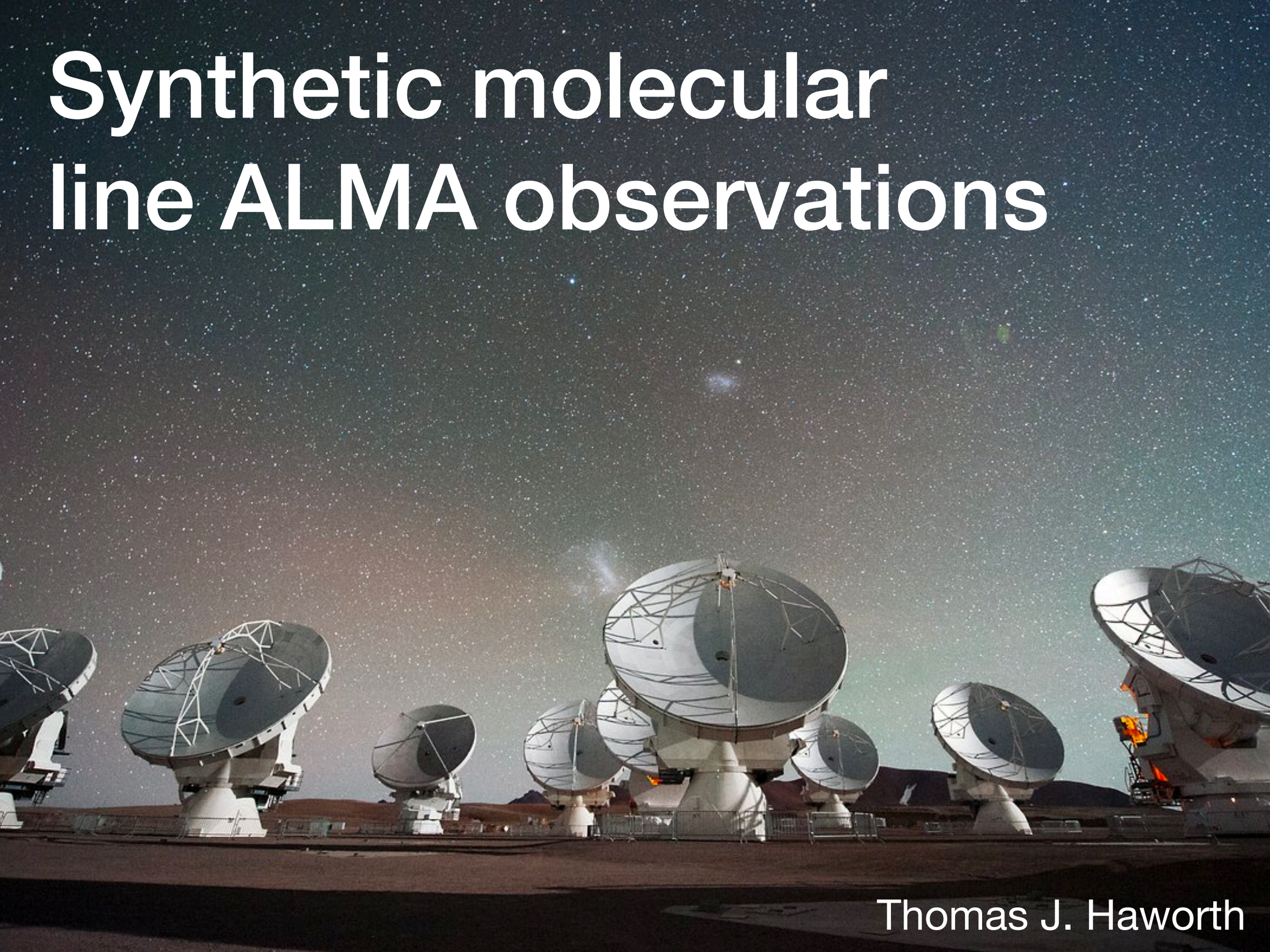
Synthetic molecular line ALMA observations



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**

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WHAT IS ALMA?

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WHAT IS ALMA?

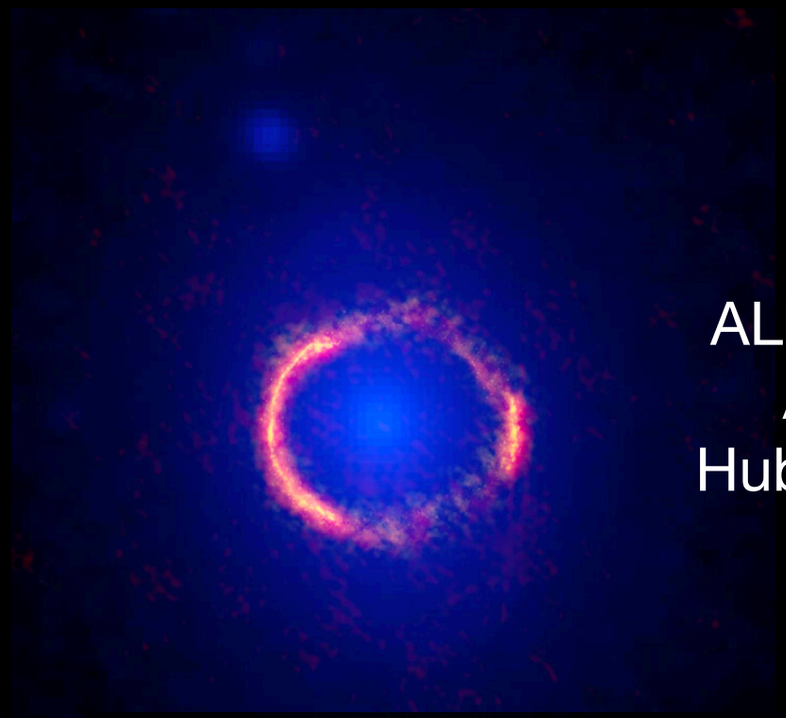
- An interferometer

- Current frequency coverage from 84-950GHz (0.3mm—3.6mm)

- Line and continuum observations

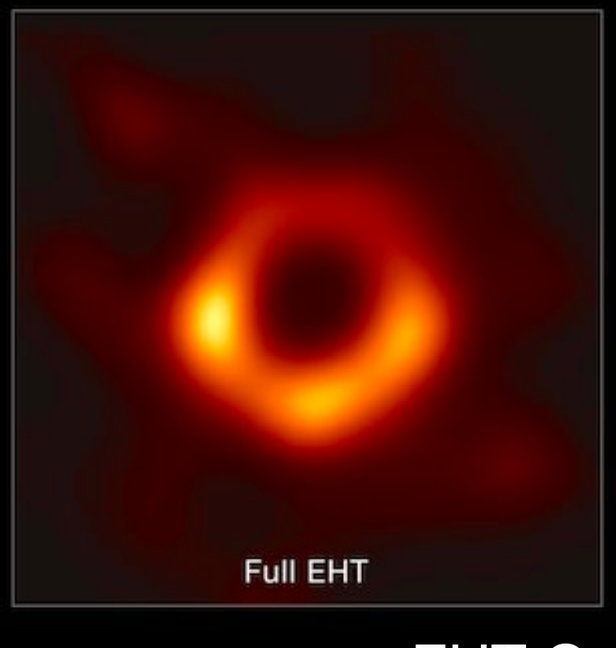
- Spatial resolution of up to 0.01”

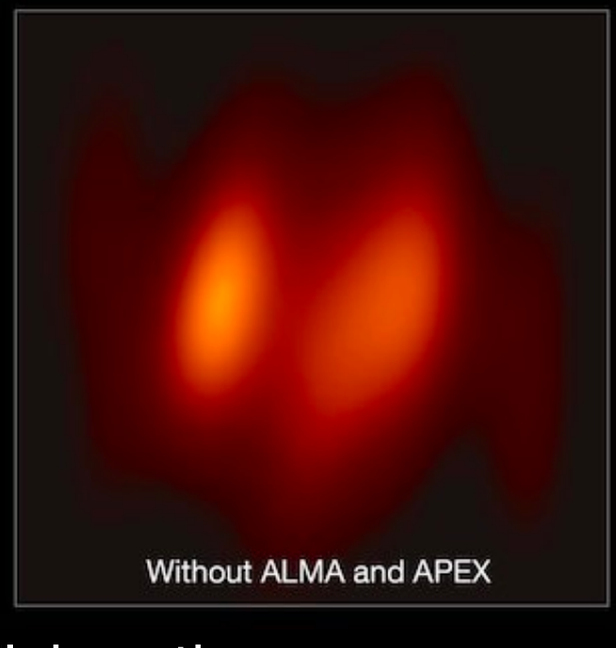
WHAT IS ALMA?



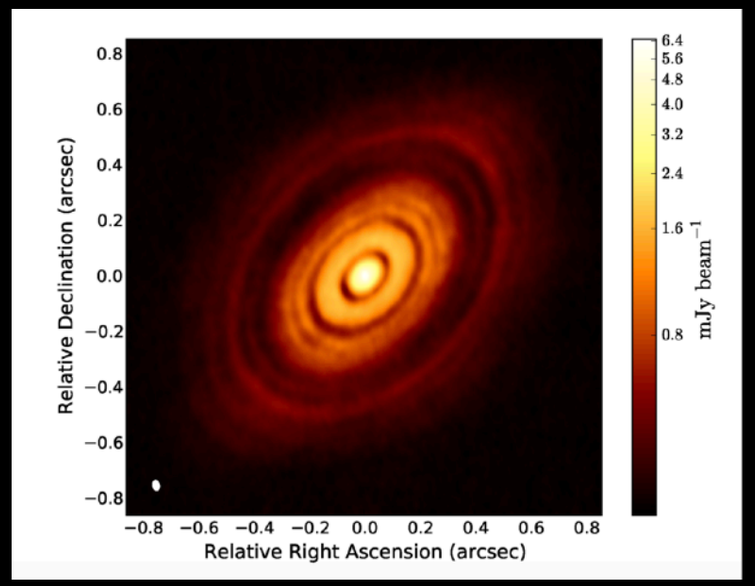
ALMA
/
Hubble

ALMA
/
Hubble

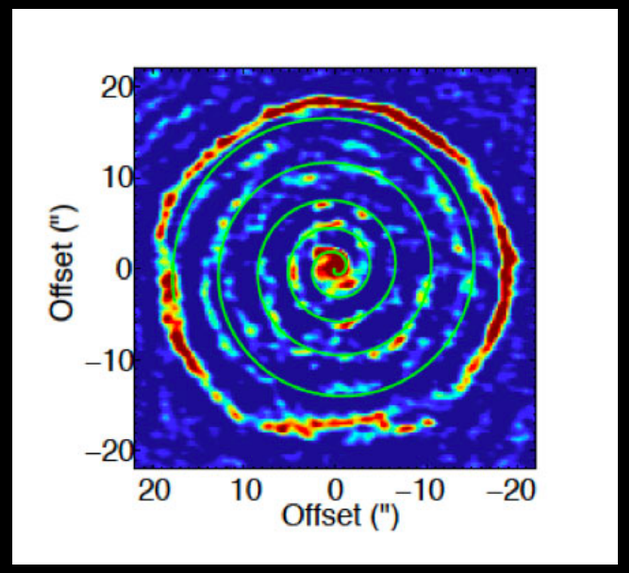




EHT Collaboration



ALMA partnership (2015)



Maercker et al. 2012

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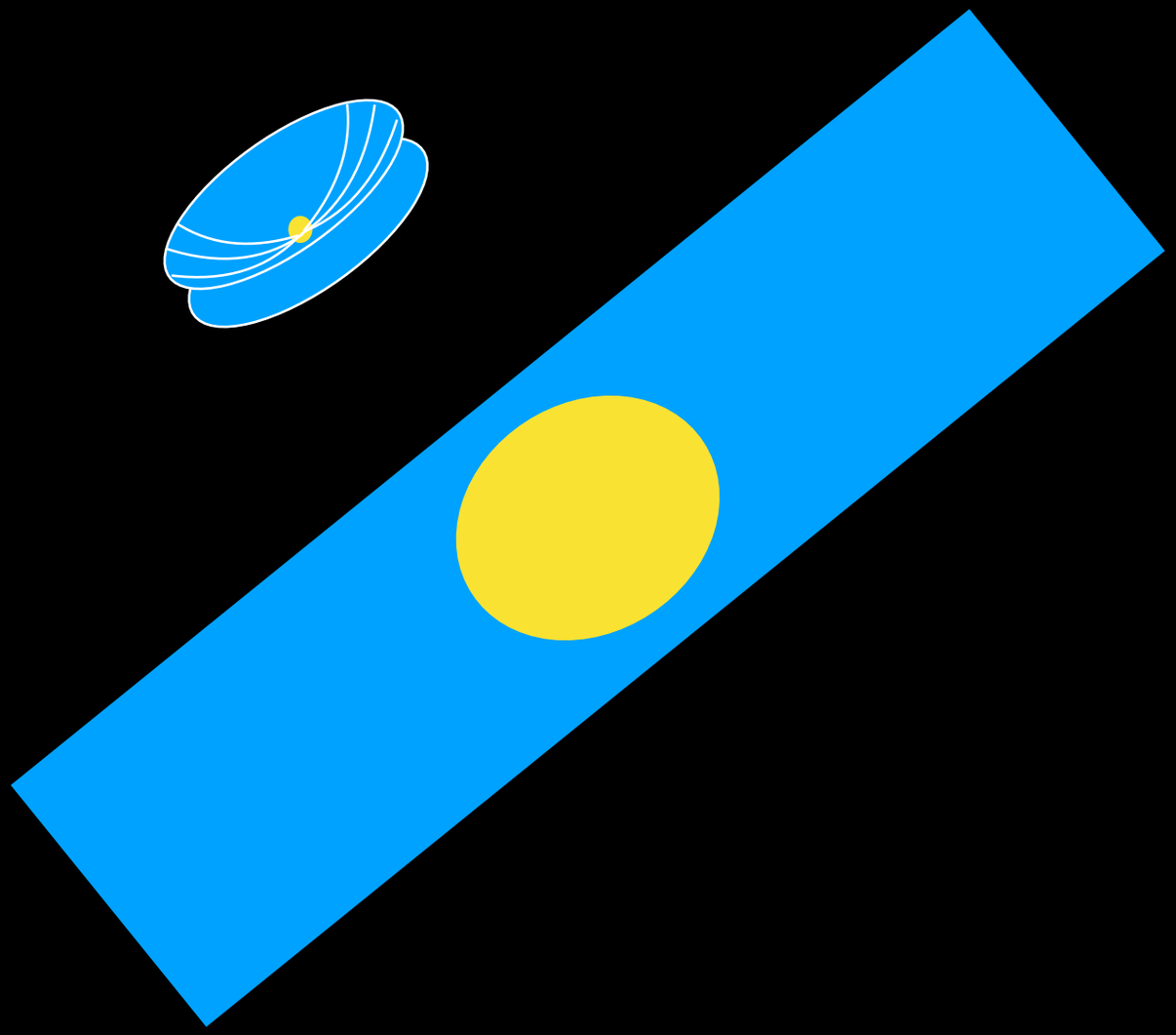
WHAT IS ALMA?



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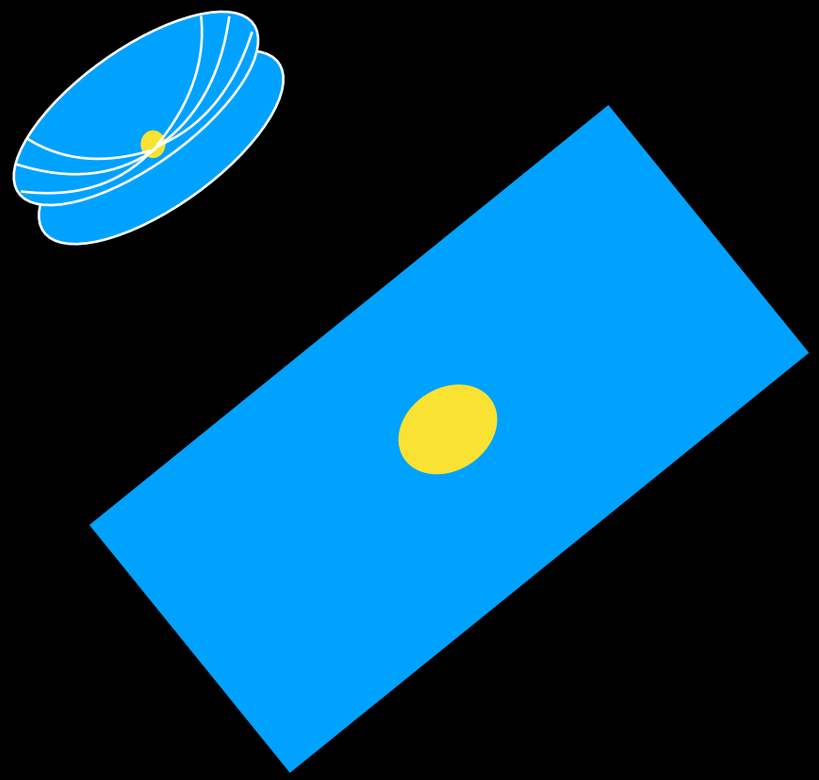

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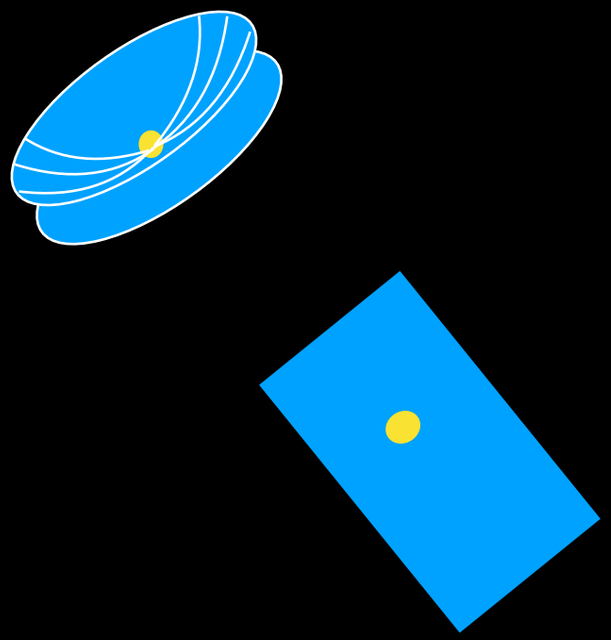

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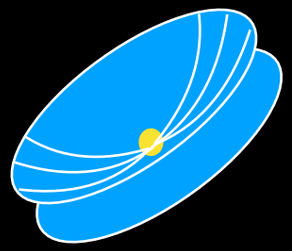

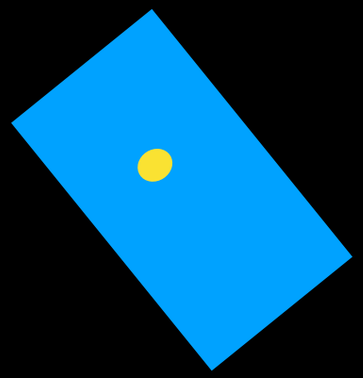

Non-trivial to plan observations

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

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ALMA configurations

Resolution and maximum scale

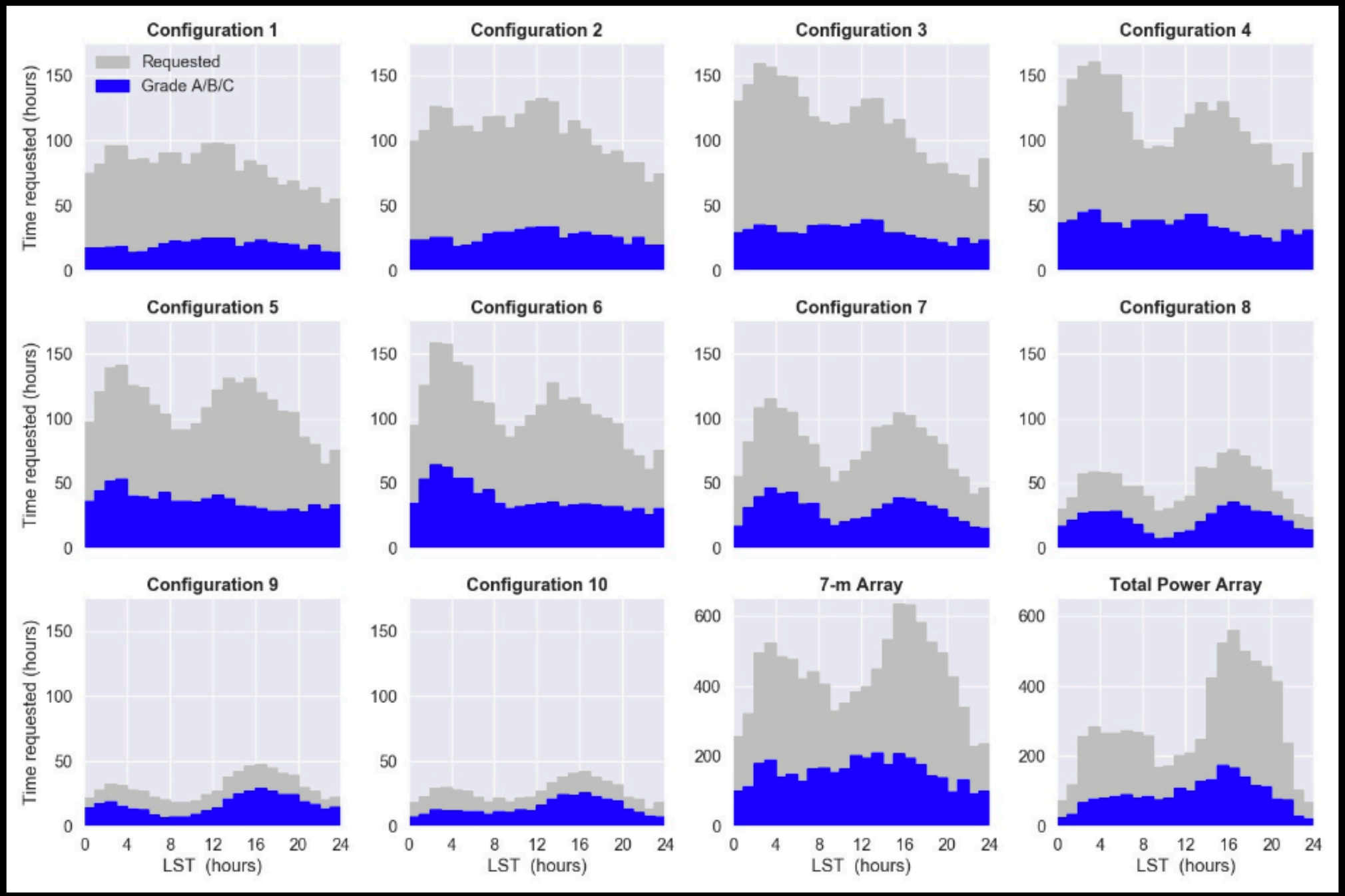
Increasing Baseline

	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
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	-	-	-

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

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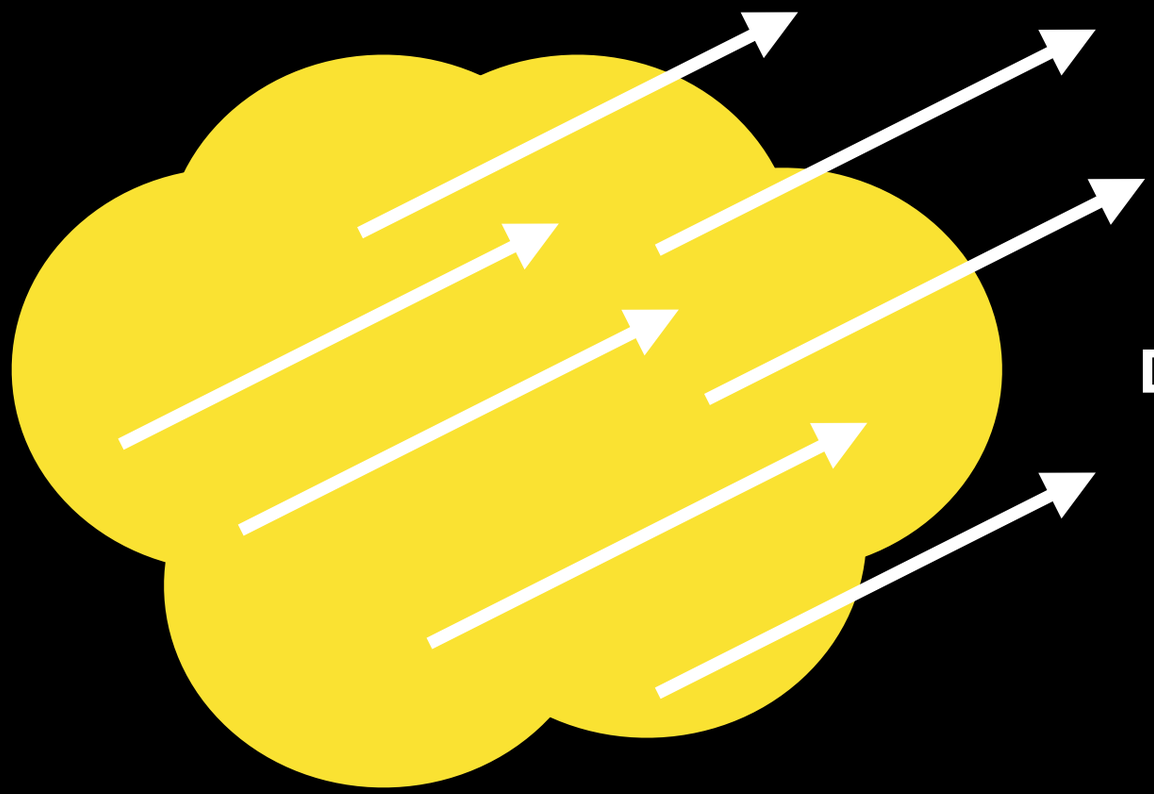
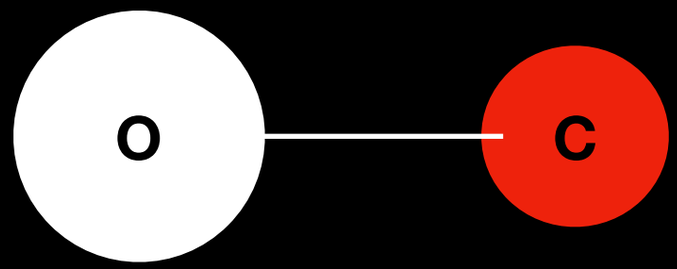
WHAT IS LINE TRANSFER?

A gas of molecules



Quantised ro-vibrational states



Diatomic rotational quantum number J

Transition (e.g. J=2—>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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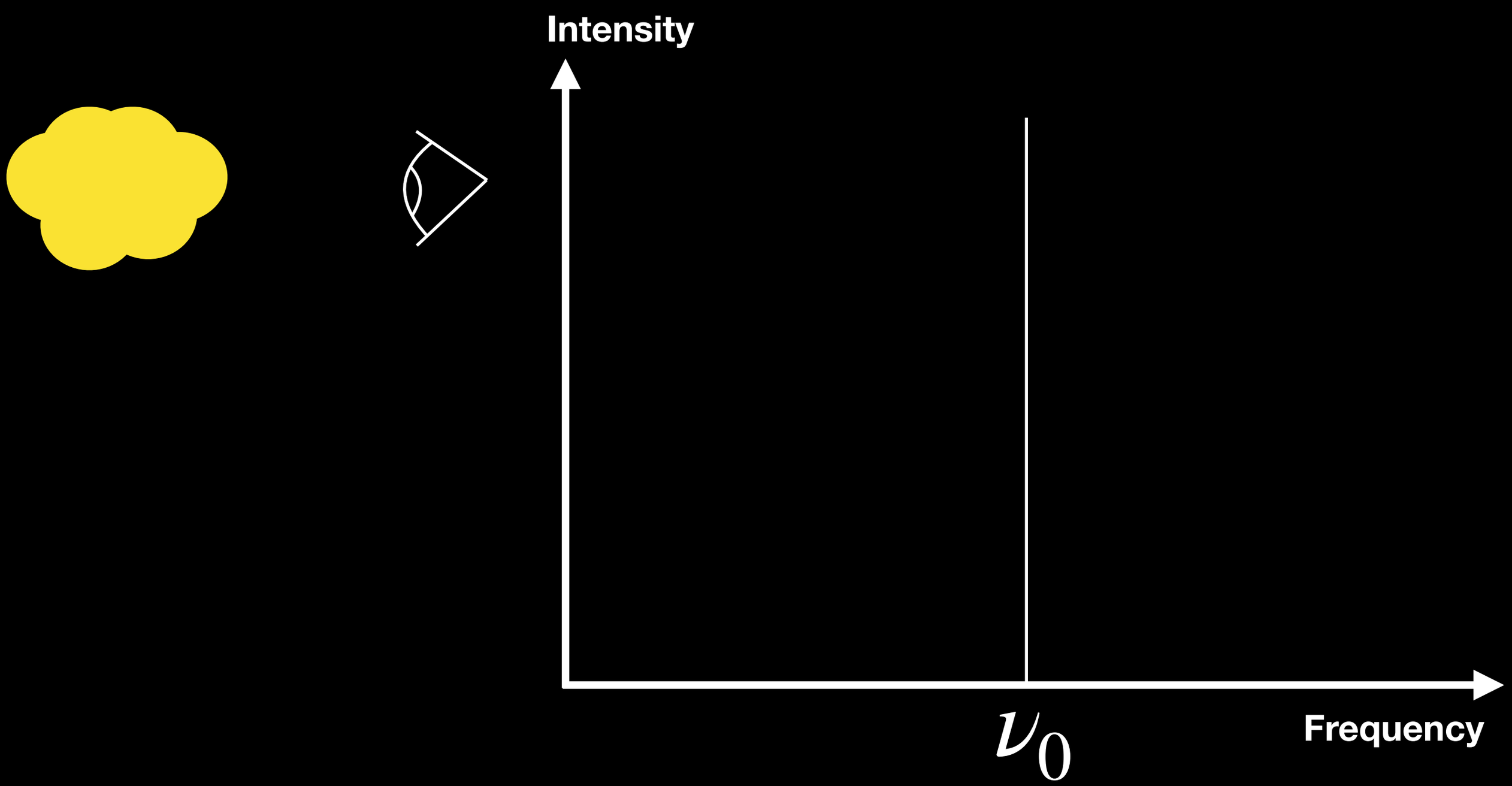
WHAT IS LINE TRANSFER?

A gas of molecules



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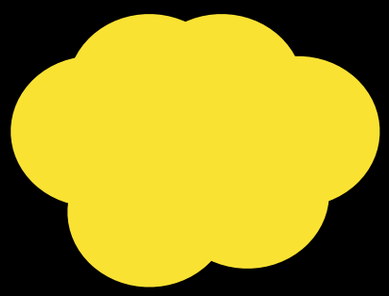
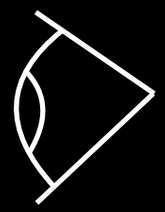
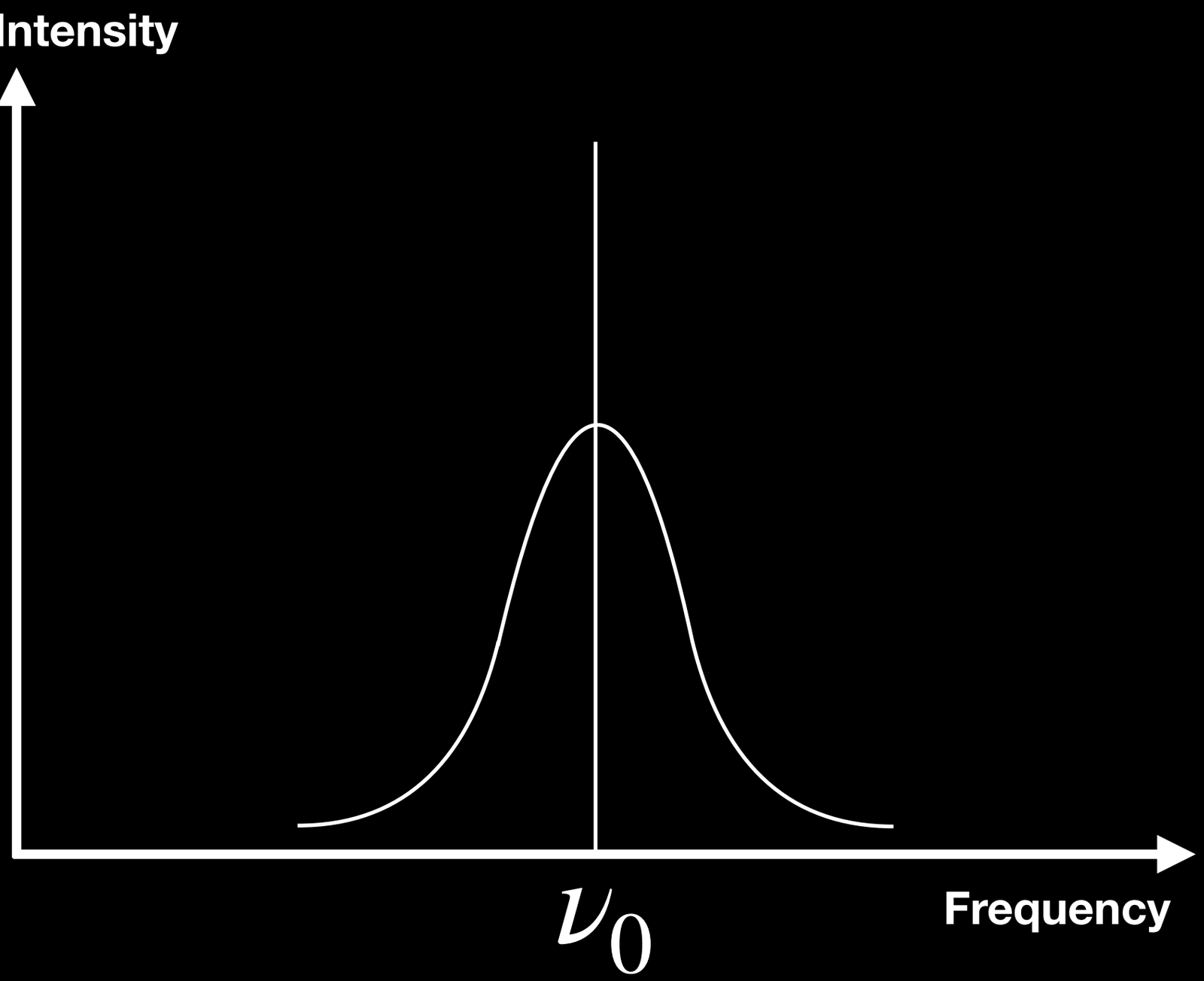




Thermal/turbulent motion



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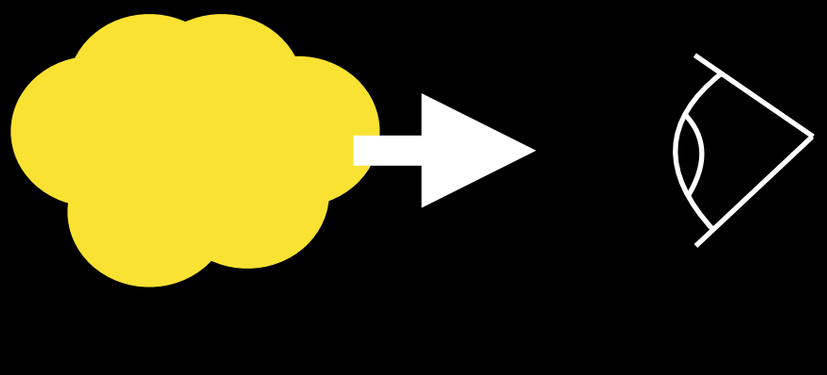
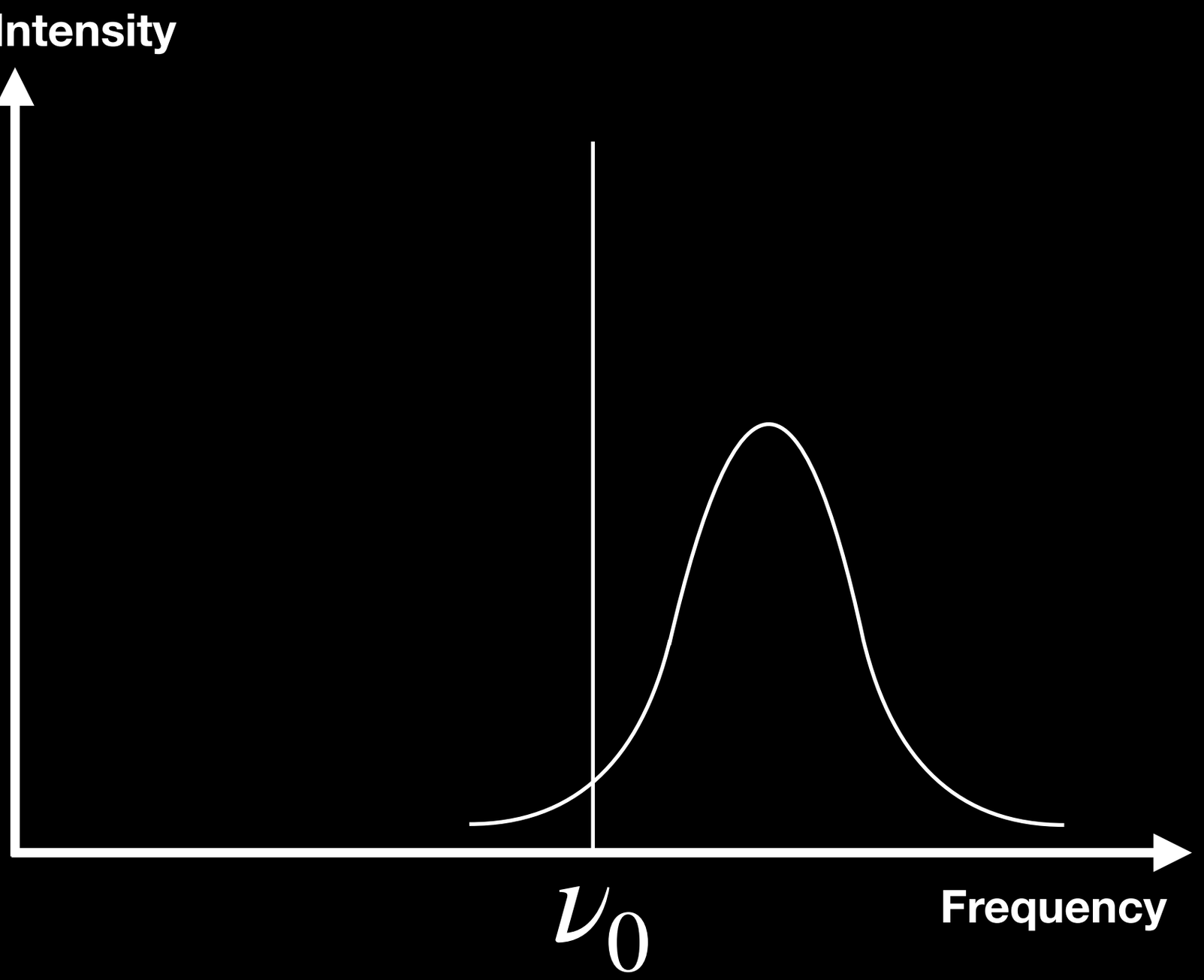


Thermal/turbulent motion

Bulk motion



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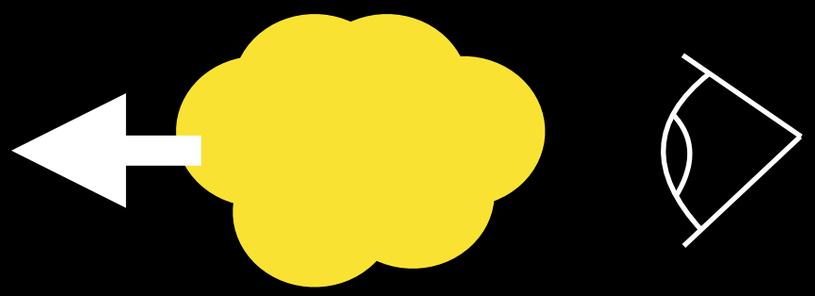
A gas of molecules



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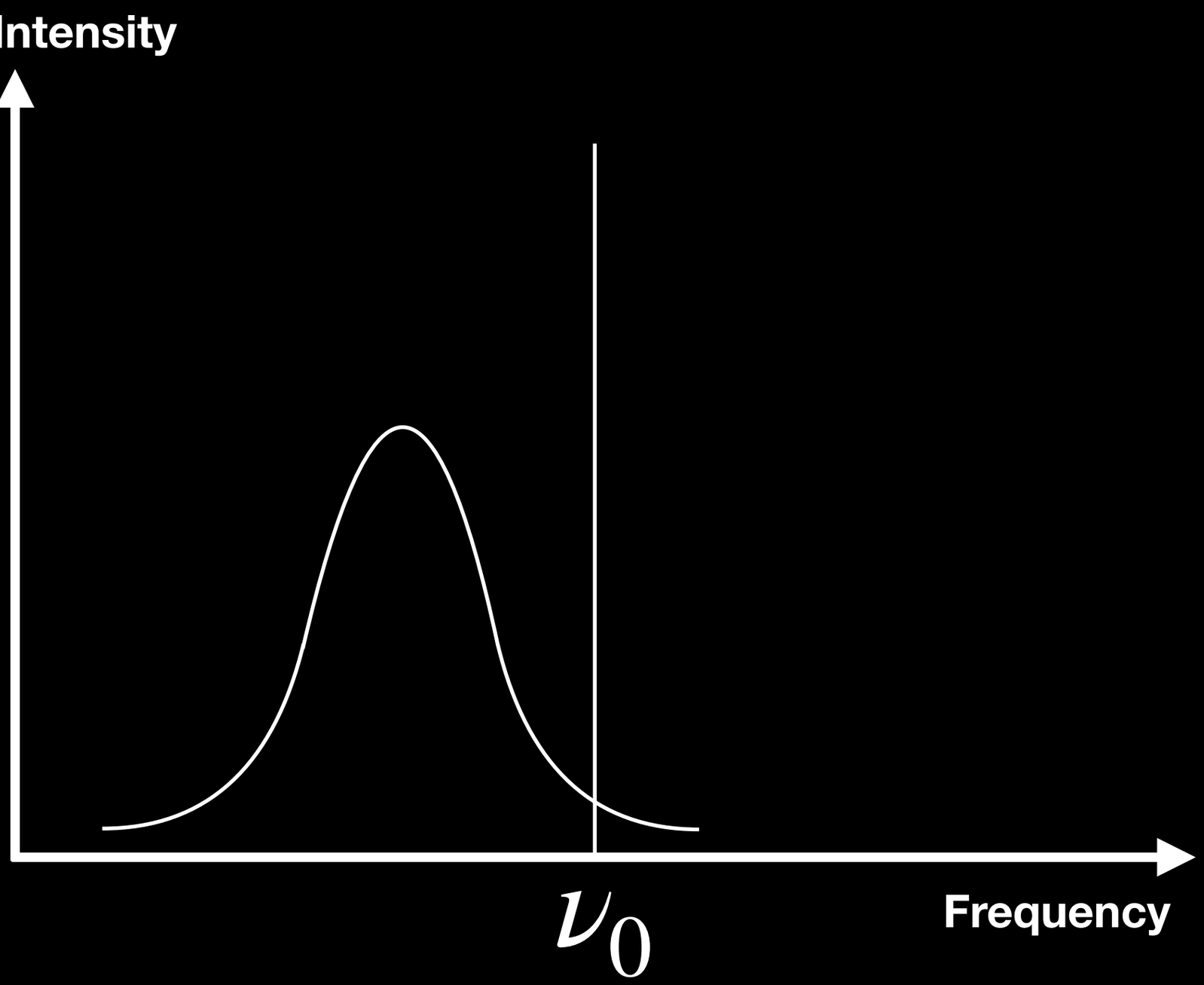

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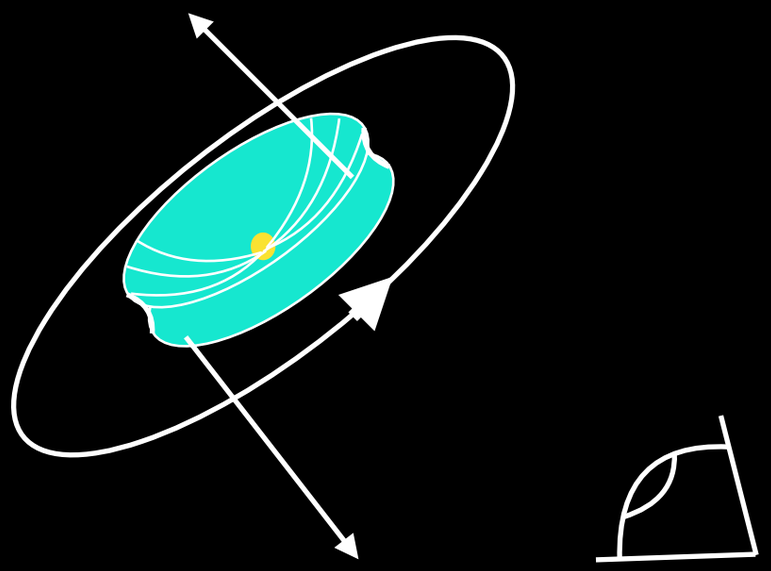

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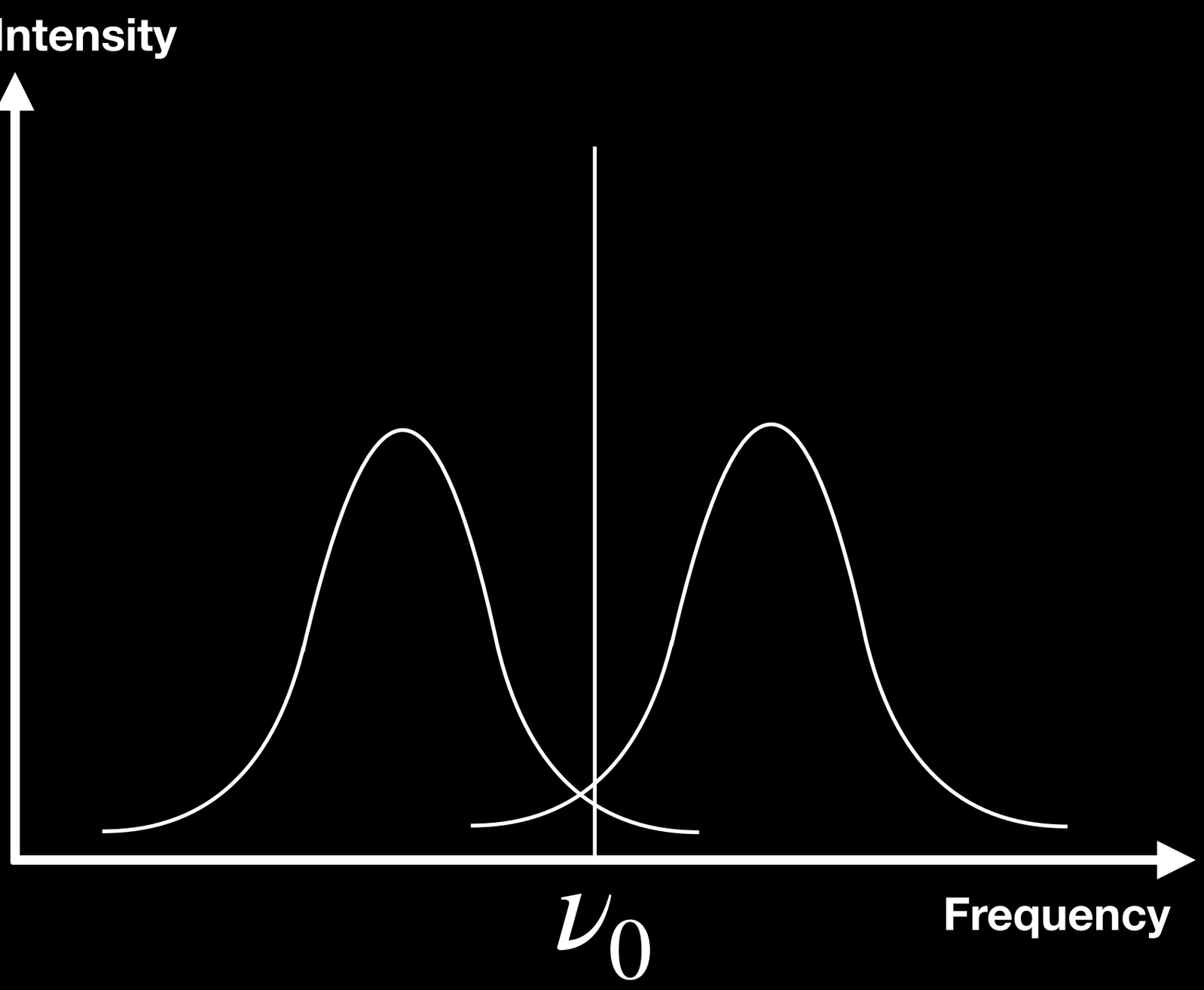

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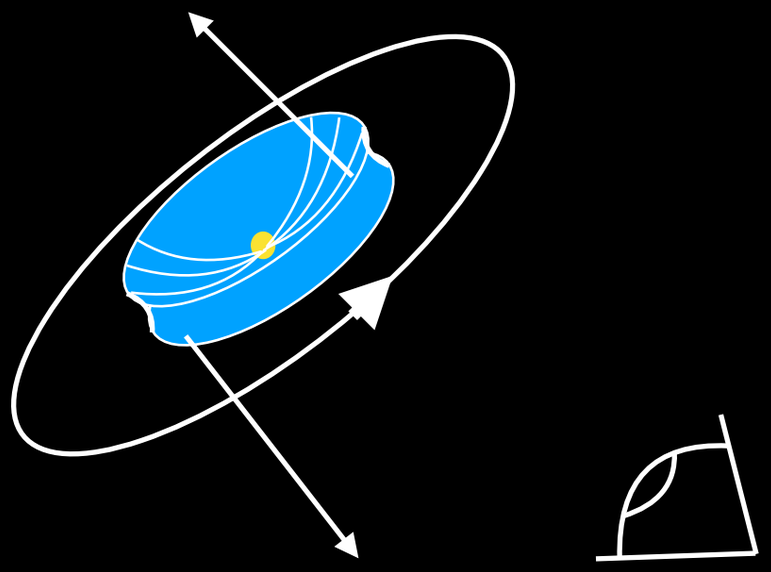

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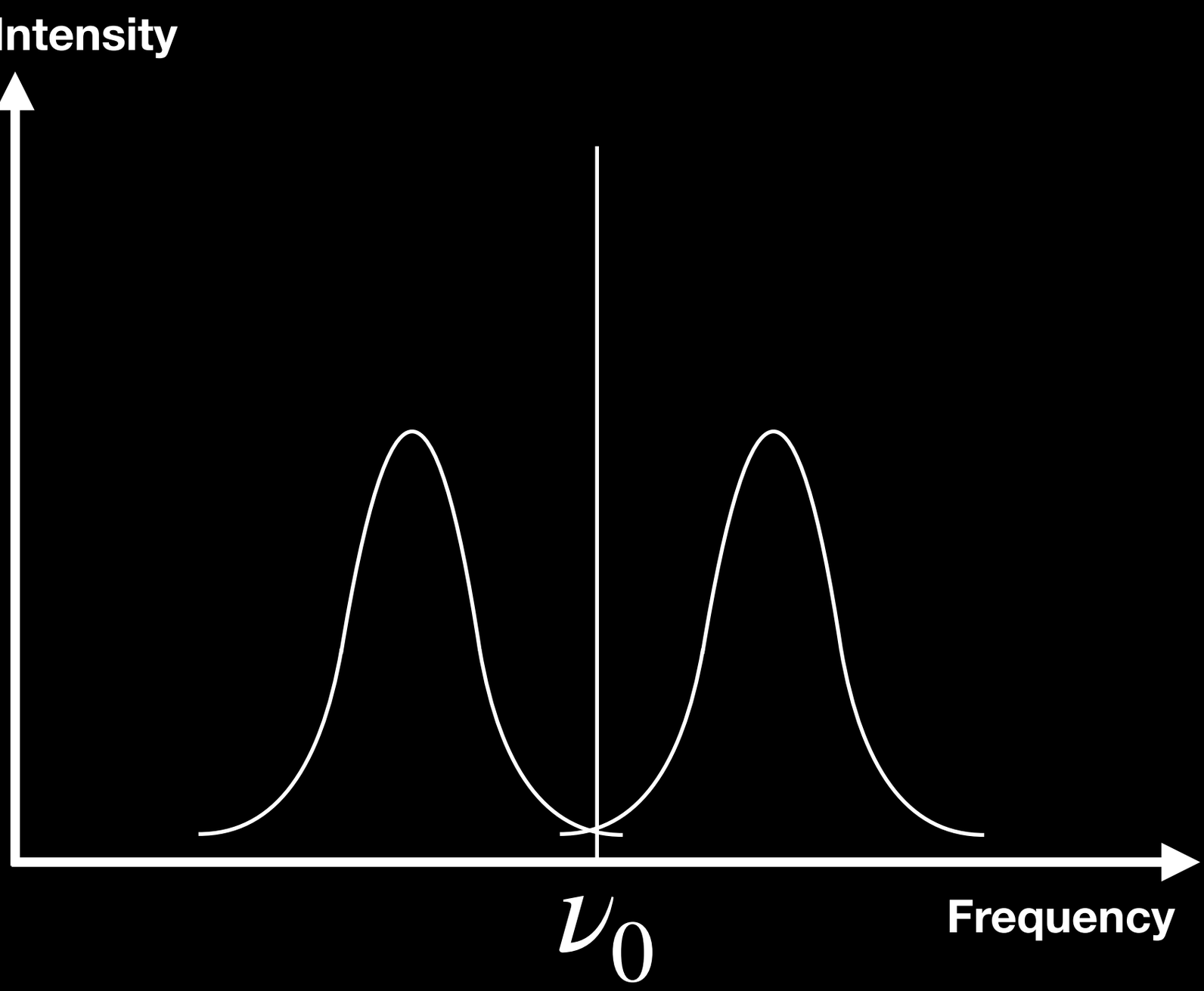

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WHAT IS LINE TRANSFER?

It is an extremely powerful means of inferring

The *kinematics*

And conditions (density, temperature, composition)

of gas in astrophysical systems

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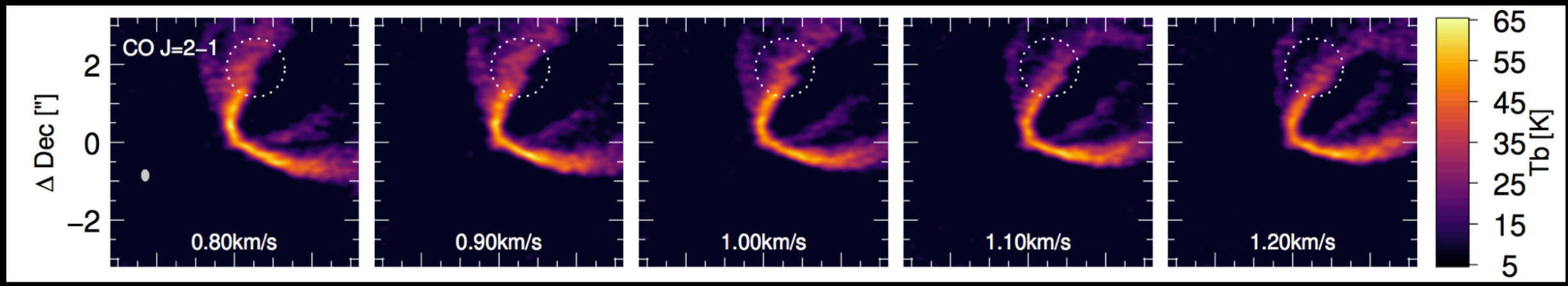
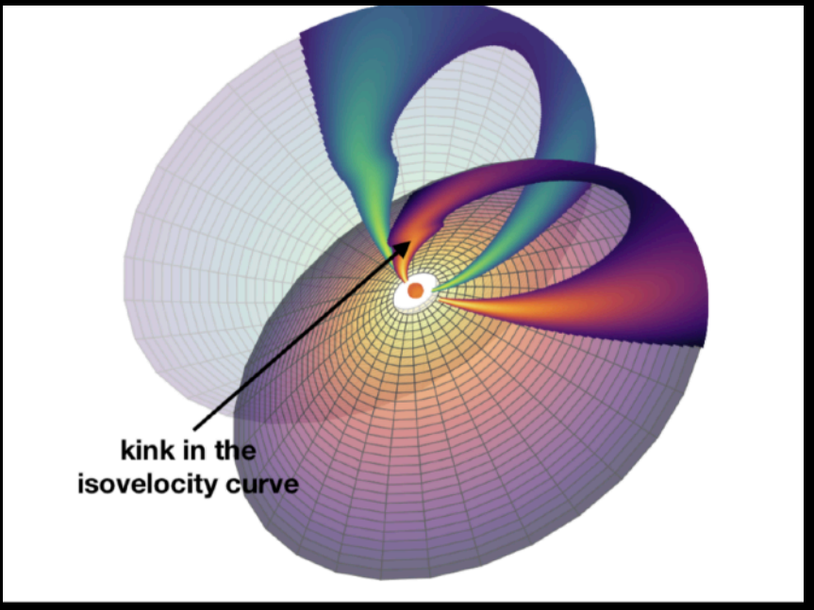
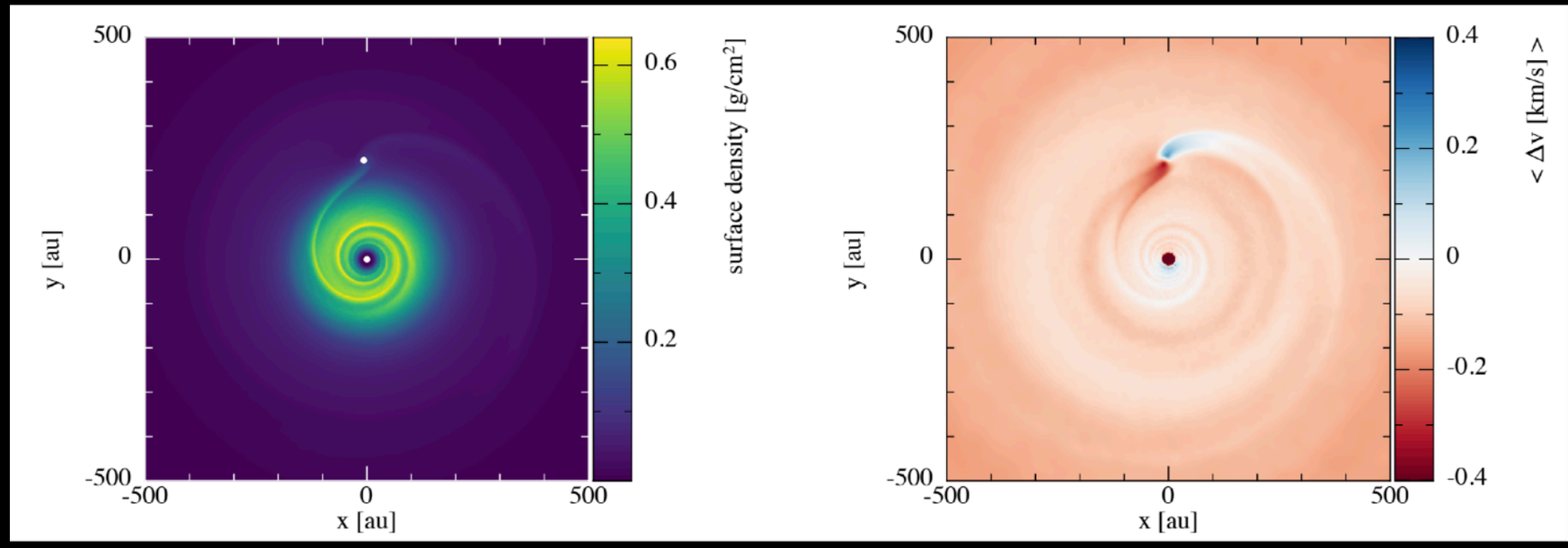
Molecular lines with ALMA







Pinte et al. (2018)

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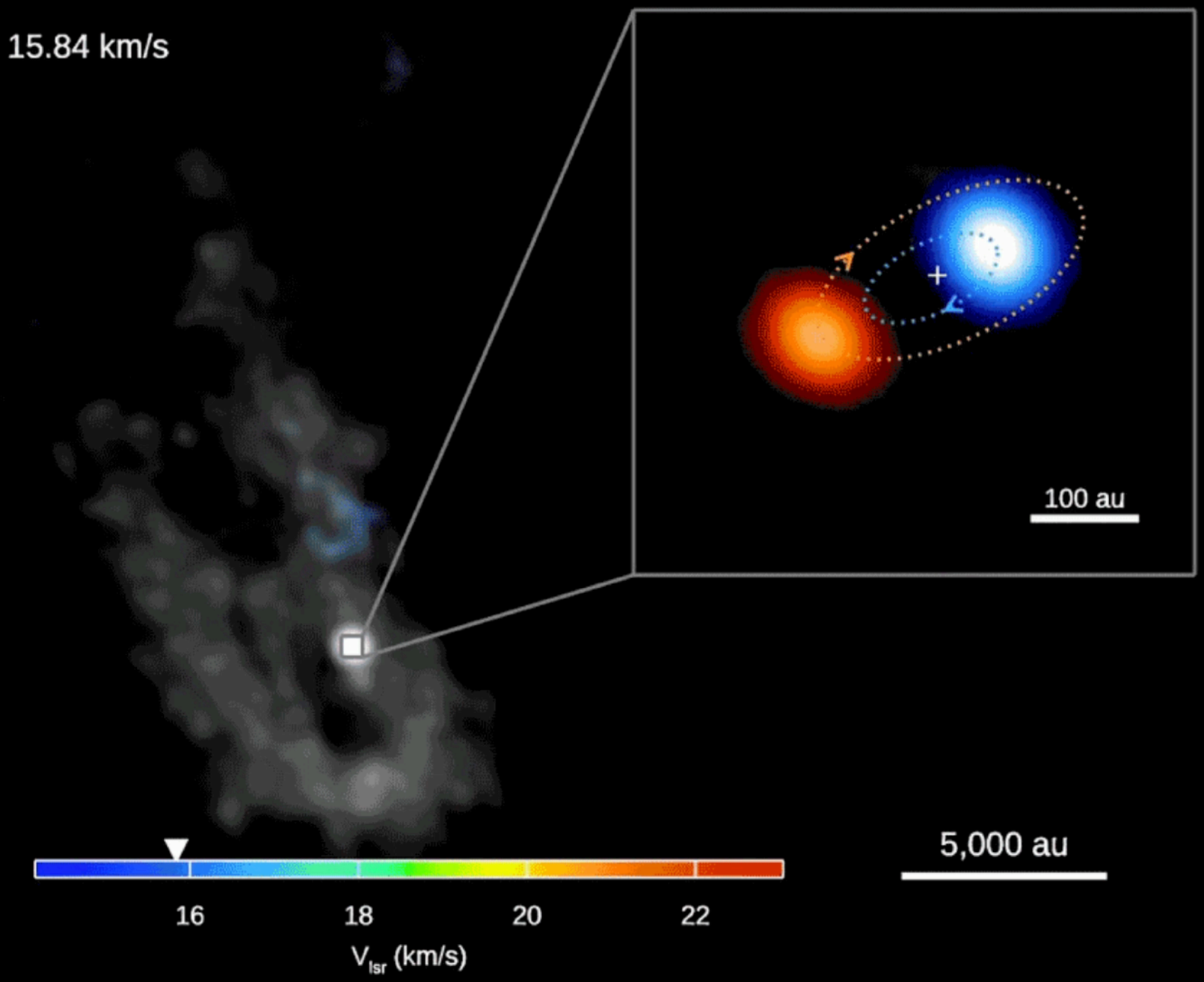
Molecular lines with ALMA



Zhang et al. (2019)

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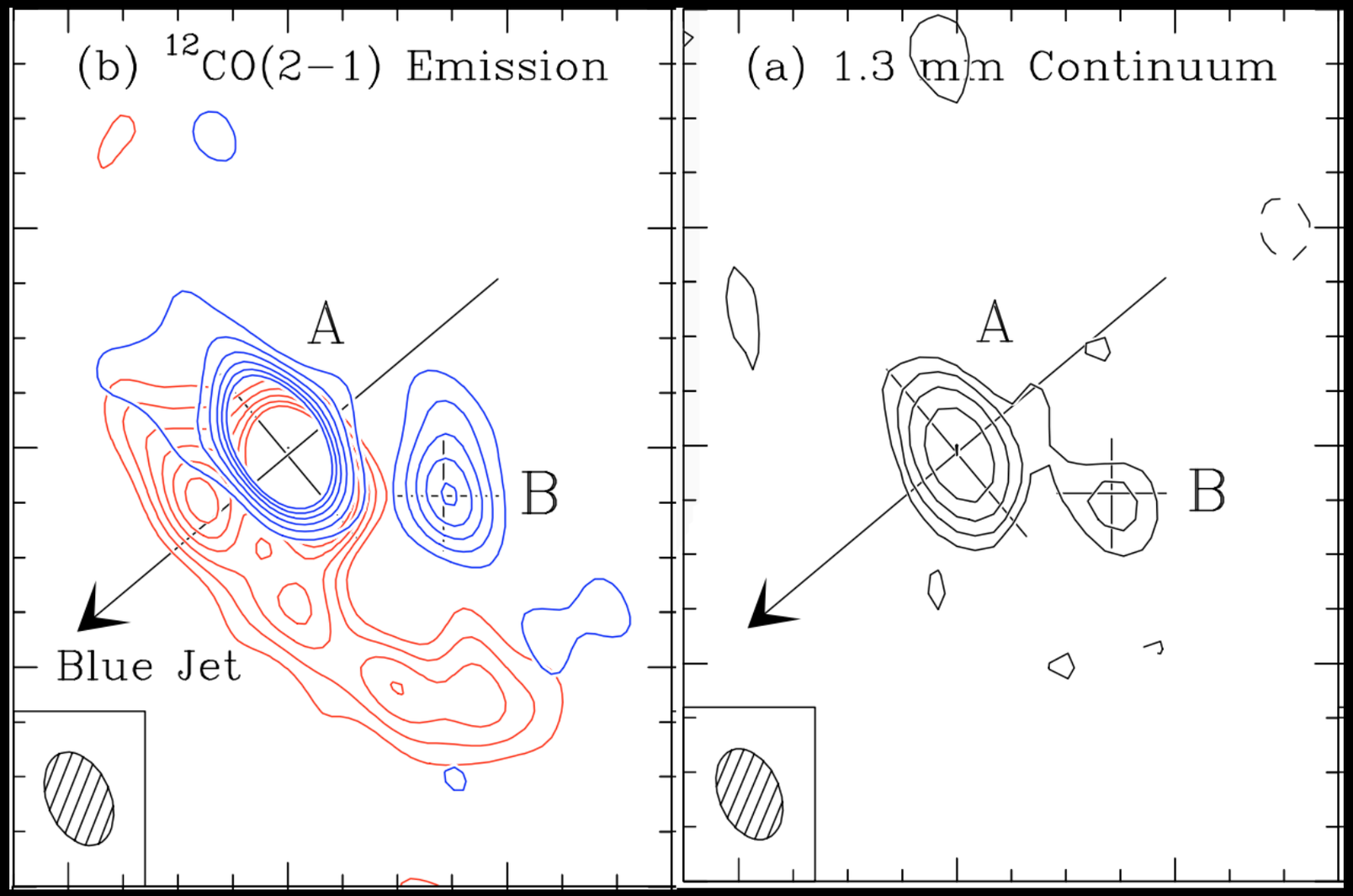
Molecular lines with ALMA

RW Aur



Cabrit et al. (2006)

PdB interferometer

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Molecular lines with ALMA

RW Aur

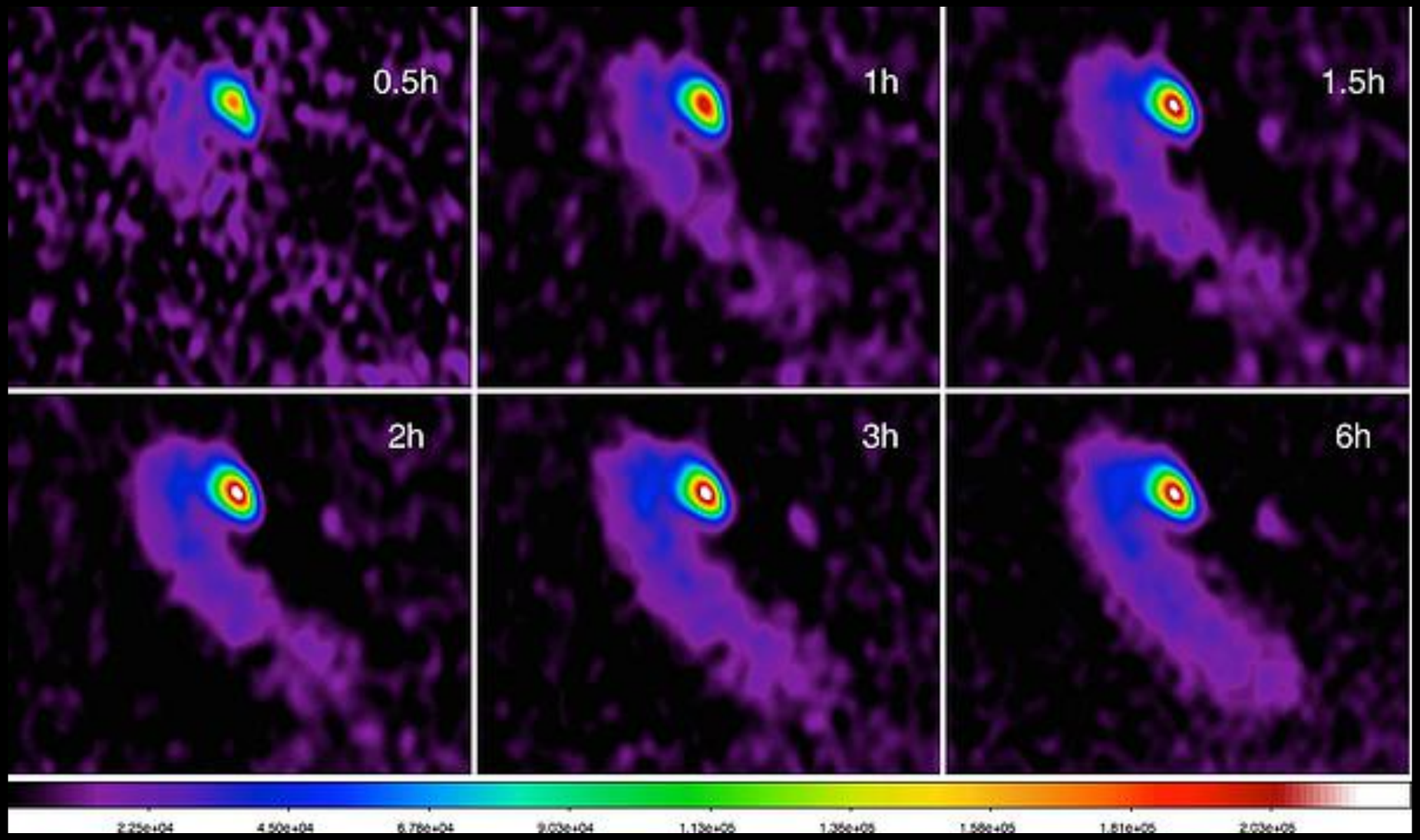
Dai
et al.
(2015)

100 AU

t

Molecular lines with ALMA

RW Aur



Dai et al. (2015)

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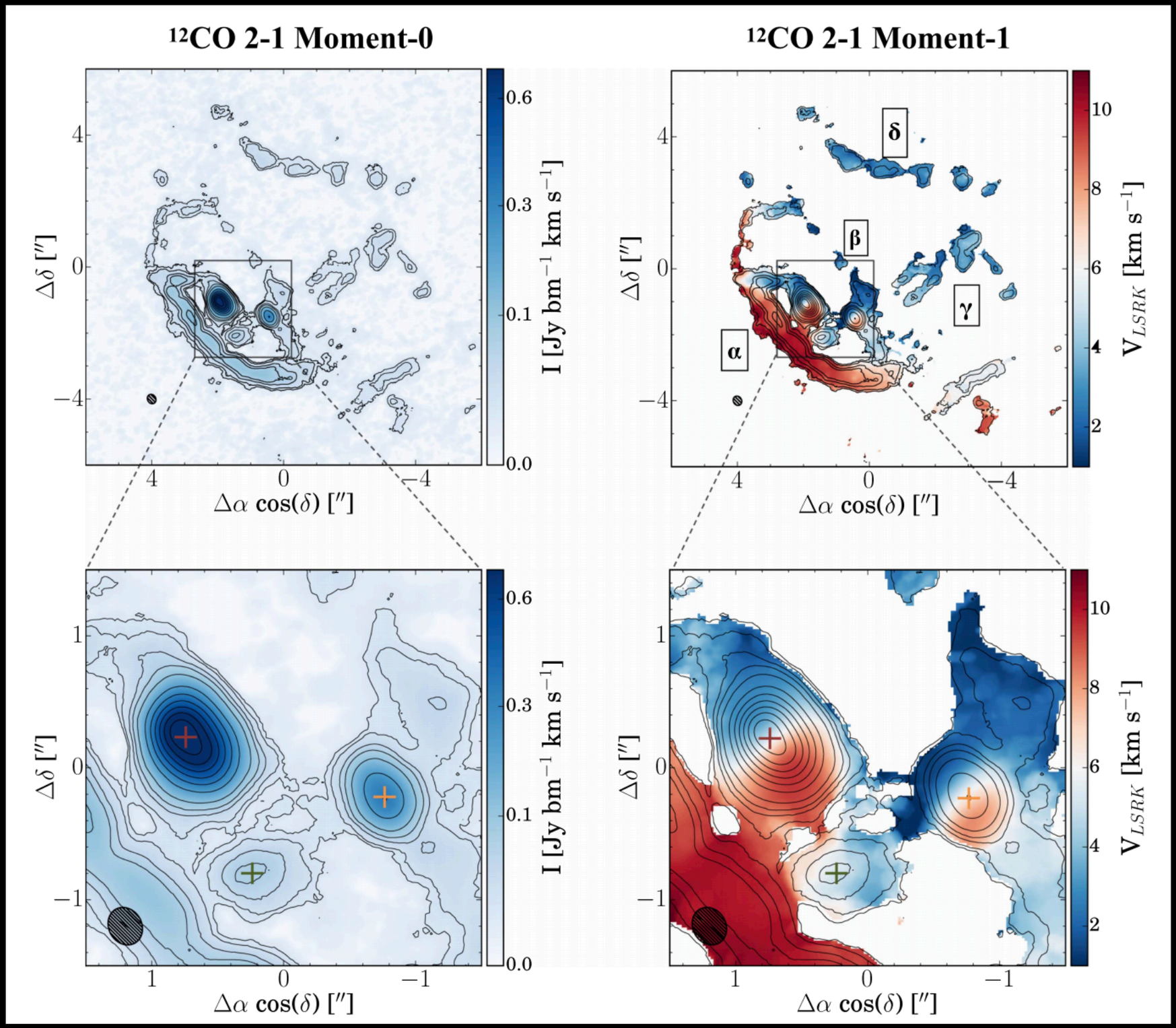
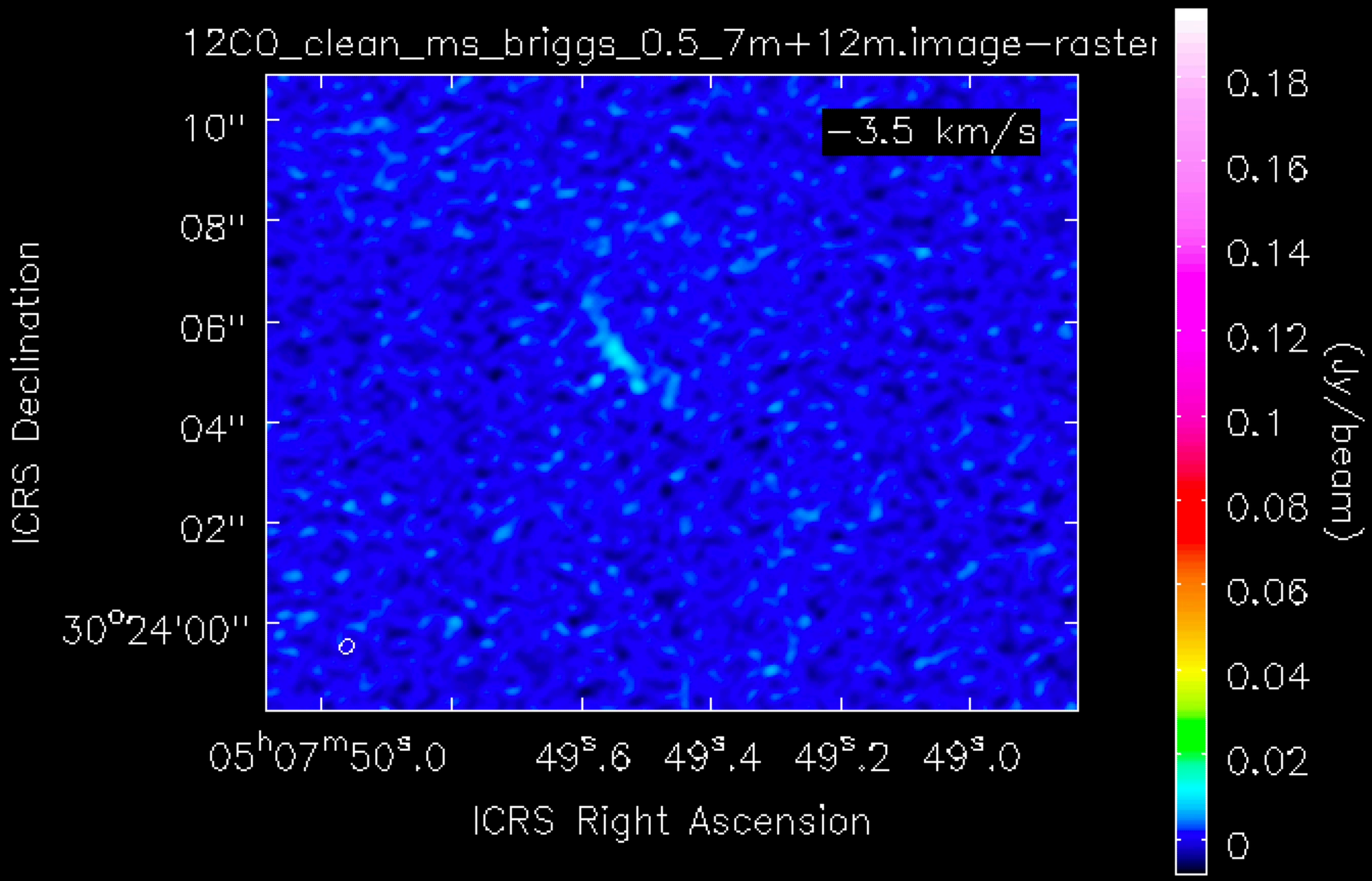
Molecular lines with ALMA



Rodriguez et al. (2018)

Molecular lines with ALMA



Rodriguez et al. (2018)

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WHAT IS LINE TRANSFER?

To solve the radiative transfer equation we need:

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

1) Emission coefficient

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

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

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

$$v_{\rm turb} = \sqrt{v_{\rm T}^2 + v_{\rm NT}^2},$$

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

WHAT IS LINE TRANSFER?

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2) Absorption coefficient

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

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

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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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NLTE

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$$\sum_{k>l} n_k A_{kl} + \sum_{k \neq l} n_k (B_{kl} J_\nu + C_{kl})$$

Solve detailed balance

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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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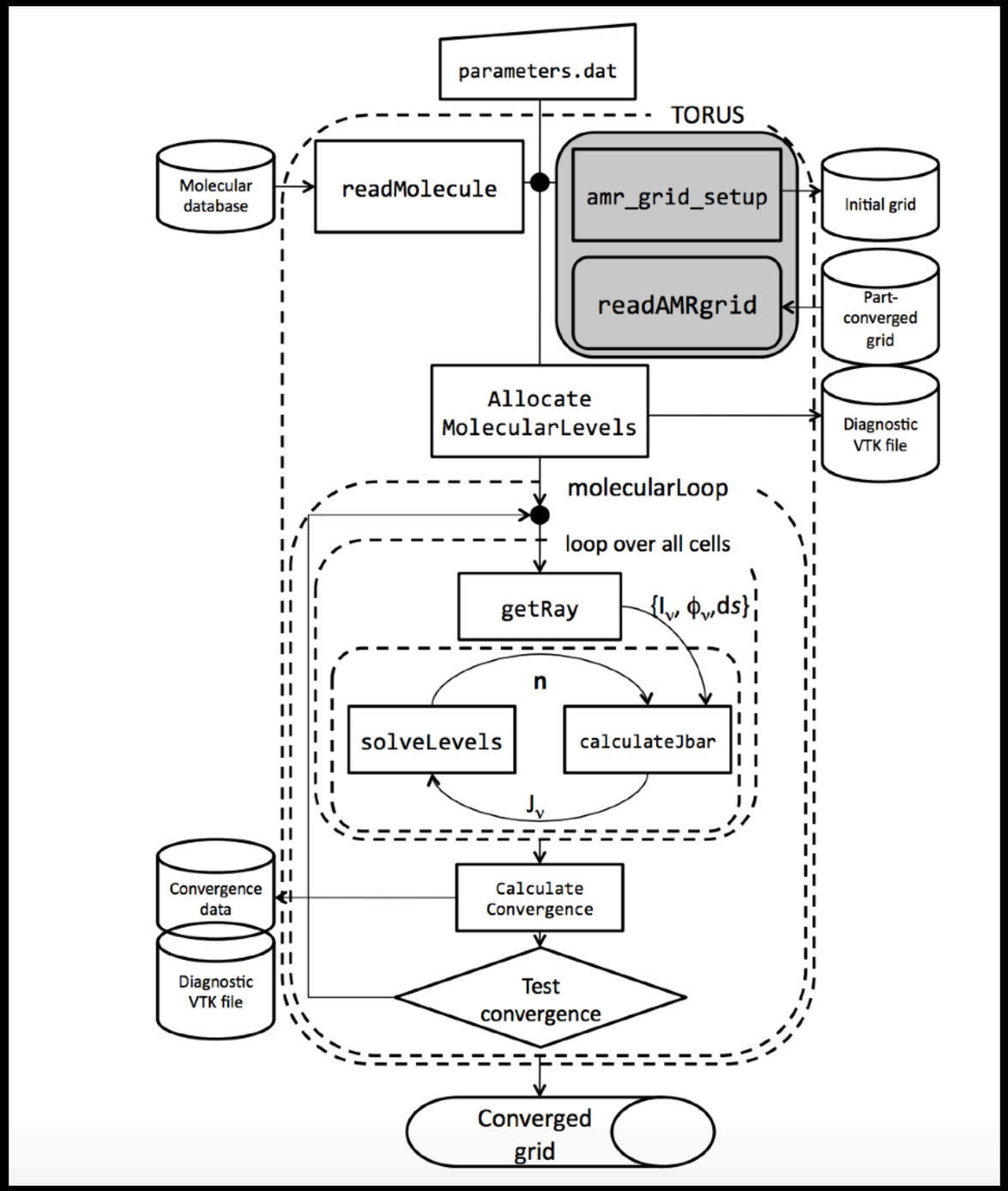
Molecular line transfer with TORUS



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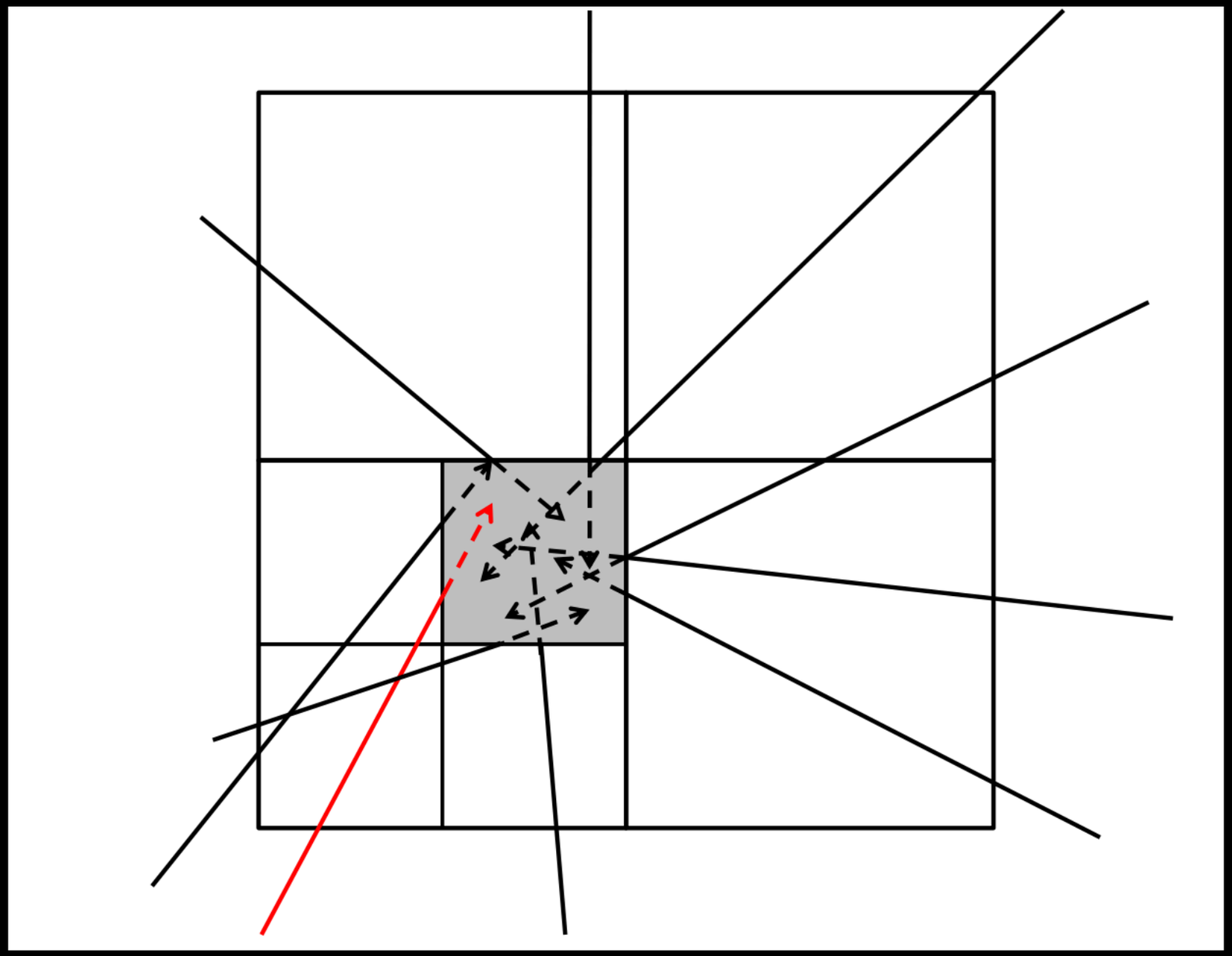
Molecular line transfer with TORUS



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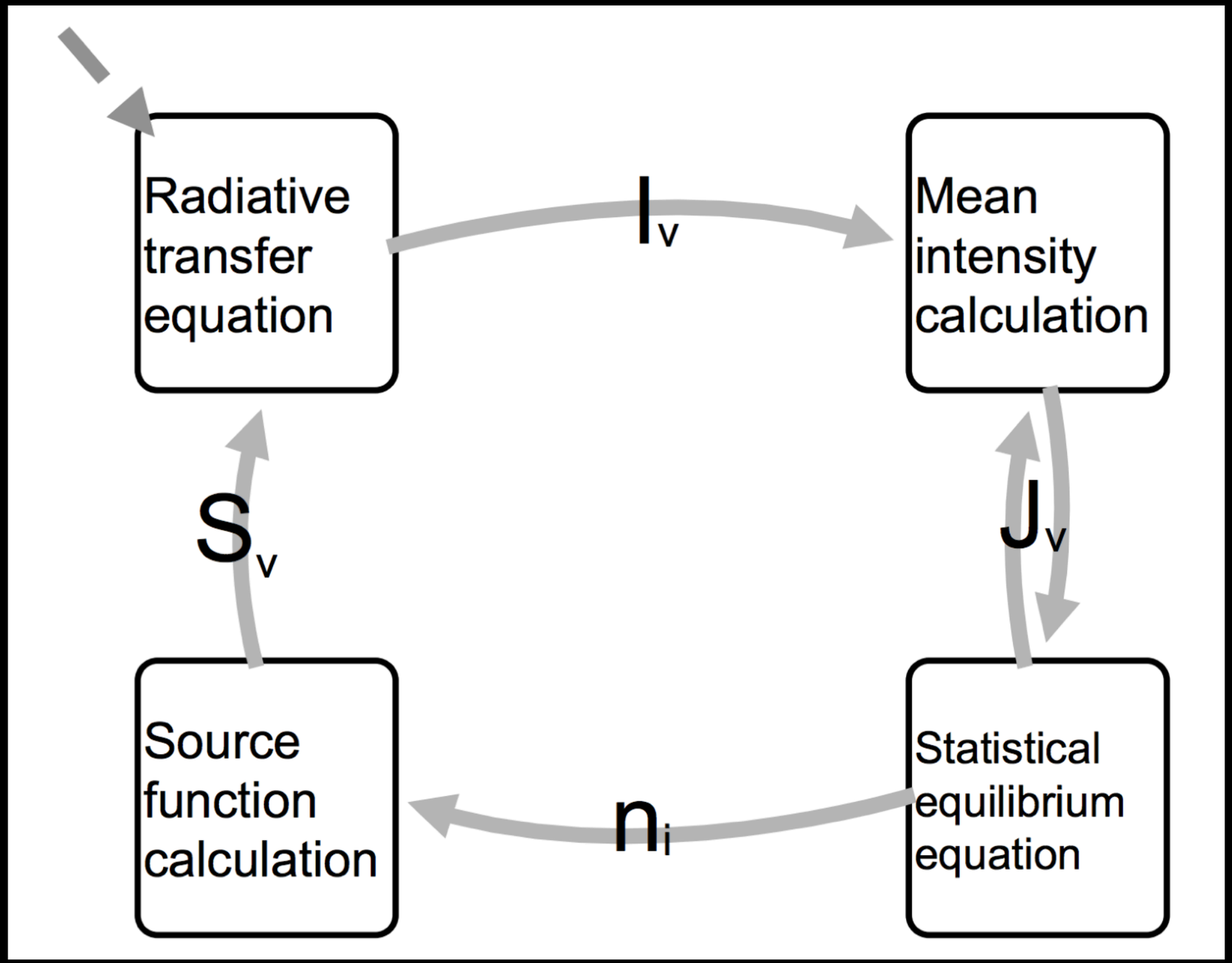
Molecular line transfer with TORUS



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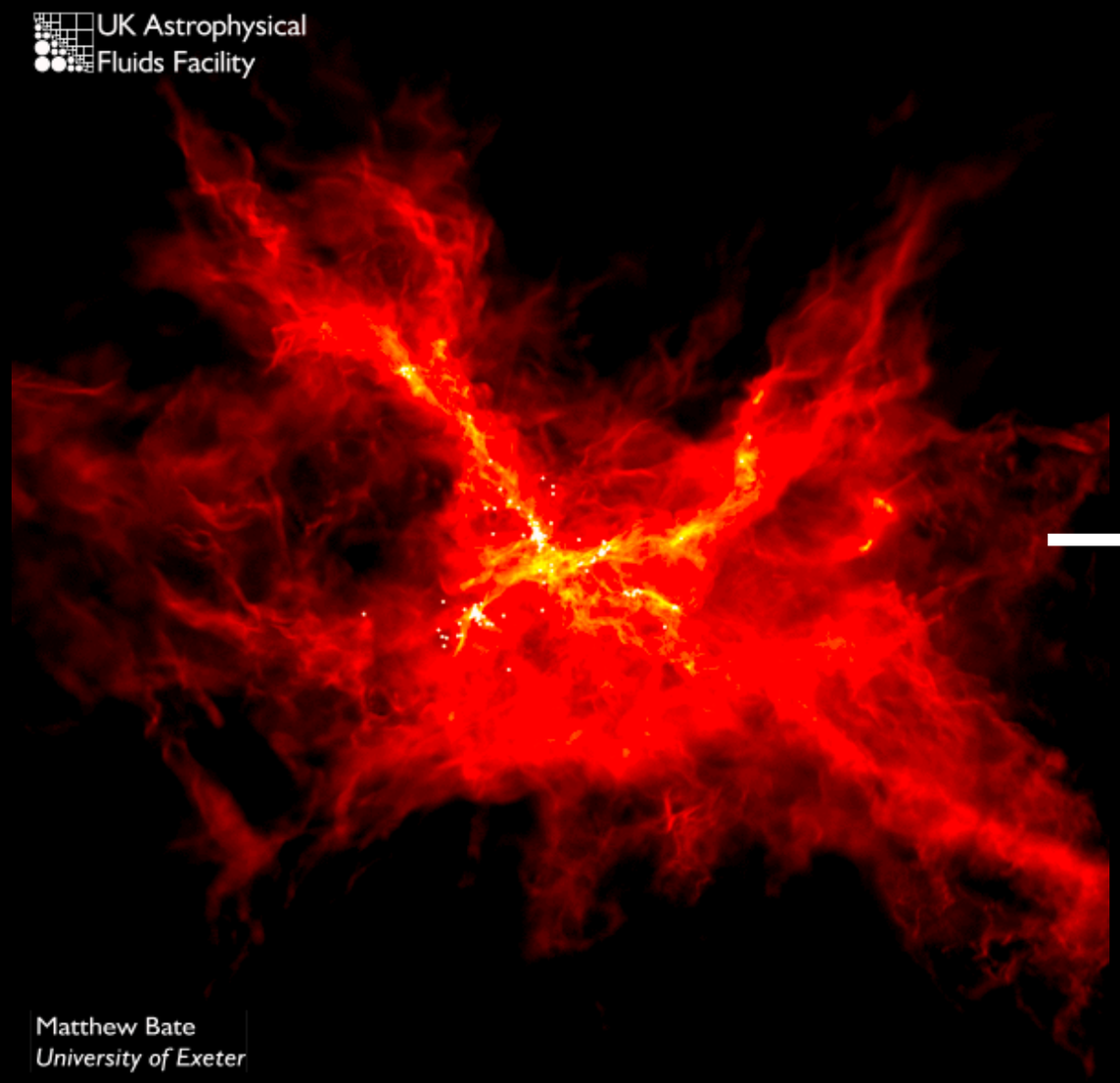
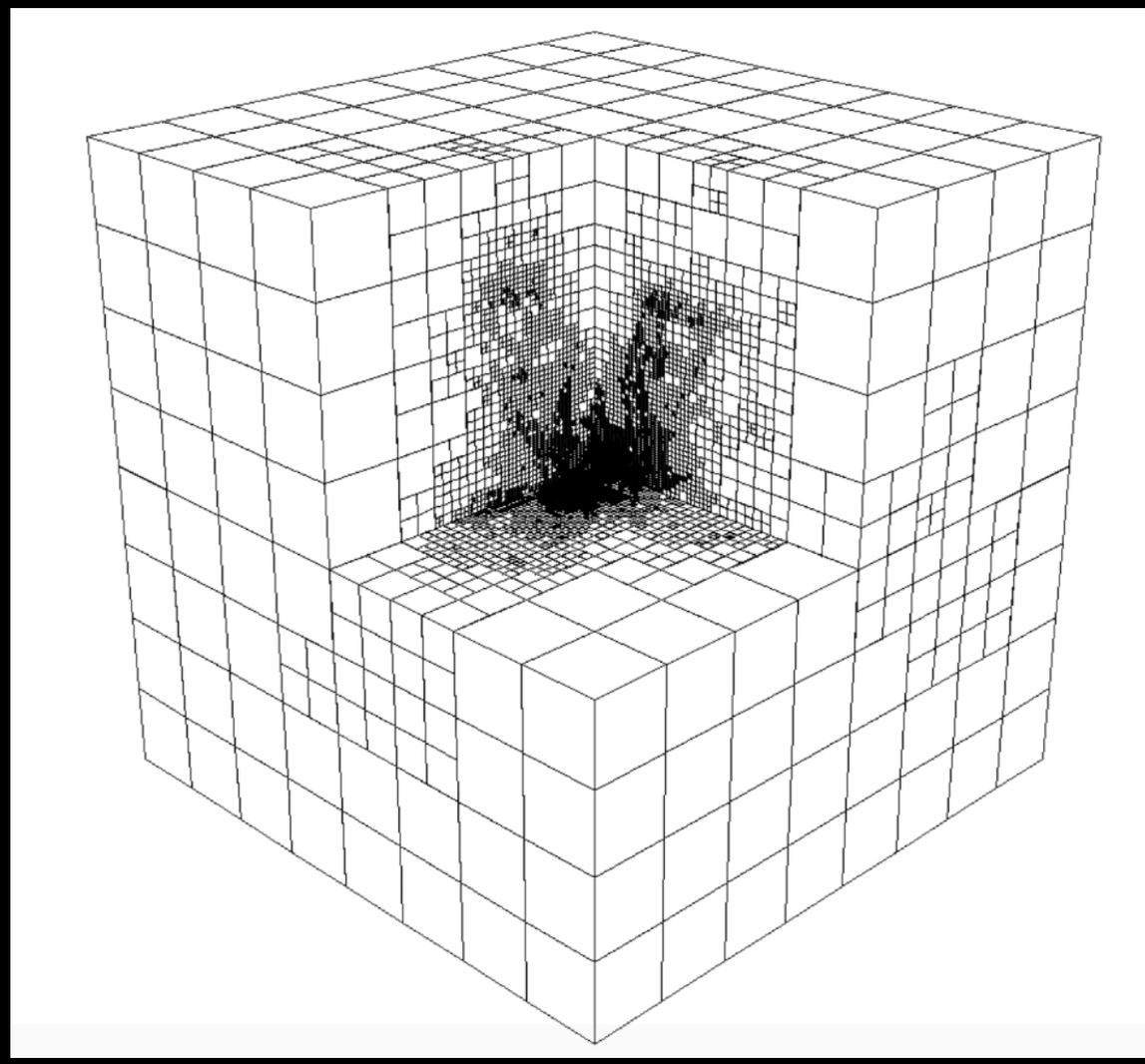
TORUS Example





Bate 2009

Rundle et al. (2010)

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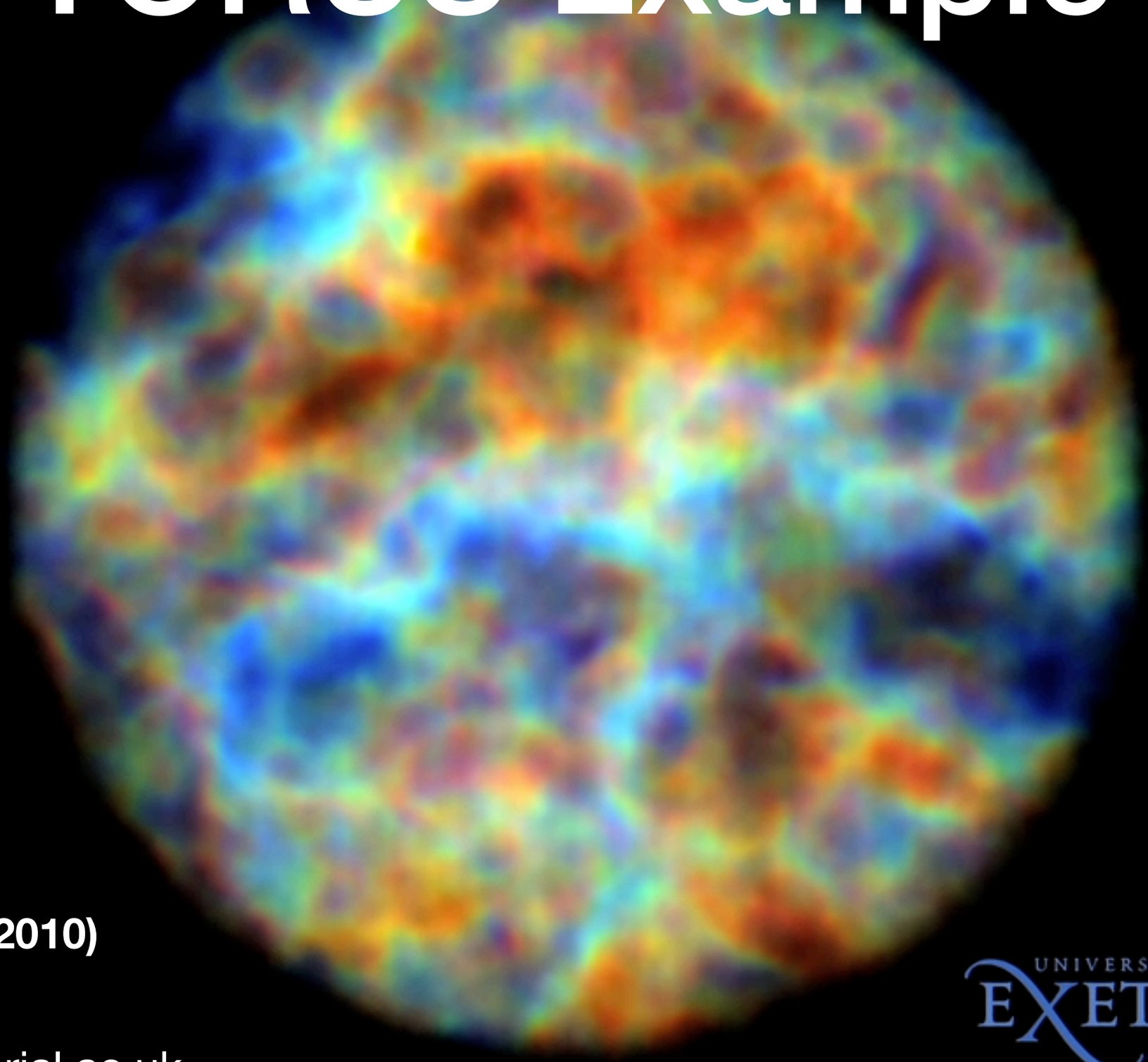
TORUS Example



Rundle et al. (2010)

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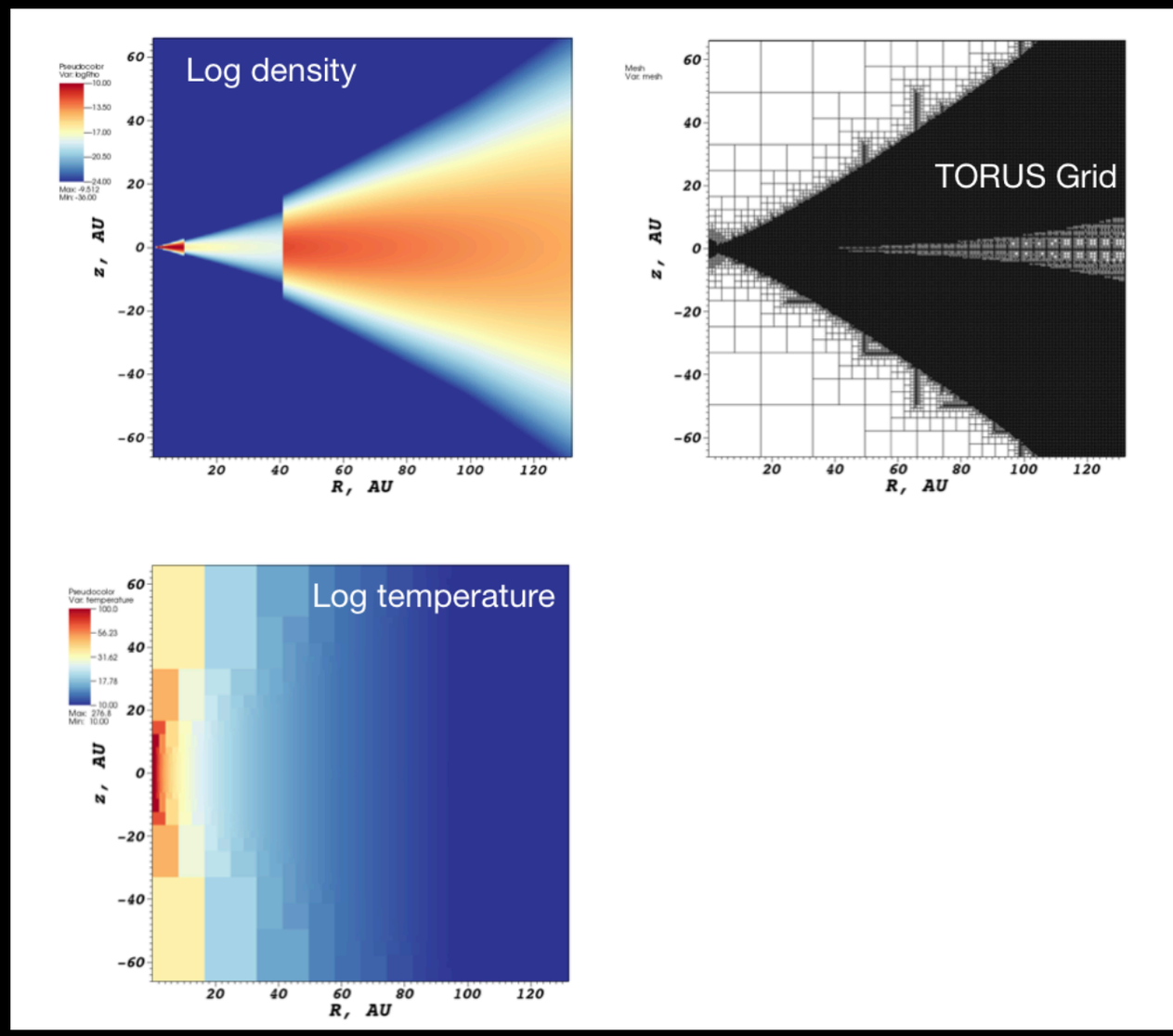
TORUS Example

A parametric disc



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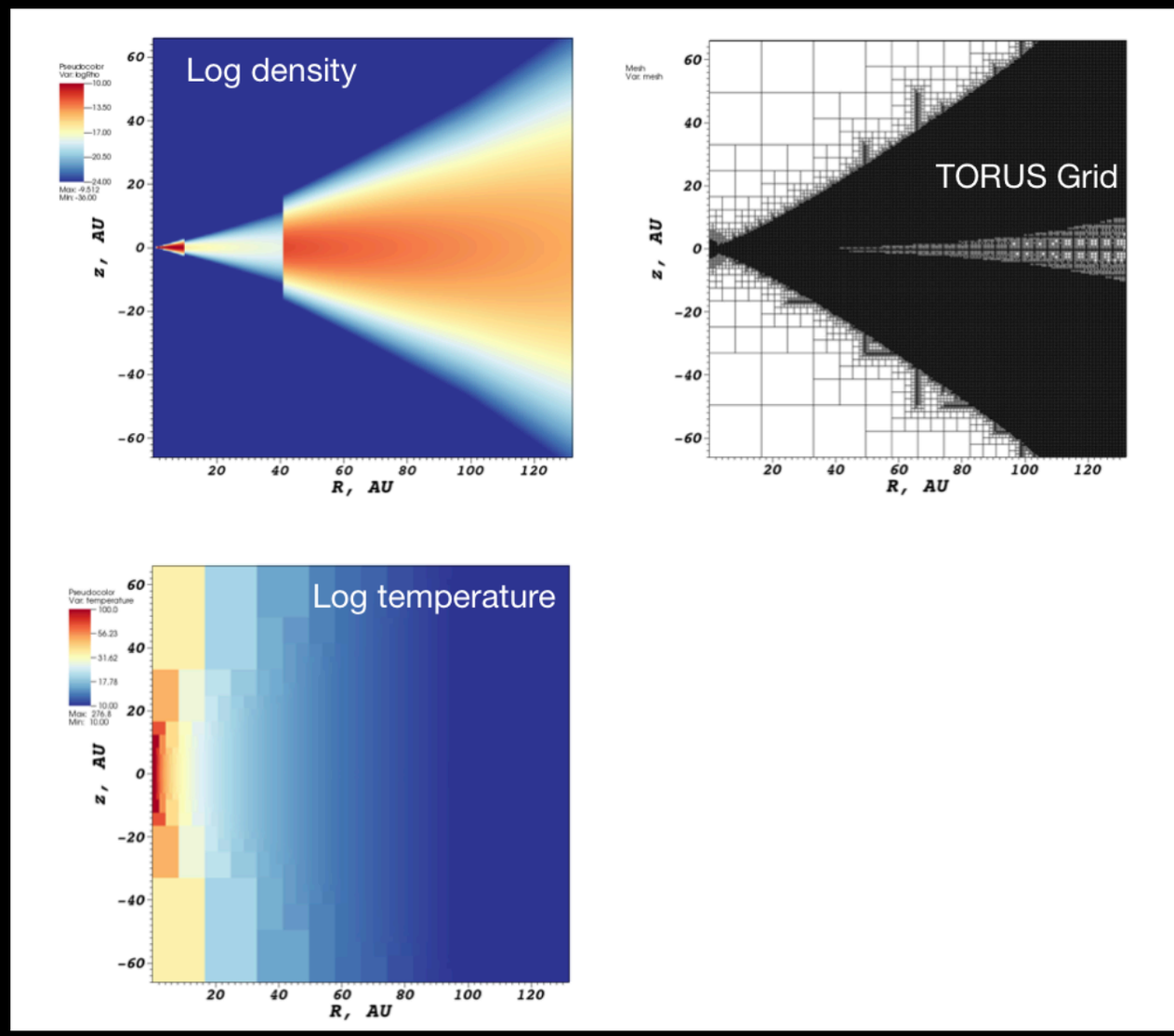
TORUS Example

A parametric disc

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

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

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



Assume LTE, consent abundance

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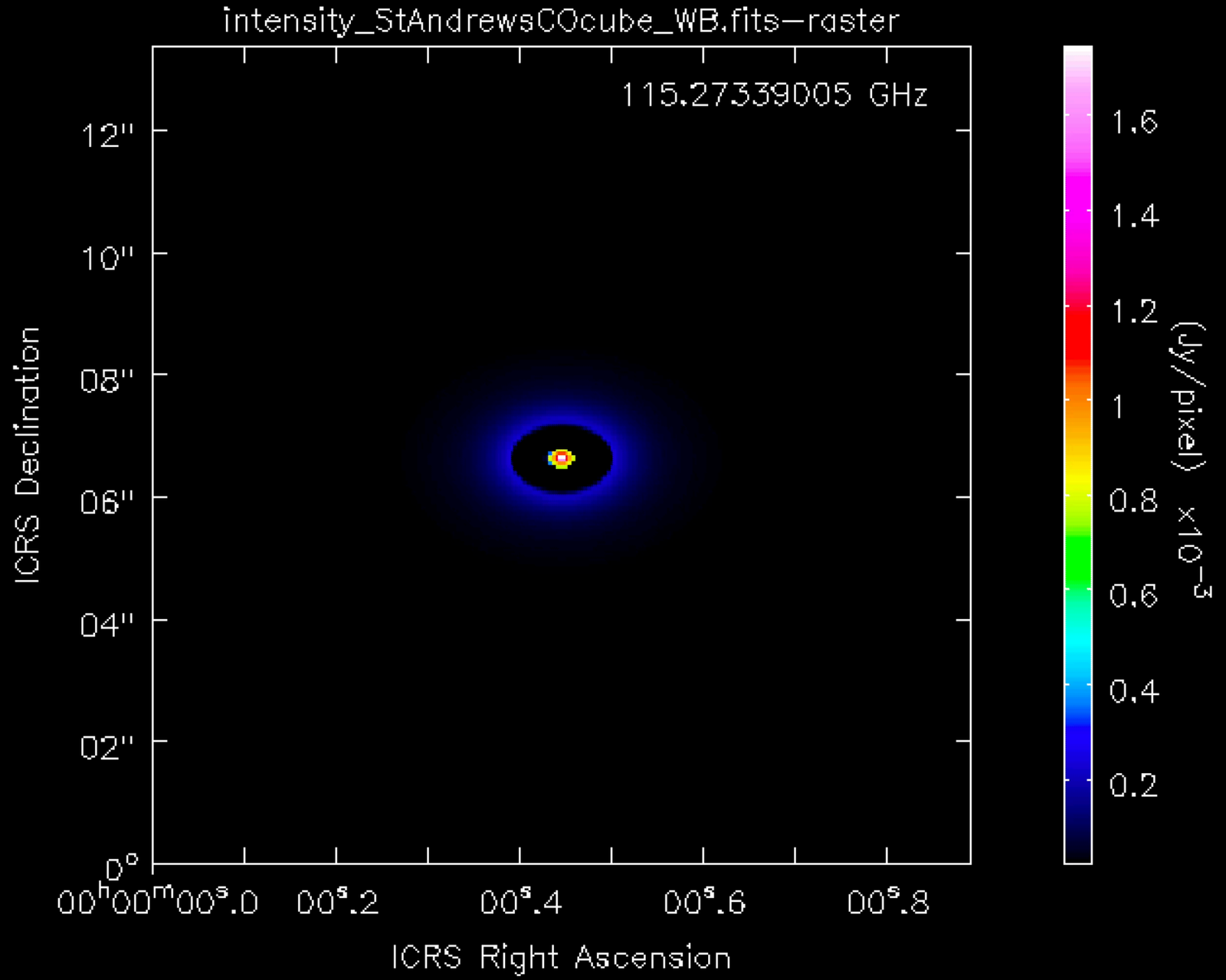
TORUS Example

Raw CO cube

Inclination of 45 degrees



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Postprocessing with CASA

Postprocessing with CASA

Simulate ALMA (VLA, SMA, etc.) observations

Clean, subtract continuum and other image processing tools

Can produce moment maps, PV diagrams etc.

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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
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	-	-	-

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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
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C43-5	θ_{res} (arcsec)	0.545	0.363	0.295	0.237	0.158	0.118	0.0838	0.0626
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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	-	-	-

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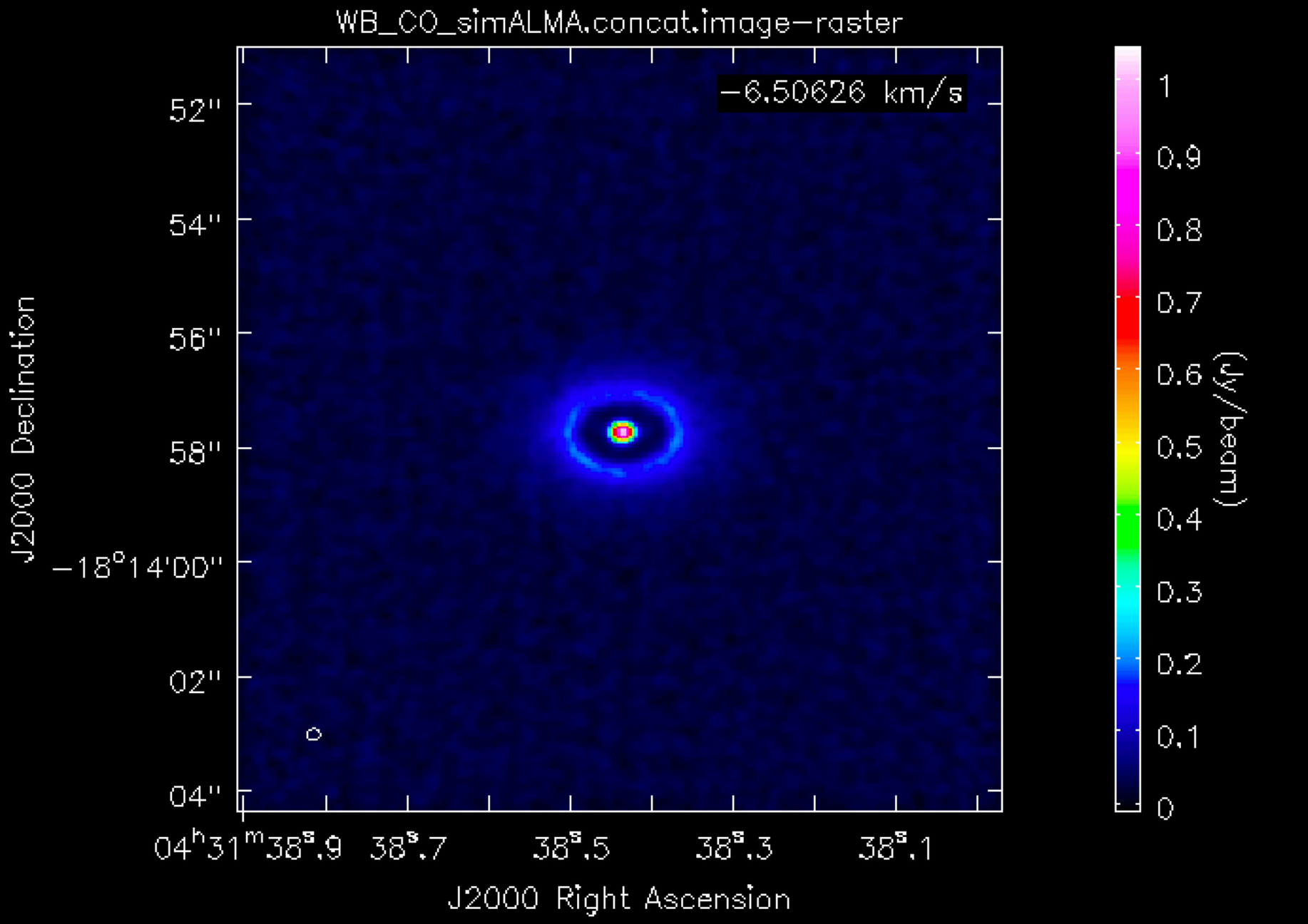
TORUS Example

Processed CO cube



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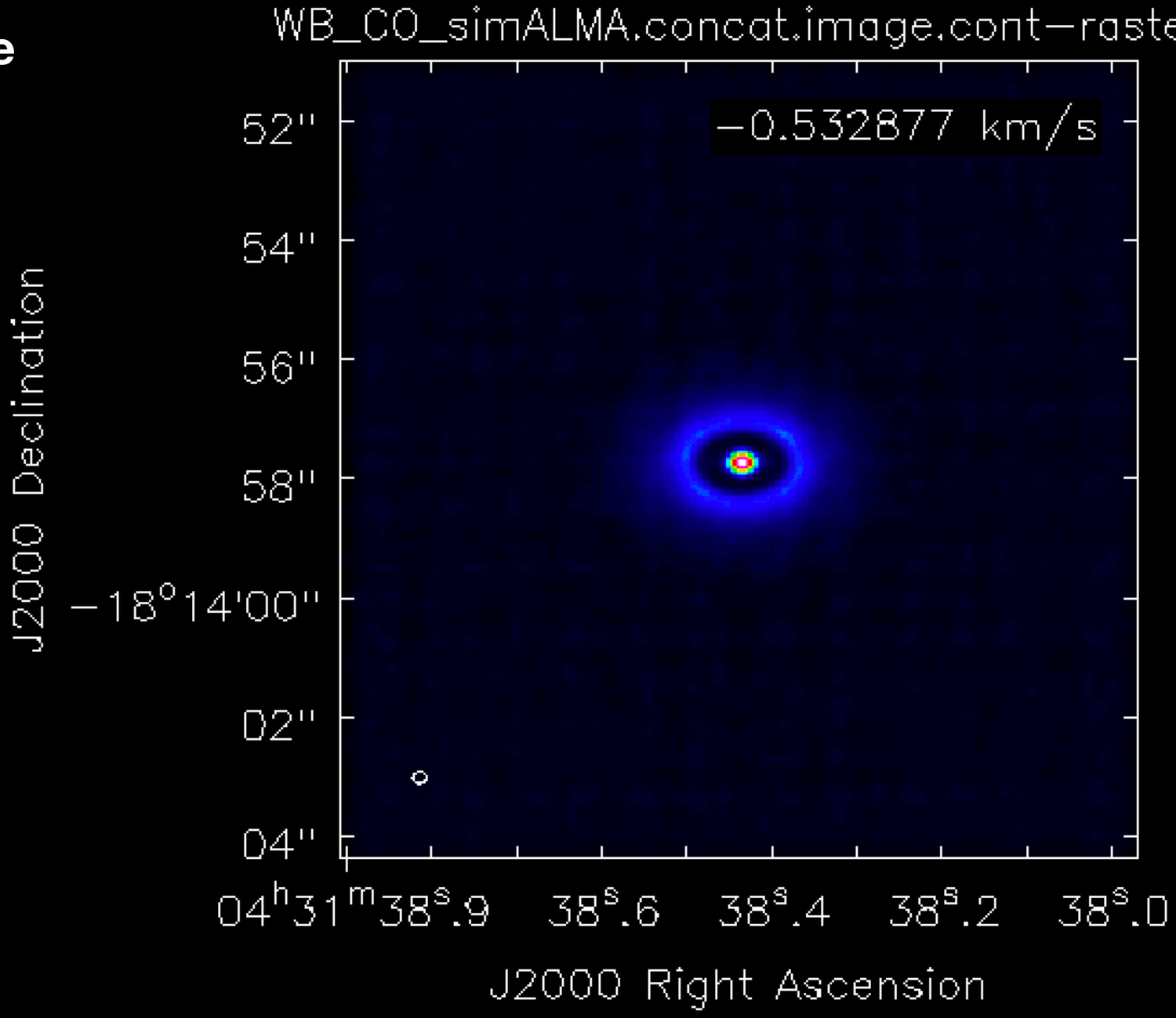
TORUS Example

Processed CO cube

Continuum only



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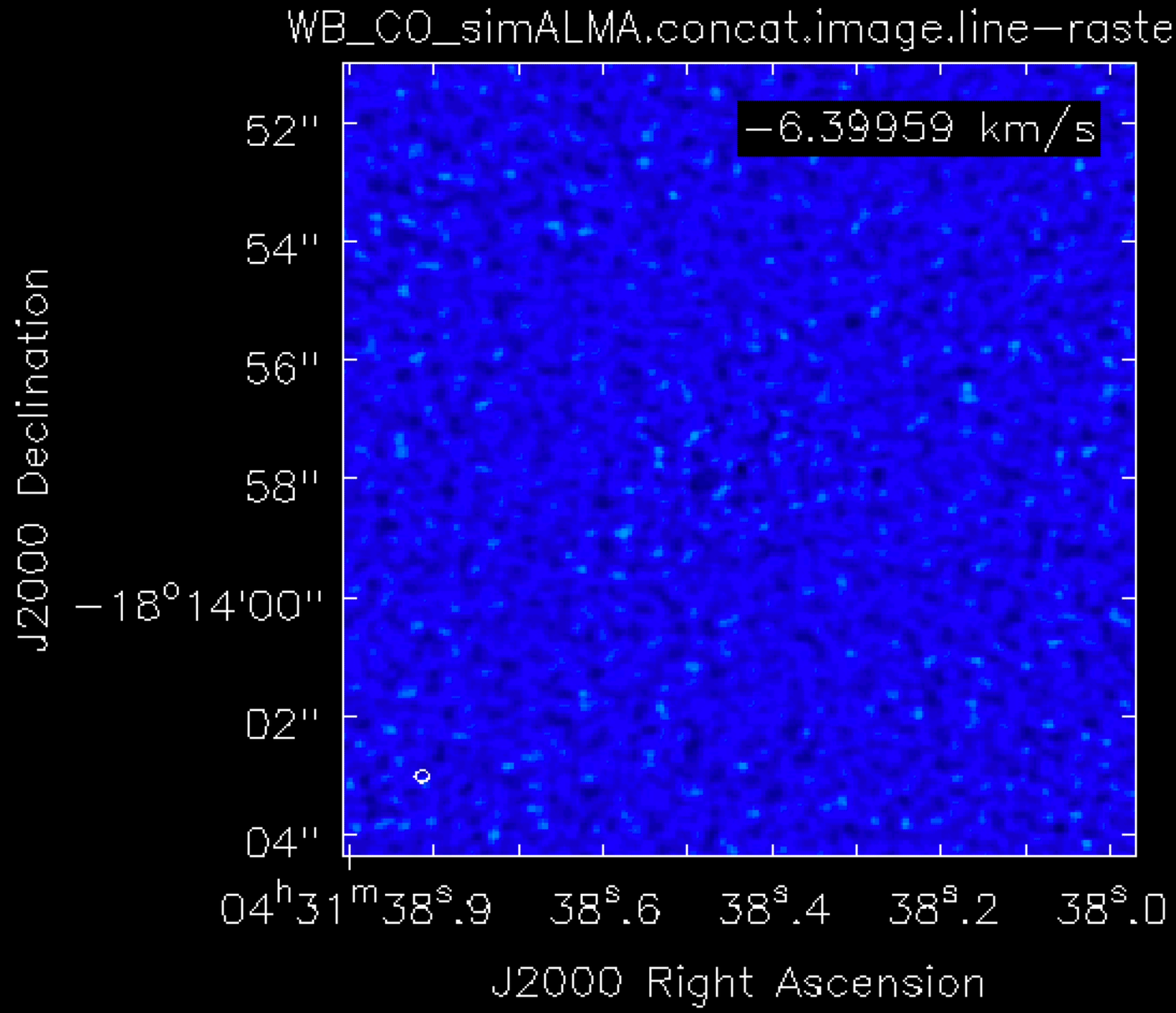
TORUS Example

Processed CO cube

Line only



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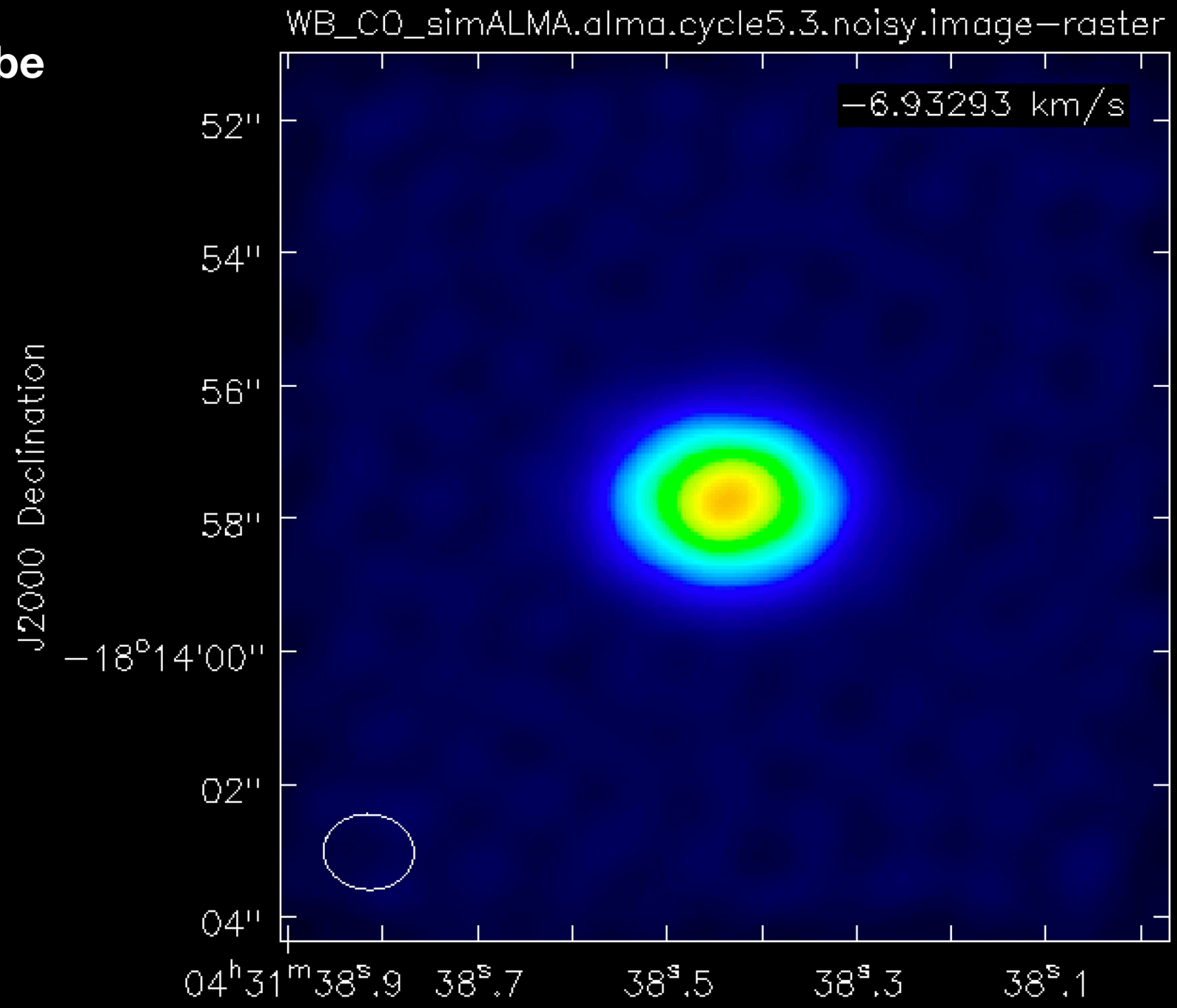
TORUS Example

Processed CO cube

Config 5.3



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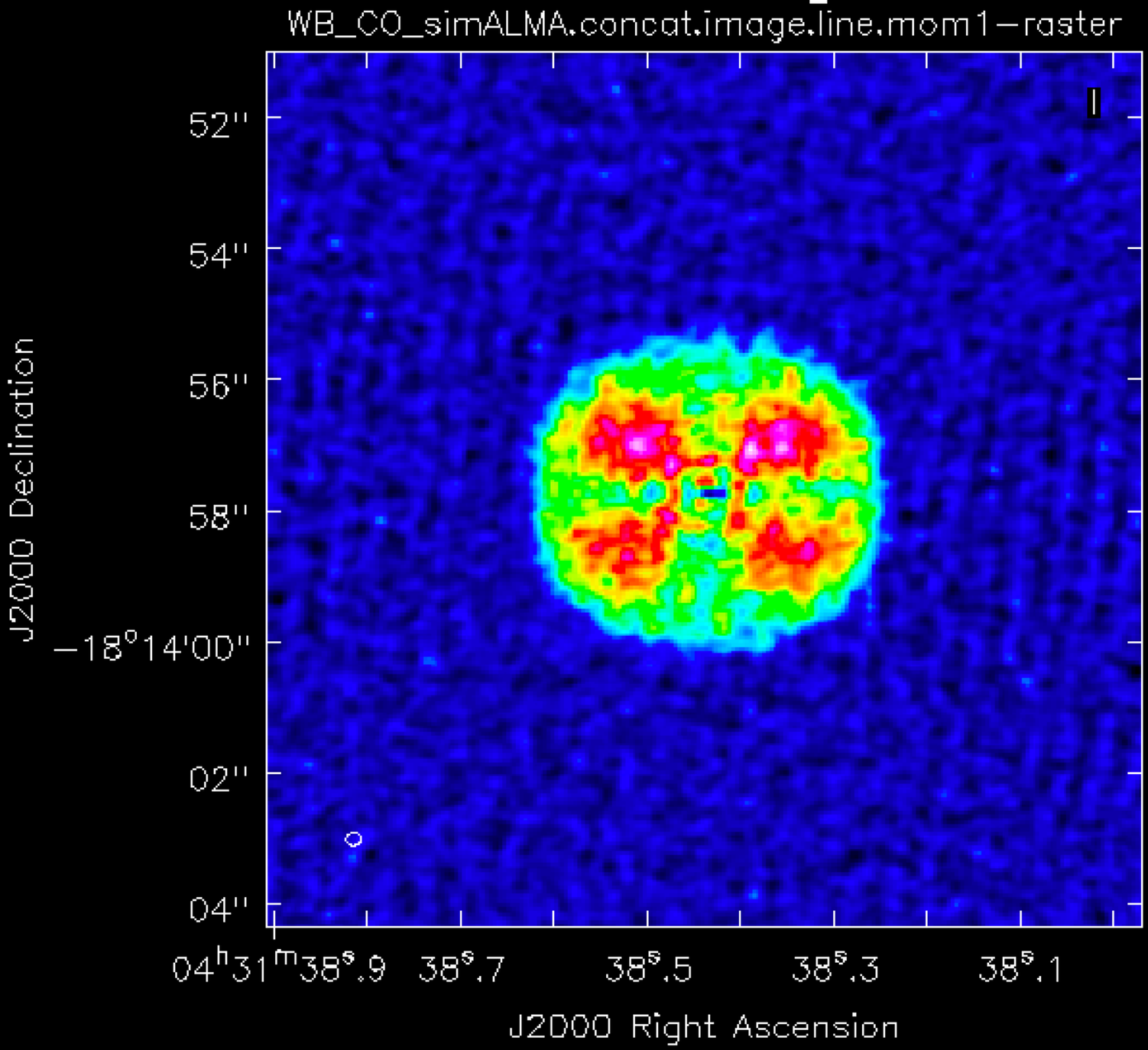
TORUS Example

Moment 0 map



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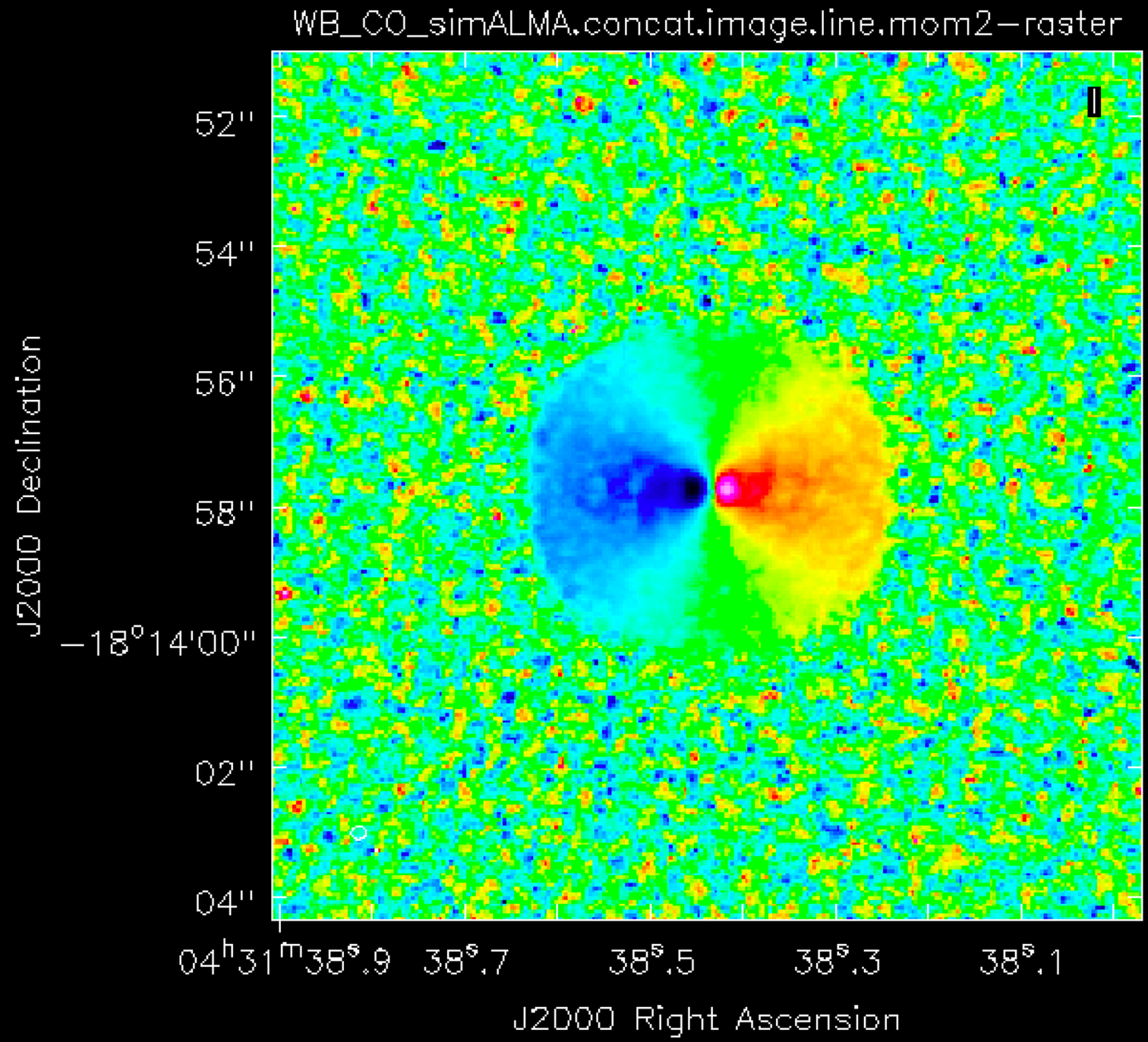
TORUS Example

Moment 1 map



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TORUS Example

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

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Further TORUS information

The TORUS radiation transfer code

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

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Further TORUS information

The TORUS radiation transfer code

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

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Further general information

Synthetic observations of star formation and the interstellar medium

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

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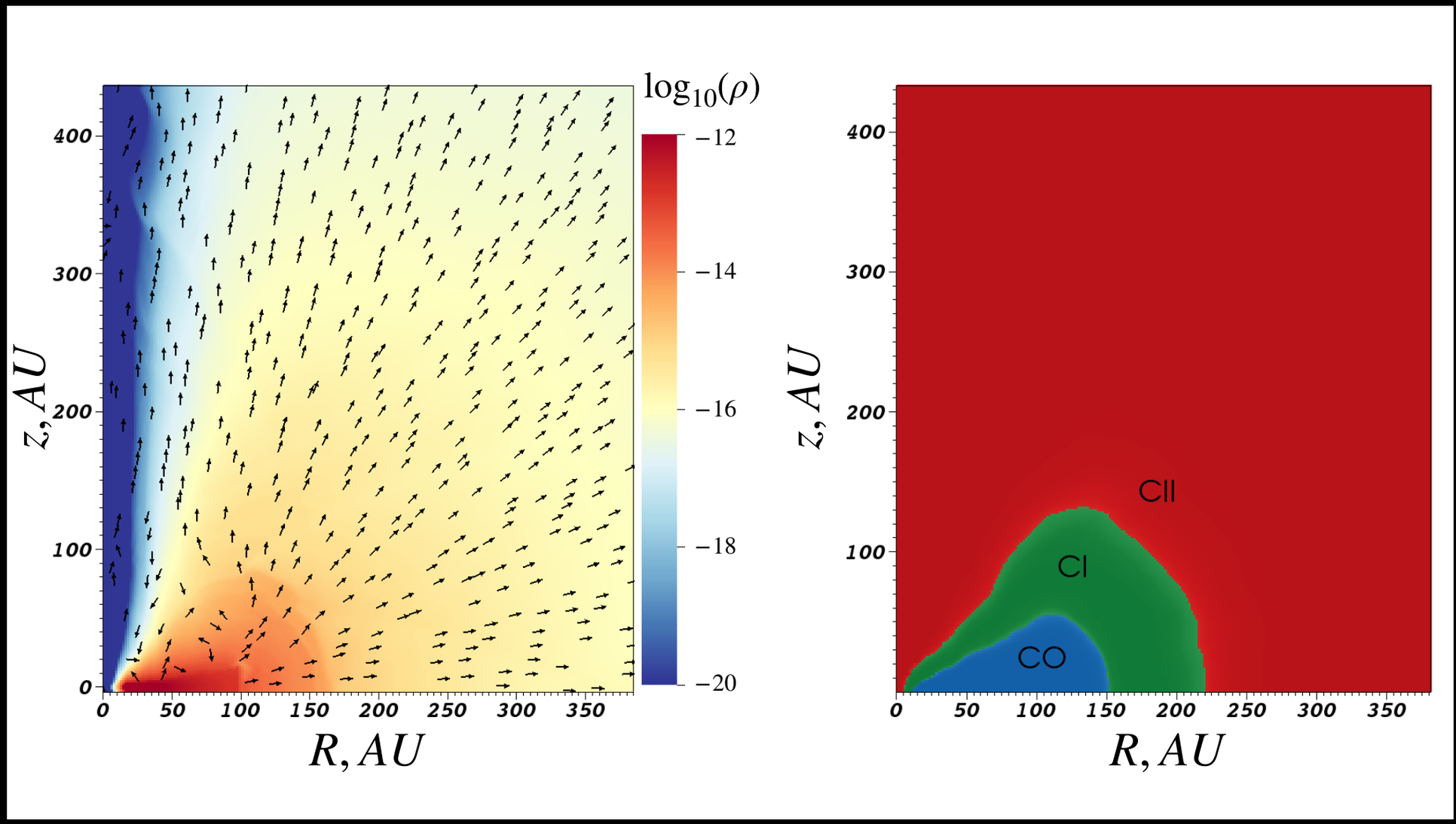
Some examples



Some examples

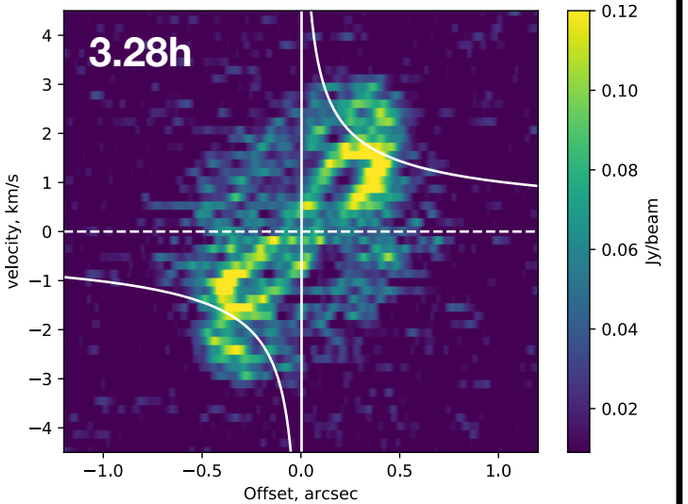
Sensitivity: 20mJy

Spectral resolution: 0.172km/s

$0.62\,M_{\odot}$**star**

$6\,M_{jup}$ **disc**

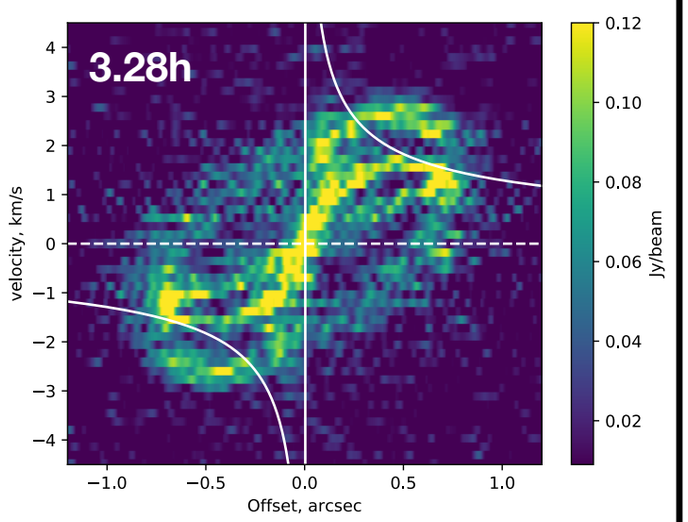
$1174\,G_0$



$1\,M_{\odot}$**star**

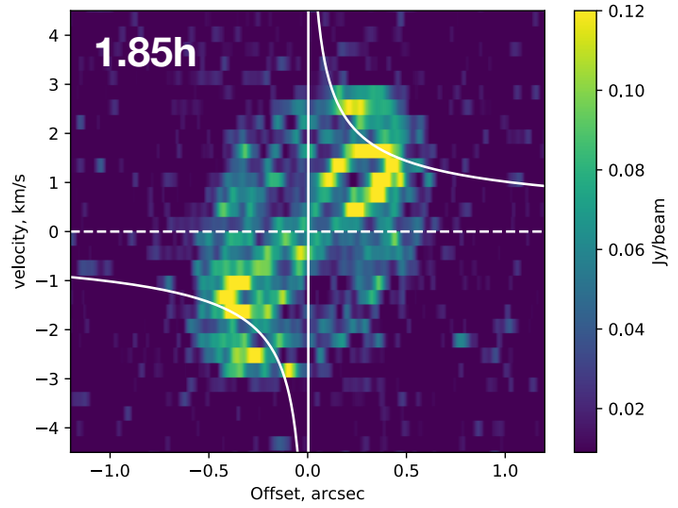
$20\,M_{jup}$ **disc**

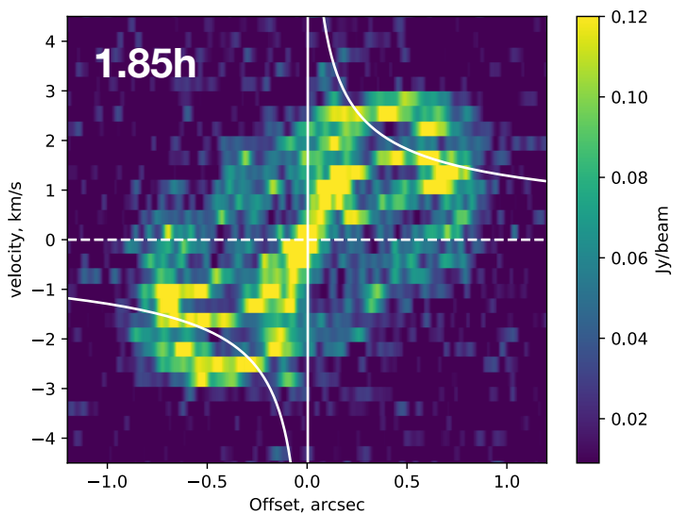
$1000\,G_0$



Sensitivity: 20mJy

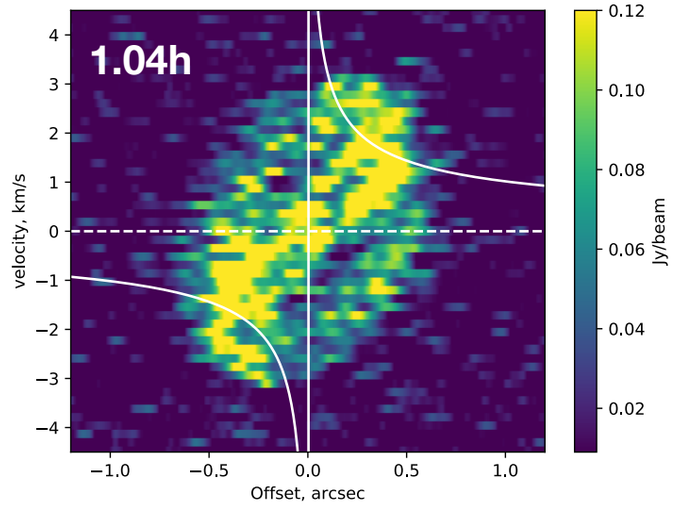
Spectral resolution: 0.344km/s

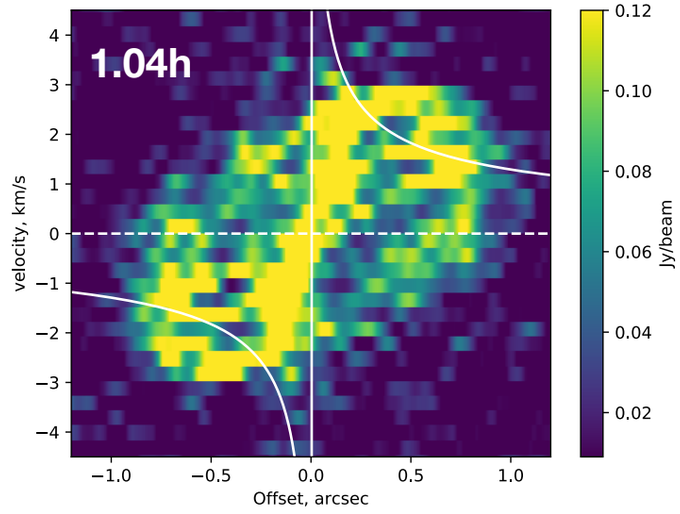




Sensitivity: 50mJy

Spectral resolution: 0.344km/s





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