# Synthetic ALMA observations of large-scale convection in 3D simulations of Red Supergiants


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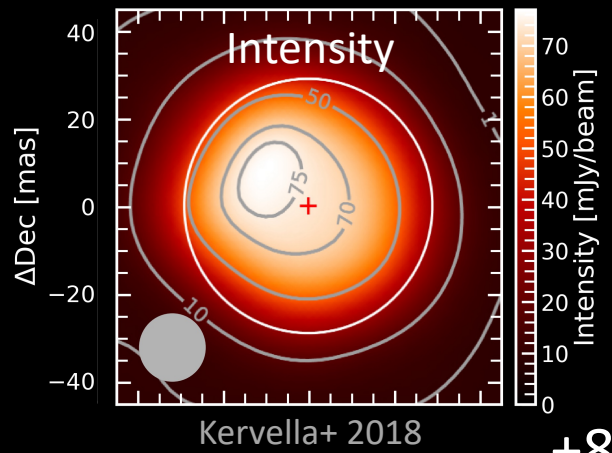
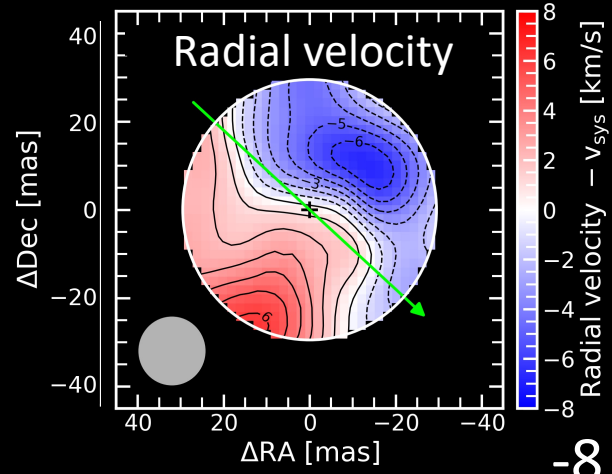
Radio Stars, MIT Haystack Observatory, Apr. 17, 2024

# Is Betelgeuse really rotating?

## ALMA observation (Betelgeuse)



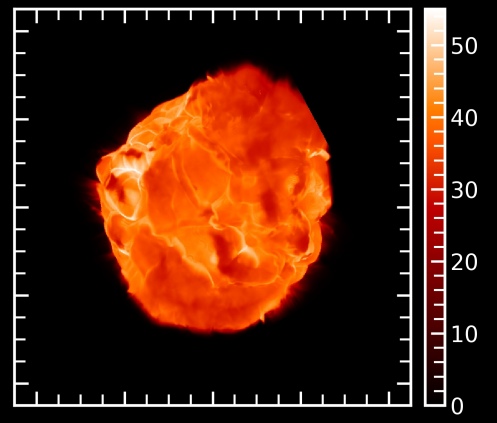

+8 km/s




-8 km/s

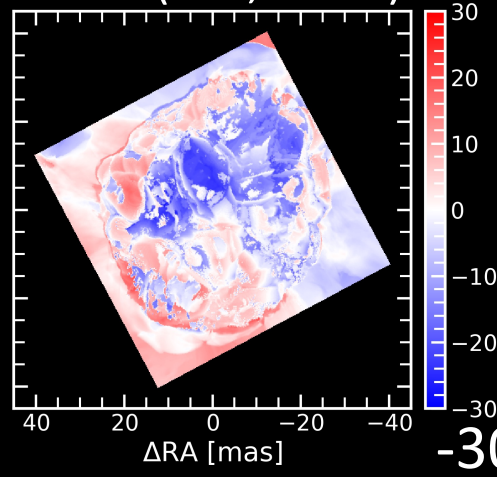
## CO5BOLD 3D simulation **(non-rotating!)**

Simulation JZM+2024 ApJL



+30 km/s

$^{28}$SiO (v=2, J=8-7)

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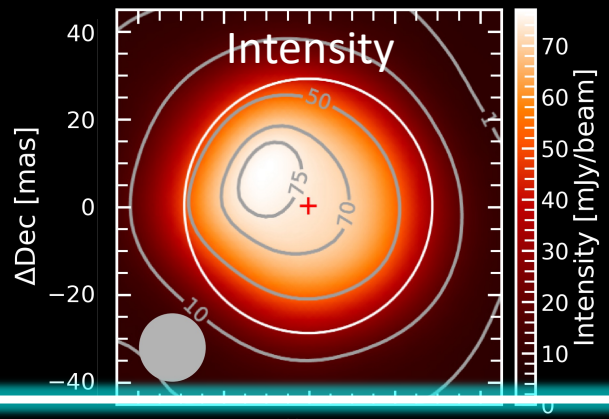
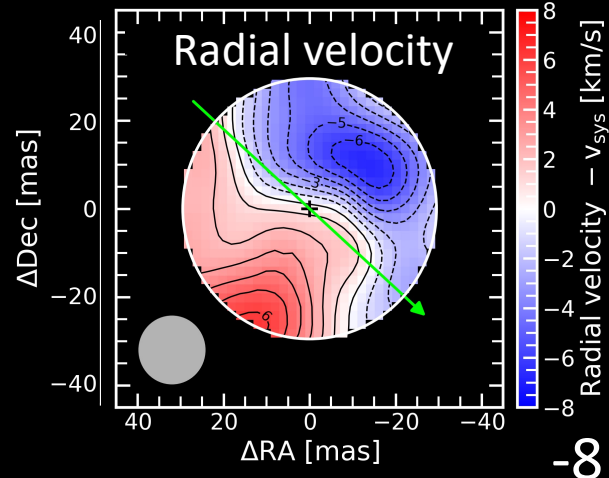
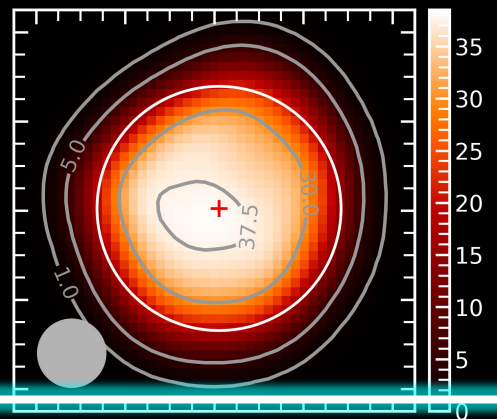



Kervella+ 2018

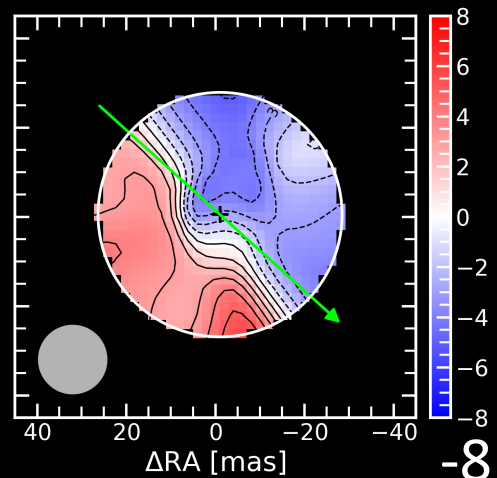



## CO5BOLD 3D simulation **(non-rotating!)**

Mock observation

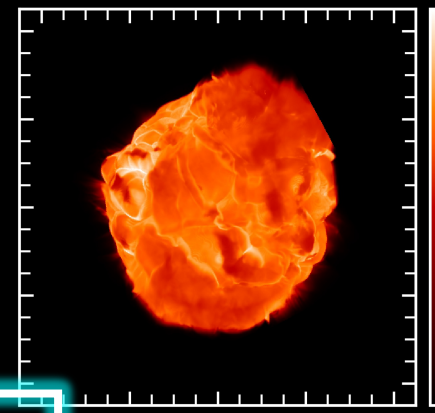


+8 km/s




-8 km/s

Simulation JZM+2024 ApJL



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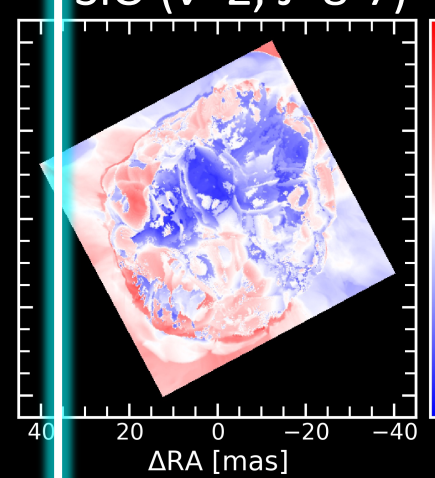



-30 km/s

# Rotation or under-resolved convection?

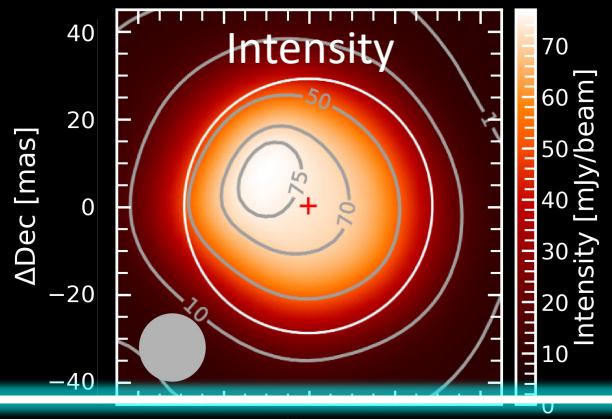
ALMA observation (Betelgeuse)

CO5BOLD 3D simulation **(non-rotating!)**

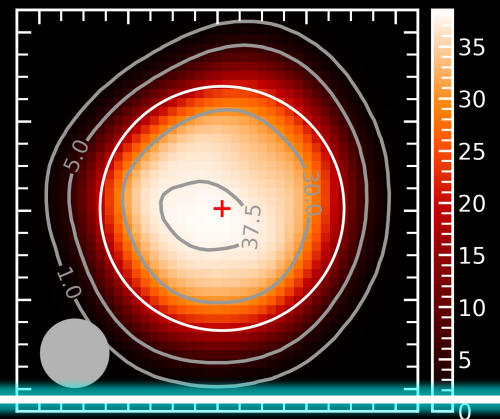
Mock observation

Simulation

JZM+2024 ApJL

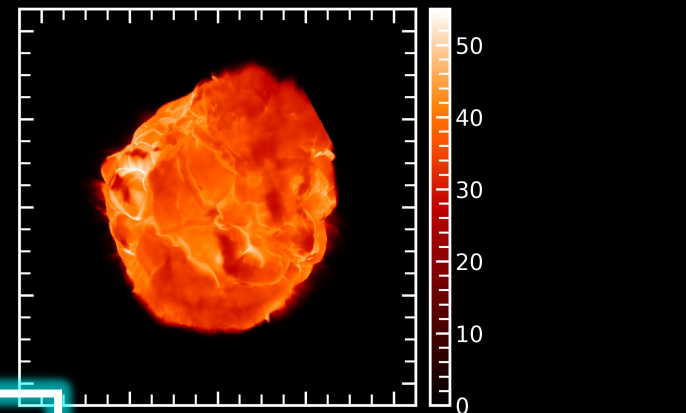



Kervella+ 2018



+8 km/s

+8 km/s



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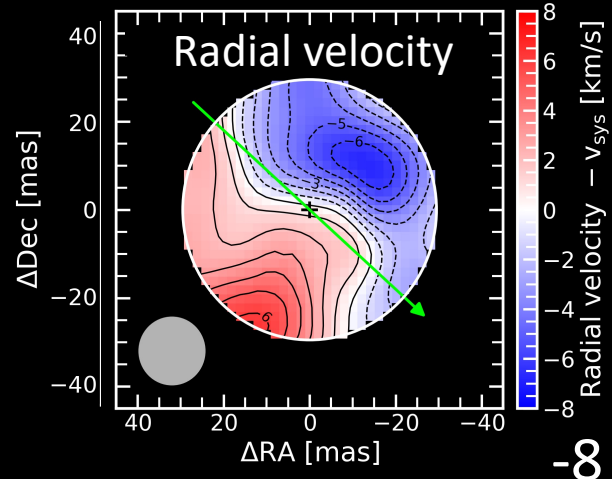
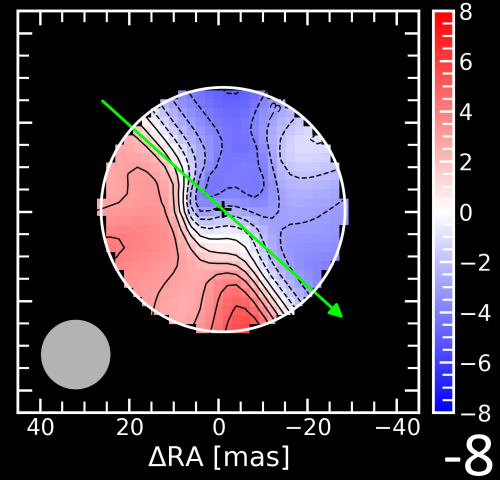
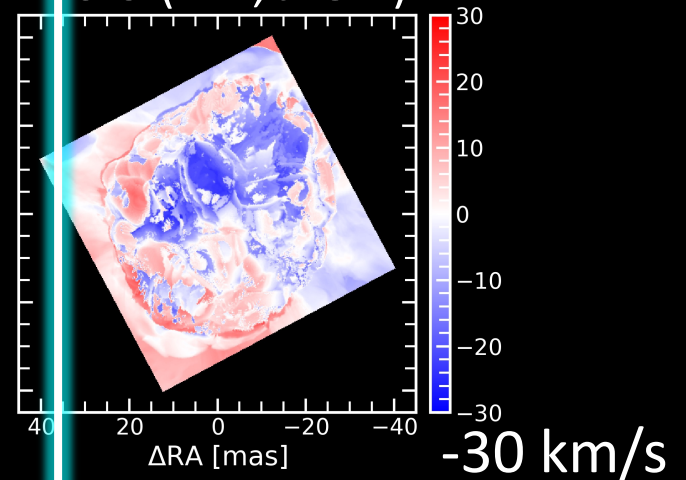



-8 km/s




-8 km/s




-30 km/s

# Method: Synthetic ALMA observation

3D radiation hydro

CO5BOLD

Freytag+2012; Chiavassa+2011

T, P

Equilibrium chemistry

FASTCHEM2

Stock+2018,2022

n(SiO)

n(e-)

n(H)

Radiative transfer

JZM+2024 ApJL

$I_\nu$

Beam convolution

T, v

Theorist

Continuum subtraction

Line profile map

Gaussian fit

RV map

Rotating disk fit

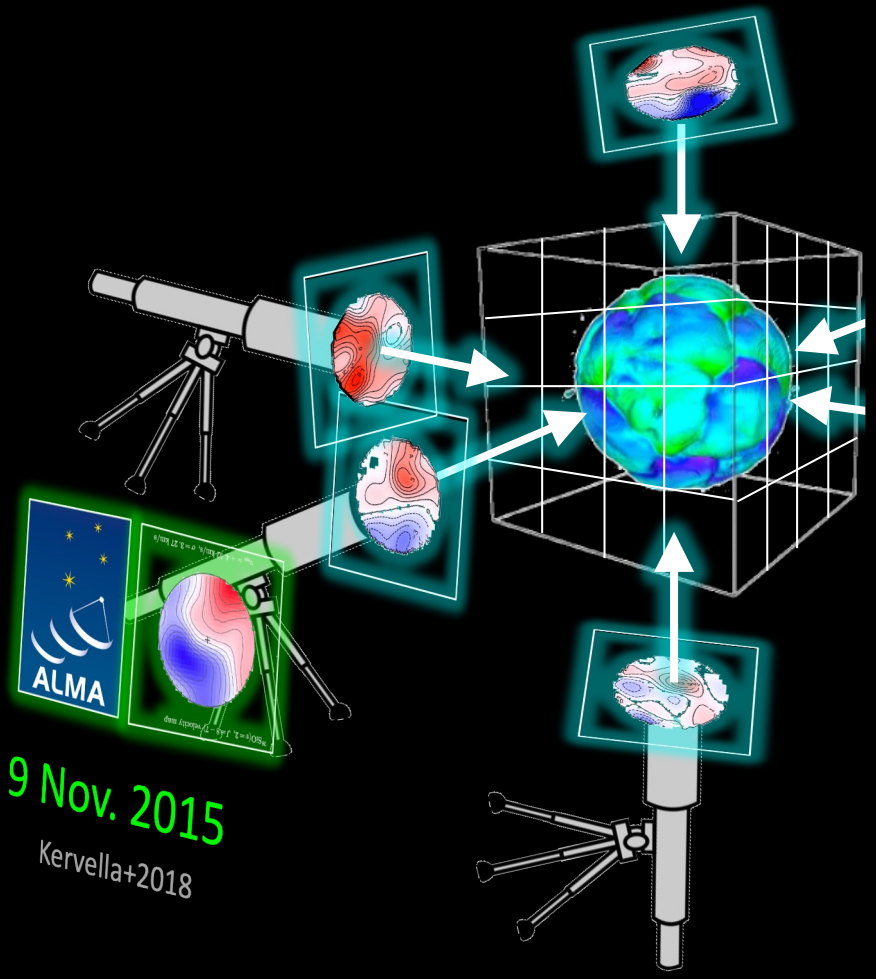
v sini

Kervella+2018

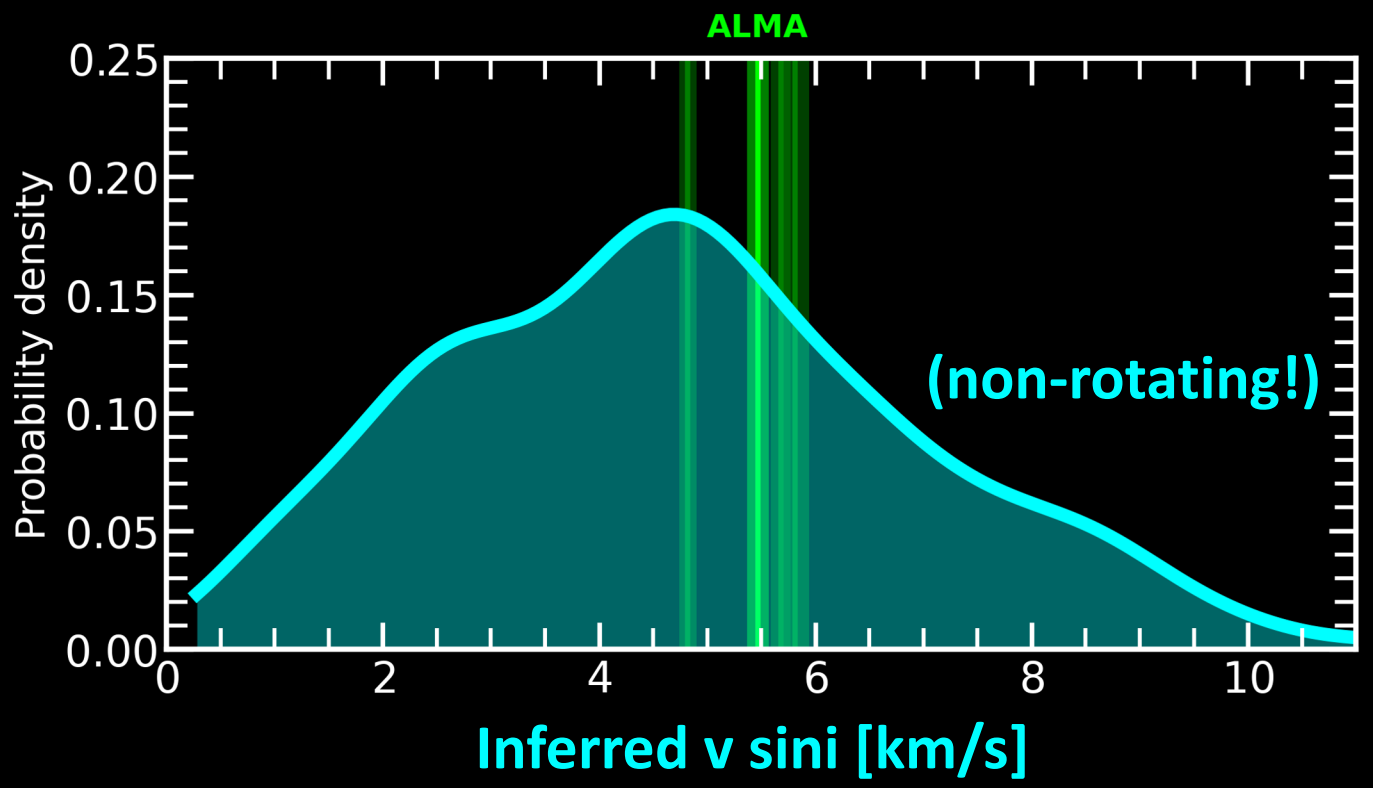
Observer

# Single-epoch Obs. with ~~ALMA~~ Virtual telescope

Non-rotating RSG appearing to spin at km/s level?



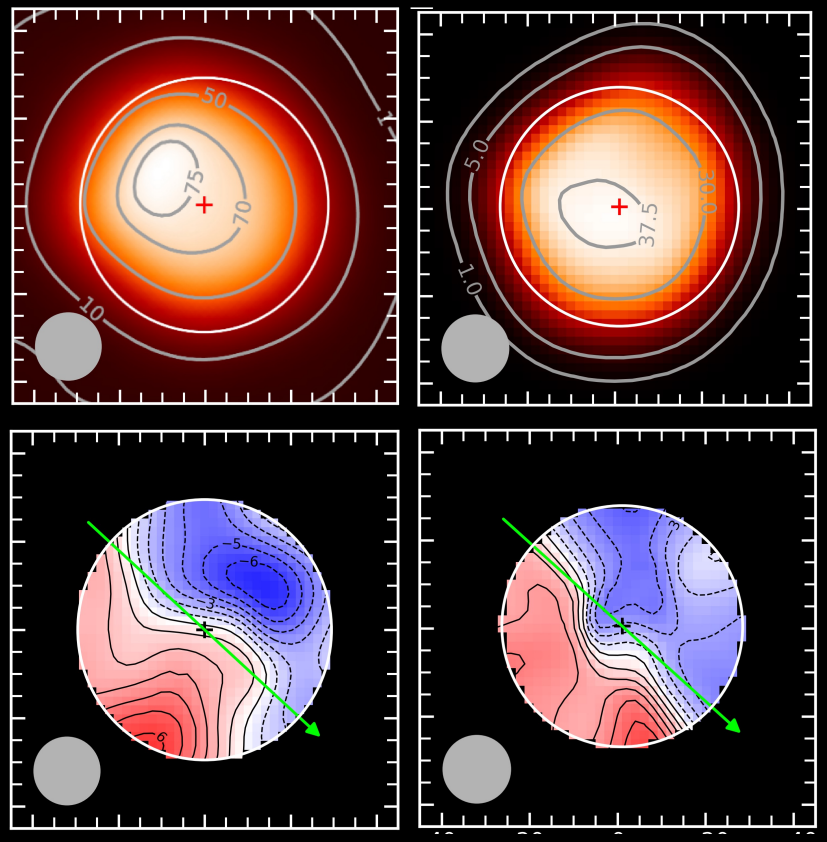

JZM+2024 ApJL



# Another higher-resolution observation?

2015 Observation

Simulation




Kervella+ 2018

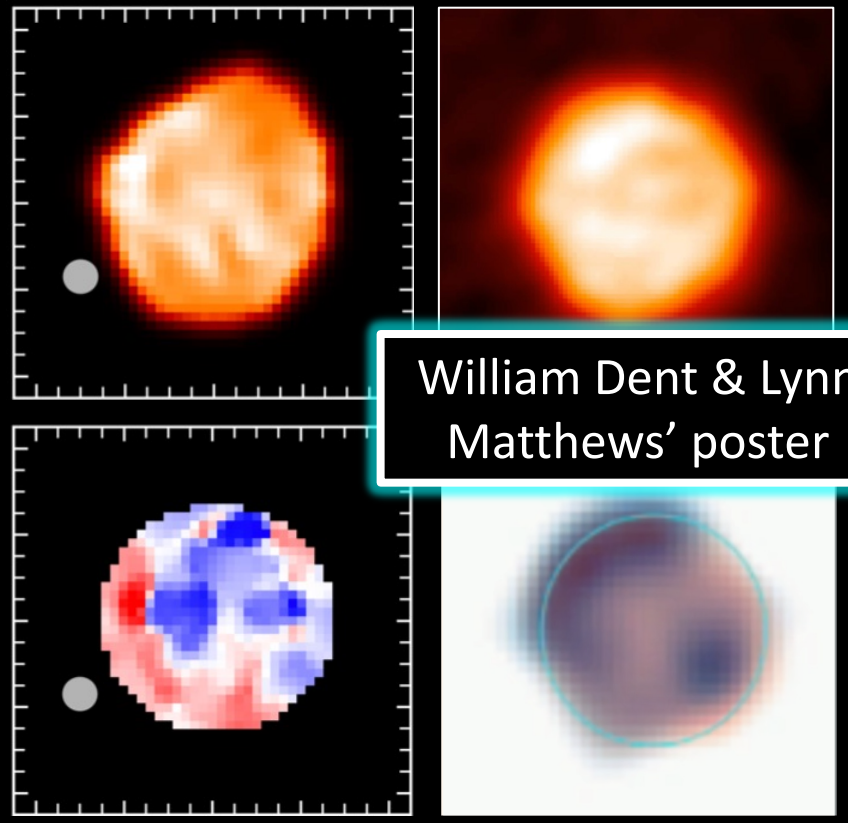
JZM+2024 ApJL

Future?

Future is now!

Simulation

2022 Observation

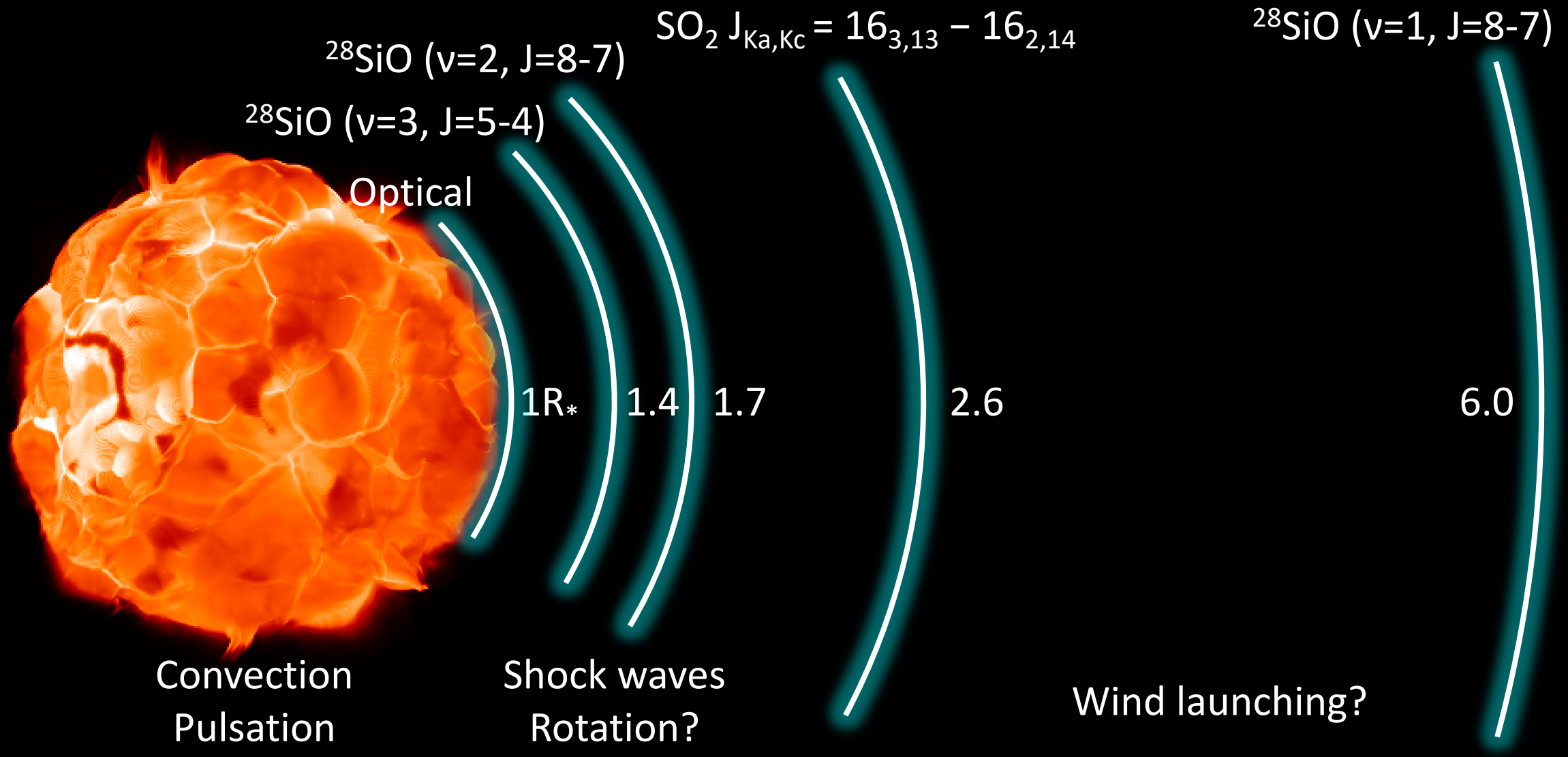


William Dent & Lynn Matthews' poster

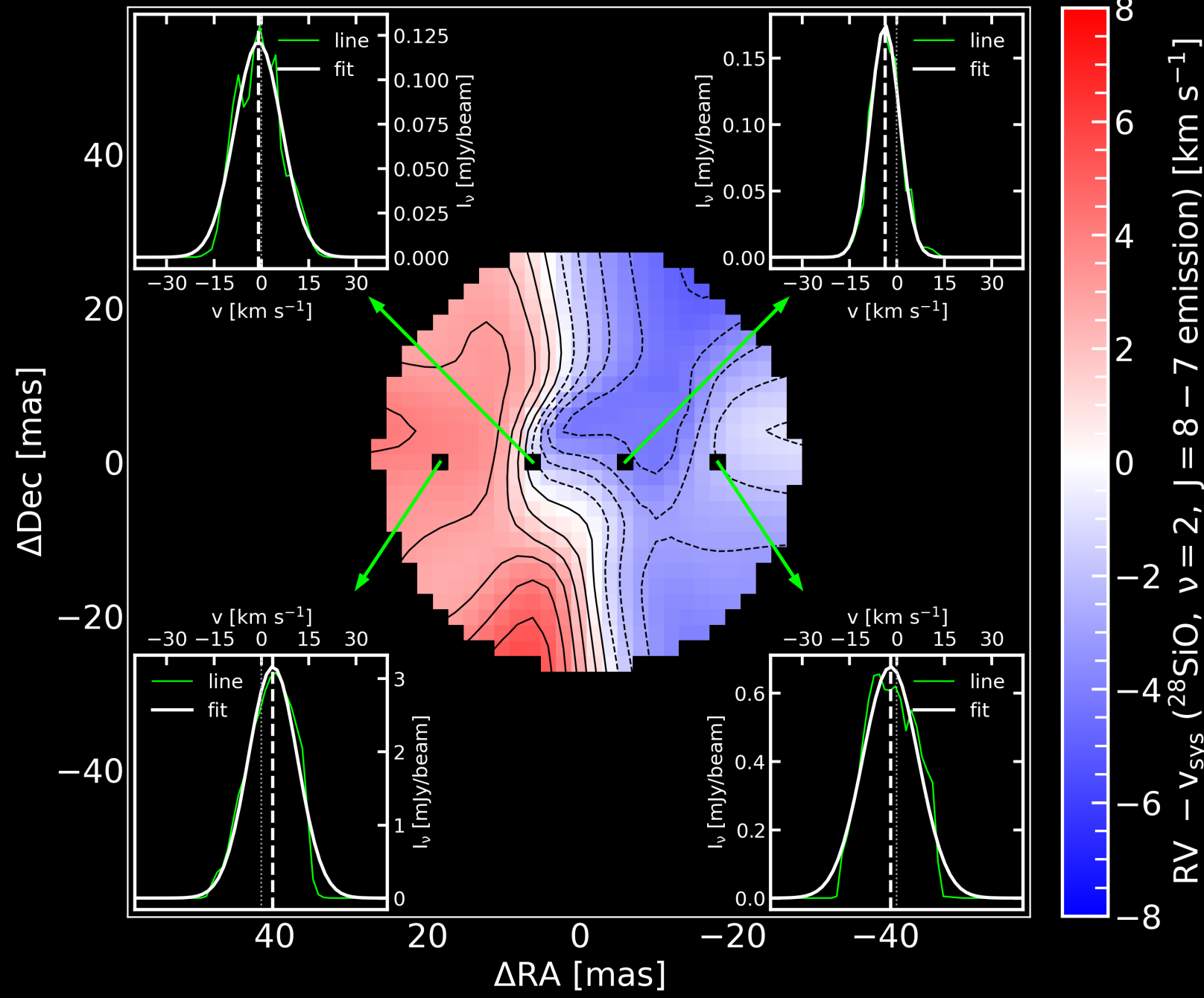
JZM+2024 ApJL

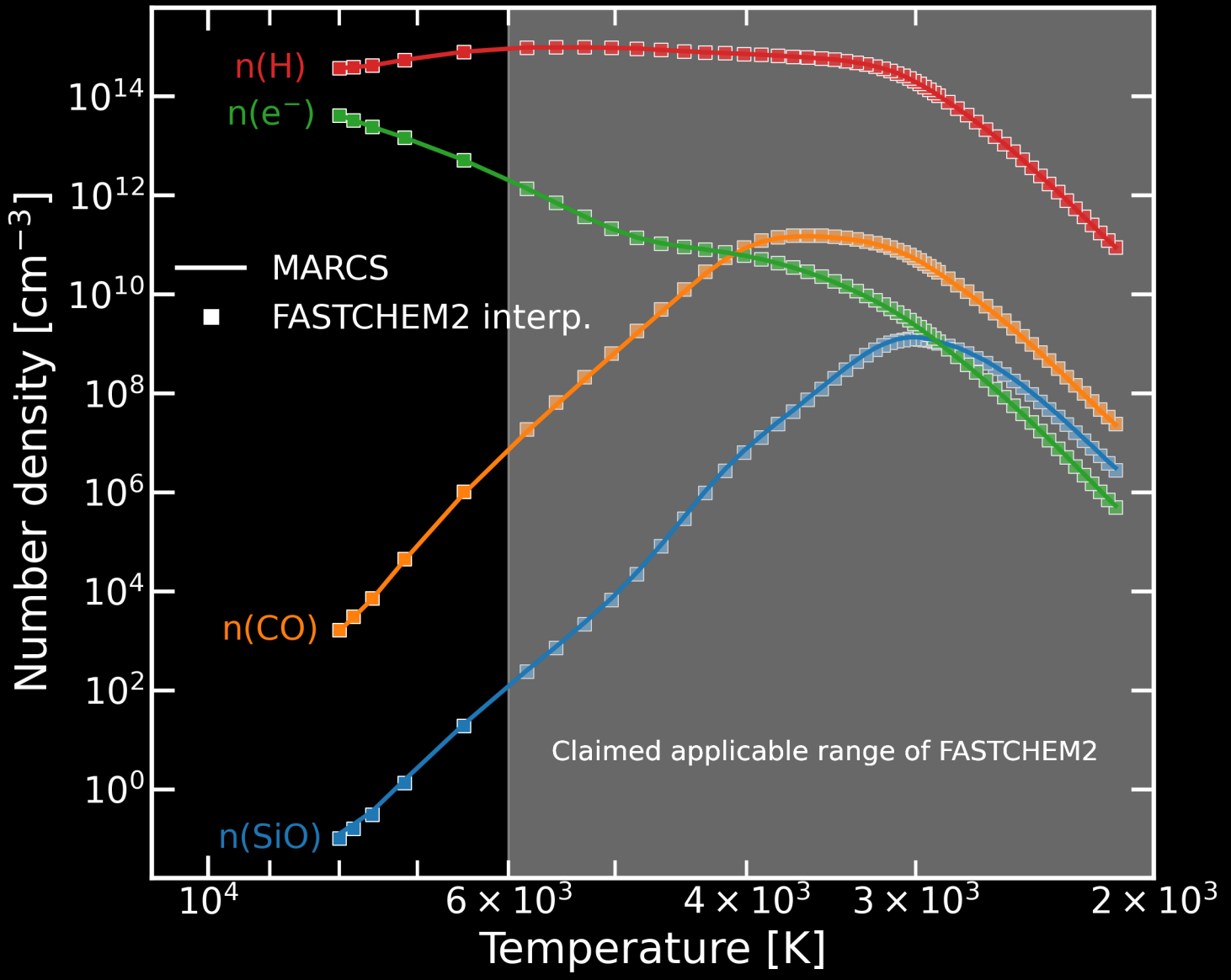
Bill Dent's talk at ALMA 10 years

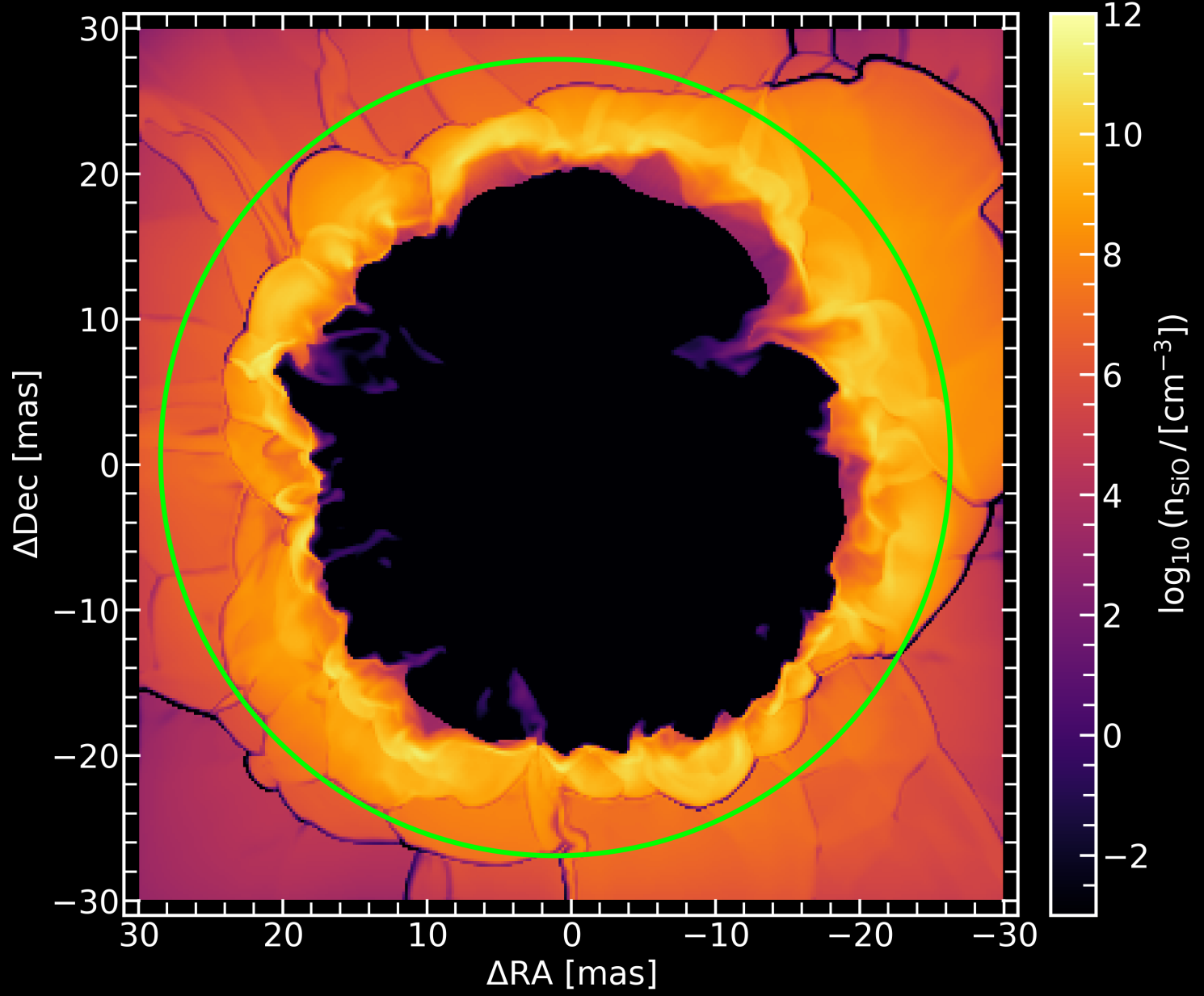
# Prospects: Resolved velocity field tomography?



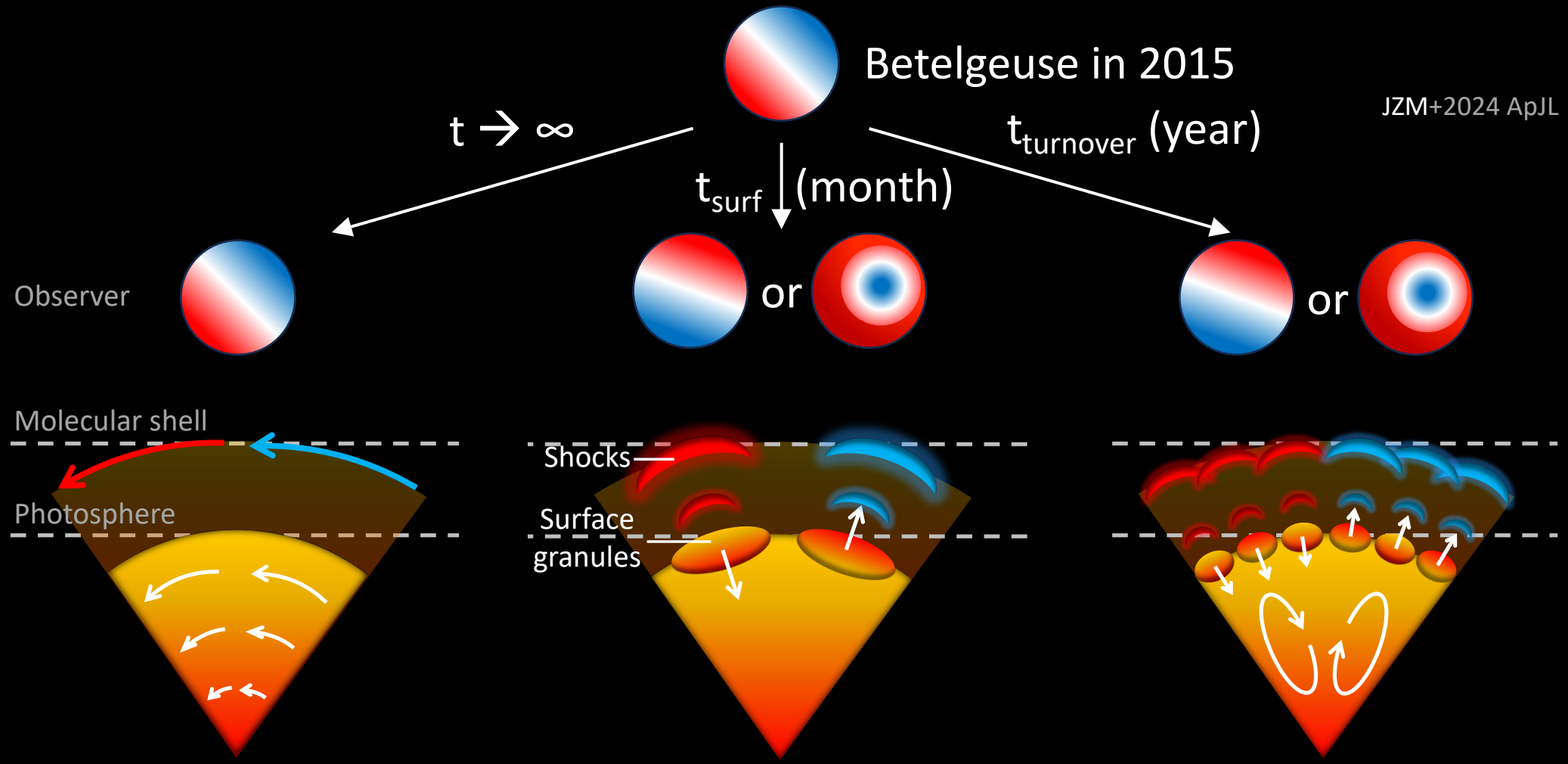

Kervella+2018, Vlemmings+2018, Homan+2018


ΔDec [mas]
ΔRA [mas]
40
20
0
−20
−40
line
fit
v [km s$^{-1}$]
$I_\nu$ [mJy/beam]
RV − $v_{sys}$ ($^{28}$SiO, ν = 2, J = 8 − 7 emission) [km s$^{-1}$]
8
6
4
2
0
−2
−4
−6
−8


n(H)
n(e⁻)
MARCS
FASTCHEM2 interp.
n(CO)
n(SiO)
Claimed applicable range of FASTCHEM2
Number density [cm⁻³]
Temperature [K]
10¹⁴
10¹²
10¹⁰
10⁸
10⁶
10⁴
10²
10⁰
10⁴
6 × 10³
4 × 10³
3 × 10³
2 × 10³


30
20
10
0
−10
−20
−30
ΔDec [mas]
30
20
10
0
−10
−20
−30
ΔRA [mas]
12
10
8
6
4
2
0
−2
log10 (nSiO/[cm−3])

# Model-independent tests for future Obs.




I. Rapid rotation

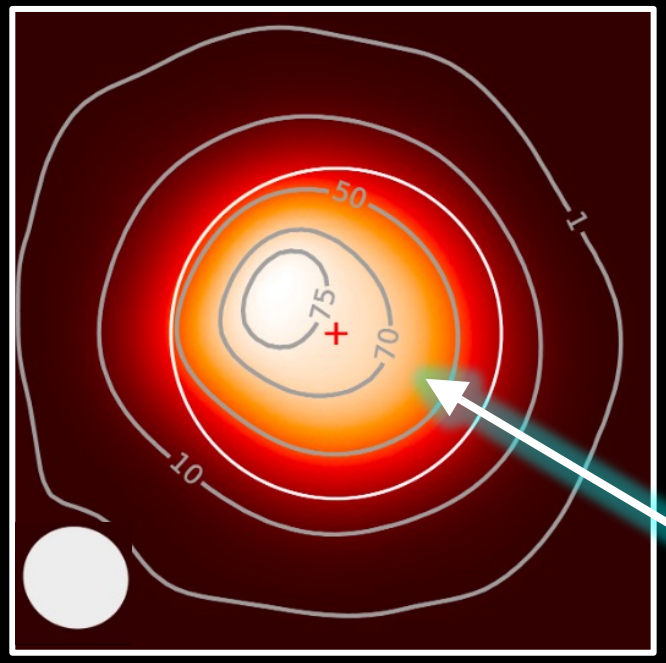
II. Large convective cells

III. Small convective cells moving coherently

# Future is now with ALMA:
# Highly resolved intensity and velocity maps

**18 mas**

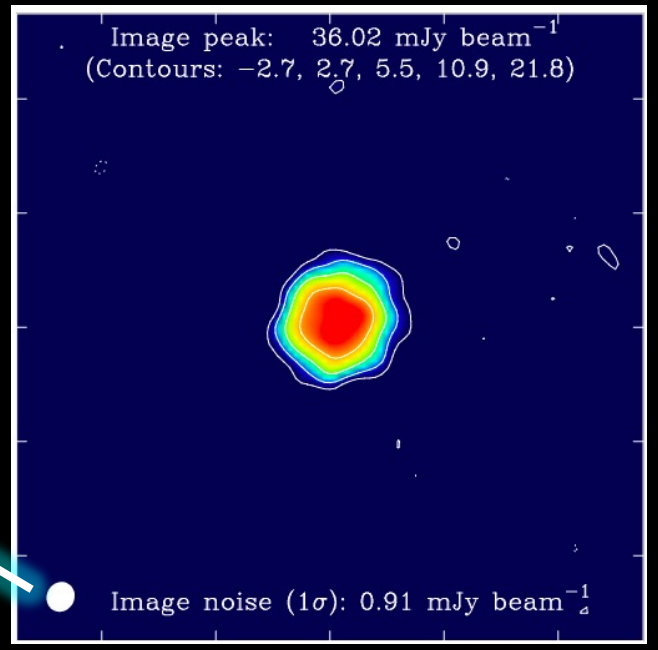
Betelgeuse in 2015




Kervella+2018

**5 mas**

AGB star R Lep in 2021




Asaki+2023

**2 mas?**

2030?

Carpenter+2020