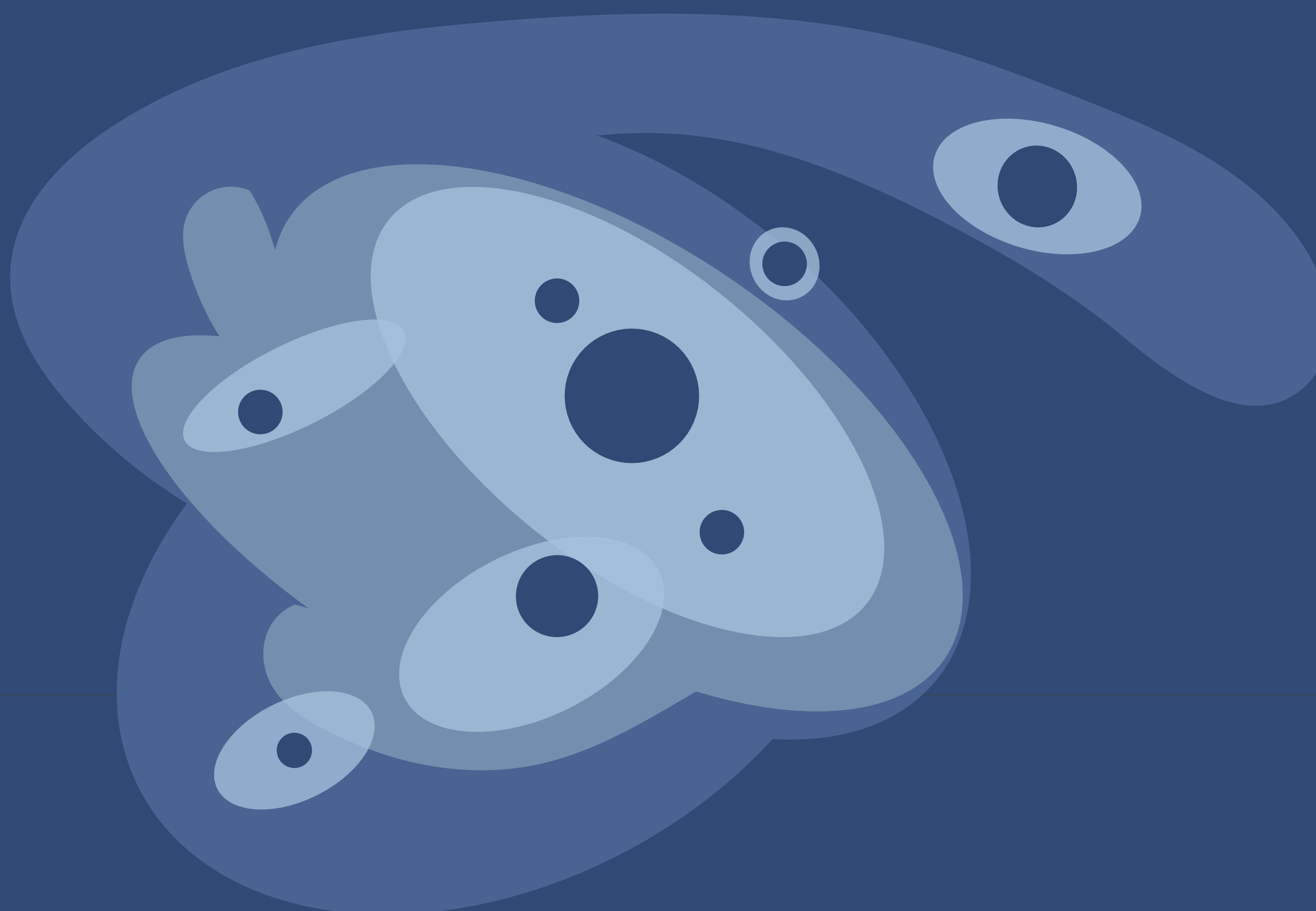
DYNAMICS AND FLOWS:
THE COMPLEX MASSIVE STAR FORMING REGION W33A



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Maud et al. 2017, MNRAS 2017 467 120
Izquierdo et al. 2018, MNRAS 2018 478 2505

Tracing the Flow - Windermere, UK, July 2018

KEY QUESTIONS - MASSIVE STAR FORMATION

- What are the initial conditions for HMSF?
- How can protostars accrete and exceed 10-20 $M_\odot$?
- How does feedback from stars affect the environment?
- Is there a clear evolutionary path? - are there indicators?

KEY QUESTIONS - MASSIVE STAR FORMATION

- What are the initial conditions for HMSF?

- How can protostars accrete and exceed 10-20 $M_{\odot}$?

  + how is this 'governed'

- How does feedback from stars affect the environment?

- Is there a clear evolutionary path? - are there indicators?

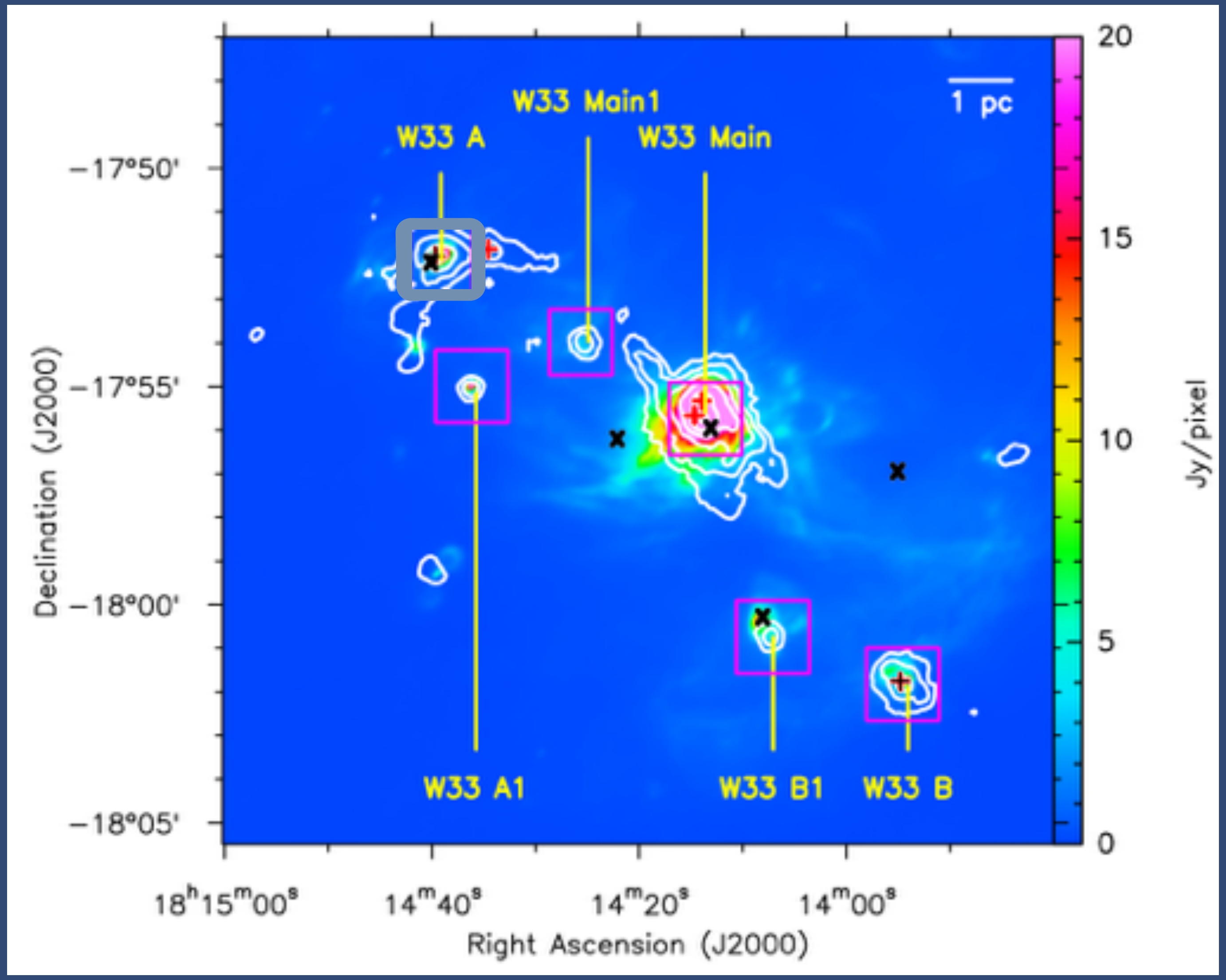
Key Questions - Massive Star Formation

- Clump collapse and core accretion…
- …after fragmentation, becomes competitive..?
- …filaments and 'fibres' interconnect sources, are these accretion flows ?

The W33 Region

- W33 - 10pc scale
- Close ~2.4 kpc
- W33A forming at least 1 massive star
  - ~3.2 x 10^4 $L_\odot$

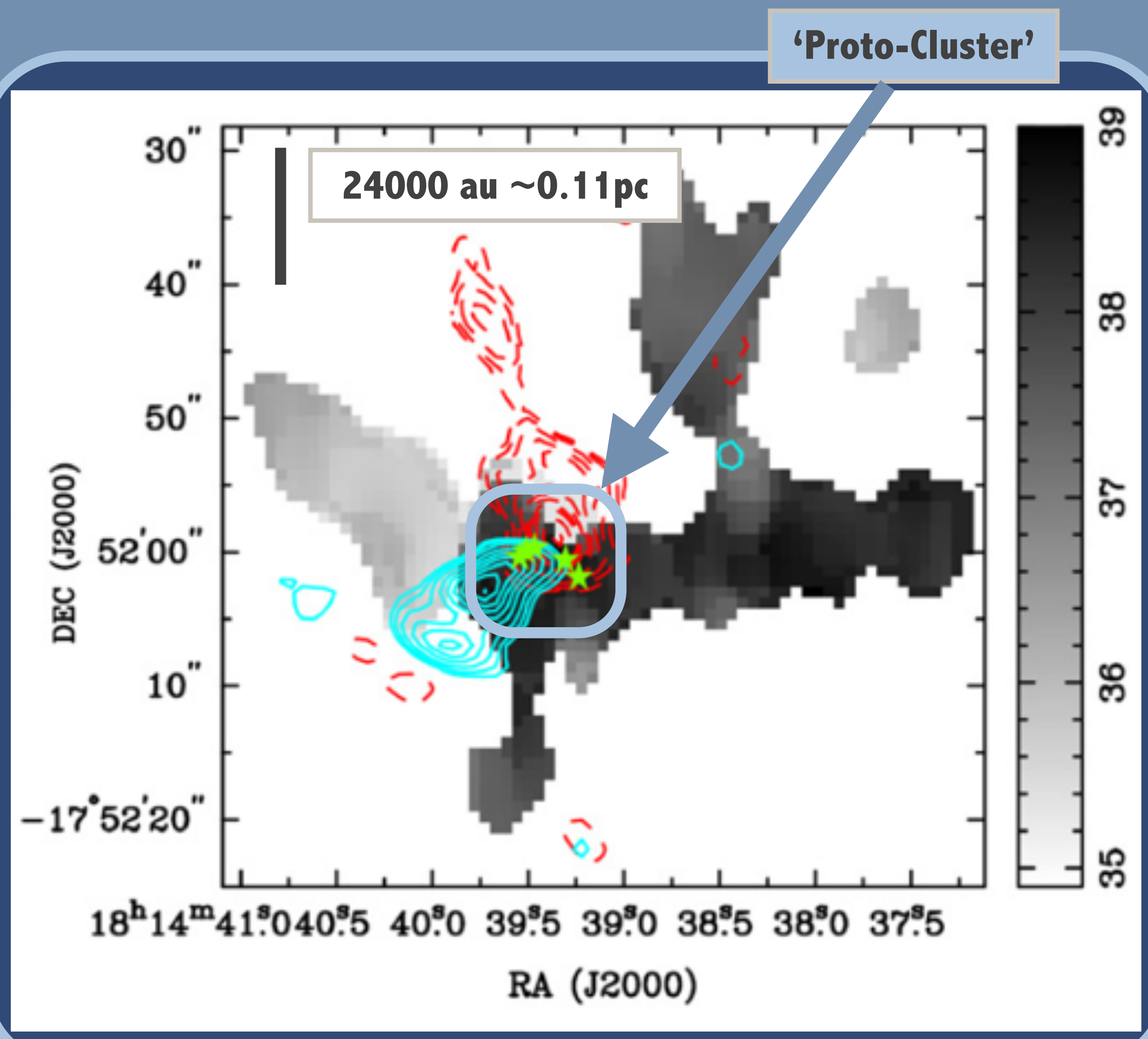
'Cluster'



Immer et al. 2014 A&A 572 63

W33A at the Convergence of Filaments

- 2 filaments merge in P-P-V space
- Multiple outflow directions



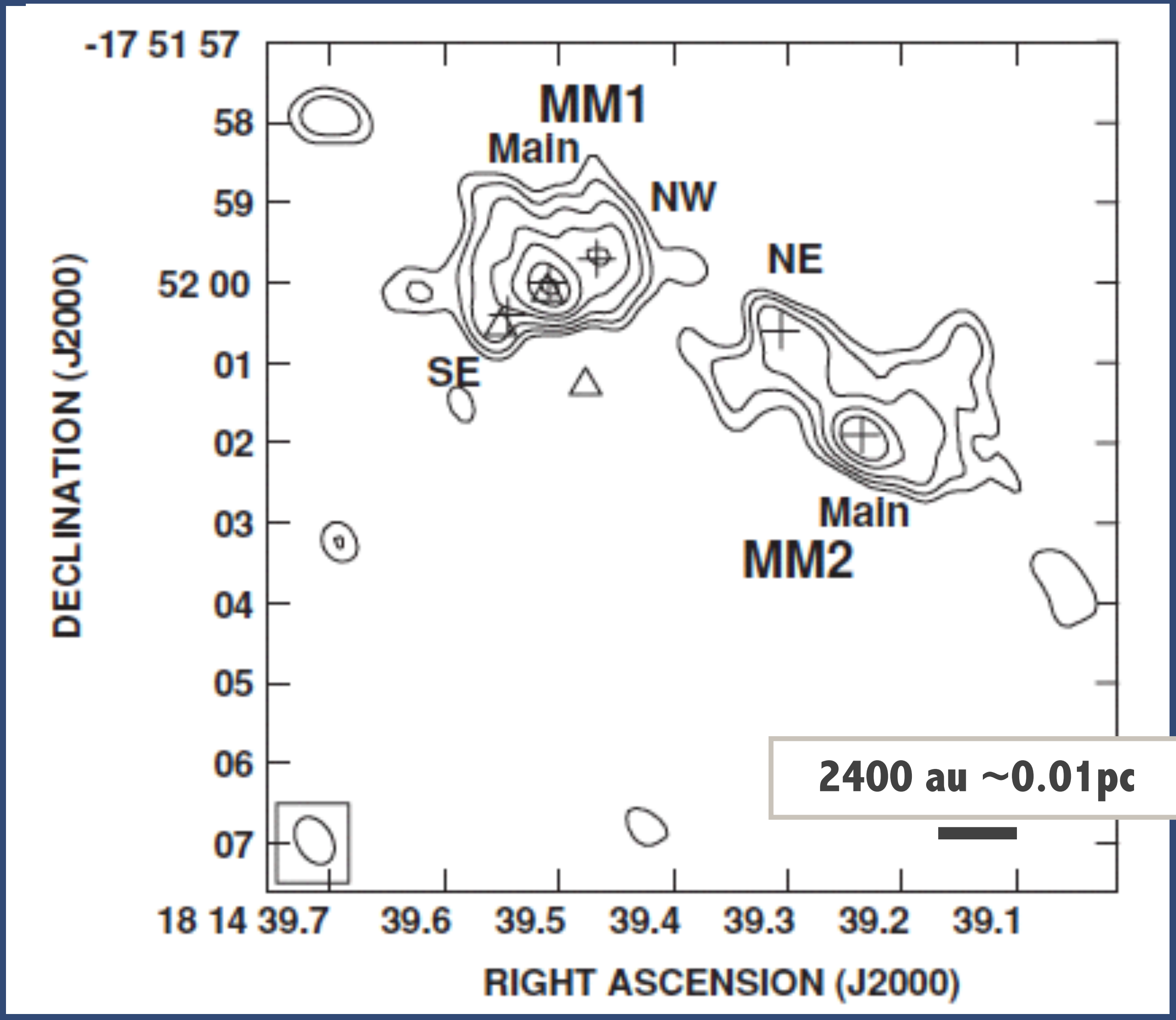
Galvan-Madrid et al. 2010 725 17

CONVERGENCE OF FILAMENTS - TO CORES

- 2 filaments merge in P-P-V space
- Multiple outflow directions
- Multiple cores
- 3-12M$_\odot$ in MM1, 24M$_\odot$ in MM2

NB: corrected to Immer distance vs. GM2010

'Proto Cluster - Core Scale'



Galvan-Madrid et al. 2010 ApJ 725 17

- SMA - 230GHz - 0.64''x 0.43''

Convergence of Filaments - to cores

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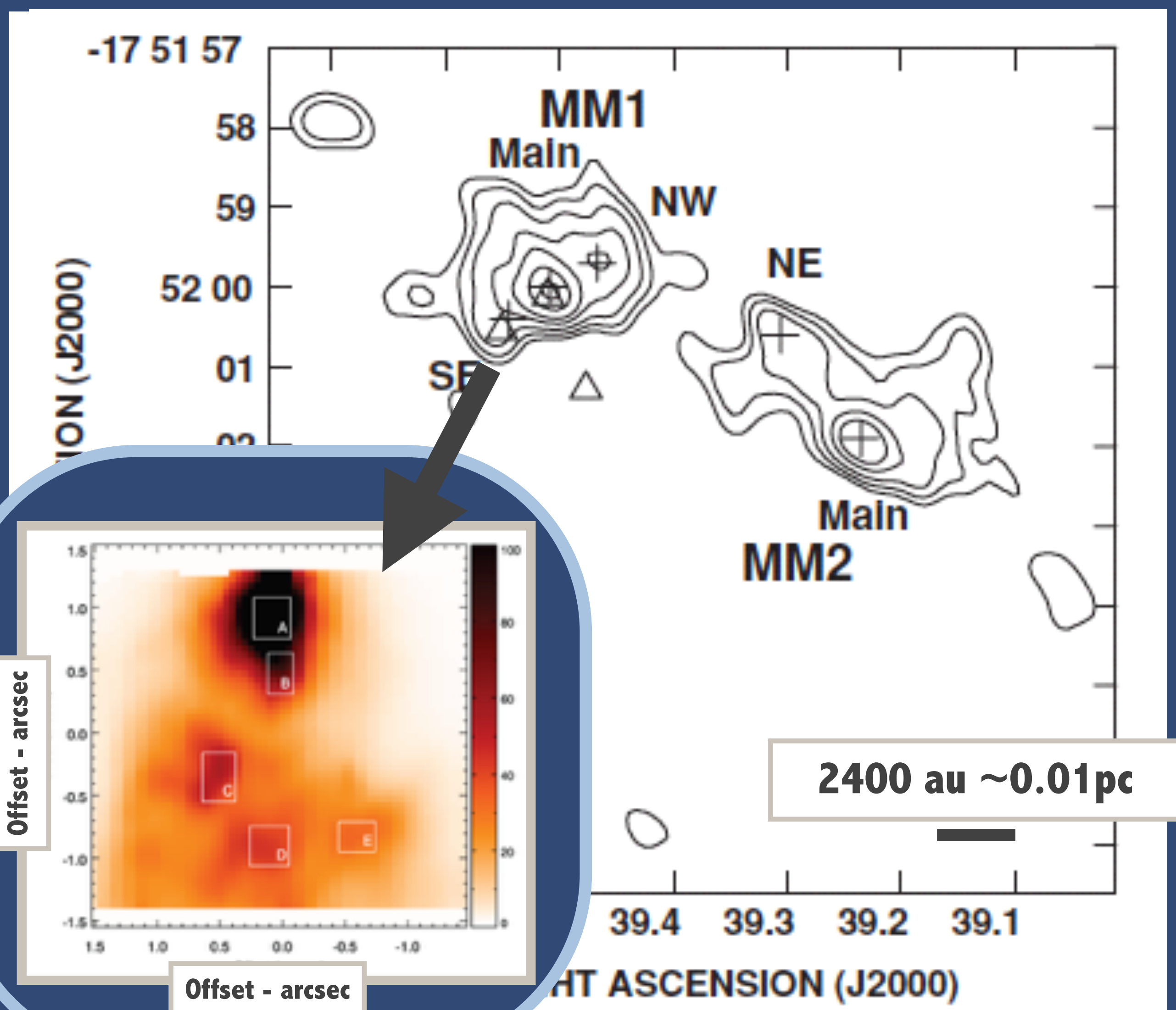

2400 au ~0.01pc

- IR reflection nebula

Davies et al. 2010 MNRAS 405 1504

Galvan-Madrid et al. 2010 ApJ 725 17

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Convergence of Filaments - to cores

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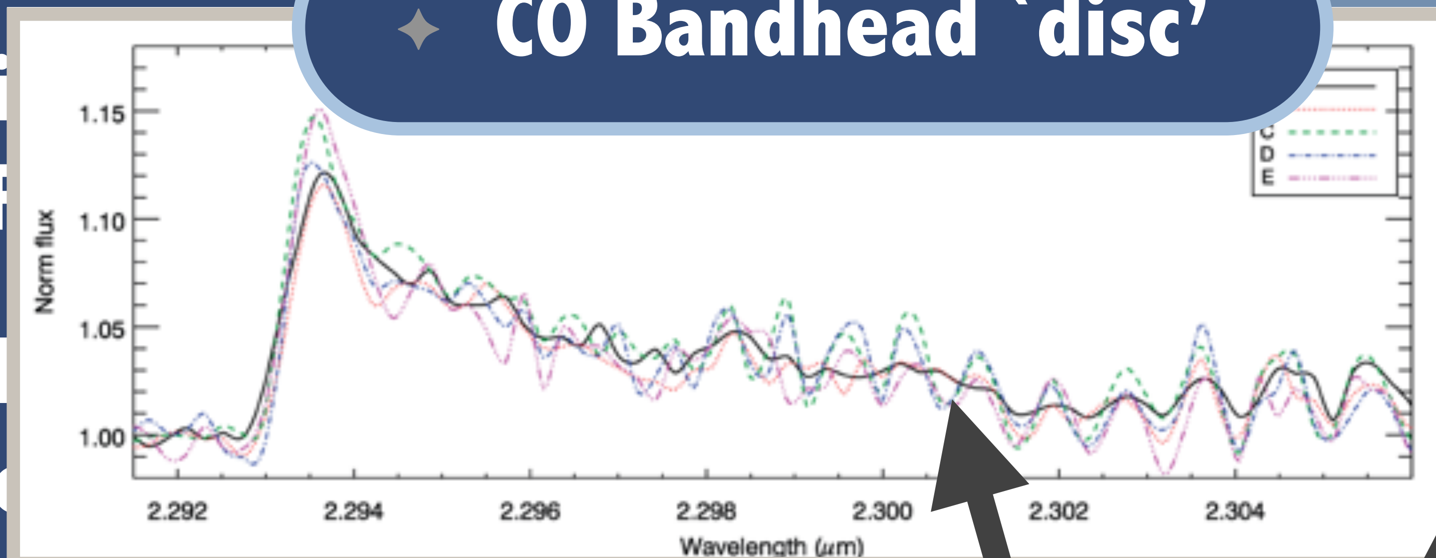
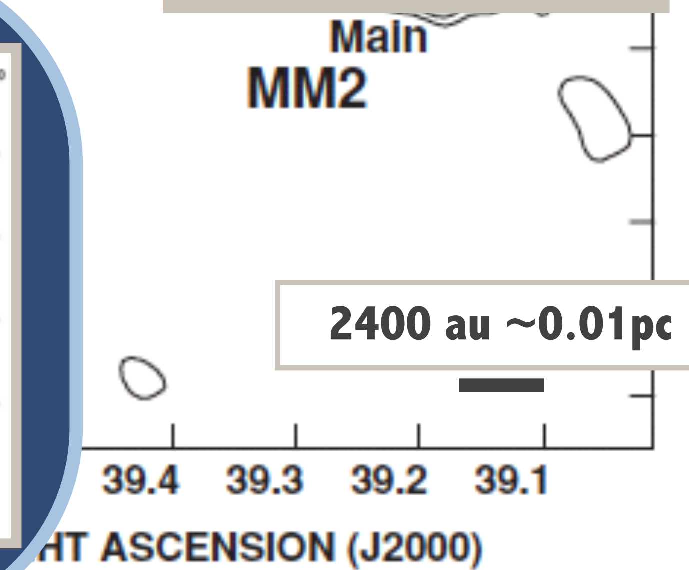
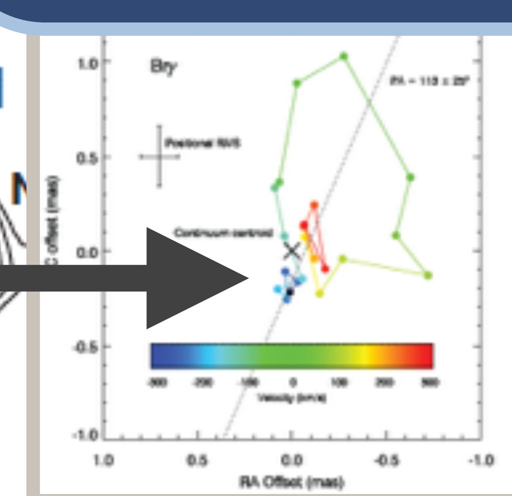
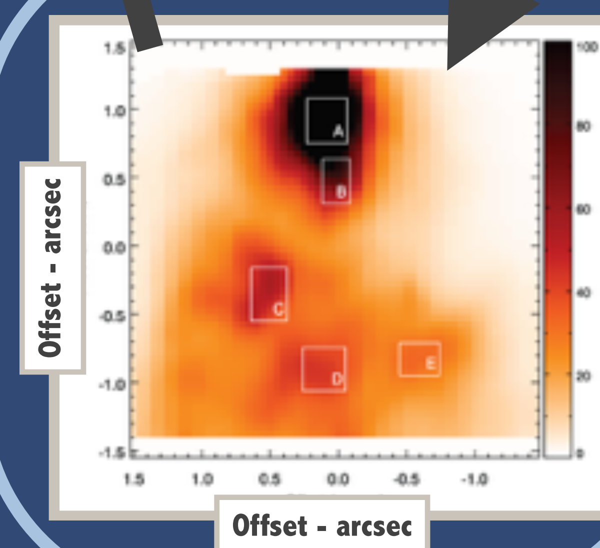


✦ CO Bandhead `disc'





✦ Brγ - Jet



✦ IR reflection nebula

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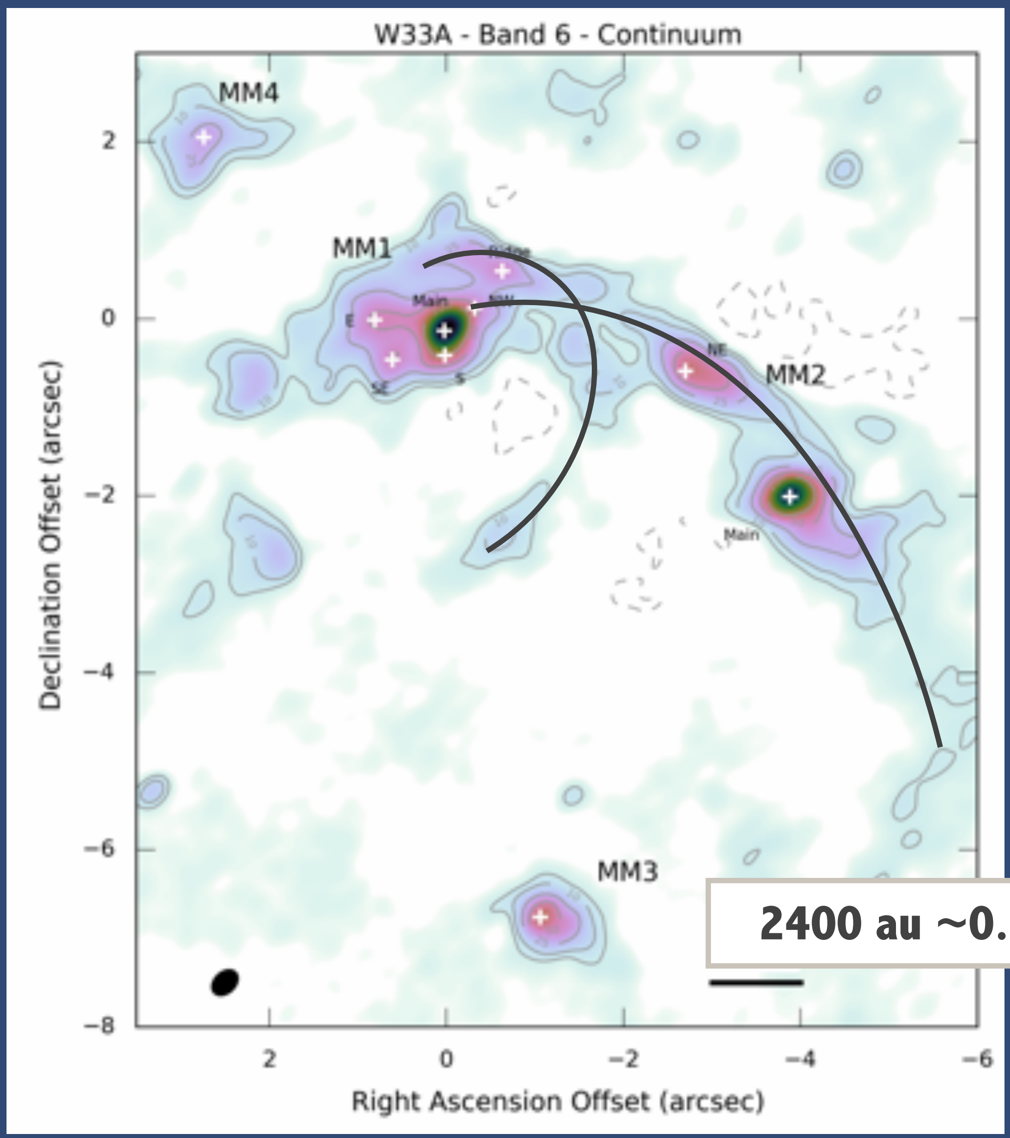
✦ SMA - 230GHz - 0.64''x 0.43''

The ALMA Perspective

- MM1 fragments
- Many more cores
  (MM1 ~2.45 $M_\odot$, MM2 ~4.60 $M_\odot$, MM3 ~0.08 $M_\odot$, MM4 ~0.63 $M_\odot$)
  Gas mass (not stellar) T ~ 80 -600 K
- MM1 & MM2 joined by dust 'filament'

'Core Scale'



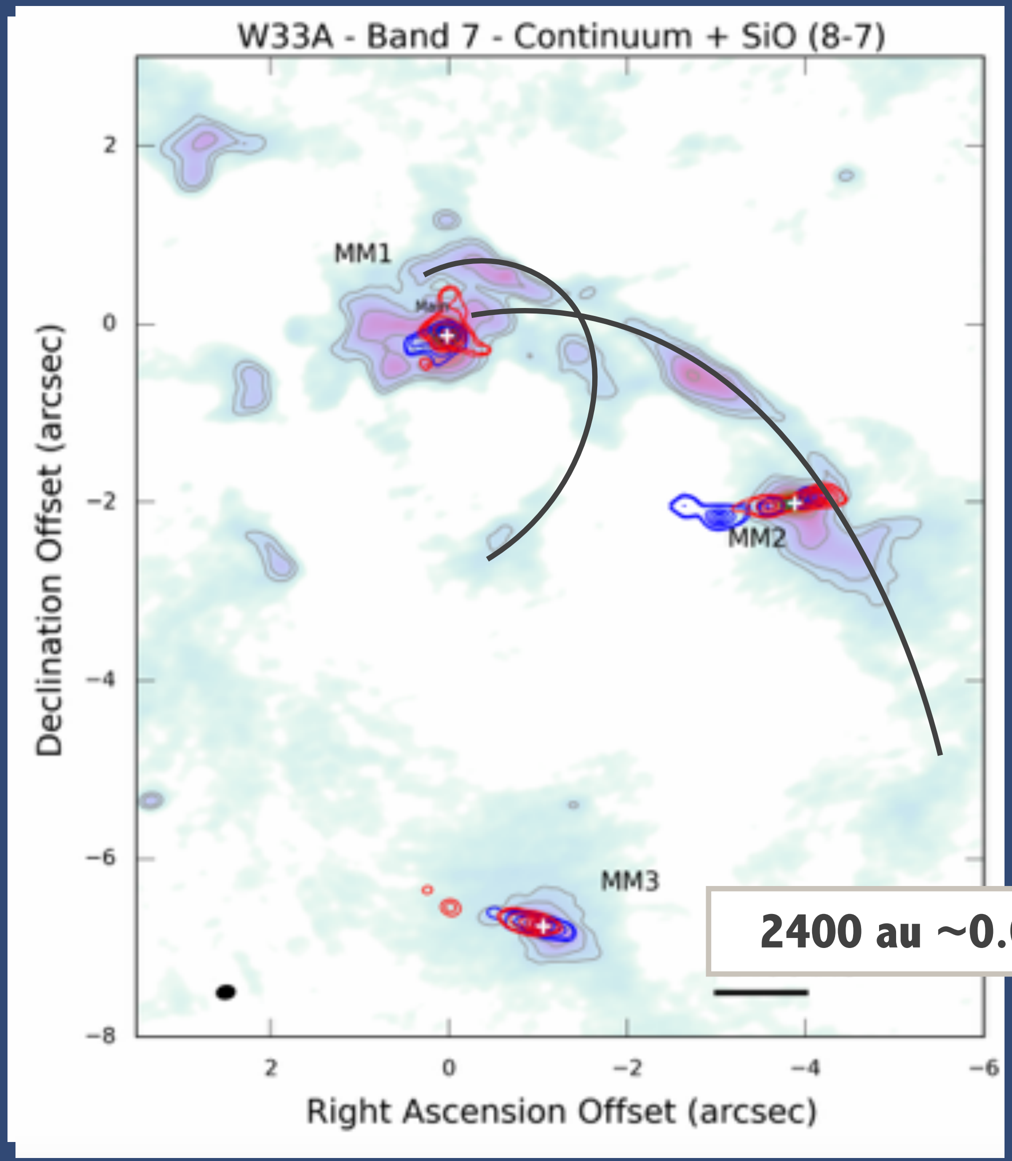
Maud et al. 2018 in prep.

- Band 6 - 230GHz - 0.33''x 0.24''

The ALMA Perspective

- Structures are coherence at Band 7
- SiO 8-7 jets

'Core Scale'



Maud et al. 2018 in prep.

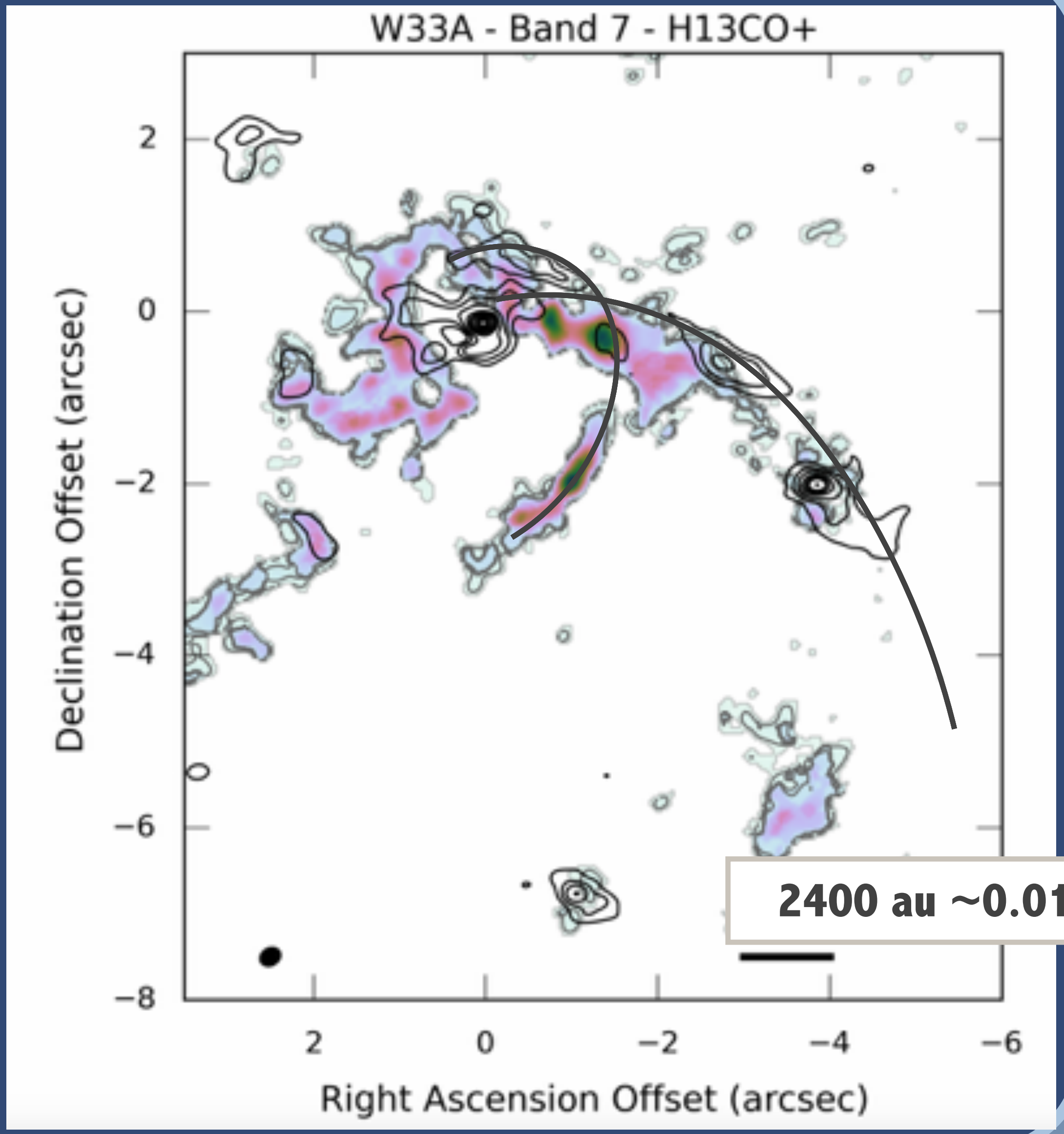
- Band 7 - 330GHz - 0.21''x 0.14''

~500 AU

The ALMA Perspective

- $H^{13}CO+$ tracing the dense filaments - $10^7 cm^{-3}$
- Co-spatial with the dust continuum
- Average Column $N_{H^{13}CO+} \sim 10^{15}$ cm^{-2}
- Mass reservoir in dense gas ~ 3.8 $M_\odot$

'Core Scale'



Maud et al. 2018 in prep.

- Band 7 - 346.99834GHz

The ALMA Perspective

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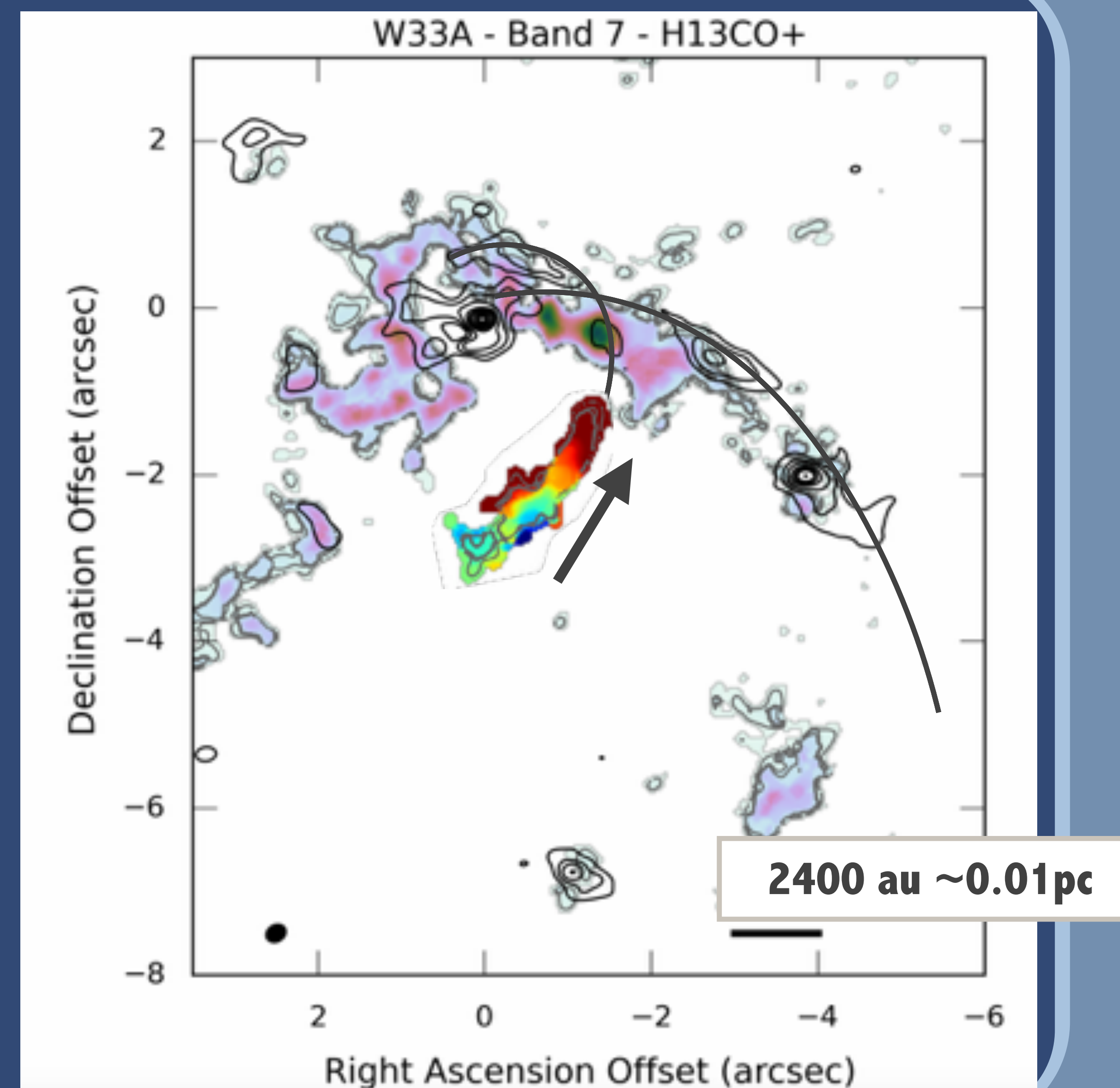
- Average Column $N_{H^{13}CO+} \sim 10^{15}\ cm^{-2}$
- Mass reservoir in dense gas ~ 3.8 $M_\odot$
- Gradient ~3km/s

'Core Scale'



Maud et al. 2018 in prep.

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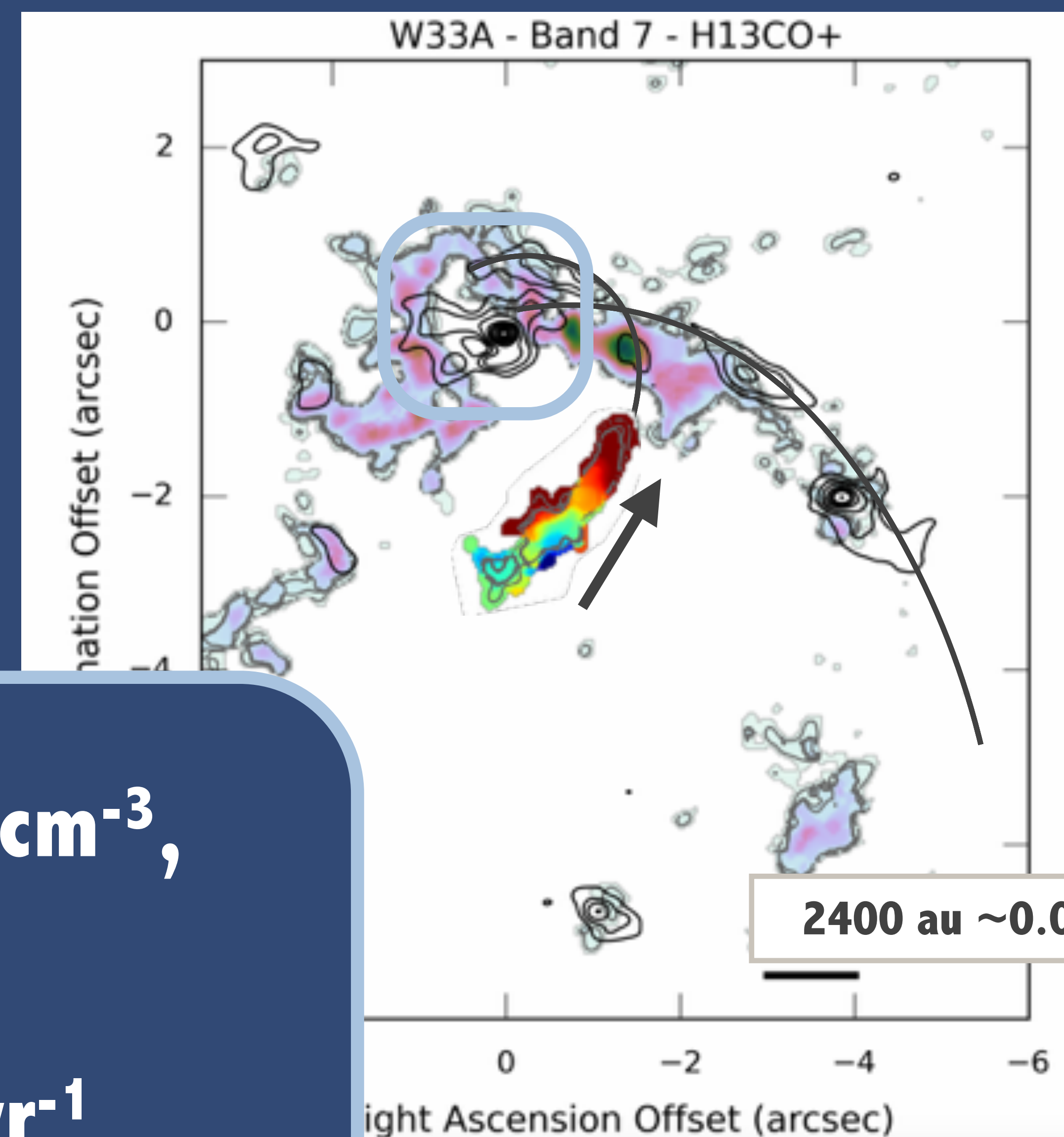
THE ALMA PERSPECTIVE

- $H^{13}CO+$ tracing the dense filaments - $10^7 cm^{-3}$
- Co-spatial with the dust continuum
- Average Column N
- M d
- Gra

- $v = 3$ km s^{-1}, $\rho_{H2} \sim 5 \times 10^7$ cm^{-3}, $A \sim \Pi r^2$, $r \sim 0.15''$
- Mass Flow ~ 5×10^{-5} $M_\odot$ yr^{-1}

'Core Scale'



Maud et al. 2018 in prep.

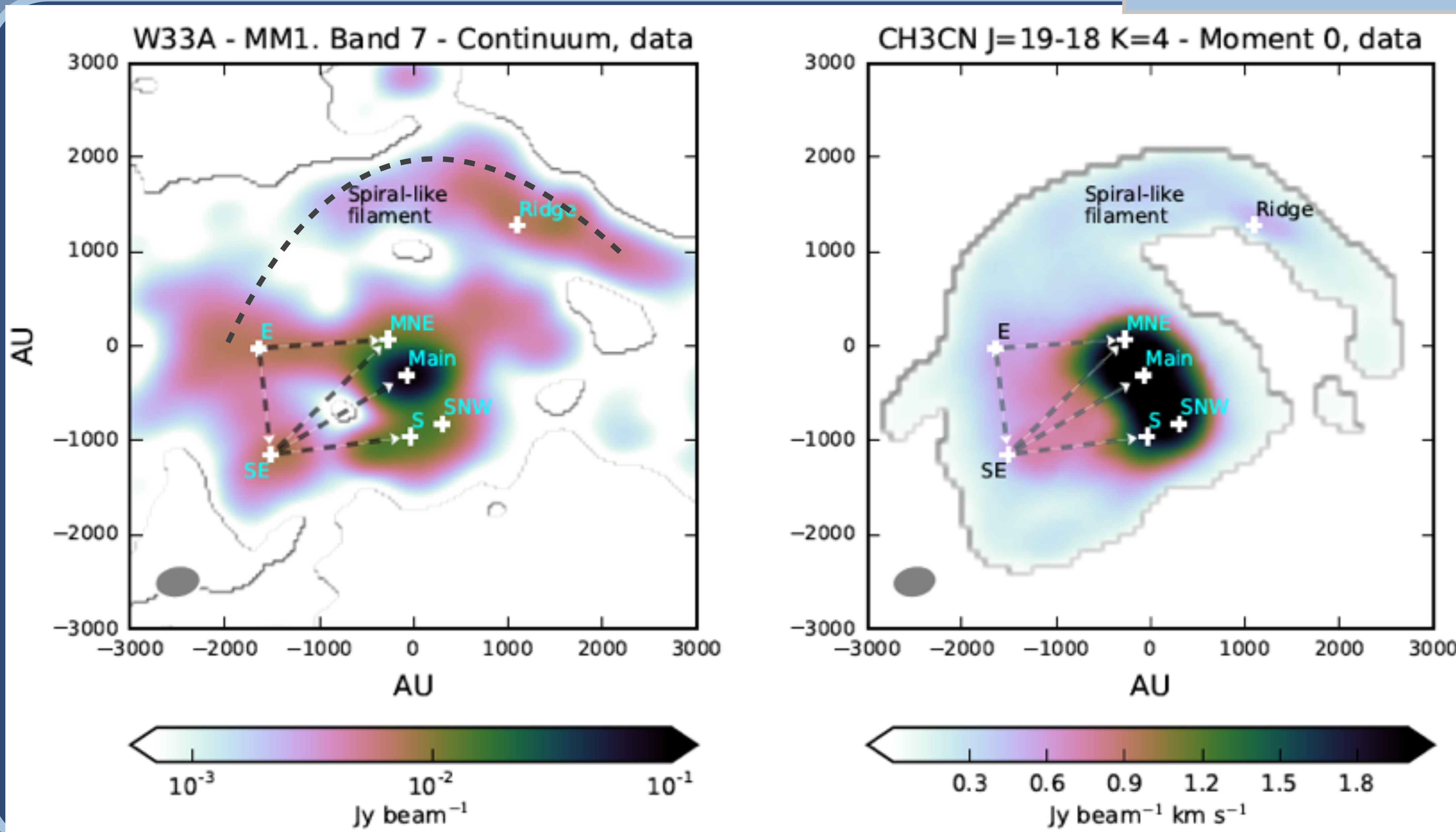
- Band 7 - 346.99834GHz

ZOOMING IN TO MM1

Maud et al. 2017, MNRAS 2017 467 120

Izquierdo et al. 2018, MNRAS 2018 478 2505

'Proto Cluster - Disk Scale'



- See the substructure - multiple sources?

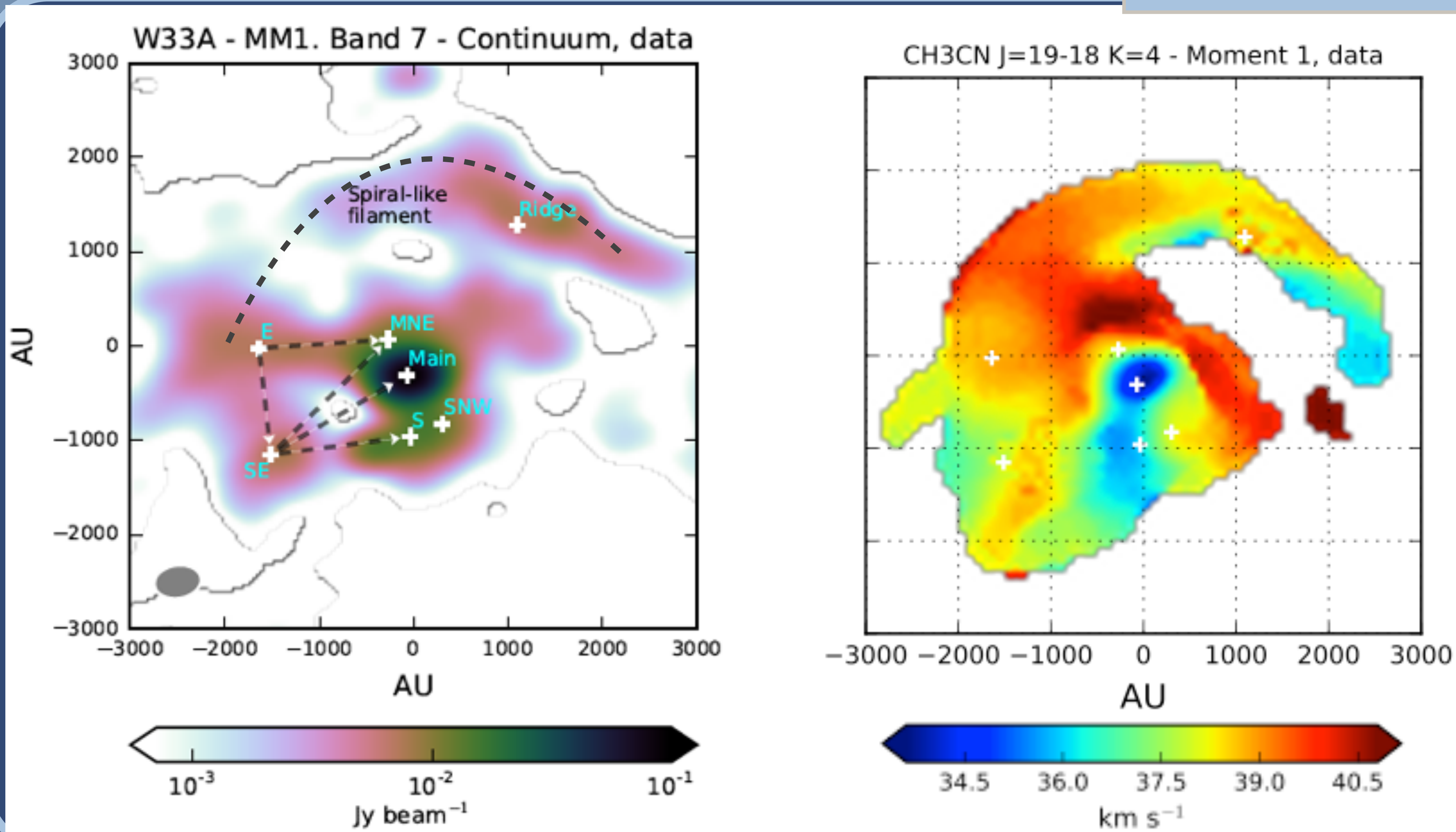
  - feeding filaments? - spiral structure?

ZOOMING IN TO MMI

Maud et al. 2017, MNRAS 2017 467 120

Izquierdo et al. 2018, MNRAS 2018 478 2505

'Proto Cluster - Disk Scale'



- Moment 1 - many gradients, no clear 'single' disc

ZOOMING IN TO MM1

Maud et al. 2017, MNRAS 2017 467 120

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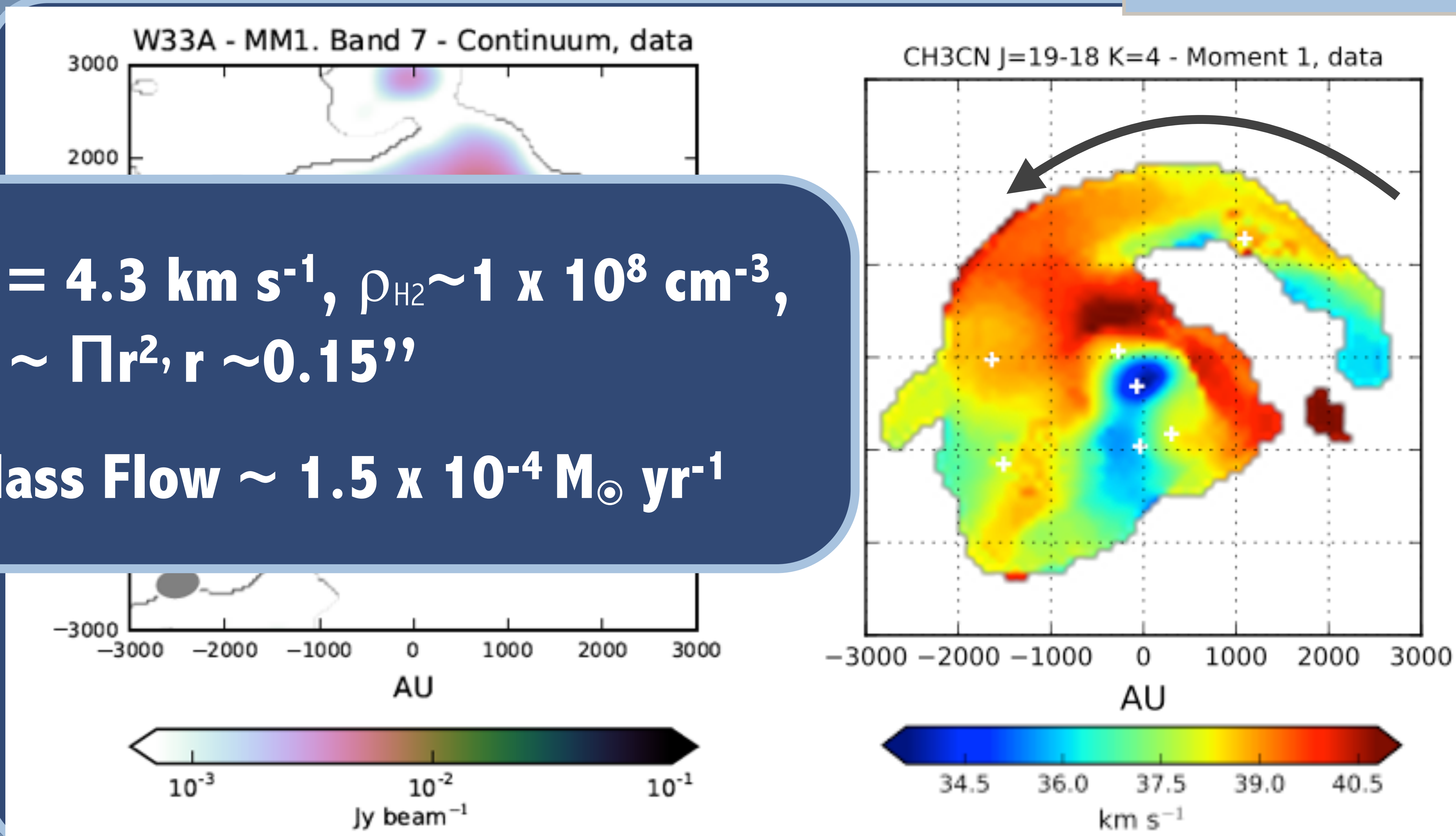
'Proto Cluster - Disk Scale'



- $v = 4.3$ km s^{-1}, $\rho_{H2} \sim 1 \times 10^{8}$ cm^{-3}, $A \sim \Pi r^{2}$, $r \sim 0.15''$
- Mass Flow ~ 1.5×10^{-4} $M_{\odot}$ yr^{-1}

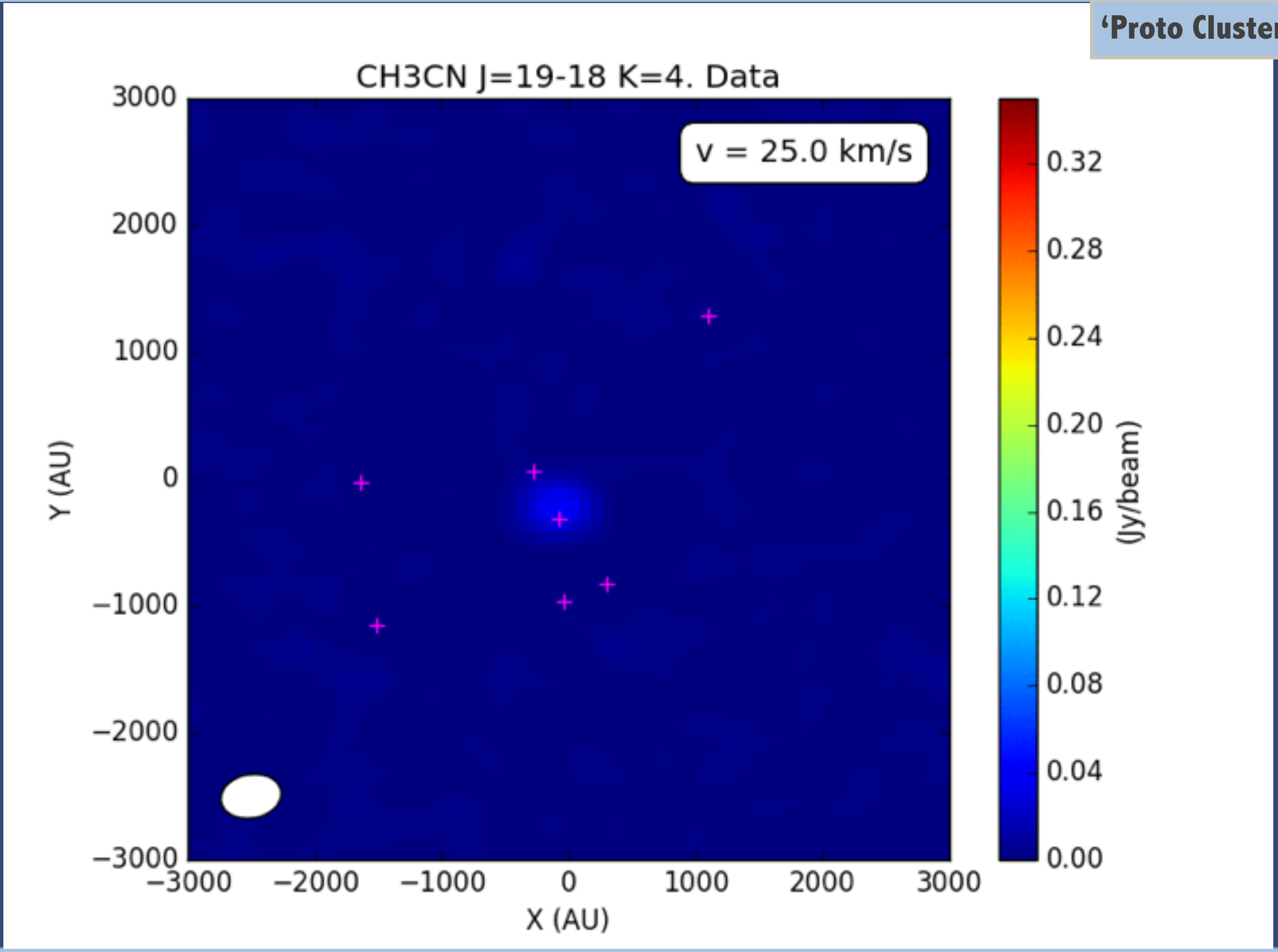
- Spiral 'feeding-filament' has clear gradient

Zooming in to MM1

Maud et al. 2017, MNRAS 2017 467 120

Izquierdo et al. 2018, MNRAS 2018 478 2505

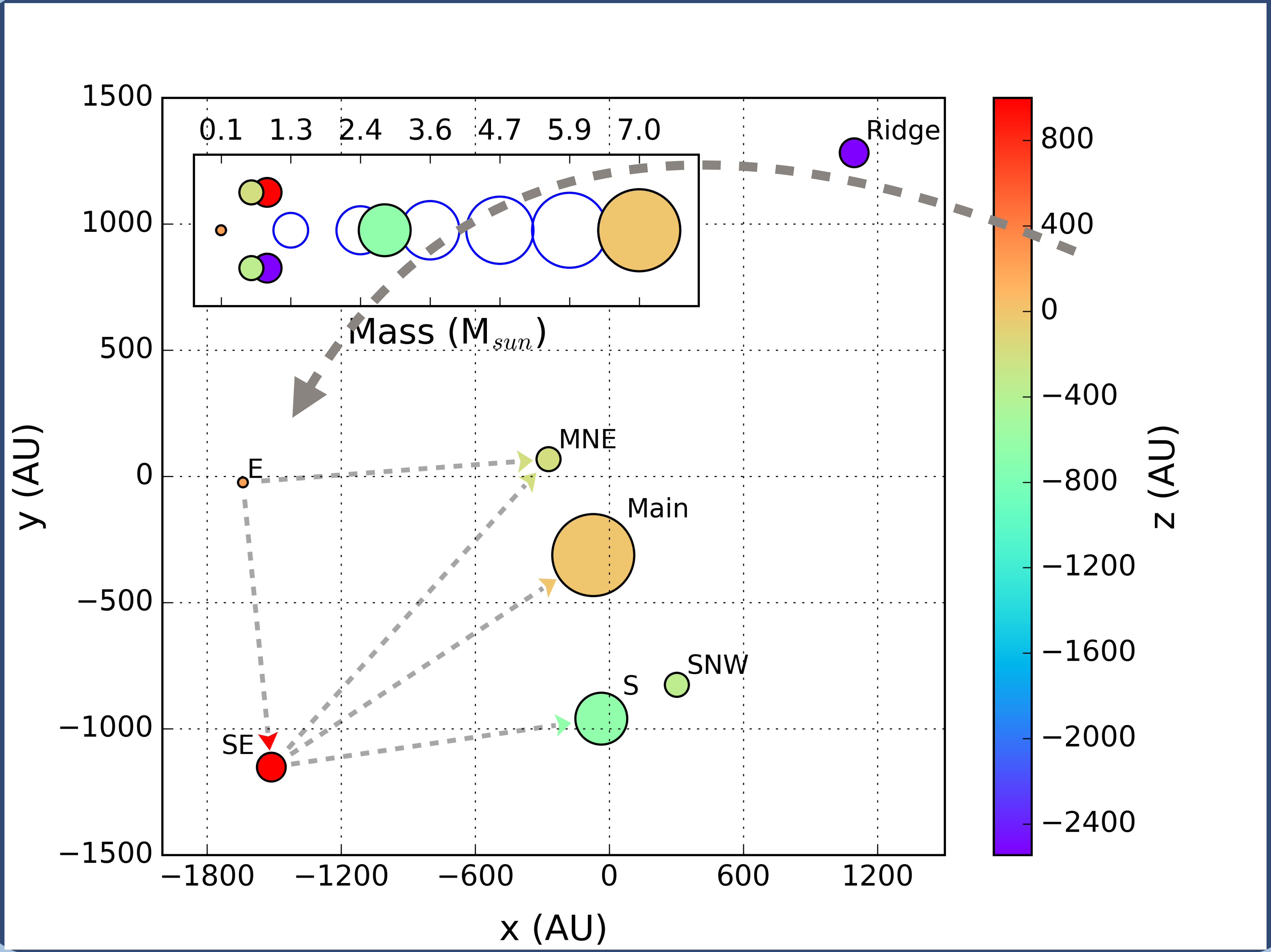
'Proto Cluster - Disk Scale'



- CH_3CN (19-18) K=4 V_{LSR} = 38.4 km/s

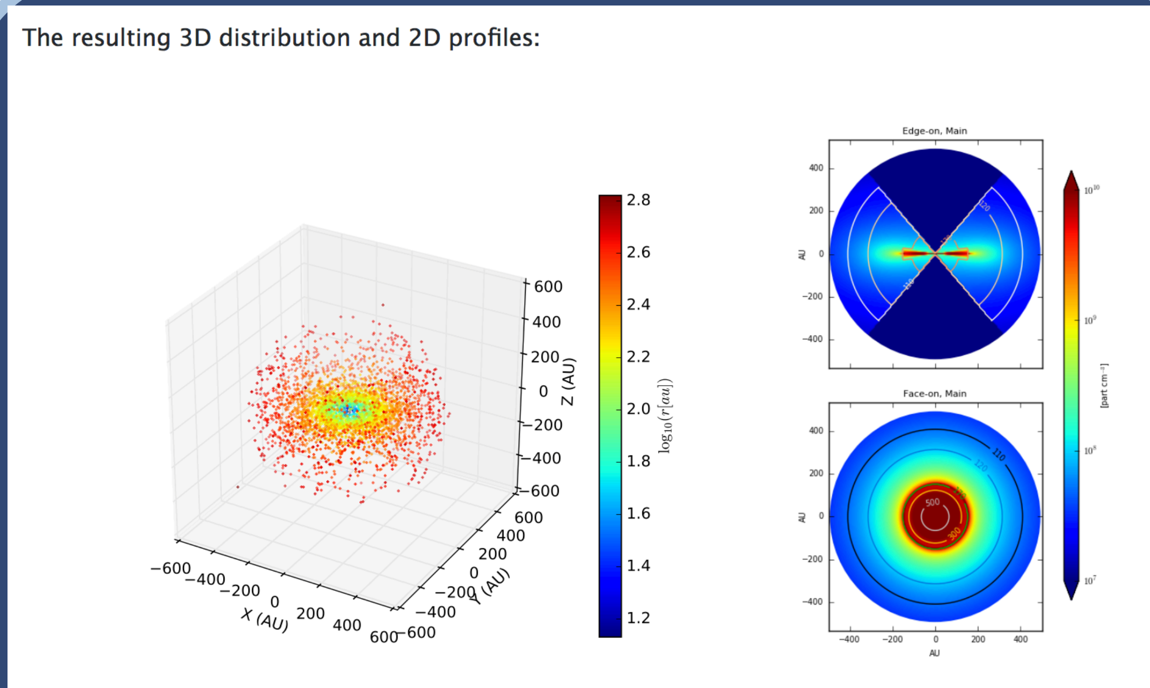
Modelling MM1

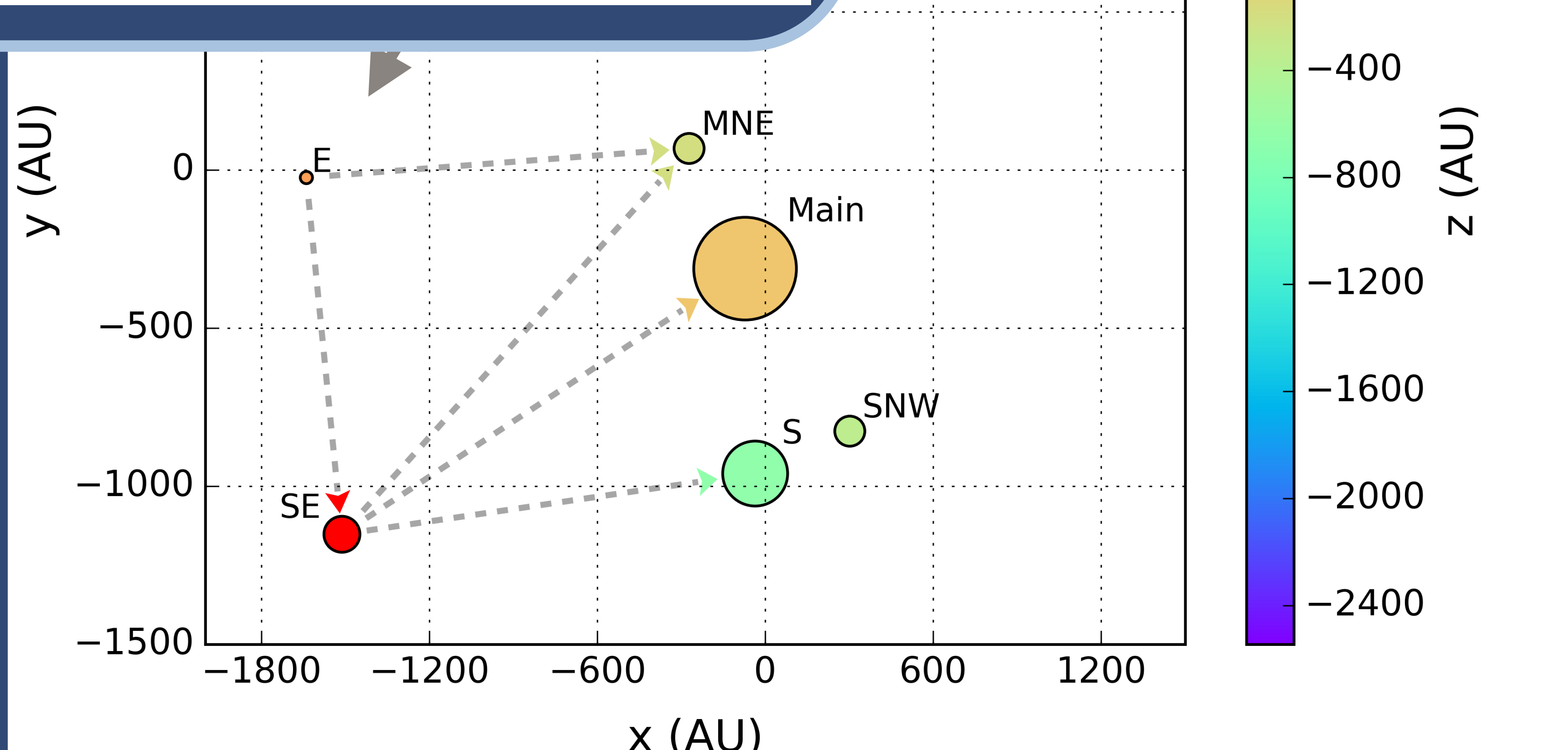
Izquierdo et al. 2018, MNRAS 2018 478 2505



- 3D environment - based on velocity gradients set position in+/-Z direction

Izquierdo et al. 2018, MNRAS 2018 478 2505

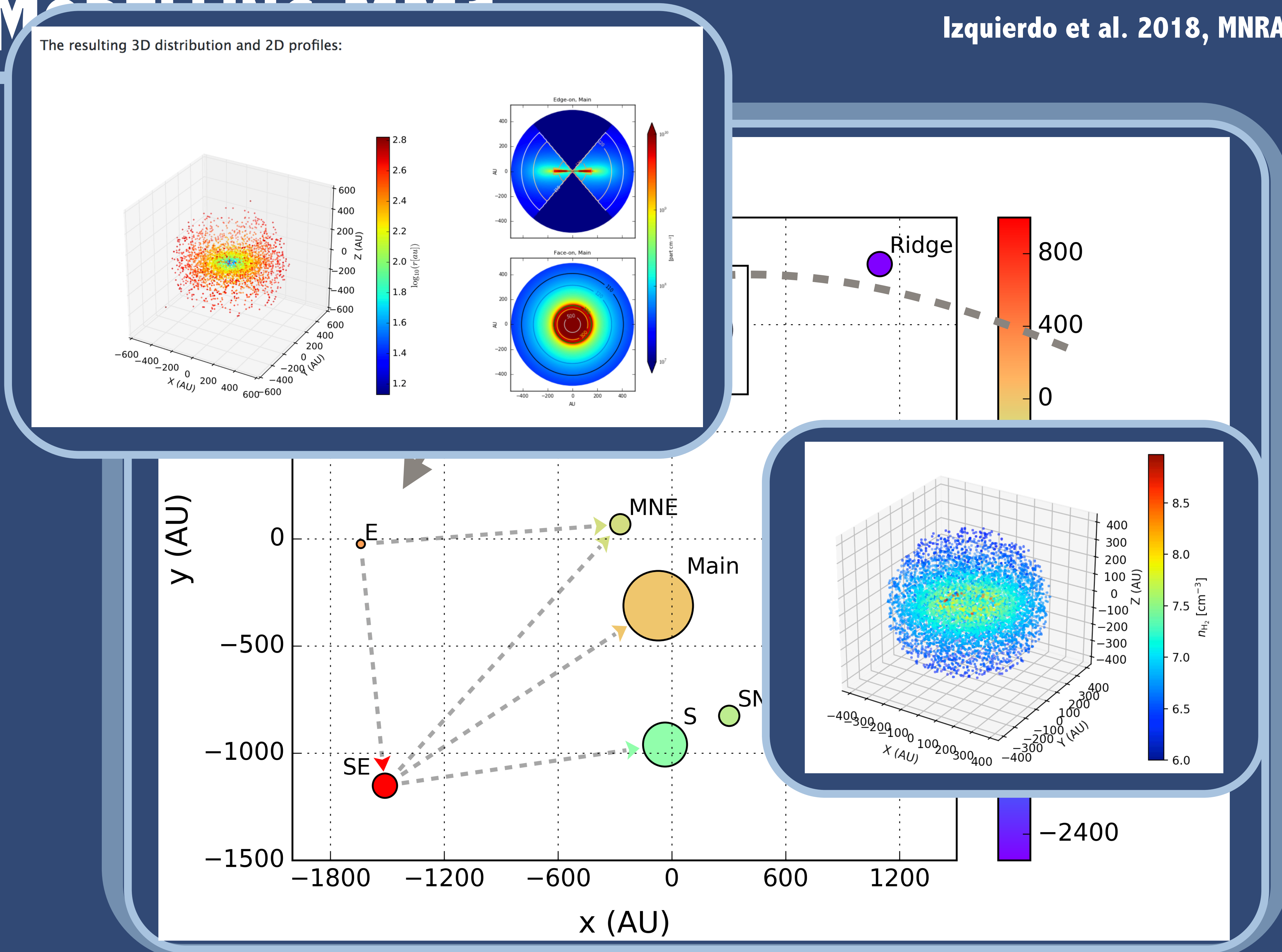




- Local models for each source - MM1, S, SW, Ridge = Ulrich envelope + disc

M

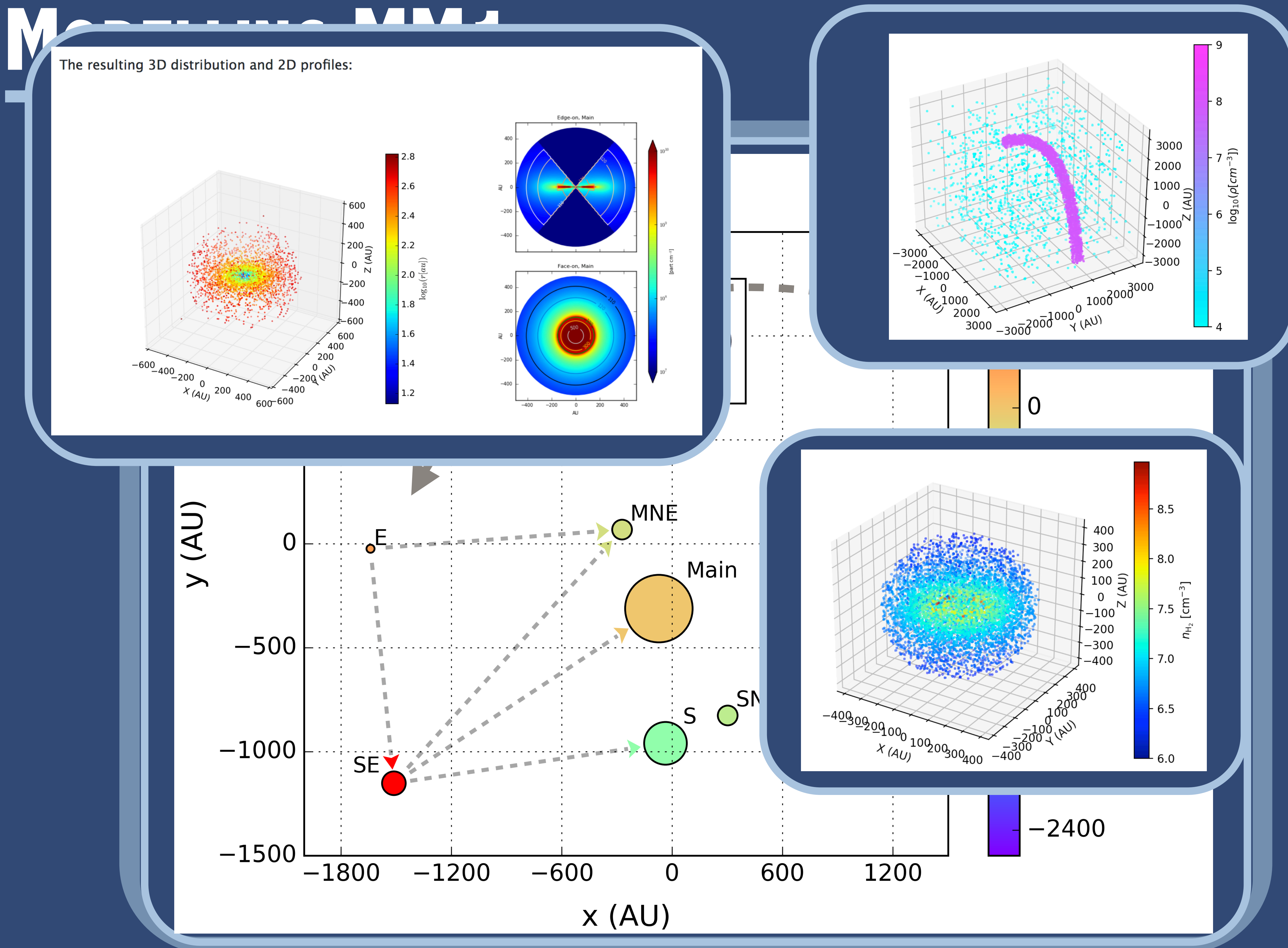
Izquierdo et al. 2018, MNRAS 2018 478 2505



- Local models for each source - E, MNE, SNW = Ulrich envelope

Modelling MM1

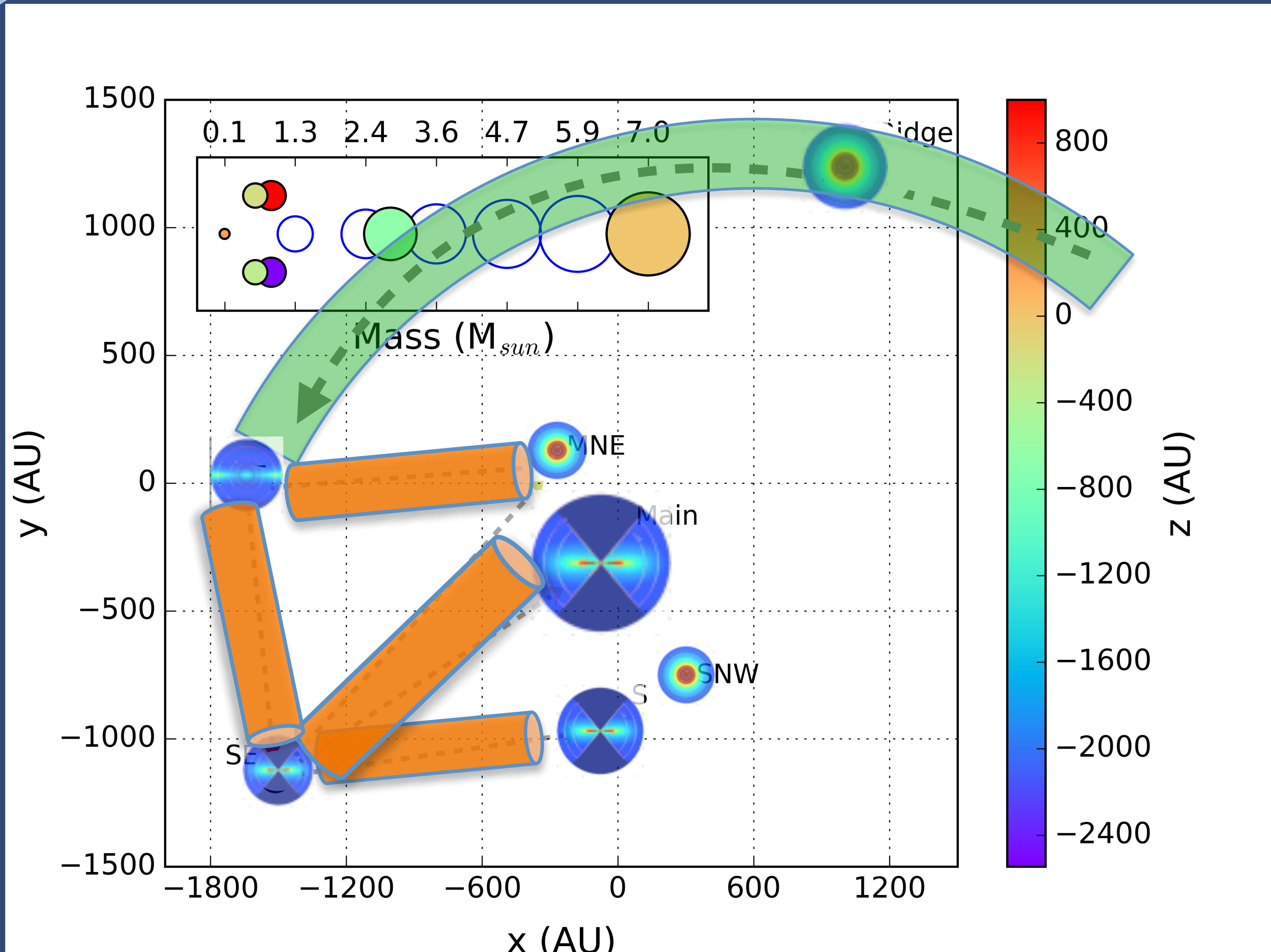
2018 478 2505



- Parabolic filament falling to centre of system mass
- Connecting filament cylinders dominated by most massive source

Modelling MM1

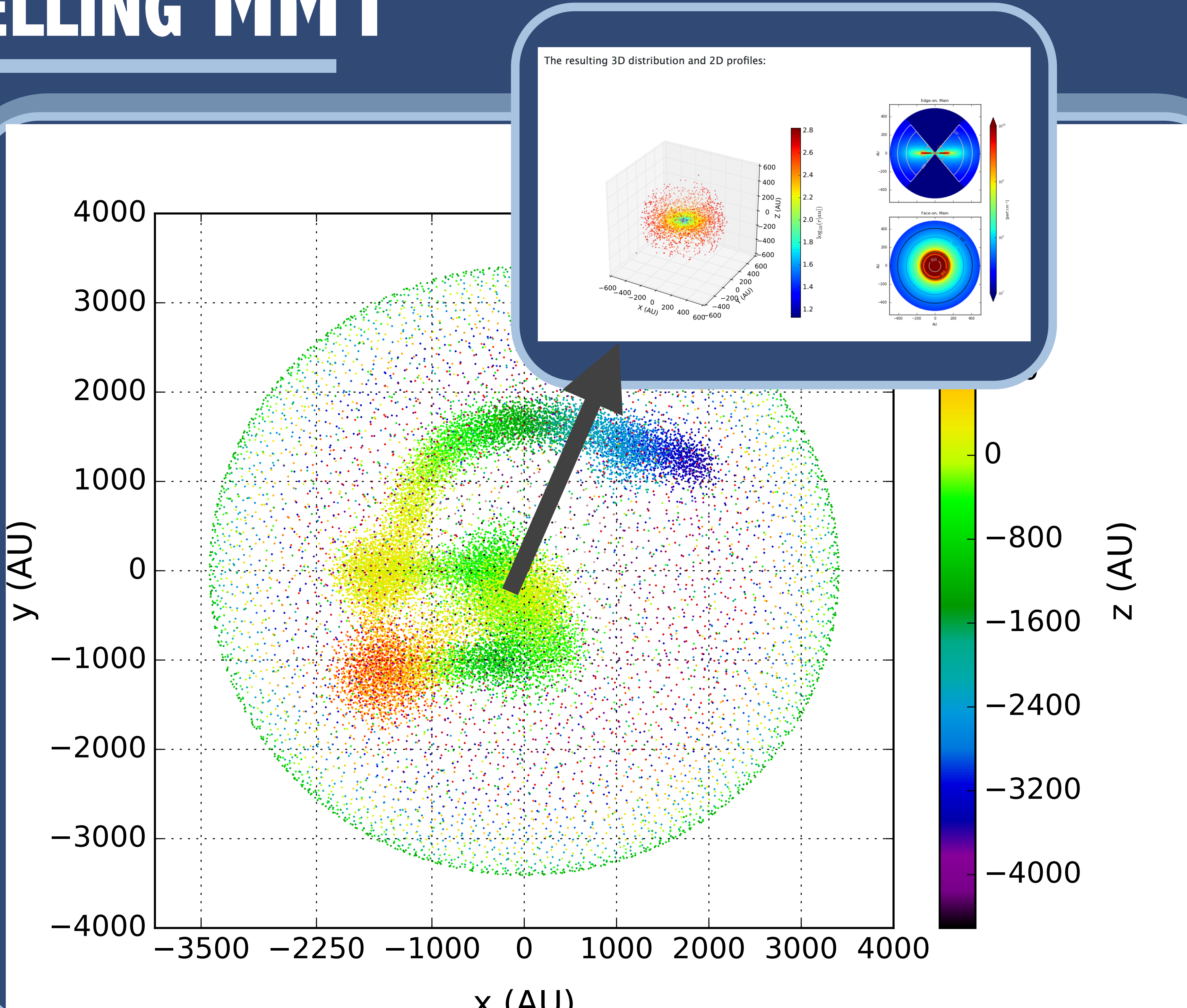
Izquierdo et al. 2018, MNRAS 2018 478 2505



- All local grids to combine for a global model grid (LIME -> CASA sim)

Modelling MM1

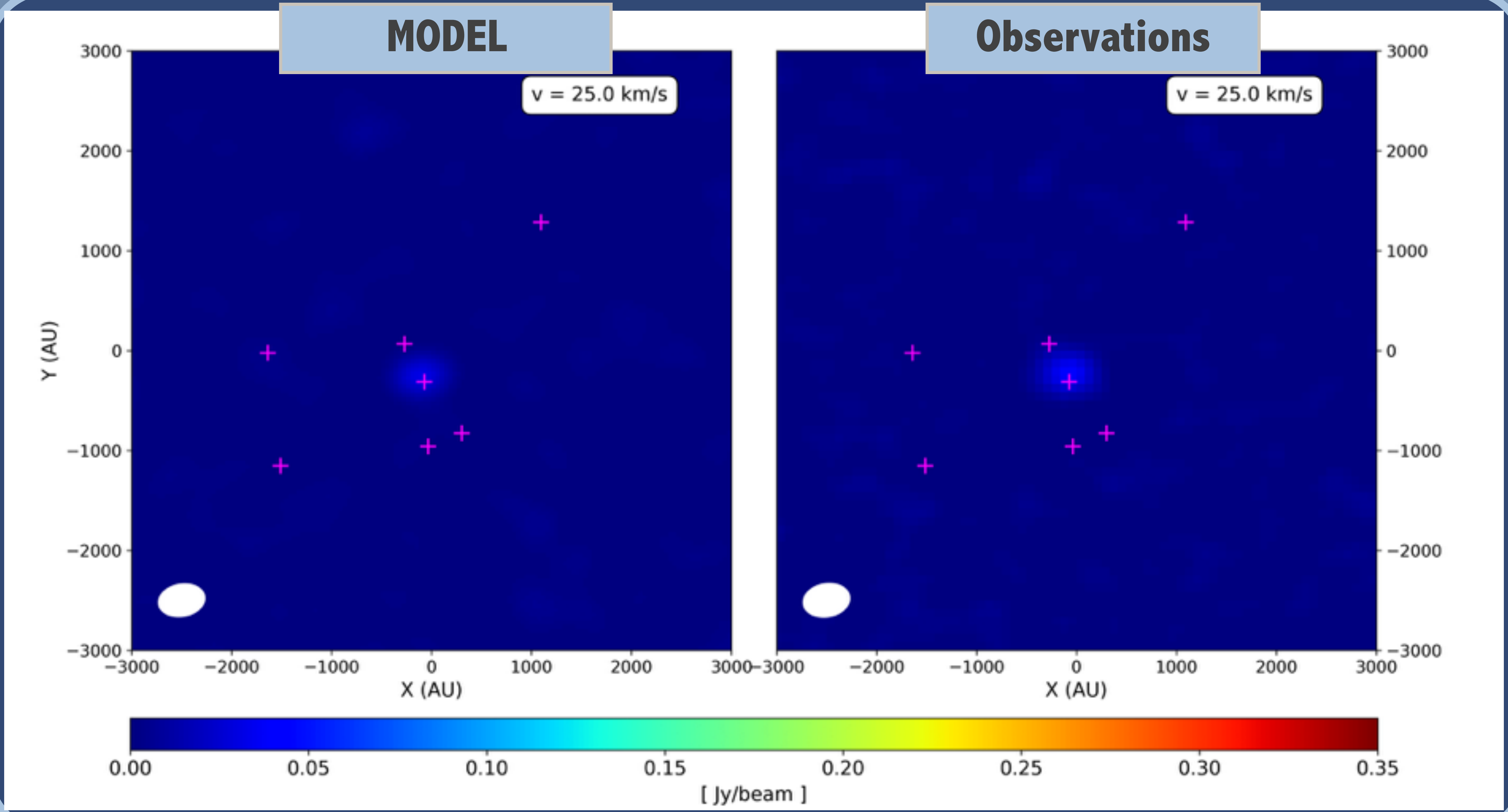
Izquierdo et al. 2018, MNRAS 2018 478 2505



- Global grid (8000 x 8000 x 8000au) - incorporating of local grids

Comparing with Observations

Izquierdo et al. 2018, MNRAS 2018 478 2505



- CH_3CN (19-18) K=4 VLSR = 38.4 km/s

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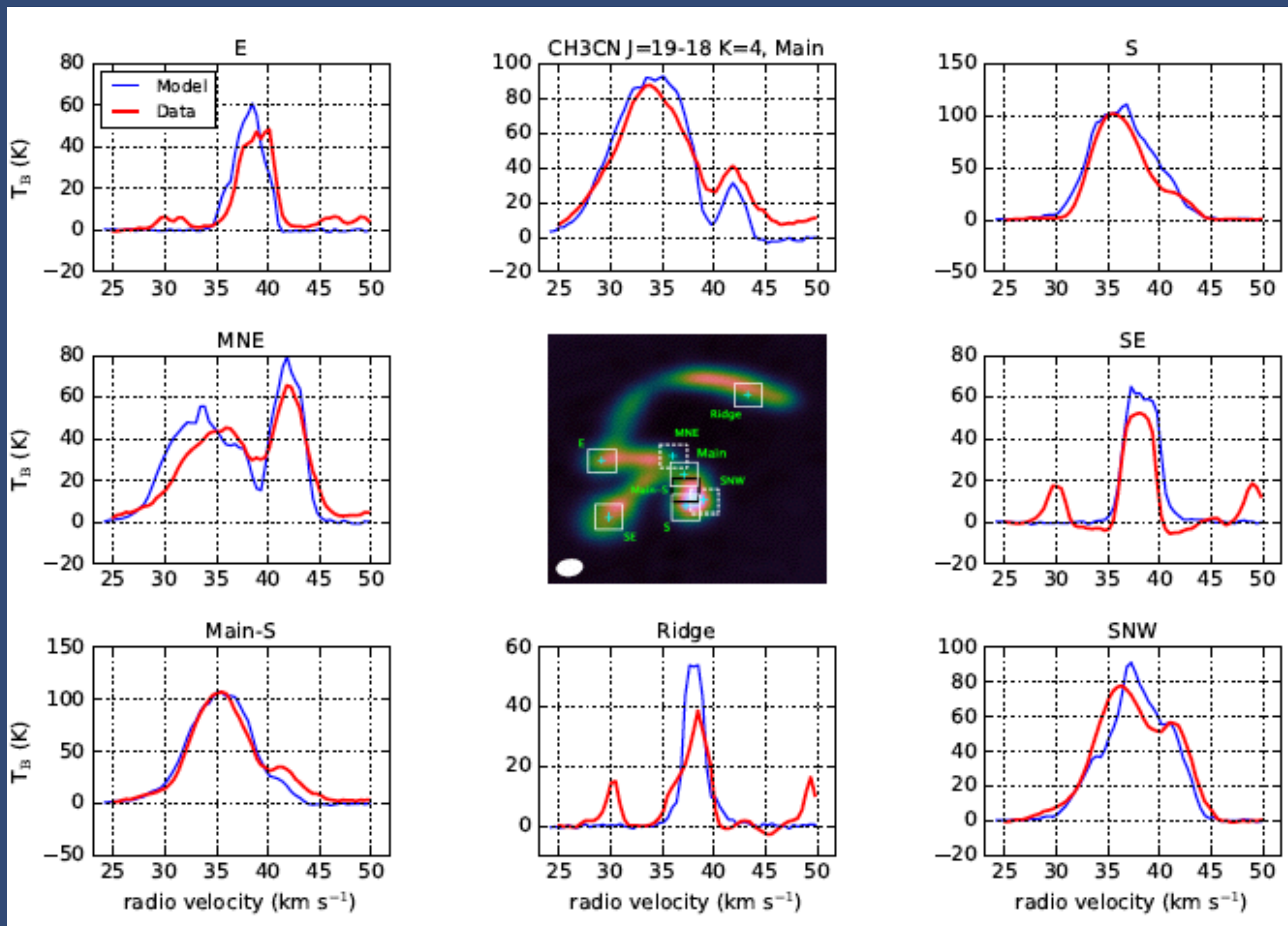
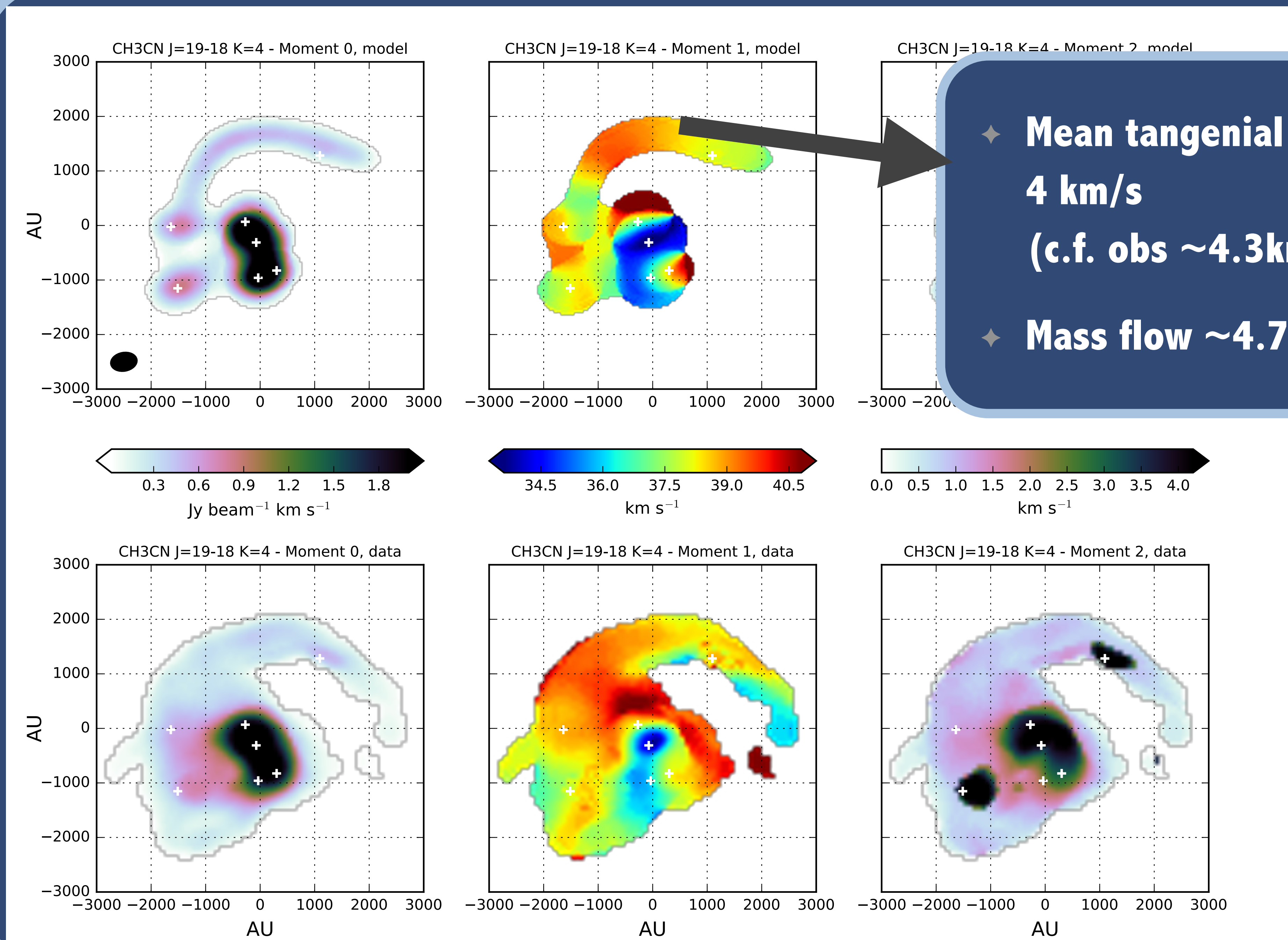
Izquierdo et al. 2018, MNRAS 2018 478 2505



- Matching of spectral features - fluxes and line widths

Comparing with Observations

Izquierdo et al. 2018, MNRAS 2018 478 2505



- Mean tangenial velocity = 4 km/s (c.f. obs ~4.3km/s)
- Mass flow ~4.7x10^{-4} M$_{\odot}$/yr

- CH_3CN (19-18) K=4 - Mom 0, Mom 1, Mom 2 comparison

Caveats & Clarifications

- First order representation
- Not designed to be a unique model - limited by data
- Large scale envelope is not included - local only
- Isothermal, contant density 'cylinder' filaments
- Comparisons with other tracers are required

- Disc *are* required to match mm flux on small scales
- In current framework, MM1 Main is $7M_{\odot}$, with $1x10^4 L_{\odot}$
- Model accretion rates ~$4x10^{-4}$ - $1x10^{-5}$ $M_{\odot}$/yr, consistent with obs. 'flow' estimates
- Filament mass flows ~0.2-$5x10^{-5}$ $M_{\odot}$/yr

Summary

- MM1 is a multiple core, heavily fragmented proto-cluster with active star formation
- Dust and gas filaments are coherent and have >2-5 $M_{\odot}$ available for accretion (excluding resolved out emission)
- The main spiral-like feeding the protocluster will deplete if not replenished within 8×10^3 years (~$0.4 M_{\odot}$ in CH_3CN)
- Intra-source filaments connect and transfer material between protostars - competitive accretion
- Complex 3D RT models are necessary to understand such clustered regions

Summary

Thank You - Any questions?

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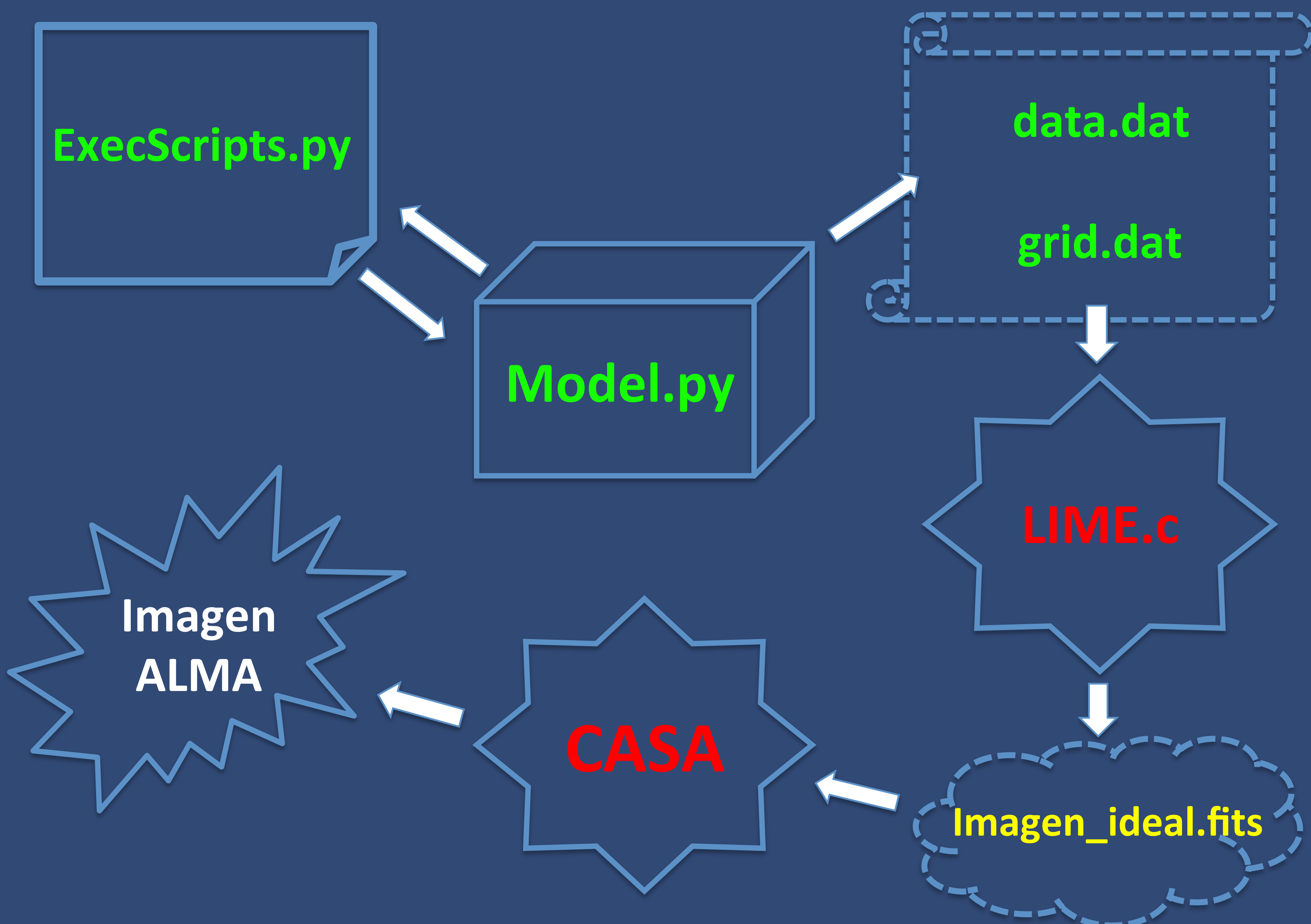
Block Diagram



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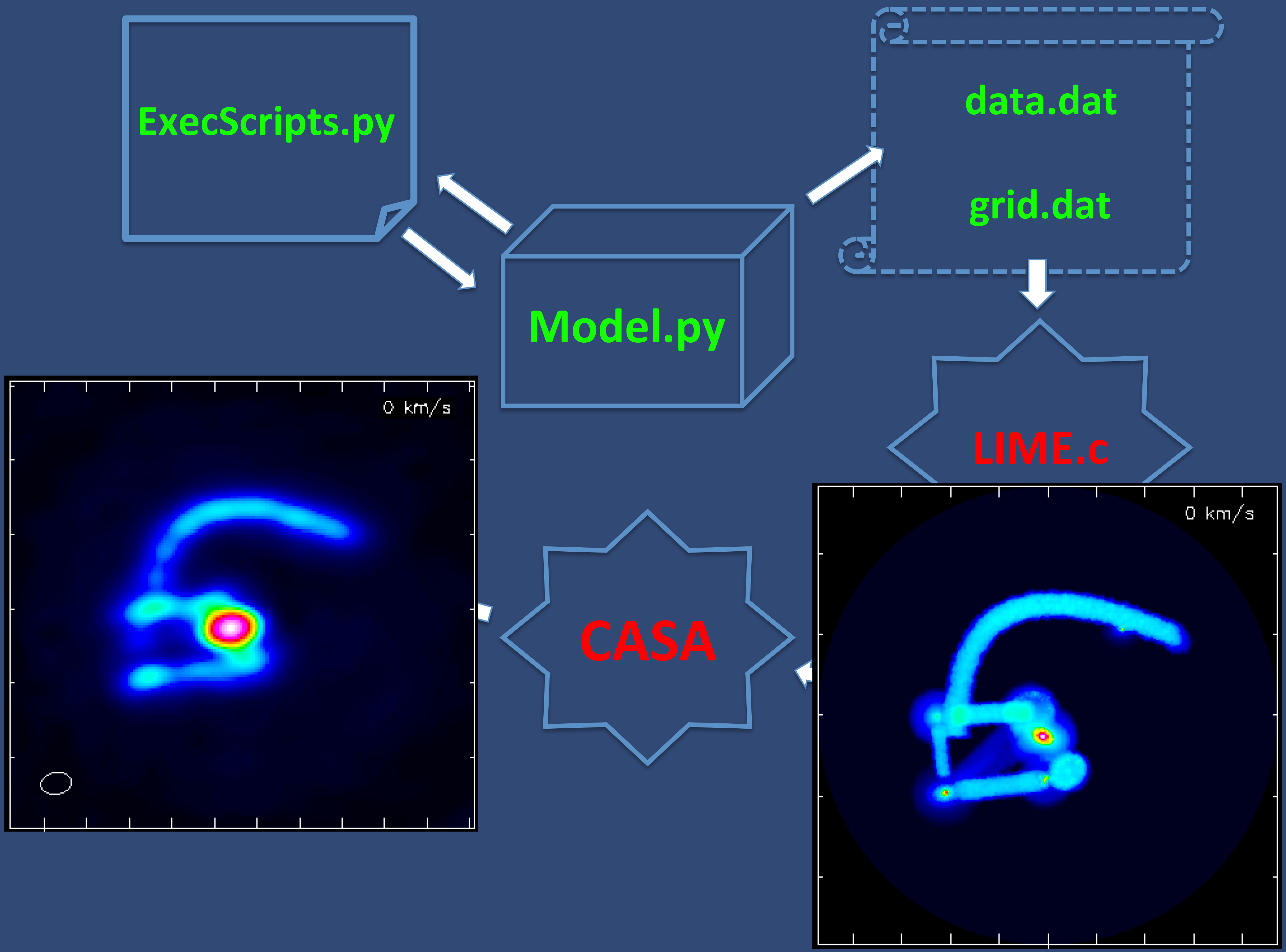
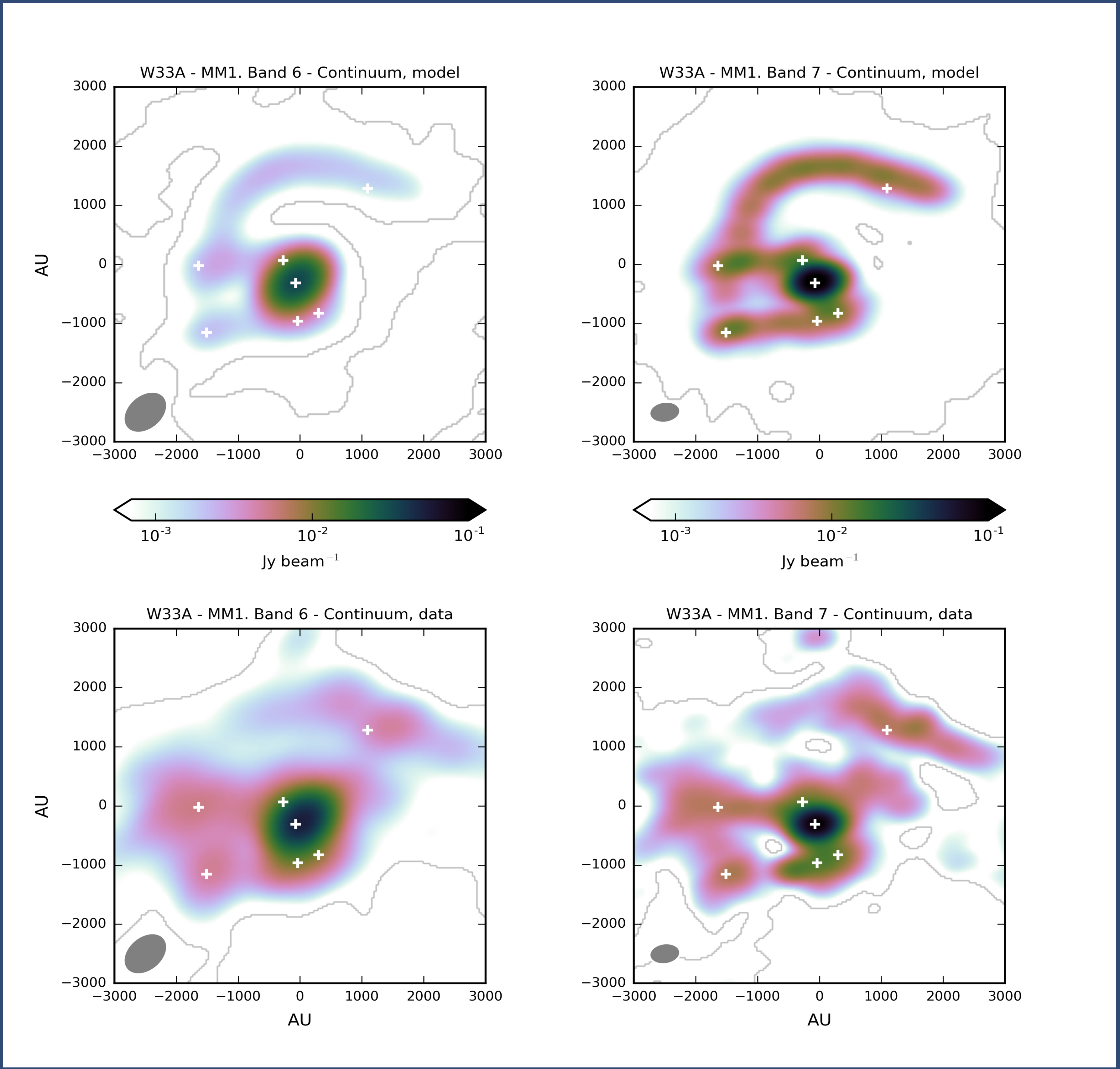
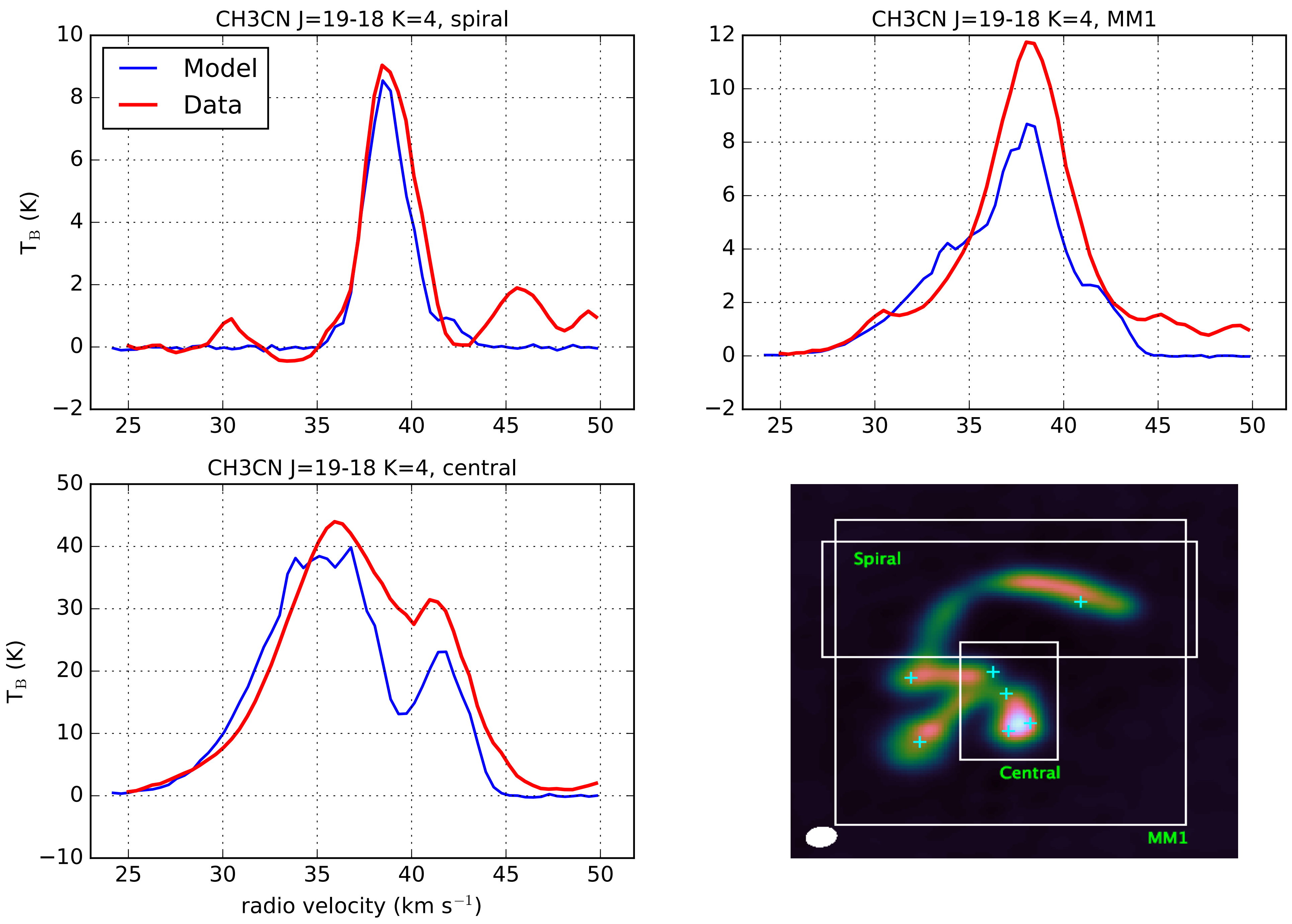


Continuum

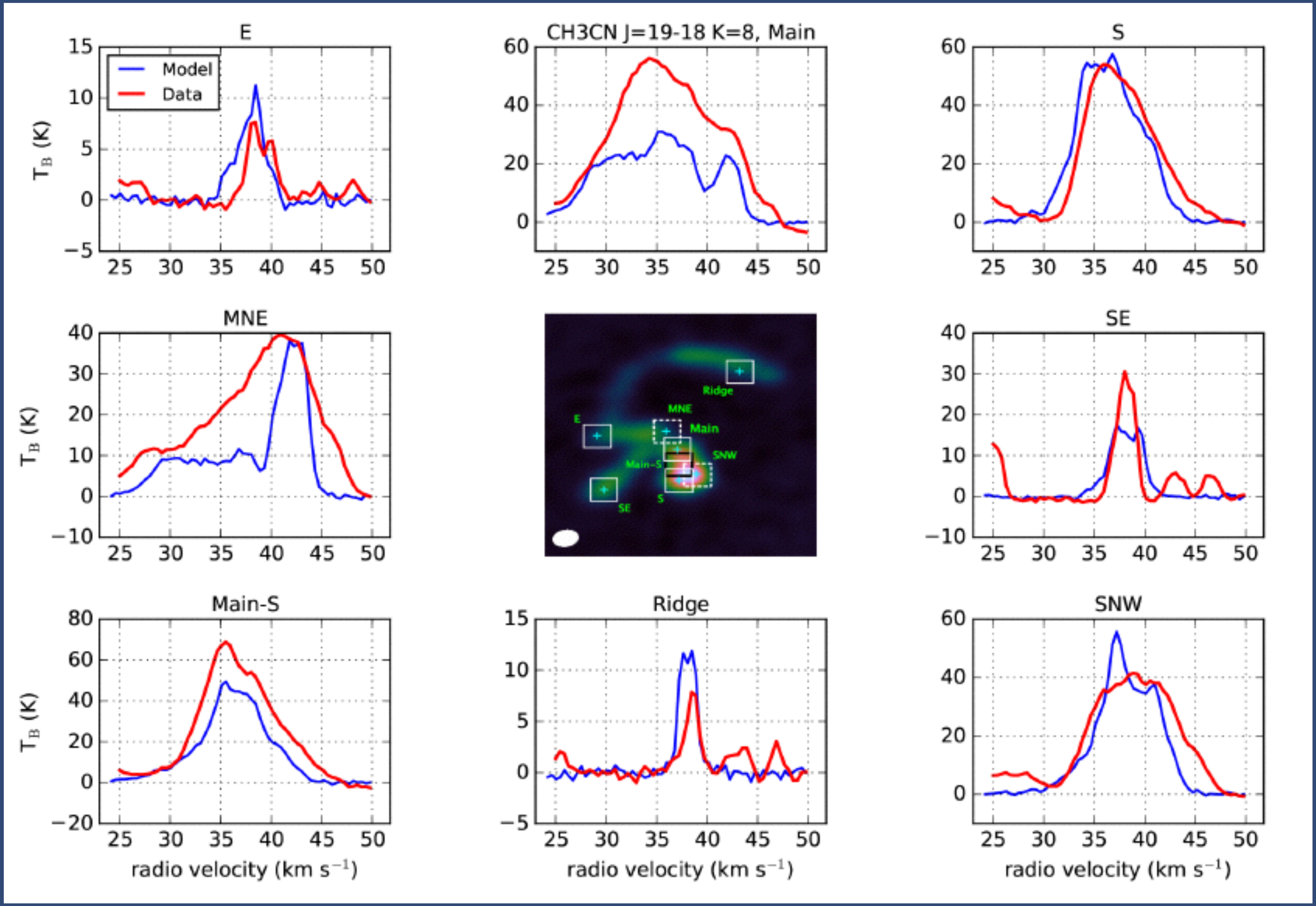


- Dust is ISM with beta = 1.7
- Cores are not separated at this resolution
- Needs a disc for mm emission
- Fluxes within 10-20%
- Calculated beta is ~0.0-0.5, RJ is not valid
- Where RJ is met becomes optically thick (i.e. in Main)

Large Regions



K=8



E
Model
Data
CH3CN J=19-18 K=8, Main
S
MNE
SE
Ridge
MNE
Main
E
SNW
Main-S
SE
S
Main-S
Ridge
SNW
T_B (K)
radio velocity (km s^{-1})

Model Equations

$$\rho_{\rm disc}(z, R) = \rho_0(R)\exp\{-z^2/2H^2(R)\},$$

$$+$$

$$\rho_{\rm env}(r,\theta) = \rho_{\rm e_0}(r/R_{\rm d})^{-3/2}\left(1+\frac{\cos\theta}{\cos\theta_0}\right)^{-1/2} \times [1+(r/R_{\rm d})^{-1}(3\cos^2\theta_0 - 1)]^{-1},$$

$$=$$

$$\rho_{\rm gas} = \rho_{\rm disc} + \rho_{\rm env}.$$

$$T_{\rm disc} = B_{\rm T}\left[\left(\frac{3GM_\star \dot{M}}{4\pi R^3\sigma}\right)\left(1-\sqrt{\frac{R_\star}{R}}\right)\right]^{1/4},$$

$$T_{\rm env}(r) \propto r^{-0.33}$$

$$T_{\rm gas} = \frac{T_{\rm disc}\rho_{\rm disc} + T_{\rm env}\rho_{\rm env}}{\rho_{\rm disc} + \rho_{\rm env}}.$$

$$+$$

$$=$$

$$\vec{v}_{disc} = \sqrt{GM_\star/R}\ \ \hat{\phi},$$

$$v_r(r,\theta) = -\left(\frac{GM_\star}{r}\right)^{1/2}\left(1+\frac{\cos\theta}{\cos\theta_0}\right)^{1/2},$$

$$v_\theta(r,\theta) = \left(\frac{GM_\star}{r}\right)^{1/2}\left(\frac{\cos\theta_0 - \cos\theta}{\sin\theta}\right)^{1/2}\left(1+\frac{\cos\theta}{\cos\theta_0}\right)^{1/2},$$

$$v_\phi(r,\theta) = \left(\frac{GM_\star}{r}\right)^{1/2}\frac{\sin\theta_0}{\sin_\theta}\left(1-\frac{\cos\theta}{\cos\theta_0}\right)^{1/2}$$

$$\boldsymbol{v}_{\rm gas} = \frac{\boldsymbol{v}_{\rm disc}\rho_{\rm disc} + \boldsymbol{v}_{\rm env}\rho_{\rm env}}{\rho_{\rm disc} + \rho_{\rm env}},$$

Disc + Envelope = Disc + Env

Extras

- Spiral - orbital energy conservation - i.e 2GM/r, also radial infall set by sound speed to give a velocity dispersion
- Filaments are cylinders where KE = GPE and gives Vel
- Iterative build up - envelopes, then inc discs for mm density