Modeling Feedback From Low-Mass Stars: Radiation, Outflows & Winds

Stella Offner
Hubble Fellow @ Yale University

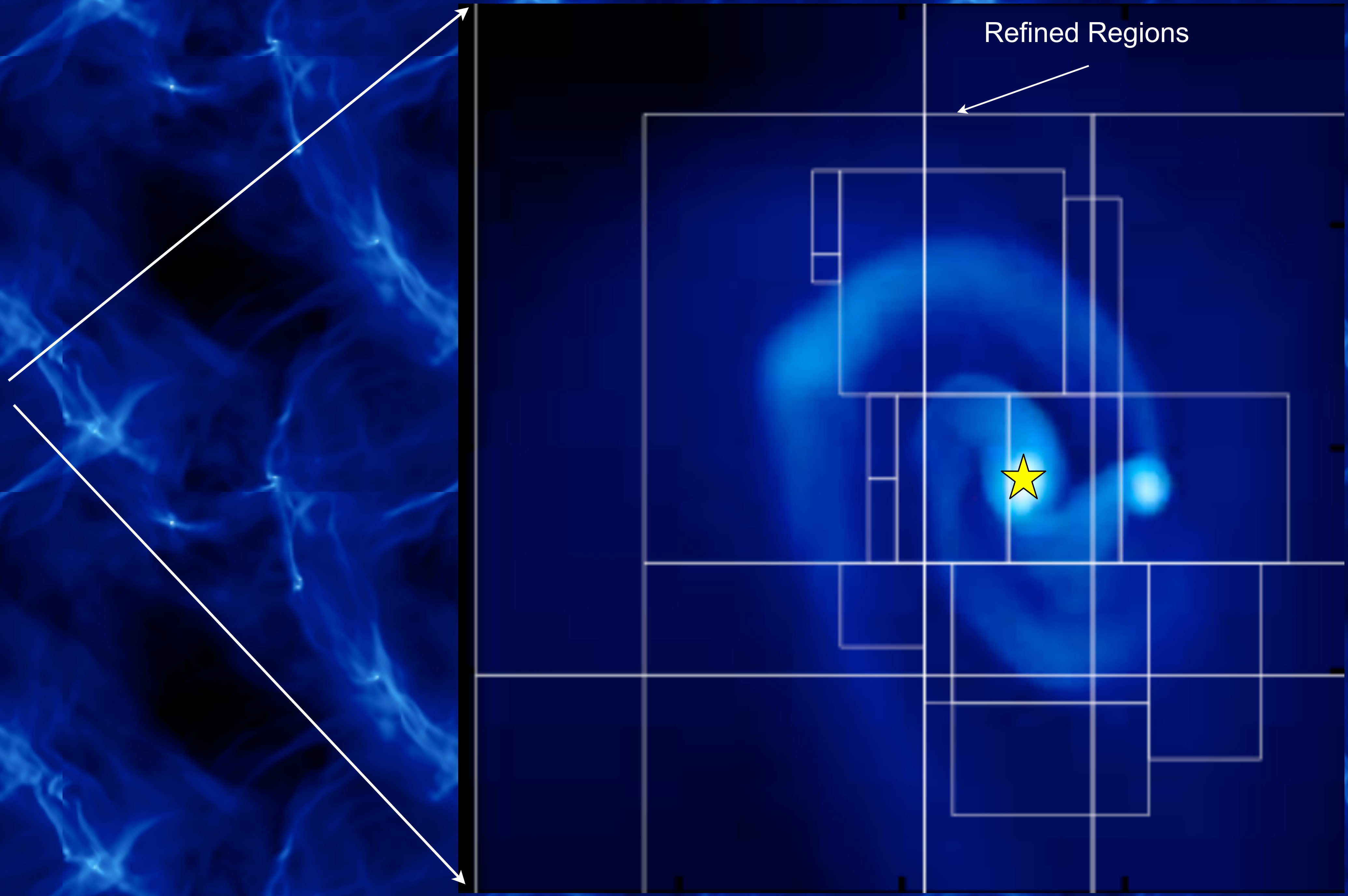
Ringberg, June, 2013

Collaborators:
Hector Arce (Yale)
Chris McKee, Richard Klein, Eve Lee (Berkeley)
Alyssa Goodman, Chris Beaumont (Harvard)

Feedback: why low-mass stars matter...

- ★How forming low-mass stars connect to their environment:
  - ★Radiation Feedback (Heating)
  - ★Protostellar Outflows (Kinematic Feedback)
  - ★Stellar Winds (Kinematic Feedback)

Numerical Modeling of Clouds, Stars & Clusters



Offner et al. 2008

Numerical Modeling of Clouds, Stars & Clusters

ORION

Radiation-Hydrodynamics

Self-Gravity

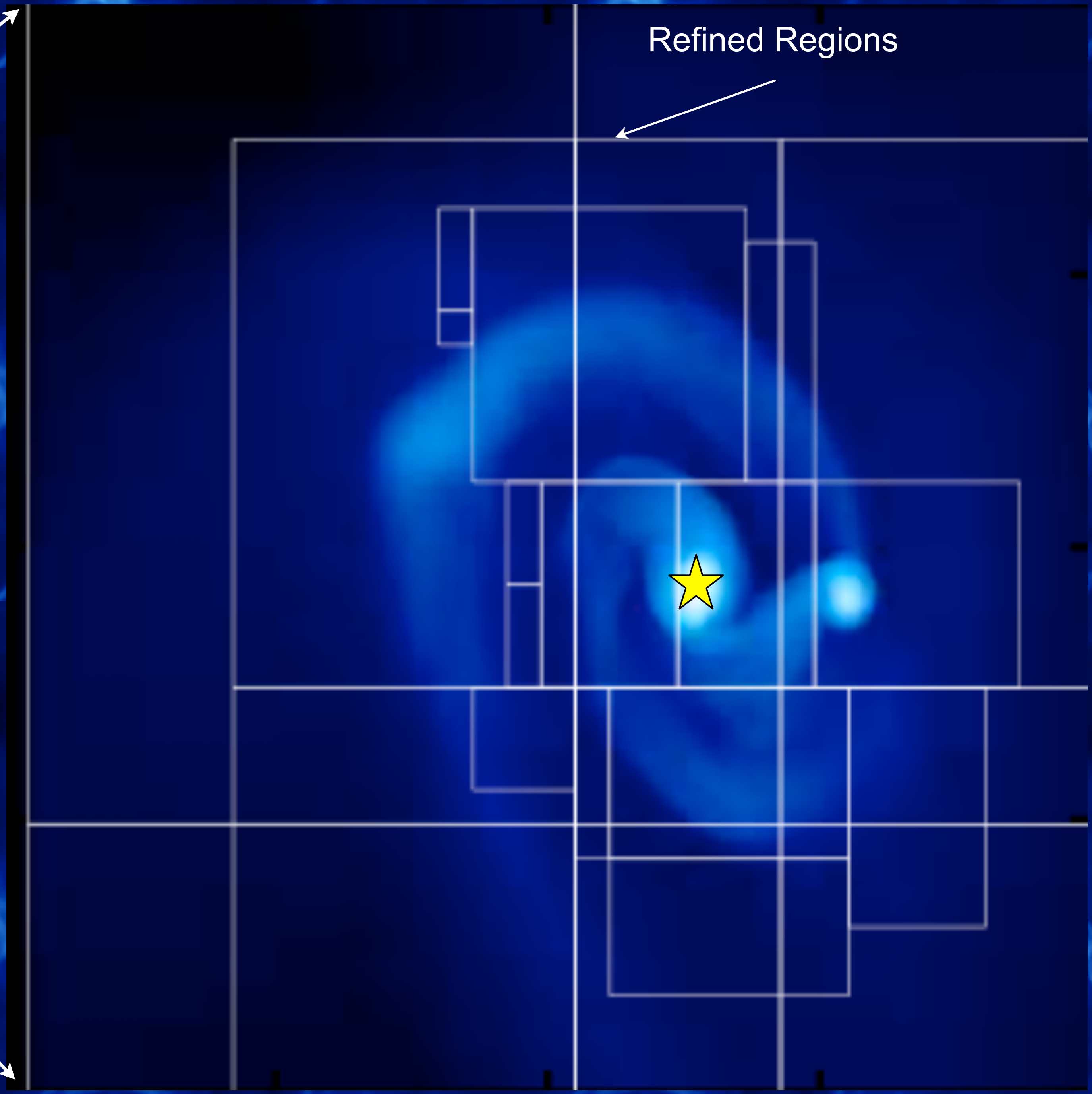
Supersonic Turbulence

"Star" Particles:

- Accrete
- Radiate
- Launch Bipolar Outflow (Matzner & Mckee)

"B Star" Particles:

- Launch Isotropic Wind



Offner et al. 2008

1. Radiation

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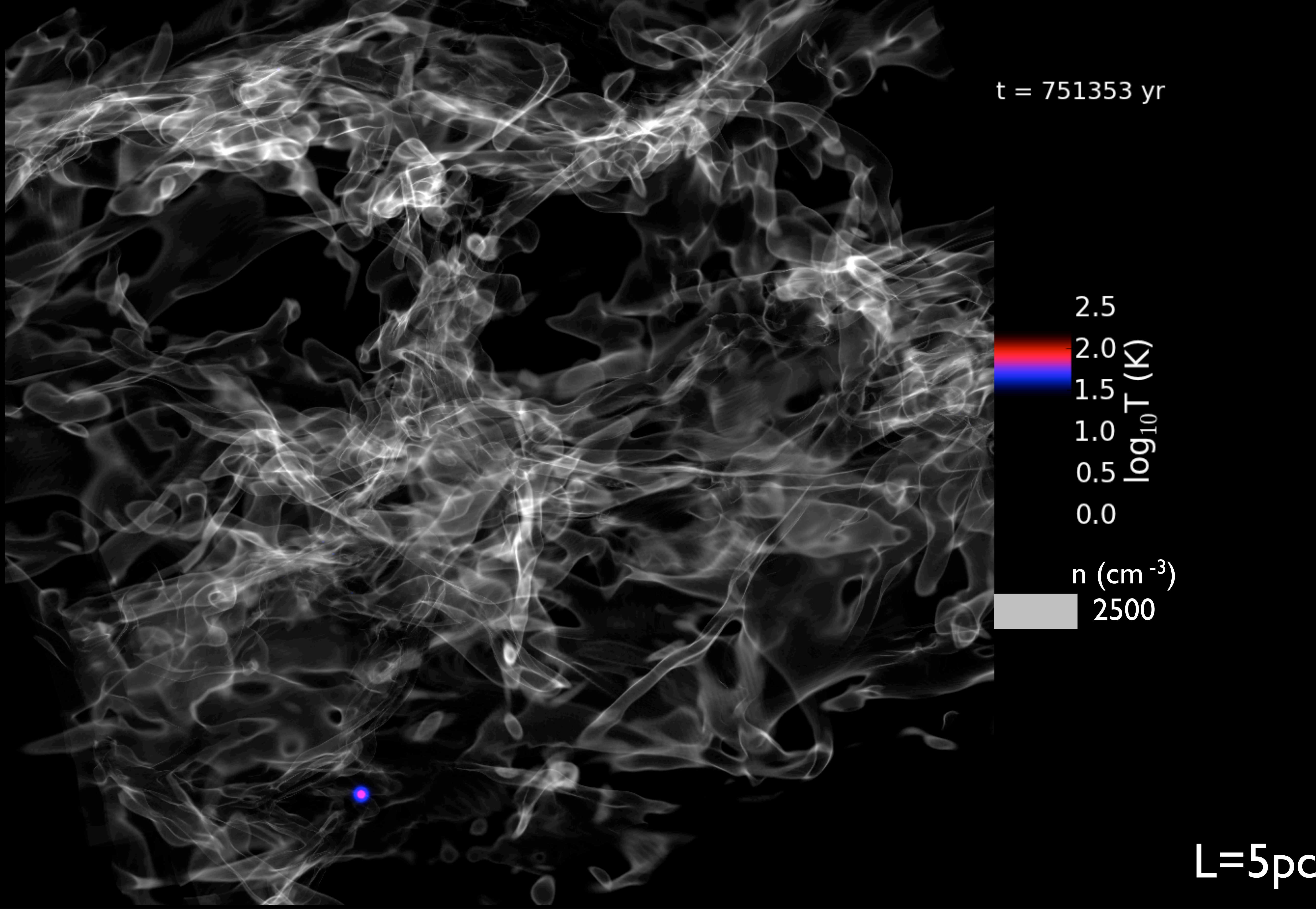
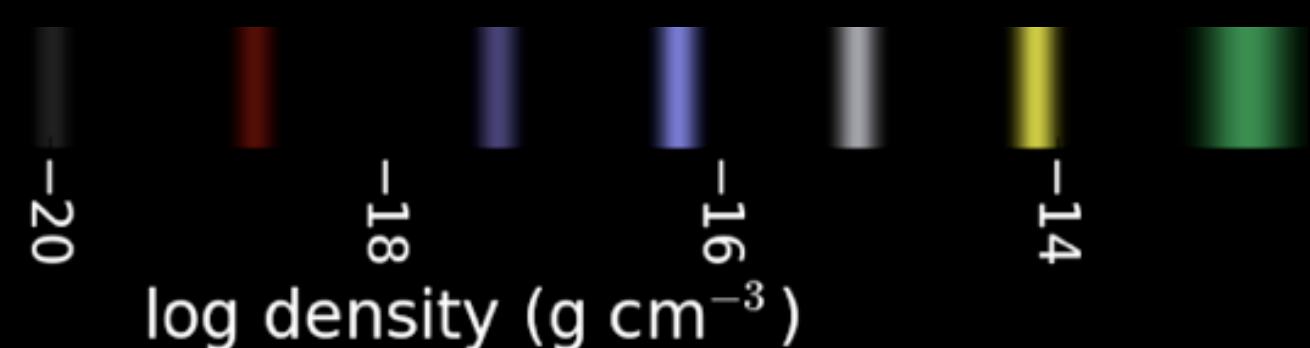


Radiative Feedback v. No Radiative Feedback

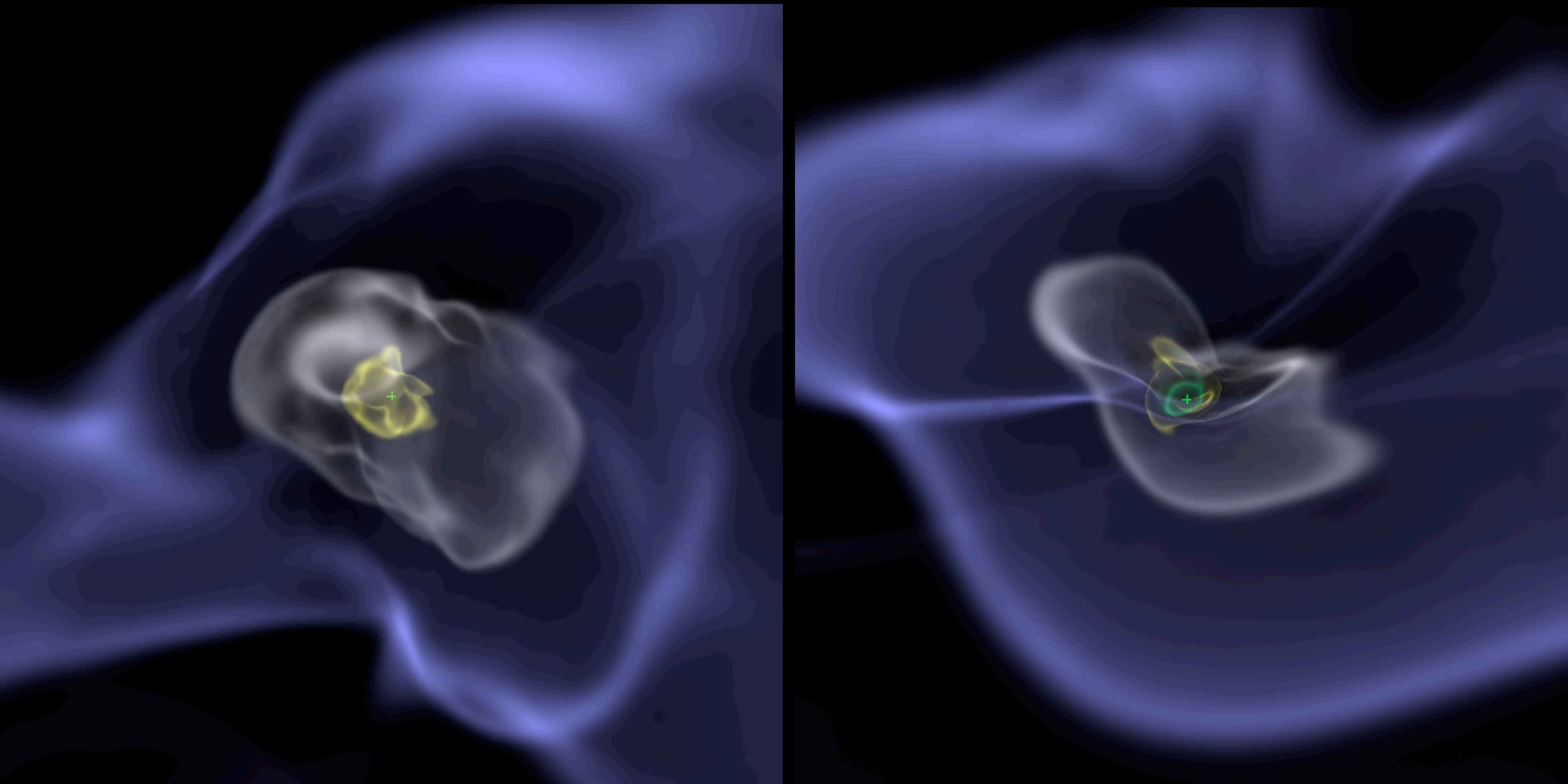
100 AU



Zoomed in views
from 1pc sim

Offner et al. 2010

Radiative Feedback v. No Radiative Feedback



100 AU

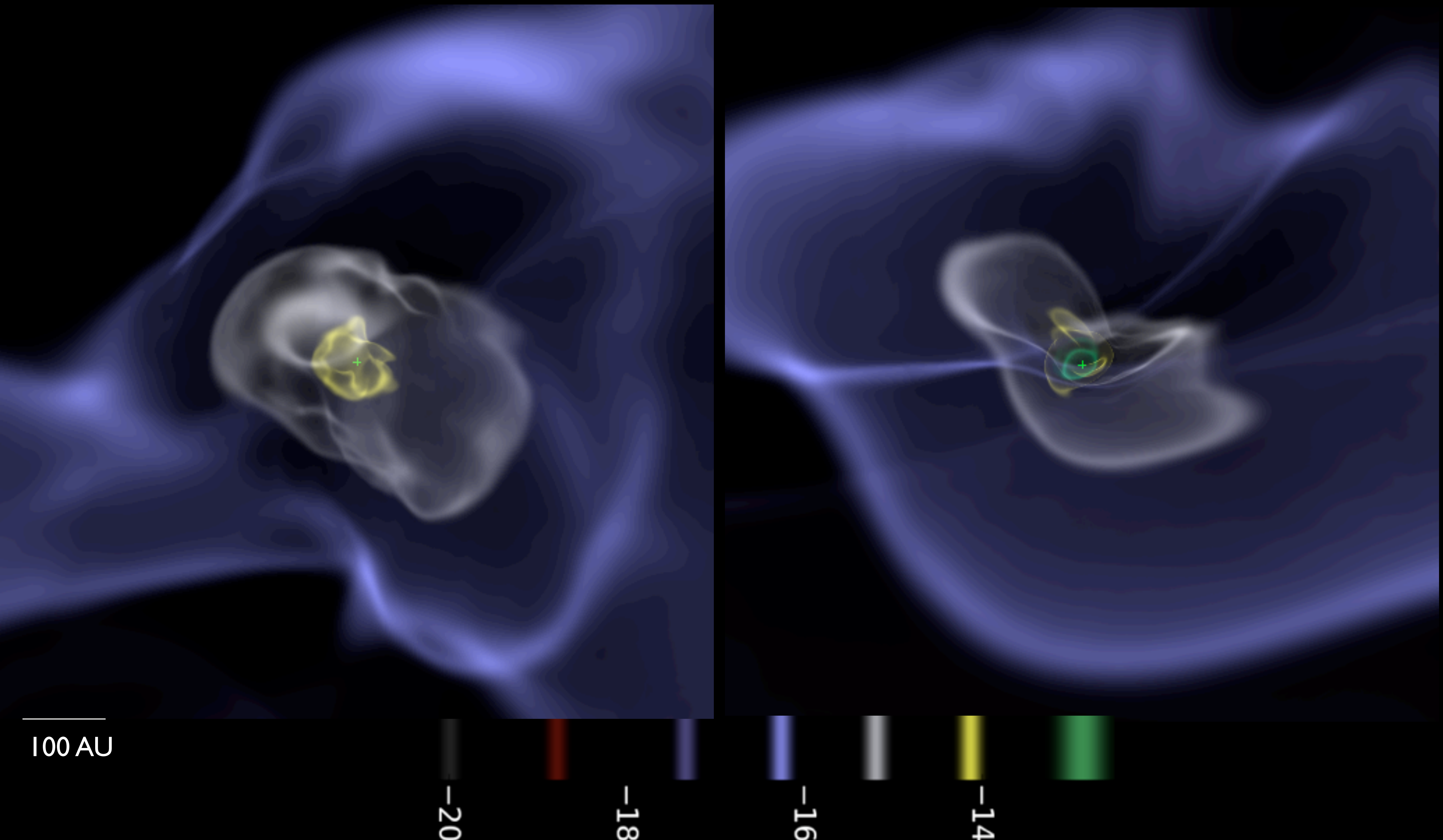
−20 −18 −16 −14

log density (g cm^{-3})

Zoomed in views
from 1pc sim

Offner et al. 2010

Radiative Feedback v. No Radiative Feedback



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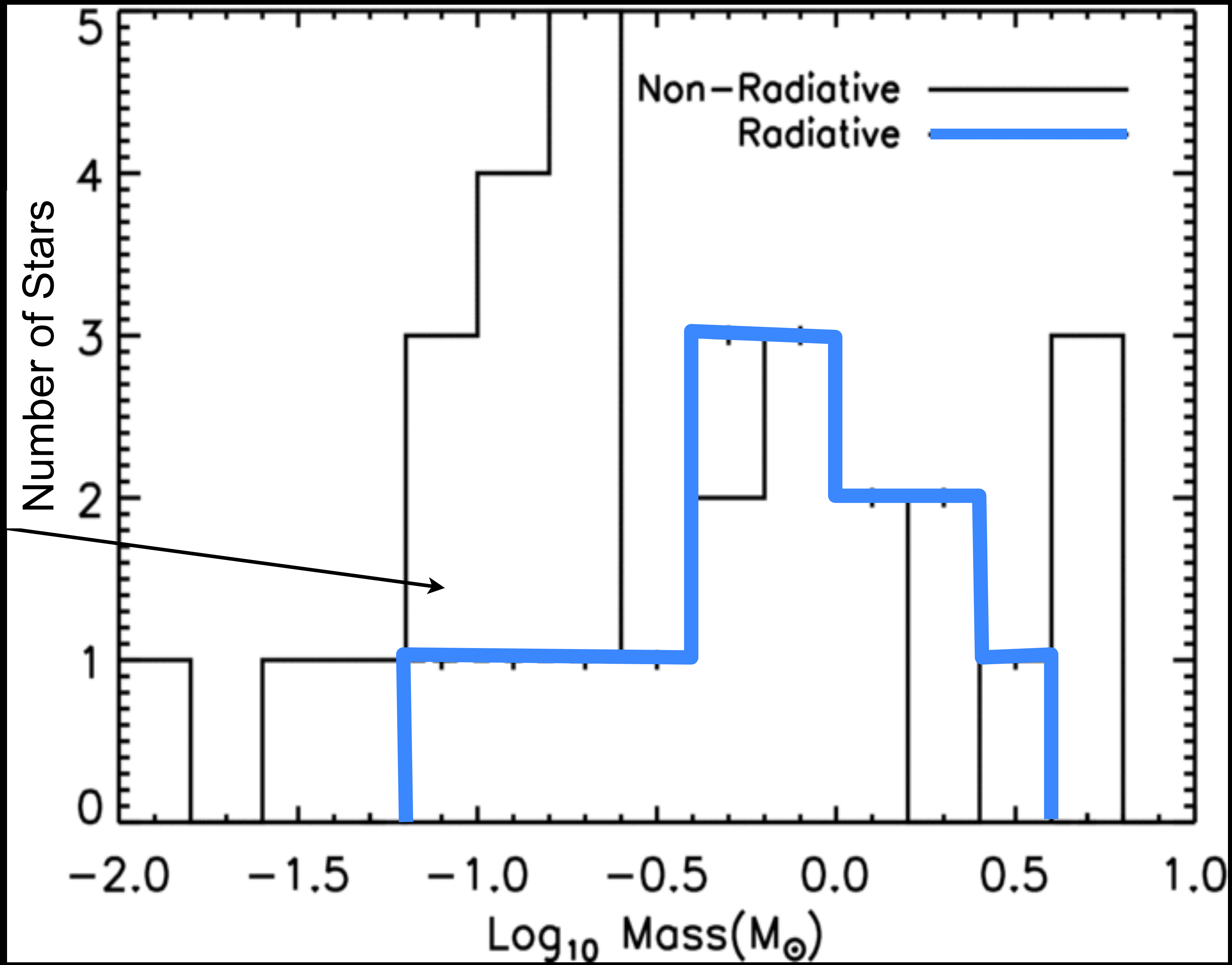
Offner et al. 2010

Stellar Masses

Radiation reduces the number of stars:

Brown Dwarfs
(M < 0.1 Msun)



Offner et al. 2009

Also Bate 2009, 2012

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Suppression

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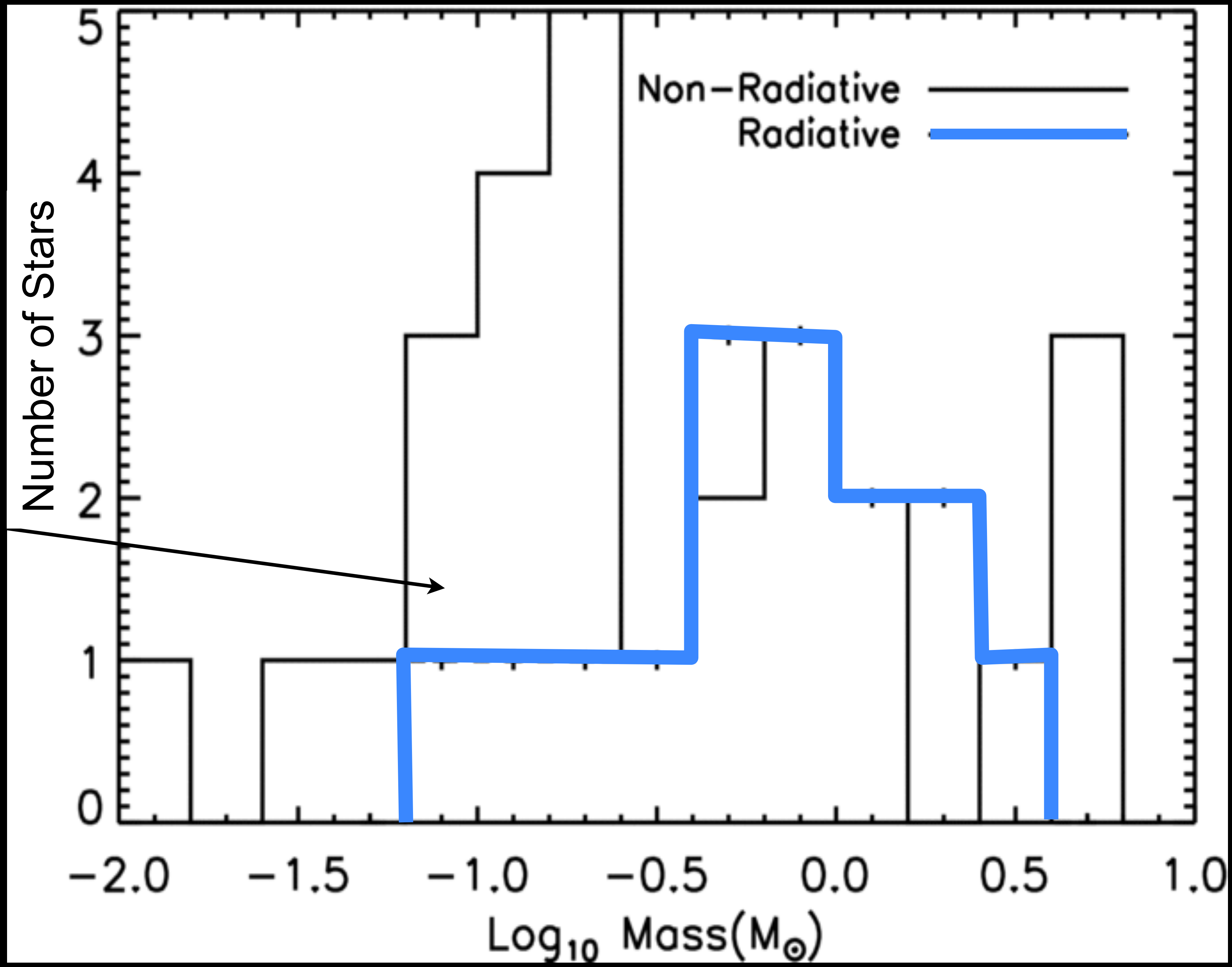

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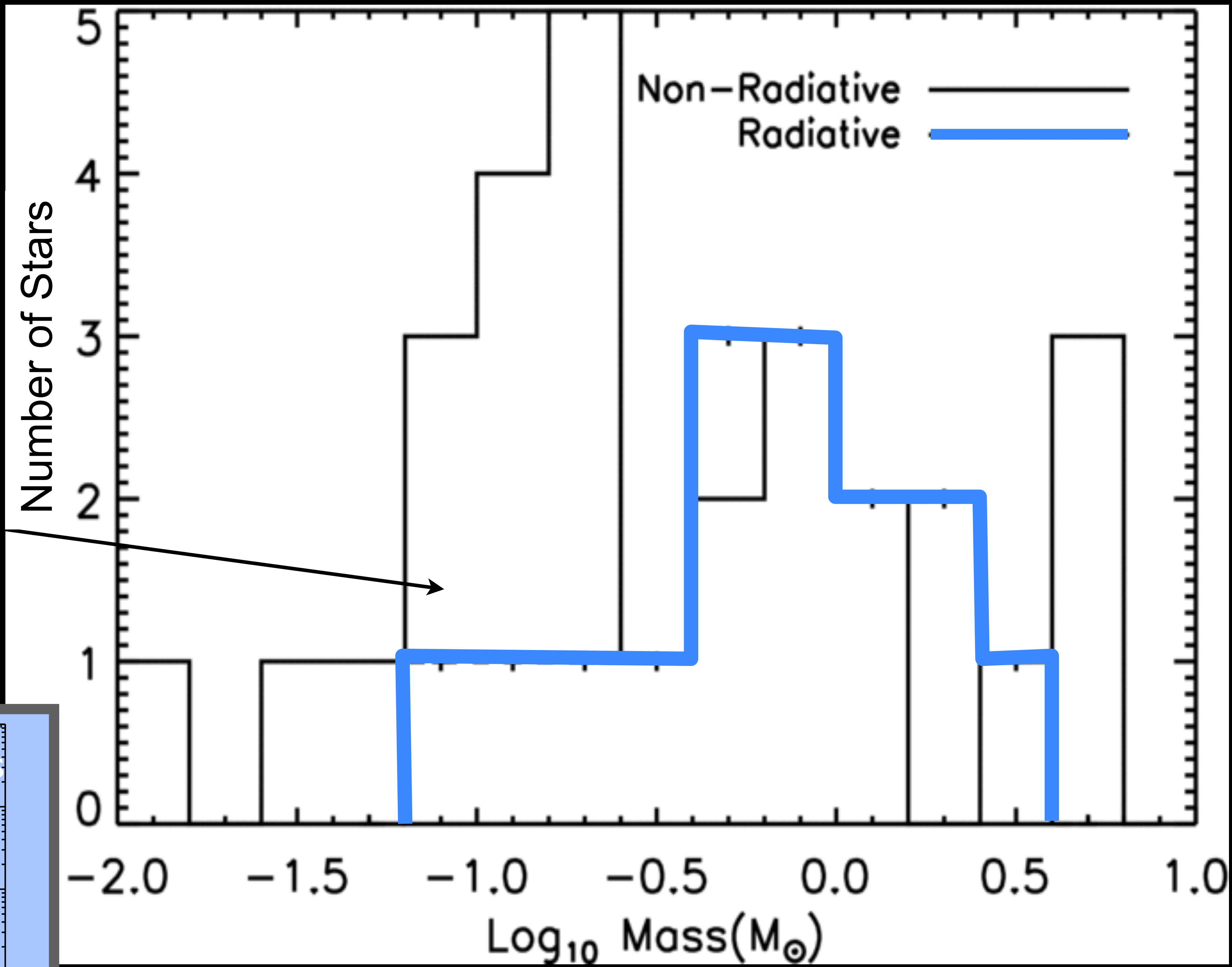

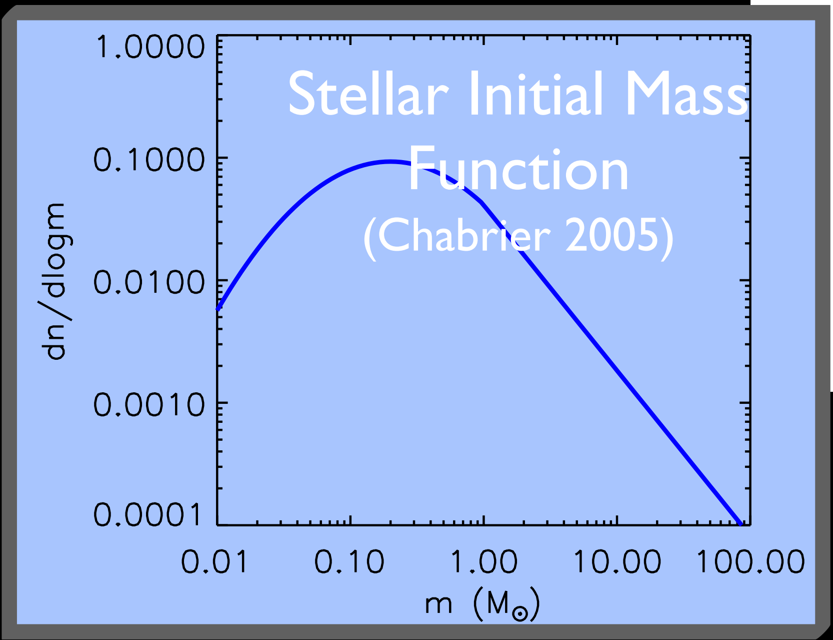

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2. Protostellar Outflows

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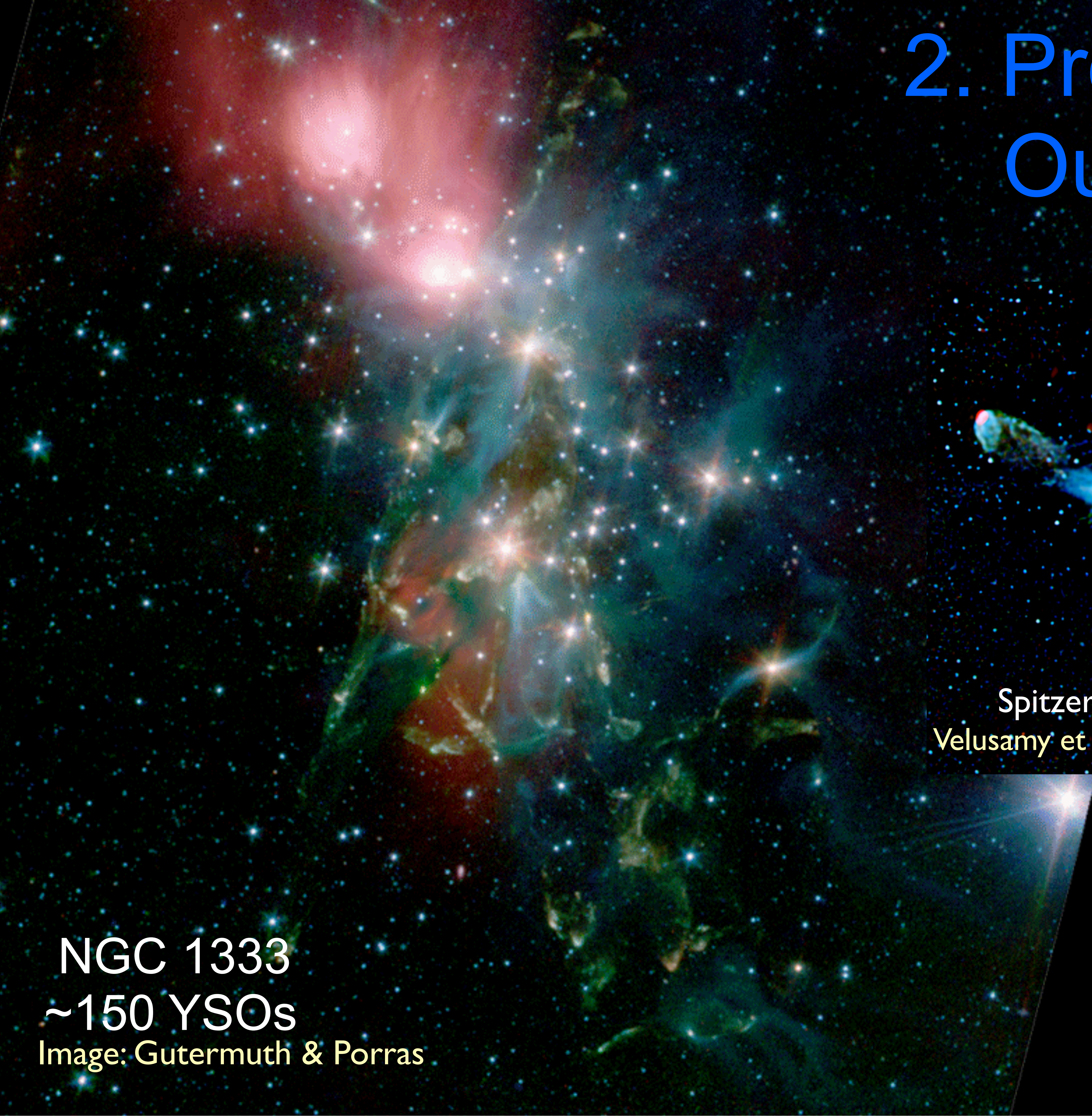
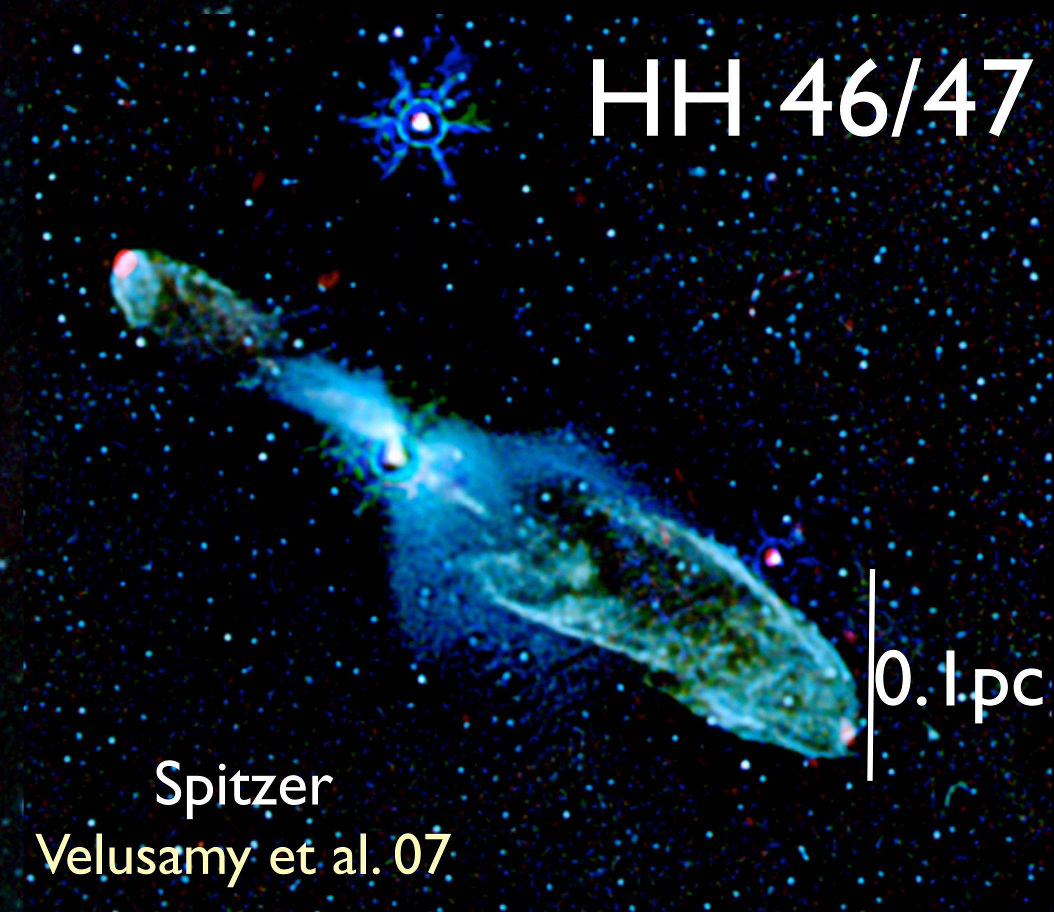
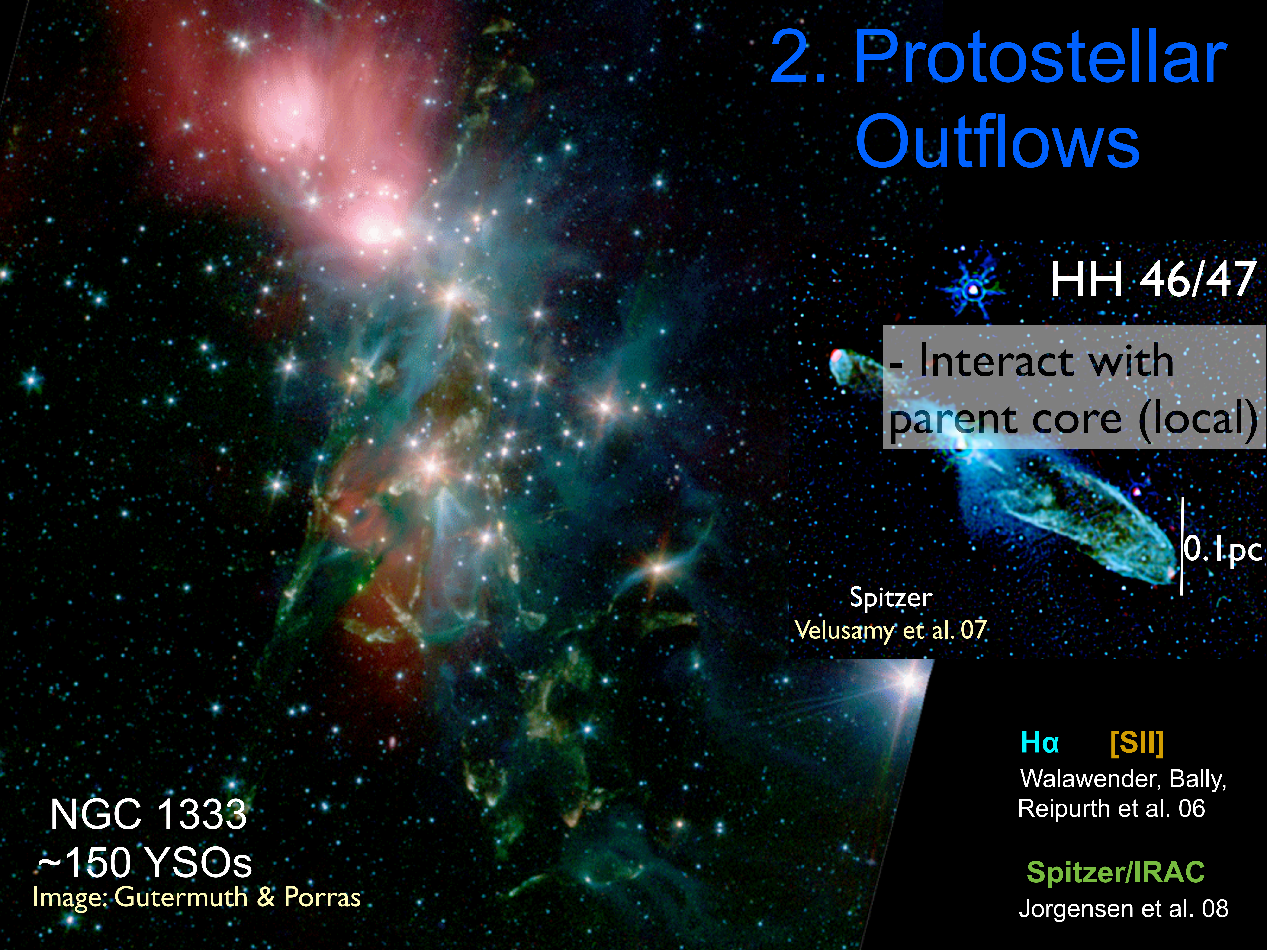


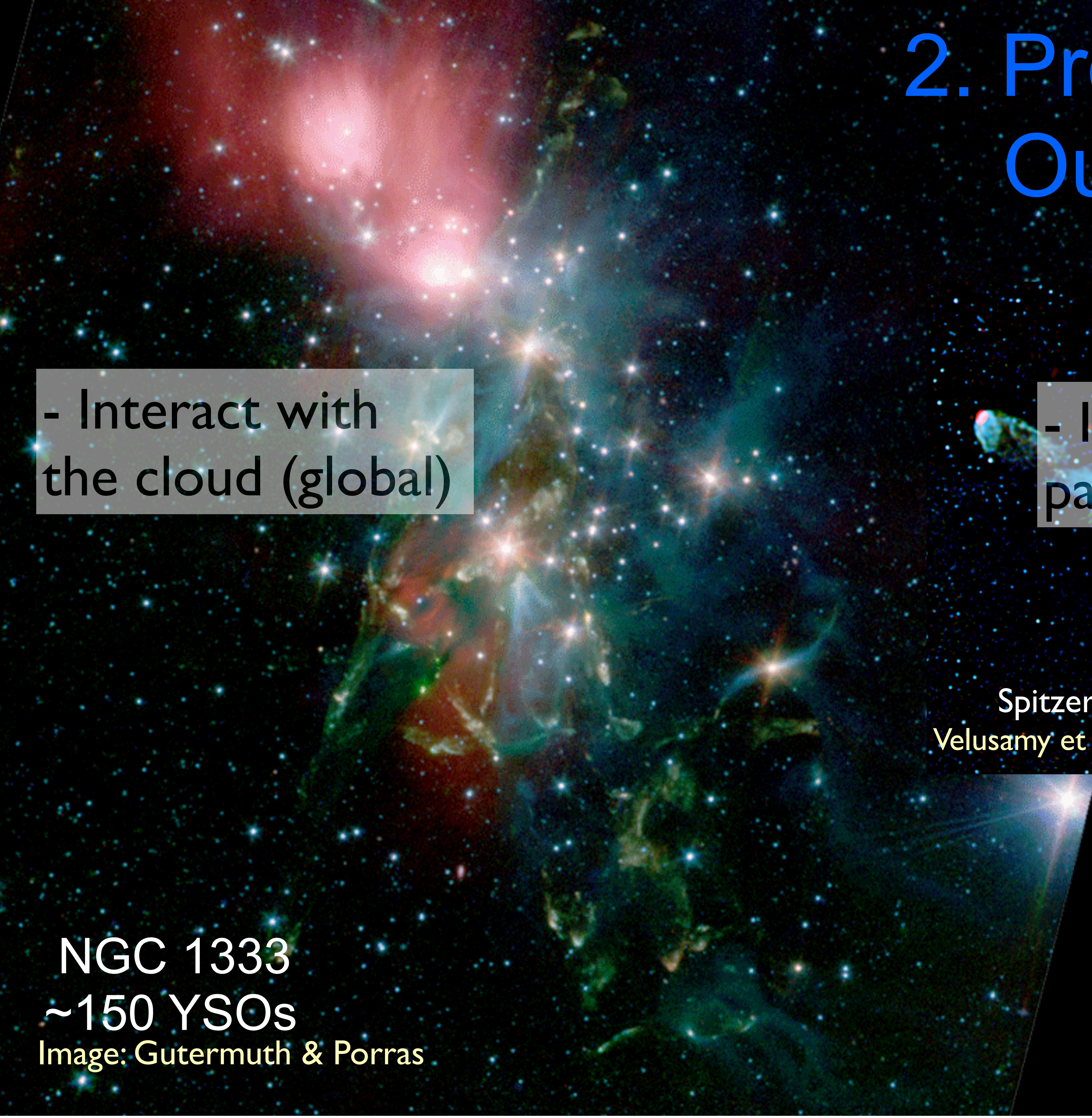


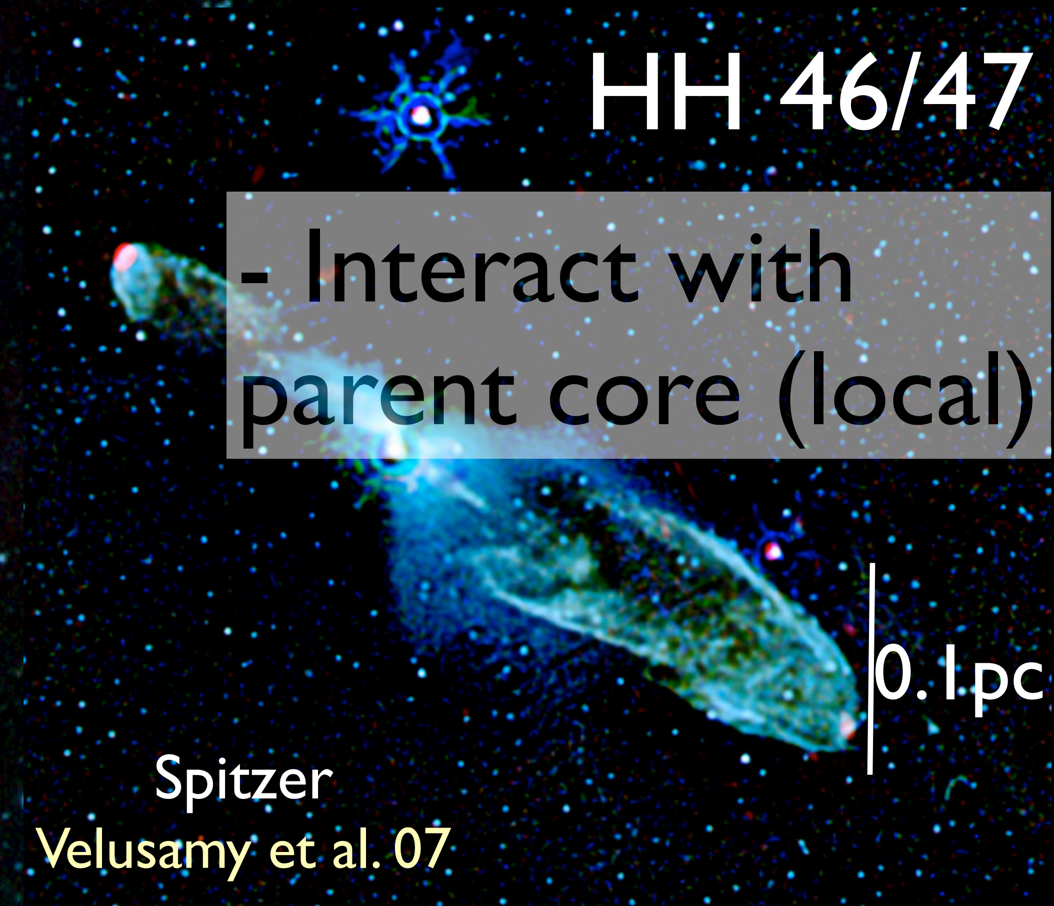
Hα [SII]
Walawender, Bally, Reipurth et al. 06

Spitzer/IRAC
Jorgensen et al. 08


2. Protostellar Outflows
HH 46/47
- Interact with parent core (local)
0.1pc
Spitzer
Velusamy et al. 07
Hα
[SII]
Walawender, Bally, Reipurth et al. 06
Spitzer/IRAC
Jorgensen et al. 08
NGC 1333
~150 YSOs
Image: Gutermuth & Porras

2. Protostellar Outflows





Hα [SII]
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Protostellar Outflows

Individual "Isolated" Core

x *y* *z*

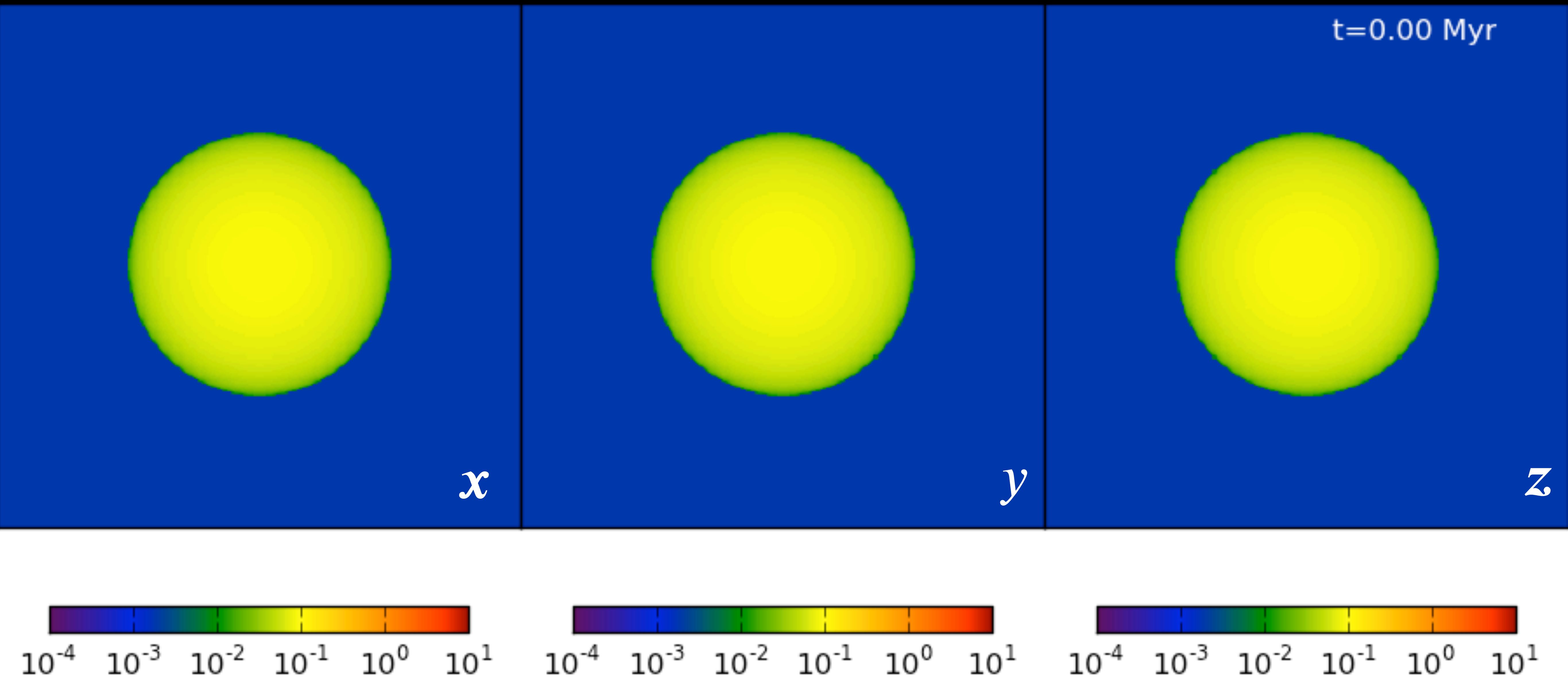
Column Density (g cm^{-2})

L=0.25pc

Offner et al. in prep.

Protostellar Outflows

Individual "Isolated" Core



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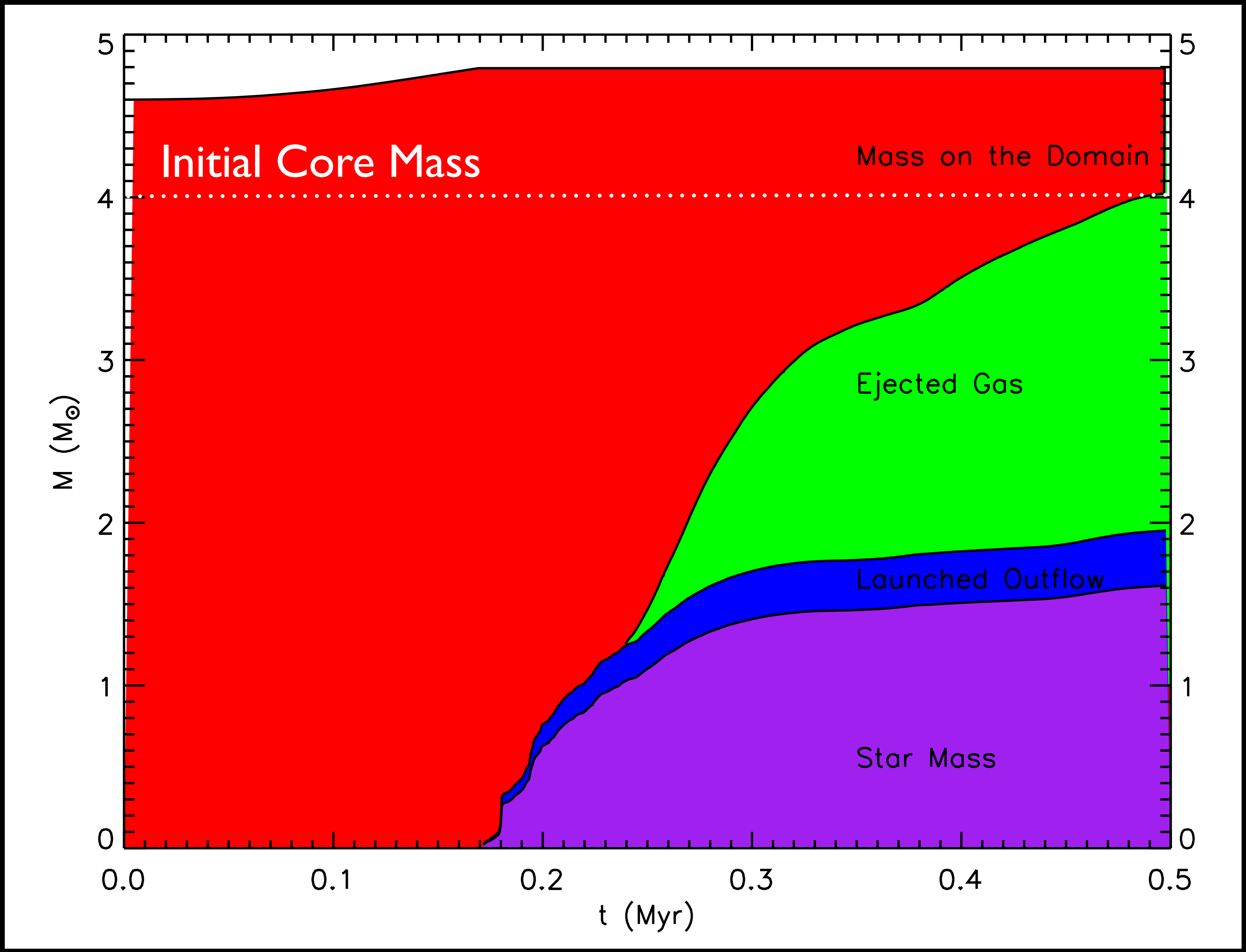
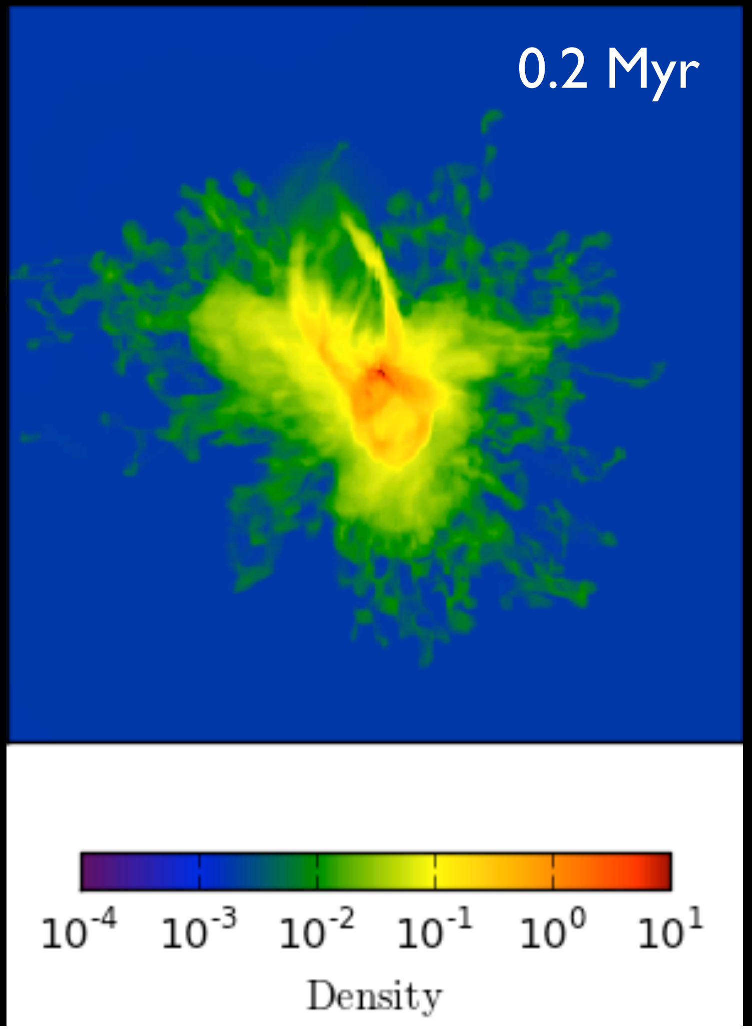
Outflow Mass Evolution



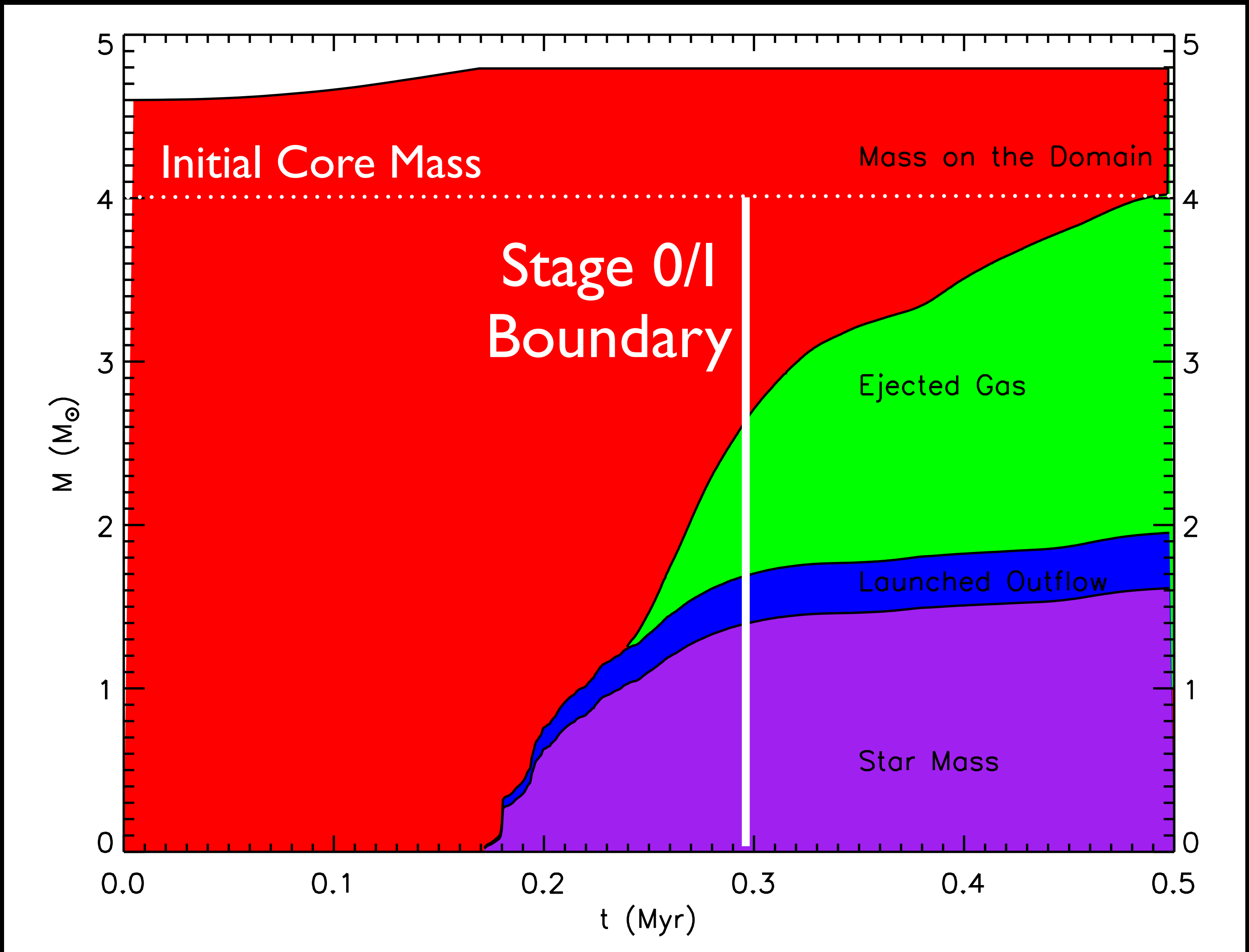


$f_{wind} = 0.2$

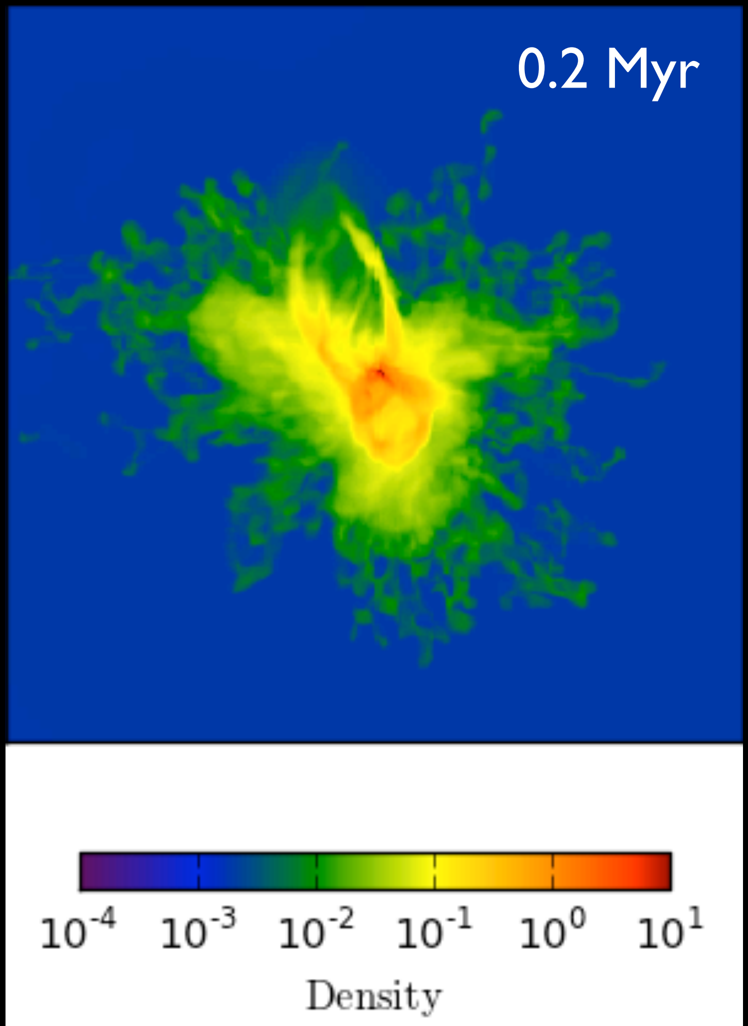
theta = 0.01

Offner & Arce in prep

Outflow Mass Evolution



- Stage 0 Defn: $M_* < M_{env}$
- Sim. Stage 0 ~ 0.1 Myr
- Obs. Class 0 ~ 0.1 Myr (Enoch et al. 08)



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Offner & Arce in prep

Outflow Mass Evolution

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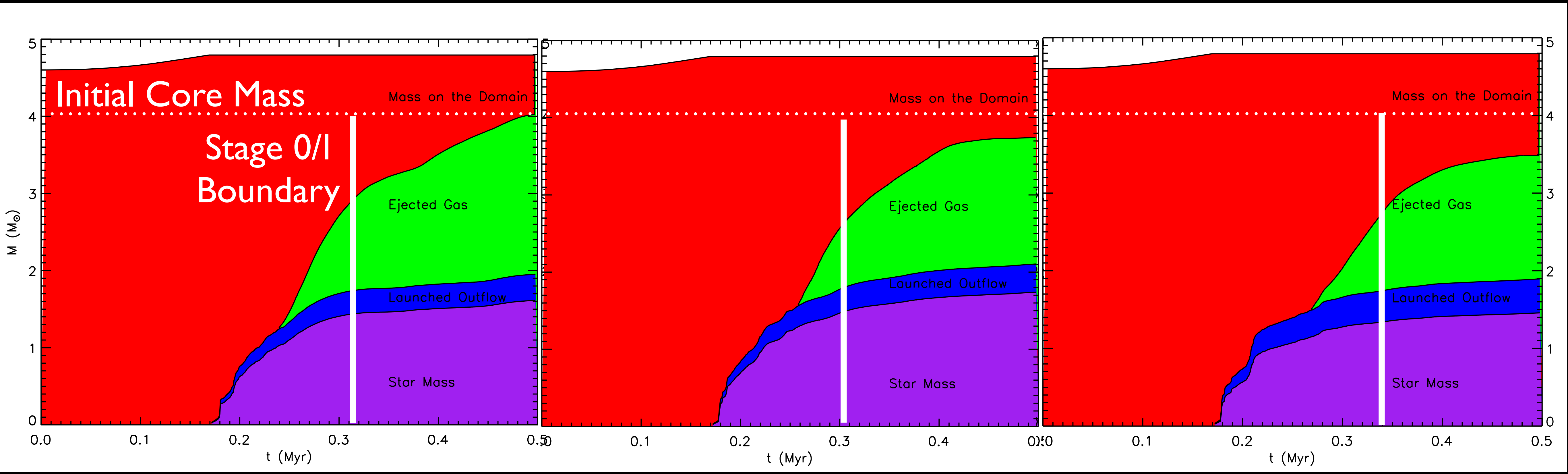


f_{wind} = 0.2
theta = 0.01

f_{wind} = 0.2
theta = 0.1

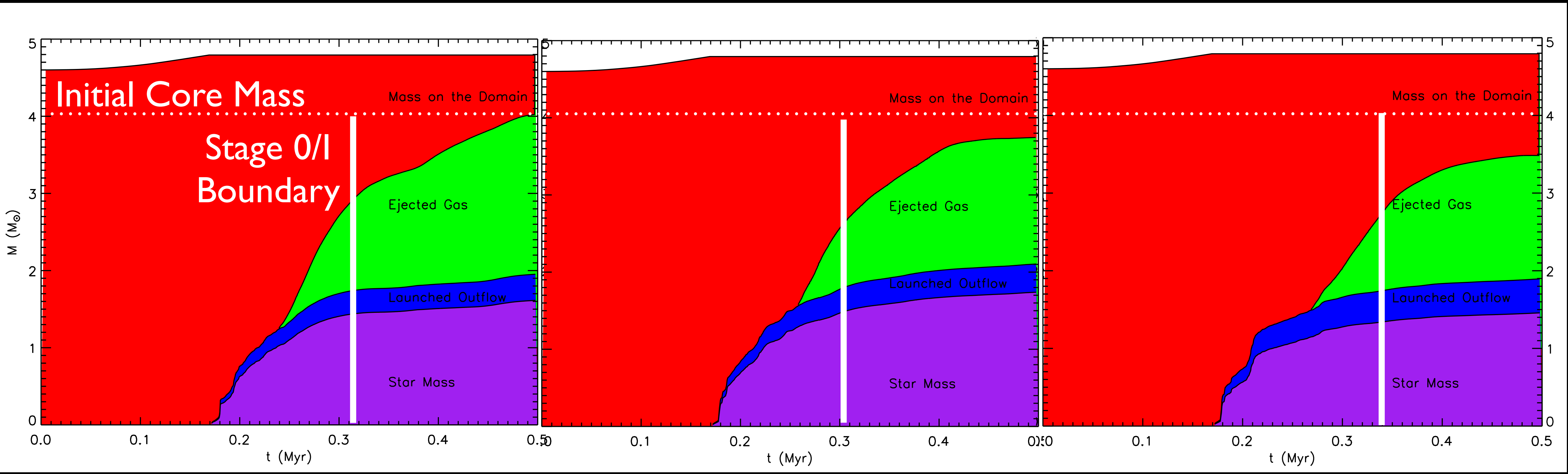
f_{wind} = 0.3
theta = 0.01

Outflow Mass Evolution

$M_* / (M_{env,i} - M_{env,f}) =$

$\varepsilon_{eff} = 0.40$ $\varepsilon_{eff} = 0.43$ $\varepsilon_{eff} = 0.36$

Offner & Arce in prep



$f_{wind} = 0.2$
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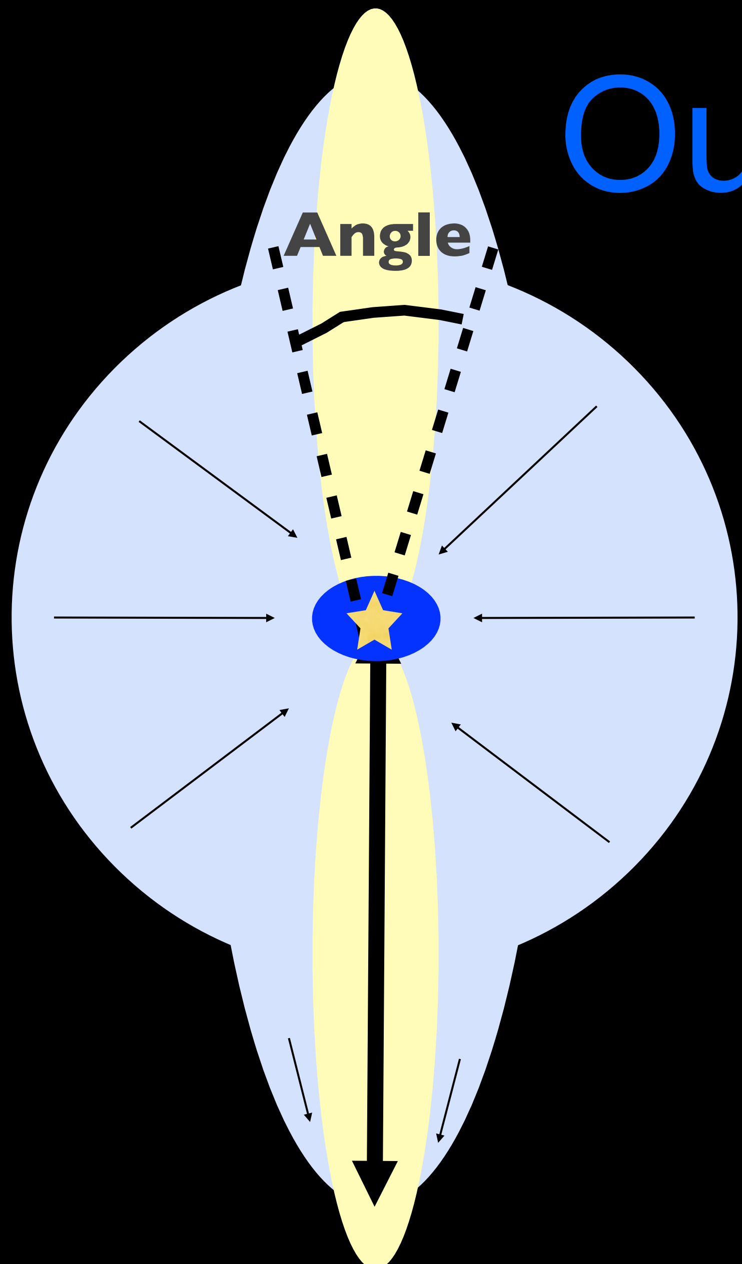
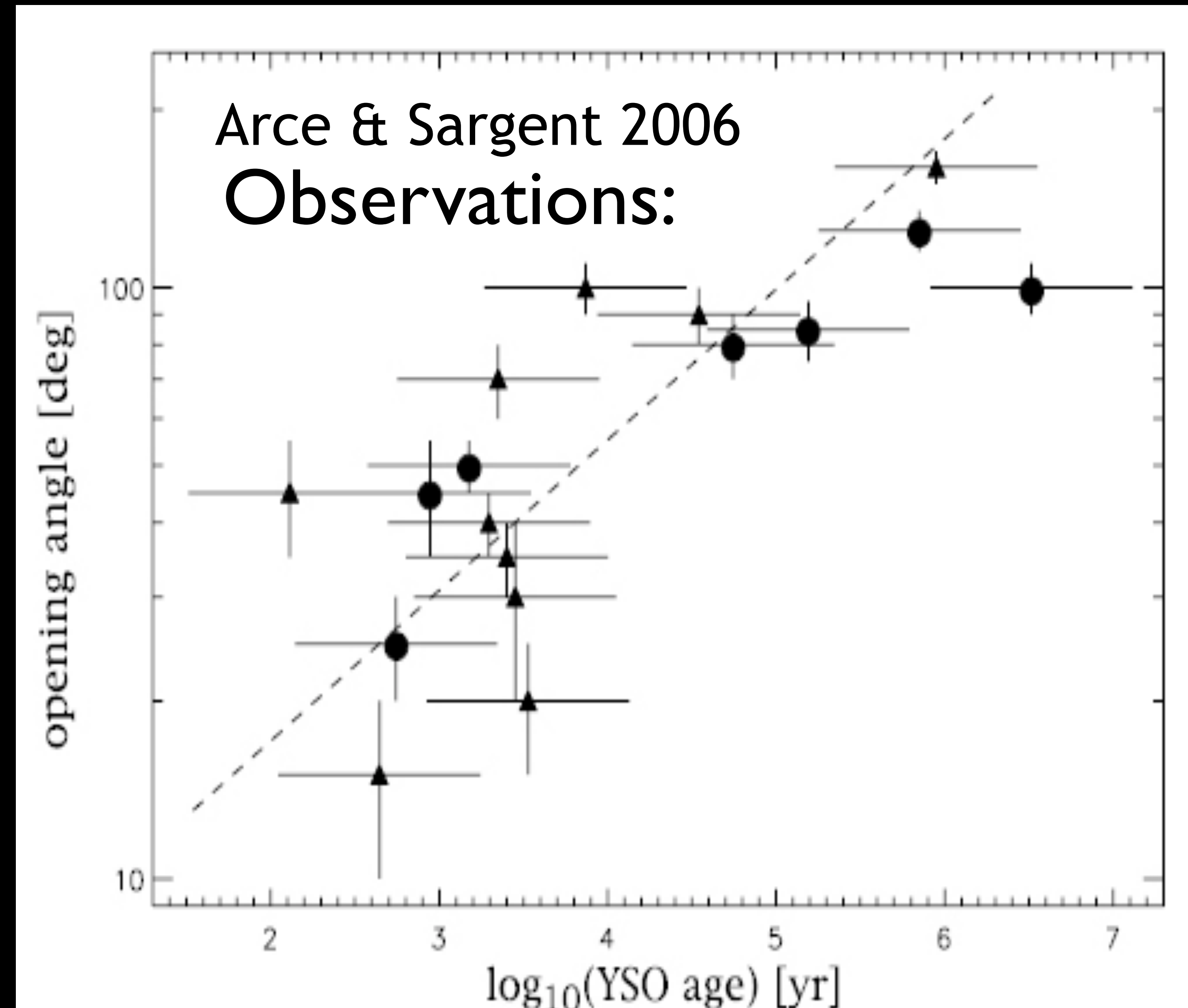
$f_{wind} = 0.3$
theta = 0.01

Outflow Broadening





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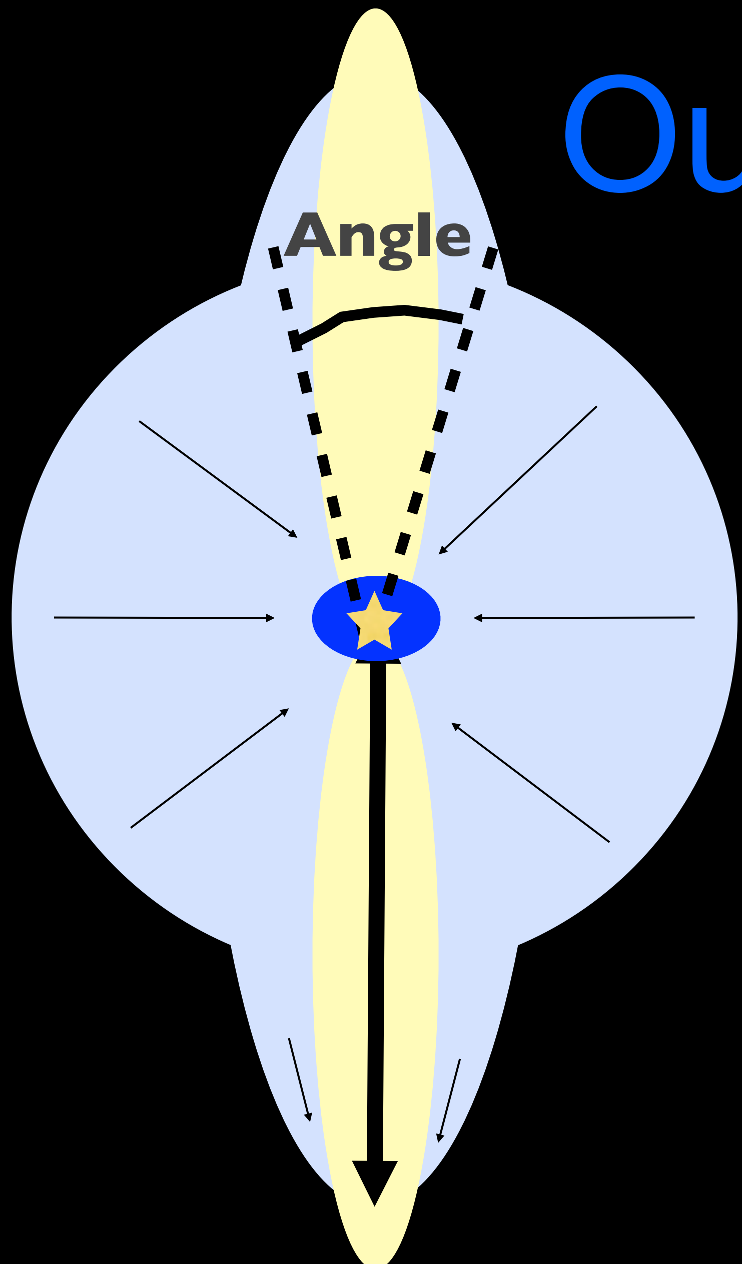
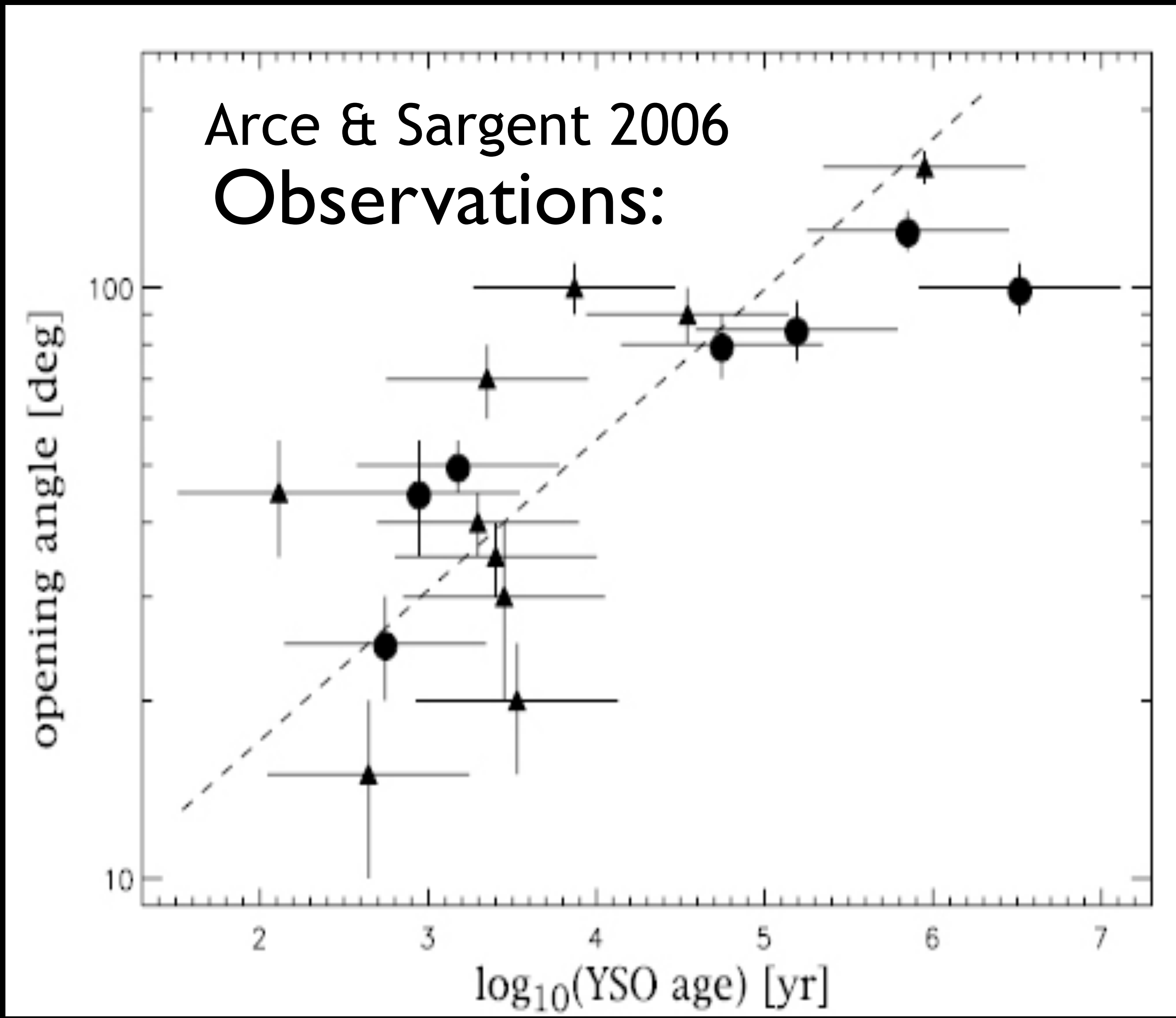
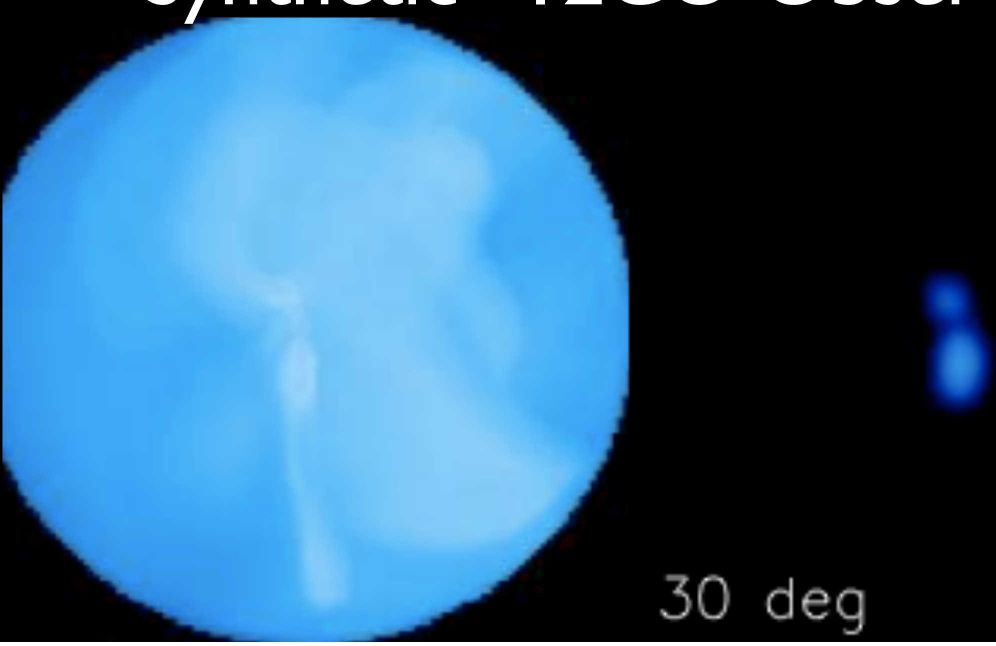




"Synthetic" 12CO Observation



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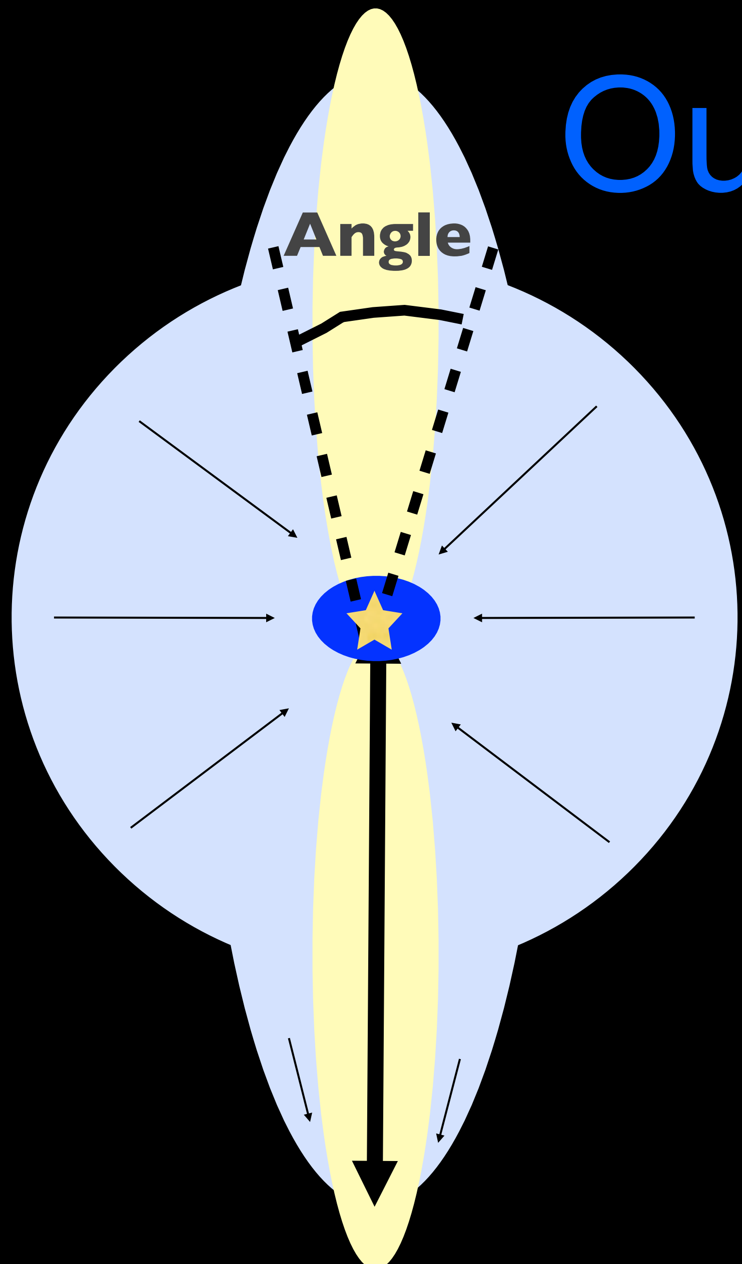

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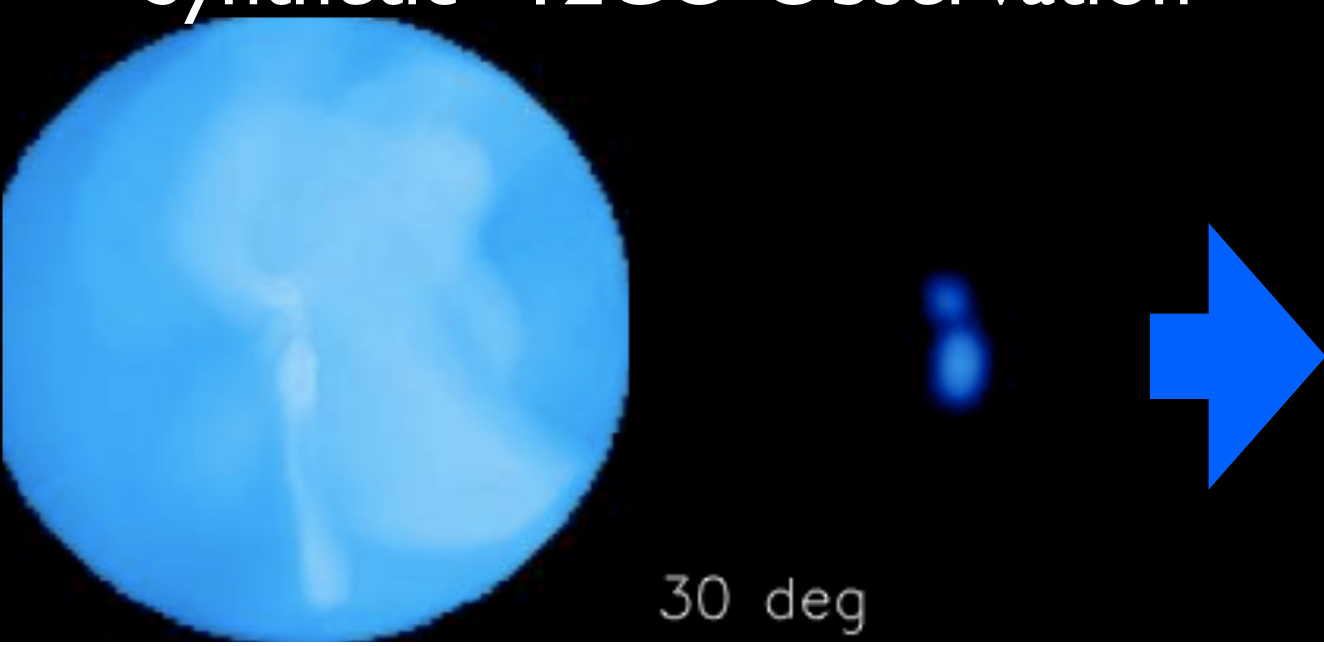

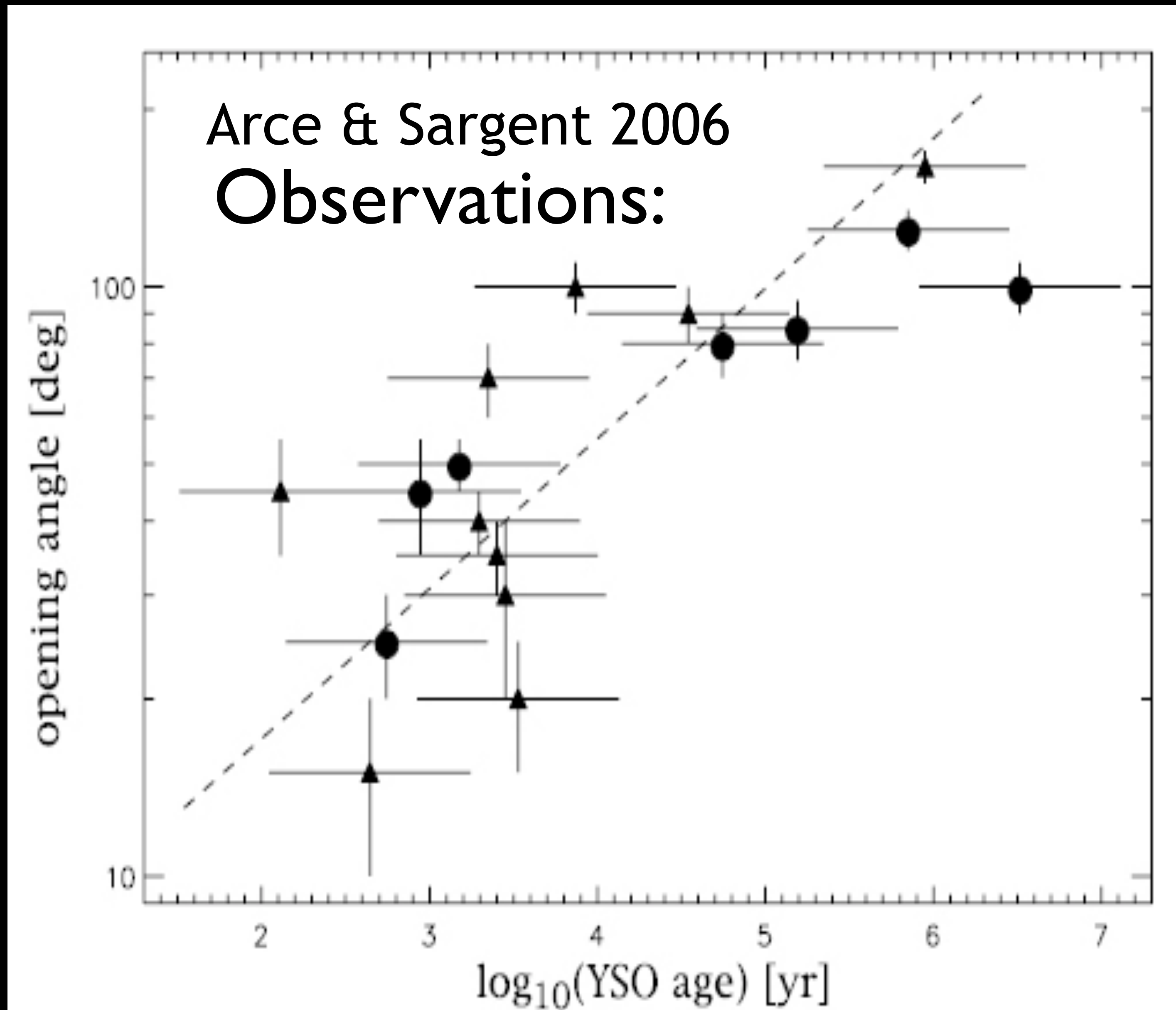

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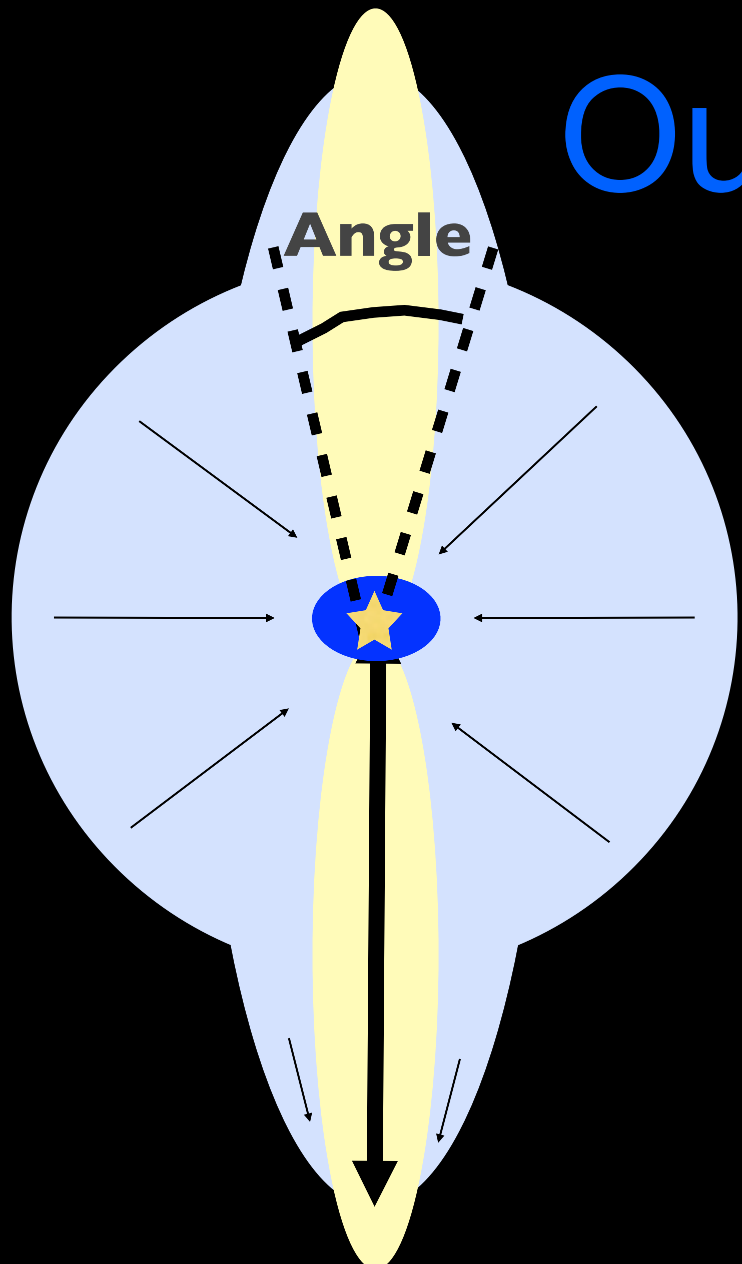

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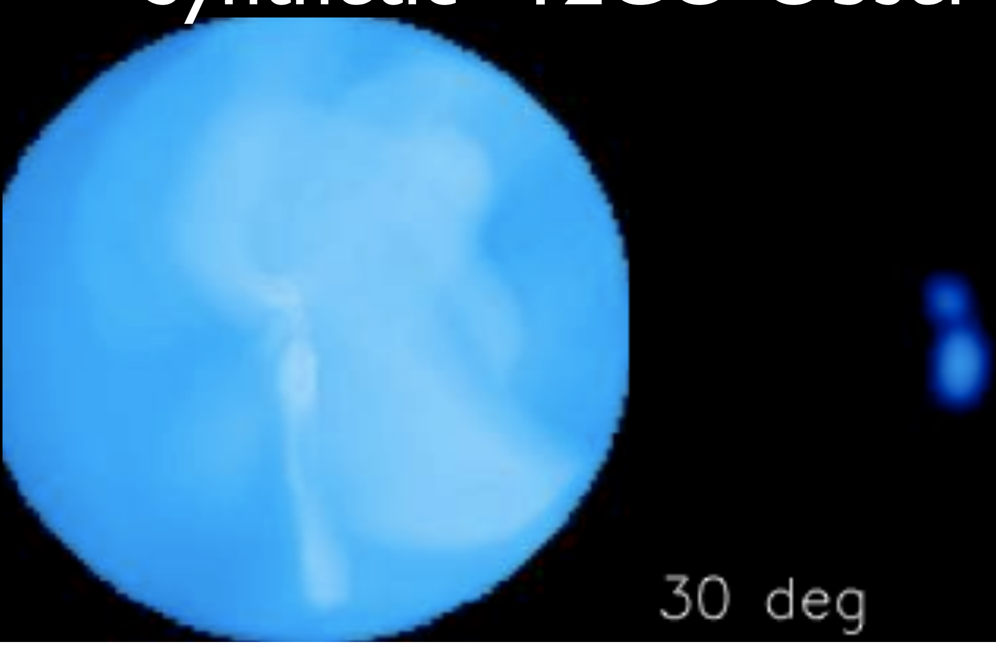

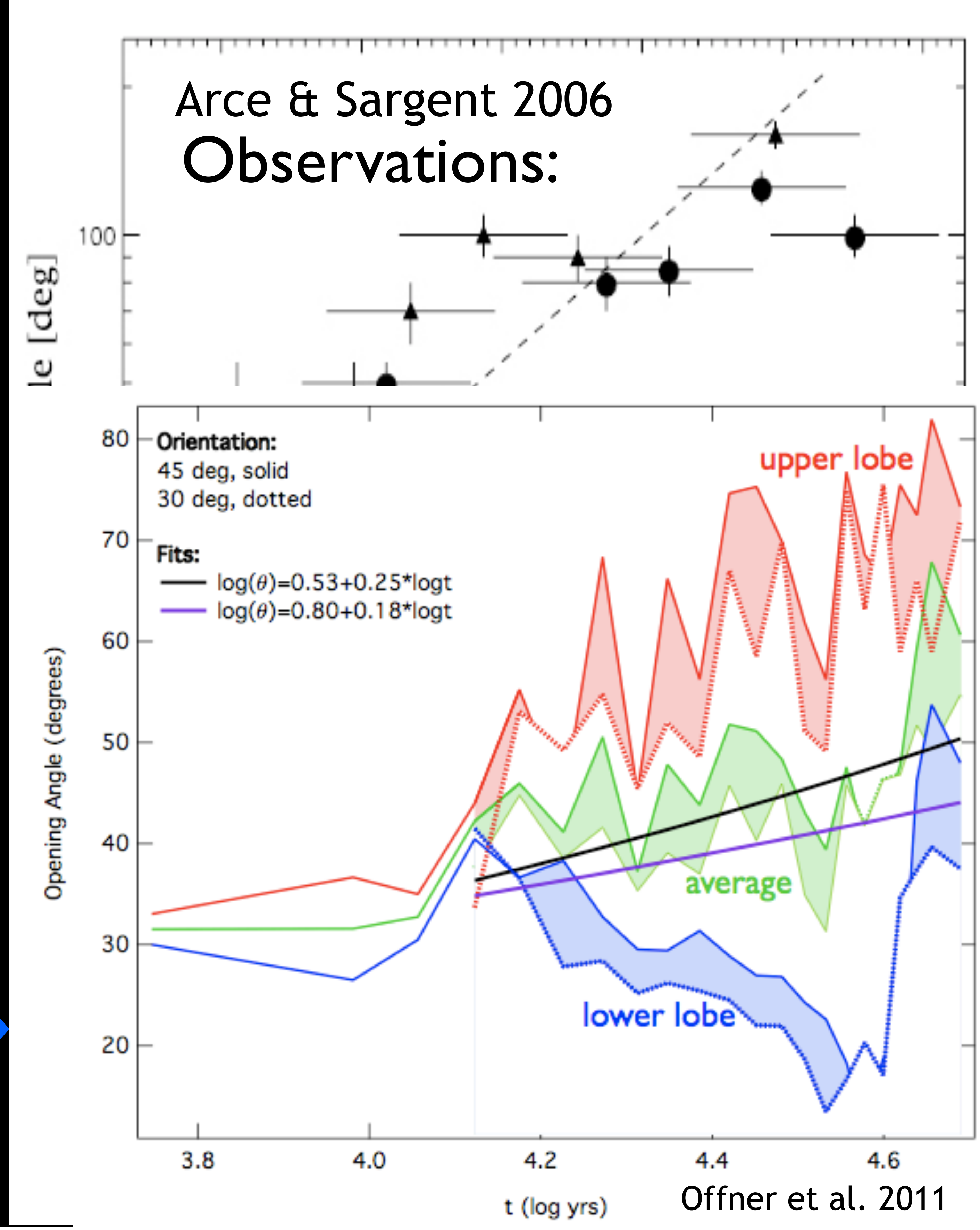

Offner et al. 2011

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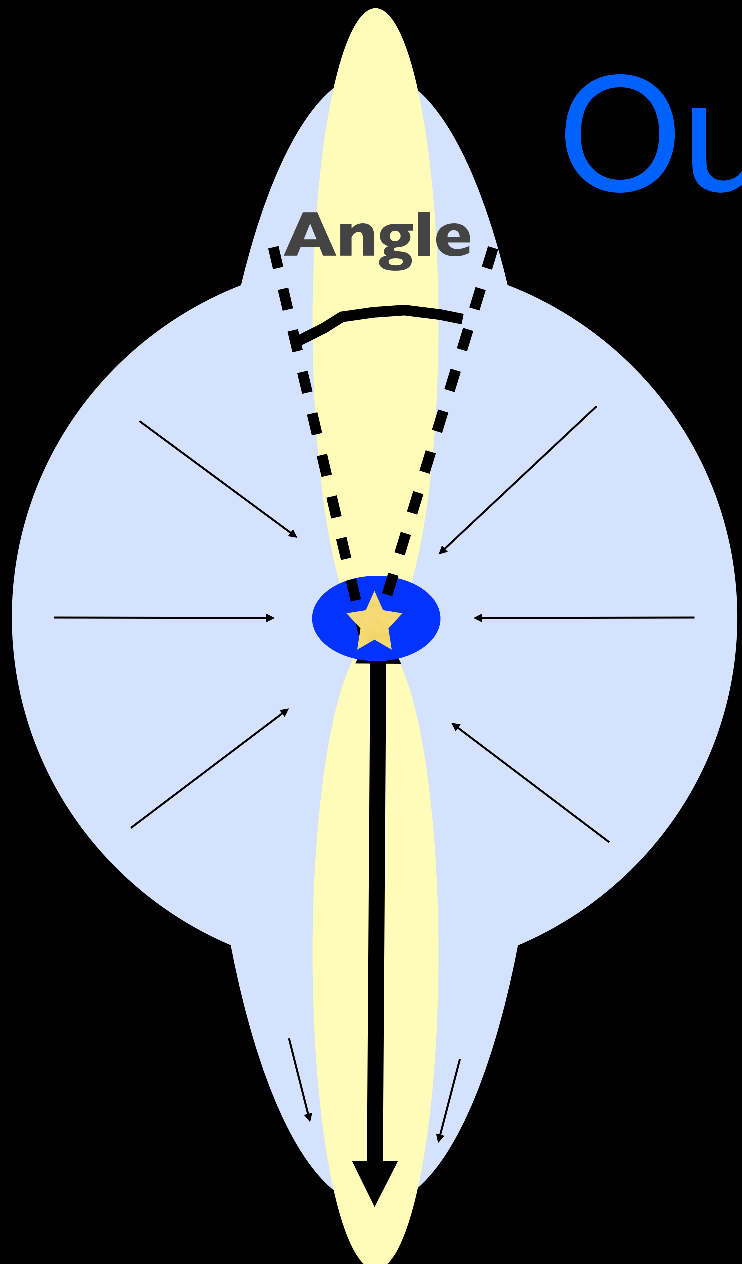

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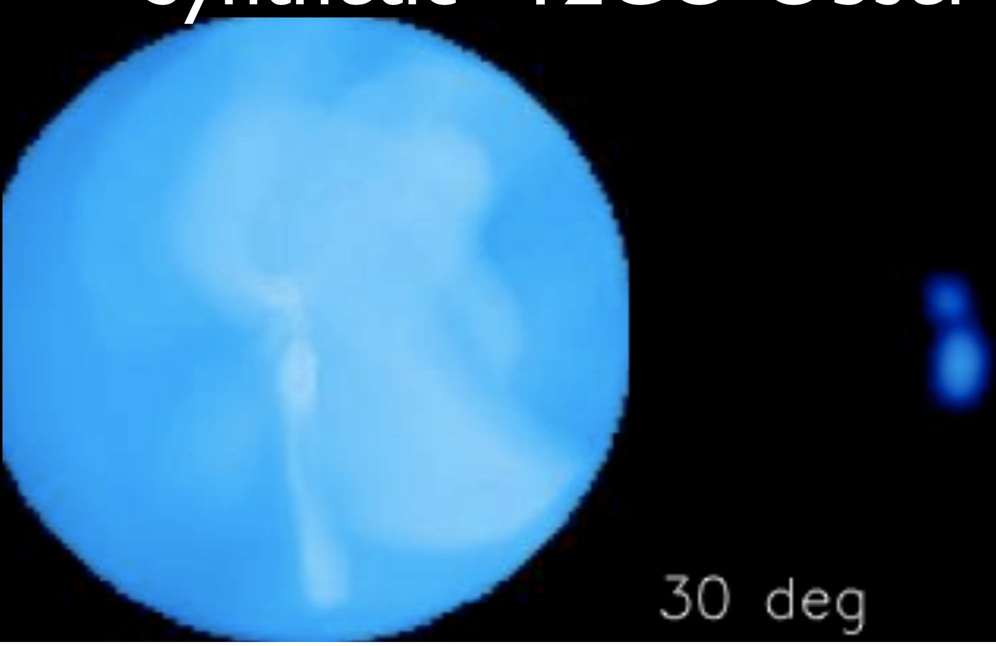
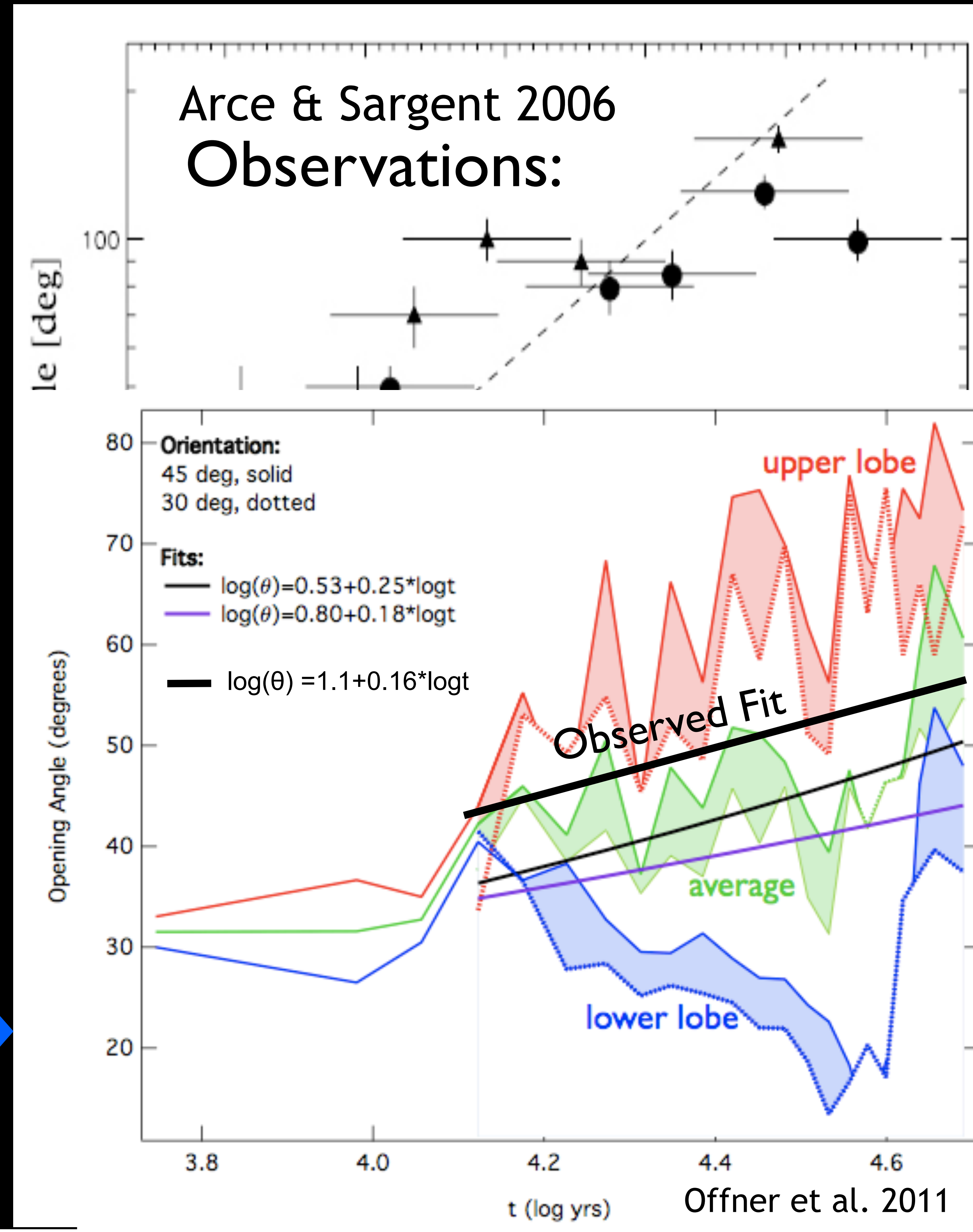




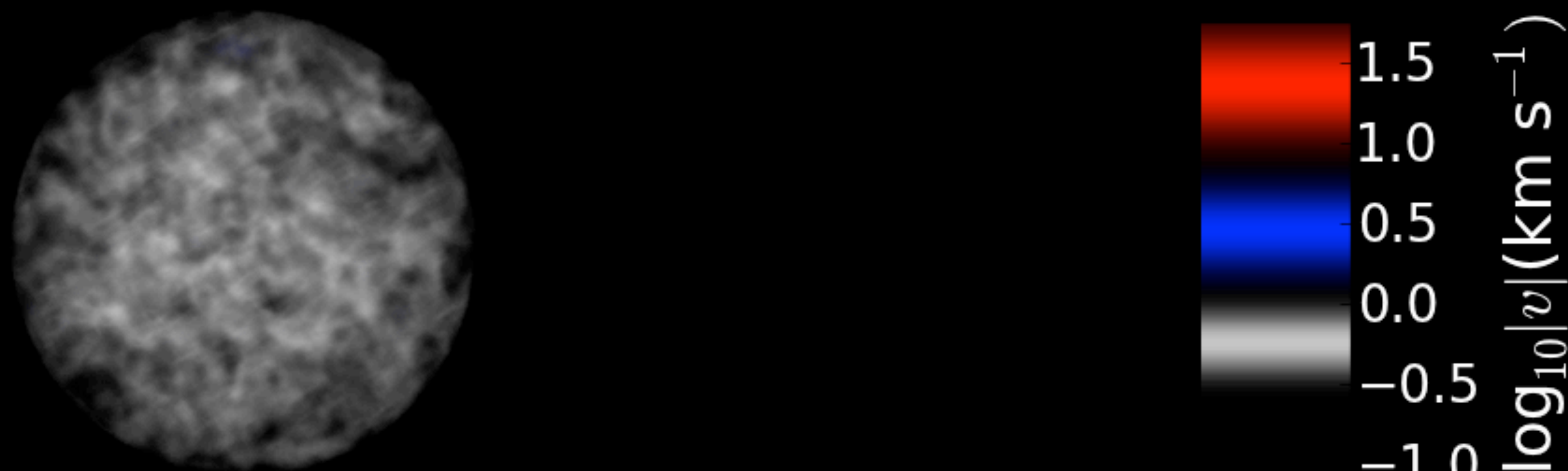
Velocity Evolution

0.1 pc

fwind = 0.2
theta = 0.01

Velocity Evolution

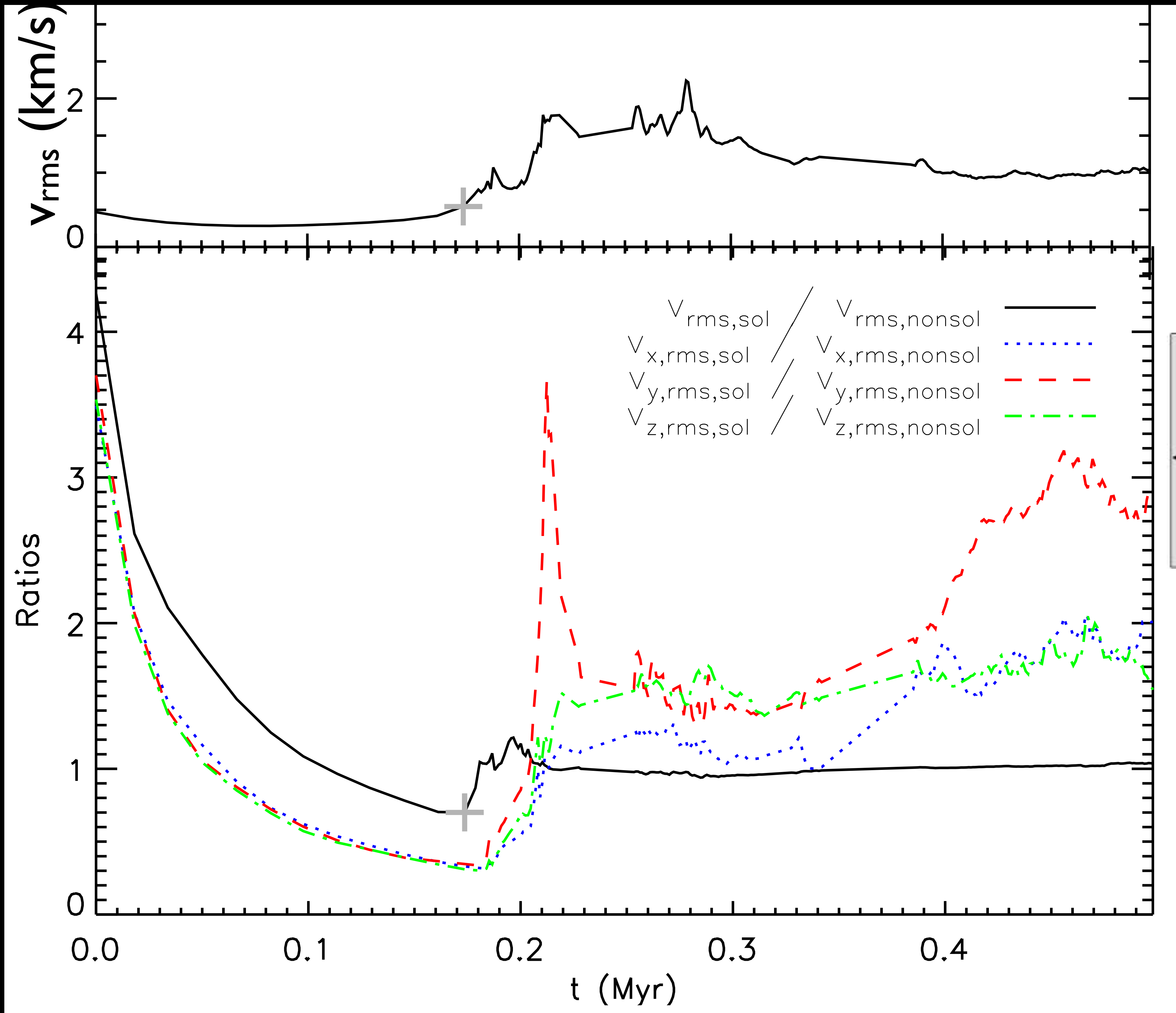
t = 0 yr



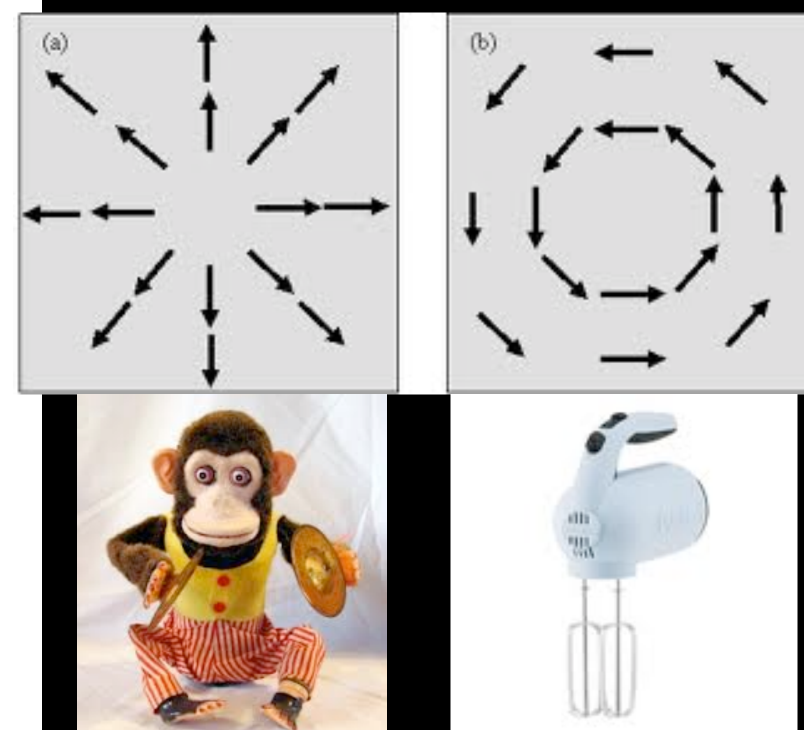
fwind = 0.2
theta = 0.01

0.1 pc

Solenoidal v. Non-Solenoidal

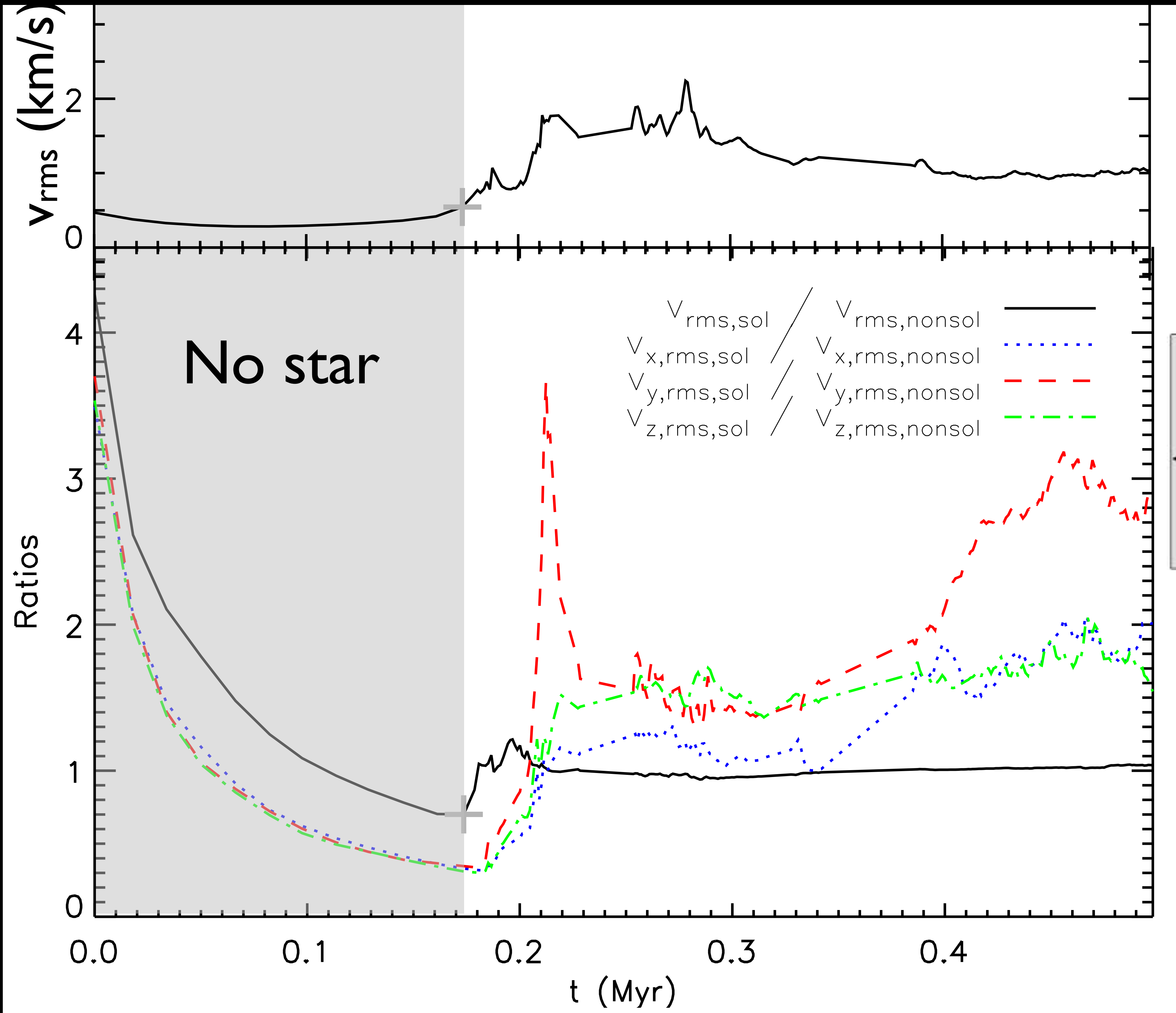


Non-Sol / Solenoidal



Offner et al. in prep.

Solenoidal v. Non-Solenoidal



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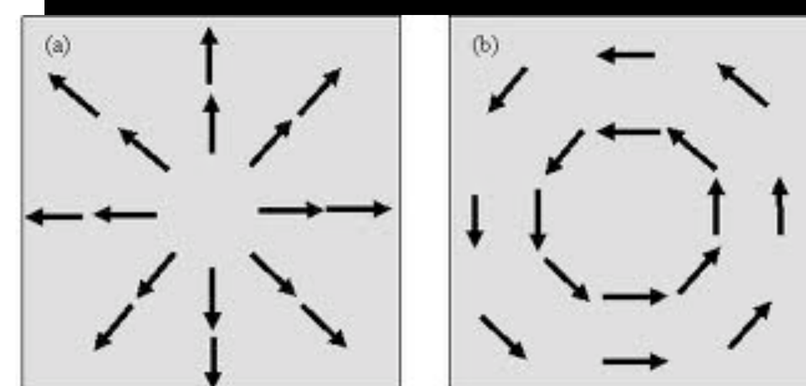

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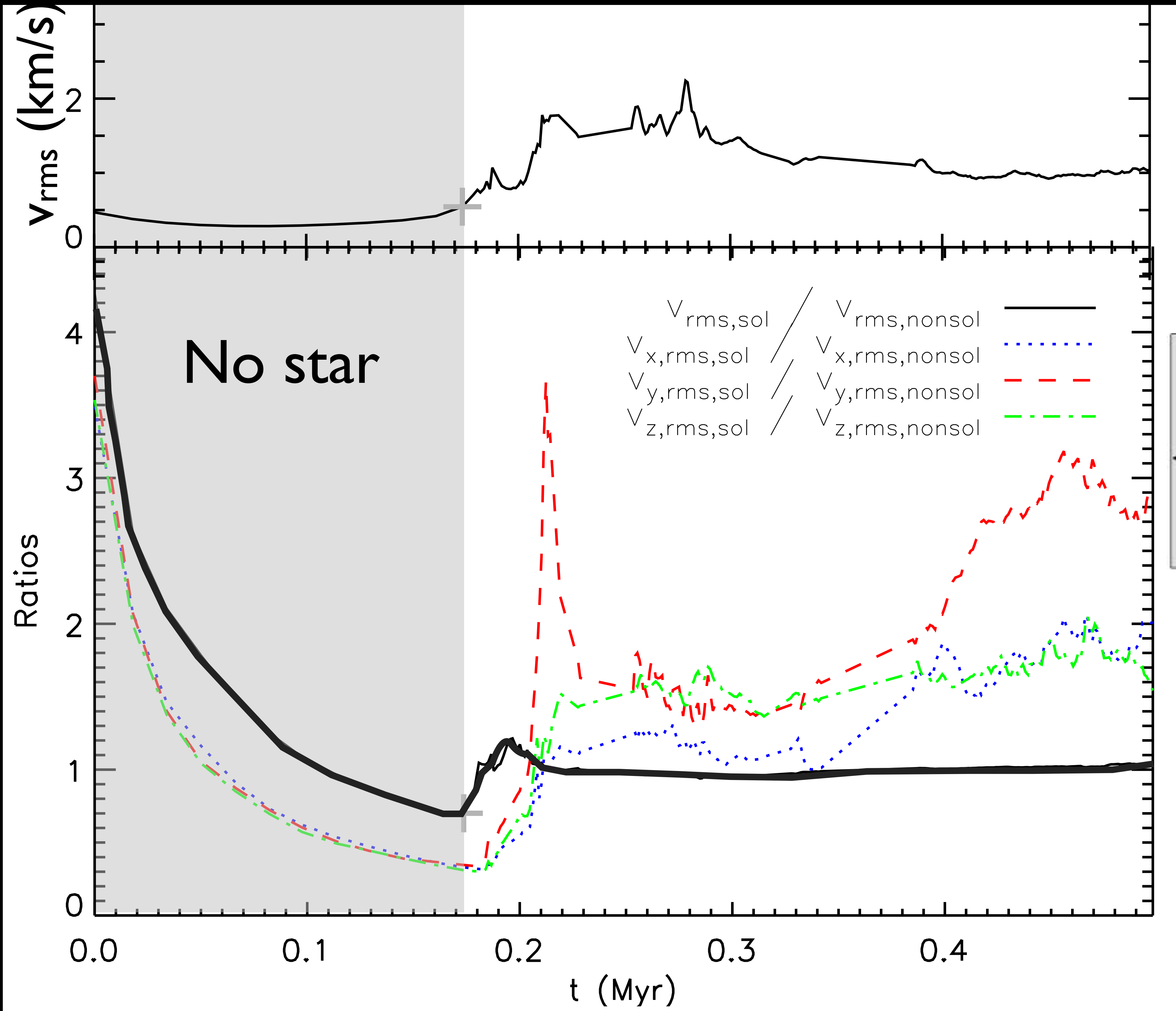

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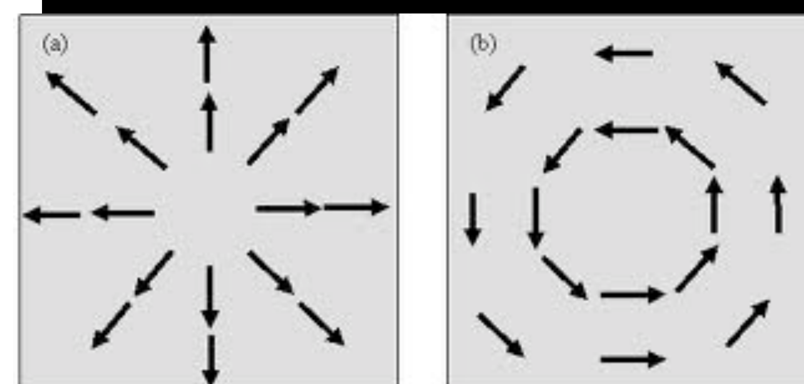

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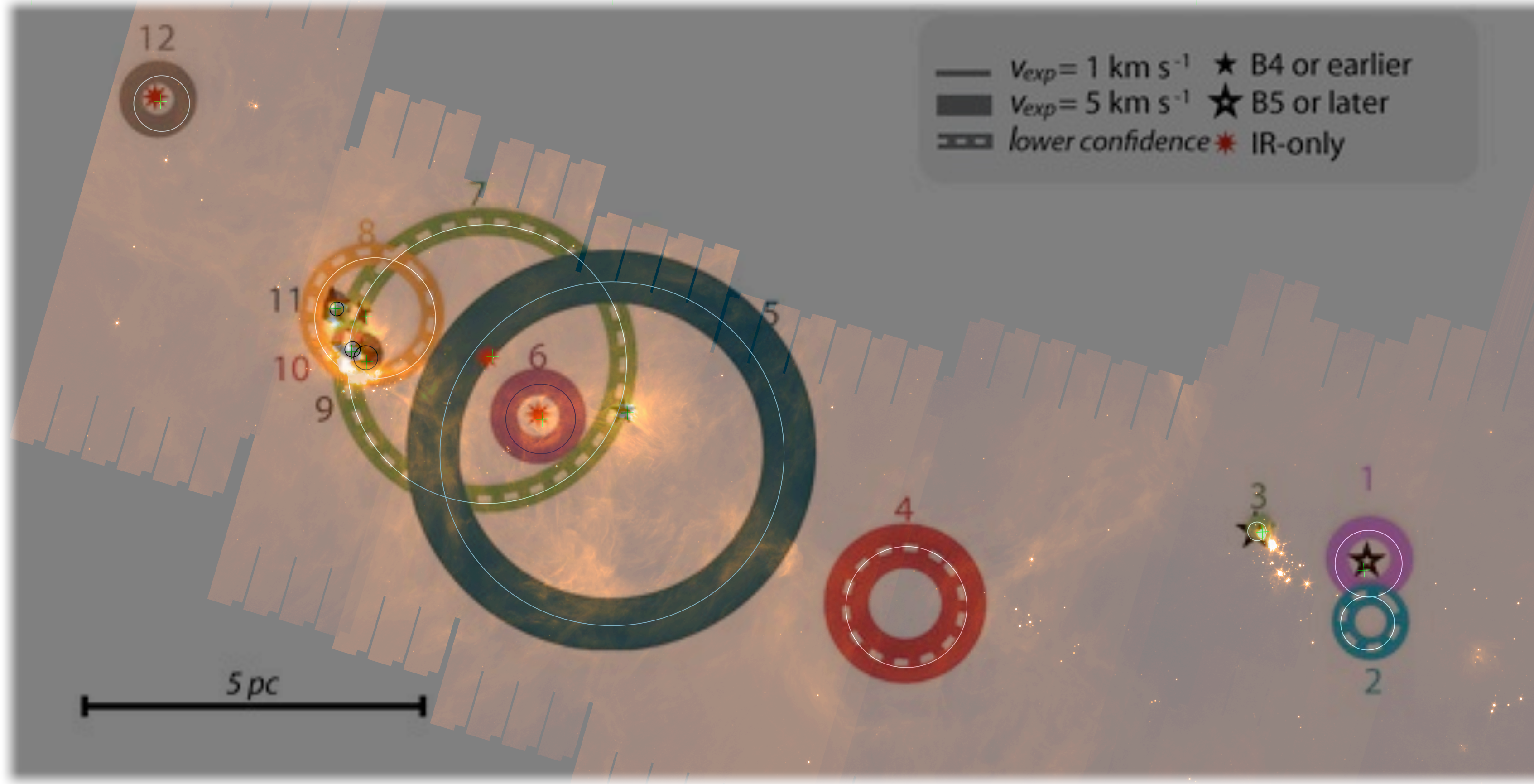

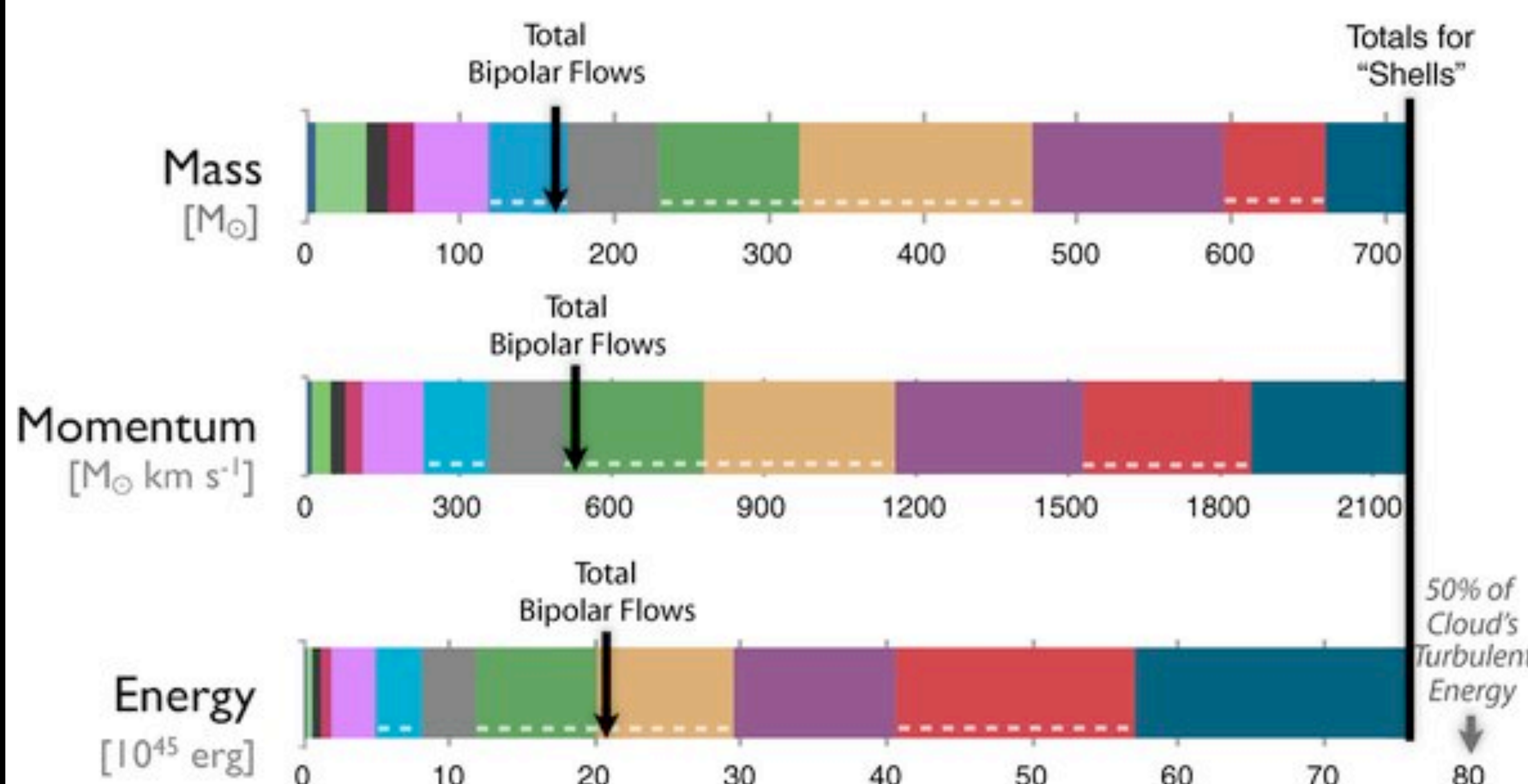

Perseus

Molecular Cloud

Arce et al. 2011

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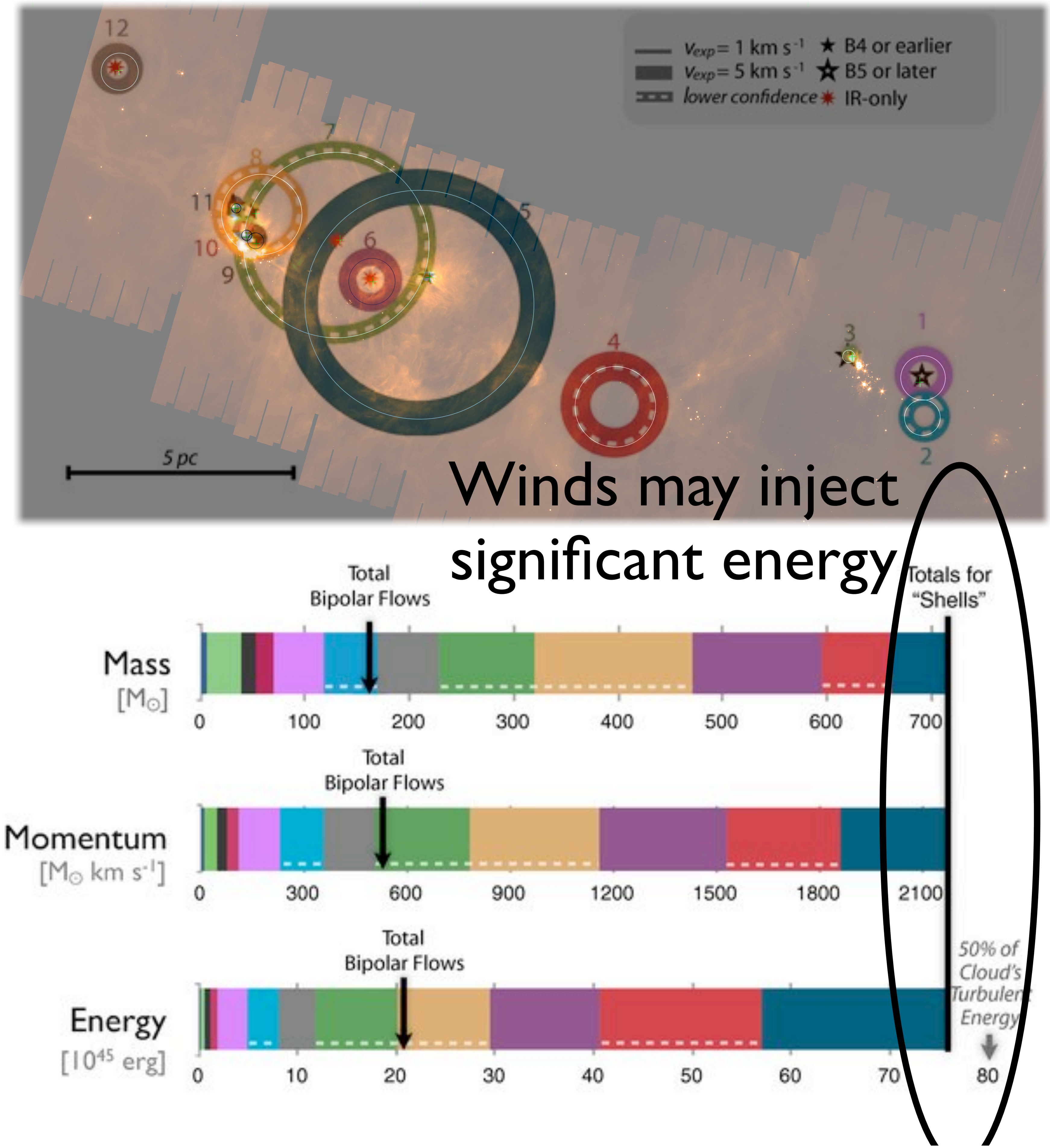


Perseus

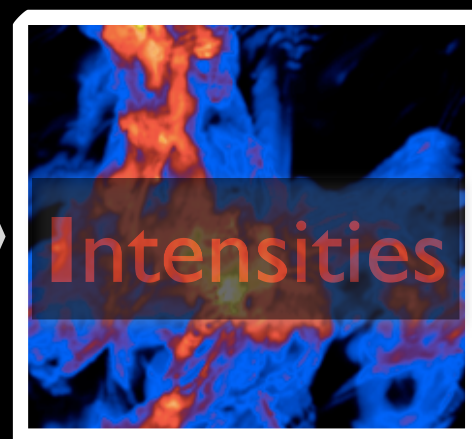
Molecular Cloud

Arce et al. 2011

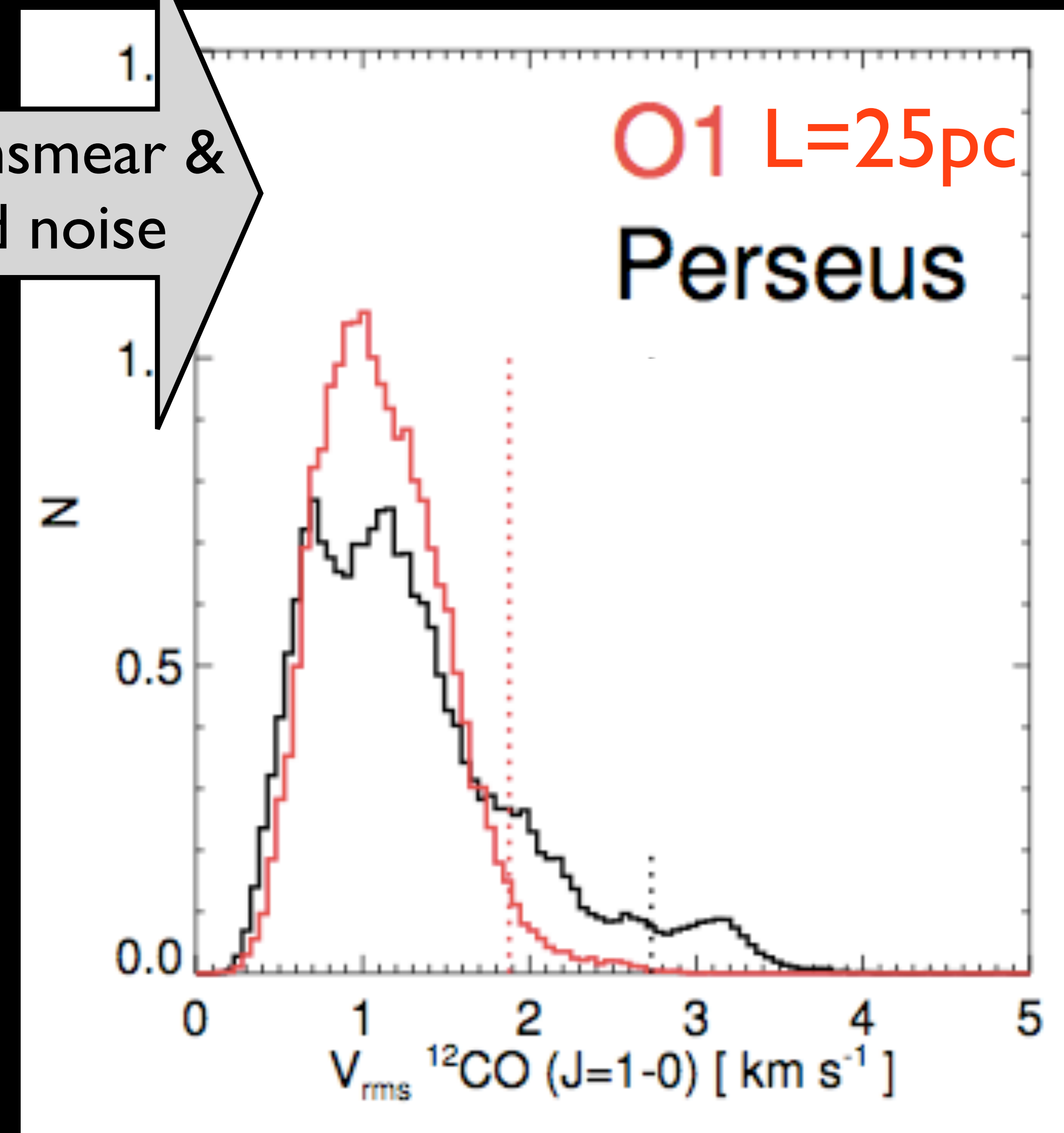
Perseus Velocity Distribution

To get "synthetic" 12CO maps:

RADMC-3D
Dullemond 2012



Beamsmear & add noise



Beaumont, Offner, Shetty, Glover & Goodman in prep.

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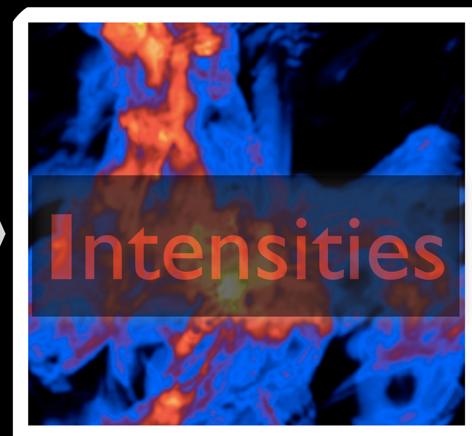

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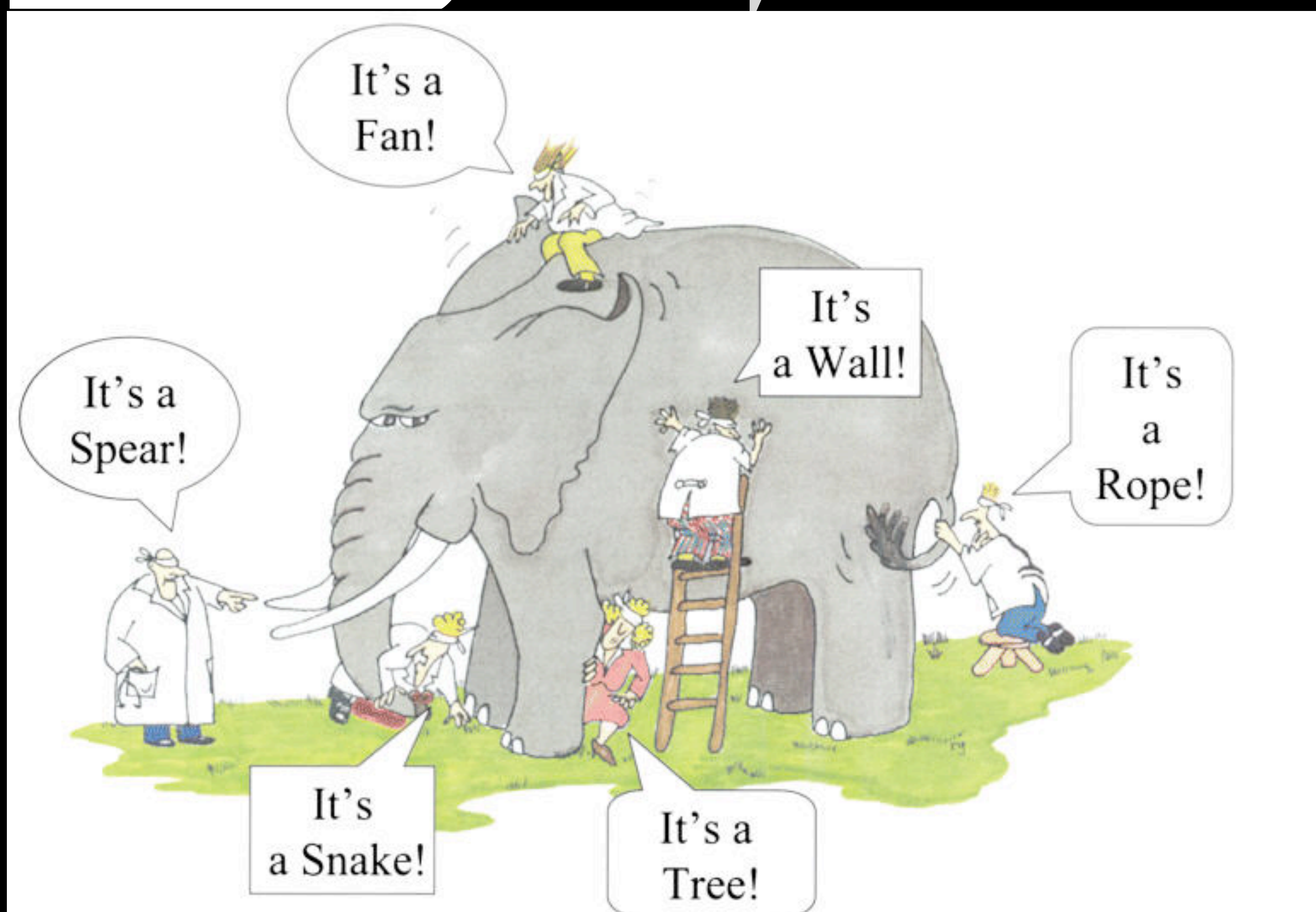

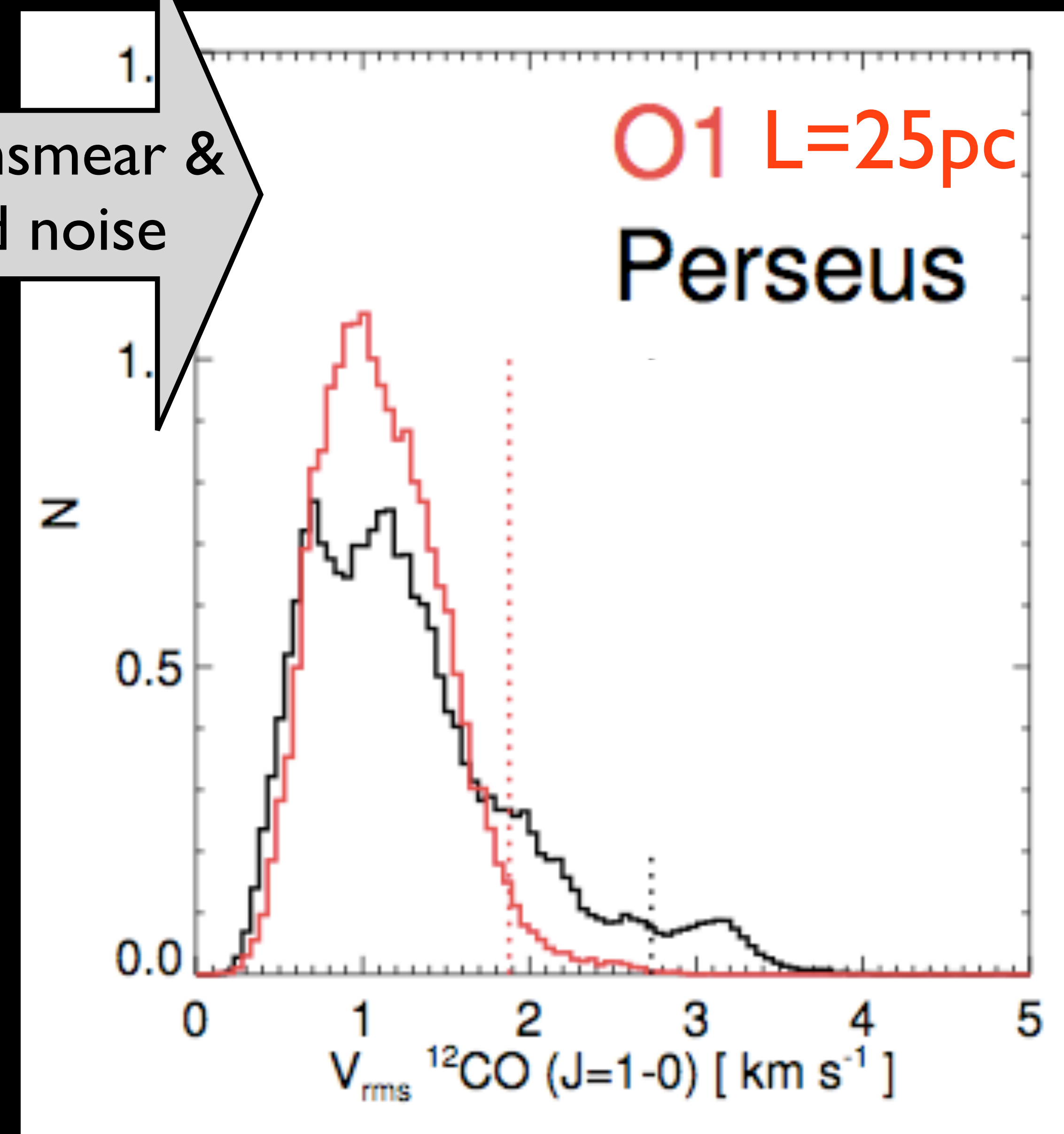

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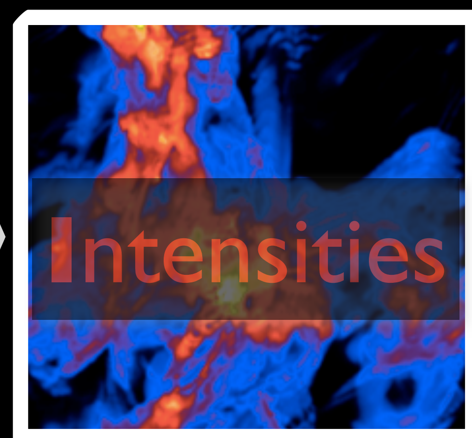

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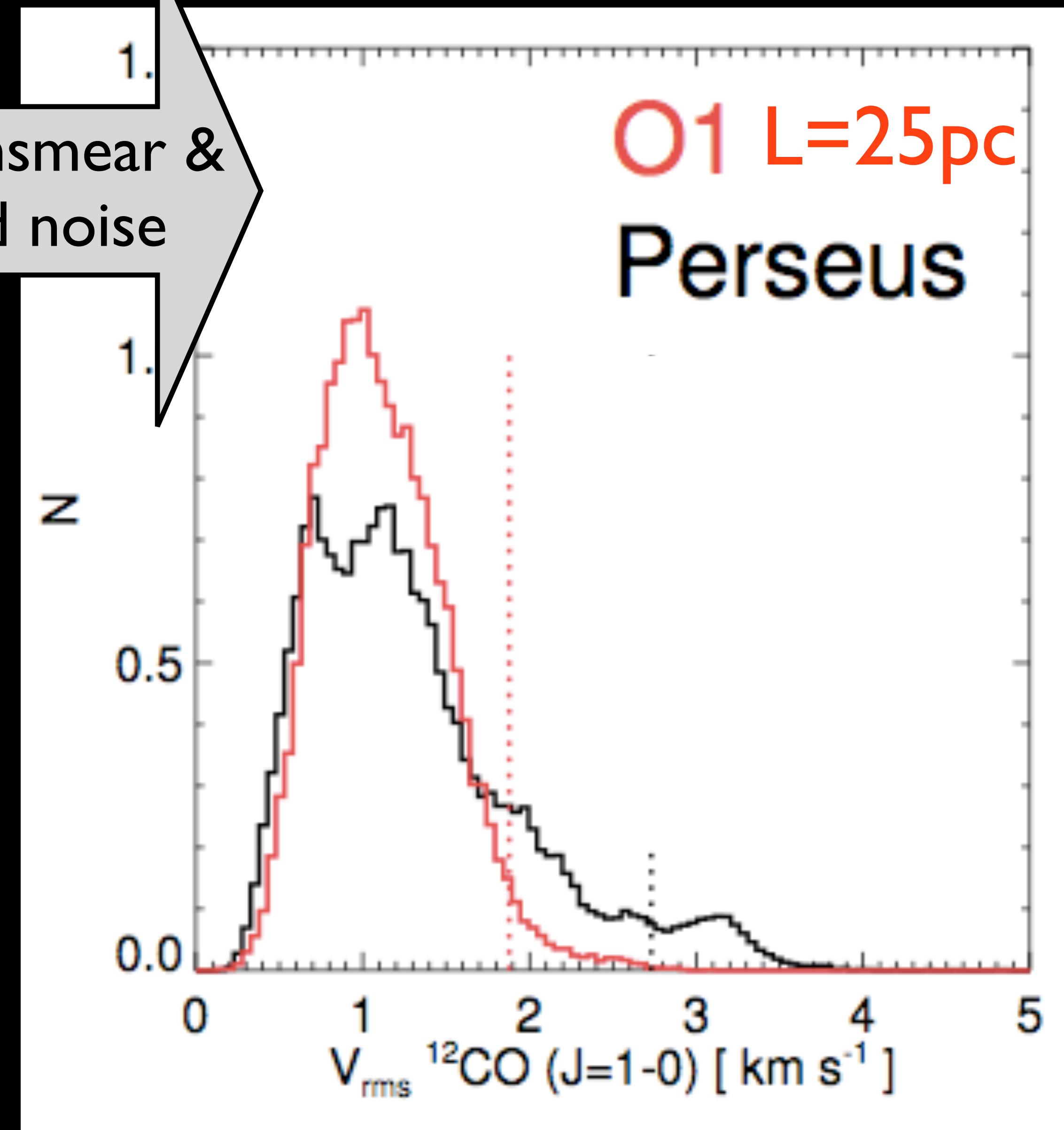

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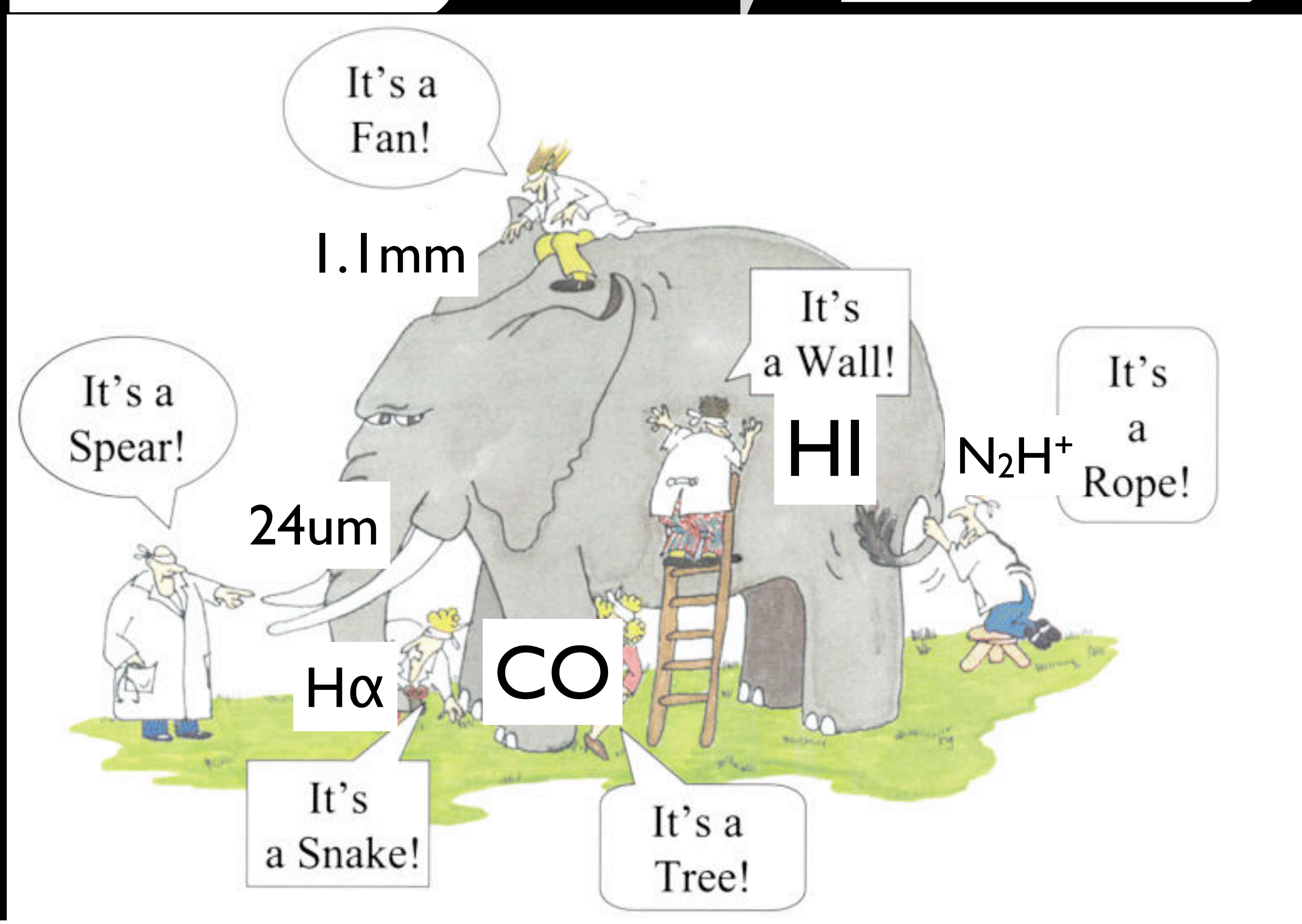

Perseus Velocity Distribution

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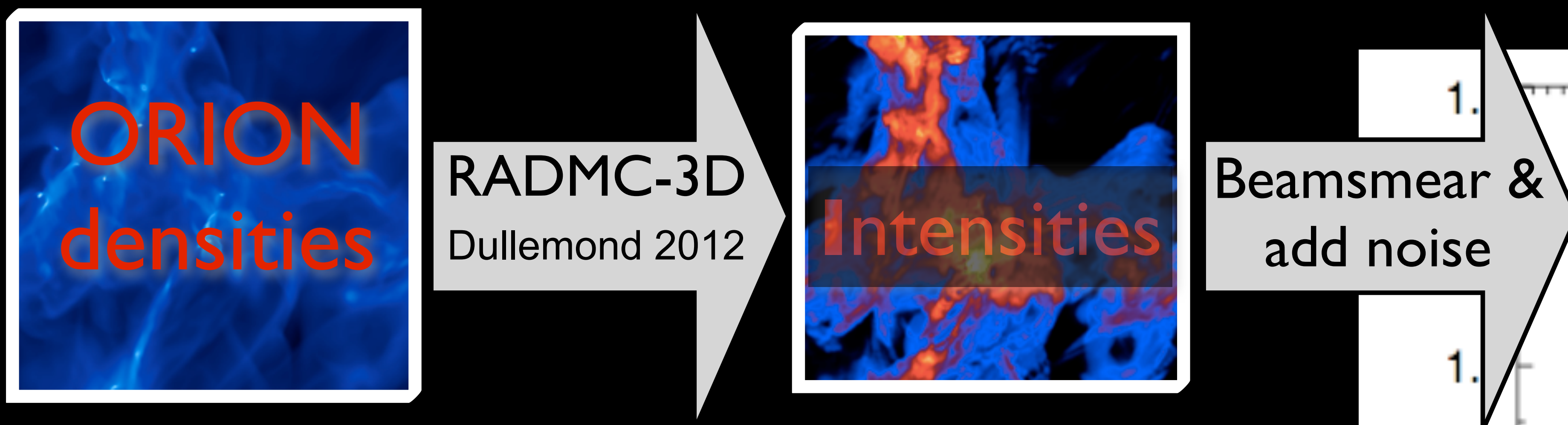

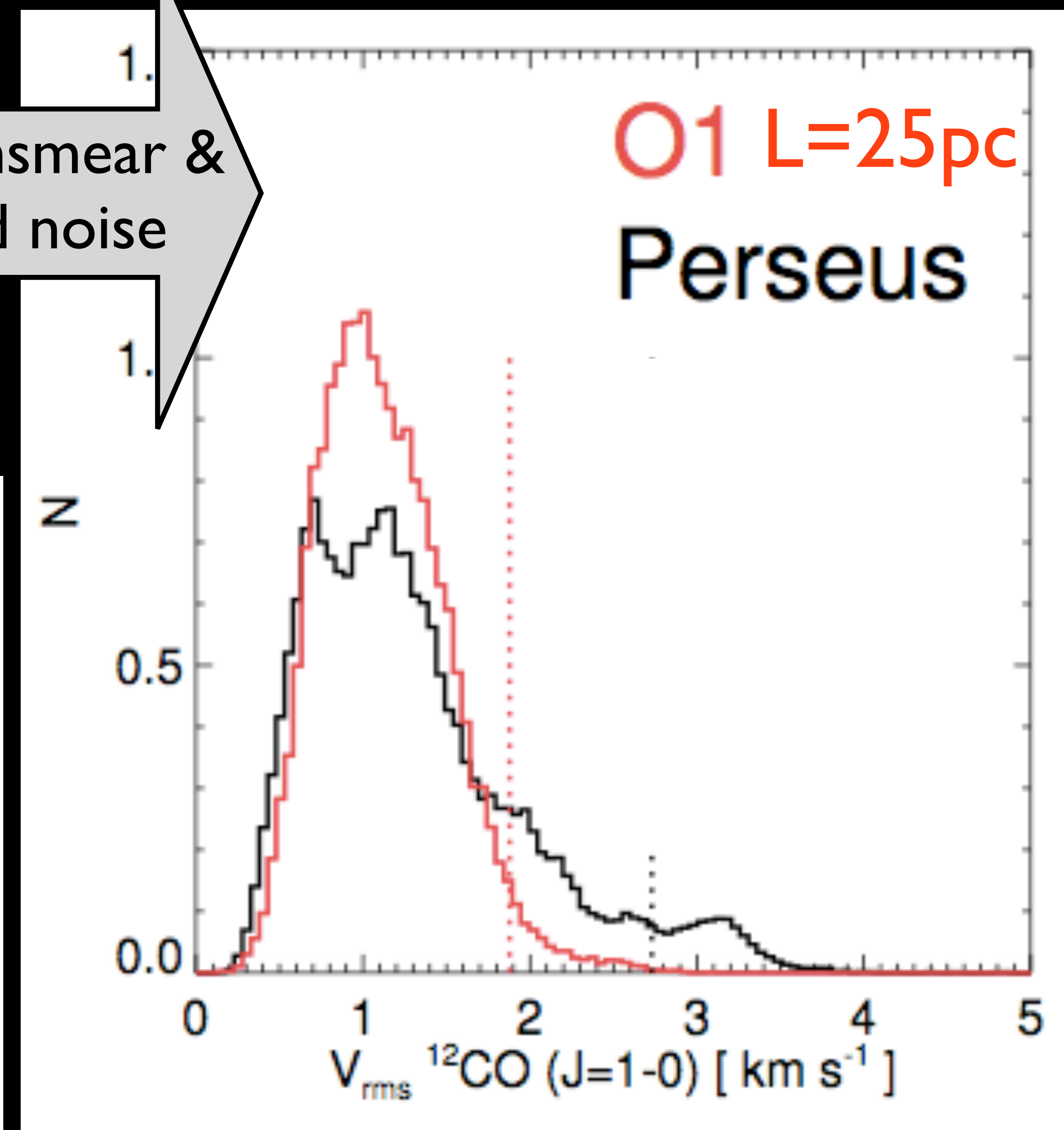

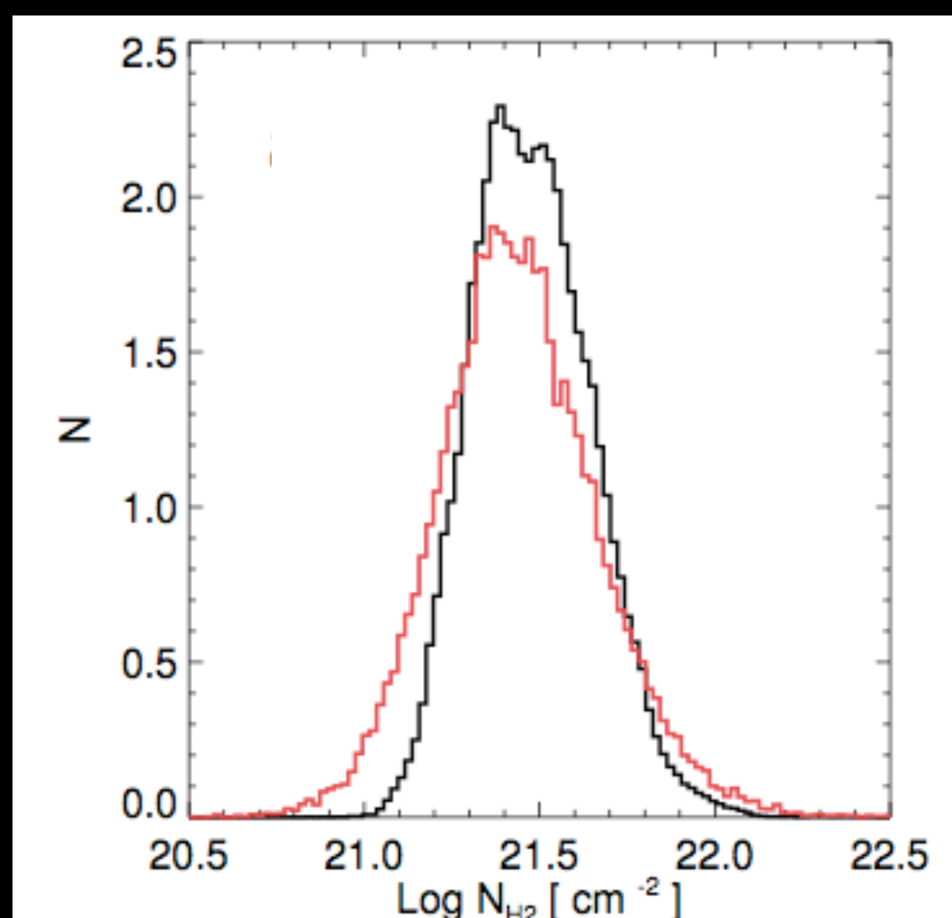

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Perseus Velocity Distribution

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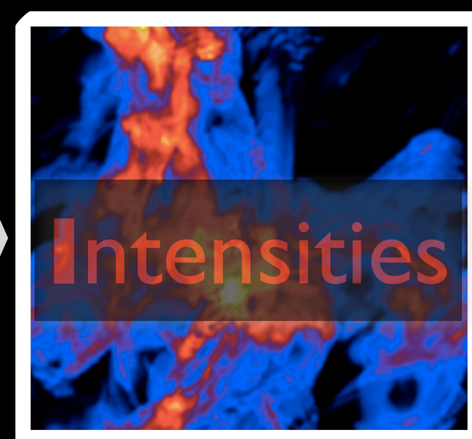

Beamsmear &
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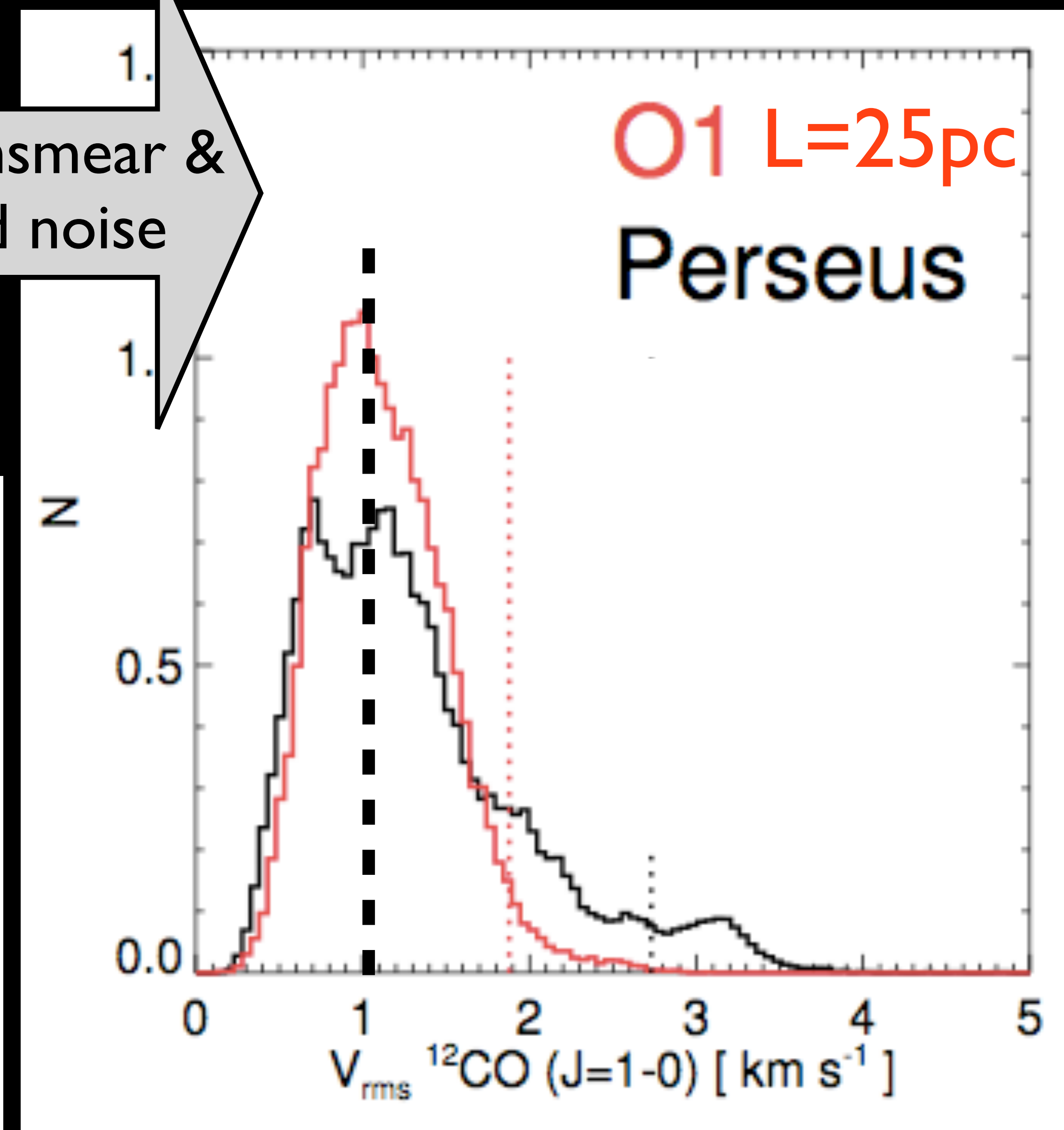
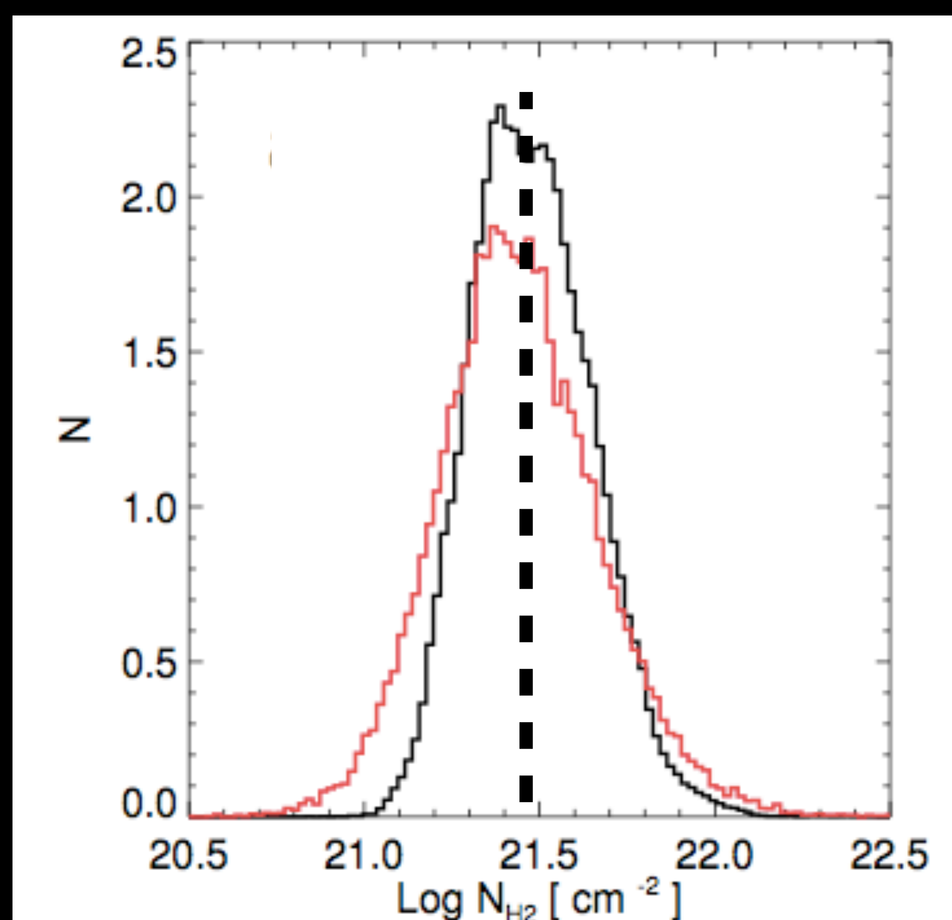


To compare match:
(1) Column Density
(2) V_{rms}



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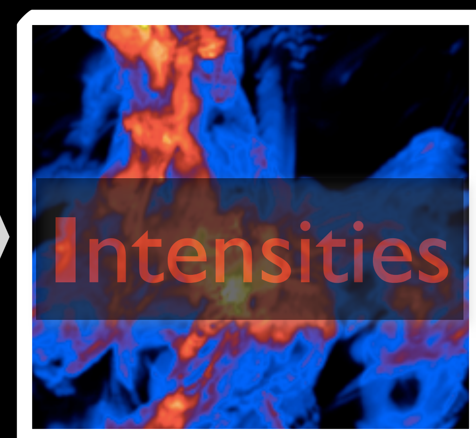
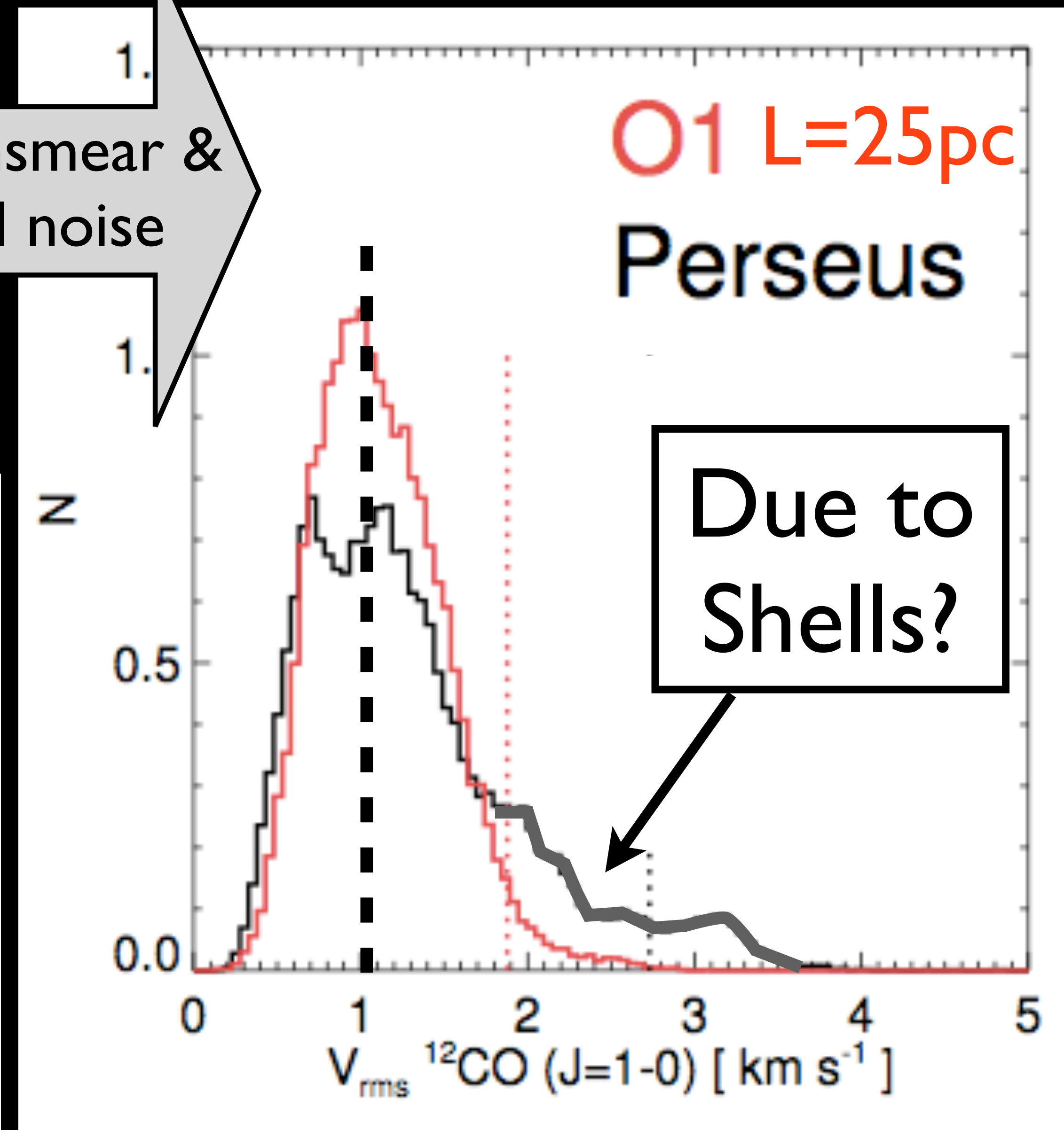
RADMC-3D
Dullemond 2012



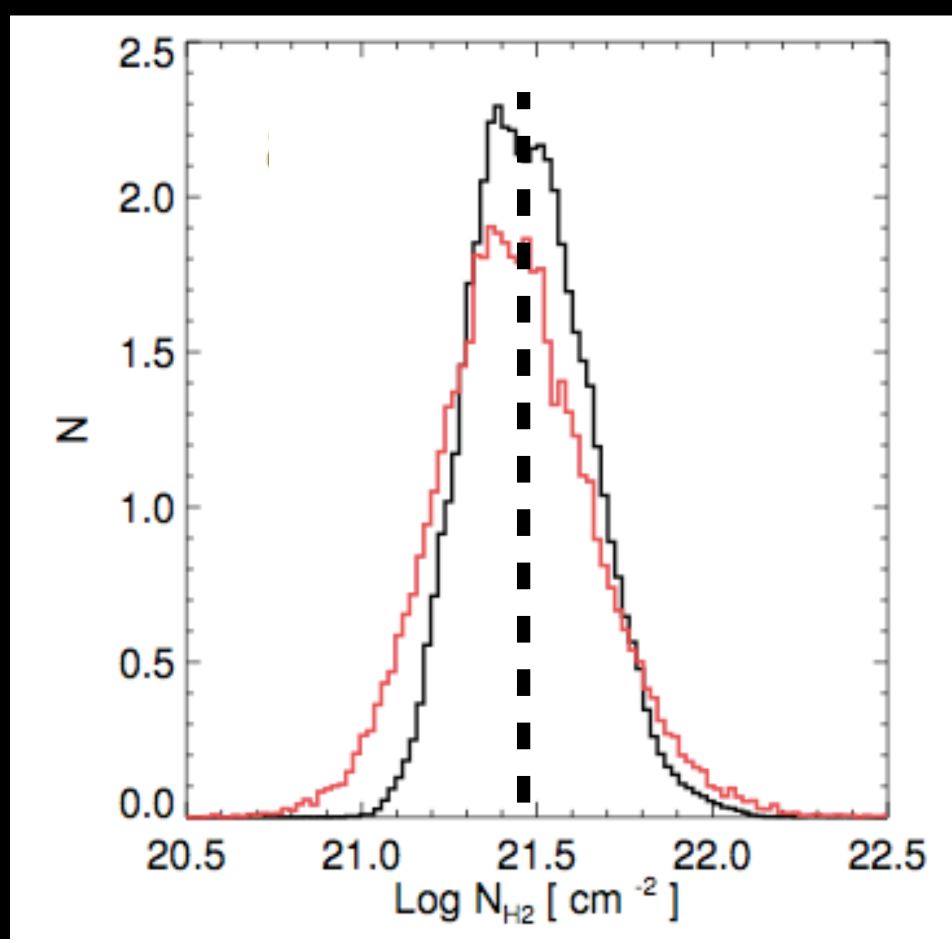
Beamsmear & add noise



To compare match:

(1) Column Density

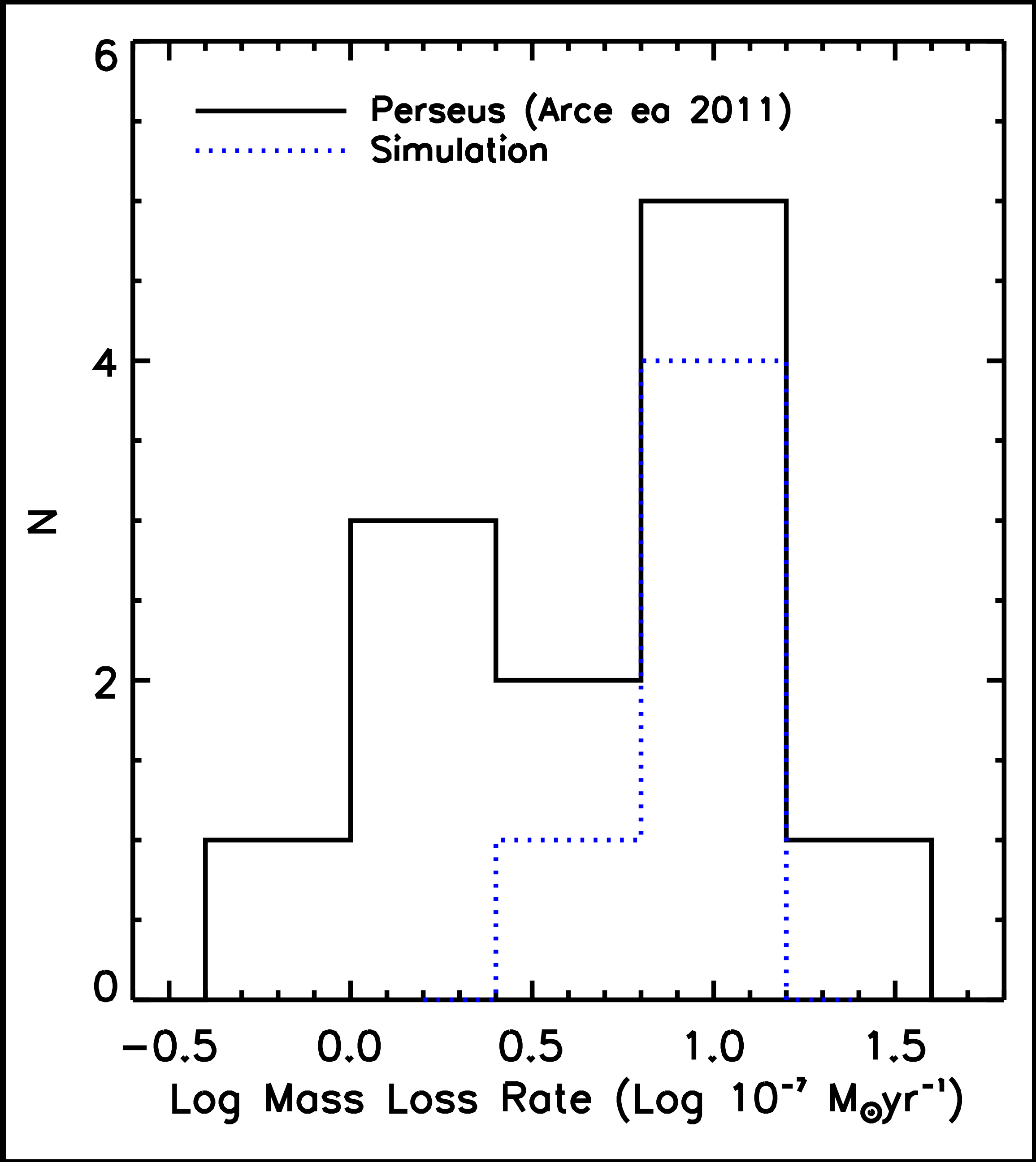
(2) V_{rms}

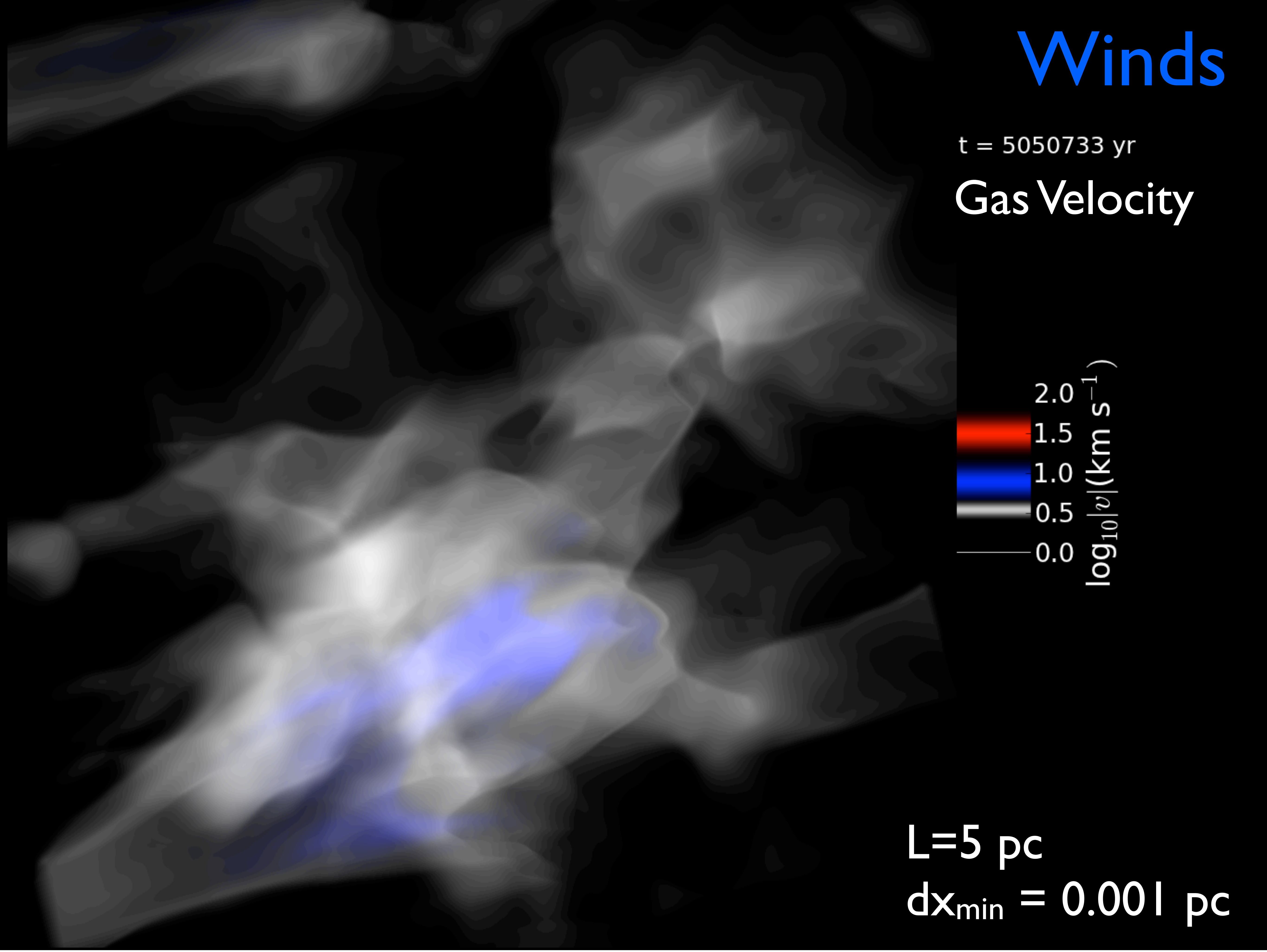


Beaumont, Offner, Shetty, Glover & Goodman in prep.

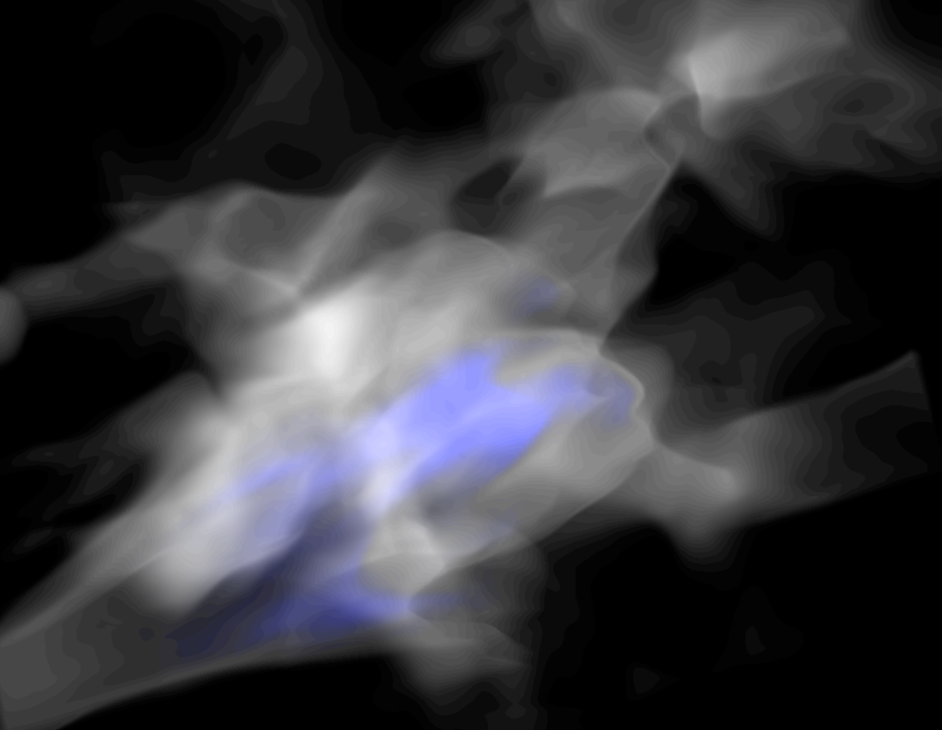
Hydrodynamic Simulation with Stellar Winds

- Stellar masses [3-15 Msun] and position randomly generated
- dM/dt = -10^{-7} M_* Msun/yr
- Launched isotropically
- Domain = 5 pc, 5 "B stars"

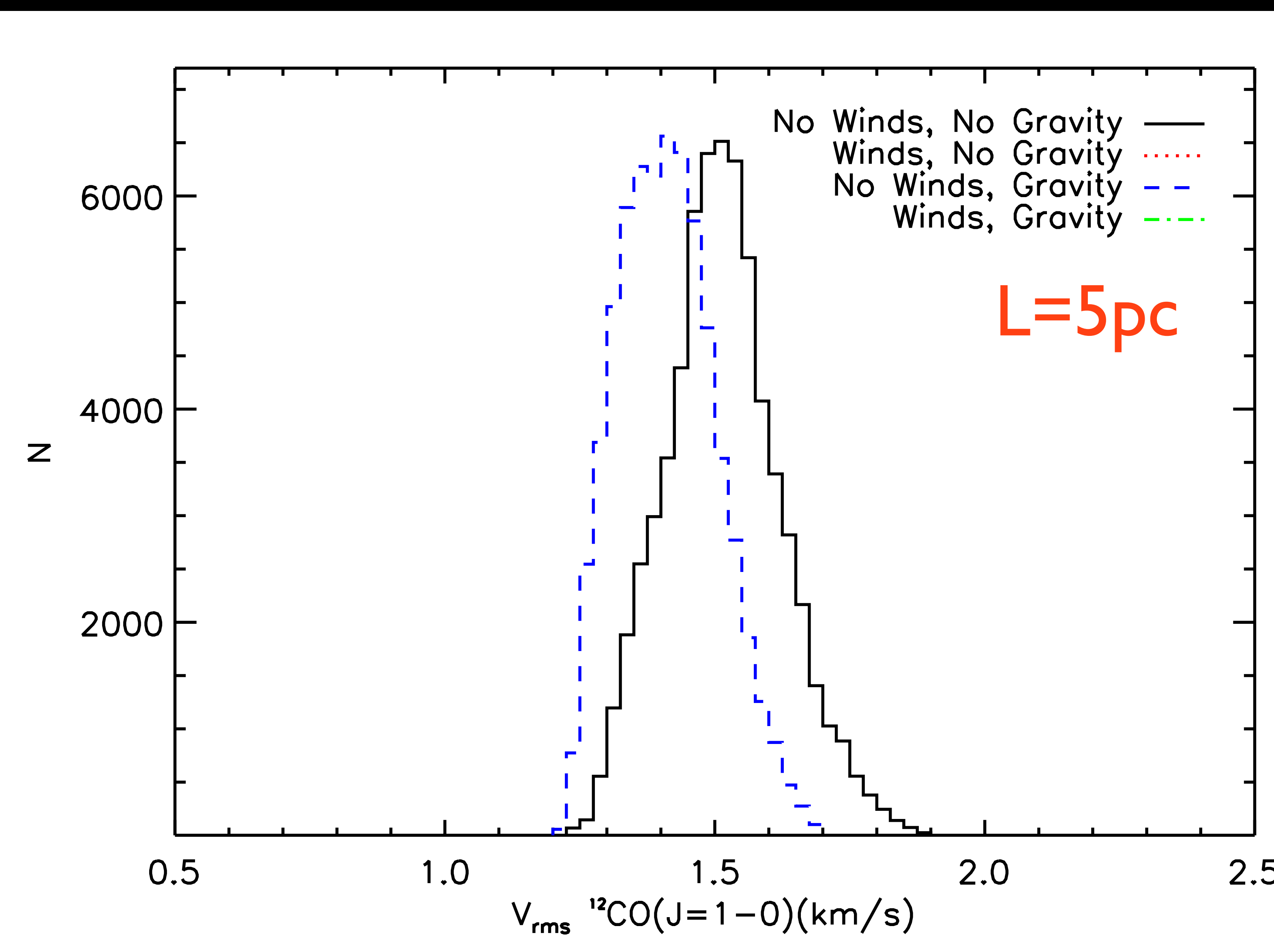


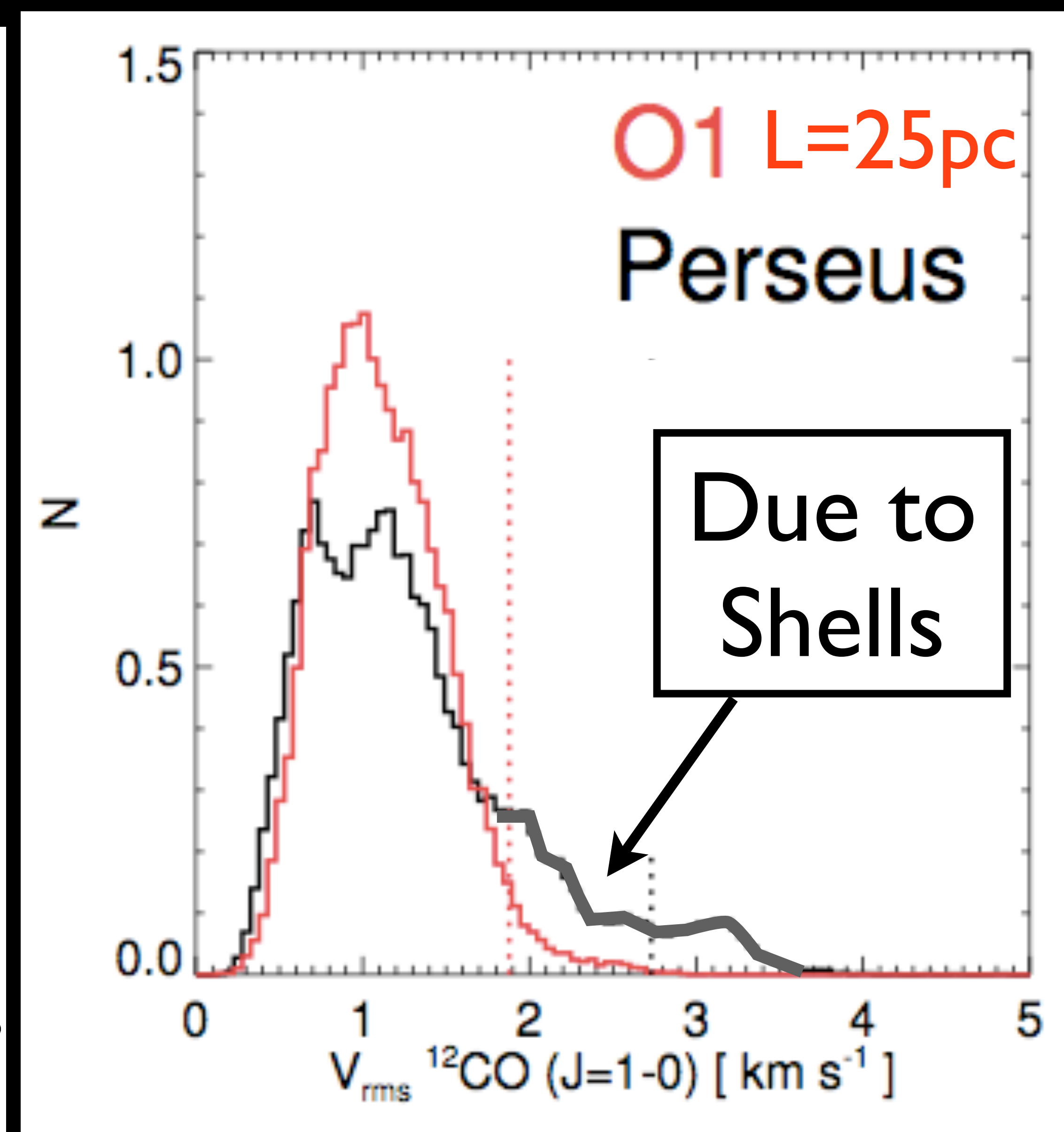


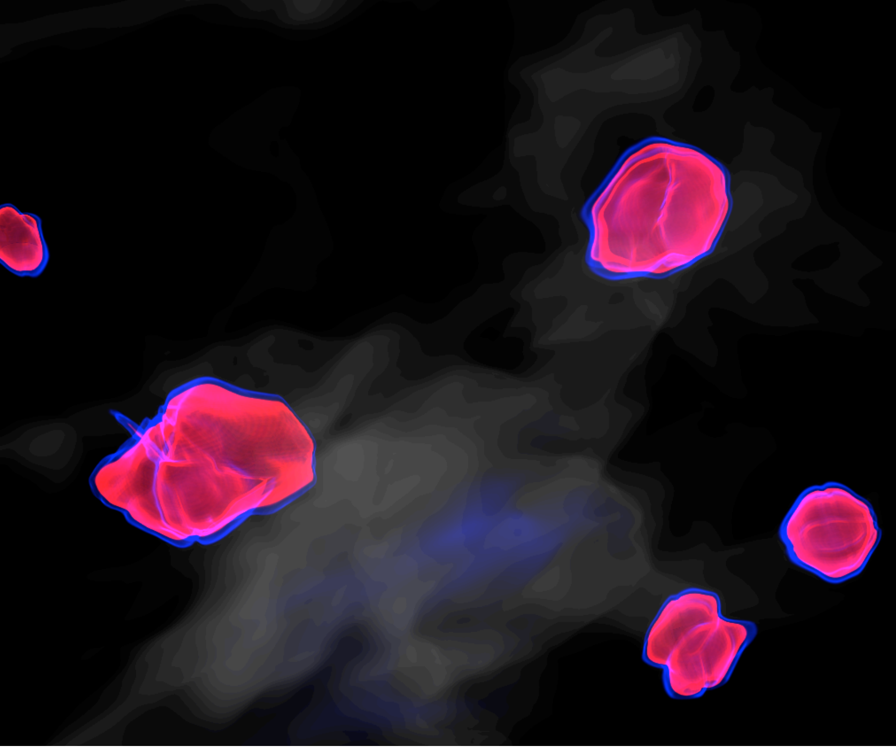
Winds
t = 5050733 yr
Gas Velocity
2.0
1.5
1.0
0.5
0.0
$\log_{10}|v|(\mathrm{km\ s^{-1}})$
L=5 pc
dx_{min} = 0.001 pc



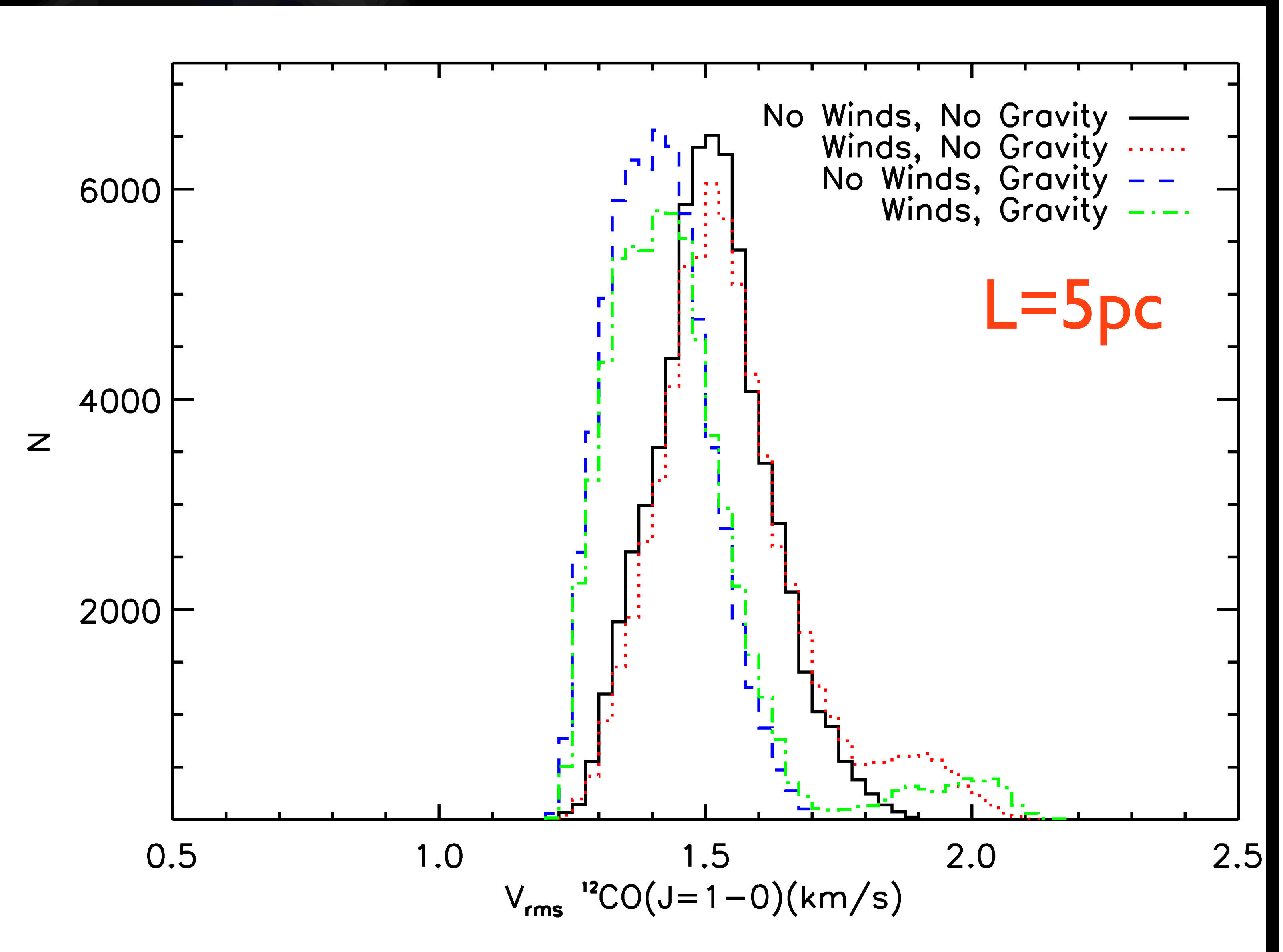
Perseus Velocity Distribution II

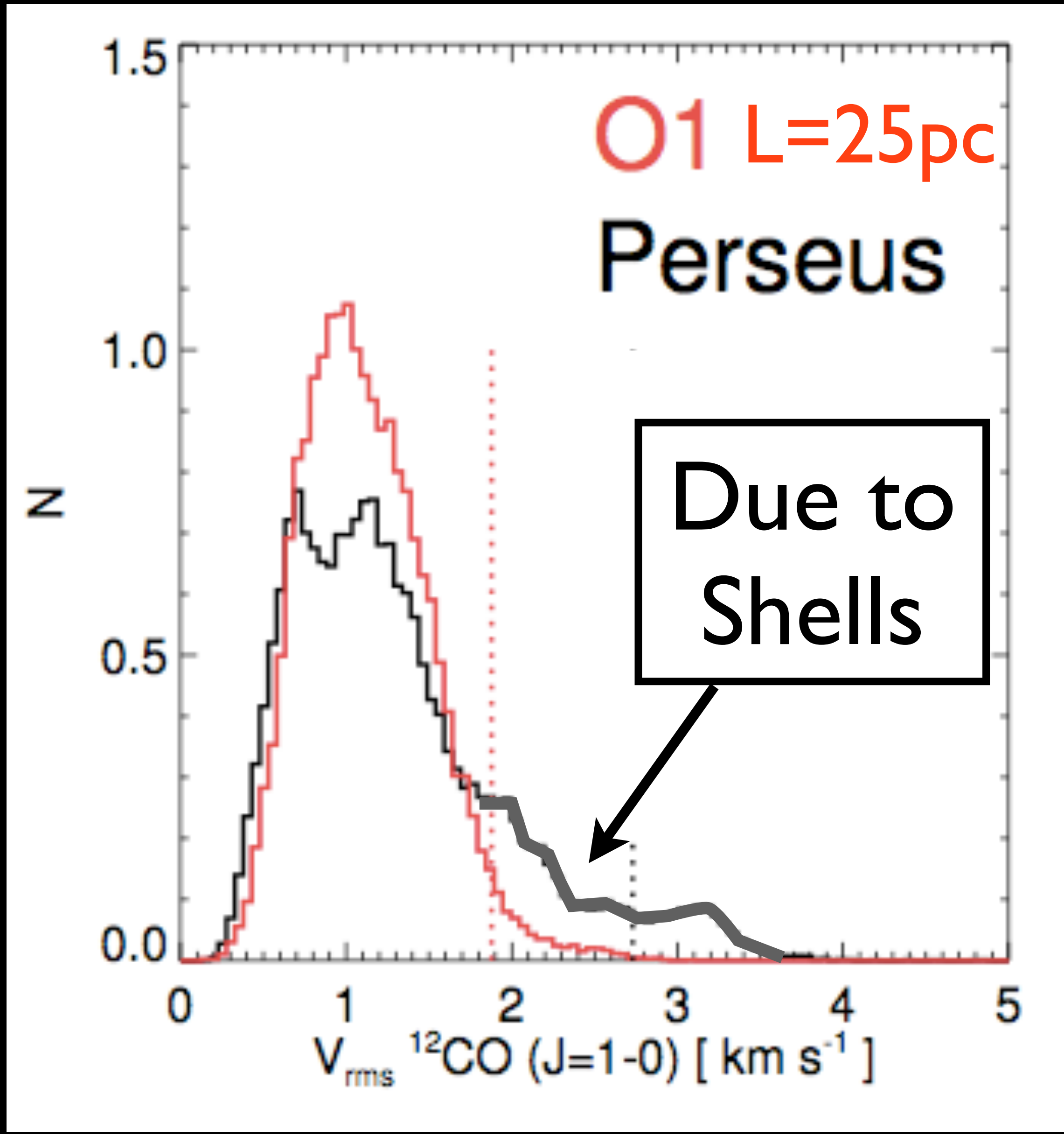


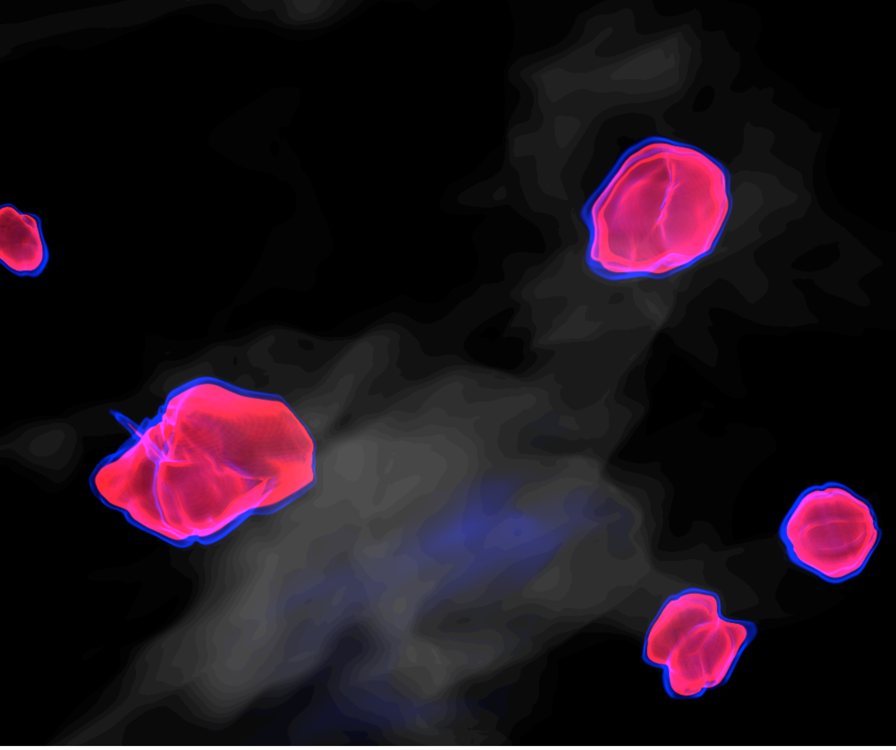




Perseus Velocity Distribution II

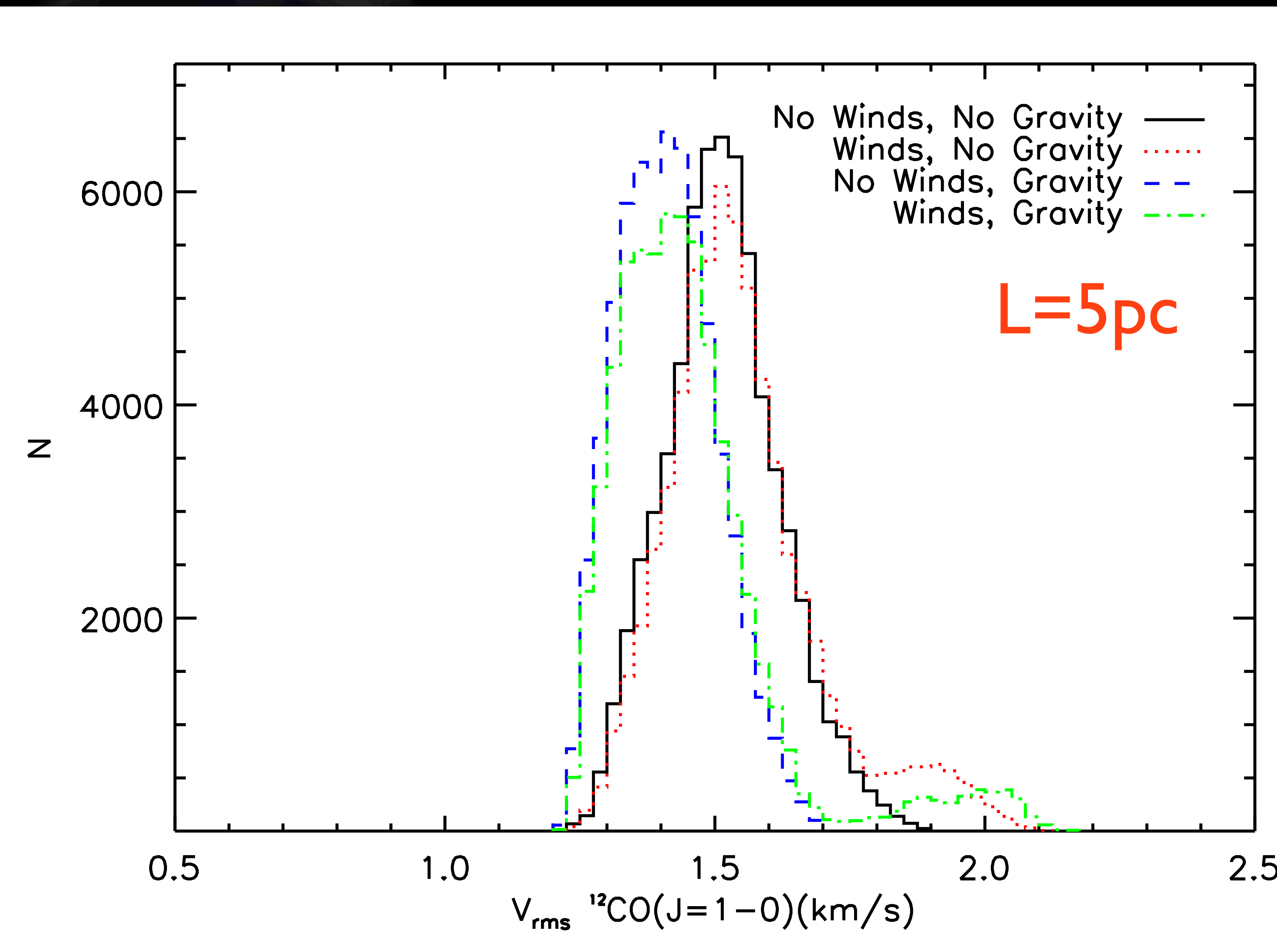


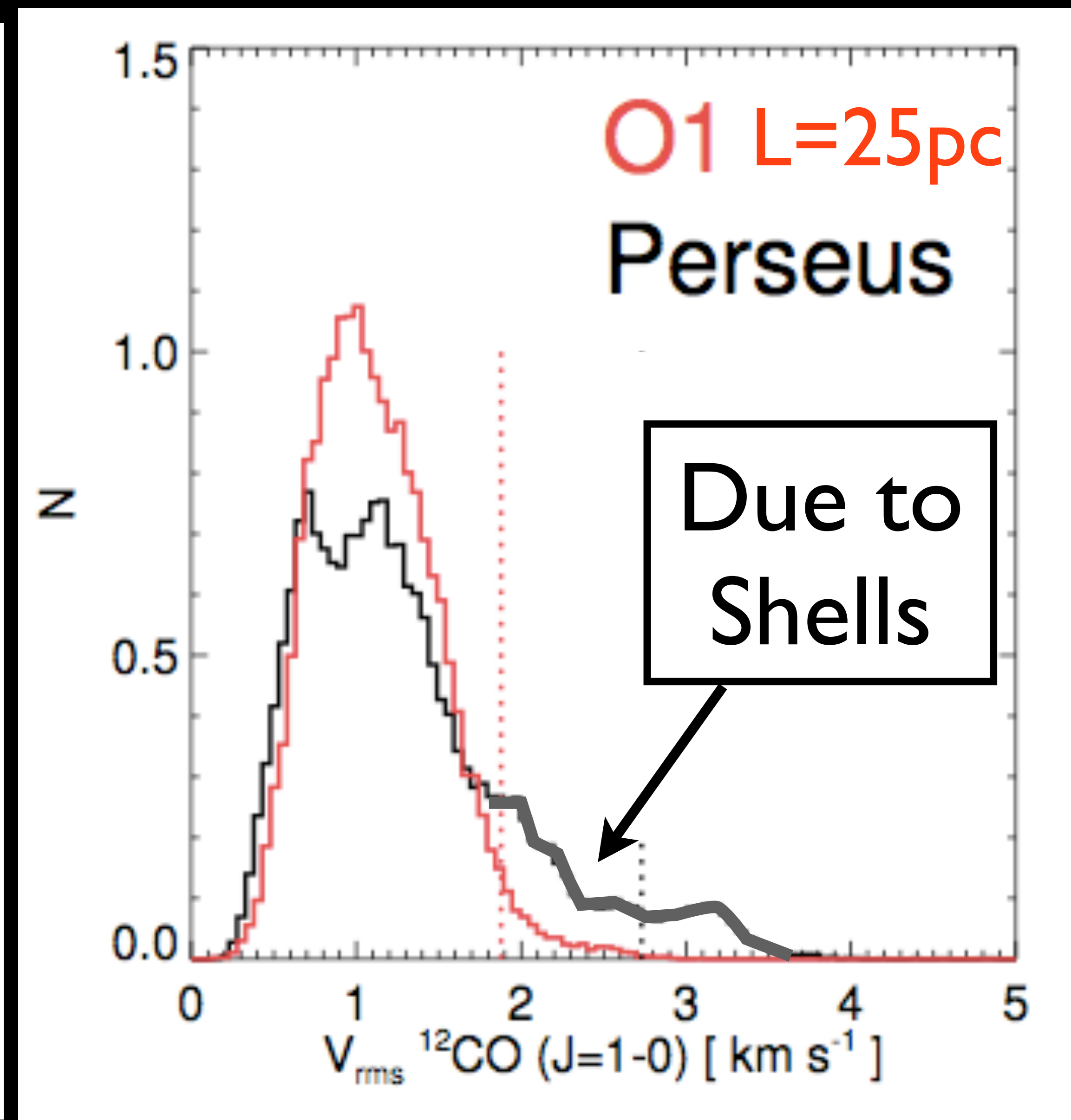




Perseus Velocity Distribution II

Do the winds drive turbulence?





Low-Mass Stars

Conclusions

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★ Radiative heating suppresses local fragmentation

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★ Outflows reduce masses by ~50% through entrainment

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Low-Mass Stars

Conclusions

- ★ Radiative heating suppresses local fragmentation
- ★ Outflows reduce masses by ~50% through entrainment
- ★ Outflows can replenish turbulent motions locally
- ★ Winds add velocity structure/turbulence in clouds; injection is comparable to turbulent decay

Questions?