Astronomical Computing

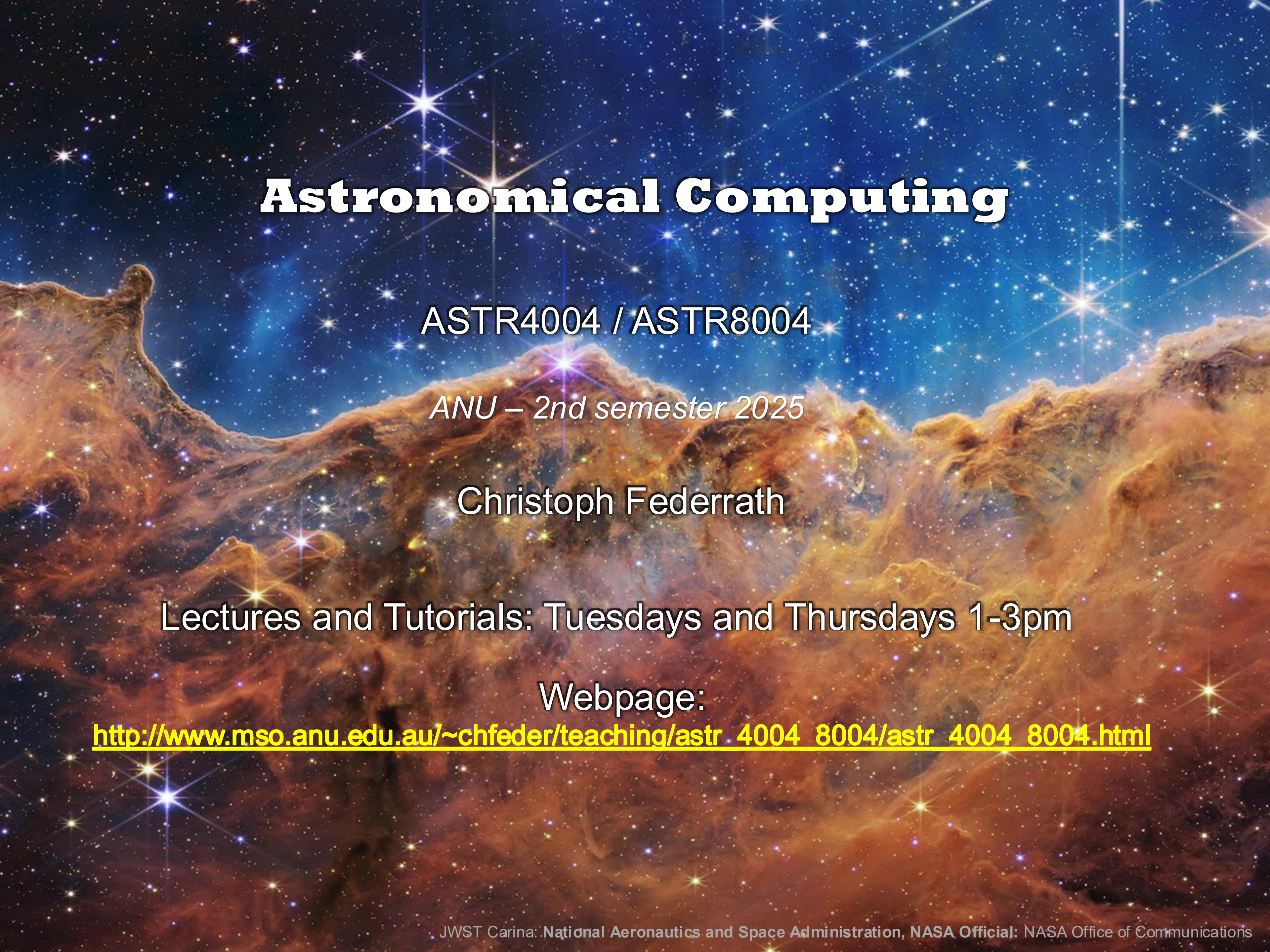
ASTR4004 / ASTR8004

ANU – 2nd semester 2025

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 1-6: taught by Christoph Federrath

Basics of shell usage, Remote computing, Plotting, Python, Statistics, Binning, MC error propagation, Fourier transformation, Parallel computing

Weeks 7-12: taught by Sven Buder and Yuxiang Qin

Regression, Neural Networks, Gaussian Processes, Monte-Carlo Markov Chain, Numerical simulations...

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 Canvas
- Please nominate yourself or someone else, if you are interested

Astronomical Computing

Assignments:

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

Help with marking assignments and exam is provided by Lewis Miller.

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Modelling/Computing
Star Formation, Turbulence, Feedback

Christoph Federrath

ANU – 2025

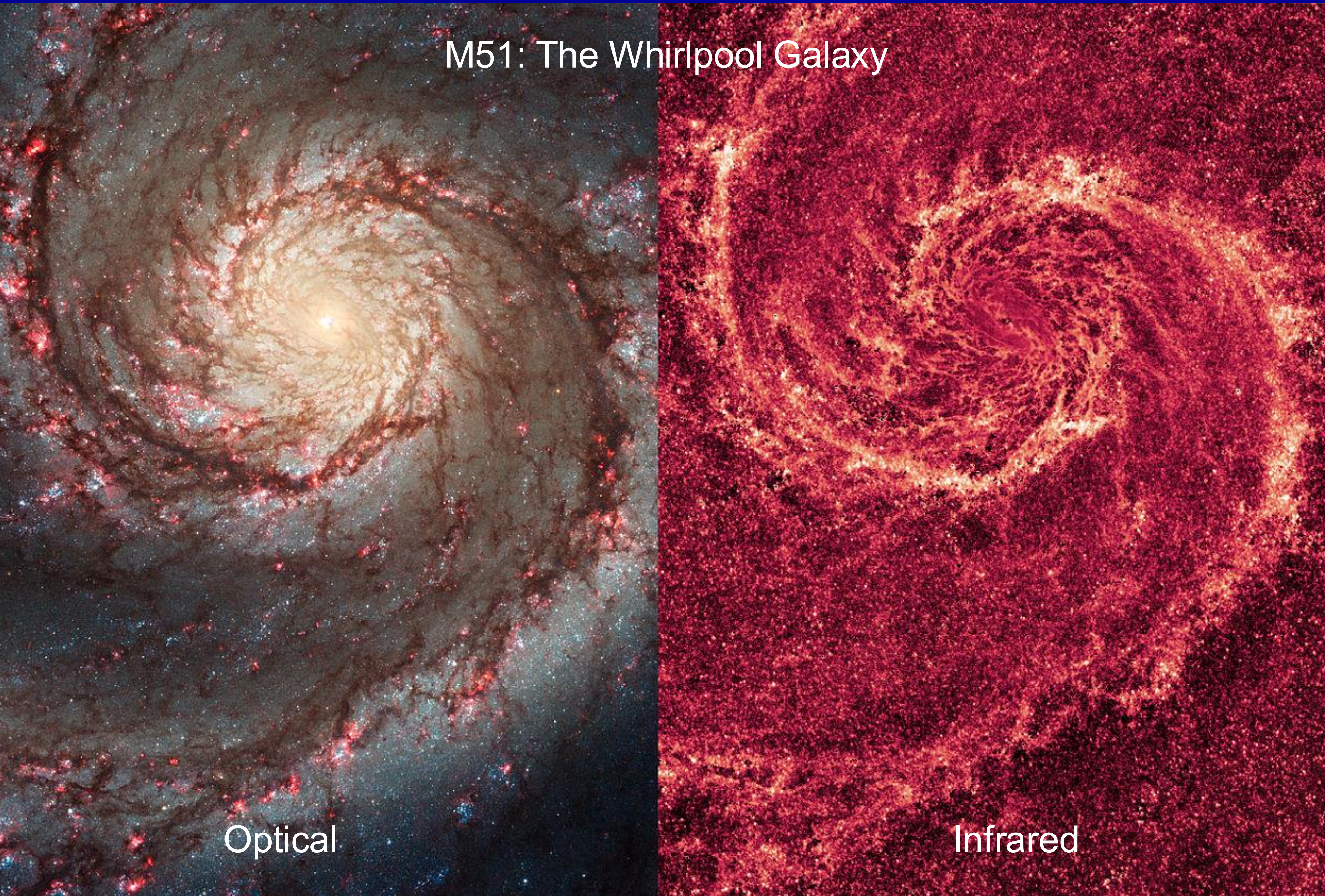
Australian Government
Australian Research Council

Australian National University

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

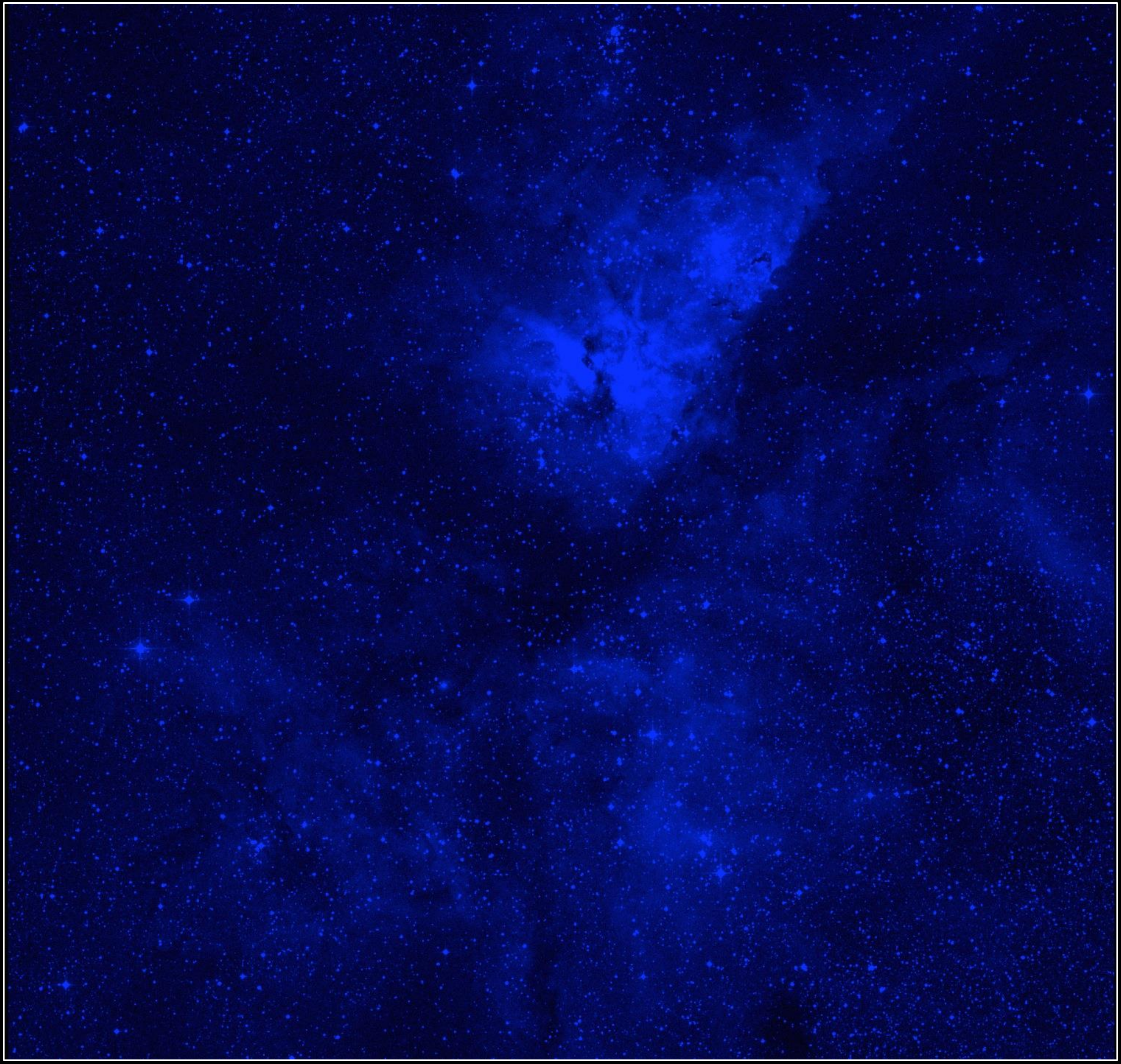
Image Credit: ESA and the HFI Consortium, IRAS 2010

Star Formation



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

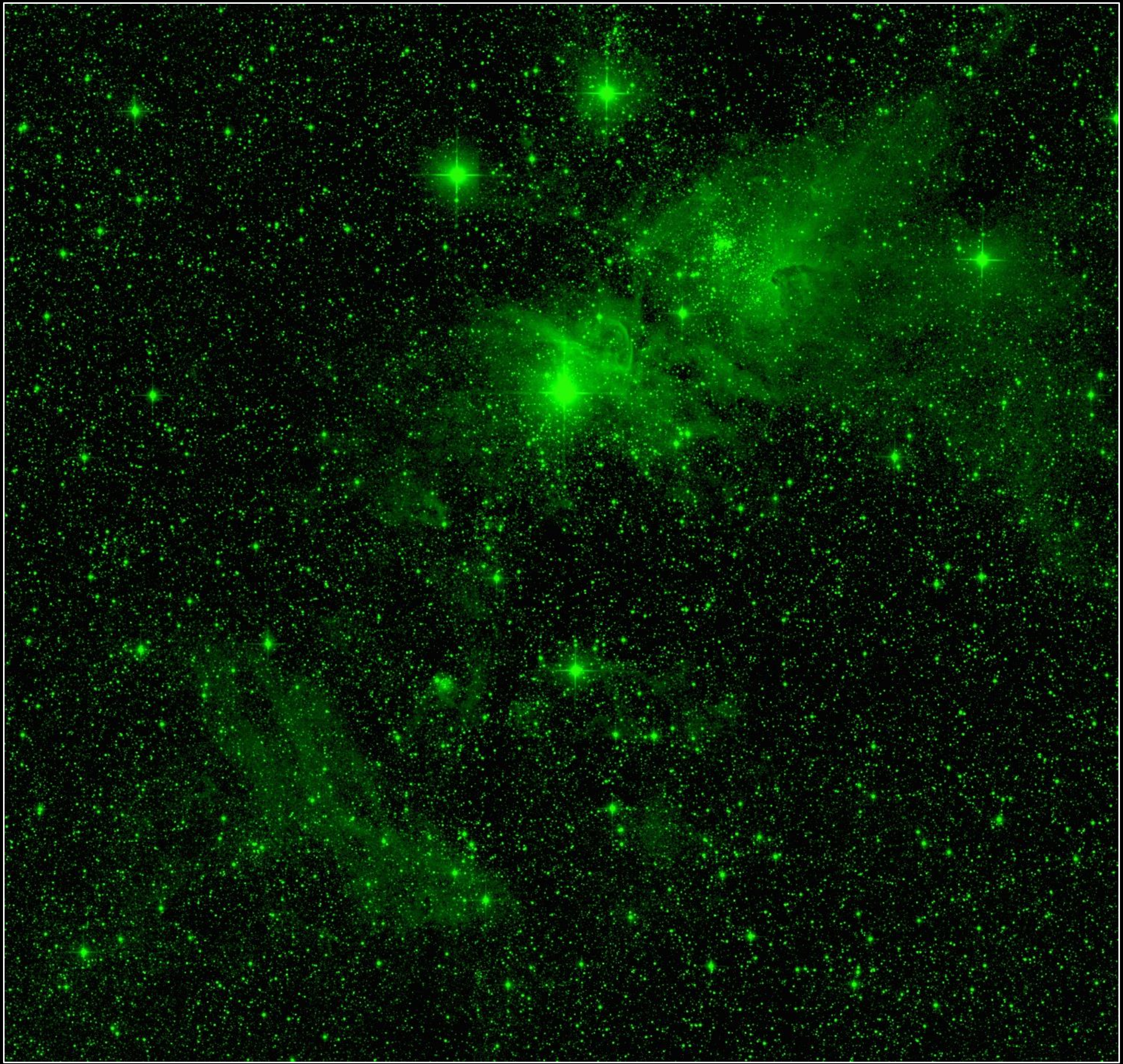
Visible Light

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

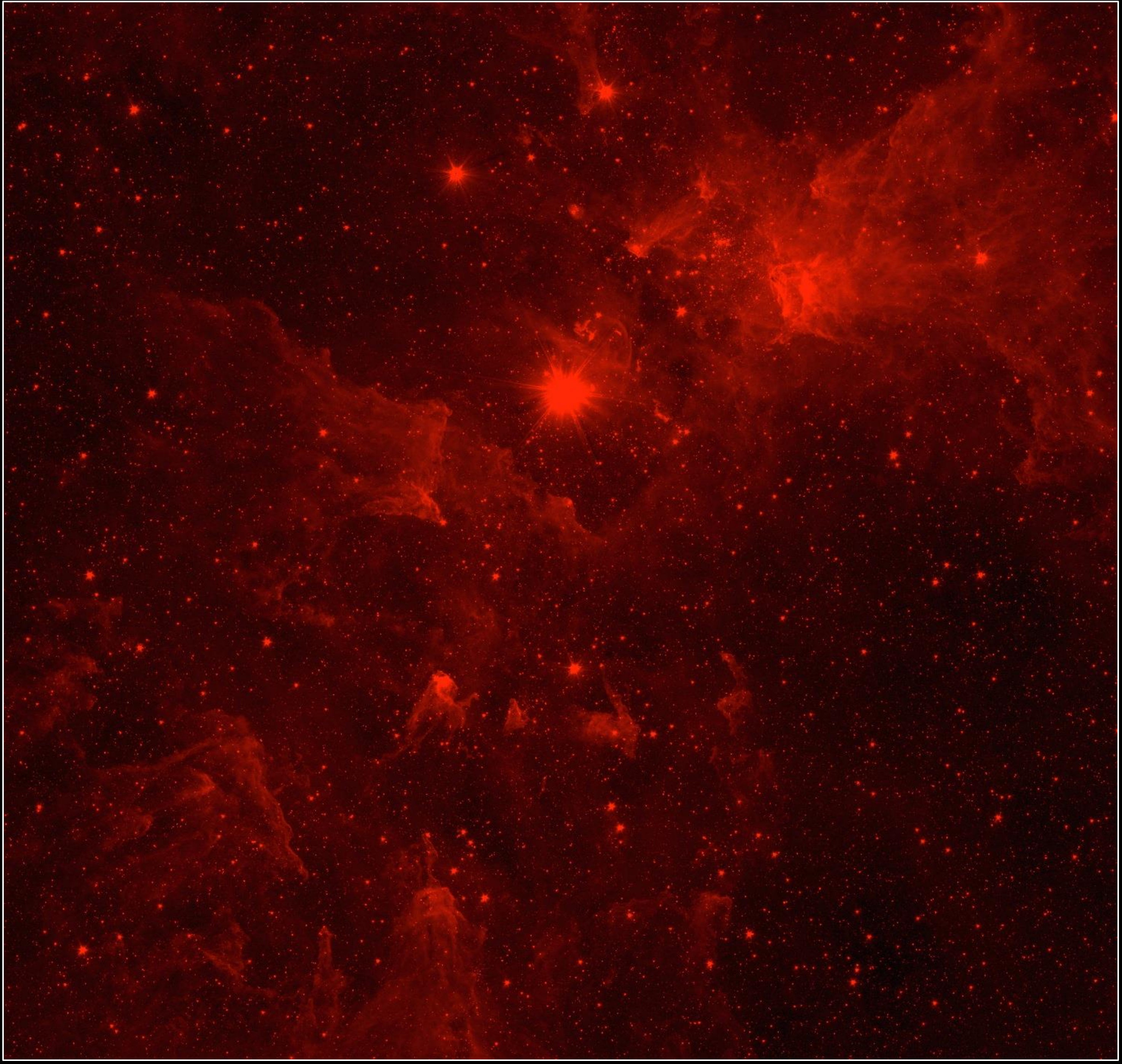
Near-Infrared

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

(Feedback → Turbulence)

Turbulence driven by

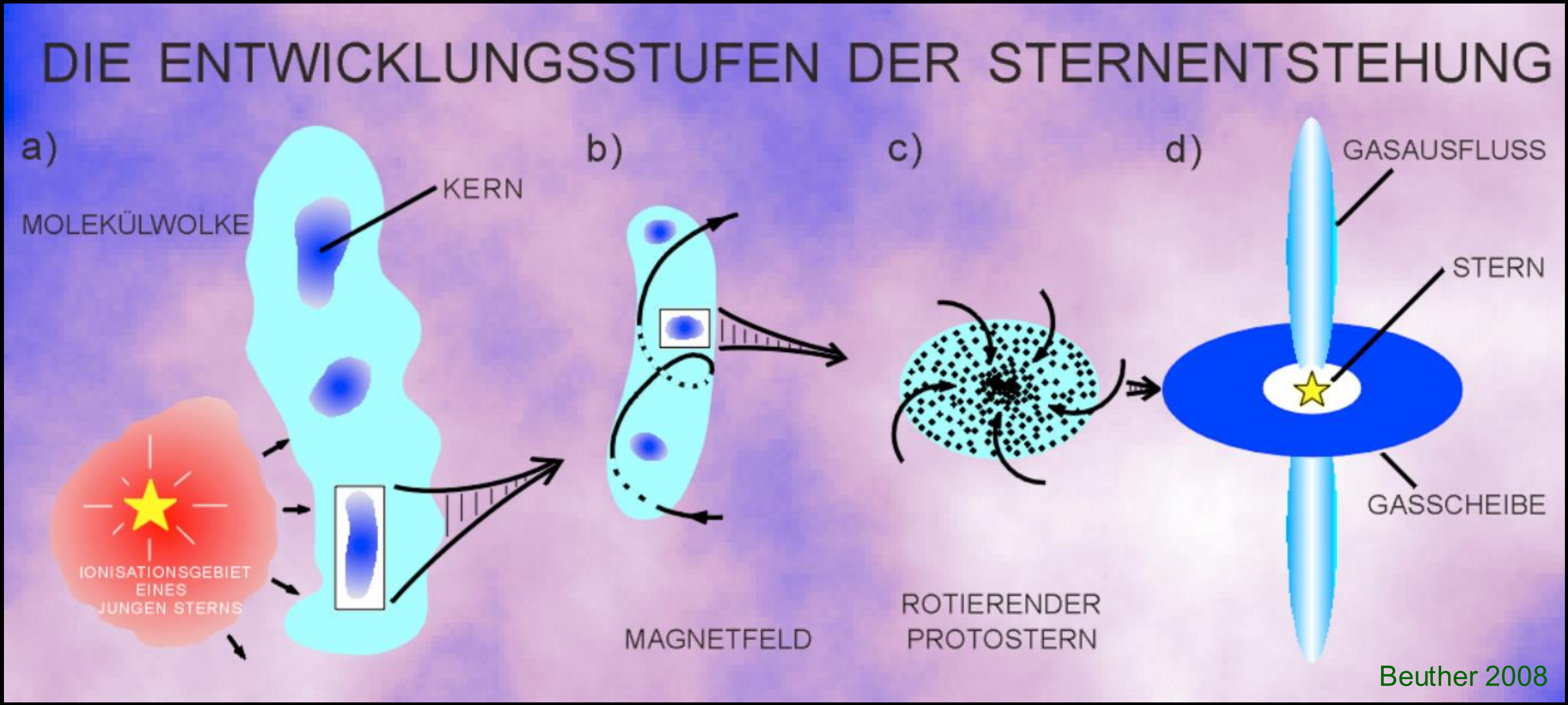
- Ionization fronts, bubbles?
- Protostellar jets/winds?
- Supernova explosions?
- MRI / shear?
- Gravitational infall?
- Galactic spiral shock?

Mac Low & Klessen (2004)

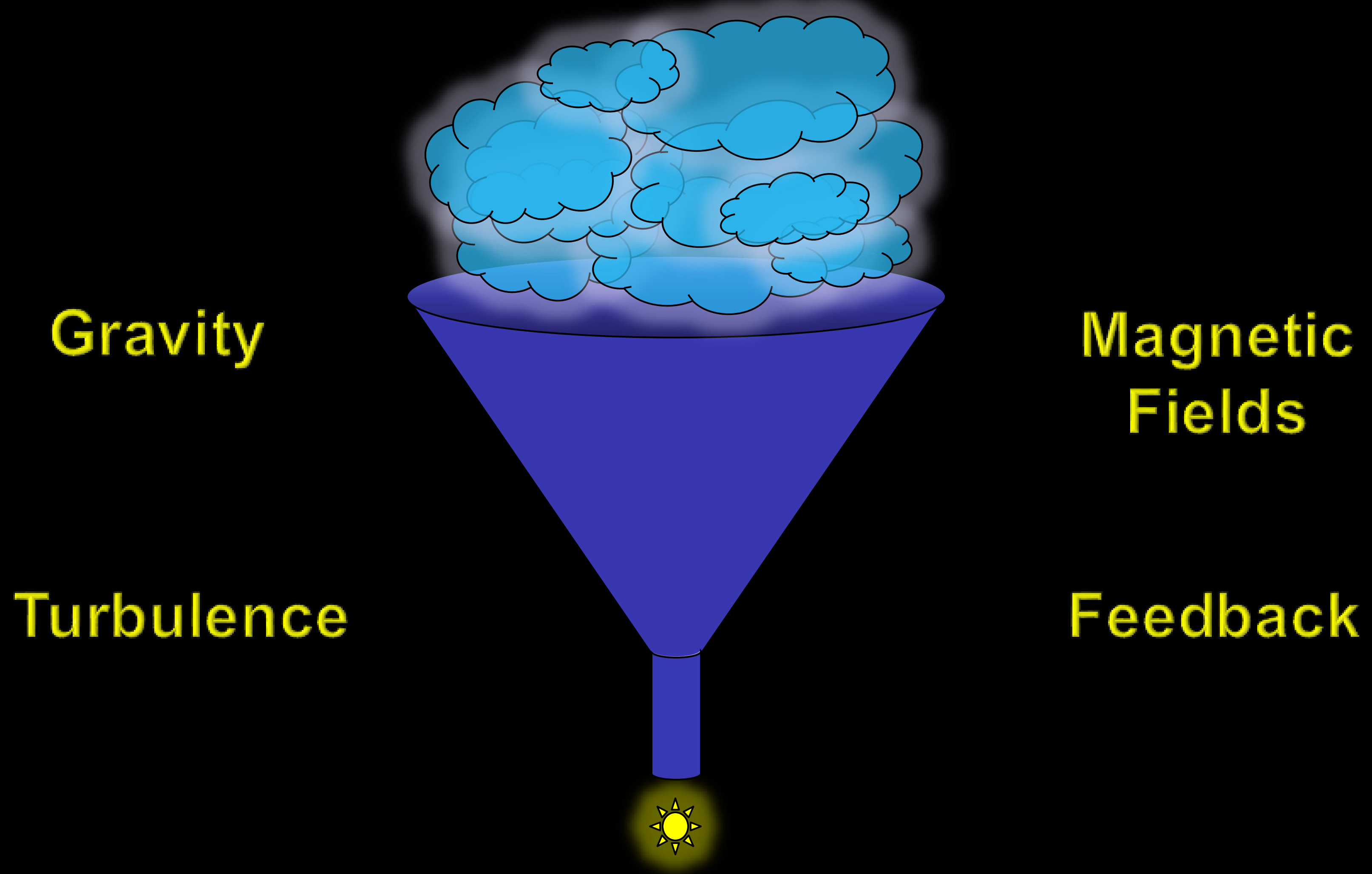
Carina Nebula, NASA, ESA, N. Smith (University of California, Berkeley), and The Hubble Heritage Team (STScI/AURA), and NOAO/AURA/NSF

The Star Formation Paradigm

Clouds → Cores → Disk + Star + Jet / Outflow



Star Formation is Inefficient



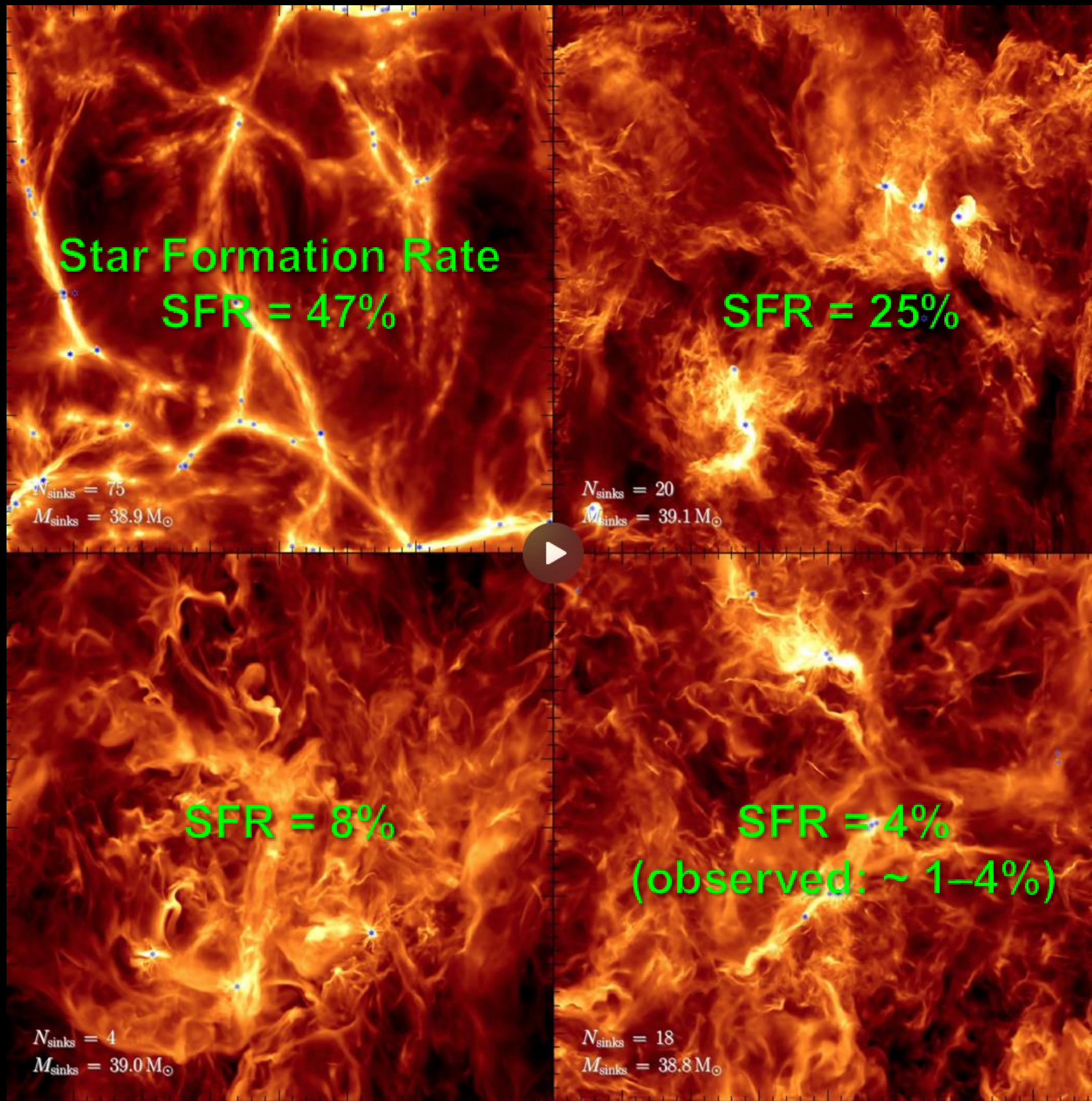
Star Formation is Inefficient

(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

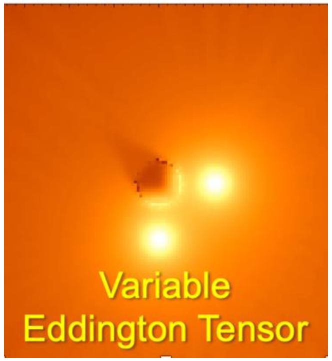


Turb+ Magnetic Fields

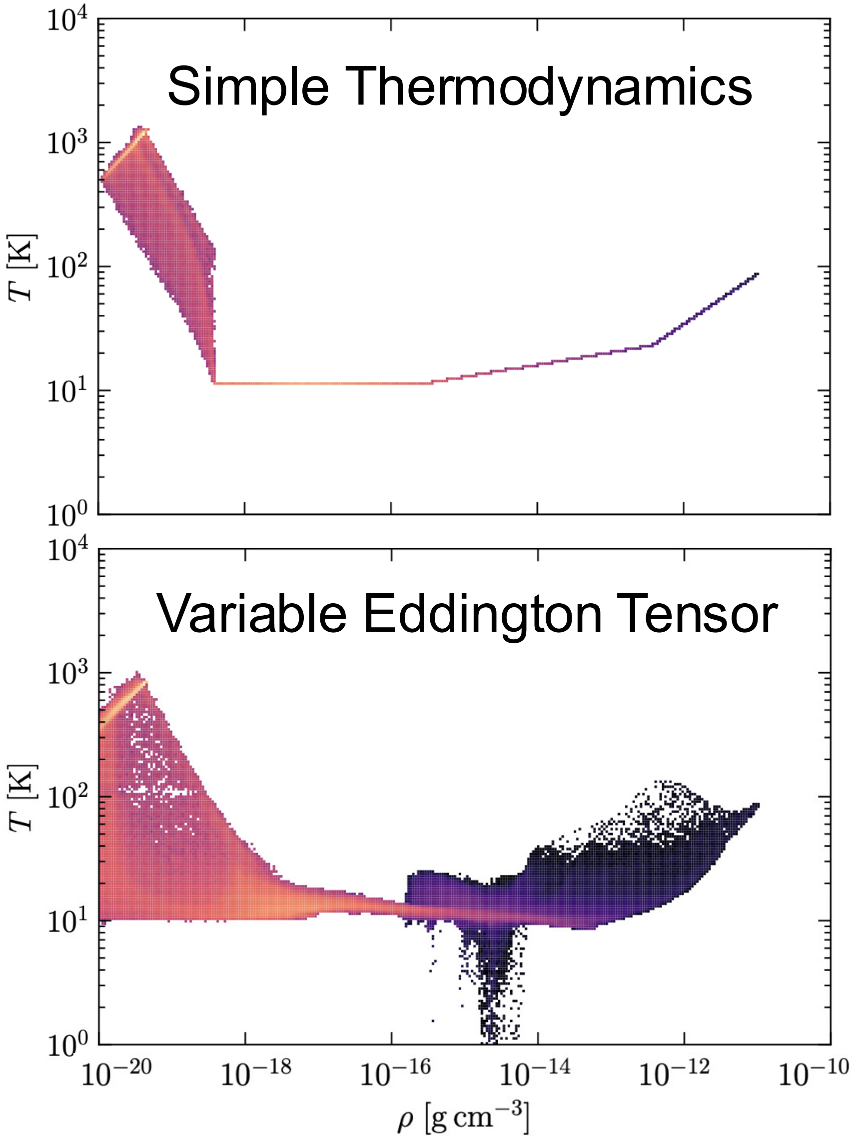
Turb+ Mag+ Jet/Outflow Feedback

(sims for Appel et al. 2023)

Modelling Radiation



(Menon et al. 2022)

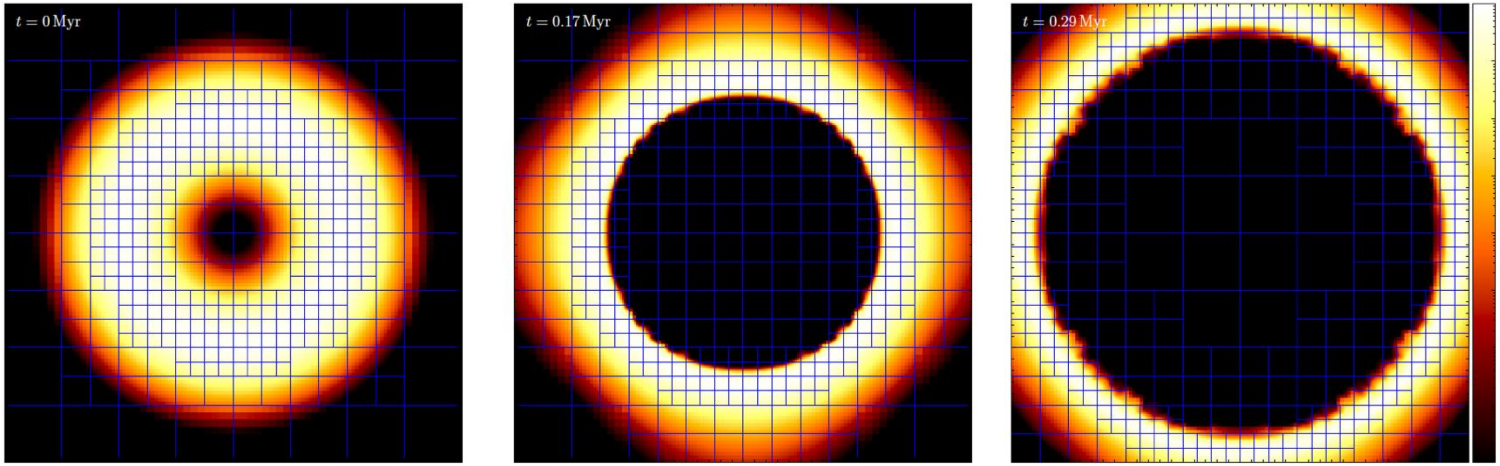


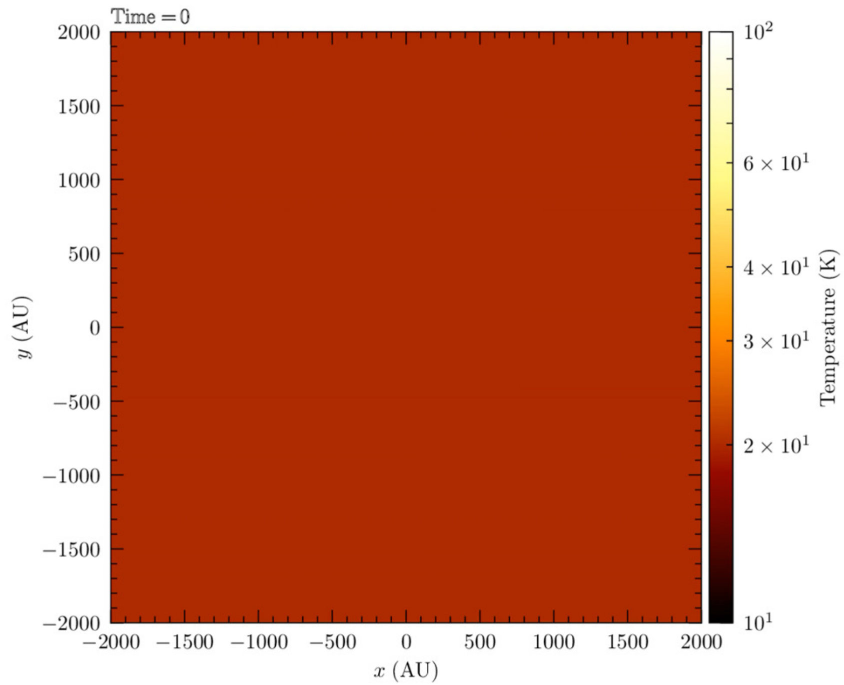
Movies available: **https://www.mso.anu.edu.au/~chfeder/pubs/vettam/vettam.html**

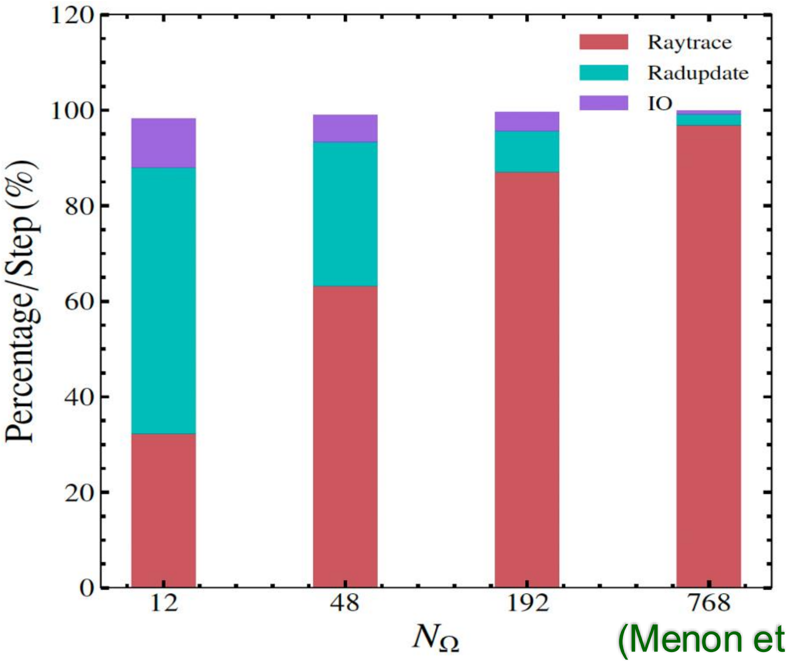
New AMR Variable Eddington Tensor (VET) method

VET with hydrid-characteristics ray-tracing on AMR

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





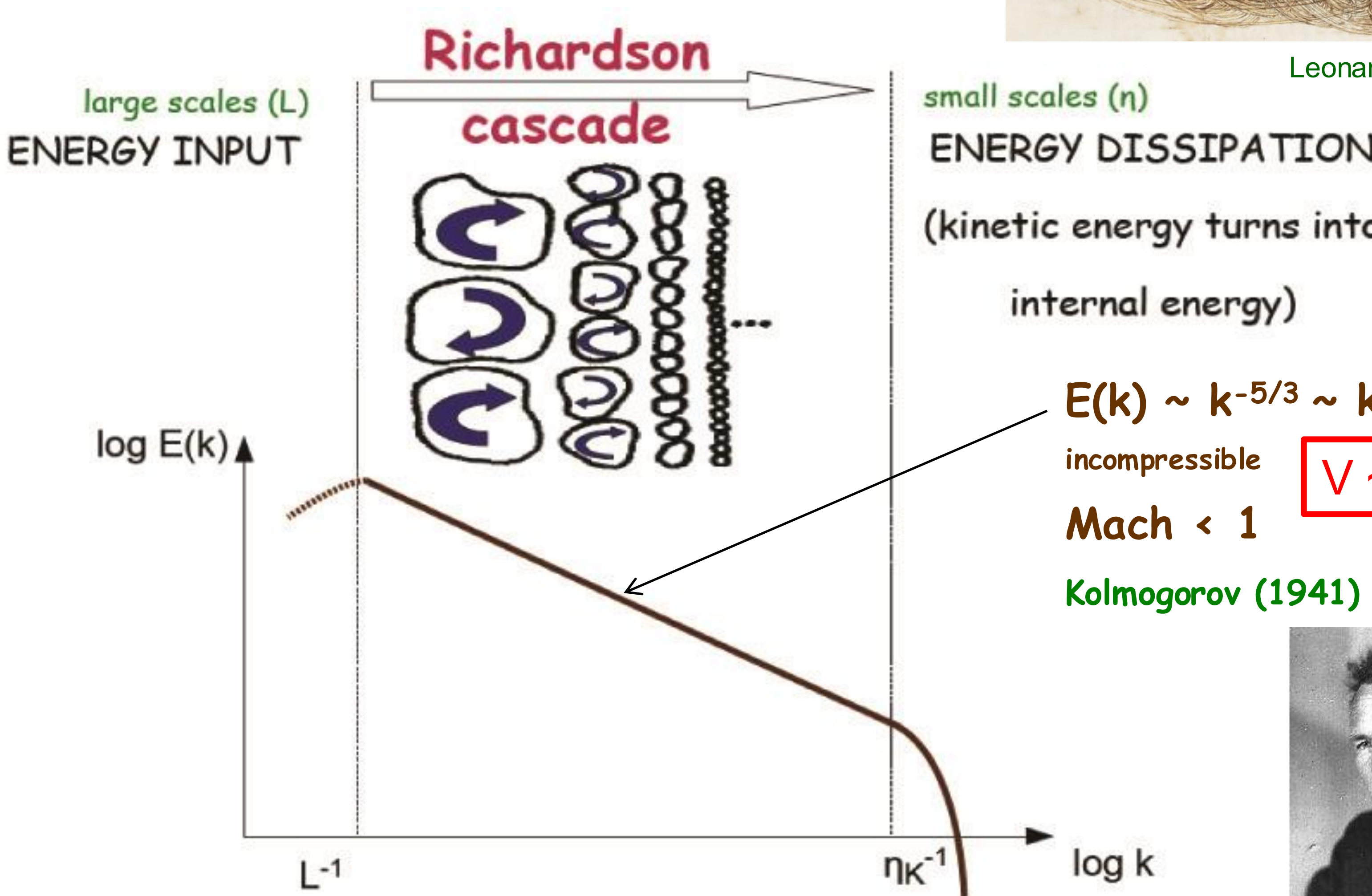


(Menon et al. 2022)

Turbulence

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

Leonardo da Vinci



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

incompressible

Mach < 1

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

Kolmogorov (1941)

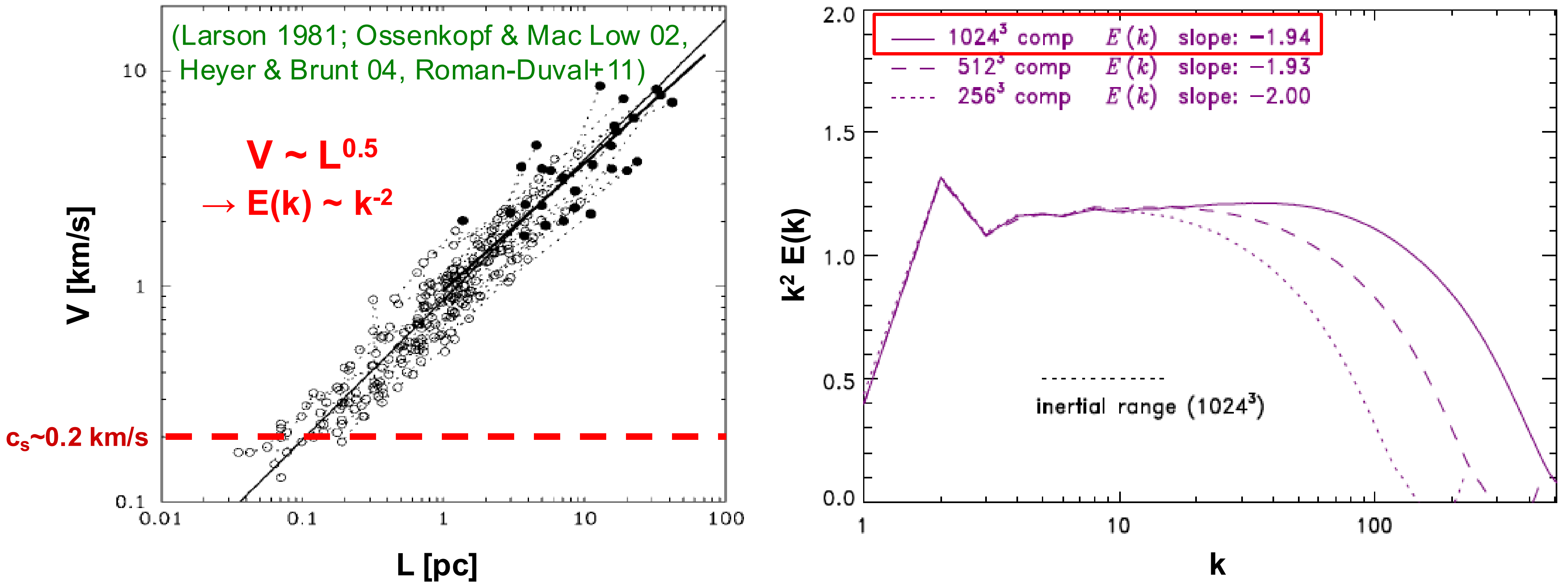
Interstellar Turbulence – scaling

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

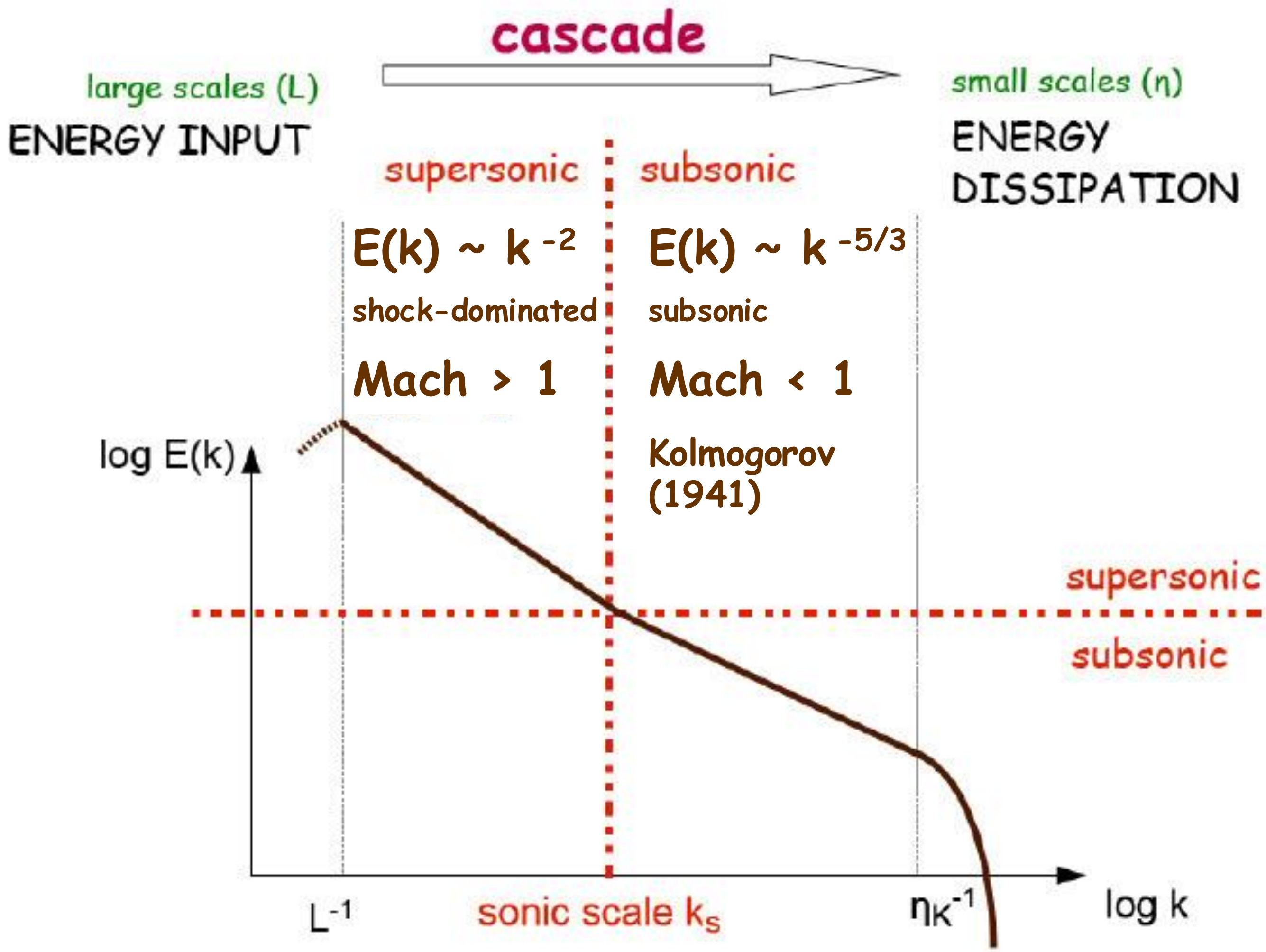
Simulation



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

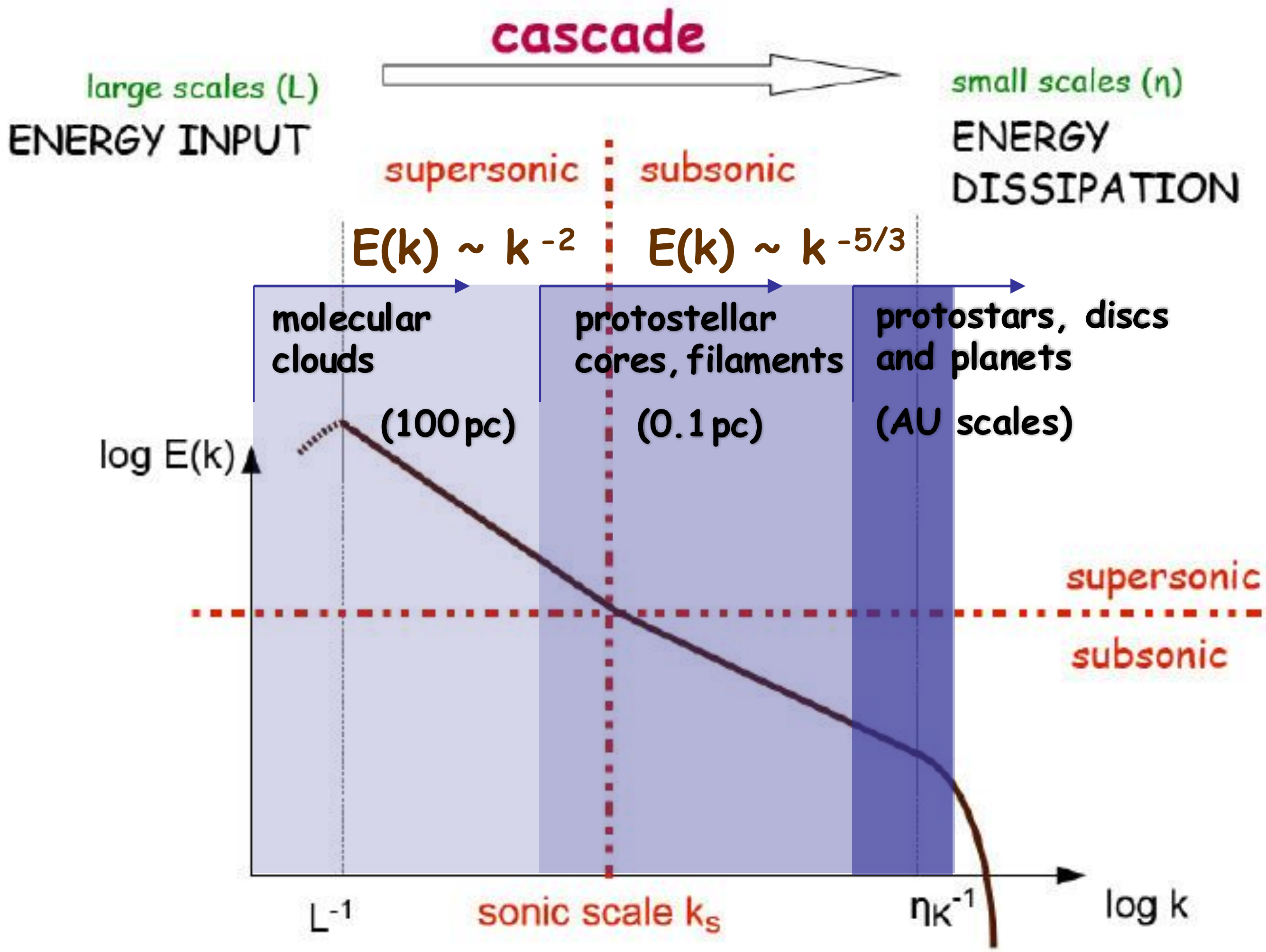
Federrath et al. (2010); see also Kritsuk et al. (2007)

- Reynolds numbers > 1000
- Kinetic energy cascade



Interstellar Turbulence

- Reynolds numbers > 1000
- Kinetic energy cascade



The sonic scale of interstellar turbulence

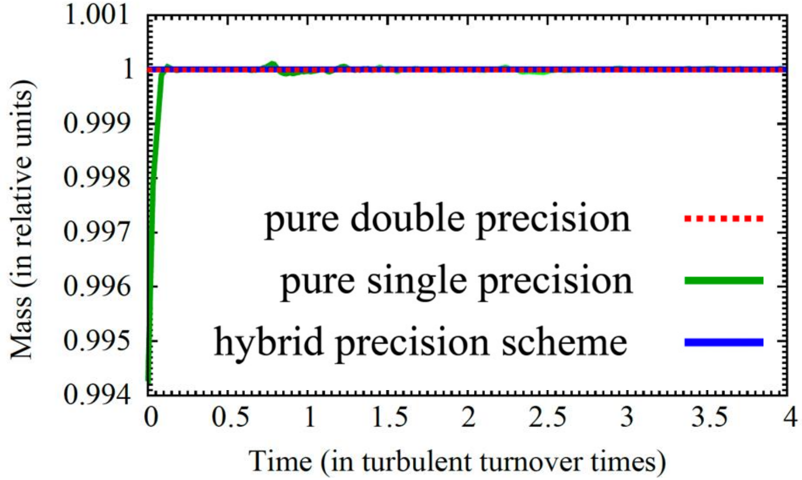
Movies and more info on the $(10k)^3$ simulation:
http://www.mso.anu.edu.au/~chfeder/pubs/sonic_scale/sonic_scale.html

Technical specifications:

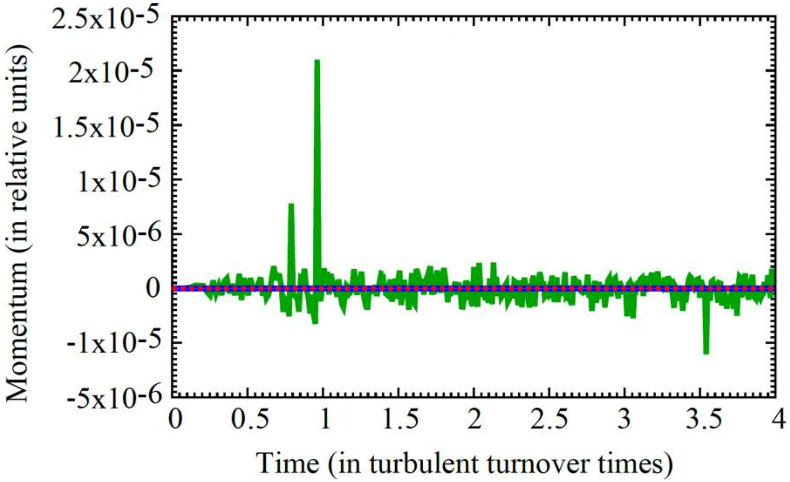
- Resolution: **$10{,}048^3$** grid cells
- 50 Million CPU-h (GCS and NCI)
- 65,536 compute cores
- 2 PB data
- Hybrid precision (SP + specific promotion to DP)

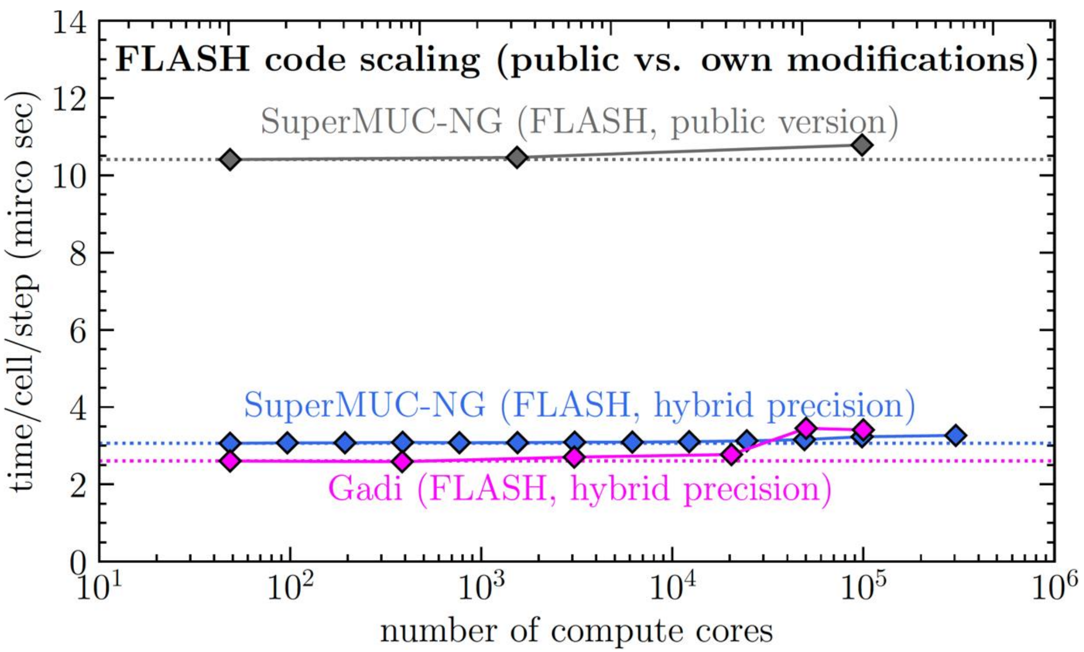
Hybrid precision and code scaling

Mass conservation



Momentum conservation

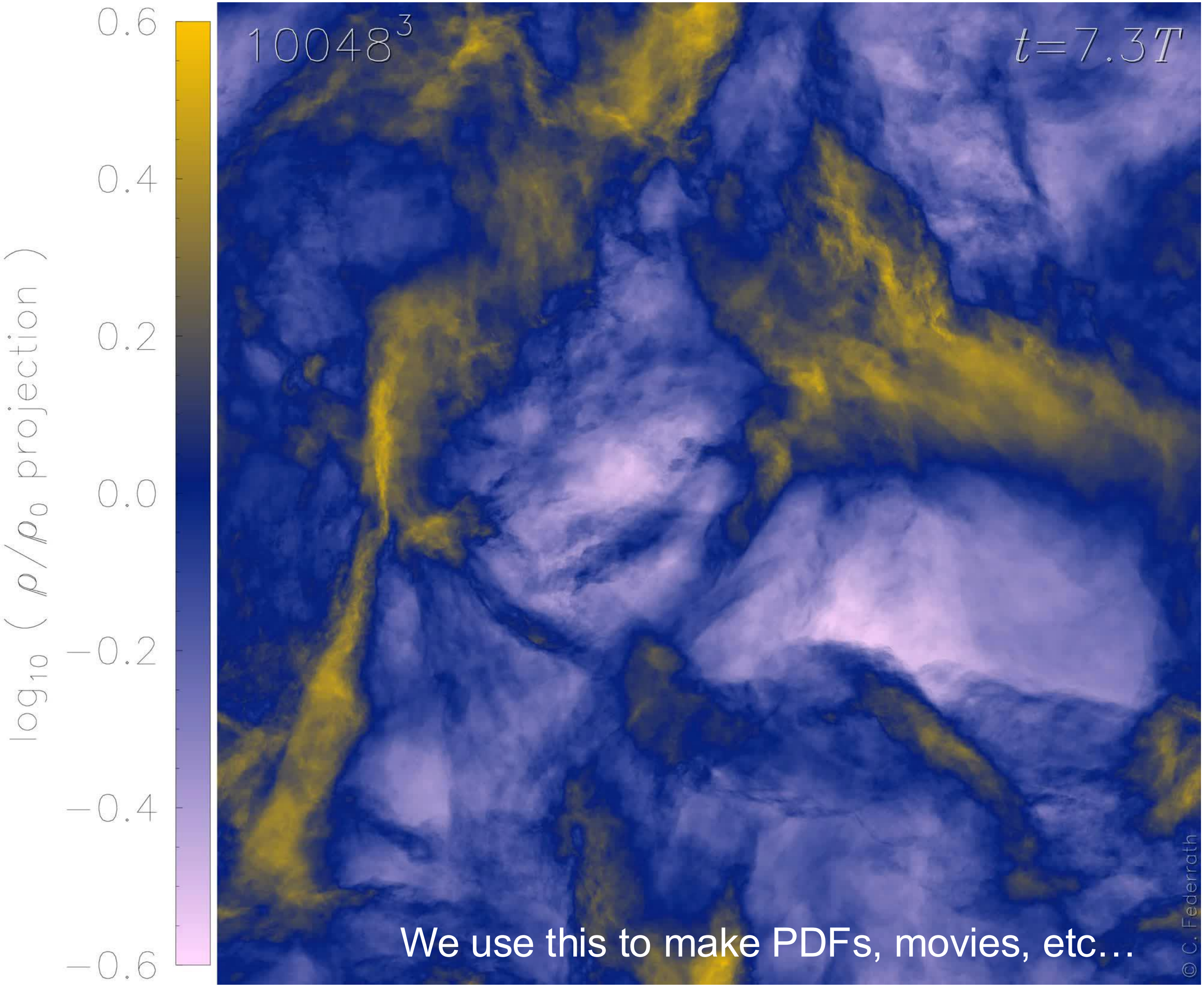




Overall changes to FLASH for this setup resulted in
- factor 3.6 higher speed
- factor 4.1 less memory

(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

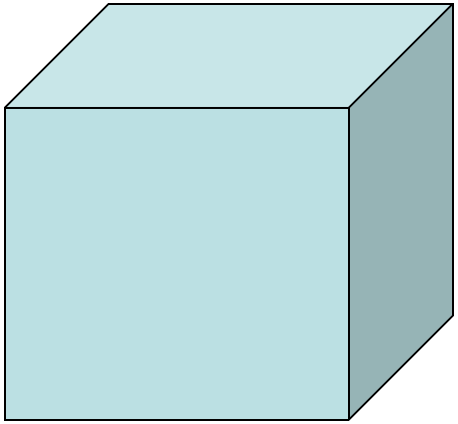
- Shear
- Jets / Outflows
- Cloud-cloud collisions
- Winds / Ionization fronts
- Spiral-arm compression
- Supernova explosions
- Gravity / Accretion

Solenoidal ↓ Compressive

Turbulence driving – solenoidal versus compressive

"Turbulence in a box"

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

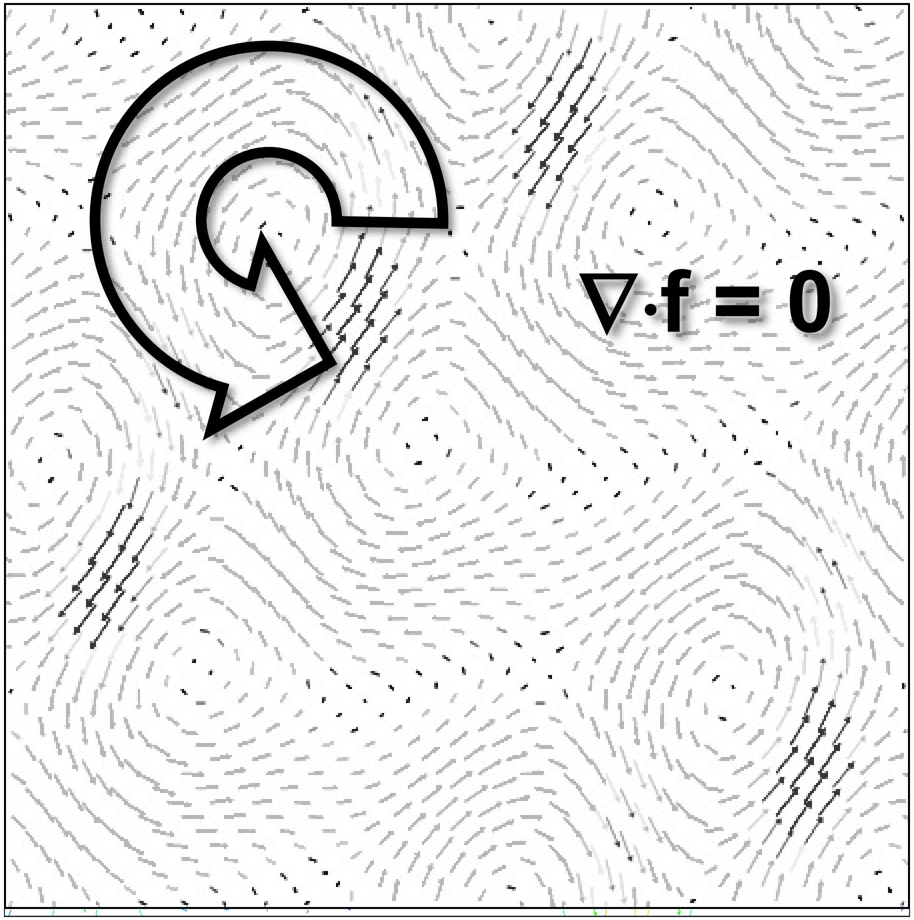


e.g., Vazquez 1994, Padoan+1997, Passot+1998, Stone+1998, Mac Low 1999, Klessen+2000, Ostriker+2001, Heitsch+2001, Cho+2002, Boldyrev+2002, Li+2003, Haugen+2004, Padoan+2004, Jappsen+2005, Ballesteros+2006, Mee+Brandenburg 2006, Kritsuk+2007, Kowal+2007, Dib+2008, Offner+2008, Schmidt+2009, Burkhart+2009,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

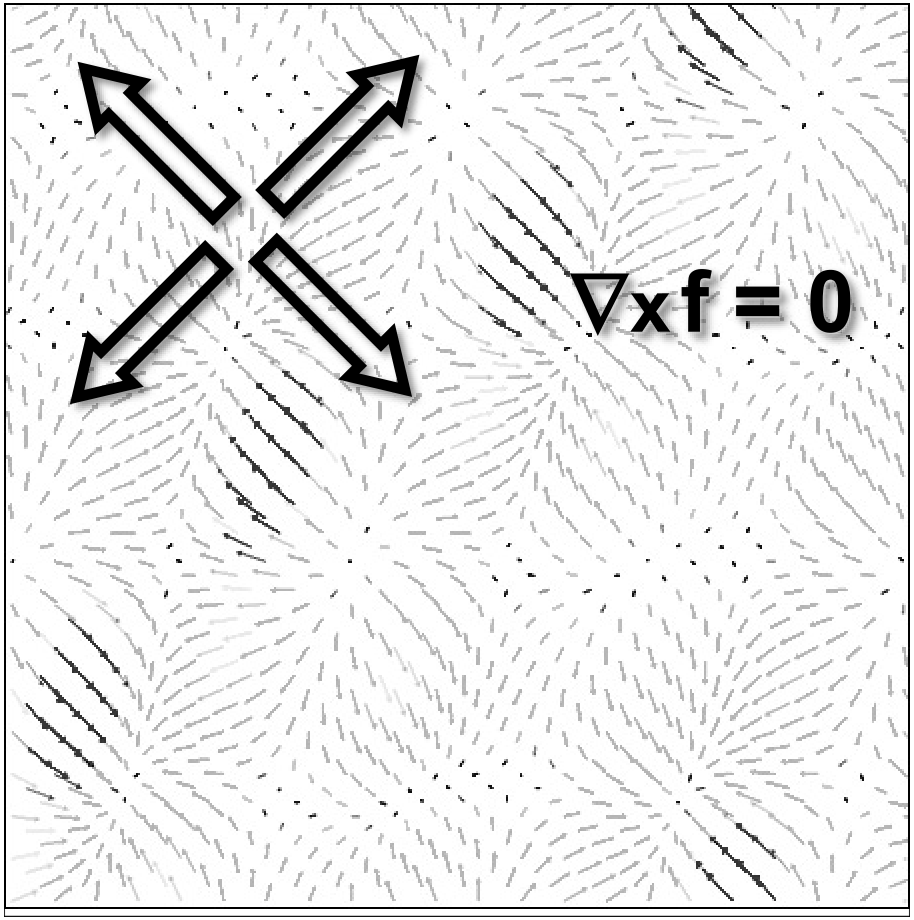
Turbulence forcing – solenoidal versus compressive

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

Solenoidal forcing



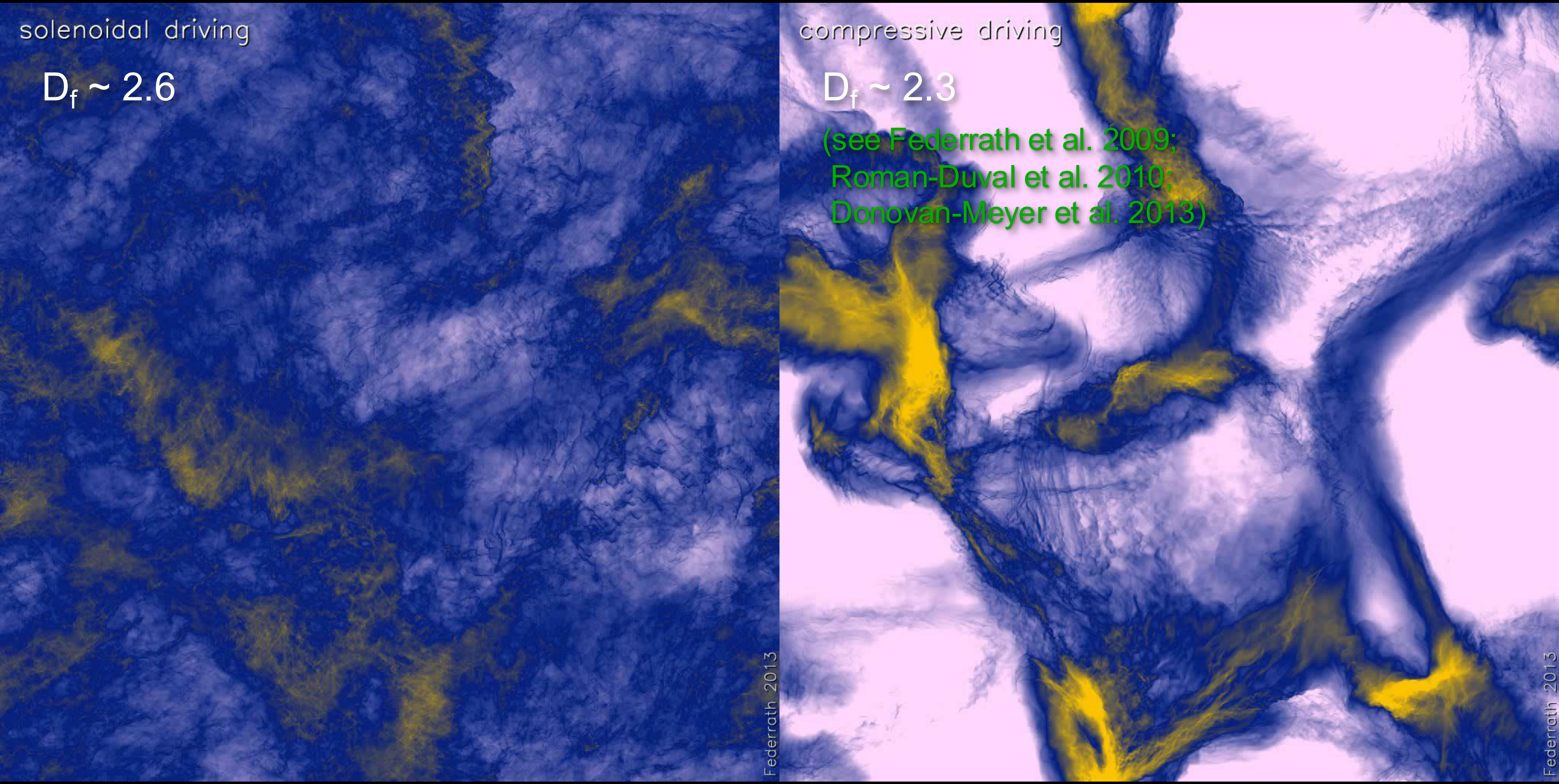
Compressive forcing



Turbulence driving – solenoidal versus compressive

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

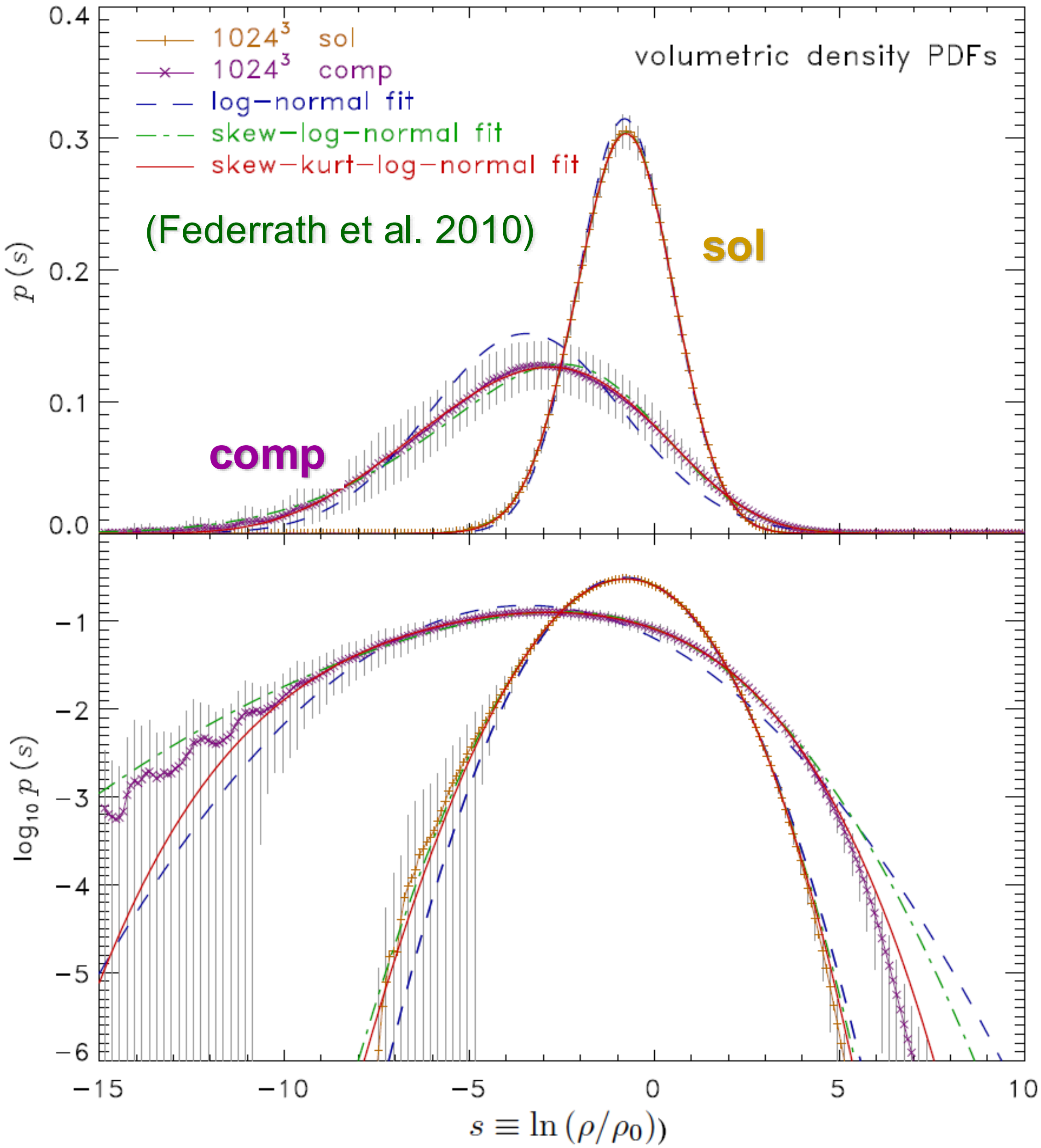
solenoidal forcing compressive forcing



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)

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

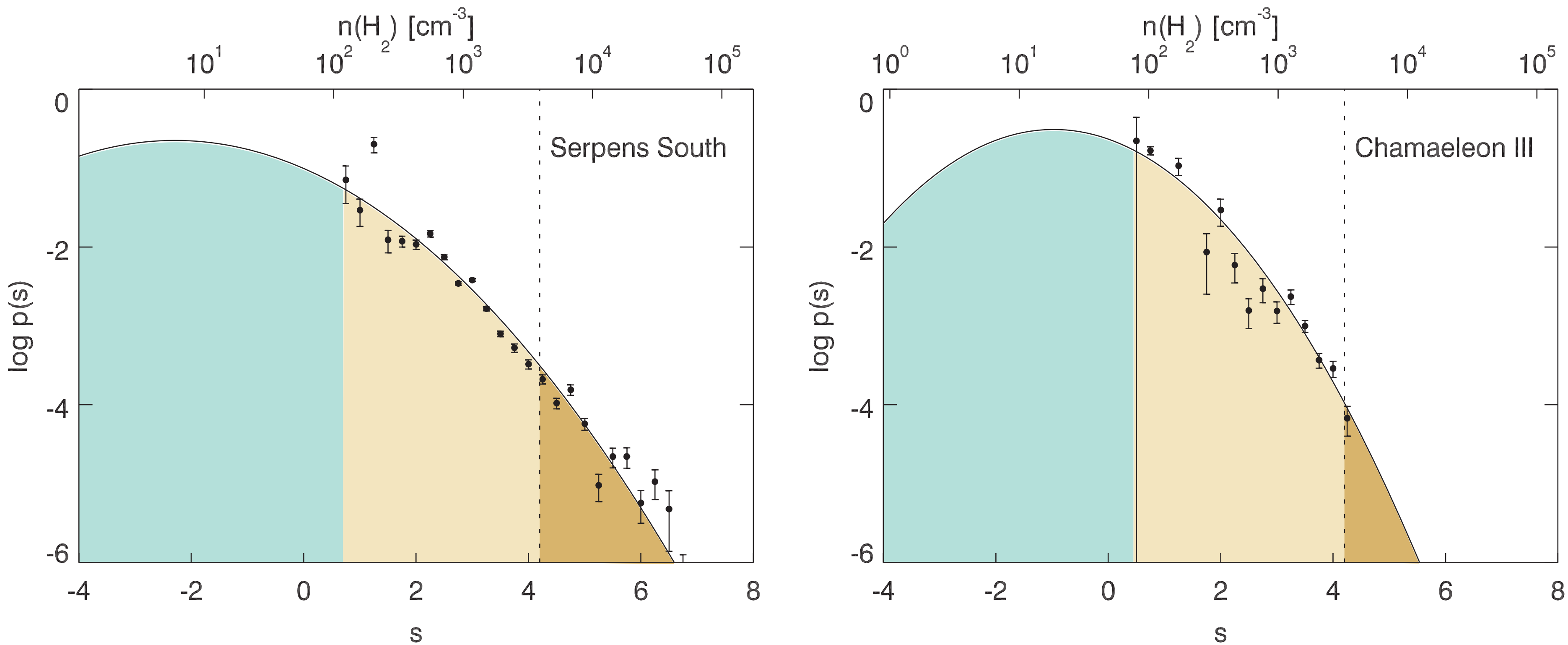
b = 1/3 (sol)

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

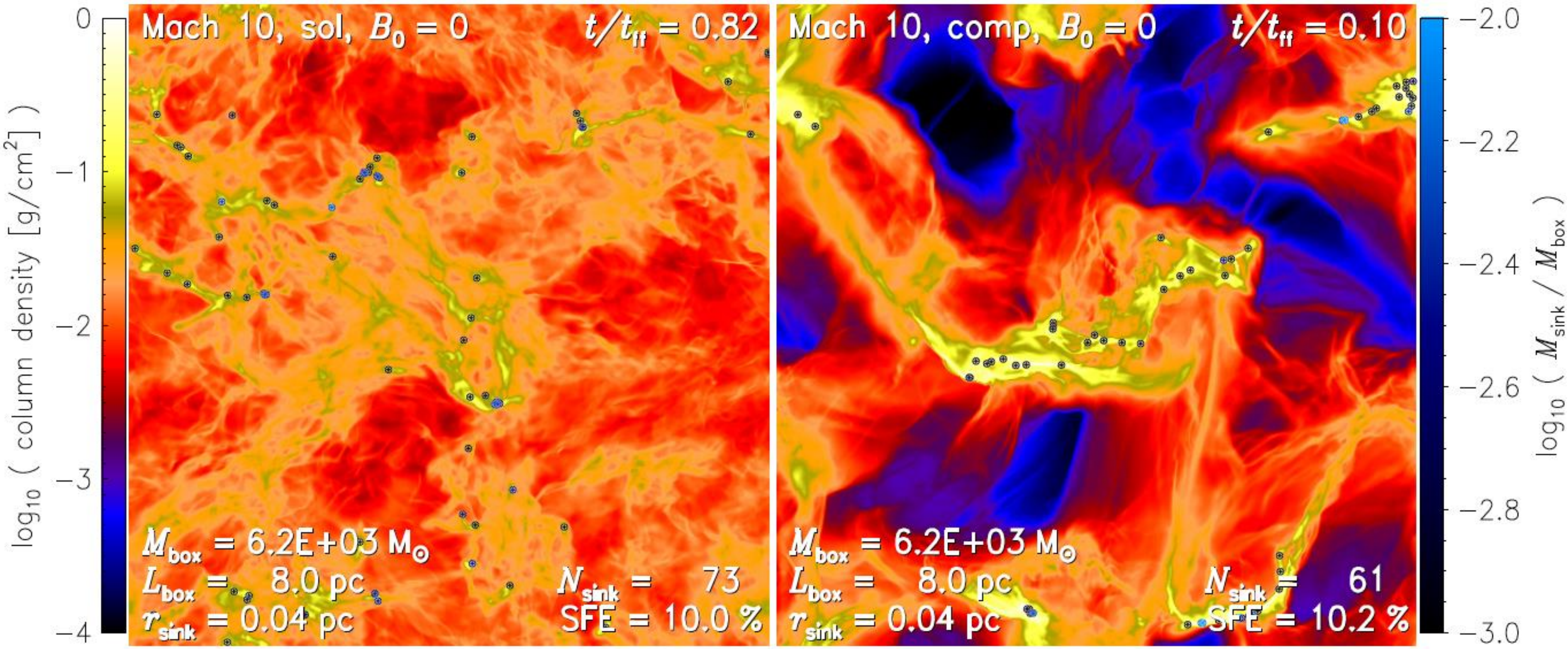
(Brunt et al. 2010a,b)

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)

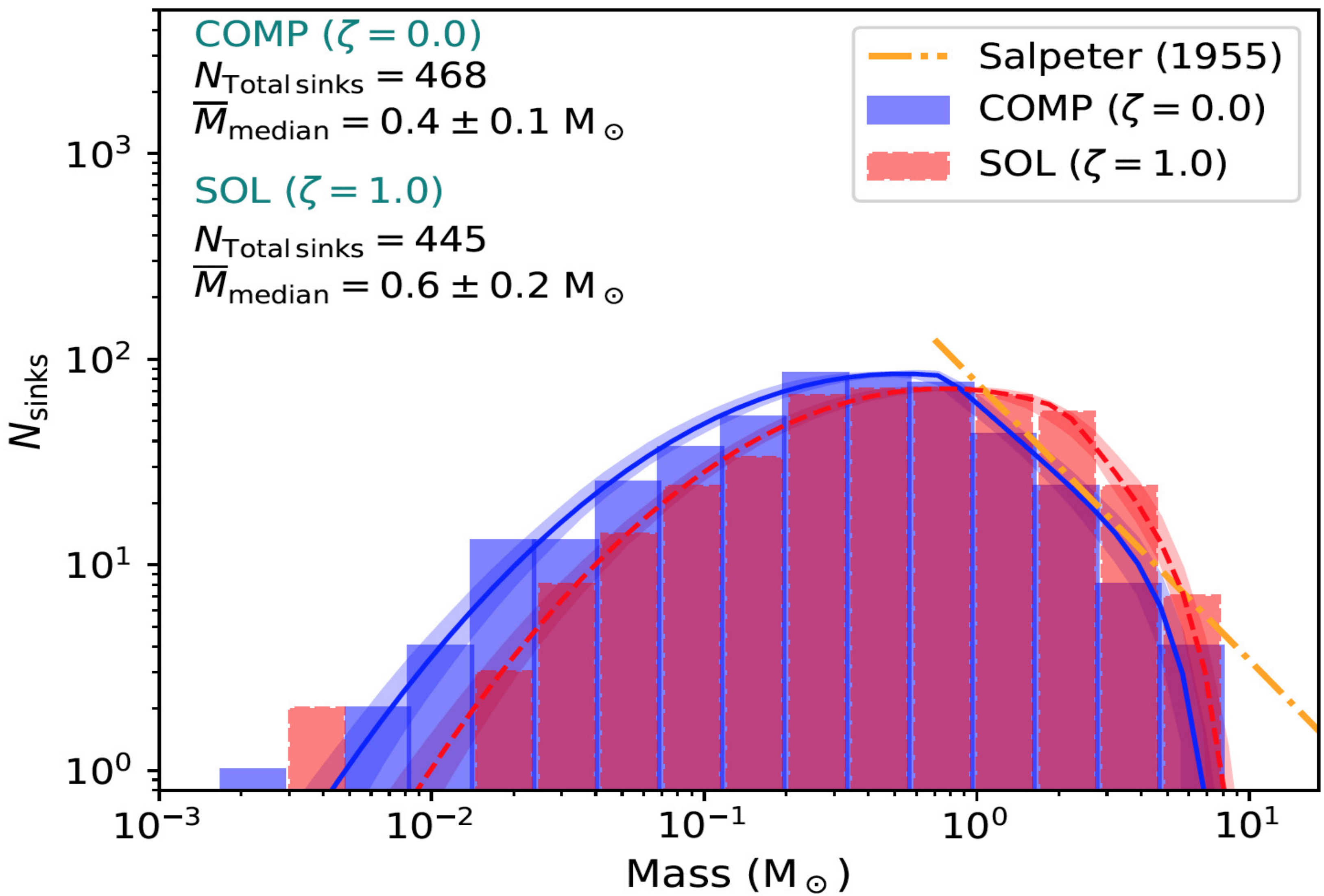


SFR_{ff} (simulation) = **0.14**	x 20	SFR_{ff} (simulation) = **2.8**
SFR_{ff} (theory) = **0.15**	x 15	SFR_{ff} (theory) = **2.3**

Turbulence driving is a key parameter for star formation!

Federrath & Klessen (2012)

Role of Turbulence Driving for Initial Mass Function



(Mathew et al. 2022)

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
→ Assignment 1

Work through the course script:

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 introductions:

http://guide.bash.academy

https://www.w3schools.com/bash/

Image credit: M. S. Povich

Astronomical Computing

Go through the Bash guide / tutorial:

- read content on your own
- do excercises (can be done in teams or on your own)

http://guide.bash.academy

https://www.w3schools.com/bash/