# High Fidelity Modeling of the Youngest Stars with Schooner

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Rajeeb Sharma (grad student*)
**Nick Reynolds (grad. student)**

# Collaborators

- VANDAM Team:
  - John Tobin (PI), Leslie Looney (Illinois), Zhi-Yun Li (Virginia), Claire Chandler (NRAO),Mike Dunham (CfA), Kaitlin Kratter (Arizona), Dominique Segura-Cox (Illinois), Sarah Sadavoy (MPIA), Laura Perez (NRAO), Carl Melis (UCSD), Robert Harris (Illinois), Lukasz Tychoniec (Leiden/AMU-Poland)
- HOPS
  - E. Furlan, W. J. Fischer, B. Ali, A. M. Stutz, T. Stanke, J. J. Tobin, S. T. Megeath, M. Osorio, L. Hartmann, N. Calvet, C. A. Poteet, J. Booker, P. Manoj, D. M. Watson, and L. Allen

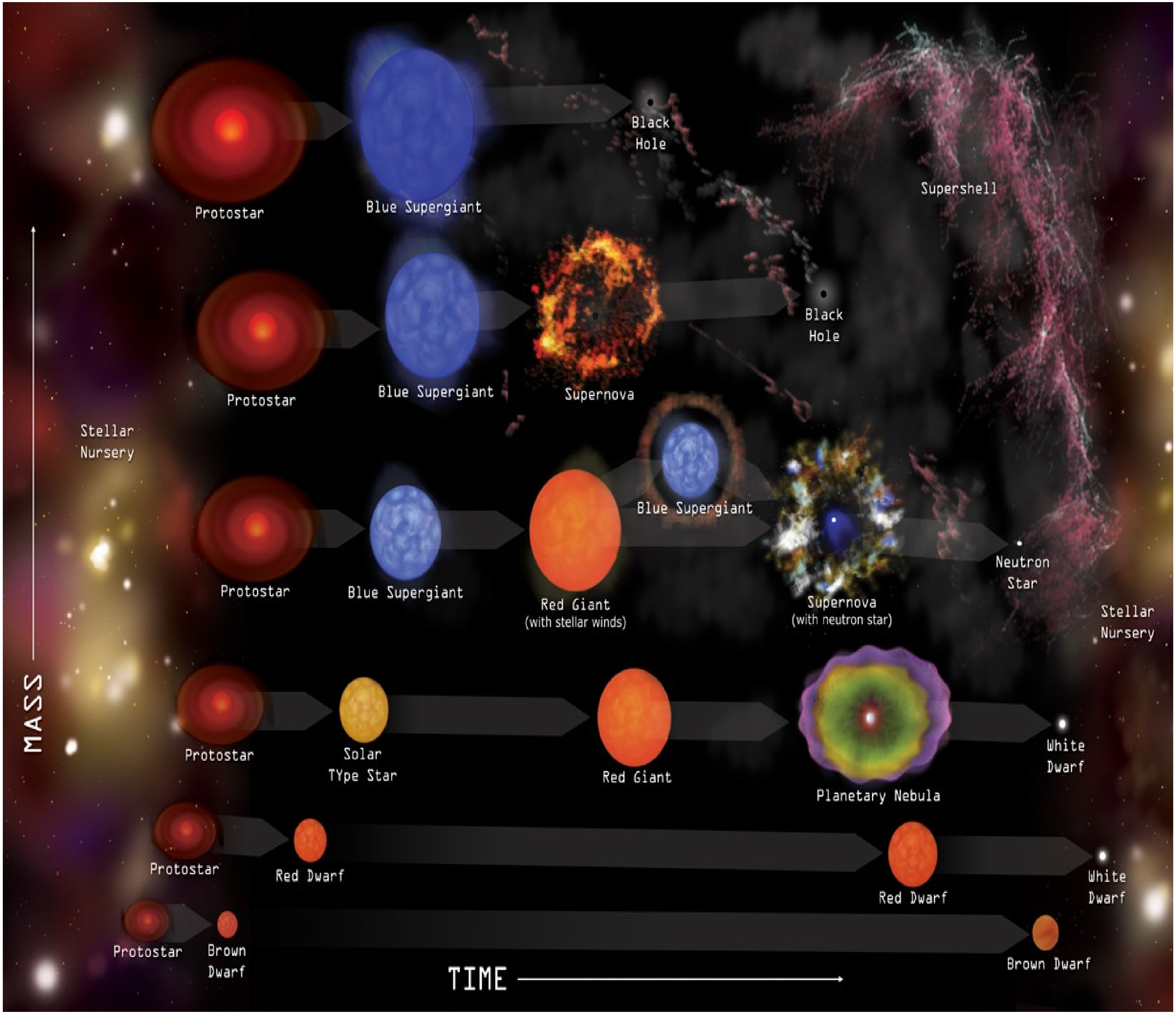
# Outline

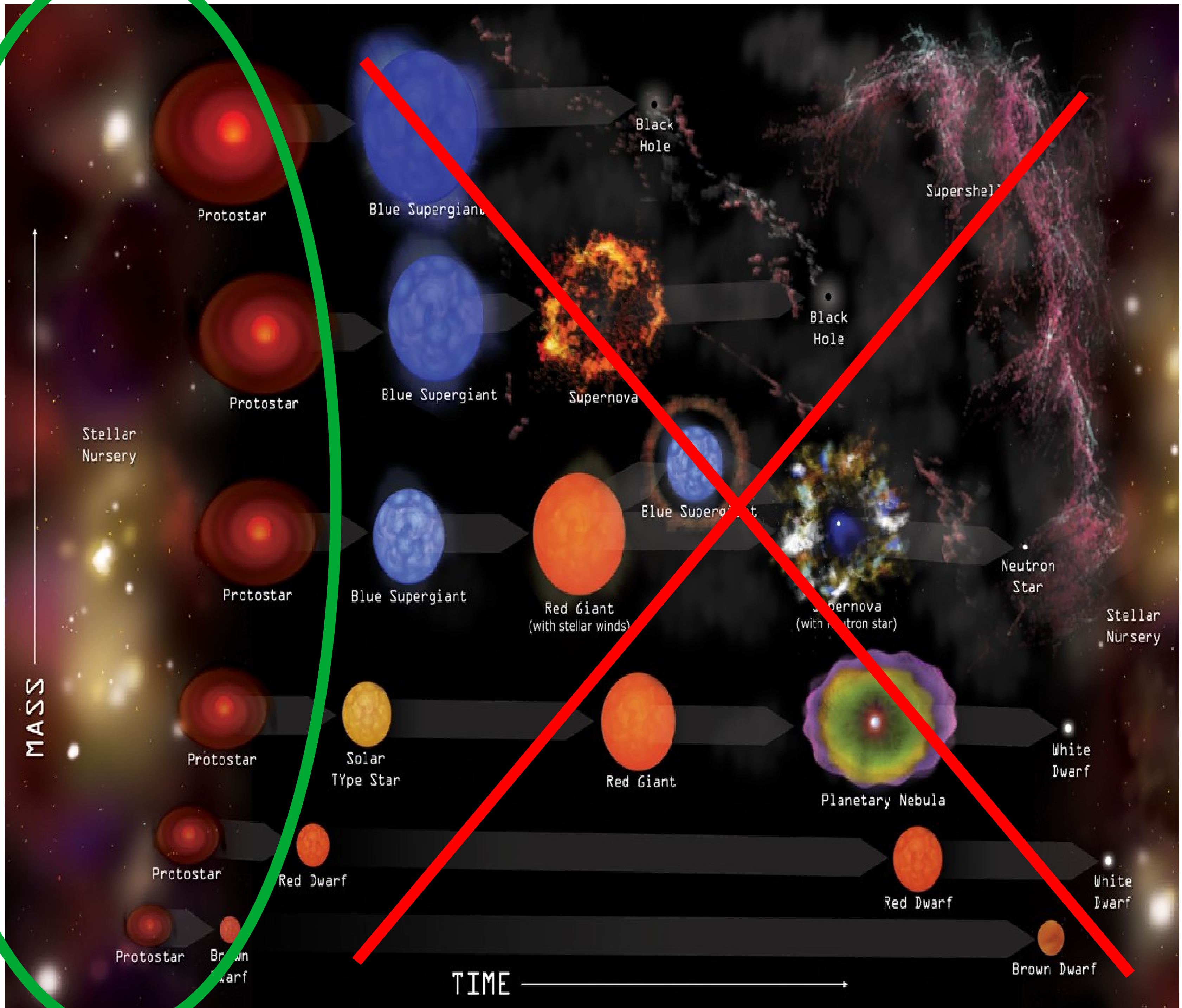
- Motivations
- Background
  - Star Formation
  - Observing/Instrumentation
- Data Gathering
- Computation Complexity
- Results
- Impacts
- Summary

# Why Should You Care?

Big Questions in Astronomy

- Where did we come from?
- What else is out there (locally)?


Black Hole
Protostar
Blue Supergiant
Supershell
Protostar
Blue Supergiant
Supernova
Black Hole
Stellar Nursery
Blue Supergiant
Protostar
Blue Supergiant
Red Giant
(with stellar winds)
Supernova
(with neutron star)
Neutron Star
Stellar Nursery
MASS
Protostar
Solar TYpe Star
Red Giant
Planetary Nebula
White Dwarf
Protostar
Red Dwarf
Red Dwarf
White Dwarf
Protostar
Brown Dwarf
TIME
Brown Dwarf



Protostar
Blue Supergiant
Black Hole
Supershell
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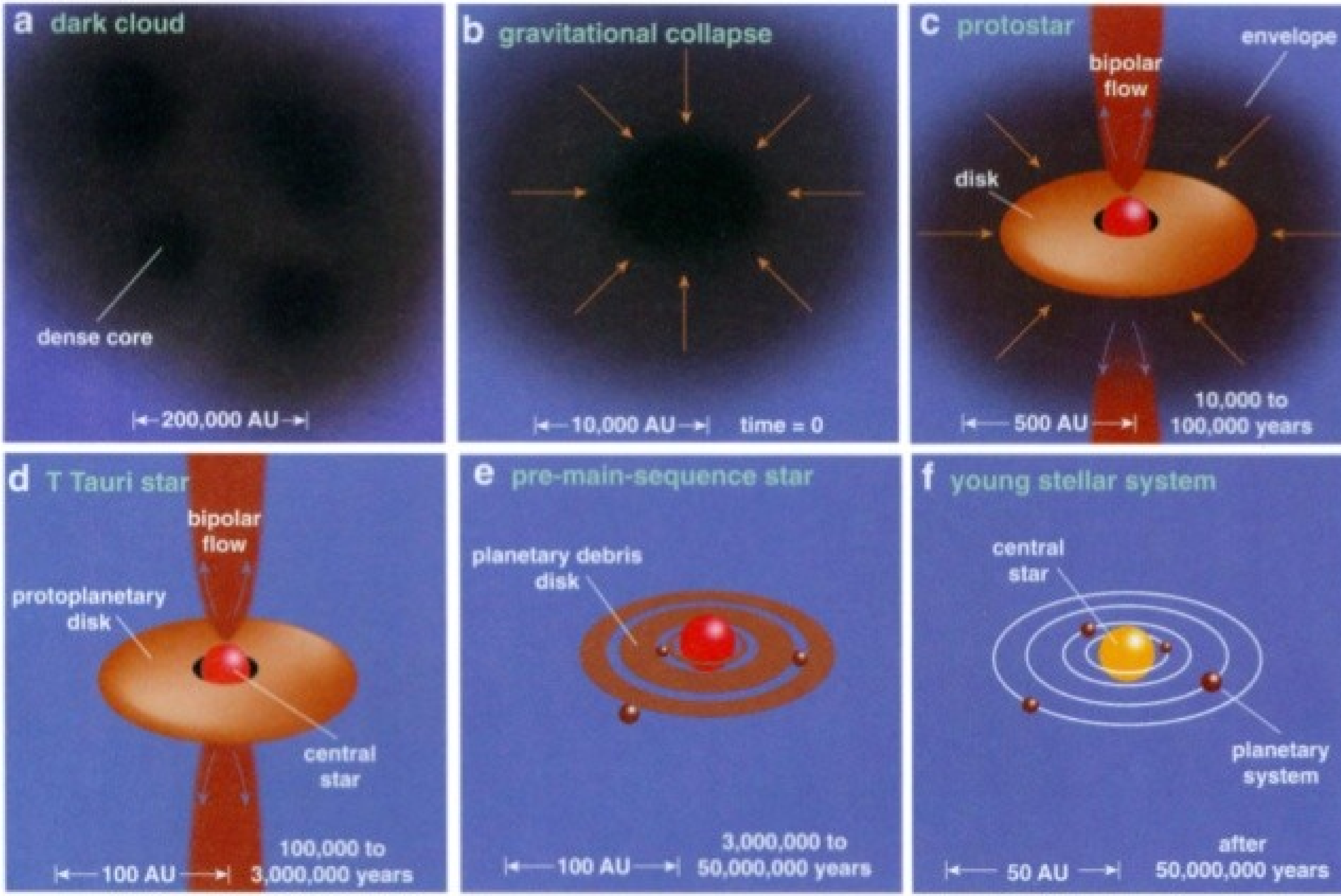
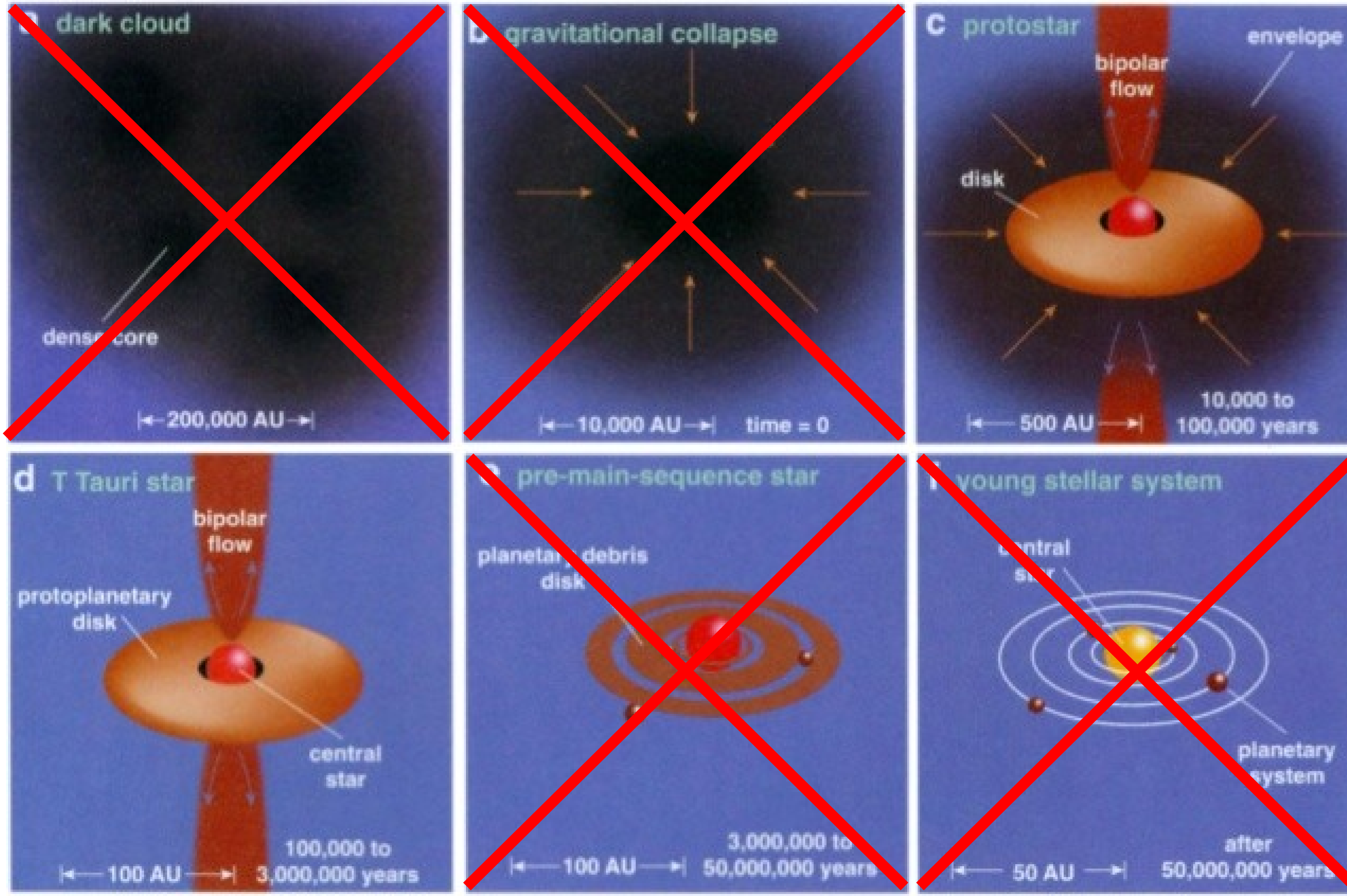
Planetary Nebula
White Dwarf
Protostar
Red Dwarf
Red Dwarf
White Dwarf
Protostar
Brown Dwarf
TIME


a dark cloud
dense core
200,000 AU
b gravitational collapse
10,000 AU
time = 0
c protostar
envelope
bipolar flow
disk
500 AU
10,000 to 100,000 years
d T Tauri star
bipolar flow
protoplanetary disk
central star
100 AU
100,000 to 3,000,000 years
e pre-main-sequence star
planetary debris disk
100 AU
3,000,000 to 50,000,000 years
f young stellar system
central star
planetary system
50 AU
after 50,000,000 years


dark cloud
core
200,000 AU
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time = 0
c protostar
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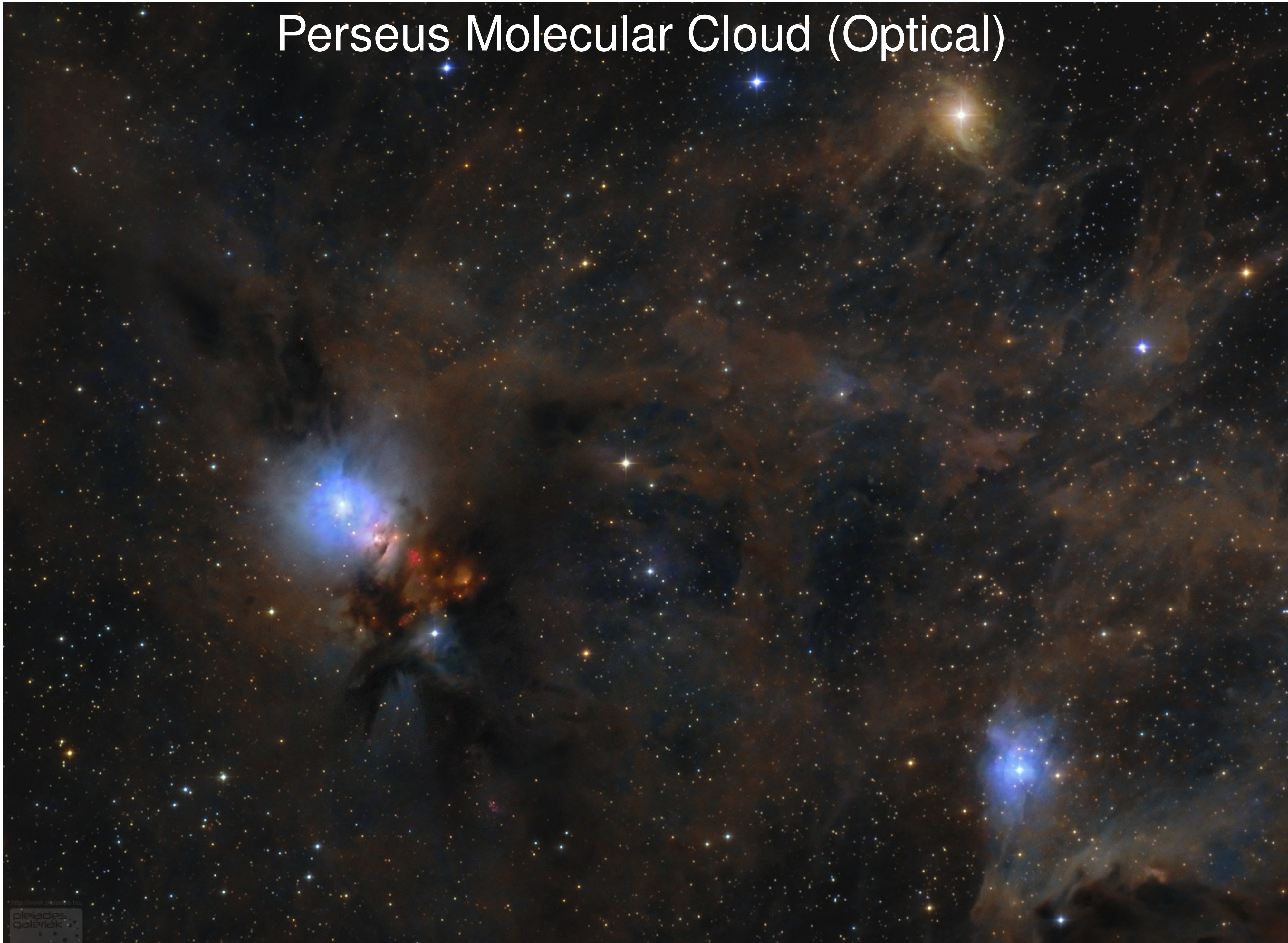
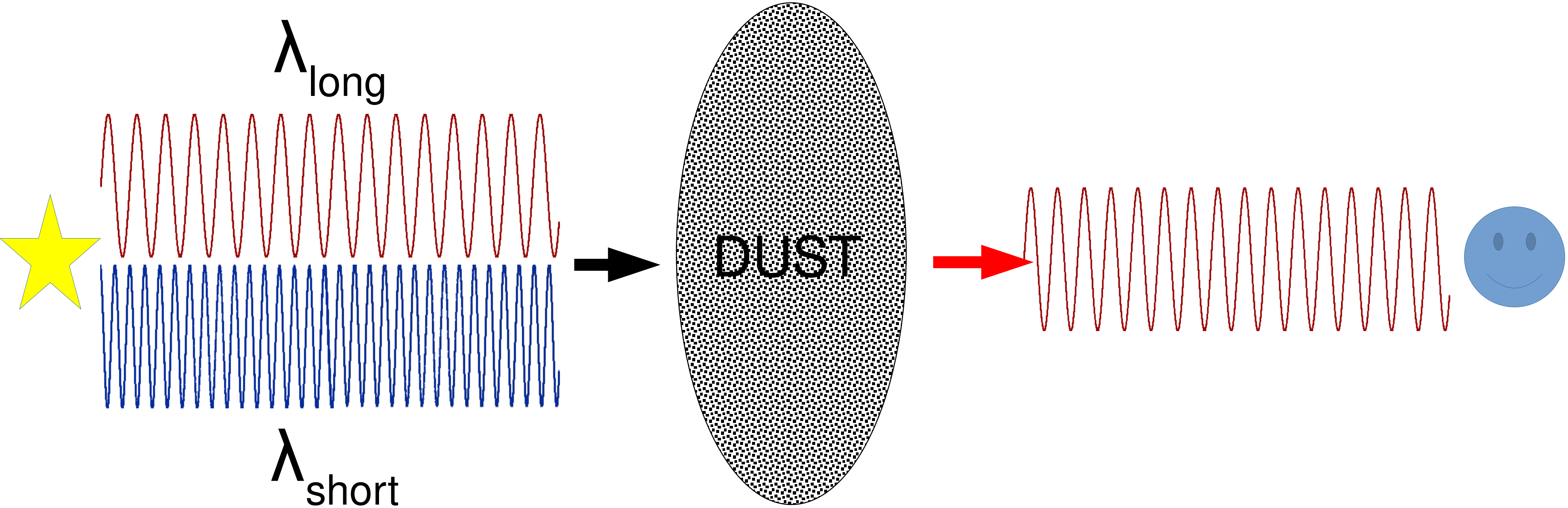
bipolar flow
protoplanetary disk
central star
100 AU
100,000 to 3,000,000 years
pre-main-sequence star
debris
disk
100 AU
3,000,000 to 50,000,000 years
young stellar system
planetary system
50 AU
after 50,000,000 years

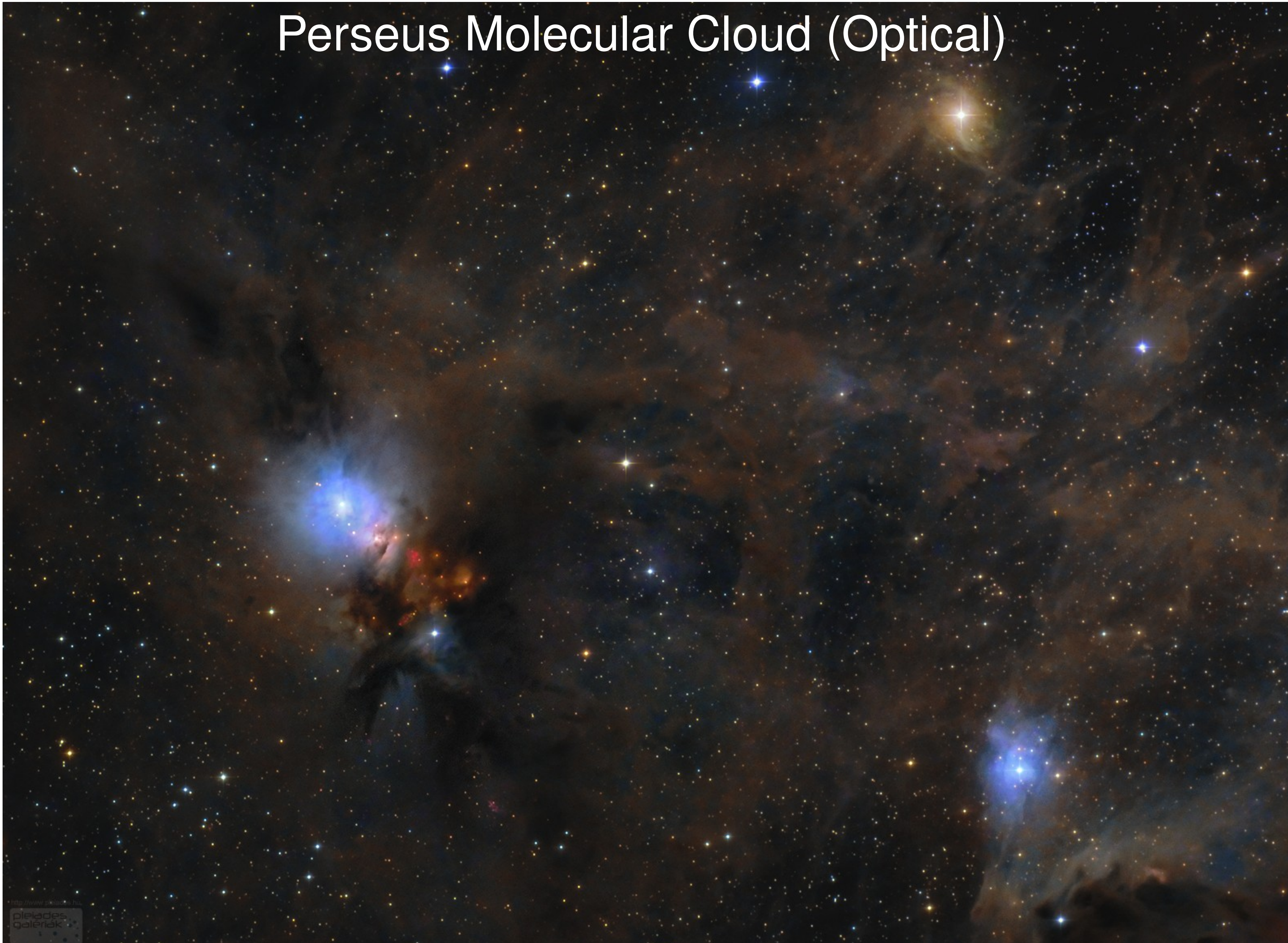
# Perseus Molecular Cloud (Optical)



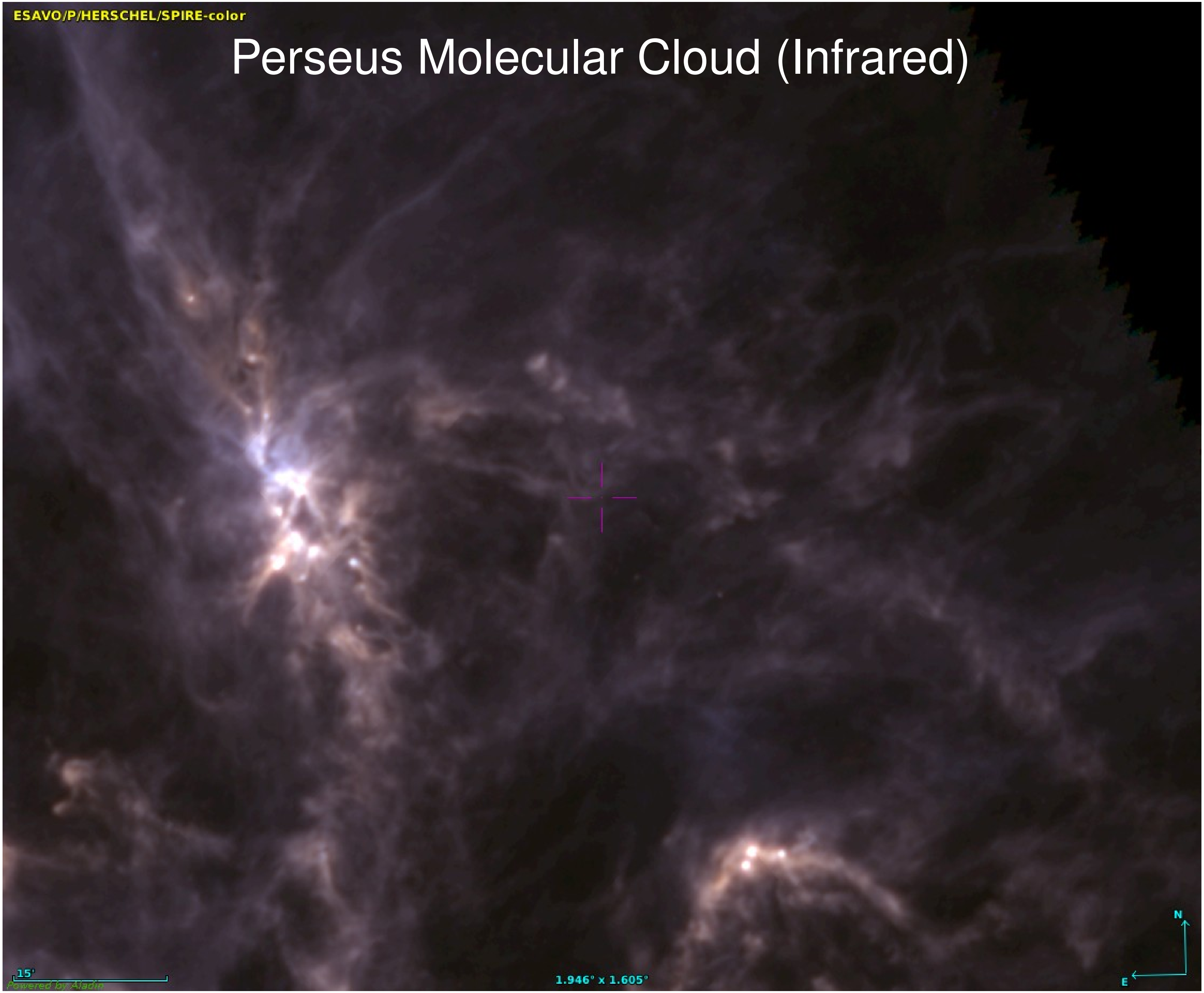
# Dust Opacity



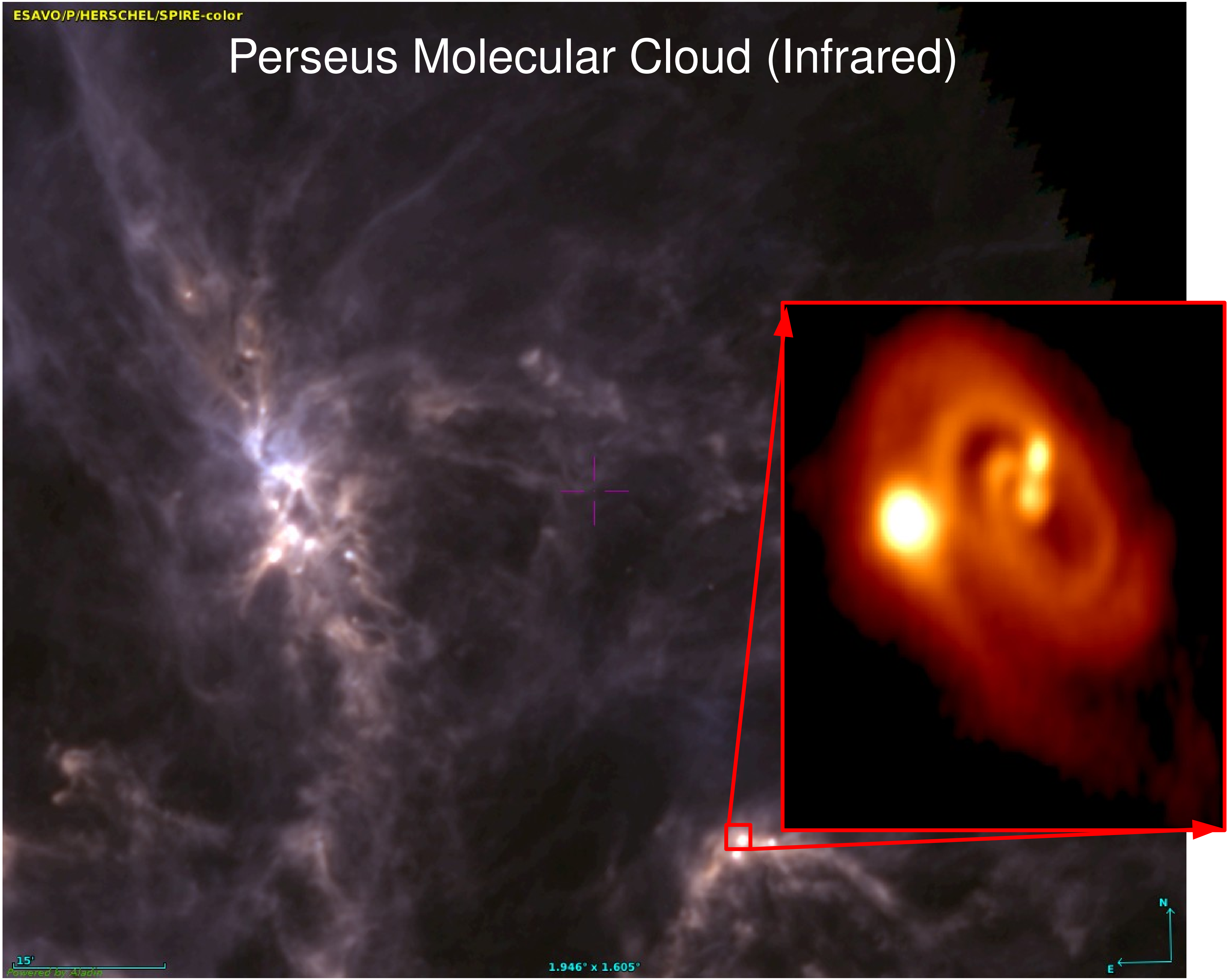

So longer wavelength, better we can "see through" the cloud


Perseus Molecular Cloud (Optical)

# Perseus Molecular Cloud (Infrared)



# Perseus Molecular Cloud (Infrared)



Great!
We solved our problem of opacity

What facilities can observe this?

# Interferometry

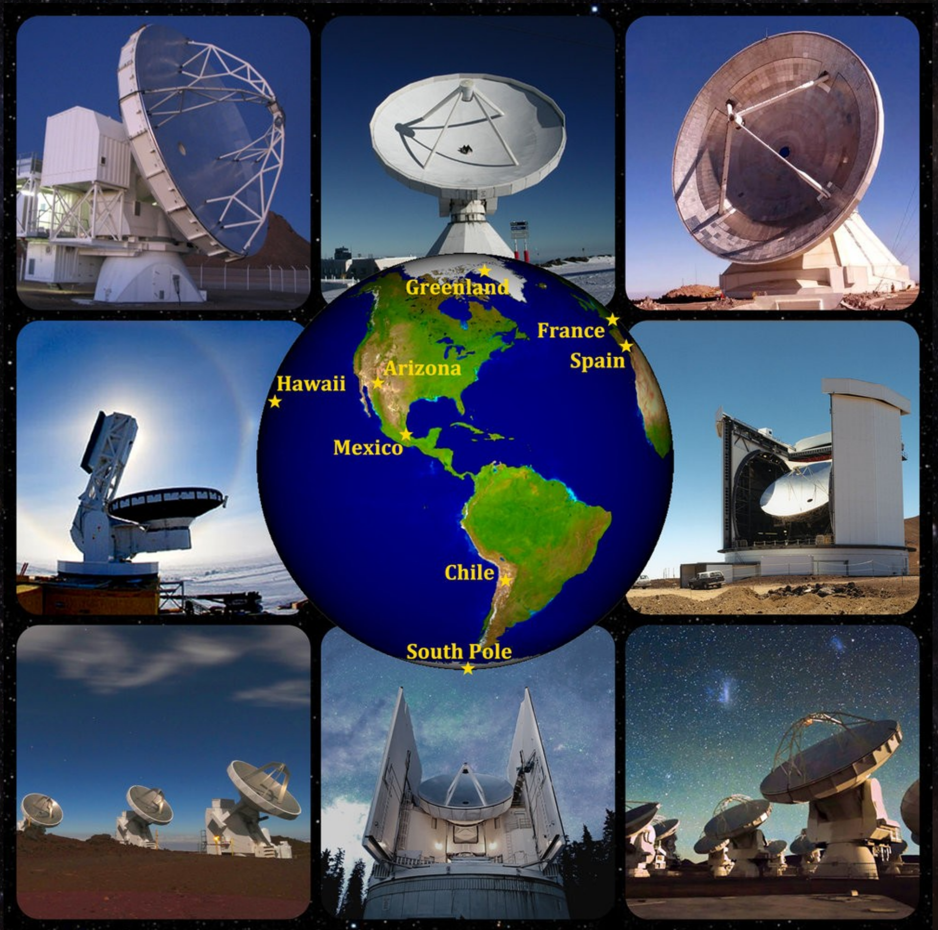
- Combine smaller telescopes to make an effective large telescope

ALMA (Chile)

# Interferometry

- Combine smaller telescopes to make an effective large telescope

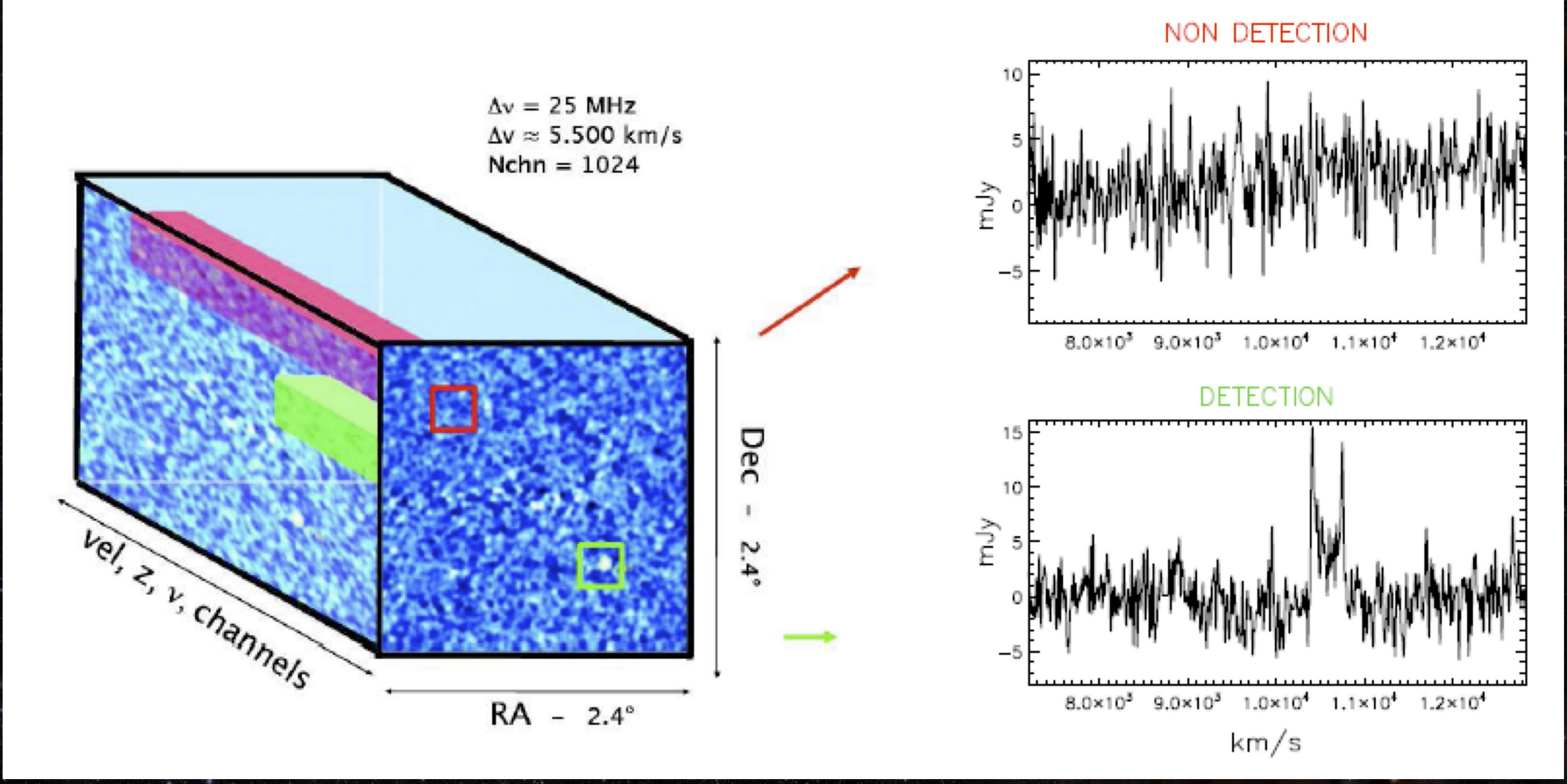
VLBI (Worldwide, EHT talk from Bouman)



Let’s get data!

# Data Cube

## Photometry & Spectroscopy



# Data Types

## Photometry/ Continuum

Tells us about dust:
- mass of system
- geometry
- high sensitivity
- fine structure

## Spectroscopy

Tells us about gas:
- molecules
- ionized material
- kinematics
- complementary view of dynamics

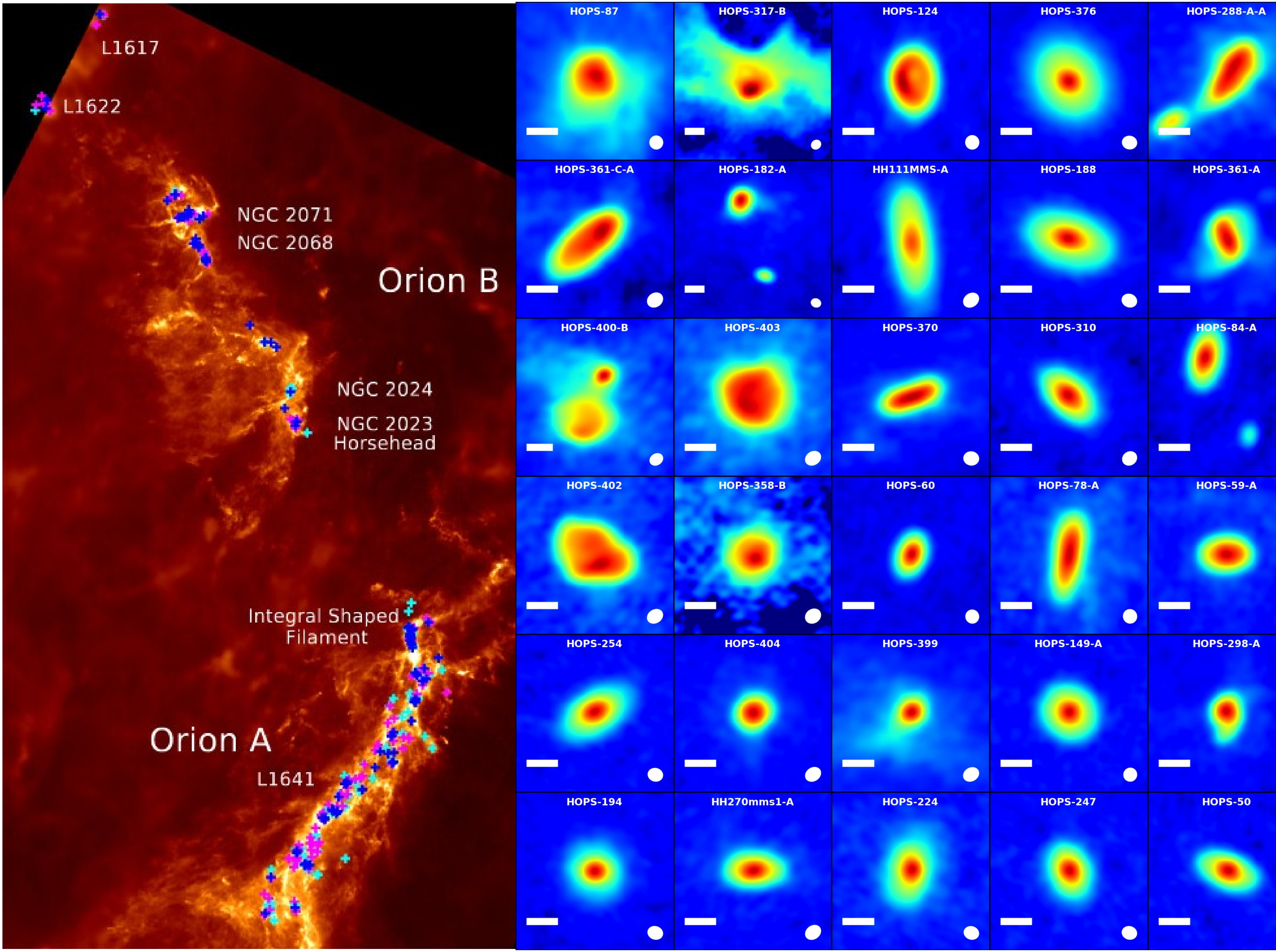
In total, we get 20-40 various parameters that can be used to describe the system.

# Science Summary

- We went from optical to radio
- Can now study properties of these systems individually and in bulk
- We have information about dust and gas
  - Information about structure, kinematics, dynamics, etc

# What do we need and why?

- Our understanding of star and planet formation is incomplete.
- Previous studies of protostellar disks have historically been heavily biased or limited sample sizes
- Until ALMA we lacked the high resolution and high sensitivity for this analysis.
- Need more complete observations for our theory folks.
- We present the first and largest unbiased survey in Orion Molecular Cloud



L1617
L1622
NGC 2071
NGC 2068
Orion B
NGC 2024
NGC 2023
Horsehead
Integral Shaped
Filament
Orion A
L1641
HOPS-87
HOPS-317-B
HOPS-124
HOPS-376
HOPS-288-A-A
HOPS-361-C-A
HOPS-182-A
HH111MMS-A
HOPS-188
HOPS-361-A
HOPS-400-B
HOPS-403
HOPS-370
HOPS-310
HOPS-84-A
HOPS-402
HOPS-358-B
HOPS-60
HOPS-78-A
HOPS-59-A
HOPS-254
HOPS-404
HOPS-399
HOPS-149-A
HOPS-298-A
HOPS-194
HH270mms1-A
HOPS-224
HOPS-247
HOPS-50

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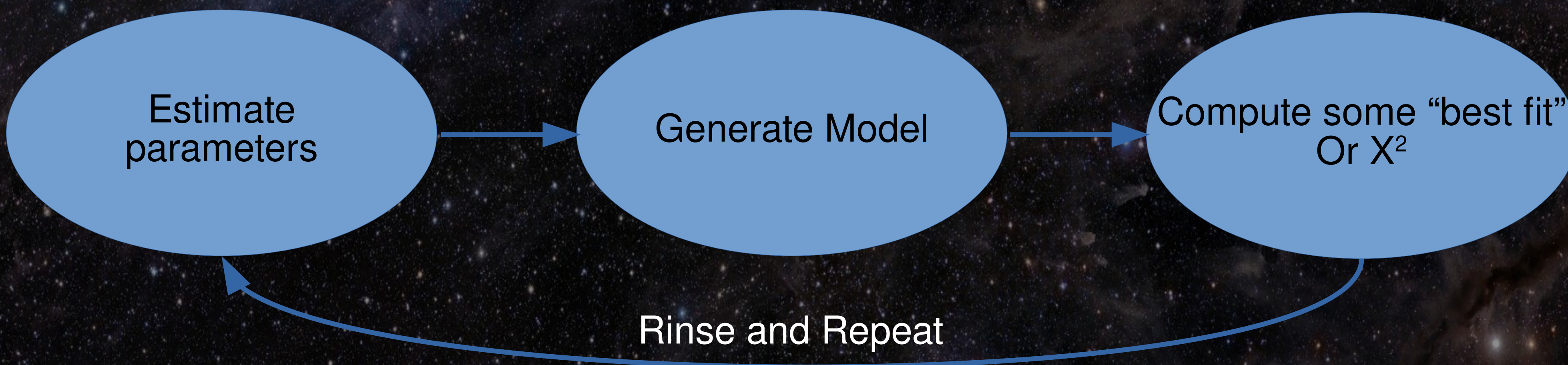
# Computation

- We now have 20-40 parameters, that are tightly correlated, to fit
- End goal: what are the parameters that "best" describe the system?

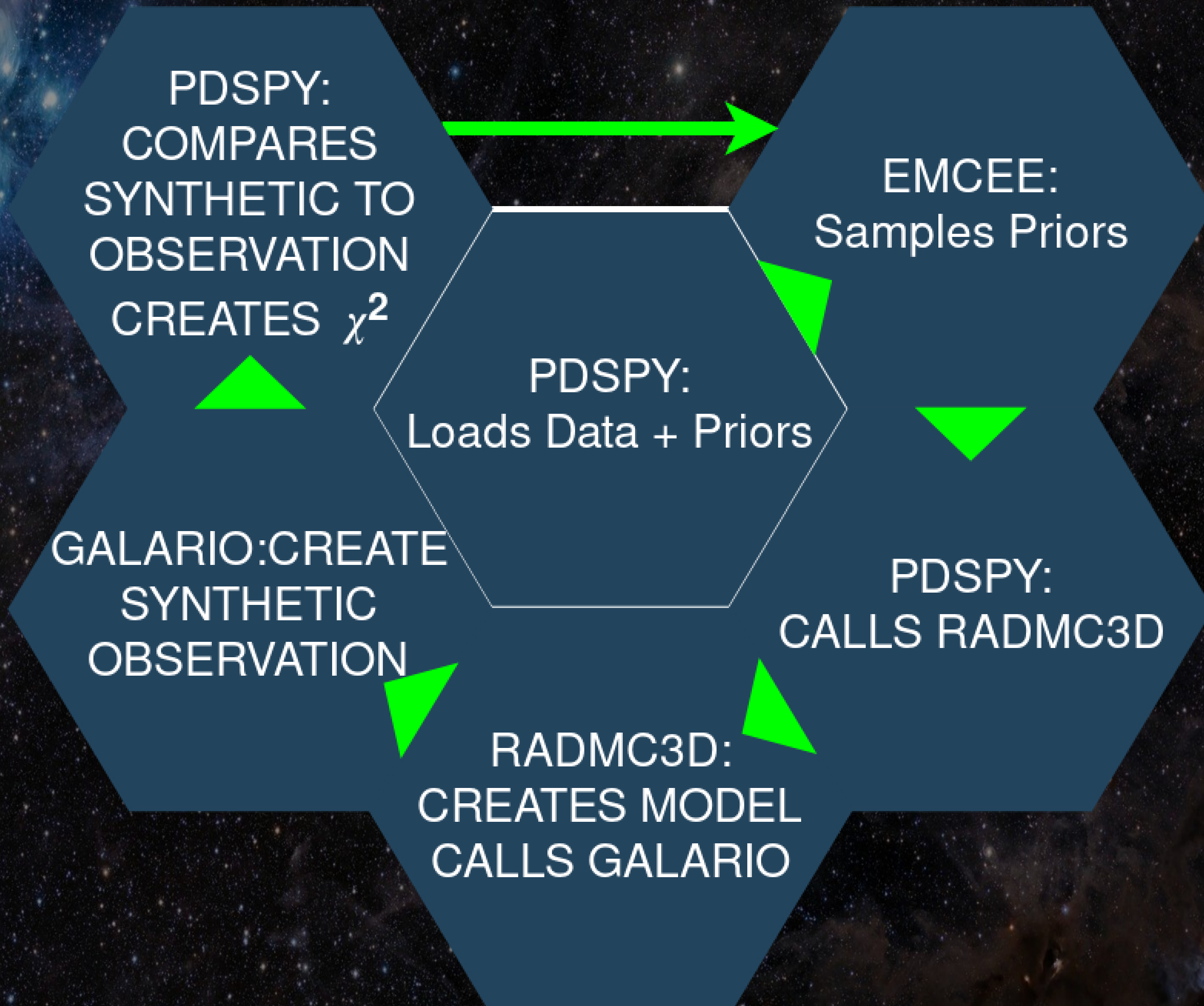



- Sounds perfect for parallelization and Bayesian Statistics

# Codes

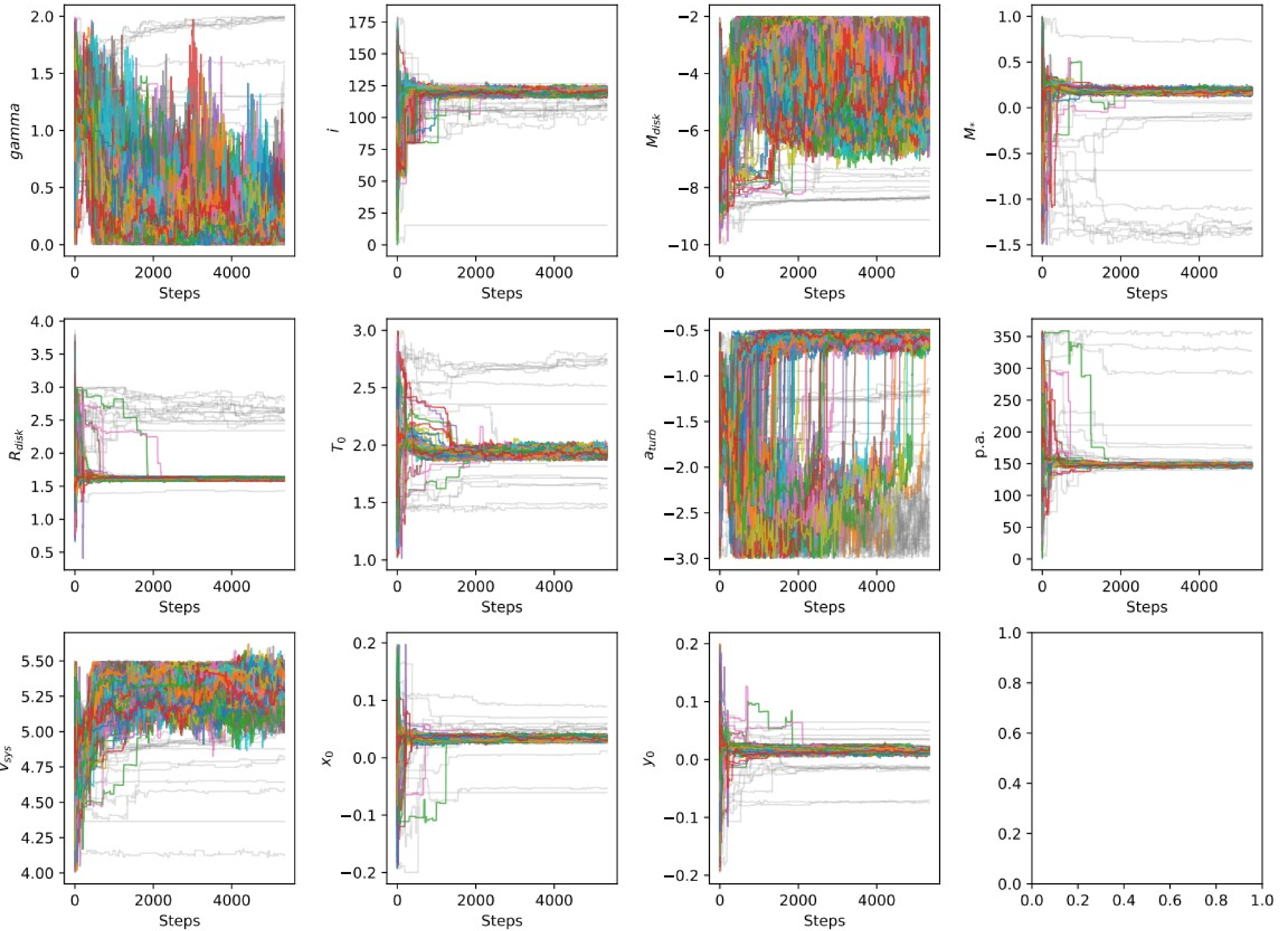
- RADMC3D (Dullemond 2012)
  www.ita.uni-heidelberg.de/~dullemond/software/radmc-3d/
- Galario (Tazzari et al. 2018)
  mtazzari.github.io/galario/
- Emcee ( Foreman-Mackey et al. 2012)
  https://github.com/dfm/emcee
- PDSPY (Sheehan et al. 2019)
  github.com/psheehan/pdspy

# Codes


PDSPY:
COMPARES
SYNTHETIC TO
OBSERVATION
CREATES $\chi^2$
EMCEE:
Samples Priors
PDSPY:
Loads Data + Priors
GALARIO:CREATE
SYNTHETIC
OBSERVATION
PDSPY:
CALLS RADMC3D
RADMC3D:
CREATES MODEL
CALLS GALARIO

# What’s the Catch?

- Numerical Convergence of the individual models (can take up to 10 minutes)
- Statistical convergence of the parameters or “walkers” (usually about 2000 timesteps)
- Both of these take time: we are generating a robust model of a protostar and its disk, generating a suite of models (200-ish) to explore phase space, and allowing these models or “walkers” to converge (usually about 2000 timesteps)


gamma
Steps
i
Steps
$M_{disk}$
Steps
$M_*$
Steps
$R_{disk}$
Steps
$T_0$
Steps
$a_{turb}$
Steps
p.a.
Steps
$v_{sys}$
Steps
$x_0$
Steps
$y_0$
Steps

# What’s the Catch?

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- 200 * 2000 * 10 minutes ≈ **60k hours**!

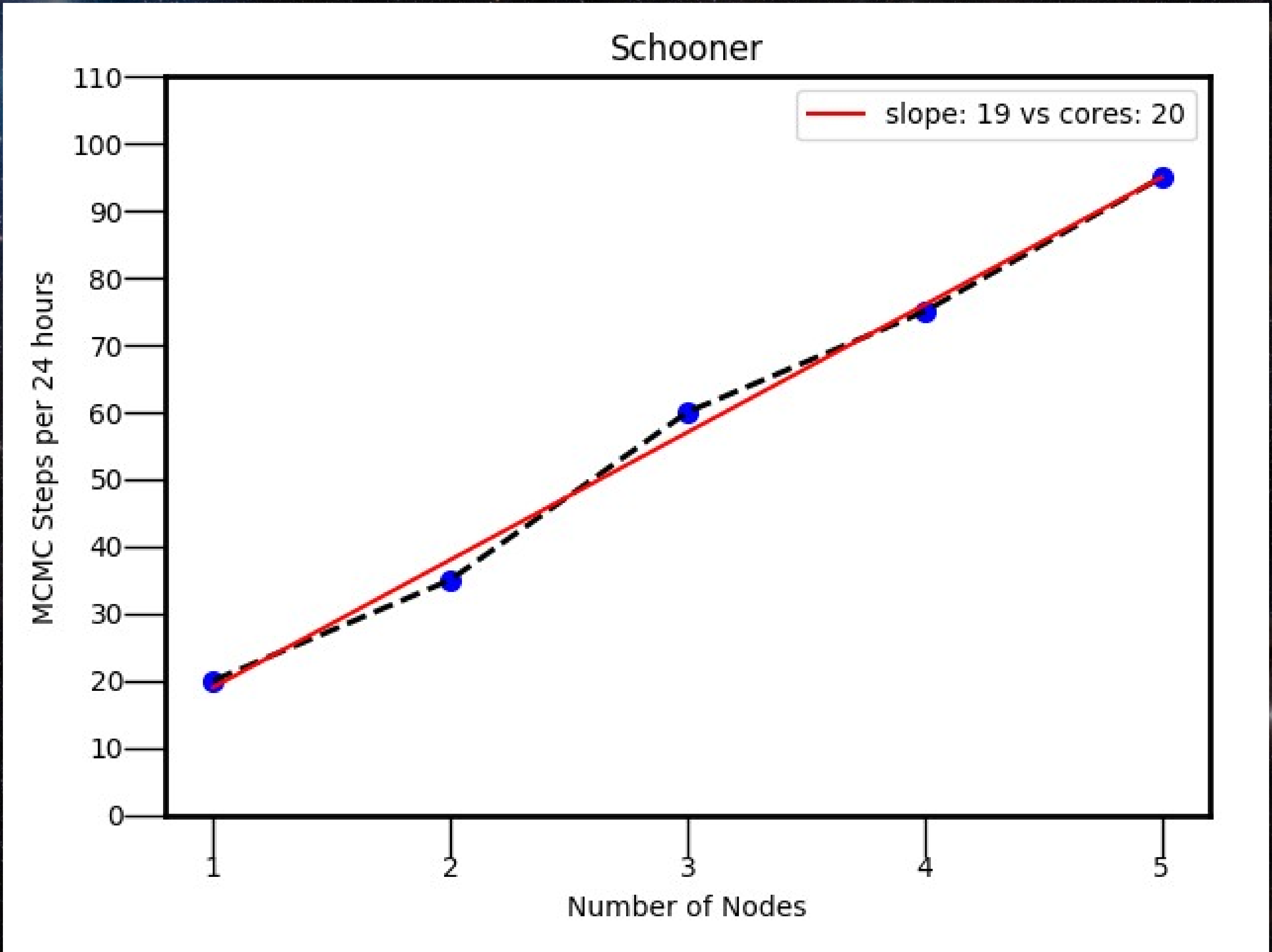
# Computing Specifics

- Our personal systems: 2 x 28 physical core CPUs
- That 60k hours is now ~ 1200 hours per source

# Schooner

- The supercomputer drastically changes the game for us
- Typical requests:
  - 5-15 nodes (100 – 300 cores)
  - About 2 weeks

# PDSPY Scalability



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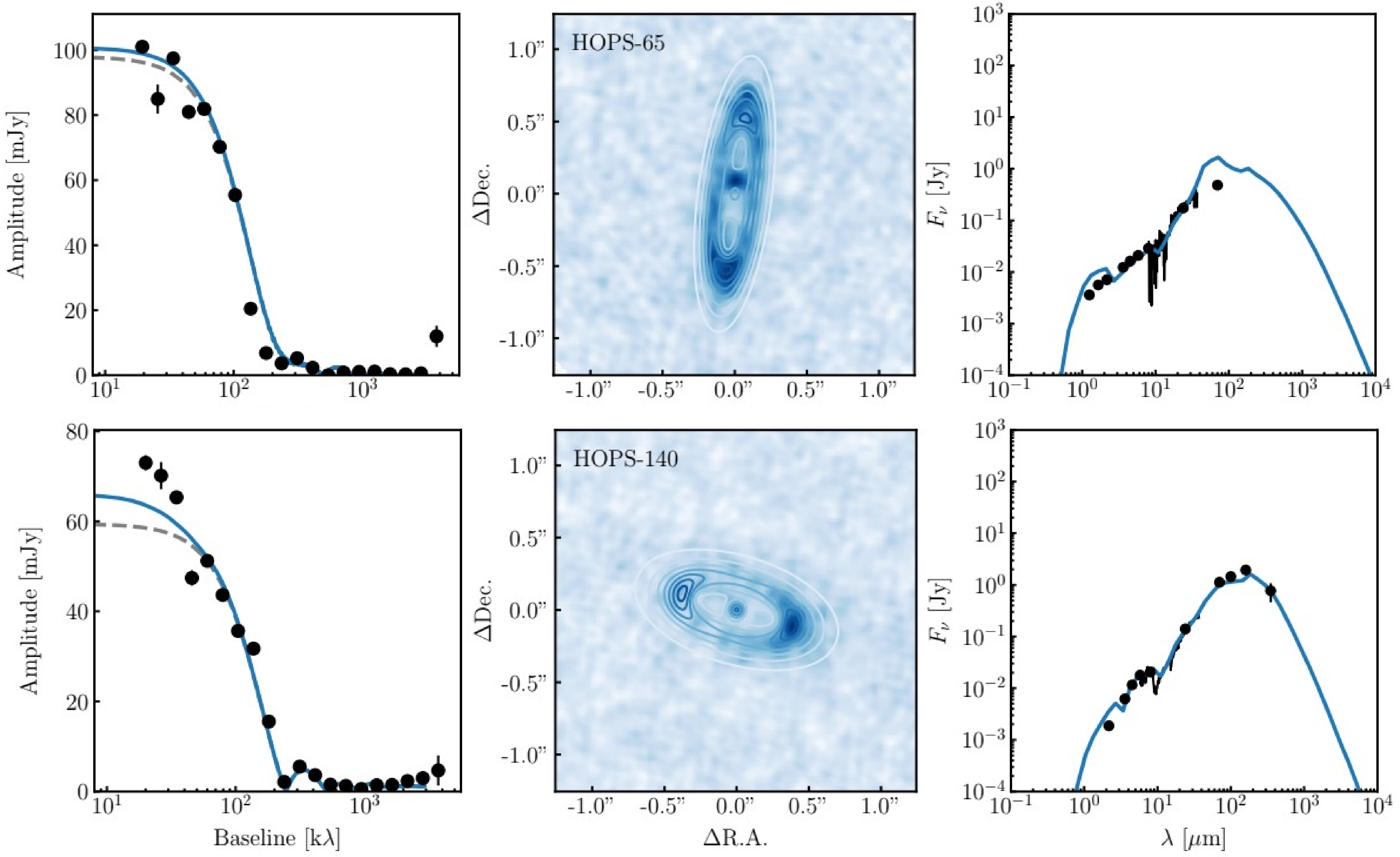
# What do we get?



# Other Facilities

- Hundreds of sources and each one can be modelled multiple times
- Using OSCER we fit about a dozen sources with high success (1 paper accepted, several submitted/in prep).

- Used OSCER to test the limits of the code and optimize it further

- Proposed to XSEDE bridges and comet (7 million CPU-hours)
- Proposal was based and accepted due to the models run on OSCER!

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# What are we answering?

- How/when/where do planets form?
- What does a typical protostellar system look like?
- In answering these statistically, we can also ask, are we unique?

# Impacts

- How/when/where do planets form?
- What does a typical protostellar system look like?

We want to do this in a statistically robust and relatively unbiased way

- This motivated the need for our pristine survey and the need for our computation time on OSCER and XSEDE

The group at OU is one of the forerunners in this field and are a part of global collaborations

- 3 proposals accepted (ALMA + XSEDE)
- 2 papers accepted (Sheehan et al. 2019 a, b)
- 1 paper submitted (Tobin et al. 2019, sub)
- 4 papers in prep (Sheehan et al., Reynolds et al. a,b, Sharma et al.)

# Summary

- Stars and planets form within dense cores in molecular clouds as protostellar systems
- We have the largest, high resolution survey of these protostars within nearby clouds (Orion, Perseus)
- Modeling these protostars to characterize their conditions to understand their formation pathways
- Used OSCER fit results to propose for XSEDE computing time
- Hopefully answer some of our starting questions

# Acknowledgements


- VANDAM Team:
  - John Tobin (PI), Leslie Looney (Illinois), Zhi-Yun Li (Virginia), Claire Chandler (NRAO),Mike Dunham (CfA), Kaitlin Kratter (Arizona), Dominique Segura-Cox (Illinois), Sarah Sadavoy (MPIA), Laura Perez (NRAO), Carl Melis (UCSD), Robert Harris (Illinois), Lukasz Tychoniec (Leiden/AMU-Poland)
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- OSCER support: Henry, Horst, the entire OSCER support staff
- CAS IT

If you are interested in astronomy/have some free time tonight;

Free Star Party!

observatory.ou.edu

When: Tonight @830

Where: Lin Hall Roof

Who can come: Everyone

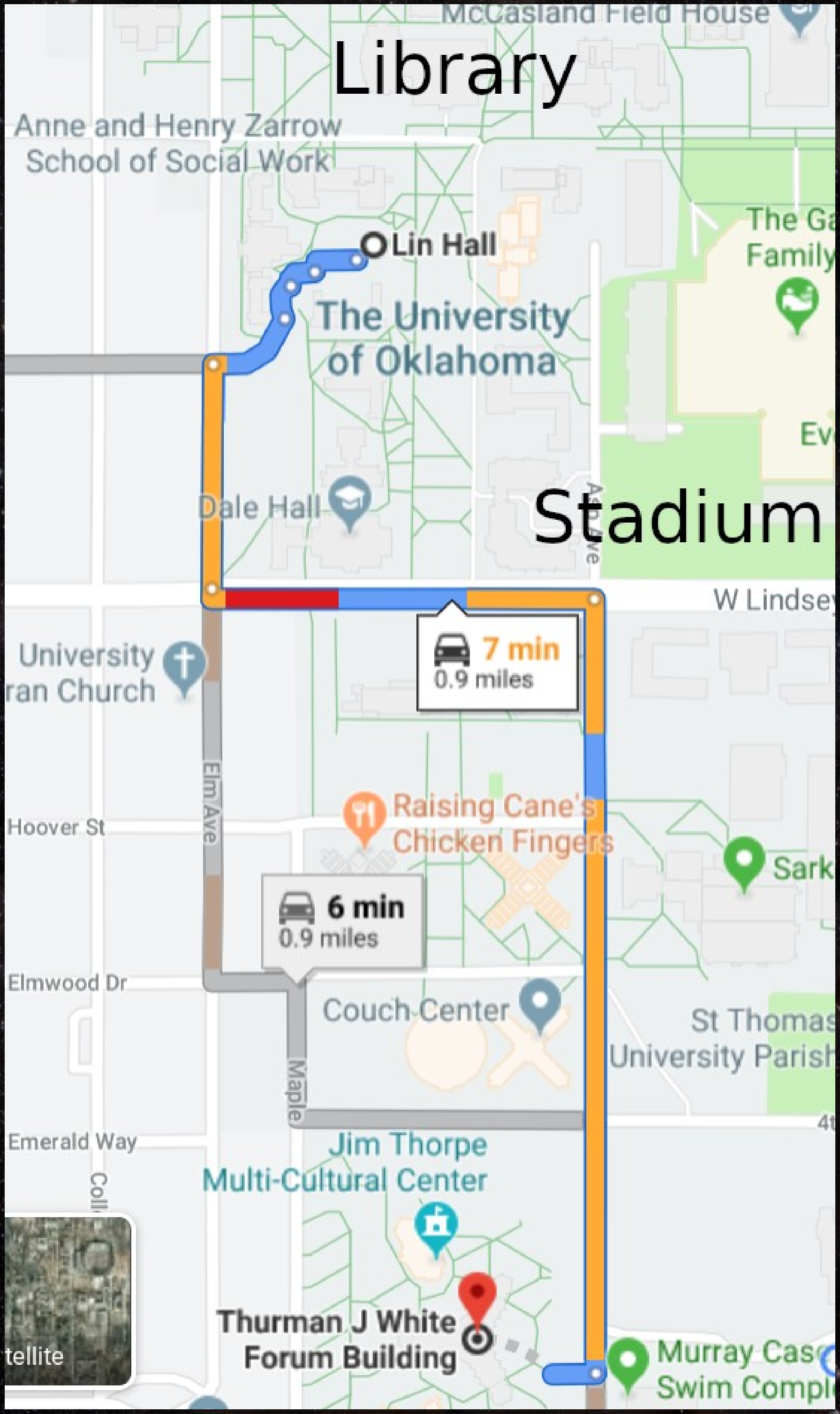
**Free Star Party!**

observatory.ou.edu

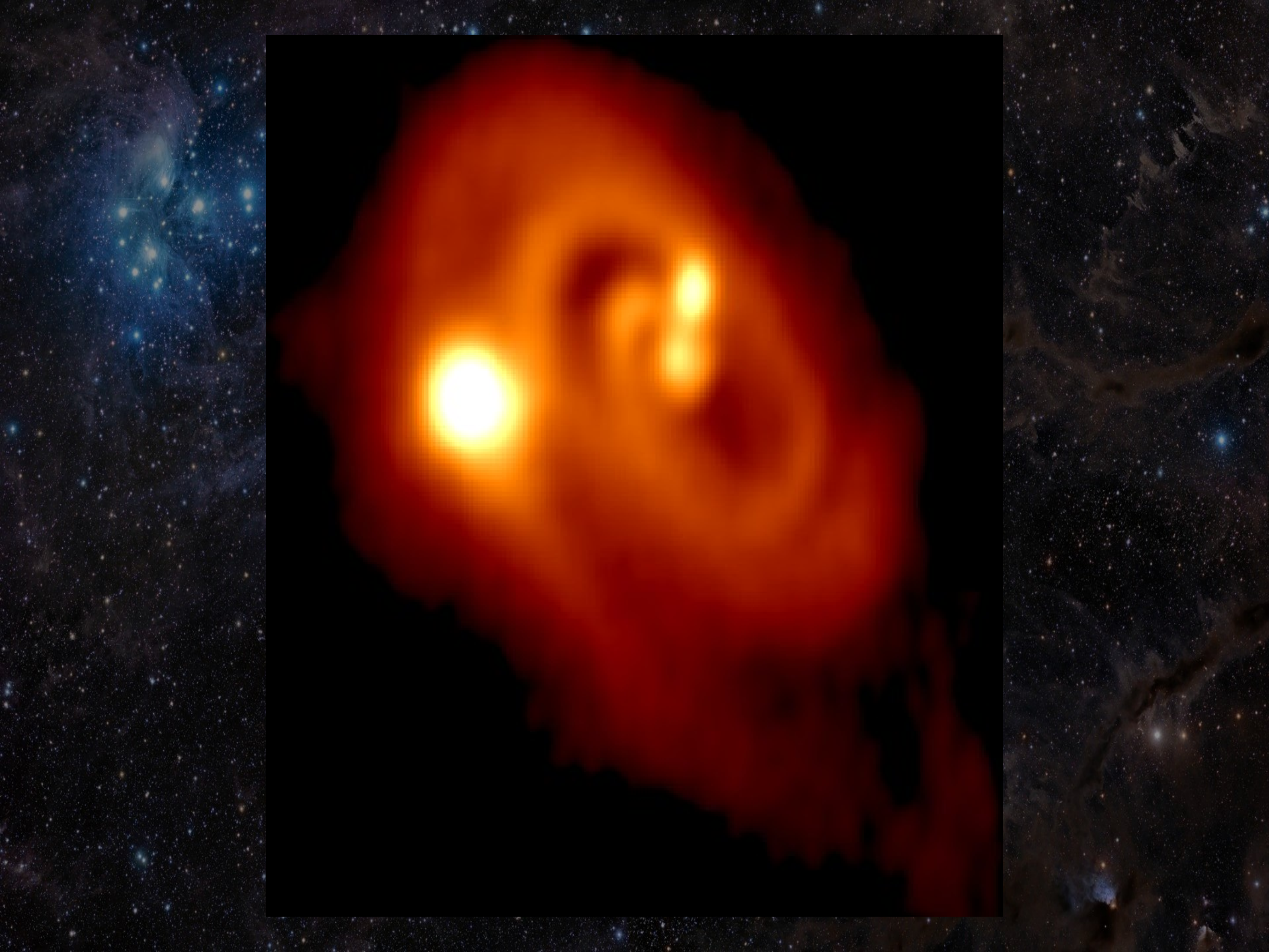
When: **Tonight @830**

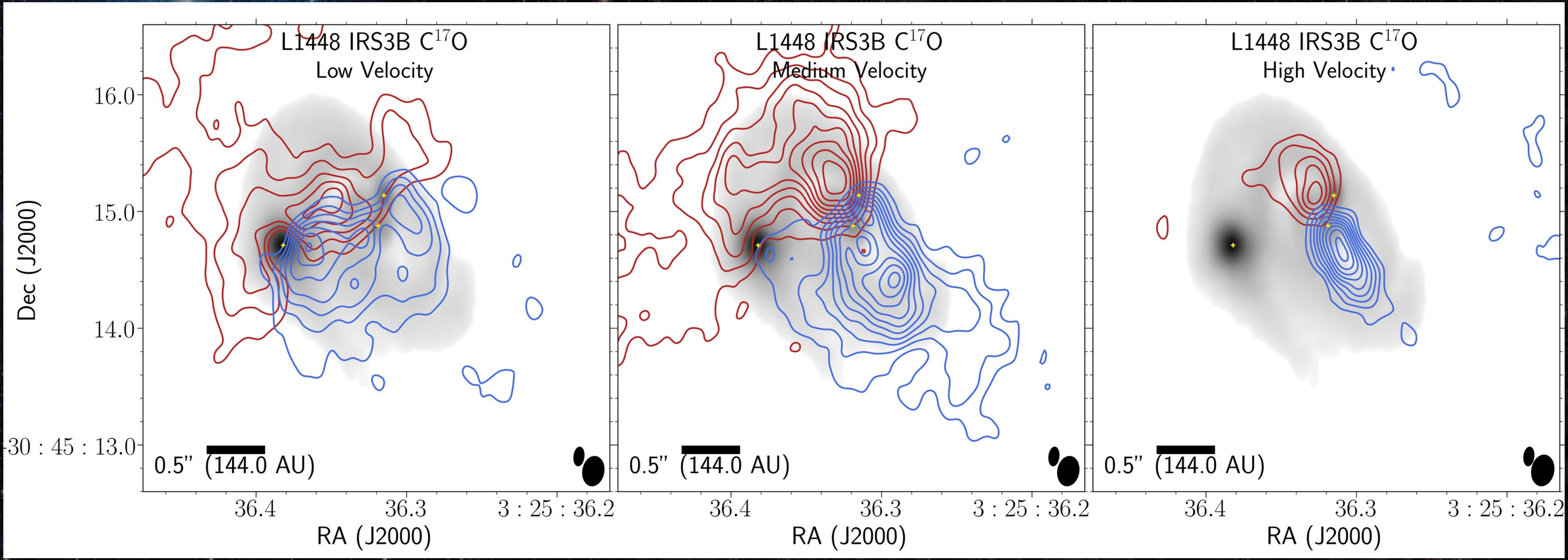
Where: **Lin Hall Roof**

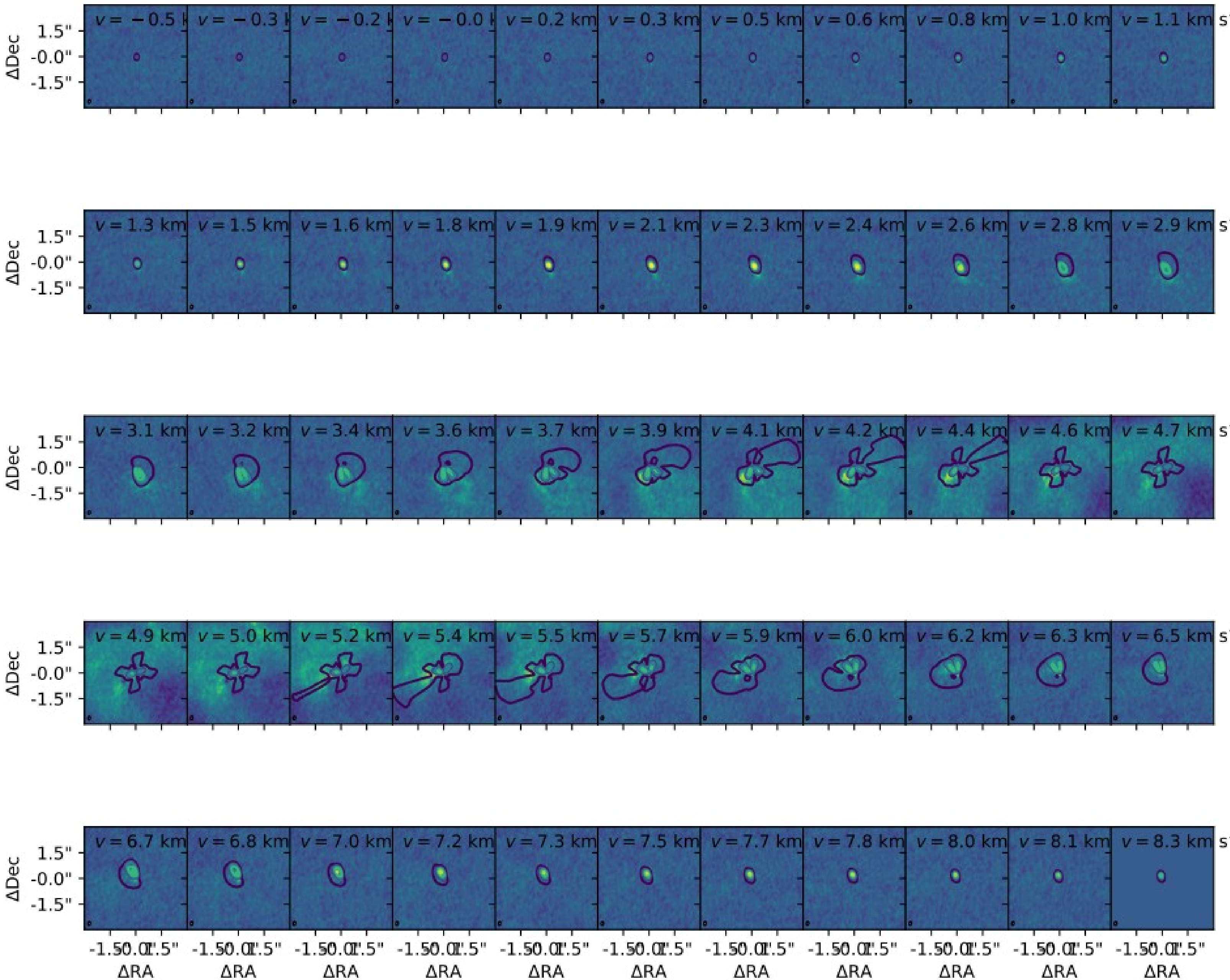
Who can come: **Everyone**

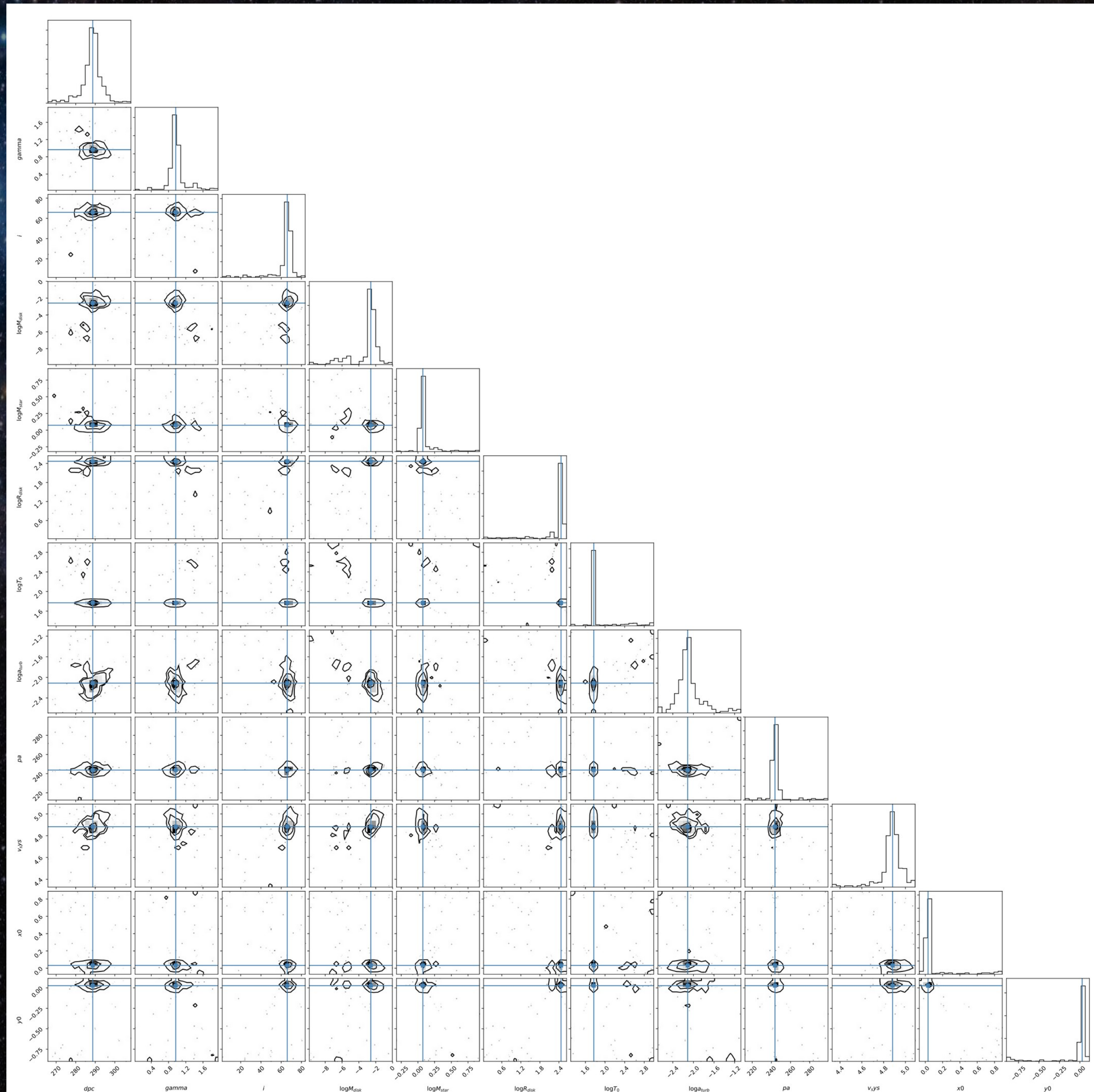


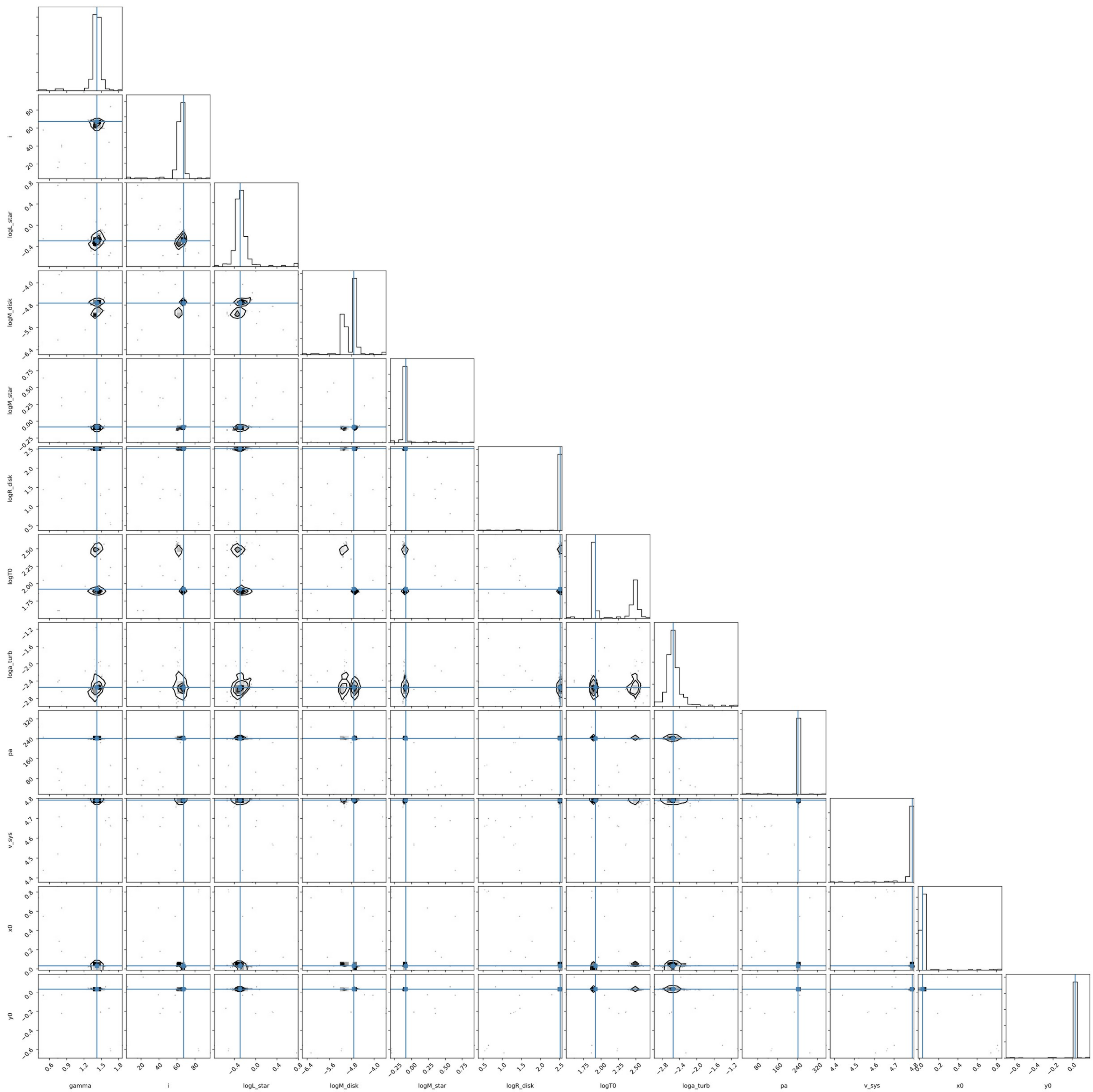
# Supplementary Material

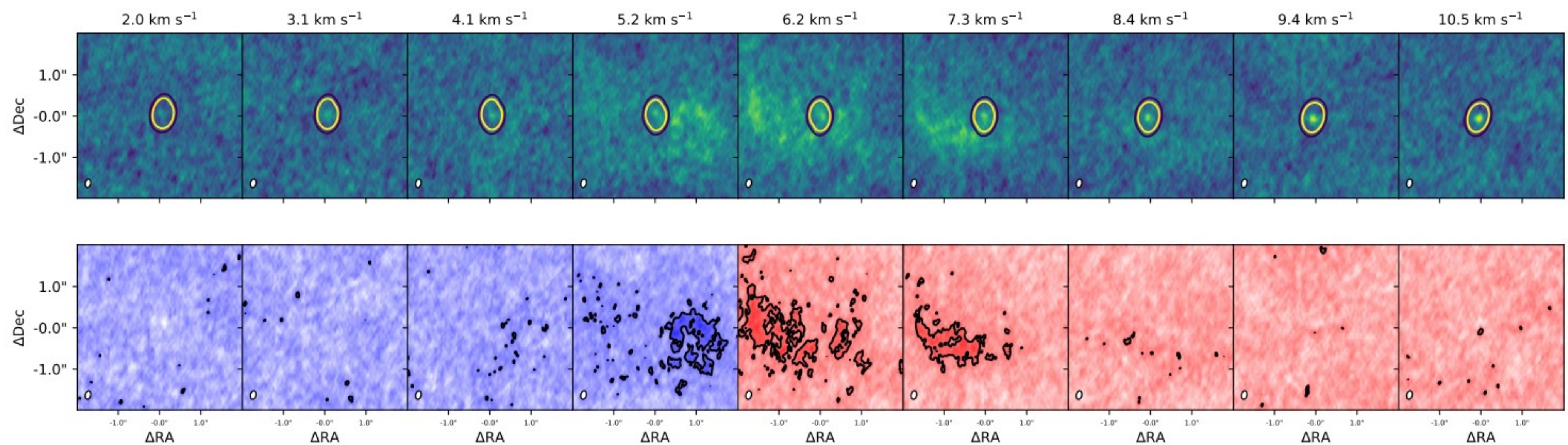



L1448 IRS3B C17O
Low Velocity
L1448 IRS3B C17O
Medium Velocity
L1448 IRS3B C17O
High Velocity
16.0
15.0
14.0
-30 : 45 : 13.0
Dec (J2000)
0.5" (144.0 AU)
0.5" (144.0 AU)
0.5" (144.0 AU)
36.4
36.3
3 : 25 : 36.2
RA (J2000)
36.4
36.3
3 : 25 : 36.2
RA (J2000)
36.4
36.3
3 : 25 : 36.2
RA (J2000)

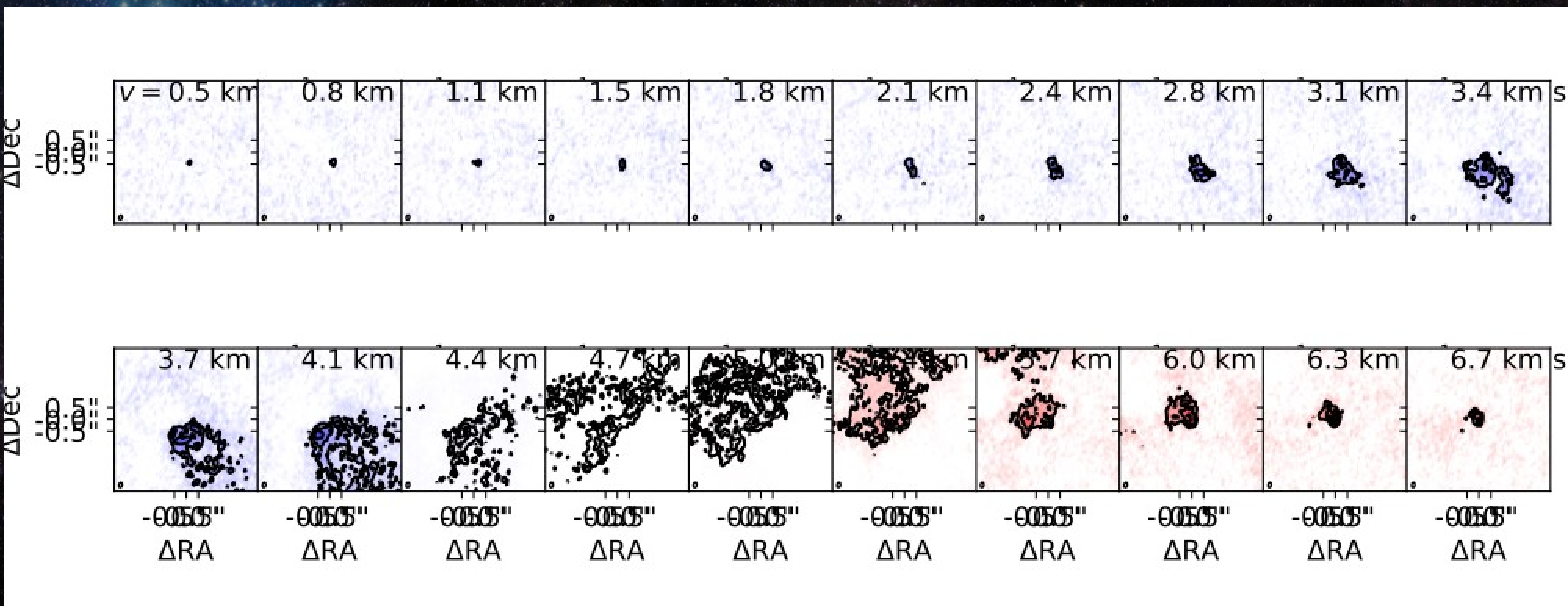

v = −0.5 k
v = −0.3 k
v = −0.2 k
v = −0.0 k
v = 0.2 km
v = 0.3 km
v = 0.5 km
v = 0.6 km
v = 0.8 km
v = 1.0 km
v = 1.1 km s⁻
v = 1.3 km
v = 1.5 km
v = 1.6 km
v = 1.8 km
v = 1.9 km
v = 2.1 km
v = 2.3 km
v = 2.4 km
v = 2.6 km
v = 2.8 km
v = 2.9 km s⁻
v = 3.1 km
v = 3.2 km
v = 3.4 km
v = 3.6 km
v = 3.7 km
v = 3.9 km
v = 4.1 km
v = 4.2 km
v = 4.4 km
v = 4.6 km
v = 4.7 km s⁻
v = 4.9 km
v = 5.0 km
v = 5.2 km
v = 5.4 km
v = 5.5 km
v = 5.7 km
v = 5.9 km
v = 6.0 km
v = 6.2 km
v = 6.3 km
v = 6.5 km s⁻
v = 6.7 km
v = 6.8 km
v = 7.0 km
v = 7.2 km
v = 7.3 km
v = 7.5 km
v = 7.7 km
v = 7.8 km
v = 8.0 km
v = 8.1 km
v = 8.3 km s⁻
ΔDec
1.5"
-0.0"
-1.5"
ΔRA
-1.5 0.0 1.5"


dpc
gamma
i
logM_disk
logM_star
logR_disk
logT_0
loga_turb
pa
v_sys
x0
y0


gamma
i
logL_star
logM_disk
logM_star
logR_disk
logT0
loga_turb
pa
v_sys
x0
y0



2.0 km s$^{-1}$
3.1 km s$^{-1}$
4.1 km s$^{-1}$
5.2 km s$^{-1}$
6.2 km s$^{-1}$
7.3 km s$^{-1}$
8.4 km s$^{-1}$
9.4 km s$^{-1}$
10.5 km s$^{-1}$
ΔDec
1.0"
-0.0"
-1.0"
ΔRA



v = 0.5 km
0.8 km
1.1 km
1.5 km
1.8 km
2.1 km
2.4 km
2.8 km
3.1 km
3.4 km s
ΔDec
3.7 km
4.1 km
4.4 km
4.7 km
6.0 km
6.3 km
6.7 km s
ΔDec
ΔRA
ΔRA
ΔRA
ΔRA
ΔRA
ΔRA
ΔRA
ΔRA
ΔRA
ΔRA

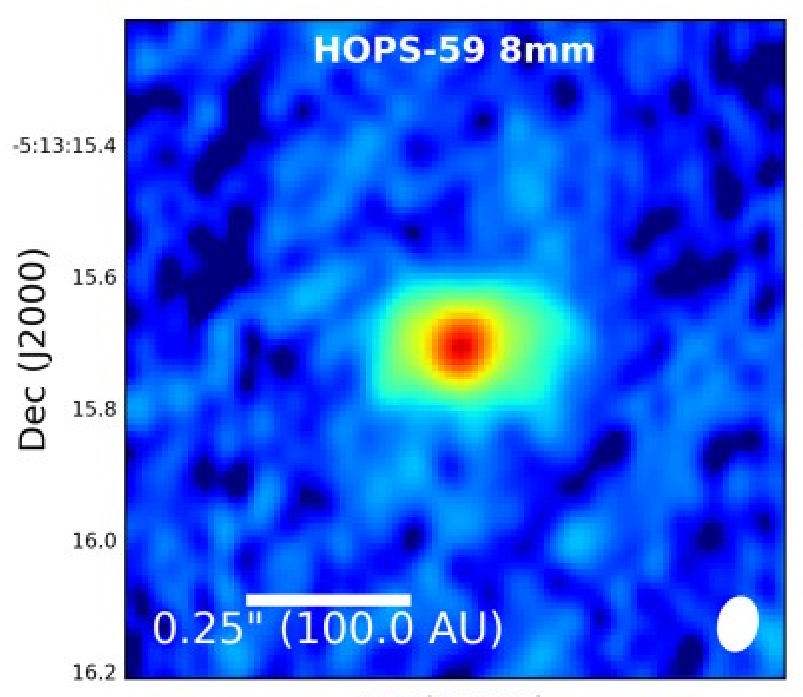
# Interferometry

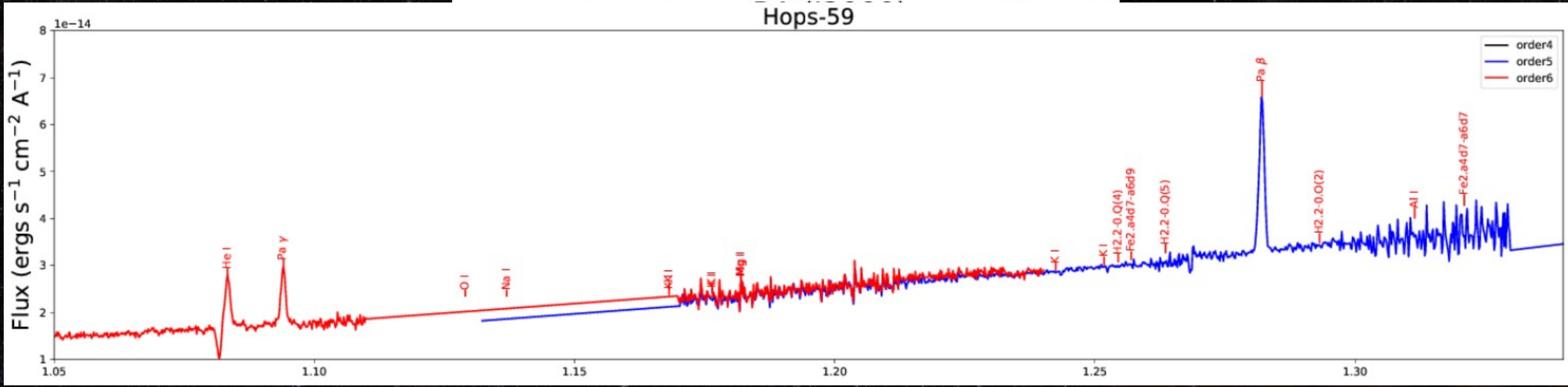
- Combine smaller telescopes to make an effective large telescope

VLA (New Mexico)

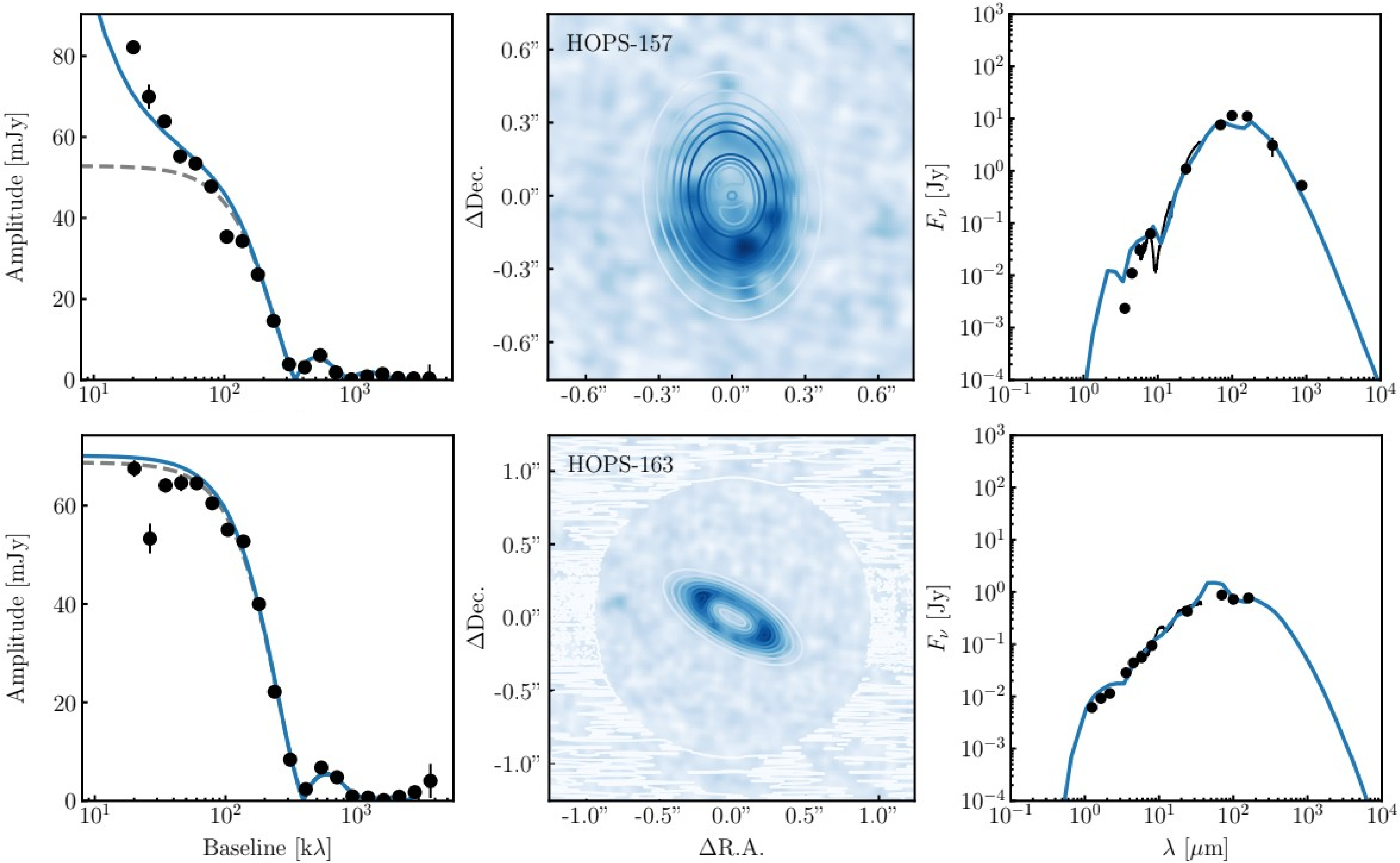
# Data Types

## Photometry vs Spectroscopy

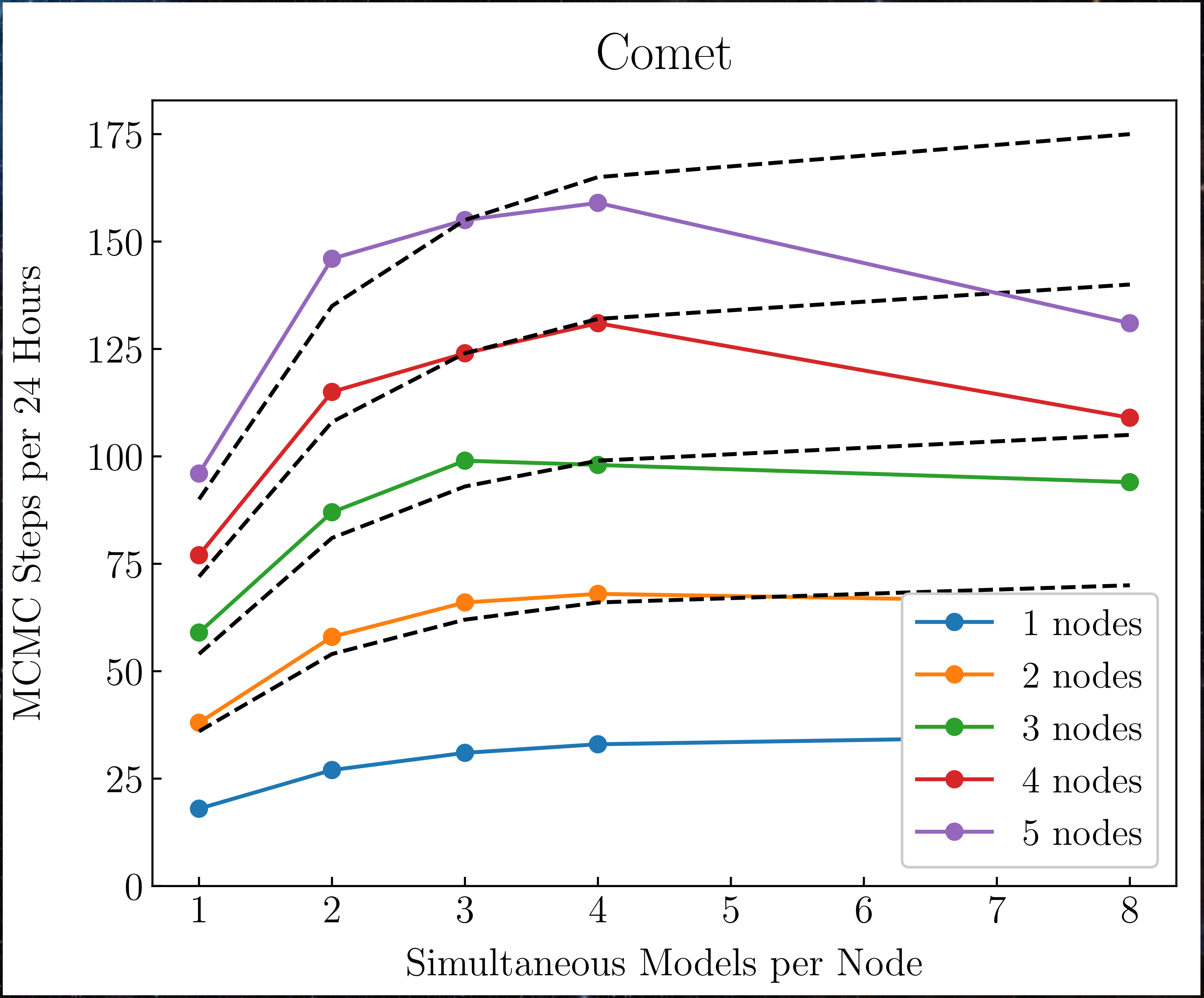


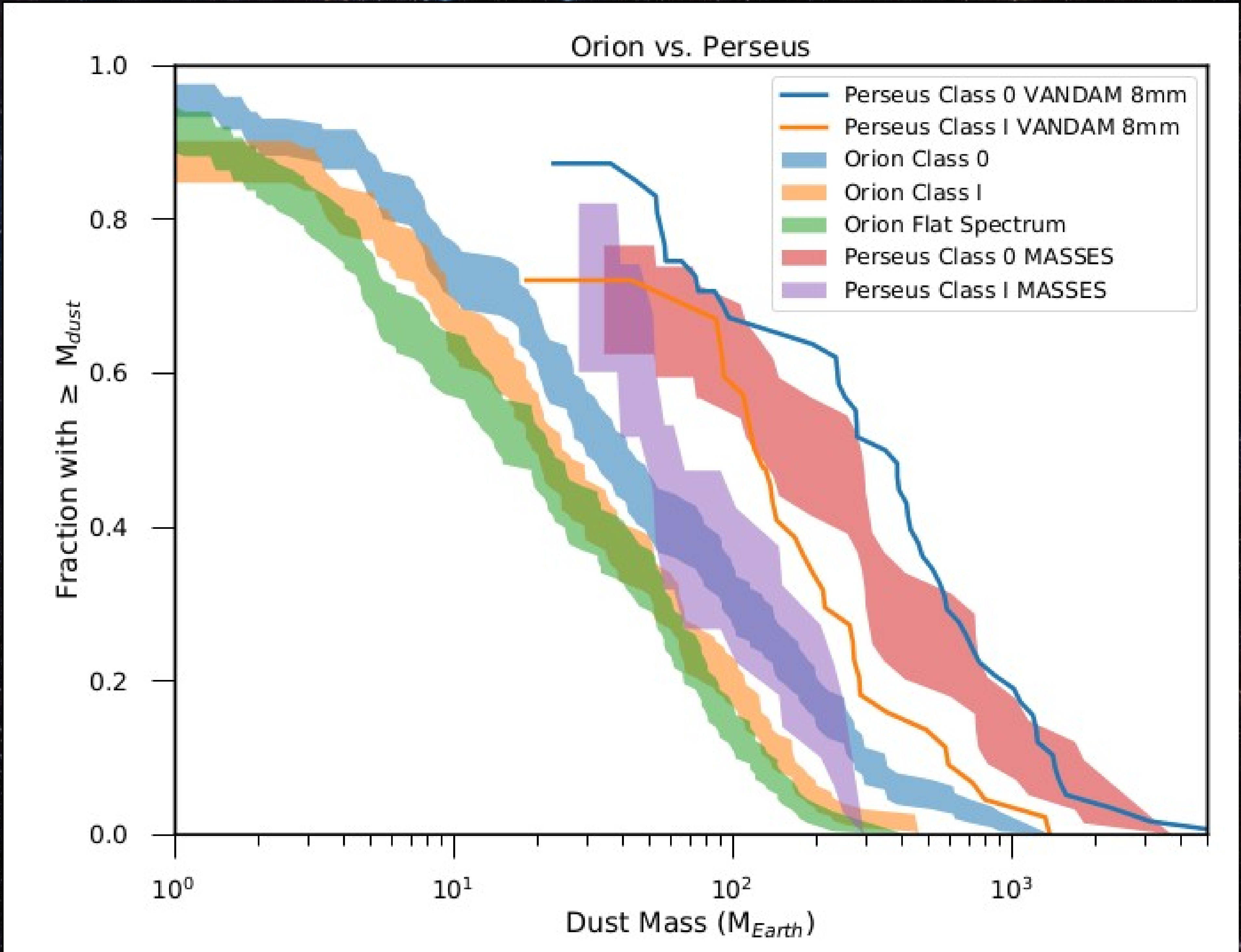



# What do we get?

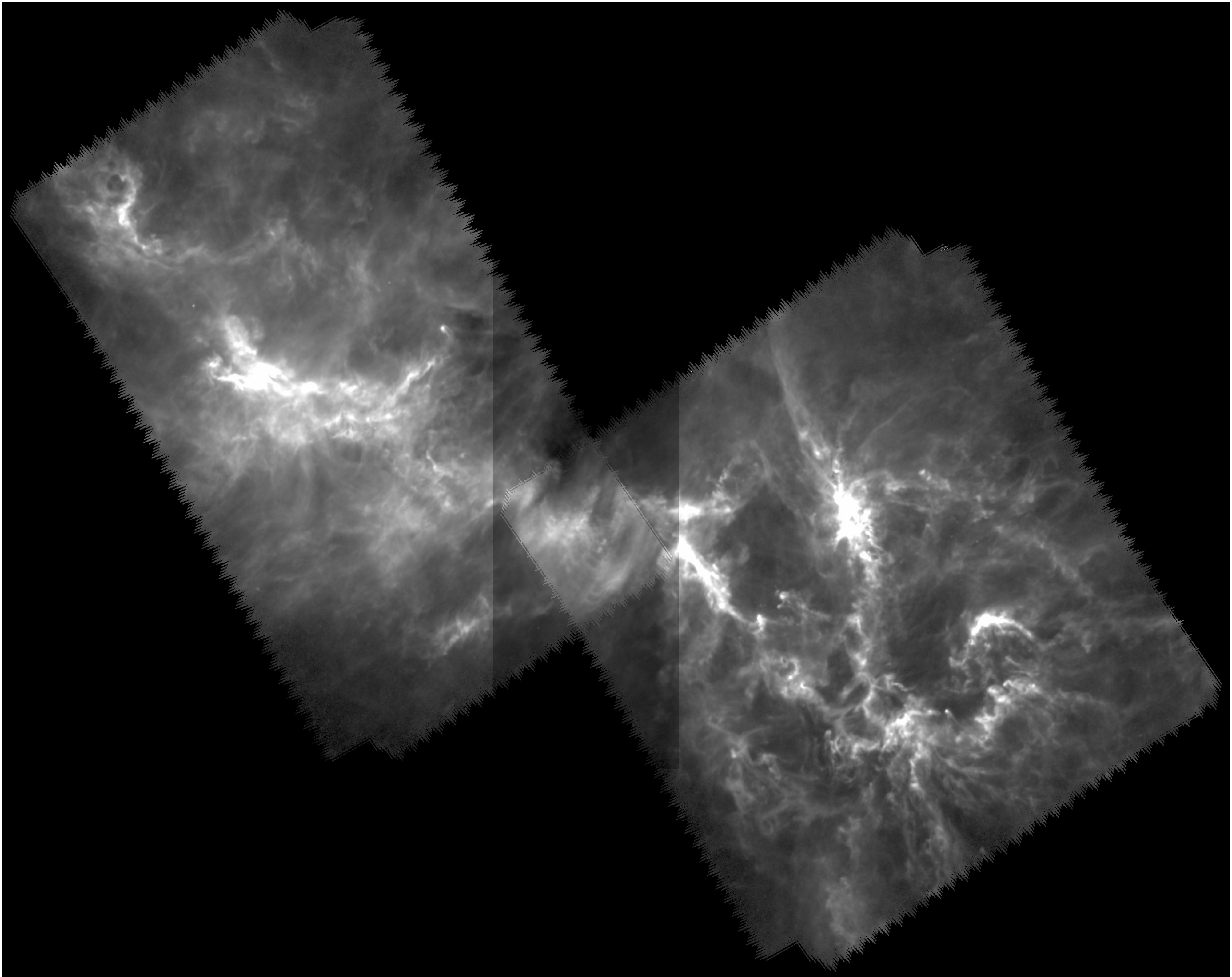


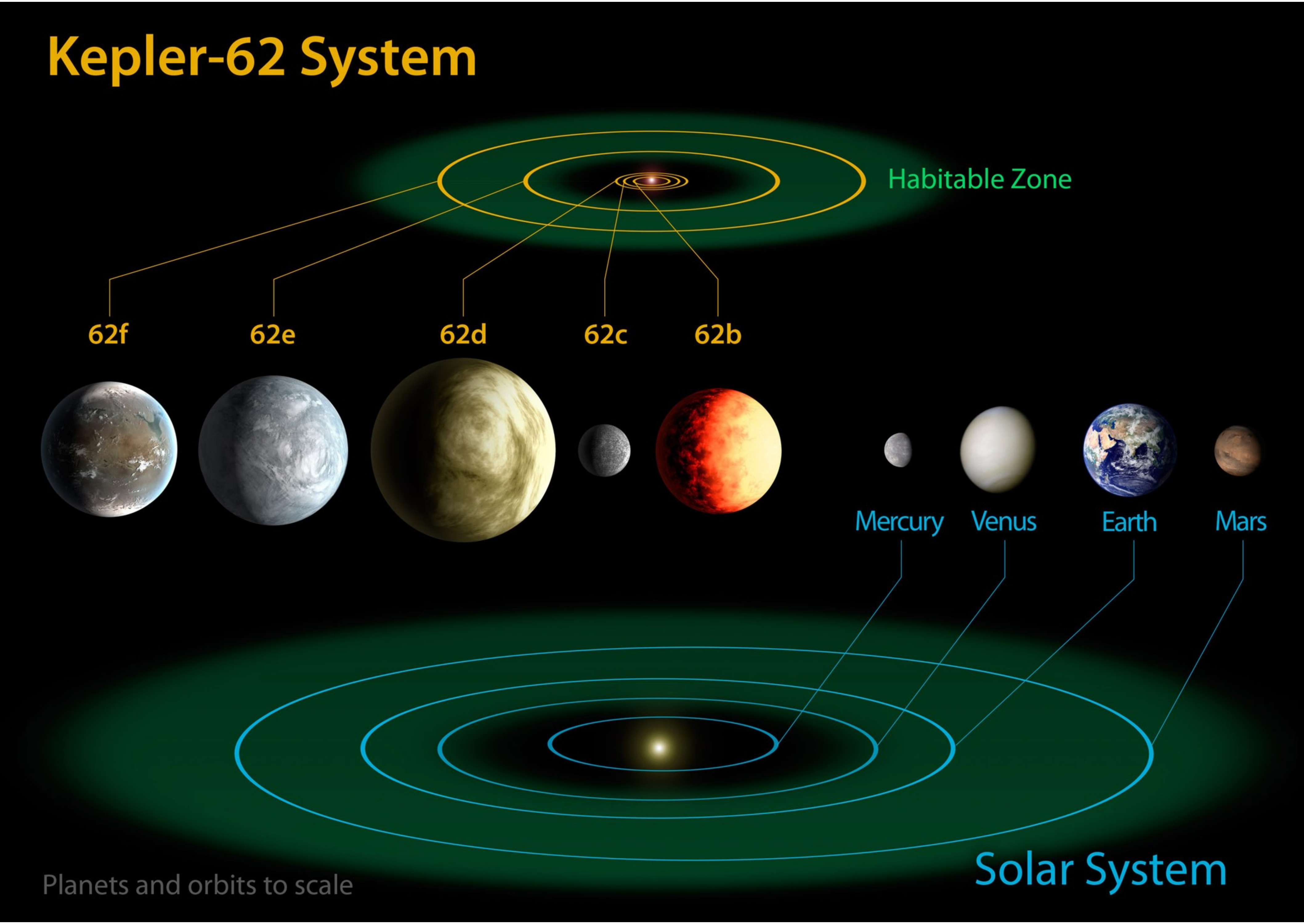
# PDSPY Scalability



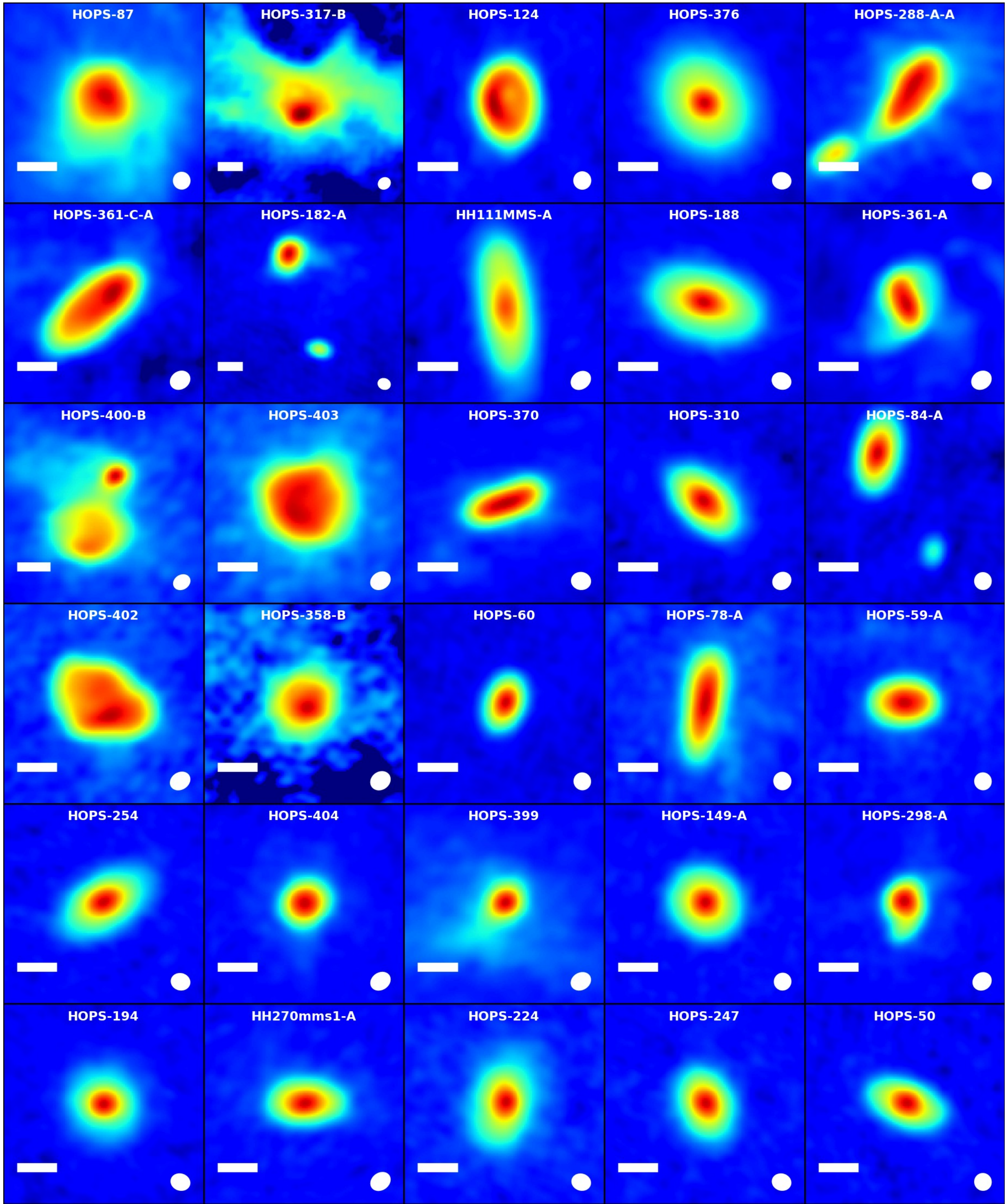


Orion vs. Perseus
Perseus Class 0 VANDAM 8mm
Perseus Class I VANDAM 8mm
Orion Class 0
Orion Class I
Orion Flat Spectrum
Perseus Class 0 MASSES
Perseus Class I MASSES
Fraction with ≥ $M_{dust}$
Dust Mass ($M_{Earth}$)
1.0
0.8
0.6
0.4
0.2
0.0
$10^0$
$10^1$
$10^2$
$10^3$

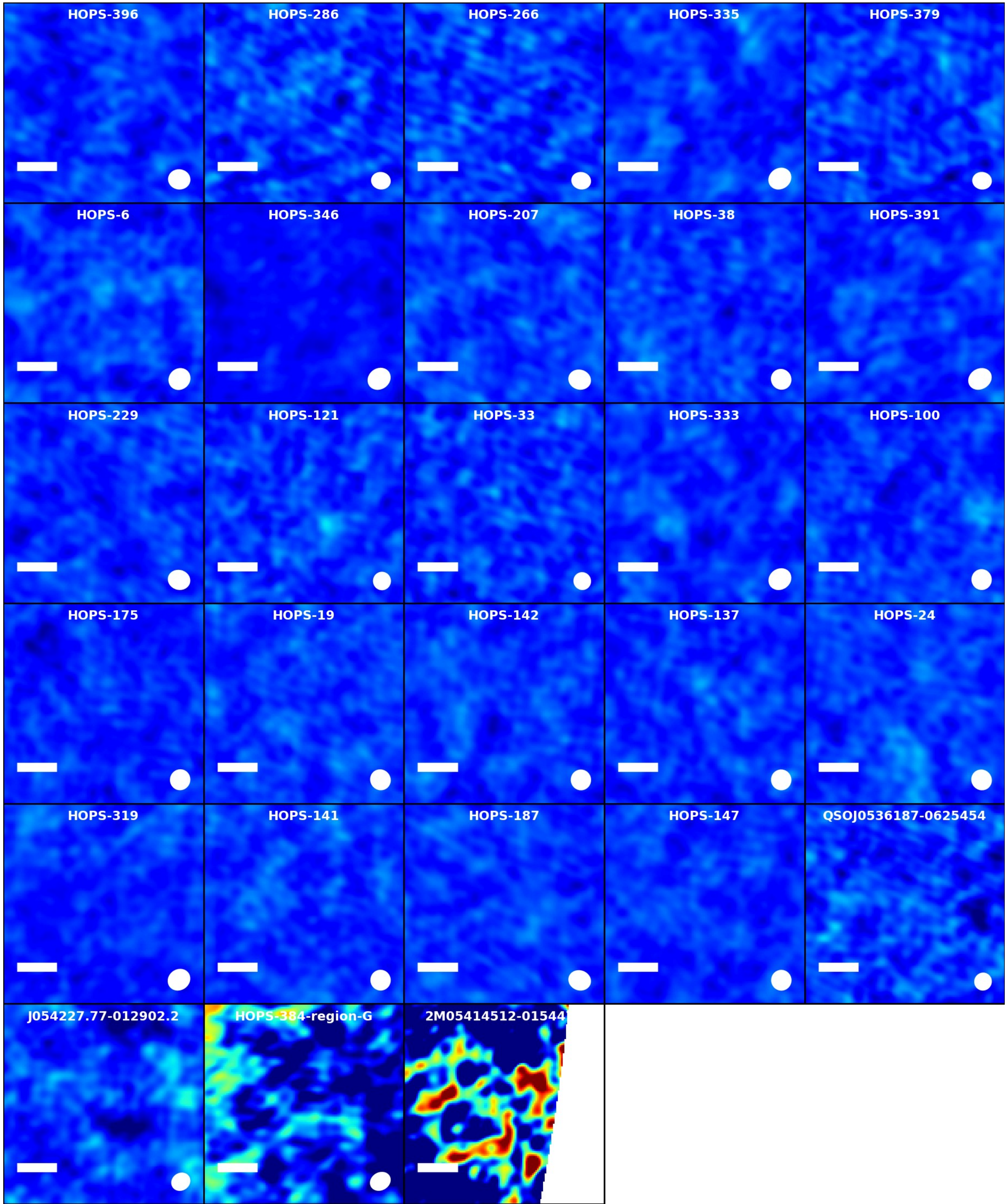



Kepler-62 System
Habitable Zone
62f
62e
62d
62c
62b
Mercury
Venus
Earth
Mars
Solar System
Planets and orbits to scale

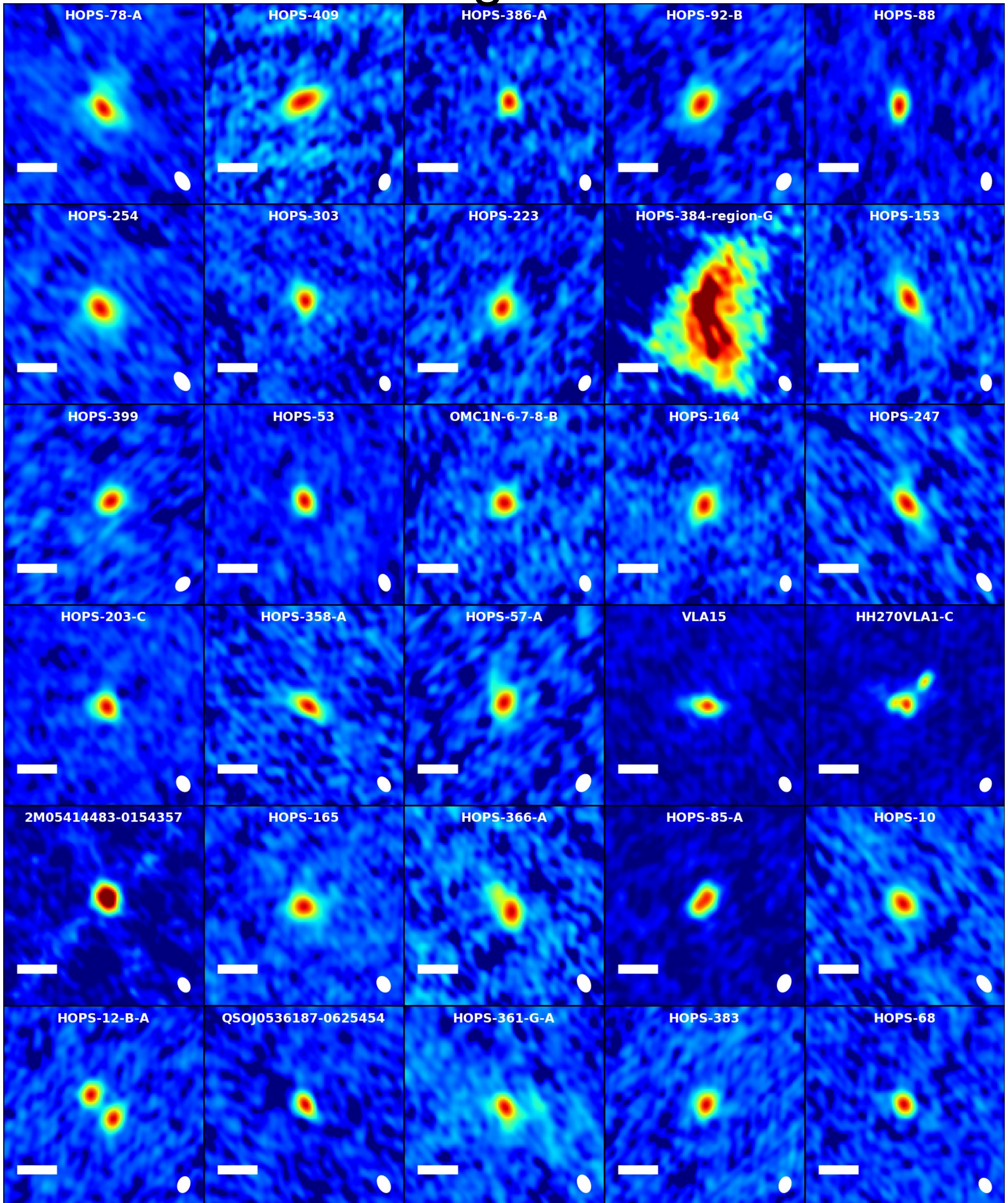
# ALMA Strong Detections



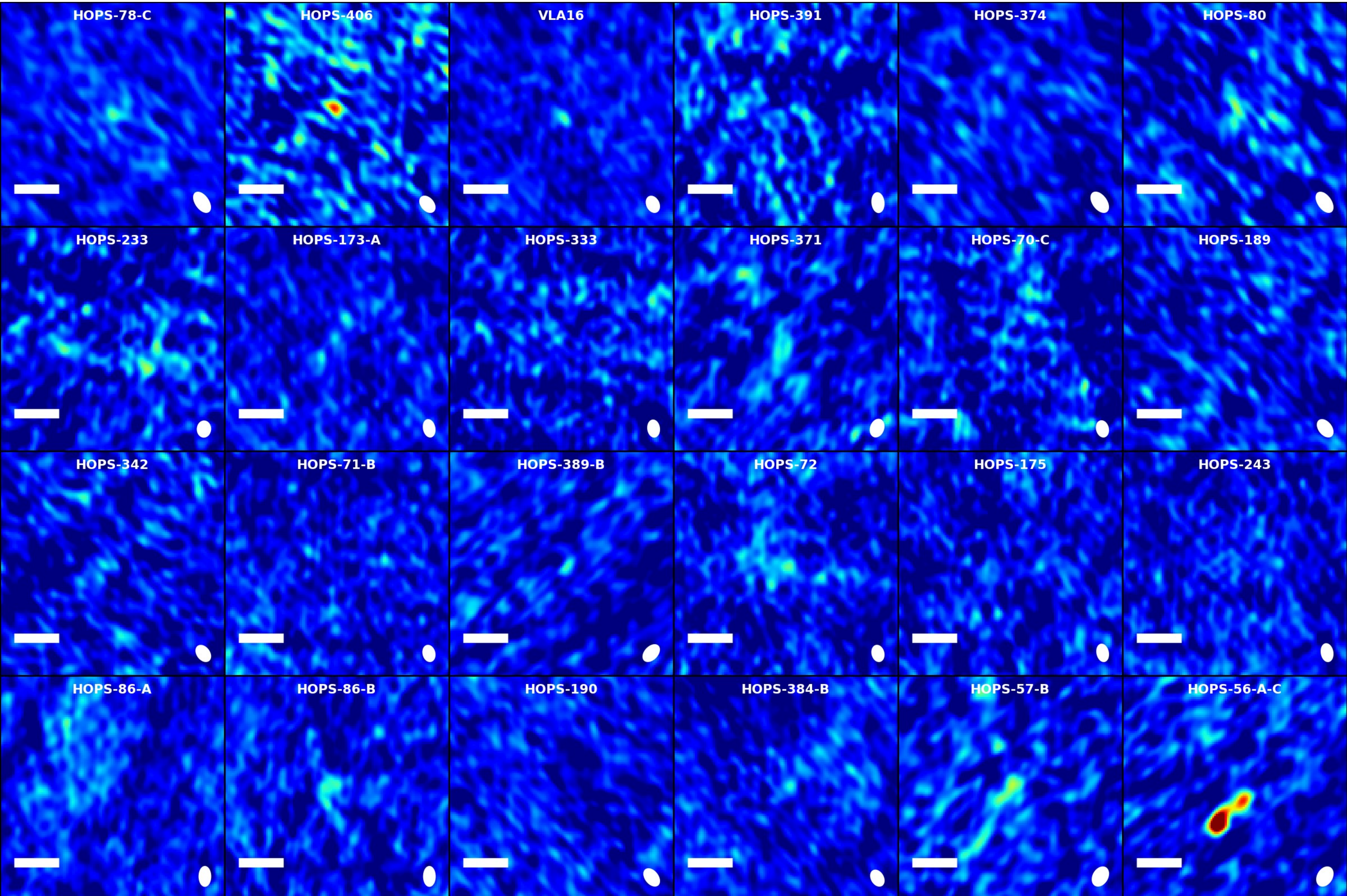
# ALMA Faint/Non Detections



# VLA Strong Detections



# VLA Faint/Non Detections



Strong VLA/ALMA Detections and their fits