Astronomical Computing

ASTR4004 / ASTR8004

ANU – 2nd semester 2024

Christoph Federrath

Lectures and Tutorials: Tuesdays and Thursdays 1-3pm

Webpage:
http://www.mso.anu.edu.au/~chfeder/teaching/astr_4004_8004/astr_4004_8004.html

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

Astronomical Computing

Topics:

- **Shell usage and scripting** (**bash**: redirect stdout/stderr, grep, top, tail, cat, wc, …)
- **Remote Computing** (ssh, rsync, nohup, …)
- **Plotting**; basics and advanced style settings (lines, axes, etc), 3D plots; webplot digitizer
- **Movies**
- **Version control systems** (Bitbucket, GitHub)
- **Quick intro to IDL** (Interactive Data Language)
- **Python**
- **Statistics** (binning, mean, rms, stddev, skewness, kurtosis, PDFs, Monte Carlo error propagation, etc.)
- **Image processing** (beam convolution, array operations, filtering, etc.)
- **Fourier transformation** (power spectra)
- **Parallel computing**
    - OpenMP, MPI (C++)
    - How to parallelise code
    - Parallel scaling

- **Weeks 7-12: taught by Sven Buder and Yuxiang Qin**: Regression, Neural Networks, Gaussian Processes, Monte-Carlo Markov Chain, ...

Image credit: M. S. Povich

Astronomical Computing

Need computer account at RSAA

–

application form on course webpage

Image credit: M. S. Povich

Astronomical Computing

Student representatives:

- Need at least two student reps (Honours/Masters, by end of week 2)
- Student rep communicates with students and course convener
- Student rep name and email address published on Wattle
- Please nominate yourself or someone else, if you are interested

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

Astronomical Computing

Assignments:

- Assessment based on 4 assignments (4 x 20%) + exam (1 x 20%)
- 1 assignment per about every 2 weeks
- Assignments published on webpage and Wattle
- Submission via Turnitin
- Feedback within 2 weeks after submission

Help with setting up computers and marking provided by Lewis Miller.

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

Modelling/Computing
Star Formation, Turbulence, Feedback

Christoph Federrath

ANU – 2024

Australian Government
Australian Research Council

Australian National University

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

Image Credit: ESA and the HFI Consortium, IRAS 2010

Star Formation

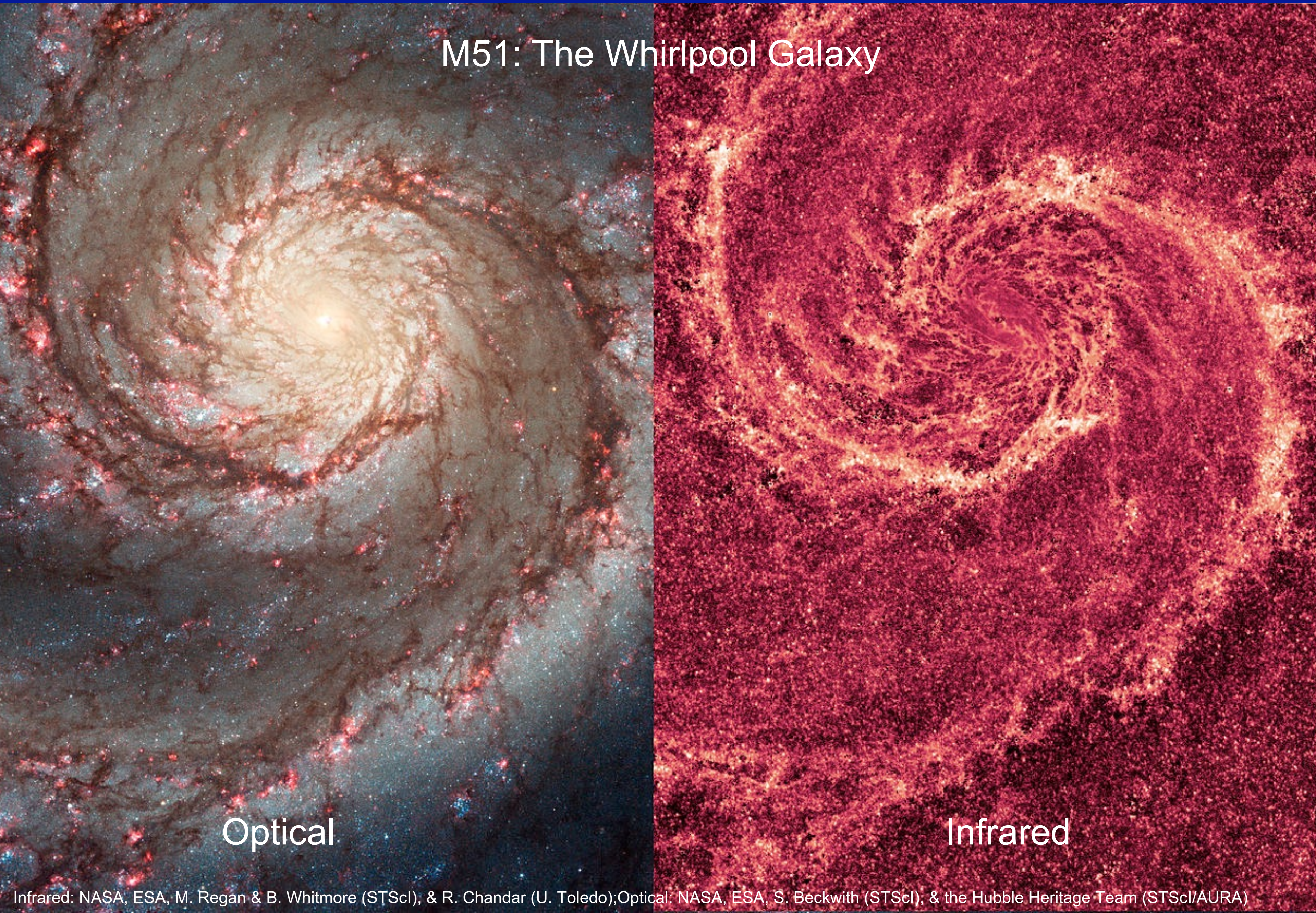
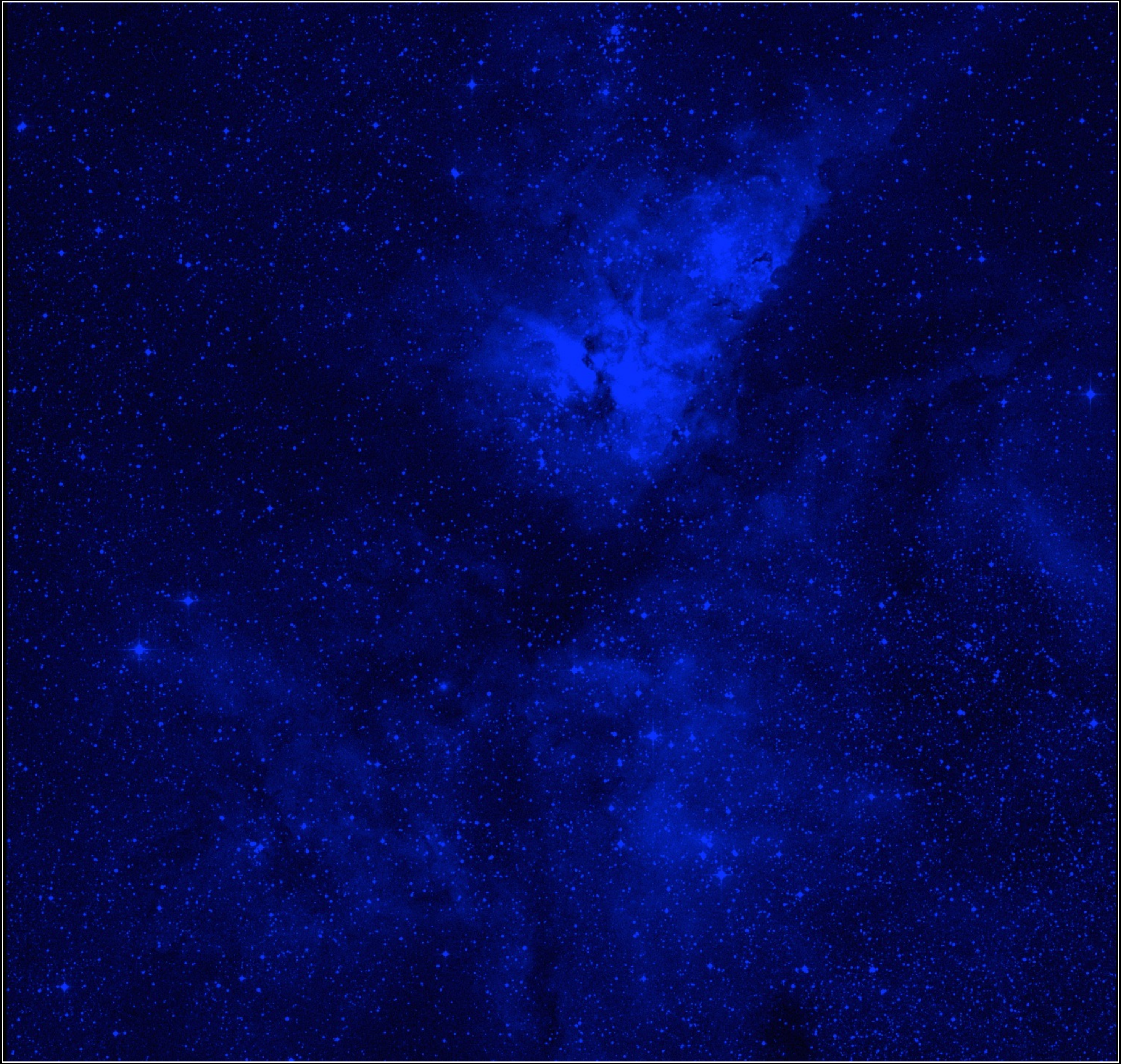



Image credit: M. S. Povich



The Great Nebula in Carina

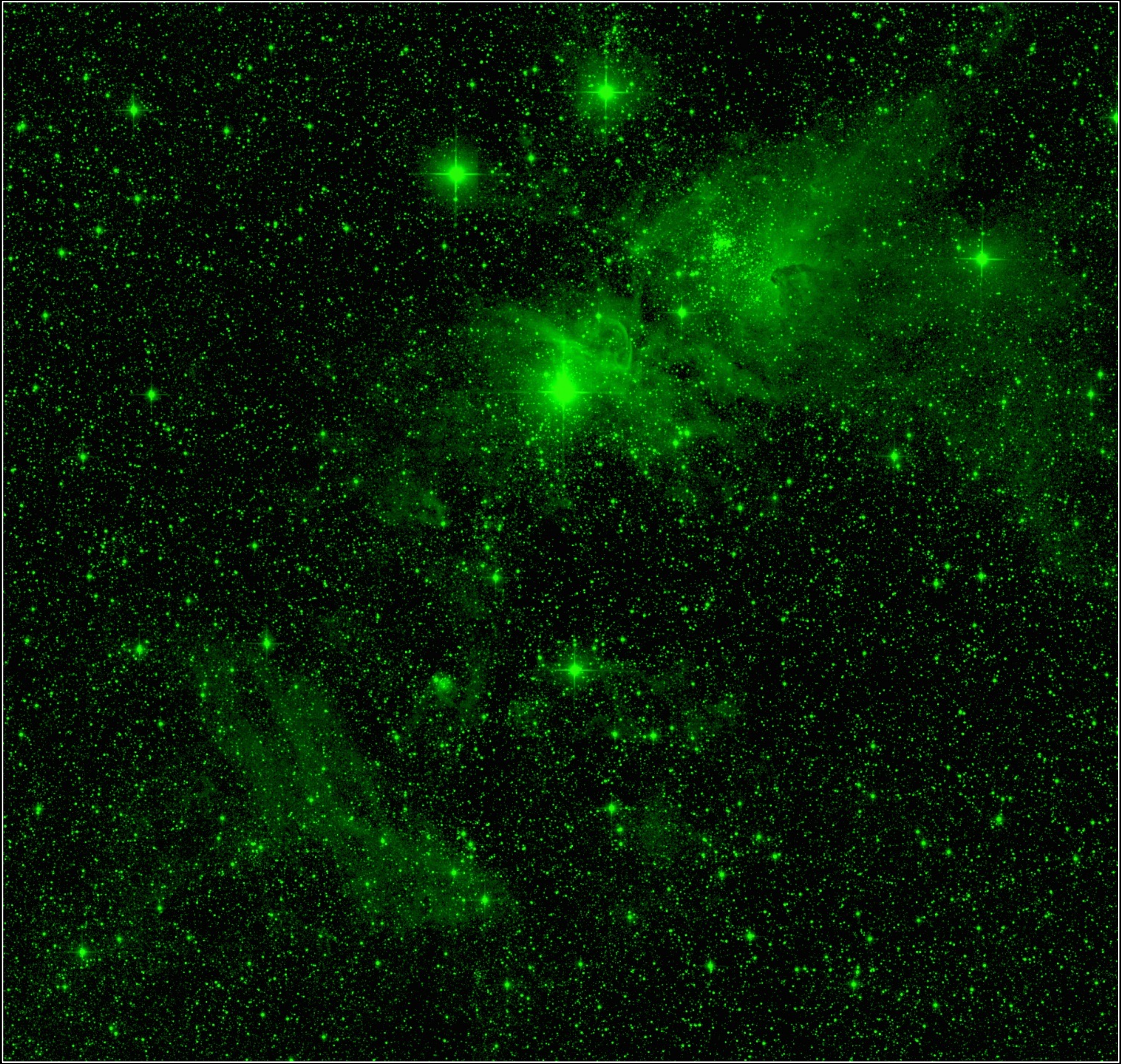
Visible Light

Digitized Sky Survey

Dark regions within the Visible nebula are obscured by dust.

New Massive Stars Found Hiding in Famous Nebula

M. S. Povich



The Great Nebula in Carina

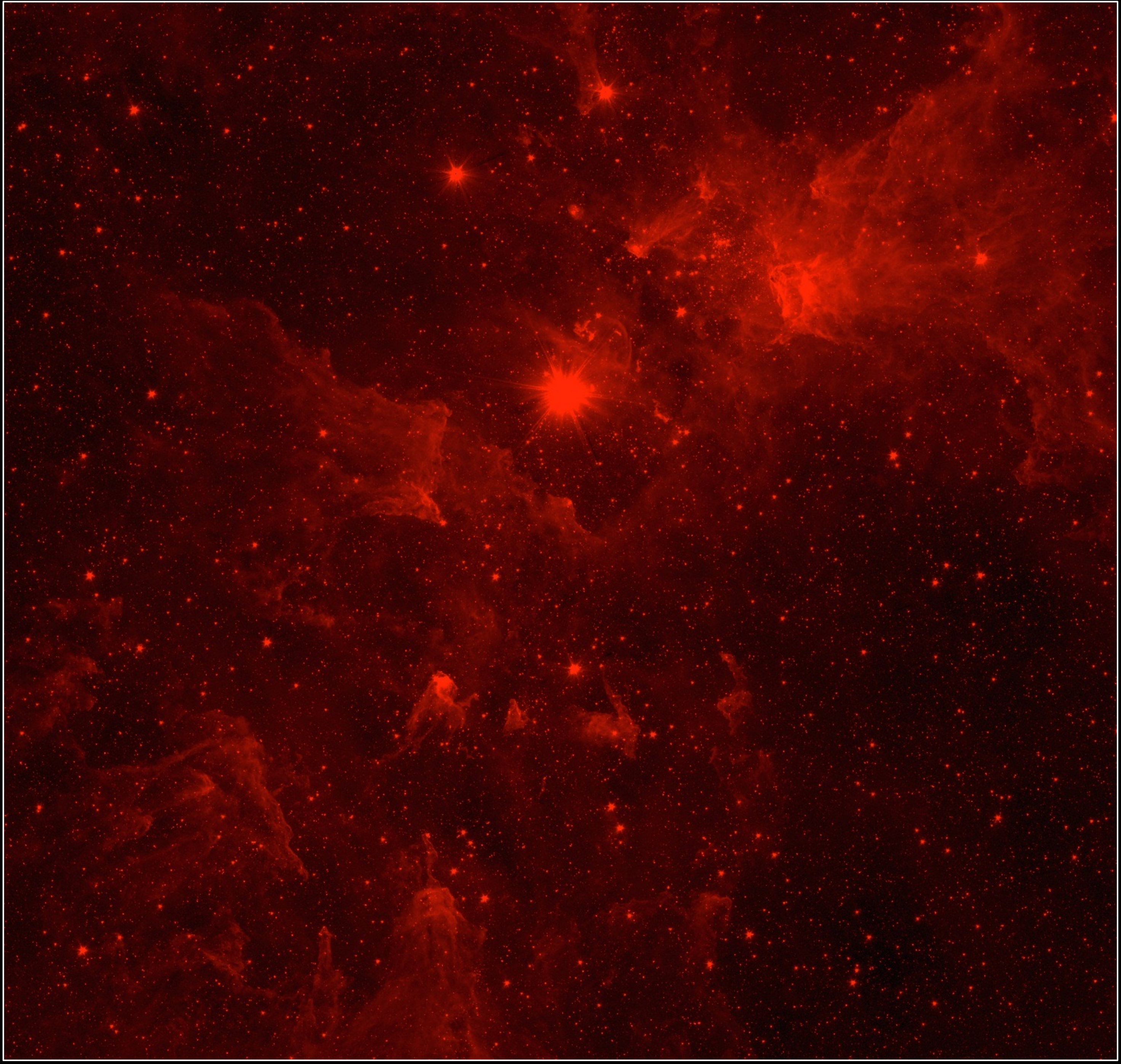
Near-Infrared

Two-Micron All-Sky Survey

Near-infrared light passes through the dust, revealing more stars.

New Massive Stars Found Hiding in Famous Nebula

M. S. Povich



The Great Nebula in Carina

Mid-Infrared

Spitzer Space Telescope

The dust clouds themselves glow in mid-infrared light.

The Great Nebula in Carina

Visible Light
Digitized Sky Survey

Near-Infrared
Two-Micron All-Sky Survey

Mid-Infrared
Spitzer Space Telescope

New Massive Stars
Found Hiding in
Famous Nebula

M. S. Povich

Turbulence → Stars → Feedback

Turbulence driven by

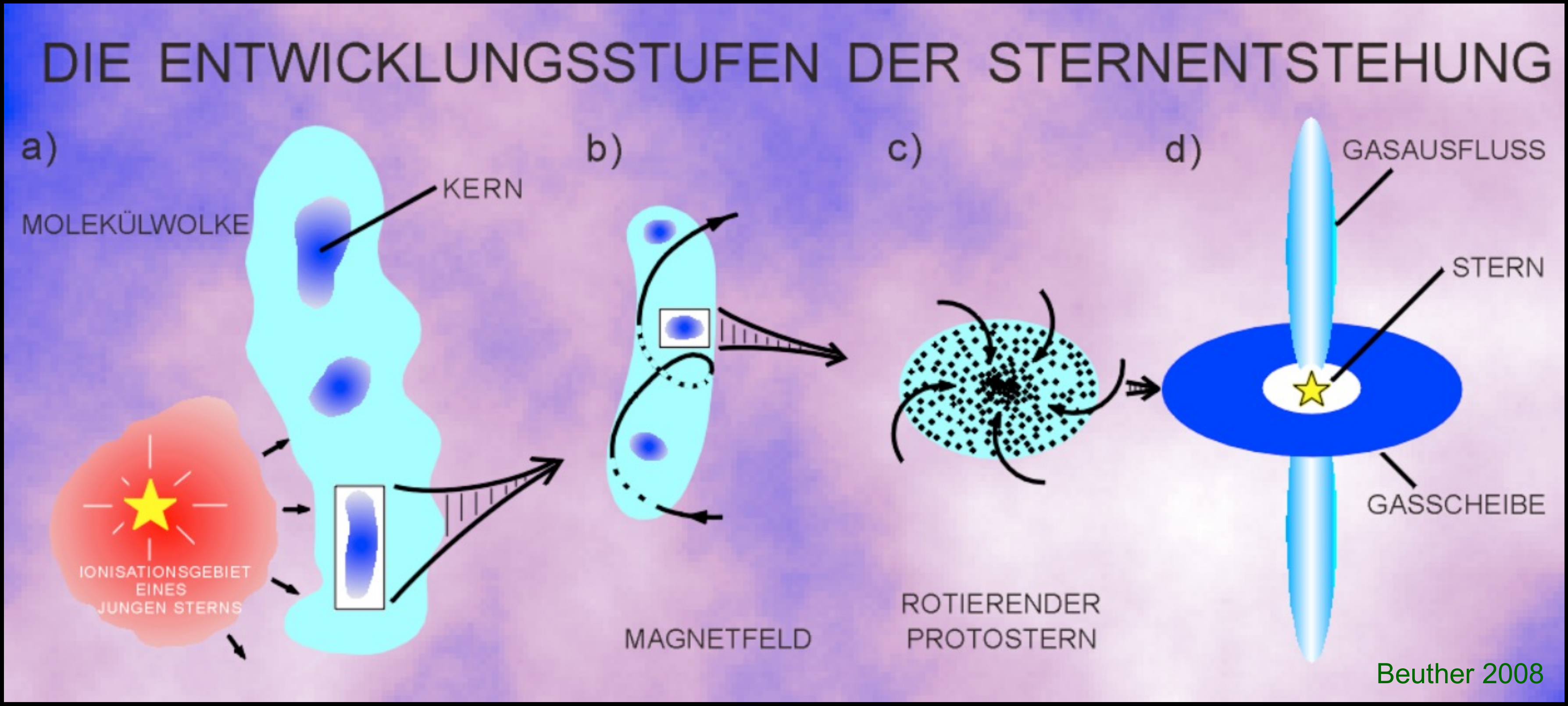
- Ionization fronts, bubbles?
- Protostellar jets/winds?
- Supernova explosions?
- MRI / shear?
- Gravitational infall?
- Galactic spiral shock?

Mac Low & Klessen (2004)

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

The Star Formation Paradigm

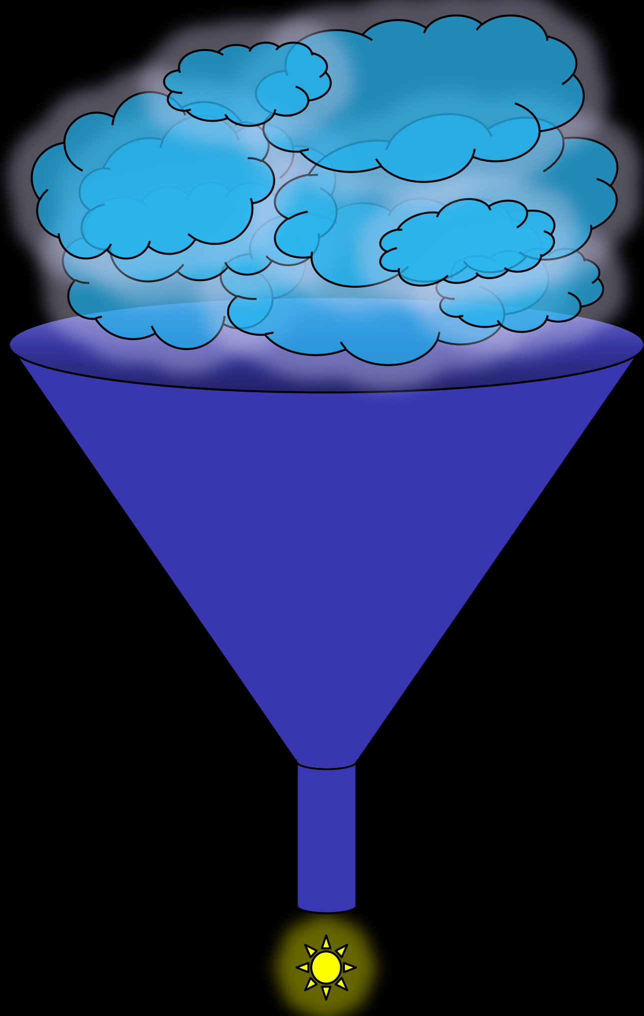
Clouds ➔ Cores ➔ Disk + Star + Jet / Outflow



Star Formation is Inefficient

Gravity

Magnetic Fields



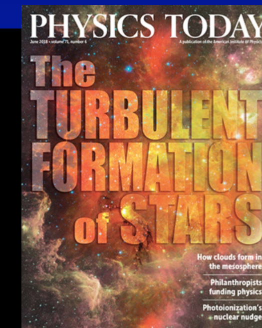
Turbulence

Feedback

Star Formation is Inefficient

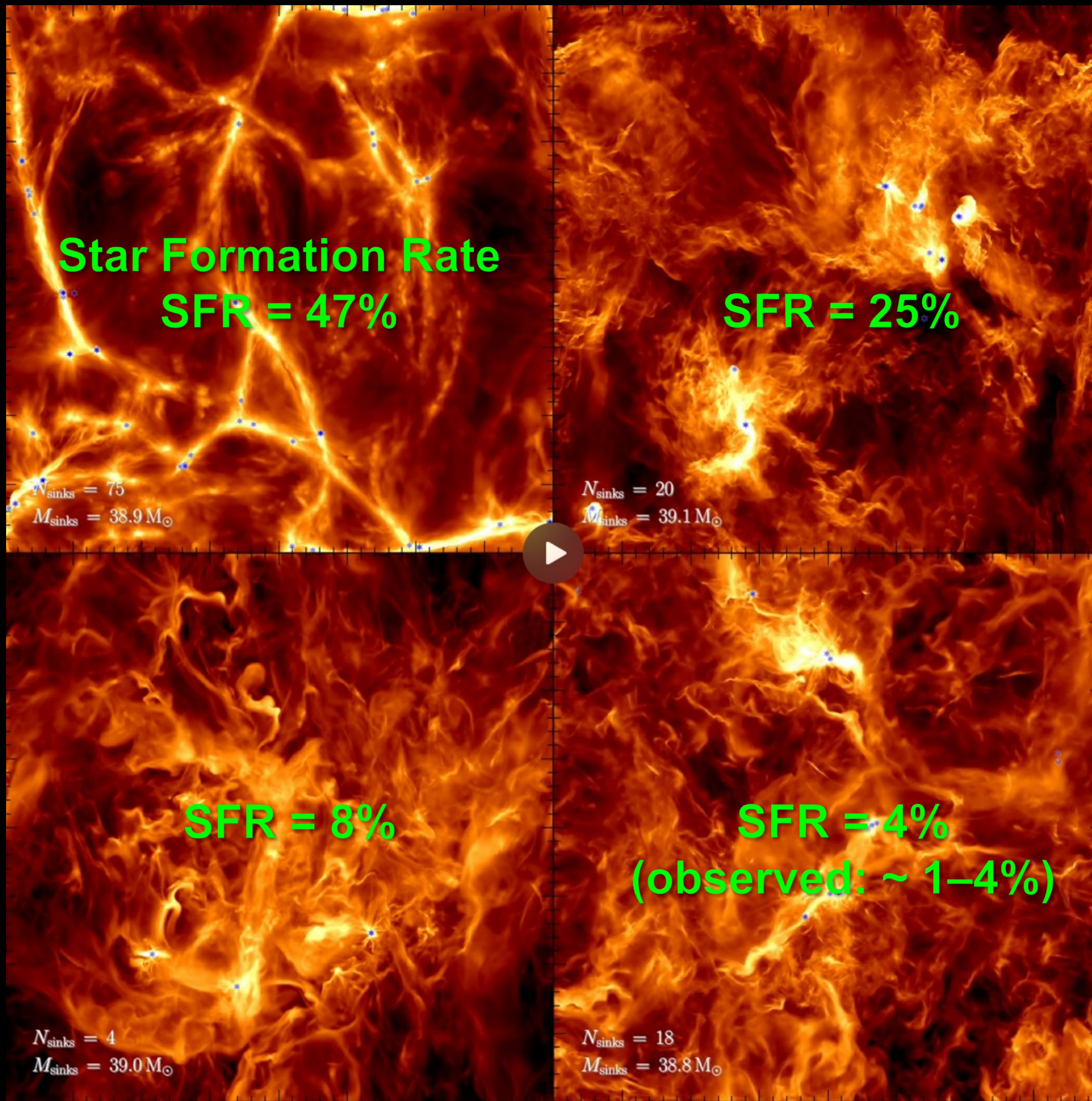
(Federrath 2015 MNRAS; 2018 *Physics Today*)

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



Gravity only

with Turbulence

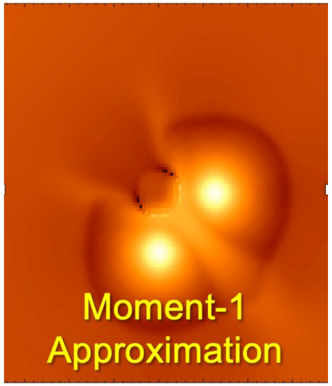


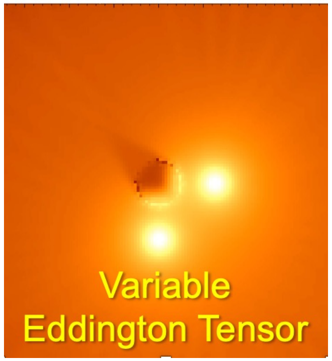
Turb+ Magnetic Fields

Turb+ Mag+ Jet/Outflow Feedback

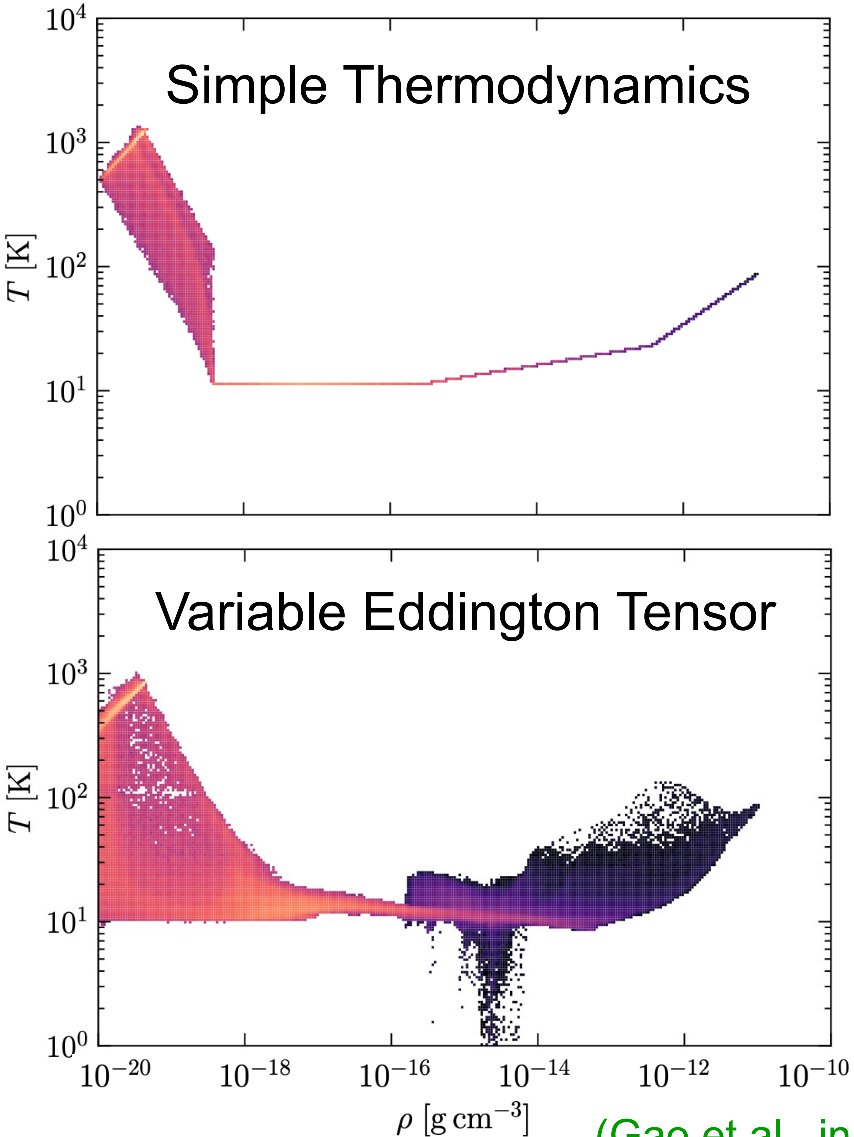
(sims for Appel et al. 2023)

Modelling Radiation





(Menon et al. 2022)



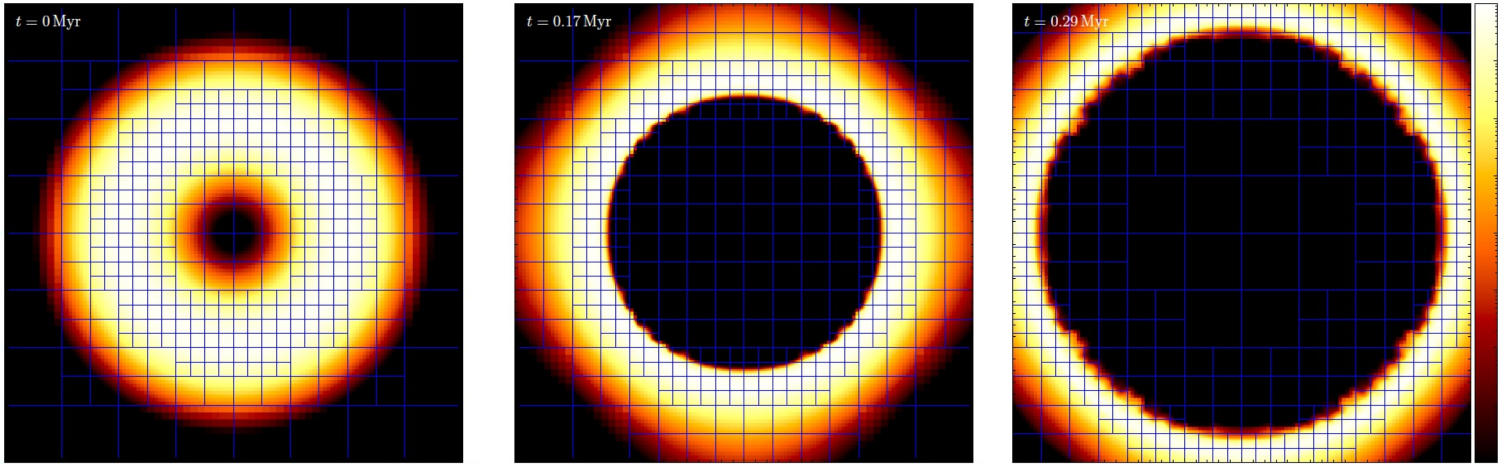
(Gao et al., in prep.)

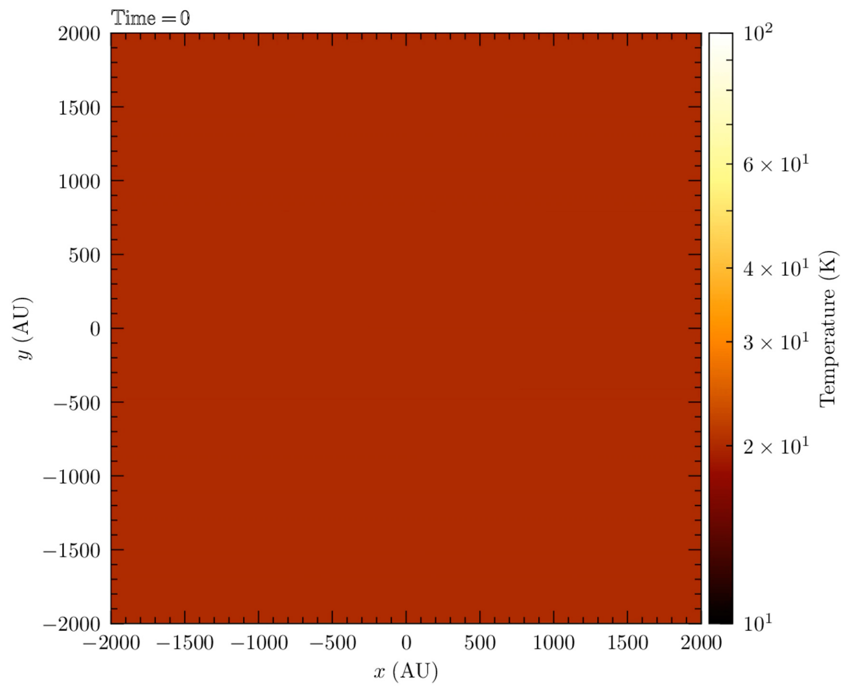
Movies available: **https://www.mso.anu.edu.au/~chfeder/pubs/vettam/vettam.html**

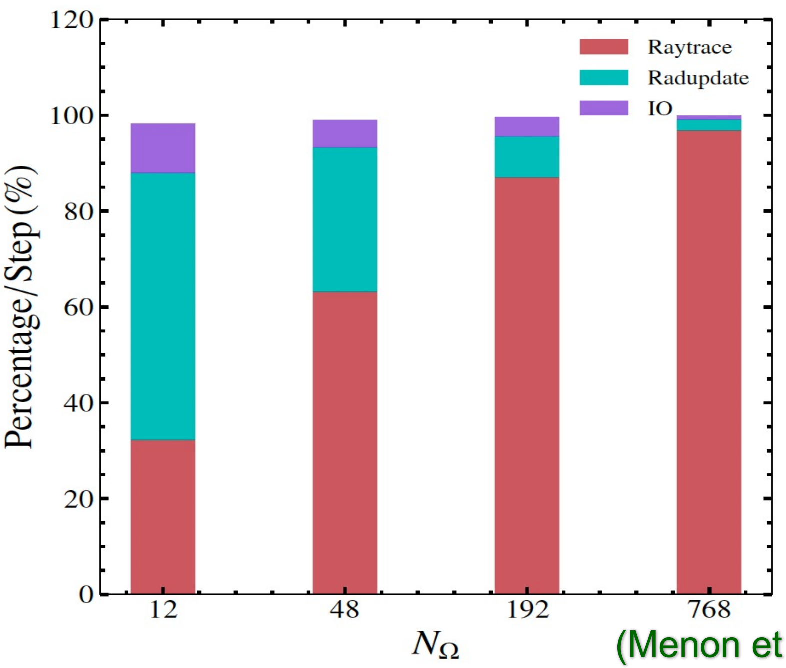
New AMR Variable Eddington Tensor (VET) method

VET with hydrid-characteristics ray-tracing on AMR

Several tests passed, including radiation pulse streaming and diffusion, Marshak wave, radiation shocks, and shadow tests





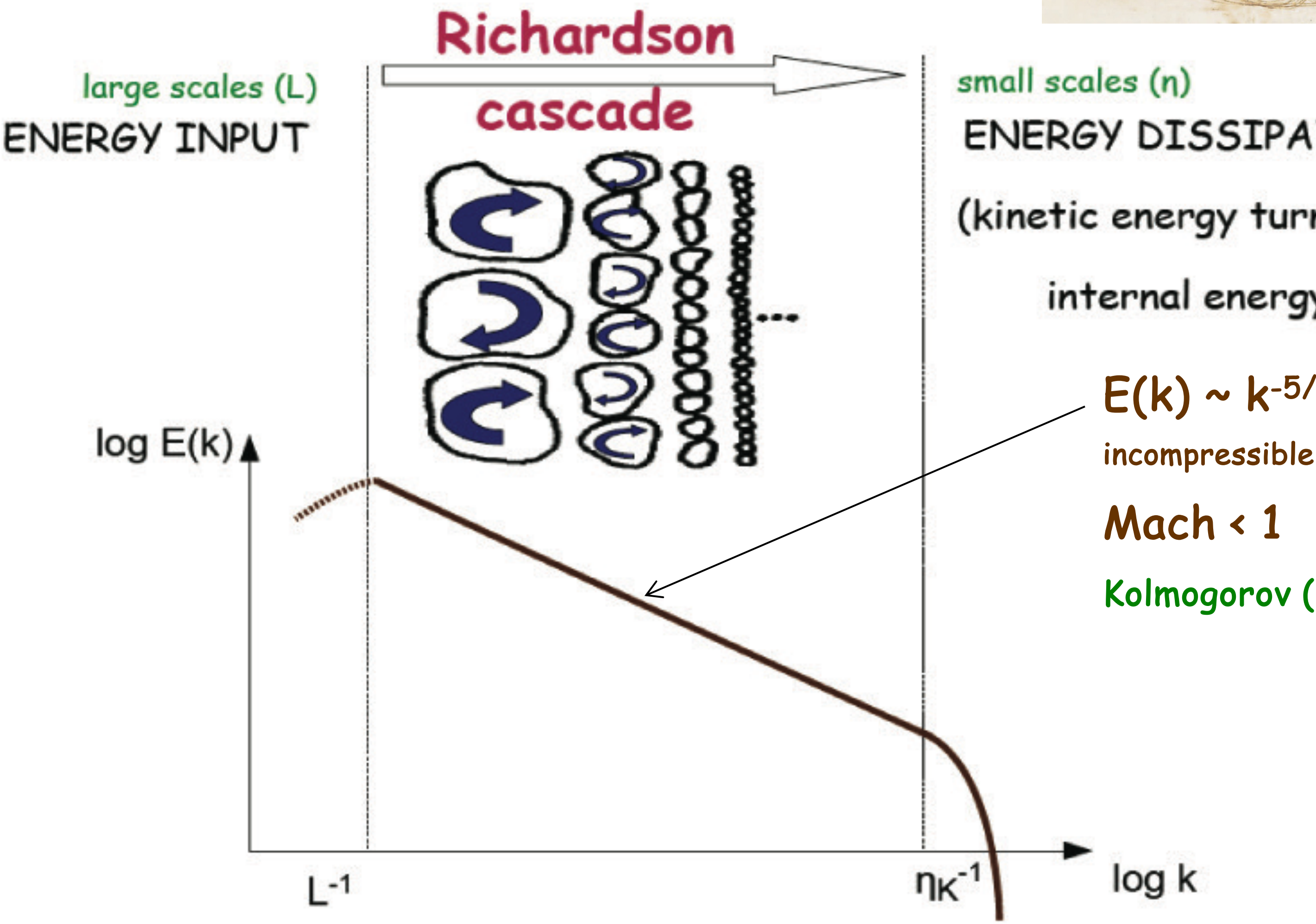


(Menon et al. 2022)

Turbulence

- Reynolds numbers > 1000
- Kinetic energy cascade

Leonardo da Vinci



$V \sim L^{1/3}$

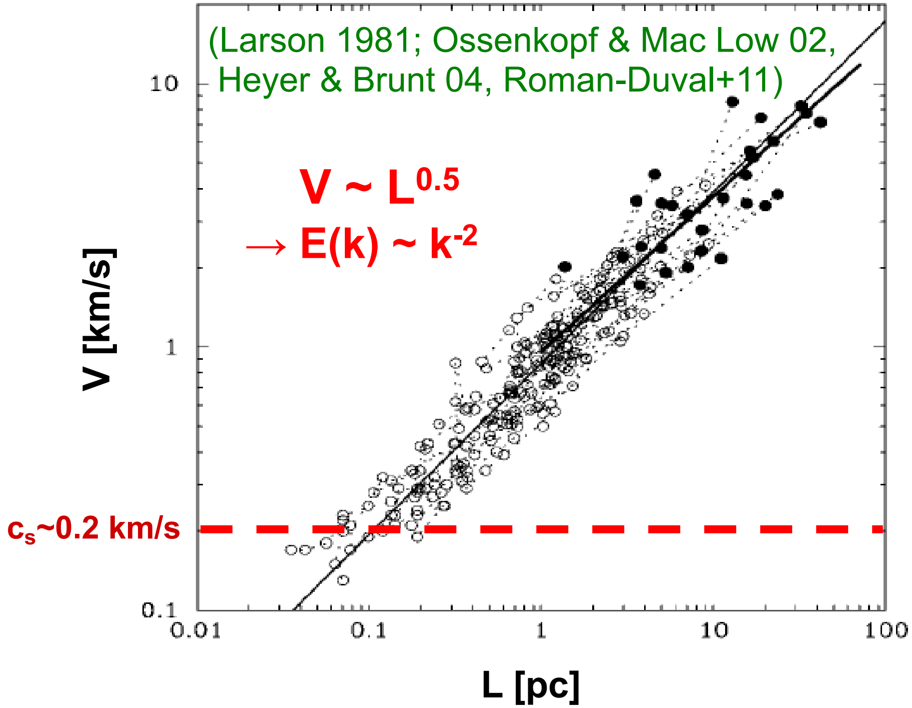
Kolmogorov (1941)

Interstellar Turbulence – scaling

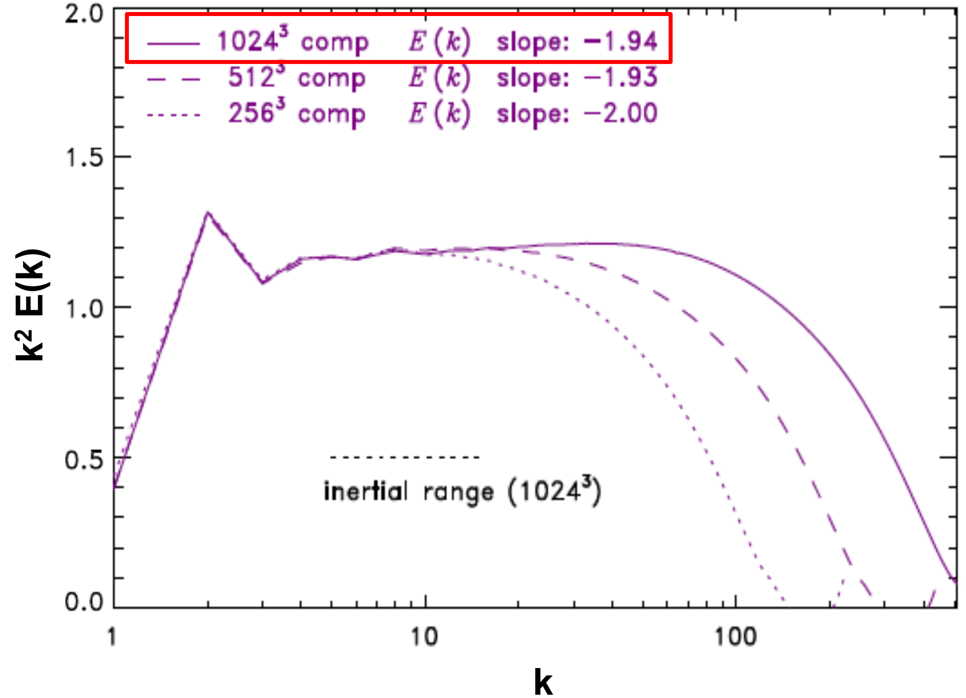
BUT: **Larson (1981) relation:** $E(k) \sim k^{-1.8\text{–}2.0}$

(see also Heyer & Brunt 2004; Ossenkopf & Mac Low 2002; Roman-Duval et al. 2011)

Observation



Simulation

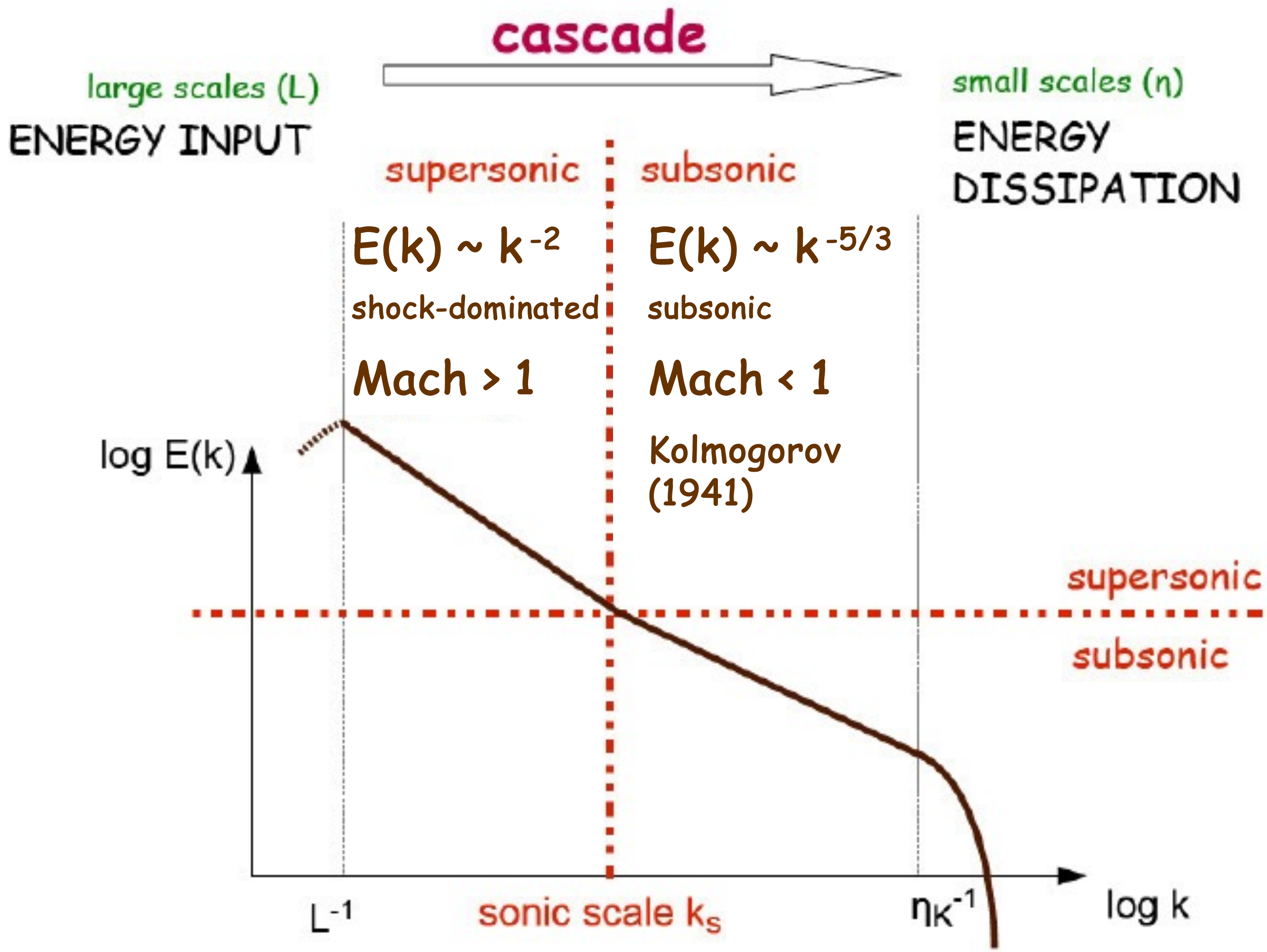


Supersonic, compressible turbulence has steeper $E(k) \sim k^{-1.9}$ than Kolmogorov ($E \sim k^{-5/3}$)

Federrath et al. (2010); see also Kritsuk et al. (2007)

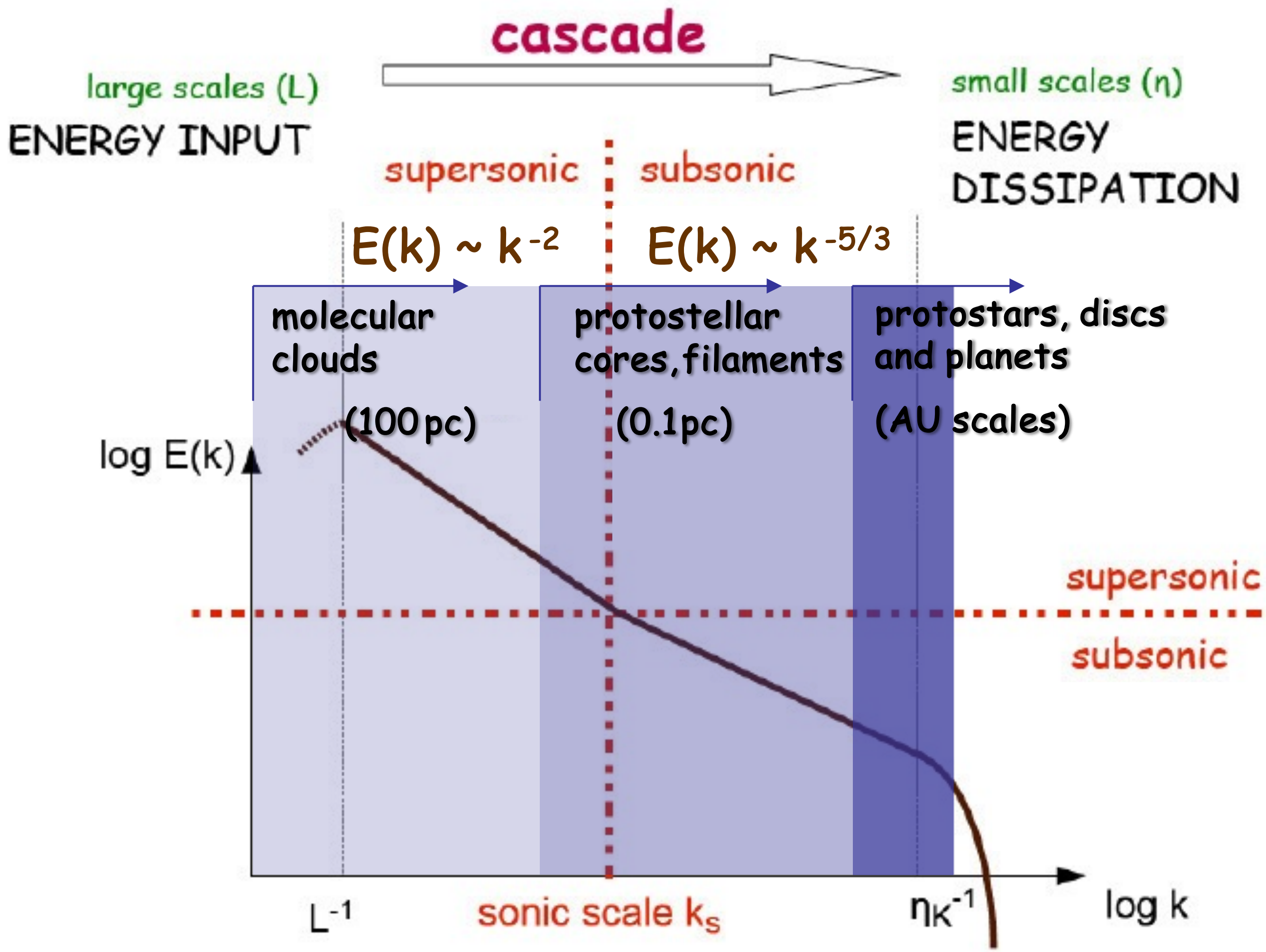
Interstellar Turbulence

- Reynolds numbers > 1000
- Kinetic energy cascade



Interstellar Turbulence

- Reynolds numbers > 1000
- Kinetic energy cascade



The sonic scale of interstellar turbulence

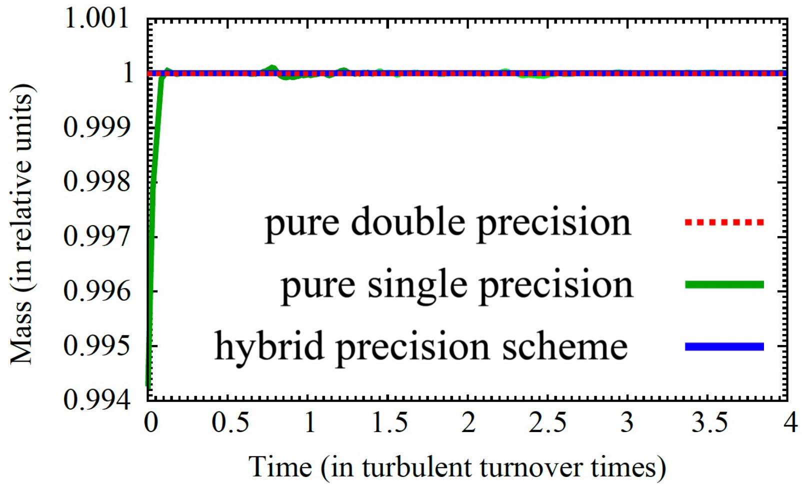
Movies and more info on the $(10k)^3$ simulation:
http://www.mso.anu.edu.au/~chfeder/pubs/sonic_scale/sonic_scale.html

Technical specifications:

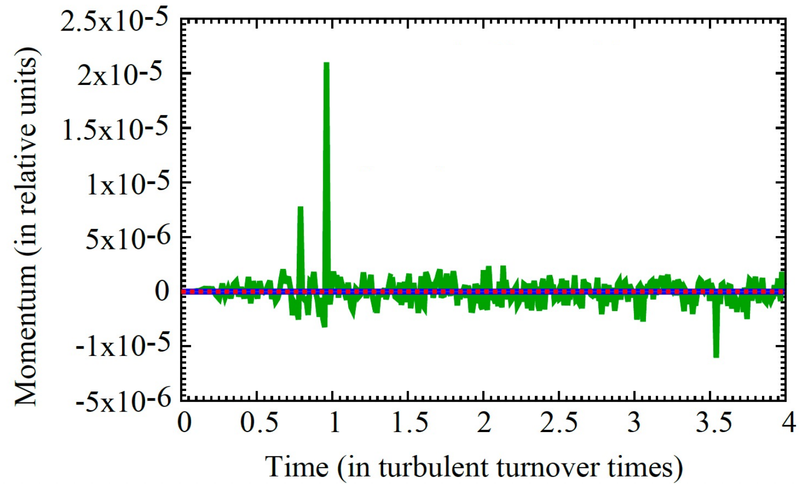
- Resolution: **$10{,}048^3$** grid cells
- 50 Million CPU-h (GCS and NCI)
- 65,536 compute cores
- 2 PB data
- Hybrid precision (SP + specific promotion to DP)

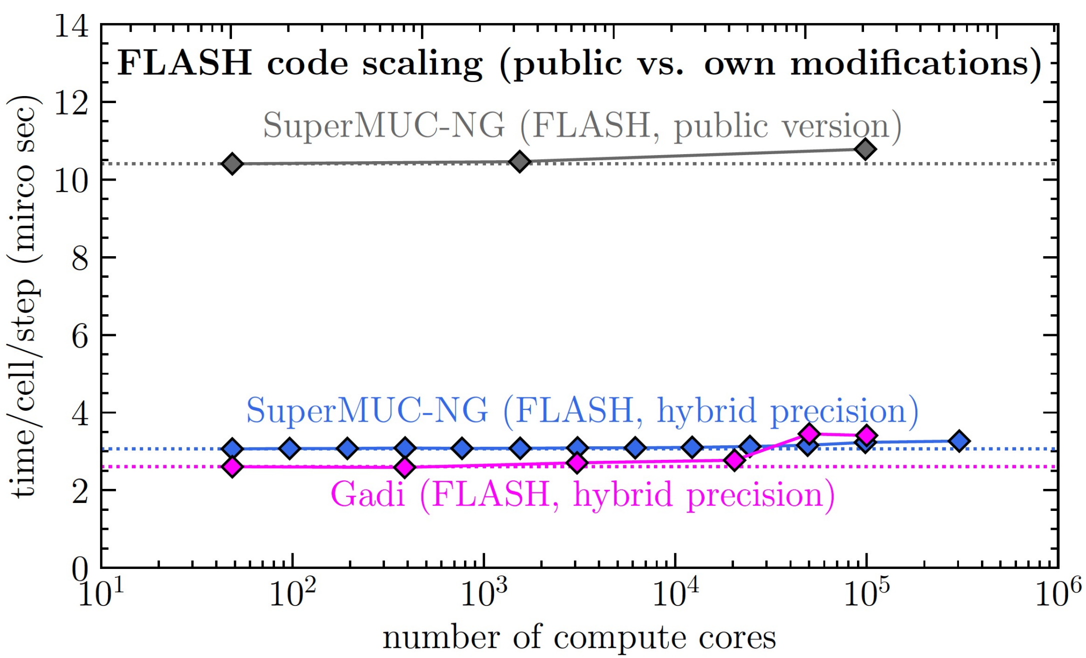
Hybrid precision and code scaling

Mass conservation



Momentum conservation



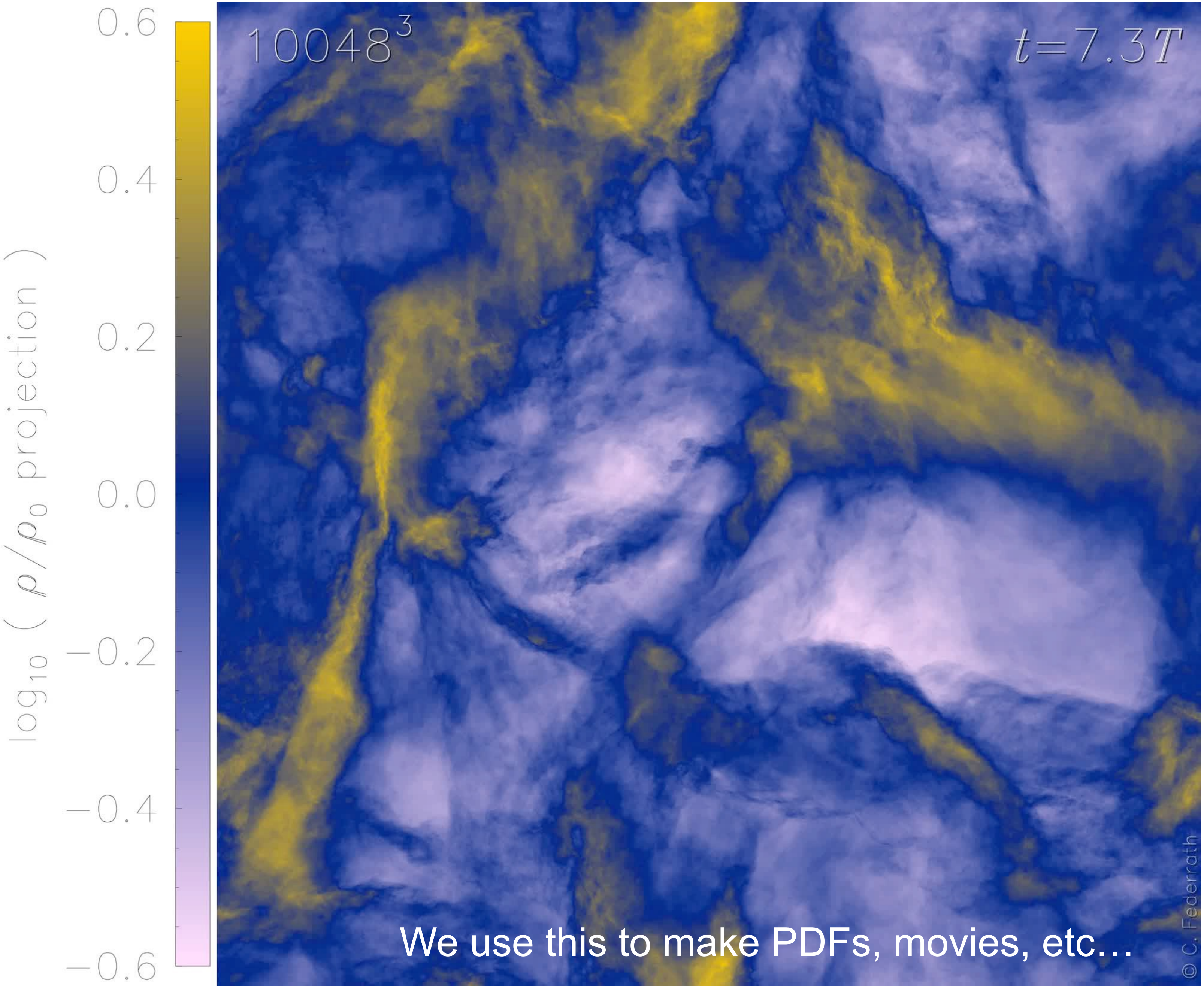


Overall changes to FLASH for this setup resulted in

- factor 3.6 higher speed
- factor 4.1 less memory

(Federrath et al. 2021, *Nature Astronomy*)

Modelling turbulence at extreme resolution (10k^3)



Turbulence is key for Star Formation

(Federrath & Klessen 2012; Federrath et al. 2017)

Turbulence → Stars → Feedback

Magnetic Fields

Dynamics
(shear)

Turbulence driven by

- Shear
- Jets / Outflows
- Cloud-cloud collisions
- Winds / Ionization fronts
- Spiral-arm compression
- Supernova explosions
- Gravity / Accretion

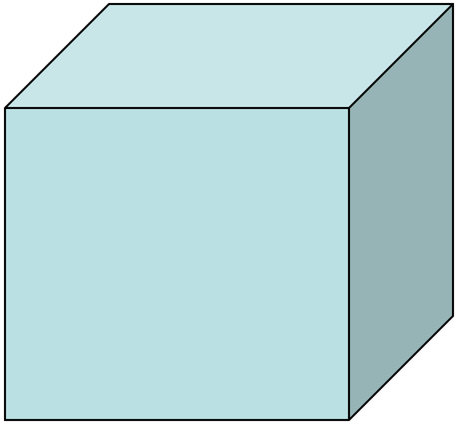
Solenoidal ↓ Compressive

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

Turbulence driving – solenoidal versus compressive

"Turbulence in a box"

- 3D, periodic boundaries
- Driven to supersonic speeds (Mach 2 - 50)
- Large-scale **Forcing Term f**

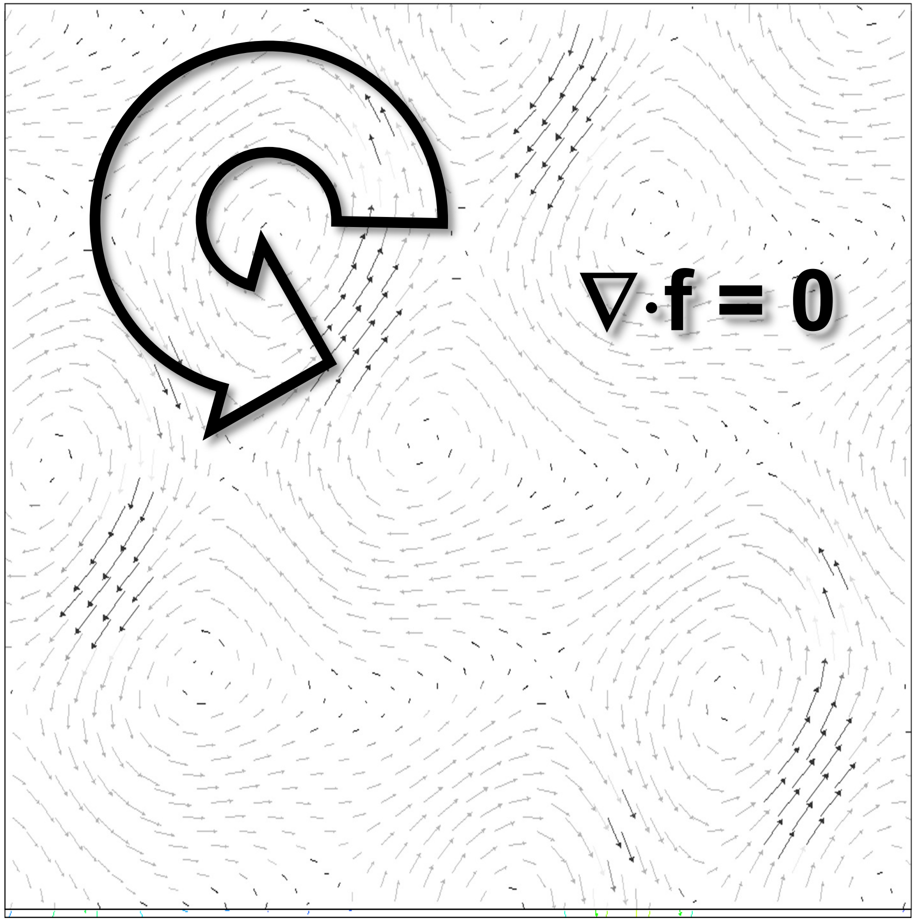


e.g., Vazquez 1994, Padoan+1997, Passot+1998, Stone+1998, Mac Low 1999, Klessen+2000, Ostriker+2001, Heitsch+2001, Cho+2002, Boldyrev+2002, Li+2003, Haugen+2004, Padoan+2004, Jappsen+2005, Ballesteros+2006, Mee+Brandenburg 2006, Kritsuk+2007, Kowal+2007, Dib+2008, Offner+2008, Schmidt+2009, Burkhart+2009, Cho+2009, Lemaster+2009, Glover+2010, Price+2011, DelSordo+2011, Collins+2012, Walch+2012, Scannapieco+2012, Pan+2012, Micic+2012, Robertson+2012, Price+2012, Bauer+2012 +++

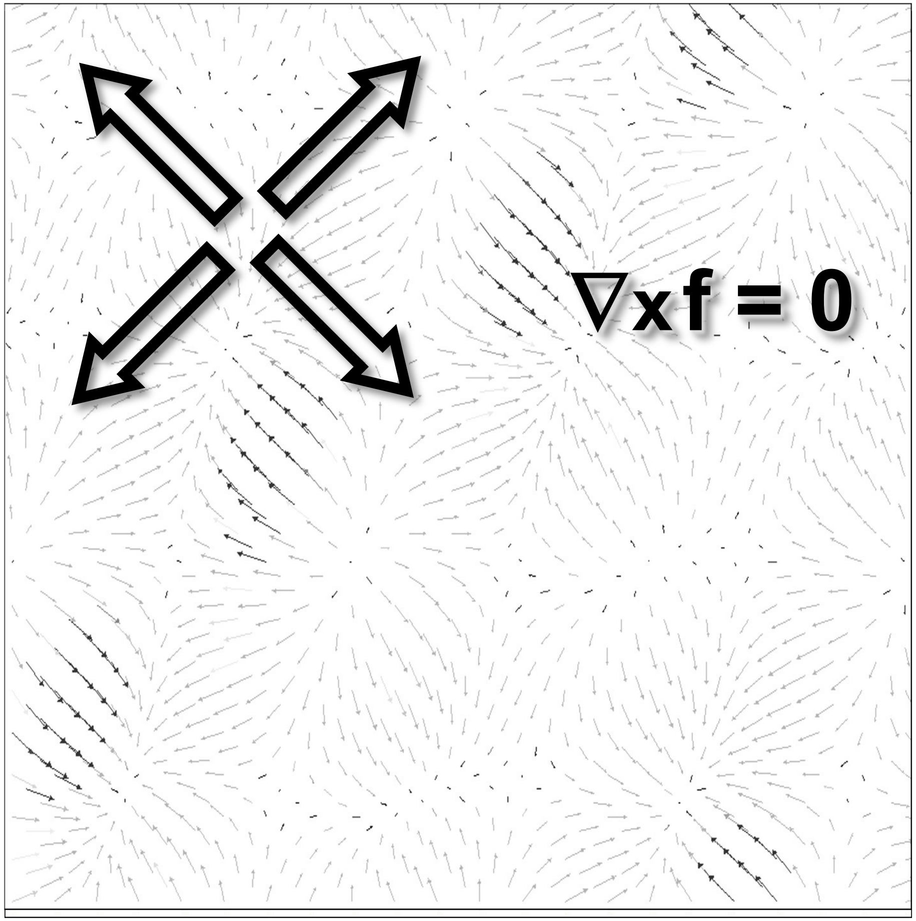
Turbulence forcing – solenoidal versus compressive

Ornstein-Uhlenbeck process (stochastic process with autocorrelation time)
→ **forcing varies smoothly in space and time,**
following a well-defined random process

Solenoidal forcing



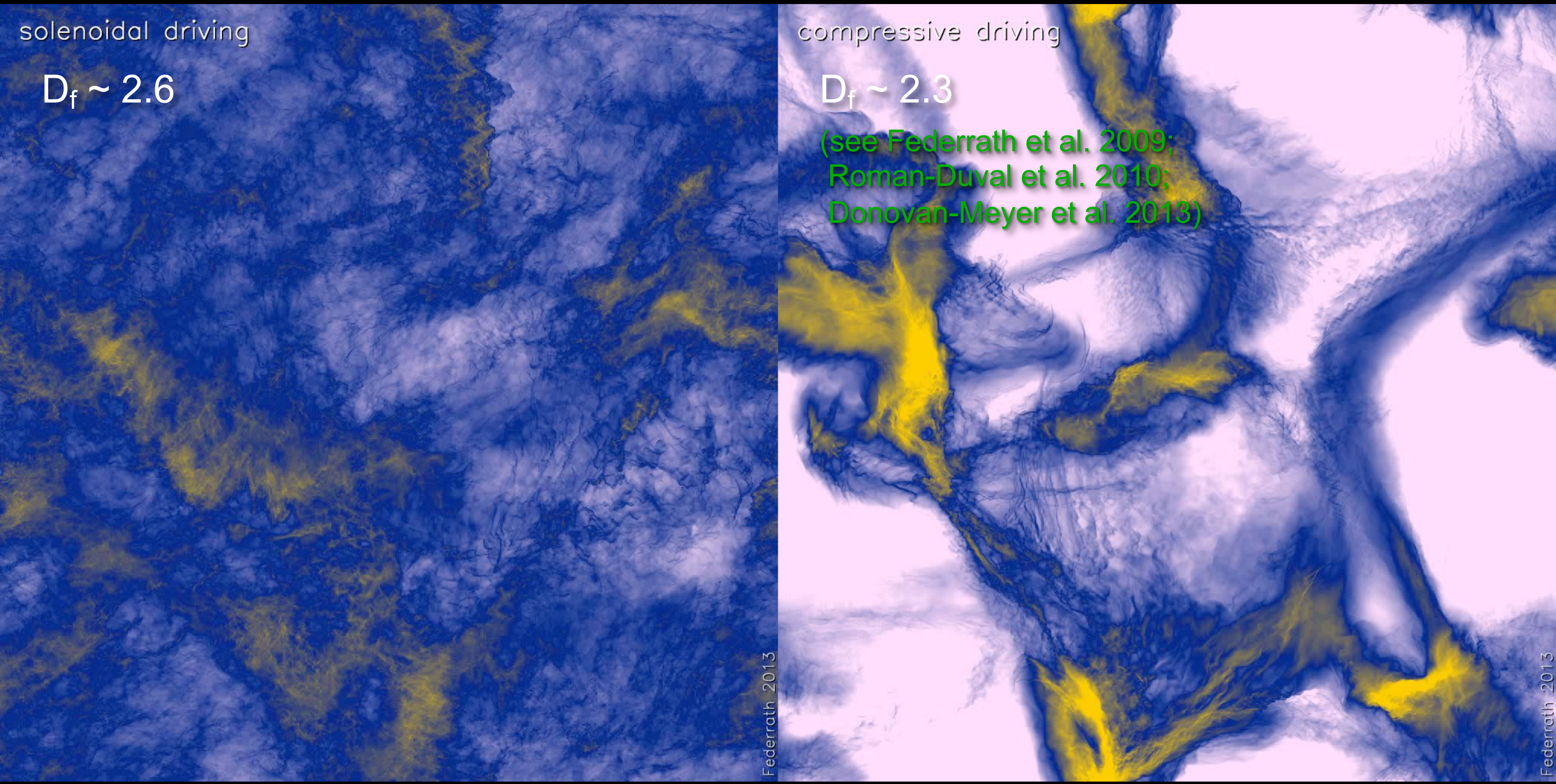
Compressive forcing



Turbulence driving – solenoidal versus compressive

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

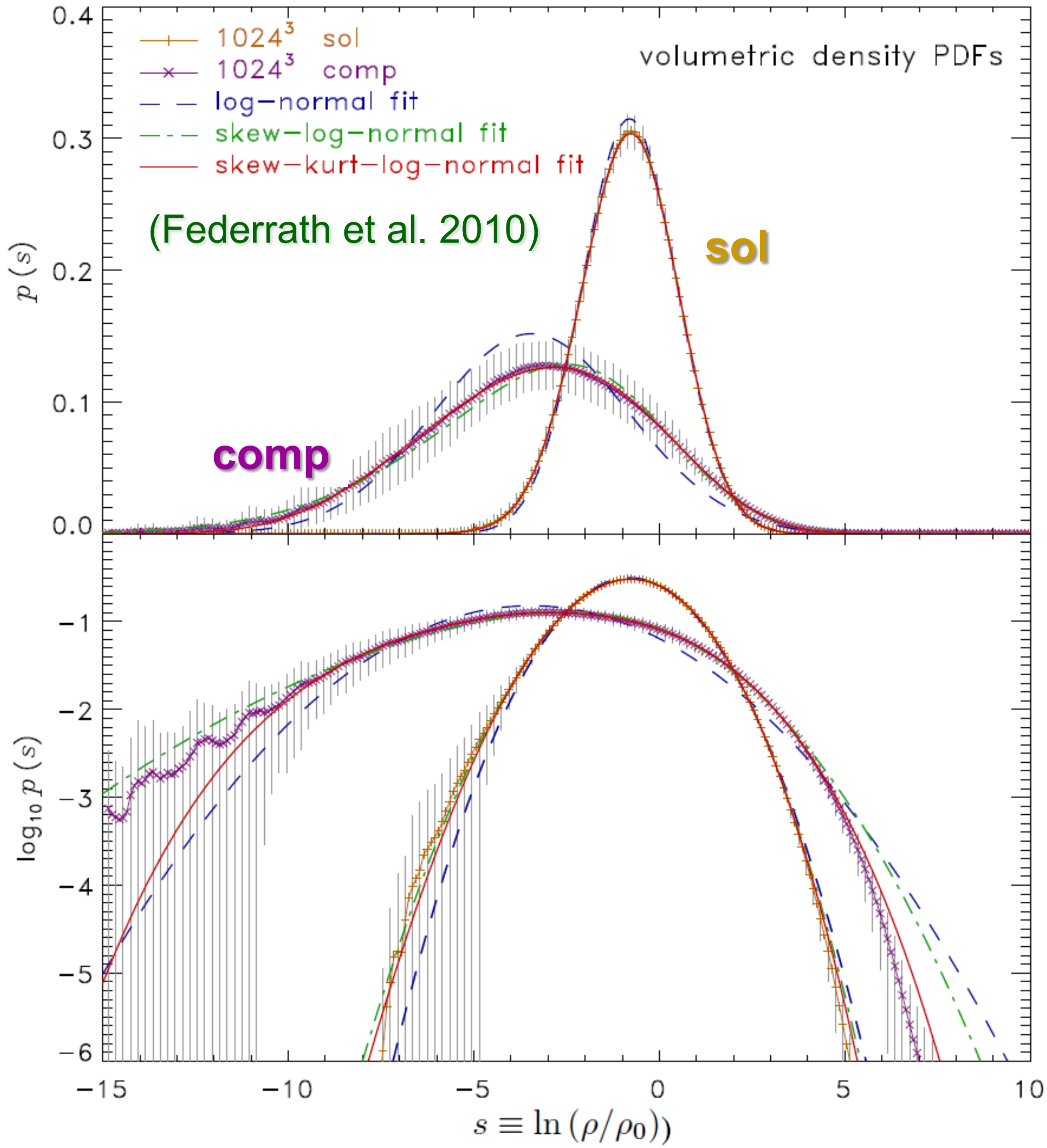
solenoidal forcing | compressive forcing



Compressive driving produces much stronger density enhancements

(Federrath 2013, MNRAS 436, 1245: Supersonic turbulence @ 4096^3 grid cells)

The density PDF



Density PDF

log-normal:

$$p_s \, \mathrm{d}s = \frac{1}{\sqrt{2\pi\sigma_s^2}} \exp\left[-\frac{(s - \langle s \rangle)^2}{2\sigma_s^2}\right] \mathrm{d}s$$

$$s \equiv \ln(\rho/\rho_0)$$

Vazquez-Semadeni (1994); Padoan et al. (1997); Ostriker et al. (2001); Hopkins (2013)

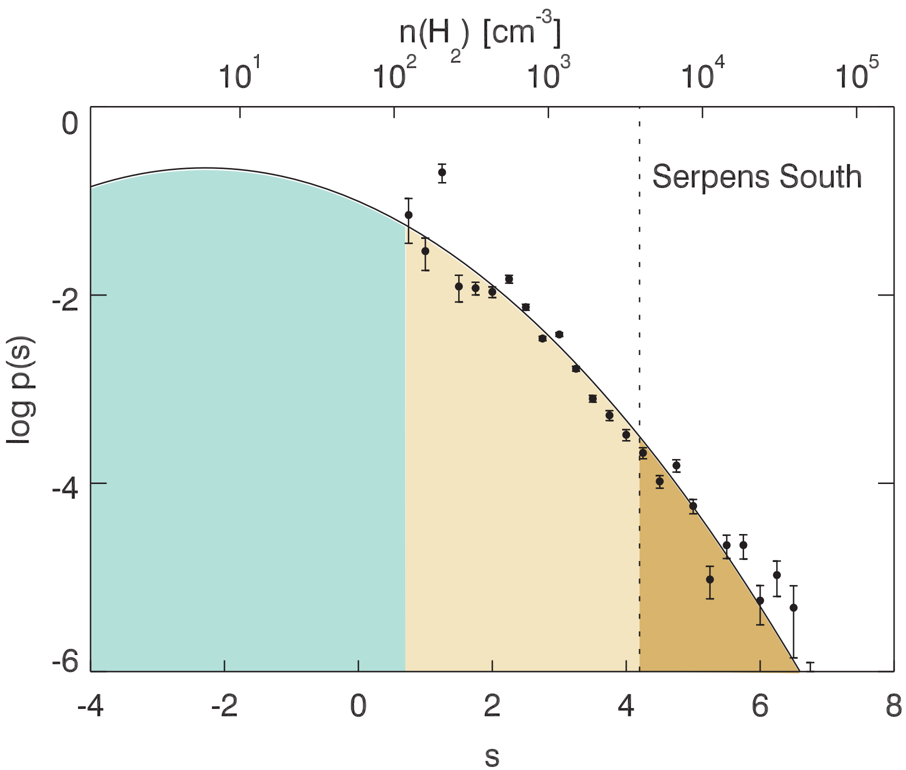
$$\sigma_s^2 = \ln\left(1 + b^2 \mathcal{M}^2\right)$$

⇒ b = 1/3 (sol)
b = 1 (comp)

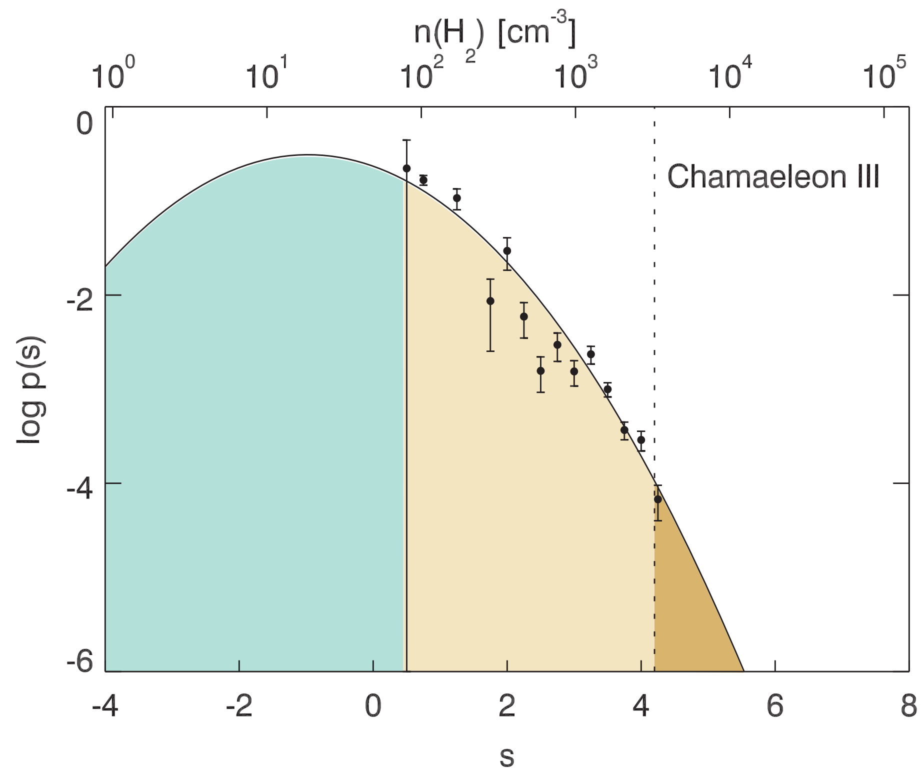
Federrath et al. (2008, 2010);
Price et al. (2011); Konstandin et al. (2012);
Molina et al. (2012); Federrath & Banerjee (2015); Nolan et al. (2015)

PDF → The dense gas fraction

Active star formation



No star formation



Kainulainen, Federrath, Henning (2014, *Science* 344, 183)

Power-law tails →
gravitational collapse

Schneider et al. 2012–2015; Federrath & Klessen 2013;
Girichidis et al. 2014; Sadavoy et al. 2014; Myers 2015; Cunningham et al., in prep.

2D → 3D
conversion

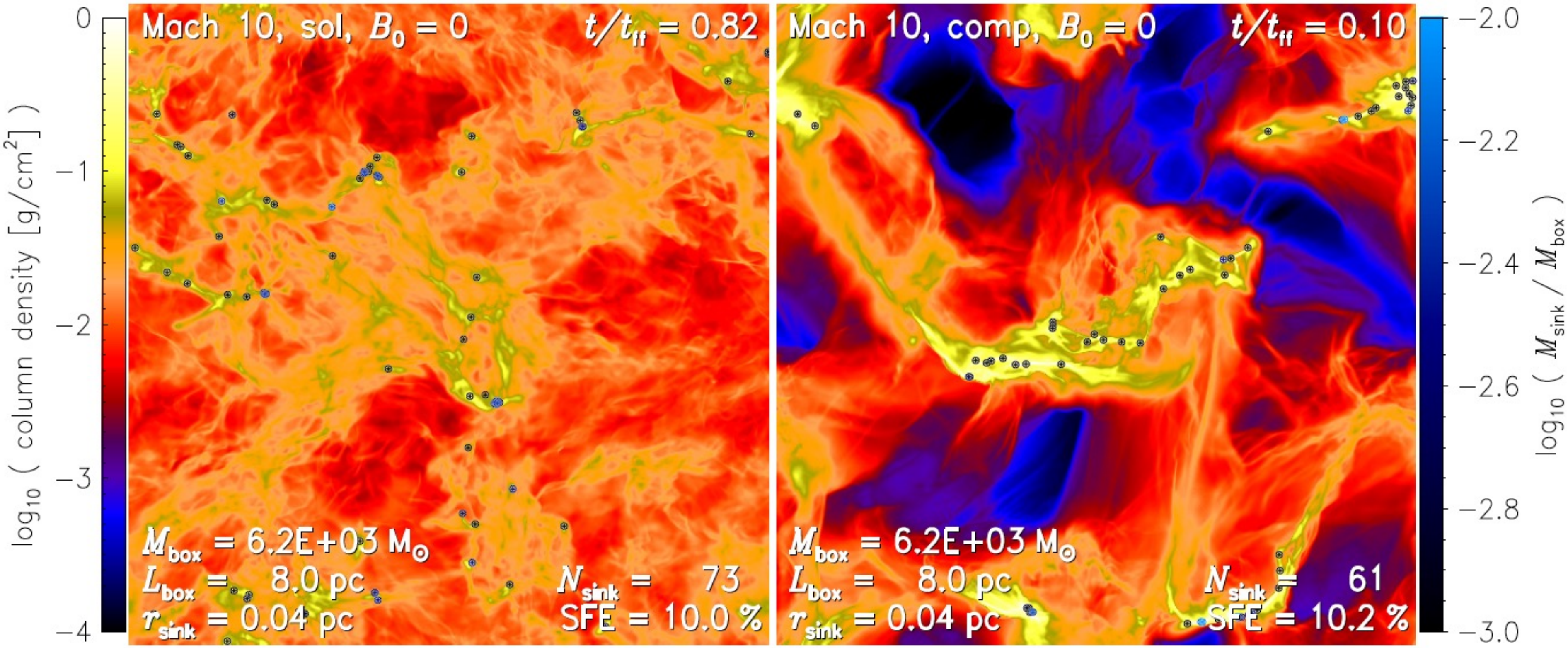
(Brunt et al. 2010a,b)

Density Distribution → Star Formation Rate

Numerical experiment for Mach 10

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

Solenoidal Driving (b=1/3) | Compressive Driving (b=1)



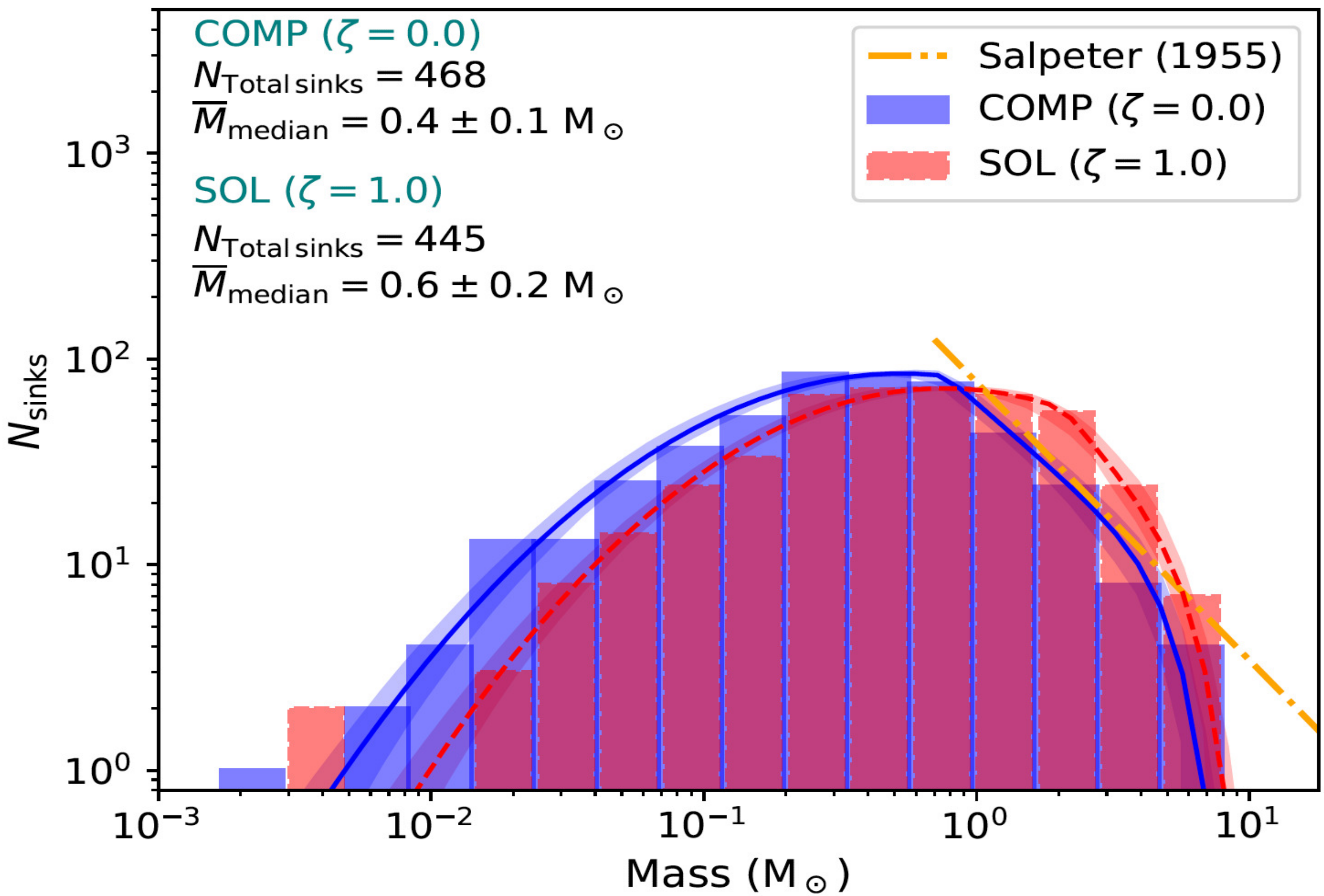
SFR_{ff} (simulation) = **0.14** x20 SFR_{ff} (simulation) = **2.8**

SFR_{ff} (theory) = **0.15** x15 SFR_{ff} (theory) = **2.3**

Turbulence driving is a key parameter for star formation!

Federrath & Klessen (2012)

Role of Turbulence Driving for Initial Mass Function



(Mathew et al. 2022)

The Star Formation Rate – Magnetic fields

Statistical Theory for the Star Formation Rate:

$$p(s) = \frac{1}{\sqrt{2\pi\sigma_s^2}} \exp\left(-\frac{(s-s_0)^2}{2\sigma_s^2}\right)$$

$$s = \ln(\rho/\rho_0) \qquad t_{\mathrm{ff}}(\rho) = \left(\frac{3\pi}{32G\rho}\right)^{1/2}$$

SFR ~ Mass/time

freefall time   **mass fraction**

$$\mathrm{SFR_{ff}} = \epsilon \int_{s_{\mathrm{crit}}}^{\infty} \frac{t_{\mathrm{ff}}(\rho_0)}{t_{\mathrm{ff}}(\rho)} \frac{\rho}{\rho_0} p(s)\,\mathrm{d}s = \epsilon \int_{s_{\mathrm{crit}}}^{\infty} \exp\left(\frac{3}{2}s\right) p(s)\,\mathrm{d}s$$

$$= \frac{\epsilon}{2} \exp\left(\frac{3}{8}\sigma_s^2\right)\left[1 + \mathrm{erf}\left(\frac{\sigma_s^2 - s_{\mathrm{crit}}}{\sqrt{2\sigma_s^2}}\right)\right]$$

MAGNETIC FIELD:

$$P_{\mathrm{th}} \rightarrow P_{\mathrm{th}} + P_{\mathrm{mag}} \qquad \mathcal{M} \rightarrow \mathcal{M}\left(1+\beta^{-1}\right)^{-1/2}$$

$$s_{\mathrm{crit}} \propto \ln\left(\alpha_{\mathrm{vir}}\,\mathcal{M}^2 \frac{\beta}{\beta+1}\right)$$

$$\sigma_s^2 = \ln\left(1 + b^2 \mathcal{M}^2 \frac{\beta}{\beta+1}\right)$$

$$\mathrm{SFR_{ff}} = \mathrm{SFR_{ff}}\left(\alpha_{\mathrm{vir}}, b, \mathcal{M}, \beta\right)$$

(Padoan & Nordlund 2011; Molina et al. 2012)

$2E_{\mathrm{kin}}/E_{\mathrm{grav}}$ **forcing**   **Mach number**   **plasma $\beta = P_{\mathrm{th}}/P_{\mathrm{mag}}$**

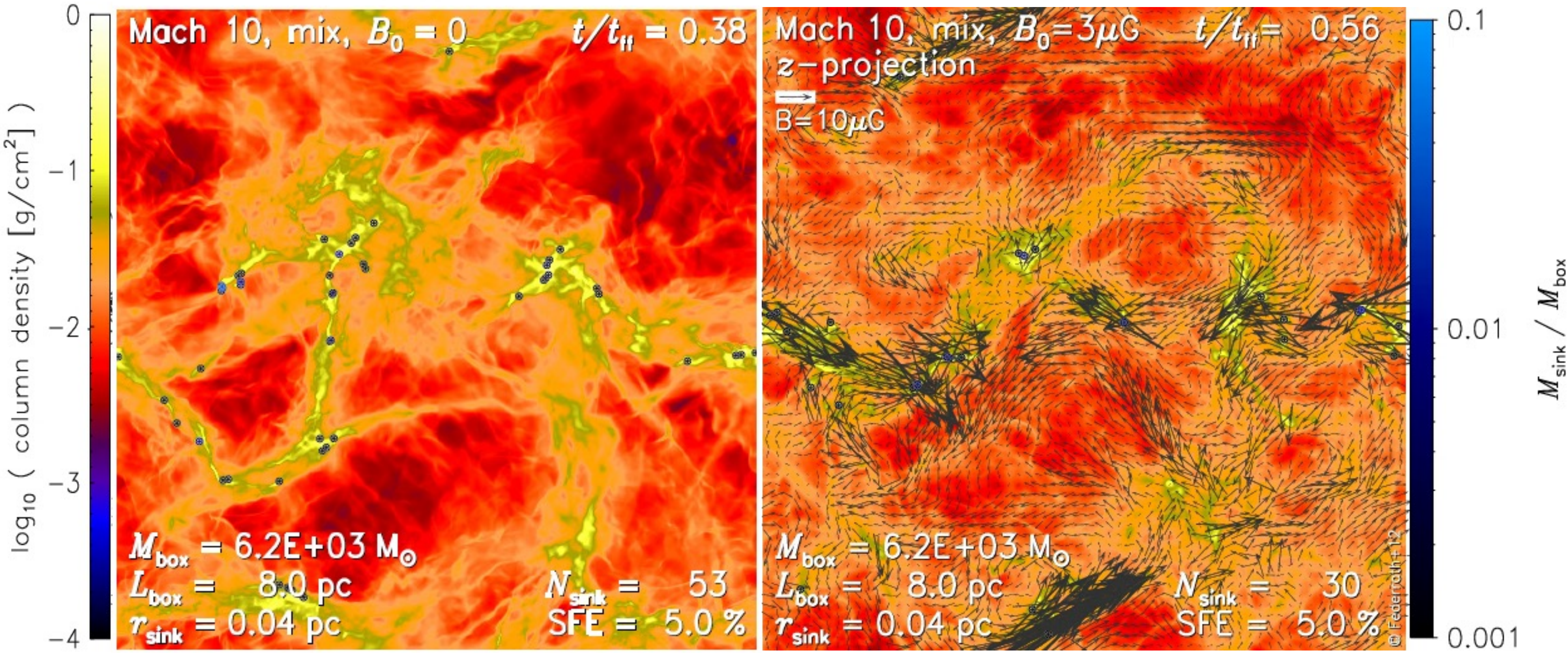
Federrath & Klessen (2012)

The Star Formation Rate – Magnetic fields

Numerical experiment for Mach 10 and $\alpha_{vir} \sim 1$

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

B=0 (M_A=∞, β = ∞) B=3μG (M_A=2.7, β = 0.2)

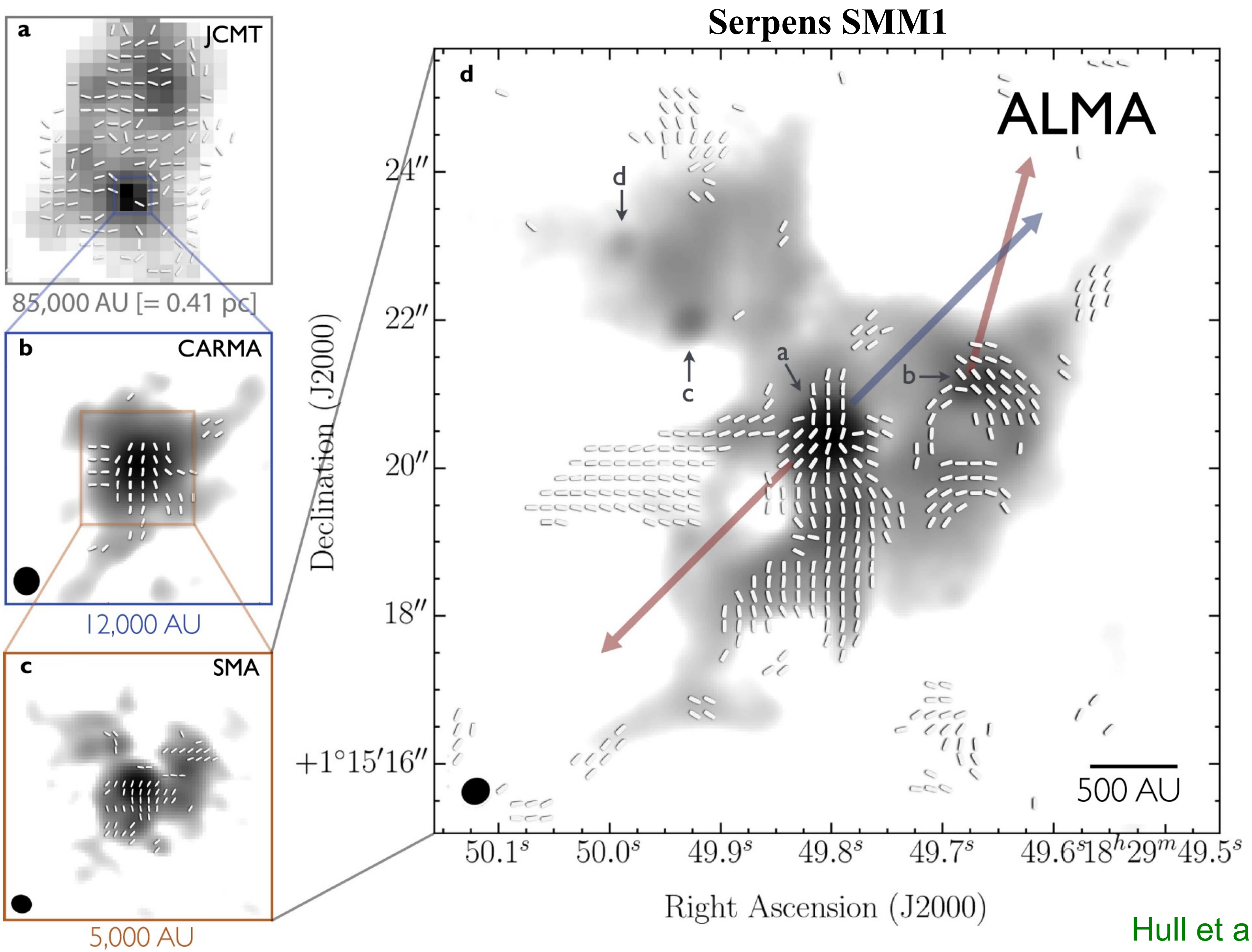


SFR_{ff} (simulation) = **0.46**	x**0.63**	SFR_{ff} (simulation) = **0.29**
SFR_{ff} (theory) = **0.45**	x**0.40**	SFR_{ff} (theory) = **0.18**

Magnetic field reduces SFR and fragmentation (by factor 2) → **IMF**

Federrath & Klessen (2012)

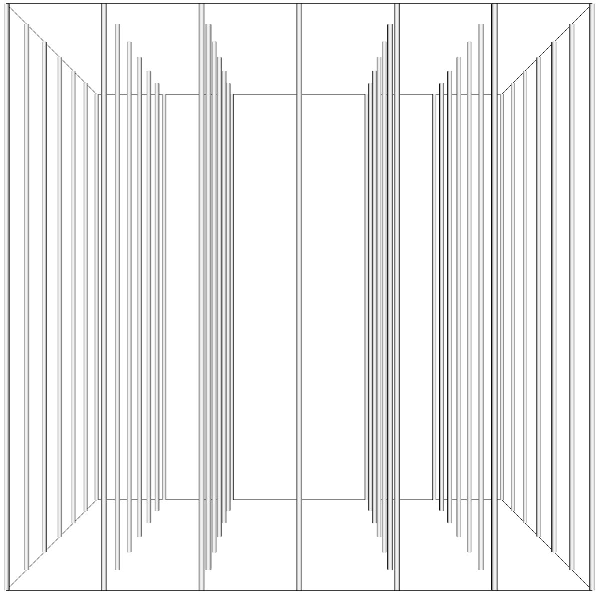
The role of magnetic field structure



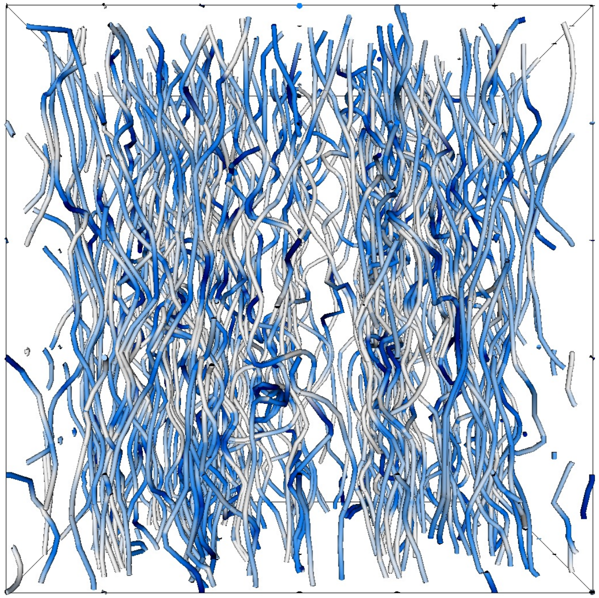
Hull et al. (2017)

The role of magnetic field structure for jet launching

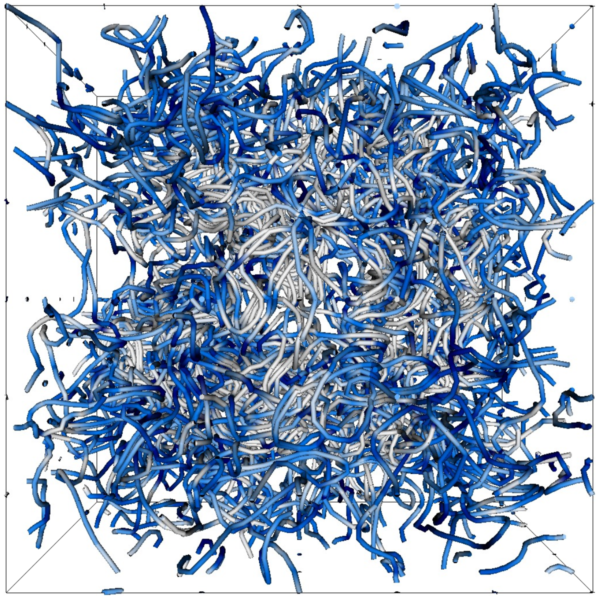
Uniform Magnetic Field



Partially Turbulent Field



Fully Turbulent Field

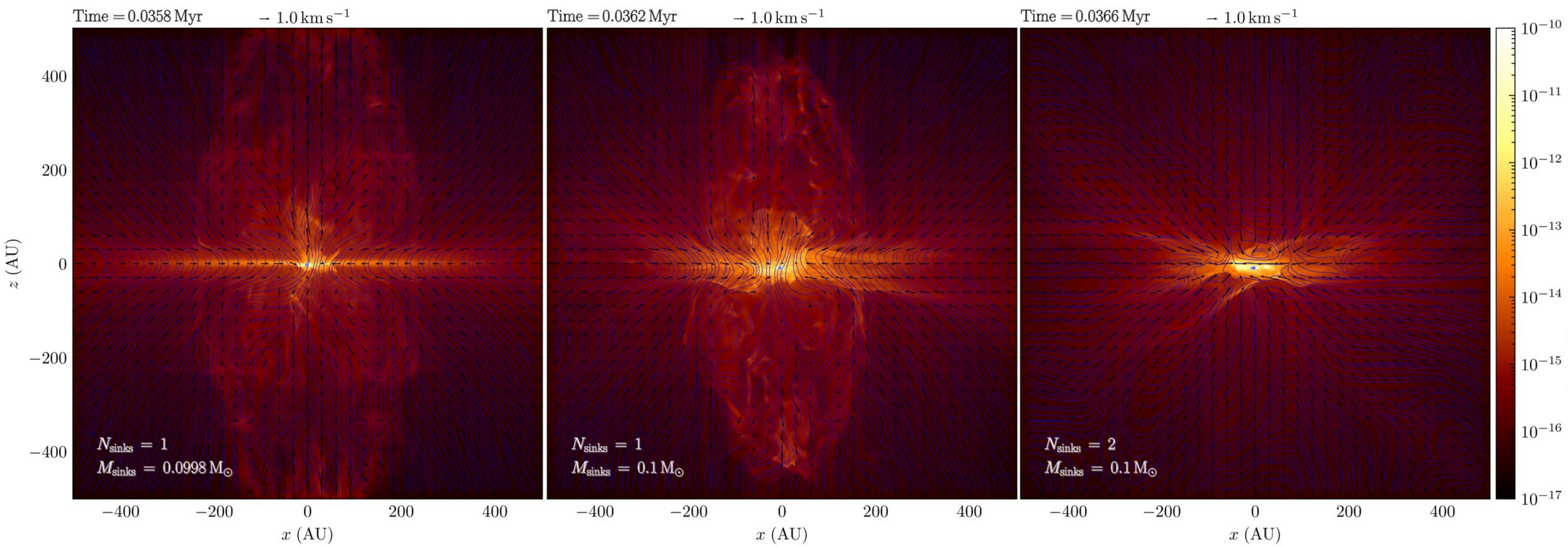


Gerrard et al. (2019)

The role of magnetic field structure for jet launching

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

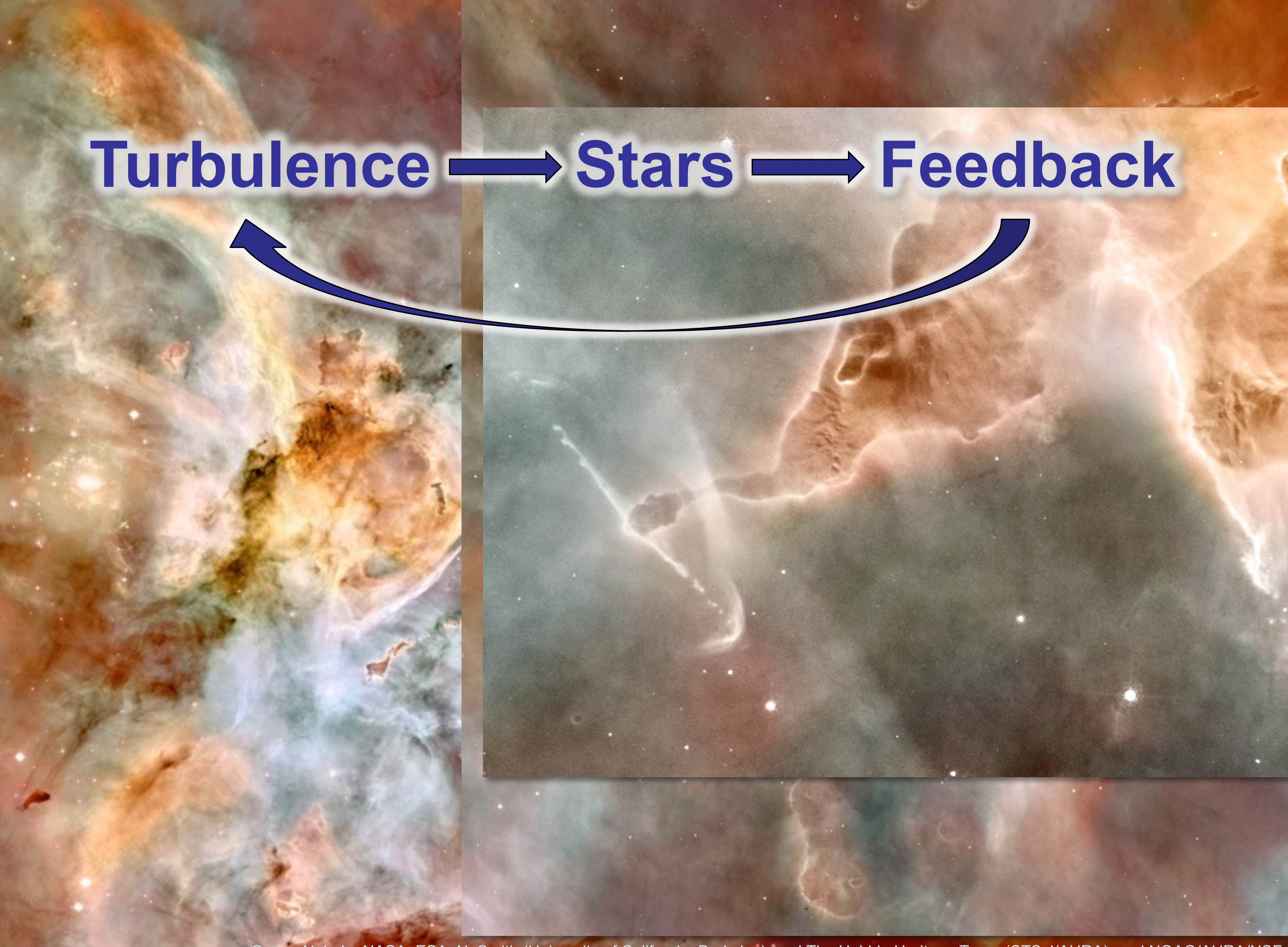
Uniform Magnetic Field | Partially Turbulent Field | Fully Turbulent Field



Gerrard et al. (2019)

→ Need ordered magnetic field component for jet launching

(Blandford & Payne 1982)

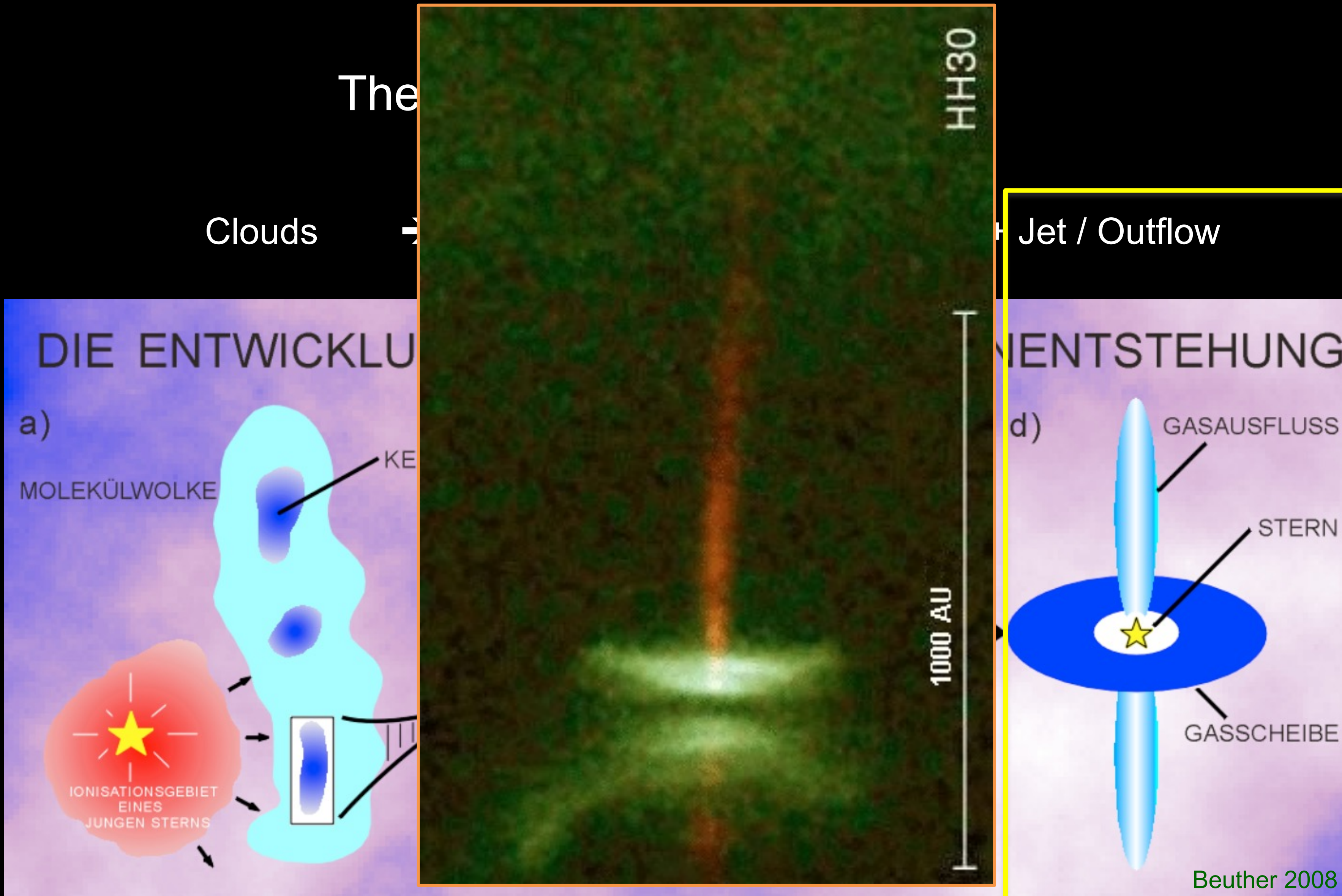


Carina Nebula, NASA, ESA, N. Smith (University of California, Berkeley), and The Hubble Heritage Team (STScI/AURA), and NOAO/AURA/NSF

The

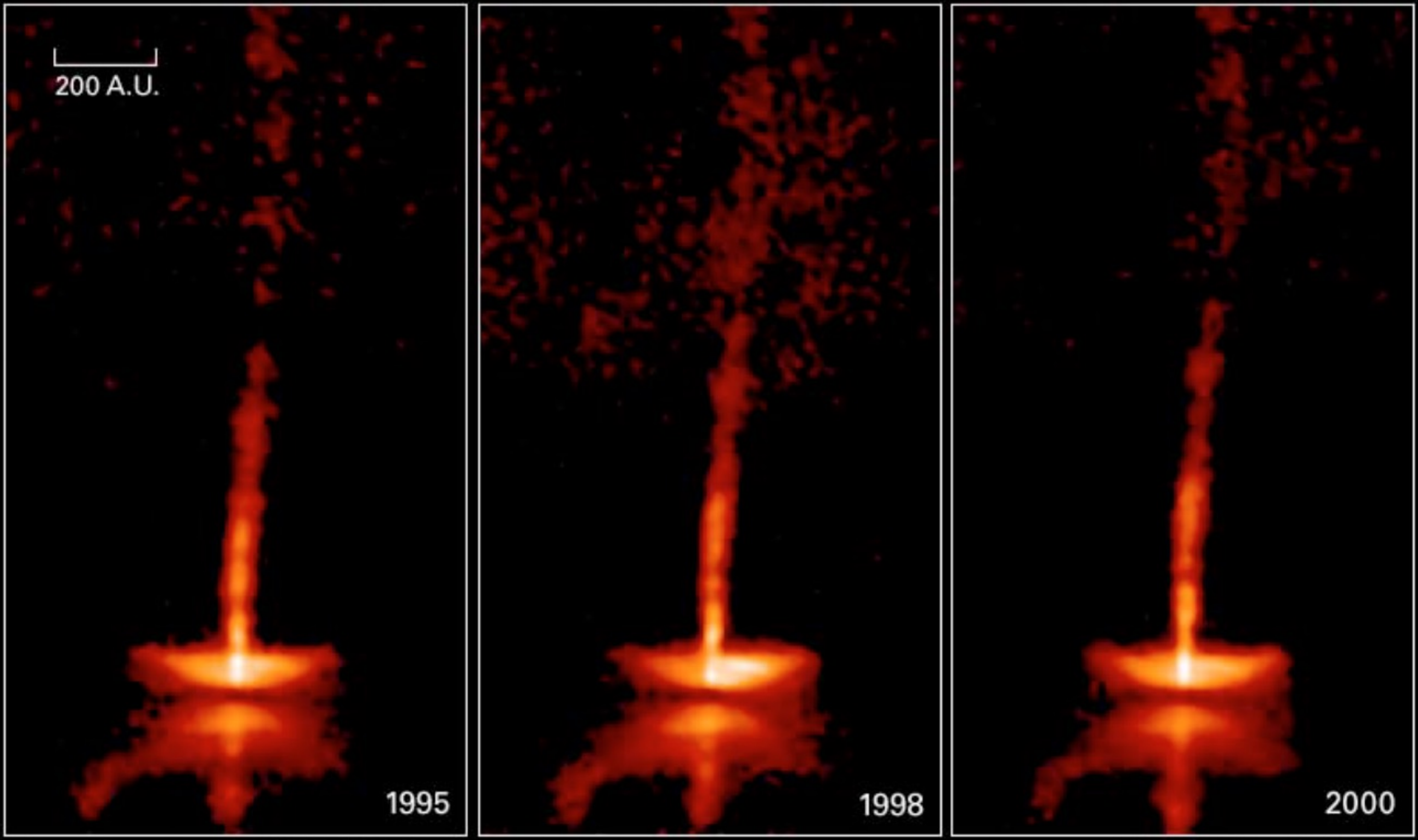
Clouds →

Jet / Outflow



Beuther 2008

Jets and Outflows

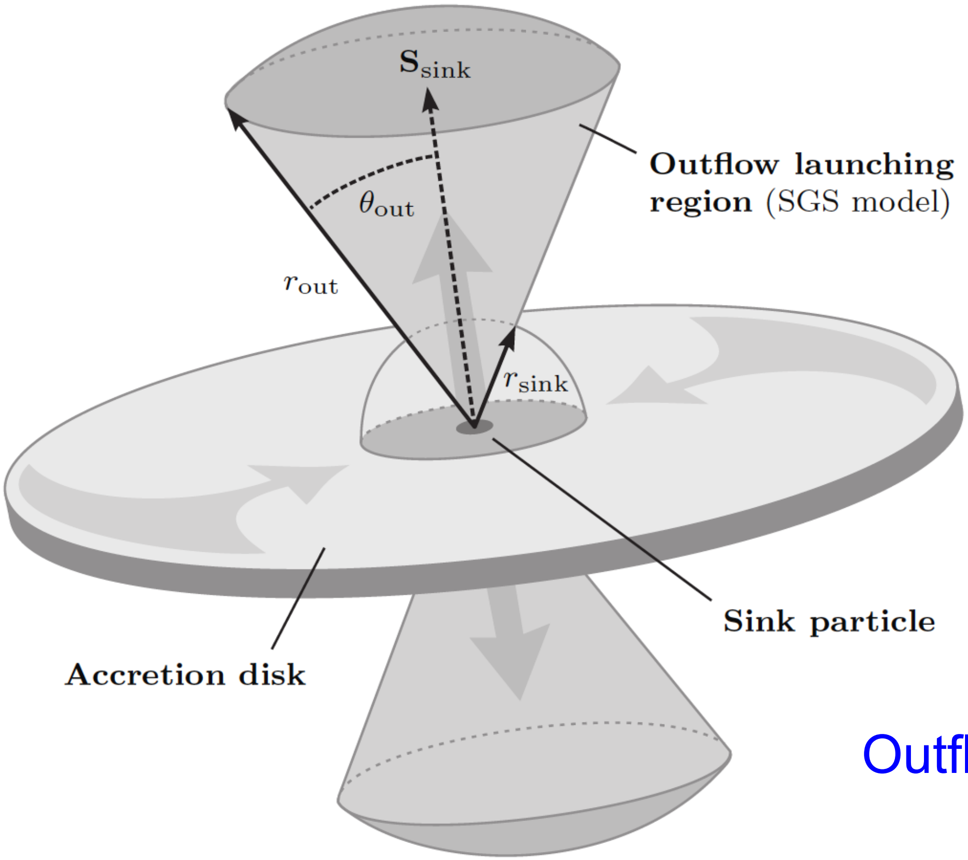


The Dynamic HH 30 Disk and Jet HST • WFPC2

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

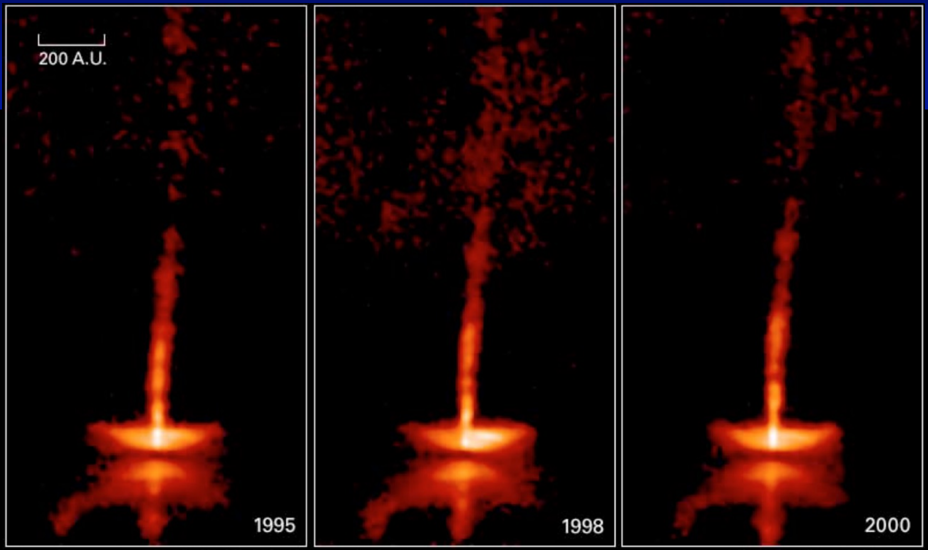
Notes. [a] The outflow velocities are dynamically computed according to the Kepler speed at the footpoint of the jet, $\lvert\mathbf{V}_{\rm out}\rvert = 100\,{\rm km\,s^{-1}}(M_{\rm sink}/0.5\,M_\odot)^{1/2}$ (see Equation 13).
References: [1] Blandford & Payne (1982); Appenzeller & Mundt (1989); Camenzind (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: $$\mathbf{L}_{\rm out} = f_{\rm a}\,(\mathbf{S}'_{\rm sink} - \mathbf{S}_{\rm sink})\cdot\mathbf{S}'_{\rm sink}/\lvert\mathbf{S}'_{\rm sink}\rvert$$

Jet/Outflow Feedback



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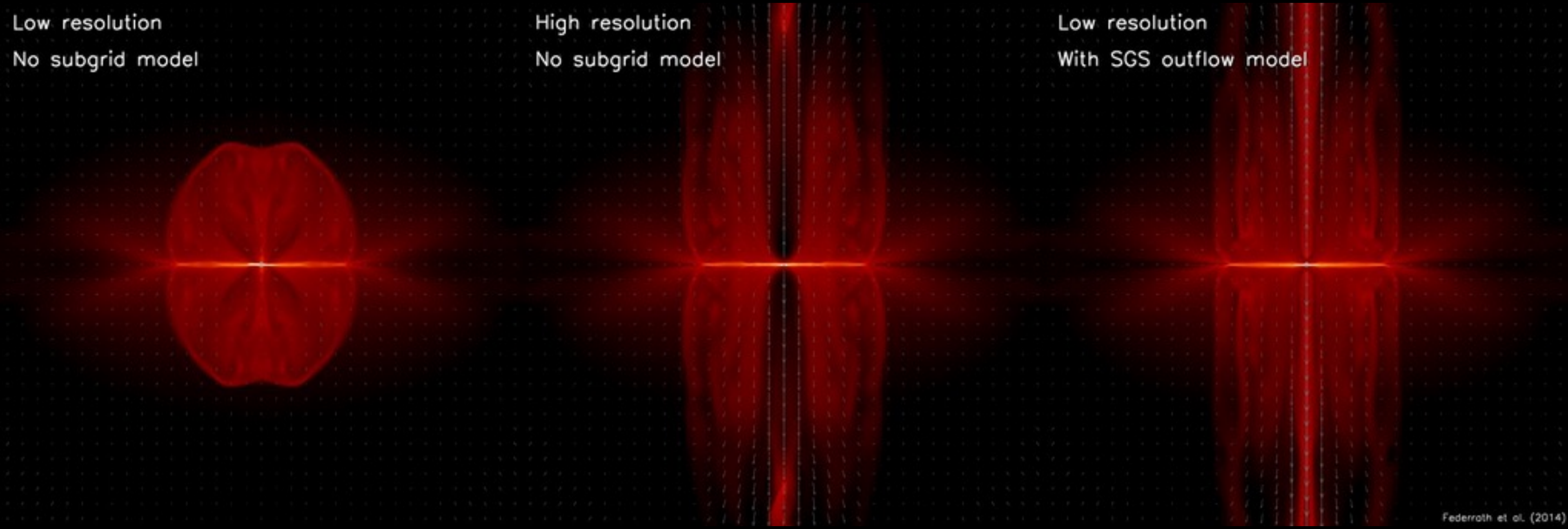
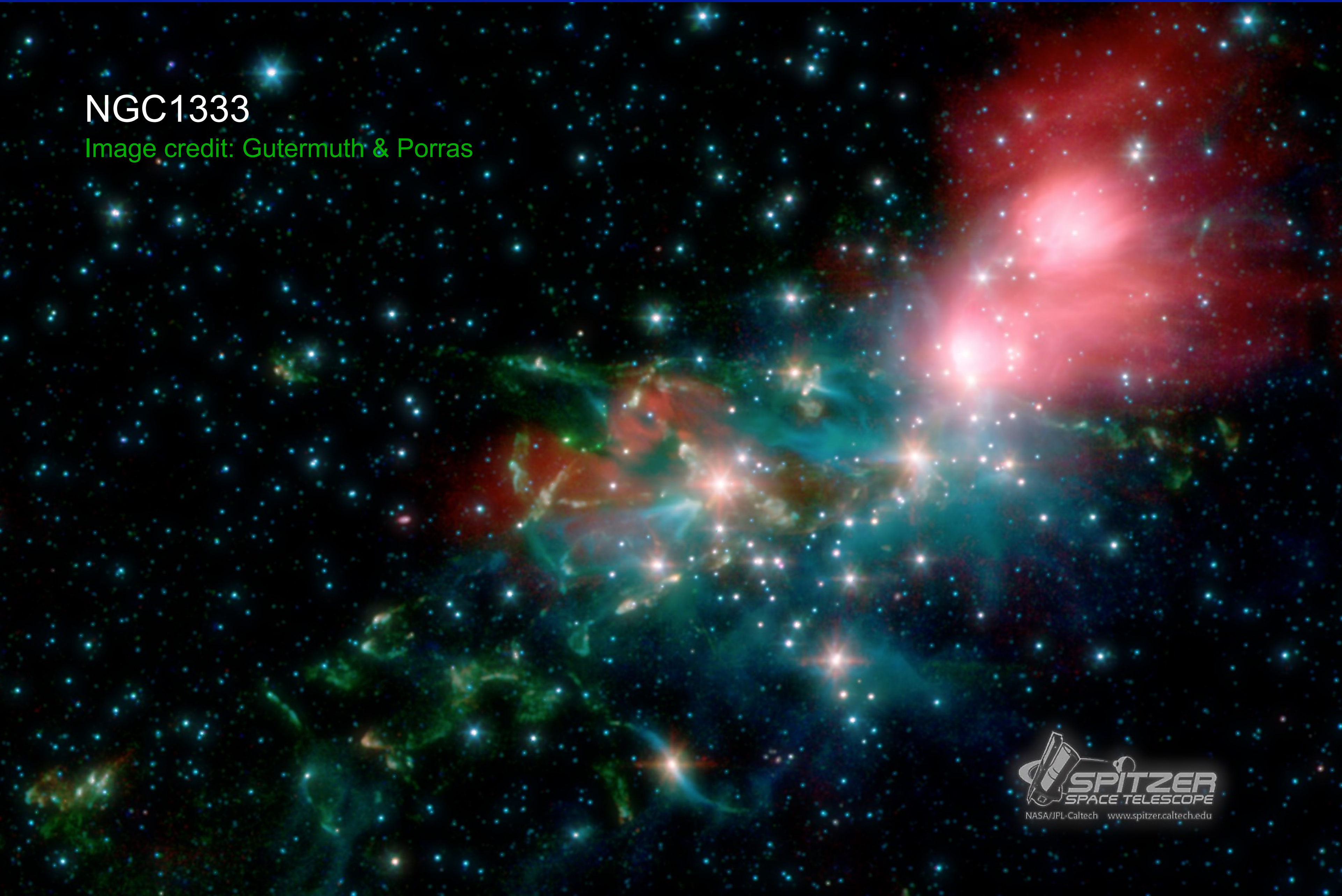


Movies available: https://www.mso.anu.edu.au/~chfeder/pubs/outflow_model/outflow_model.html

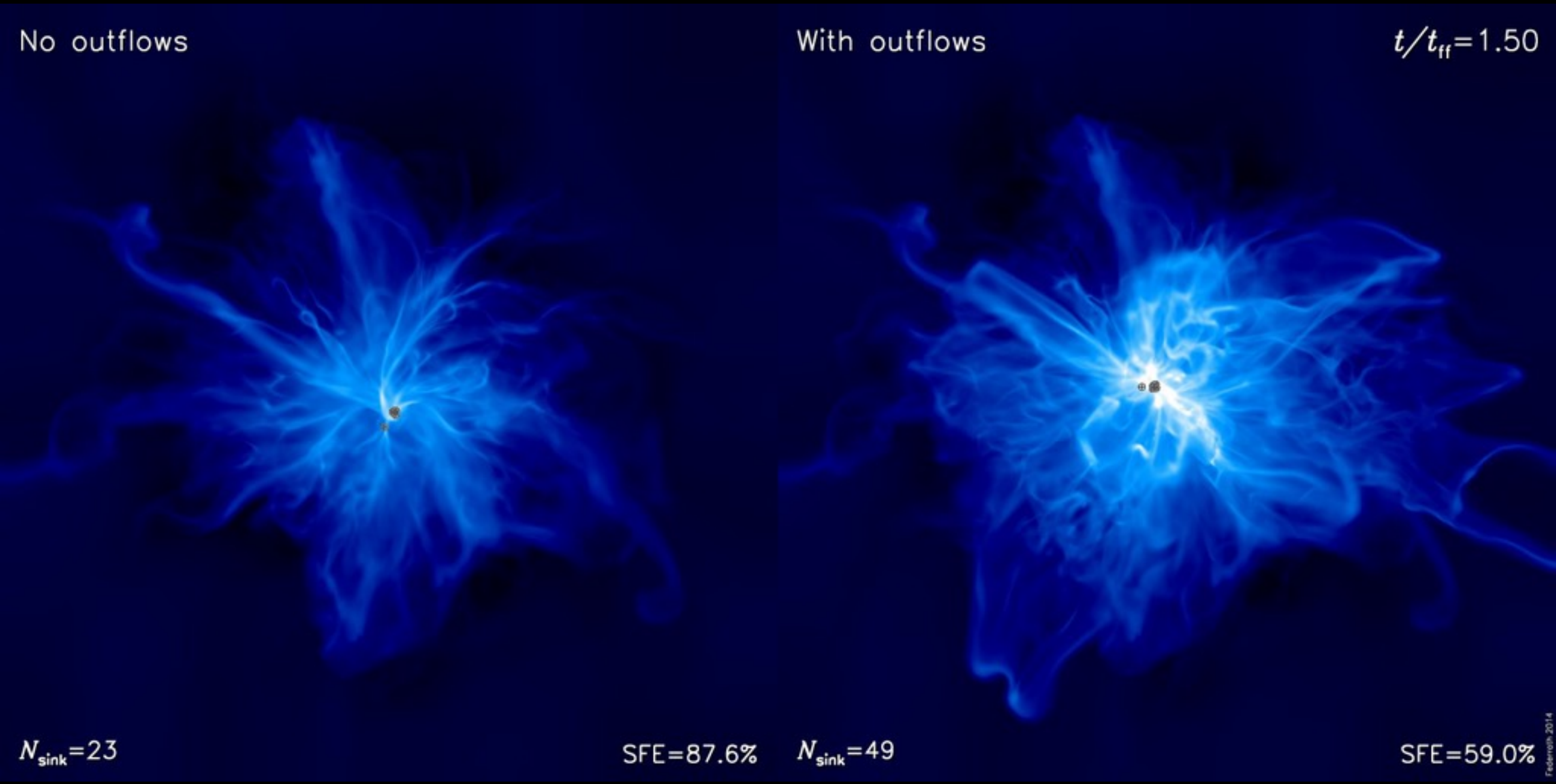
Federrath et al. 2014, ApJ 790, 128

Star Formation – Outflow/Jet Feedback



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

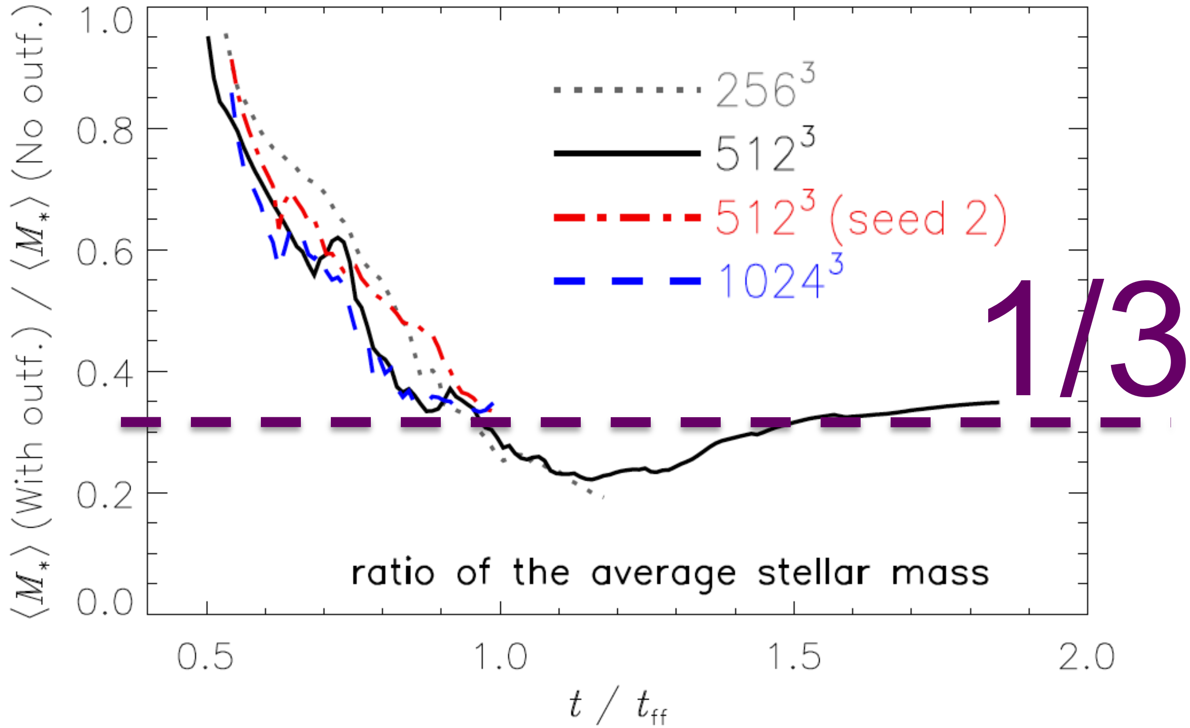


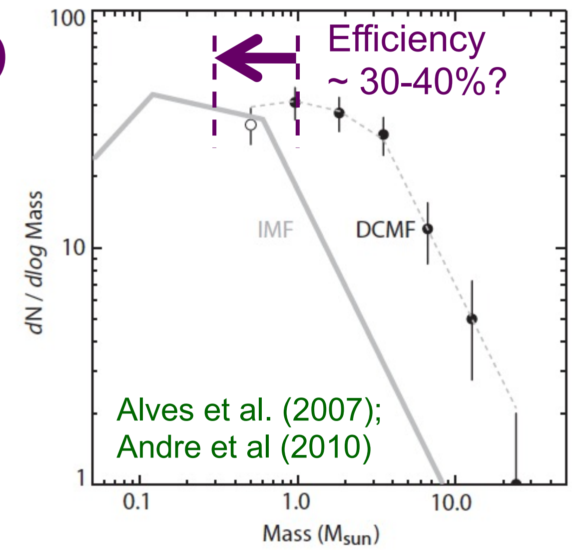
Without jets/outflows

With jets/outflows

Federrath et al. 2014, ApJ 790, 128

The role of outflow/jet feedback for star cluster formation



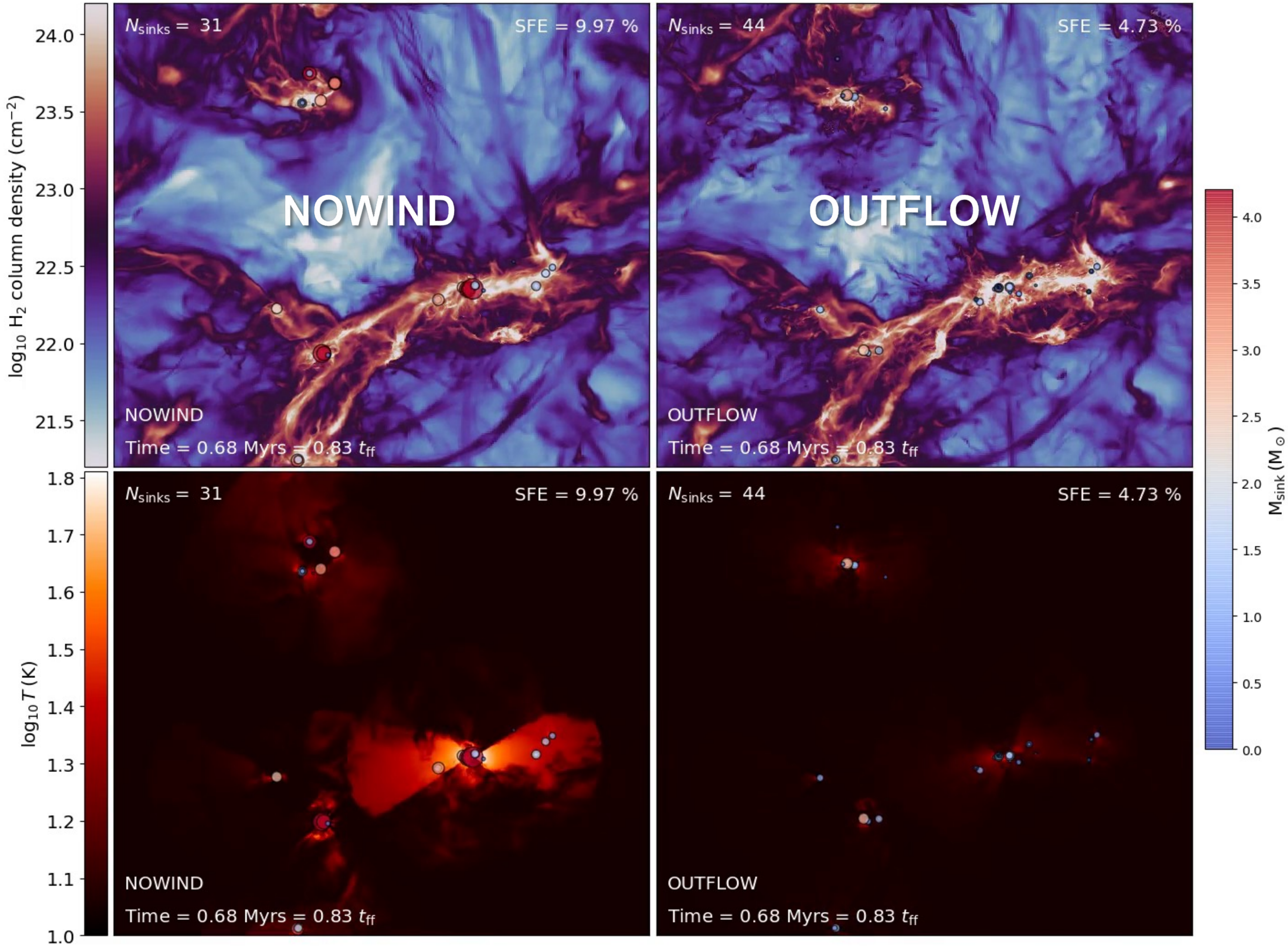


RESULTS:

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

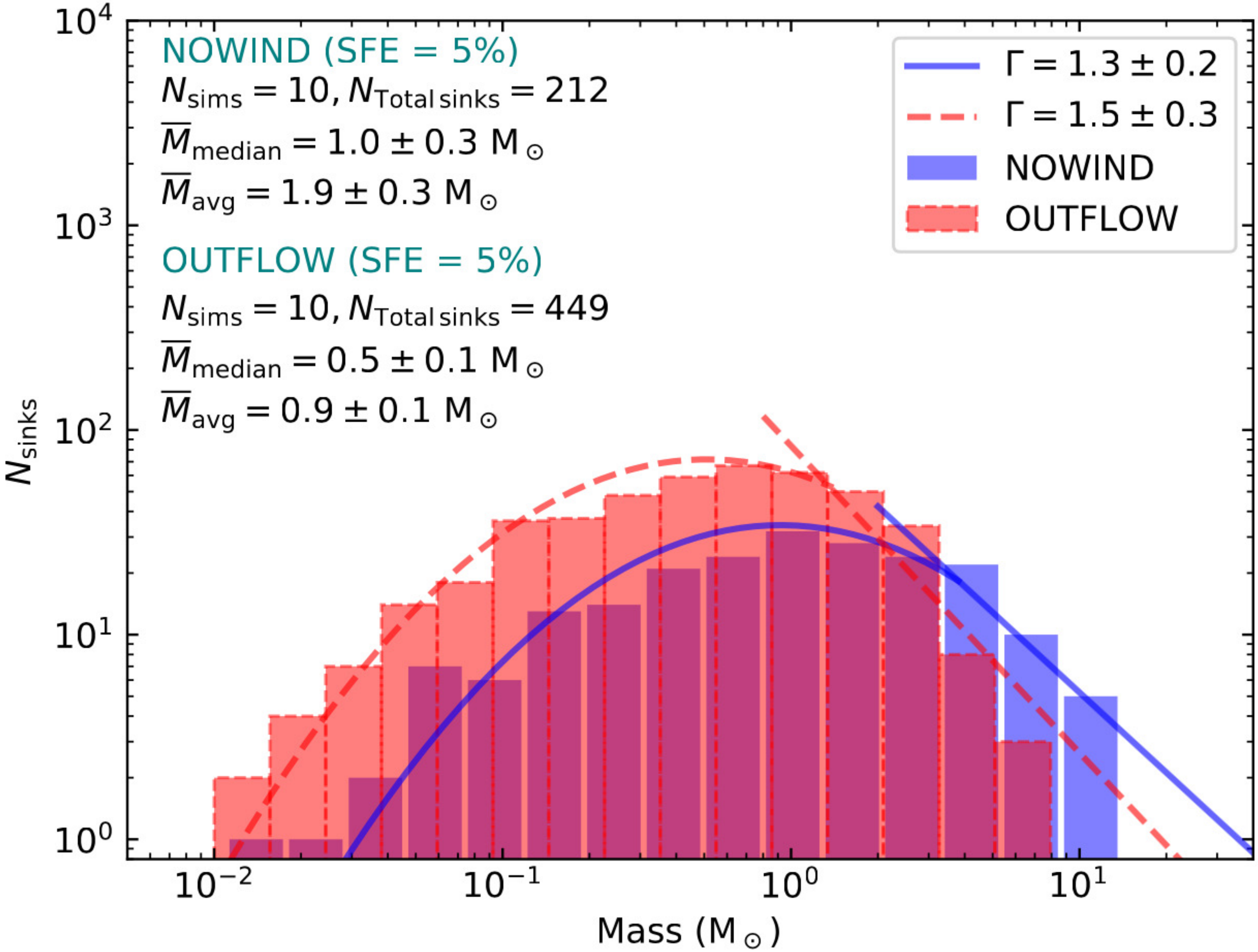
Role of Jet/Outflow Feedback for the IMF

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



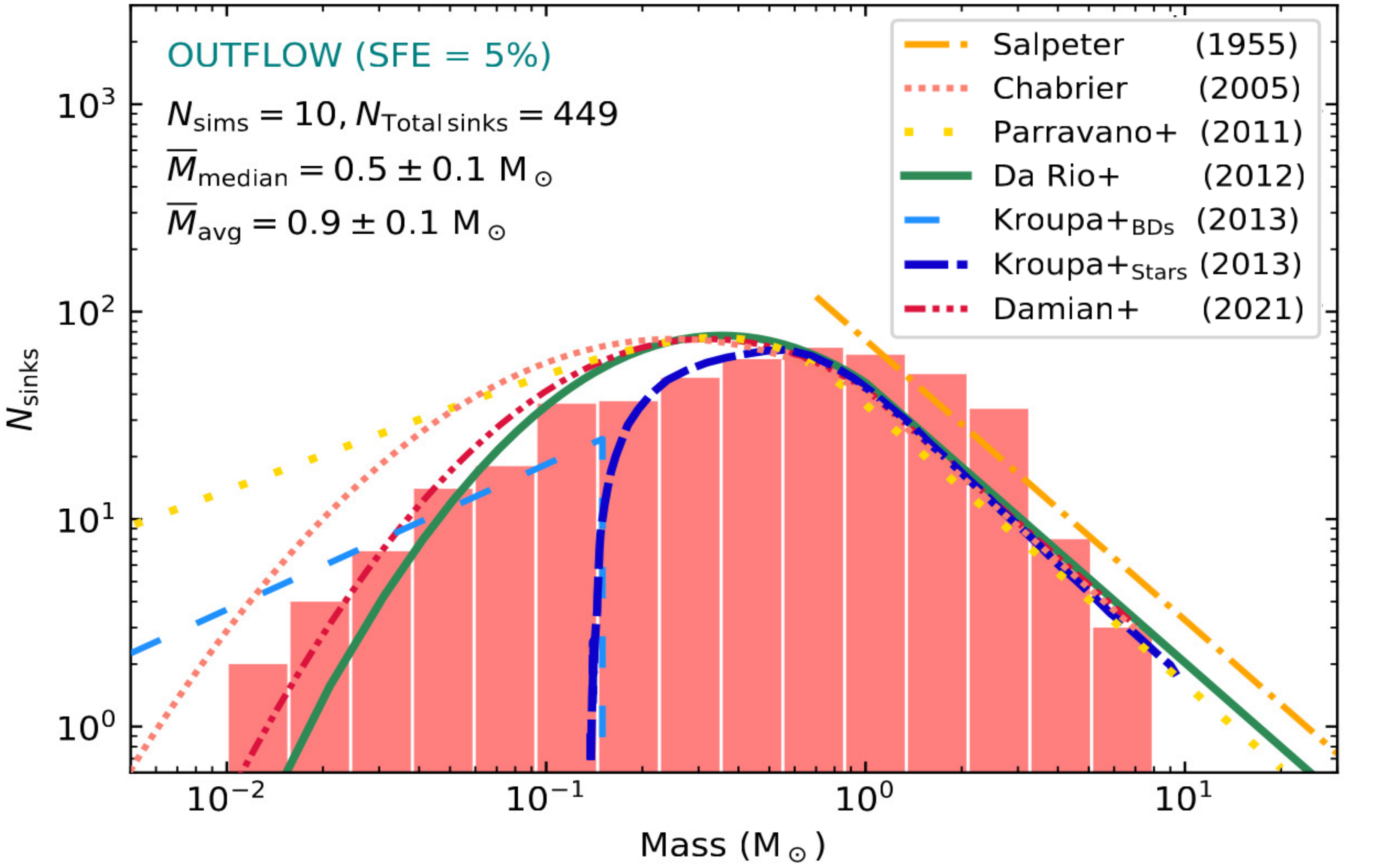
(Mathew & Federrath 2021)

Role of Jet/Outflow Feedback for the IMF



(Mathew & Federrath 2021)

Role of Jet/Outflow Feedback for the IMF



(Mathew & Federrath 2021)

Conclusions

Analysis of Observational Data and Simulation/Modelling strongly rely on Computing

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

Astronomical Computing

ASTR4004 / ASTR8004

NEXT:
Setting up computers, Bash and shell scripting…

Start by going through the prerequisits:

http://www.mso.anu.edu.au/~chfeder/teaching/astr_4004_8004/astr_4004_8004.html

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

Astronomical Computing

Introduction to Bash and shell scripting

Bash is a shell program designed to listen to your commands and do what you tell it to.

Bash is a simple tool in a vast toolbox of programs that lets you interact with your system using a text-based interface.

Distinguish *Interactive* and *Non-interactive* mode

Useful shell commands:

cd, ls, grep, rsync, redirect stdout/stderr, top, tail, cat, wc, nohup, screen, nice

Good Bash introduction: **http://guide.bash.academy**

Image credit: M. S. Povich

Astronomical Computing

Now let's go through the Bash guide:

- first, read content on your own (sections 1-3)
- then do the excercises (can be done in teams or on your own)

http://guide.bash.academy

Image credit: M. S. Povich