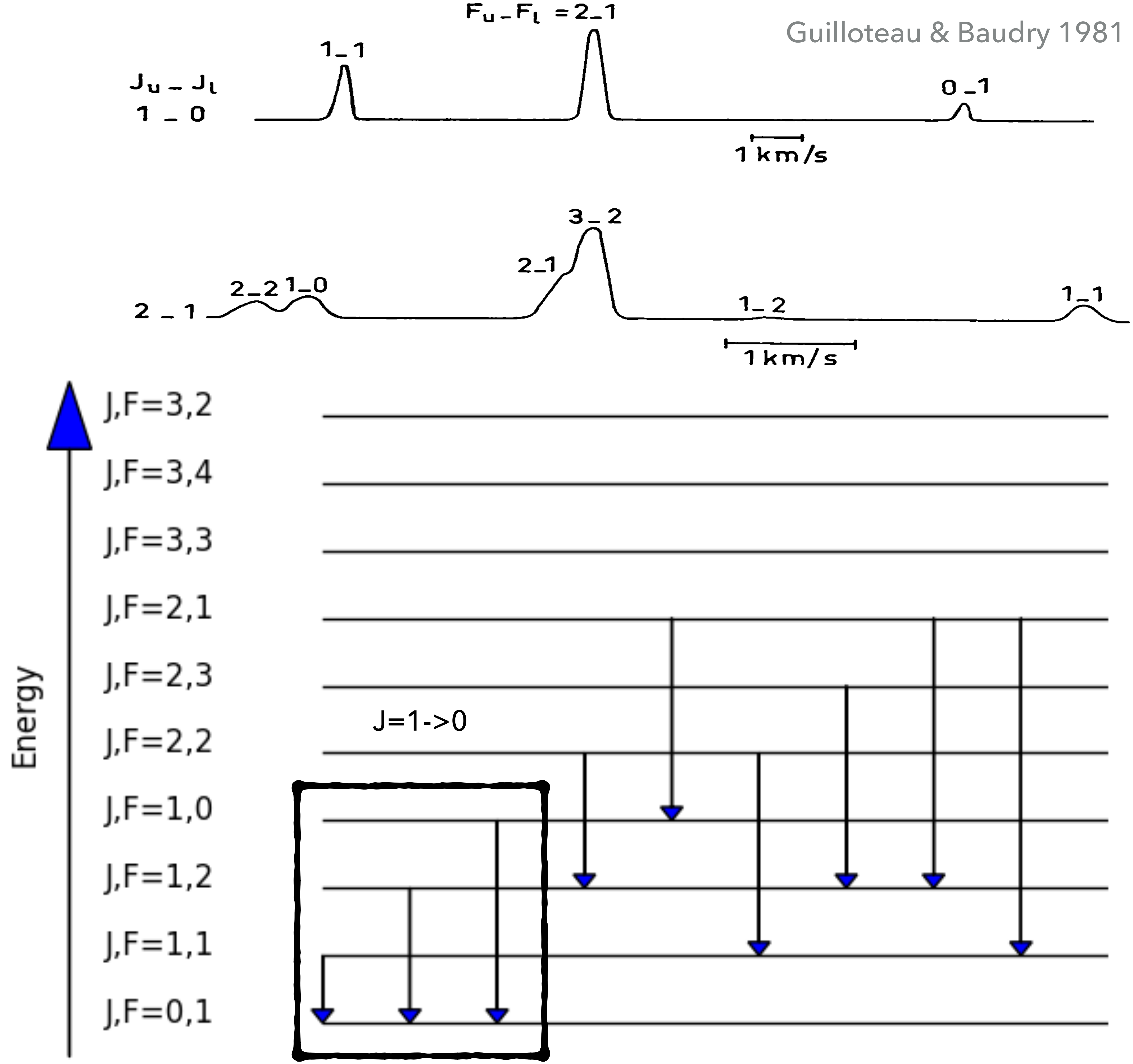

Guilloteau & Baudry 1981
Fu – Fl = 2–1
1–1
Ju – Jl
1 – 0
0 –1
1 km/s
3 – 2
2–1
2–2 1–0
2 – 1
1– 2
1–1
1 km/s
Energy
J,F=3,2
J,F=3,4
J,F=3,3
J,F=2,1
J,F=2,3
J,F=2,2
J,F=1,0
J,F=1,2
J,F=1,1
J,F=0,1


Guilloteau & Baudry 1981
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1 - 0
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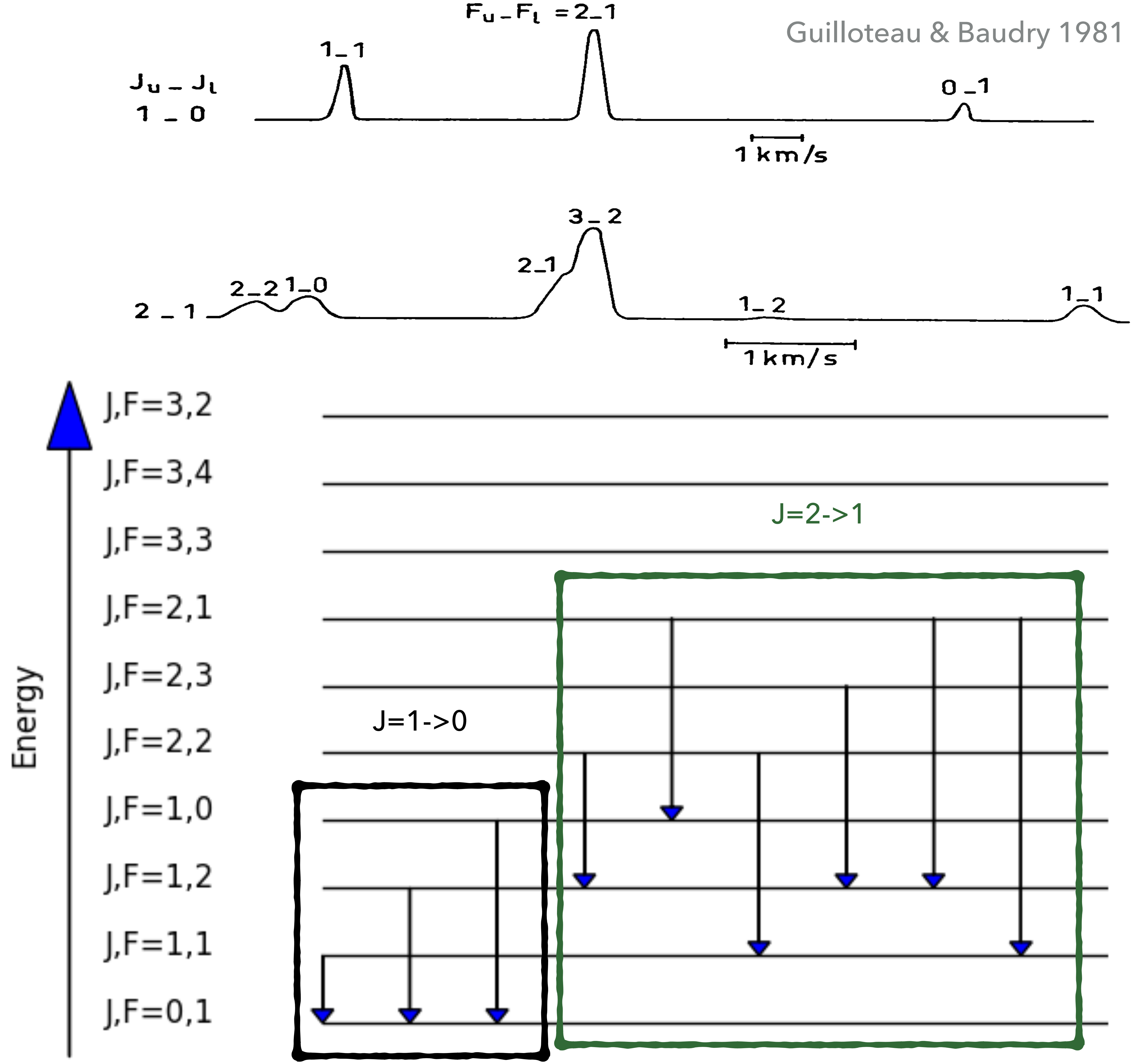
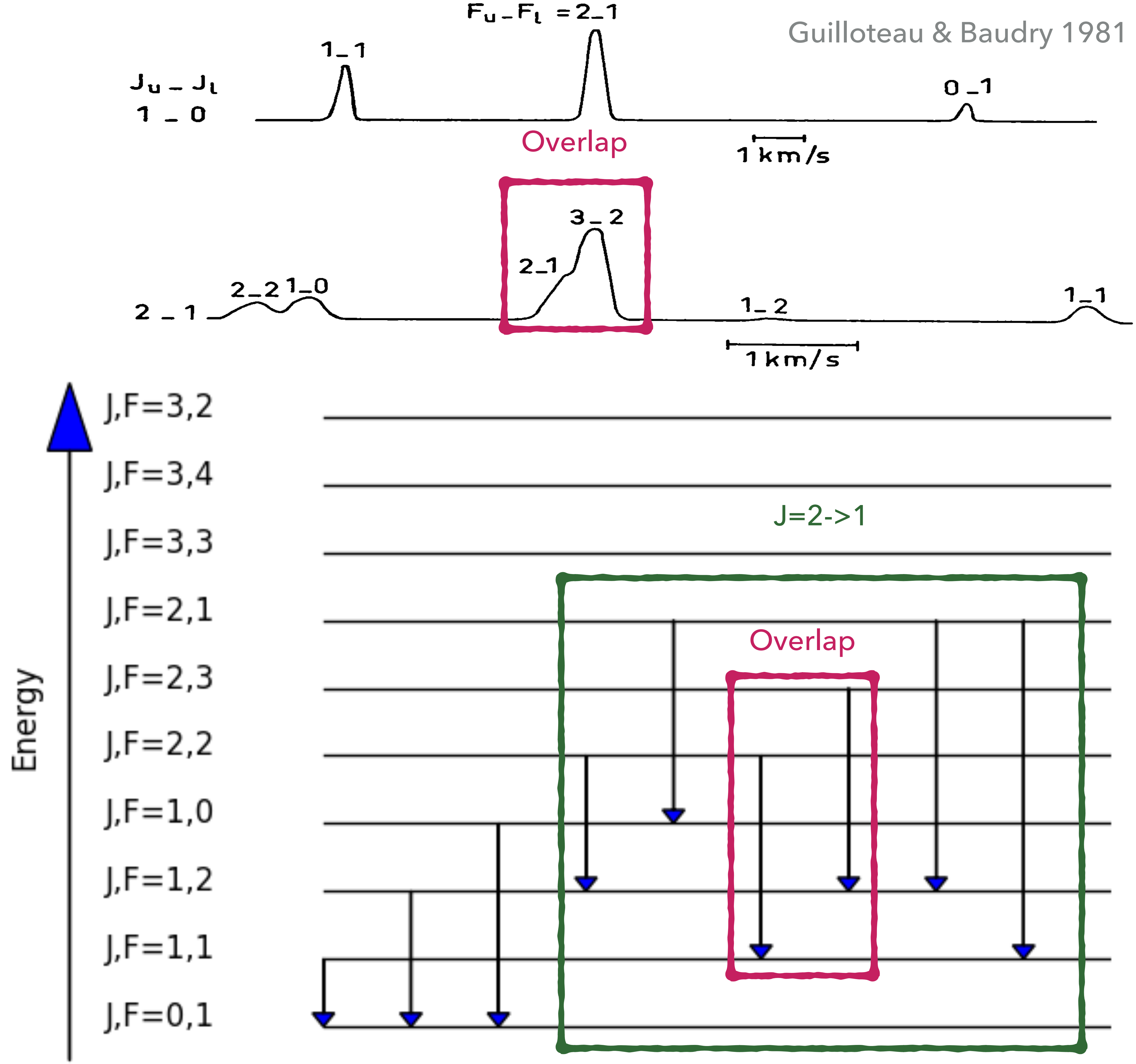
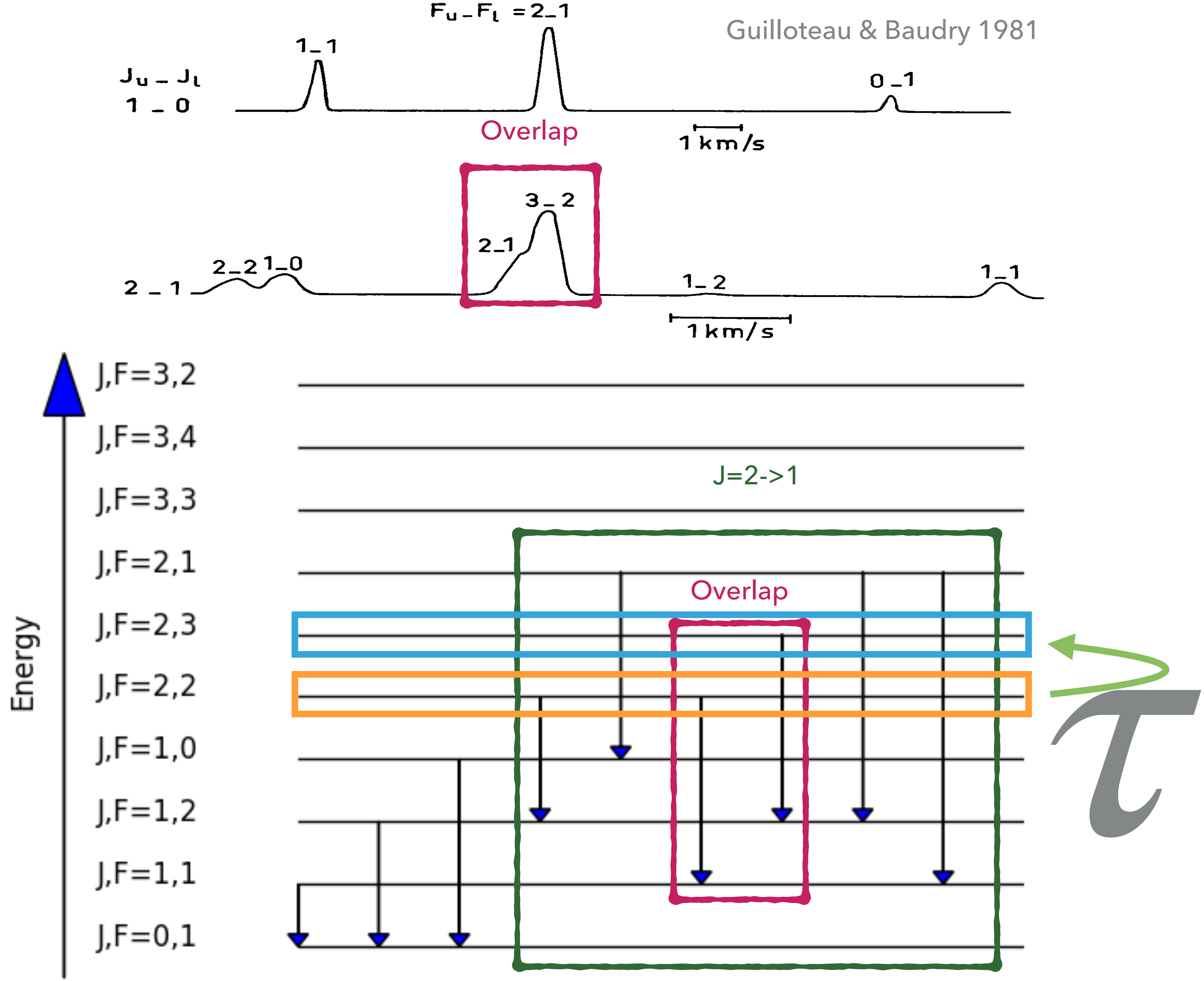
1 km/s
3-2
2-1
2-2 1-0
2 - 1
1-2
1-1
1 km/s
Energy
J,F=3,2
J,F=3,4
J,F=3,3
J,F=2,1
J,F=2,3
J,F=2,2
J,F=1,0
J,F=1,2
J,F=1,1
J,F=0,1
J=1->0

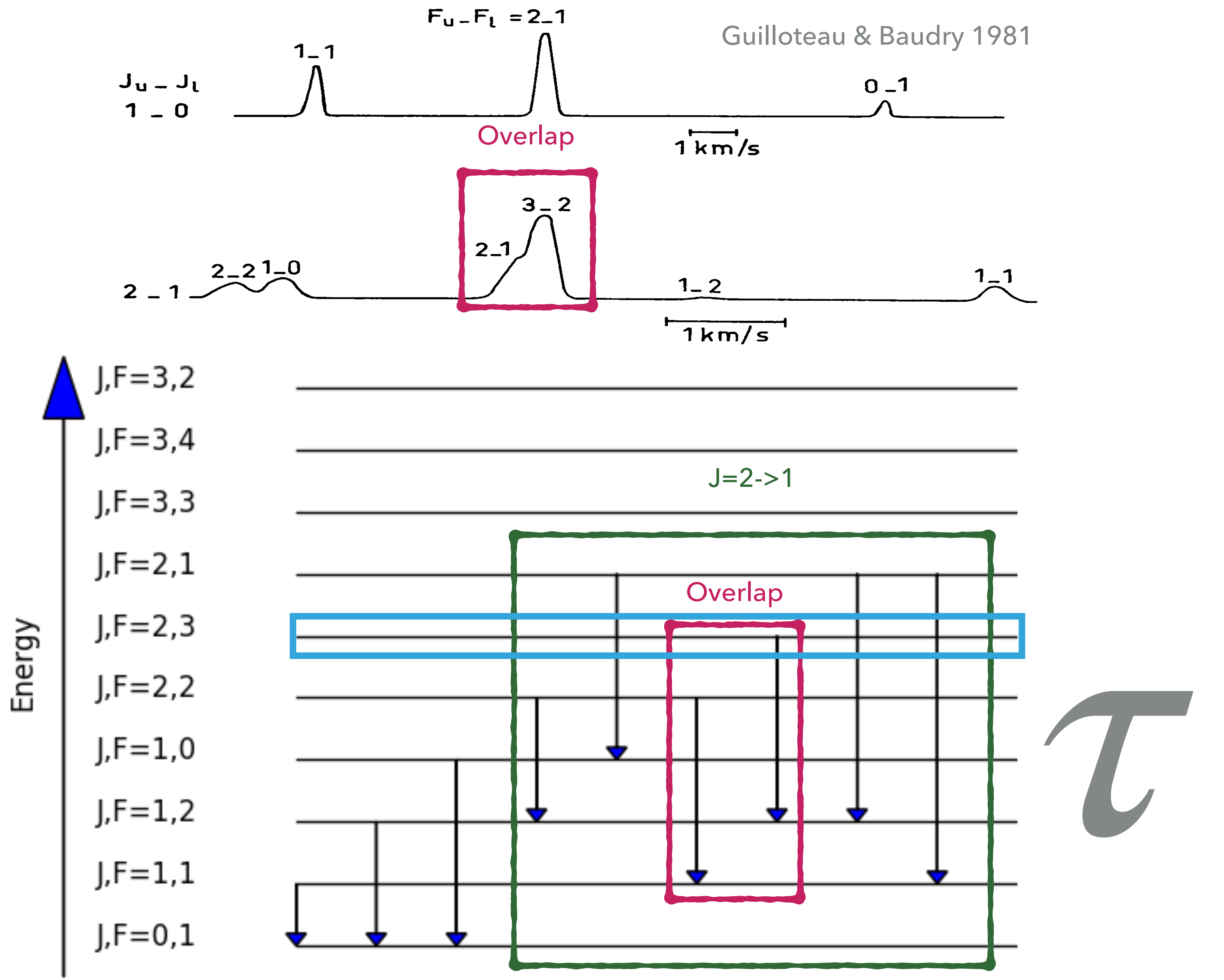


Guilloteau & Baudry 1981
Fu – Fl = 2–1
1–1
Ju – Jl
1 – 0
0 –1
1 km/s
3 – 2
2–1
2–2 1–0
2 – 1
1– 2
1–1
1 km/s
Energy
J,F=3,2
J,F=3,4
J,F=3,3
J,F=2,1
J,F=2,3
J,F=2,2
J,F=1,0
J,F=1,2
J,F=1,1
J,F=0,1
J=2->1
J=1->0

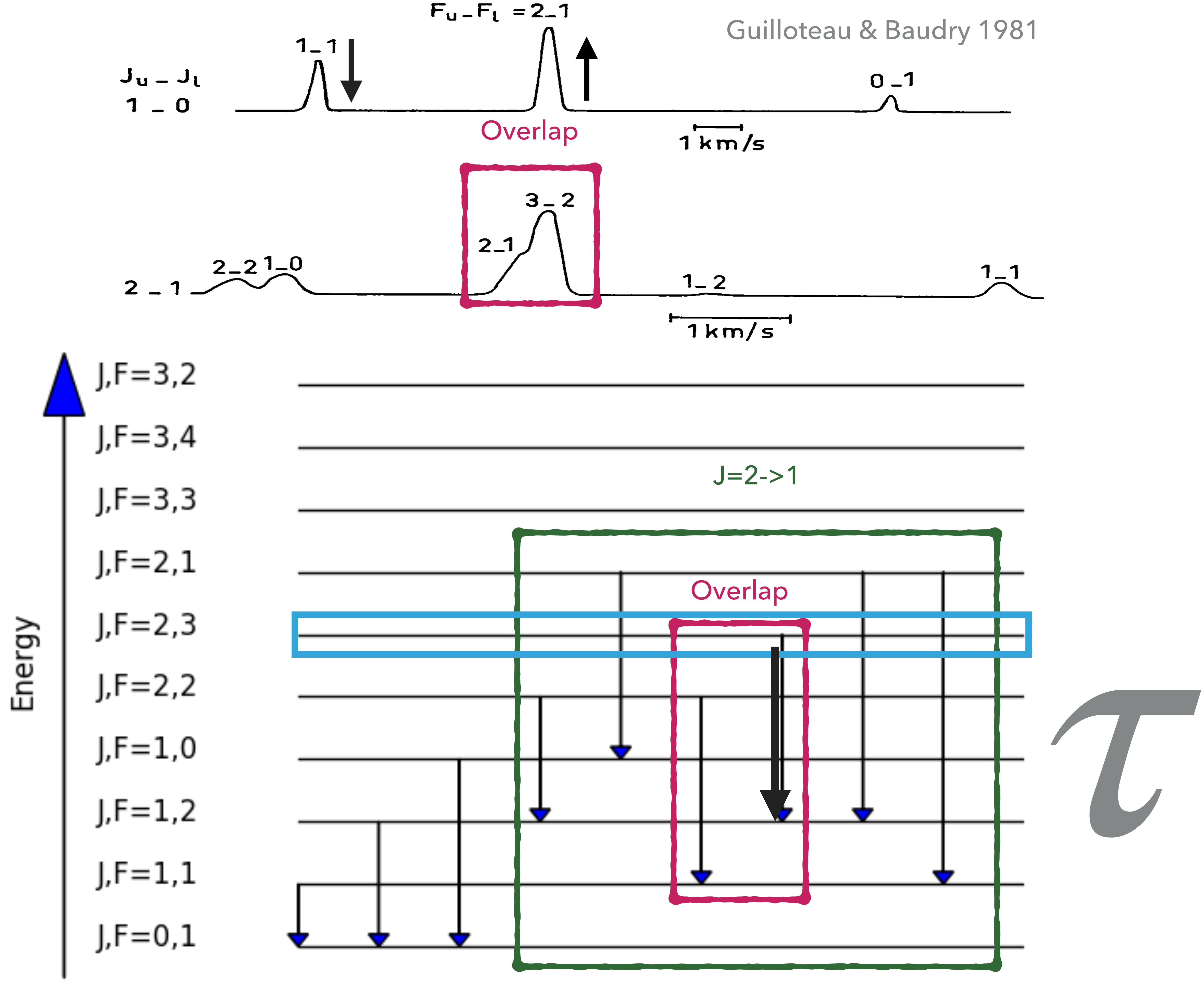


Guilloteau & Baudry 1981
Fu - Fl = 2-1
1-1
Ju - Jl
1 - 0
0-1
Overlap
1 km/s
3-2
2-1
2-2 1-0
2 - 1
1-2
1-1
1 km/s
Energy
J,F=3,2
J,F=3,4
J,F=3,3
J,F=2,1
J,F=2,3
J,F=2,2
J,F=1,0
J,F=1,2
J,F=1,1
J,F=0,1
J=2->1
Overlap

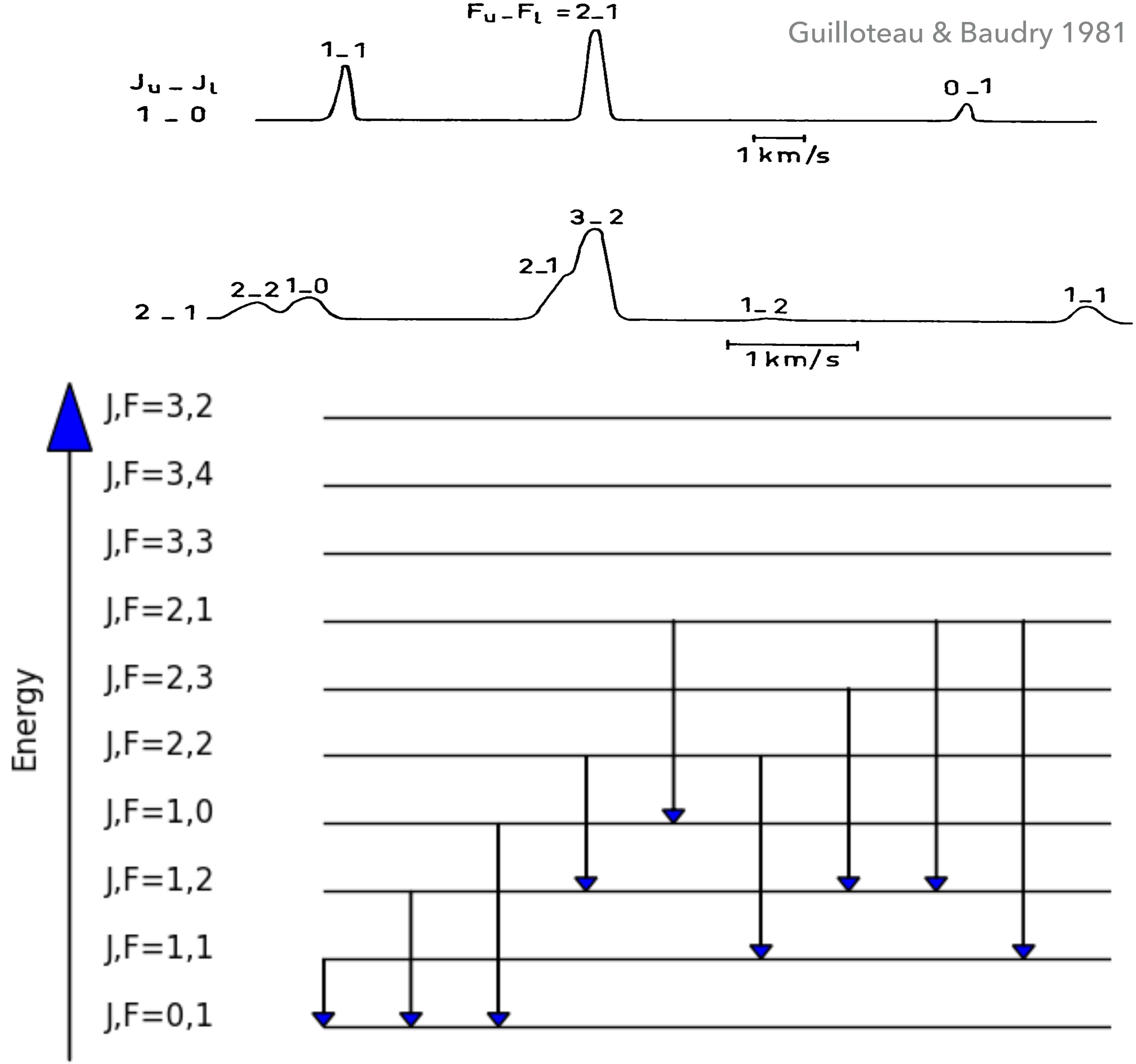

Guilloteau & Baudry 1981
Fu - Fl = 2-1
1-1
Ju - Jl
1 - 0
0-1
Overlap
1 km/s
3-2
2-1
2-2 1-0
2 - 1
1-2
1-1
1 km/s
J,F=3,2
J,F=3,4
J,F=3,3
J,F=2,1
J,F=2,3
J,F=2,2
J,F=1,0
J,F=1,2
J,F=1,1
J,F=0,1
Energy
J=2->1
Overlap
τ

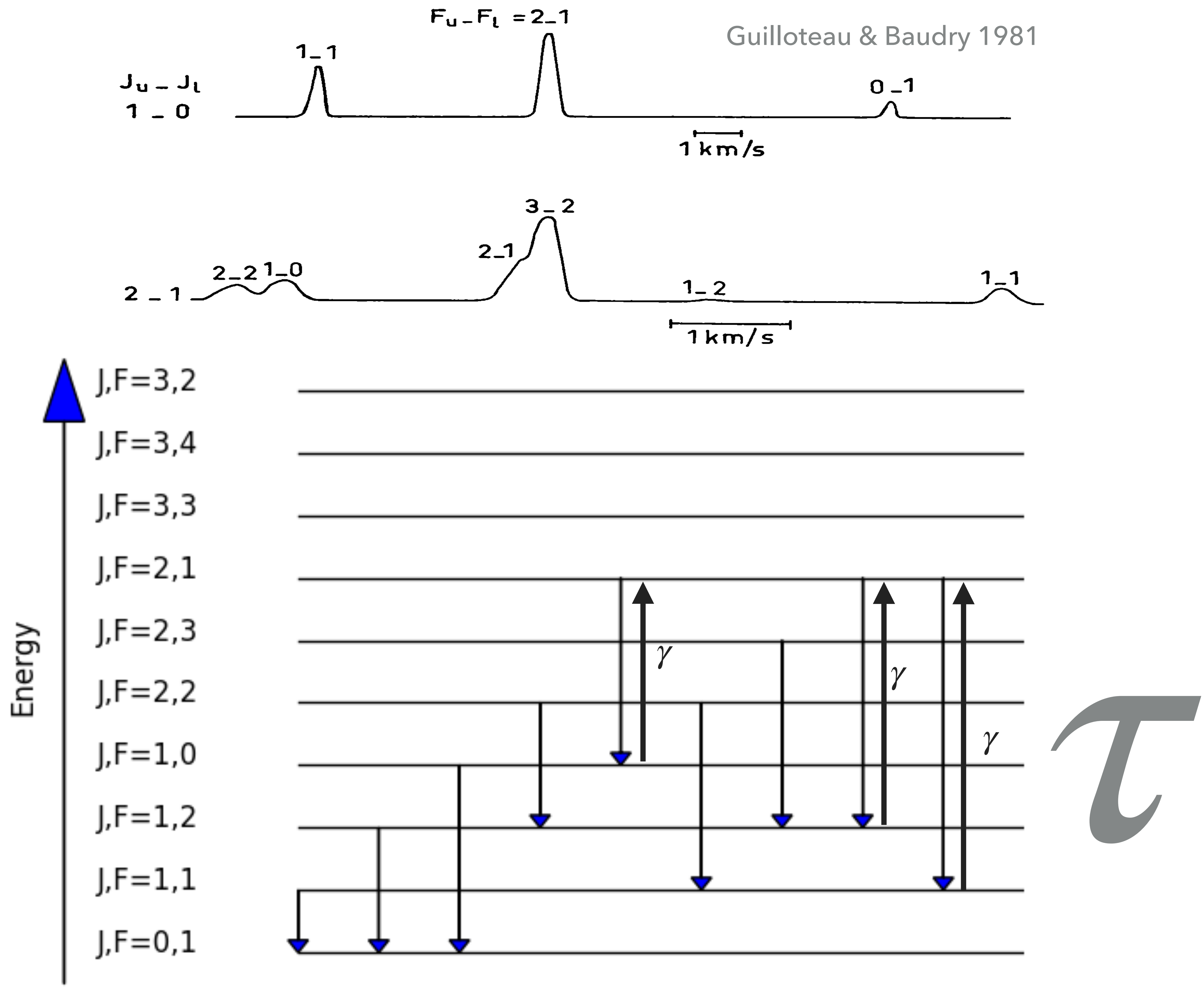


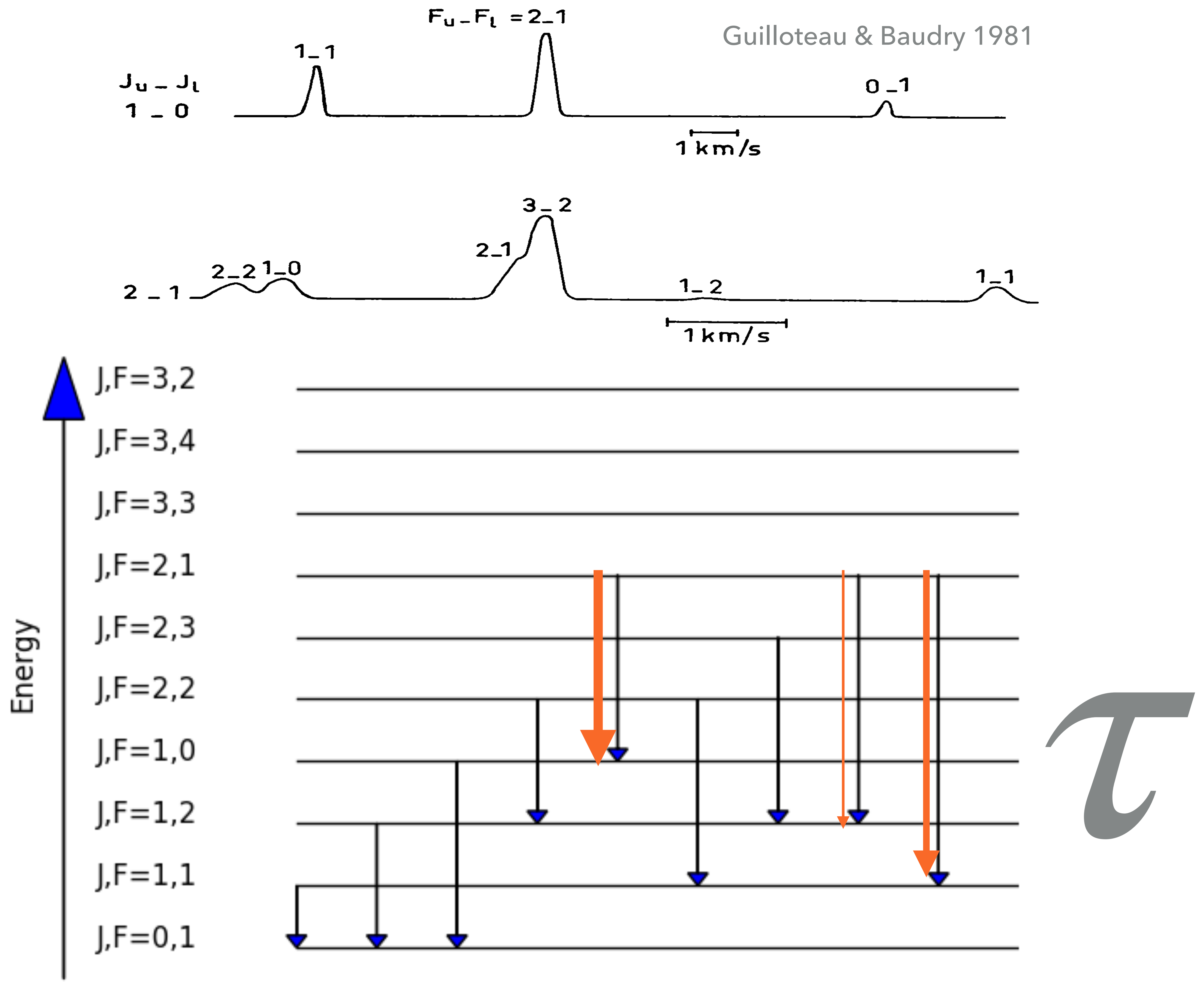
Guilloteau & Baudry 1981
Fu - Fl = 2-1
1-1
Ju - Jl
1 - 0
0-1
Overlap
1 km/s
3-2
2-1
2-2 1-0
2 - 1
1-2
1-1
1 km/s
J,F=3,2
J,F=3,4
J,F=3,3
J,F=2,1
J,F=2,3
J,F=2,2
J,F=1,0
J,F=1,2
J,F=1,1
J,F=0,1
Energy
J=2->1
Overlap
τ



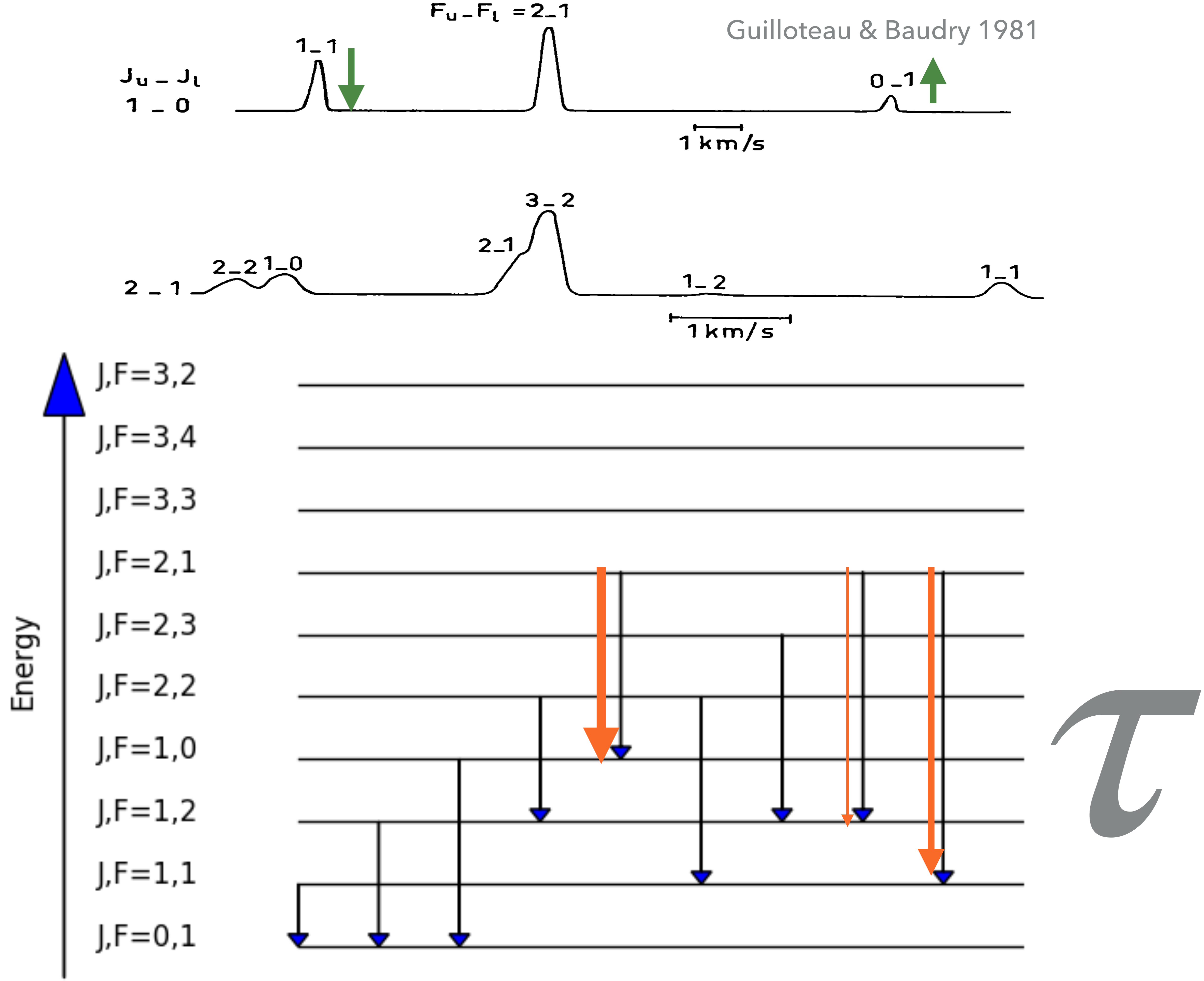
Guilloteau & Baudry 1981
Fu – Fl = 2–1
1–1
Ju – Jl
1 – 0
0–1
Overlap
1 km/s
3–2
2–1
2–2 1–0
2 – 1
1–2
1–1
1 km/s
Energy
J,F=3,2
J,F=3,4
J,F=3,3
J,F=2,1
J,F=2,3
J,F=2,2
J,F=1,0
J,F=1,2
J,F=1,1
J,F=0,1
J=2->1
Overlap
τ


Guilloteau & Baudry 1981
$F_u - F_l$ = 2–1
$J_u - J_l$
1 – 0
1–1
0–1
1 km/s
3–2
2–1
2–2
1–0
2 – 1
1–2
1–1
1 km/s
Energy
J,F=3,2
J,F=3,4
J,F=3,3
J,F=2,1
J,F=2,3
J,F=2,2
J,F=1,0
J,F=1,2
J,F=1,1
J,F=0,1

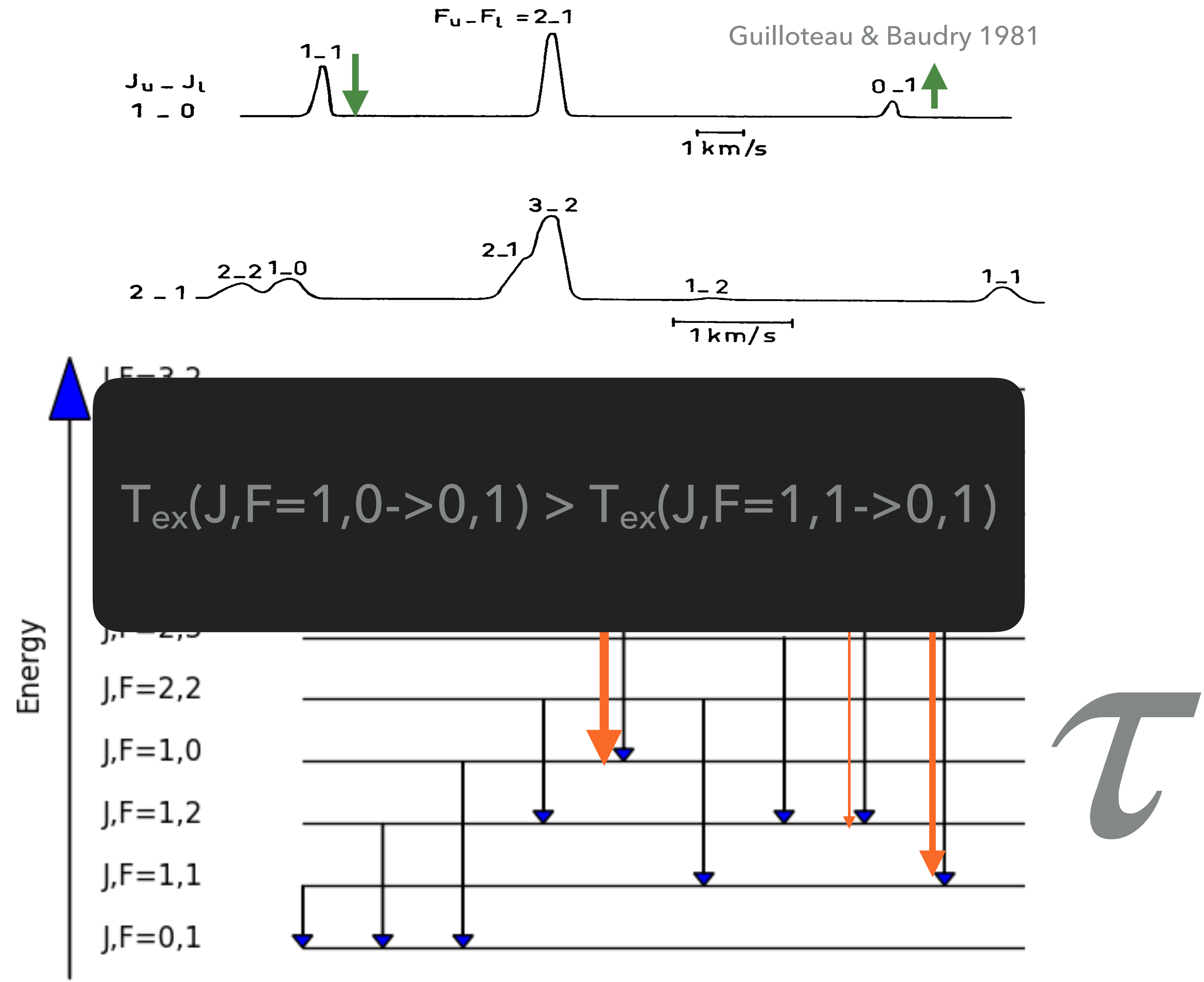

Guilloteau & Baudry 1981
Fu - Fl = 2-1
1-1
0-1
Ju - Jl
1 - 0
1 km/s
3-2
2-1
2-2 1-0
2 - 1
1-2
1-1
1 km/s
Energy
J,F=3,2
J,F=3,4
J,F=3,3
J,F=2,1
J,F=2,3
J,F=2,2
J,F=1,0
J,F=1,2
J,F=1,1
J,F=0,1
γ
γ
γ
τ



Guilloteau & Baudry 1981
Fu – Fl = 2–1
1–1
Ju – Jl
1 – 0
0–1
1 km/s
3–2
2–1
2–2
1–0
2 – 1
1–2
1–1
1 km/s
J,F=3,2
J,F=3,4
J,F=3,3
J,F=2,1
J,F=2,3
J,F=2,2
J,F=1,0
J,F=1,2
J,F=1,1
J,F=0,1
Energy
τ



Guilloteau & Baudry 1981
$F_u - F_l$ = 2_1
1_1
0_1
$J_u - J_l$
1 _ 0
1 km/s
3_2
2_1
2_2
1_0
2 _ 1
1_2
1_1
1 km/s
J,F=3,2
J,F=3,4
J,F=3,3
J,F=2,1
J,F=2,3
J,F=2,2
J,F=1,0
J,F=1,2
J,F=1,1
J,F=0,1
Energy
τ



T_{ex}(J,F=1,0->0,1) > T_{ex}(J,F=1,1->0,1)

CONCLUSIONS: WHAT WAS MISSING TO FULLY UNDERSTAND HCN HFA?

- Models with detailed physical structure
  - Velocity field and Line width alter $\tau(\nu)$
- Precise hyperfine collisional rates
  - Correct population balance
- Observations covering several positions with increasing radii

CONCLUSIONS: RADIATIVE TRANSFER ON HCN AND ITS ISOTOPOLOGUES

- Physical structure essential to get correct collisional excitation: improved with Herschel/SPIRE
- Optically thin isotopologues essential to measure line widths
- All spectral features reproduced:
  - double-peak, red-blue asymmetry (RBA), HFA, line width
  - Foreground layer @ 8.1 km/s: needed for correct RBA
- Low HCN/$H^{13}CN$ ratio: HCN not depleted in ^{13}C

PERSPECTIVES

- Chemistry:
  - Roueff et al. 2015 chemical fractionation model does not work for HCN.
    - No changes for CO: X(CO) >> X(HCN)
- Nitrogen isotopic ratios:
  - $H^{13}CN/HC^{15}N$ can be used: upper limit on $HCN/HC^{15}N$
  - spatial information disentangles:
    radiative transfer effects | fractionation
- HCN HFA and RBA, a new probe for velocity field and turbulence dissipation in prestellar cores down to the inner parts?