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Nitrogen Isotopic Ratio From Prestellar Cores To Disks

$^{14}N/^{15}N$ in the Solar system

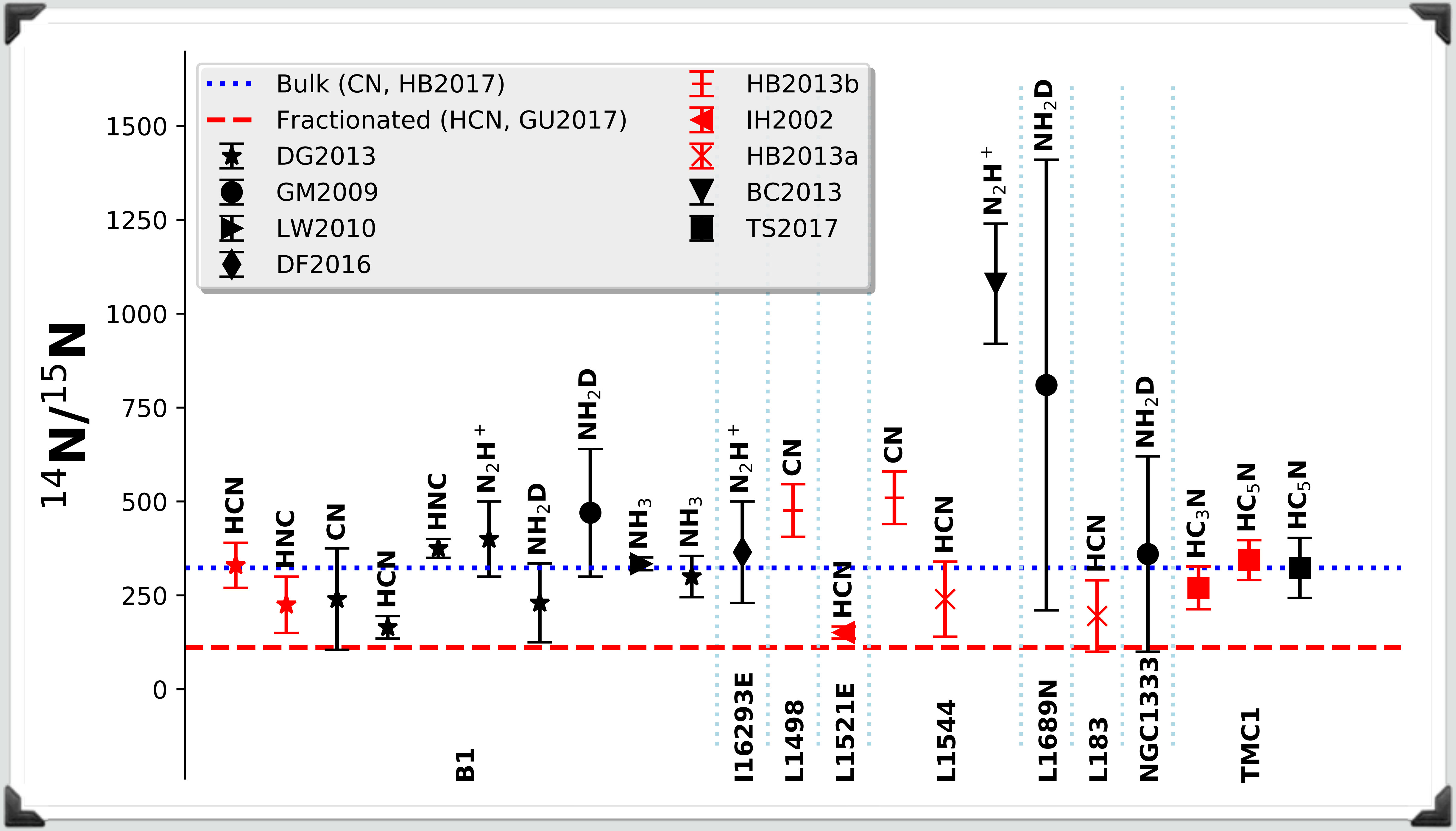
- The $^{14}N/^{15}N$ ratio displays a wide range of variations in the Solar System, from 50 to 440.
- Remarkably all comets show approximately the same
  $^{14}N/^{15}N$ ratio independent of carrier:
  - $^{14}N/^{15}N = 144 \pm 3$ (Hily-Blant 2017).
- This value is one third of the $^{14}N/^{15}N$ ratio of the bulk.
- Nitrogen in comets comes from a minor reservoir already separated at the PSN stage.

$^{14}N/^{15}N$ in protoplanetary disks

- $^{14}N/^{15}N$ has been measured in a few disks with ALMA:
  - $C^{14}N/C^{15}N$ = 323 ± 30 (Hily-Blant 2017).
  - $HCN/HC^{15}N$ = 111 ± 19 (Hily-Blant 2017 & Guzman 2017).
- These values show us that we have two reservoirs of nitrogen in protoplanetary disks:
  - Remarkably the ratio between the two reservoirs is 3 just as in the Solar system.

$^{14}N/^{15}N$ in the local ISM

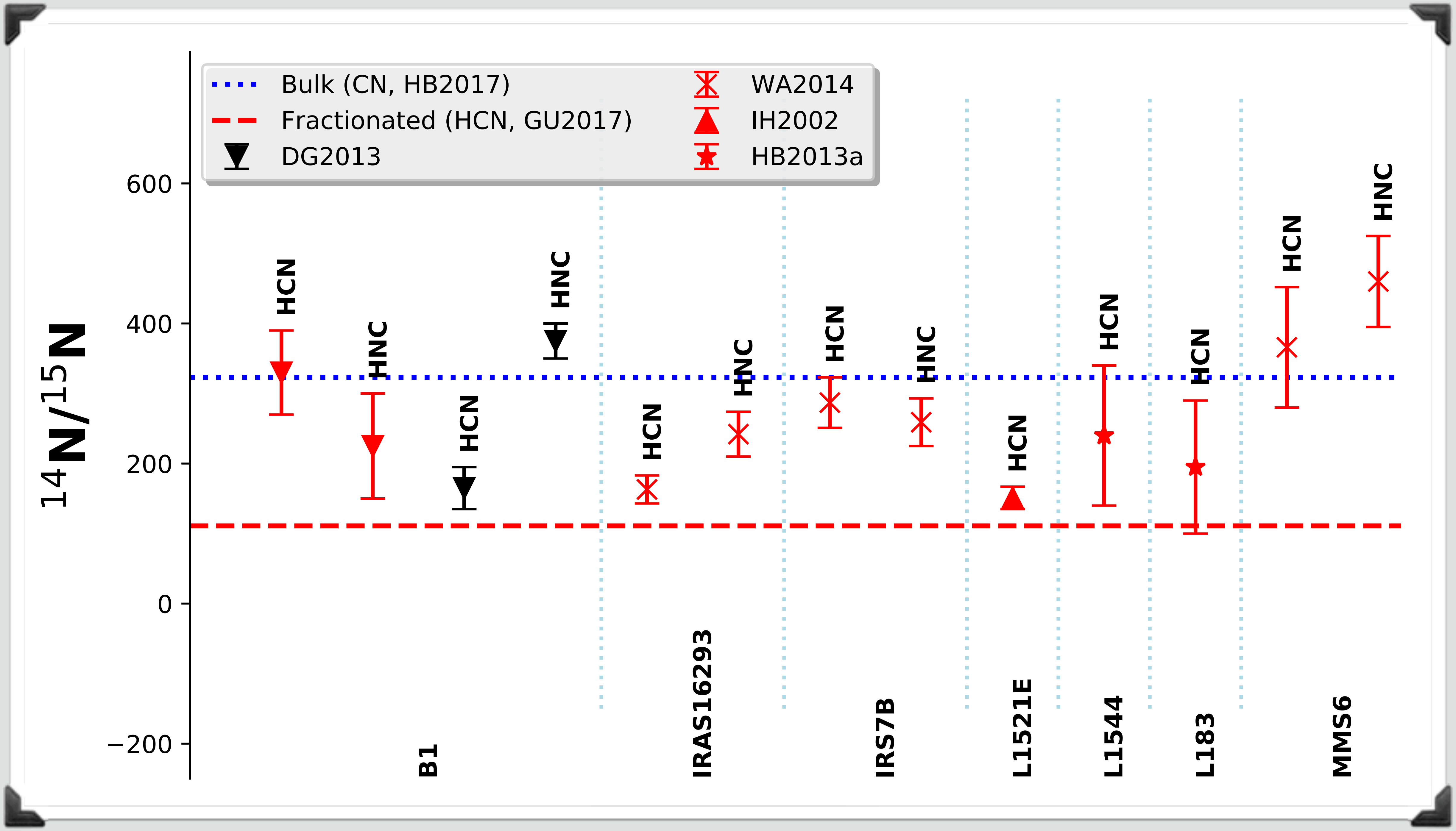
- $^{14}N/^{15}N$ measurements in the ISM display a large range of values from ~120 to ~1200.



$^{14}N/^{15}N$ Measurements in the local ISM

$^{14}N/^{15}N$ in the local ISM

- $^{14}N/^{15}N$ measurements in the ISM display a large range of values from ~120 to ~1200.
- The lowest values being usually measured in nitriles (HCN or HNC).



HCN/HC^{15}N measurements

$^{14}N/^{15}N$ in the local ISM

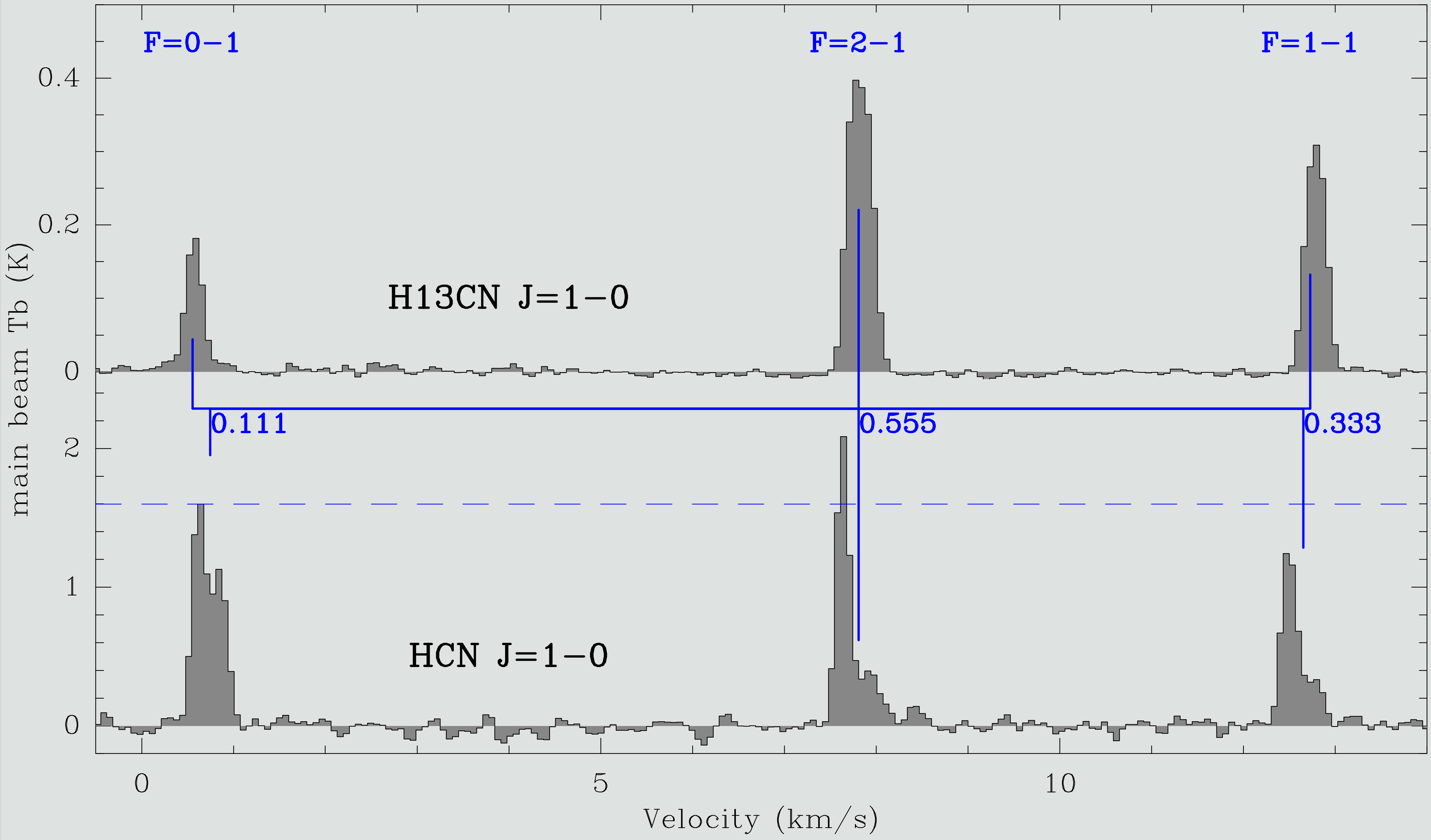
- $^{14}N/^{15}N$ measurements in the ISM display a large range of values from ~120 to ~1200.
- The lowest values being usually measured in nitriles (HCN or HNC).
- Of these two, HCN is the most desirable target:
  - It has a resolved hyperfine structure, which distributes the optical depth.
  - Problem: the hyperfine structure presents hyperfine anomalies.

Measuring $HCN/HC^{15}N$

- Most $HCN/HC^{15}N$ use the double isotopologue method:
  - $HCN/HC^{15}N = H^{13}CN/HC^{15}N \times {}^{12}C/{}^{13}C$
- Problem: observations and modelling do not agree on the fractionation of carbon in HCN.
  - Observations suggest HCN is rich in ^{13}C (Daniel 2013)
  - Models predict HCN is poor in ^{13}C (Roueff 2015)
- Solution: measure $HCN/HC^{15}N$ and $HCN/H^{13}CN$ directly!
- Target: L1498 a well studied prestellar core (Tafalla 2004&2006)

Hyperfine Anomalies of HCN

- Phenomenon: HF components not consistent with a single excitation temperature.
- Origins: Radiative trapping caused by HF overlap, which leads to radiative pumping of specific HF levels (Guilloteau 1981).
- Consequences: HCN HF ratios are sensitive to column density, velocity field and line width (Gonzalez-Alfonso 1993).
- Solution: Treat hyperfine overlap at the excitation level (Daniel 2008)



HCN J=1→0 anomalies contrasted with $H^{13}CN$ J=1→0

Modelling the HCN, $H^{13}CN$ and $HC^{15}N$ emission of L1498

- We obtained a density profile by fitting the density and dust temperature to a cut on the continuum maps.

Continuum emission:

$$I_\nu = 2\int \kappa_\nu n_{\mathrm{H}_2}(x)\mu_{\mathrm{H}_2} m_{\mathrm{H}} B_\nu[T_{\mathrm{d}}(x)]dx$$

H_2 density:

$$n_{\mathrm{H}_2}(r) = \frac{n_0}{1+(r/r_0)^\alpha}$$

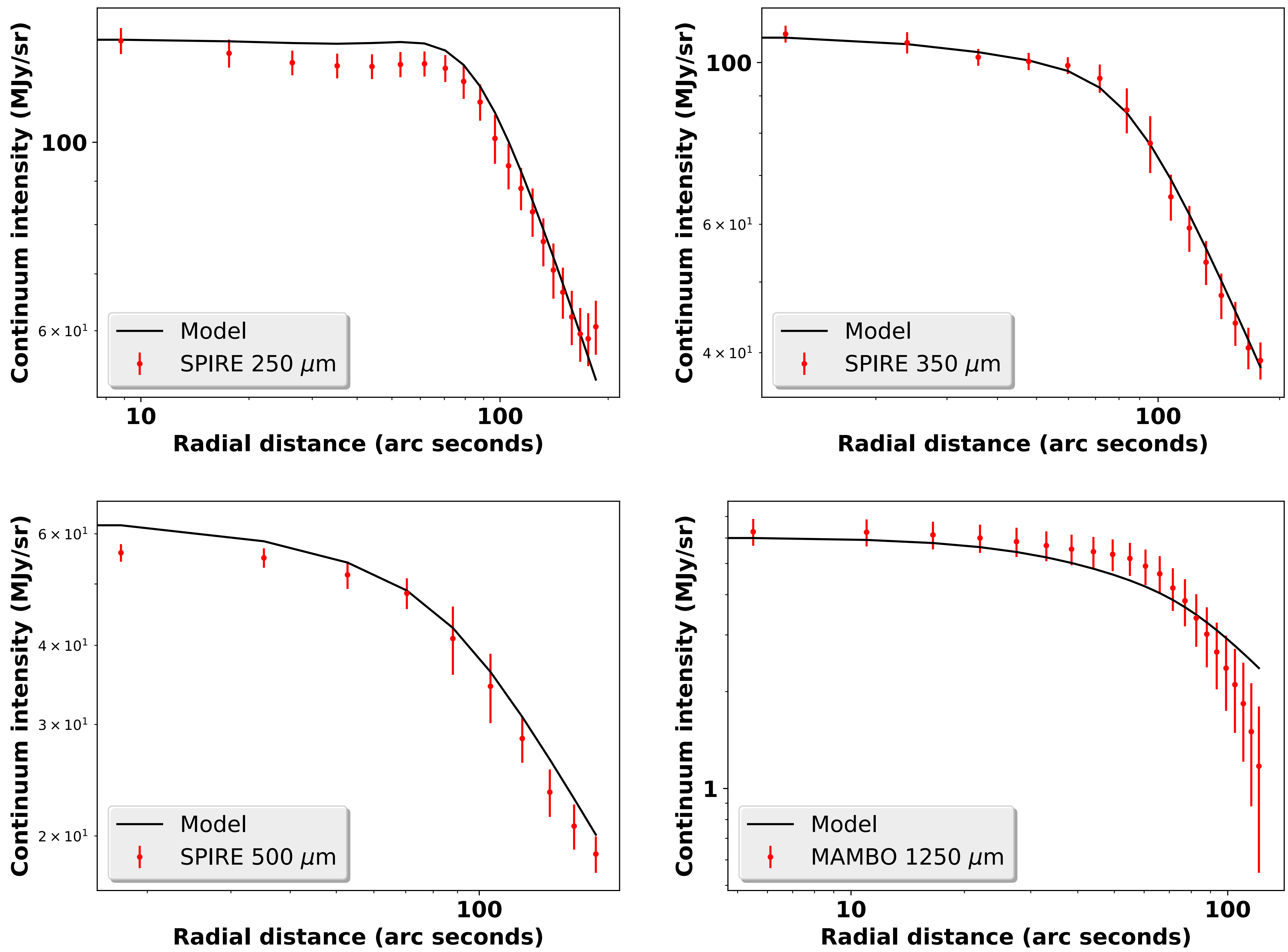
Dust temperature:

$$T_{\mathrm{d}}(r) = T_{\mathrm{in}} + \frac{T_{\mathrm{out}} - T_{\mathrm{in}}}{2}\left(1 + \tanh\frac{r - r_d}{\Delta r_d}\right)$$

Dust opacity:

$$\kappa_\nu = \kappa_{250}(\lambda/250\ \mu\mathrm{m})^{-\beta}$$

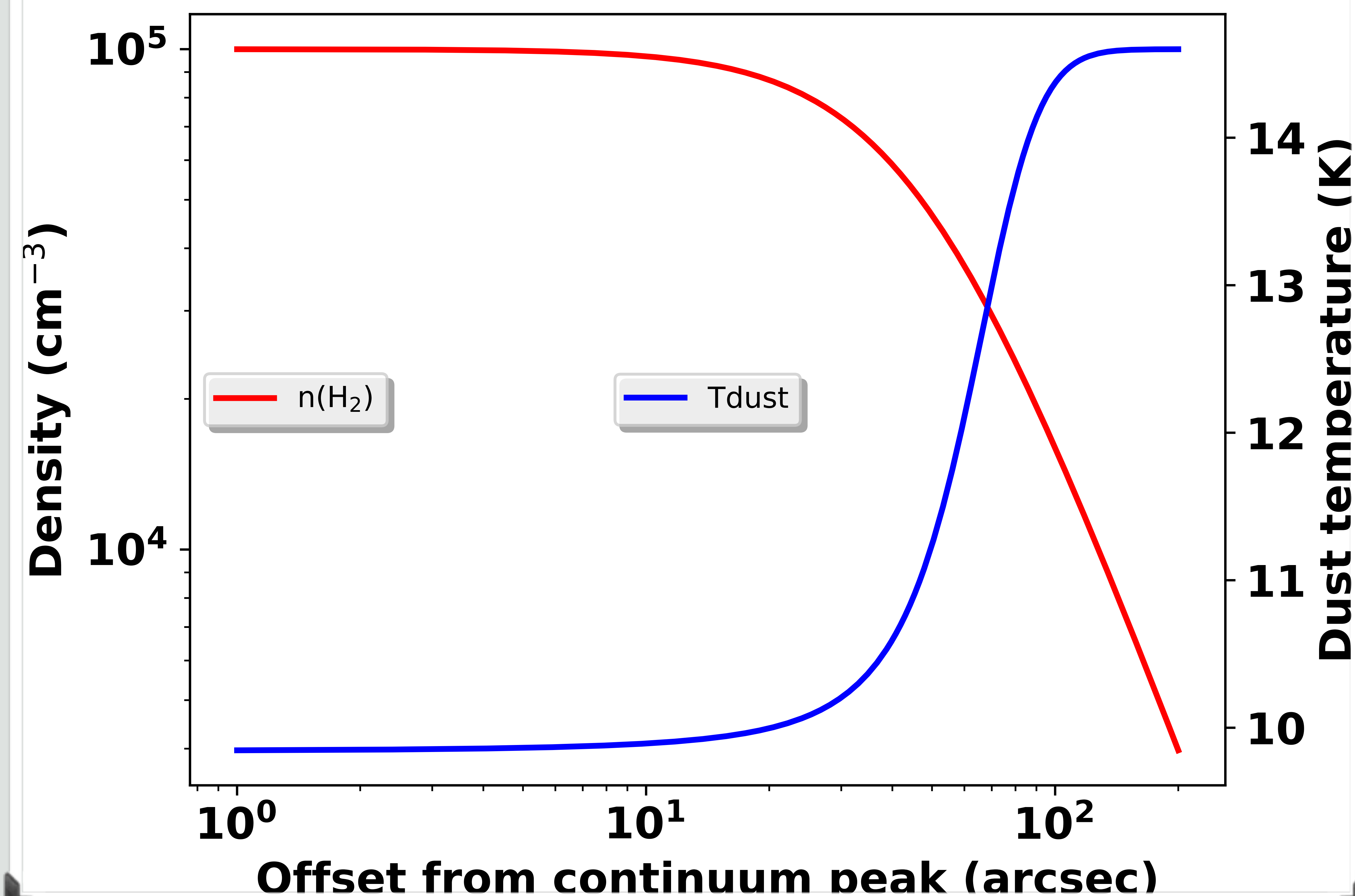
Fitting the dust emission



Fits to the continuum emission of L1498

Continuum fit results

Parameter	Value	Unit
n_0	$1.00 \pm 0.16 \times 10^5$	cm-3
r_0	47 ± 6	arcsec
α	2.2 ± 0.1	
T_{in}	9.8 ± 0.5	K
T_{out}	14.6 ± 0.3	K
r_d	61 ± 3	arcsec
Δr_d	26 ± 10	arcsec
β	1.56 ± 0.04	



Derived H_2 density and dust temperature for L1498

Radiative transfer model of L1498

- We obtained a density profile by fitting the density and dust temperature to a cut on the continuum maps.
- The remaining parameters we need to consider:
    - Velocity field: 3 parameters
    - Non thermal dispersion: 4 parameters
    - Abundance of HCN: 3 parameters
    - Abundance of the rare isotopologues: 2 parameters

Exploration of the parameters with MCMC

- This is a parameter space with 12 dimensions.
- We needed a efficient way to explore this parameter space.
  - We chose the EMCEE implementation of the Affine Invariant Markov chain Monte Carlo (MCMC) Ensemble sampler.
- Result: Calibration-limited HCN isotopologue ratios and precise physical conditions.

HCN abundance:

$$X(r) = \begin{cases} \frac{X_0}{\eta} & \text{if } r < r_1 \\ \frac{X_1}{\eta} & \text{if } r \geqslant r_1 \end{cases}$$

Velocity Field:

$$V(r) = V_c e^{-\frac{(r - r_V)^2}{2\Delta r_V^2}}$$

Non thermal velocity dispersion:

$$\sigma_{\mathrm{nth}}(r) = \sigma_0 + \frac{\sigma_{\mathrm{ext}} - \sigma_0}{\pi}\left[\frac{\pi}{2} + \tanh\left(\frac{r - r_j}{\Delta r_j}\right)\right]$$

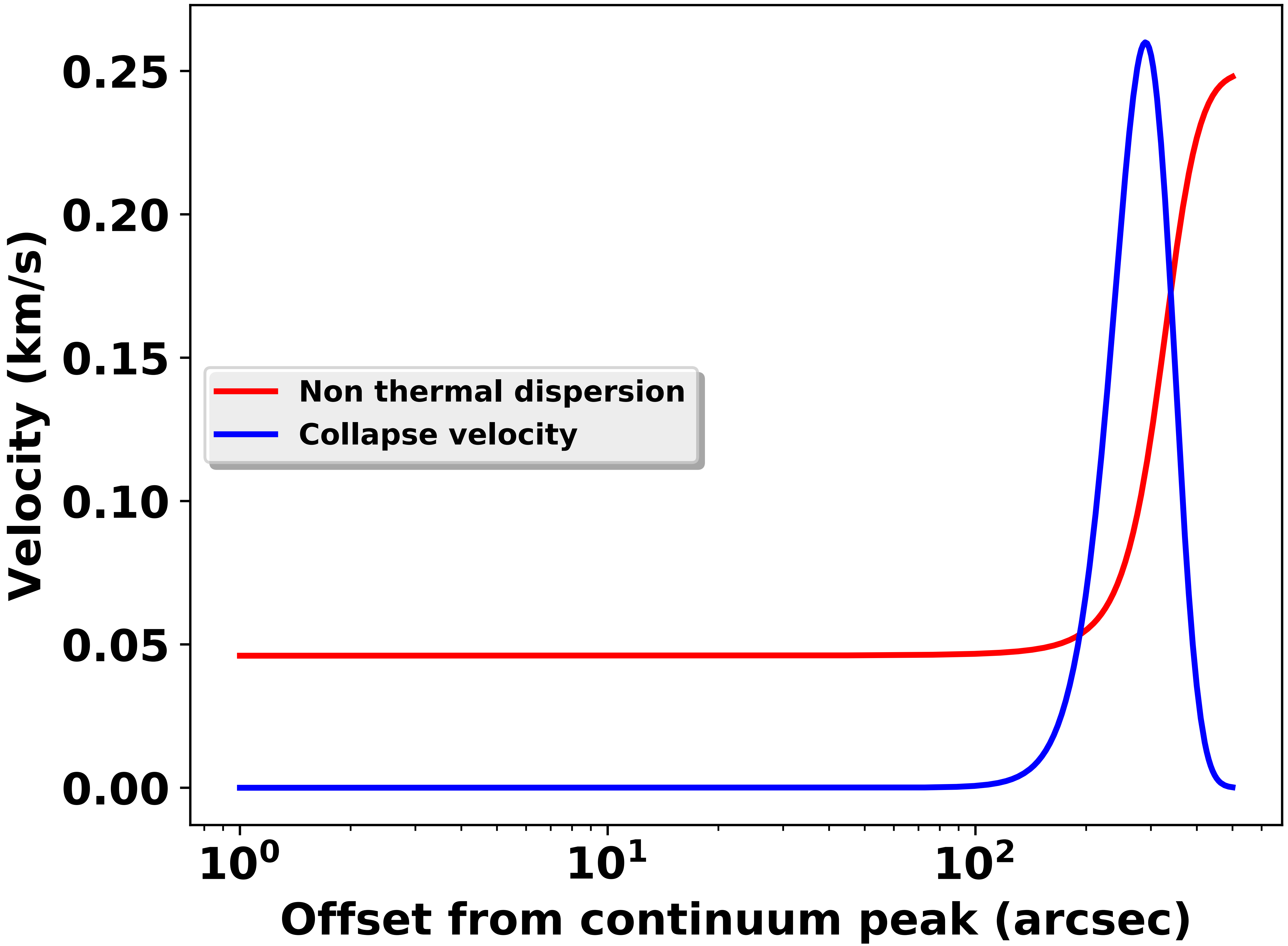
HCN abundance, velocity and non thermal dispersion

Continuum fit results

Parameter	Value	Unit
n_{ext}	500	cm^{-3}
T_{kin}	10	K
V_c	-0.26±0.02	kms
r_V	290±8	arcsec
Δr_V	55±8	arcsec
σ_0	0.046±0.03	kms
σ_{ext}	0.25±0.08	kms

Continuum fit results

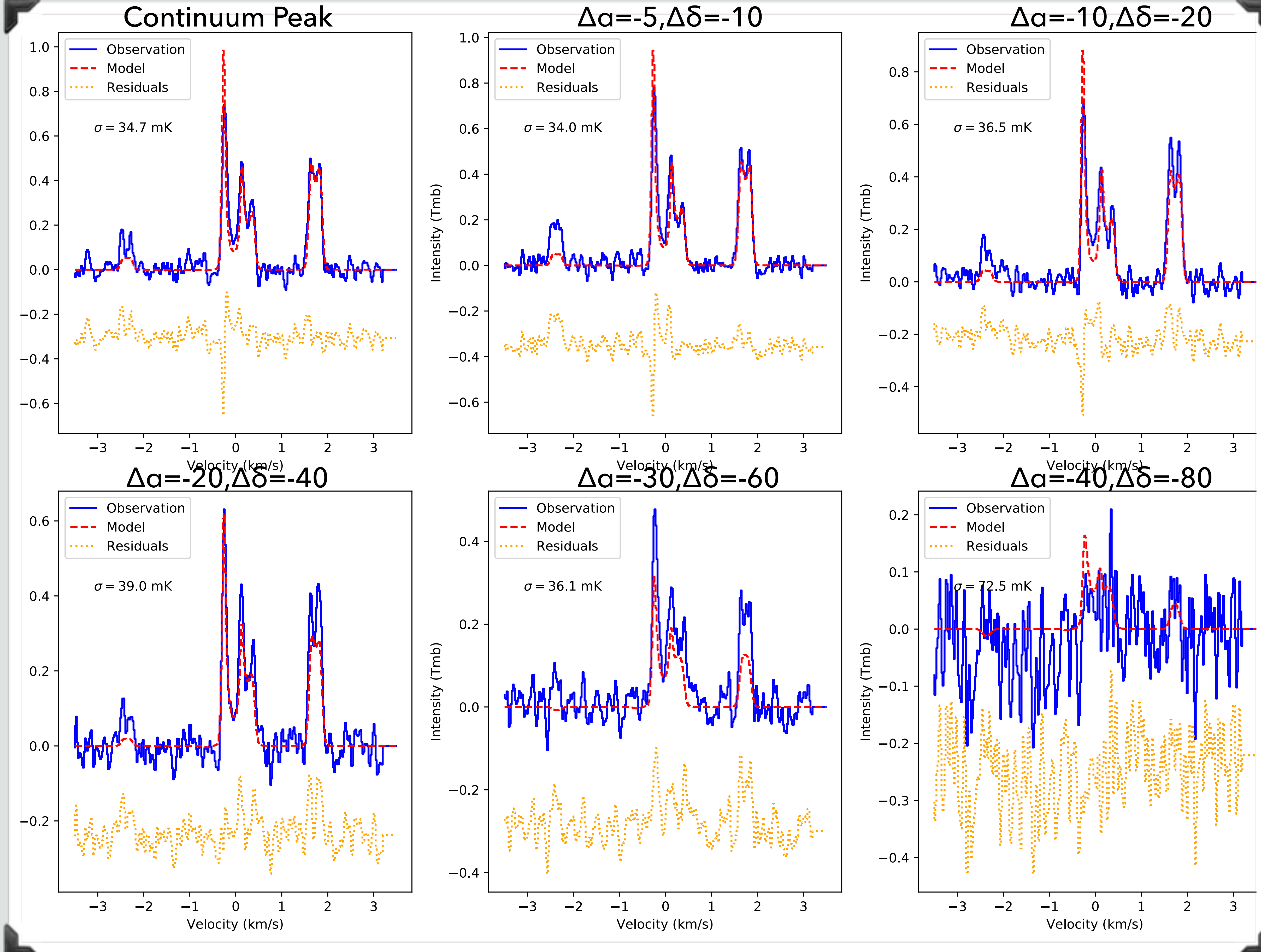
Parameter	Value	Unit
r_j	320±14	arcsec
Δr_j	78±14	arcsec
X_0	$2.6 \pm 0.2 \times 10^{-9}$	
X_1	$6.1 \pm 0.4 \times 10^{-9}$	
r_1	33±8	arcsec
$\eta(H^{13}CN)$	45±3	
$\eta(HC^{15}N)$	338±28	



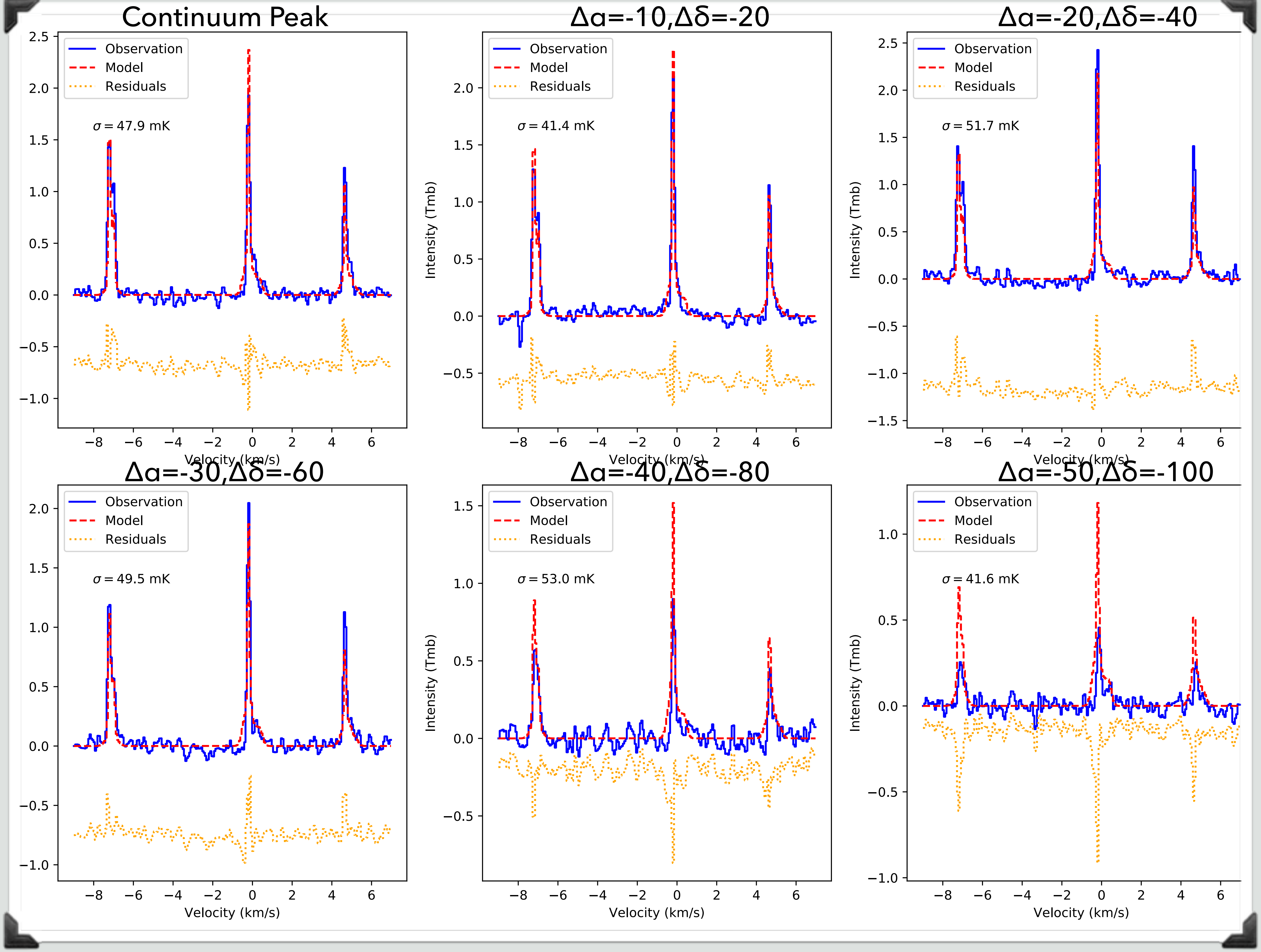
Velocity field and non thermal dispersion in L1498

Implications of the measured velocity field

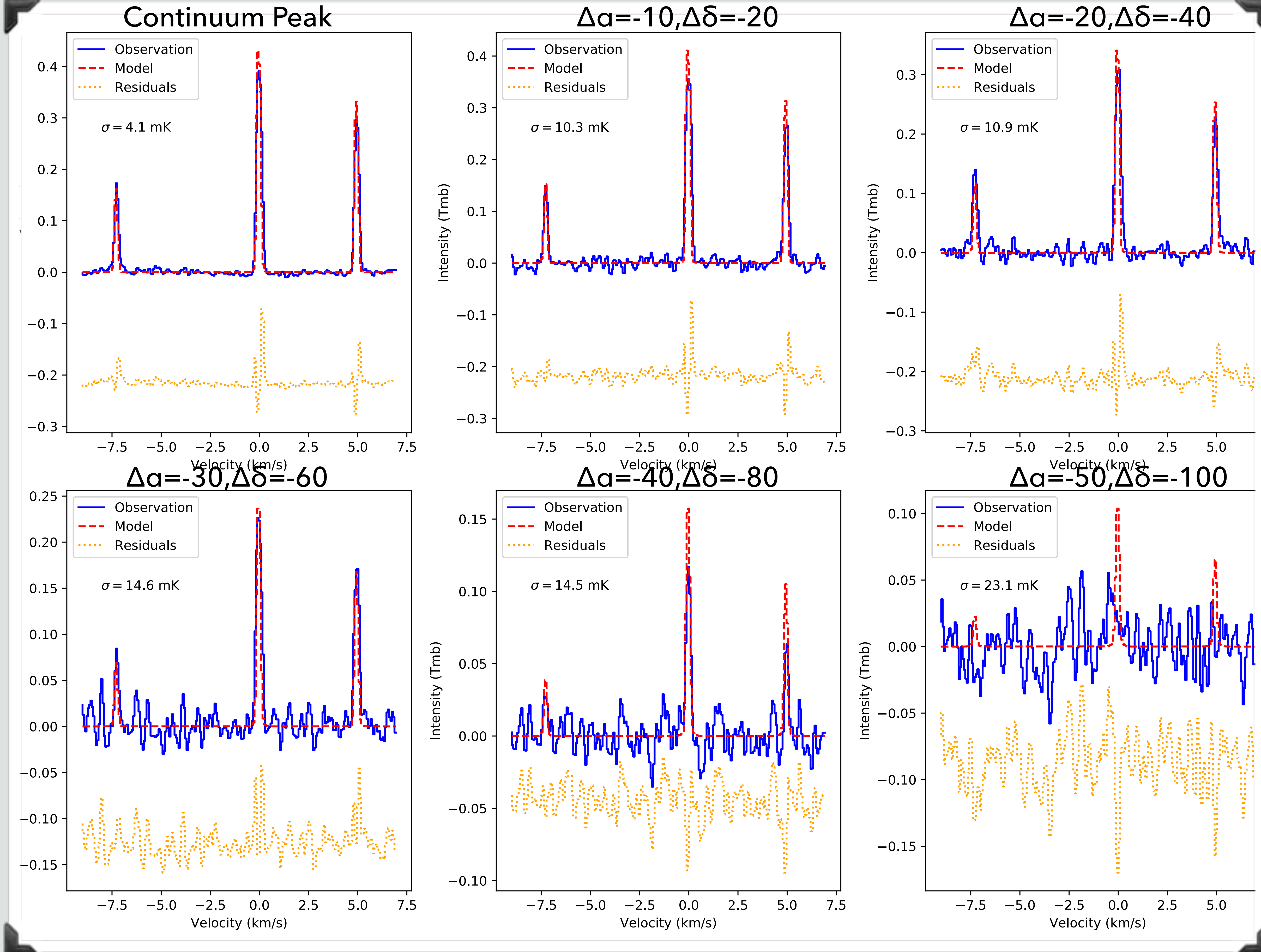
- Derived velocity field (Collapse outside) consistent with early evolutionary states of PSCs (Lesaffre 2005).
- A similar velocity field was recovered for L694-2 and L1197 (Lee 2007).
  - In both cases HCN J→0 emission was well reproduced under this kind of profile.



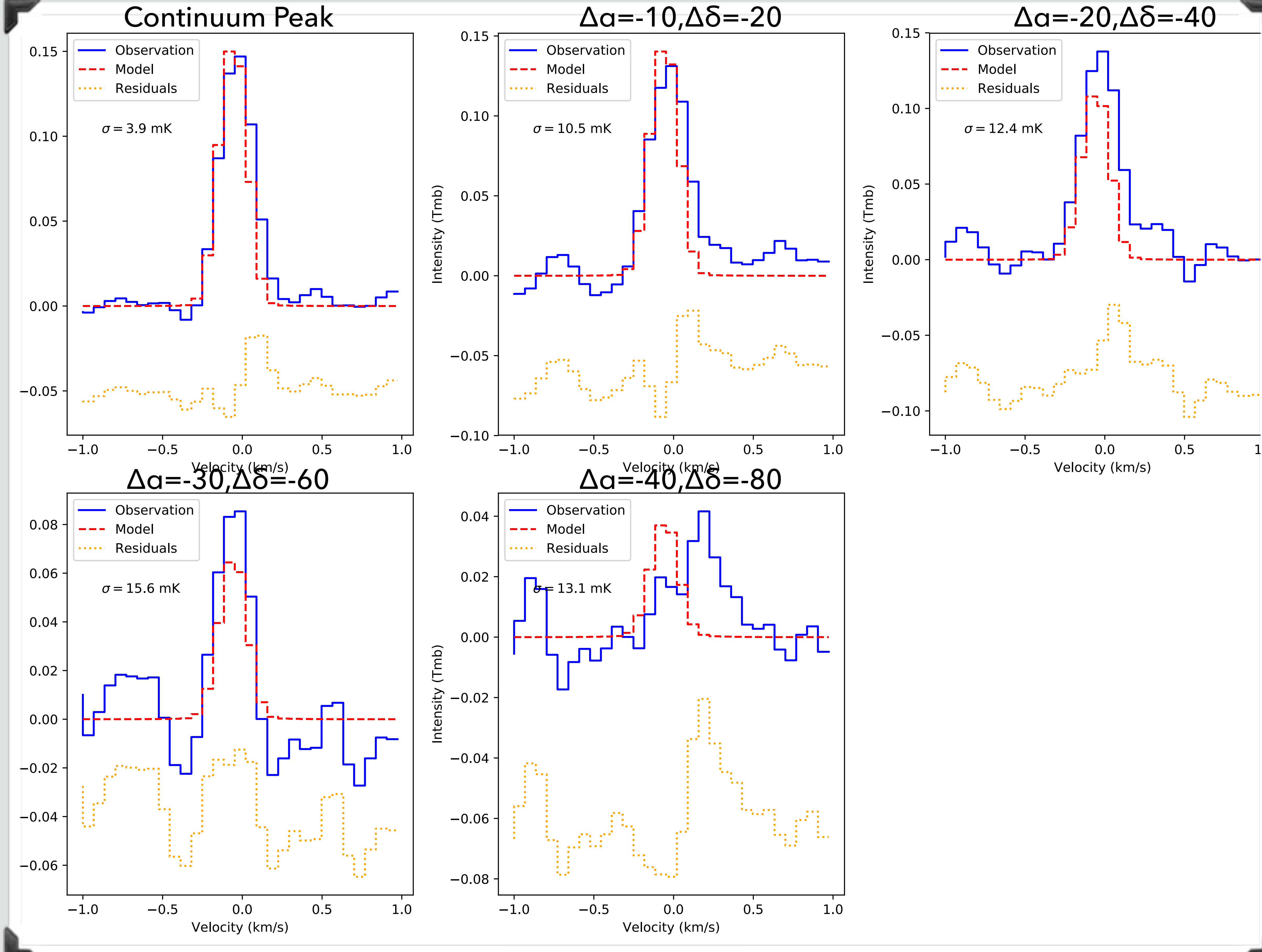
Best fit HCN J=3→2 towards L1498



Best fit HCN J=1→0 towards L1498



Best fit $H^{13}CN$ $J=1\rightarrow0$ towards L1498



Best fit $HC^{15}N$ J=1→0 towards L1498

Accurate HCN isotopic ratios in L1498

- $HCN/HC^{15}N = 338 \pm 28$
- $HCN/H^{13}CN = 45 \pm 3$
- $H^{13}CN/HC^{15}N = 7.5 \pm 0.8$
- Uncertainties ~10%, comparable to calibration uncertainties.
- Uncertainties due to collisional rates:
    - Mitigated by the latest HCN-H_2 HF collisional rates (Lique et al. in preparation).

Implications

- $H^{13}CN/HC^{15}N$ consistent with Ikeda 2002.
  - Which suggest that single T_{ex} $H^{13}CN/HC^{15}N$ measurements are valid.
- $HCN/H^{13}CN$ smaller than 70.
  - Inconsistent with chemical models ($HCN/H^{13}CN$ 90-140 Roueff 2015).
  - Fractioning in C in the same sense as in Daniel 2013 ($HCN/H^{13}CN = 30 \pm 7$)

Applying $HCN/H^{13}CN$ in L1498 to previous $H^{13}CN/HC^{15}N$

- $HCN/HC^{15}N$ in L1544 becomes 157±37 ($H^{13}CN/HC^{15}N$ = 3.5±0.8, Hily-Blant 2013)
- $HCN/HC^{15}N$ in L183 becomes 131±29 ($H^{13}CN/HC^{15}N$ = 2.9±0.6, Hily-Blant 2013)
- This values agree with the value measured by Daniel 2013 in B1.
- L1498 is less evolved than L1544:
  - Is $H^{13}CN/HC^{15}N$ a time dependant quantity?

Conclusions

- HCN is not fractionated in nitrogen in L1498.
- HCN J=3→2 spectra were fundamental in determining the velocity field.
- L1498 is in an early evolutionary stage for a PSC ($n_0(H_2)$~10^5 cm^{-3}, collapse outside).
- HCN is heavily fractionated in carbon in L1498.
- $H^{13}CN/HC^{15}N$ smaller in evolved PSCs (L1544)
    - Is this due to carbon or nitrogen fractionation?
        - Answer in more direct measurements of HCN/$HC^{15}N$ in PSCs