

Synthetic molecular line ALMA observations



Thomas J. Haworth

This session

1. Brief introduction to ALMA

2. Brief introduction to line radiative transfer

3. Modelling ALMA observations with TORUS and CASA

WHAT IS ALMA?

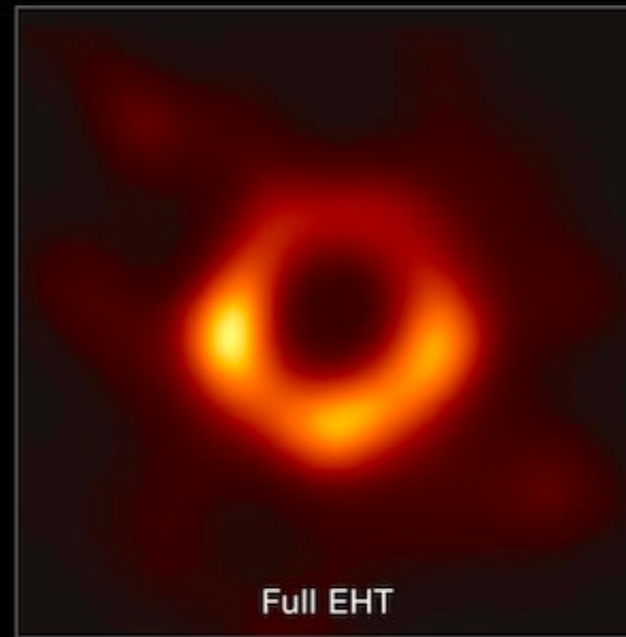
WHAT IS ALMA?

- An interferometer
- Current frequency coverage from 84-950GHz (0.3mm—3.6mm)
- Line and continuum observations
- Spatial resolution of up to 0.01"

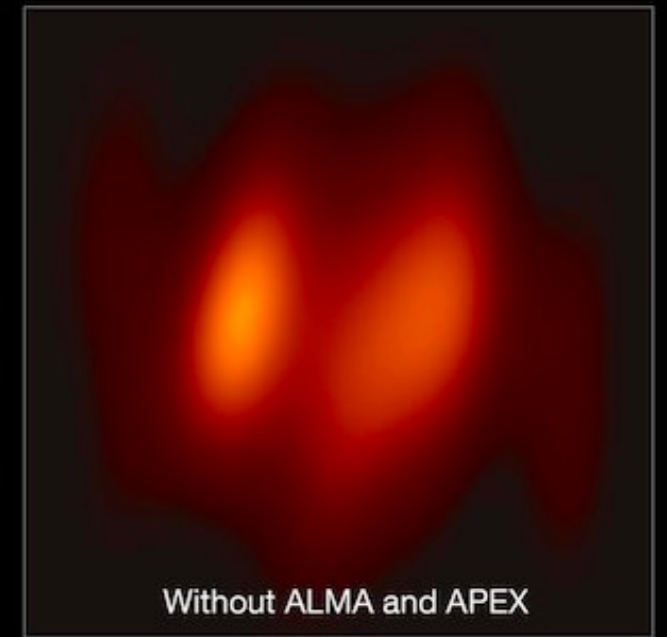
WHAT IS ALMA?



ALMA
/
Hubble



Full EHT

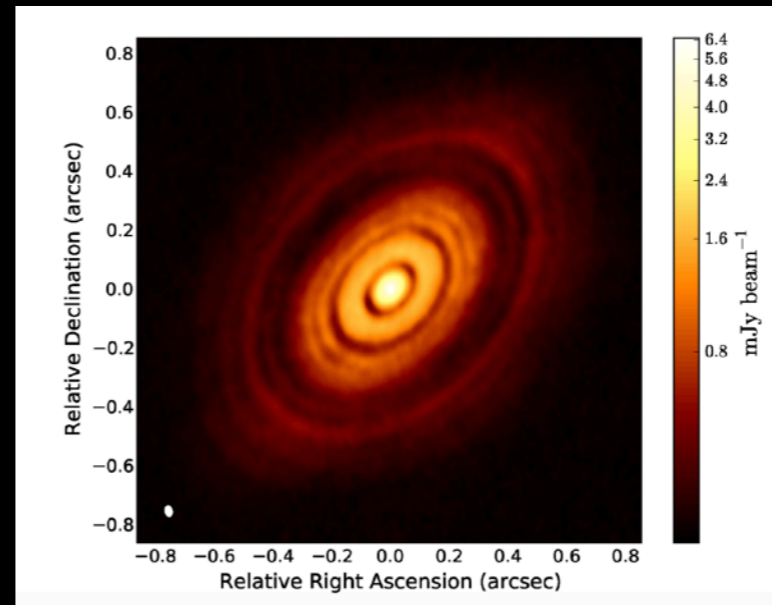


Without ALMA and APEX

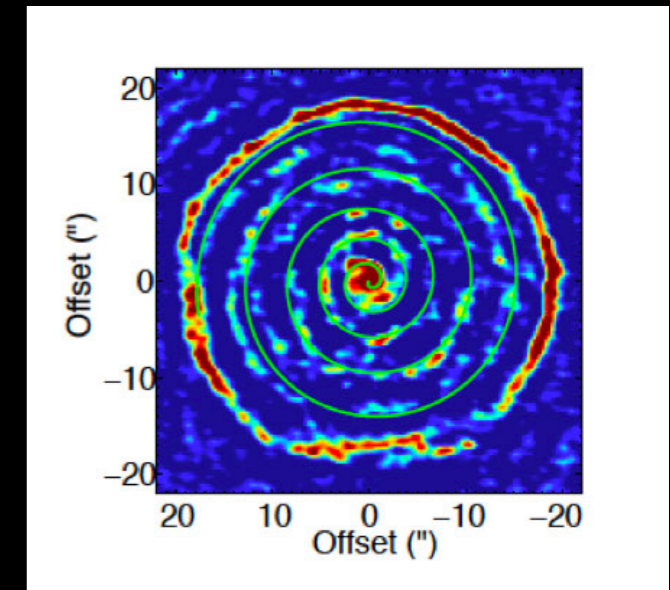
EHT Collaboration



ALMA
/
Hubble

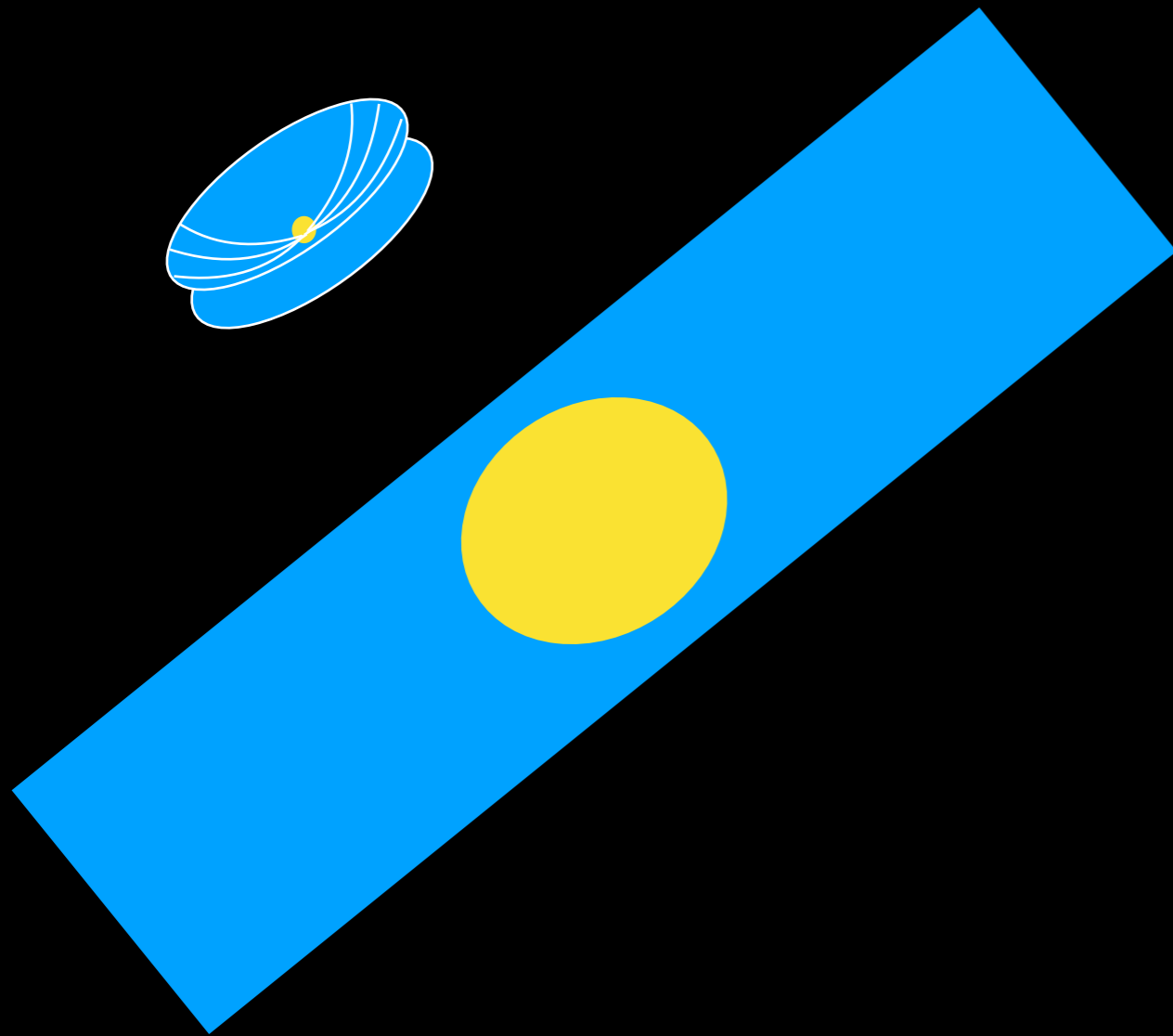


ALMA partnership (2015)

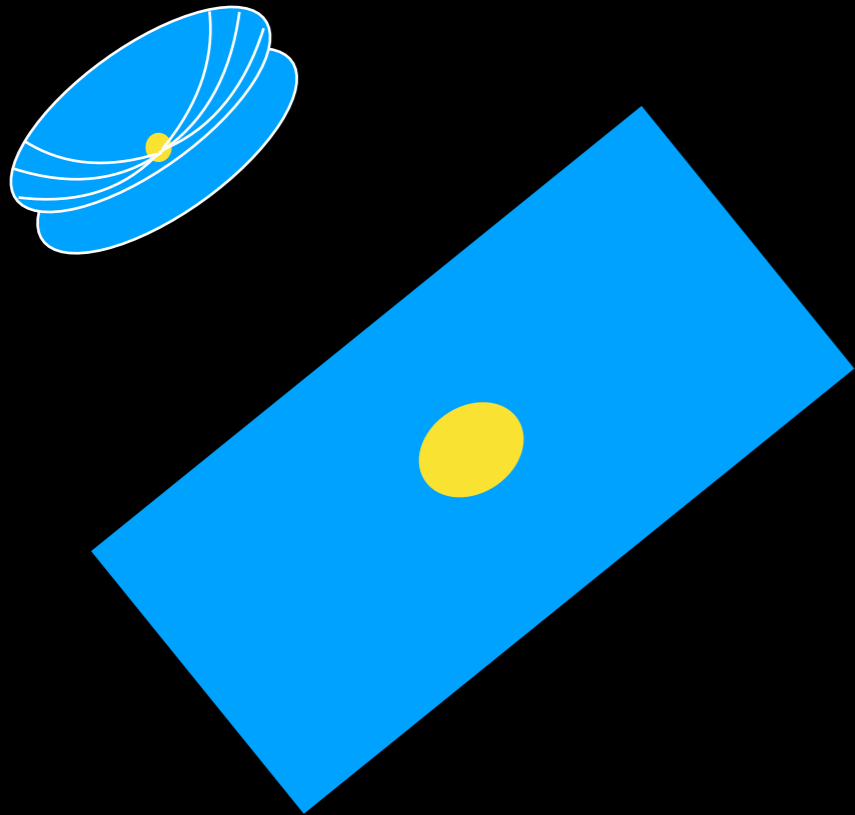


Maercker et al. 2012

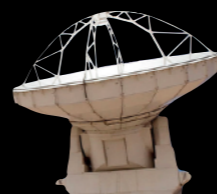
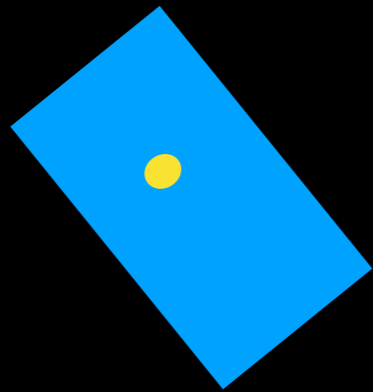
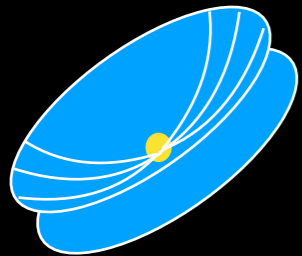
WHAT IS ALMA?



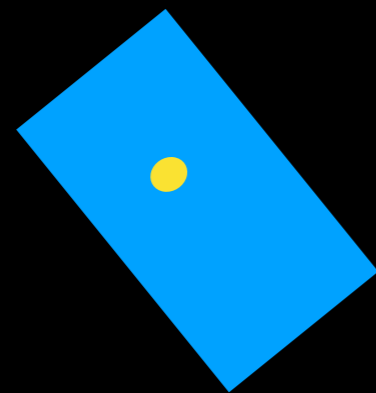
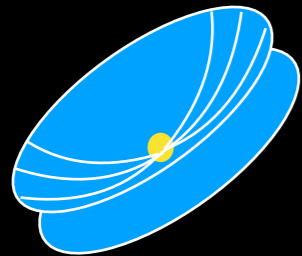
WHAT IS ALMA?



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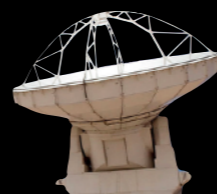


WHAT IS ALMA?



Non-trivial to plan observations

**Configuration(s) and time on source
need to be carefully chosen**



ALMA configurations

Resolution and maximum scale

	Band	3	4	5	6	7	8	9	10
	Frequency (GHz)	100	150	185	230	345	460	650	870
Configuration									
7-m	θ_{res} (arcsec)	12.5	8.35	6.77	5.45	3.63	2.72	1.93	1.44
	θ_{MRS} (arcsec)	66.7	44.5	36.1	29.0	19.3	14.5	10.3	7.67
C43-1	θ_{res} (arcsec)	3.38	2.25	1.83	1.47	0.98	0.735	0.52	0.389
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C43-2	θ_{res} (arcsec)	2.3	1.53	1.24	0.999	0.666	0.499	0.353	0.264
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C43-9	θ_{res} (arcsec)	0.057	0.038	0.0308	0.0248	0.0165	-	-	-
	θ_{MRS} (arcsec)	0.814	0.543	0.44	0.354	0.236	-	-	-
C43-10	θ_{res} (arcsec)	0.042	0.028	0.0227	0.0183	0.0122	-	-	-
	θ_{MRS} (arcsec)	0.496	0.331	0.268	0.216	0.144	-	-	-

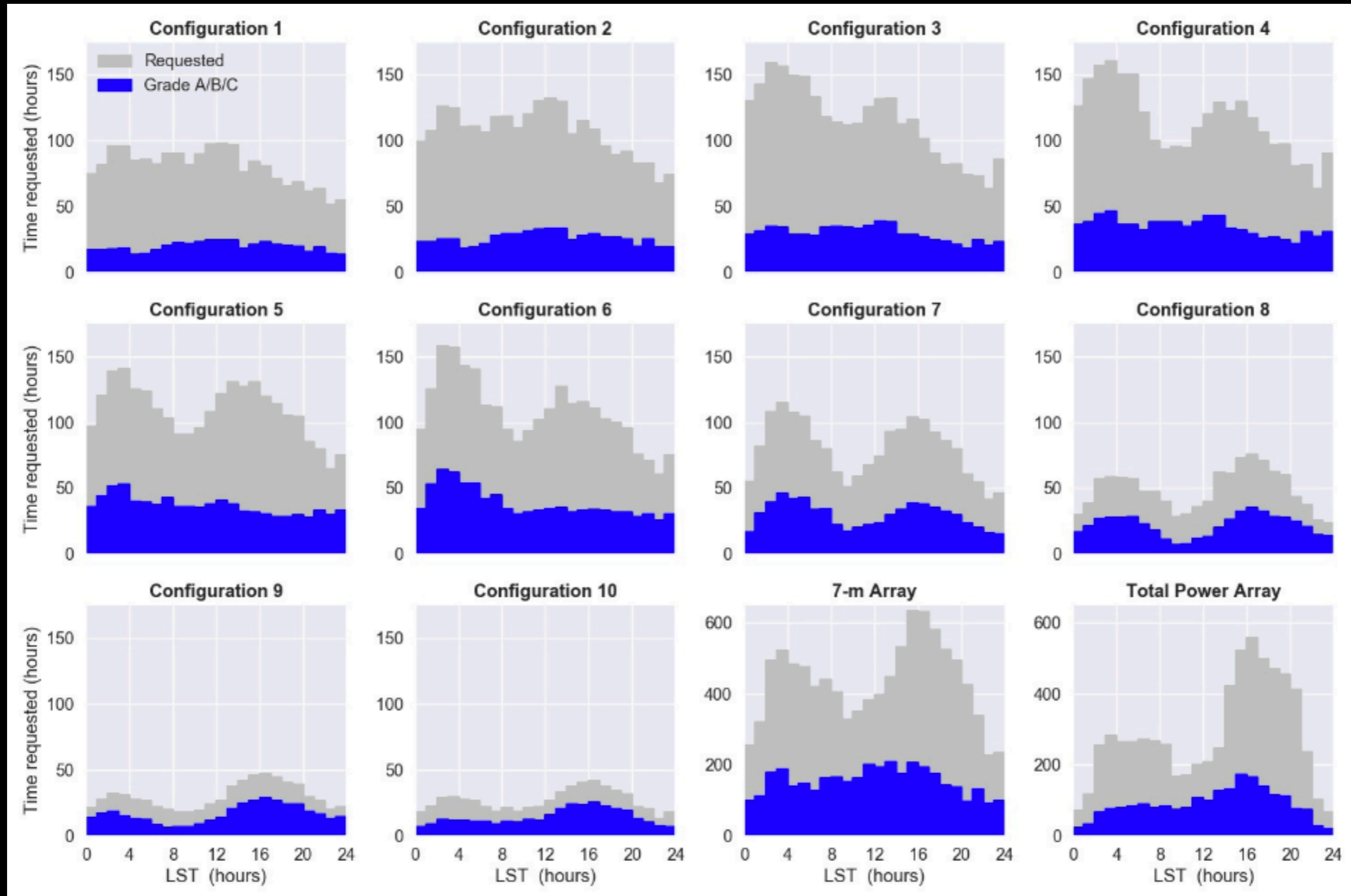
Increasing
Baseline



Table 7.1 in ALMA technical handbook

ALMA configurations

Requested/awarded time



WHAT IS ALMA?

It is also one of the most competitive facilities to obtain time on (~1 in 10 success rate)

Synthetic observations help to significantly boost that success rate

e.g. in cycle 7 I had 3/4 successful

ALMA SUMMARY

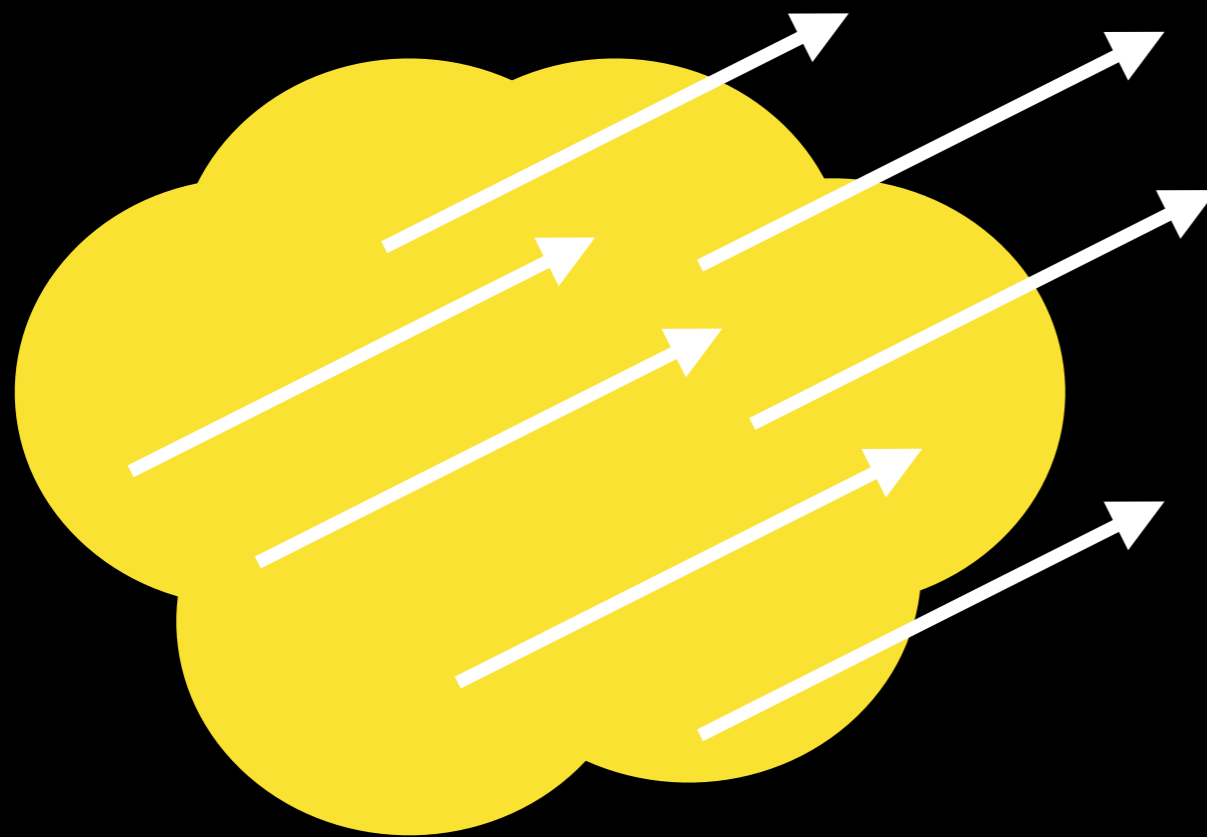
**World leading (sub)mm observatory
(sensitivity/resolution)**

Widely applied across astrophysics

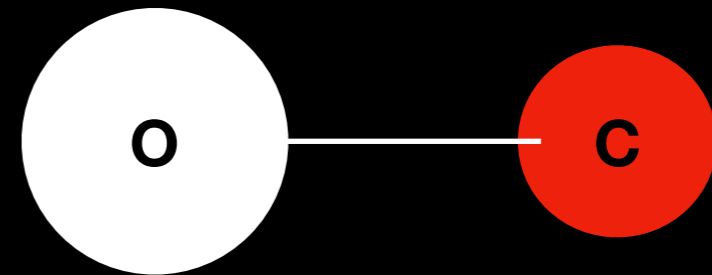
The ability to model its response is important

WHAT IS LINE TRANSFER?

A gas of molecules



Quantised ro-vibrational states



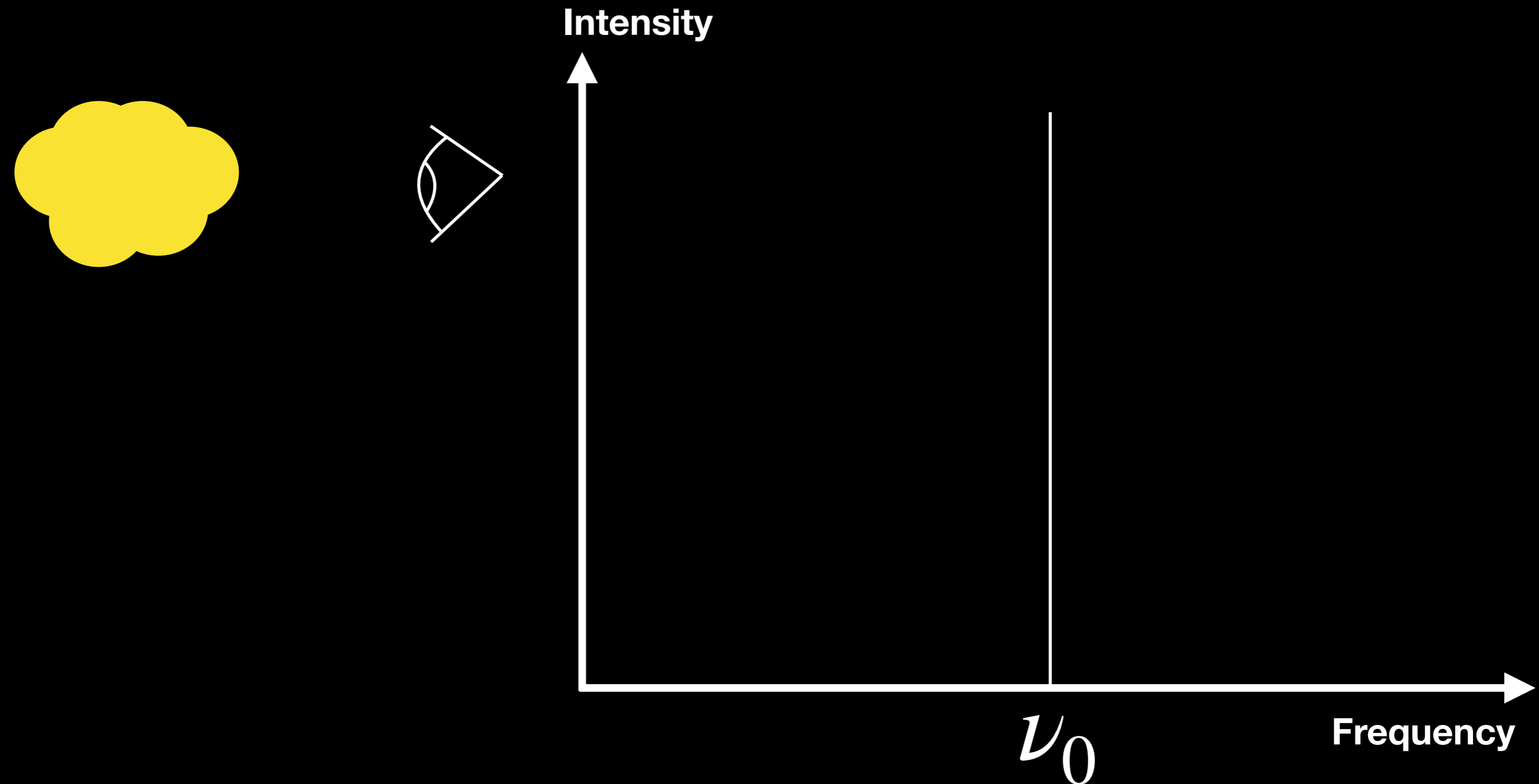
Diatomic rotational quantum number J

Transition (e.g. $J=2 \rightarrow 1$) is accompanied by photon emission at characteristic frequency ν_0

Permanent dipole moment necessary for dipolar rotational transition
(faint transition of H_2 as a quadrupole)

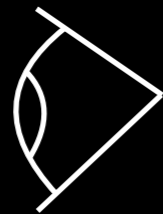
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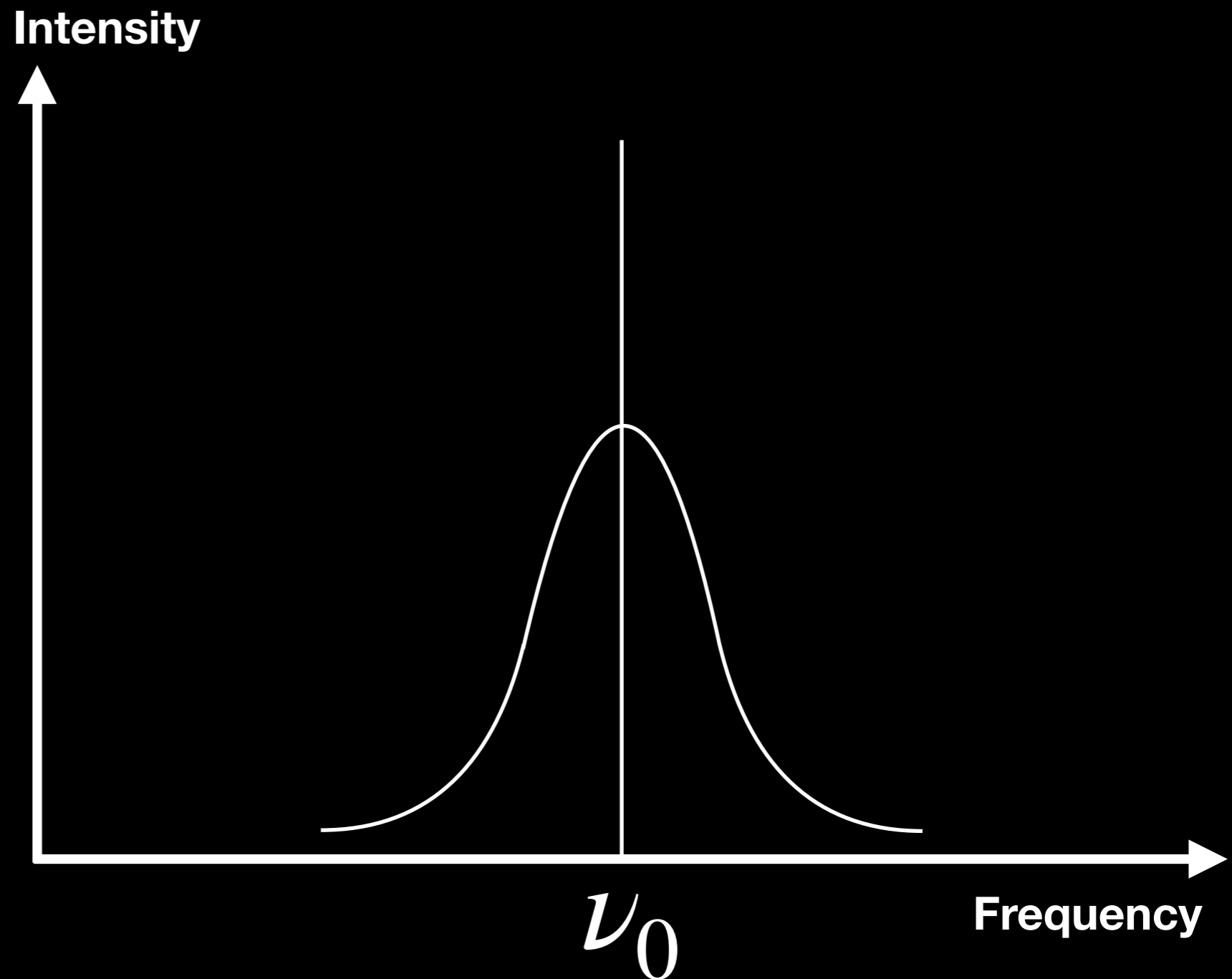


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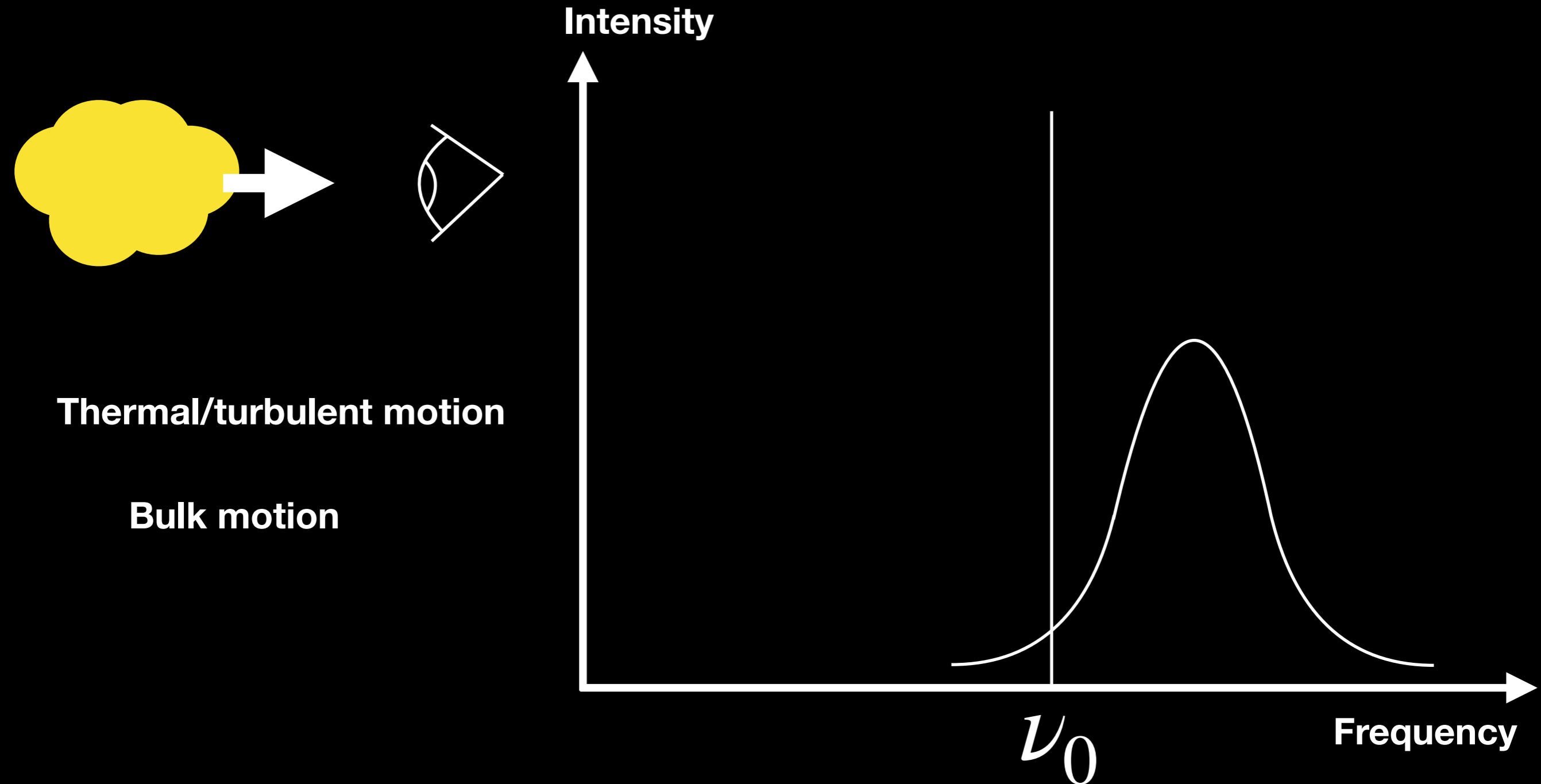


Thermal/turbulent motion



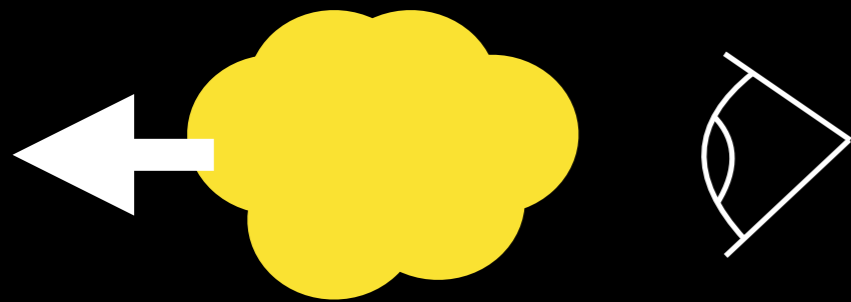
WHAT IS LINE TRANSFER?

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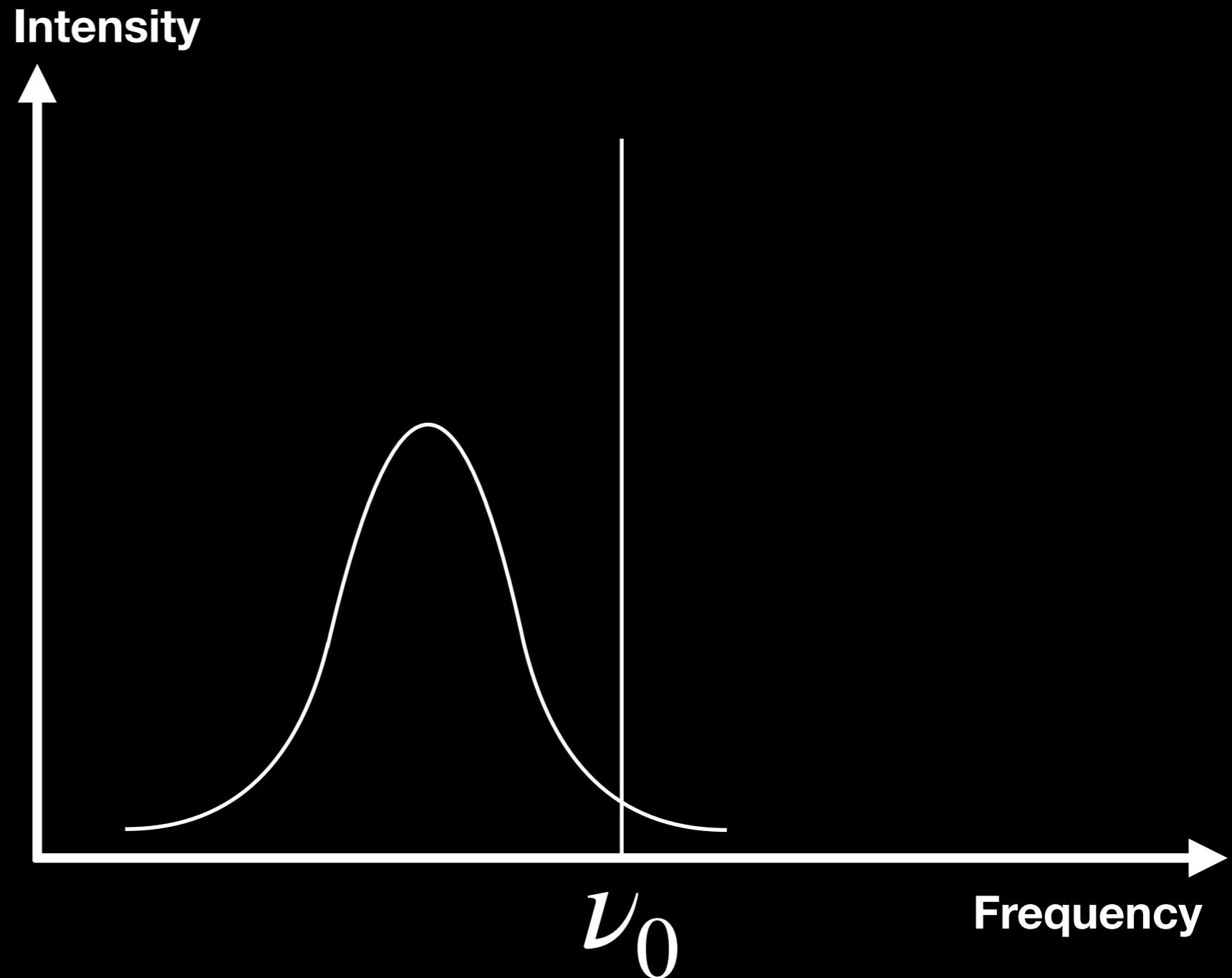
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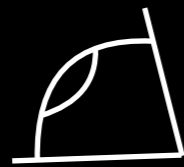
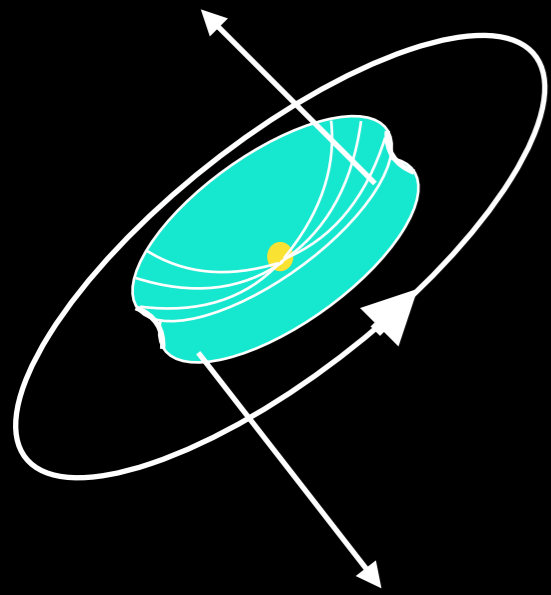
Thermal/turbulent motion

Bulk motion



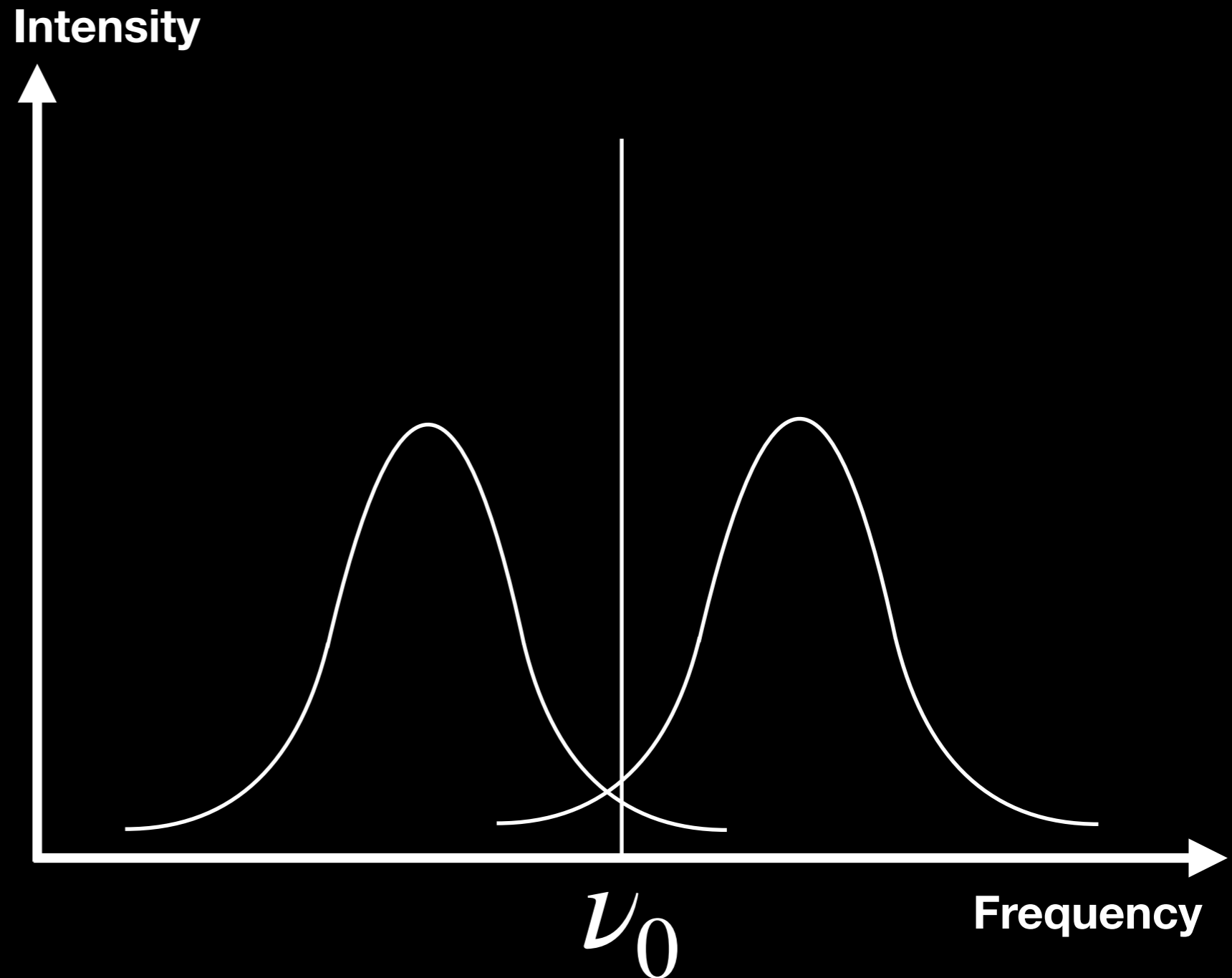
WHAT IS LINE TRANSFER?

A gas of molecules



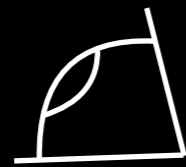
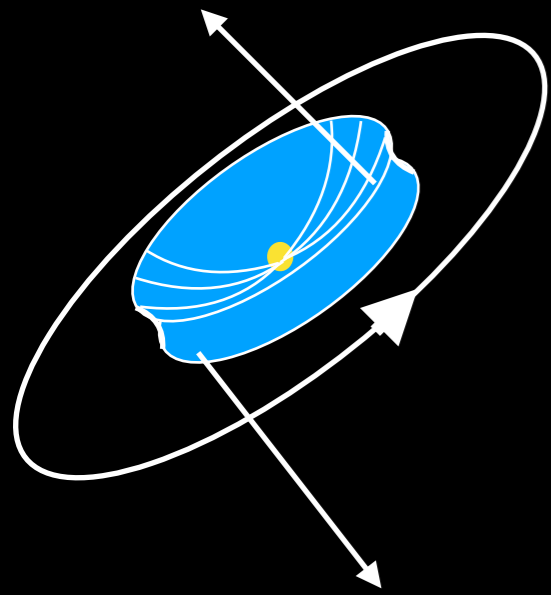
Thermal/turbulent motion

Bulk motion



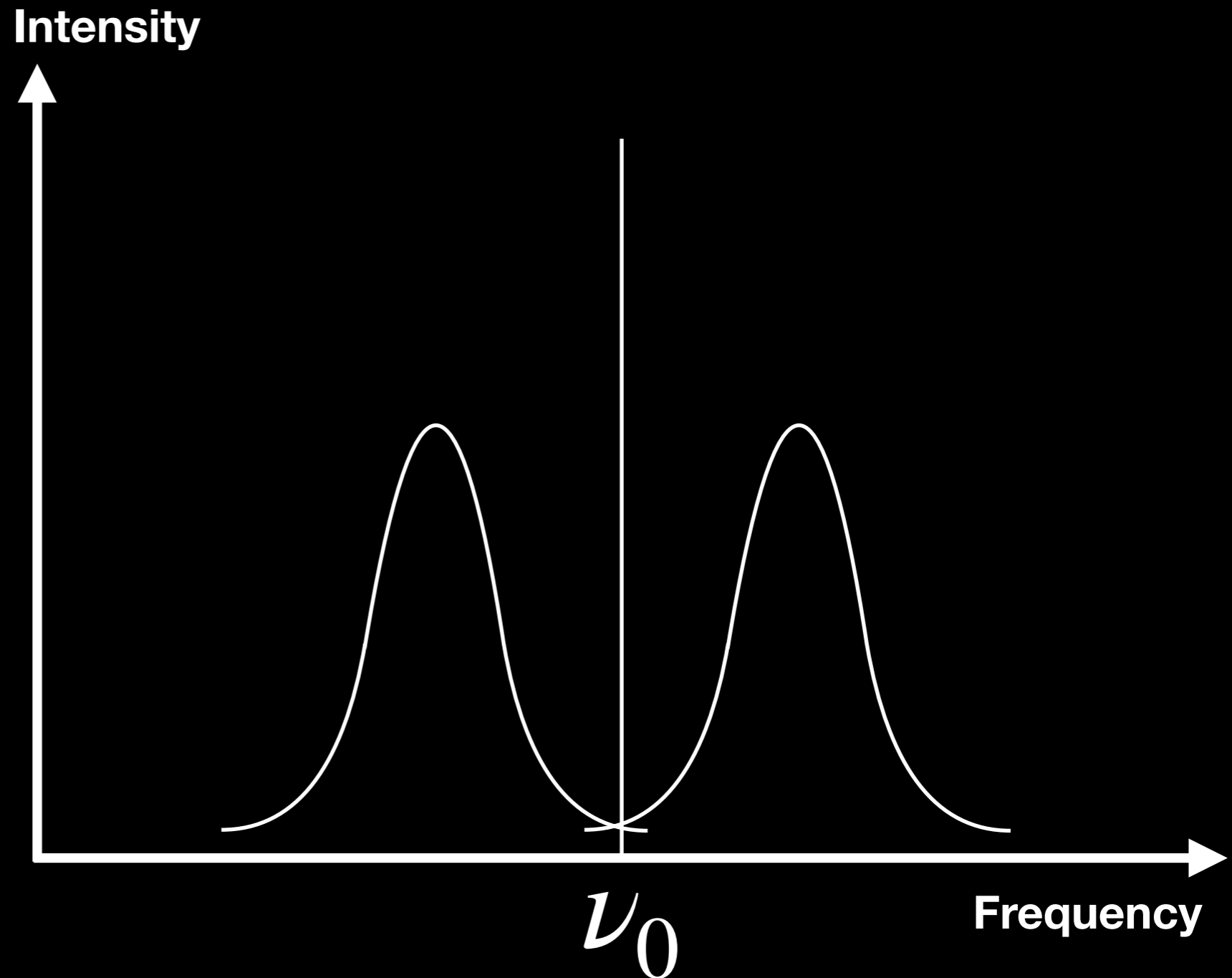
WHAT IS LINE TRANSFER?

A gas of molecules



Thermal/turbulent motion

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WHAT IS LINE TRANSFER?

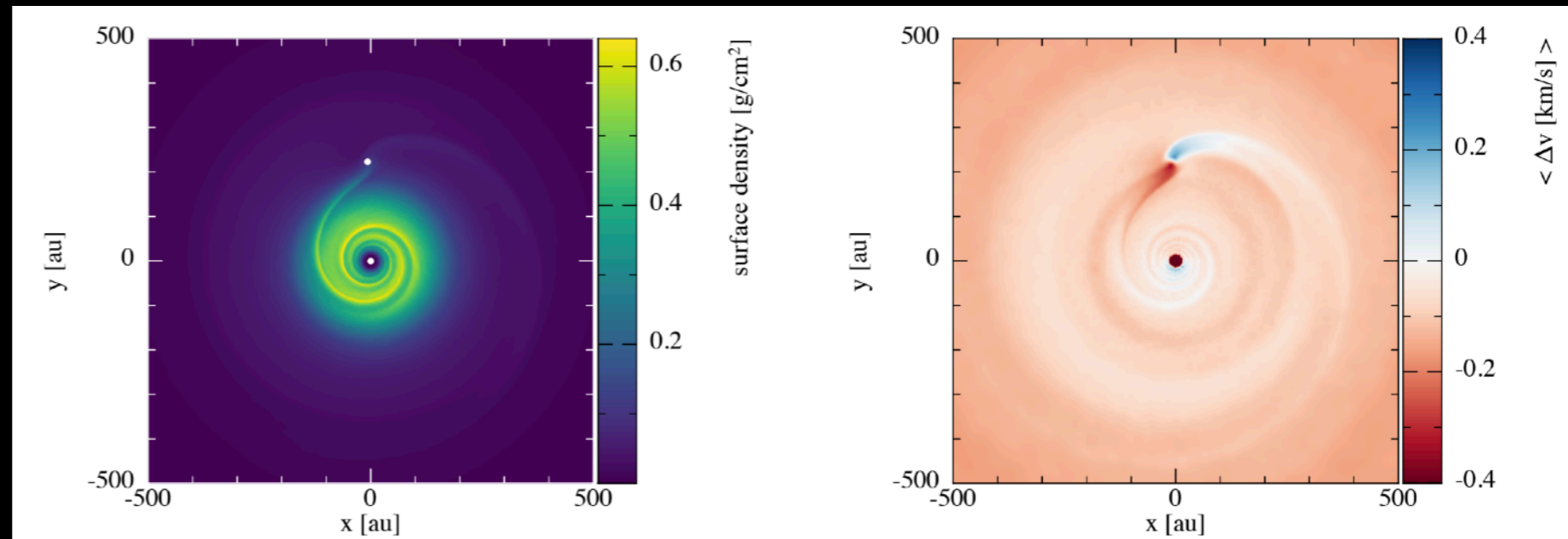
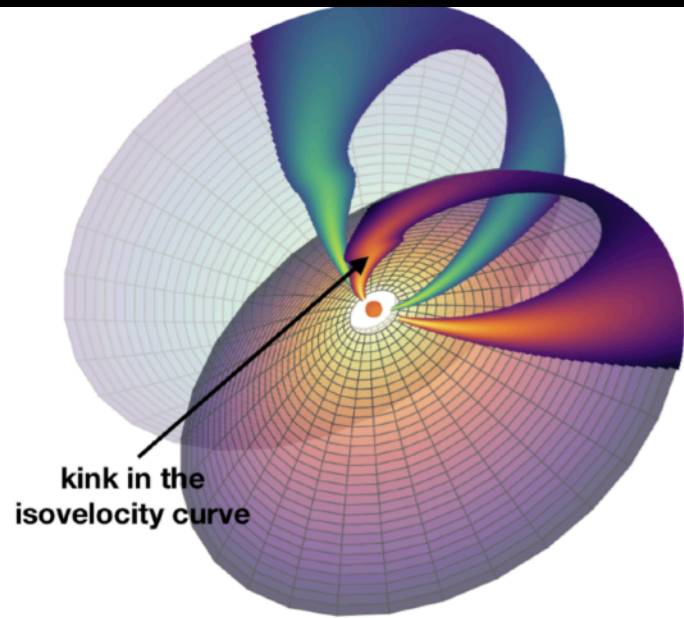
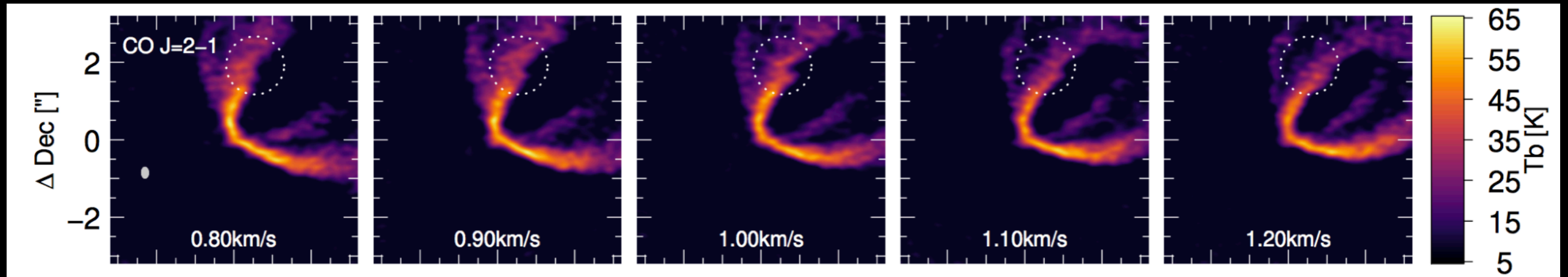
It is an extremely powerful means of inferring

The kinematics

And conditions (density, temperature, composition)

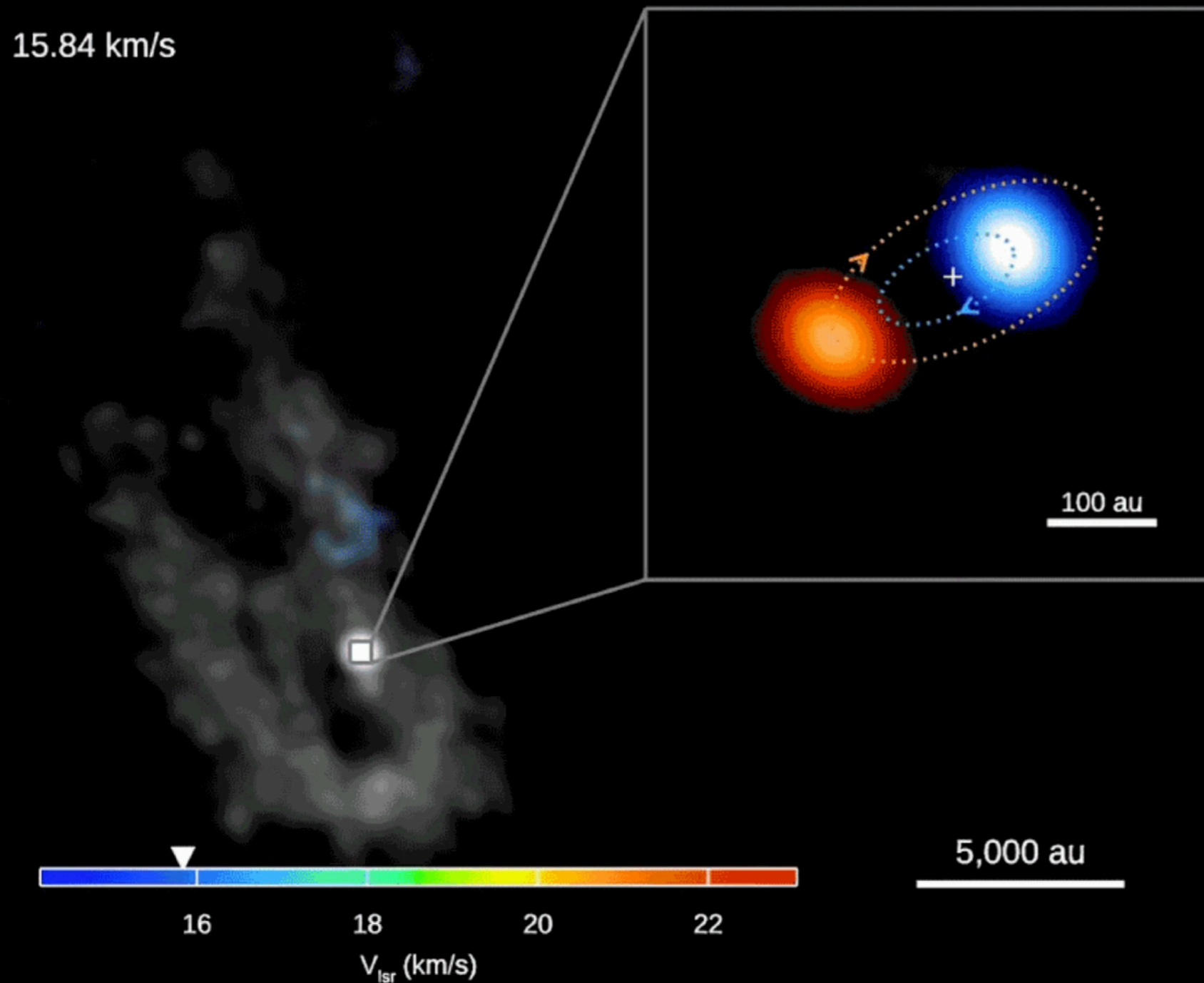
of gas in astrophysical systems

Molecular lines with ALMA



Pinte et al. (2018)

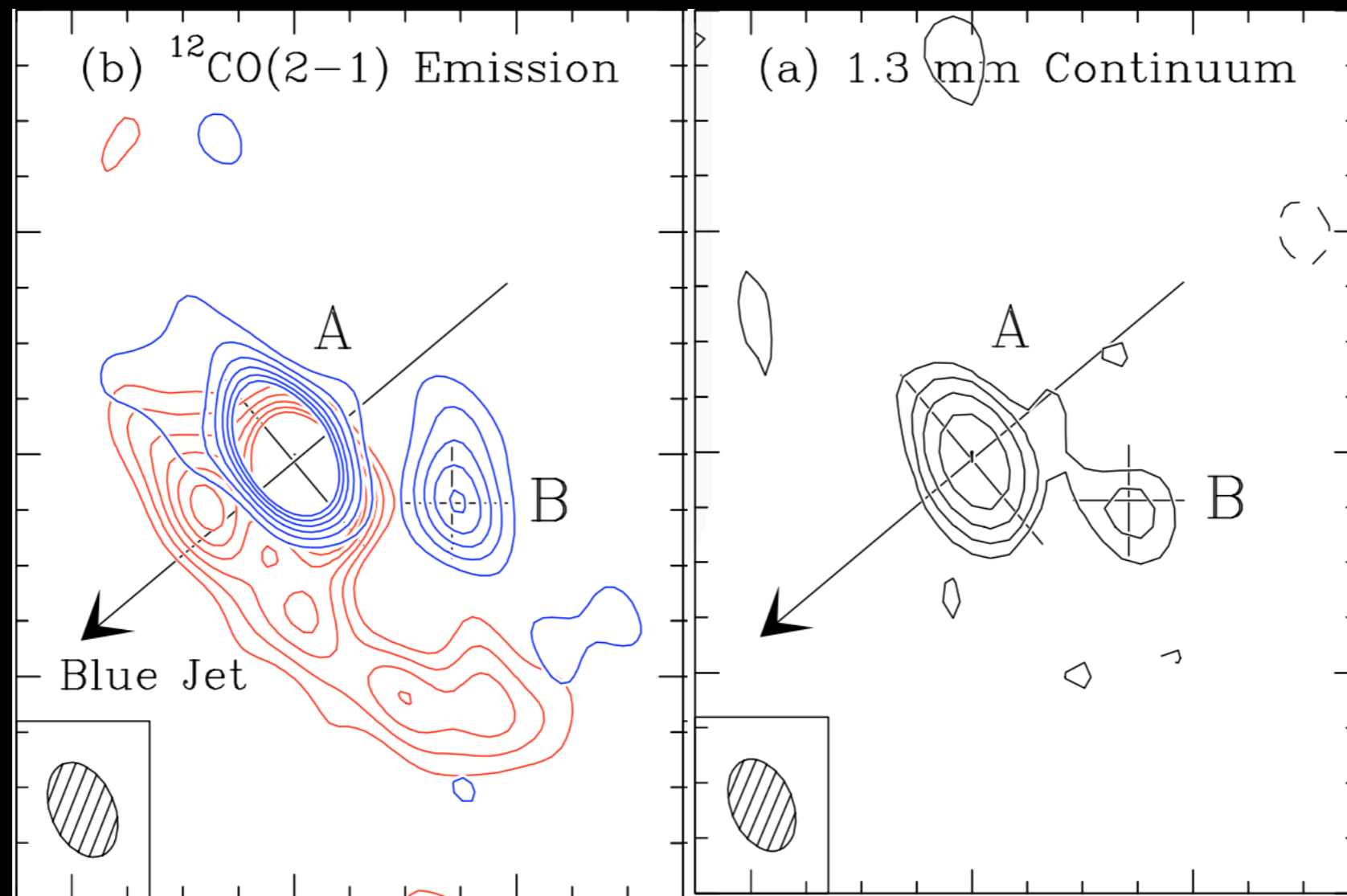
Molecular lines with ALMA



Zhang et al.
(2019)

Molecular lines with ALMA

RW Aur



Cabrit
et al.
(2006)

PdB interferometer

Molecular lines with ALMA

RW Aur

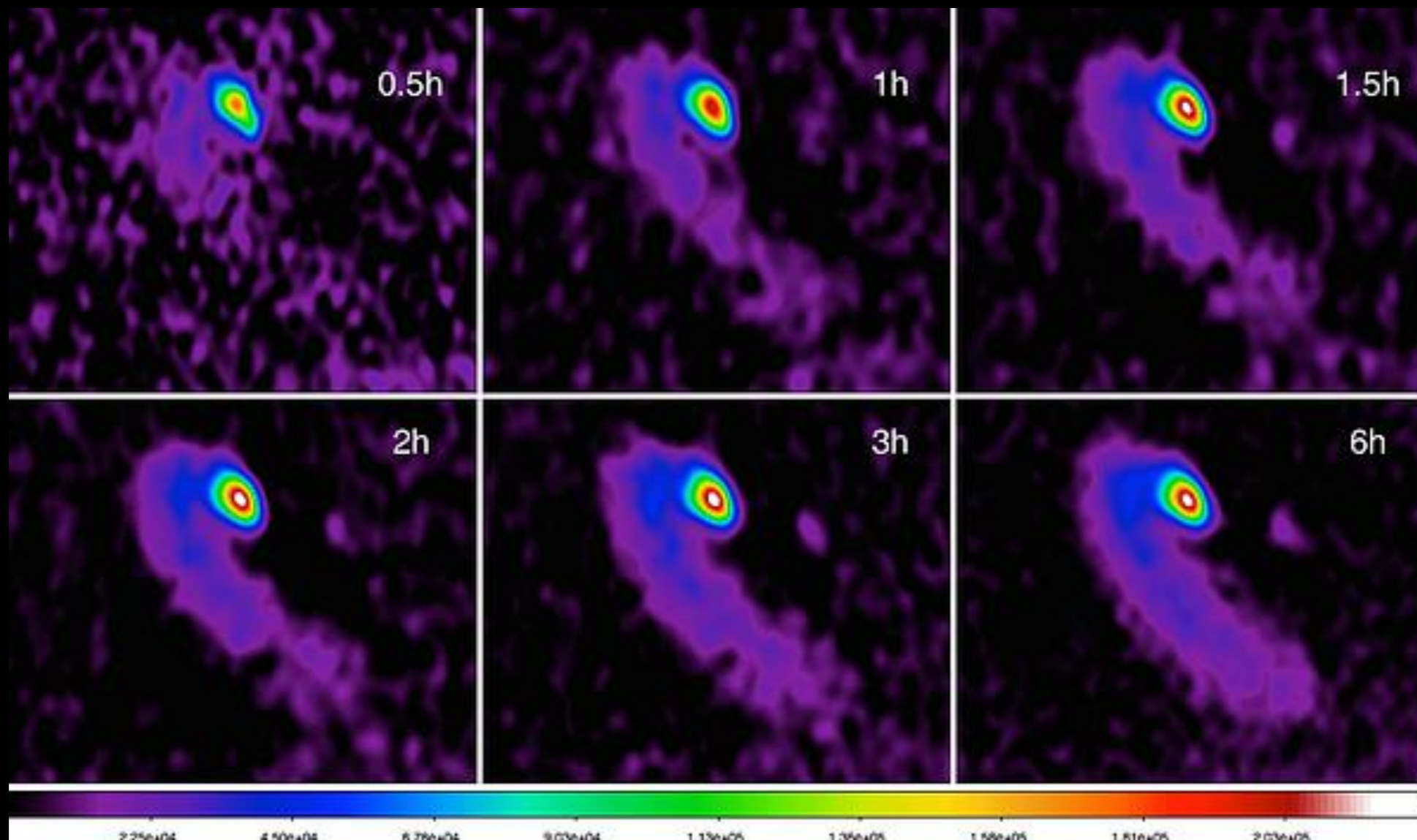


Dai
et al.
(2015)

100 AU

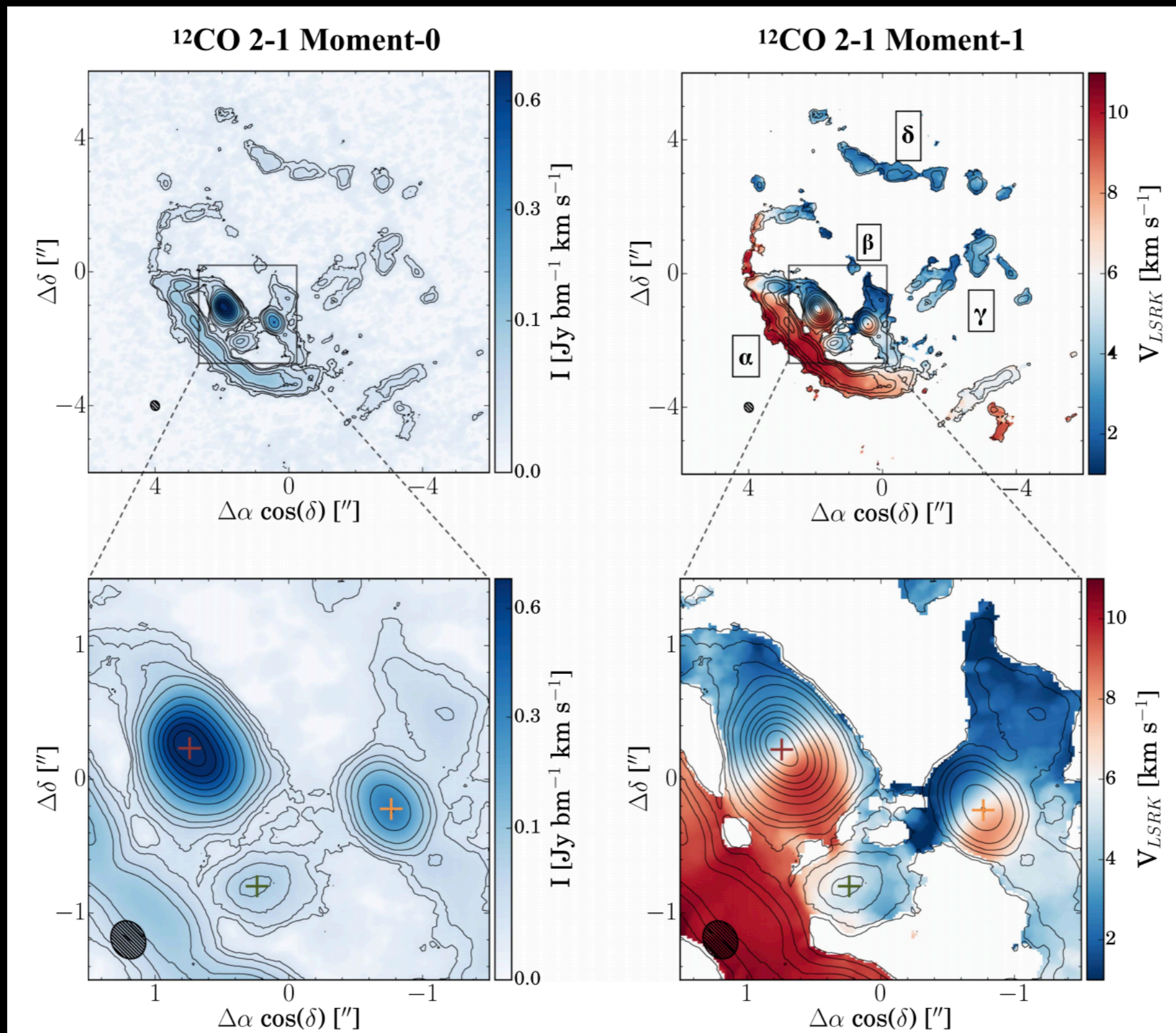
Molecular lines with ALMA

RW Aur



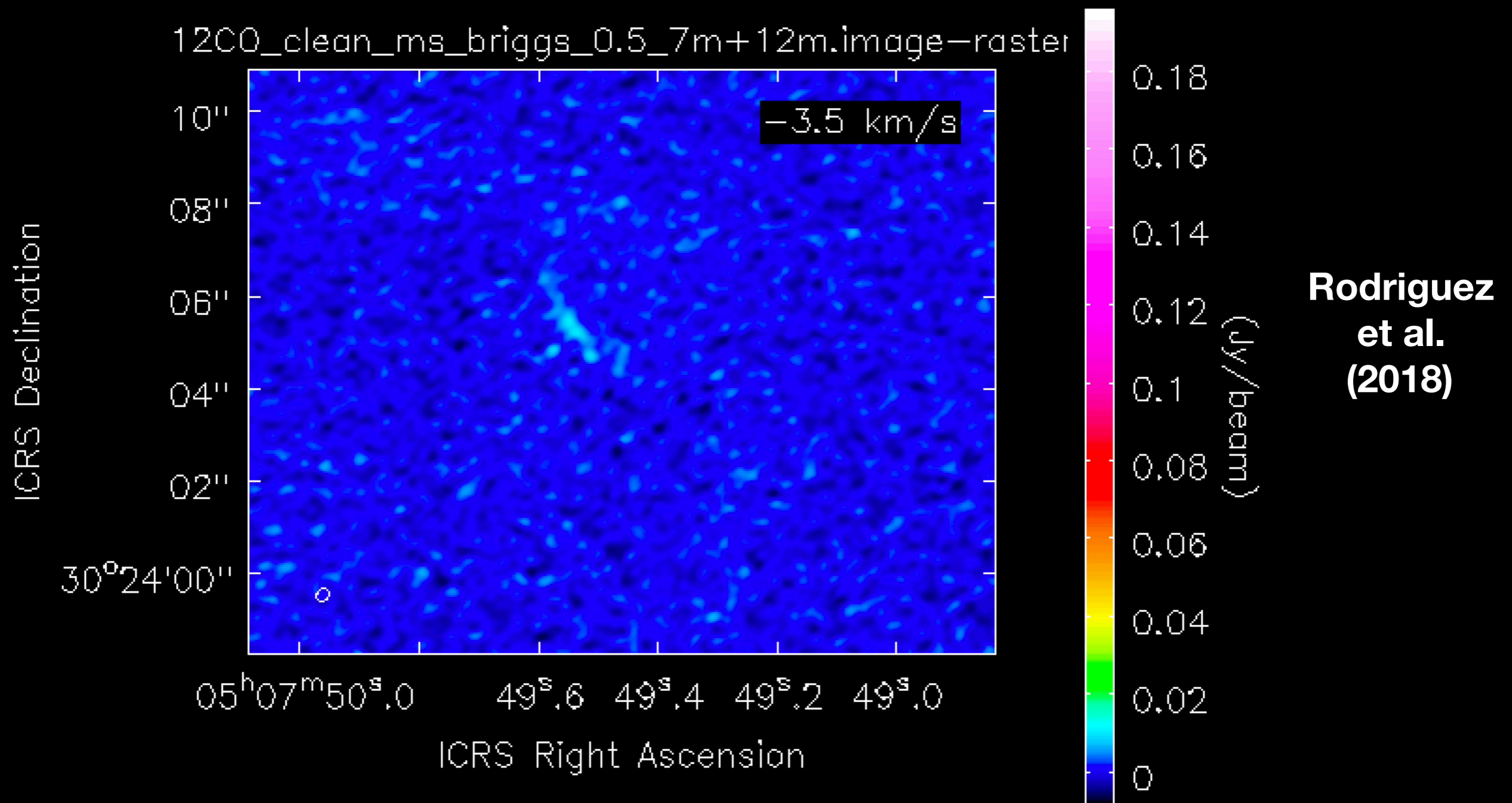
**Dai
et al.
(2015)**

Molecular lines with ALMA



Rodriguez
et al.
(2018)

Molecular lines with ALMA



WHAT IS LINE TRANSFER?

To solve the radiative transfer equation we need:

1) Emission coefficient

$$j_\nu = \frac{h\nu_0}{4\pi} (n_u A_{ul}) \phi_\nu$$

$$\frac{dI_\nu}{d\tau_\nu} = \frac{j_\nu}{\alpha_\nu} - I_\nu$$

2) Absorption coefficient

$$\alpha_\nu = \frac{h\nu_0}{4\pi} (n_l B_{lu} - n_u B_{ul}) \phi_\nu$$

See e.g. Rundle et al. (2010), Hogerheijde & van der Tak (2000)

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$$\alpha_\nu = \frac{h\nu_0}{4\pi} (n_l B_{lu} - n_u B_{ul}) \phi_\nu$$

$$\phi_\nu = \frac{c}{v_{\text{turb}} \nu_0 \sqrt{\pi}} \exp\left(-\frac{\Delta v^2}{v_{\text{turb}}^2}\right)$$

$$v_{\text{turb}} = \sqrt{v_T^2 + v_{\text{NT}}^2},$$

See e.g. Rundle et al. (2010), Hogerheijde & van der Tak (2000)

WHAT IS LINE TRANSFER?

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We need to solve for
the level populations
 n_i

See e.g. Rundle et al. (2010), Hogerheijde & van der Tak (2000)

LTE

Local thermodynamic equilibrium

Assume that levels are thermally distributed

$$\frac{n_i}{\sum_i N_i} = \frac{\exp\left[-\frac{E_i}{k_B T}\right]}{z(T)}$$

Can solve the level populations analytically using Boltzmann distribution

Reasonable in dense regions without steep gradients

NLTE

Radiative transitions become important.

Much harder to solve

$$n_l \left[\sum_{k < l} A_{lk} + \sum_{k \neq l} (B_{lk} J_\nu + C_{lk}) \right] =$$
$$\sum_{k > l} n_k A_{kl} + \sum_{k \neq l} n_k (B_{kl} J_\nu + C_{kl})$$

Solve detailed balance

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Solve detailed balance

Molecular line transfer with TORUS

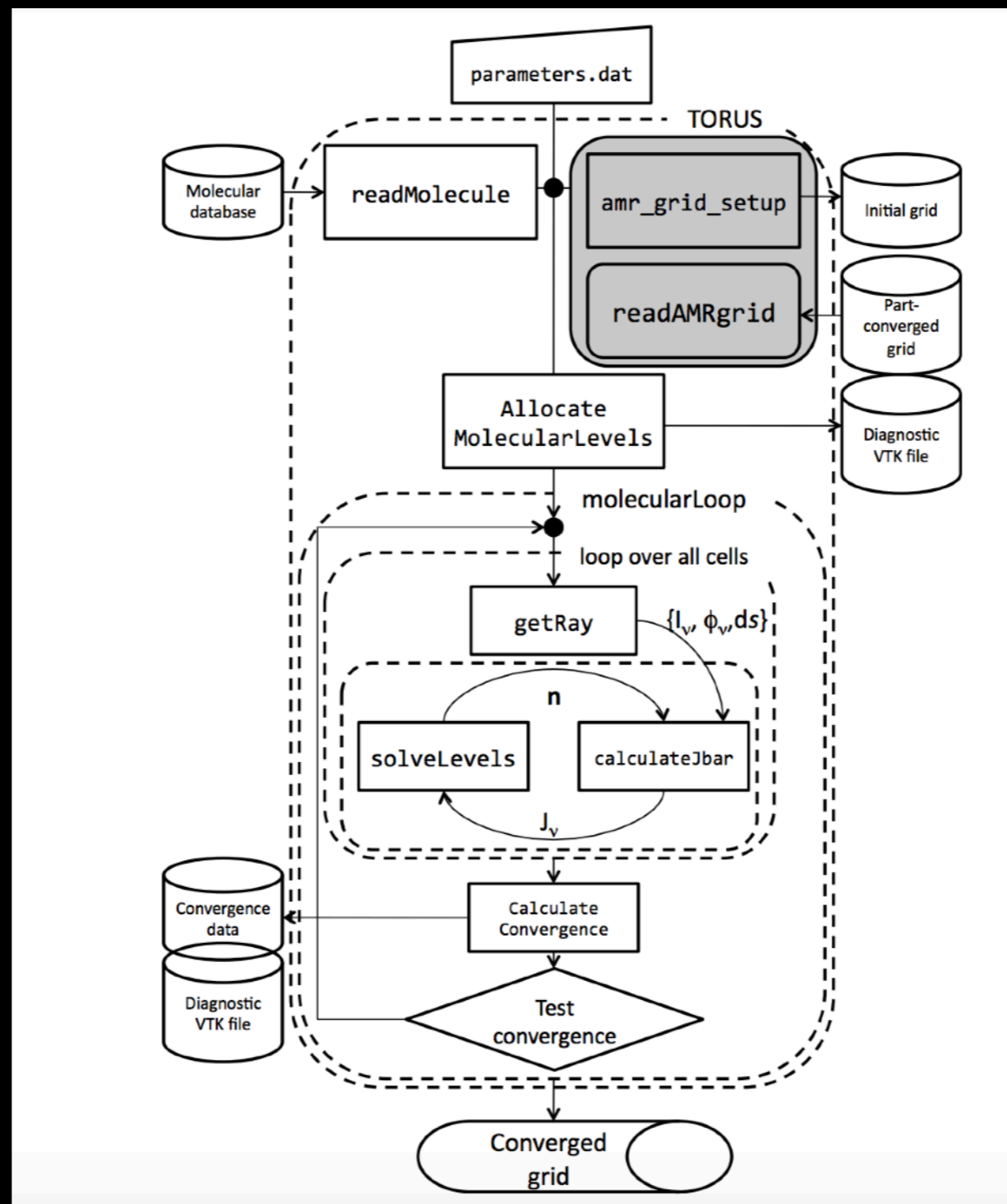
LTE or NLTE

Can rig up models from scratch

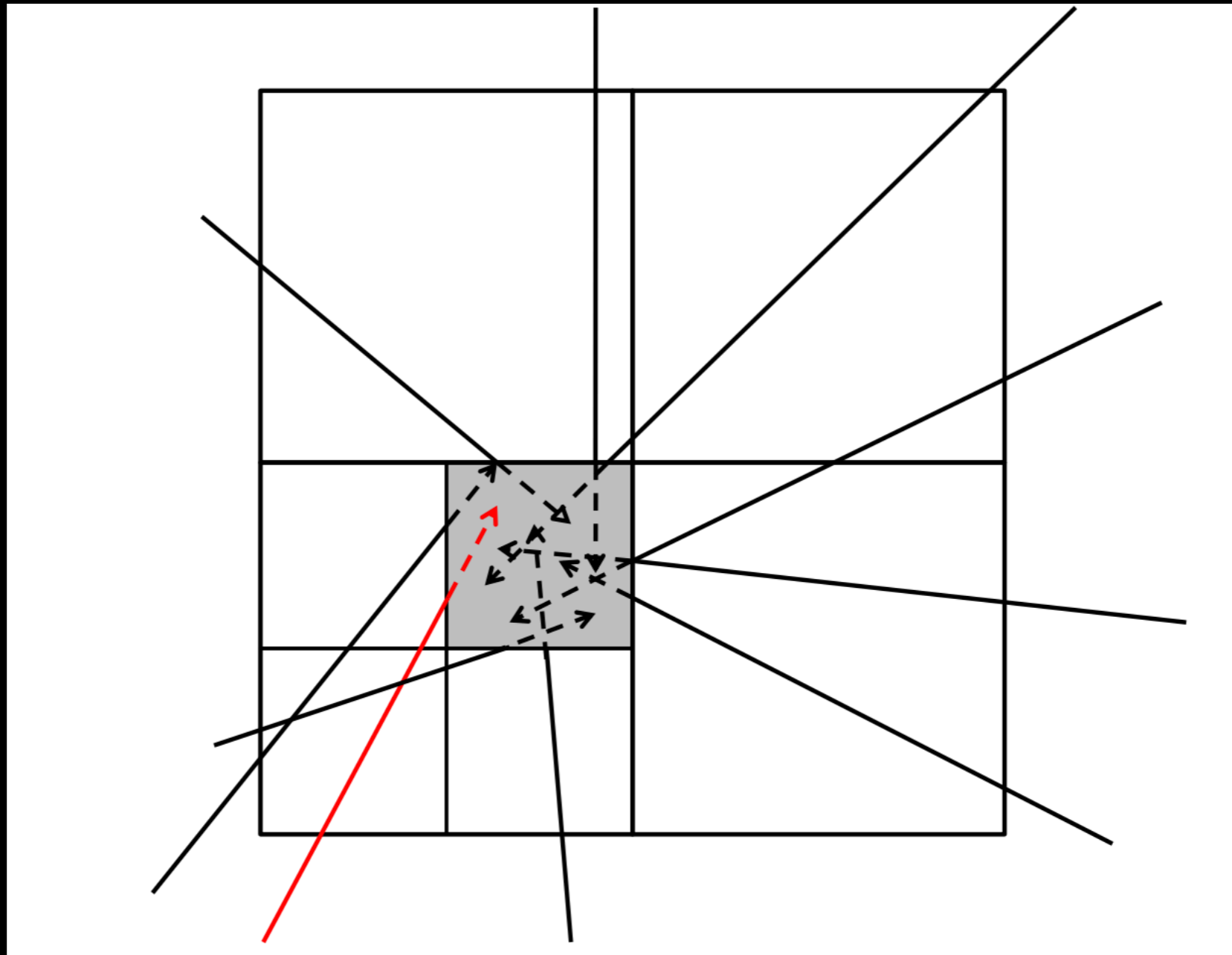
Postprocess grid/SPH model results

Rundle et al. (2010)
Harries et al. (2019)

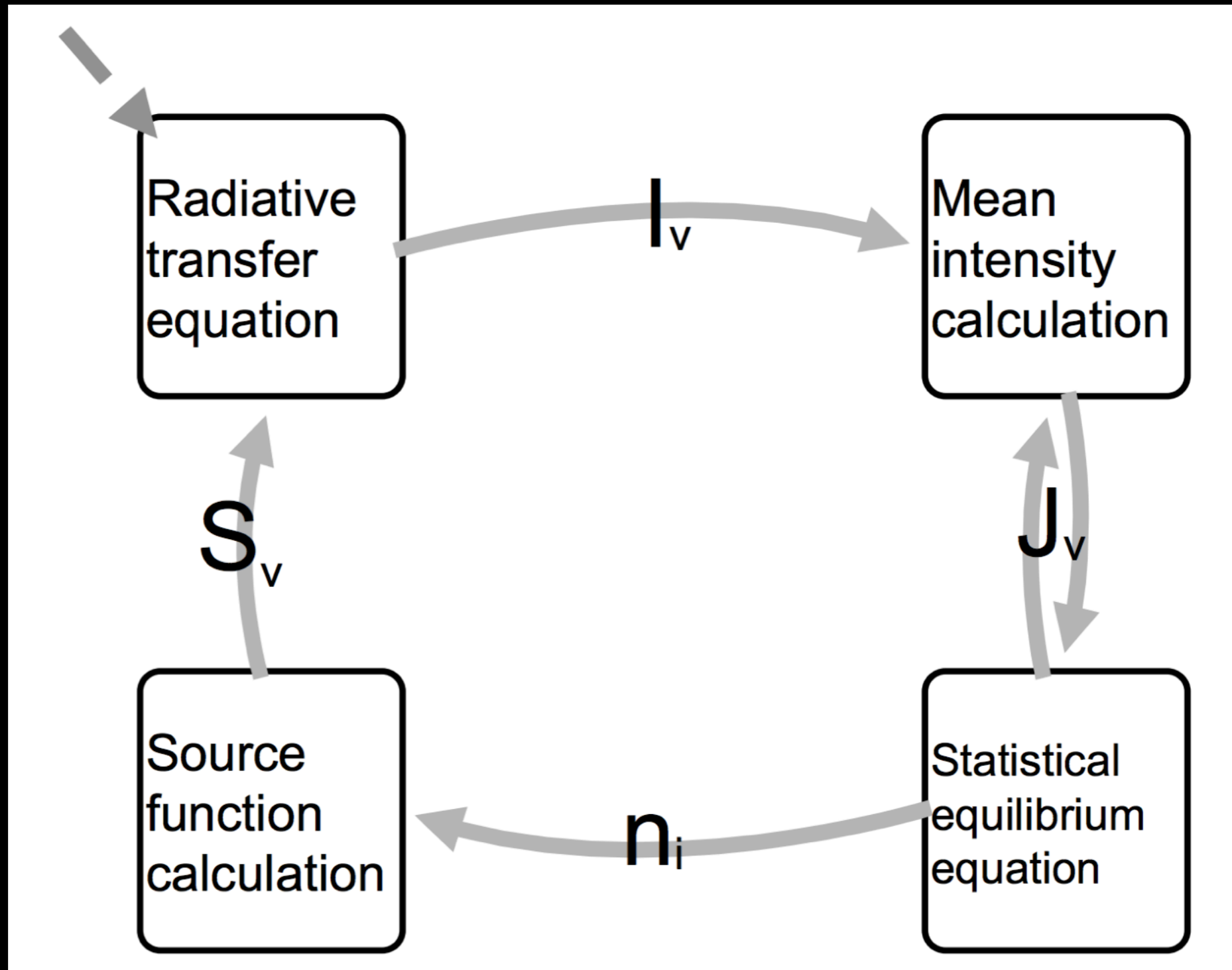
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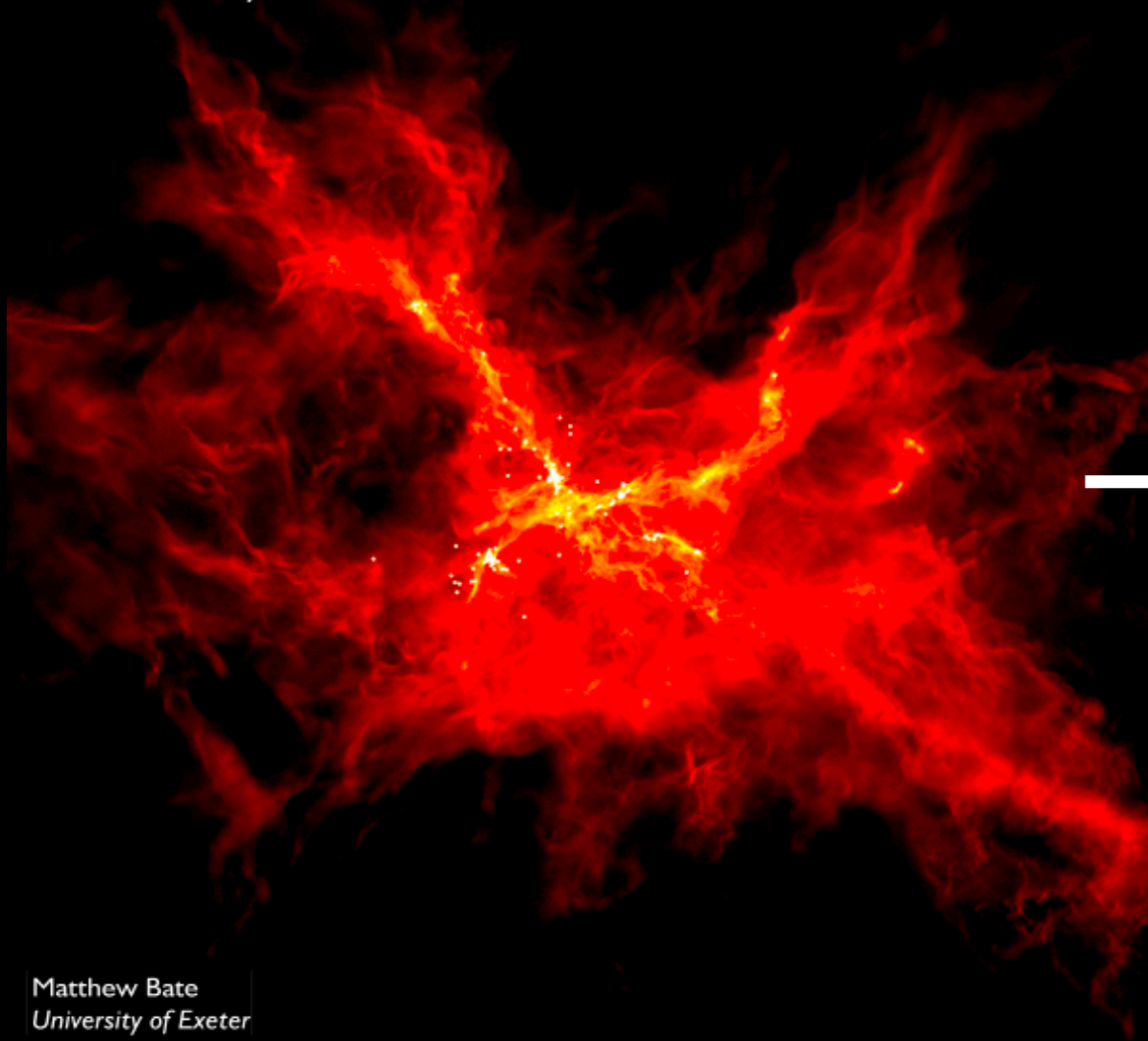


Molecular line transfer with TORUS



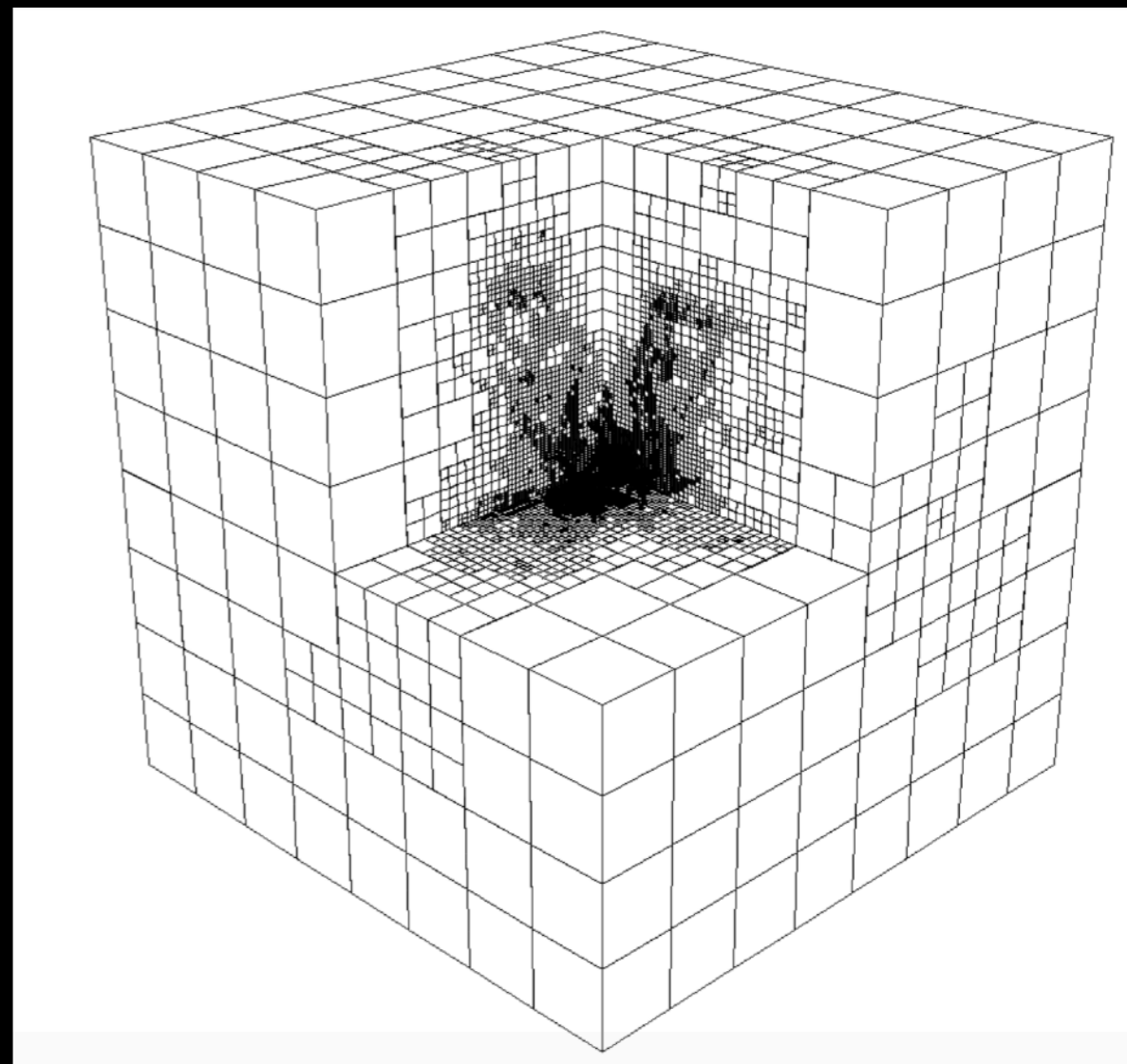
TORUS Example

UK Astrophysical
Fluids Facility



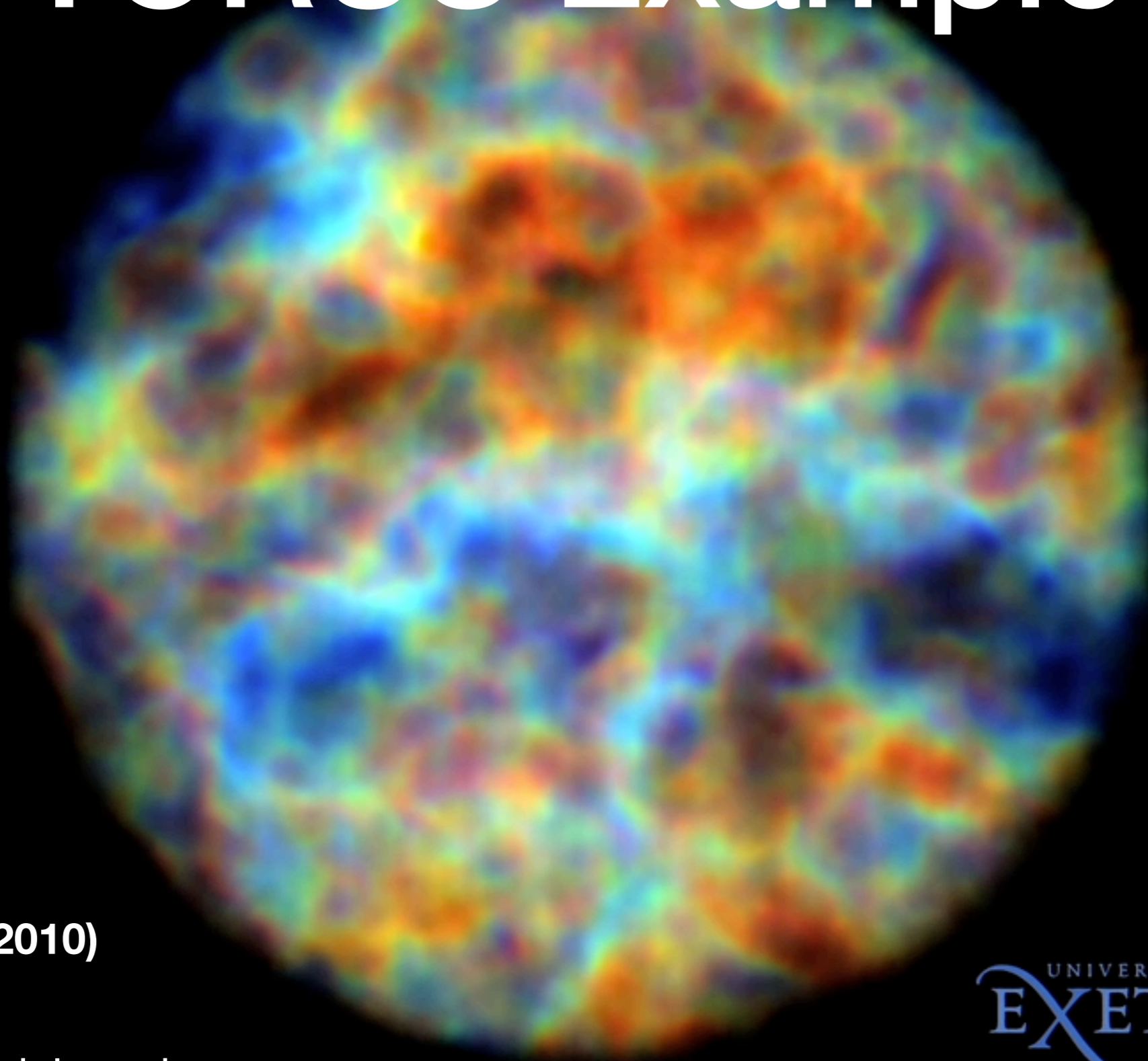
Matthew Bate
University of Exeter

Bate 2009



Rundle et al. (2010)

TORUS Example

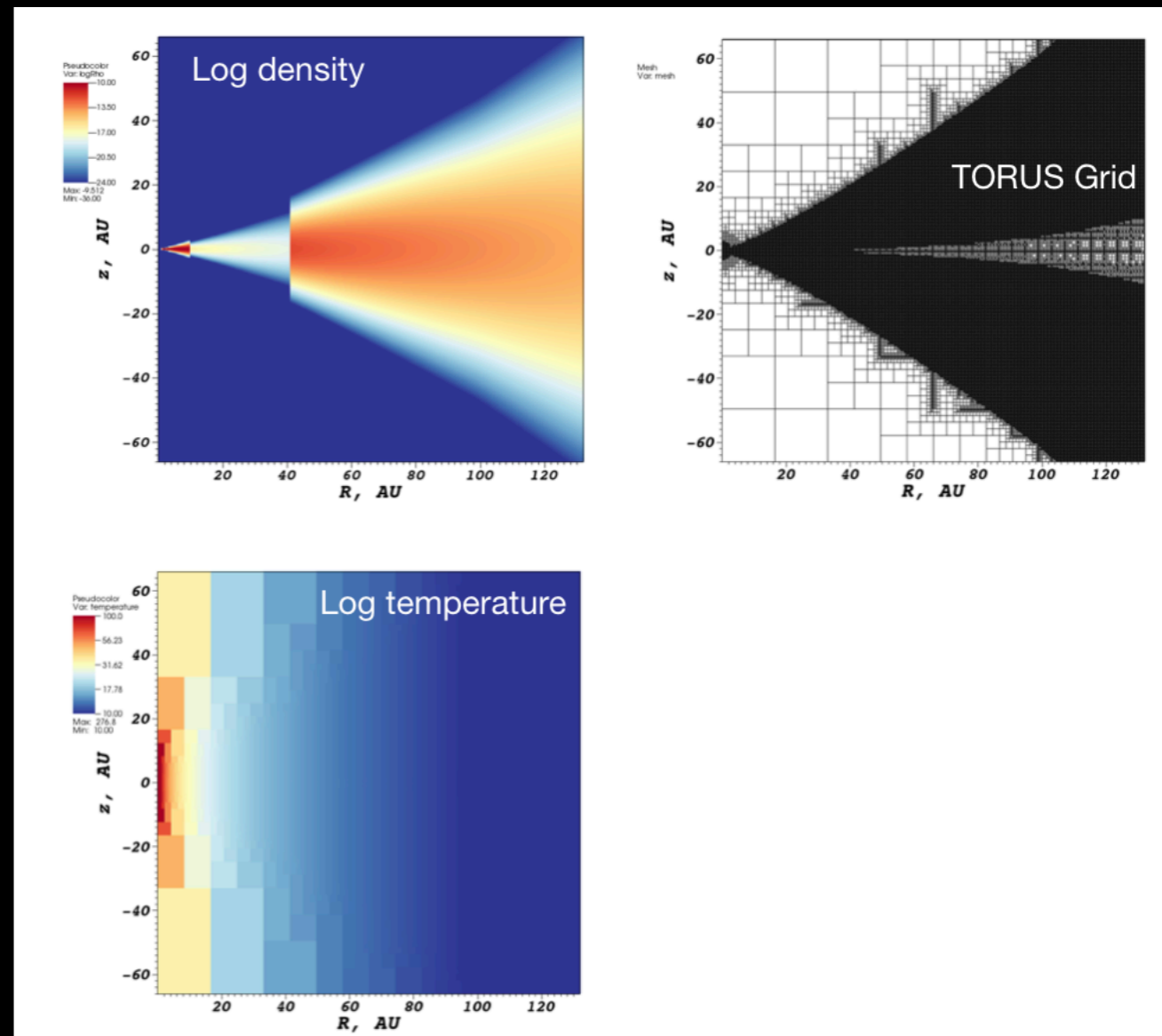


Rundle et al. (2010)

t.haworth@imperial.ac.uk

TORUS Example

A parametric disc



TORUS Example

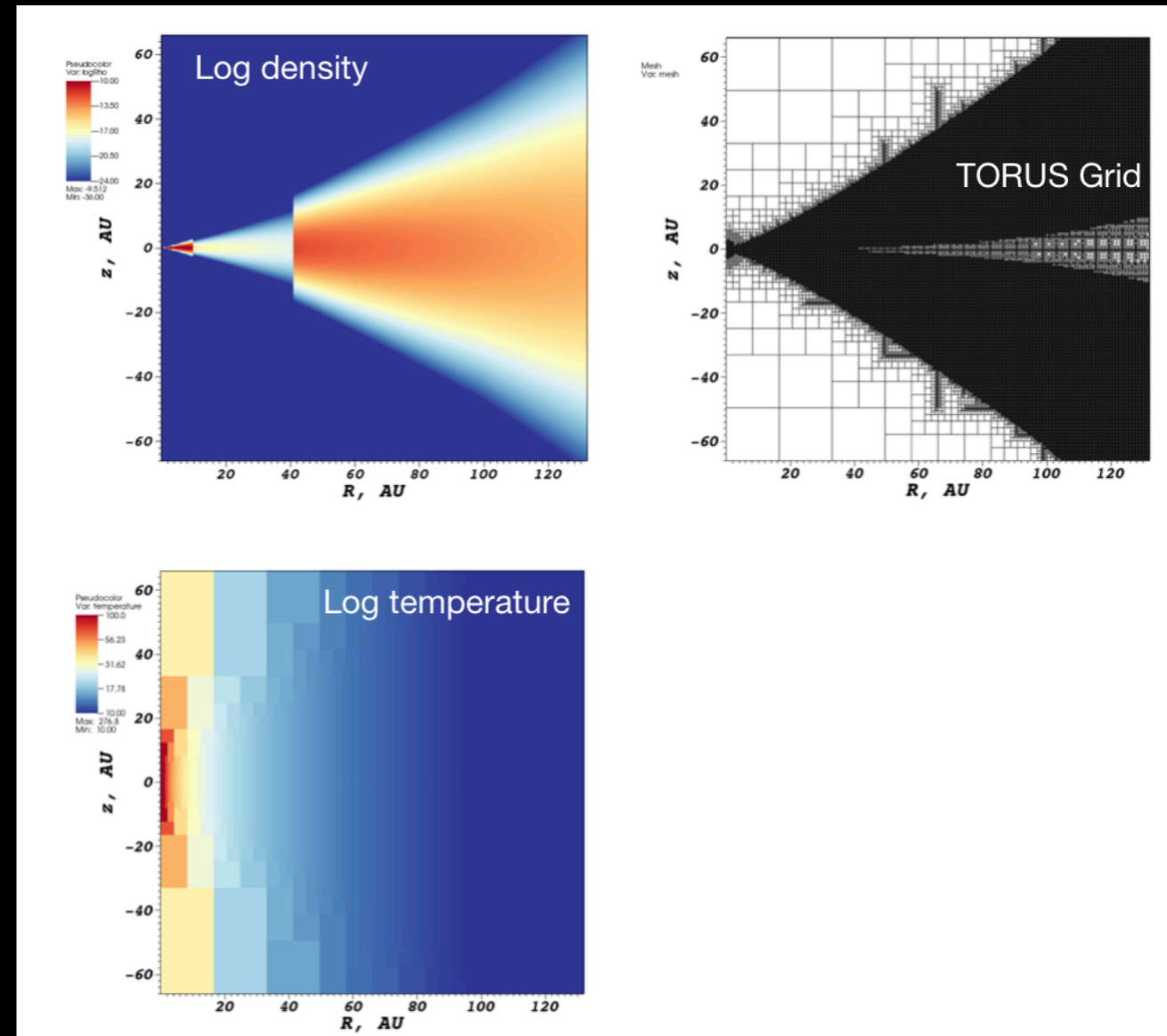
A parametric disc

$$\Sigma = \Sigma_0 \left(\frac{R}{R_c} \right)^{-\gamma} \exp \left[- \left(\frac{R}{R_c} \right)^{2-\gamma} \right]$$

$$\rho(R, z) = \rho_{mid} \exp(-z^2/(2H^2))$$

$$T(r, z) = \begin{cases} T_{mid} + (T_{atm} - T_{mid}) \left[\sin \left(\frac{\pi z}{2z_q} \right) \right]^{2\delta} & \text{if } z < z_q \\ T_{atm} & \text{if } z \geq z_q \end{cases}$$

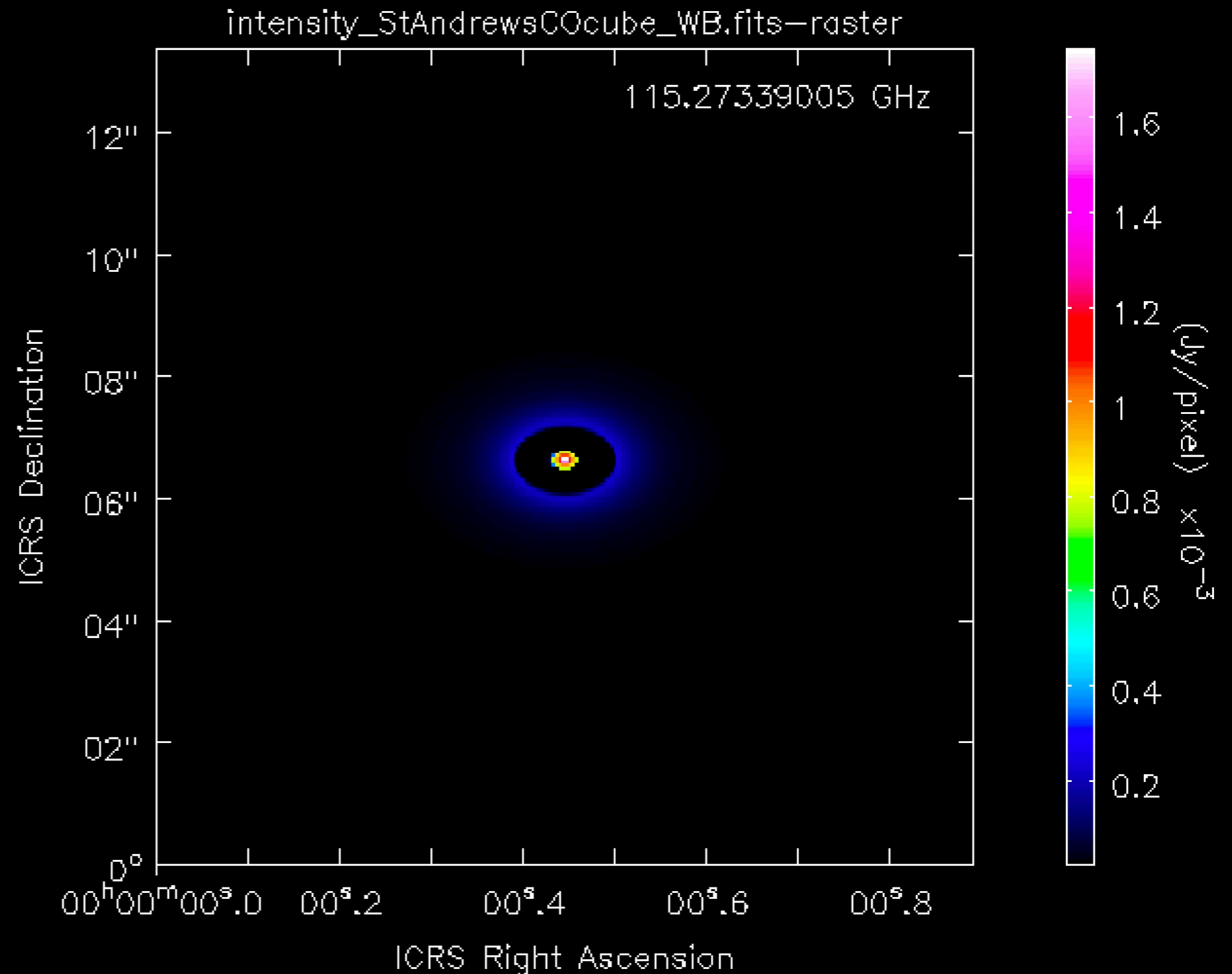
Assume LTE, constant abundance



TORUS Example

Raw CO cube

Inclination of
45 degrees



Postprocessing with CASA

The screenshot shows the NRAO website header with the logo and tagline "Enabling forefront research into the Universe at radio wavelengths". Navigation links include "Log On", "Visit Public Website", and "Contact Us". A search bar is present with the text "Search NRAO..." and a "Go" button. A main navigation bar contains "Home", "About NRAO", "Science", "Research Facilities", "Observing", and "Opportunities".

About CASA

- News & Events
- Download
- Documentation
- Getting Help
- Acknowledgements

About CASA

CASA, the *Common Astronomy Software Applications* package, is being developed with the primary goal of supporting the data post-processing needs of the next generation of radio astronomical telescopes such as [ALMA](#) and [VLA](#). The package can process both interferometric and single dish data. The CASA infrastructure consists of a set of C++ tools bundled together under an iPython interface as data reduction tasks. This structure provides flexibility to process the data via task interface or as a python script. In addition to the data reduction tasks, many post-processing tools are available for even more flexibility and special purpose reduction needs.



CASA is developed by an international consortium of scientists based at the National Radio Astronomical Observatory (NRAO), the European

CASA Docs

CASA Guides

Newsletter

CASA Docs:
Official documentation now includes all [tasks](#)!

Help us improve CASA:
short [user survey](#).

Postprocessing with CASA

Simulate ALMA (VLA, SMA, etc.) observations

Clean, subtract continuum and other image processing tools

Can produce moment maps, PV diagrams etc.

Postprocessing with CASA

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	θ_{MRS} (arcsec)	0.814	0.543	0.44	0.354	0.236	-	-	-
C43-10	θ_{res} (arcsec)	0.042	0.028	0.0227	0.0183	0.0122	-	-	-
	θ_{MRS} (arcsec)	0.496	0.331	0.268	0.216	0.144	-	-	-

Increasing
Baseline



Postprocessing with CASA

Our example: ~100AU at 50pc is about 2 arcseconds in size

	Band	3	4	5	6	7	8	9	10
	Frequency (GHz)	100	150	185	230	345	460	650	870
Configuration									
7-m	θ_{res} (arcsec)	12.5	8.35	6.77	5.45	3.63	2.72	1.93	1.44
	θ_{MRS} (arcsec)	66.7	44.5	36.1	29.0	19.3	14.5	10.3	7.67
C43-1	θ_{res} (arcsec)	3.38	2.25	1.83	1.47	0.98	0.735	0.52	0.389
	θ_{MRS} (arcsec)	28.5	19.0	15.4	12.4	8.25	6.19	4.38	3.27
C43-2	θ_{res} (arcsec)	2.3	1.53	1.24	0.999	0.666	0.499	0.353	0.264
	θ_{MRS} (arcsec)	22.6	15.0	12.2	9.81	6.54	4.9	3.47	2.59
C43-3	θ_{res} (arcsec)	1.42	0.943	0.765	0.615	0.41	0.308	0.218	0.163
	θ_{MRS} (arcsec)	16.2	10.8	8.73	7.02	4.68	3.51	2.48	1.86
C43-4	θ_{res} (arcsec)	0.918	0.612	0.496	0.399	0.266	0.2	0.141	0.106
	θ_{MRS} (arcsec)	11.2	7.5	6.08	4.89	3.26	2.44	1.73	1.29
C43-5	θ_{res} (arcsec)	0.545	0.363	0.295	0.237	0.158	0.118	0.0838	0.0626
	θ_{MRS} (arcsec)	6.7	4.47	3.62	2.91	1.94	1.46	1.03	0.77
C43-6	θ_{res} (arcsec)	0.306	0.204	0.165	0.133	0.0887	0.0665	0.0471	0.0352
	θ_{MRS} (arcsec)	4.11	2.74	2.22	1.78	1.19	0.892	0.632	0.472
C43-7	θ_{res} (arcsec)	0.211	0.141	0.114	0.0917	0.0612	0.0459	0.0325	0.0243
	θ_{MRS} (arcsec)	2.58	1.72	1.4	1.12	0.749	0.562	0.398	0.297
C43-8	θ_{res} (arcsec)	0.096	0.064	0.0519	0.0417	0.0278	-	-	-
	θ_{MRS} (arcsec)	1.42	0.947	0.768	0.618	0.412	-	-	-
C43-9	θ_{res} (arcsec)	0.057	0.038	0.0308	0.0248	0.0165	-	-	-
	θ_{MRS} (arcsec)	0.814	0.543	0.44	0.354	0.236	-	-	-
C43-10	θ_{res} (arcsec)	0.042	0.028	0.0227	0.0183	0.0122	-	-	-
	θ_{MRS} (arcsec)	0.496	0.331	0.268	0.216	0.144	-	-	-

Postprocessing with CASA

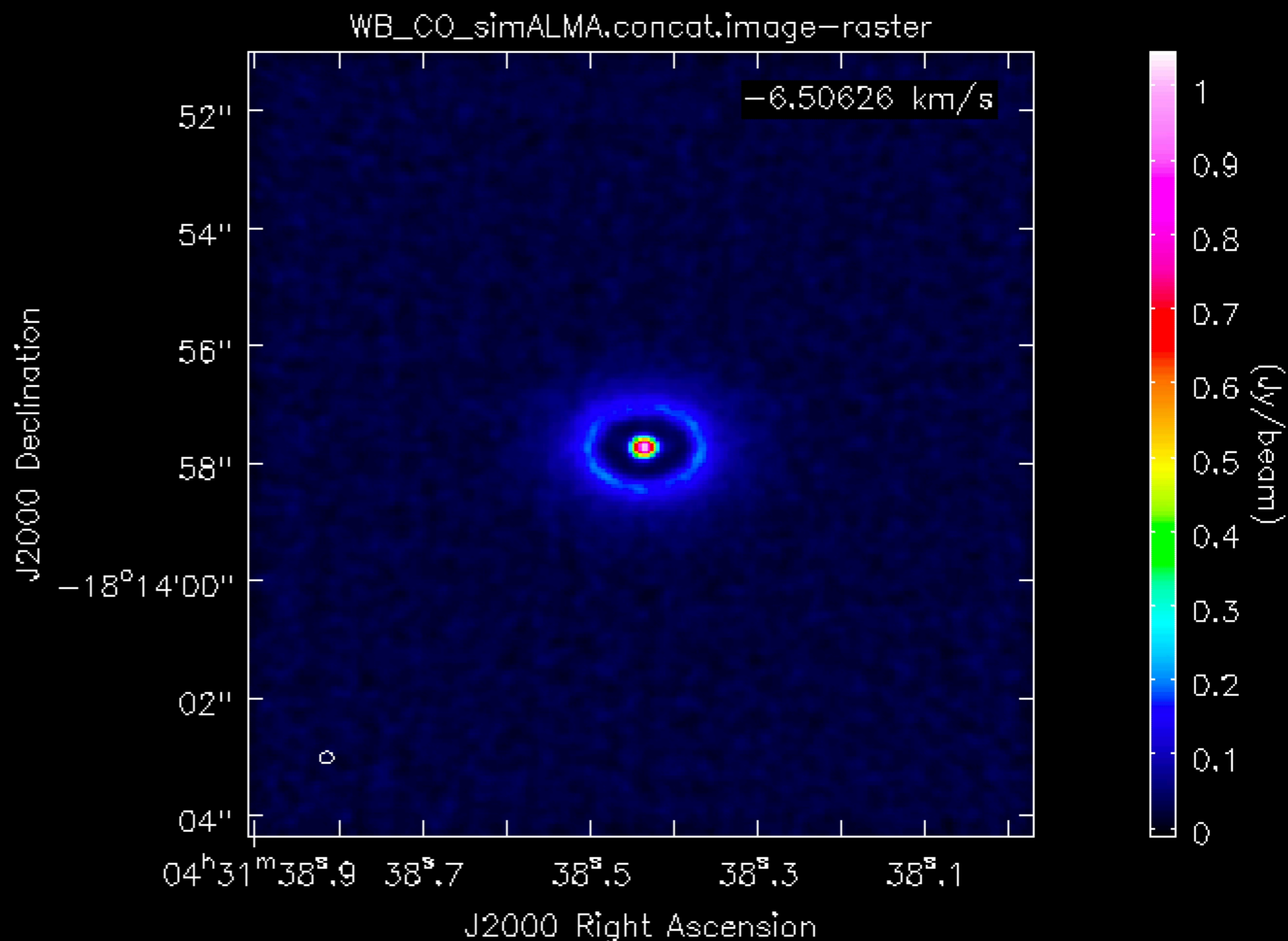
Increasing
Baseline



	Band	3	4	5	6	7	8	9	10
	Frequency (GHz)	100	150	185	230	345	460	650	870
Configuration									
7-m	θ_{res} (arcsec)	12.5	8.35	6.77	5.45	3.63	2.72	1.93	1.44
	θ_{MRS} (arcsec)	66.7	44.5	36.1	29.0	19.3	14.5	10.3	7.67
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	θ_{MRS} (arcsec)	1.42	0.947	0.768	0.618	0.412	-	-	-
C43-9	θ_{res} (arcsec)	0.057	0.038	0.0308	0.0248	0.0165	-	-	-
	θ_{MRS} (arcsec)	0.814	0.543	0.44	0.354	0.236	-	-	-
C43-10	θ_{res} (arcsec)	0.042	0.028	0.0227	0.0183	0.0122	-	-	-
	θ_{MRS} (arcsec)	0.496	0.331	0.268	0.216	0.144	-	-	-

TORUS Example

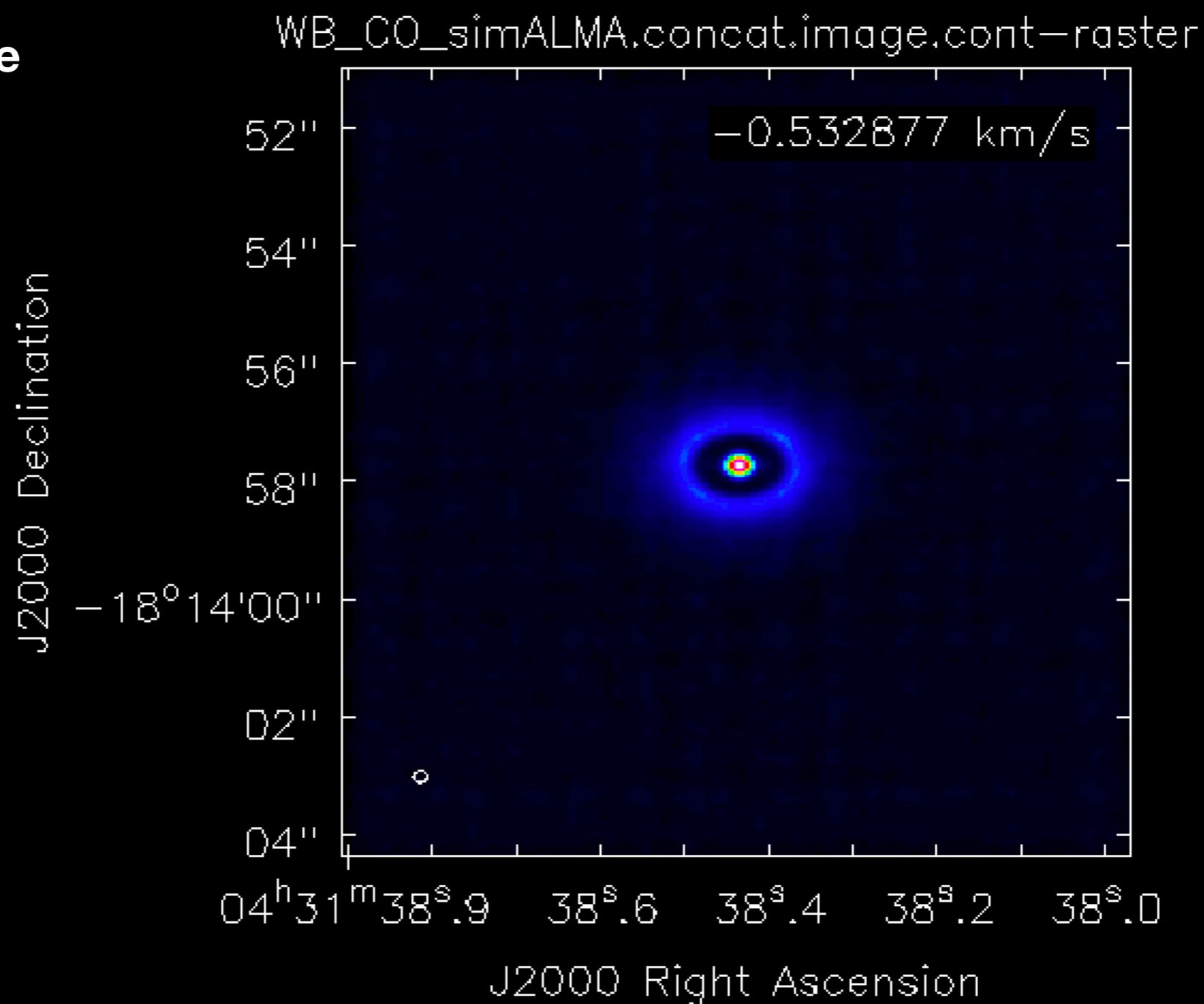
Processed CO cube



TORUS Example

Processed CO cube

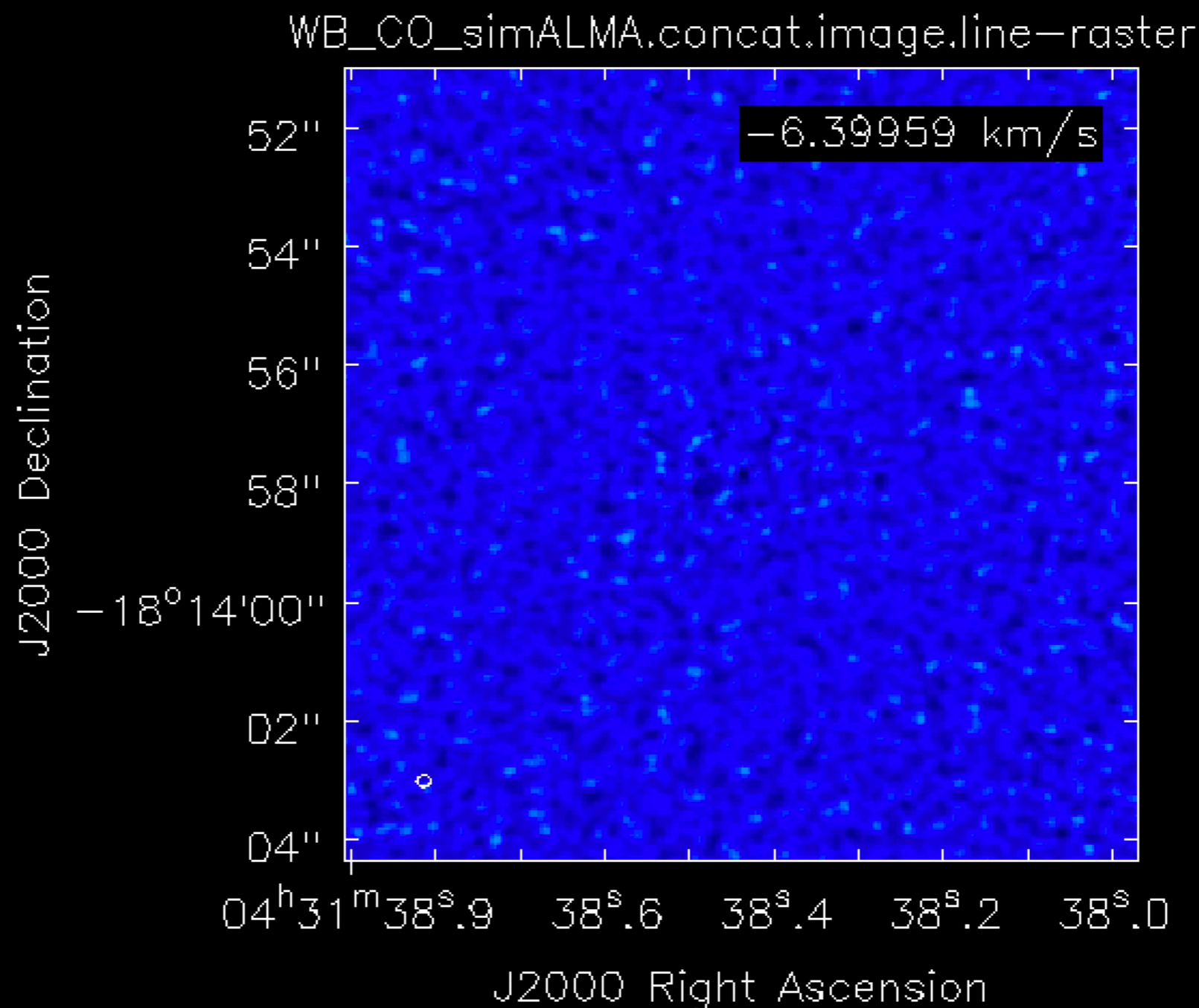
Continuum only



TORUS Example

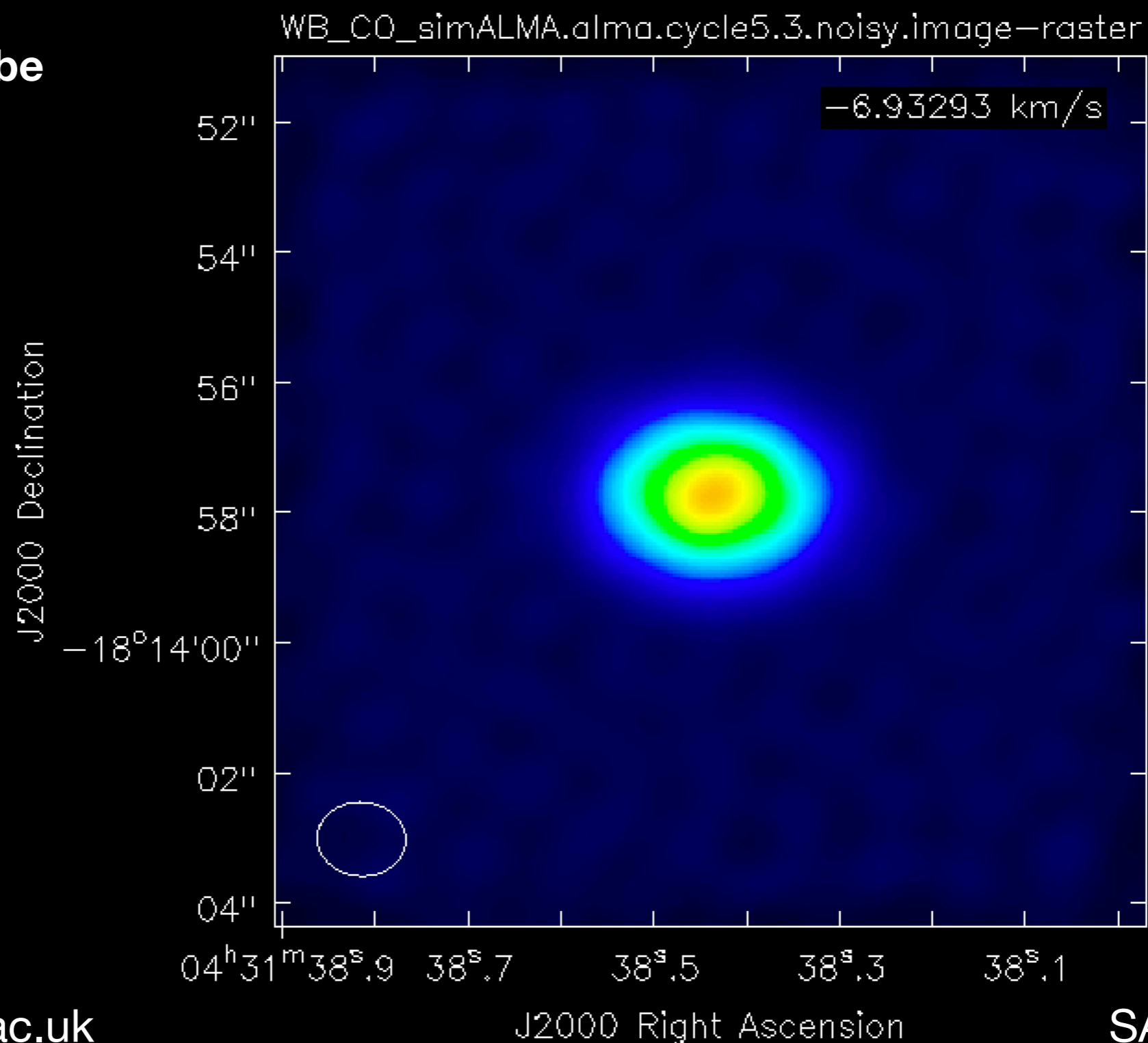
Processed CO cube

Line only



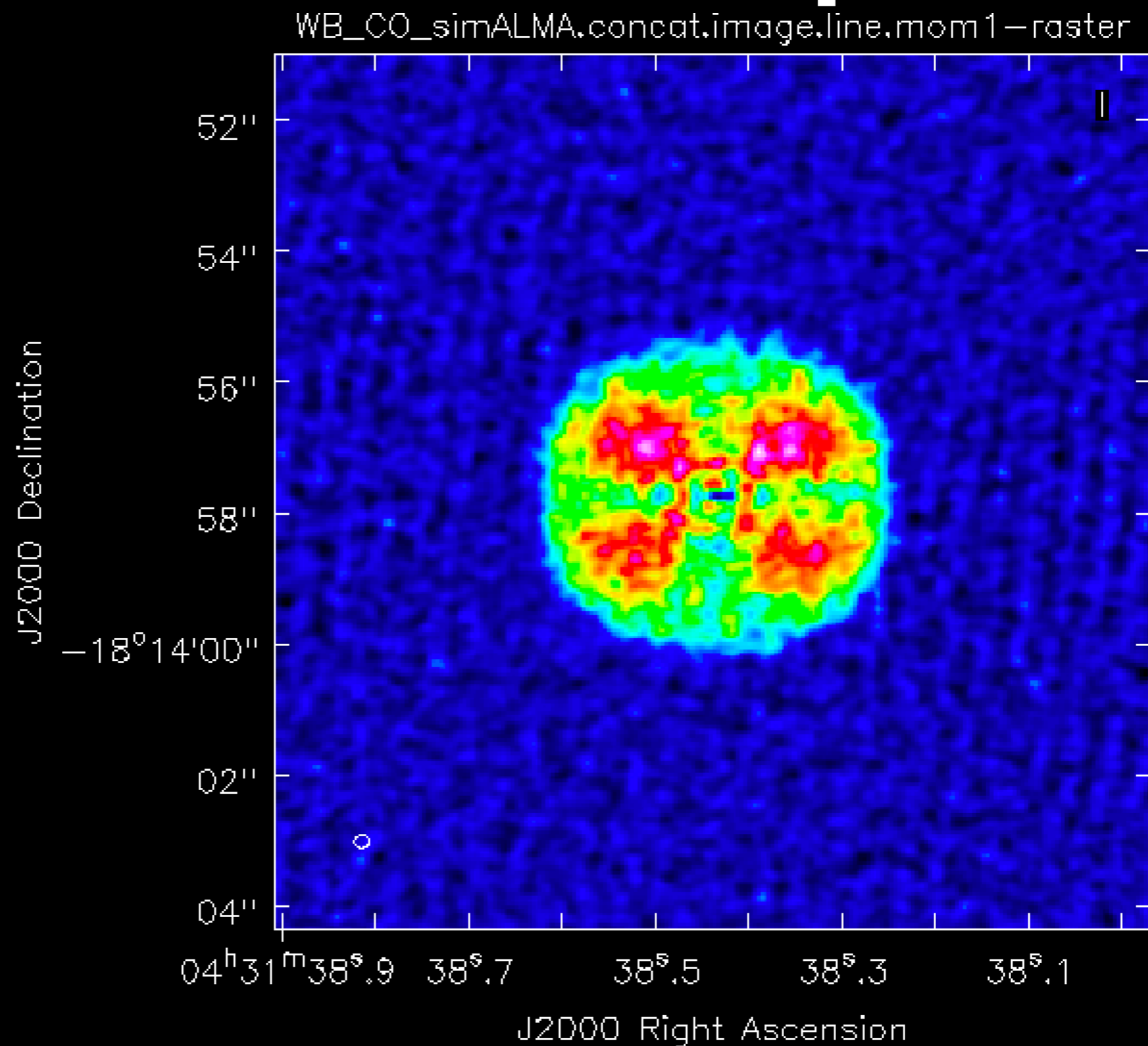
TORUS Example

Processed CO cube
Config 5.3



TORUS Example

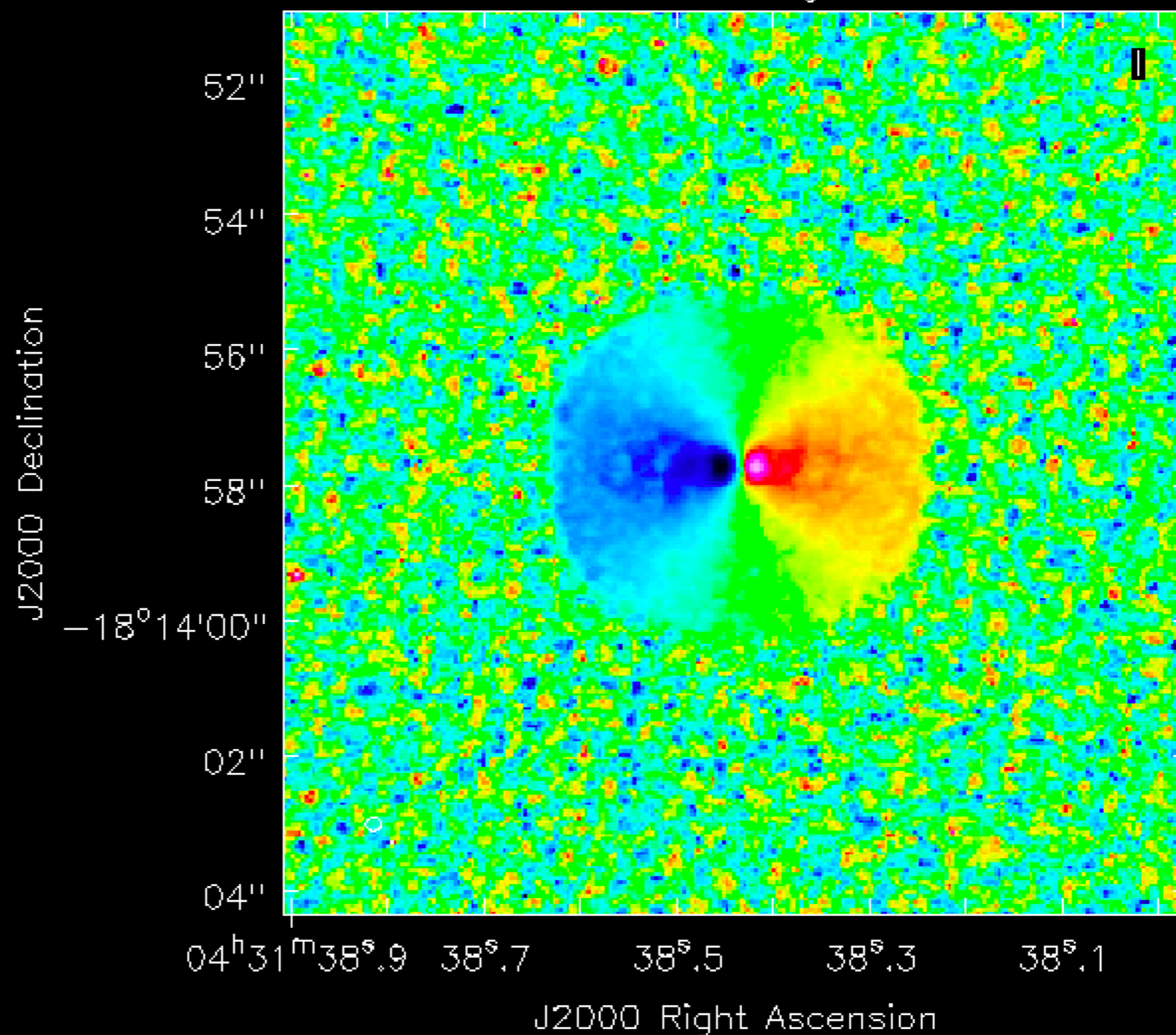
Moment 0 map



TORUS Example

WB_CO_simALMA.concat.image.line.mom2-raster

Moment 1 map



TORUS Example

Will also do a self-gravitating disc example in the hands on session

Further TORUS information

The TORUS radiation transfer code

Harries et al. (2018), *Astronomy & Computing*, 27, 63

Further TORUS information



The TORUS radiation transfer code

Harries et al. (2018), *Astronomy & Computing*, 27, 63

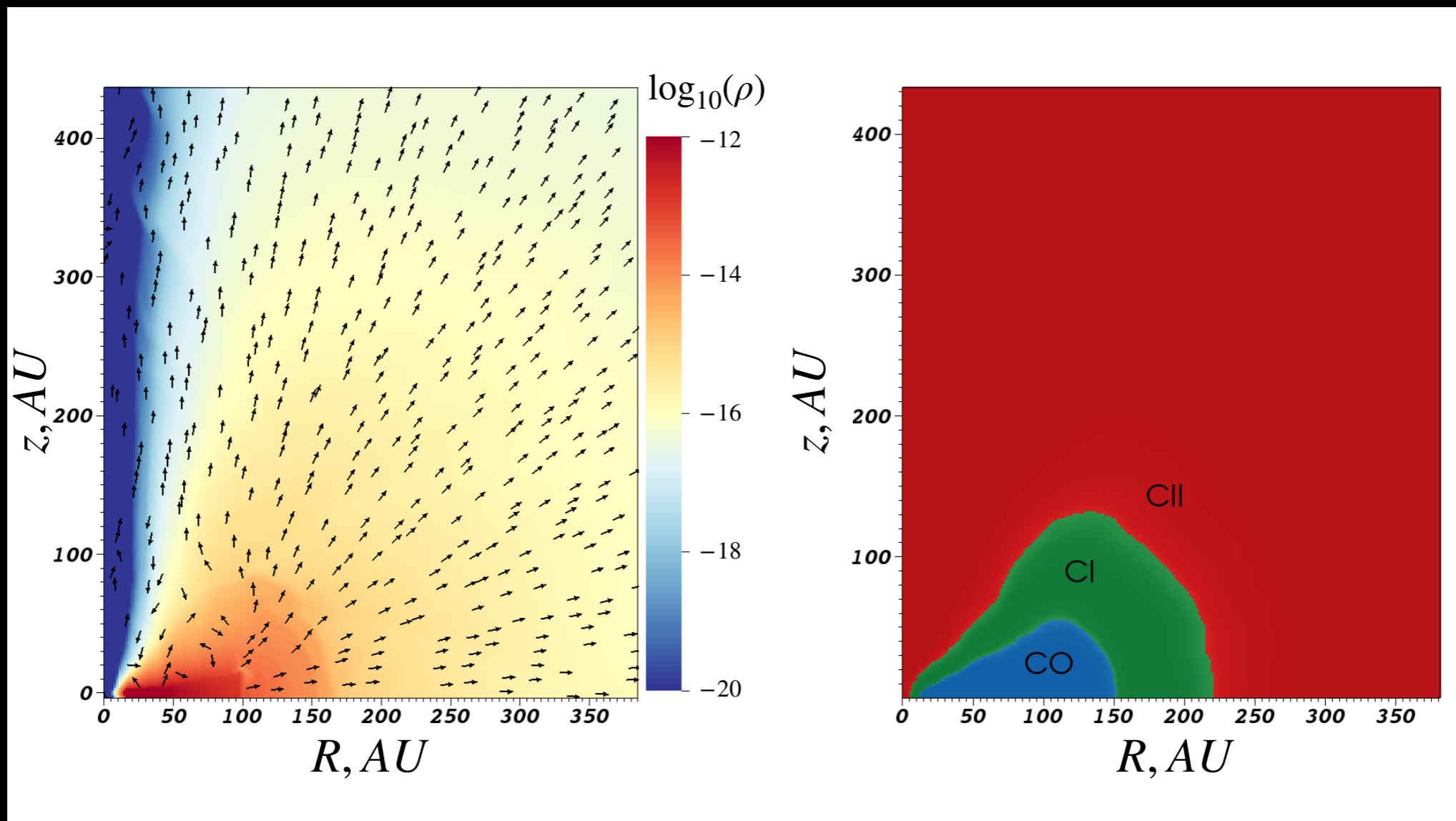
Further general information



Synthetic observations of star formation and the interstellar medium

Haworth et al. (2018), *New Astronomy Reviews*, 82, 1

Some examples



Some examples

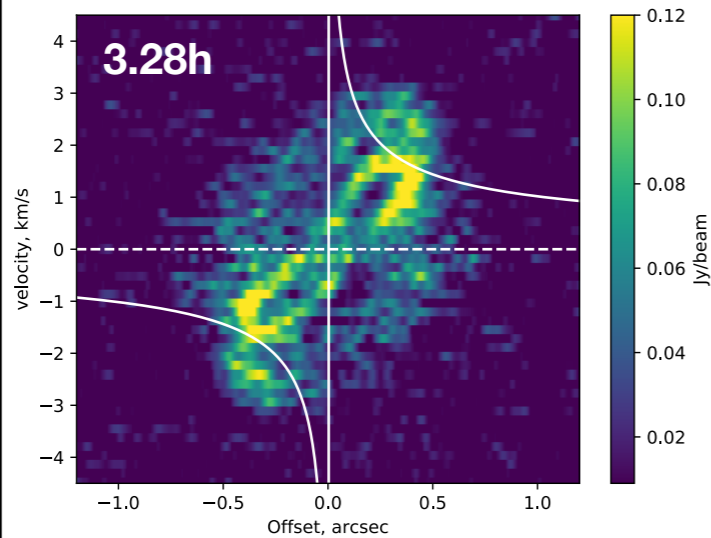
$0.62 M_{\odot}$ star

$6 M_{jup}$ disc

$1174 G_0$

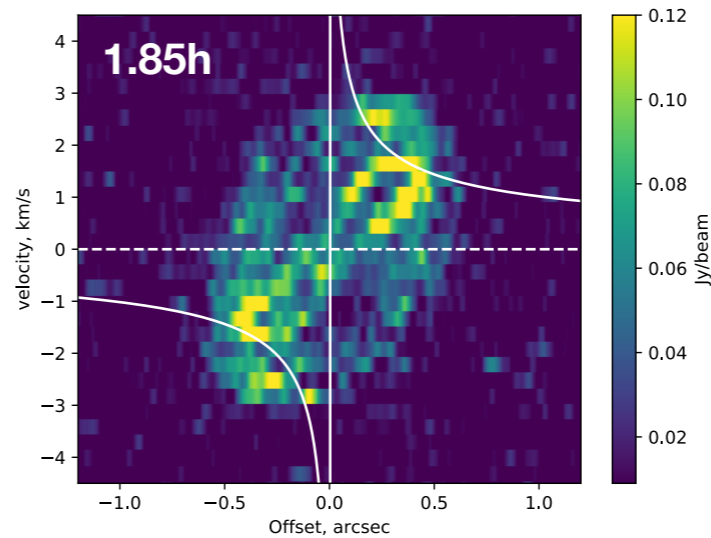
Sensitivity: 20mJy

Spectral resolution: 0.172km/s



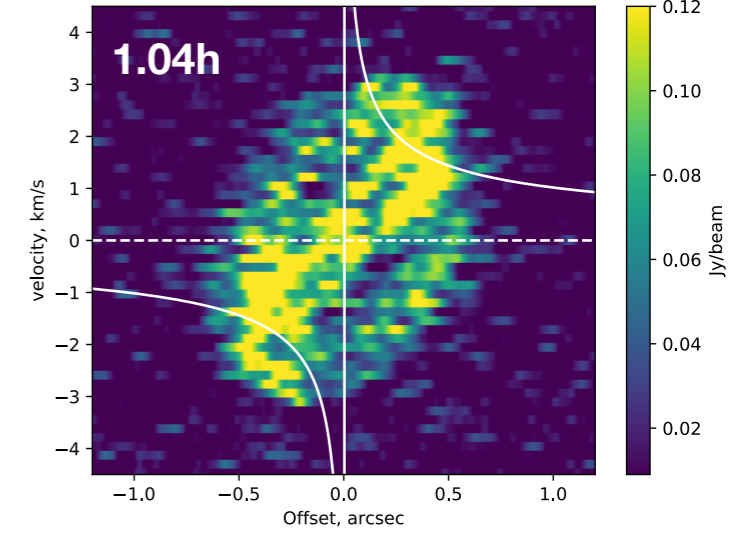
Sensitivity: 20mJy

Spectral resolution: 0.344km/s



Sensitivity: 50mJy

Spectral resolution: 0.344km/s

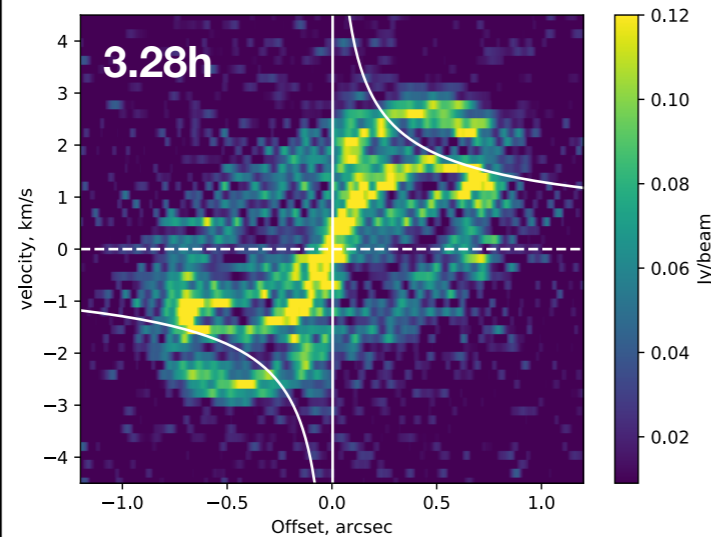


$1 M_{\odot}$ star

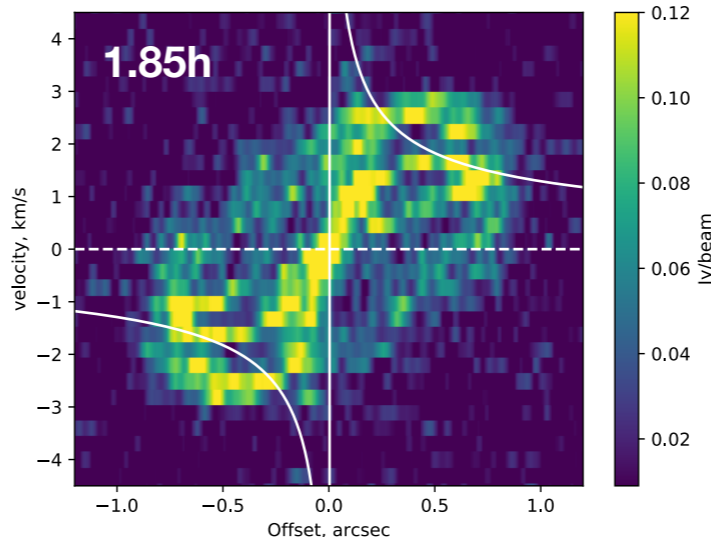
$20 M_{jup}$ disc

$1000 G_0$

3.28h



1.85h



1.04h

