First Look at Protostars

High Fidelity Modeling of the Youngest Stars with Schooner

John Tobin, Patrick Sheehan
Rajeeb Sharma, **Nick Reynolds**

Oklahoma Supercomputing Symposium 2019

Collaborators

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- HOPS
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Outline

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

Why Should You Care?

- Open Questions in Astronomy
  - Where did we come from?
  - What else is out there?
  - What will happen to us?

Why Should You Care?

- Open Questions in Astronomy
  - Where did we come from?
  - What else is out there?
  - What will happen to us?
- Questions we try to address
  - Where did we come from?
  - What else is out there (locally)?

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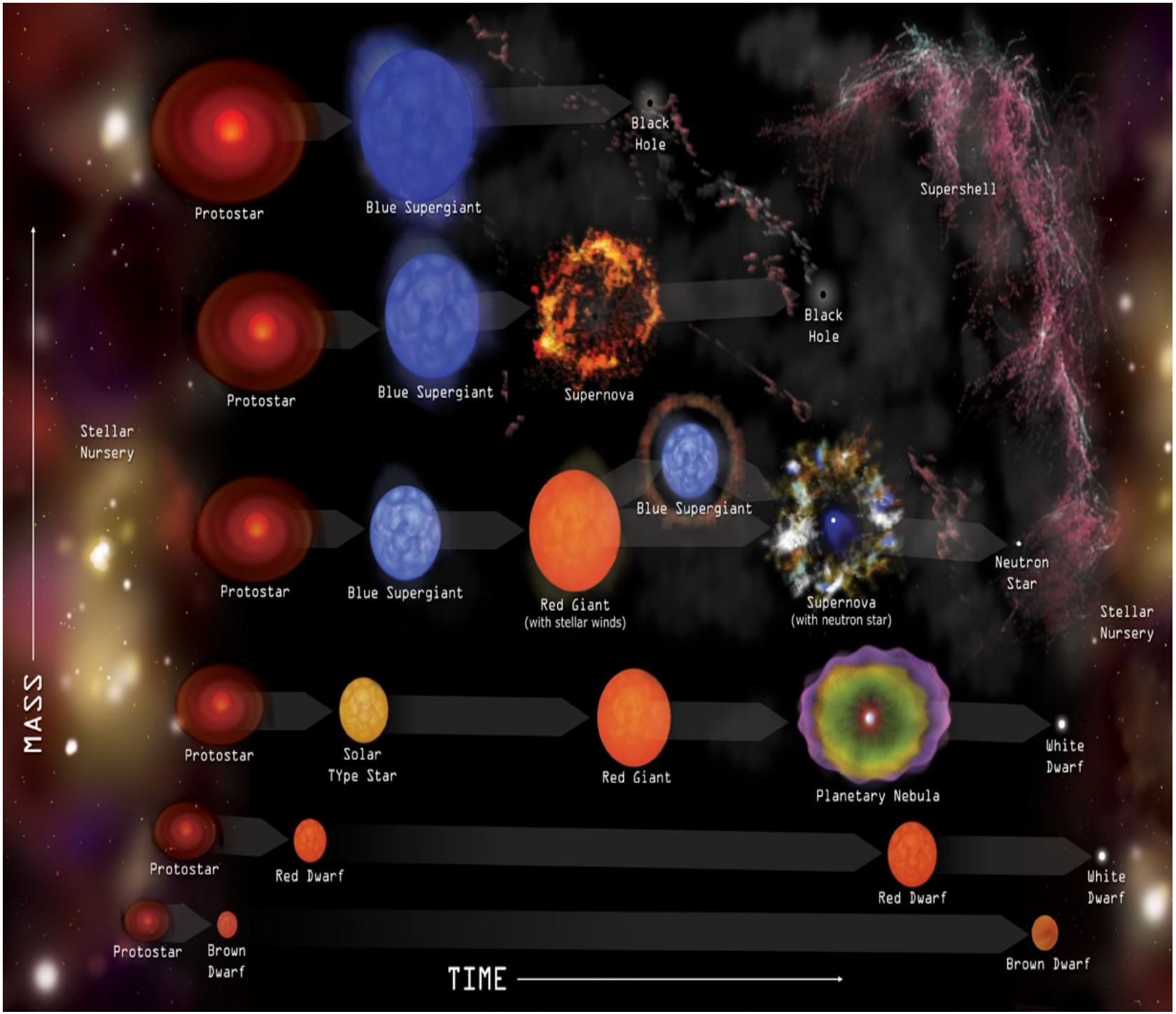
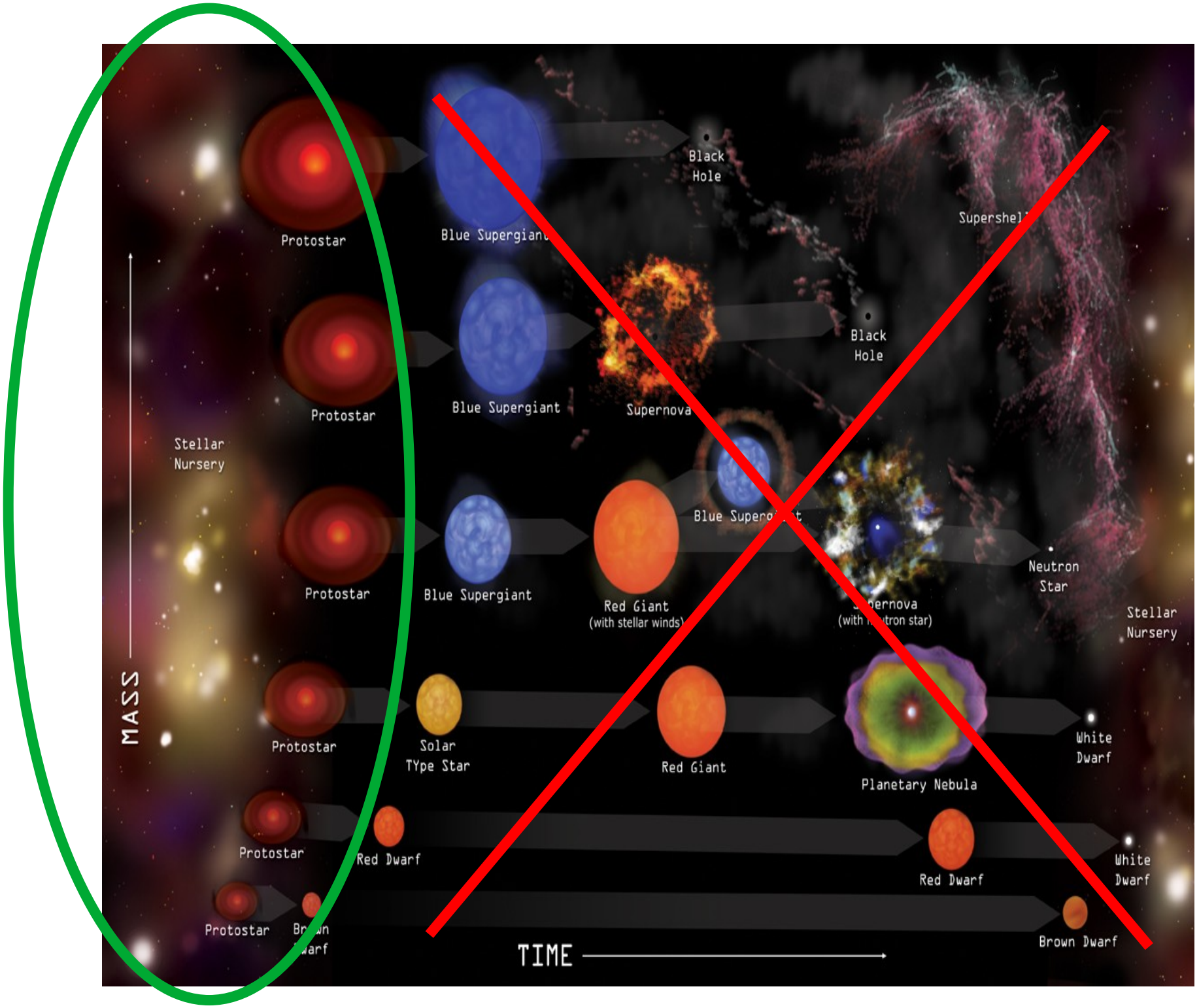

Protostar
Blue Supergiant
Black Hole
Supershell
Protostar
Blue Supergiant
Supernova
Black Hole
Stellar Nursery
Protostar
Blue Supergiant
Blue Supergiant
Red Giant (with stellar winds)
Supernova (with neutron star)
Neutron Star
Stellar Nursery
MASS
Protostar
Solar TYpe Star
Red Giant
Planetary Nebula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


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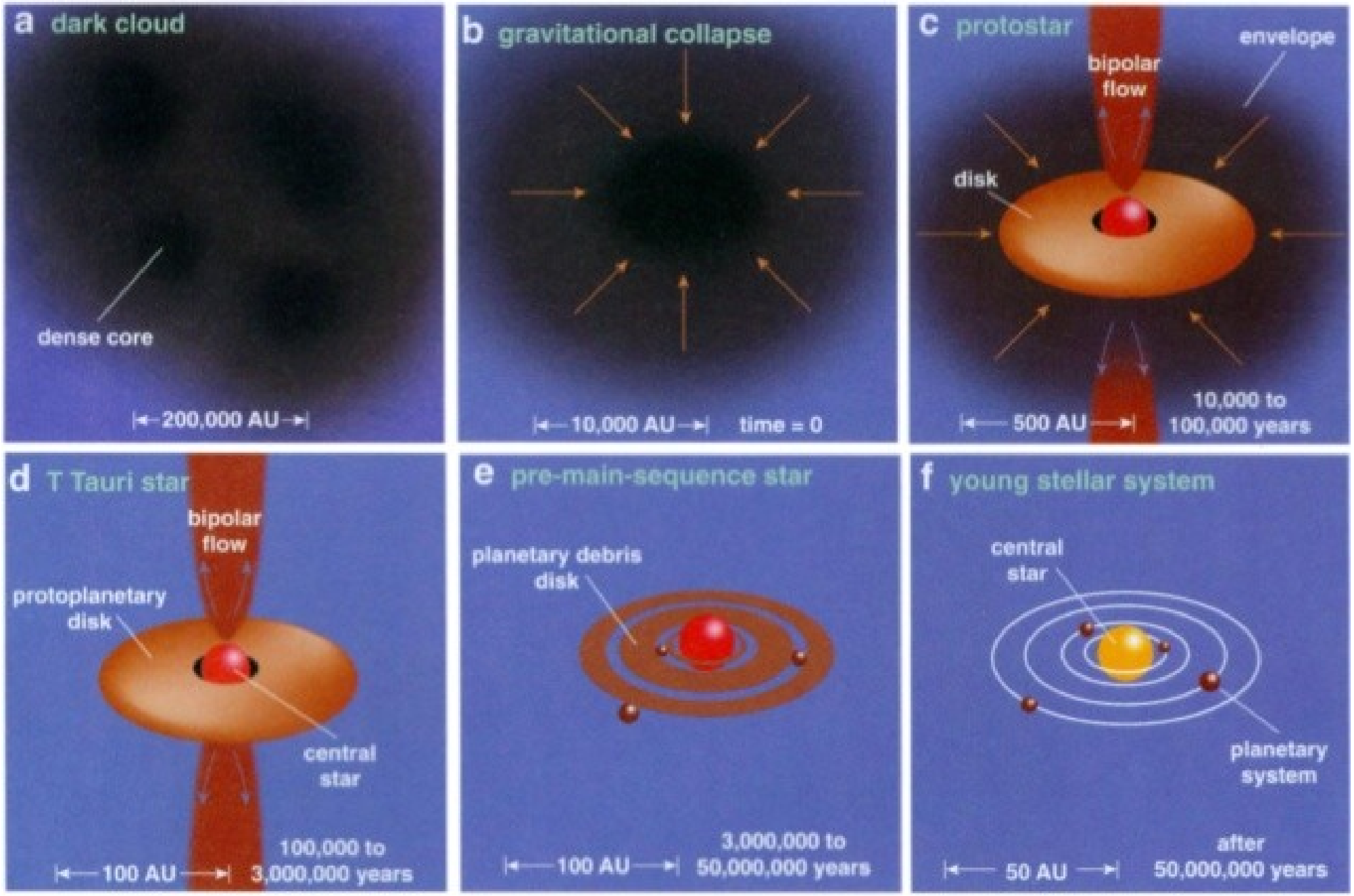
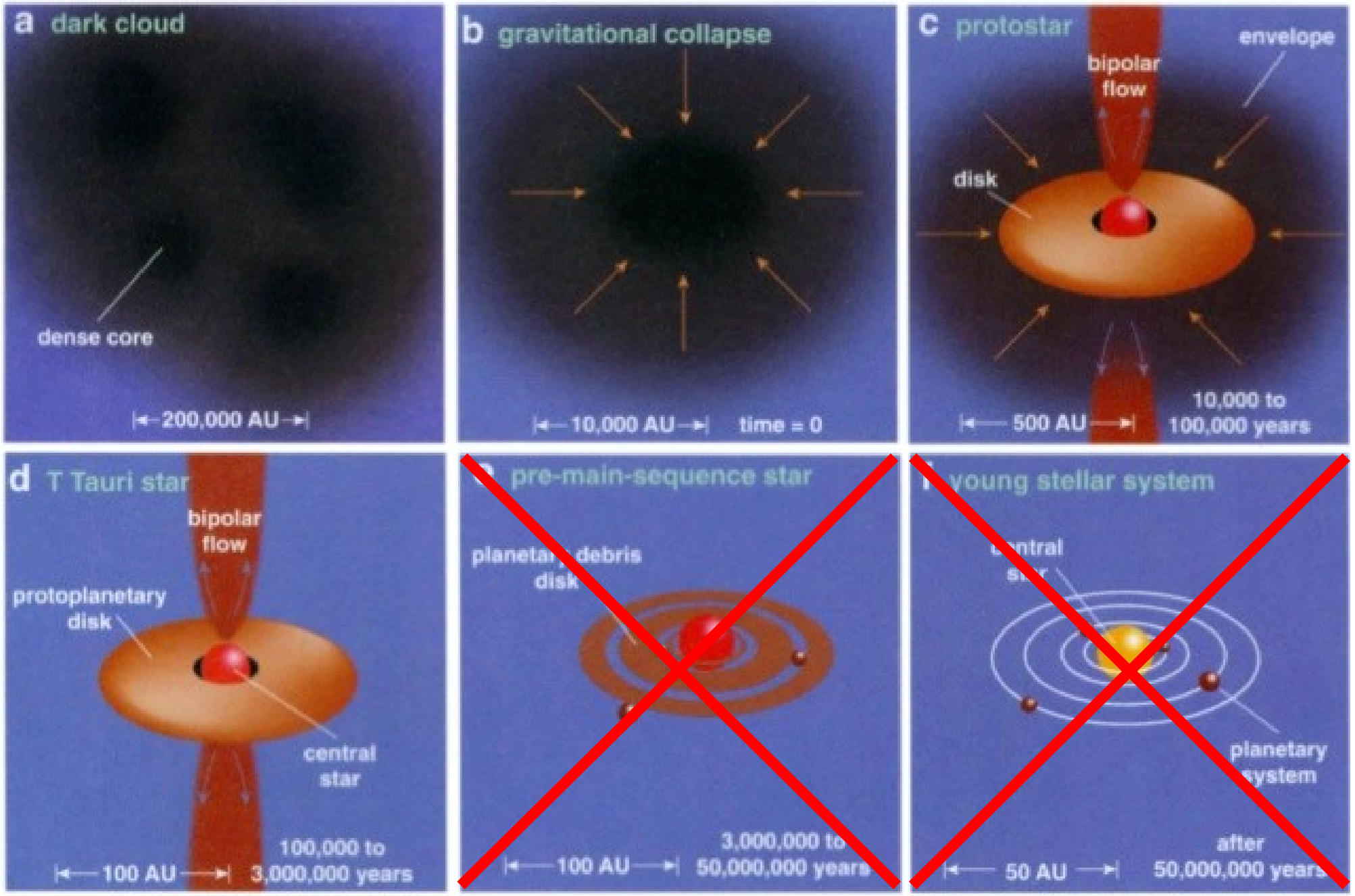
TIME


a dark cloud
dense core
200,000 AU
b gravitational collapse
10,000 AU
time = 0
c protostar
bipolar flow
envelope
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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young stellar system
planetary system
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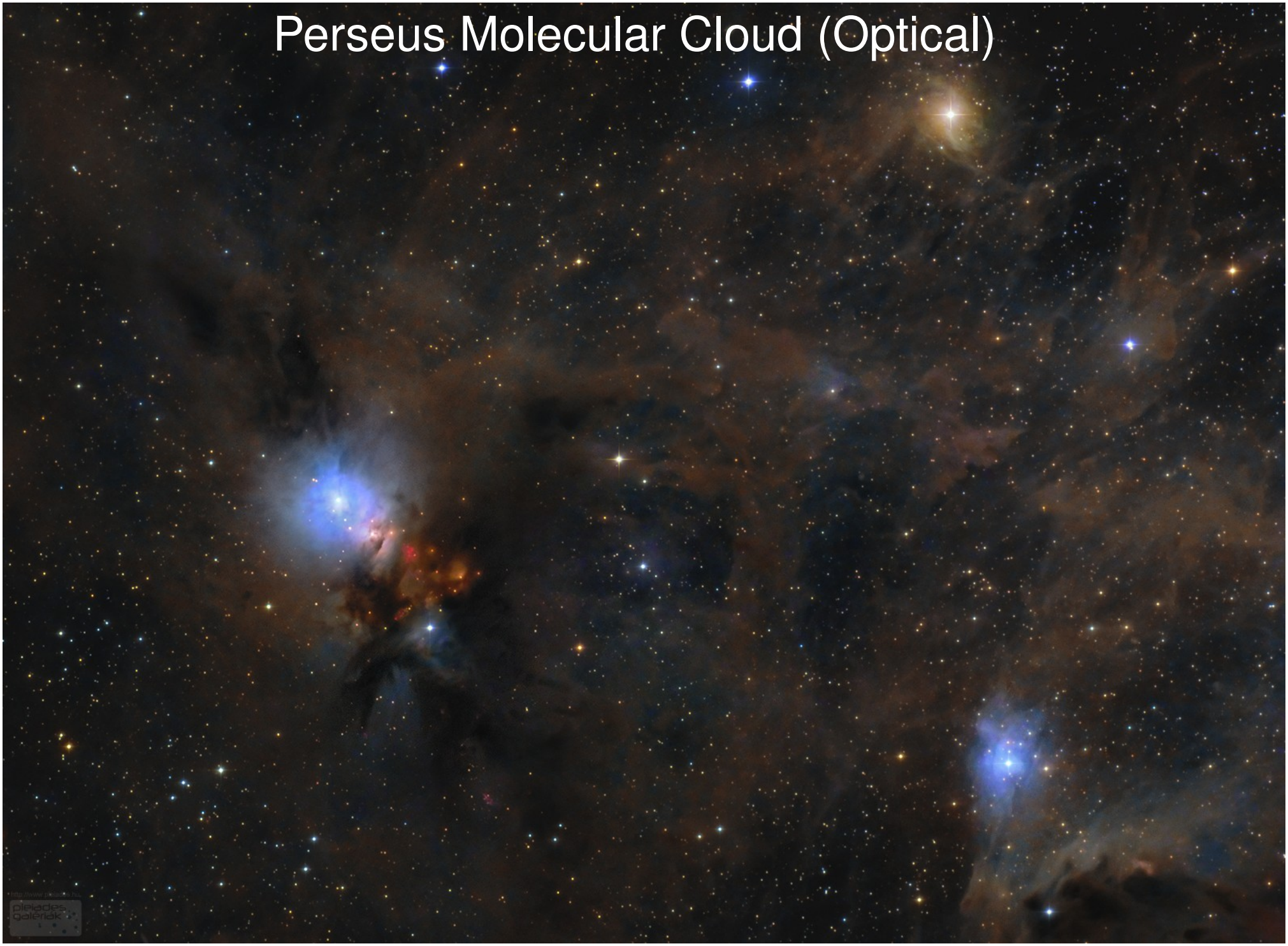
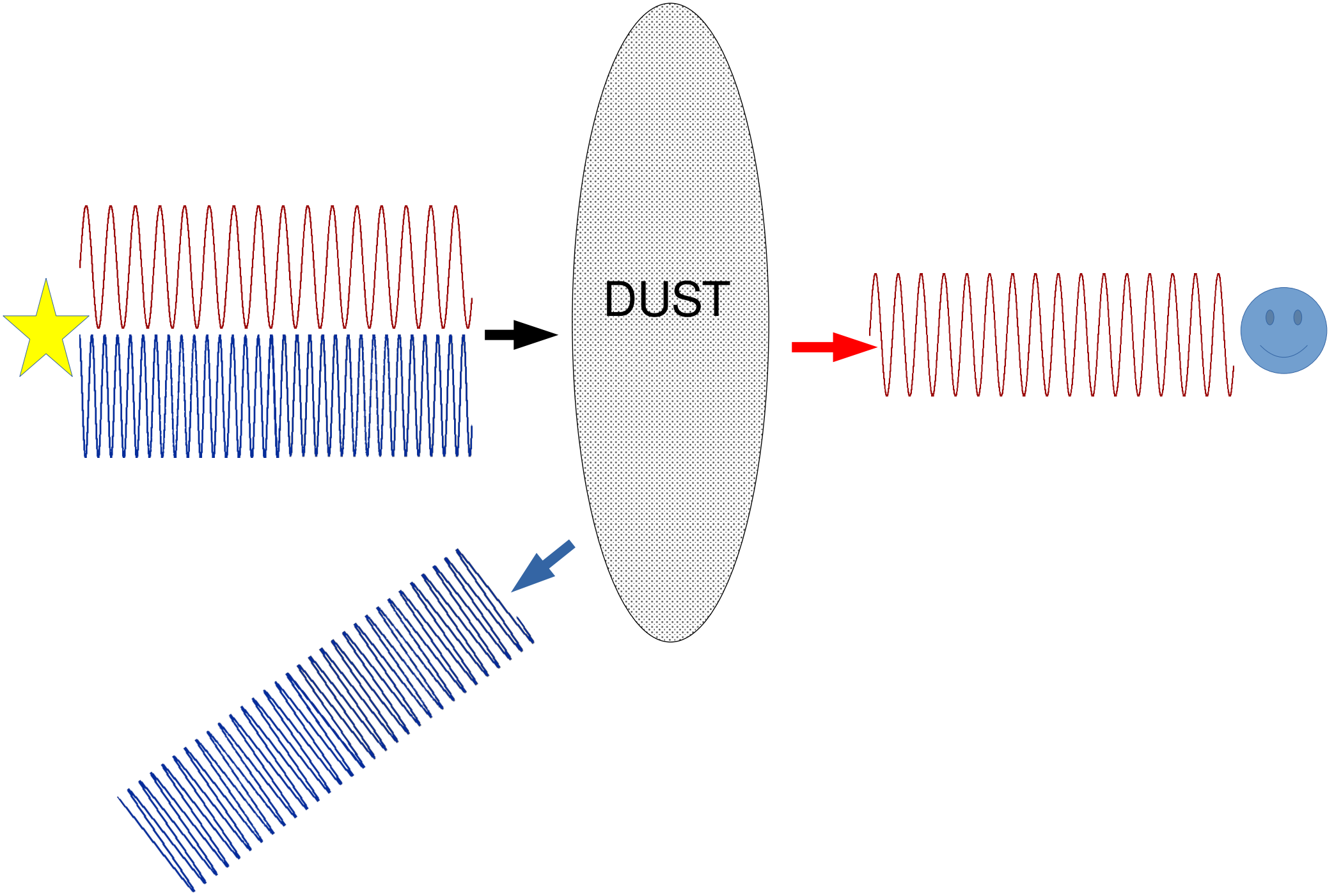
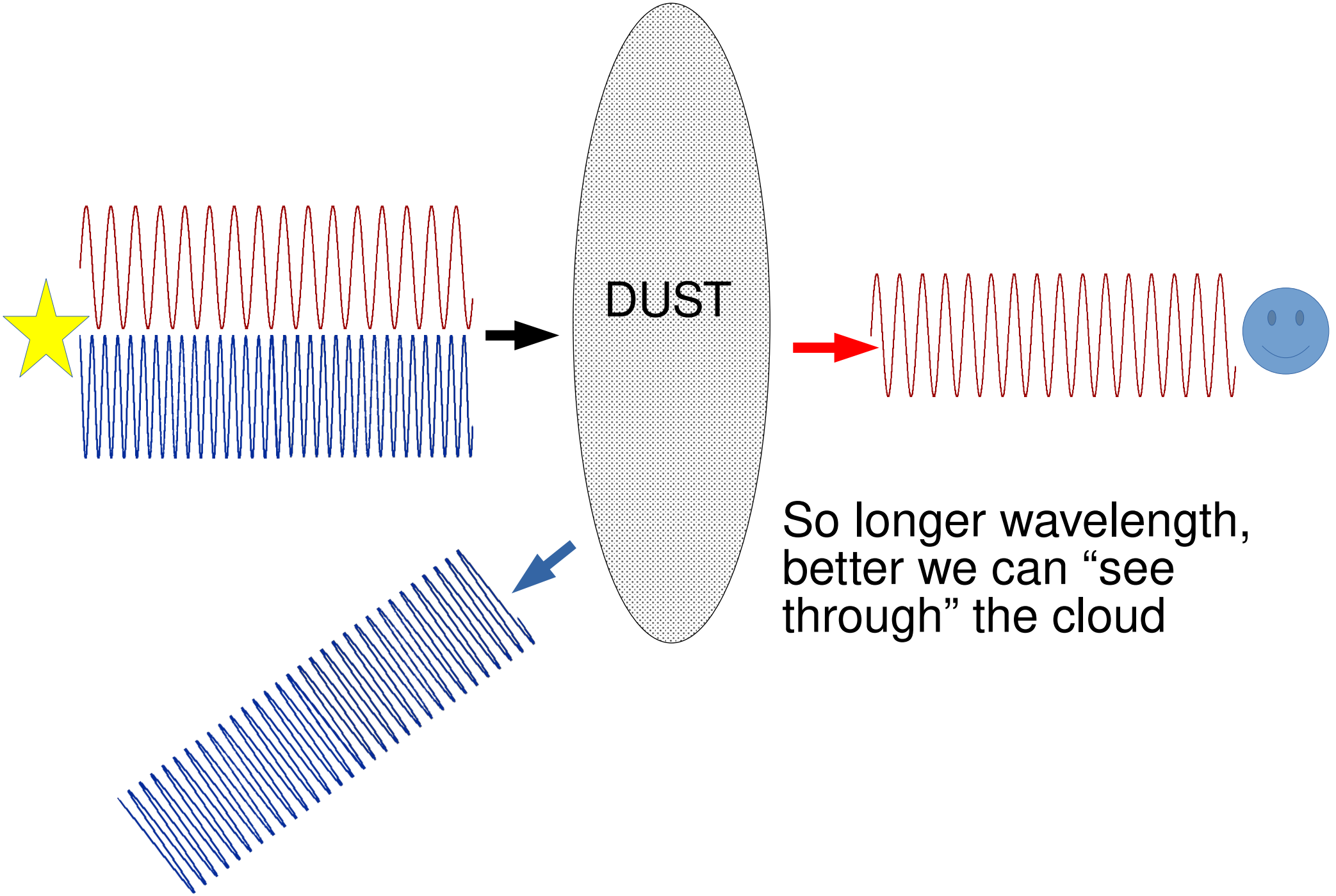
Perseus Molecular Cloud (Optical)



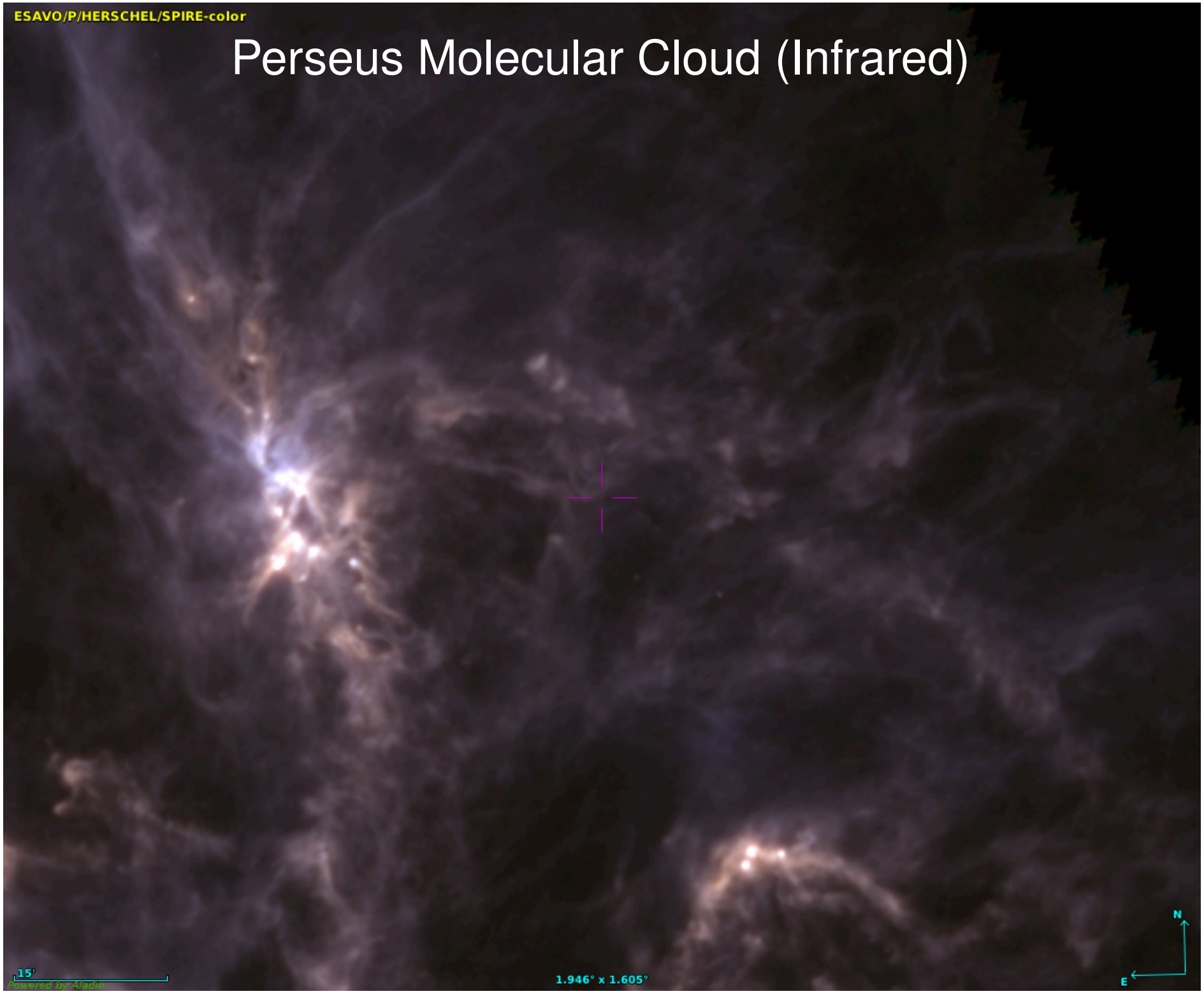
Dust Opacity



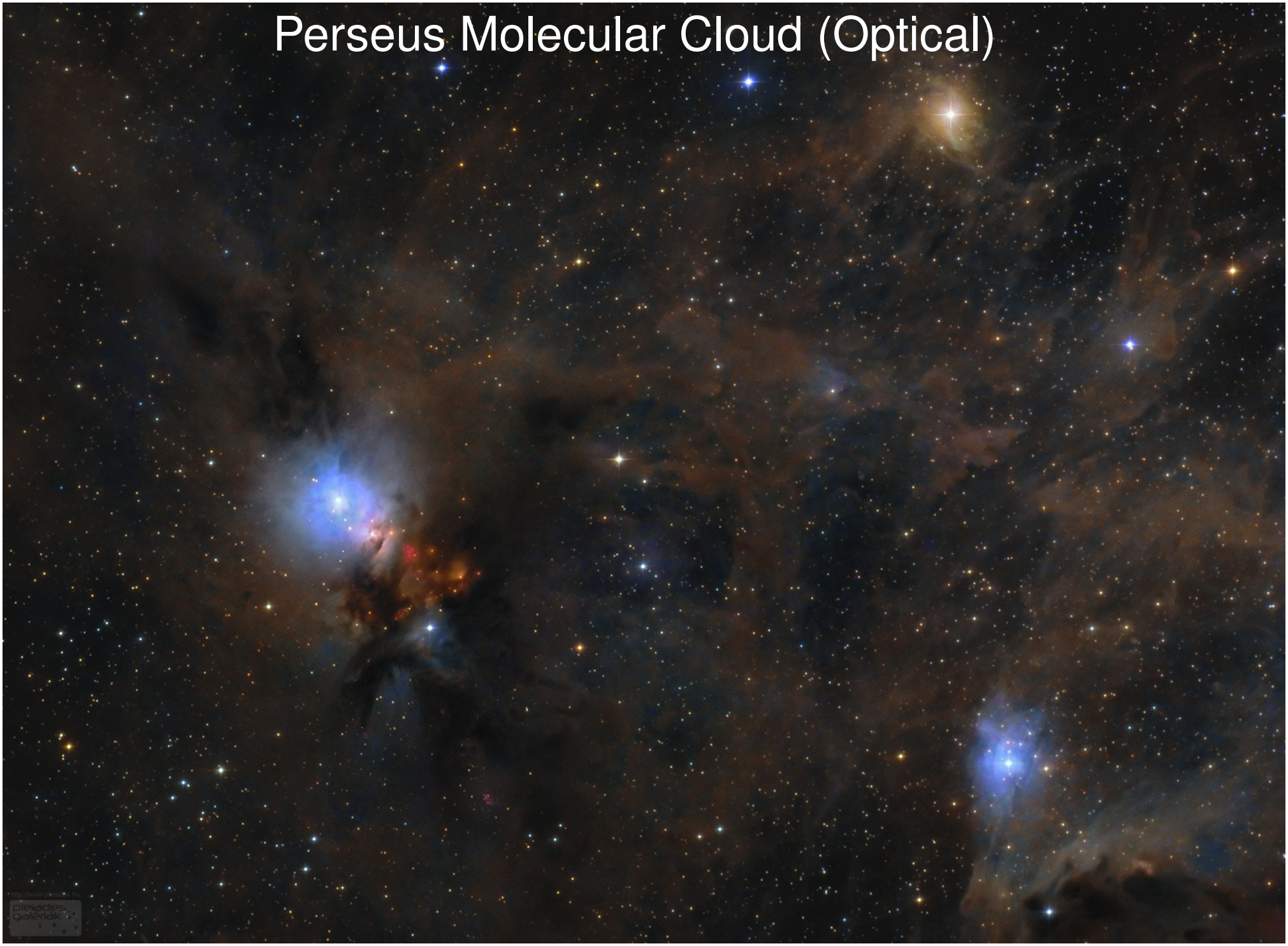
Dust Opacity



So longer wavelength, better we can “see through” the cloud


ESAVO/P/HERSCHEL/SPIRE-color
Perseus Molecular Cloud (Infrared)
15'
Powered by Aladin
1.946° x 1.605°
N
E

Perseus Molecular Cloud (Optical)



Great!
We solved our problem of opacity


Not quite...

Resolution

$$\theta \sim \frac{\lambda}{D}$$

Let's say we want to resolve something 100pc (326 lyr) away with 10AU resolution and we want to use radio wavelengths (1000 μm), means we need a telescope a **mile** wide!!!

Unreasonable

Interferometry

- Combine smaller telescopes to make an effective large telescope

Interferometry

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ALMA (Chile)

Interferometry

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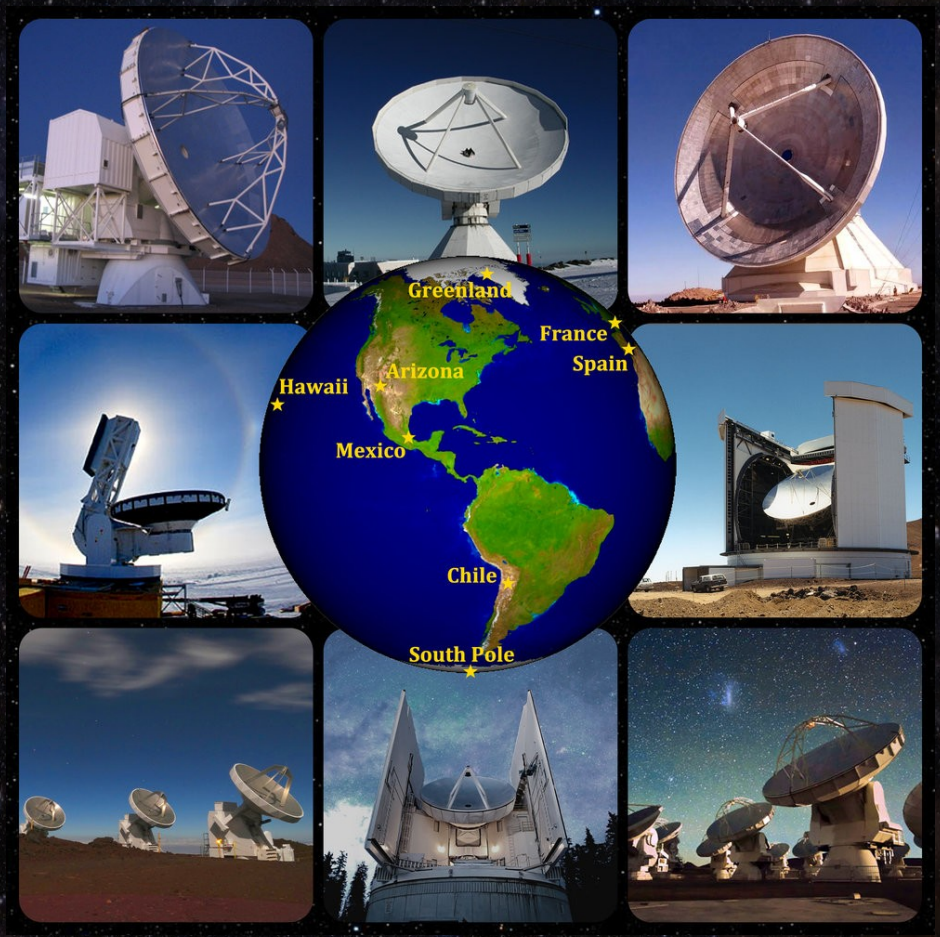
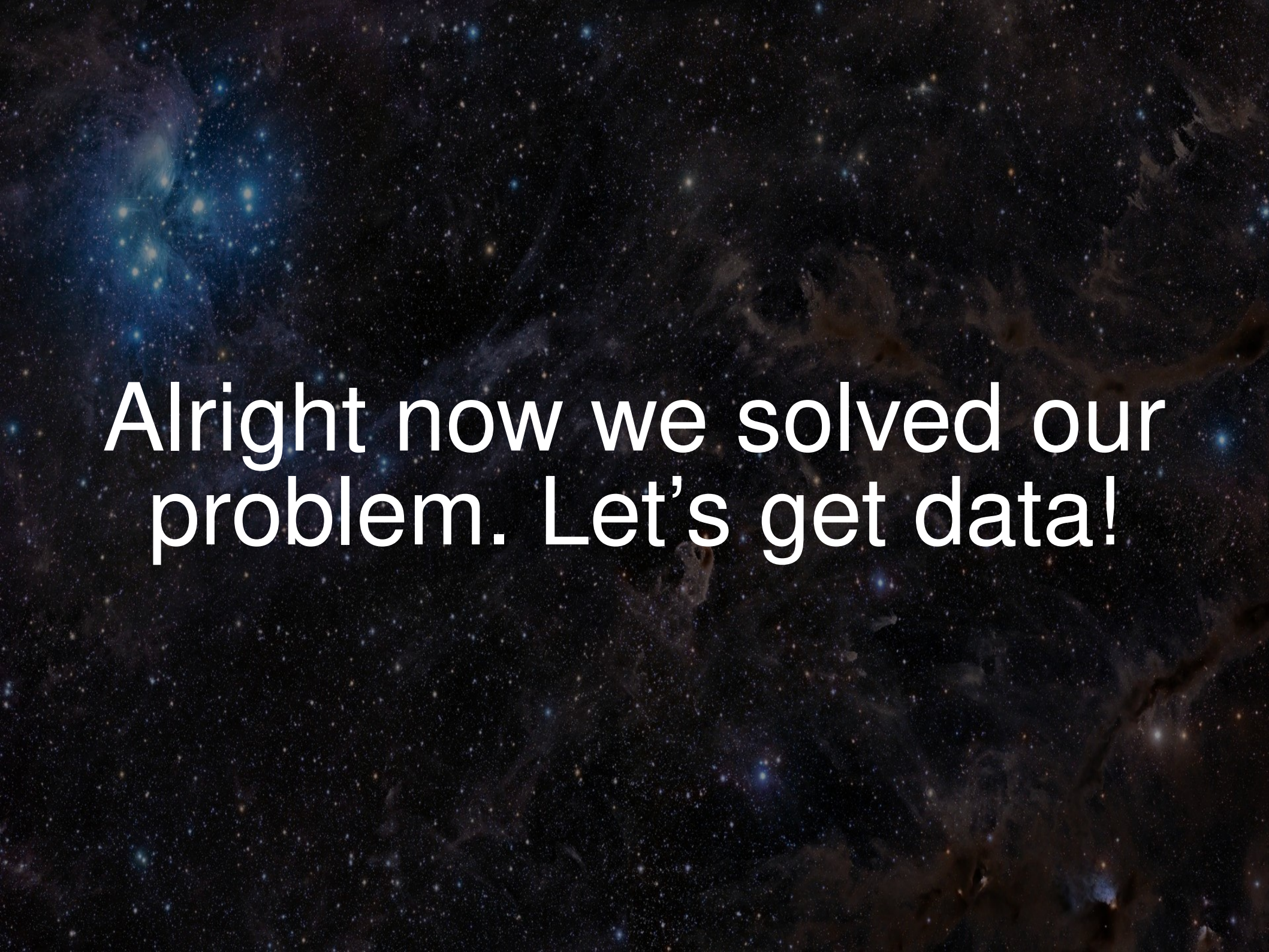
VLA (New Mexico)

Interferometry

- Combine smaller telescopes to make an effective large telescope

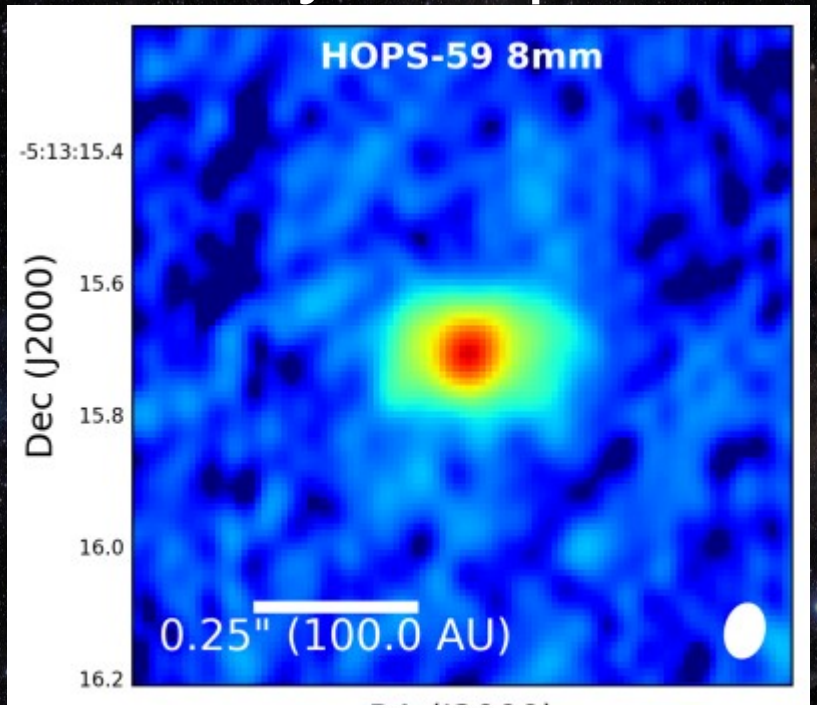
VLBI (Worldwide, EHT talk from Bouman)

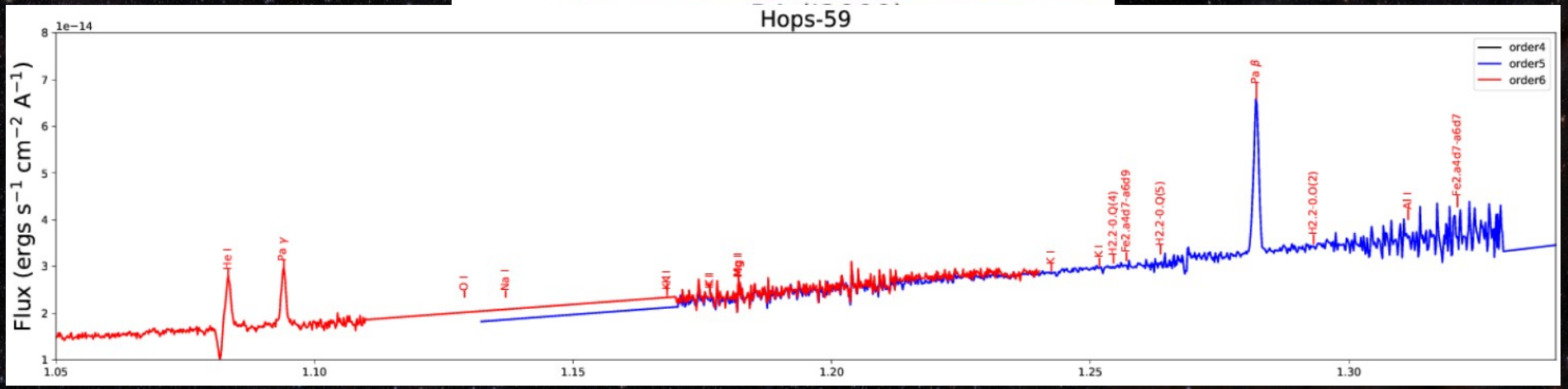



Alright now we solved our problem. Let’s get data!

Data Types

Photometry vs Spectroscopy





Data Types

Photometry

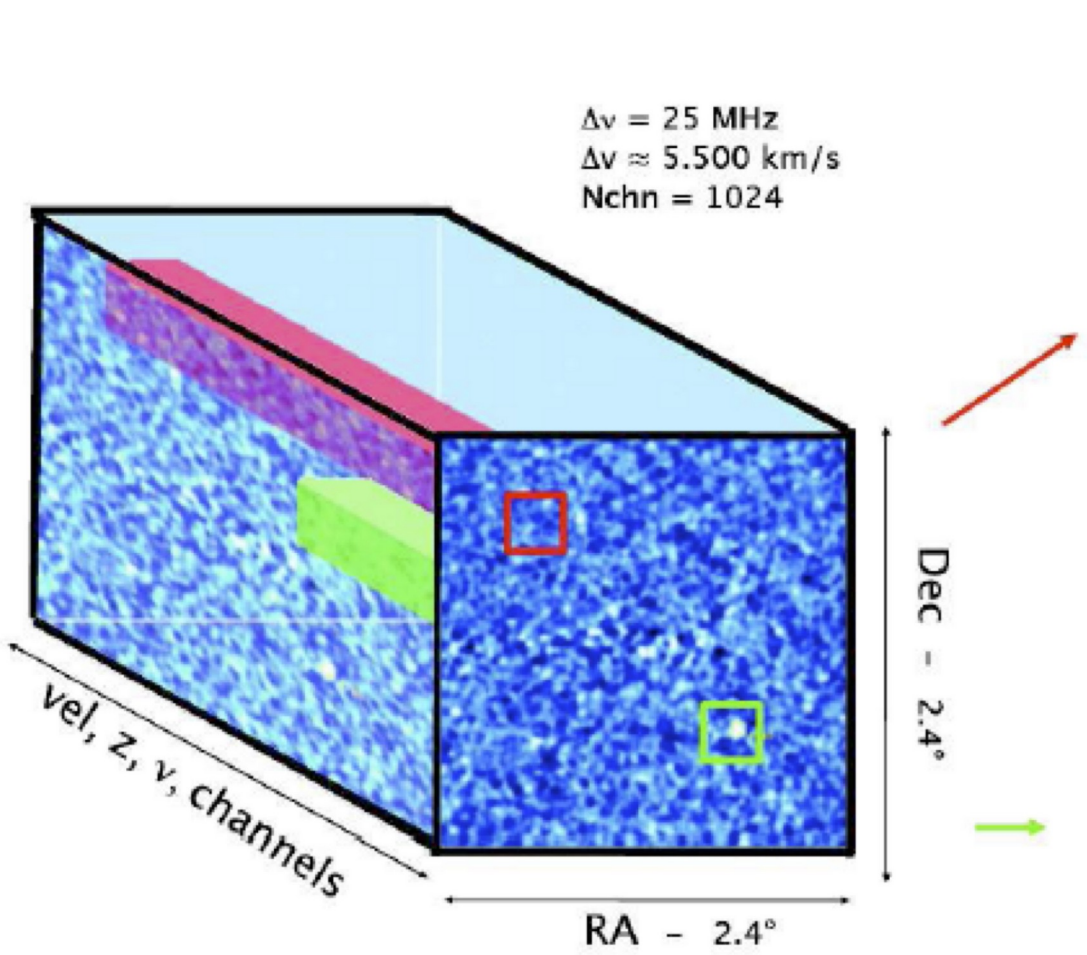
Tells us about dust:
- amount of material
- geometry
- fine structure
- morphology

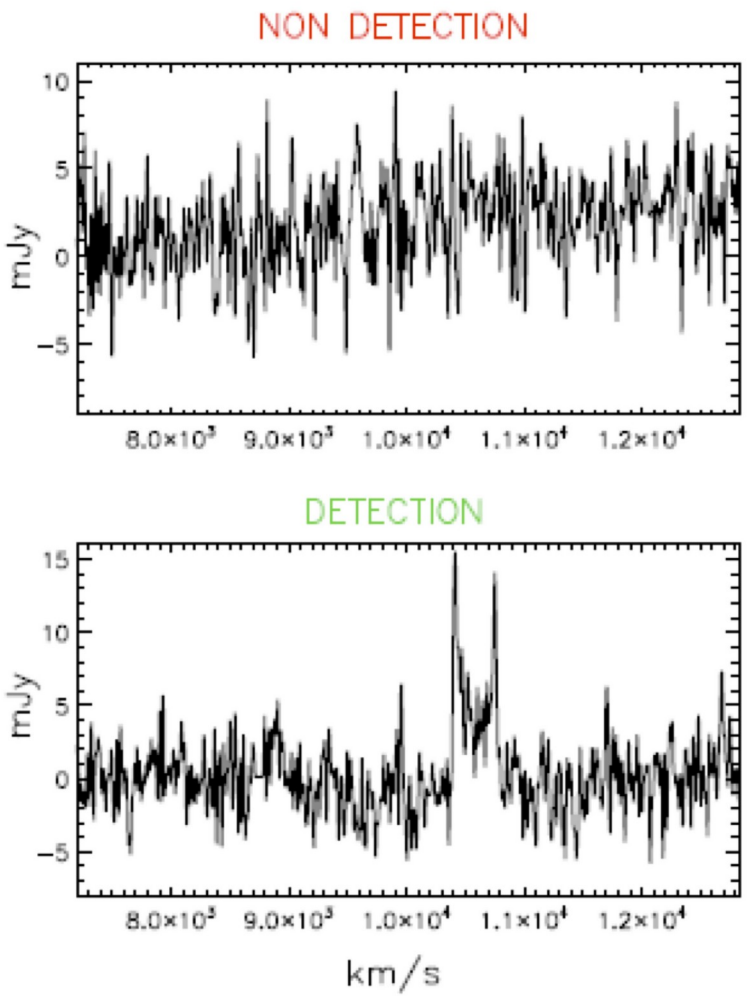
Spectroscopy

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

Data Types

Photometry & Spectroscopy



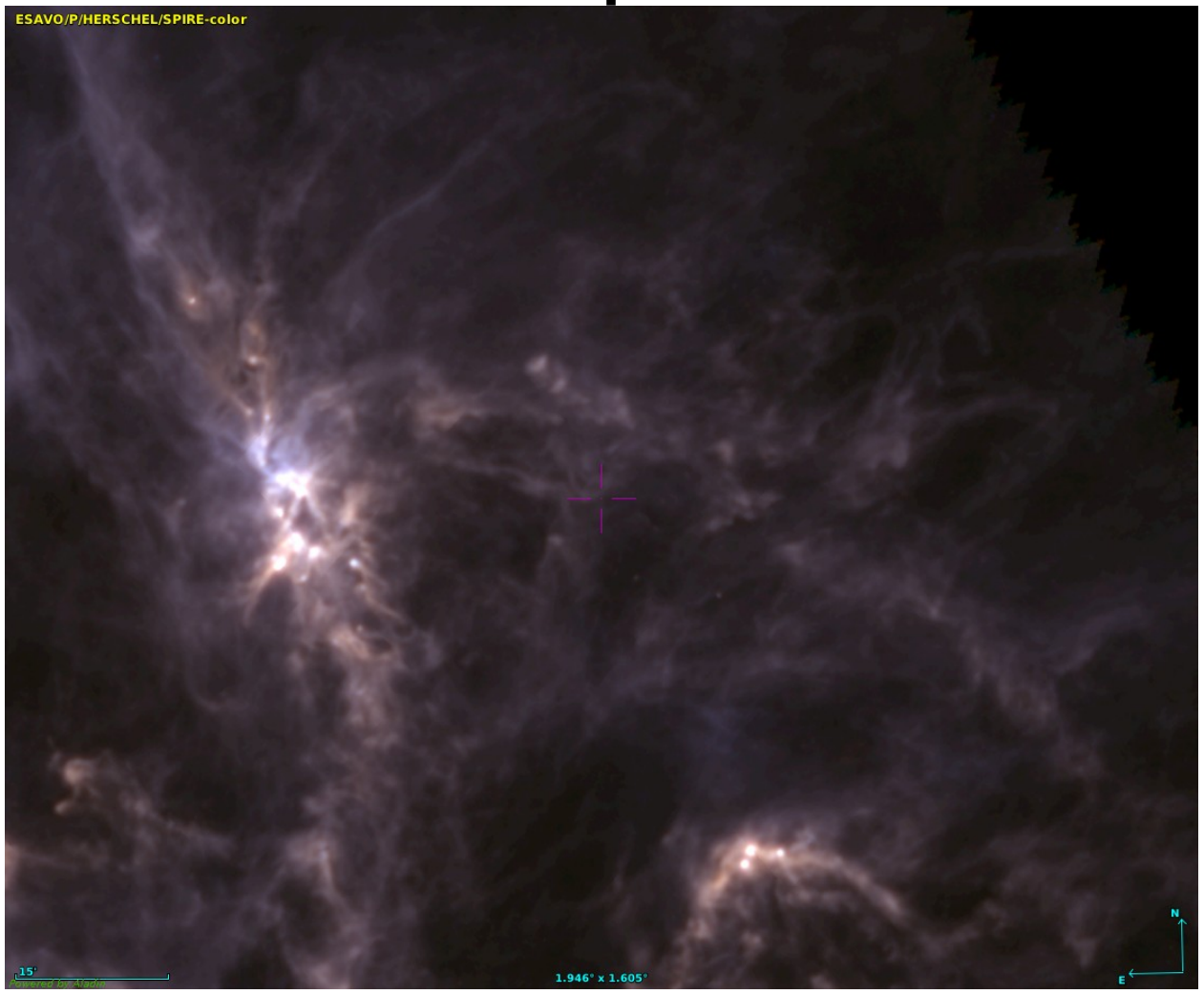


Science Summary

- We went from optical...

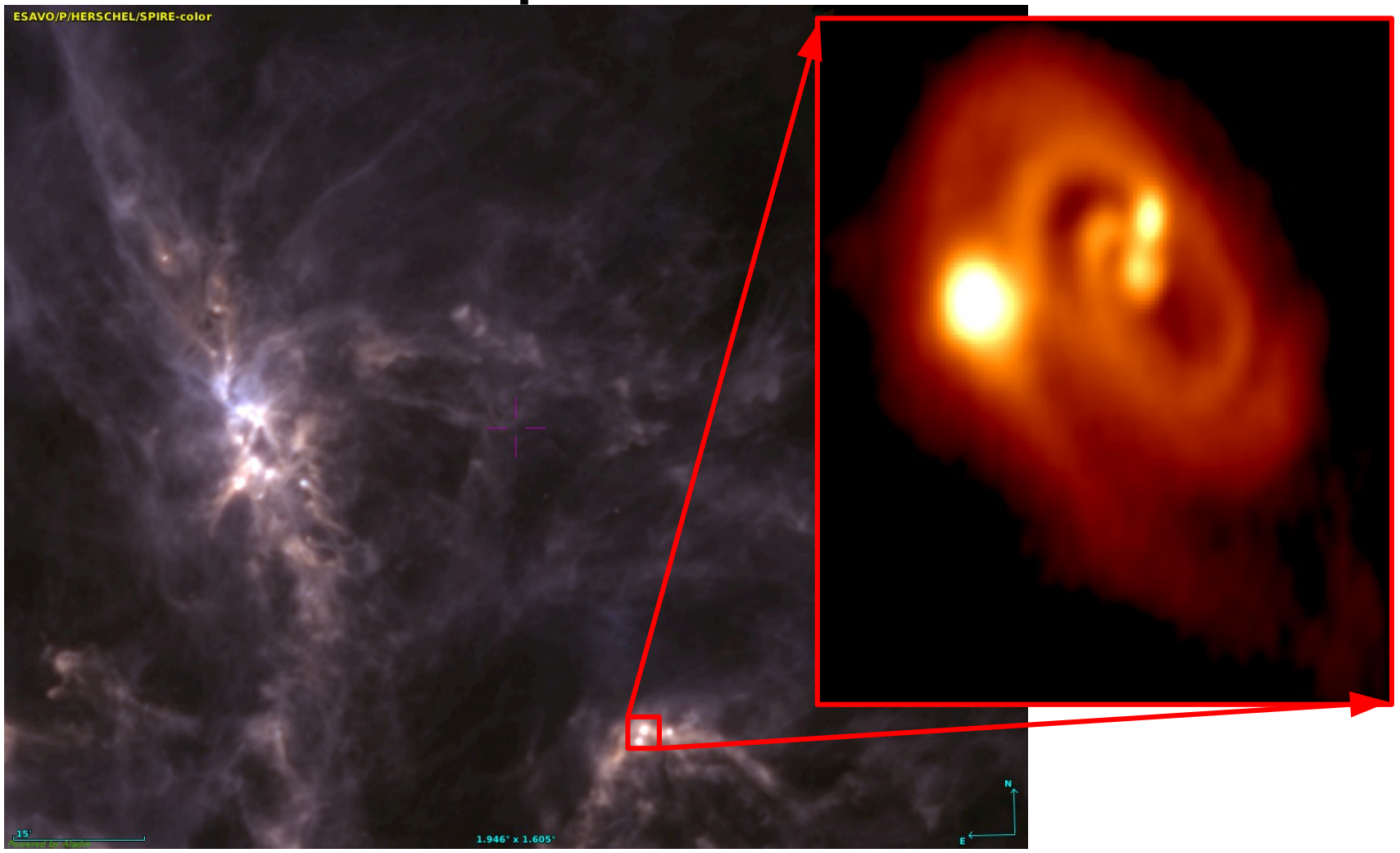
Science Summary

- We went from optical to IR...



Science Summary

- We went from optical to radio...

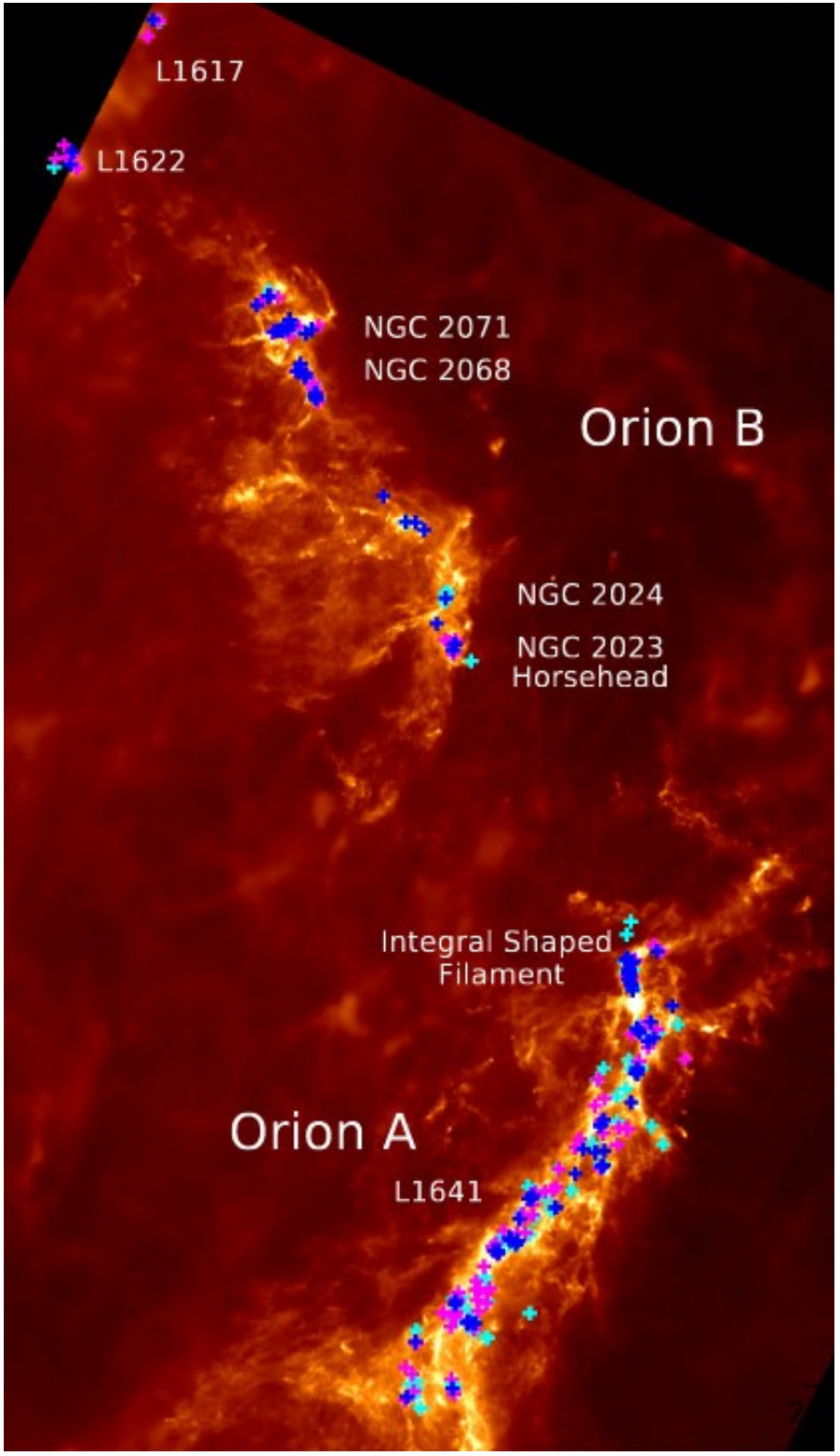


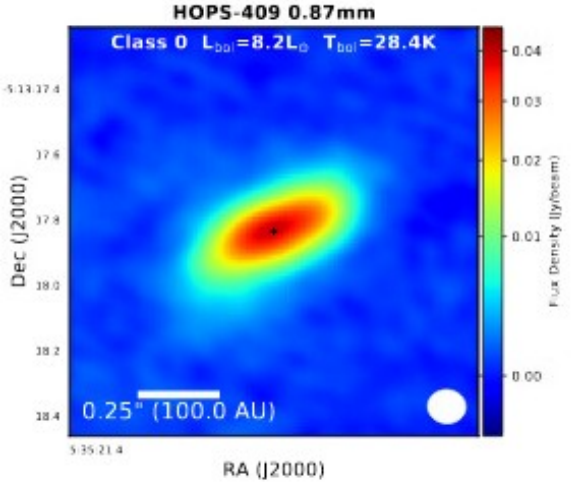
Science Summary

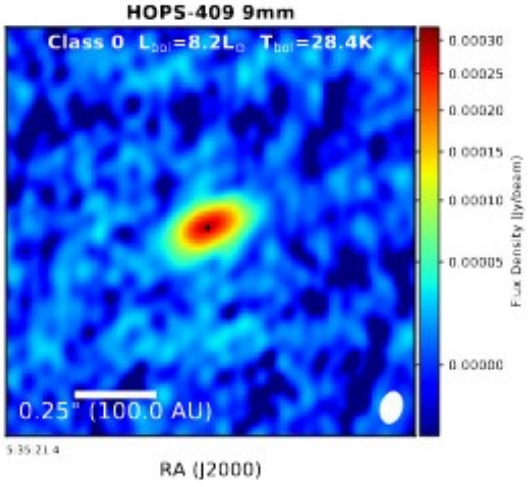
- We went from optical to radio
- Can now study properties of these systems individually and in bulk
- We have information about dust and gas
  - Information about structure, kinematics, dynamics, etc

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 the advent of the VLA and especially ALMA, high resolution and high sensitivity was scarce.
- 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-409 0.87mm
Class 0 L_{bol}=8.2$L_\odot$ T_{bol}=28.4K
0.25" (100.0 AU)
Dec (J2000)
RA (J2000)
Flux Density (Jy/beam)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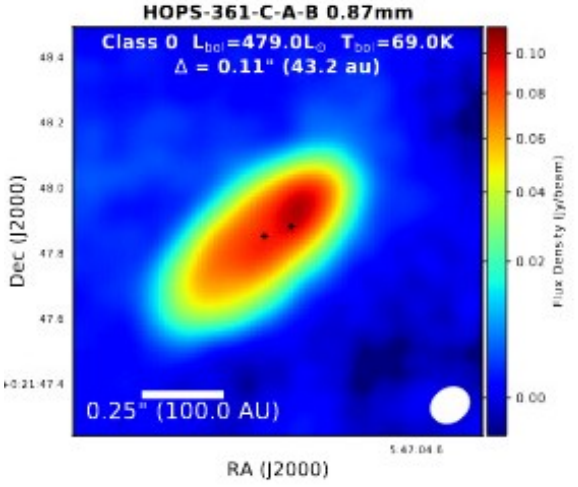
HOPS-361-C-A-B 0.87mm
Class 0 L_{bol}=479.0$L_\odot$ T_{bol}=69.0K
Δ = 0.11" (43.2 au)
0.25" (100.0 AU)
Dec (J2000)
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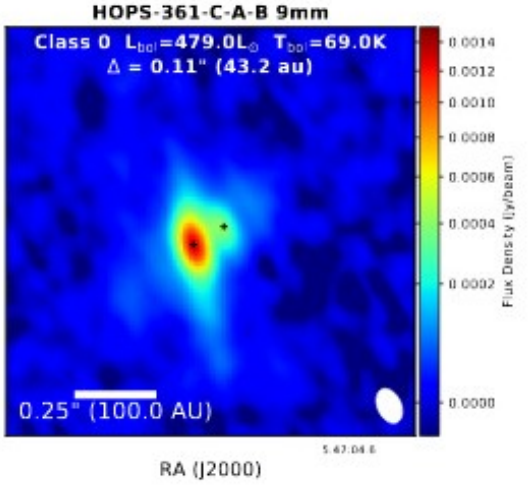
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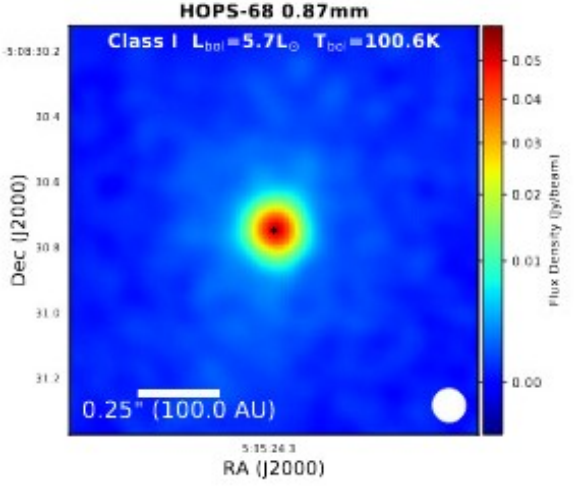
HOPS-68 0.87mm
Class I L_{bol}=5.7$L_\odot$ T_{bol}=100.6K
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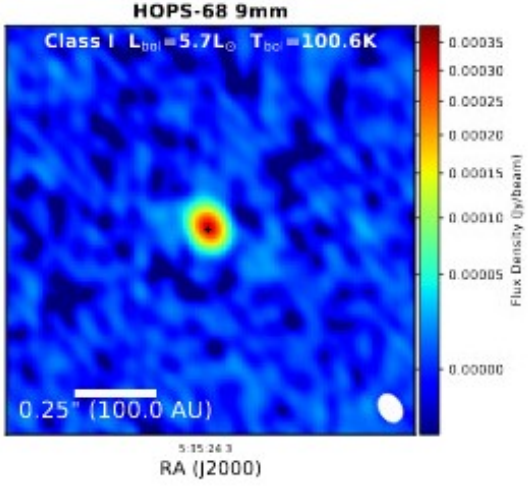
RA (J2000)
Flux Density (Jy/beam)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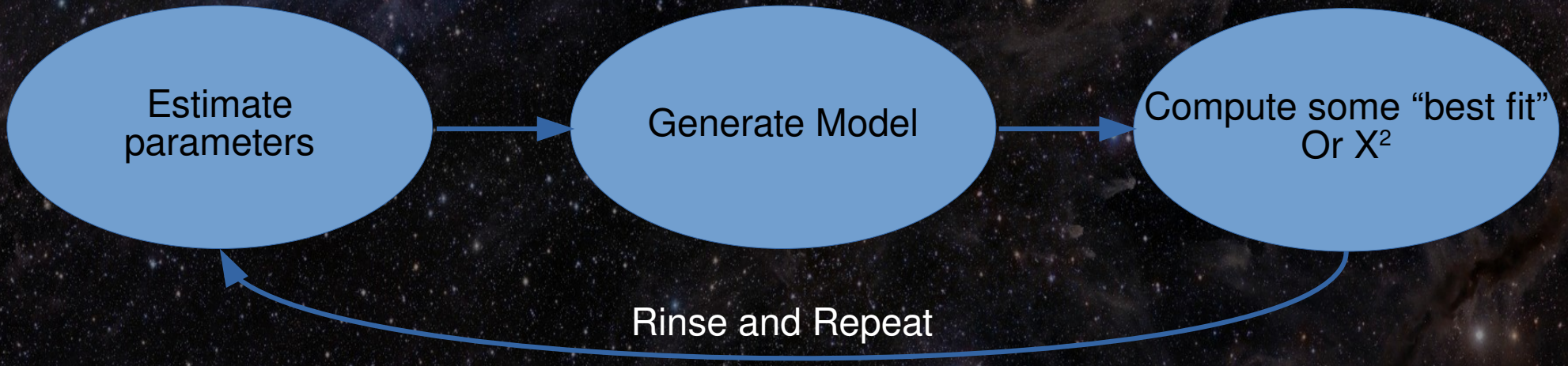
Computation

- 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

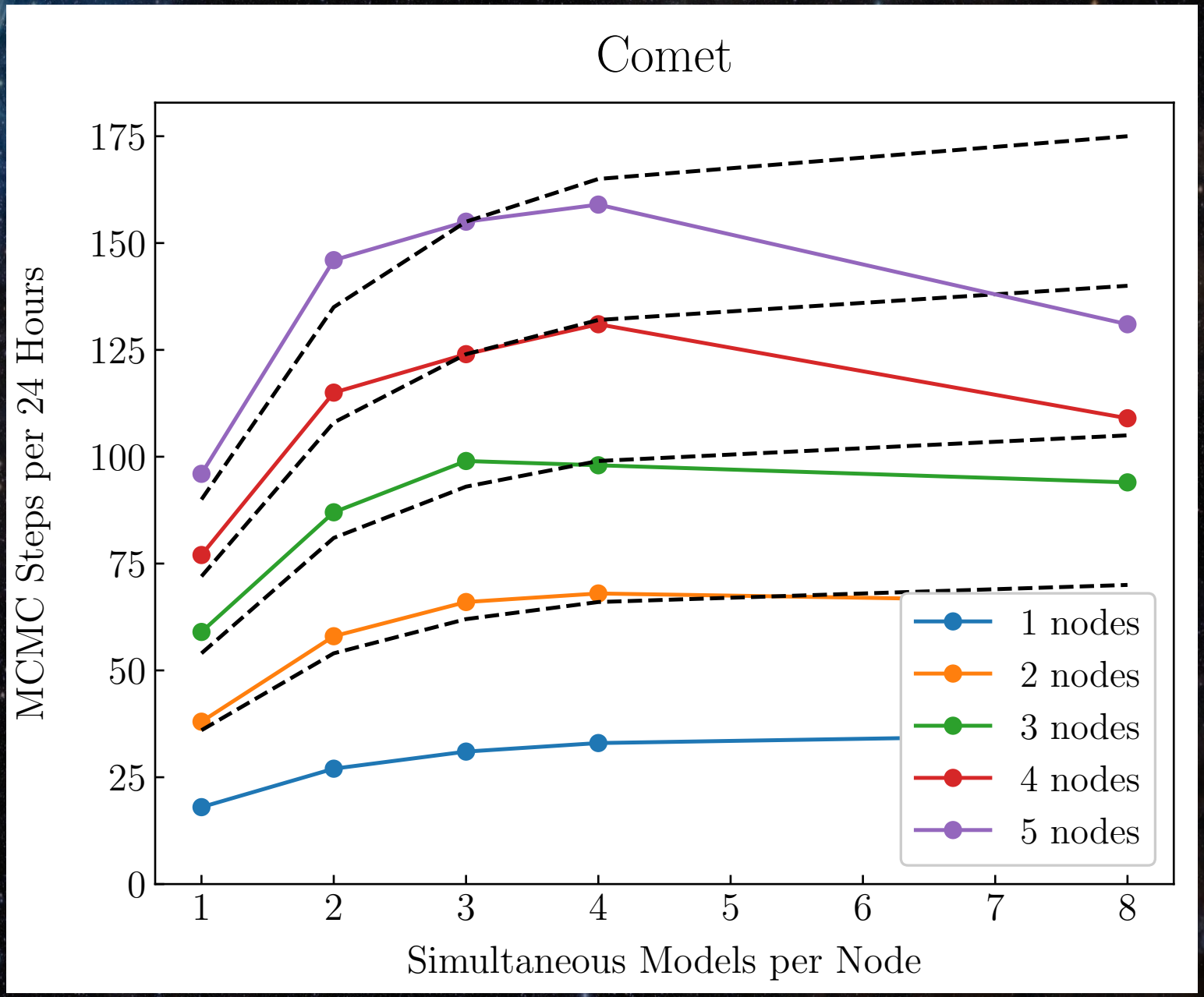
RADMC3D (Dullemond 2012)

PDSPY (Sheehan et al. 2019)

PDSPY Scalability

Picture will go here

PDSPY Scalability



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)

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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

  Better…. But we have ~100 sources and each one can be modelled multiple times (remember those molecules?)

Schooner

- The supercomputer drastically changes the game for us
- Typical requests:
  - 5-15 nodes (100 – 300 cores)
  - Full allowed time (48 hours)
  - 5+ separate runs (sometimes more or less depending on degeneracy)
- CPU core performance focus (not GPU ready)

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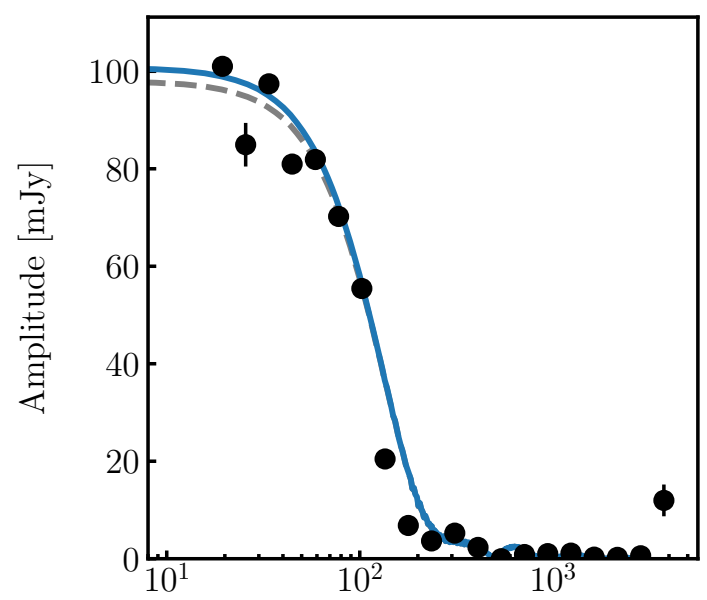
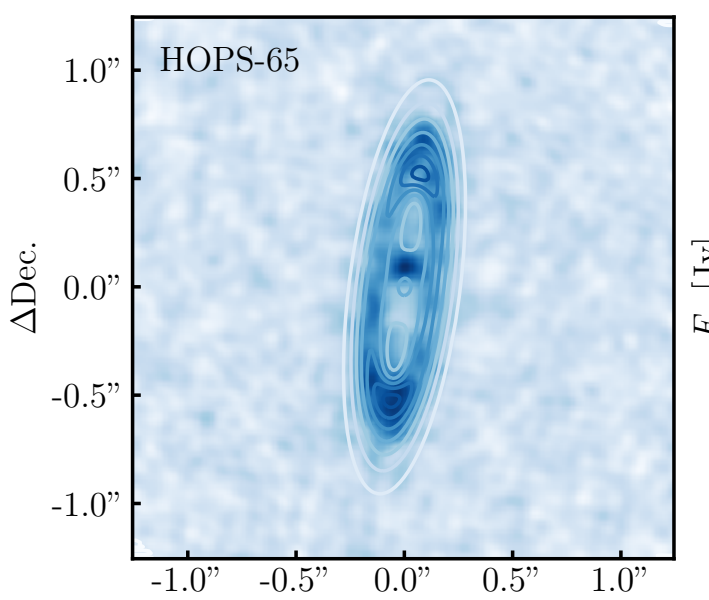
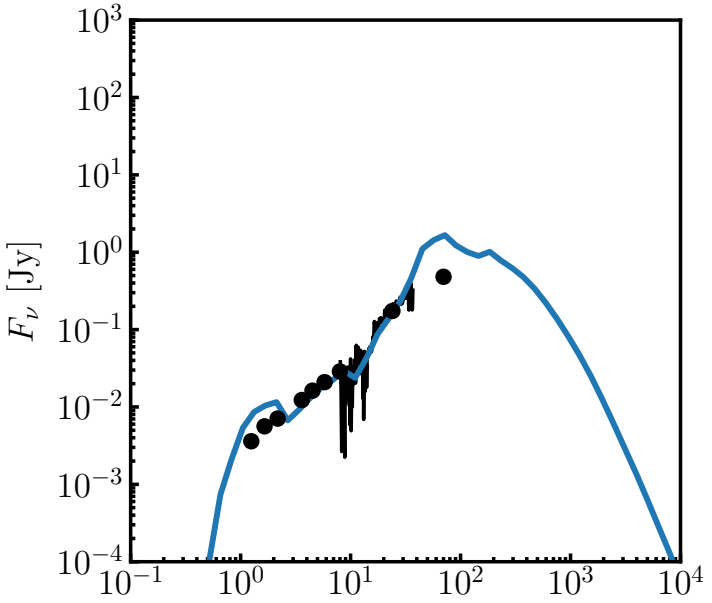
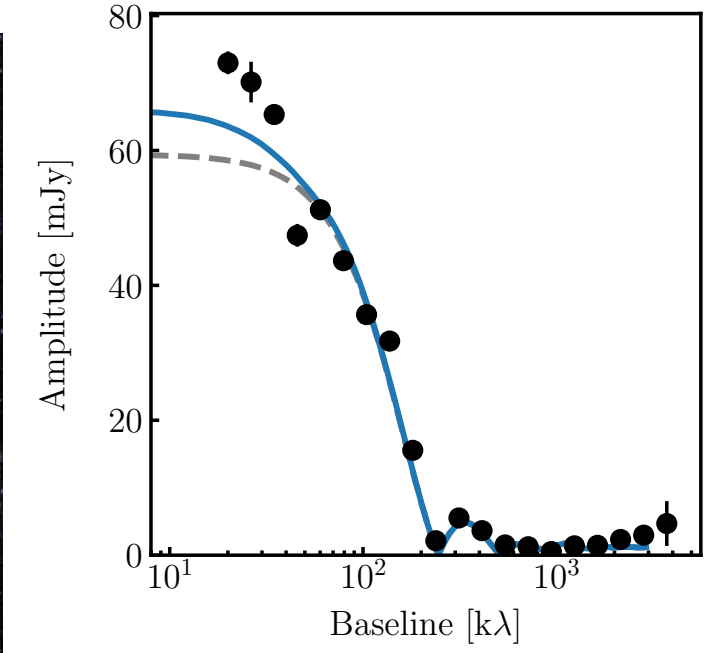
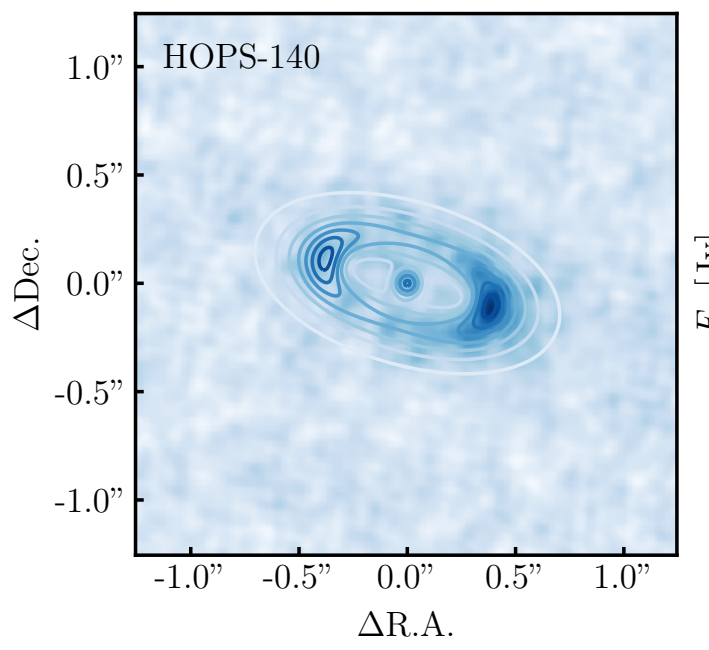
What do we get?

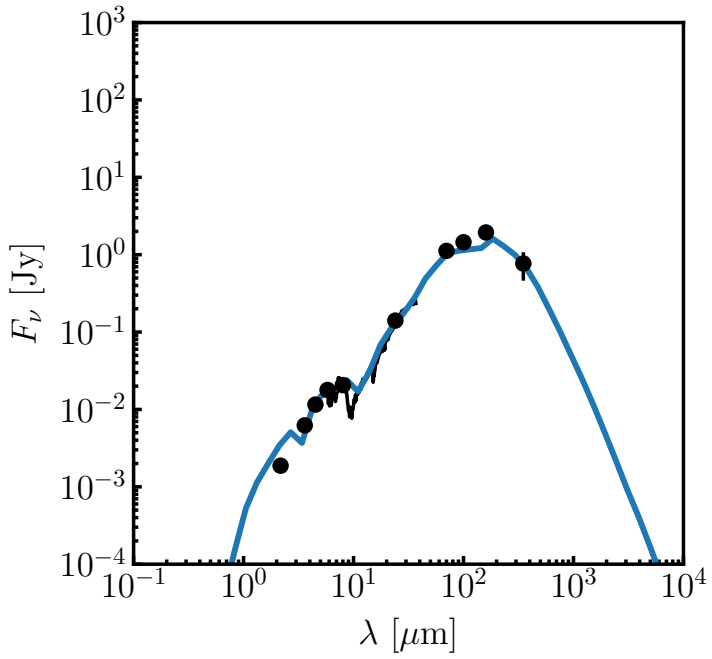












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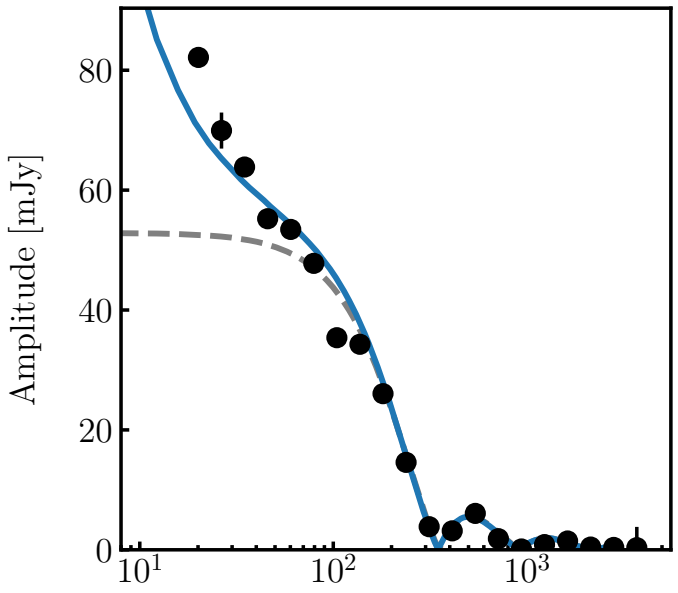

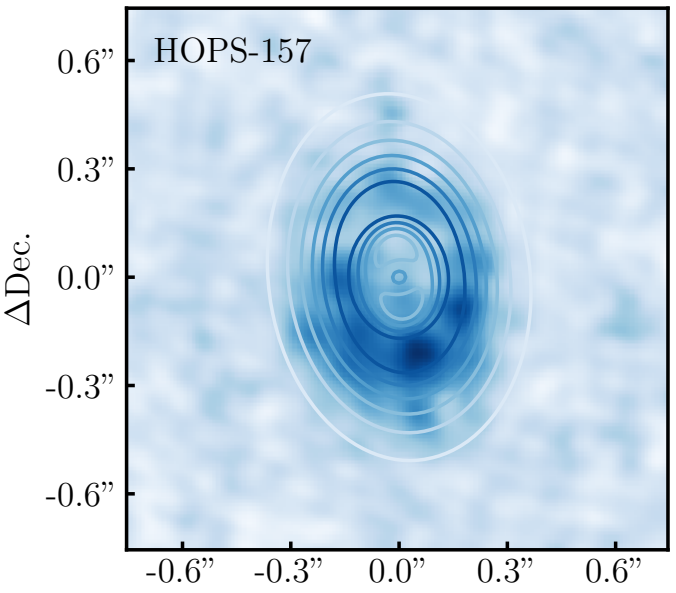

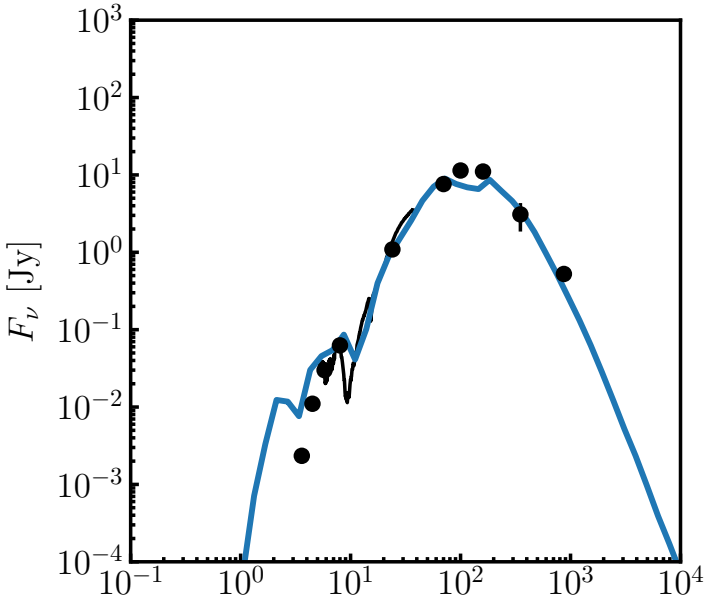

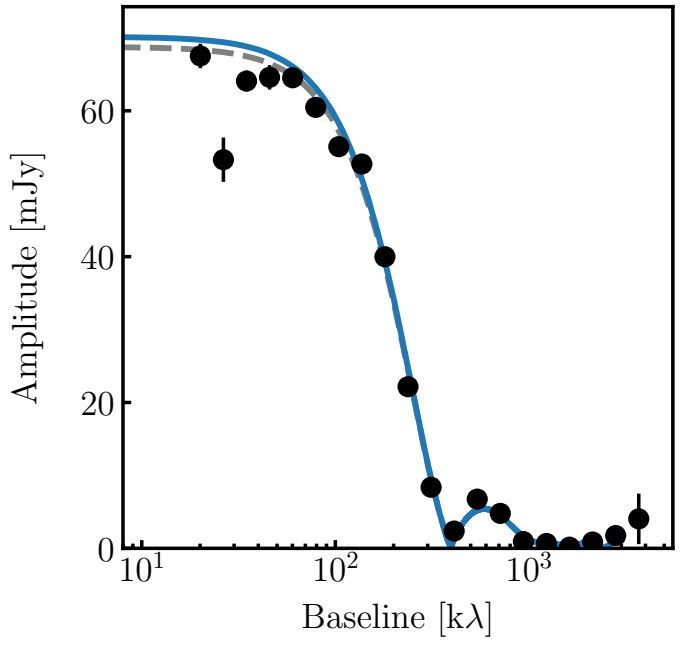

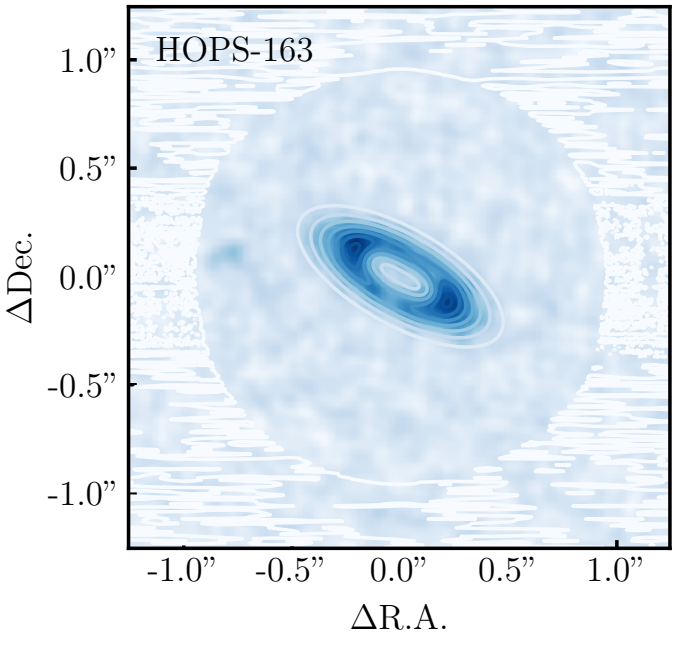

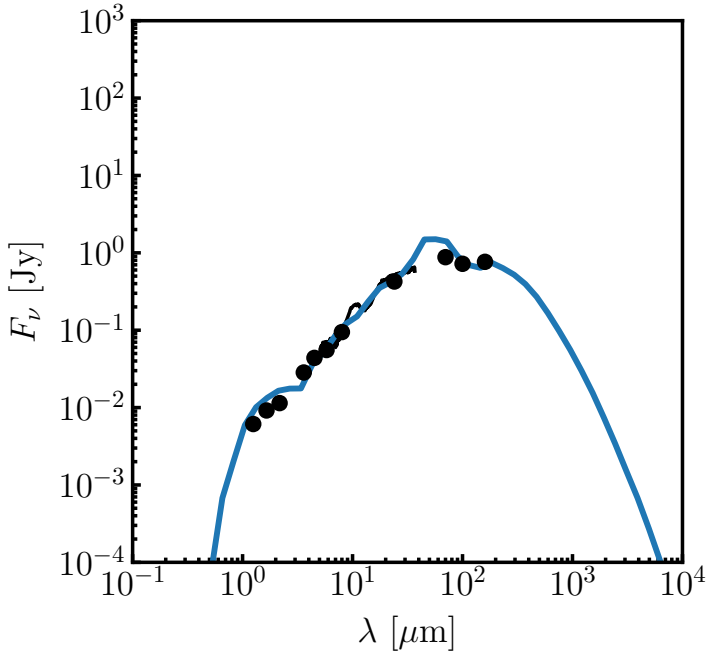

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What are we answering?

- How/when/where do stellar multiples form?
- How/when/where do planets form?
- When does chemical enrichment happen?
- In answering these statistically, we can also ask, are we unique?

Impacts

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

- This motivates the need for our pristine survey
- Need to complete more models
- And a lot more supercomputing time!!!

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

Summary

- Stars and planets form within dense cores in molecular clouds and start out 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
- Hopefully answer some of our starting questions

Acknowledgements

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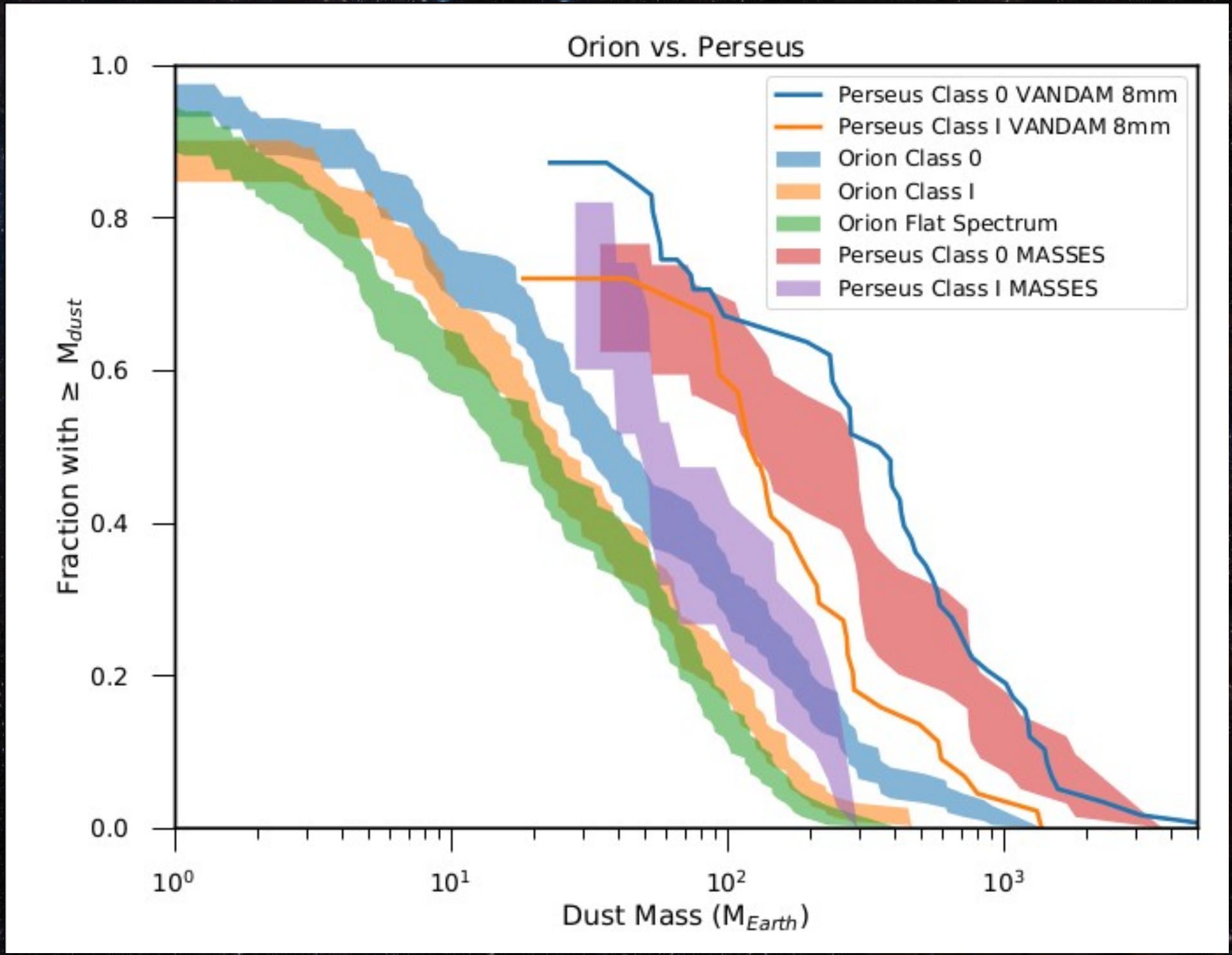
Orion vs. Perseus
Perseus Class 0 VANDAM 8mm
Perseus Class I VANDAM 8mm
Orion Class 0
Orion Class I
Orion Flat Spectrum
Perseus Class 0 MASSES
Perseus Class I MASSES
Fraction with ≥ M_{dust}
Dust Mass (M_{Earth})
1.0
0.8
0.6
0.4
0.2
0.0
10^0
10^1
10^2
10^3