Sternentstehung - Star Formation

Winter term 2024/2025

Henrik Beuther, Thomas Henning & Caroline Gieser

15.10 Today: Introduction & Overview (Beuther)
22.10 Physical processes I (Beuther)
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12.11 Molecular clouds as birth places of stars (Beuther)
19.11 Molecular clouds (cont.), Jeans Analysis (Henning)
26.11 Collapse models I (Beuther)
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11.02 Examination week, no star formation lecture

Book: Stahler & Palla: The Formation of Stars, Wileys

More Information and the current lecture files: http://www.mpia.de/homes/beuther/lecture_ws2425.html

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Last week

- Isothermal sphere, hydrostatic equilibrium, Bonnor-Ebert sphere

- Rotational support

- Magnetic support and ambipolar diffusion

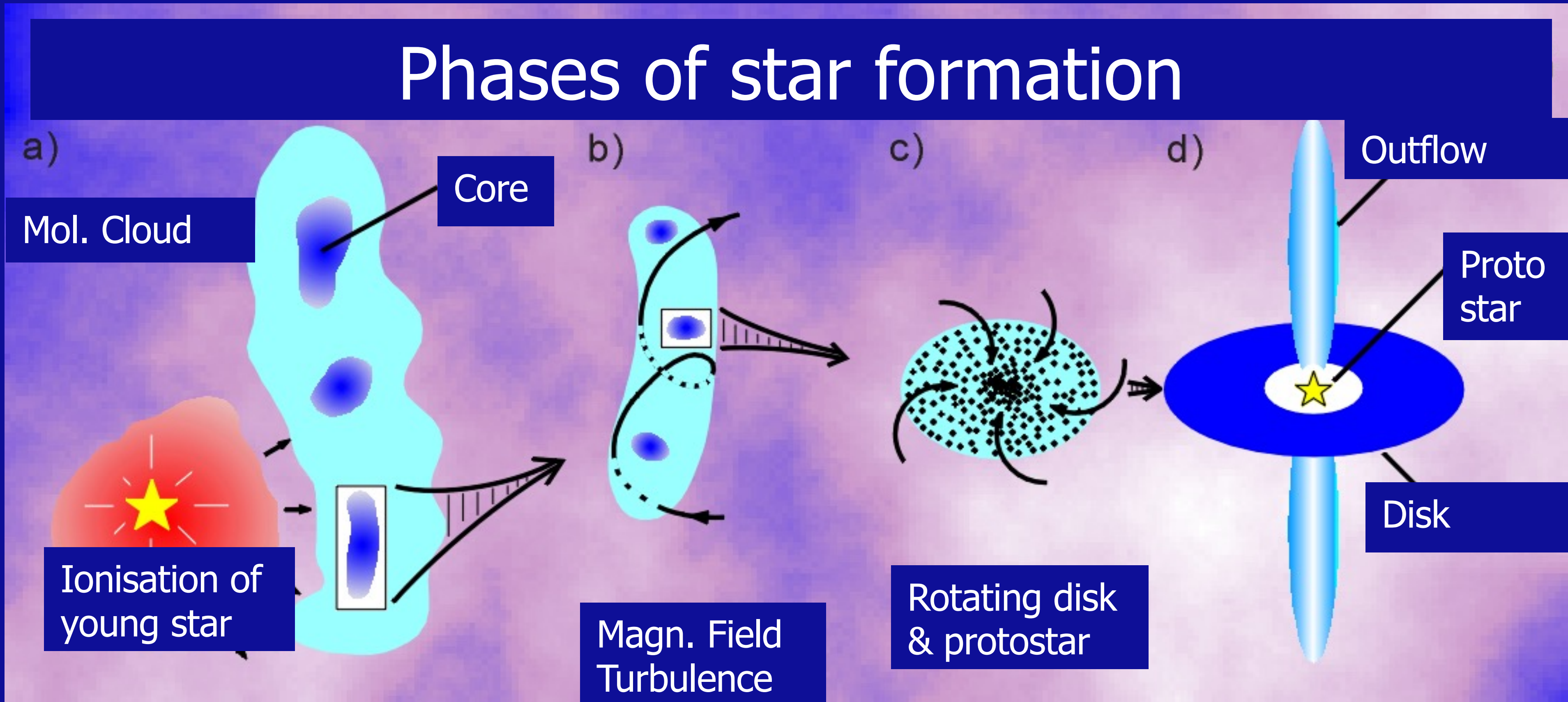
Topics today

- Continuation of collapse models

- Simulation examples

- Observational signature

Star formation paradigm



https://www.mpifr-bonn.mpg.de/473576/starform

From stability to collapse

Important equations:

Goal: M_r variable with time in set of differential equations:

Mass within radius r: $M_r = \int 4\pi r^2 \rho dr \rightarrow \partial M_r/\partial r = 4\pi r^2 \rho$

Continuity equation (spherical): $\partial\rho/\partial t = -1/r^2 \, \partial(r^2 \rho u)/\partial r$ u: velocity

Combine both equations $\rightarrow \partial M_r/\partial t = -4\pi r^2 \rho u$

Hydrostatic momentum eq.: $\partial u/\partial t + u\partial u/\partial r = -1/\rho \, \mathrm{grad}(P) - \mathrm{grad}(\Phi)$

With $P = \rho a_t^2$ for the ideal isothermal gas and $\mathrm{grad}(\Phi) = -GM_r/r^2$

$\rightarrow \partial u/\partial t + u\partial u/\partial r = -a_t^2/\rho \, \partial\rho/\partial r - GM_r/r^2$

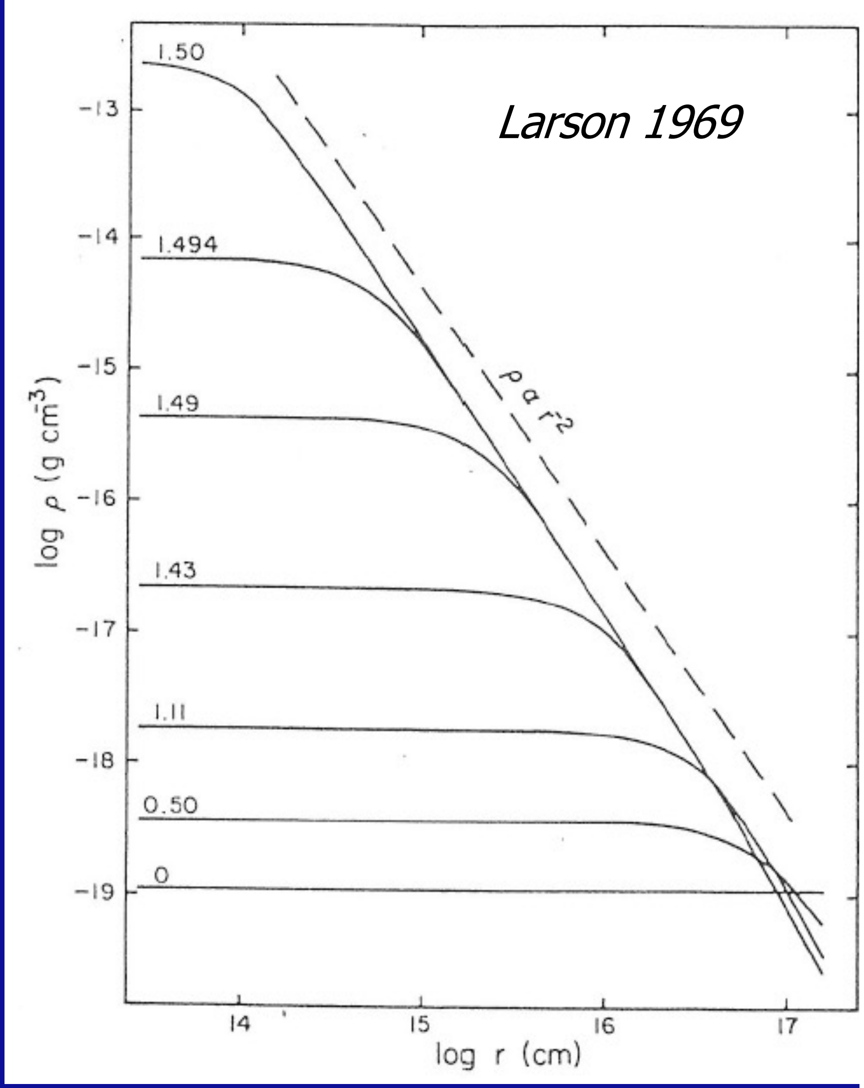
Early 1D collapse simulations

- Results from early 1D calculations (Larson 1969)
  Initial conditions: $1M_{sun}$ core, $\rho(t=0) = 10^{-19}g/cm^3 \sim 10^5 cm^{-3}$, $T(t=0)=10K$

- Nonhomologous evolution:
  After about 1 t_{ff} (10^5-10^6years), a central hydrostatic core and a free-falling inner envelope has evolved.

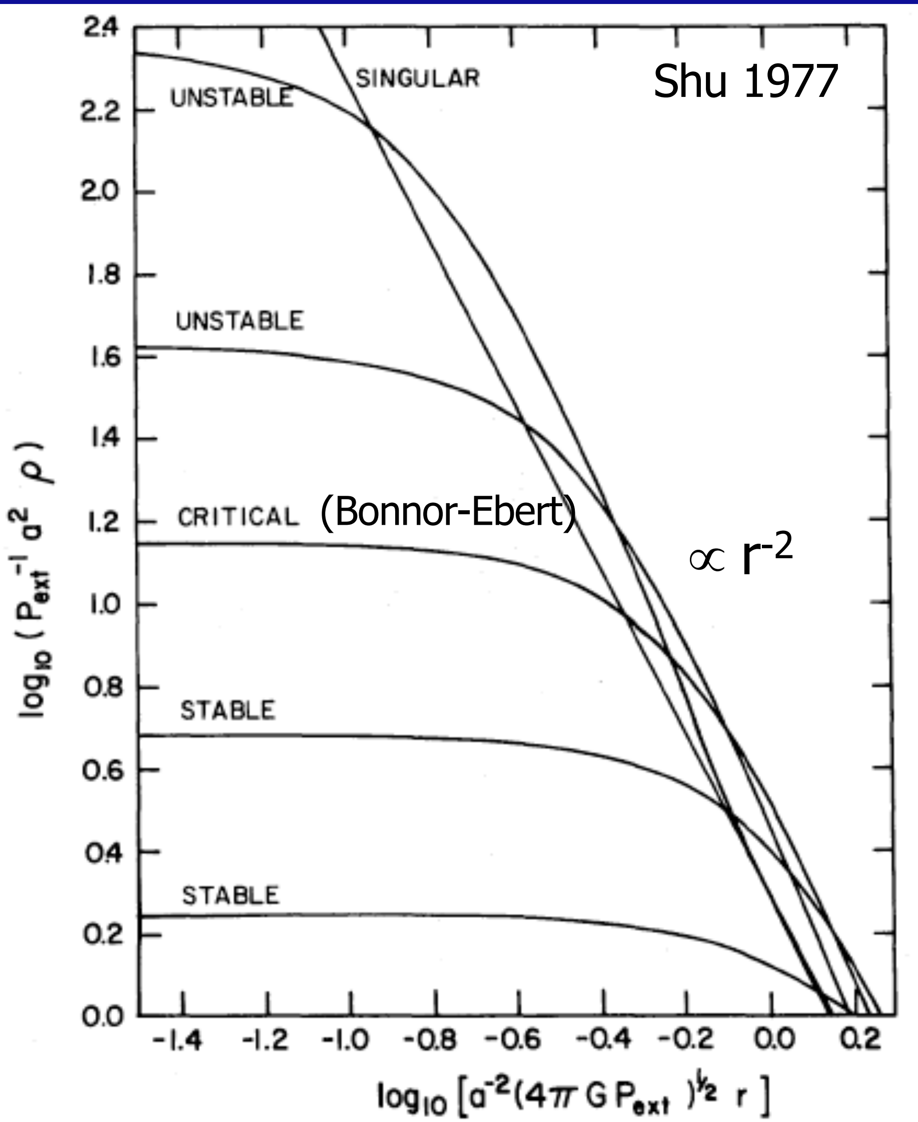
- Density profile in free-falling envelope
  First order explanation:
  Steady state flow: $\partial M_r/\partial t = -4\pi r^2 \rho u$ =const
  and $E_{kin}=E_{grav}$: $1/2mu^2 = Gm^2/r$
  → $u = (2Gm/r)^{1/2}$
  → $1/(4\pi r^2 \rho) = (2Gm/r)^{1/2}$
  → $\rho \sim r^{-3/2}$

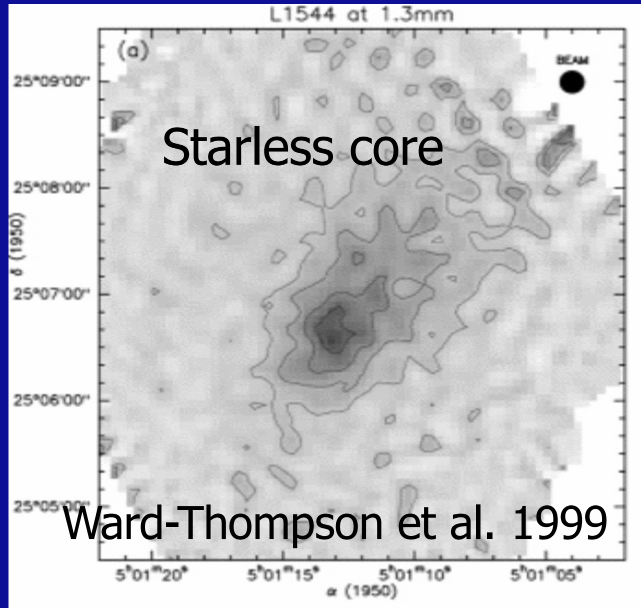
- Outer static envelope like hydrostatic equilibrium → $\rho \sim r^{-2}$

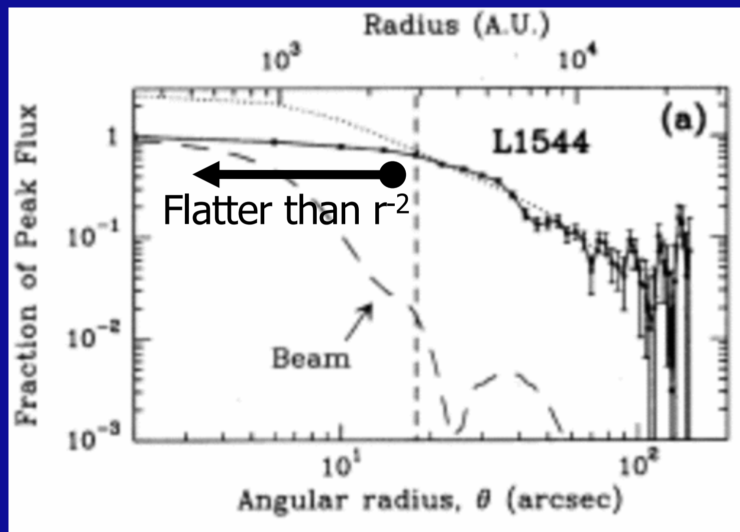


Singular isothermal sphere (SIS)

Another "famous" paper in 1977 by Frank Shu, starts with singular isothermal sphere. Outer density profile again $\rho \sim r^{-2}$.







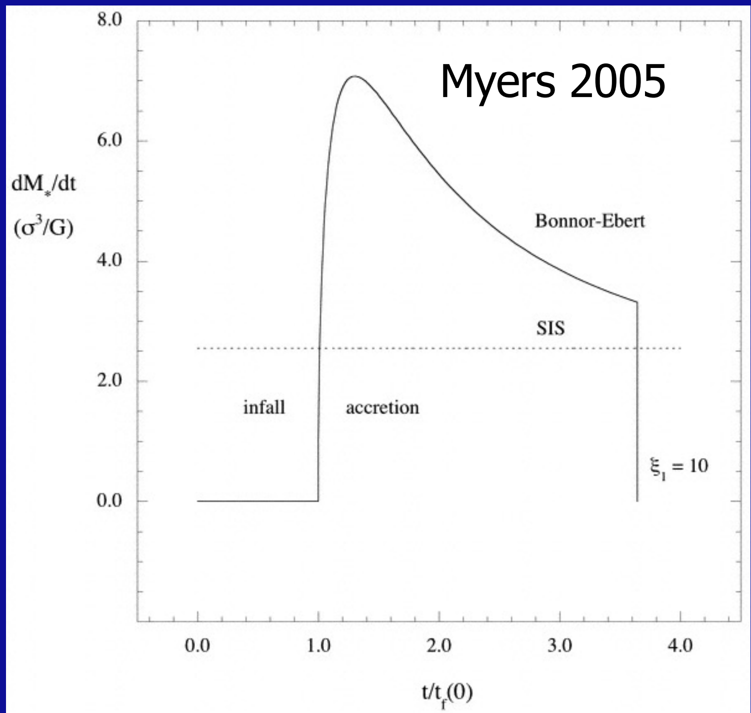
Accretion rate

For a singular isothermal sphere (SIS) one gets

Mass accretion rate: $\dot{M} = \partial M_r/\partial t = \lim_{r \to 0} -4\pi r^2 \rho u \sim a_t^3/G$

For a typical sound speed of 0.2km/s at T=10K:
$\dot{M} \sim 2 \times 10^{-6} \times (T/10K)\ M_{sun}/yr$
→ Hence $1M_{sun}$ star would form in 5×10^5 yr.

Using different initial conditions, e.g. Bonnor-Ebert spheres, one can get:

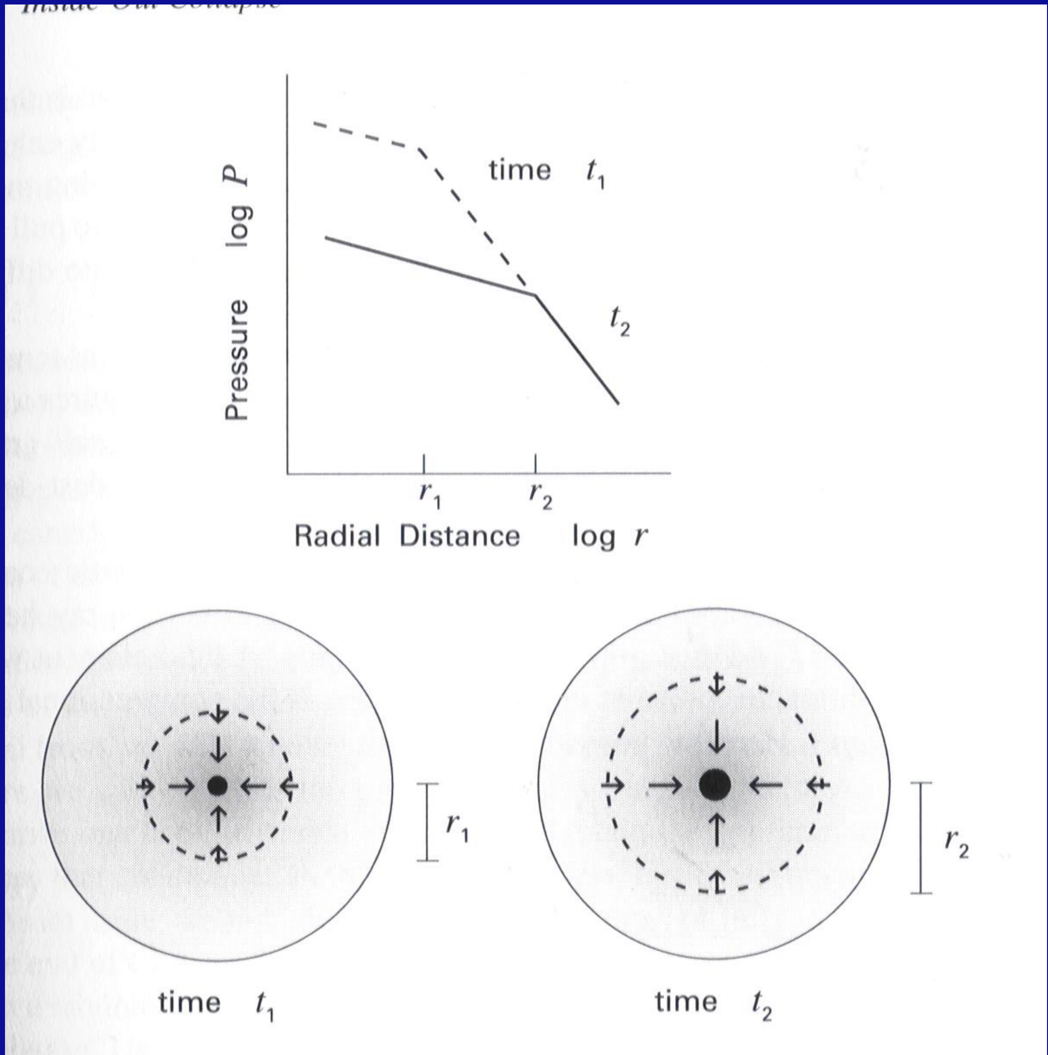


Initial free-fall phase until protostar has formed.

Then collapse continues in an inside-out mode but with varying accretion rate.

Collapse of a core VII

SIS scenario: inner free-falling gas causes an inner pressure decrease
→ A rarefaction wave moves outward. Within rarefaction wave
→ Gas is free-falling because of missing pressure support.



However, SIS special and unrealistic case.

More realistic simulations always show global collapse
→ Usually no rarefaction waves and less pronounced inside-out collapse.

Topics today

- Continuation of collapse models

- Simulation examples

- Observational signature

Simulation example I

UK Astrophysical Fluids Facility

SPH simulation with gravity and super-sonic turbulence.

Initial conditions:

Uniform density
$500M_{sun}$
0.8pc diameter
Initial T=10K

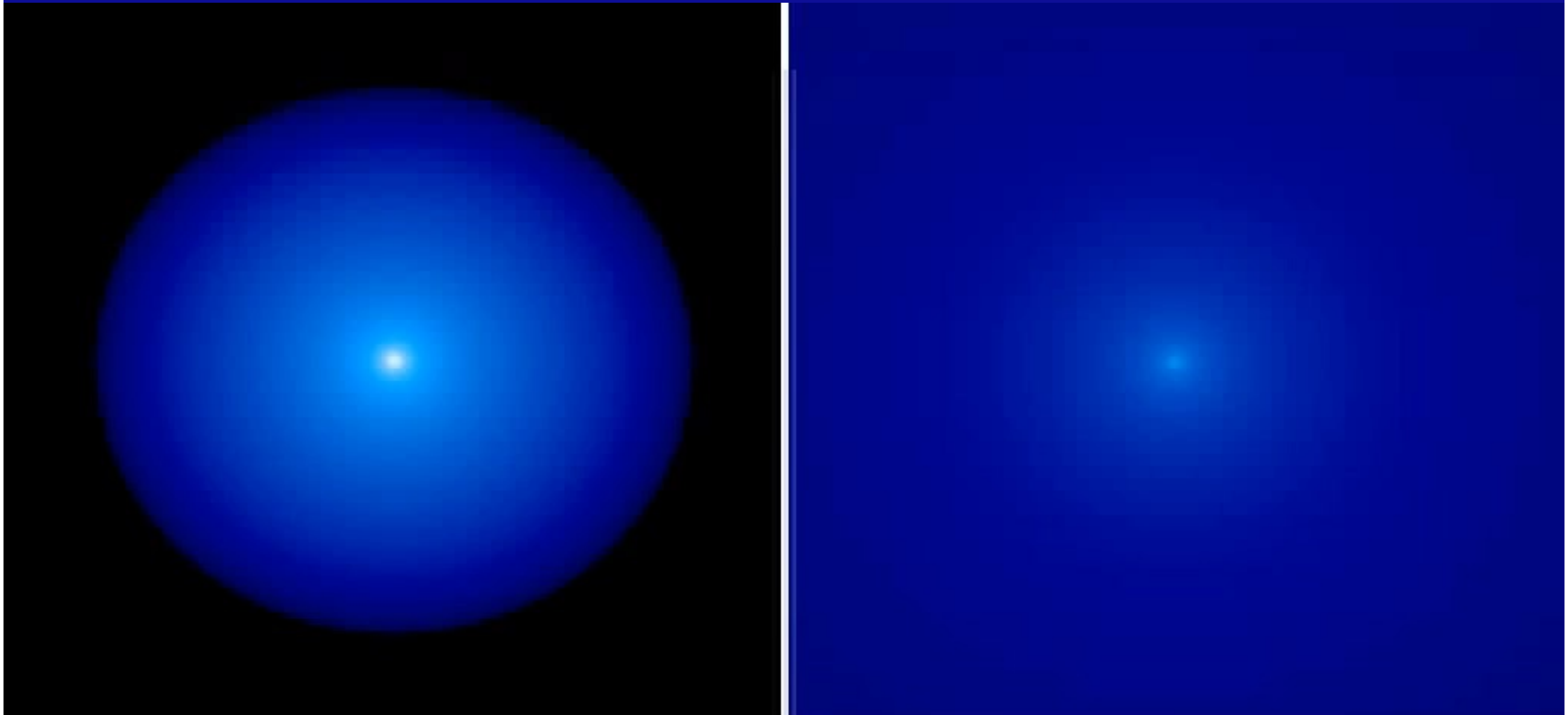
Bate et al. 2009

Matthew Bate

University of Exeter

More simulations can be found at: www.astro.ex.ac.uk/people/mbate/Animations/

Simulation example II



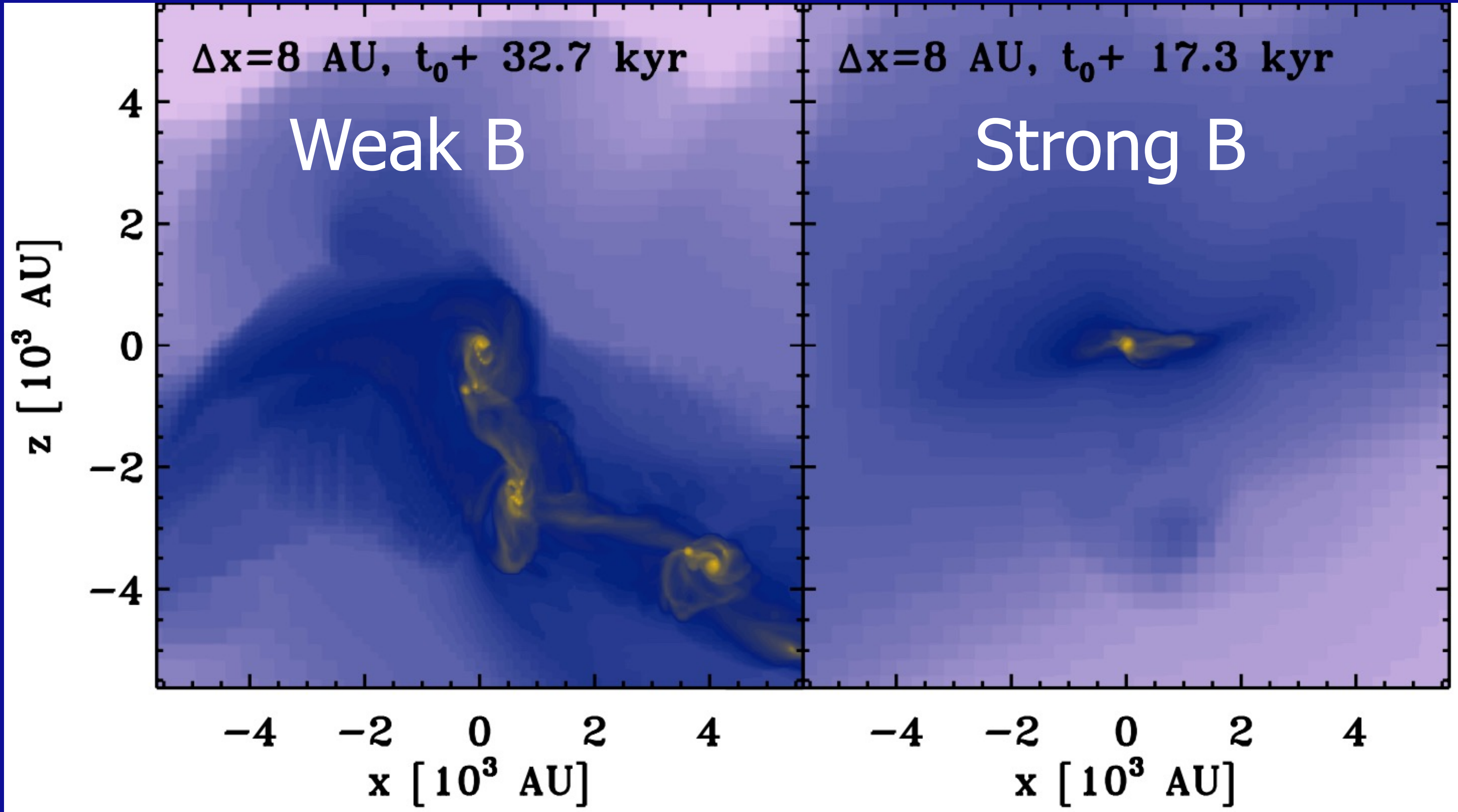
AMR grid-based simulation with gravity, super-sonic turbulence and radiative feedback.

Krumholz et al. 2007

Initial conditions: $100M_{sun}$, 0.8pc diameter

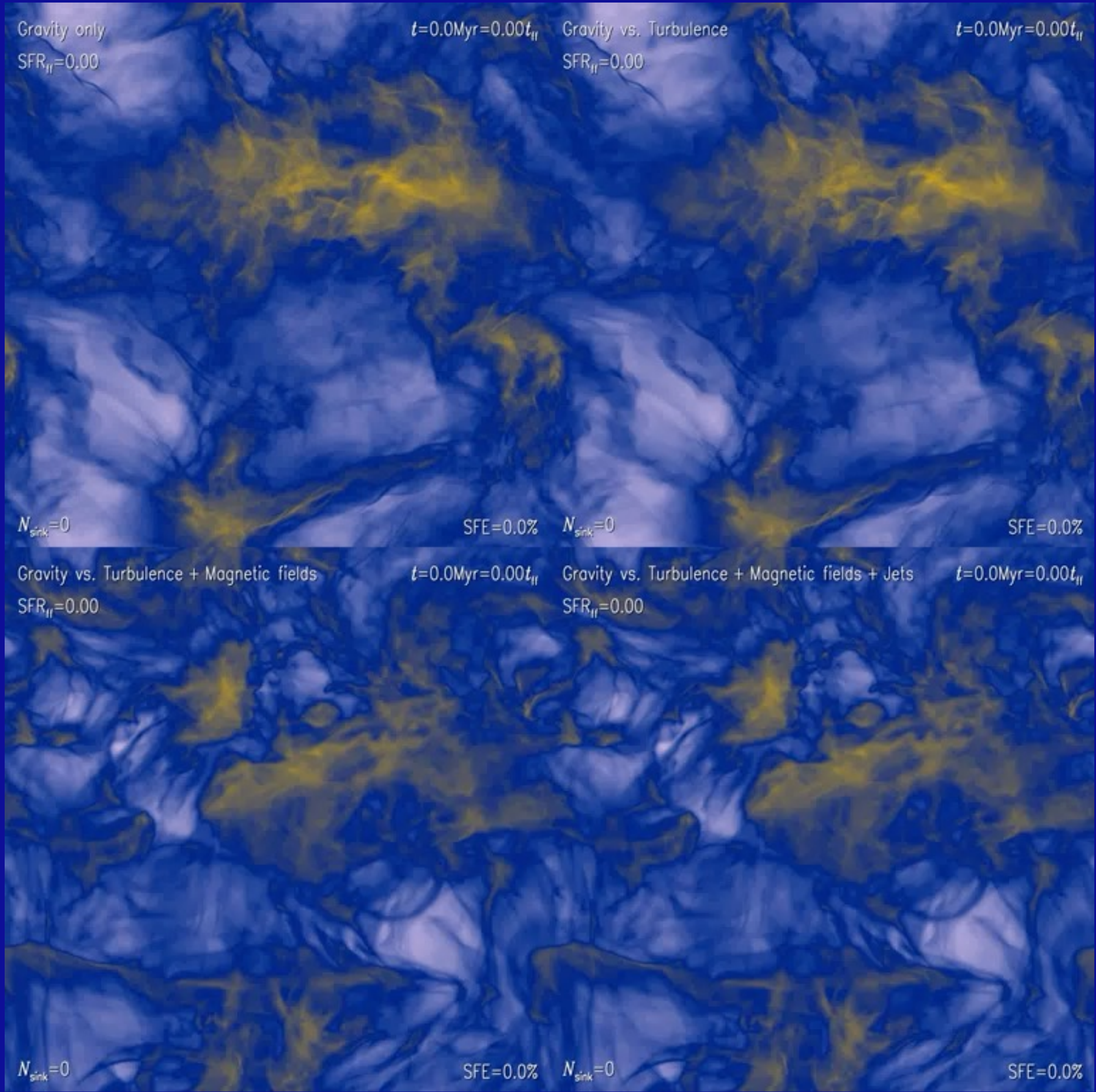
More simulations at: *https://www.mso.anu.edu.au/~krumholz/movies.html*

Simulation example III



Commercon et al. 2011

Simulation example IV



Federrath 2015

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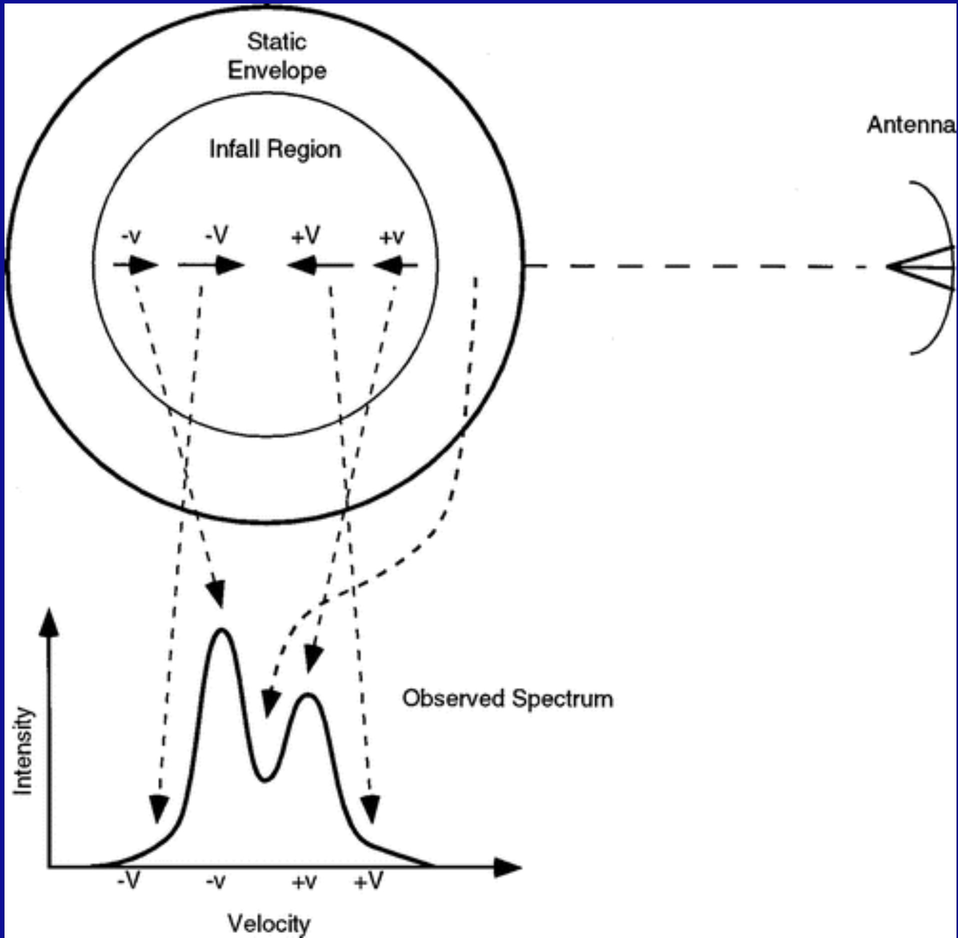
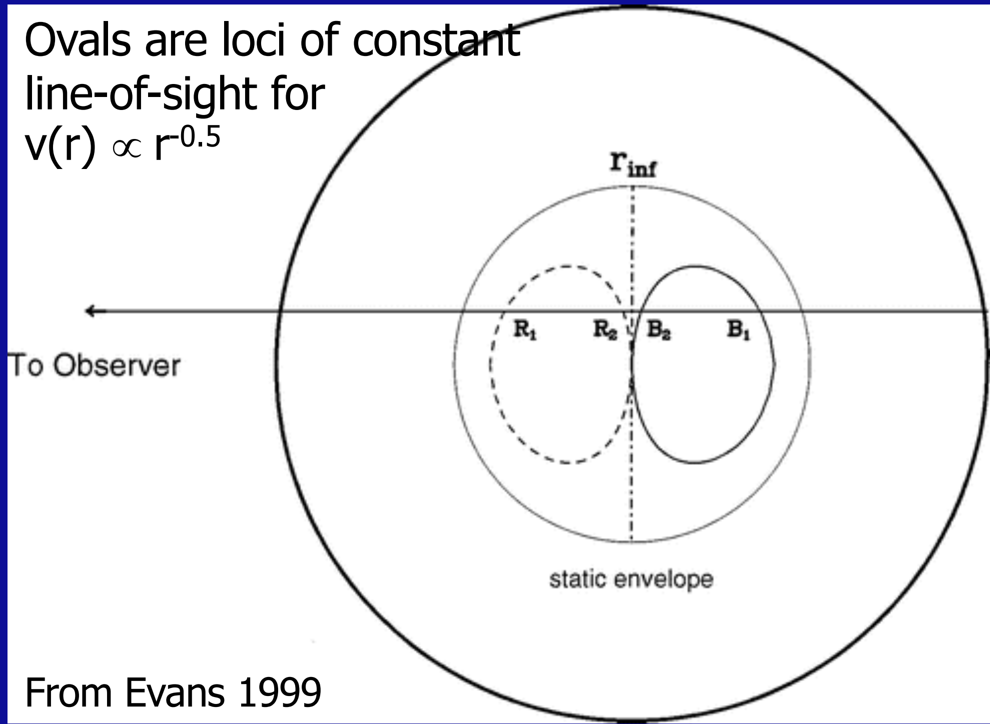
Infall signatures I

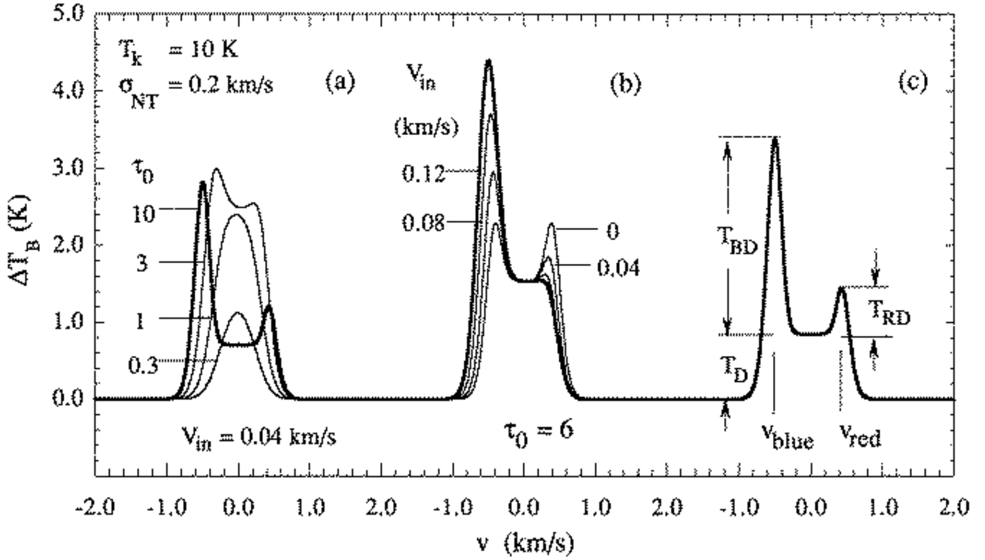




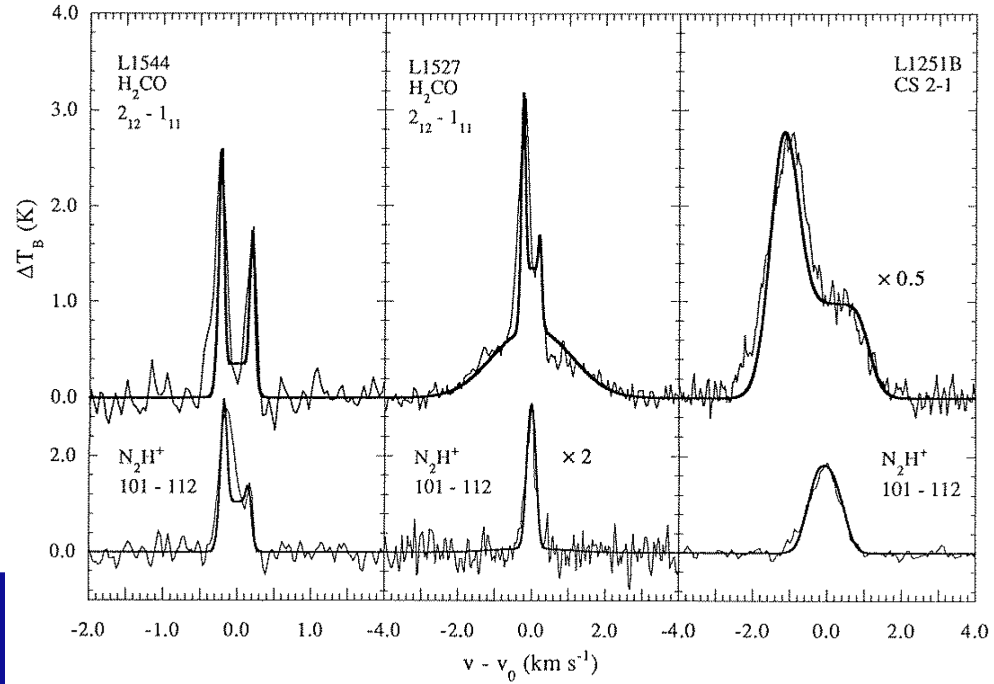
1. Rising T_{ex} along line of sight
2. Velocity gradient
3. Line optically thick
4. An additional optically thin line peaks at center

Infall signatures II

Models



Spectra and fits (Myers et al. 1996)

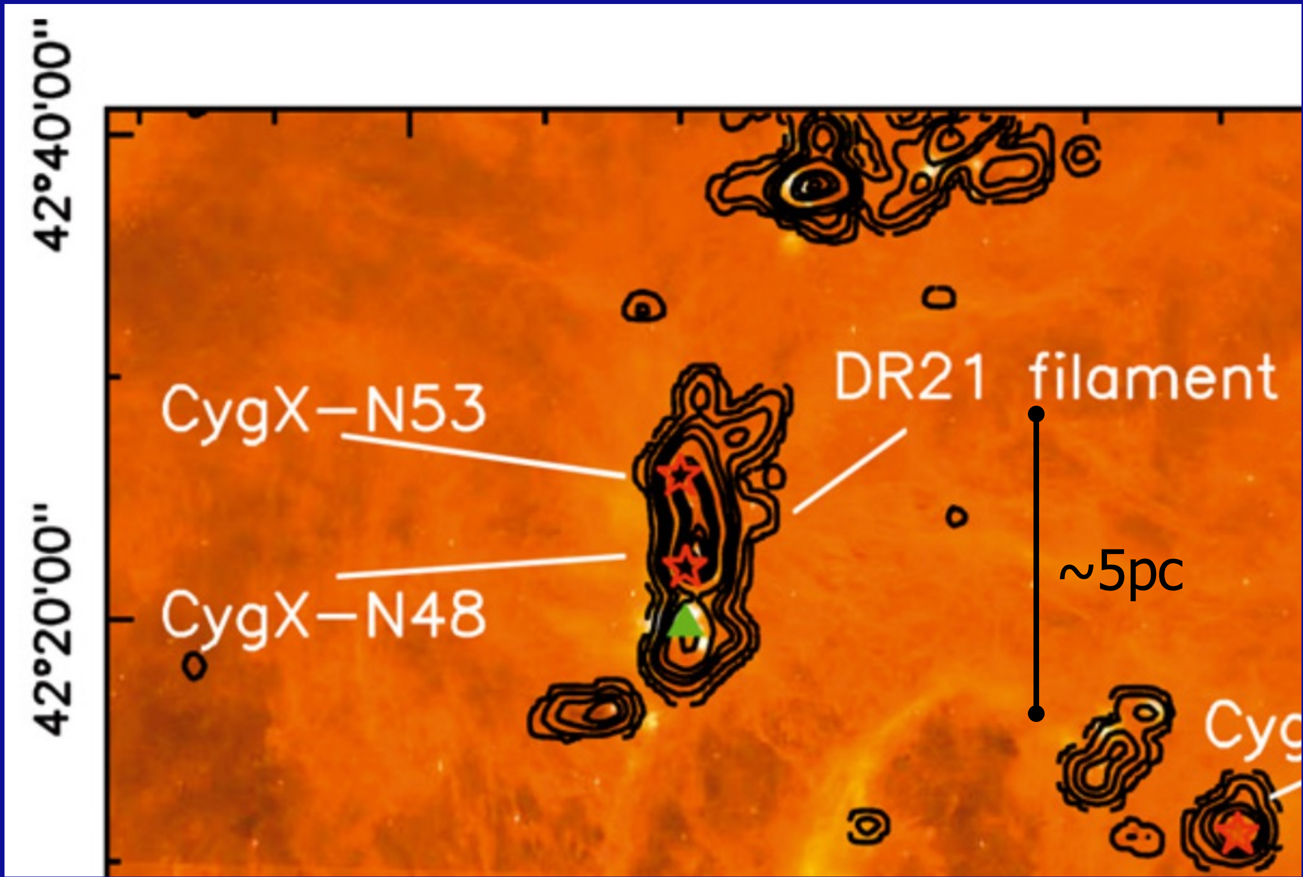


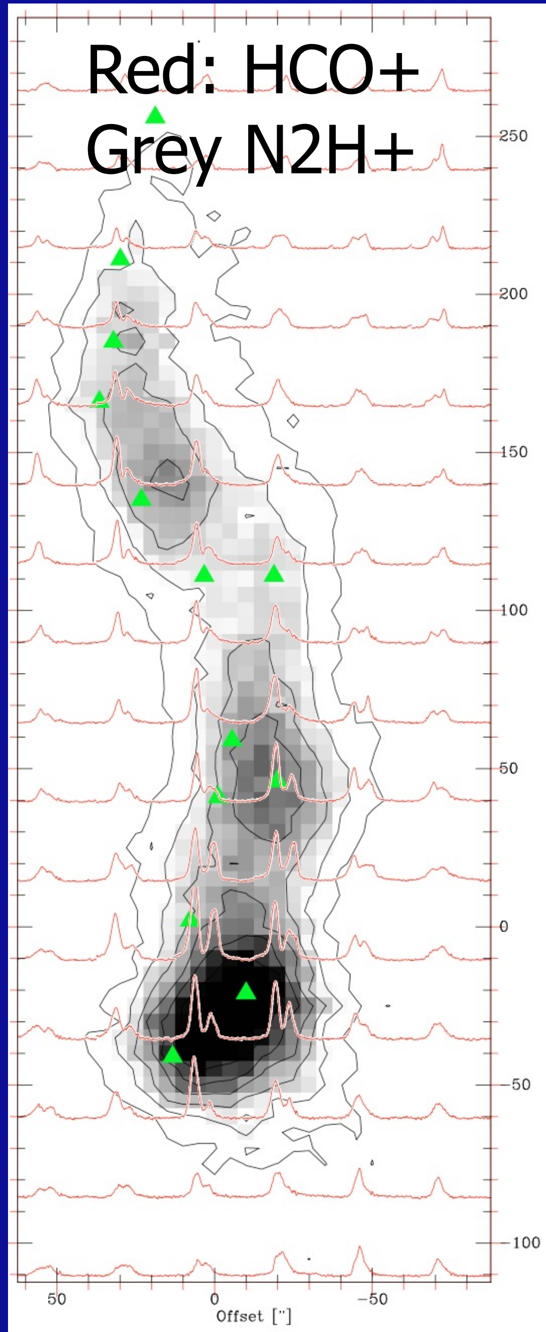
Model with two uniform regions along the line of sight with velocity dispersion σ and peak optical depth τ_0 → infall velocity v_{in}:

$$v_{in} \approx \sigma^2/(v_{red}-v_{blue}) * \ln((1+\exp(T_{BD}/T_D))/(1+\exp(T_{RD}/T_D)))$$

In low-mass regions v_{in} is usually of the order 0.1 km/s. In high-mass regions V_{in} can exceed 1km/s and hence be supersonic.

Extended infall



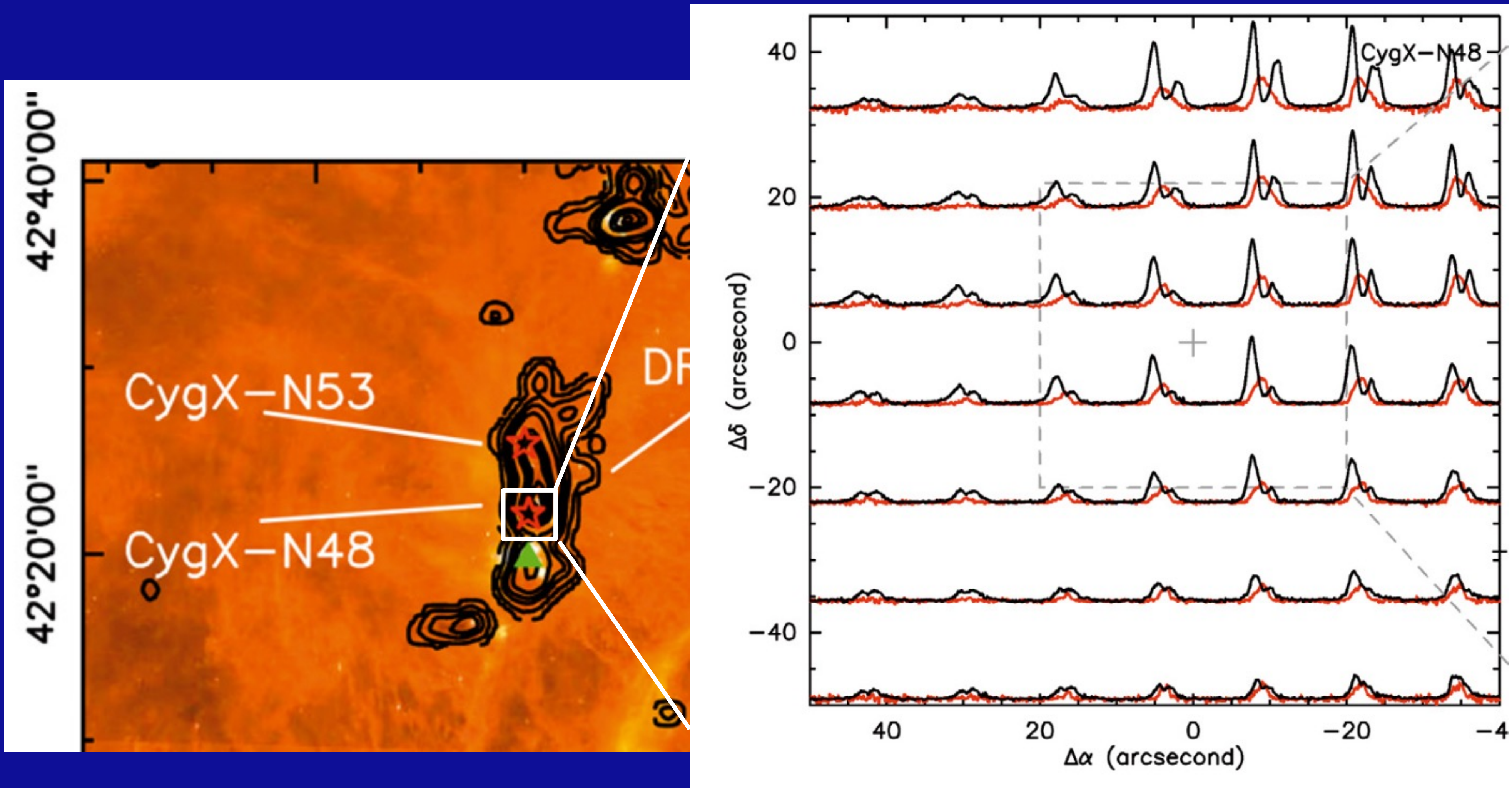


Csengeri et al. 2011

Schneider et al. 2010

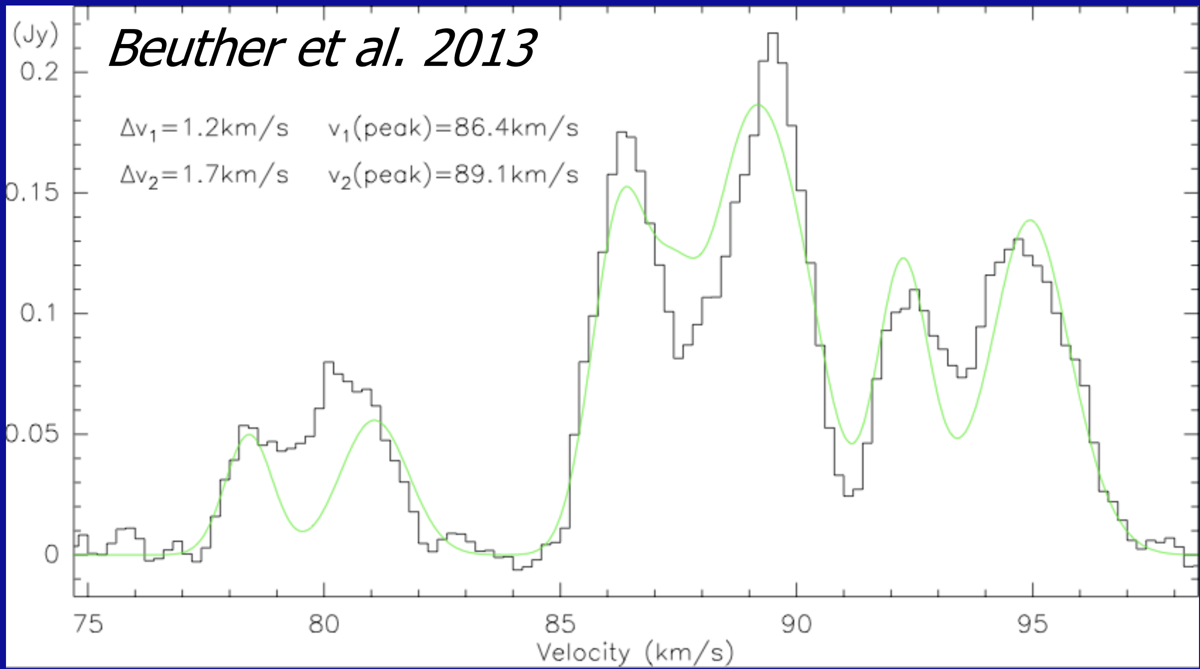
Extended infall

HCO+ & H13CO+



Csengeri et al. 2011

Infall signatures III



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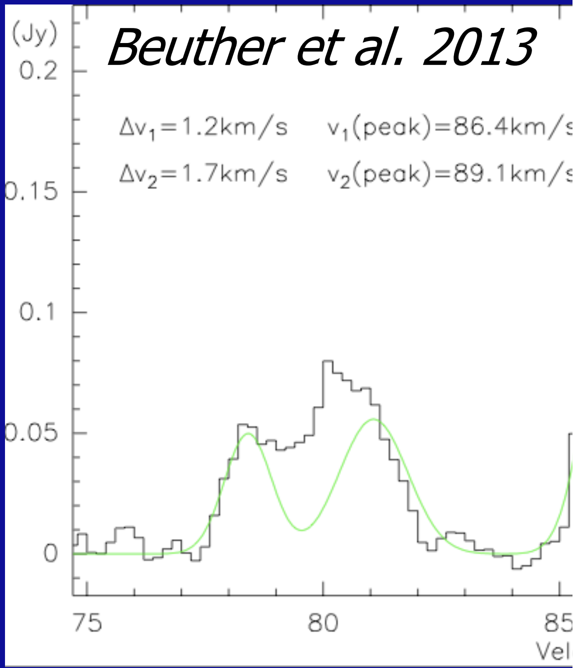
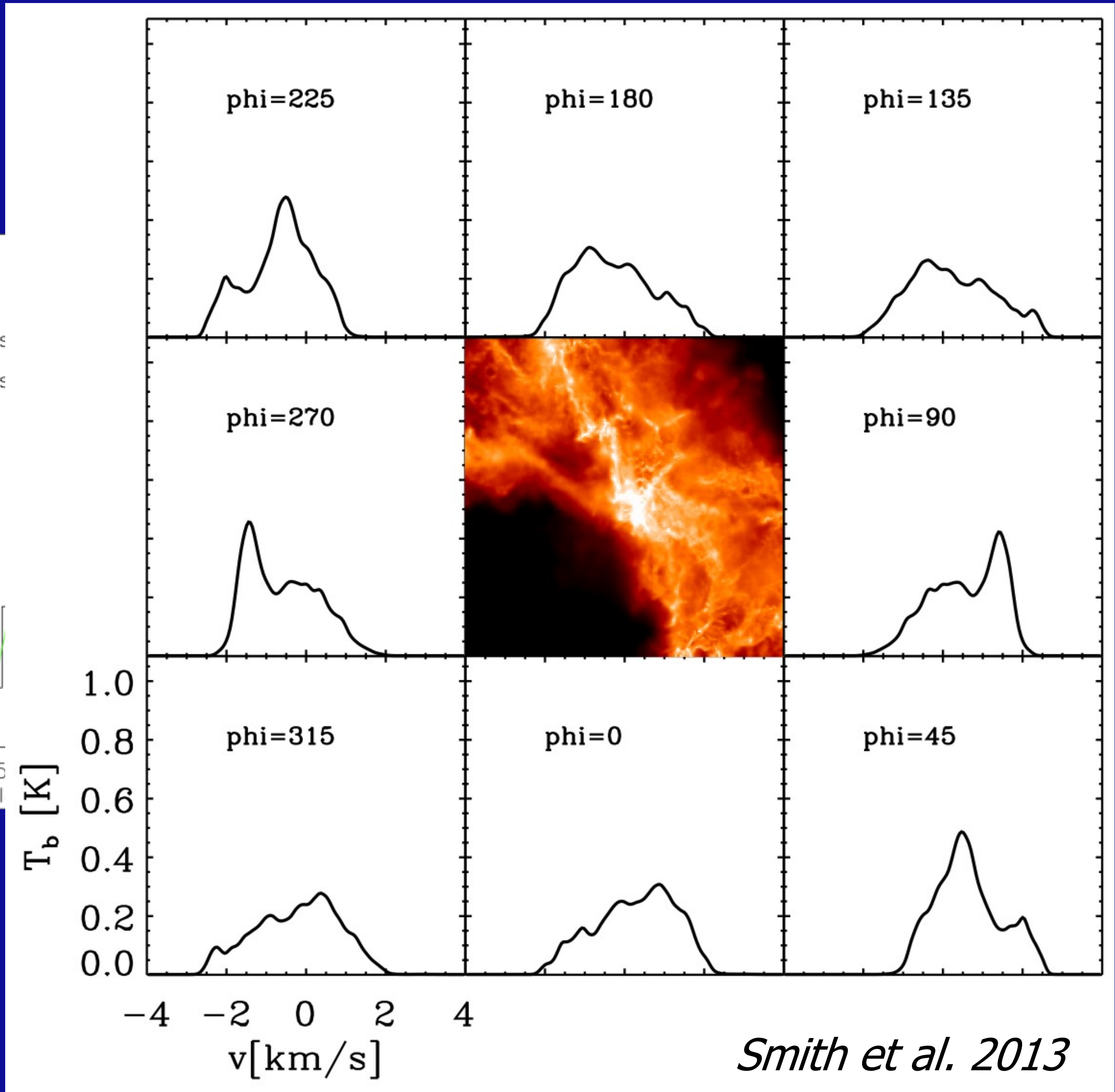
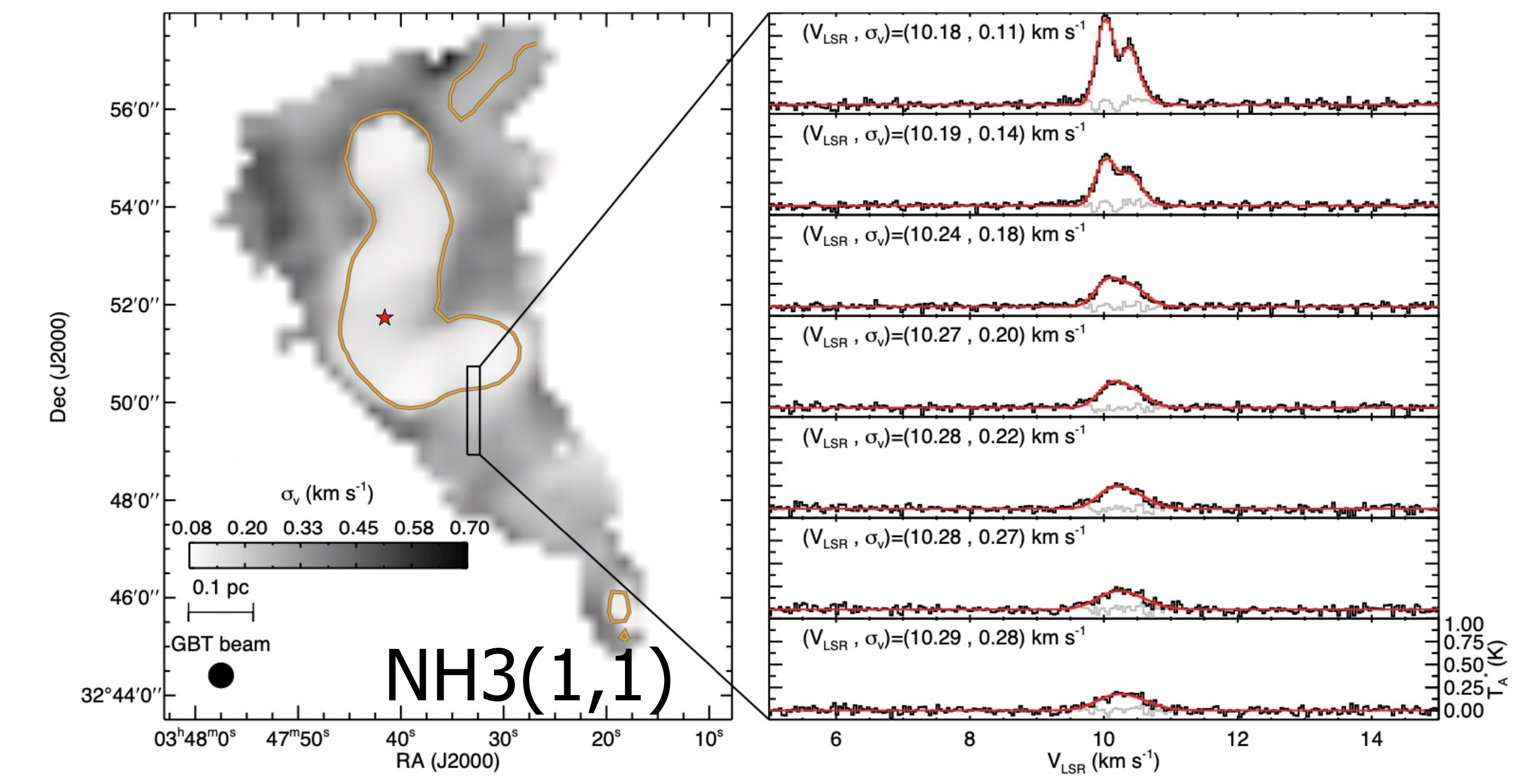


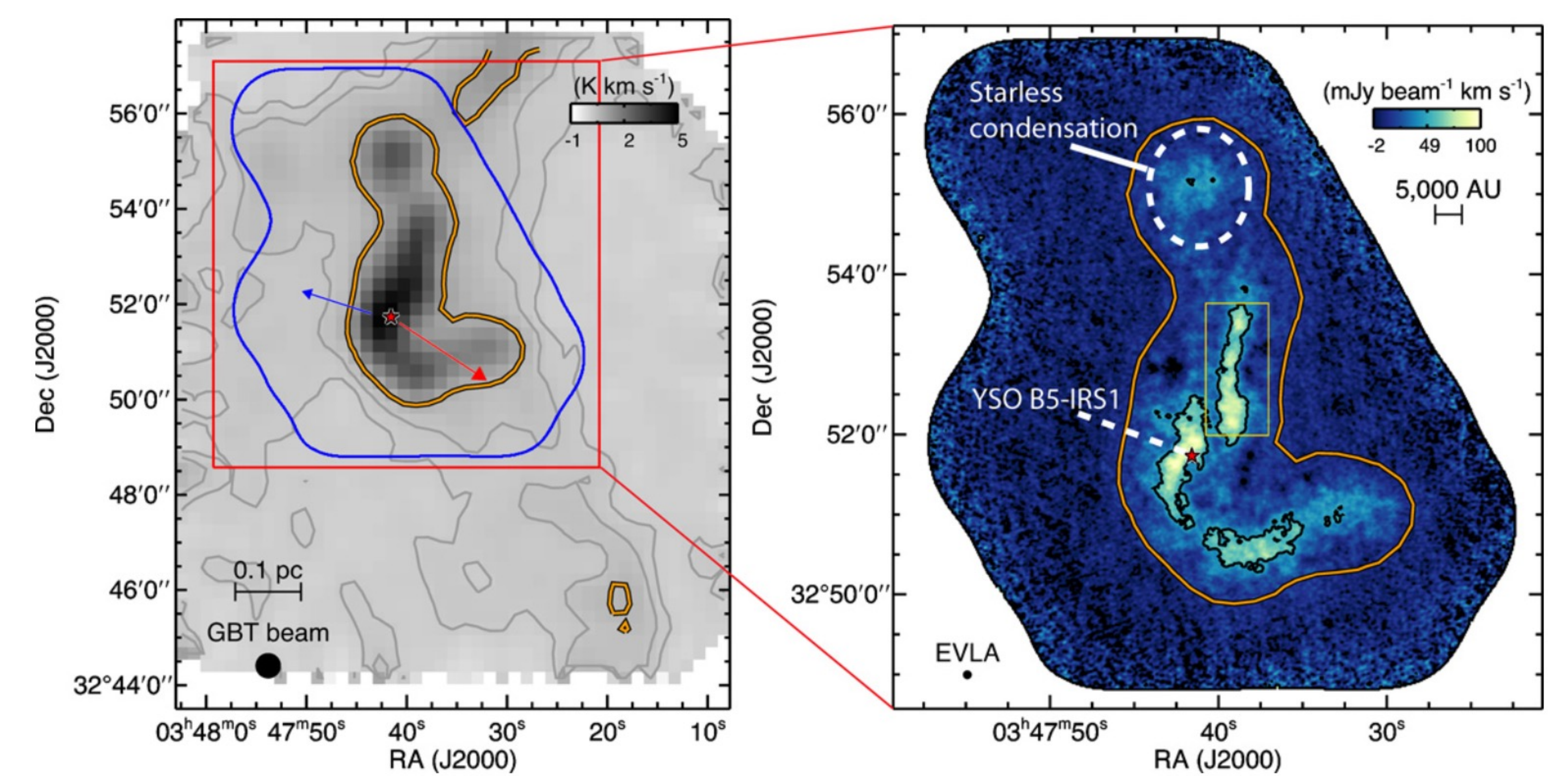


Transition to coherence



Pineda et al. 2010, 2011

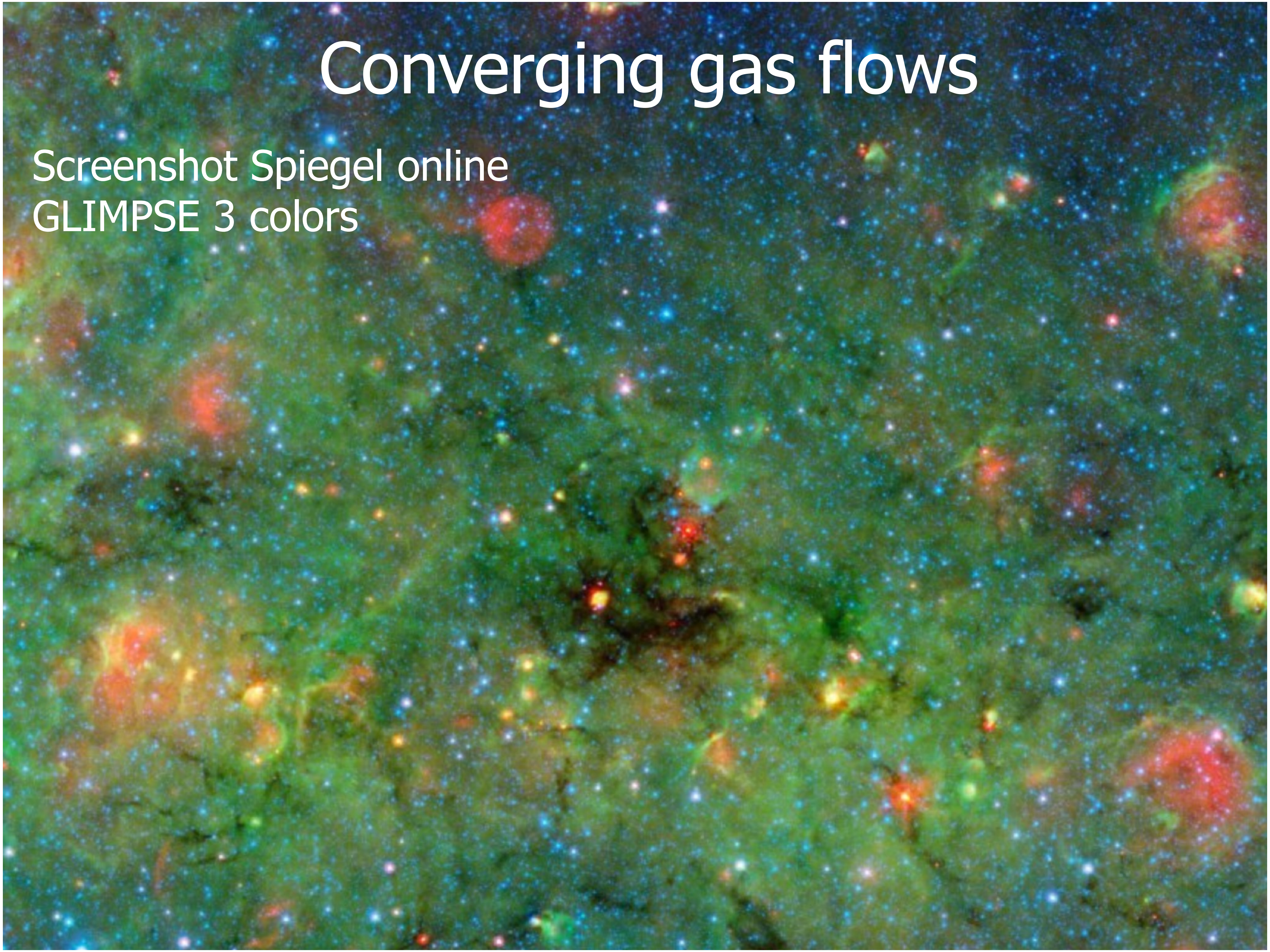
Transition to coherence



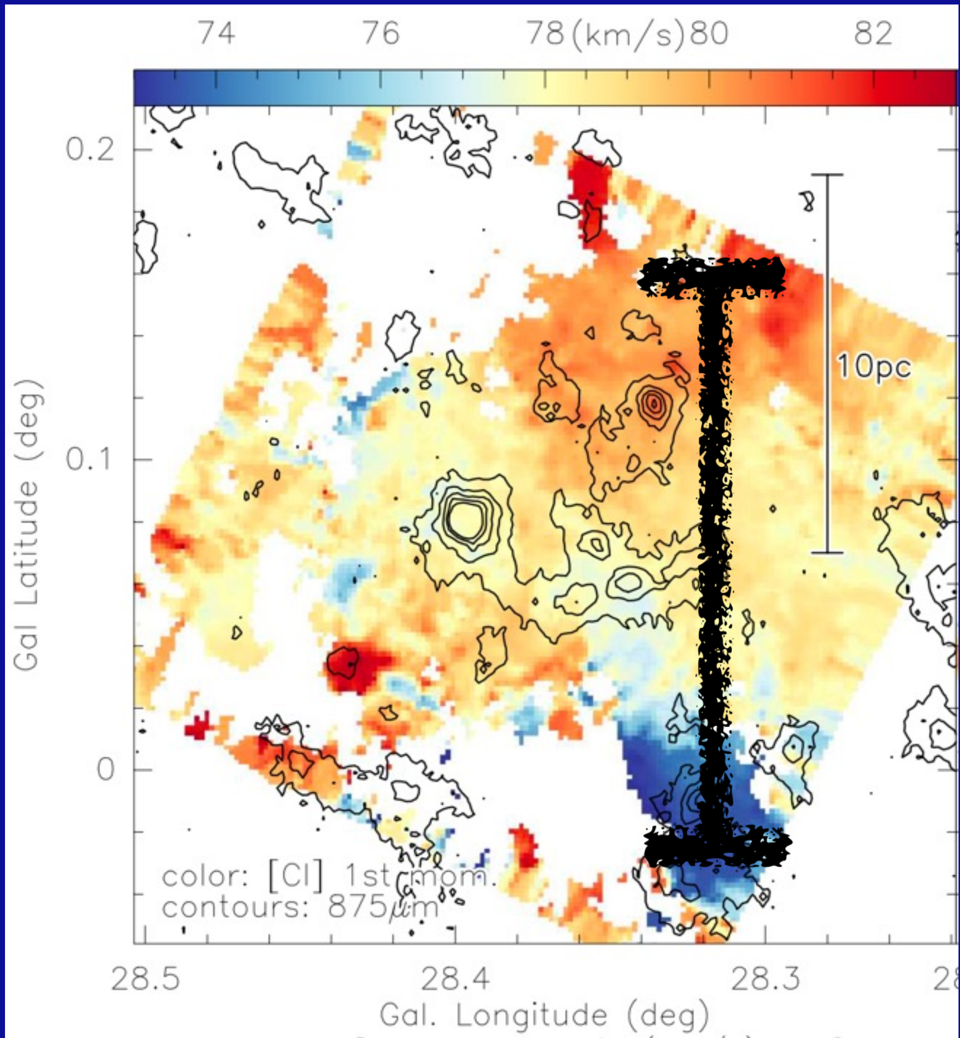
Pineda et al. 2010, 2011

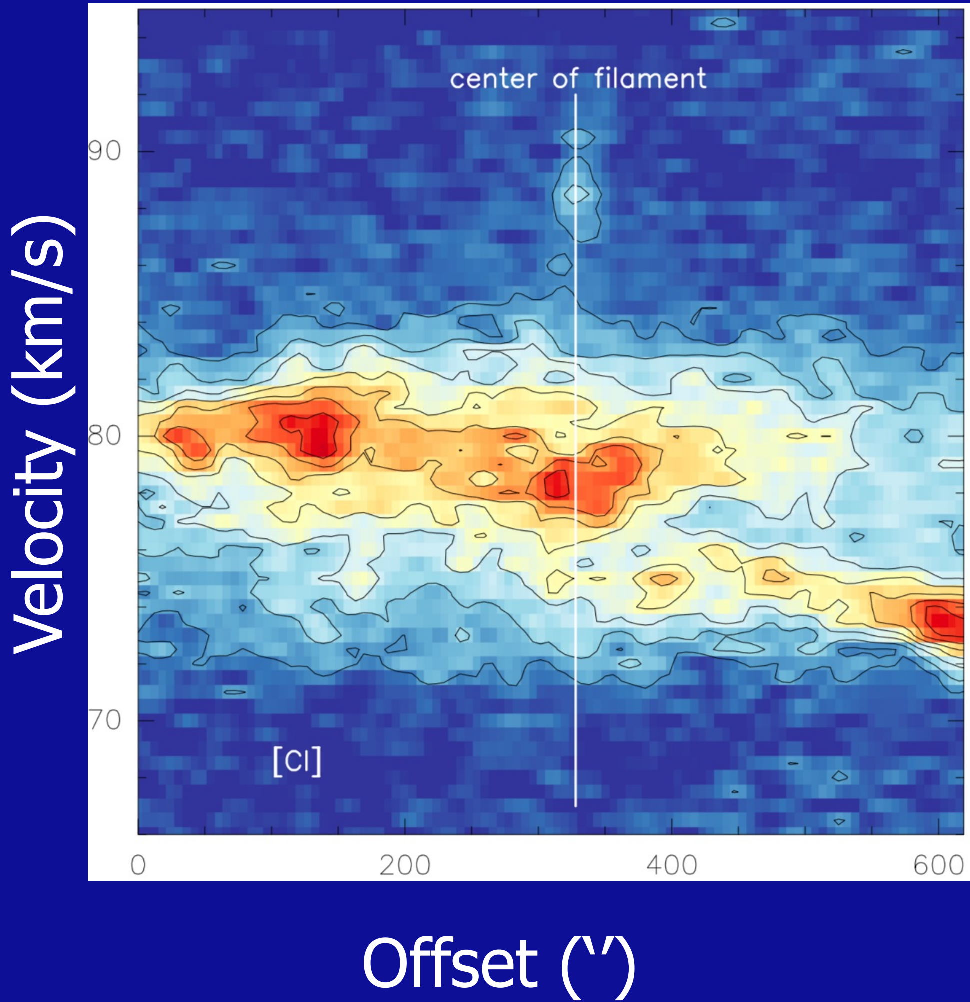
Converging gas flows

Screenshot Spiegel online
GLIMPSE 3 colors



Converging gas flows





Beuther et al. 2020

Summary

- From stability to collapse, early models

- Simulations with different physical ingredients

- Observational signatures

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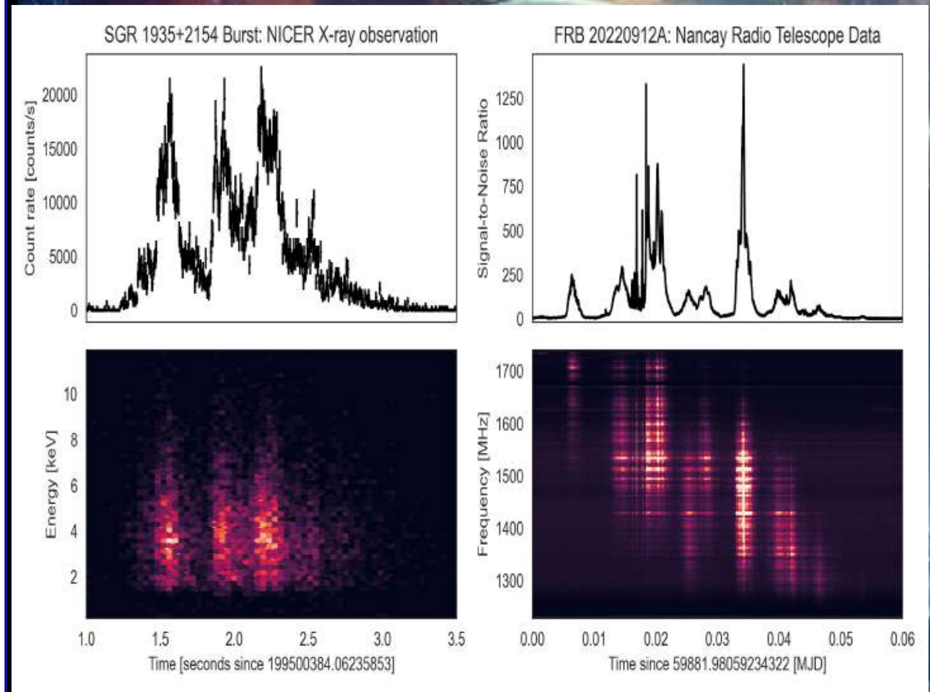
Heidelberg Joint Astronomical Colloquium Winter Semester 2024/25

Tuesday December 3rd Main Lecture Theatre, Philosophenweg 12, 16:30 CEST

Daniela Huppenkothen

(University of Amsterdam)

Hacking the Universe:



Leveraging Data Science in High-Energy Astrophysics and Beyond

https://www.physik.uni-heidelberg.de/hephysto/

Host: Ivelina Momcheva (moncheva@mpia.de)

Image Credit: DALL-E 3