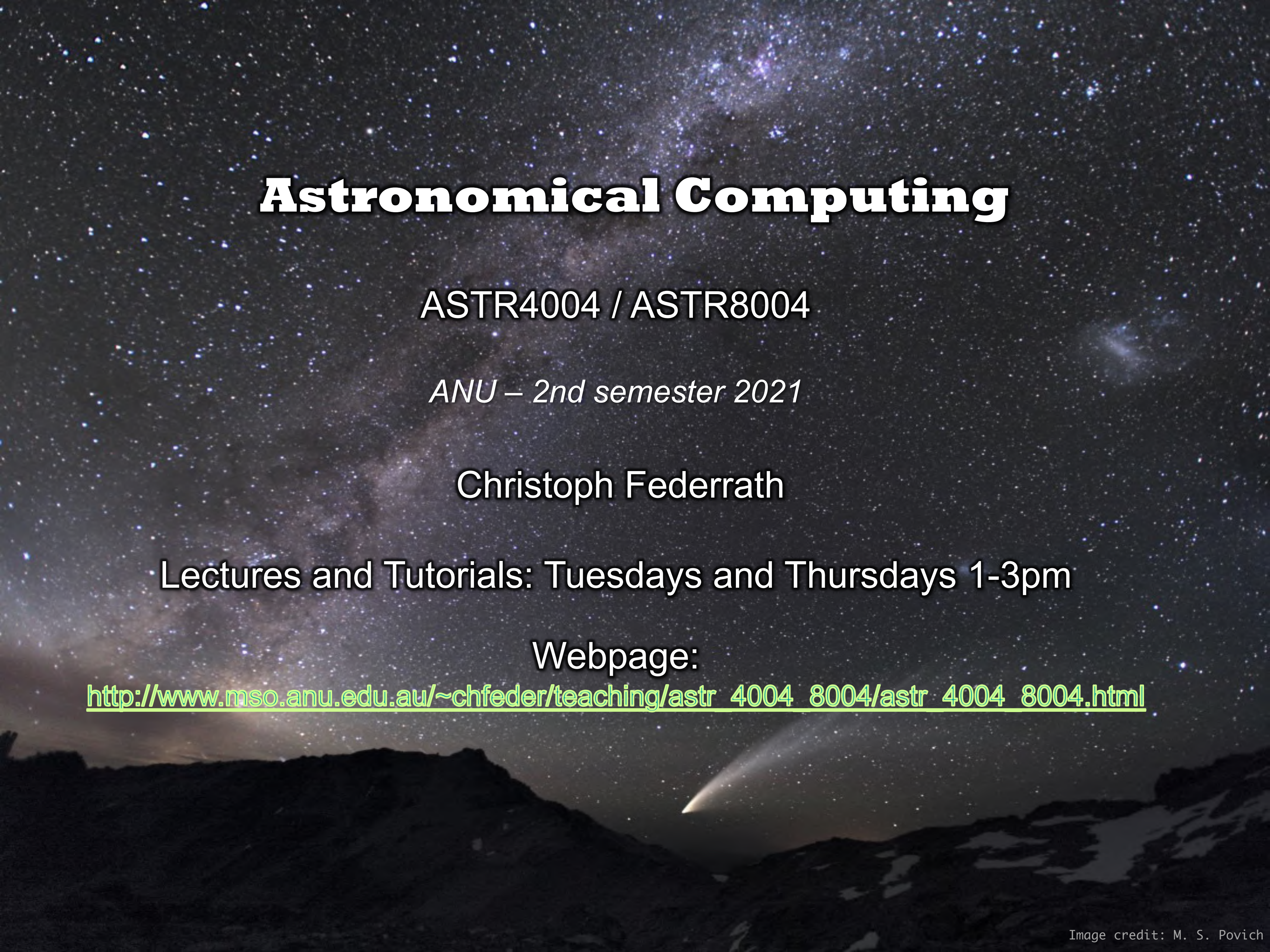


Astronomical Computing

ASTR4004 / ASTR8004

ANU – 2nd semester 2021

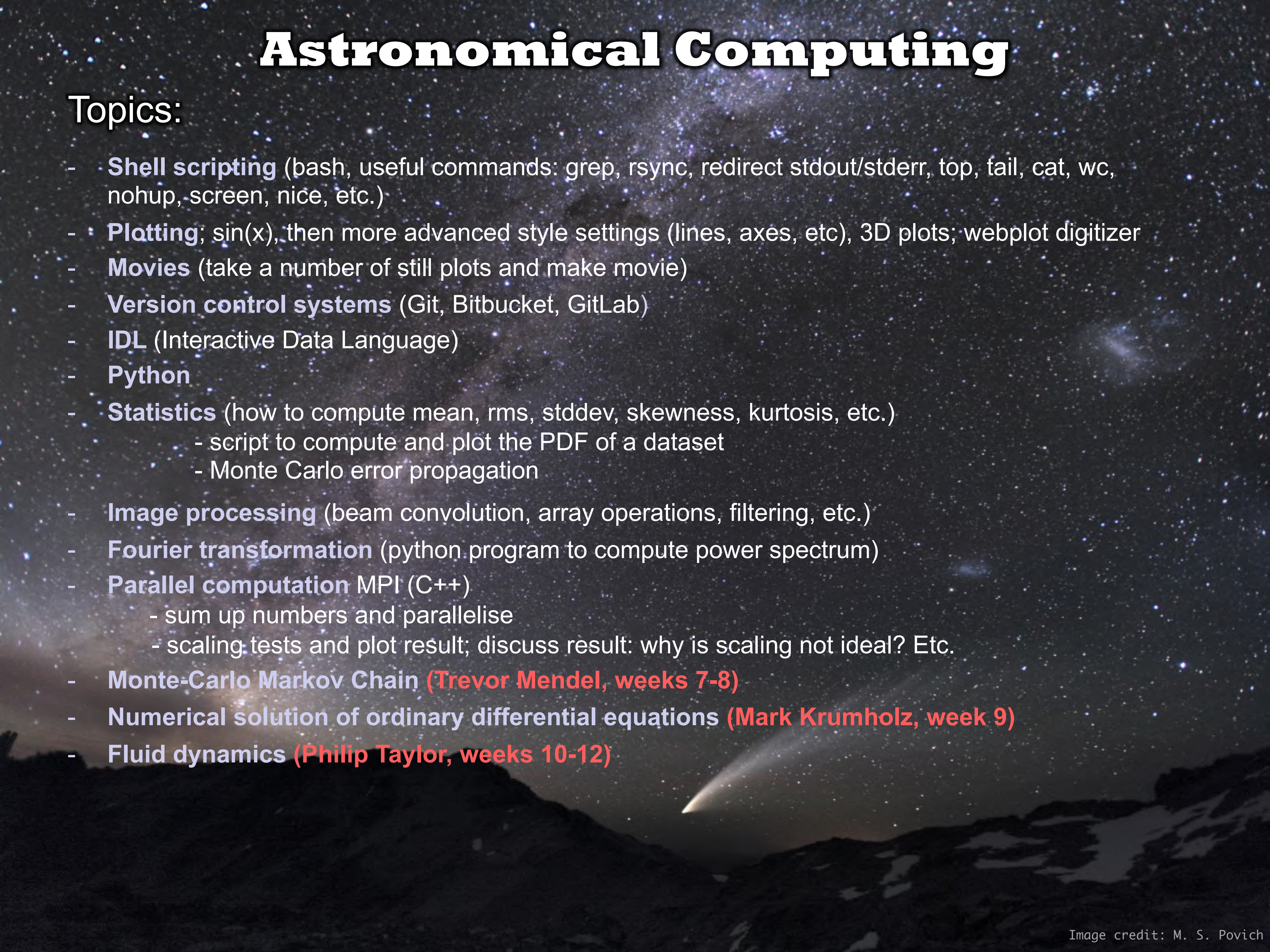
Christoph Federrath

Lectures and Tutorials: Tuesdays and Thursdays 1-3pm

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

Image credit: M. S. Povich

Astronomical Computing



Topics:

- **Shell scripting** (bash, useful commands: grep, rsync, redirect stdout/stderr, top, tail, cat, wc, nohup, screen, nice, etc.)
- **Plotting**; sin(x), then more advanced style settings (lines, axes, etc), 3D plots; webplot digitizer
- **Movies** (take a number of still plots and make movie)
- **Version control systems** (Git, Bitbucket, GitLab)
- **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** (python program to compute power spectrum)
- **Parallel computation** MPI (C++)
    - sum up numbers and parallelise
    - scaling tests and plot result; discuss result: why is scaling not ideal? Etc.
- **Monte-Carlo Markov Chain** **(Trevor Mendel, weeks 7-8)**
- **Numerical solution of ordinary differential equations** **(Mark Krumholz, week 9)**
- **Fluid dynamics** **(Philip Taylor, weeks 10-12)**

Image credit: M. S. Povich

Astronomical Computing

Need computer account at RSAA

–

application form on course webpage

Image credit: M. S. Povich

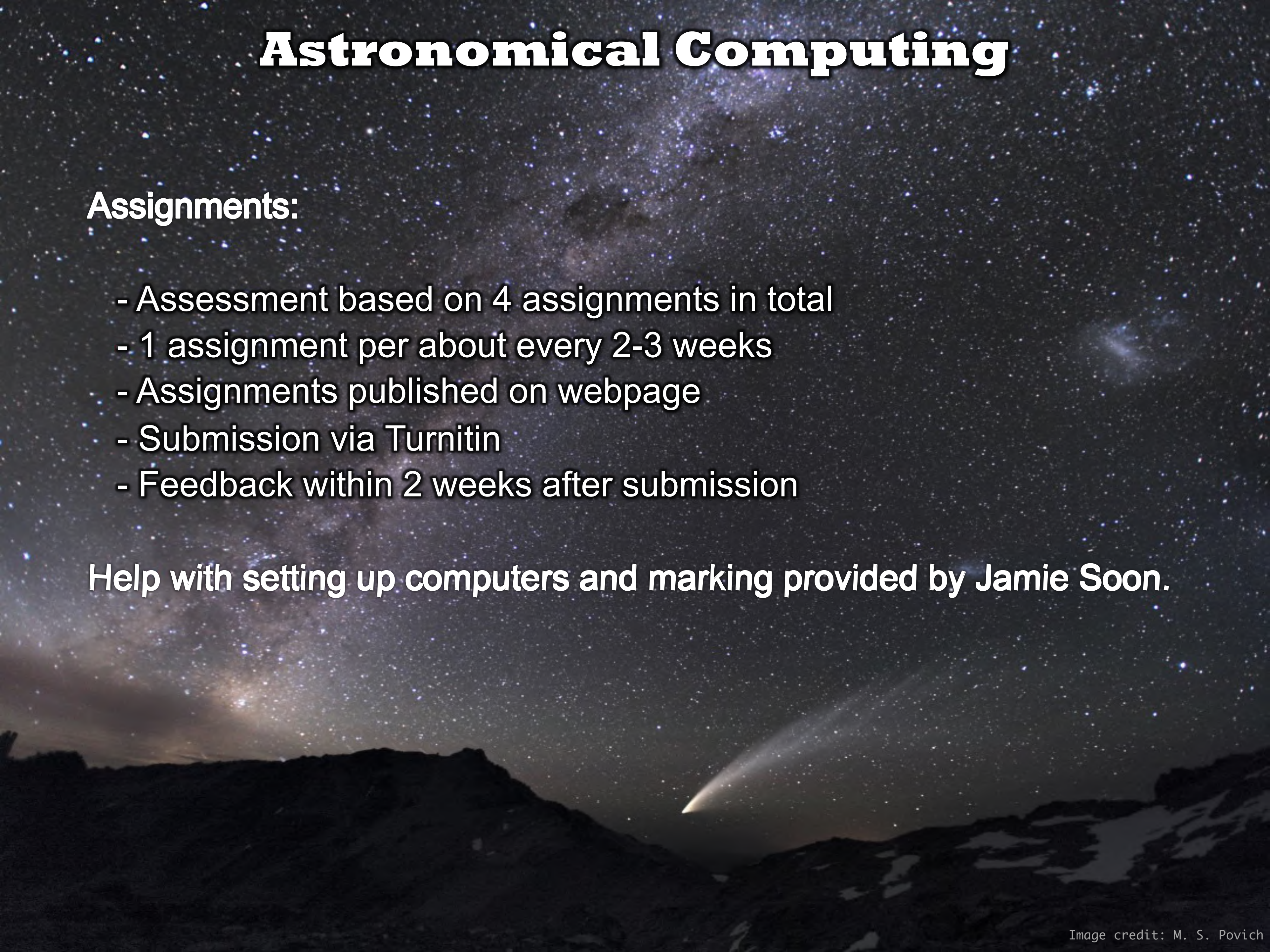
Astronomical Computing

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

Image credit: M. S. Povich

Astronomical Computing

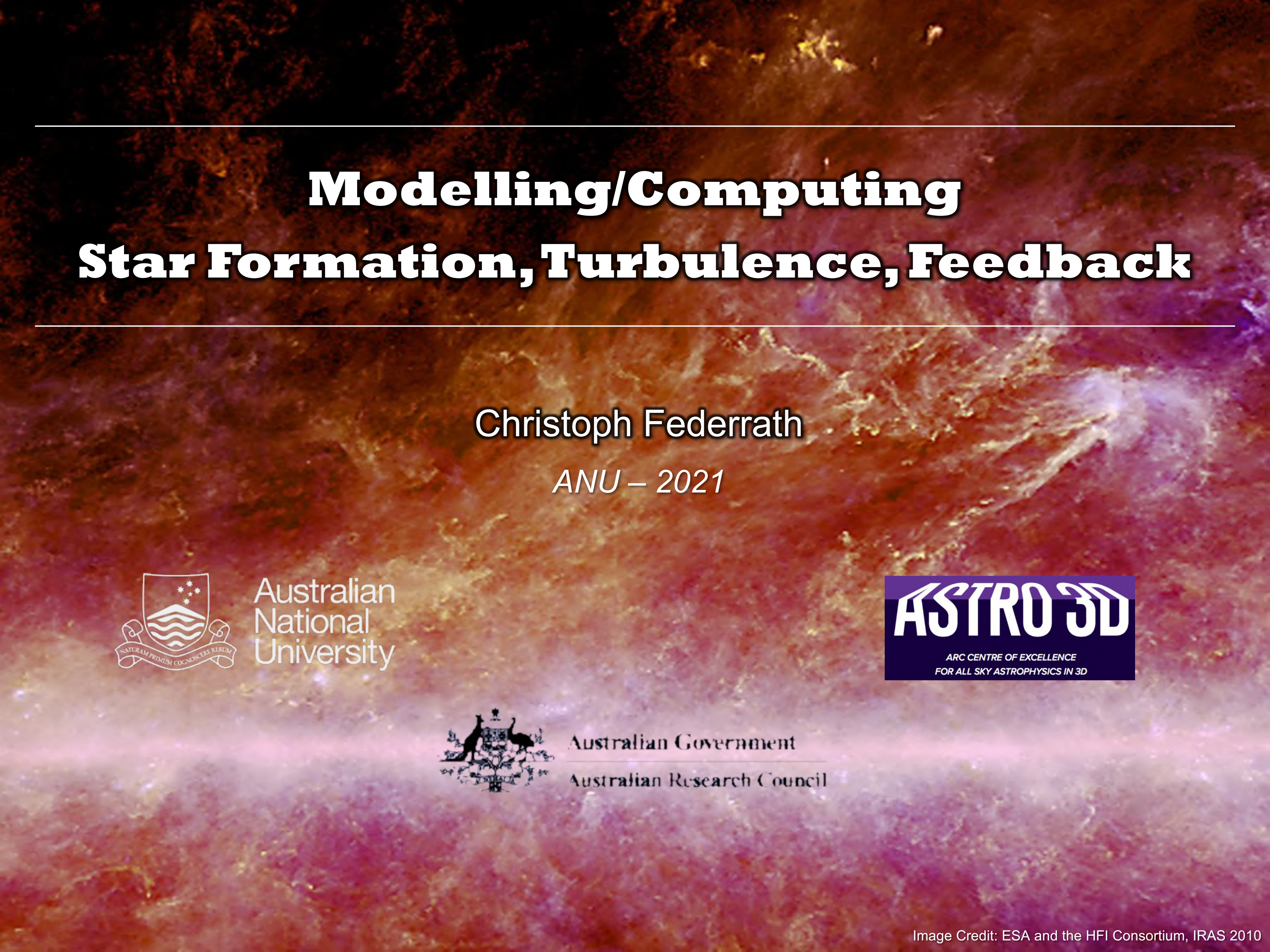


Assignments:

- 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.

Image credit: M. S. Povich



Modelling/Computing
Star Formation, Turbulence, Feedback

Christoph Federrath

ANU – 2021

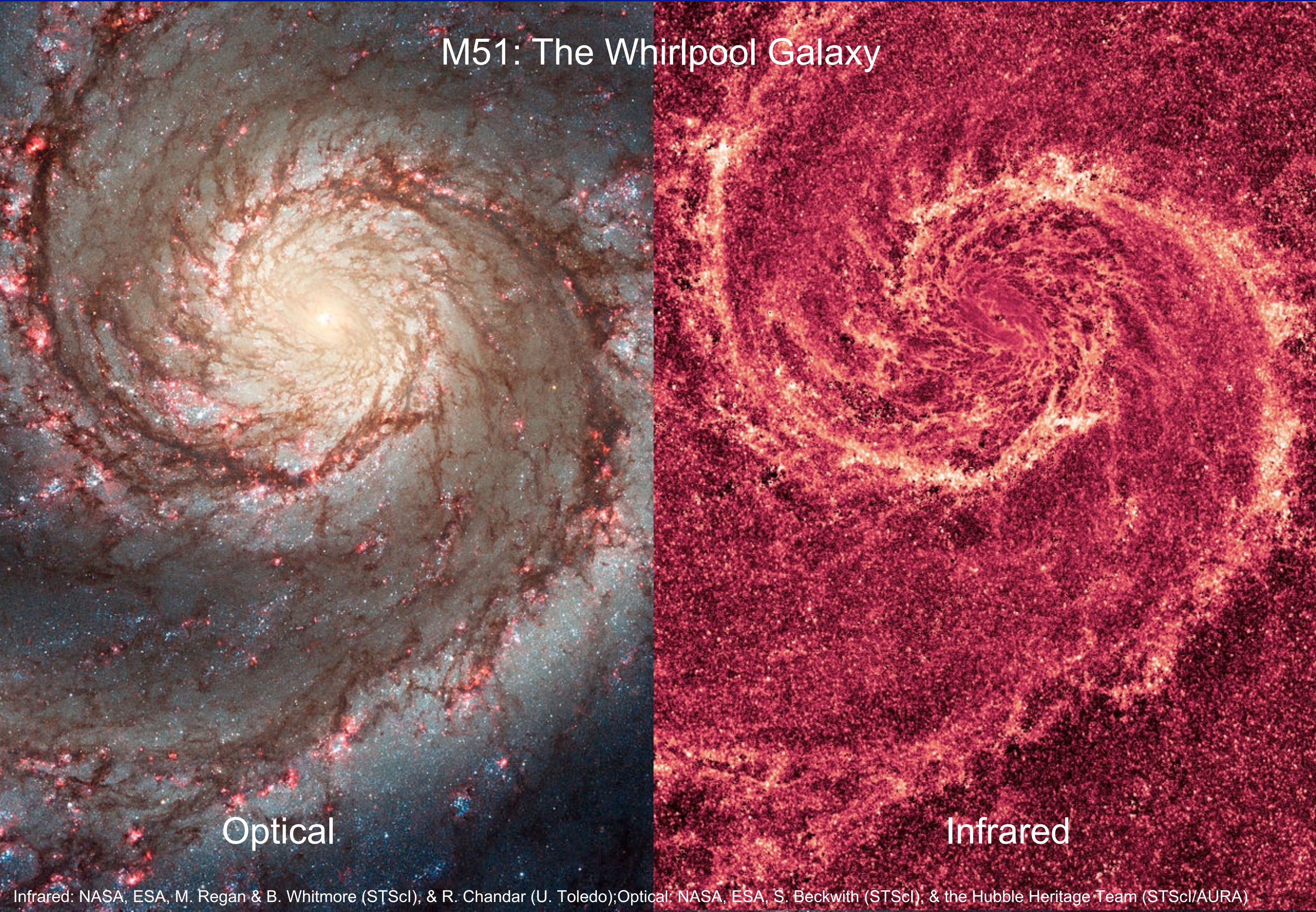
Australian
National
University

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

Australian Government
Australian Research Council

Image Credit: ESA and the HFI Consortium, IRAS 2010

Star Formation



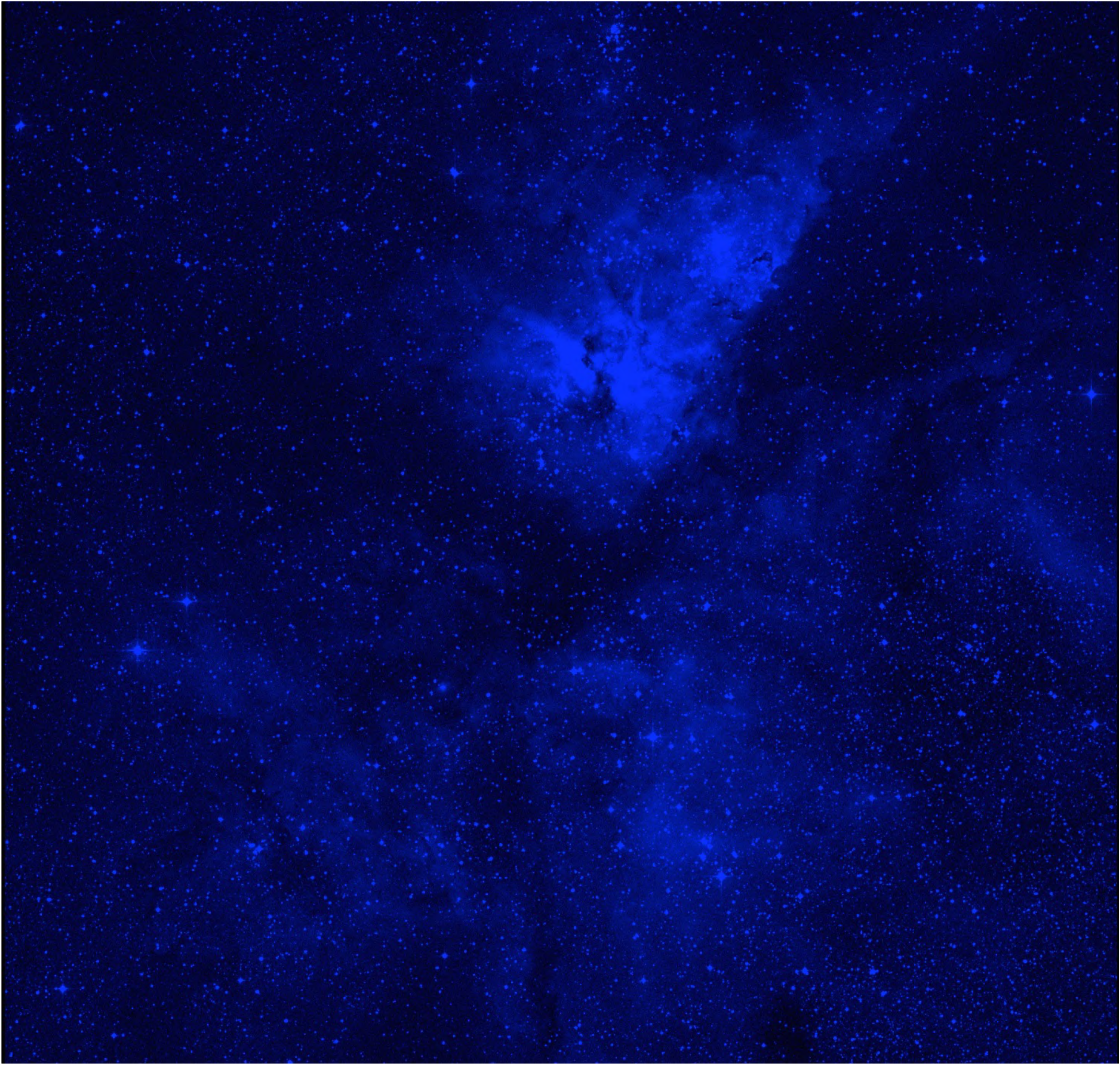
M51: The Whirlpool Galaxy

Optical

Infrared

Infrared: NASA, ESA, M. Regan & B. Whitmore (STScI), & R. Chandar (U. Toledo);Optical: NASA, ESA, S. Beckwith (STScI), & the Hubble Heritage Team (STScI/AURA)

Image credit: M. S. Povich



The Great Nebula in Carina

Visible Light

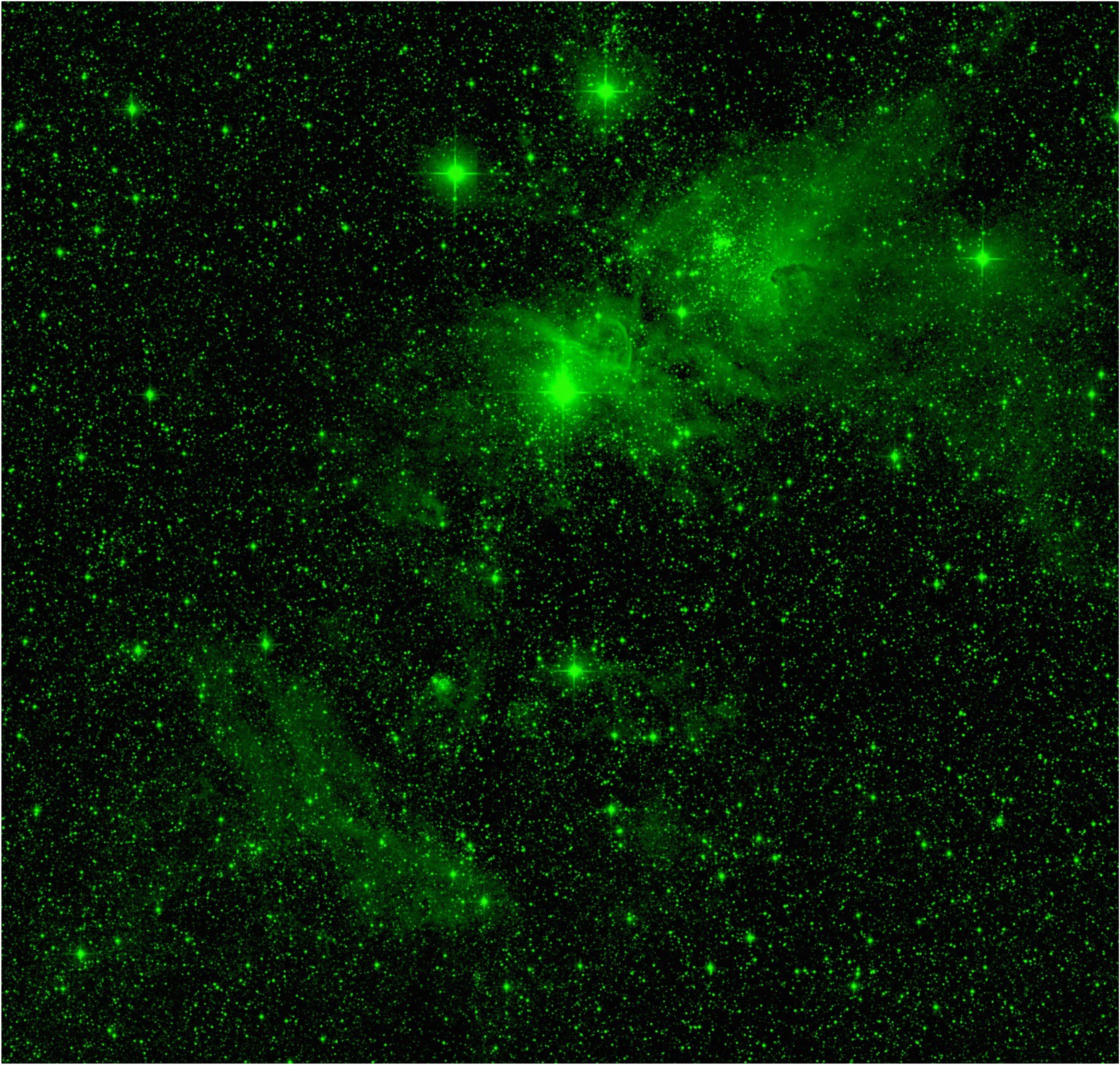
Digitized Sky Survey

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



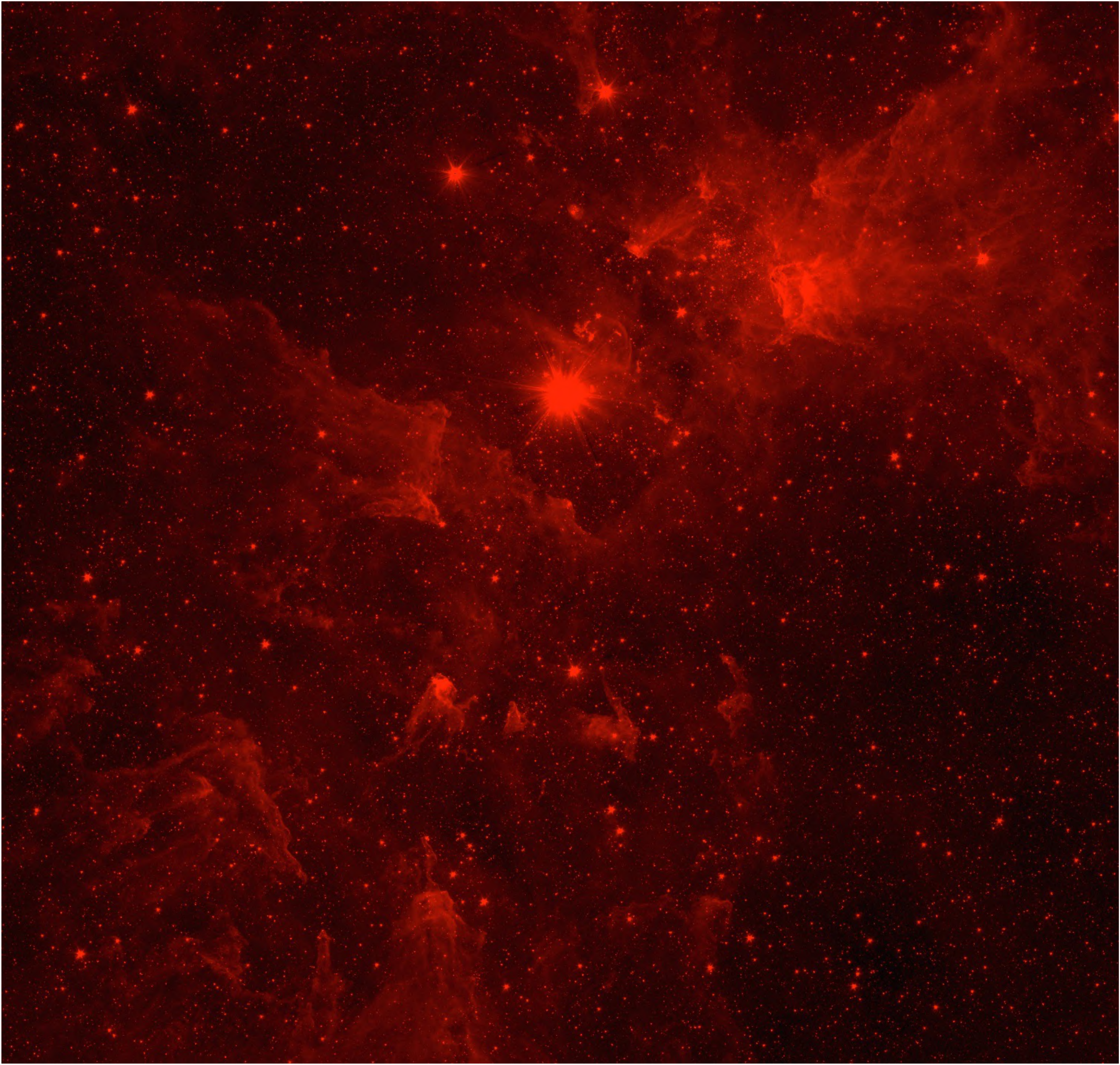
Near-Infrared

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.

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

Turbulence driven by

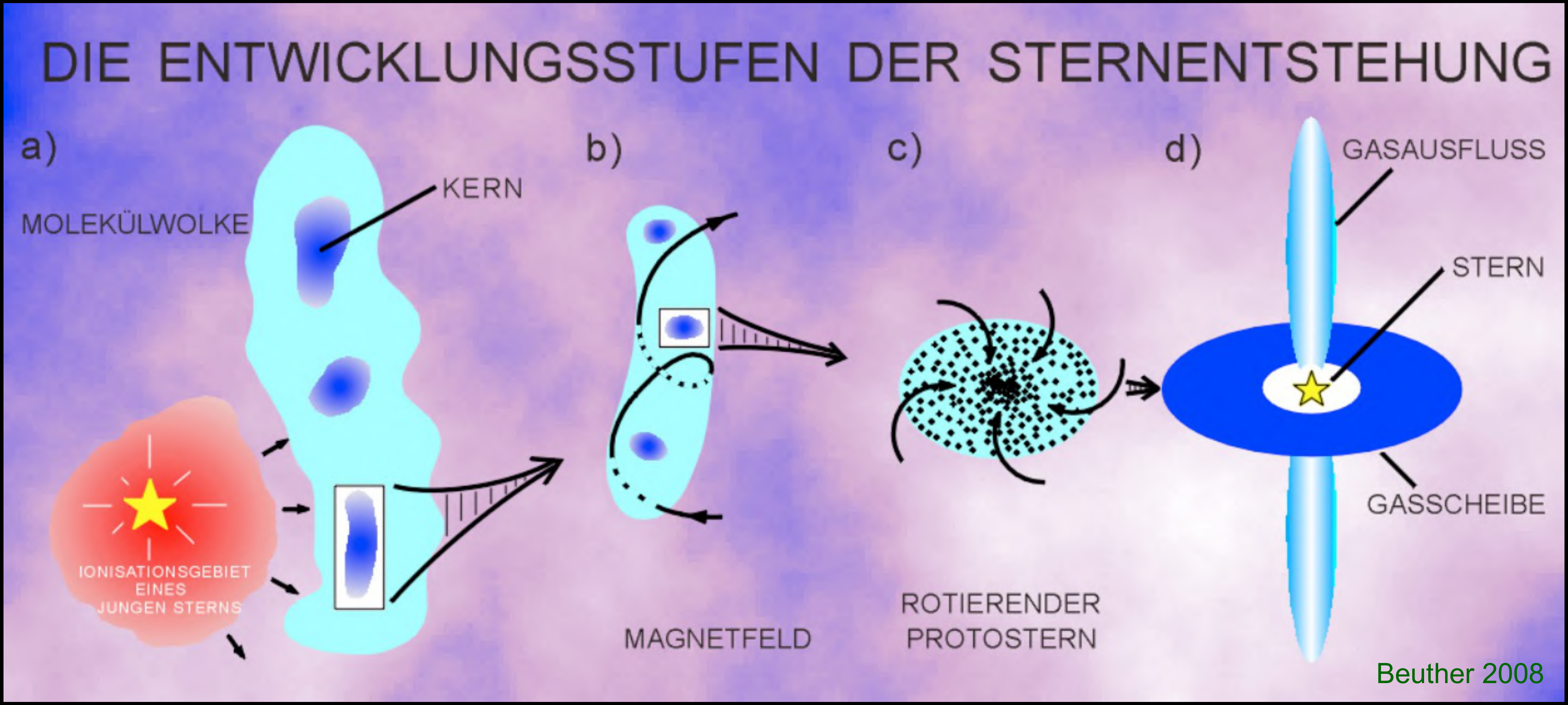
- Ionization fronts, bubbles?
- Protostellar jets/winds?
- Supernova explosions?
- MRI / shear?
- Gravitational infall?
- Galactic spiral shock?

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



Beuther 2008

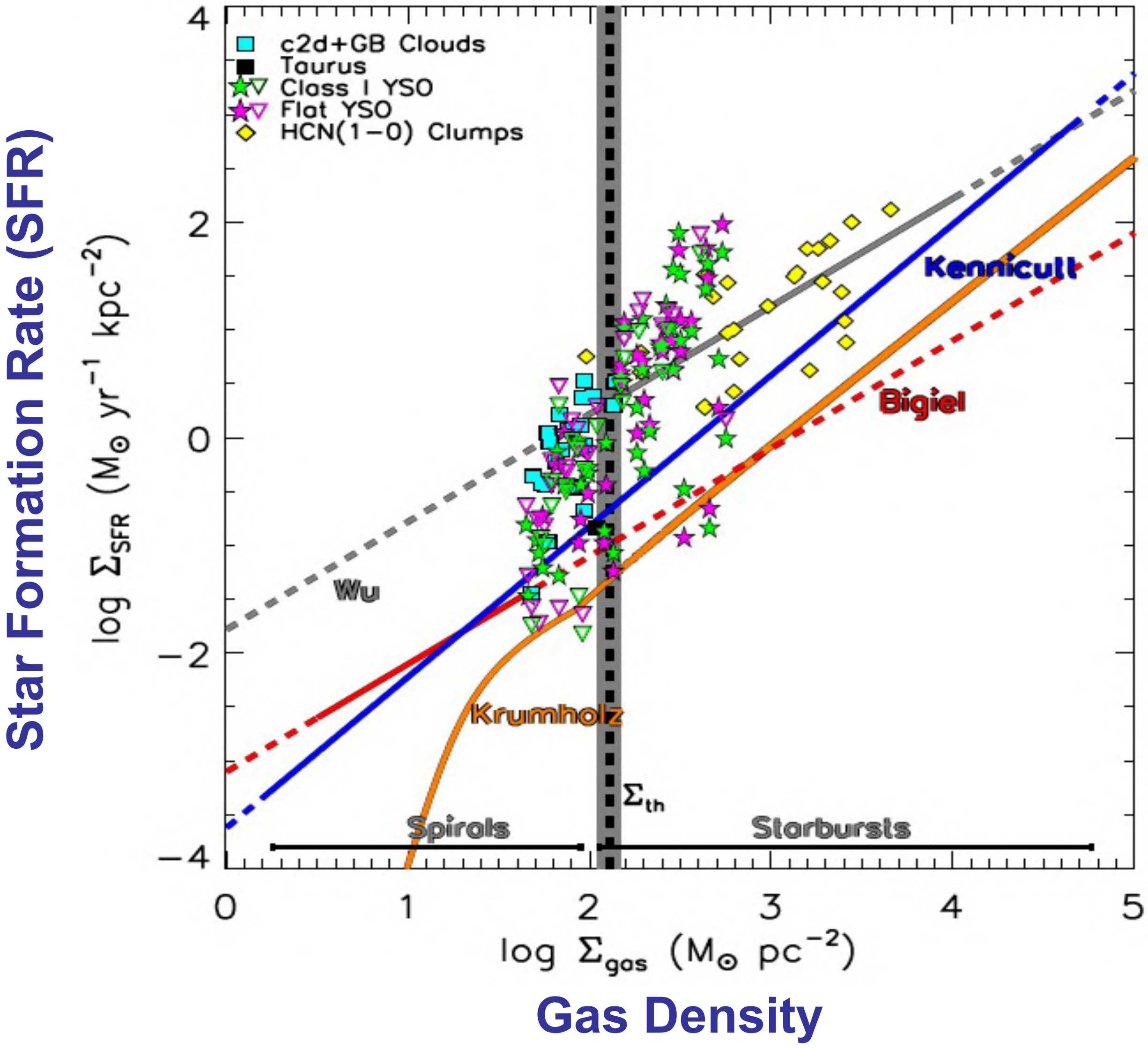
Star Formation Rate

Pipe Nebula ***Rho Ophiuchi Cloud***

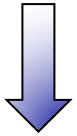
$$\mathrm{SFR}_{\mathrm{Oph}} = 15 \times \mathrm{SFR}_{\mathrm{Pipe}}$$

(Lada et al. 2010)

Universal star formation "law"?



Scatter?



Observational scatter and physical variations caused by

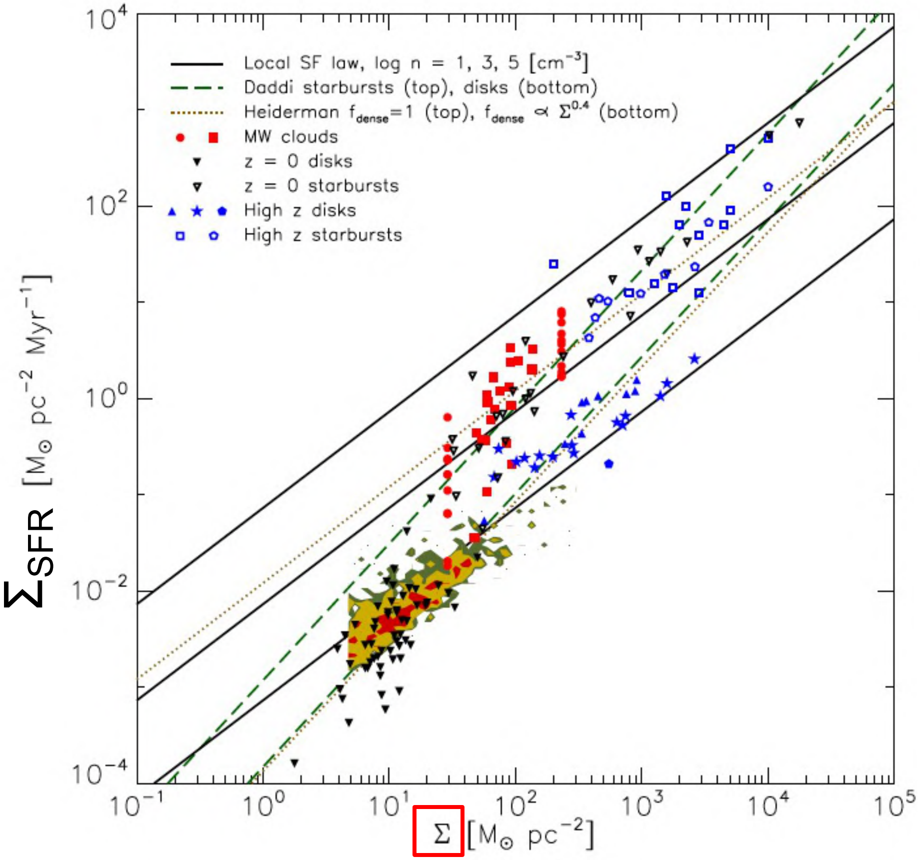
Turbulence

(Heiderman et al. 2010; Lada et al. 2010, Gutermuth et al. 2011)

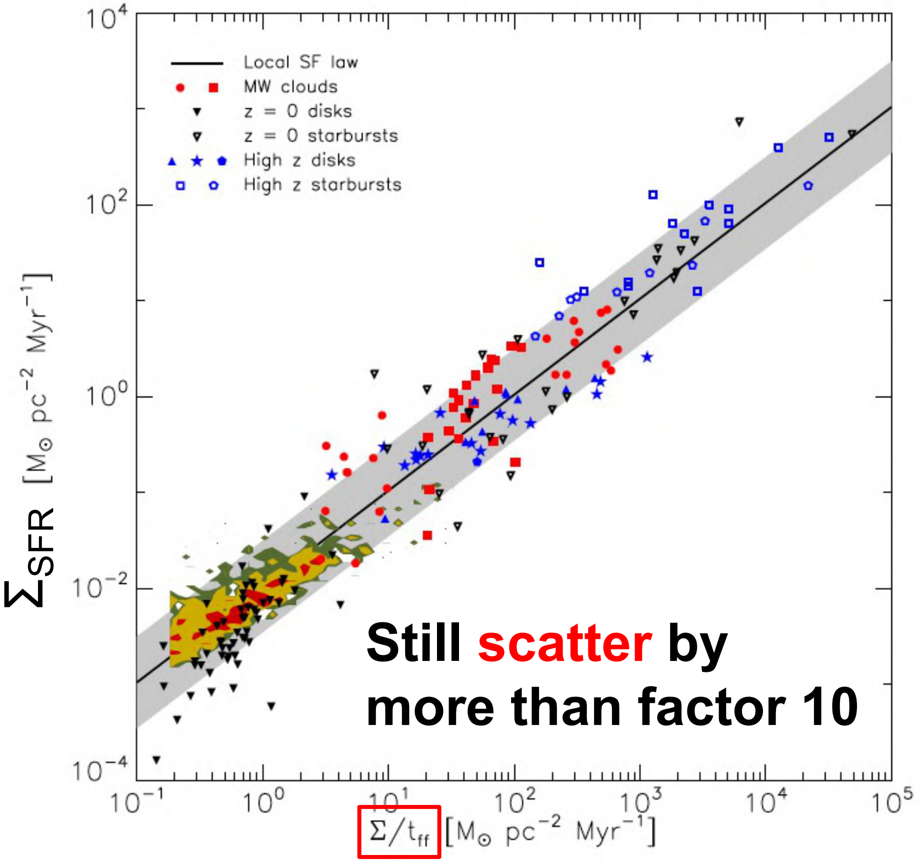
Physical Variations in the Universal Star Formation Law

Krumholz, Dekel, McKee (2012)

A more universal star formation “law”



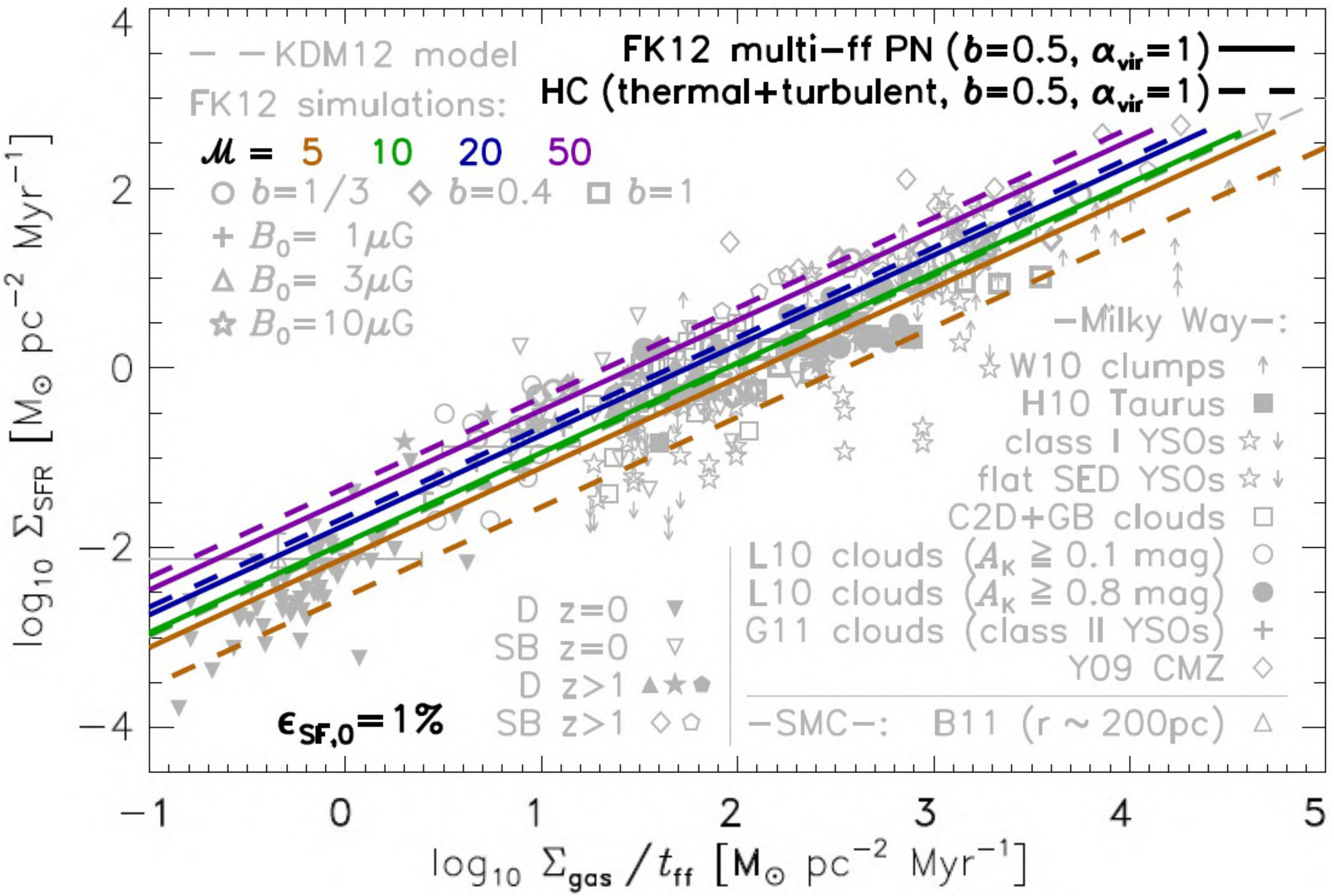
just Σ_{gas}
(classical Kennicutt-Schmidt relation)



Still scatter by more than factor 10

divide Σ_{gas}
by single (mean)
freefall time t_{ff}

Physical Variations in the Universal Star Formation Law



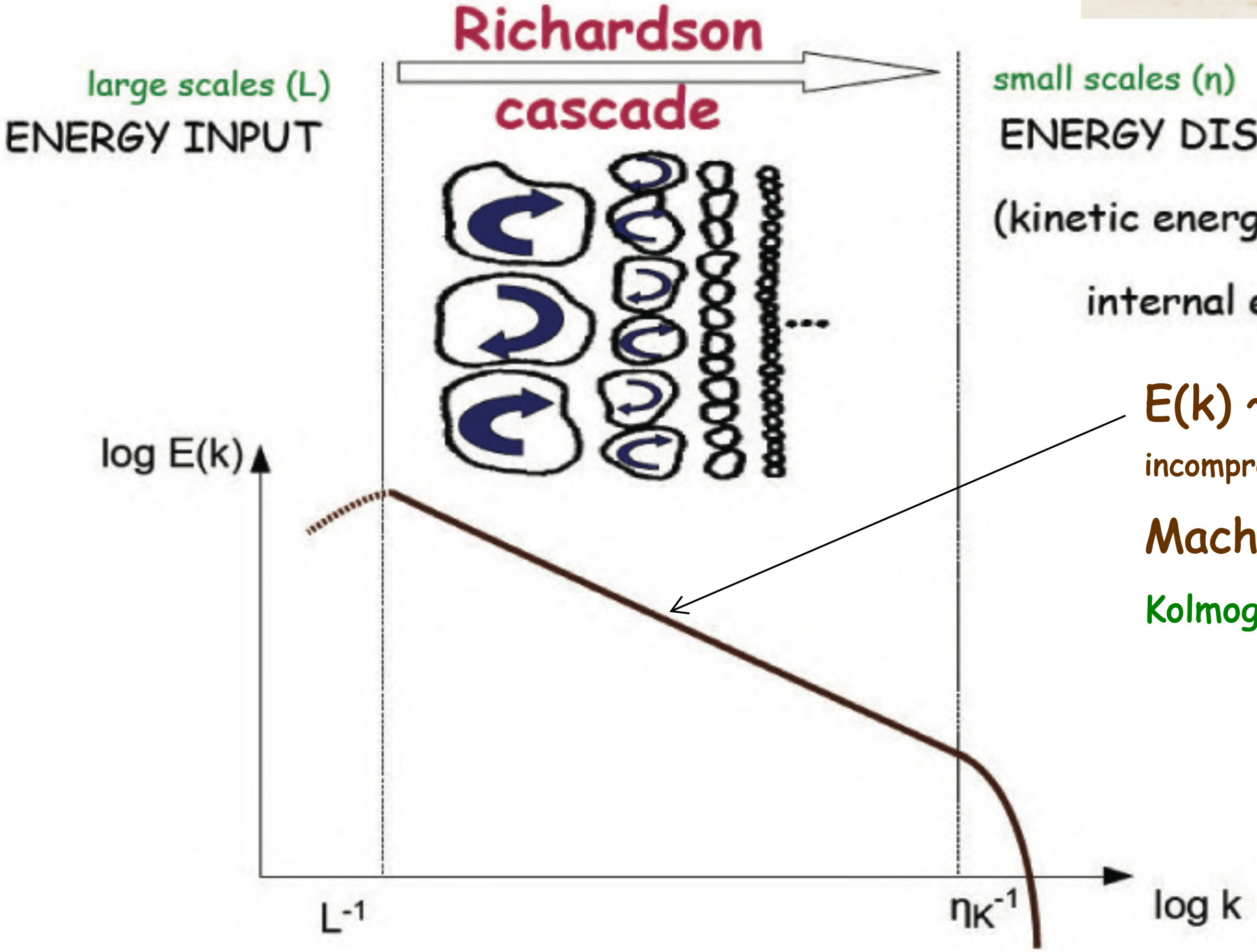
→ **Scatter caused by variations in the TURBULENCE**
(Mach number, driving, etc.)

Federrath (2013, MNRAS 436, 3167);
see also Salim, Federrath, Kewley (2015, ApJ 806, L36)

Turbulence

- **Reynolds numbers > 1000**
- **Kinetic energy cascade**

Leonardo da Vinci



$E(k) \sim k^{-5/3} \sim k^{-1.67}$

incompressible

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

Mach < 1

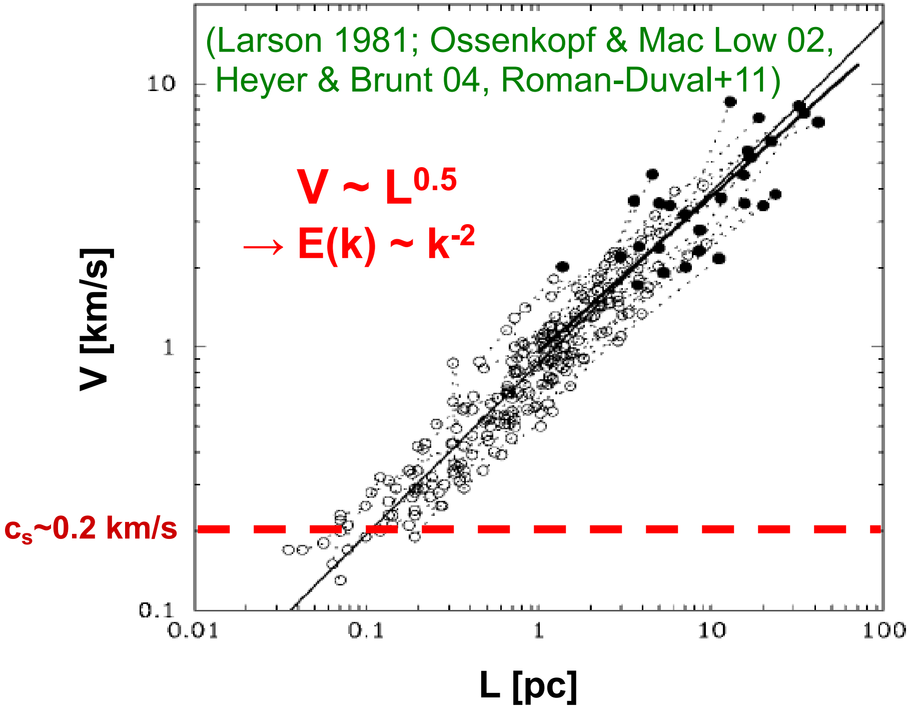
Kolmogorov (1941)

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



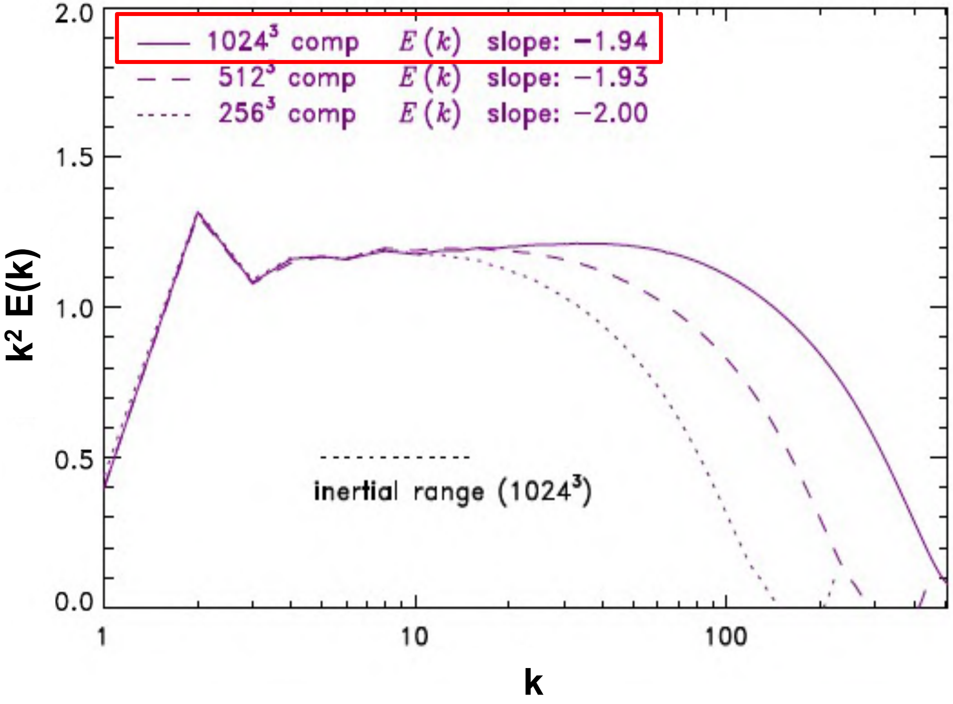
(Larson 1981; Ossenkopf & Mac Low 02, Heyer & Brunt 04, Roman-Duval+11)

$V \sim L^{0.5}$

$\rightarrow E(k) \sim k^{-2}$

c_s~0.2 km/s

Simulation

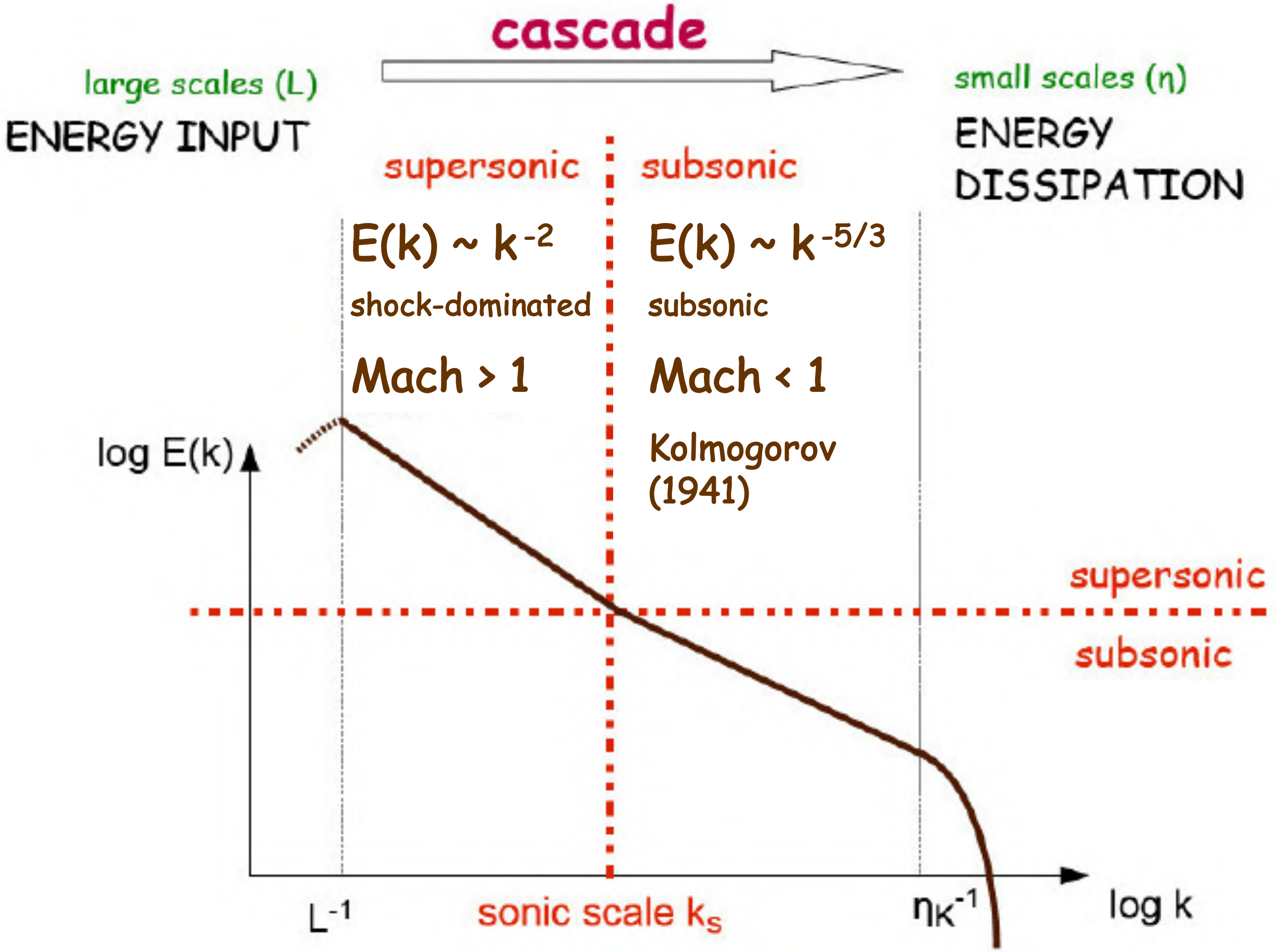


Supersonic, compressible turbulence has steeper $E(k) \sim k^{-1.9}$ than Kolmogorov ($E \sim k^{-5/3}$)

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

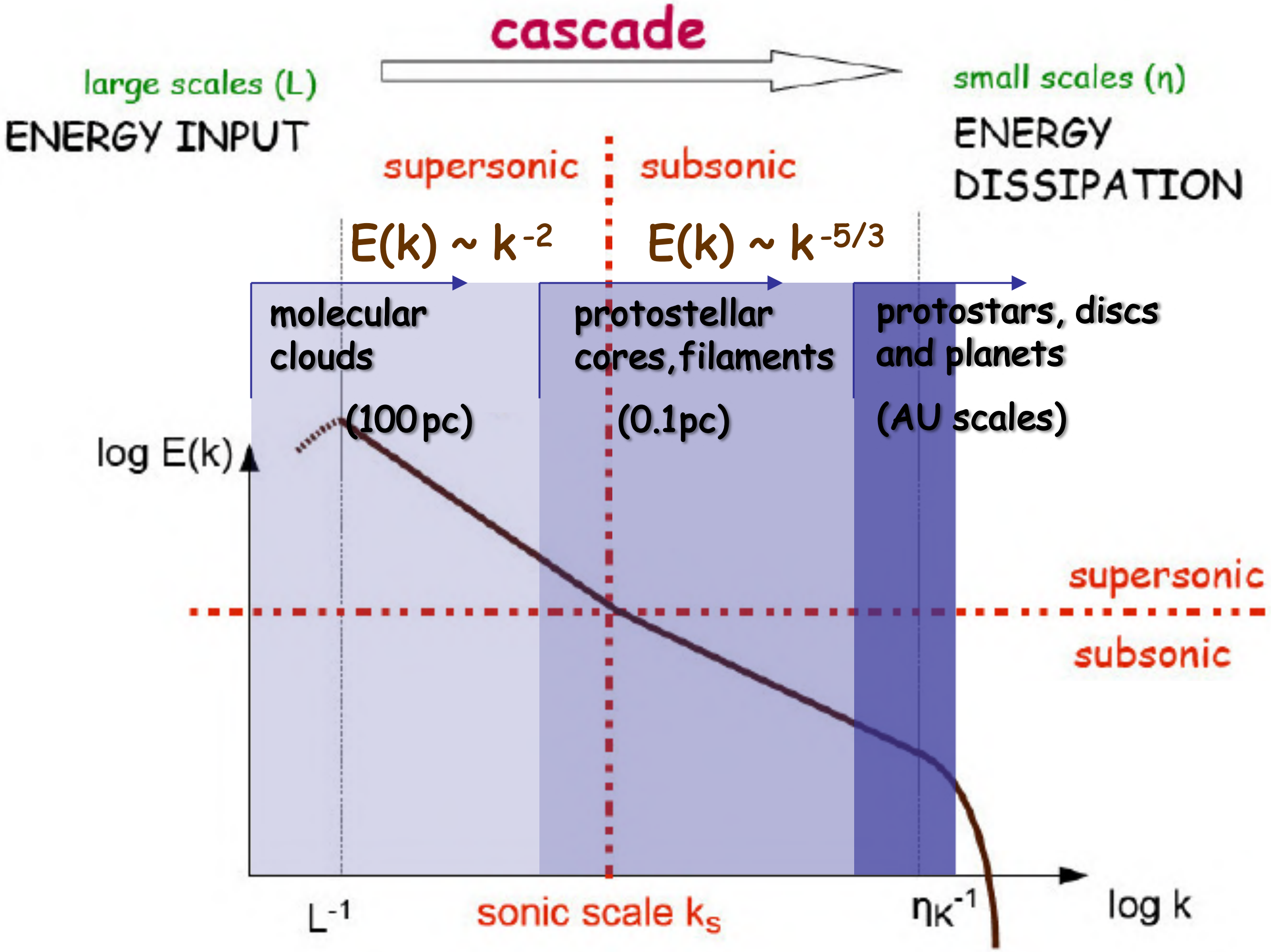
Interstellar Turbulence

- Reynolds numbers > 1000
- Kinetic energy cascade

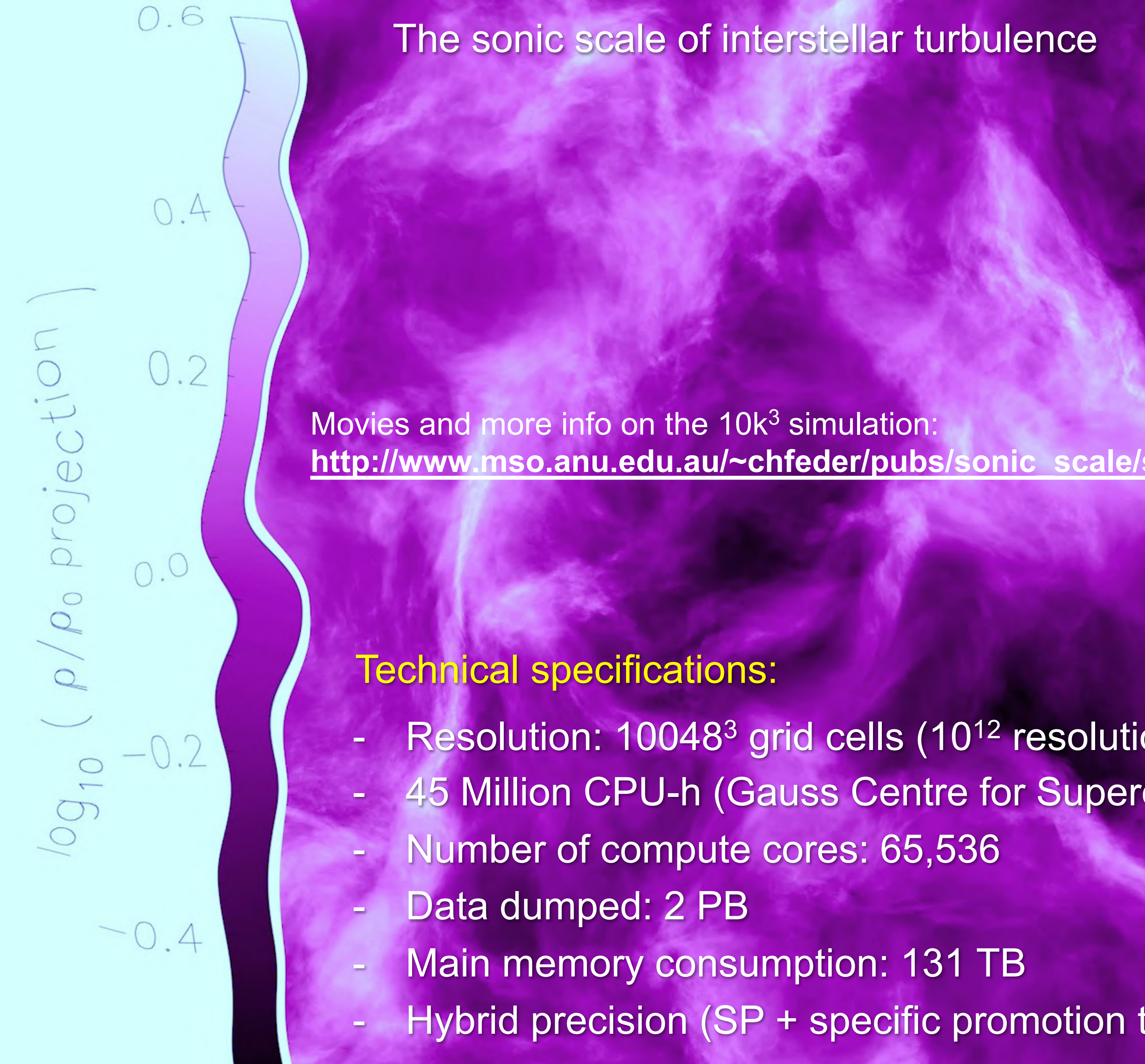


Interstellar Turbulence

- Reynolds numbers > 1000
- Kinetic energy cascade



The sonic scale of interstellar turbulence



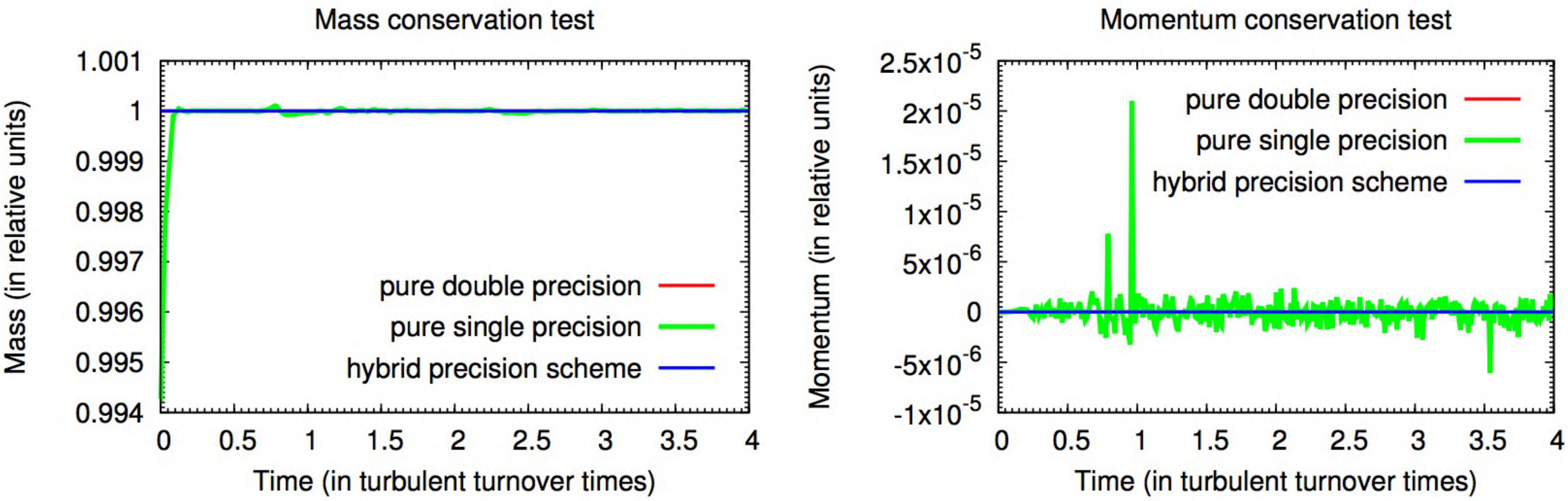
Movies and more info on the 10k^3 simulation:
http://www.mso.anu.edu.au/~chfeder/pubs/sonic_scale/sonic_scale.html

Technical specifications:

- Resolution: 10048^3 grid cells (10^{12} resolution elements)
- 45 Million CPU-h (Gauss Centre for Supercomputing)
- Number of compute cores: 65,536
- Data dumped: 2 PB
- Main memory consumption: 131 TB
- Hybrid precision (SP + specific promotion to DP)

Modelling turbulence at extreme resolution (10k^3)

Hybrid numerical precision scheme:

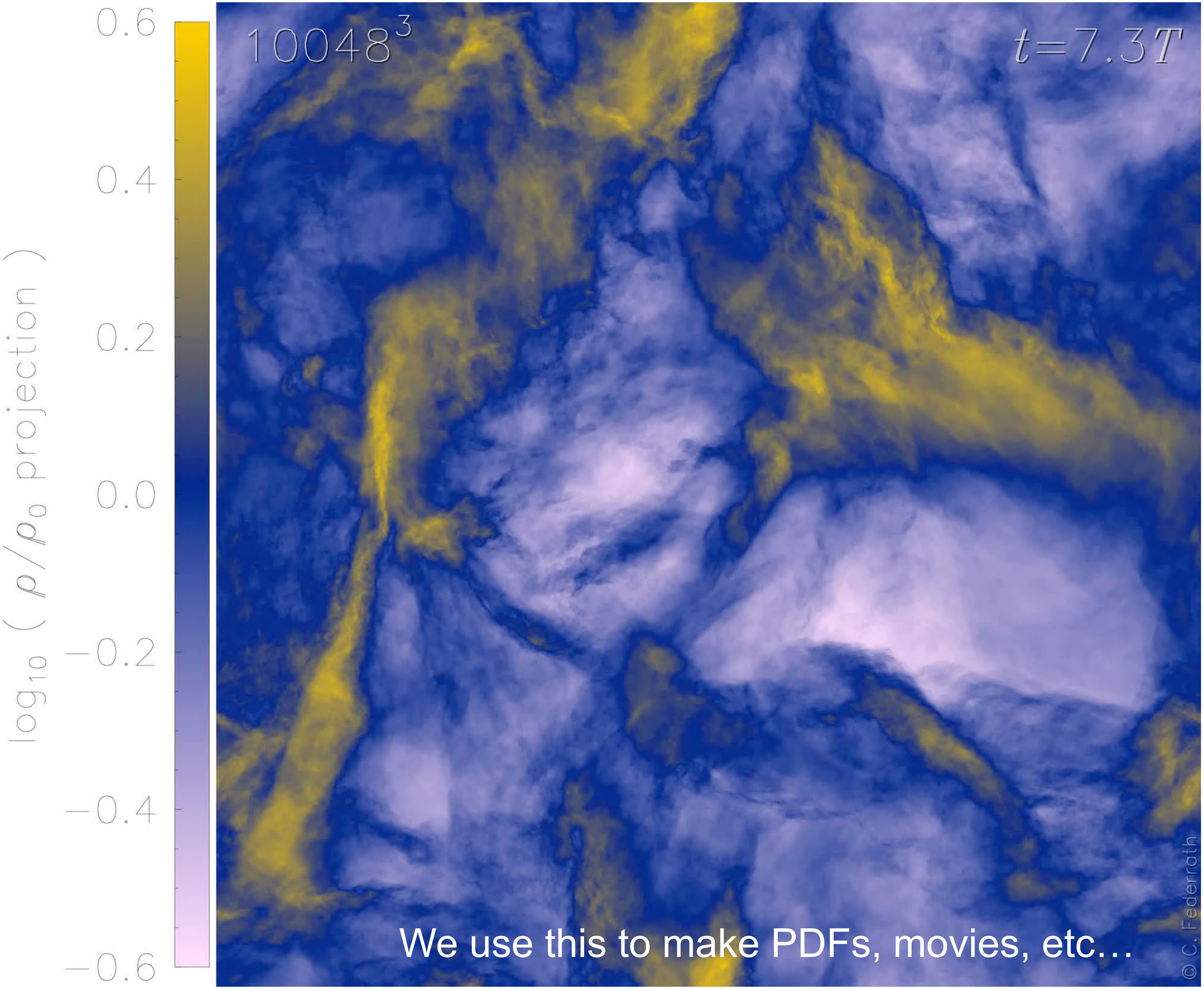


Overall changes to FLASH for this setup resulted in

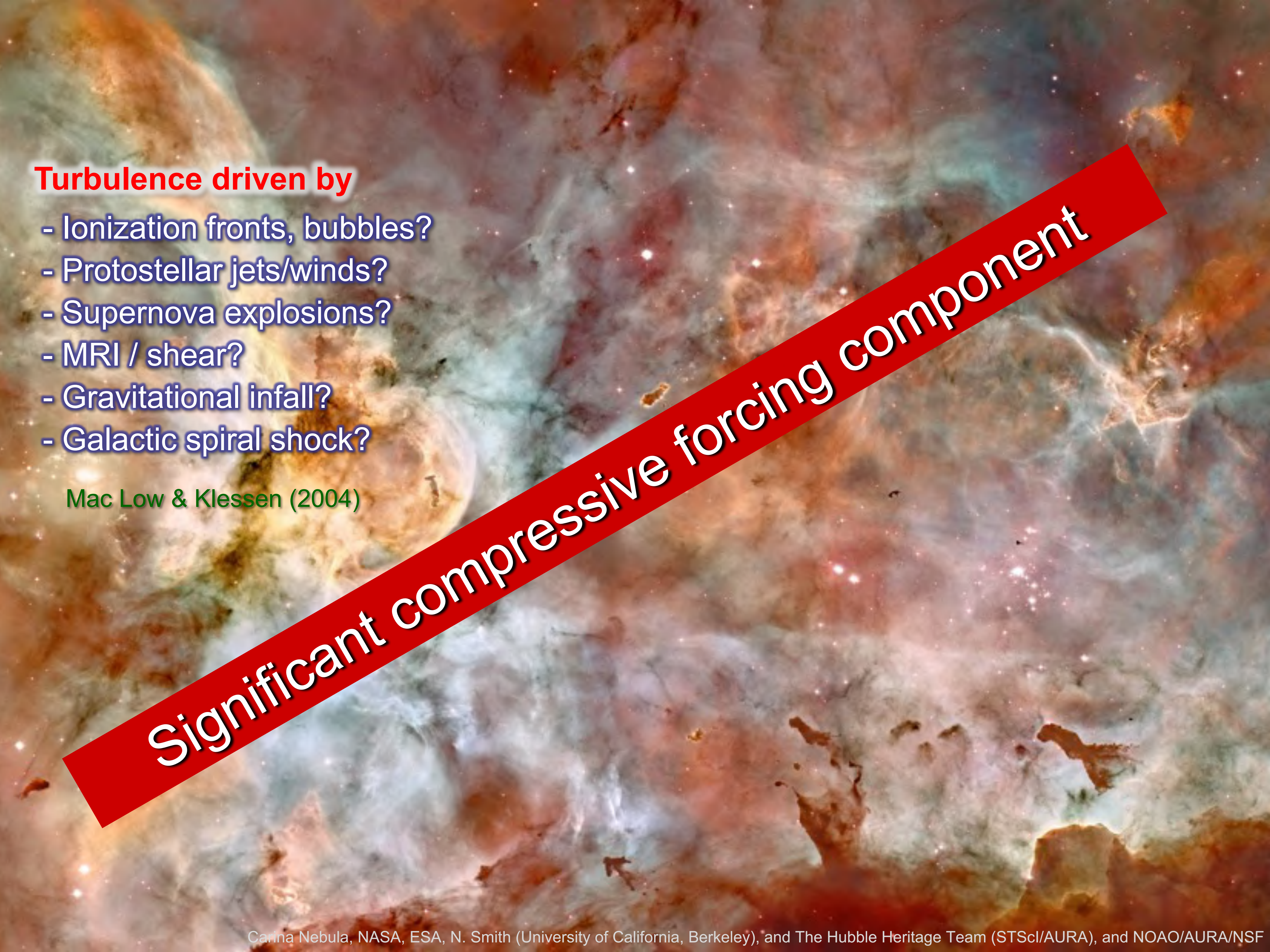
- factor 3.6 higher speed
- factor 4.1 less memory requirement

Federrath et al. 2021, Nature Astronomy

Modelling turbulence at extreme resolution ($10k^3$)



We use this to make PDFs, movies, etc…



Turbulence driven by

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

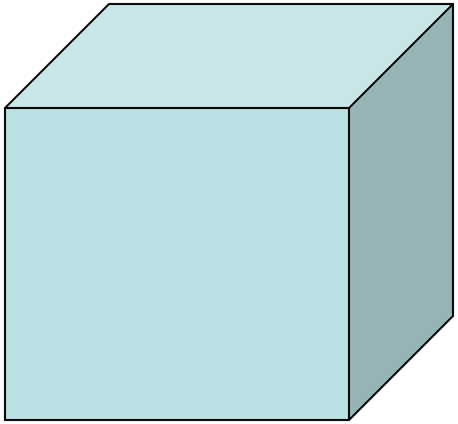
Mac Low & Klessen (2004)

Significant compressive forcing component

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)

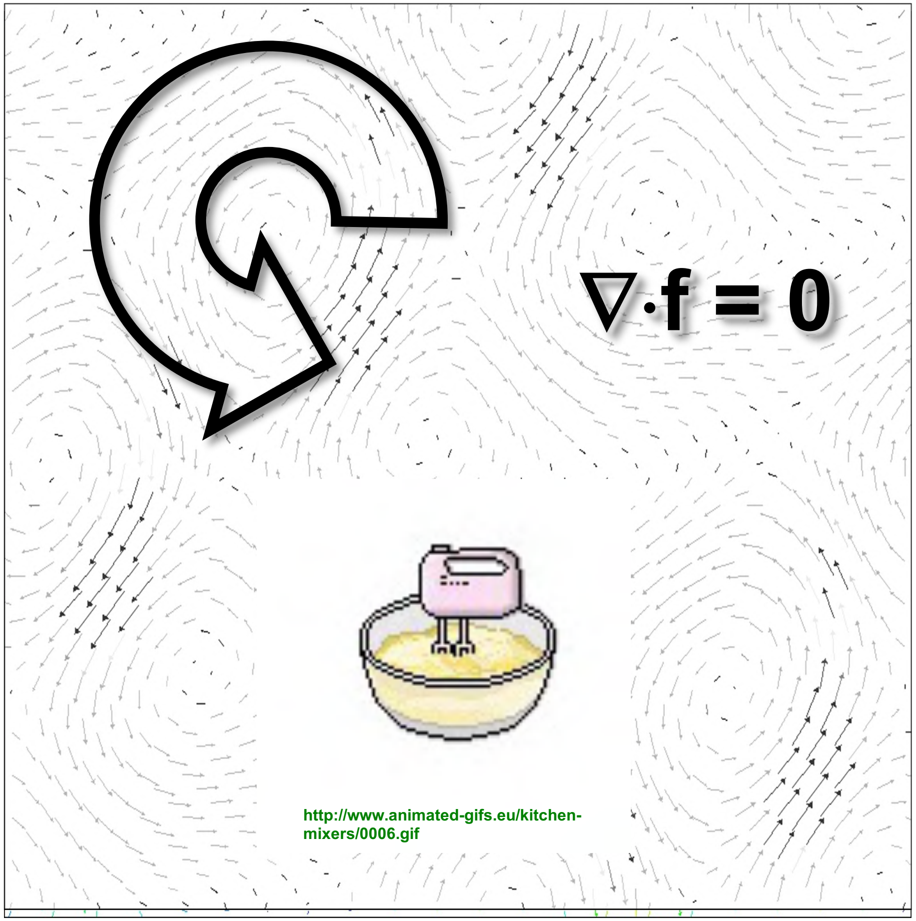
○ Large-scale **Forcing Term f**

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 driving – solenoidal versus compressive

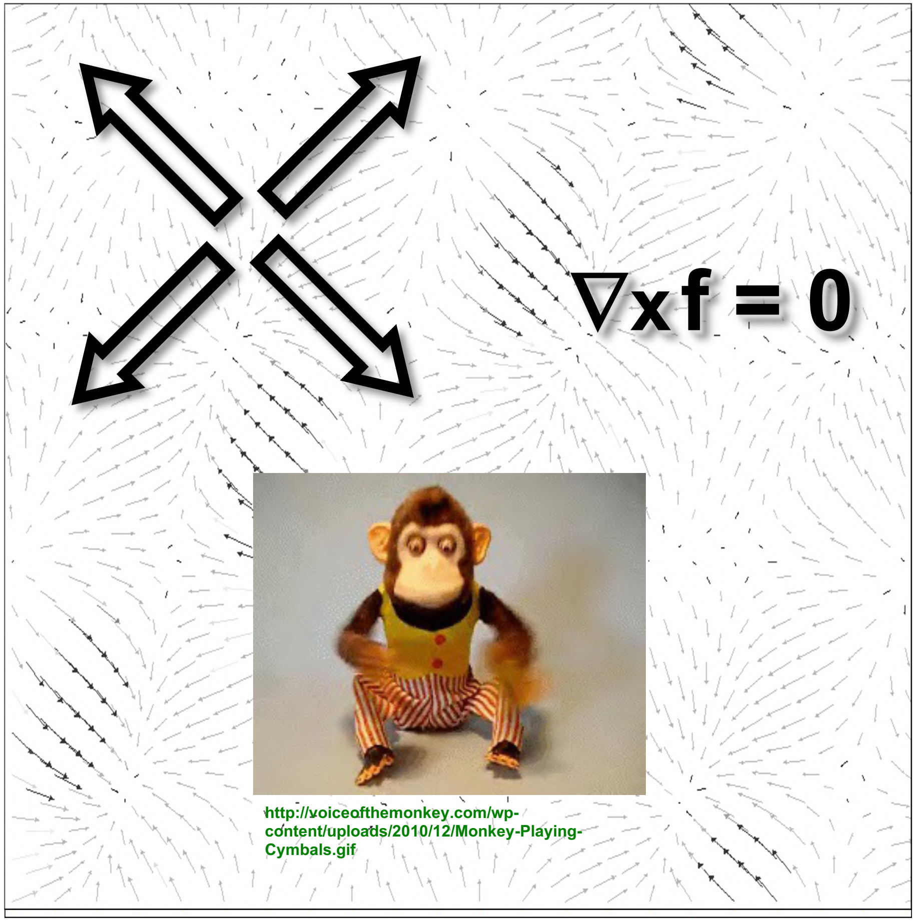
Ornstein-Uhlenbeck process (stochastic process with autocorrelation time)
→ **forcing varies smoothly in space and time,**
following a well-defined random process

Solenoidal forcing



http://www.animated-gifs.eu/kitchen-mixers/0006.gif

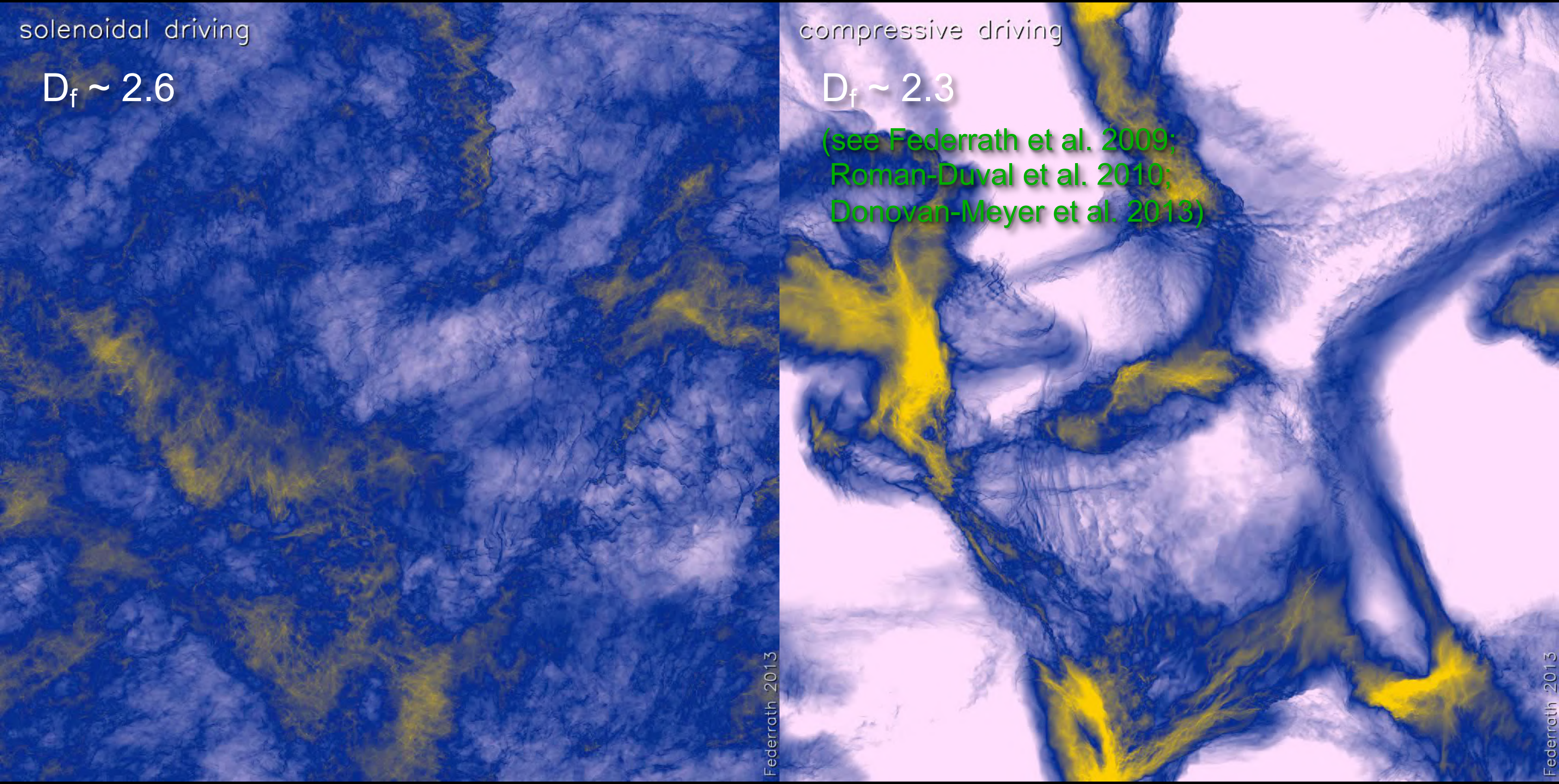
Compressive forcing



http://voiceofthemonkey.com/wp-content/uploads/2010/12/Monkey-Playing-Cymbals.gif

Turbulence driving – solenoidal versus compressive

solenoidal forcing   Column Density   compressive forcing



$D_f \sim 2.6$

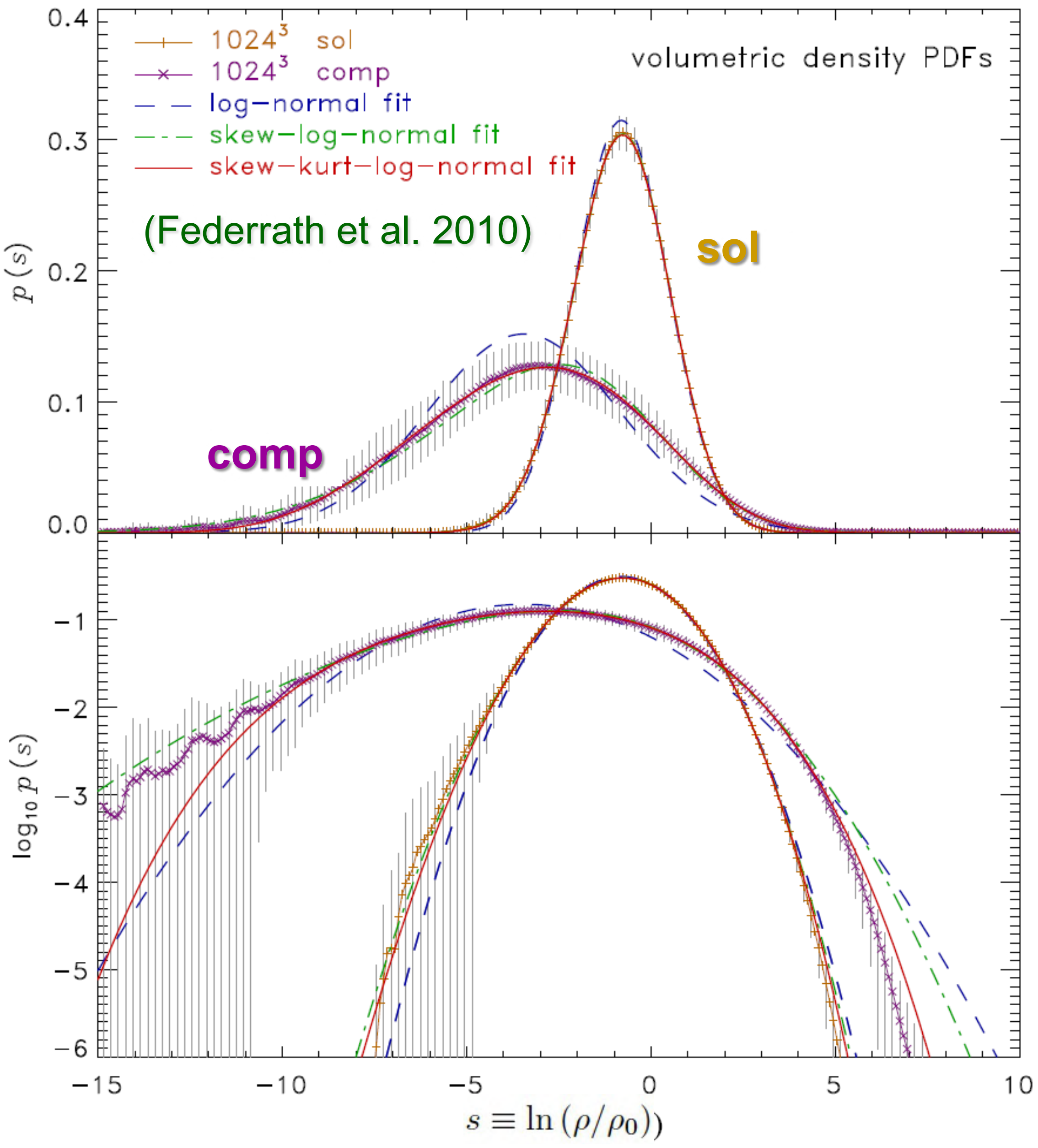
$D_f \sim 2.3$

(see Federrath et al. 2009;
Roman-Duval et al. 2010;
Donovan-Meyer et al. 2013)

Compressive forcing produces 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)

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

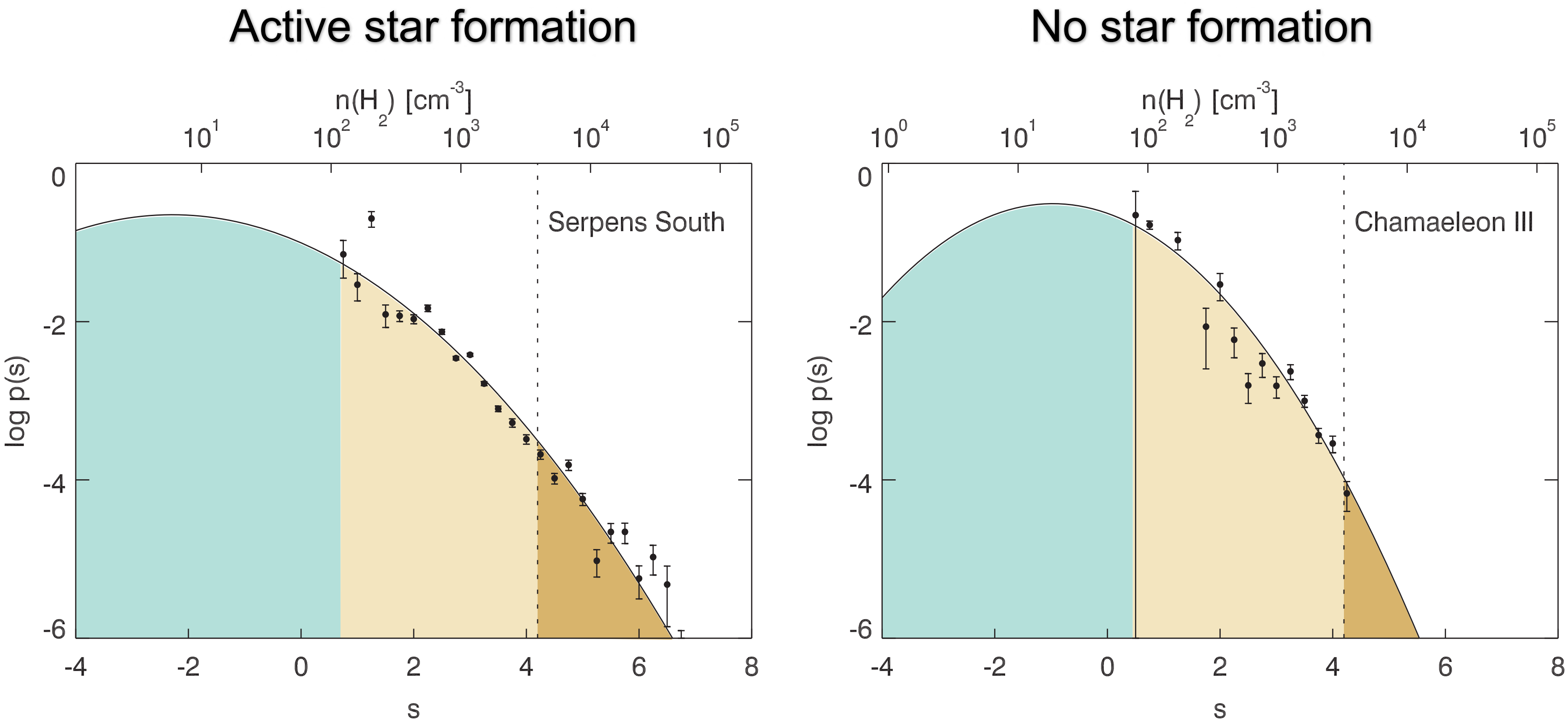
⇒

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 (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)

Turbulence → Density PDF

Density PDF → Star Formation Rate

Why is star formation so inefficient?

Density PDF → Star Formation Rate

Density PDF is key for star formation theories:

- **Initial Mass Function** (Padoan & Nordlund 02, Hennebelle & Chabrier 08,09,
- **Star Formation Efficiency** (Elmegreen 08, Federrath & Klessen 13)
- **Kennicutt-Schmidt relation** (Elmegreen 02, Krumholz & McKee 05, Tassis 07, Ostriker+10, Elmegreen 11, Veltchev+11, Hopkins 12, Federrath 13, Salim+15)
- **Star Formation Rate** (Krumholz & McKee 05, Padoan & Nordlund 11, Renaud+12, Federrath & Klessen 2012)

All based on integrals over the turbulent density PDF

$$\mathrm{SFR_{ff}} = \frac{\epsilon_{\mathrm{core}}}{\phi_t} \int_{x_{\mathrm{crit}}}^{\infty} x p(x)\, dx$$

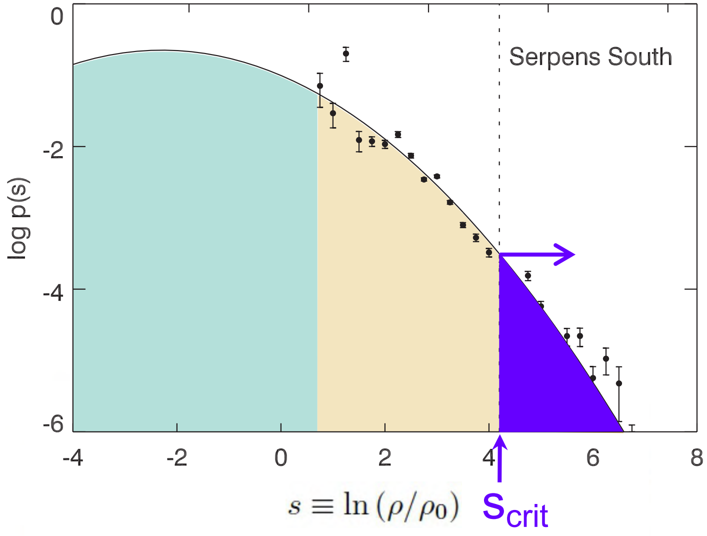
Krumholz & McKee (2005), Padoan & Nordlund (2011); Hennebelle & Chabrier (2011,2013)

The Star Formation Rate

Statistical Theory for the Star Formation Rate:

SFR ~ Mass/time

$$\mathrm{SFR}_{\mathrm{ff}} = \epsilon \int_{s_{\mathrm{crit}}}^{\infty} \overbrace{\frac{t_{\mathrm{ff}}(\rho_0)}{t_{\mathrm{ff}}(\rho)}}^{\textbf{freefall time}} \overbrace{\frac{\rho}{\rho_0}}^{\textbf{mass fraction}} p(s)\,\mathrm{d}s$$



Hennebelle & Chabrier (2011) : “multi-freefall model”

Federrath & Klessen (2012)

The Star Formation Rate

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

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

Hennebelle & Chabrier (2011) : “multi-freefall model”

Federrath & Klessen (2012)

The Star Formation Rate

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

$$\begin{aligned} \mathrm{SFR_{ff}} &= \epsilon \int_{s_{\mathrm{crit}}}^{\infty} \overbrace{\frac{t_{\mathrm{ff}}(\rho_0)}{t_{\mathrm{ff}}(\rho)}}^{\textbf{freefall time}} \overbrace{\frac{\rho}{\rho_0}}^{\textbf{mass fraction}} p(s)\,\mathrm{d}s = \epsilon \int_{s_{\mathrm{crit}}}^{\infty} \exp\left(\frac{3}{2}s\right) p(s)\,\mathrm{d}s \\ &= \frac{\epsilon}{2} \exp\left(\frac{3}{8}\sigma_s^2\right)\left[1 + \mathrm{erf}\left(\frac{\sigma_s^2 - s_{\mathrm{crit}}}{\sqrt{2\sigma_s^2}}\right)\right] \end{aligned}$$

Hennebelle & Chabrier (2011) : “multi-freefall model”

From sonic and Jeans scales:

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

(Krumholz & McKee 2005, Padoan & Nordlund 2011)

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

$2\,E_{\mathrm{kin}}/E_{\mathrm{grav}}$ **forcing** **Mach number**

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

(e.g., Federrath et al. 2008)

Federrath & Klessen (2012)

Density PDF → Star Formation Rate

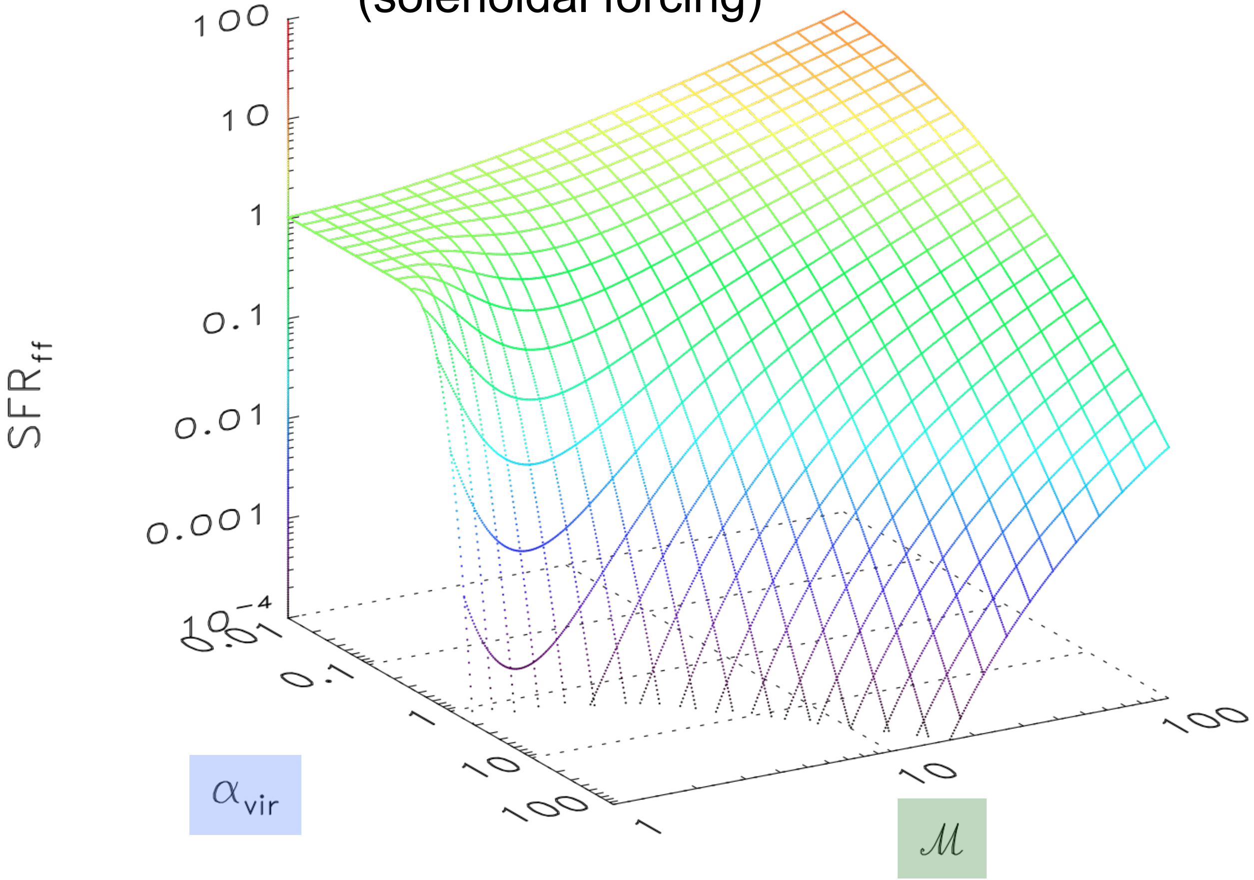
$\mathrm{SFR_{ff}} = \mathrm{SFR_{ff}}\,(\alpha_{\mathrm{vir}}, b, \mathcal{M})$

$2\,E_{\mathrm{kin}}/E_{\mathrm{grav}}$ **forcing** **Mach number**

---

forcing parameter (b=0.33) multi−freefall

(solenoidal forcing)

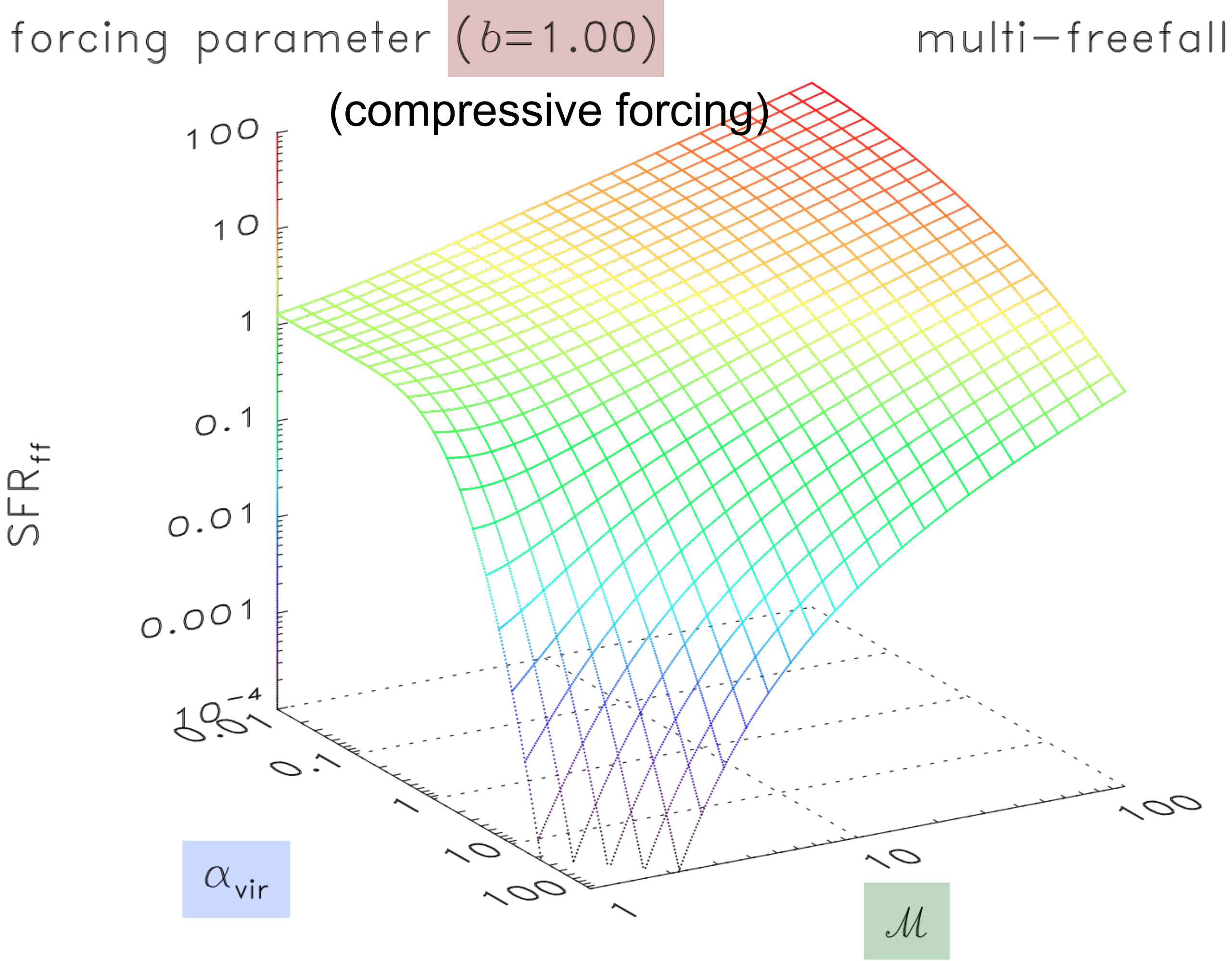


Federrath & Klessen (2012)

Density PDF → Star Formation Rate

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

$2\,E_{\mathrm{kin}}/E_{\mathrm{grav}}$ **forcing** **Mach number**



Federrath & Klessen (2012)

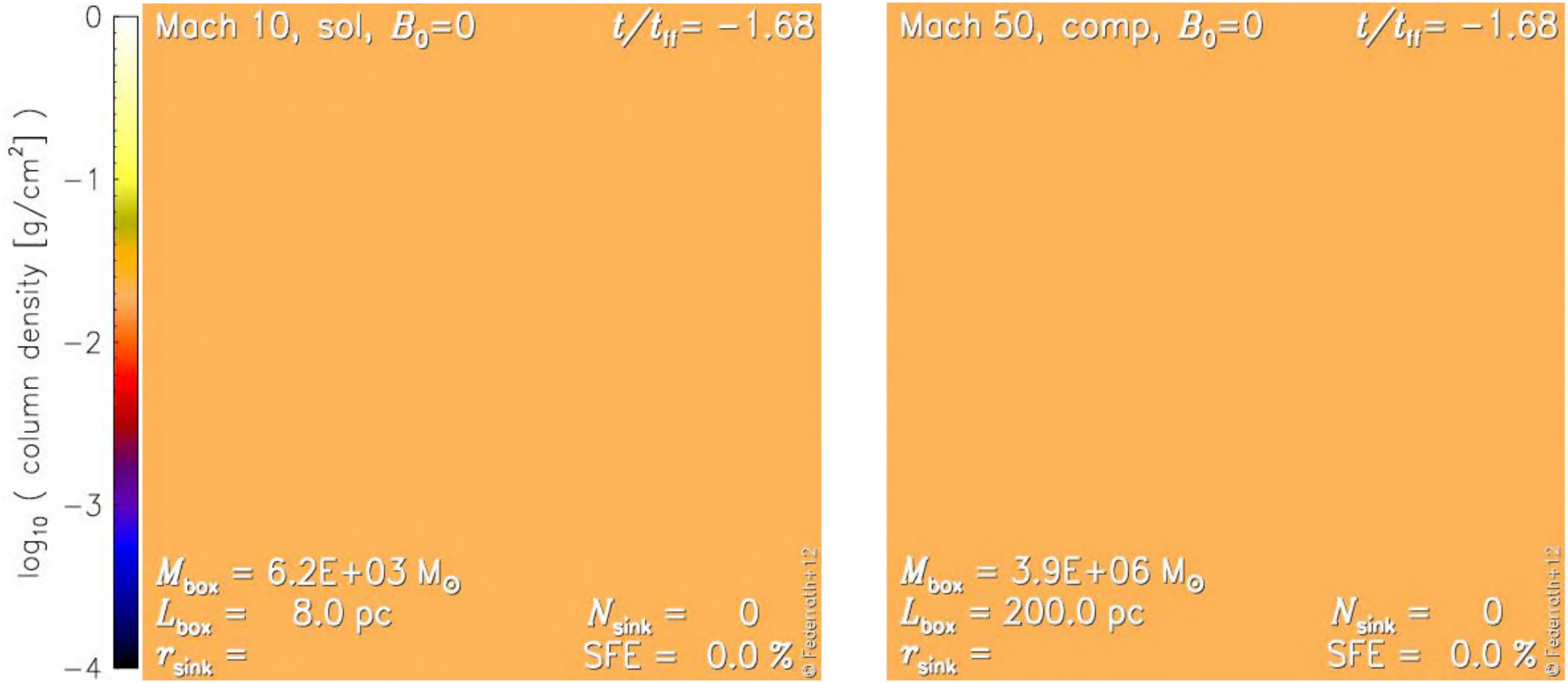
$\mathrm{SFR_{ff}} = \mathrm{SFR_{ff}}\left(\alpha_{\mathrm{vir}}, b, \mathcal{M}\right)$

Density PDF → Star Formation Rate

Numerical Simulation varying the turbulent Mach number:

Mach 10 solenoidal forcing

Mach 50 compressive forcing



$\mathrm{SFR_{ff}}$ (simulation) = **0.14** x **52** $\mathrm{SFR_{ff}}$ (simulation) = **7.3**

$\mathrm{SFR_{ff}}$ (theory) = **0.15** x **52** $\mathrm{SFR_{ff}}$ (theory) = **7.8**

Theory and Simulations agree

Federrath & Klessen (2012)

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

$$\mathrm{SFR}_{\mathrm{ff}} = \epsilon \int_{s_{\mathrm{crit}}}^{\infty} \overbrace{\frac{t_{\mathrm{ff}}(\rho_0)}{t_{\mathrm{ff}}(\rho)}}^{\text{freefall time}} \overbrace{\frac{\rho}{\rho_0}}^{\text{mass fraction}} p(s)\,\mathrm{d}s = \epsilon \int_{s_{\mathrm{crit}}}^{\infty} \exp\left(\frac{3}{2}s\right) p(s)\,\mathrm{d}s$$

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

MAGNETIC FIELD:

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

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

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

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

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

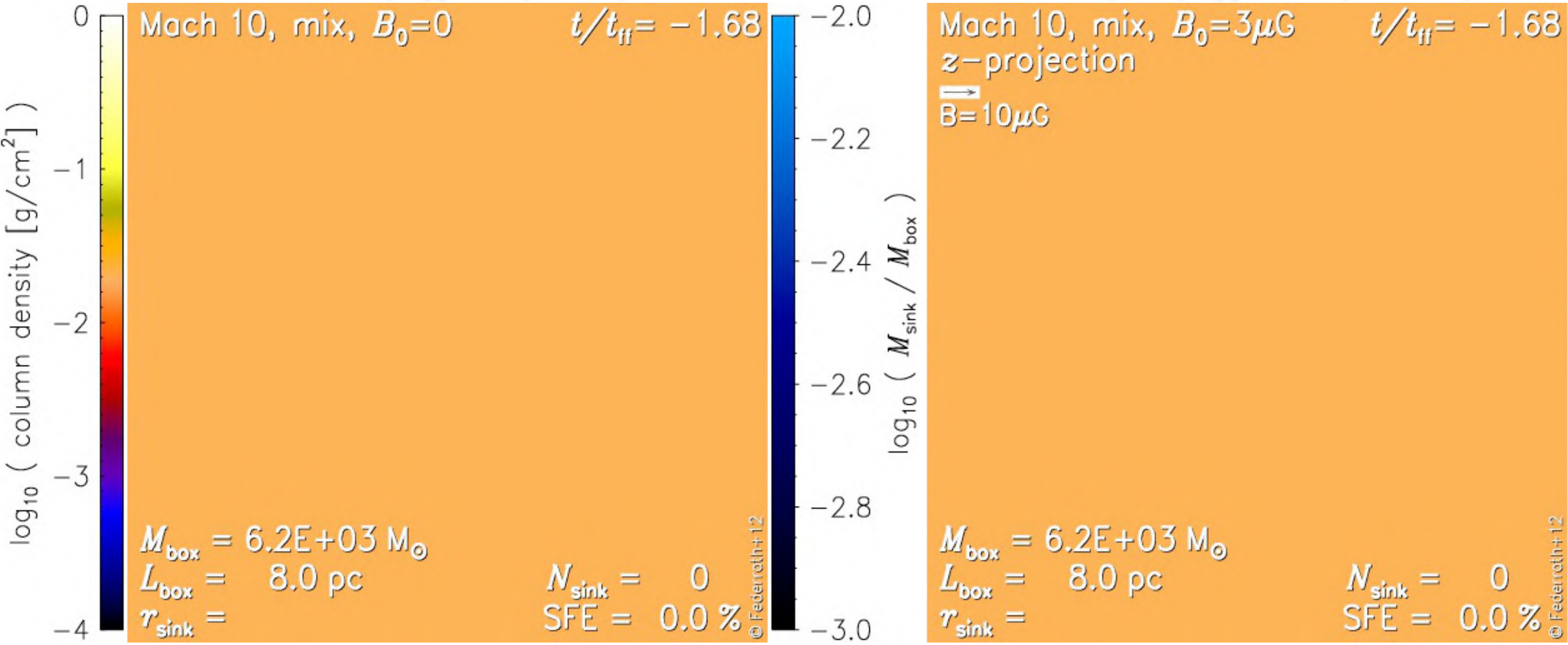
$2\,E_{\mathrm{kin}}/E_{\mathrm{grav}}$ **forcing** **Mach number** **plasma $\beta = P_{\mathrm{th}}/P_{\mathrm{mag}}$**

Federrath & Klessen (2012)

The Star Formation Rate – Magnetic fields

Numerical Test for Mach 10 with mixed forcing

B=0 ($M_A = \infty$, $\beta = \infty$) *B*=3μG ($M_A = 2.7$, $\beta = 0.2$)



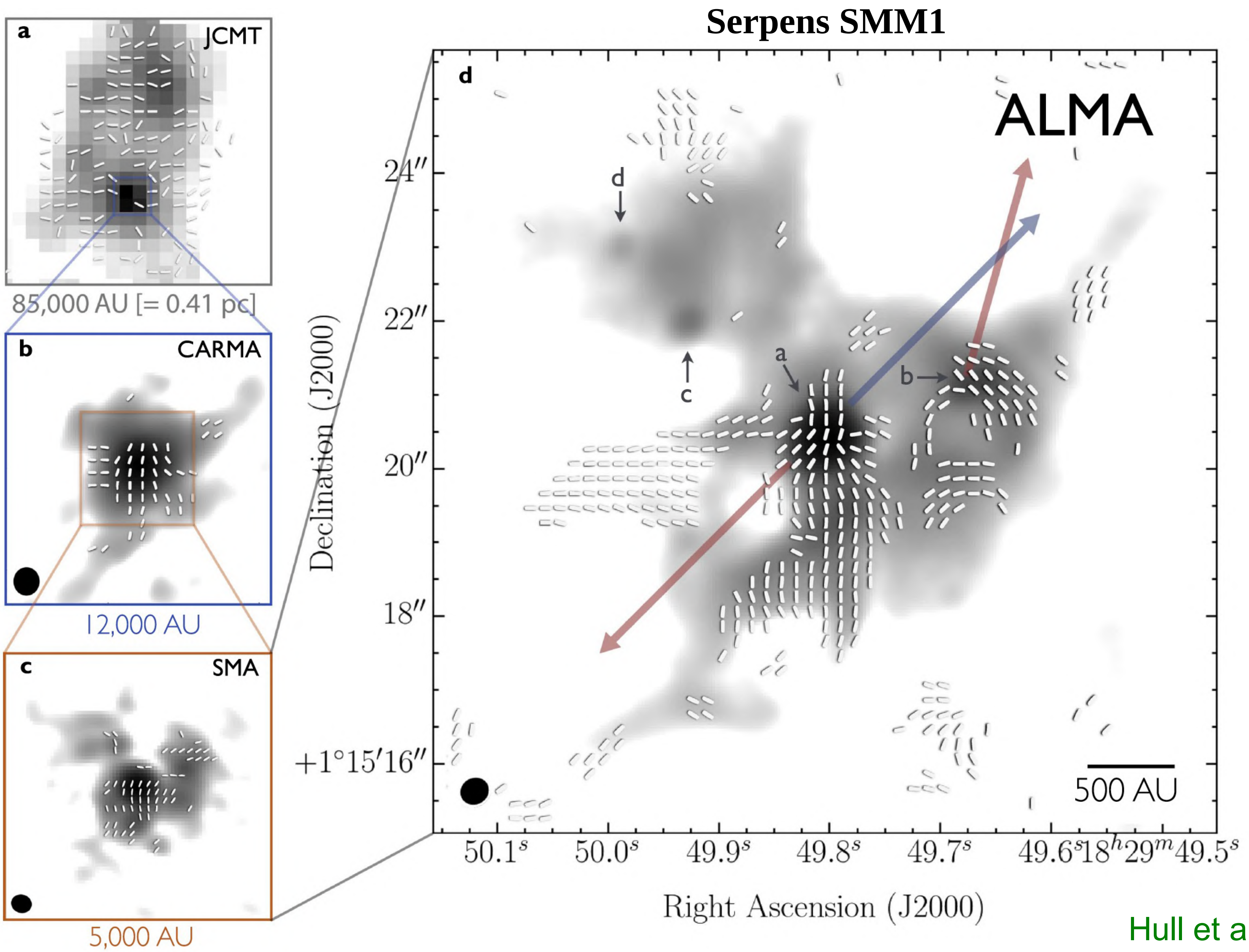
SFR_{ff} (simulation) = **0.46** x **0.63** SFR_{ff} (simulation) = **0.29**

SFR_{ff} (theory) = **0.45** x **0.40** SFR_{ff} (theory) = **0.18**

Magnetic field reduces SFR and fragmentation (by factor ~2).

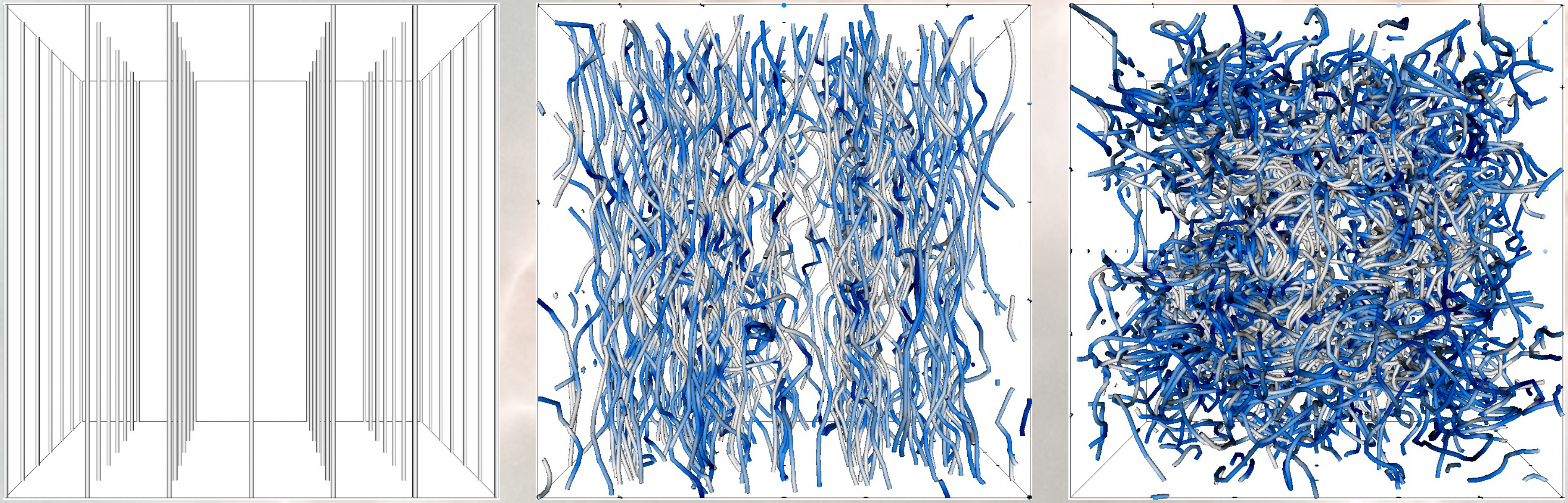
Padoan & Nordlund (2011); Padoan et al. (2012); Federrath & Klessen (2012)

The role of magnetic field structure



Hull et al. (2017)

The role of magnetic field structure for jet launching



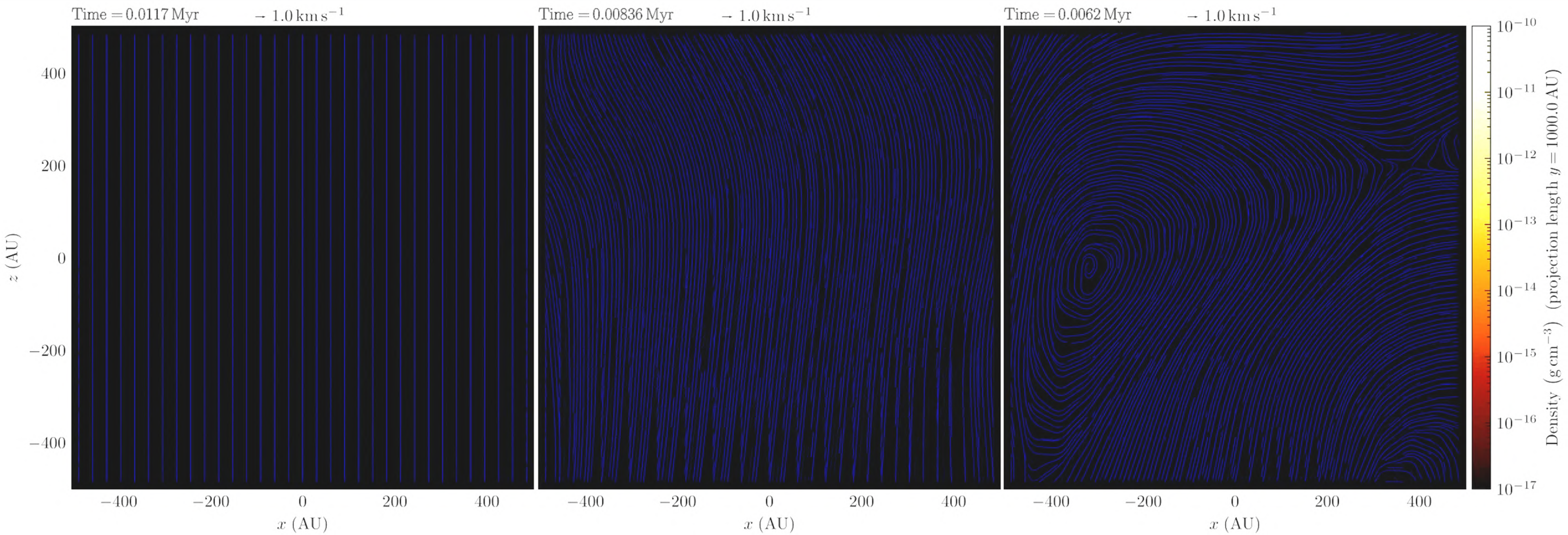
Uniform Magnetic Field

Partially Turbulent Field

Fully Turbulent Field

Gerrard et al. (2019)

The role of magnetic field structure for jet launching



Uniform Magnetic Field

Partially Turbulent Field

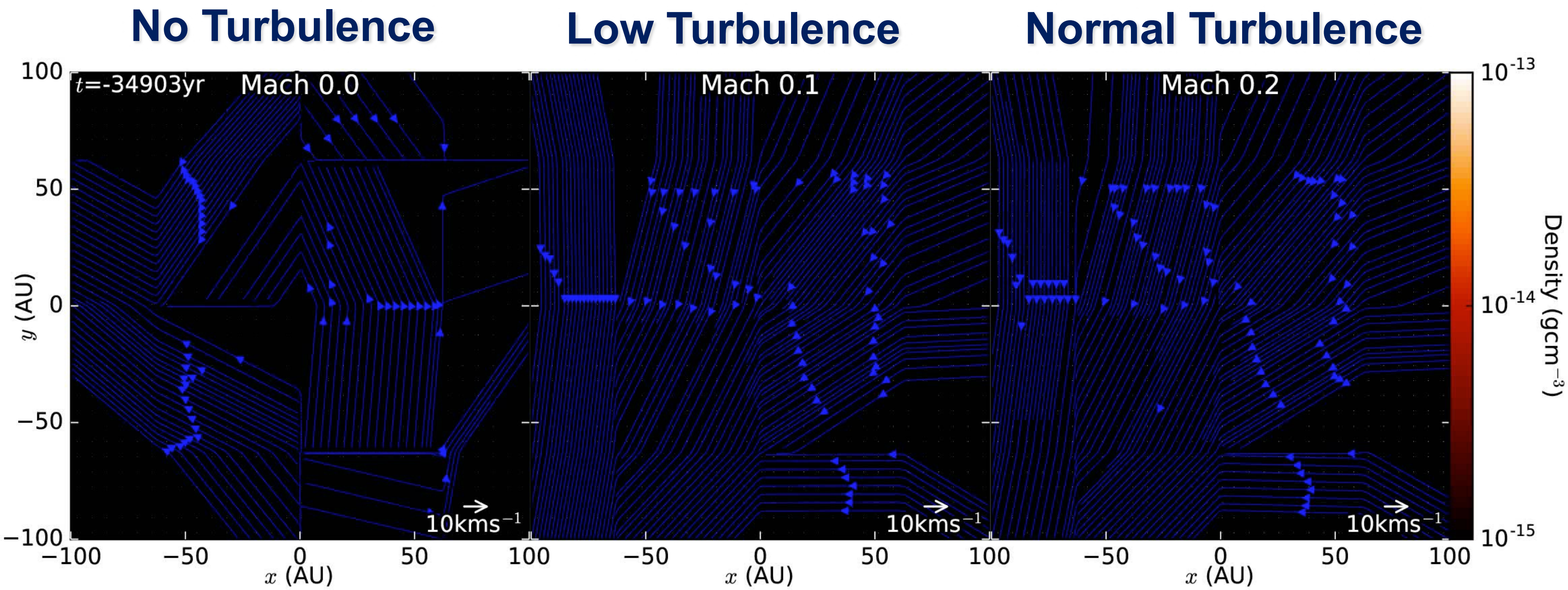
Fully Turbulent Field

Gerrard et al. (2019)

→ Need ordered magnetic field component for jet launching

(Blandford & Payne 1982)

Built-up of circum-binary disks



Turbulence makes bigger disks → relevant for planet formation

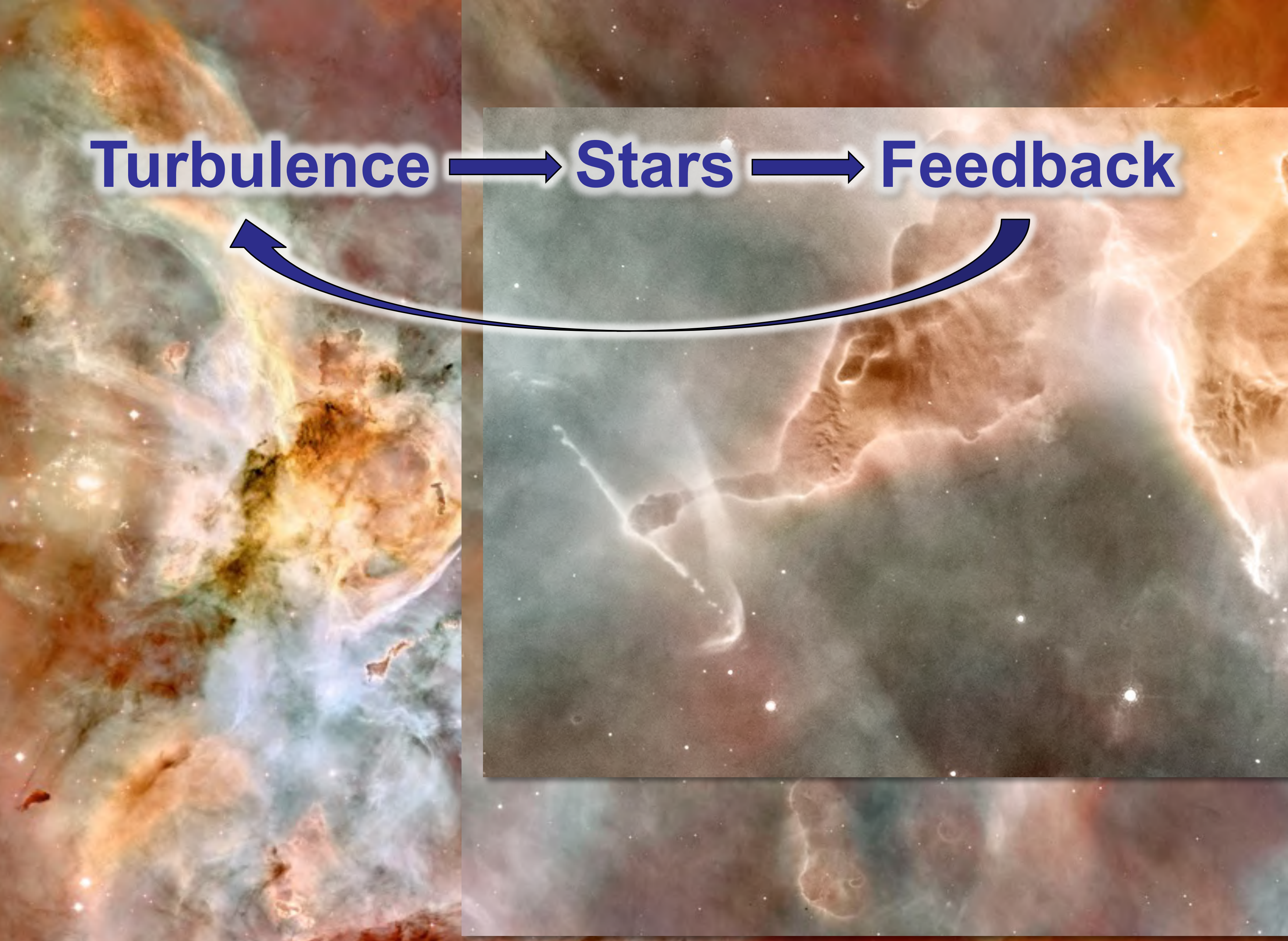
Magnetic field structure is key for outflow/jet launching

Kuruwita & Federrath (2019)

Turbulence → Density PDF

Density PDF → Star Formation Rate

Why is star formation so inefficient?



Turbulence → Stars → Feedback

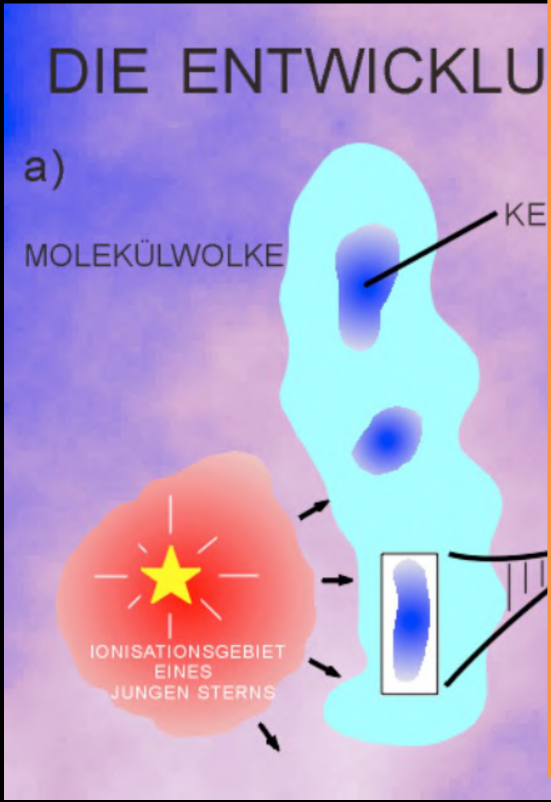
Carina Nebula, NASA, ESA, N. Smith (University of California, Berkeley), and The Hubble Heritage Team (STScI/AURA), and NOAO/AURA/NSF

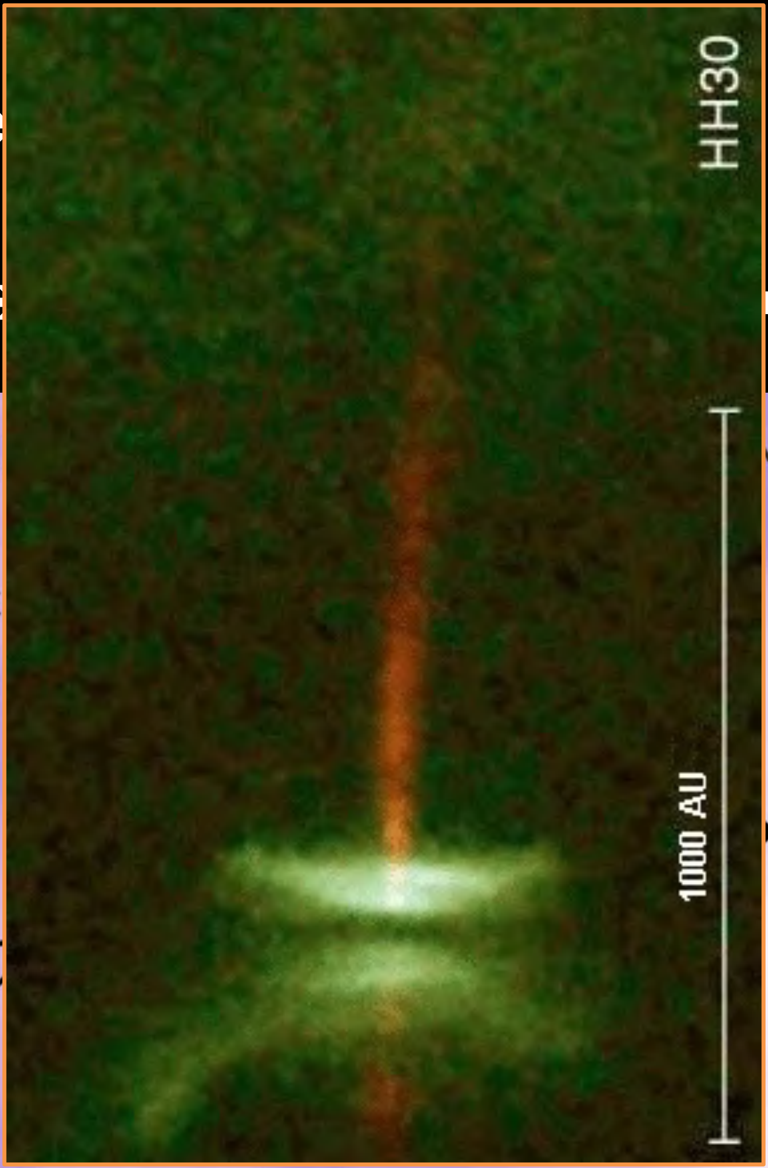
Star Formation

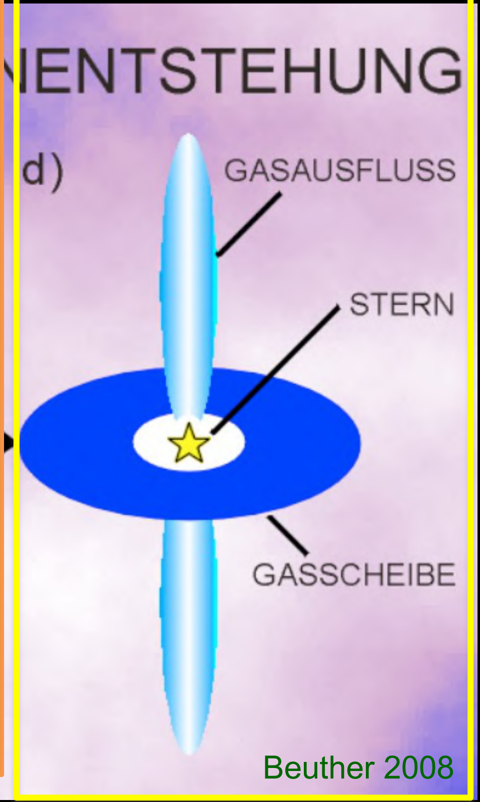
The

Clouds

Jet / Outflow

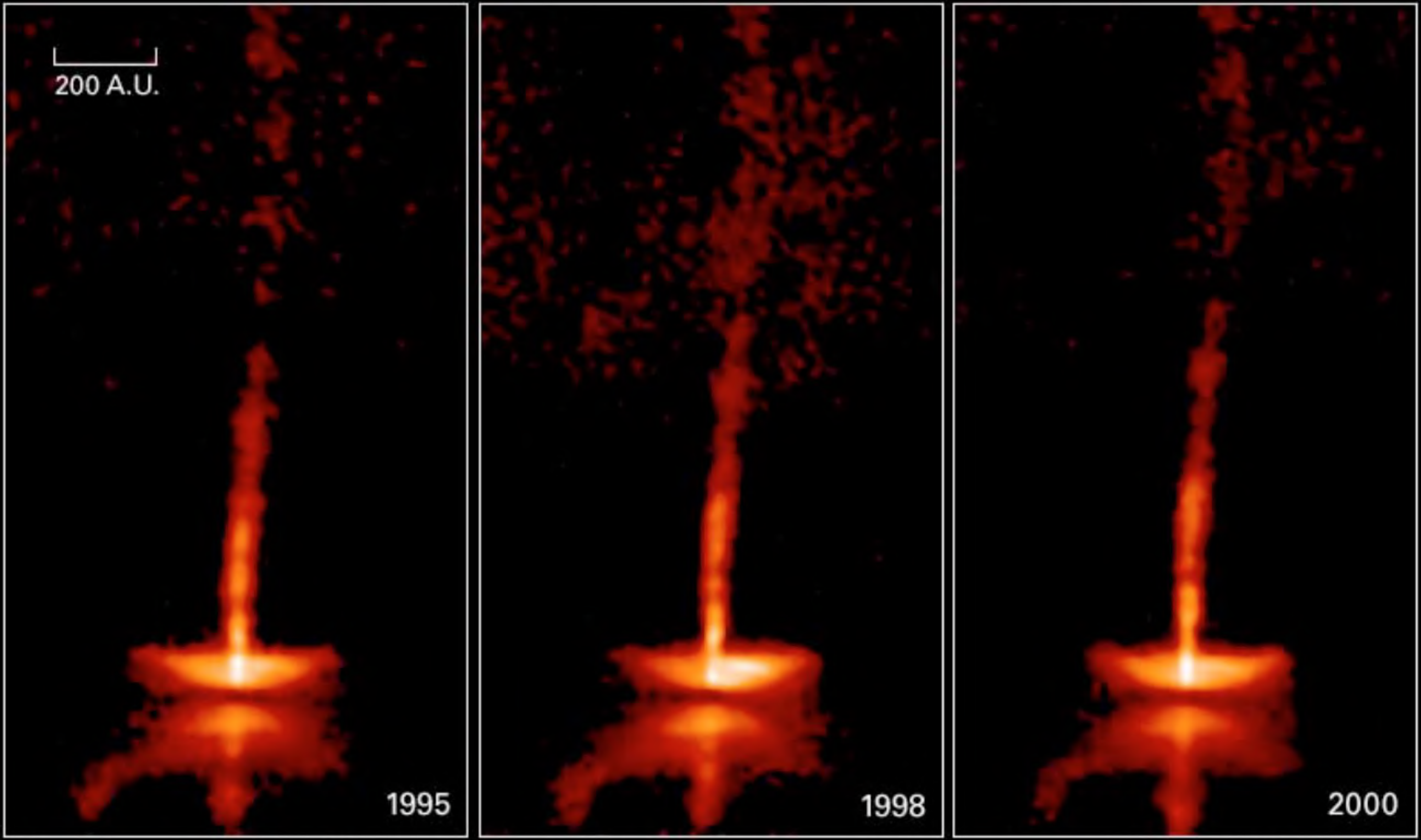






Beuther 2008

Jets and Outflows

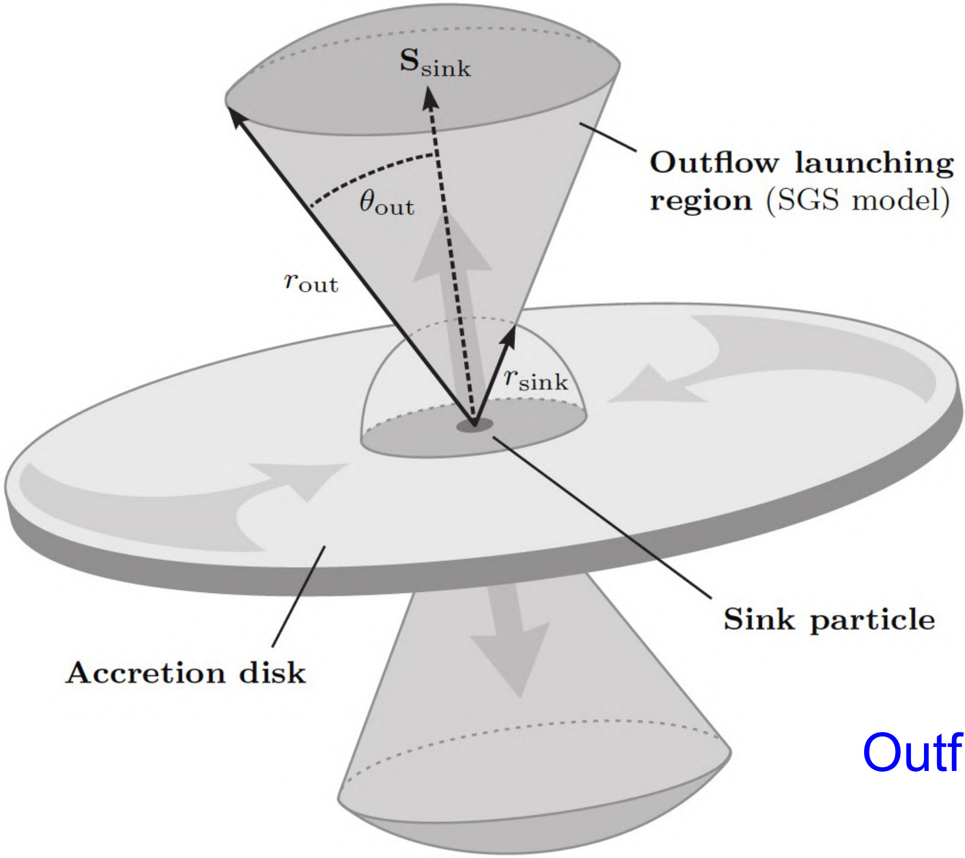


The Dynamic HH 30 Disk and Jet HST • WFPC2

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

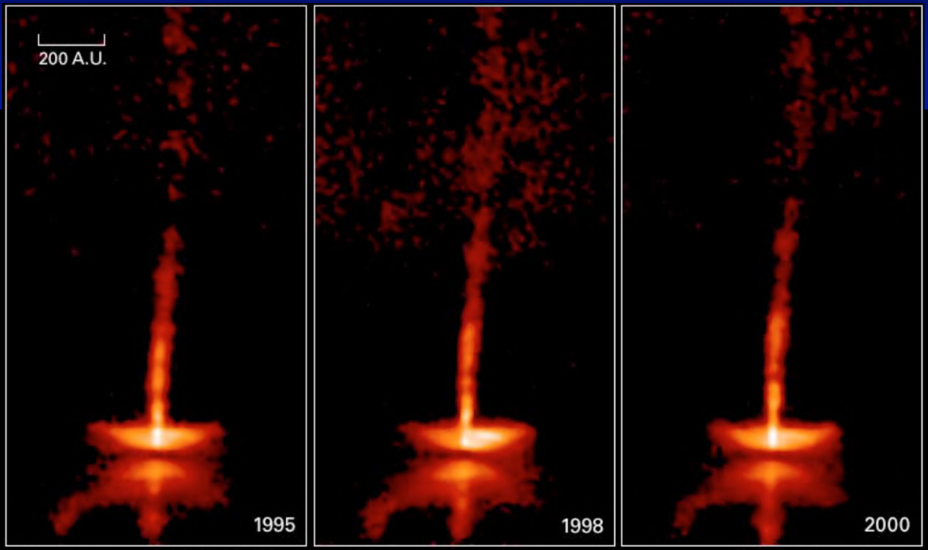
Notes. [a] The outflow velocities are dynamically computed according to the Kepler speed at the footpoint of the jet, $\lvert\mathbf{V}_{\rm out}\rvert = 100\,{\rm km\,s^{-1}}(M_{\rm sink}/0.5\,M_\odot)^{1/2}$ (see Equation 13). References: [1] Blandford & Payne (1982); Appenzeller & Mundt (1989); Camenzind (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: $\lvert\mathbf{V}_{\rm out}\rvert = \left(\dfrac{GM_{\rm sink}}{10\,R_\odot}\right)^{1/2} = 100\,{\rm km\,s^{-1}}\,\left(\dfrac{M_{\rm sink}}{0.5\,M_\odot}\right)^{1/2}$

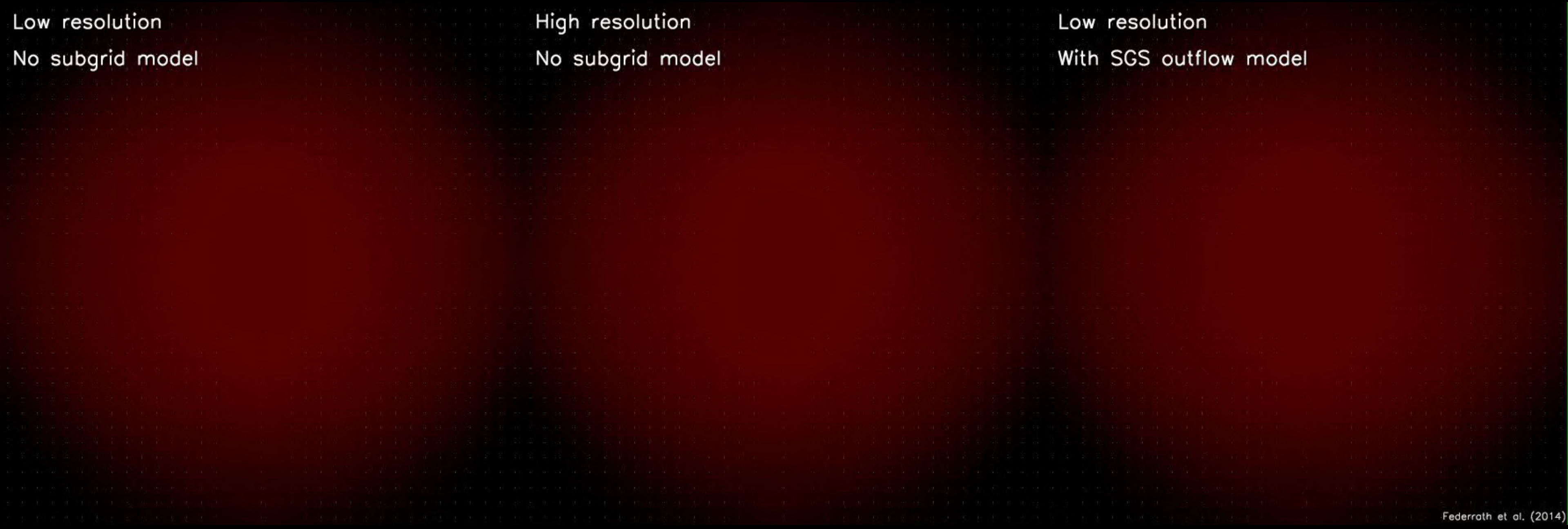
Outflow angular momentum: $\mathbf{L}_{\rm out} = f_{\rm a}\,(\mathbf{S}'_{\rm sink} - \mathbf{S}_{\rm sink})\cdot\mathbf{S}'_{\rm sink}/\lvert\mathbf{S}'_{\rm sink}\rvert$

Jet/Outflow Feedback



The Dynamic HH 30 Disk and Jet HST • WFPC2

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



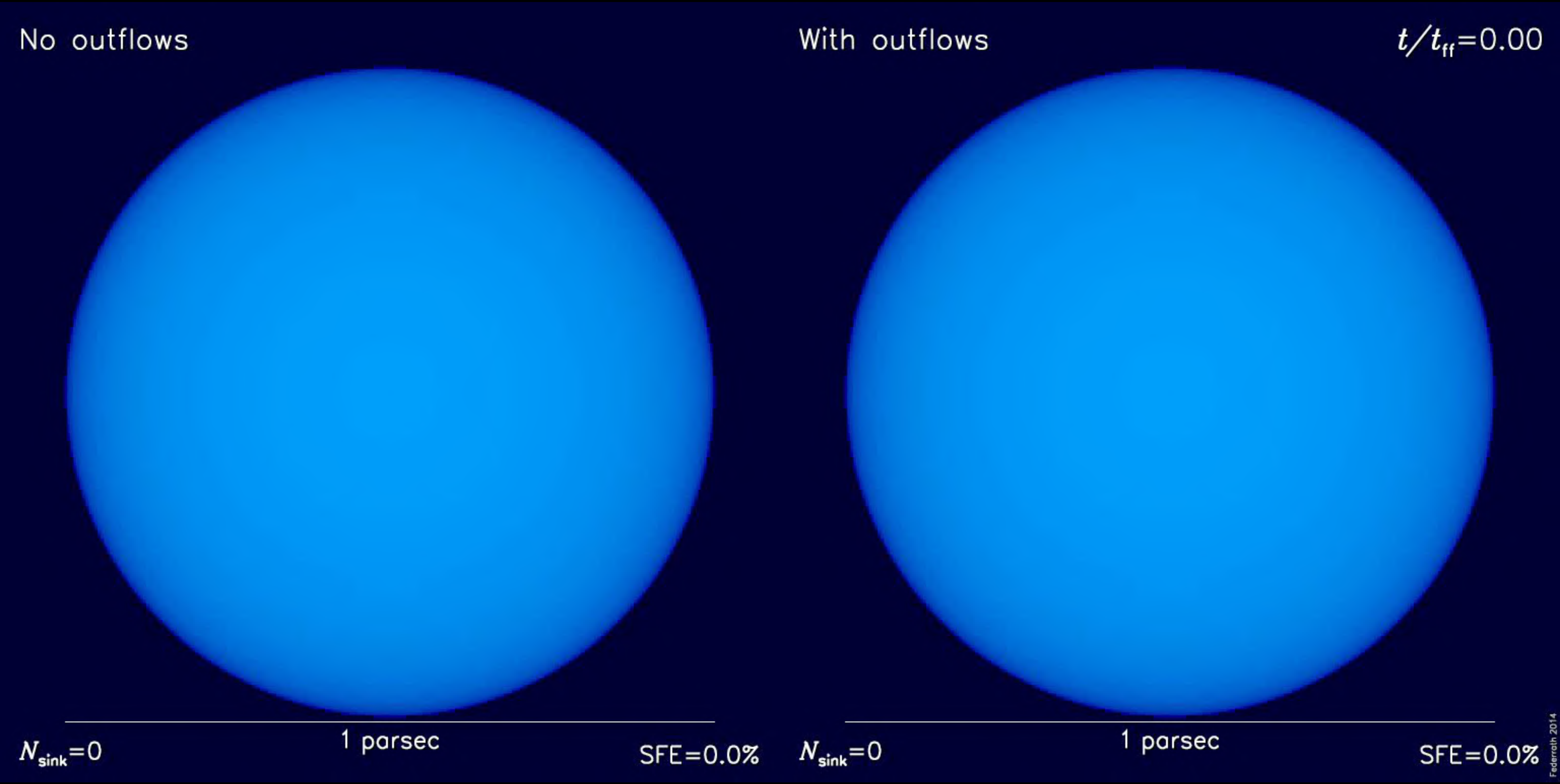
Federrath et al. 2014, ApJ 790, 128

Star Formation – Outflow/Jet Feedback

NGC1333

Image credit: Gutermuth & Porras

The role of outflow/jet feedback for star cluster formation

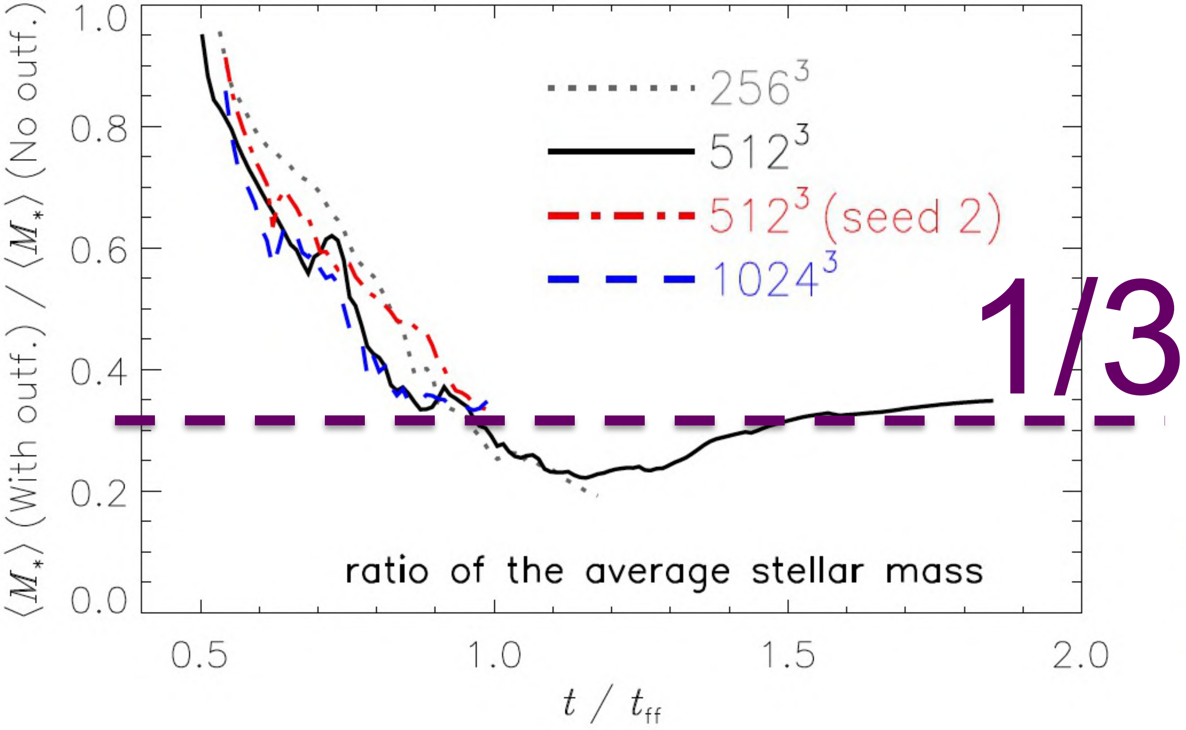


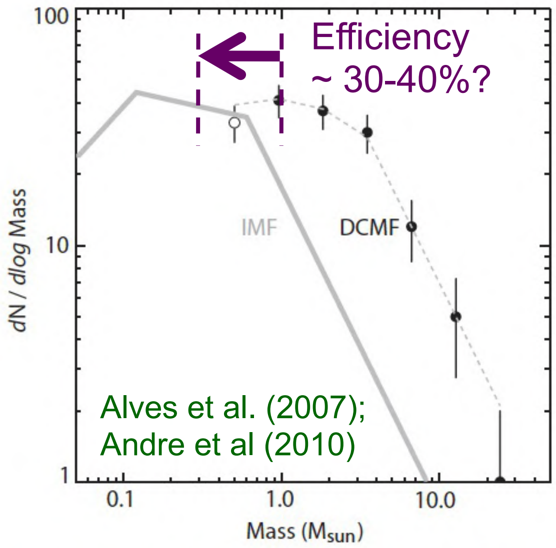
SGS off

SGS on

Federrath et al. 2014, ApJ 790, 128

The role of outflow/jet feedback for star cluster formation





Efficiency ~ 30-40%?

Alves et al. (2007);
Andre et al (2010)

RESULTS:

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

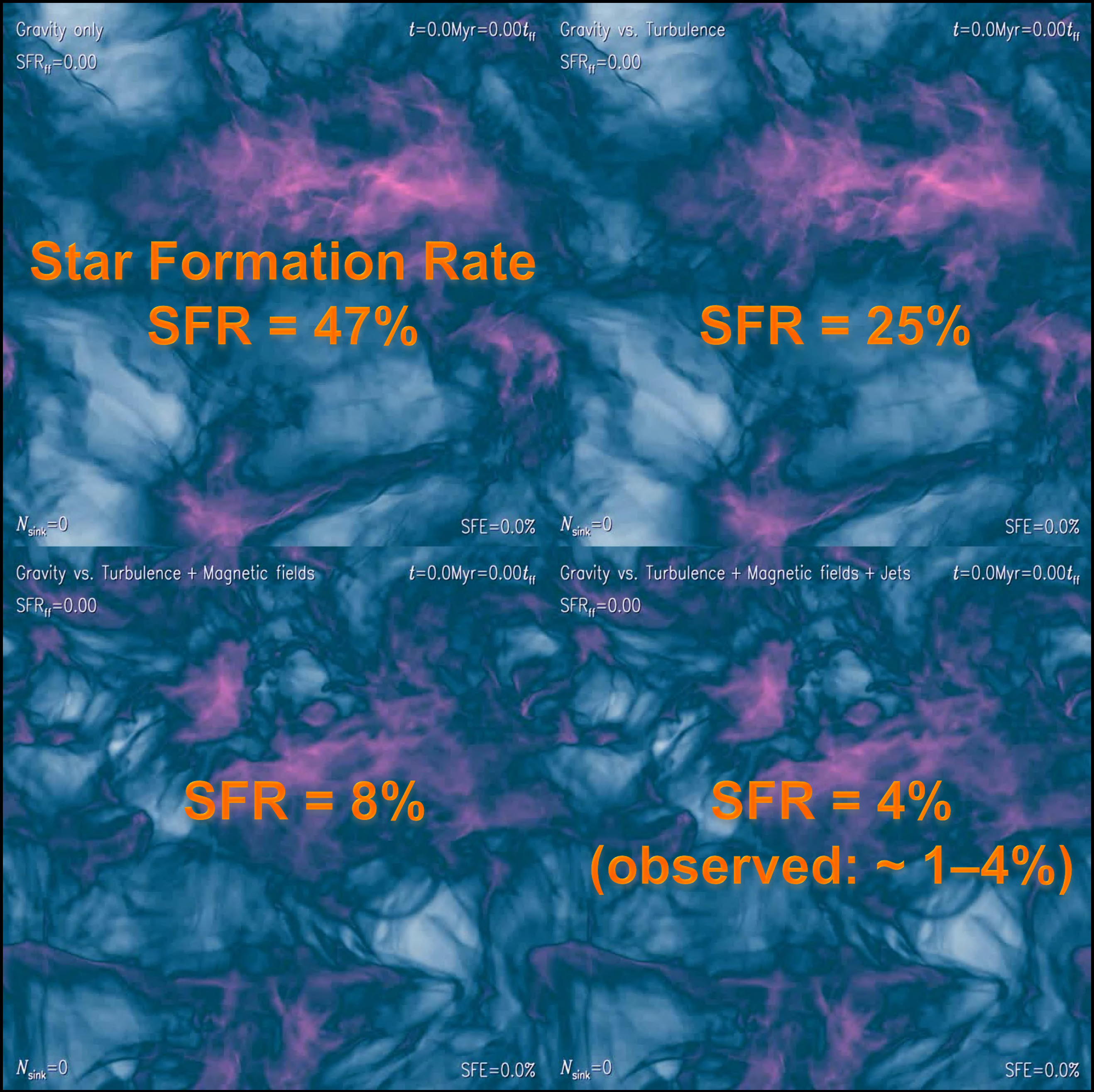
Star Formation is Inefficient

1. Gravity?
2. Turbulence?
3. Magnetic Fields?
4. Feedback?

Star Formation is Inefficient

(Federrath 2015 MNRAS; 2018 *Physics Today*)

Gravity only



Star Formation Rate
SFR = 47%

SFR = 25%

SFR = 8%

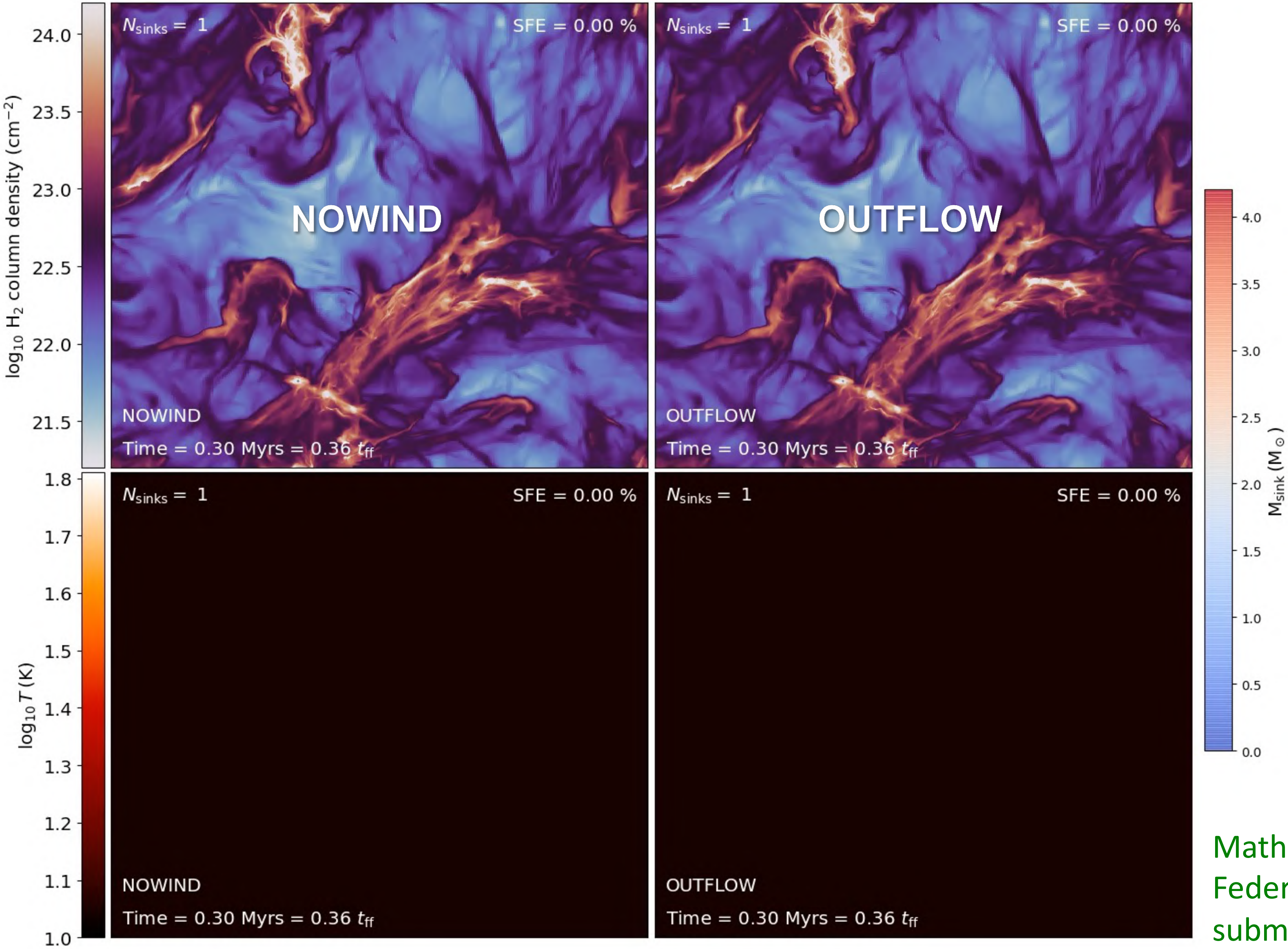
SFR = 4%
(observed: ~ 1–4%)

with
Turbulence

Turb+
Magnetic
Fields

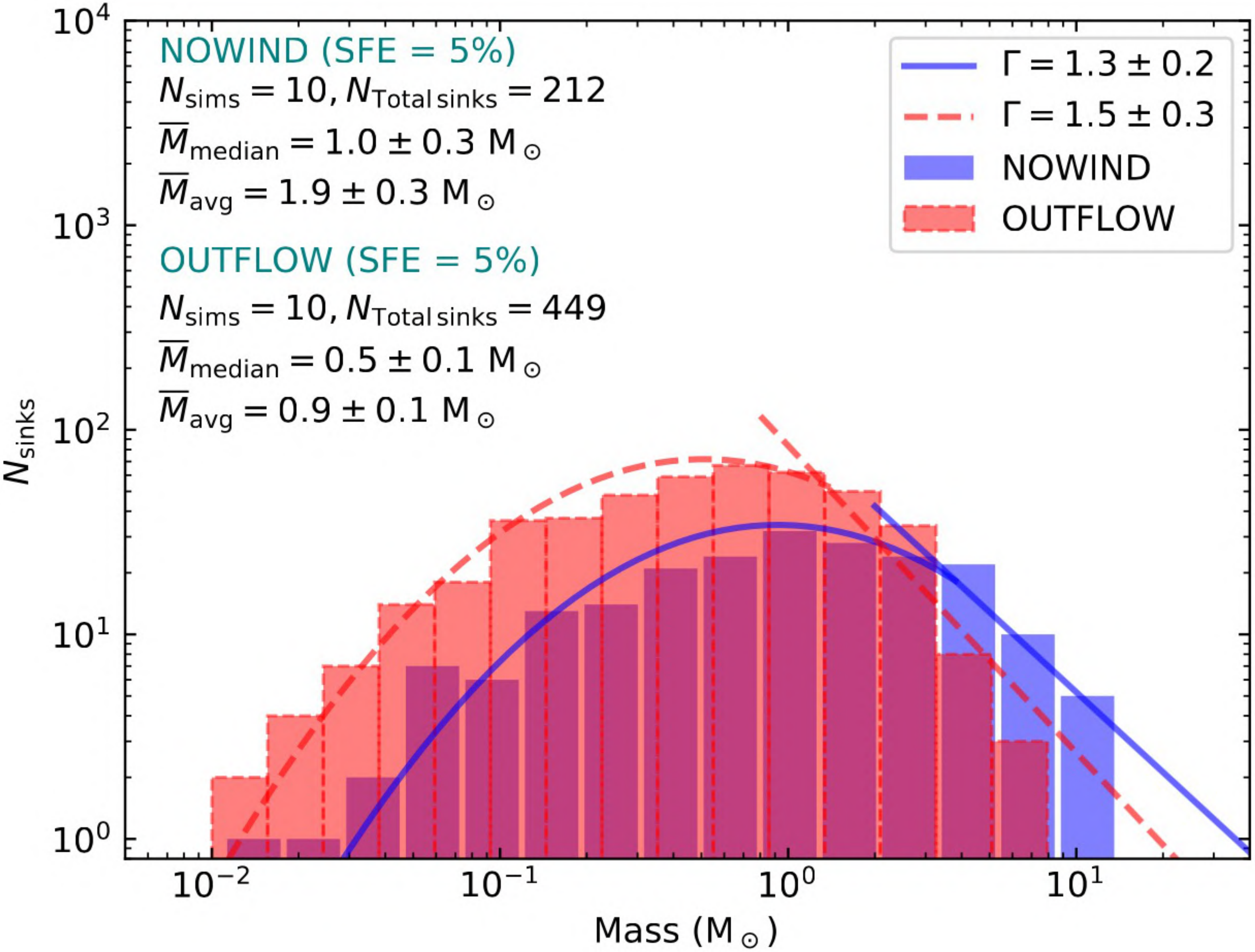
Turb+
Mag+
Jet/Outflow
Feedback

Role of Jet/Outflow Feedback for the IMF



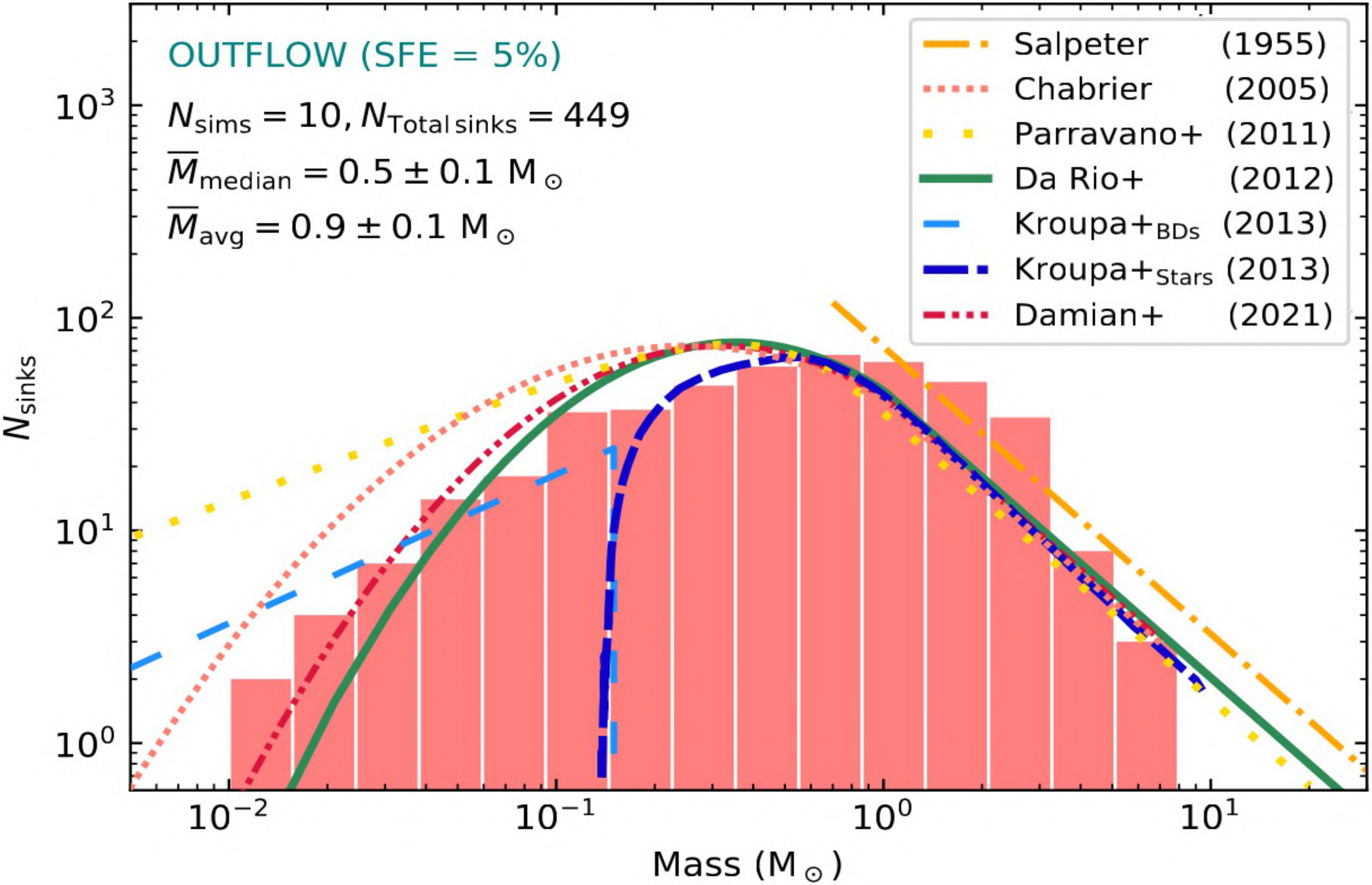
Mathew & Federrath 2021, submitted

Role of Jet/Outflow Feedback for the IMF



(Mathew & Federrath 2021, submitted)

Role of Jet/Outflow Feedback for the IMF



(Mathew & Federrath 2021, submitted)

Conclusions

Analyses of observational data and simulations heavily rely on computing

Astronomical Computing

Astronomical Computing

ASTR4004 / ASTR8004

NEXT:
Setting up your computer, 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

Image credit: M. S. Povich

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.

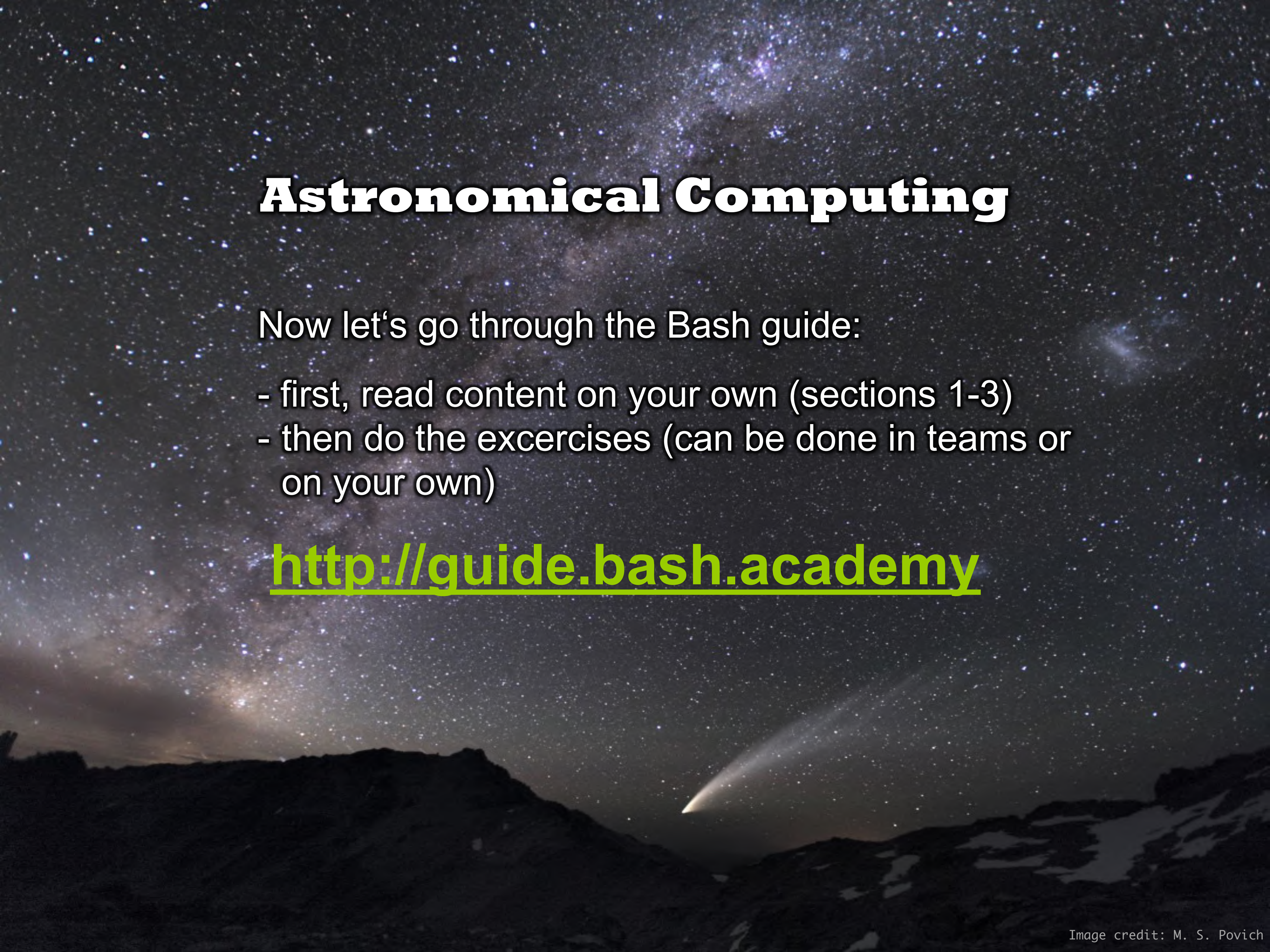
Distinguish *Interactive* and *Non-interactive* mode

Useful shell commands:

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