

Astronomical Computing

ASTR4004 / ASTR8004

ANU – 2nd semester 2023

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

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** (how to compute mean, rms, stddev, skewness, kurtosis, etc.)
 - script to compute and plot the PDF of a dataset
 - Monte Carlo error propagation
- **Image processing** (beam convolution, array operations, filtering, etc.)
- **Fourier transformation** (power spectra)
- **Parallel computing**
 - OpenMP; MPI (C++)
 - how to parallelise code
 - scaling tests and plot result; discuss result: why is scaling not ideal?
- **Weeks 7-12: taught by Yuan-Sen Ting**: Regression, PCA, Monte-Carlo Markov Chain, ...

Astronomical Computing

The background of the slide is a composite image of a night sky. The Milky Way galaxy is visible as a dense band of stars and dust, stretching diagonally across the frame. In the lower right, a comet with a bright nucleus and a long, faint tail is visible. The bottom of the image shows the dark, silhouetted peaks of a mountain range or rugged terrain.

Need computer account at RSAA
—
application form on course webpage

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

Astronomical Computing

Assignments:

- Assessment based on 4 assignments in total
- 1 assignment per about every 2-3 weeks
- Assignments published on webpage
- Submission via Turnitin
- Feedback within 2 weeks after submission

Help with setting up computers and marking provided by Jamie Soon.

Modelling/Computing Star Formation, Turbulence, Feedback

Christoph Federrath

ANU – 2023



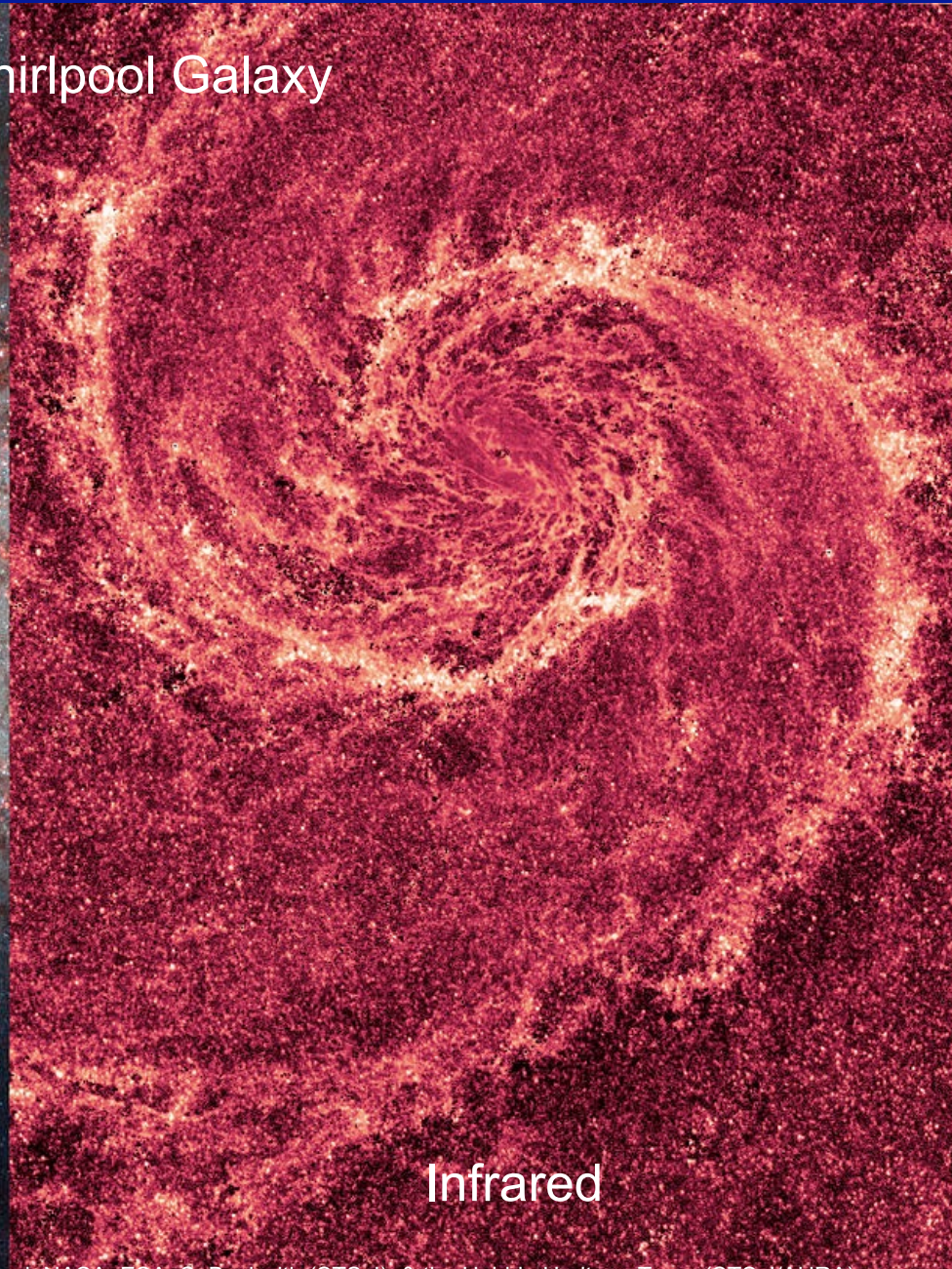
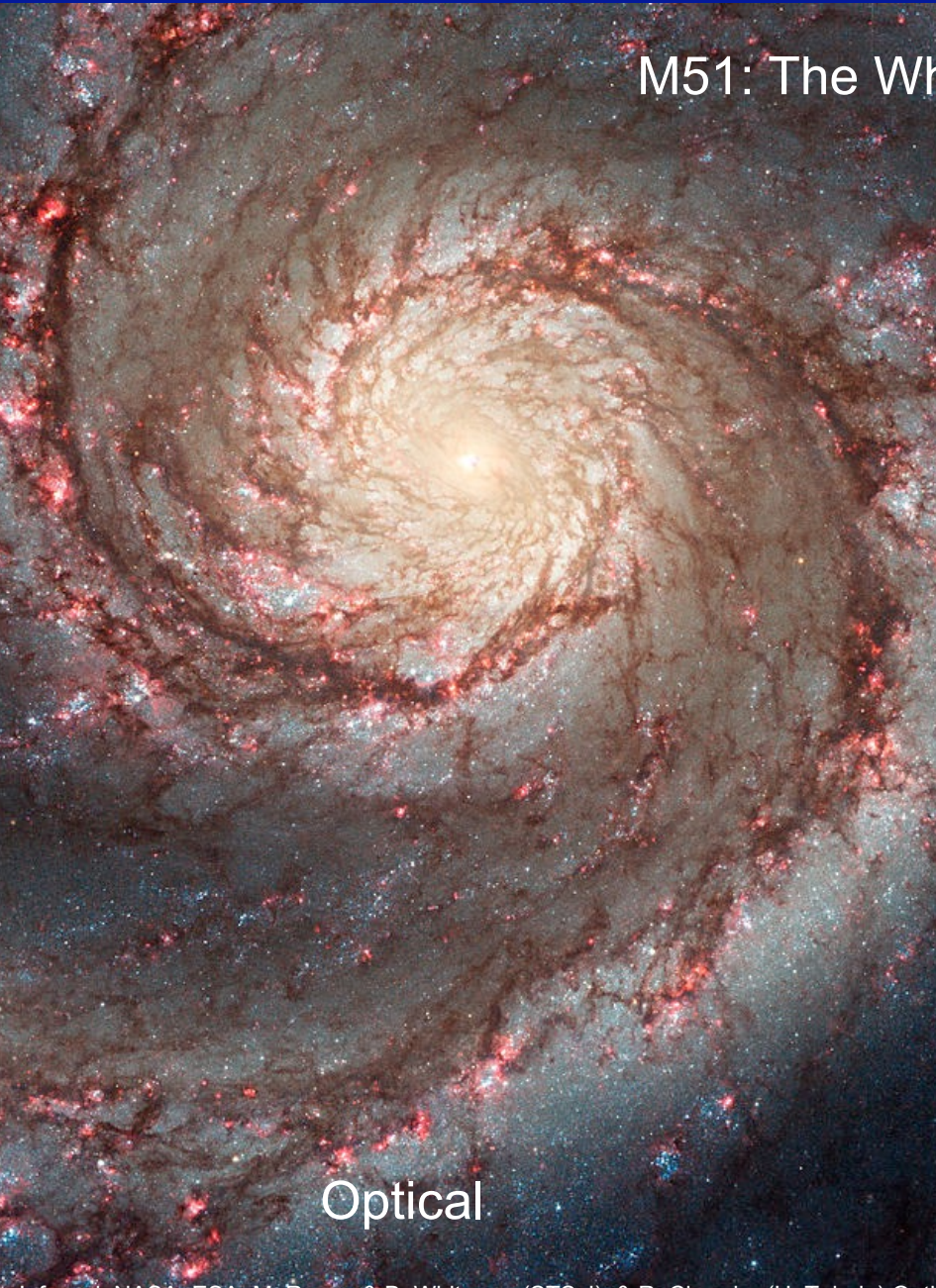
Australian Government
Australian Research Council



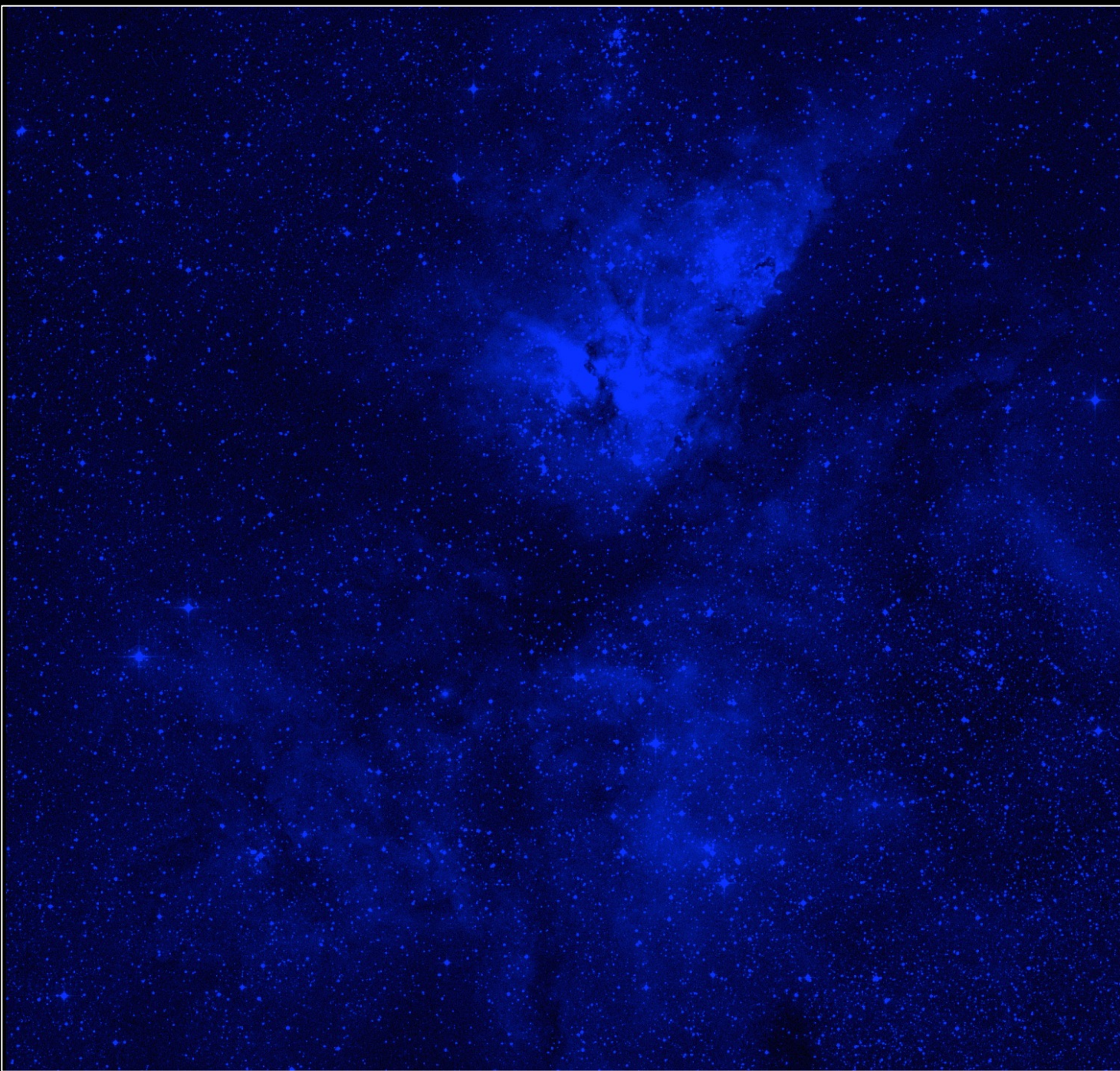
Australian
National
University



M51: The Whirlpool Galaxy







The Great Nebula in Carina

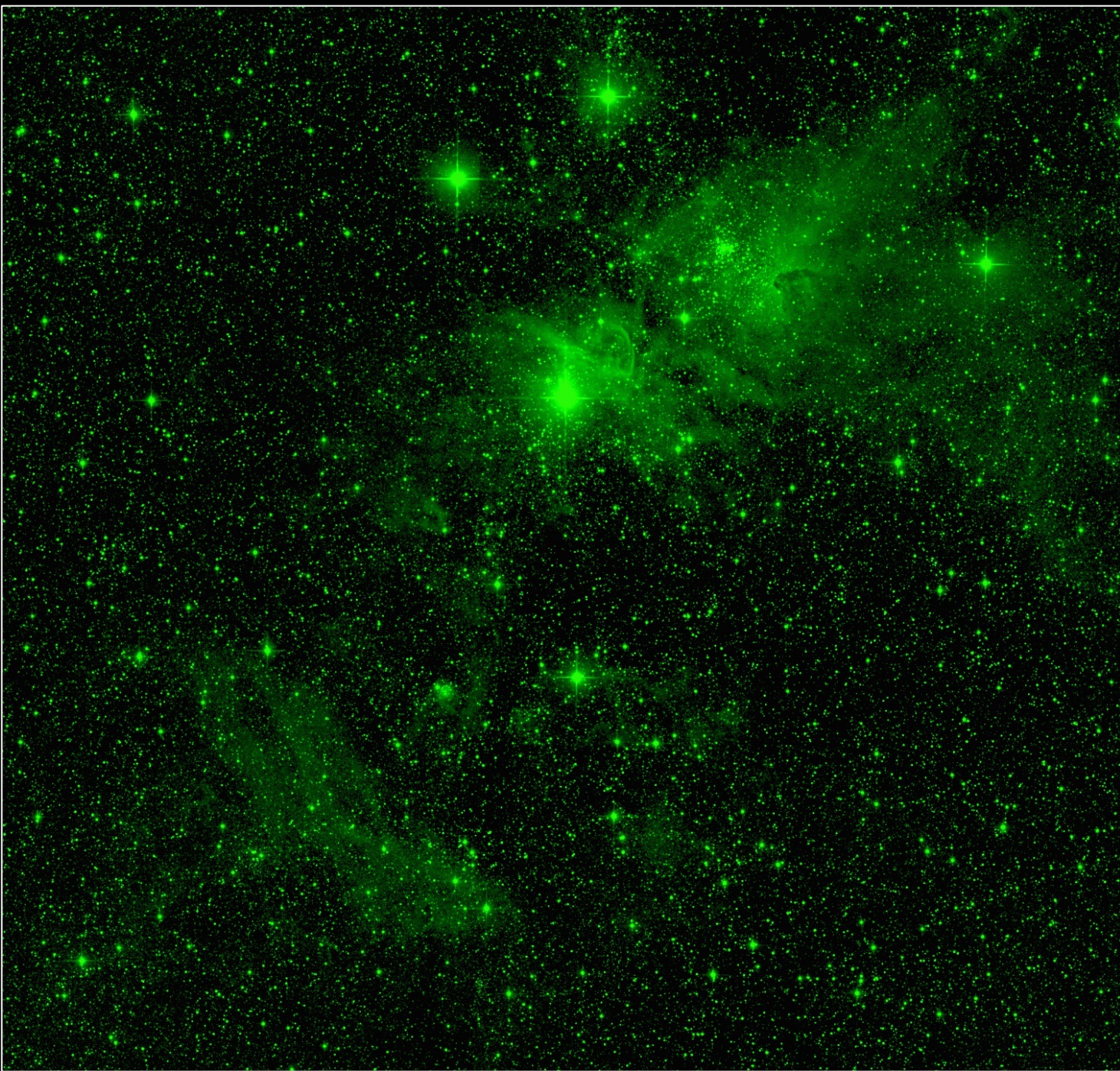
Visible Light

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

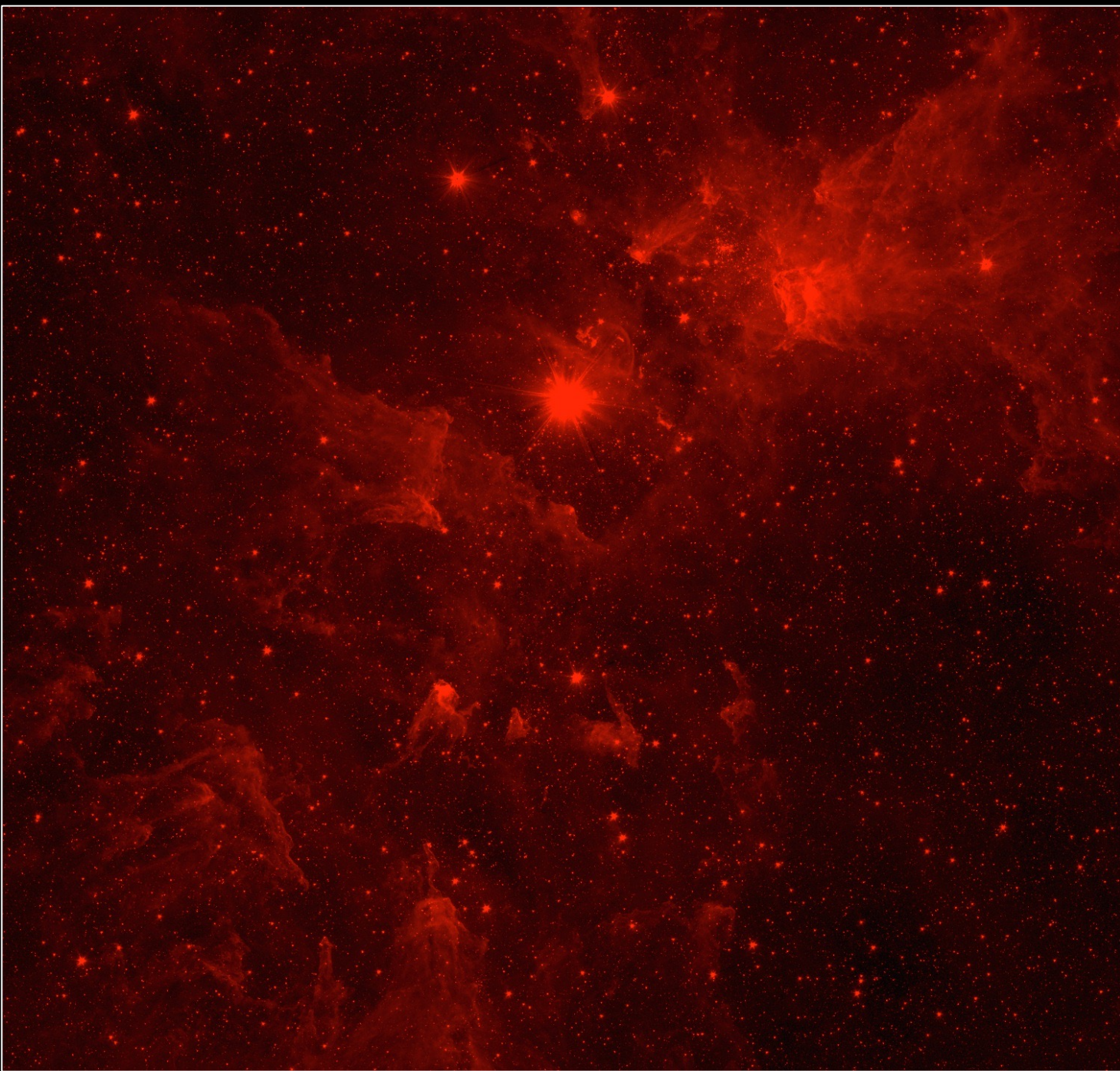
Near-Infrared

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.

New Massive Stars
Found Hiding in
Famous Nebula

M. S. Povich

The Great Nebula in Carina

Visible Light

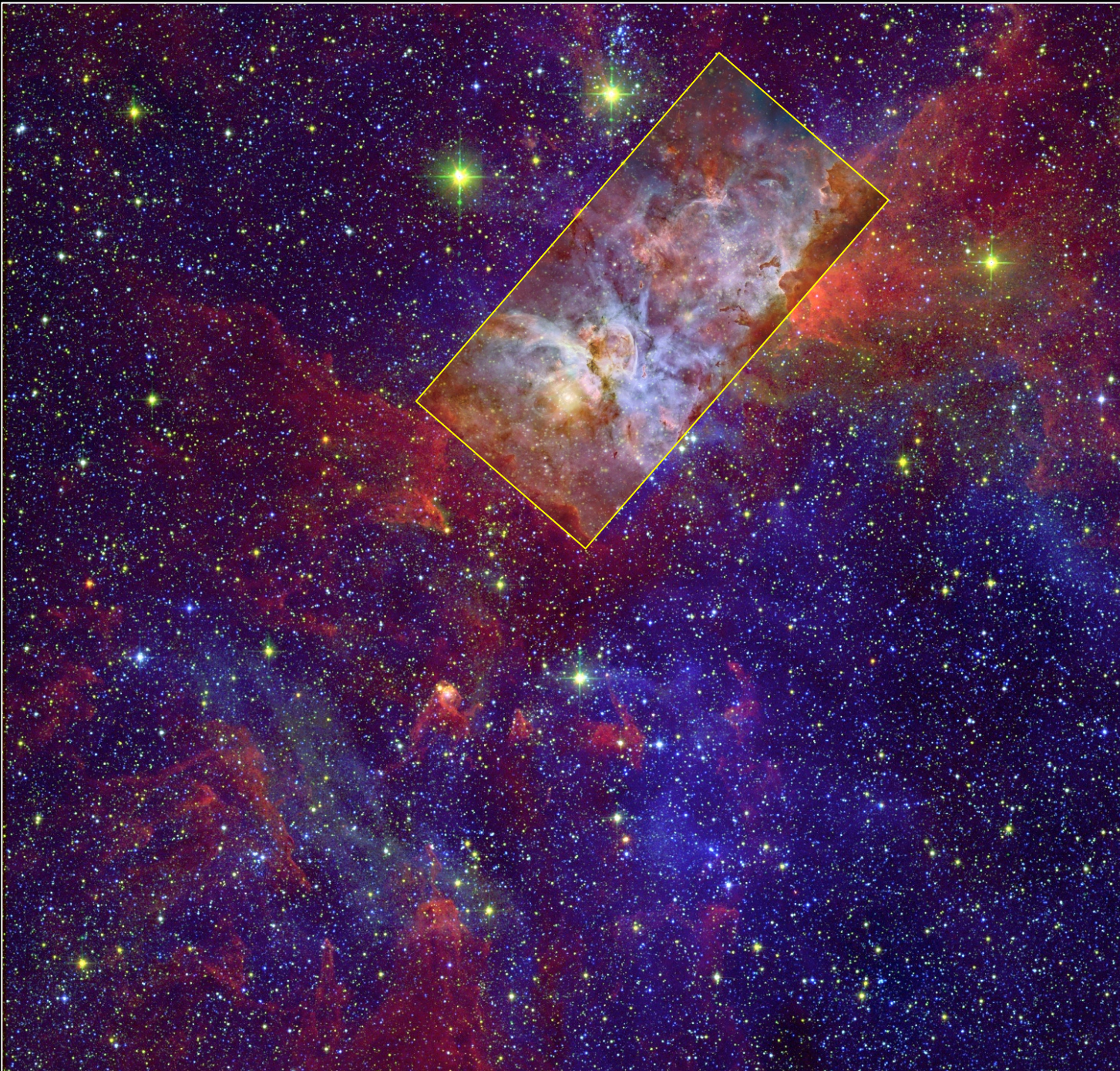
Digitized Sky Survey

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

```
graph LR; A[Turbulence] --> B[Stars]; B --> C[Feedback]; C --> A;
```

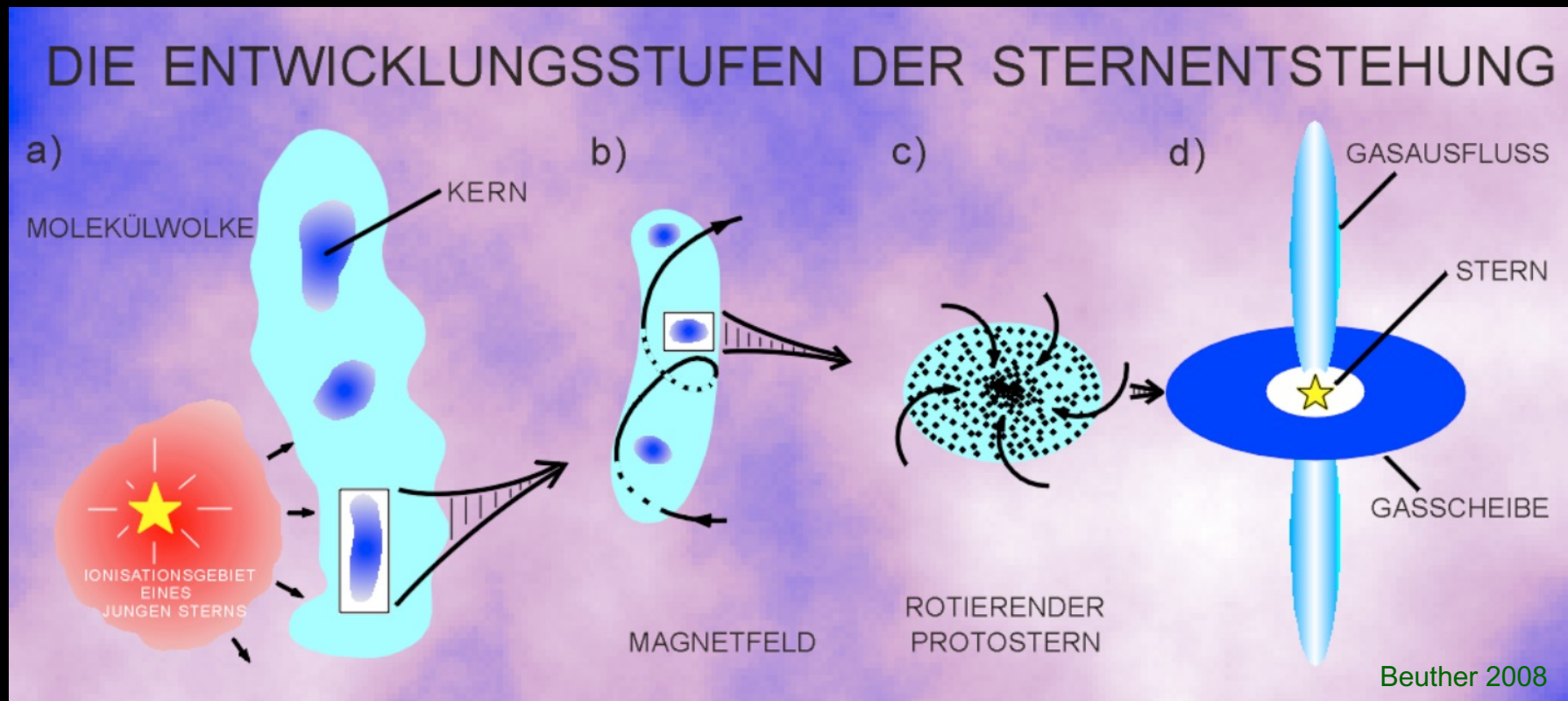
Turbulence driven by

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

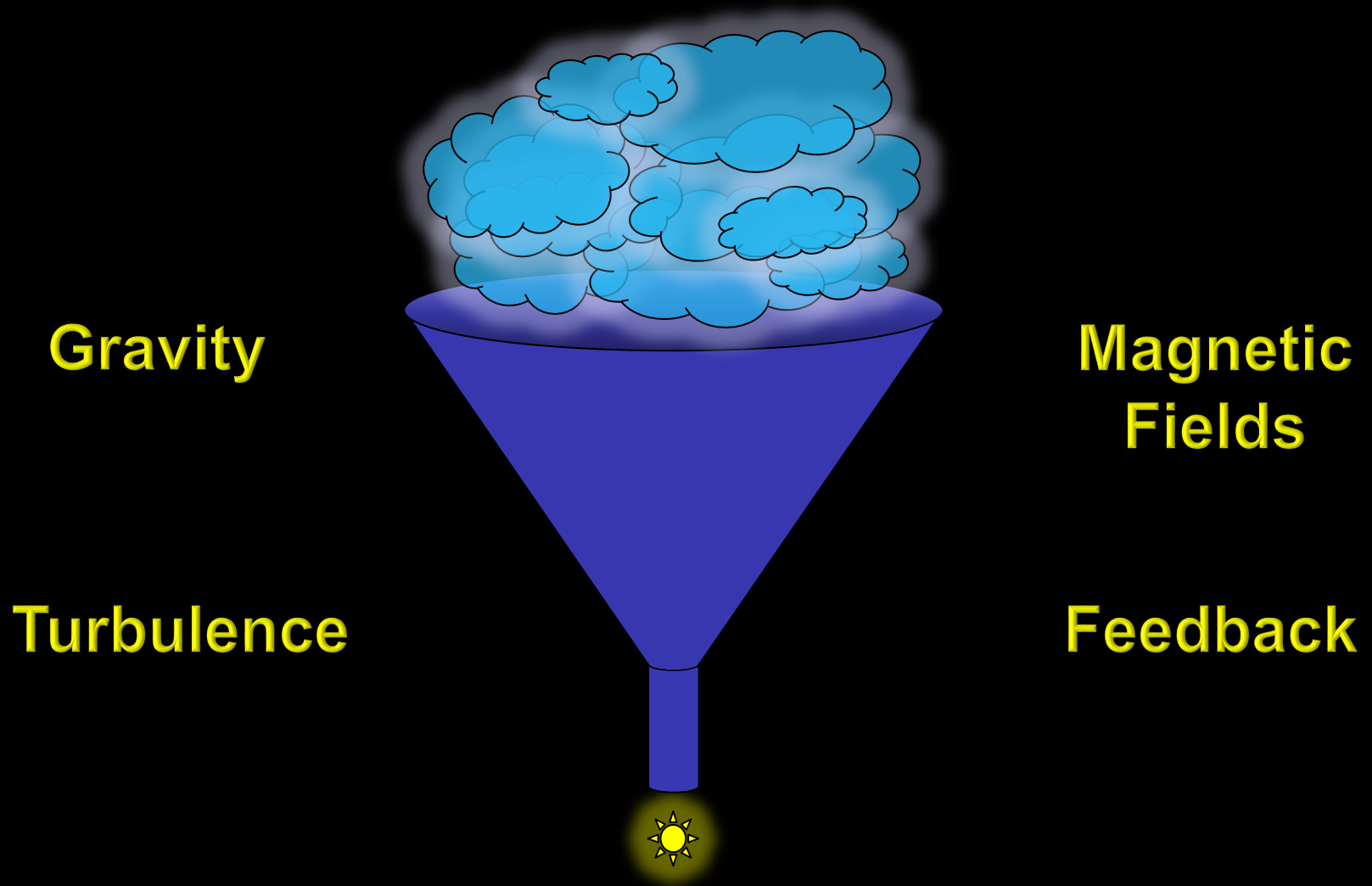
Mac Low & Klessen (2004)

The Star Formation Paradigm

Clouds → Cores → Disk + Star + Jet / Outflow



Star Formation is Inefficient



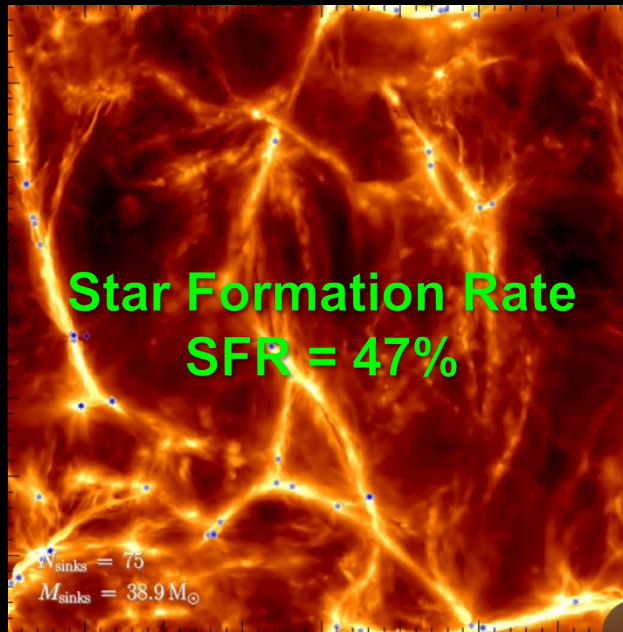
Star Formation is Inefficient

(Federrath 2015 MNRAS; 2018 *Physics Today*)

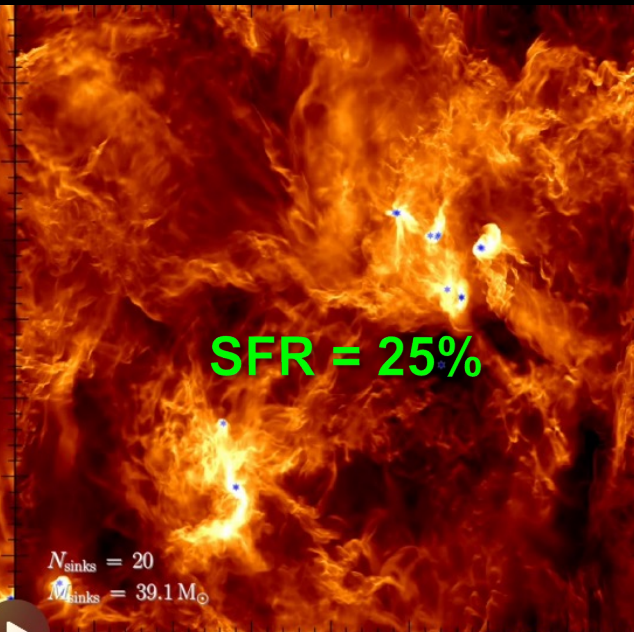
Movies available: http://www.mso.anu.edu.au/~chfeder/pubs/ineff_sf/ineff_sf.html



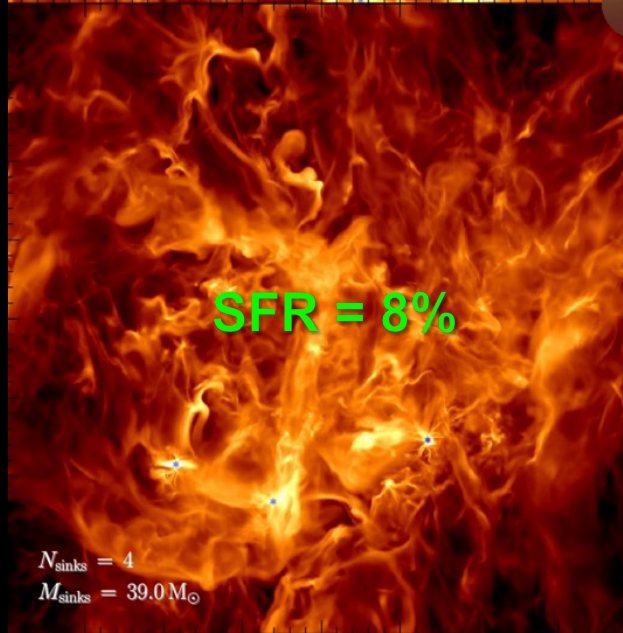
Gravity
only



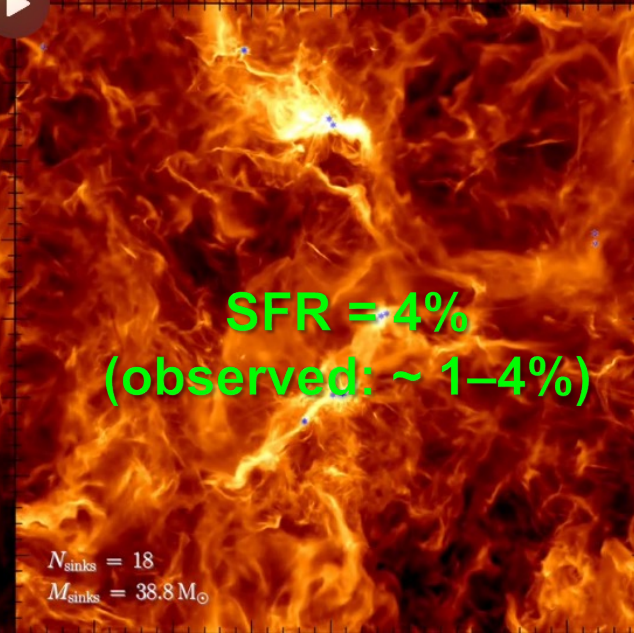
with
Turbulence



Turb+
Magnetic
Fields



SFR = 4%
(observed: ~ 1–4%)

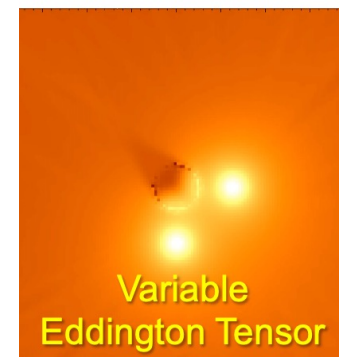
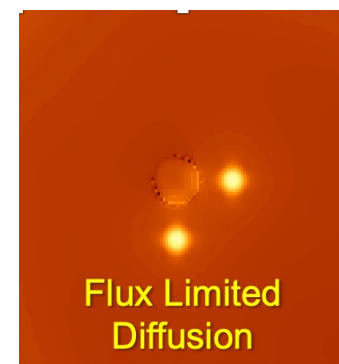
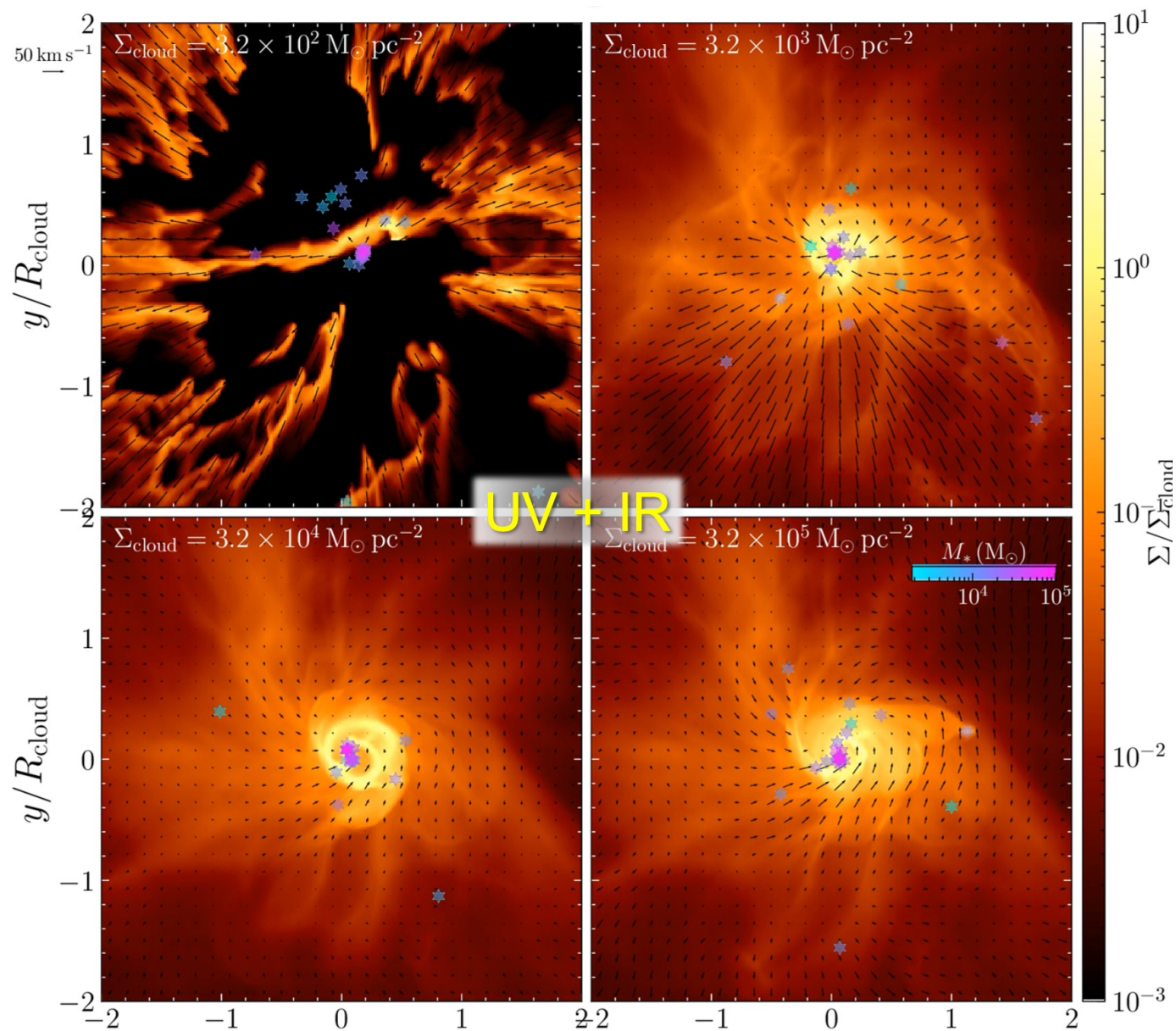


Turb+
Mag+
Jet/Outflow
Feedback

(sims for Appel
et al. 2023)

Modelling Radiation

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

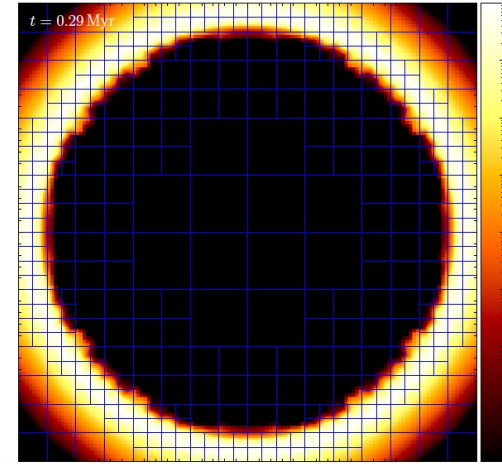
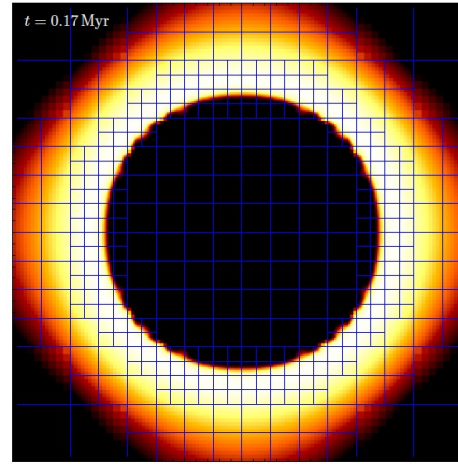
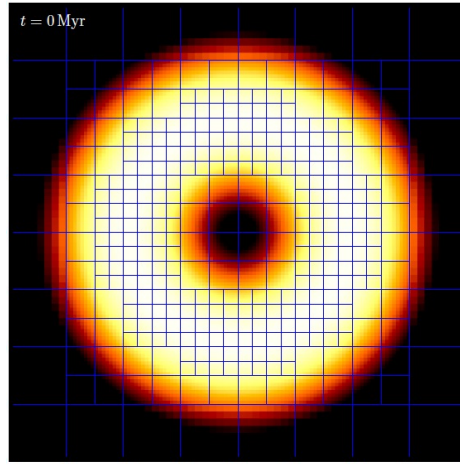


(Menon et al. 2022 a,b,c)

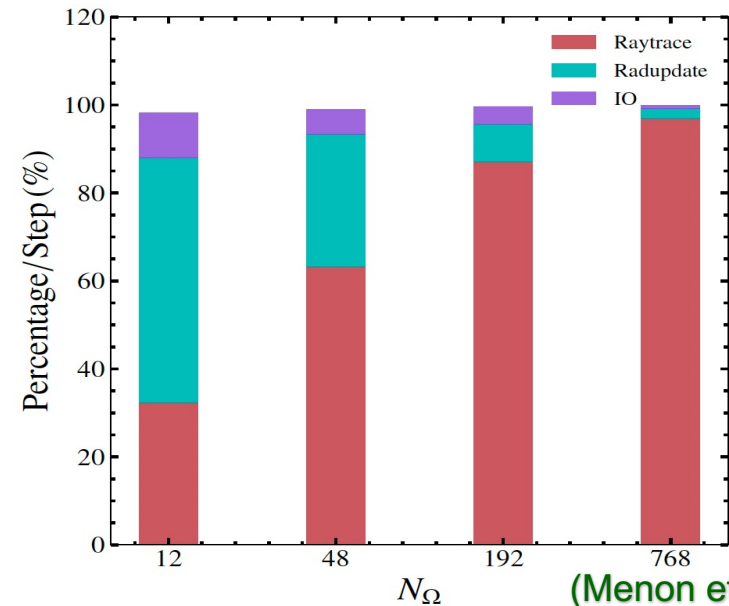
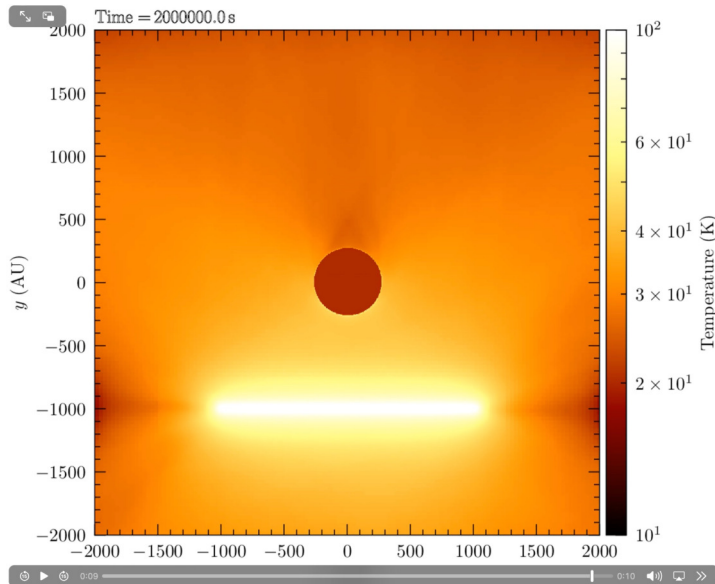
New AMR Variable Eddington Tensor (VET) method

VET with hybrid-characteristics ray-tracing on AMR

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



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



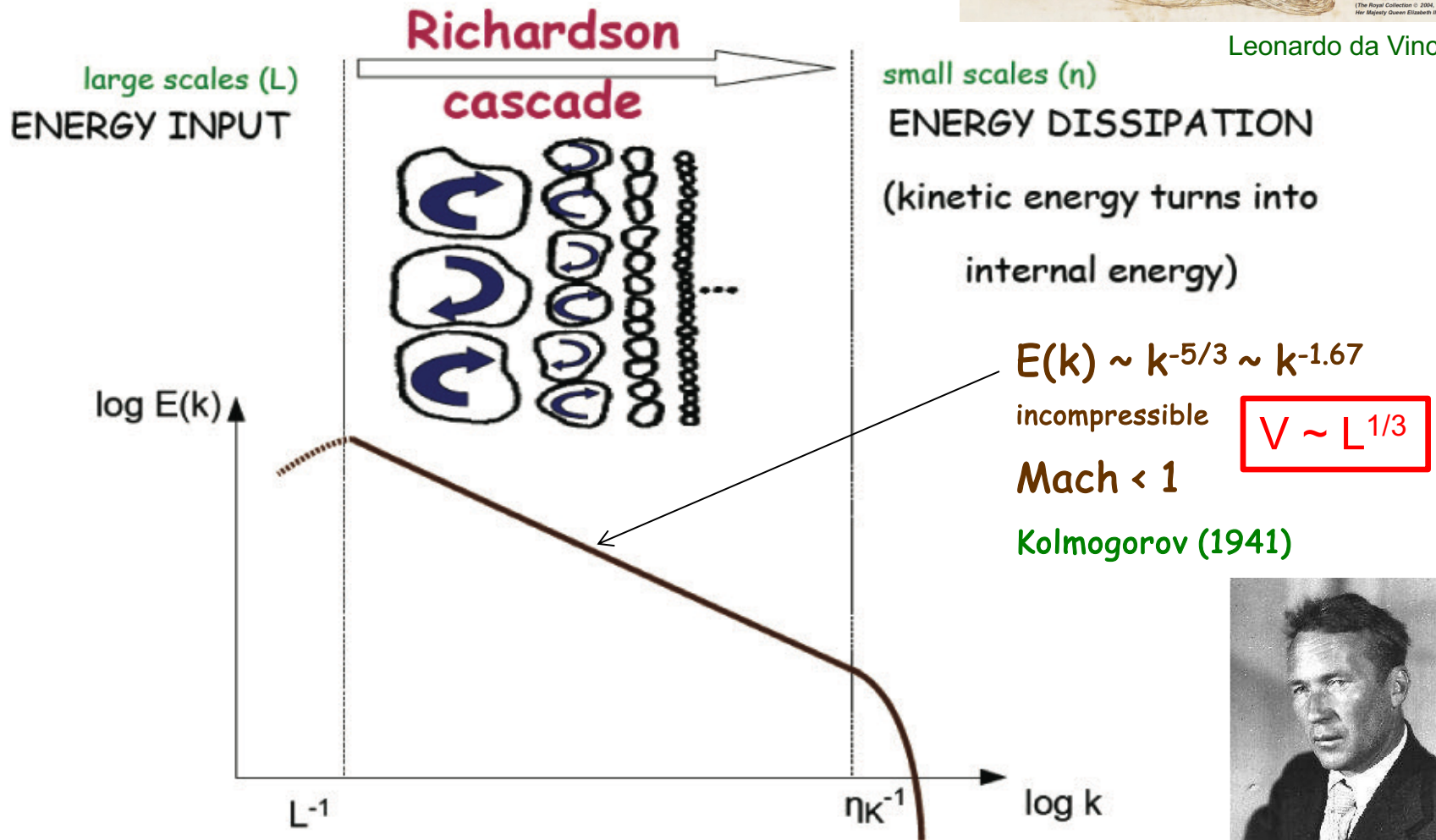
(Menon et al. 2022)

Turbulence

- Reynolds numbers > 1000
- Kinetic energy cascade



Leonardo da Vinci

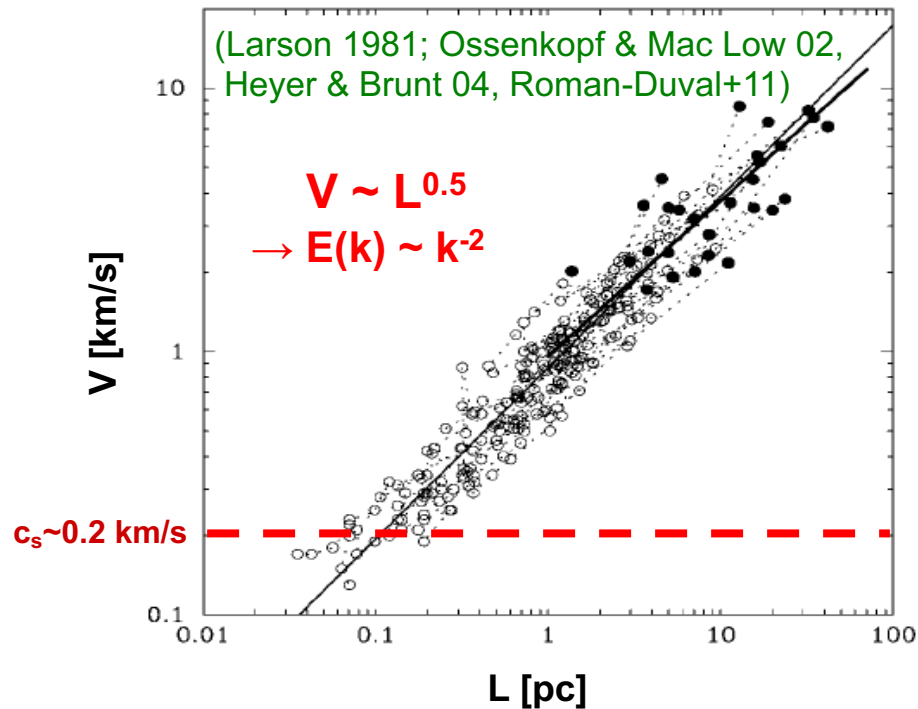


Interstellar Turbulence – scaling

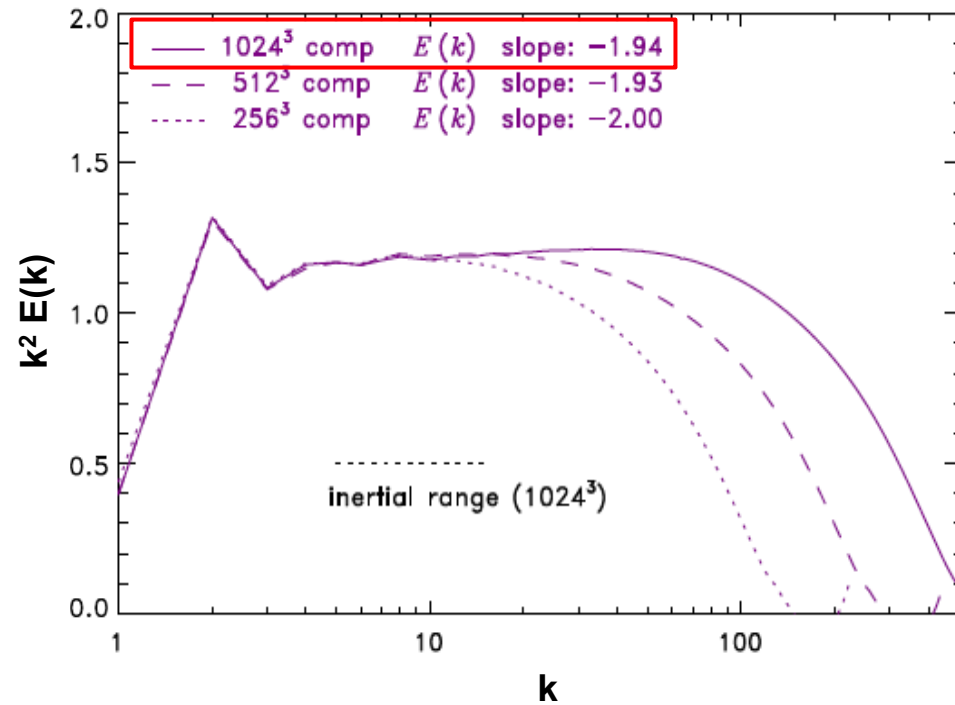
BUT: Larson (1981) relation: $E(k) \sim k^{-1.8-2.0}$

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

Observation



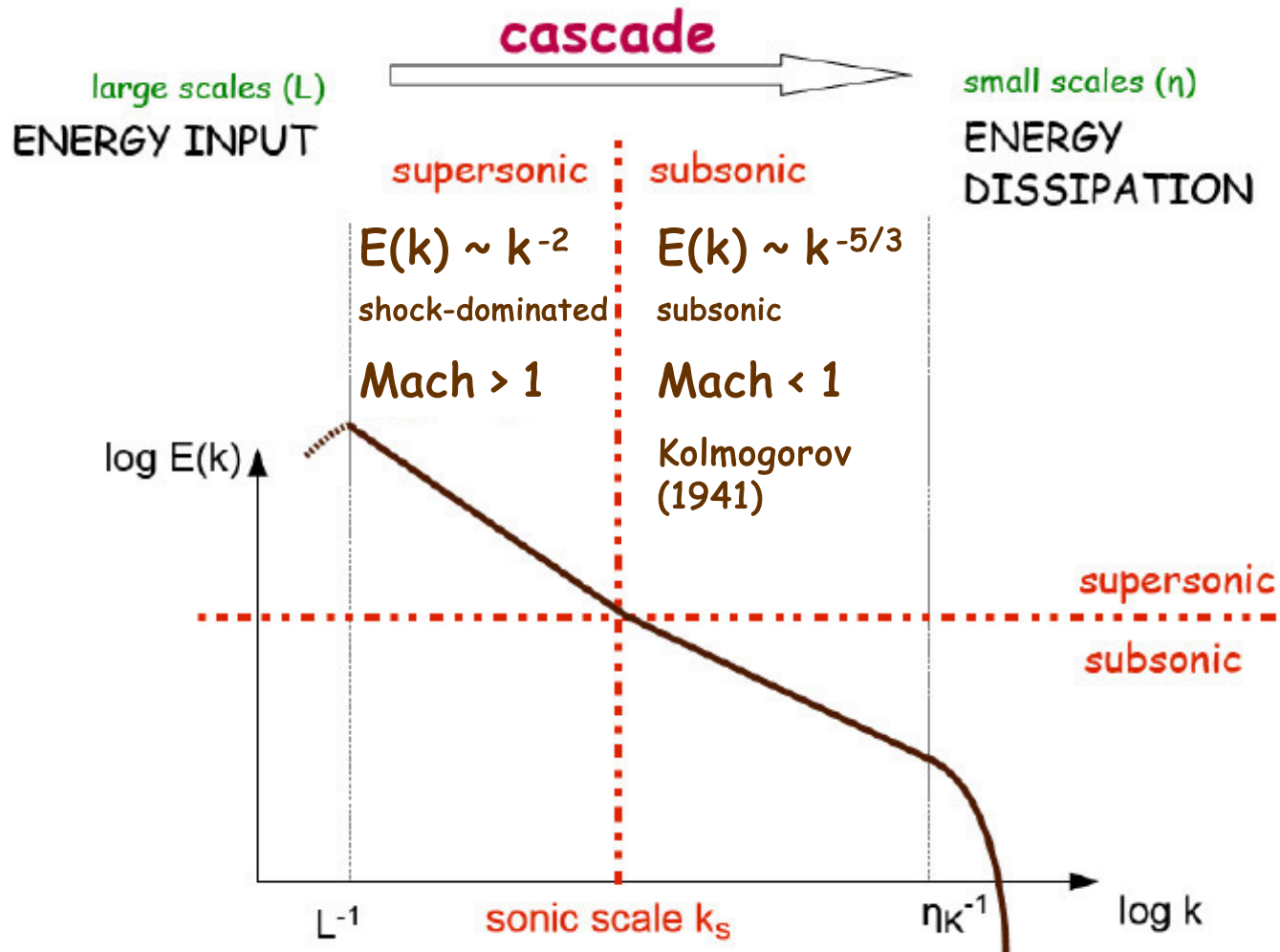
Simulation



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

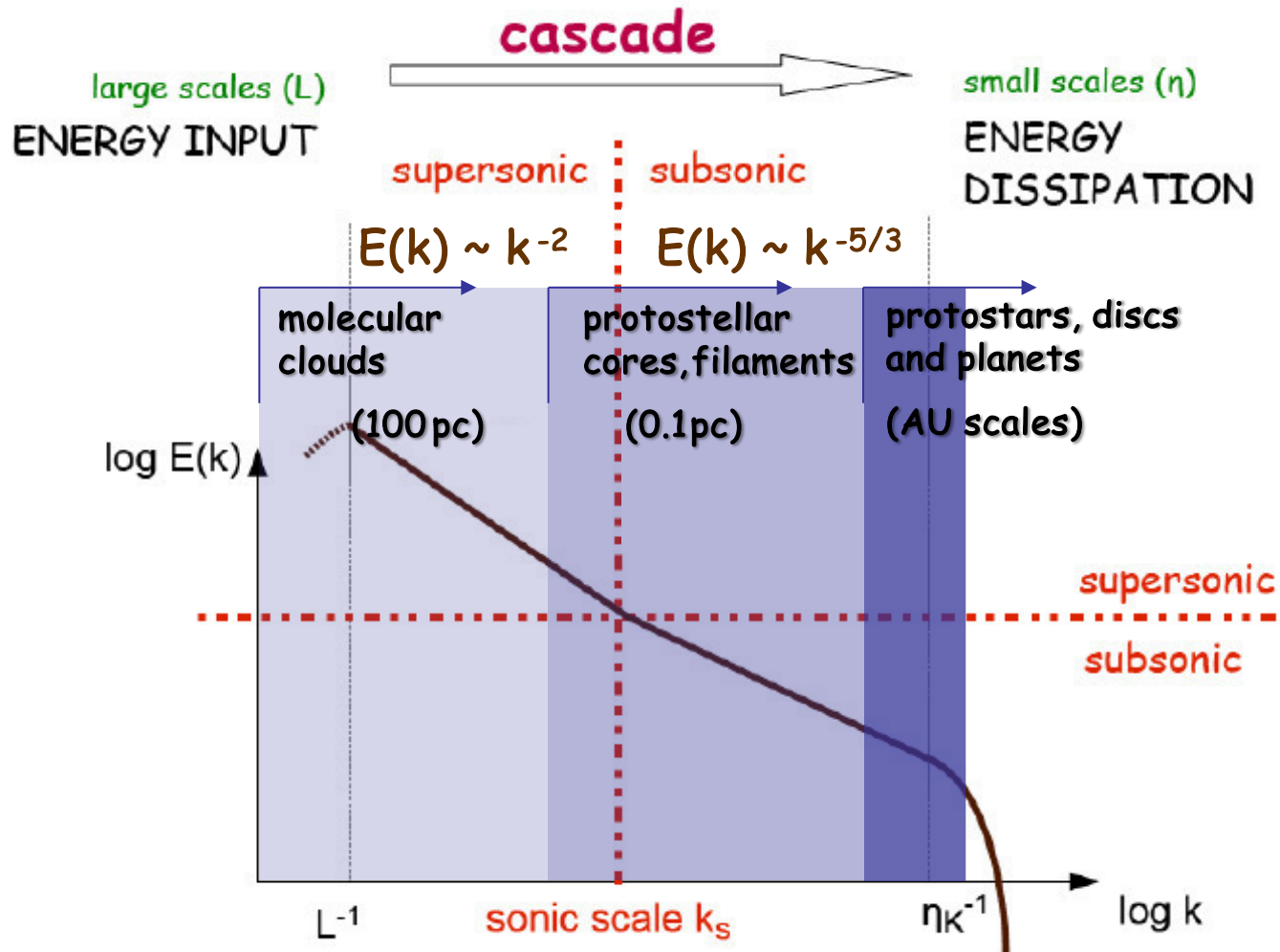
Interstellar Turbulence

- 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

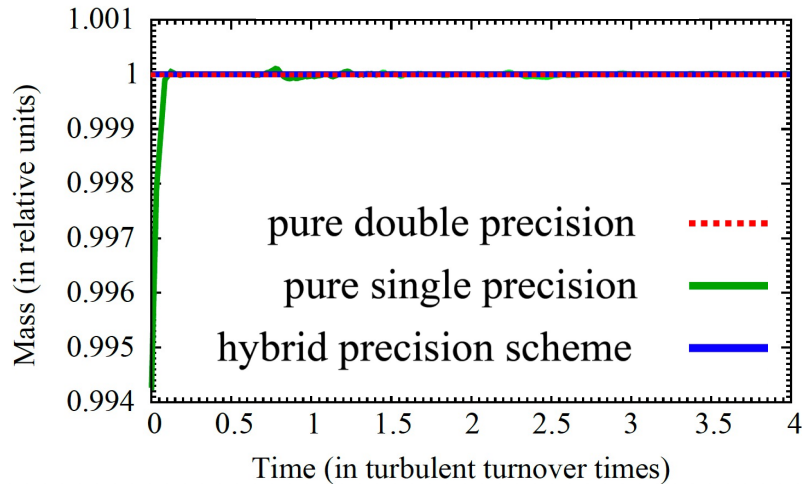
Technical specifications:

- Resolution: **10,048³** grid cells
- 50 Million CPU-h (GCS and NCI)
- 65,536 compute cores
- 2 PB data
- Hybrid precision (SP + specific promotion to DP)

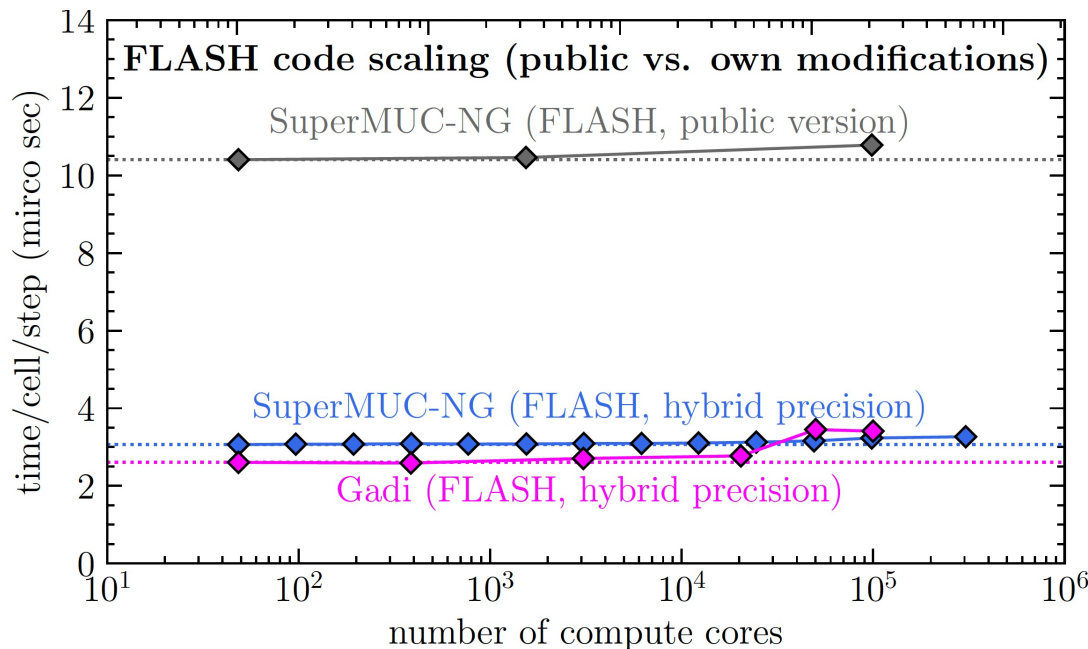
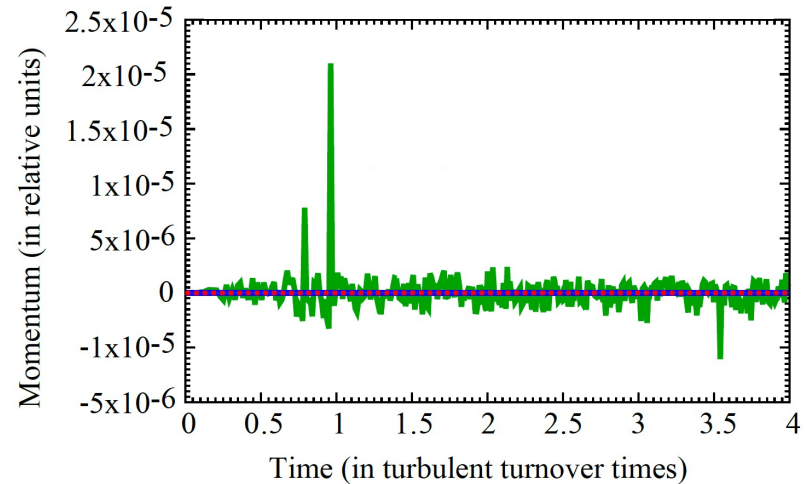


Hybrid precision and code scaling

Mass conservation



Momentum conservation

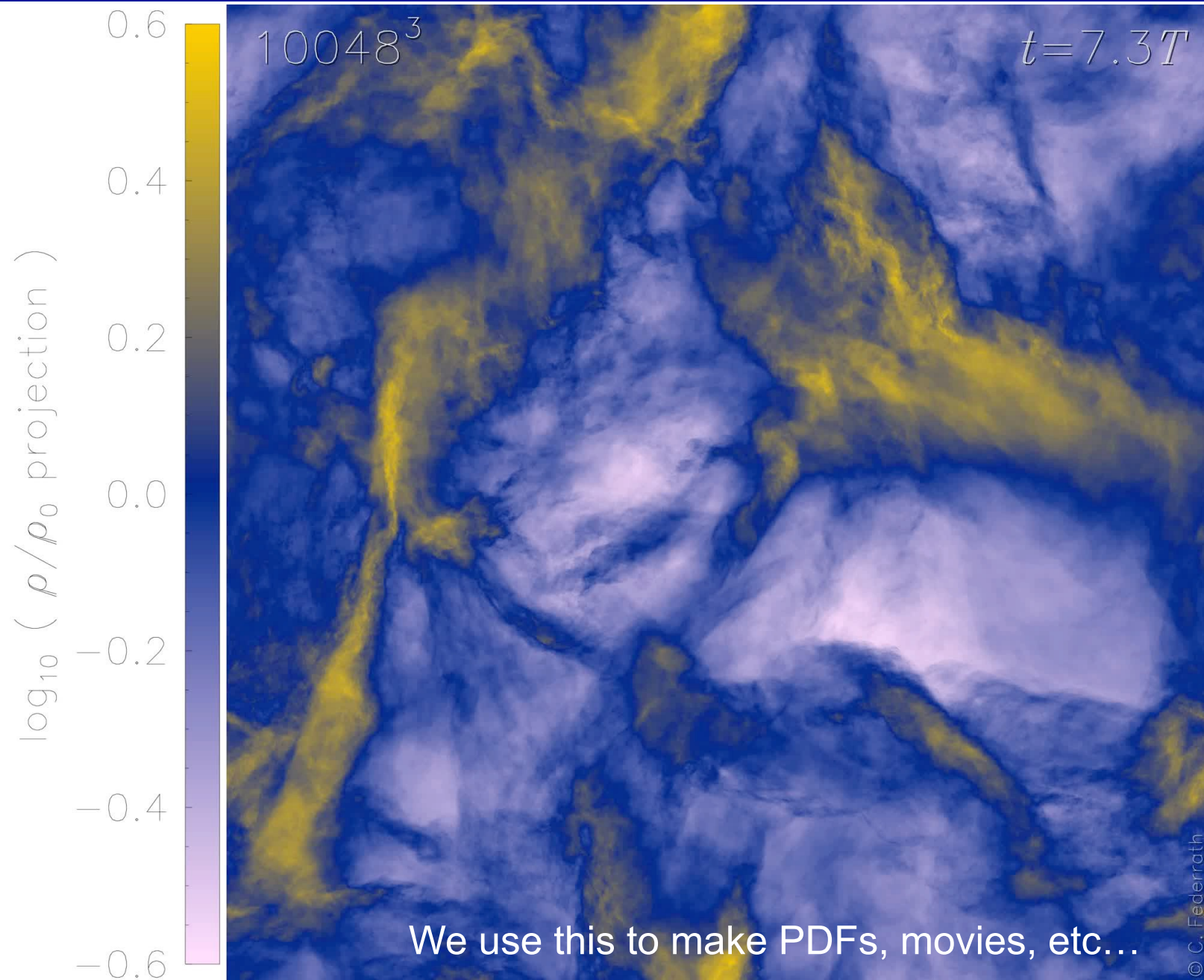


Overall changes to FLASH for this setup resulted in

- 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

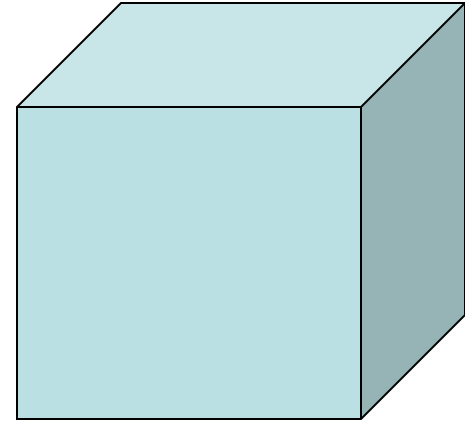
Solenoidal

Compressive

Turbulence driving – solenoidal versus compressive

“Turbulence in a box”

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



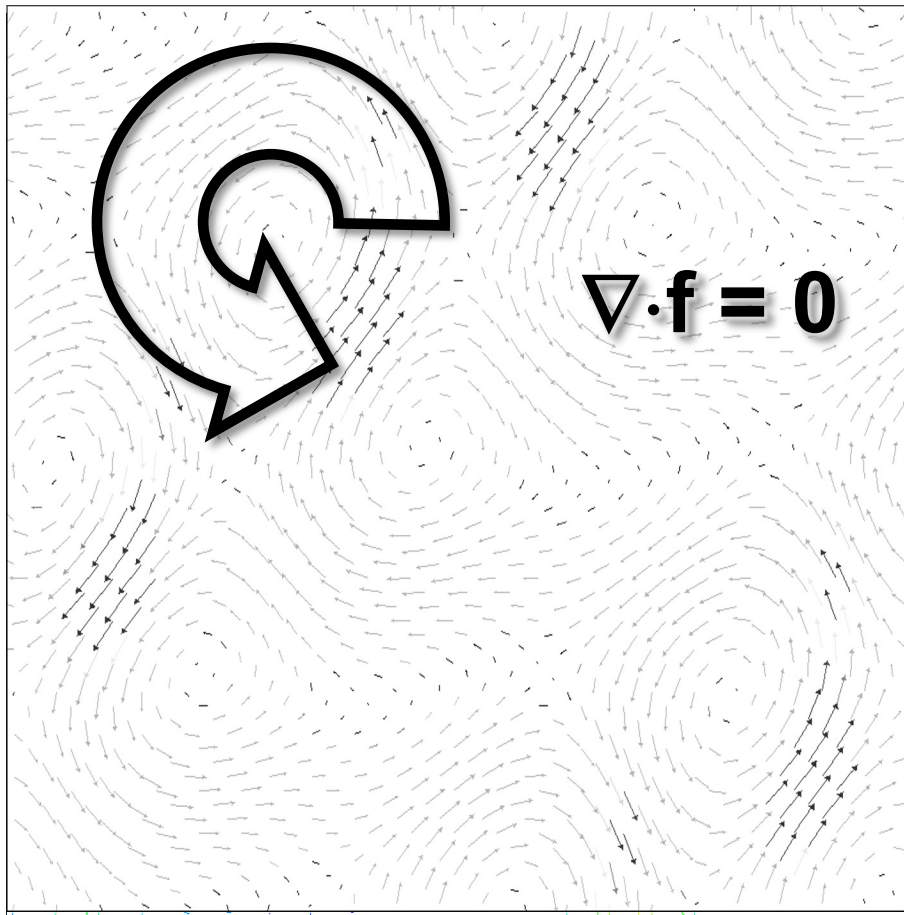
e.g., Vazquez 1994, Padoan+1997, Passot+1998, Stone+1998, Mac Low 1999, Klessen+2000, Ostriker+2001, Heitsch+2001, Cho+2002, Boldyrev+2002, Li+2003, Haugen+2004, Padoan+2004, Jappsen+2005, Ballesteros+2006, Mee+Brandenburg 2006, Kritsuk+2007, Kowal+2007, Dib+2008, Offner+2008, Schmidt+2009, Burkhart+2009, 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

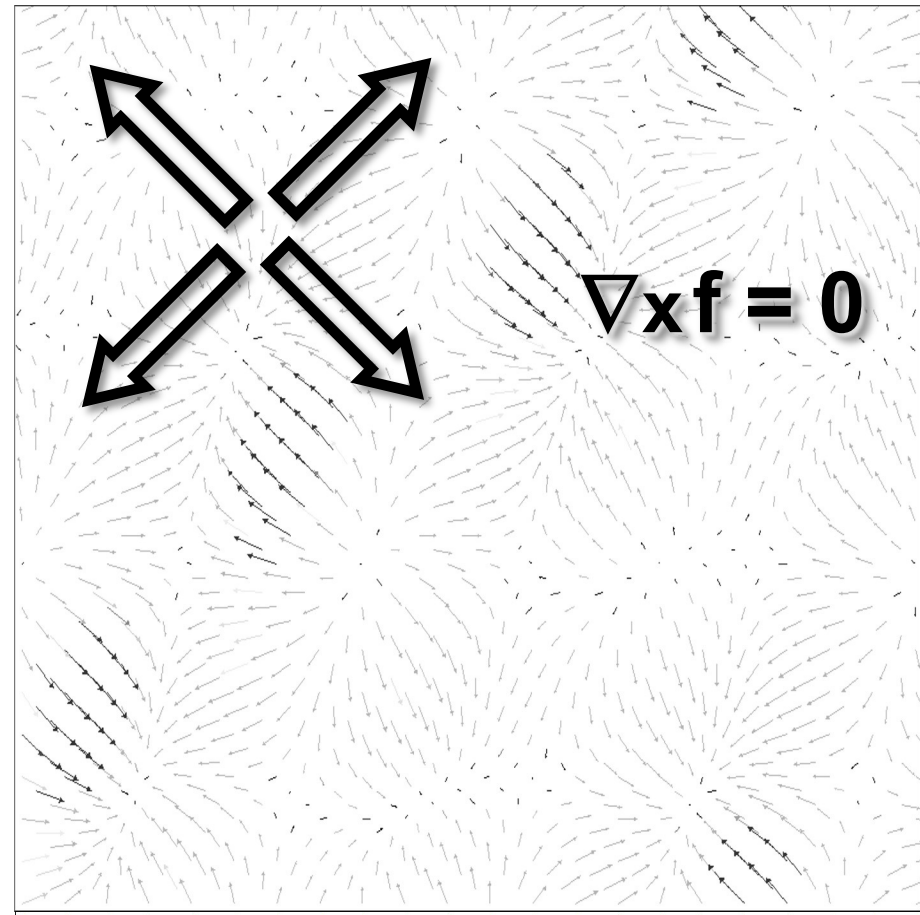
Ornstein-Uhlenbeck process (stochastic process with autocorrelation time)

→ **forcing varies smoothly in space and time,**
following a well-defined random process

Solenoidal forcing



Compressive forcing

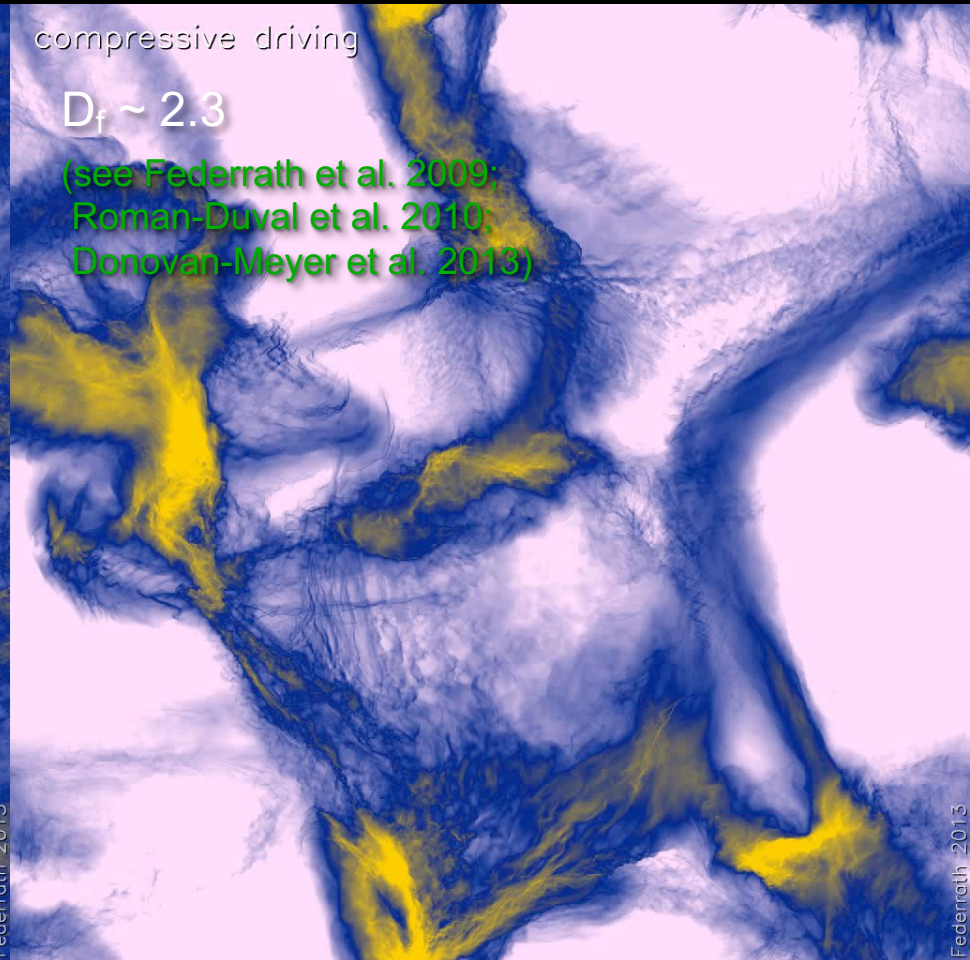
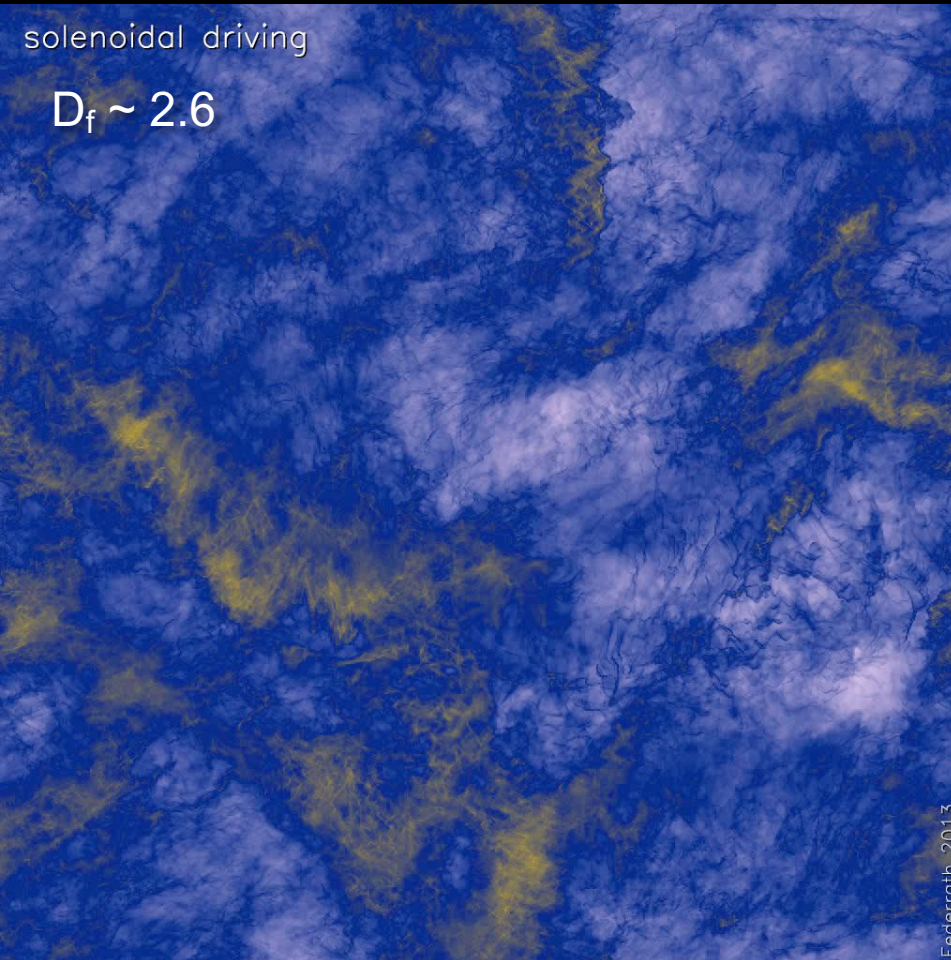


Turbulence driving – solenoidal versus compressive

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

solenoidal forcing

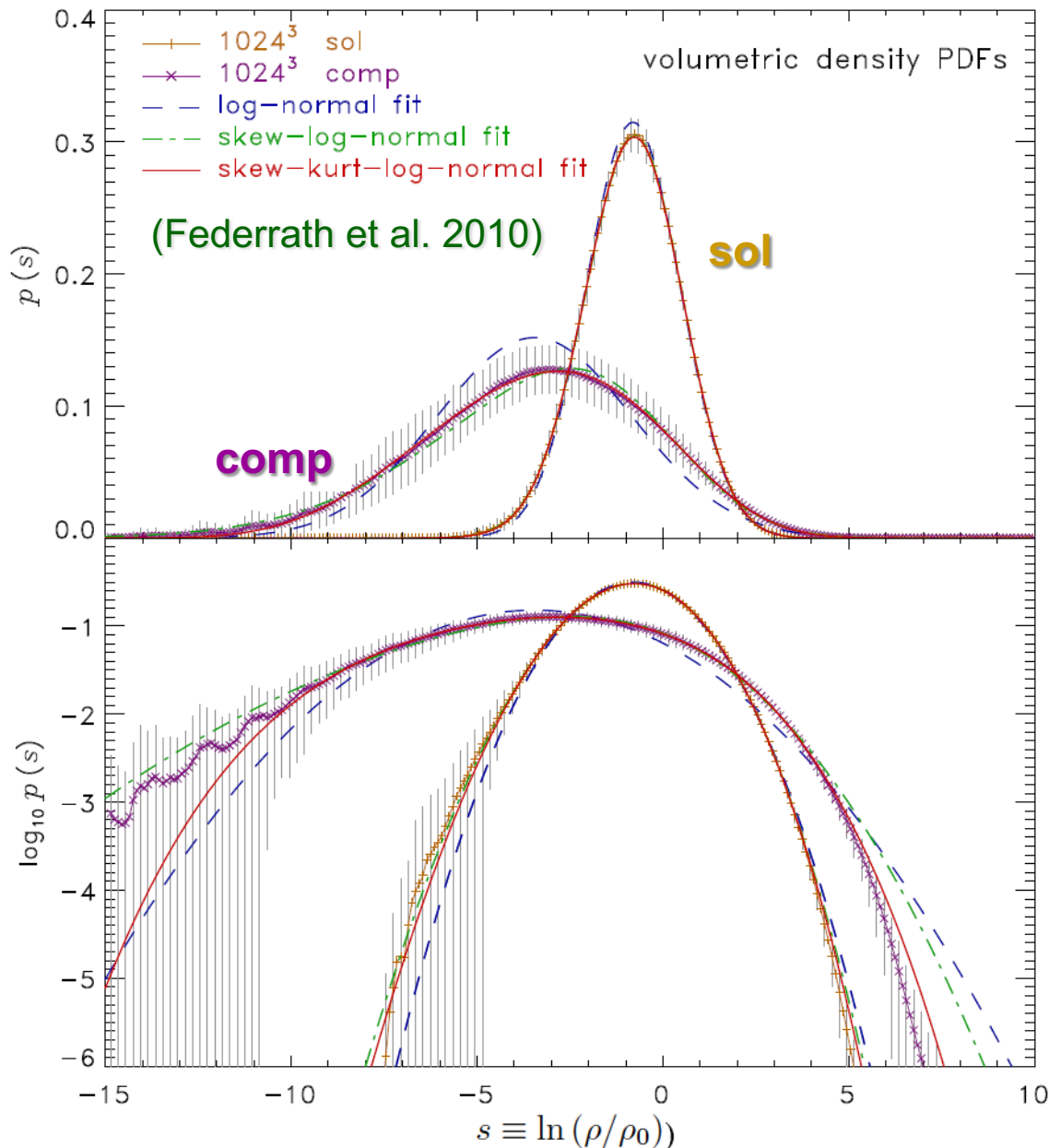
compressive forcing



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:

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

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

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

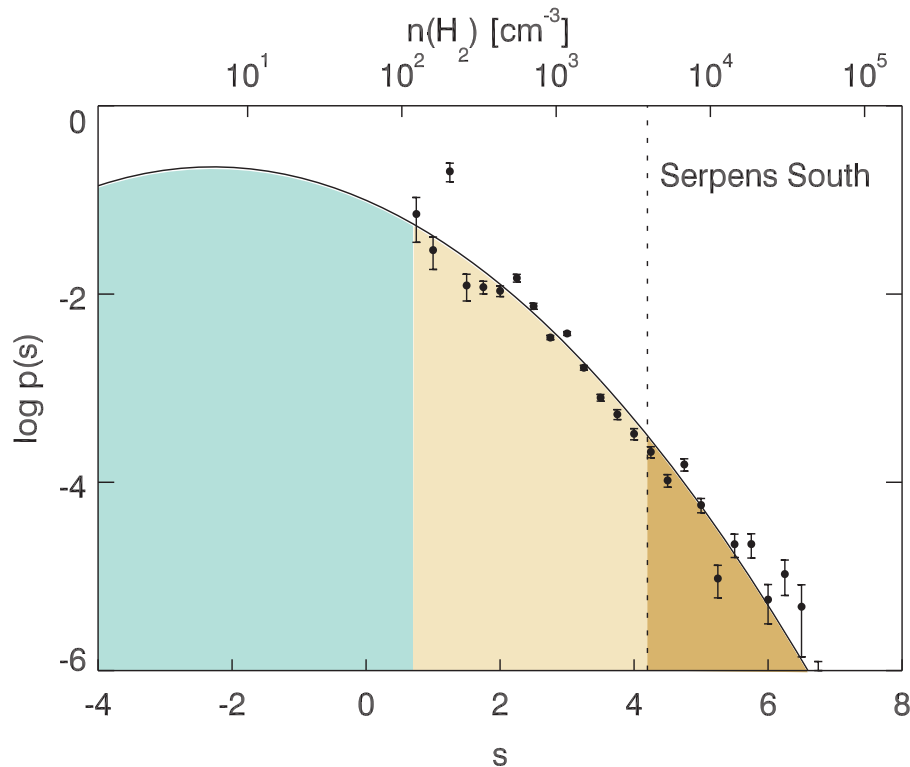
$$\sigma_s^2 = \ln(1 + b^2 \mathcal{M}^2)$$

$$\begin{aligned} & \longrightarrow b = 1/3 \text{ (sol)} \\ & \longrightarrow b = 1 \text{ (comp)} \end{aligned}$$

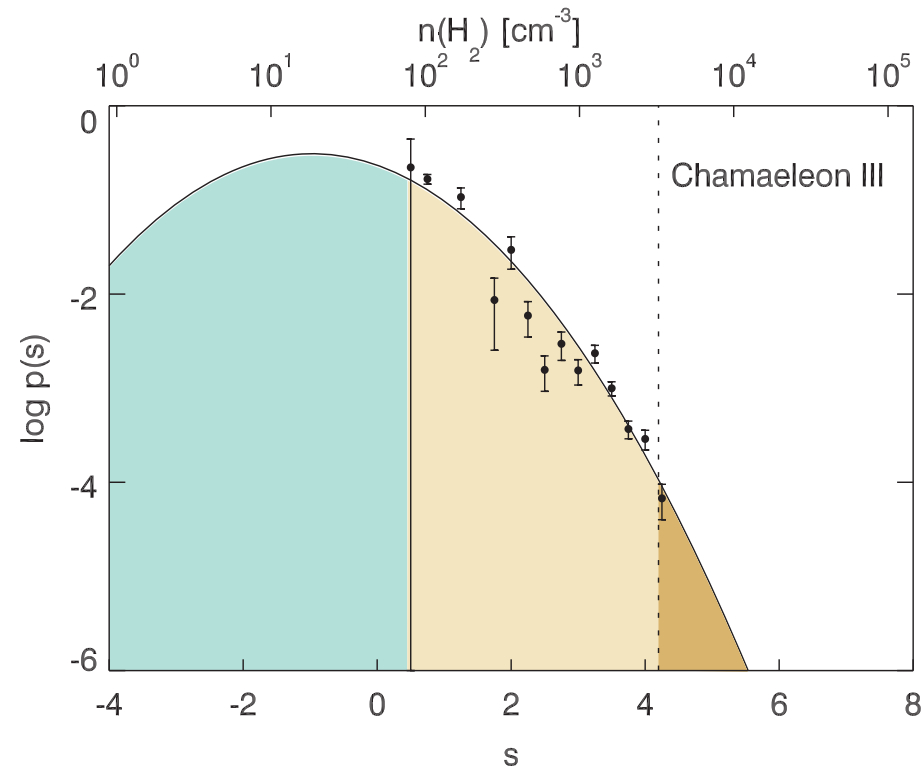
Federrath et al. (2008, 2010);
Price et al. (2011); Konstandin et al. (2012);
Molina et al. (2012); Federrath & Banerjee
(2014); Nolan et al. (2015)

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)

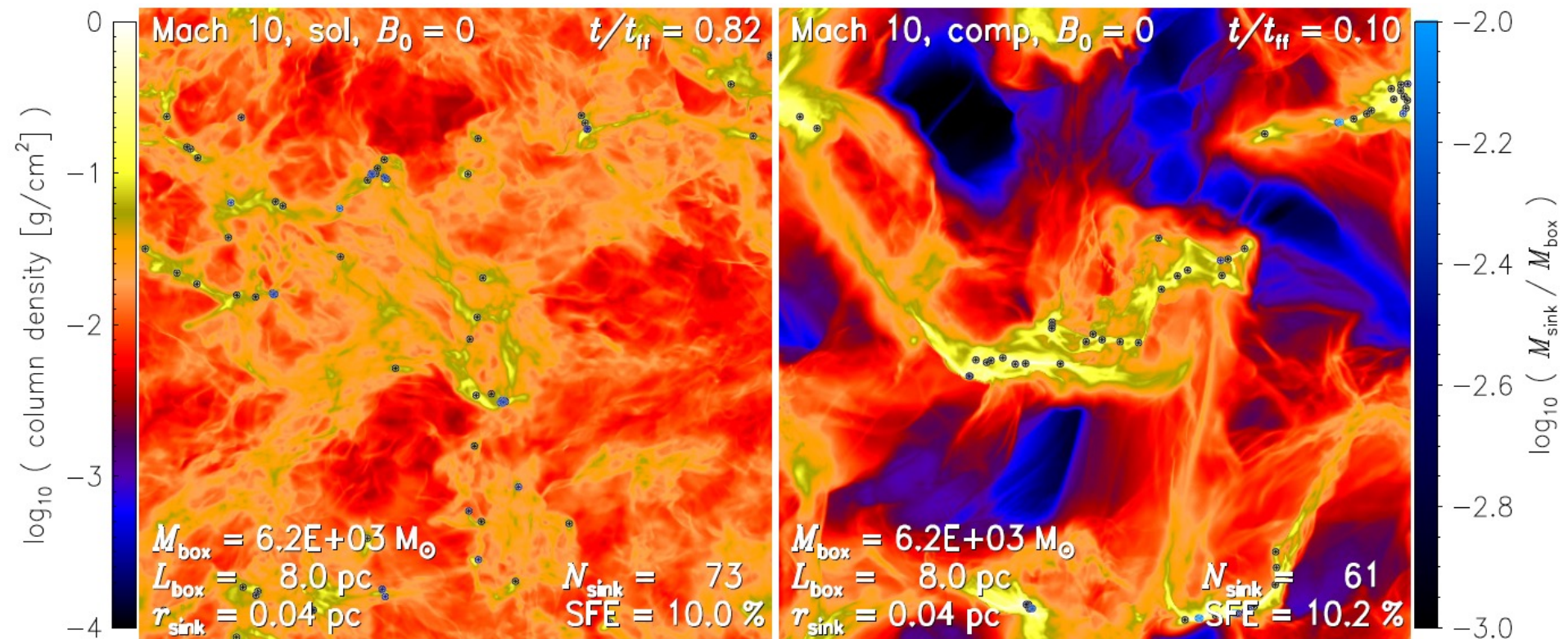
Density Distribution → Star Formation Rate

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

SFR_{ff} (theory) = 0.15

x20

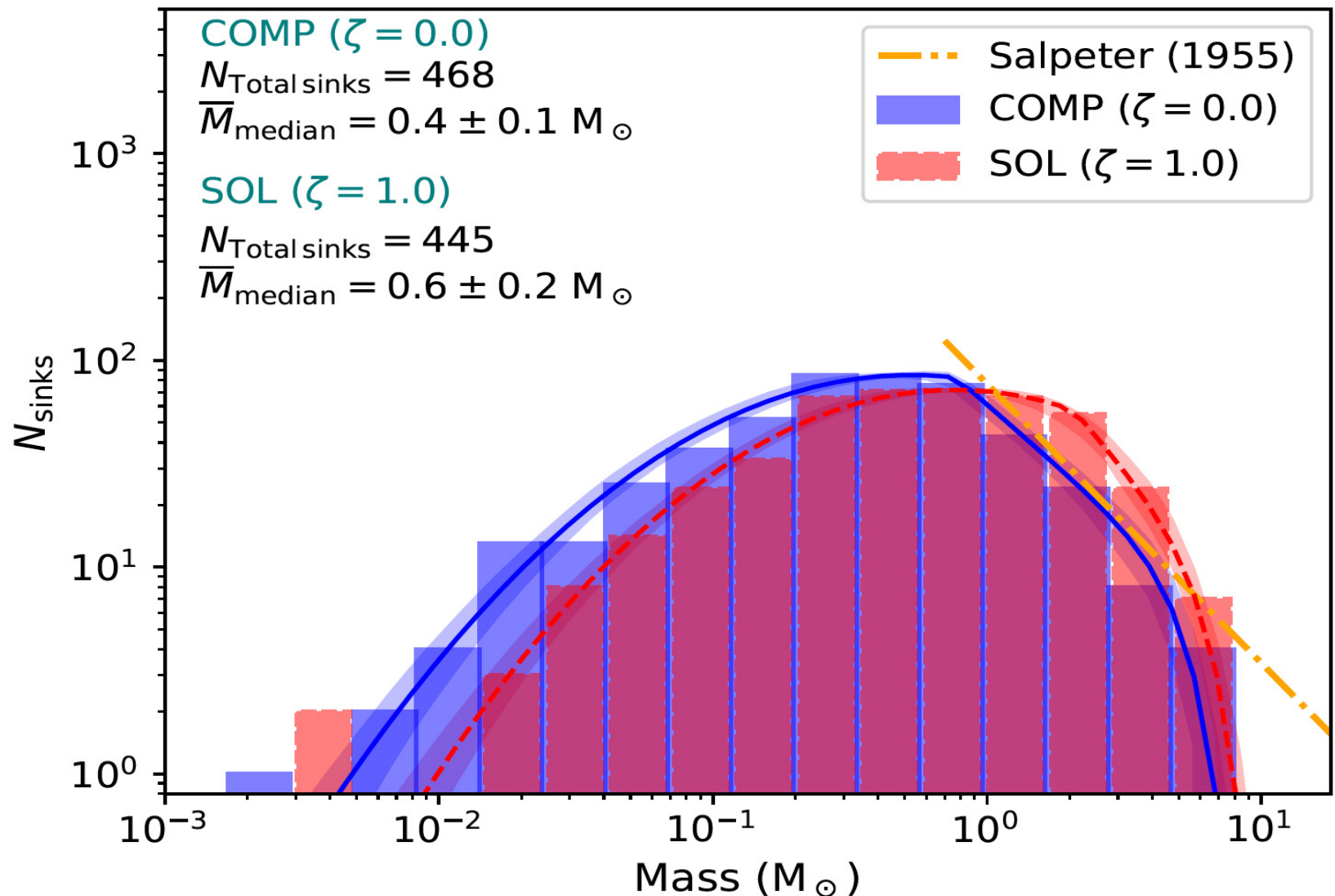
x15

SFR_{ff} (simulation) = 2.8

SFR_{ff} (theory) = 2.3

Turbulence driving is a key parameter for star formation!

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:

SFR ~ Mass/time freefall time mass fraction

$$\begin{aligned} \text{SFR}_{\text{ff}} &= \epsilon \int_{s_{\text{crit}}}^{\infty} \frac{t_{\text{ff}}(\rho_0)}{t_{\text{ff}}(\rho)} \frac{\rho}{\rho_0} p(s) \, ds = \epsilon \int_{s_{\text{crit}}}^{\infty} \exp\left(\frac{3}{2}s\right) p(s) \, ds \\ &= \frac{\epsilon}{2} \exp\left(\frac{3}{8}\sigma_s^2\right) \left[1 + \text{erf}\left(\frac{\sigma_s^2 - s_{\text{crit}}}{\sqrt{2}\sigma_s^2}\right) \right] \end{aligned}$$

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

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

MAGNETIC FIELD:

$$P_{\text{th}} \rightarrow P_{\text{th}} + P_{\text{mag}} \quad \mathcal{M} \rightarrow \mathcal{M} (1 + \beta^{-1})^{-1/2}$$

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

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

$$\text{SFR}_{\text{ff}} = \text{SFR}_{\text{ff}}(\alpha_{\text{vir}}, b, \mathcal{M}, \beta)$$

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

$2E_{\text{kin}}/E_{\text{grav}}$

forcing

Mach number

plasma $\beta = P_{\text{th}}/P_{\text{mag}}$

Federrath & Klessen (2012)

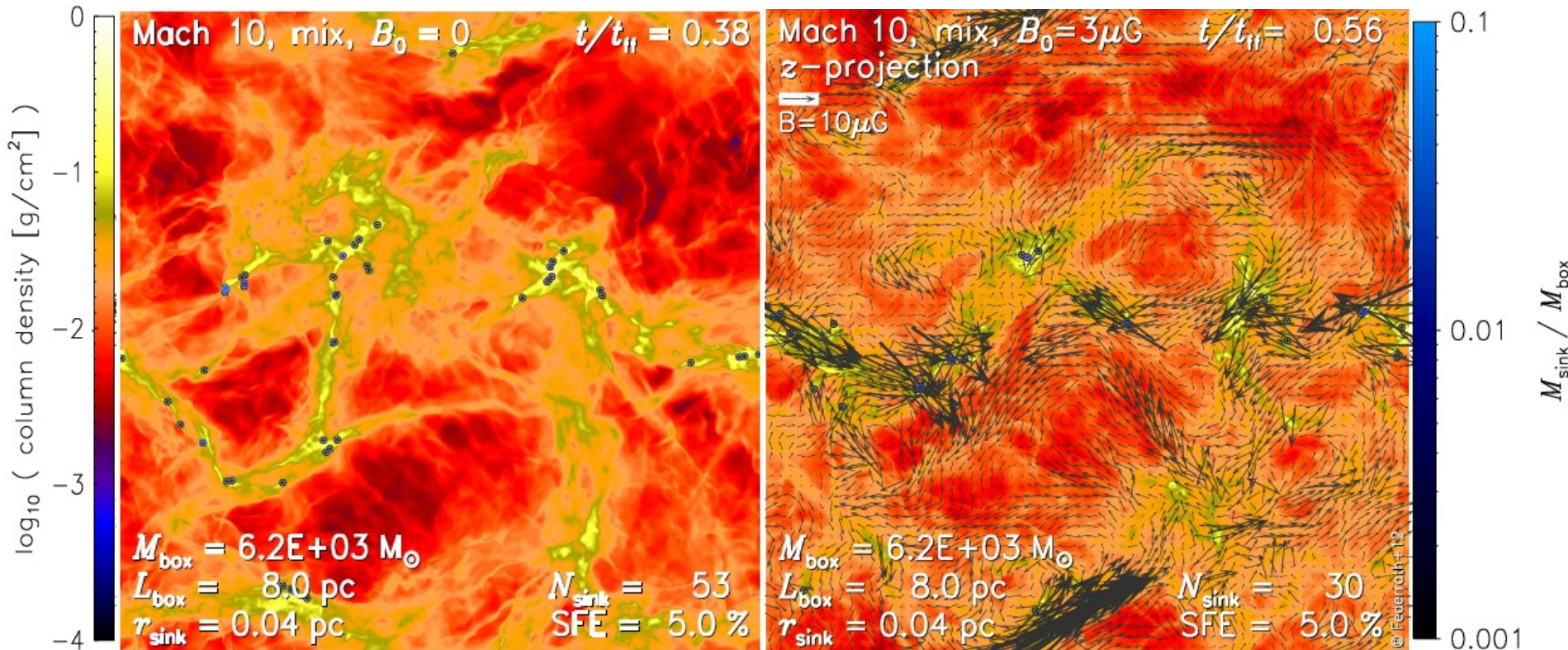
The Star Formation Rate – Magnetic fields

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

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

$B=0$ ($M_A=\infty$, $\beta=\infty$)

$B=3\mu\text{G}$ ($M_A=2.7$, $\beta=0.2$)



SFR_{ff} (simulation) = **0.46**

x0.63

SFR_{ff} (simulation) = **0.29**

SFR_{ff} (theory) = **0.45**

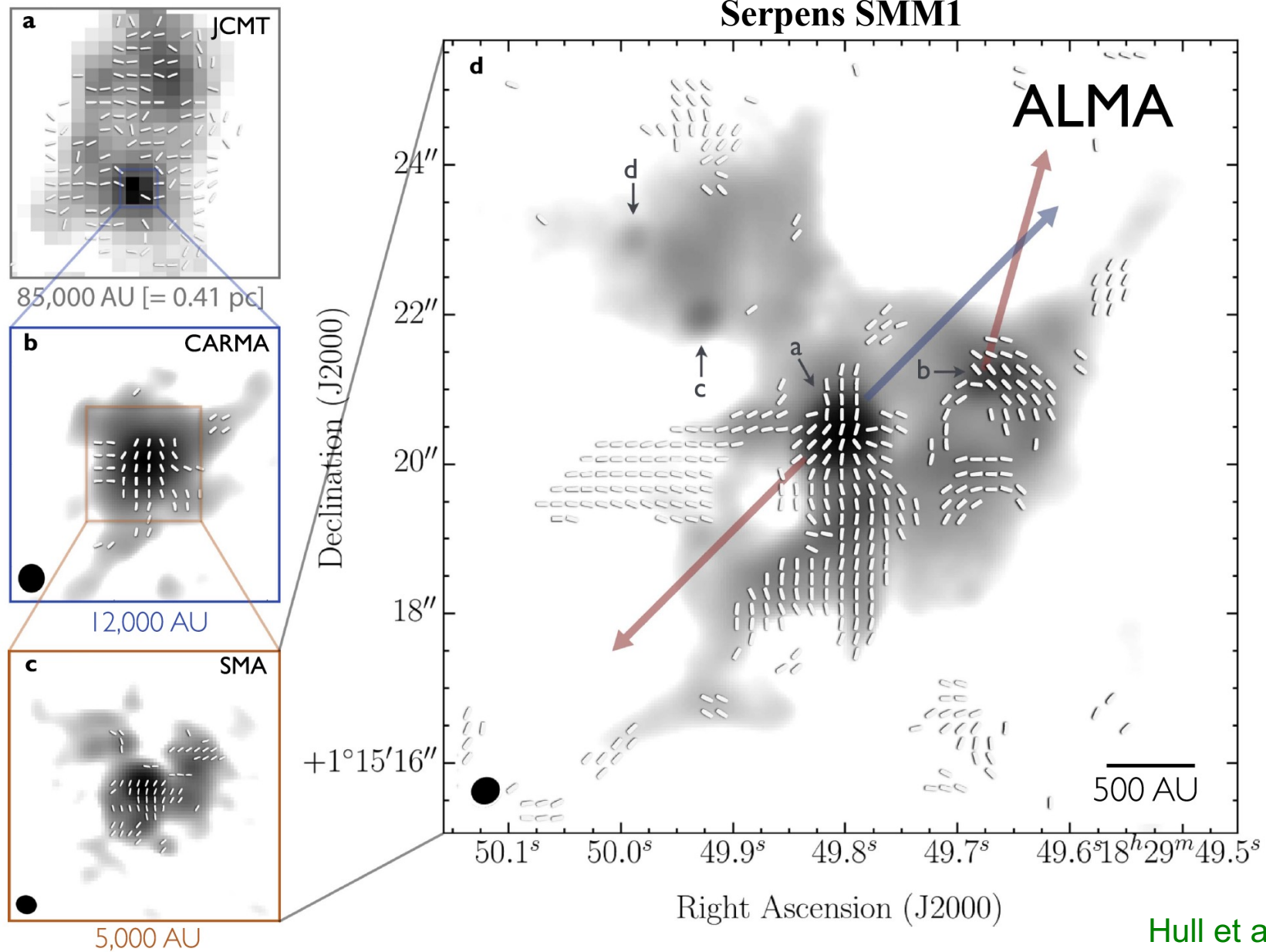
x0.40

SFR_{ff} (theory) = **0.18**

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

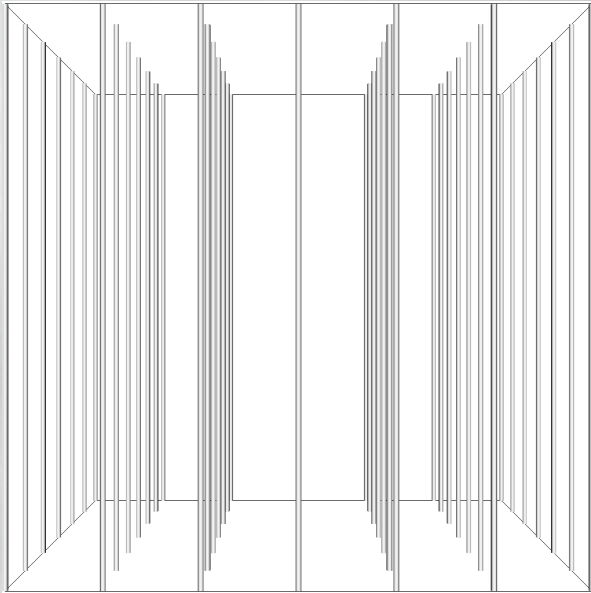
Federrath & Klessen (2012)

The role of magnetic field structure

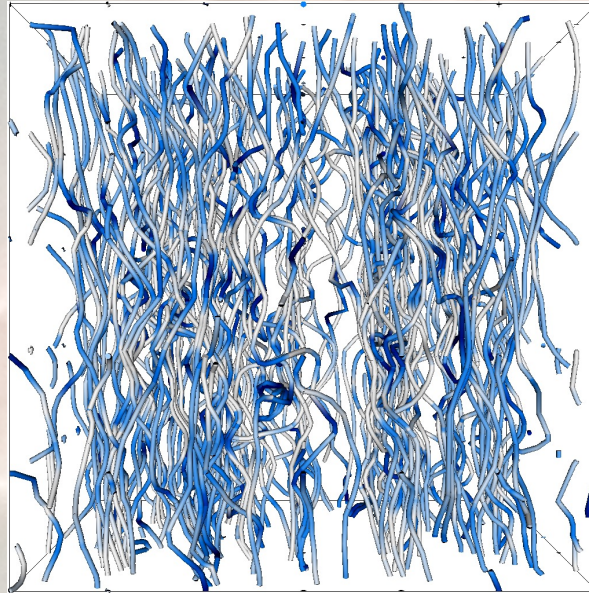


The role of magnetic field structure for jet launching

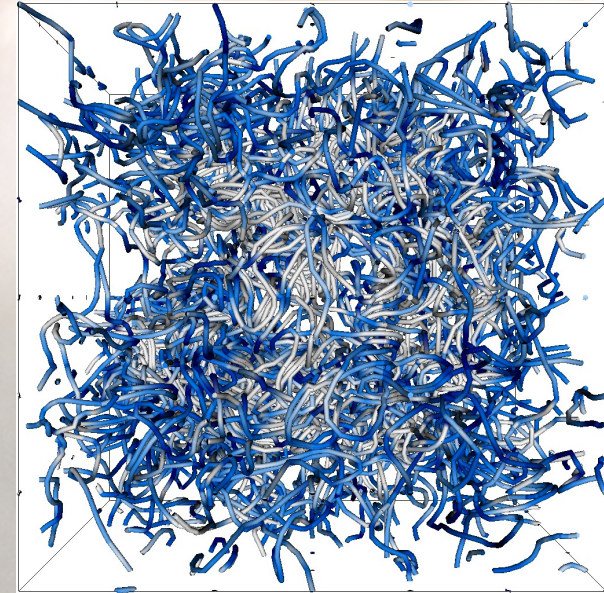
Uniform Magnetic Field



Partially Turbulent Field



Fully Turbulent Field



Gerrard et al. (2019)

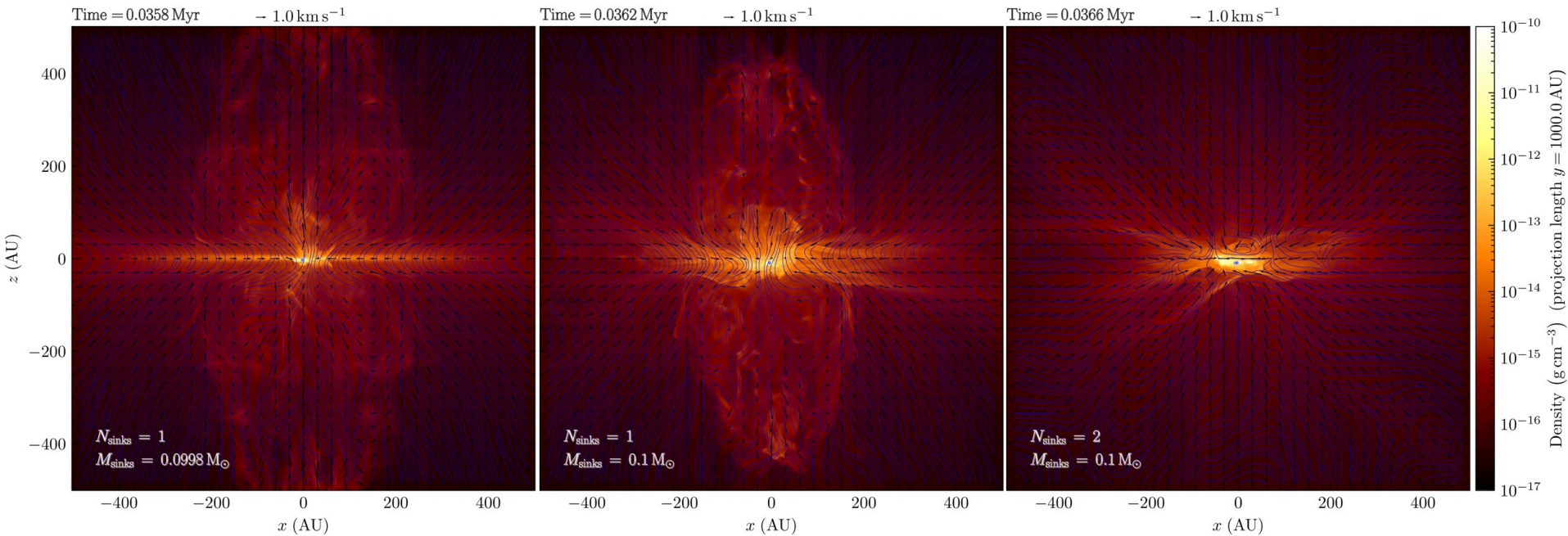
The role of magnetic field structure for jet launching

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)

Turbulence → Stars → Feedback

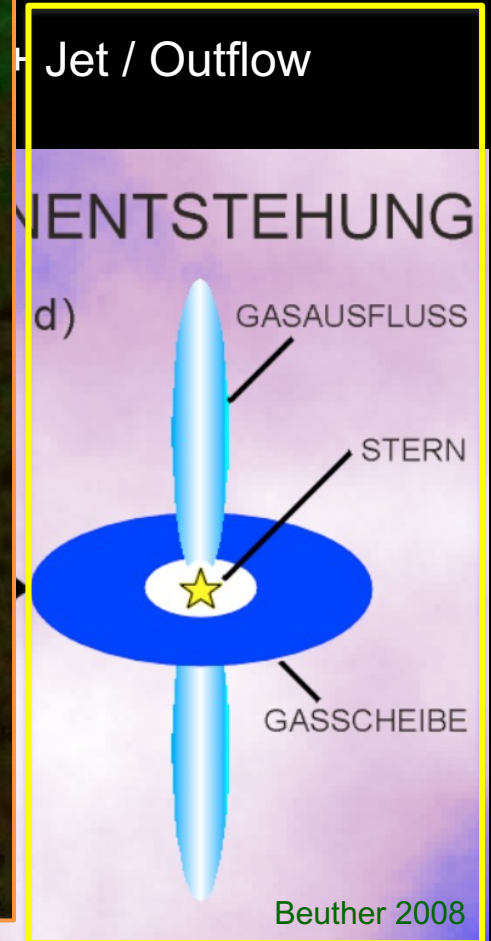
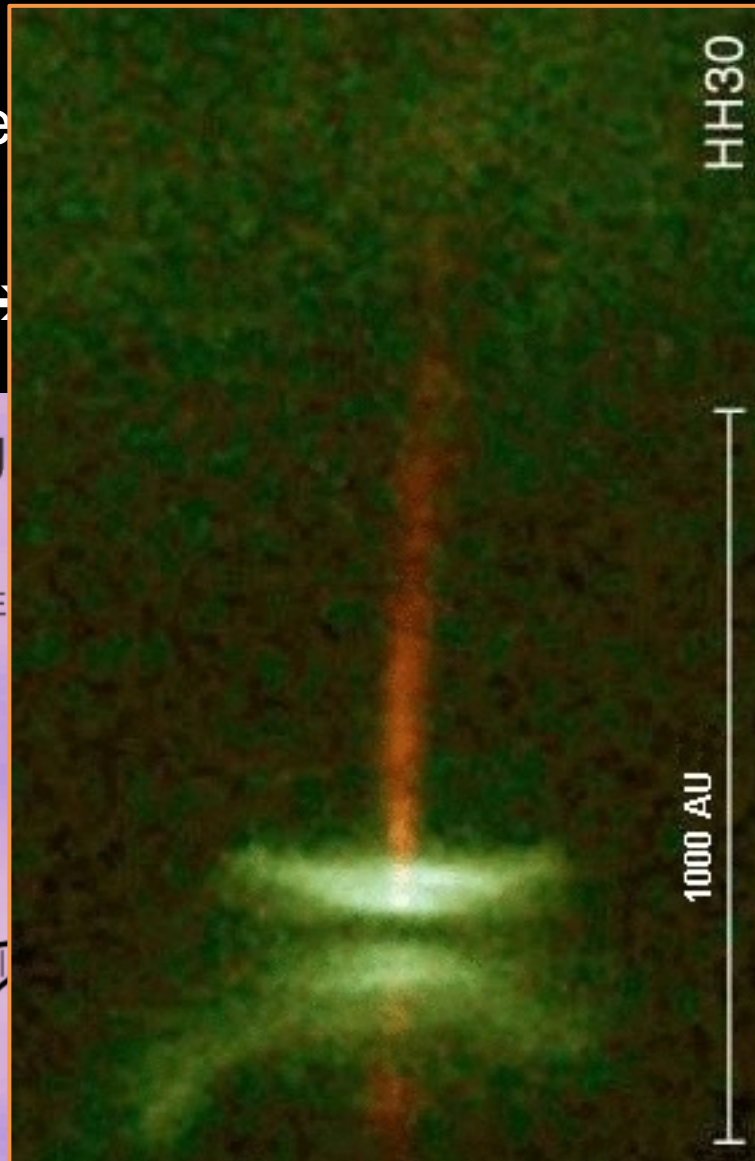
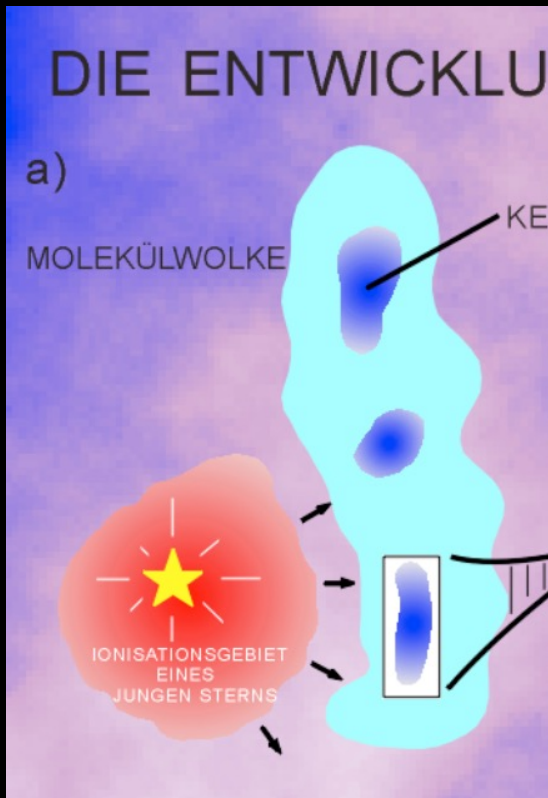


The

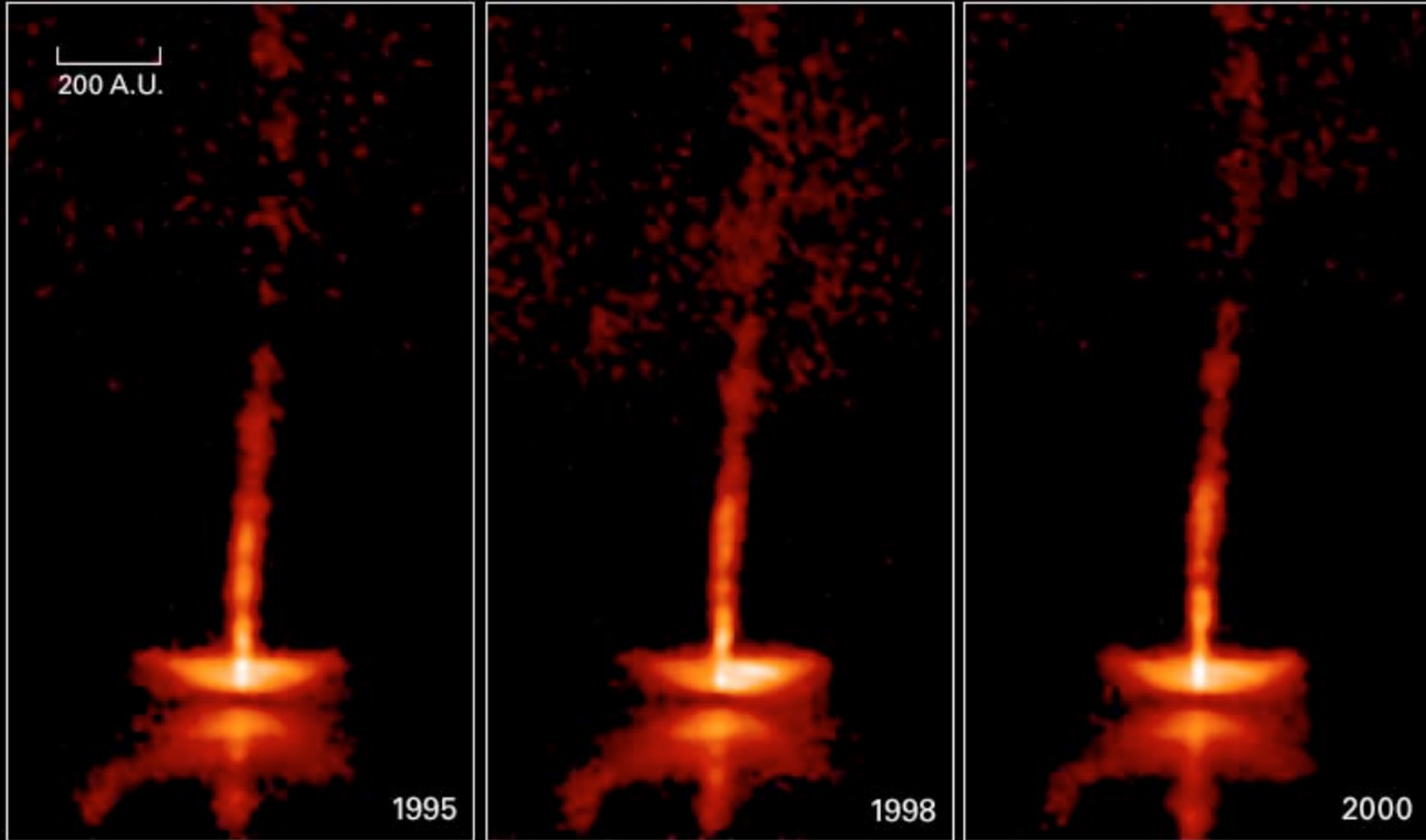
Clouds



Jet / Outflow



Jets and Outflows



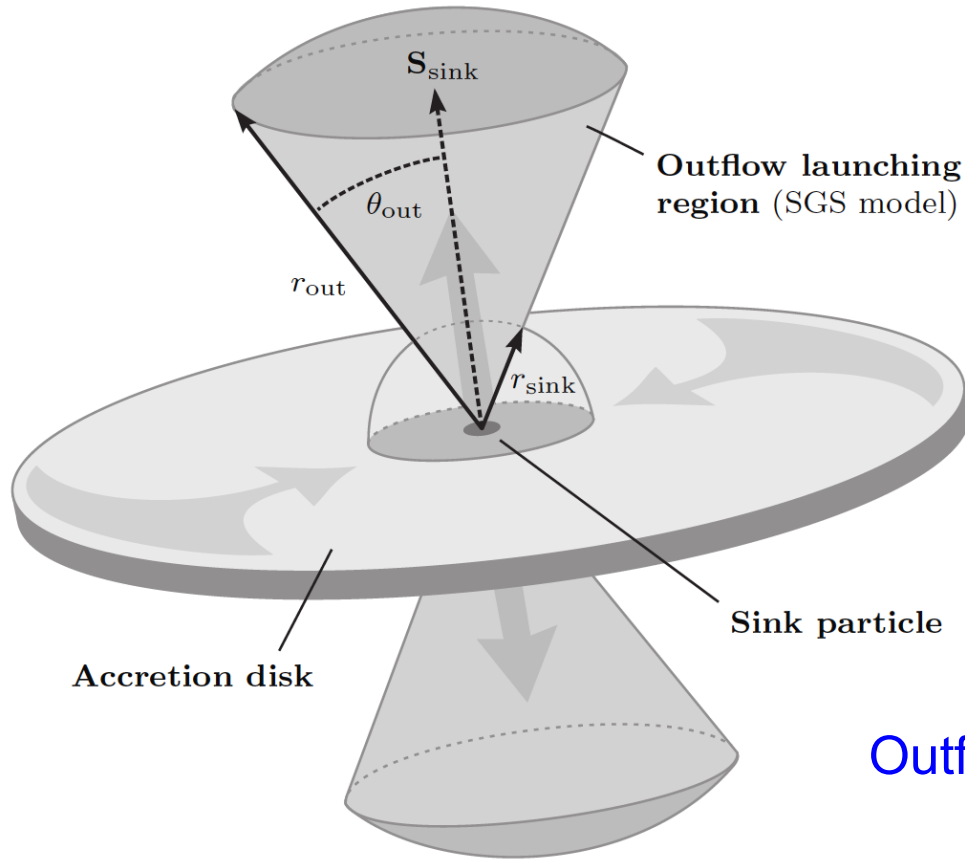
The Dynamic HH 30 Disk and Jet

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	θ_{out}	30°	[1]
Mass Transfer Fraction	f_m	0.3	[2]
Jet Speed Normalization ^a	$ \mathbf{V}_{\text{out}} $	100 km s^{-1}	[3]
Angular Momentum Fraction	f_a	0.9	[4]
Outflow Radius	r_{out}	$16 \Delta x$	Section 4

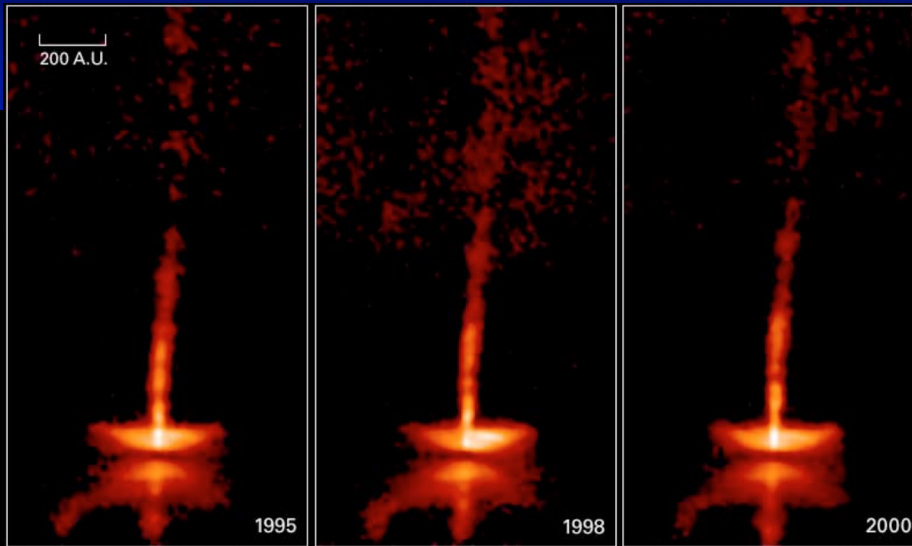
Notes. ^a The outflow velocities are dynamically computed according to the Kepler speed at the footpoint of the jet, $|\mathbf{V}_{\text{out}}| = 100 \text{ km s}^{-1} (M_{\text{sink}}/0.5 M_\odot)^{1/2}$ (see Equation 13). References: [1] Blandford & Payne (1982); Appenzeller & Mundt (1989); Camenzind (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:
$$M_{\text{out}} = f_m \dot{M}_{\text{acc}} \Delta t$$

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

Outflow angular momentum:
$$\mathbf{L}_{\text{out}} = f_a (\mathbf{S}'_{\text{sink}} - \mathbf{S}_{\text{sink}}) \cdot \mathbf{S}'_{\text{sink}} / |\mathbf{S}'_{\text{sink}}|$$

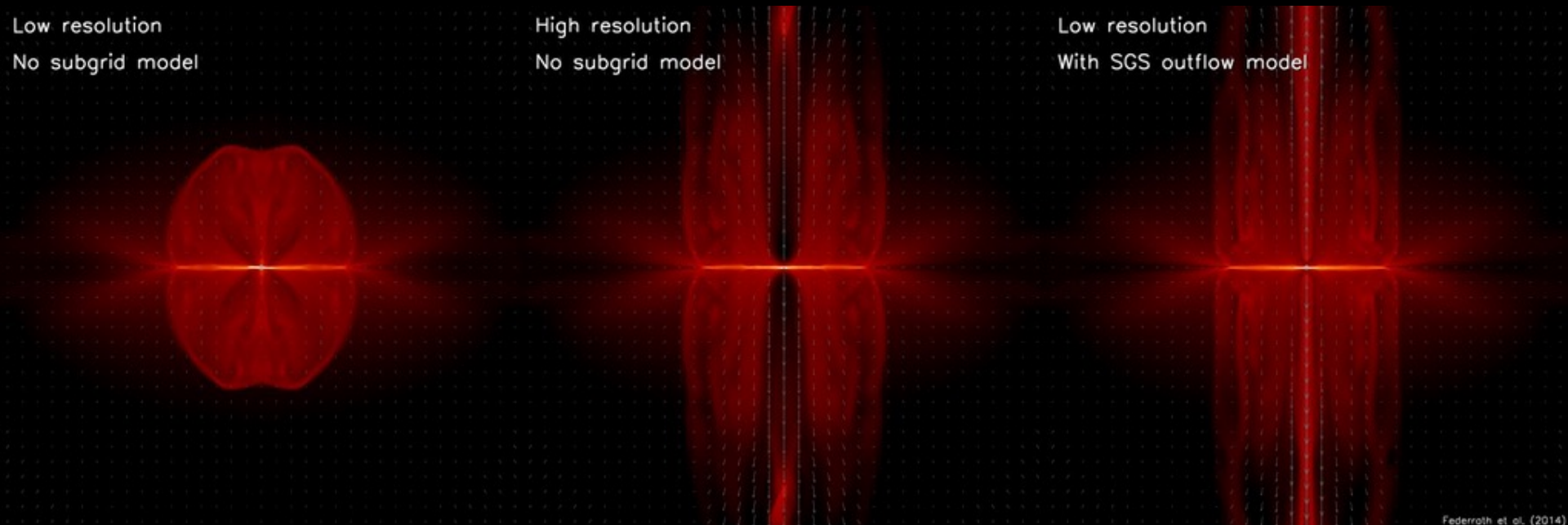
Jet/Outflow Feedback



The Dynamic HH 30 Disk and Jet

HST • WFPC2

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



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

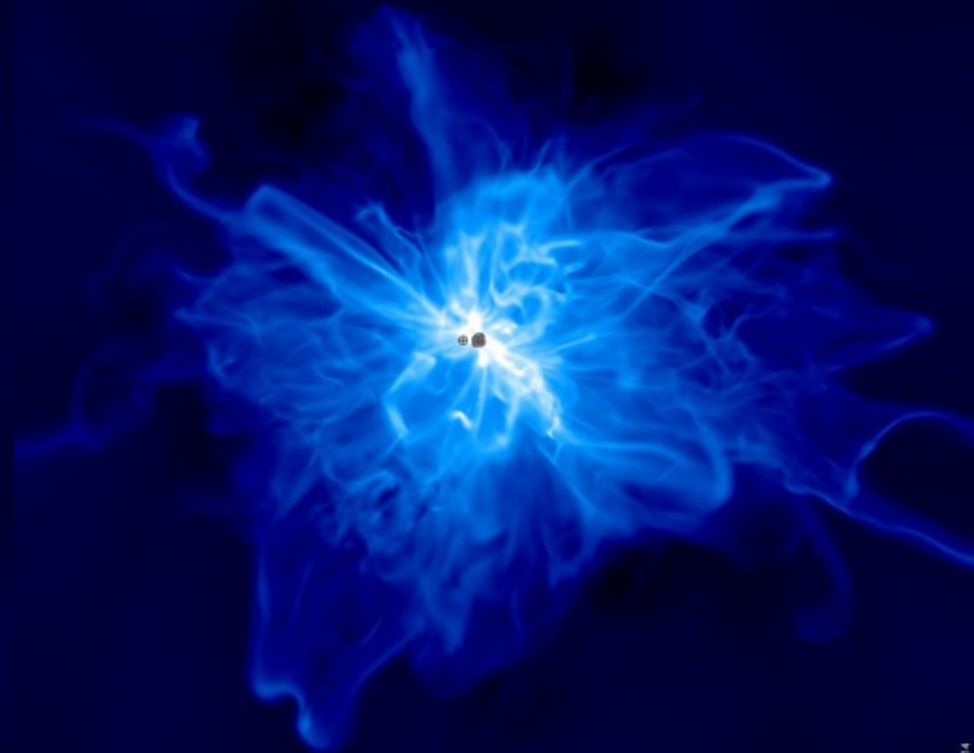
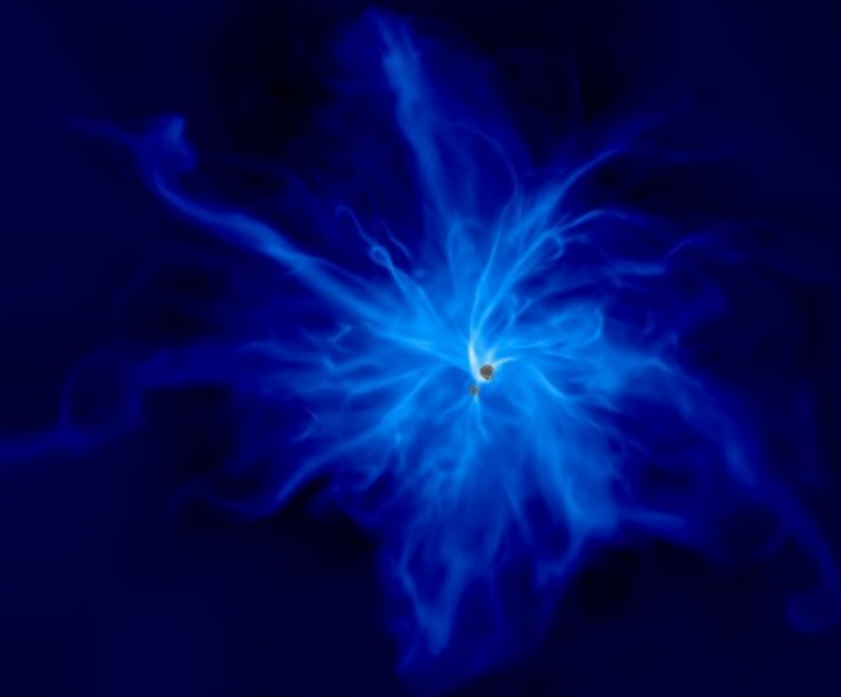
The role of outflow/jet feedback for star cluster formation

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

No outflows

With outflows

$t/t_{\text{ff}} = 1.50$



$N_{\text{sink}} = 23$

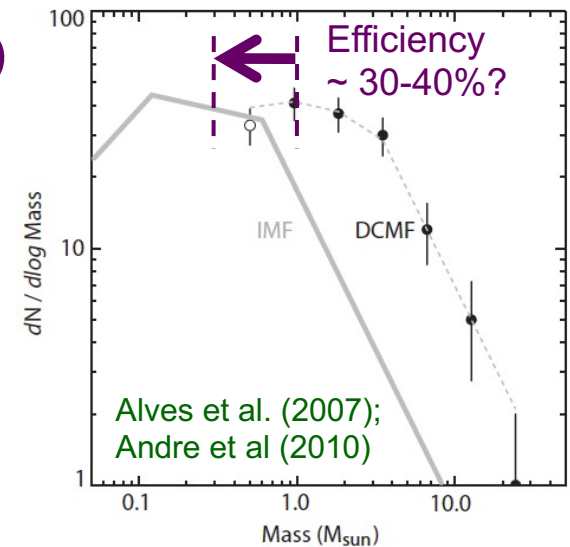
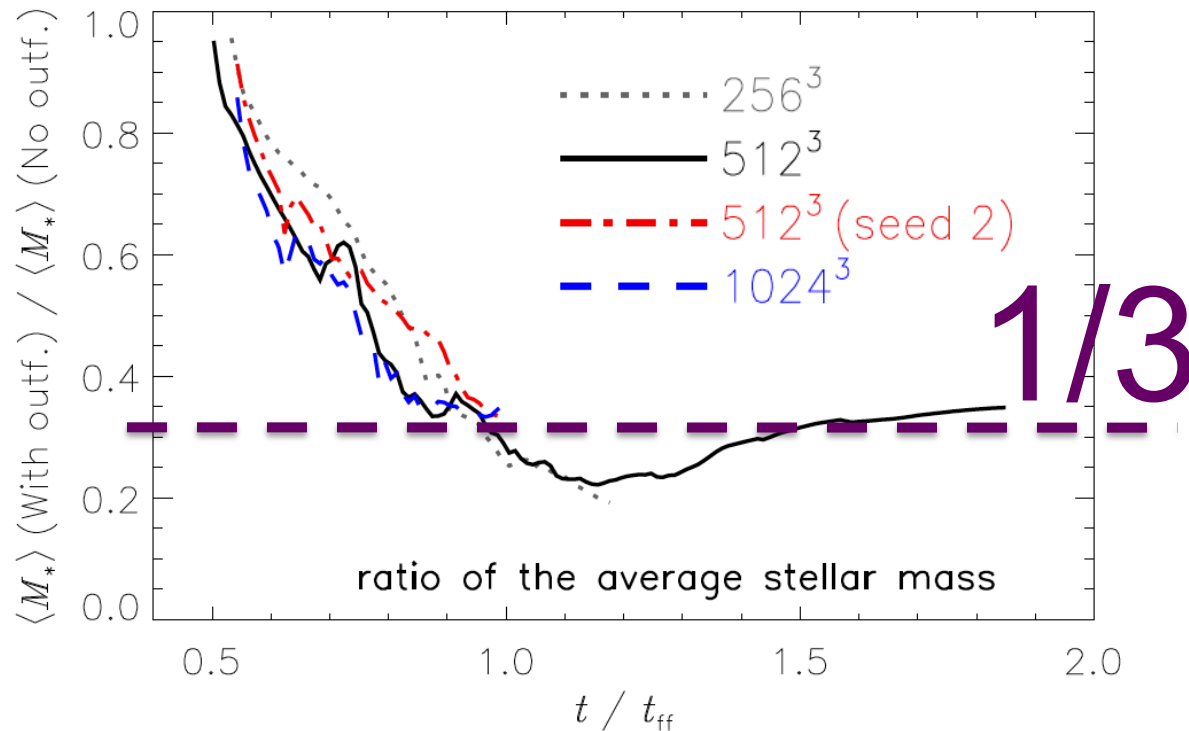
SFE = 87.6% $N_{\text{sink}} = 49$

SFE = 59.0%

Without jets/outflows

With jets/outflows

The role of outflow/jet feedback for star cluster formation

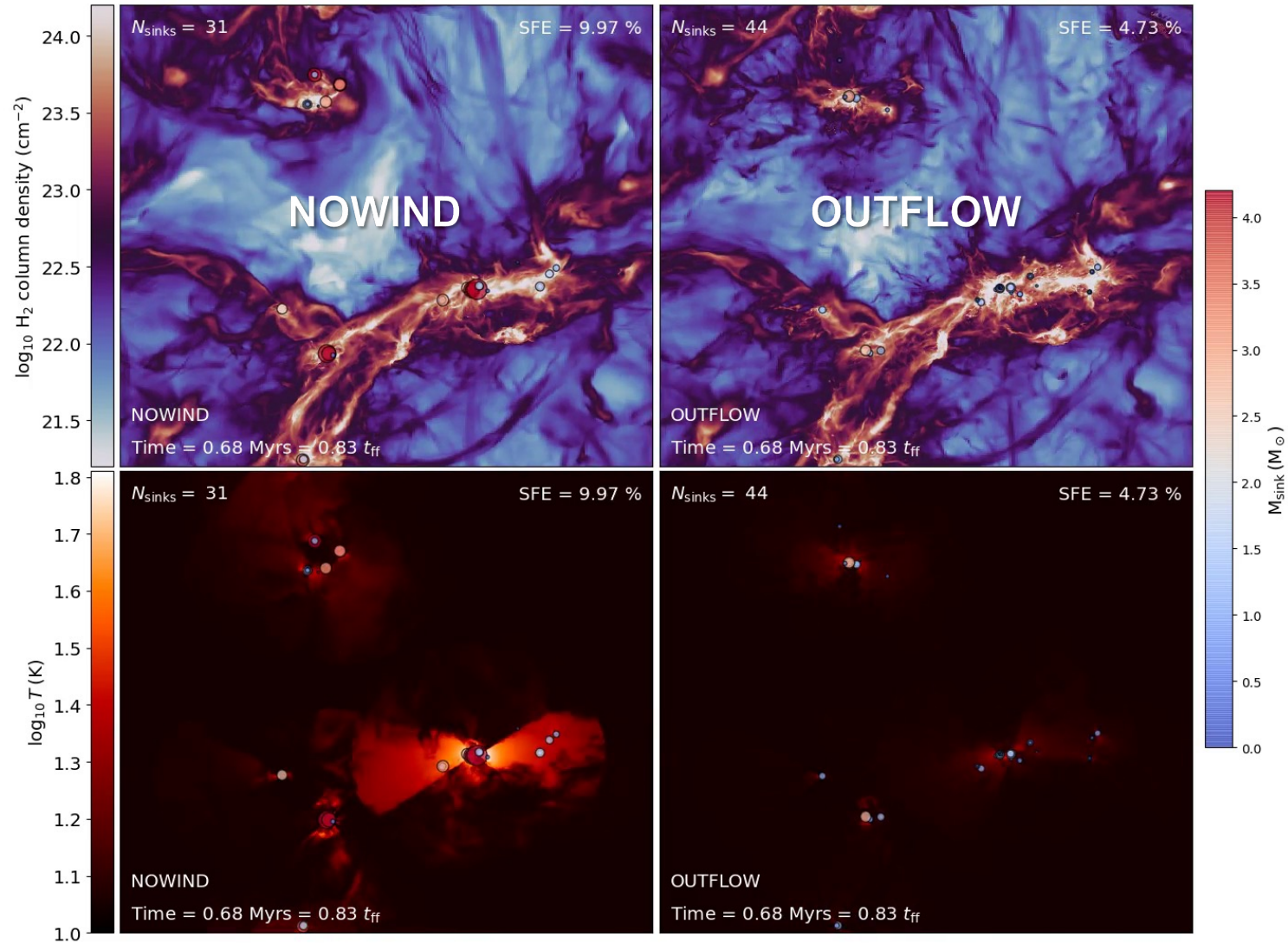


RESULTS:

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

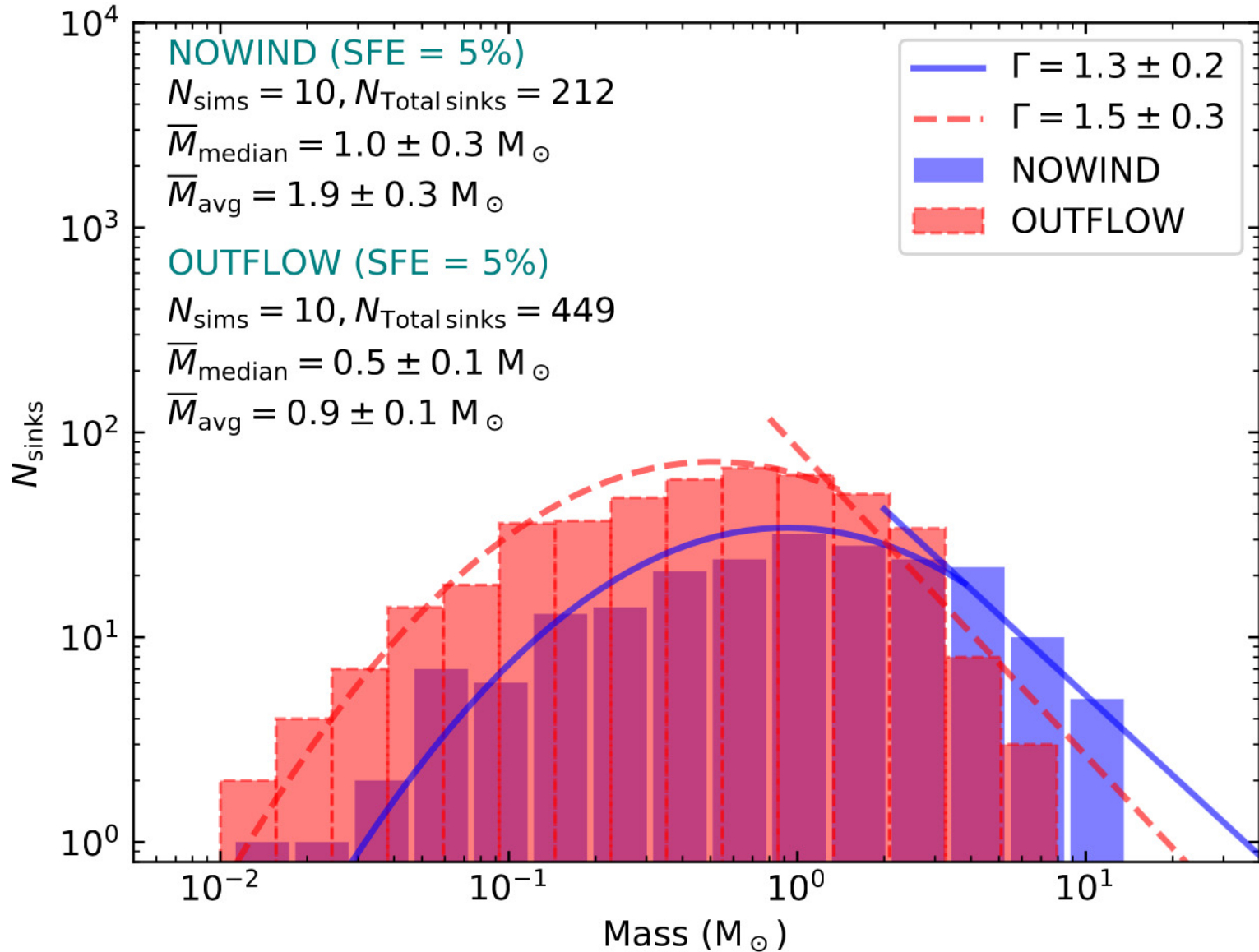
Role of Jet/Outflow Feedback for the IMF

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

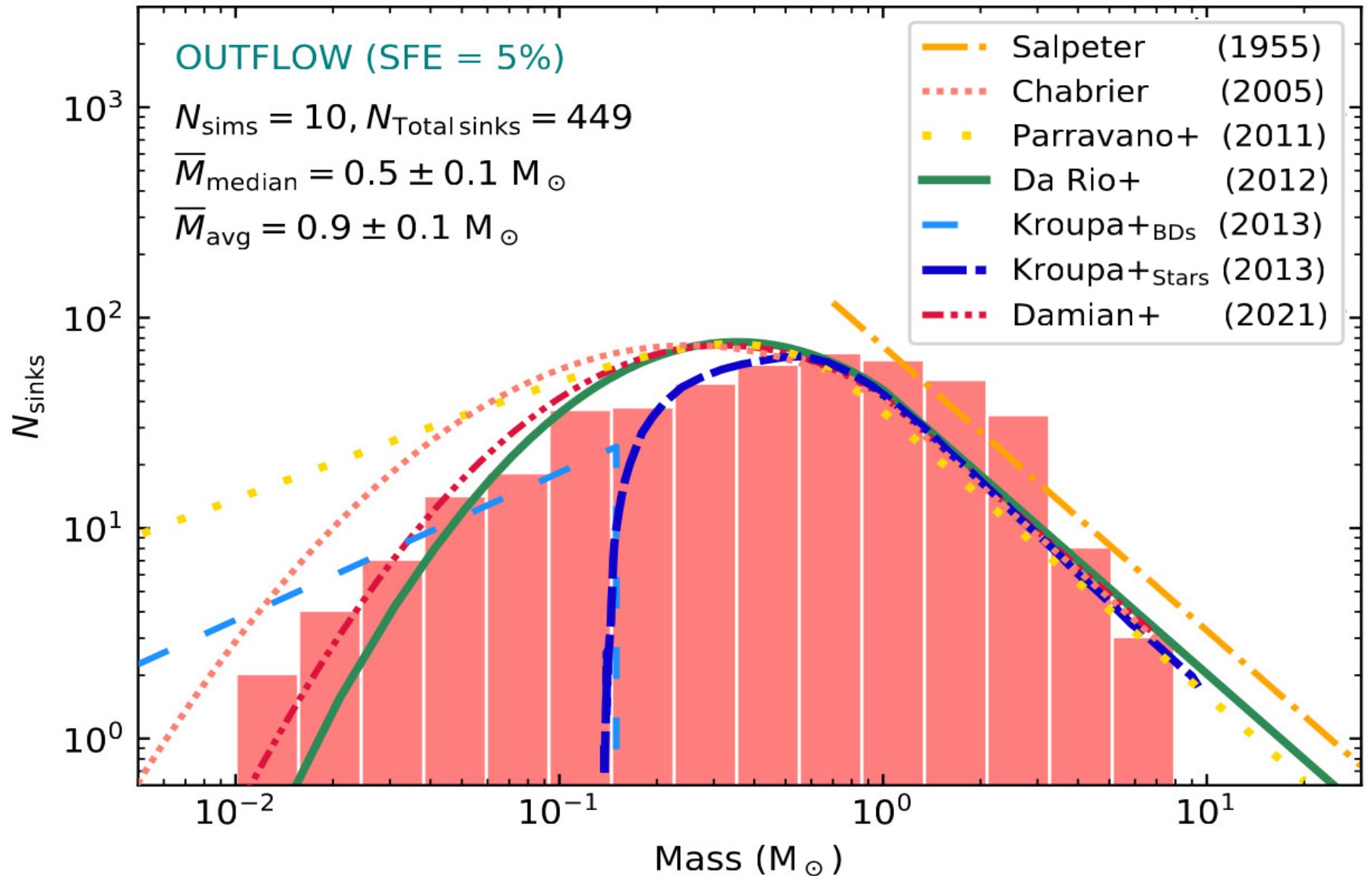


(Mathew & Federrath 2021)

Role of Jet/Outflow Feedback for the IMF



Role of Jet/Outflow Feedback for the IMF



(Mathew & Federrath 2021)



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

Astronomical Computing

ASTR4004 / ASTR8004

NEXT:

Setting up your computer, Bash and shell scripting...

Start by going through the prerequisites:

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

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>

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>