The Gas Dynamics in Star Formation and Turbulence

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Australian Government
Australian Research Council

Australian National University

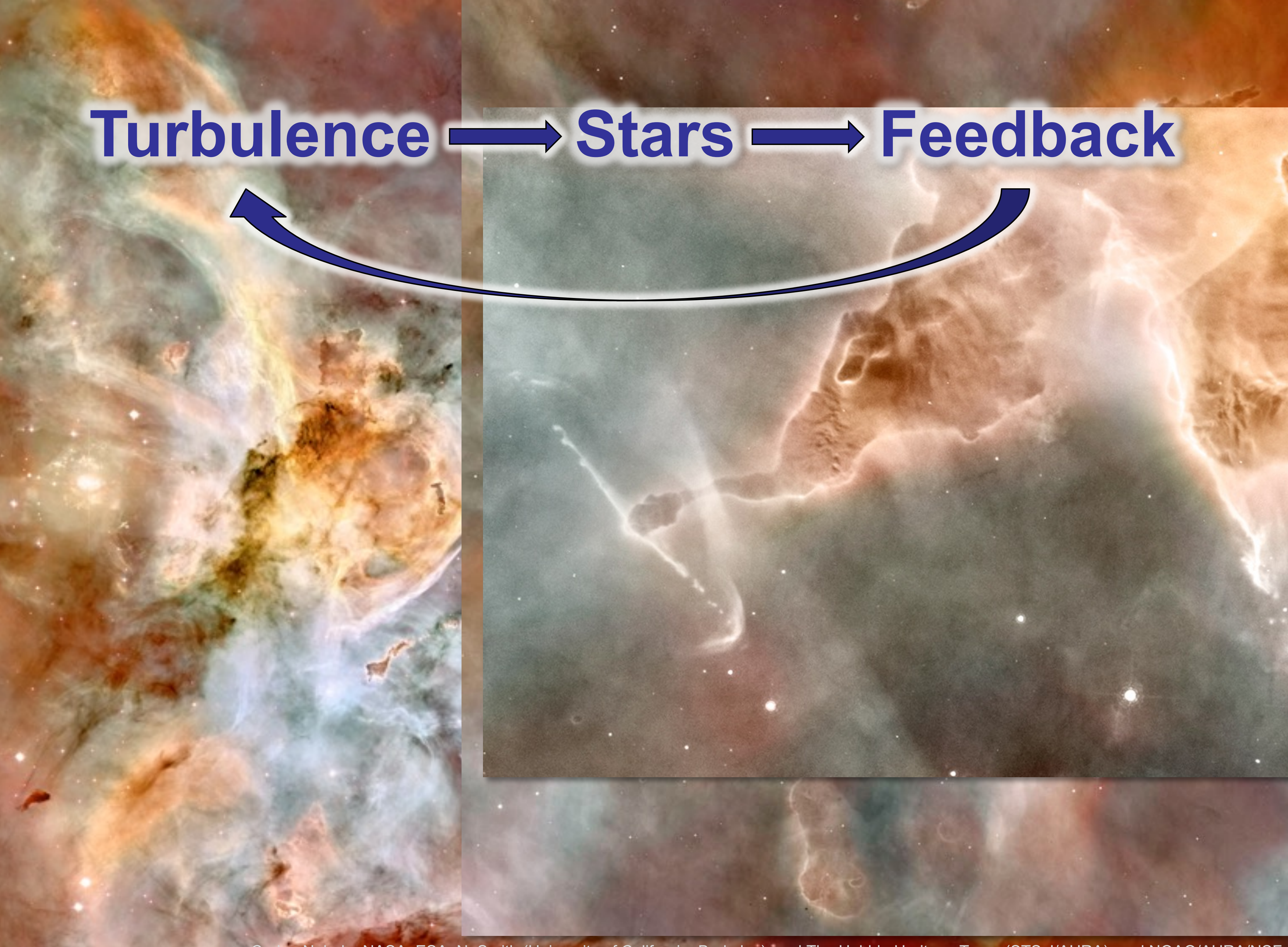
ASTRO 3D
ARC CENTRE OF EXCELLENCE FOR ALL SKY ASTROPHYSICS IN 3D

Turbulence → Density PDF

Density PDF → Star Formation Rate

Why is star formation so inefficient?

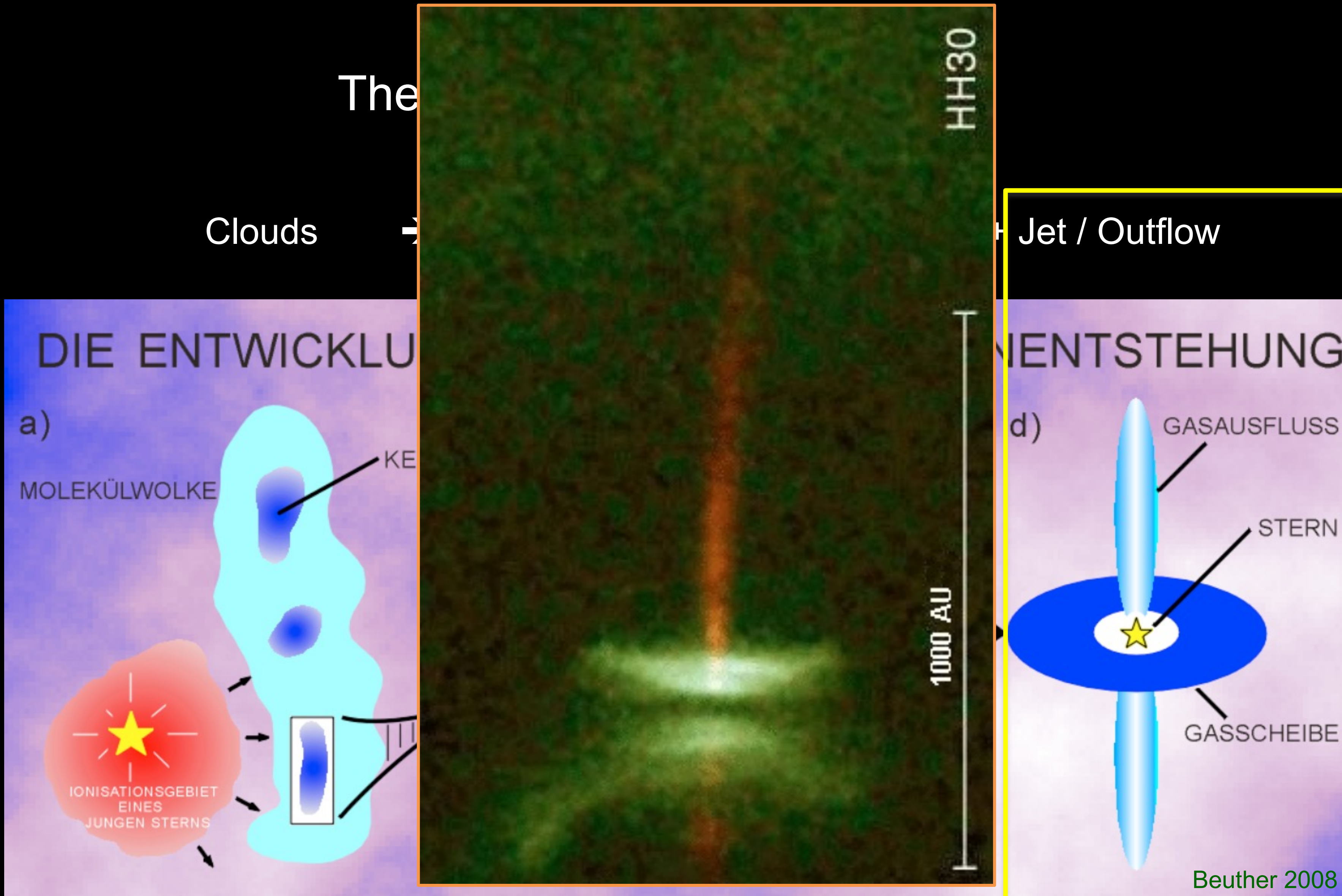
JWST Carina: **National Aeronautics and Space Administration, NASA Official:** NASA Office of Communications



Carina Nebula, NASA, ESA, N. Smith (University of California, Berkeley), and The Hubble Heritage Team (STScI/AURA), and NOAO/AURA/NSF

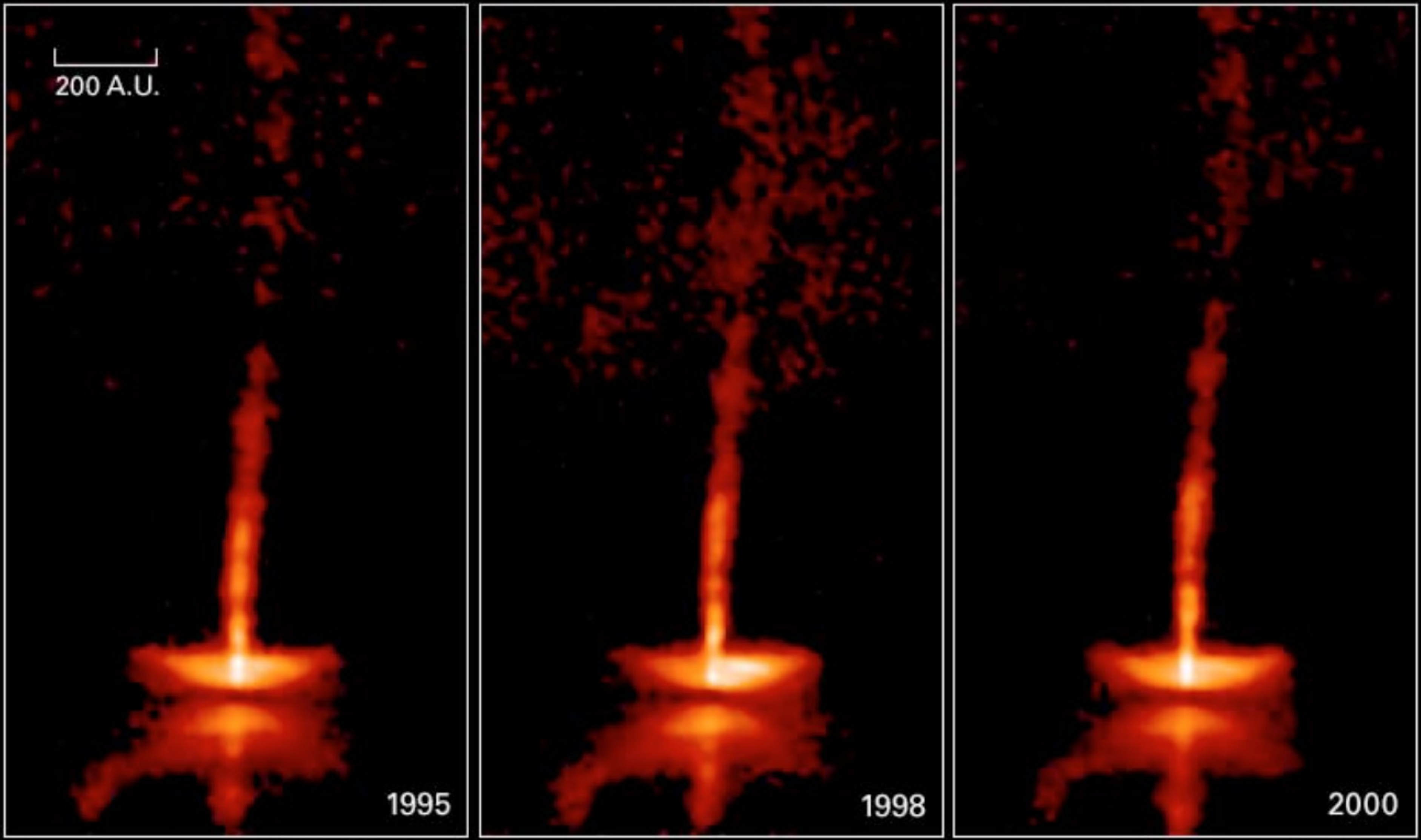
The

Clouds → Jet / Outflow



Beuther 2008

Jets and Outflows

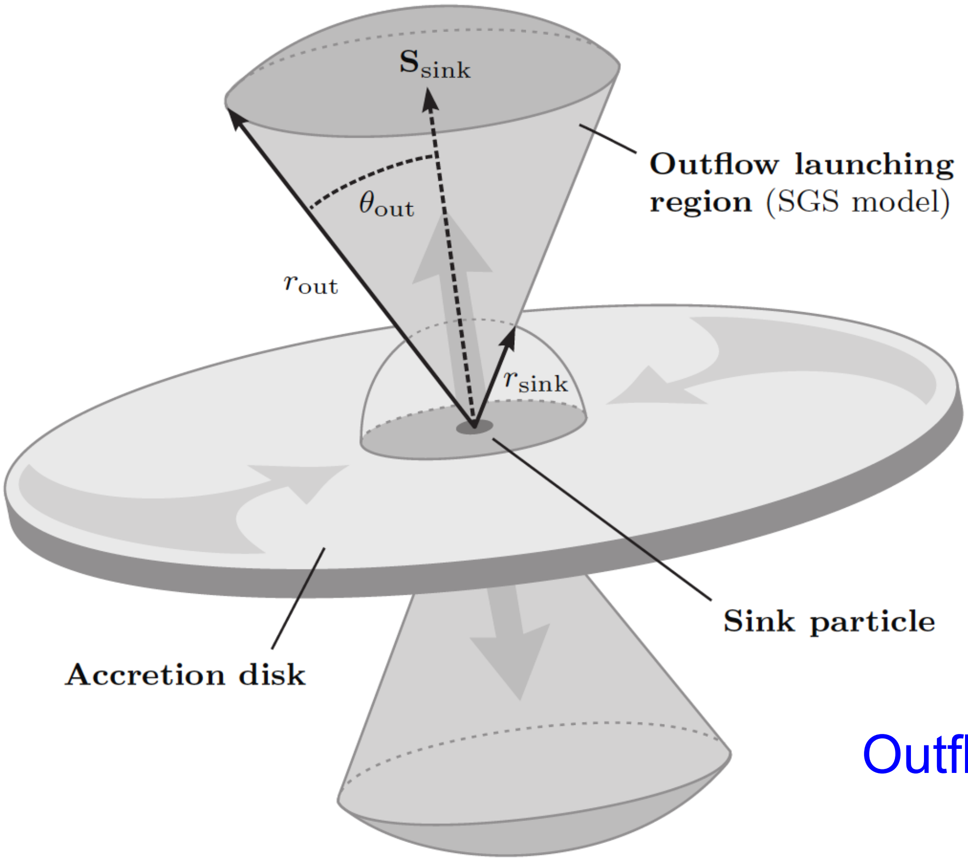


The Dynamic HH 30 Disk and Jet HST • WFPC2

NASA and A. Watson (Instituto de Astronomía, UNAM, Mexico) • STScI-PRC00-32b

Sink Particles as Star Formation Subgrid Model

Federrath et al. 2014, ApJ 790, 128



List of SGS outflow parameters.

SGS Parameter	Symbol	Default	Reference
Outflow Opening Angle	$\theta_{\rm out}$	30°	[1]
Mass Transfer Fraction	$f_{\rm m}$	0.3	[2]
Jet Speed Normalization[a]	$\lvert\mathbf{V}_{\rm out}\rvert$	$100\,{\rm km\,s^{-1}}$	[3]
Angular Momentum Fraction	$f_{\rm a}$	0.9	[4]
Outflow Radius	$r_{\rm out}$	$16\,\Delta x$	Section 4

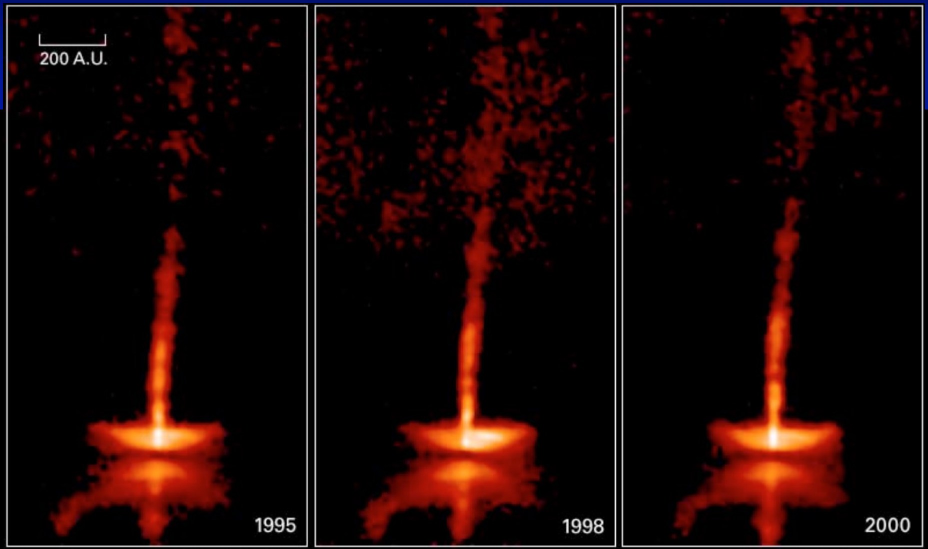
Notes. [a] The outflow velocities are dynamically computed according to the Kepler speed at the footpoint of the jet, $\lvert\mathbf{V}_{\rm out}\rvert = 100\,{\rm km\,s^{-1}}(M_{\rm sink}/0.5\,M_\odot)^{1/2}$ (see Equation 13).
References: [1] Blandford & Payne (1982); Appenzeller & Mundt (1989); Camenzind (1990); [2] Hartmann & Calvet (1995); Calvet (1998); Tomisaka (1998); Bacciotti et al. (2002); Tomisaka (2002); Lee et al. (2006); Cabrit et al. (2007); Lee et al. (2007); Hennebelle & Fromang (2008); Duffin & Pudritz (2009); Bacciotti et al. (2011); Price et al. (2012); Seifried et al. (2012); [3] Herbig (1962); Snell et al. (1980); Blandford & Payne (1982); Draine (1983); Uchida & Shibata (1985); Shibata & Uchida (1985, 1986); Pudritz & Norman (1986); Wardle & Königl (1993); Bacciotti et al. (2000); Königl & Pudritz (2000); Bacciotti et al. (2002); Banerjee & Pudritz (2006); Machida et al. (2008); [4] Pelletier & Pudritz (1992); Bacciotti et al. (2002); Banerjee & Pudritz (2006); Hennebelle & Fromang (2008).

Outflow mass: $$M_{\rm out} = f_{\rm m}\dot{M}_{\rm acc}\Delta t$$

Outflow velocity: $$\lvert\mathbf{V}_{\rm out}\rvert = \left(\frac{GM_{\rm sink}}{10\,R_\odot}\right)^{1/2} = 100\,{\rm km\,s^{-1}}\left(\frac{M_{\rm sink}}{0.5\,M_\odot}\right)^{1/2}$$

Outflow angular momentum: $$\mathbf{L}_{\rm out} = f_{\rm a}\left(\mathbf{S}'_{\rm sink} - \mathbf{S}_{\rm sink}\right)\cdot\mathbf{S}'_{\rm sink}/\lvert\mathbf{S}'_{\rm sink}\rvert$$

Jet/Outflow Feedback



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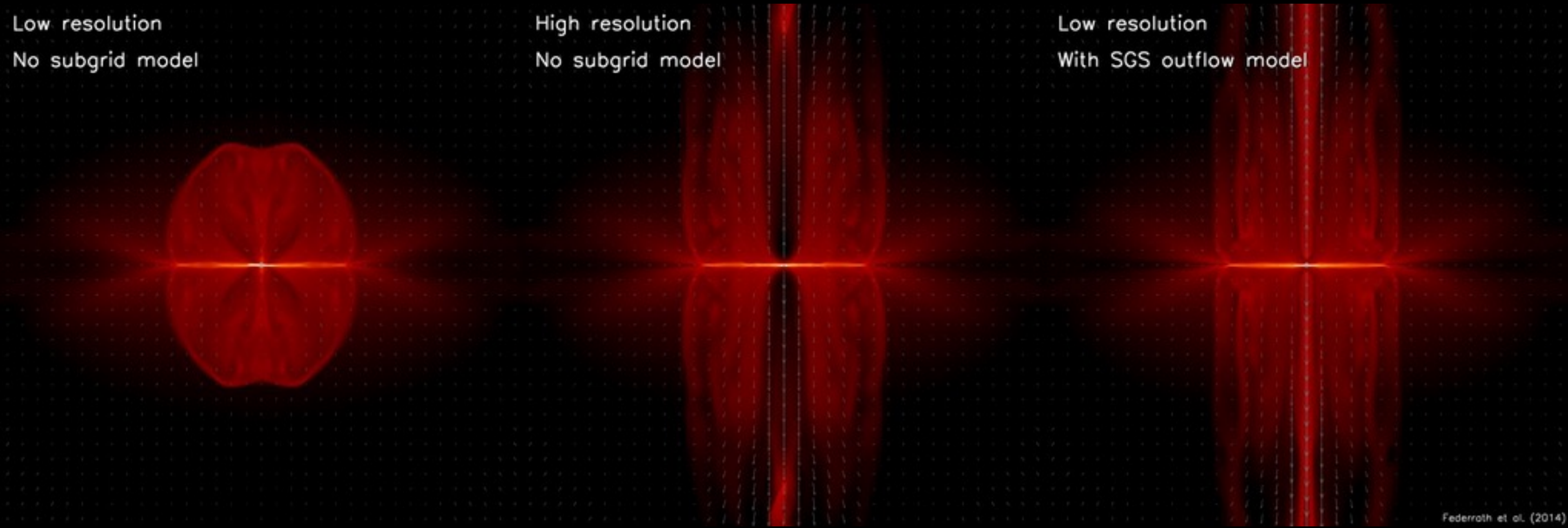


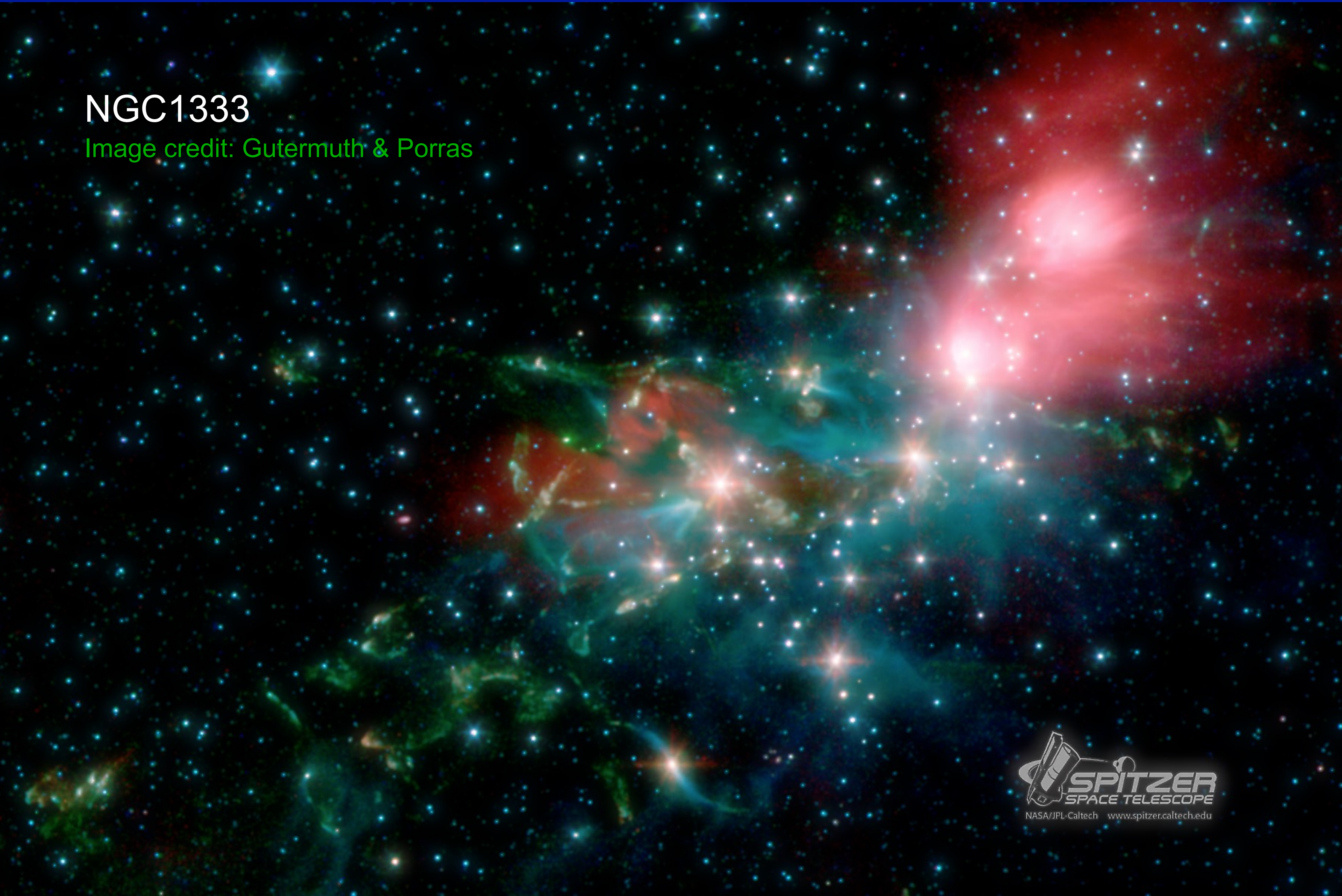
Movies available: https://www.mso.anu.edu.au/~chfeder/pubs/outflow_model/outflow_model.html

Federrath et al. 2014, ApJ 790, 128

Star Formation – Outflow/Jet Feedback

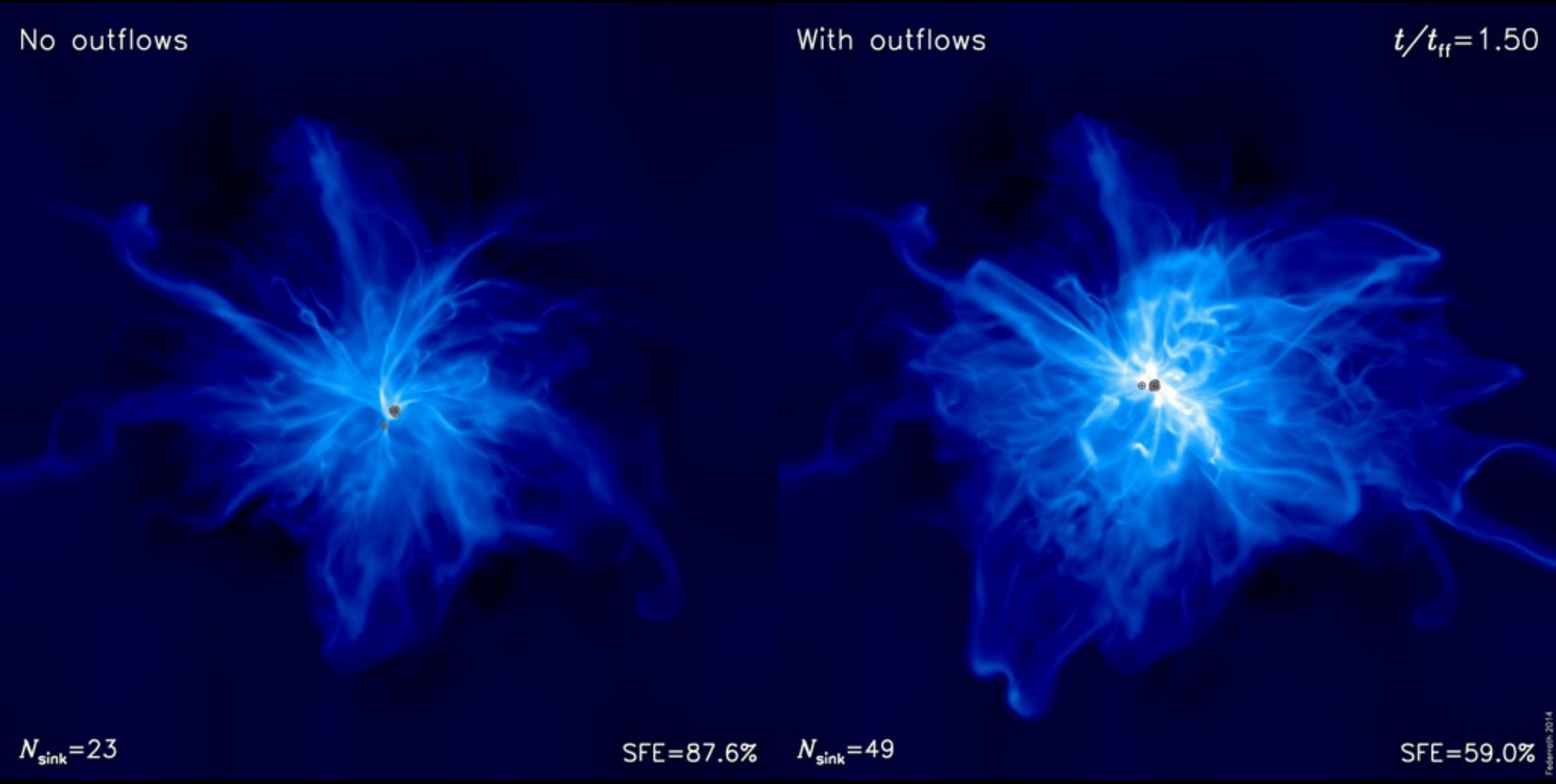
NGC1333

Image credit: Gutermuth & Porras



The role of outflow/jet feedback for star cluster formation

Movies available: https://www.mso.anu.edu.au/~chfeder/pubs/outflow_model/outflow_model.html

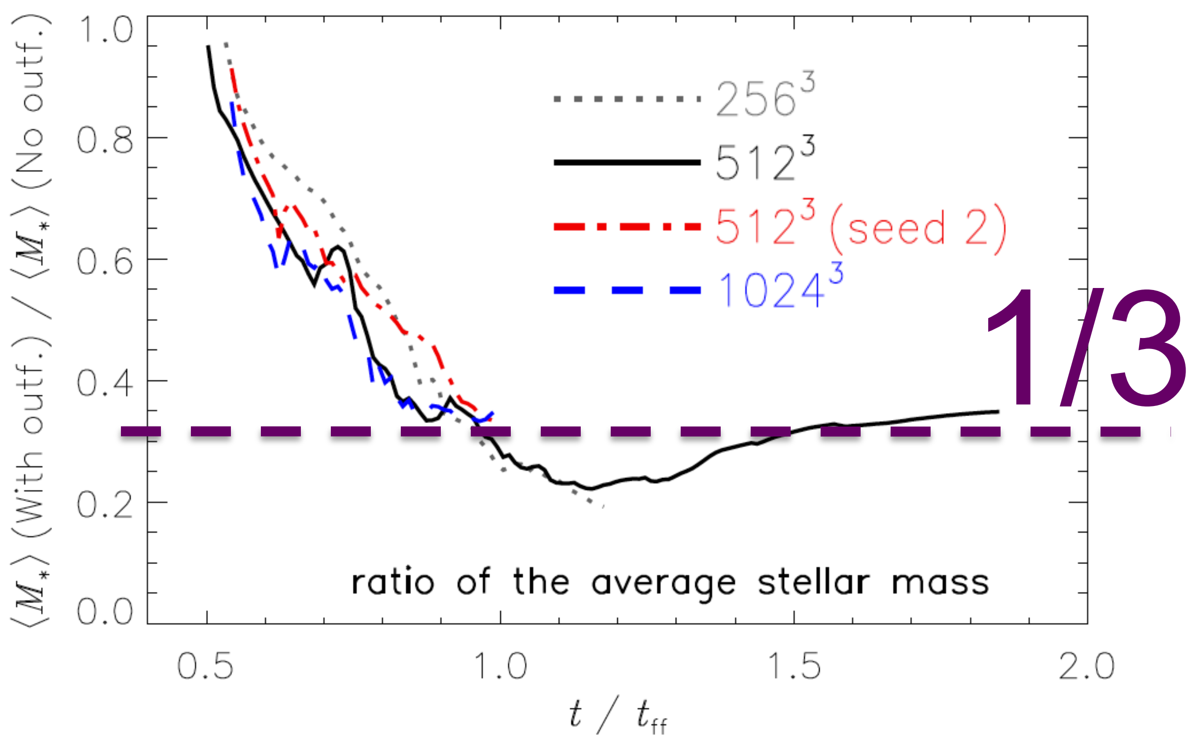


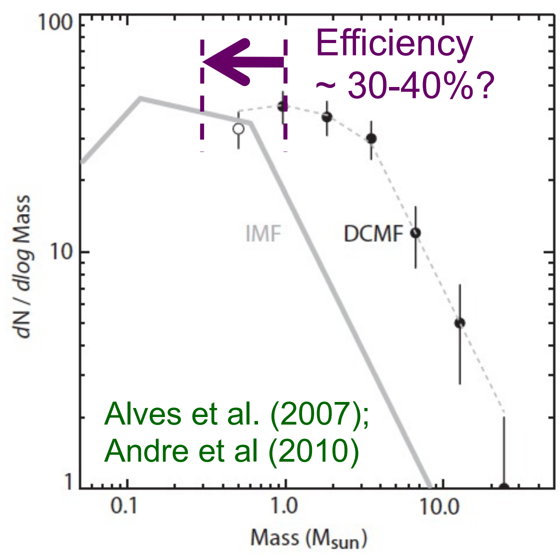
Without jets/outflows

With jets/outflows

Federrath et al. 2014, ApJ 790, 128

The role of outflow/jet feedback for star cluster formation





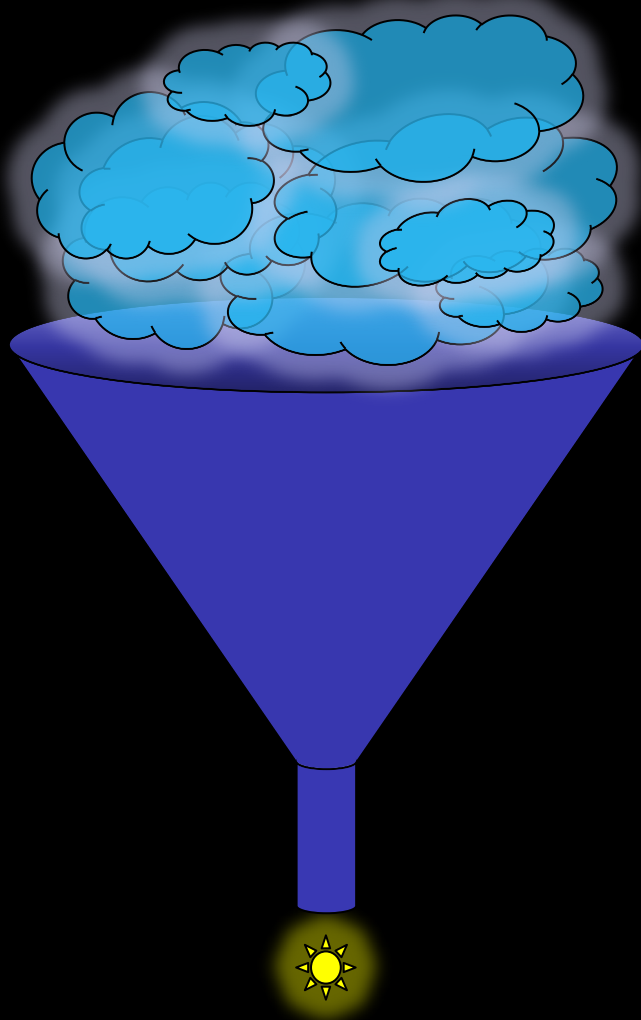
RESULTS:

- Outflow/Jet feedback reduces the SFR by factor ~ 2
- Outflow/Jet feedback reduces average star mass by factor ~ 3

Star Formation is Inefficient

Gravity

Magnetic Fields



Turbulence

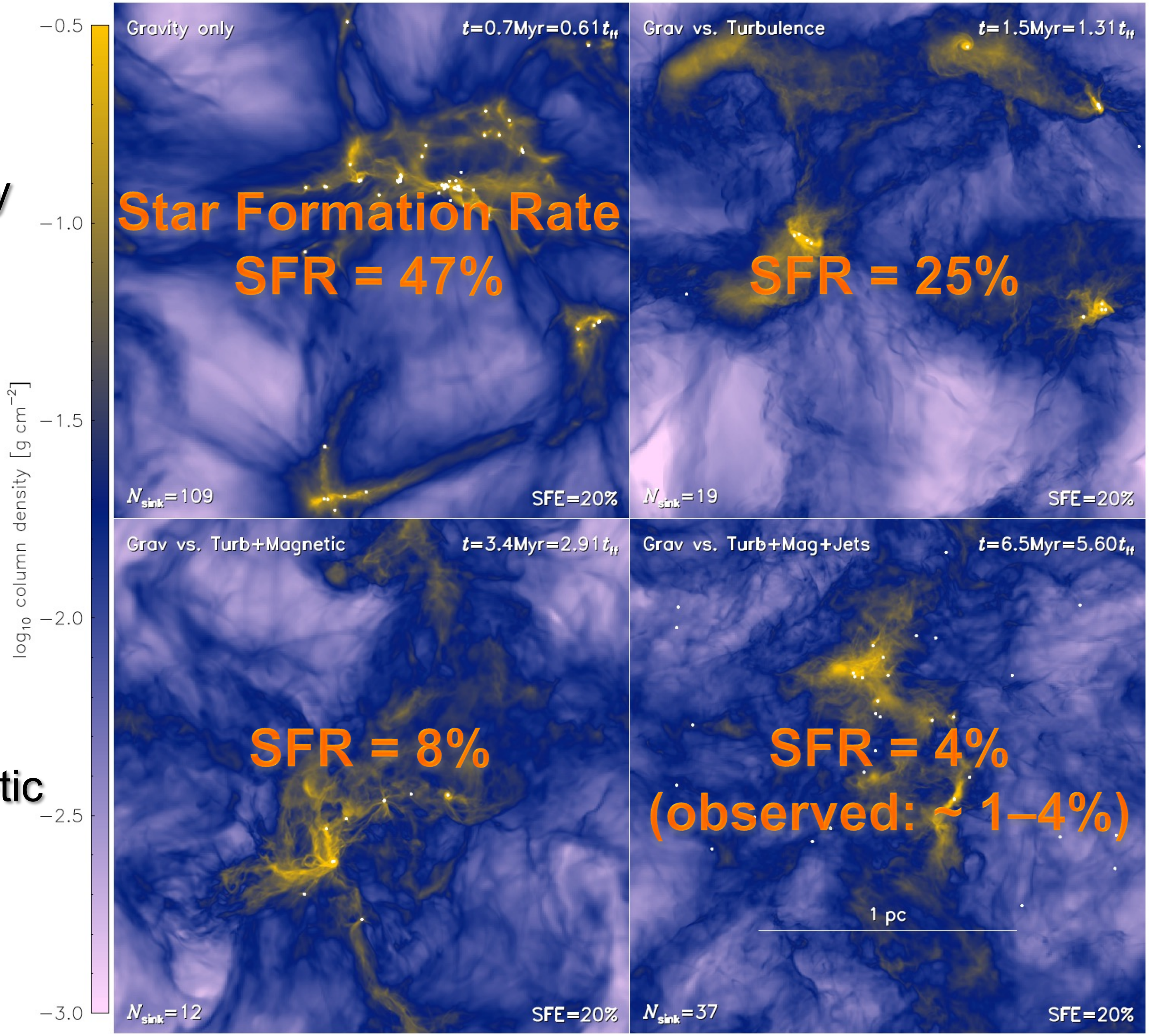
Feedback

Star Formation is Inefficient (Federrath 2015 MNRAS; 2018 *Physics Today*)

Movies available: **http://www.mso.anu.edu.au/~chfeder/pubs/ineff_sf/ineff_sf.html**

Gravity only

Turbulence



Turb+ Magnetic Fields

Turb+ Mag+ Jet/Outflow Feedback

Summary

- Supersonic, magnetized turbulence is key for star formation

  - SFR from density PDF depends on
    virial parameter, forcing parameter, Mach number, plasma beta

  - Very good agreement between theory, simulations and observations

- Jet/outflow feedback in star cluster formation:

  - Star formation rate reduced by ~2x
  - Average star mass reduced by ~3x → Initial Mass Function!

- Star Formation is inefficient →

  Only combination of

  Gravity + Turbulence + Magnetic Fields + Feedback

  gives realistic Star Formation Rates

ALL OF THIS INVOLVES HYDRODYNAMICS!

Astrophysical fluid/gas dynamics

- Differs from “laboratory” and/or engineering fluid dynamics in the relative importance of certain effects.

  - Compressibility
  - Gravity
  - Magnetic fields

  Generally important

  - Radiation forces
  - Relativistic effects

  Sometimes important

  - Viscosity — sometimes invoked to mimic turbulence
  - Surface tension
  - Presence of solid boundaries

  Generally unimportant

(adopted from Bai lecture notes)

Derivation of Hydrodynamical Equations

- Introduction of fluid variables
- Conservation laws for mass, momentum, energy
- Equation of state to close the system
- Validity of the fluid approach

→ Write down…