

Astronomical Computing

ASTR4004 / ASTR8004

ANU – 2nd semester 2026

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** (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 1-3, 8-9, 11-12: taught by Christoph Federrath

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

Rest of course: taught by Sven Buder and Yuxiang Qin

Regression, Neural Networks, Gaussian Processes, Monte-Carlo Markov Chain

Astronomical Computing

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 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.

Modelling/Computing Star Formation, Turbulence, Feedback

Christoph Federrath

ANU – 2026



Australian Government
Australian Research Council



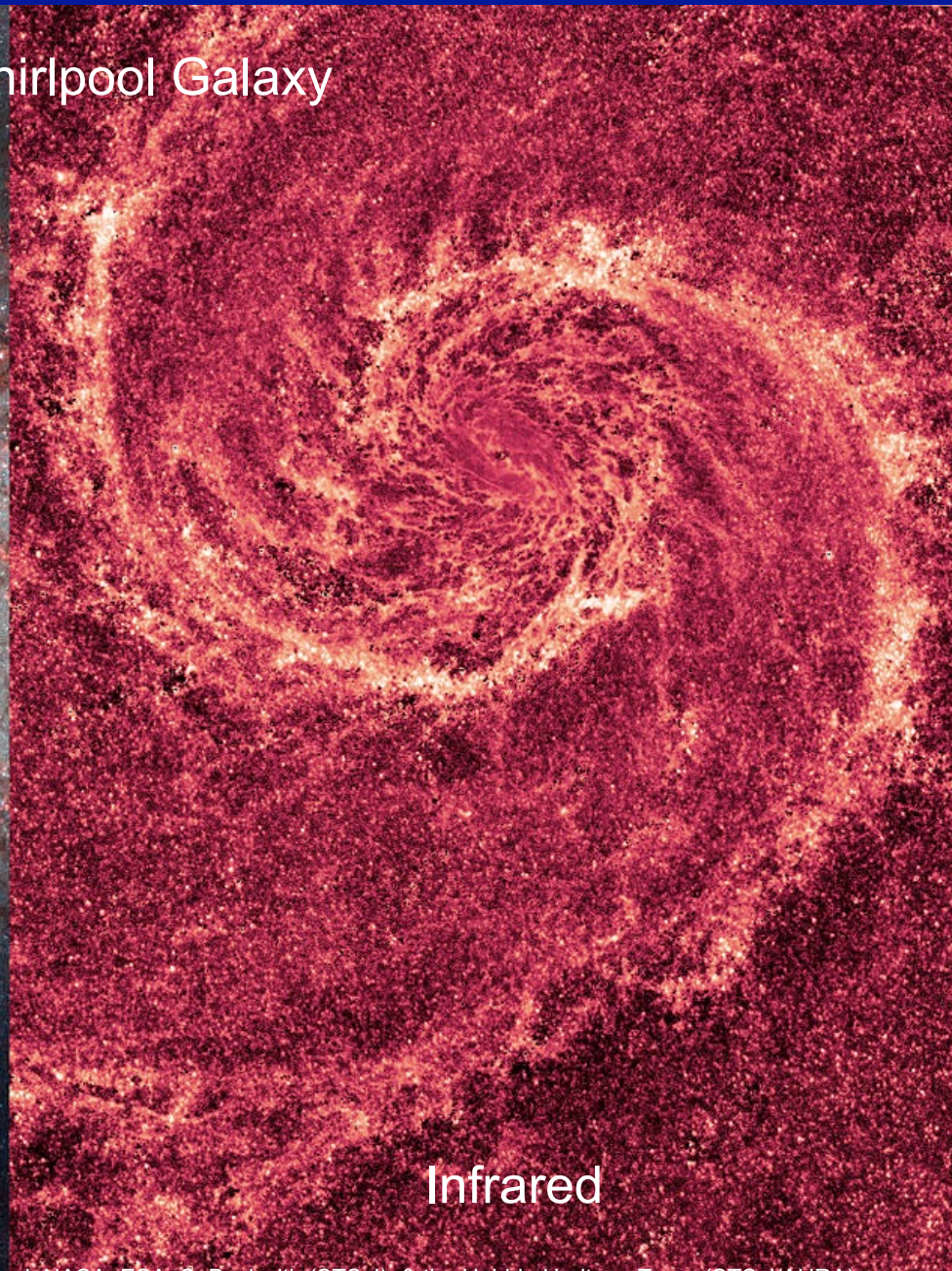
Australian
National
University



M51: The Whirlpool Galaxy



Optical



Infrared



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

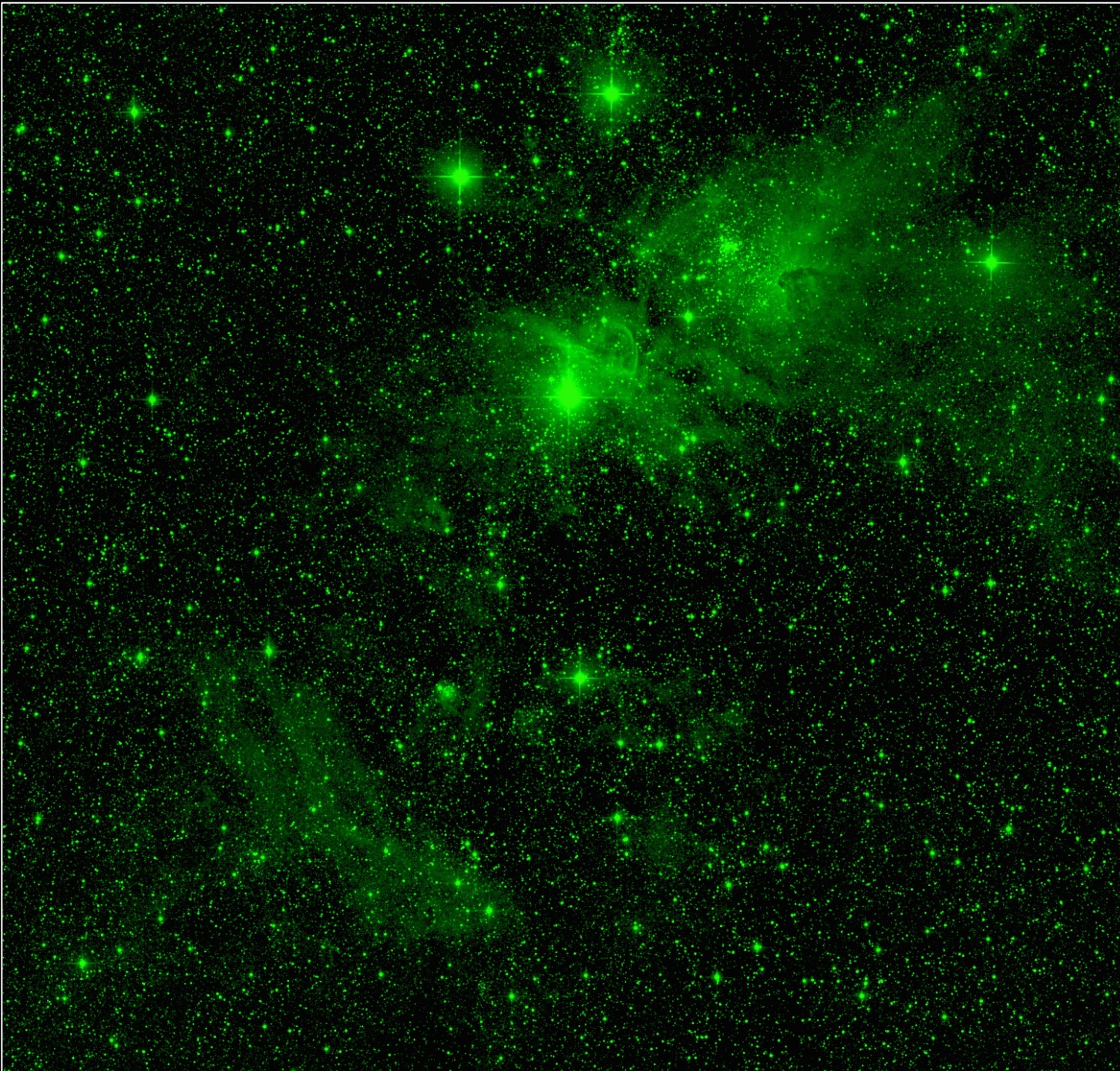
Near-Infrared

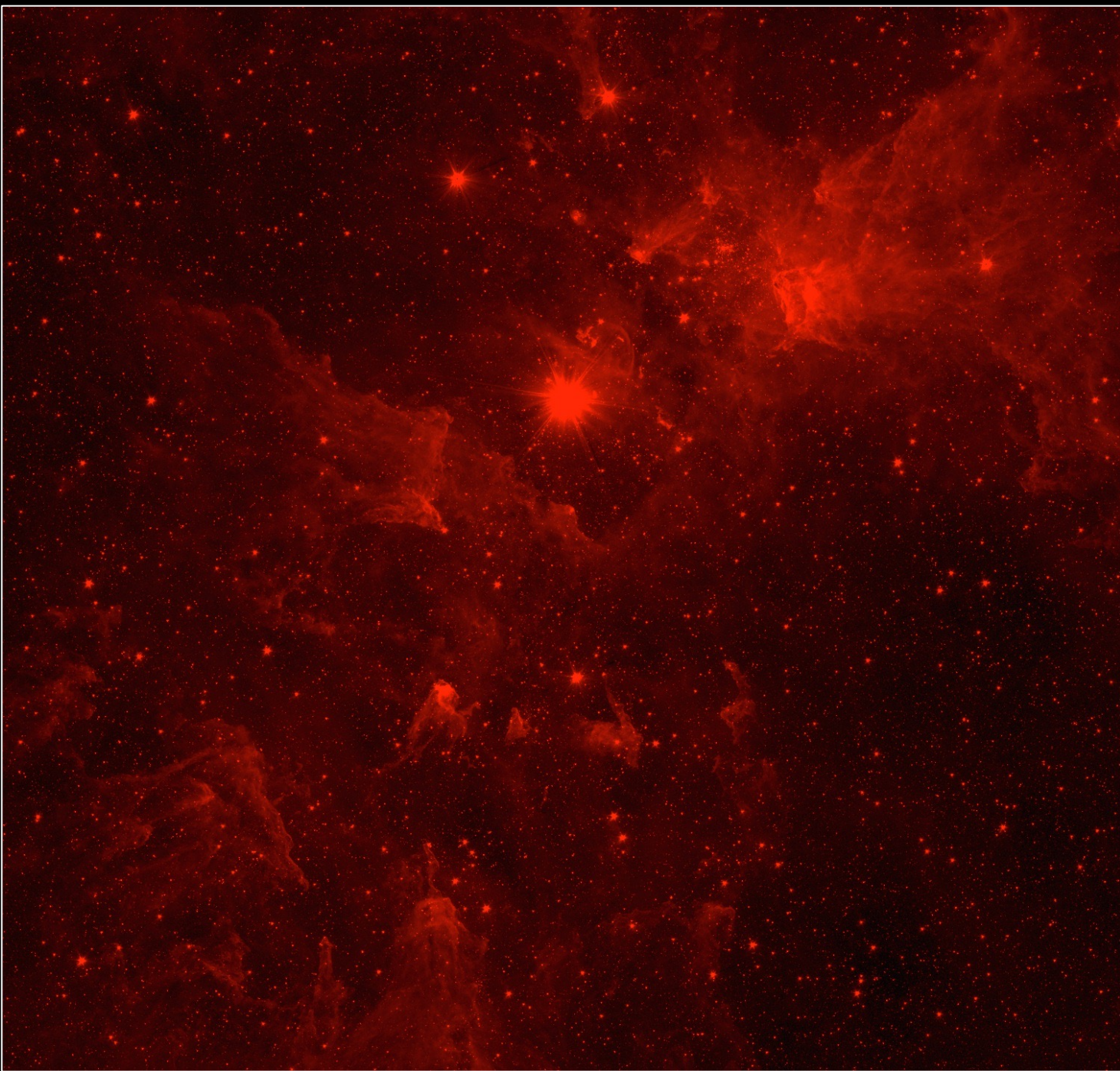
Two-Micron All-Sky Survey

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

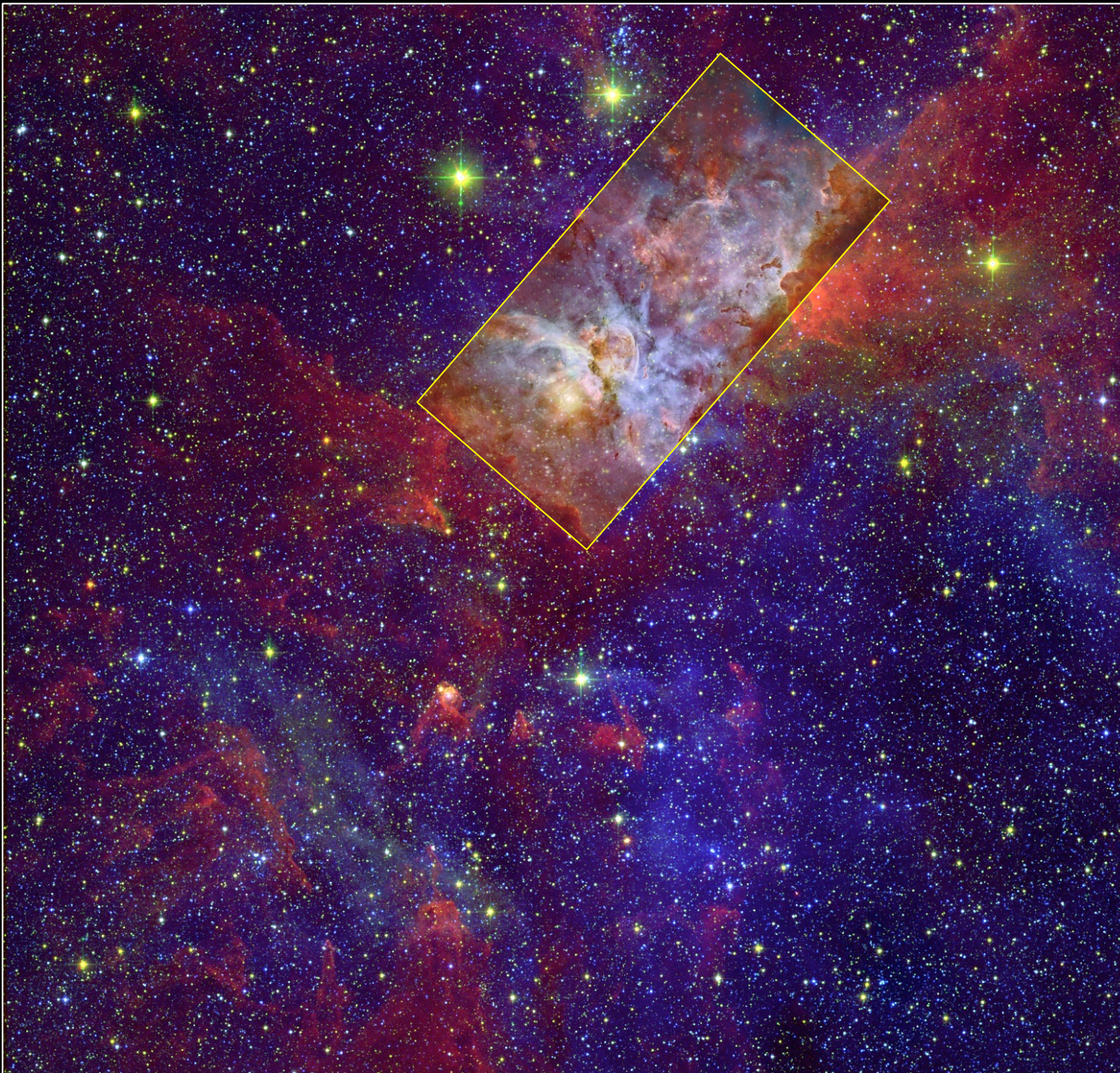
Digitized Sky Survey

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

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graph LR; Turbulence --> Stars; Stars --> Feedback; Feedback --> Turbulence;
```

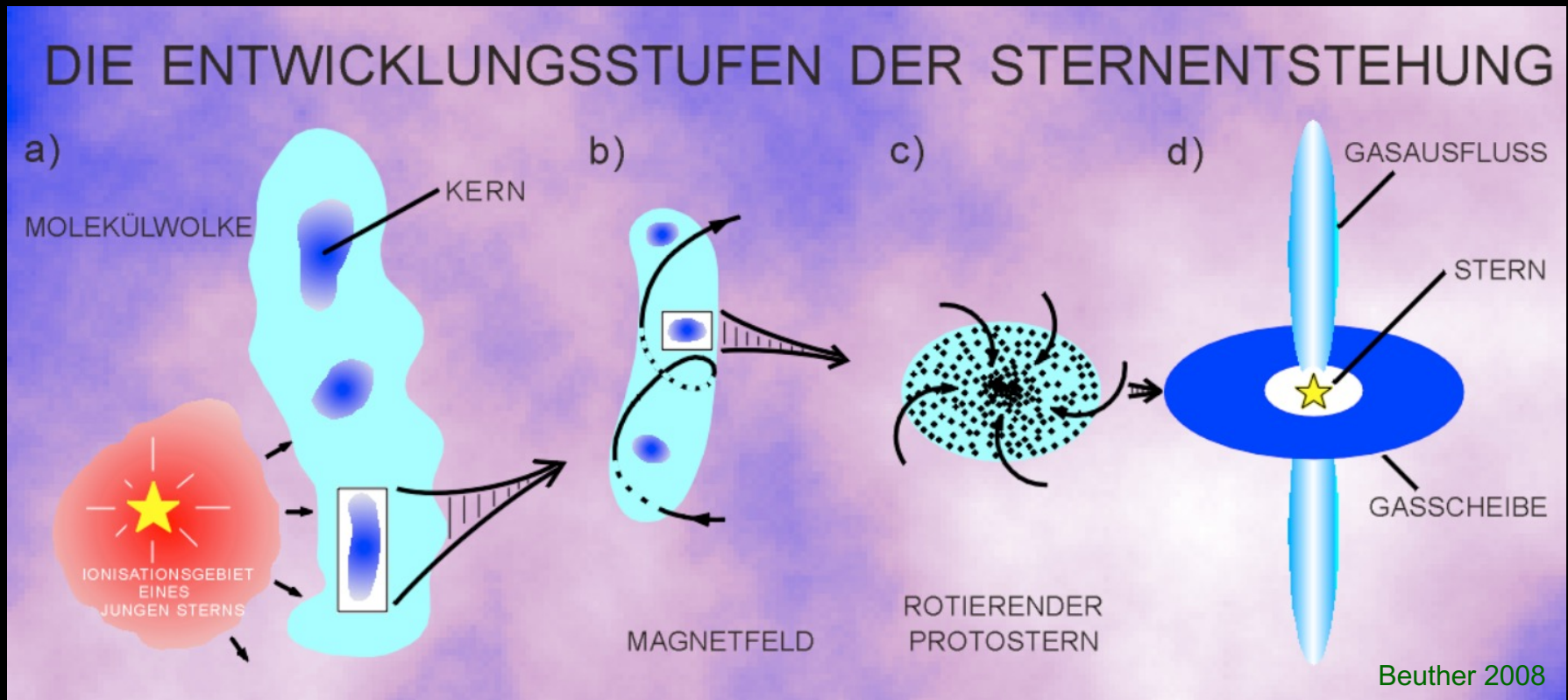
Turbulence driven by

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

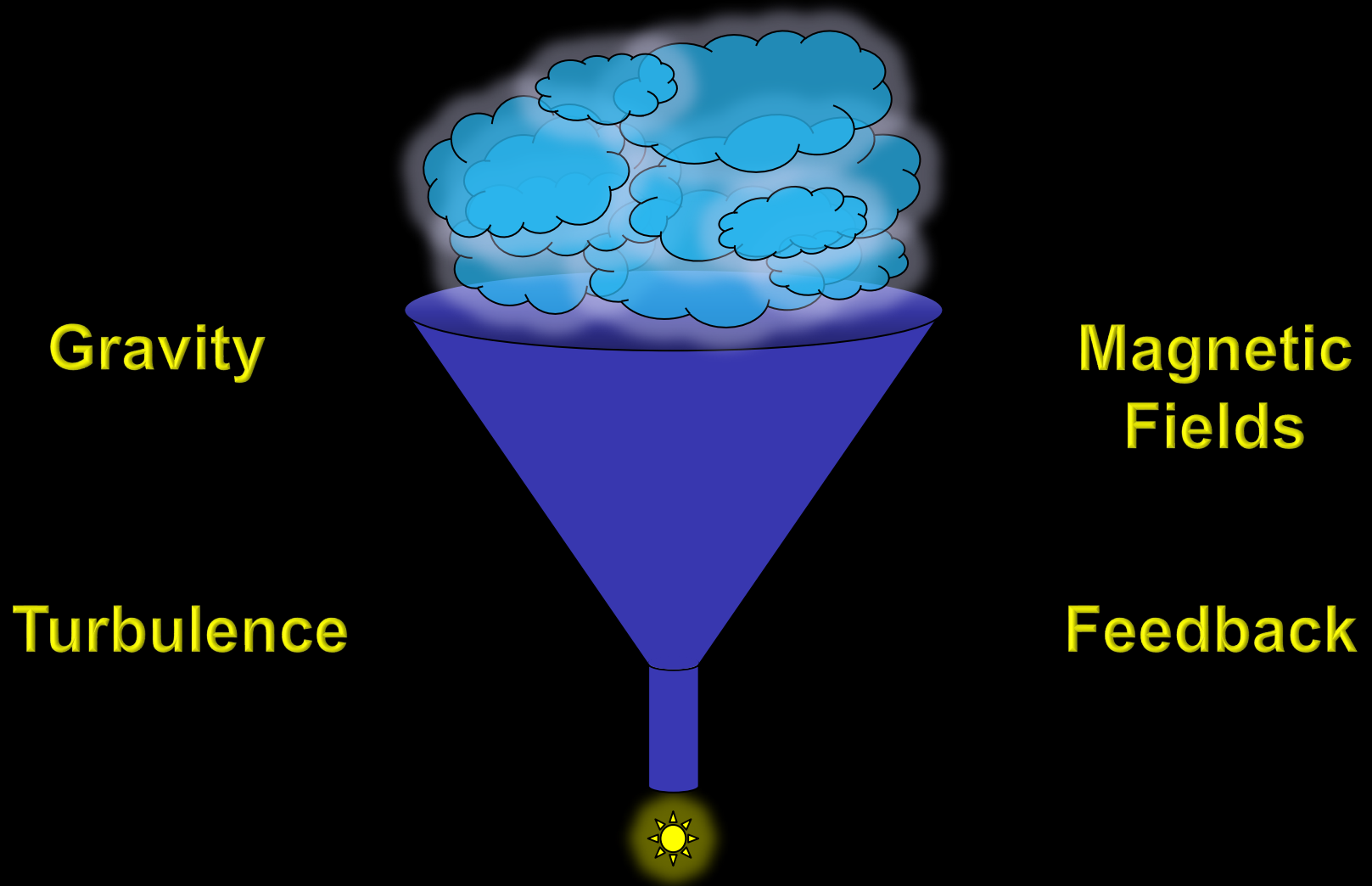
Mac Low & Klessen (2004)

The Star Formation Paradigm

Clouds → Cores → Disk + Star + Jet / Outflow



Star Formation is Inefficient



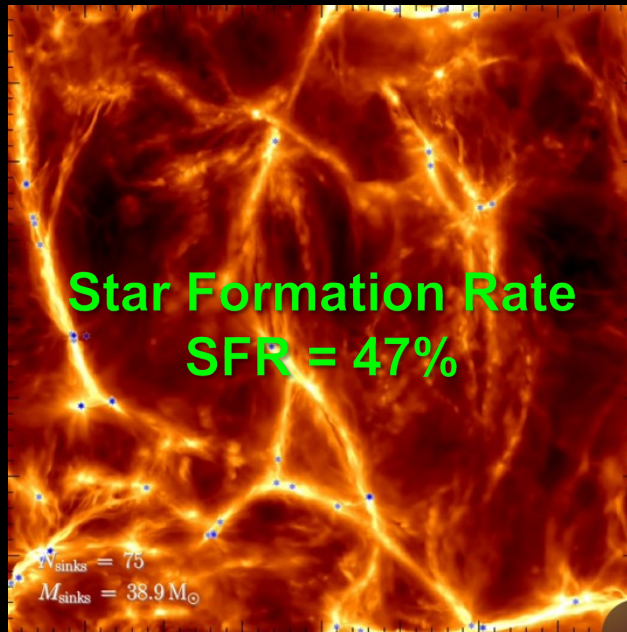
Star Formation is Inefficient

(Federrath 2015 MNRAS; 2018 *Physics Today*)

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



Gravity
only

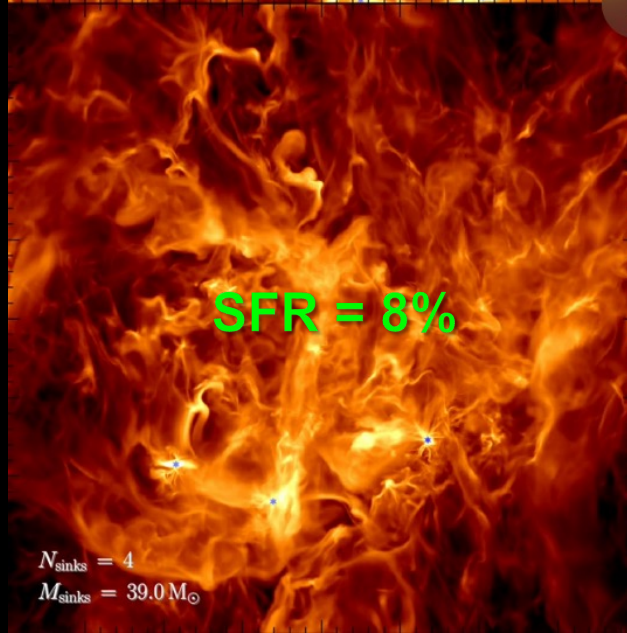


SFR = 25%

$N_{\text{sinks}} = 20$
 $M_{\text{sinks}} = 39.1 M_{\odot}$

with
Turbulence

Turb+
Magnetic
Fields



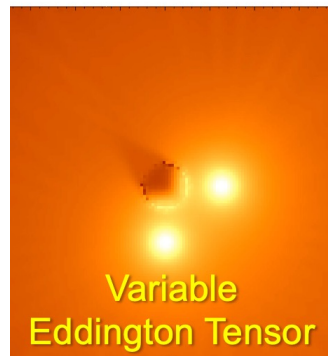
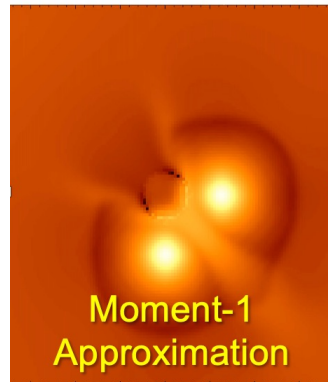
SFR = 4%
(observed: ~ 1–4%)

$N_{\text{sinks}} = 18$
 $M_{\text{sinks}} = 38.8 M_{\odot}$

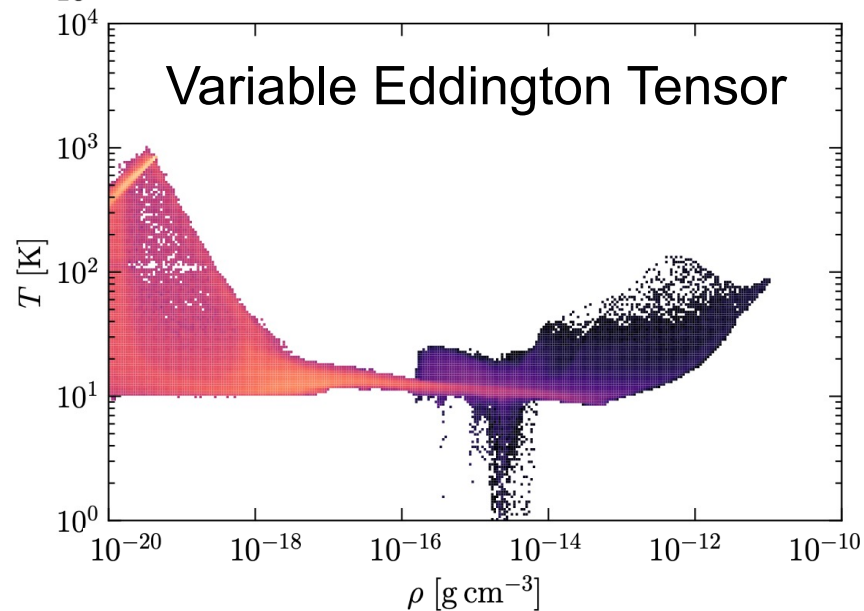
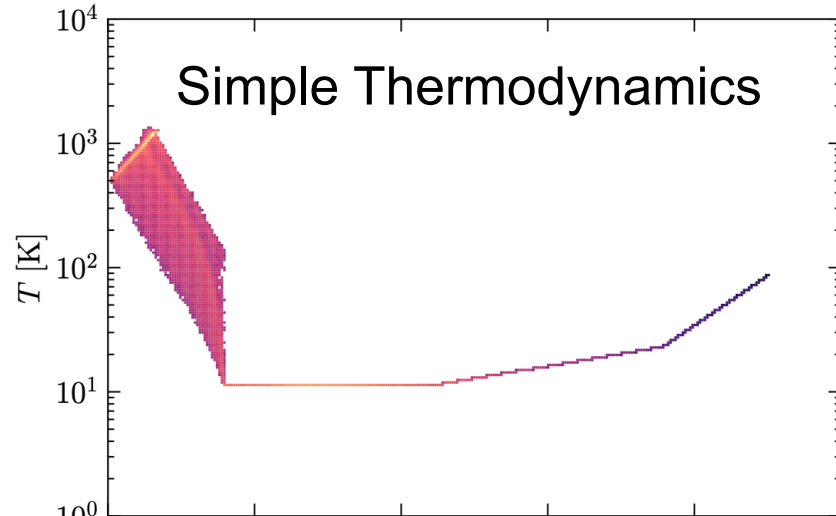
Turb+
Mag+
Jet/Outflow
Feedback

(sims for Appel
et al. 2023)

Modelling Radiation



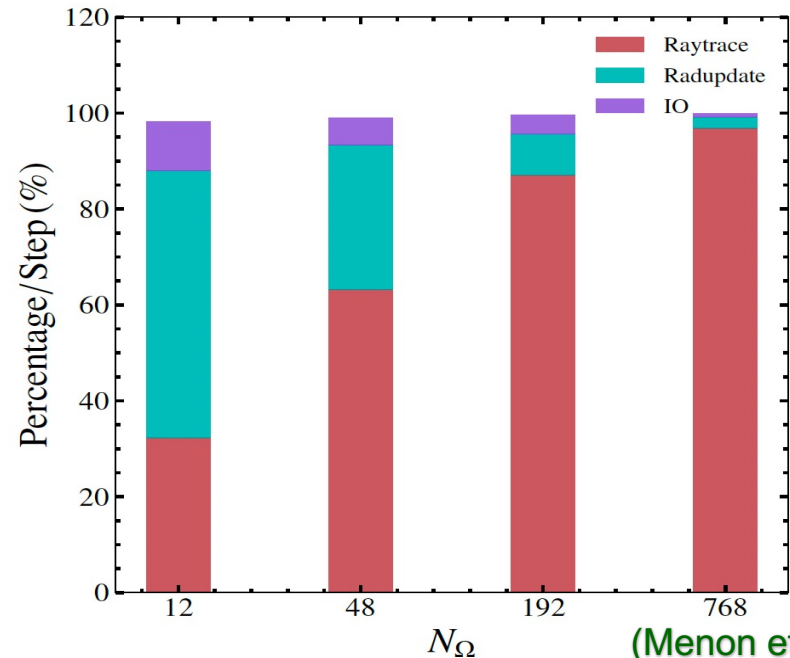
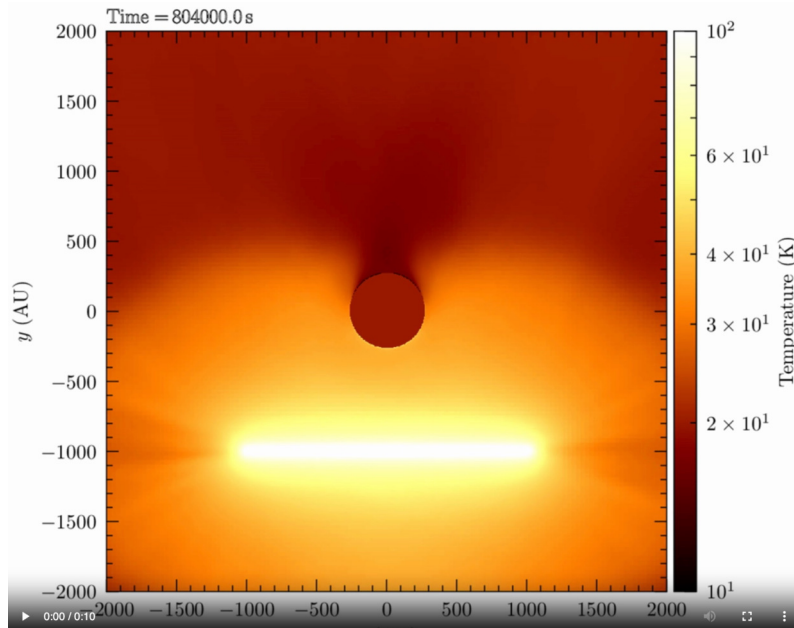
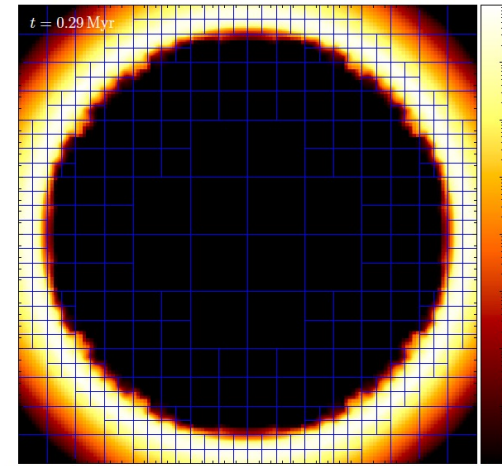
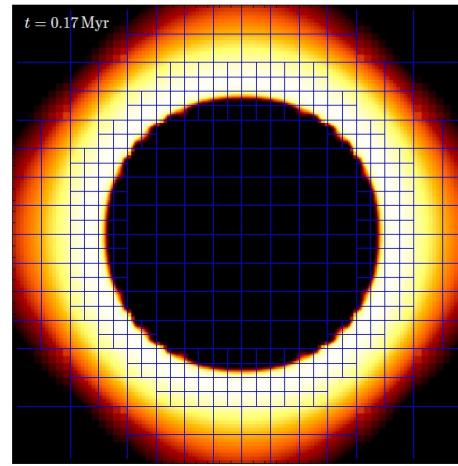
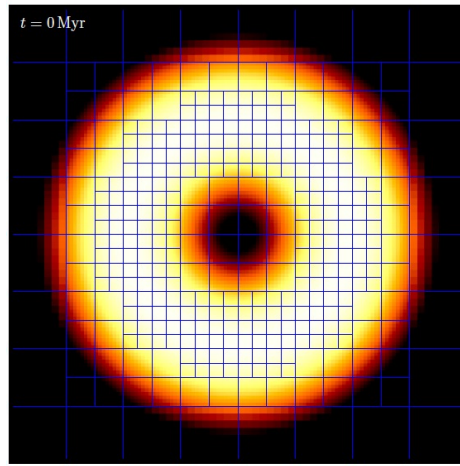
(Menon et al. 2022)



New AMR Variable Eddington Tensor (VET) method

VET with hybrid-characteristics ray-tracing on AMR

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



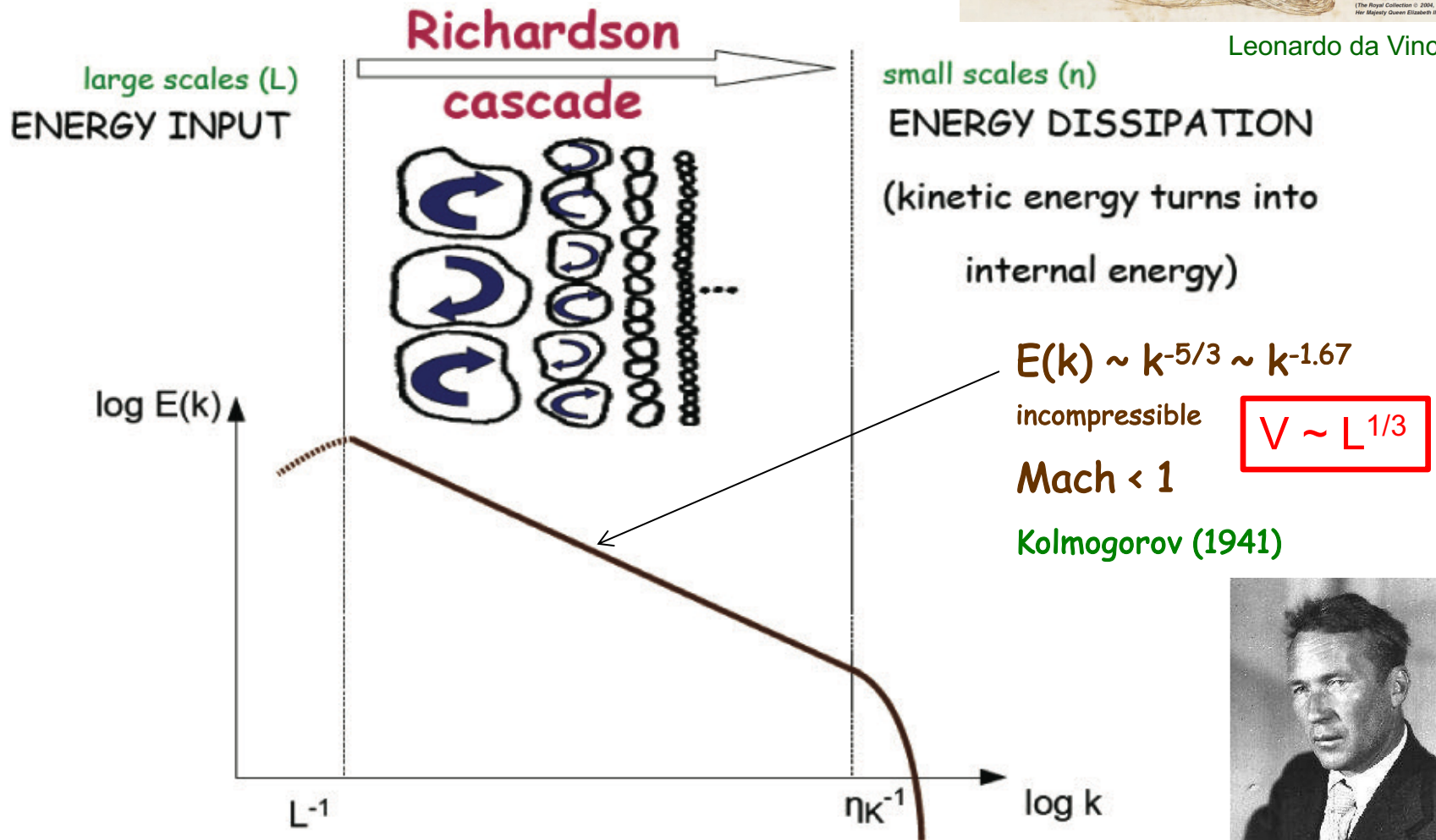
(Menon et al. 2022)

Turbulence

- Reynolds numbers > 1000
- Kinetic energy cascade



Leonardo da Vinci

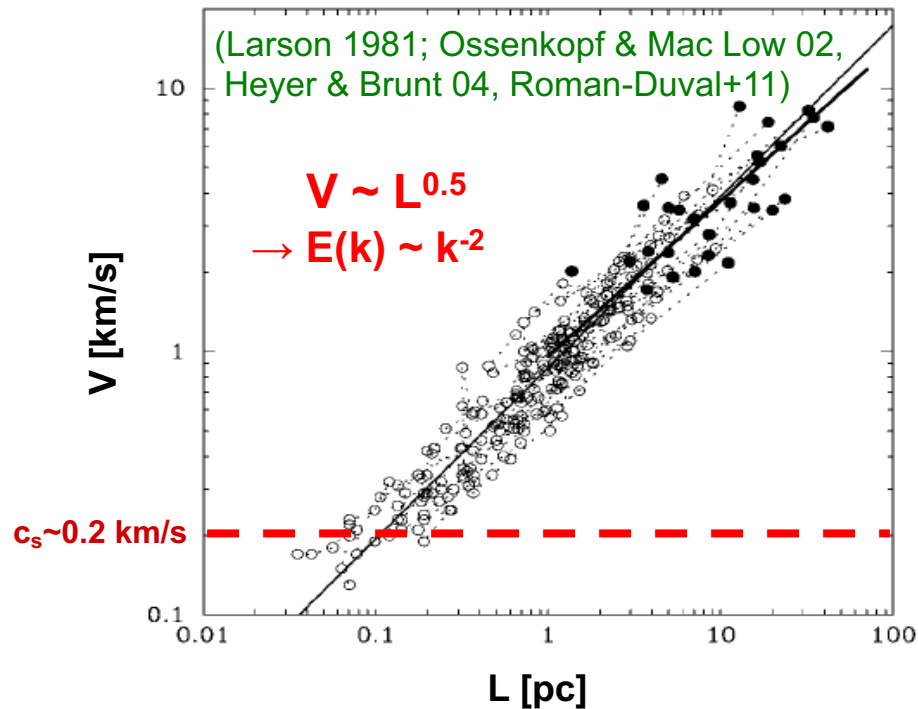


Interstellar Turbulence – scaling

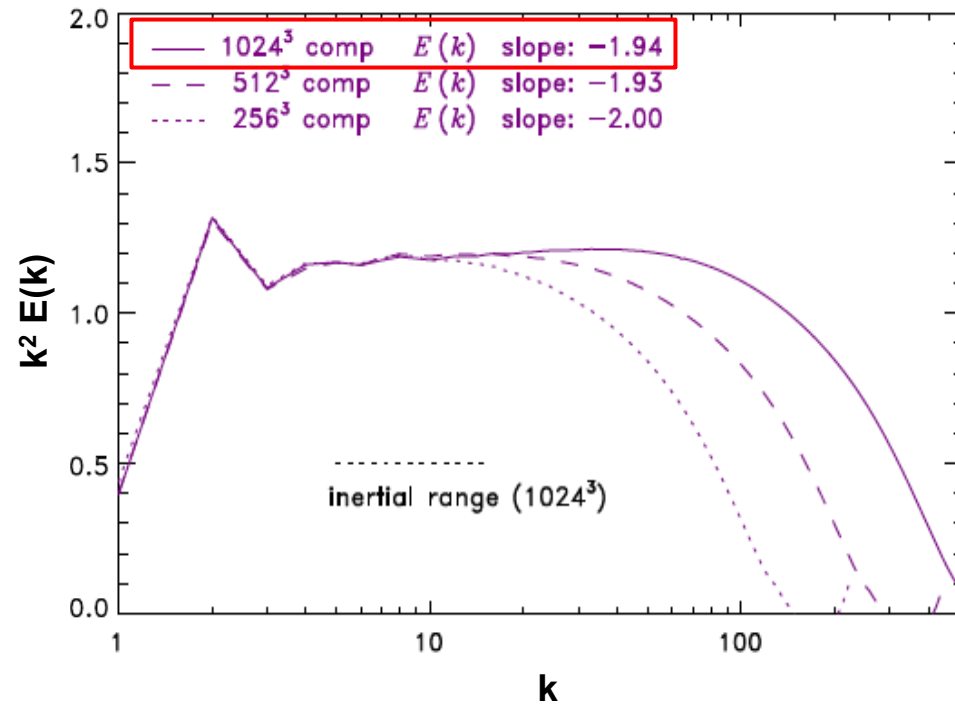
BUT: Larson (1981) relation: $E(k) \sim k^{-1.8-2.0}$

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

Observation



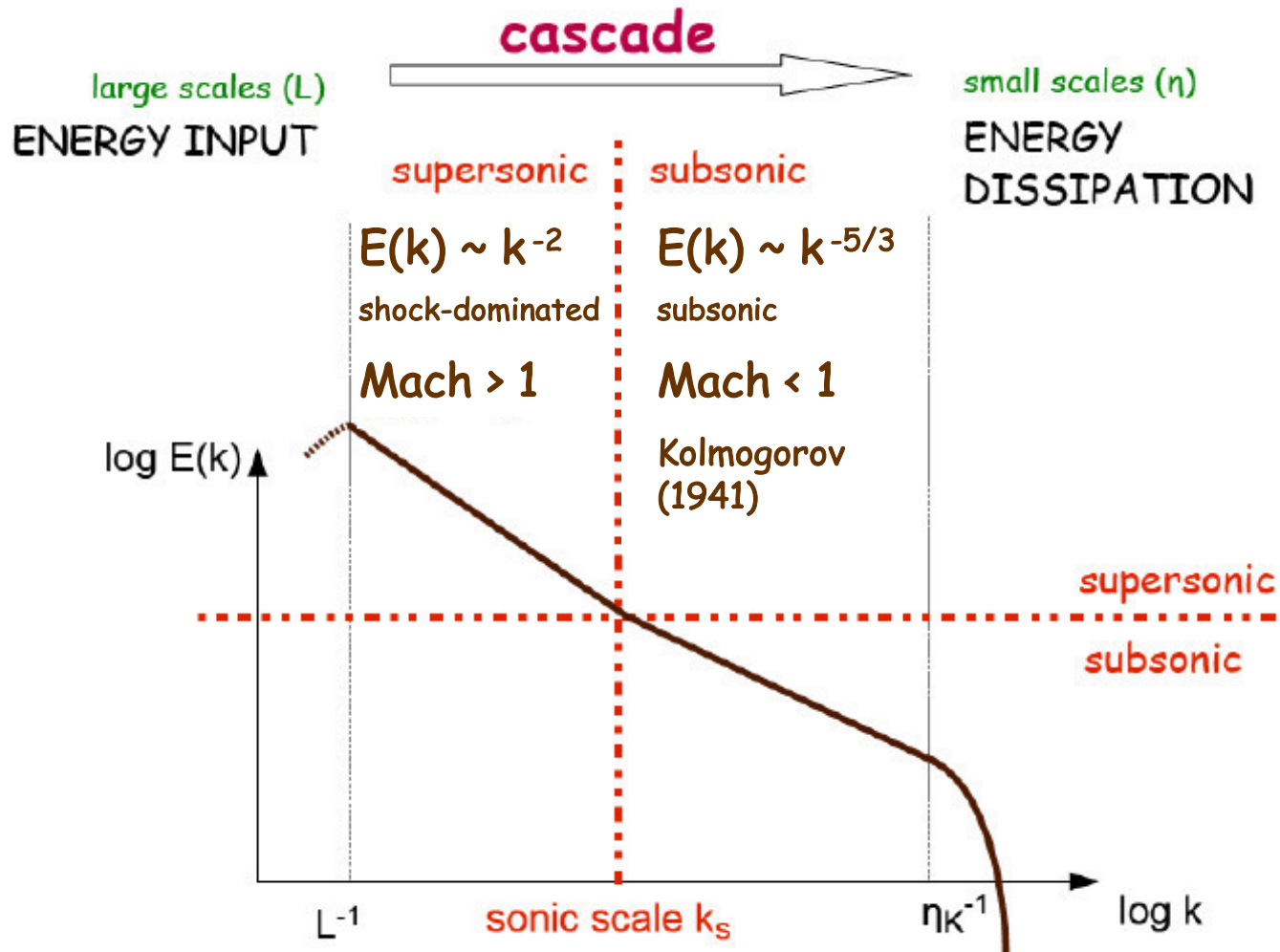
Simulation



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

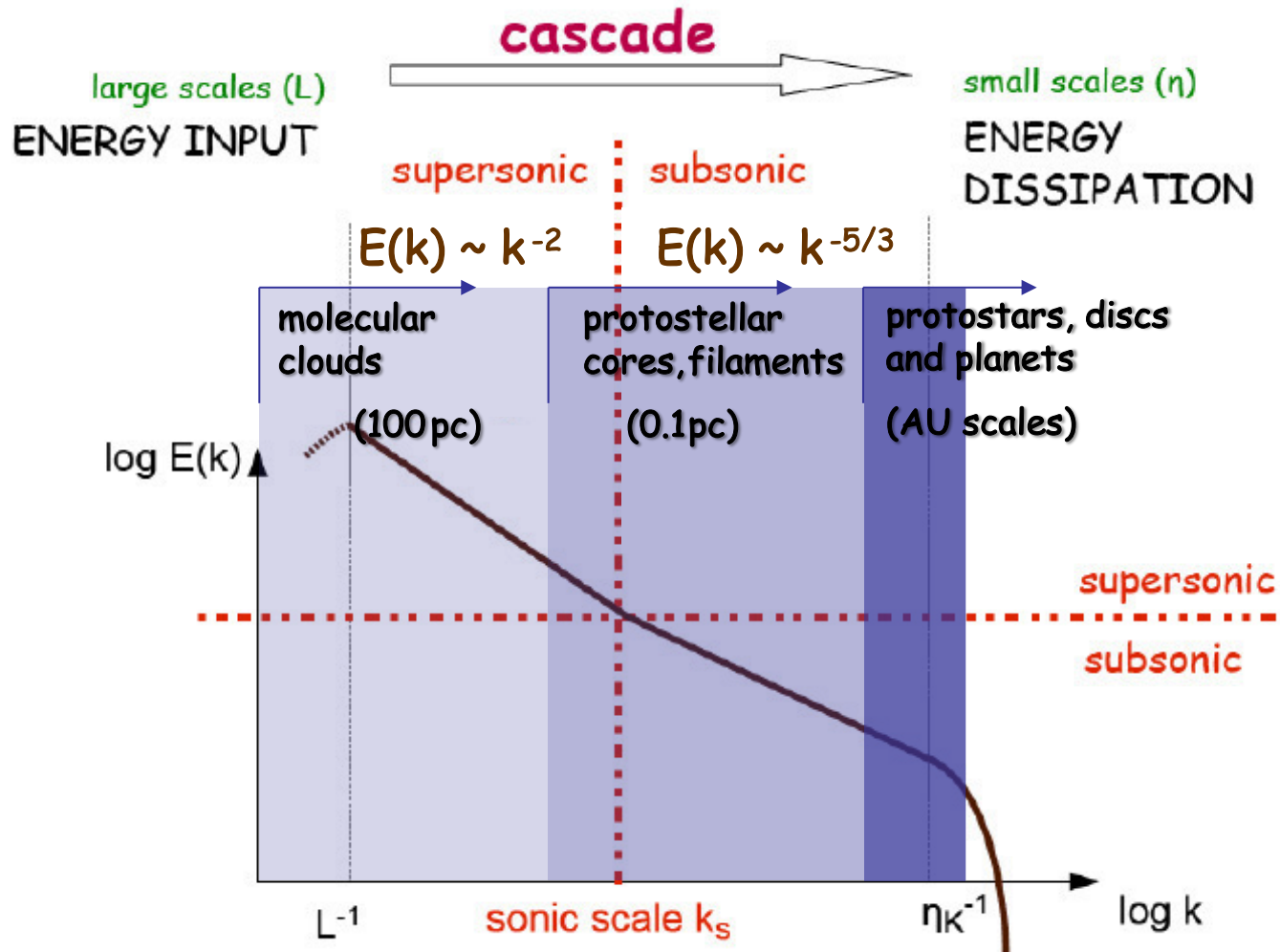
Interstellar Turbulence

- 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

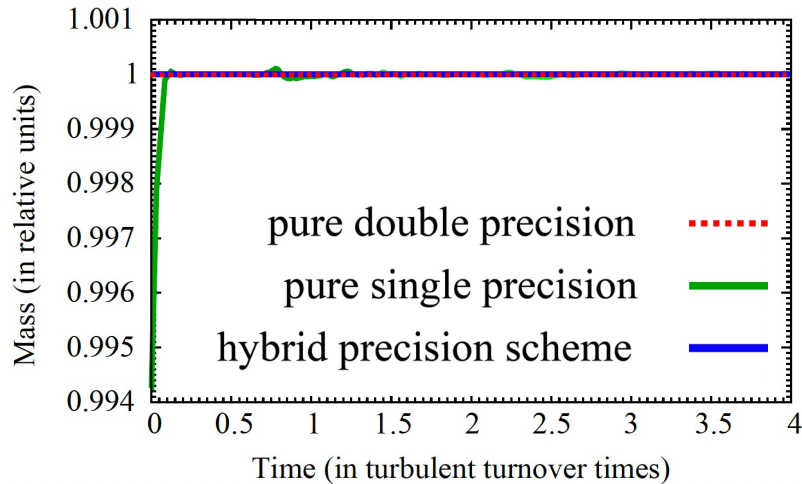
Technical specifications:

- 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)

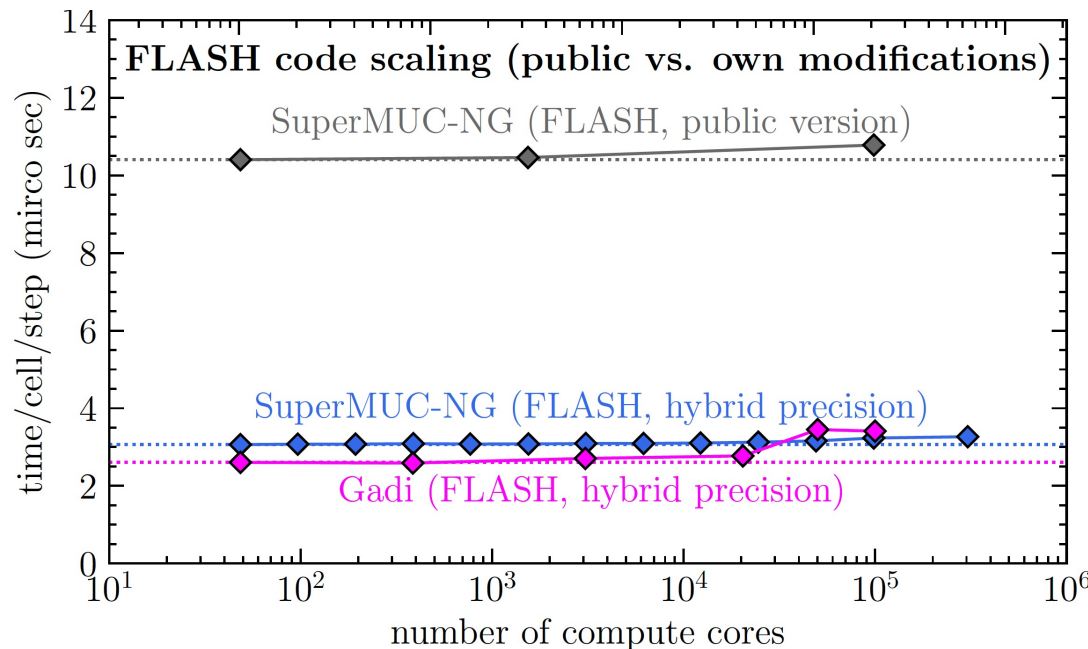
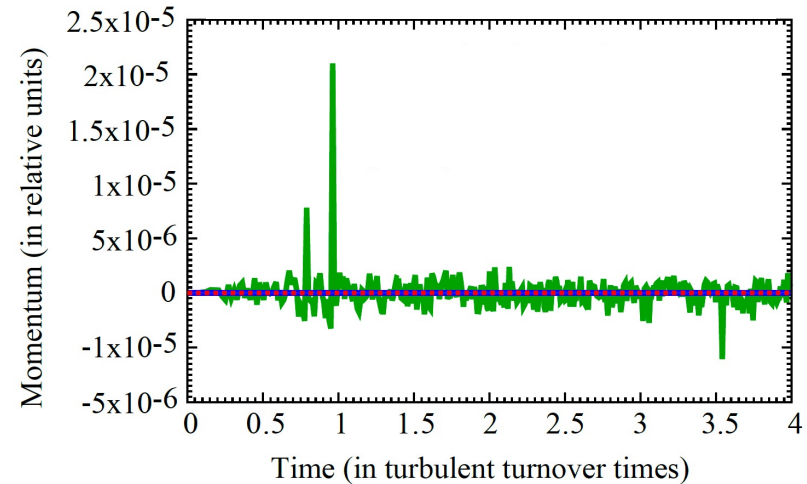


Hybrid precision and code scaling

Mass conservation



Momentum conservation

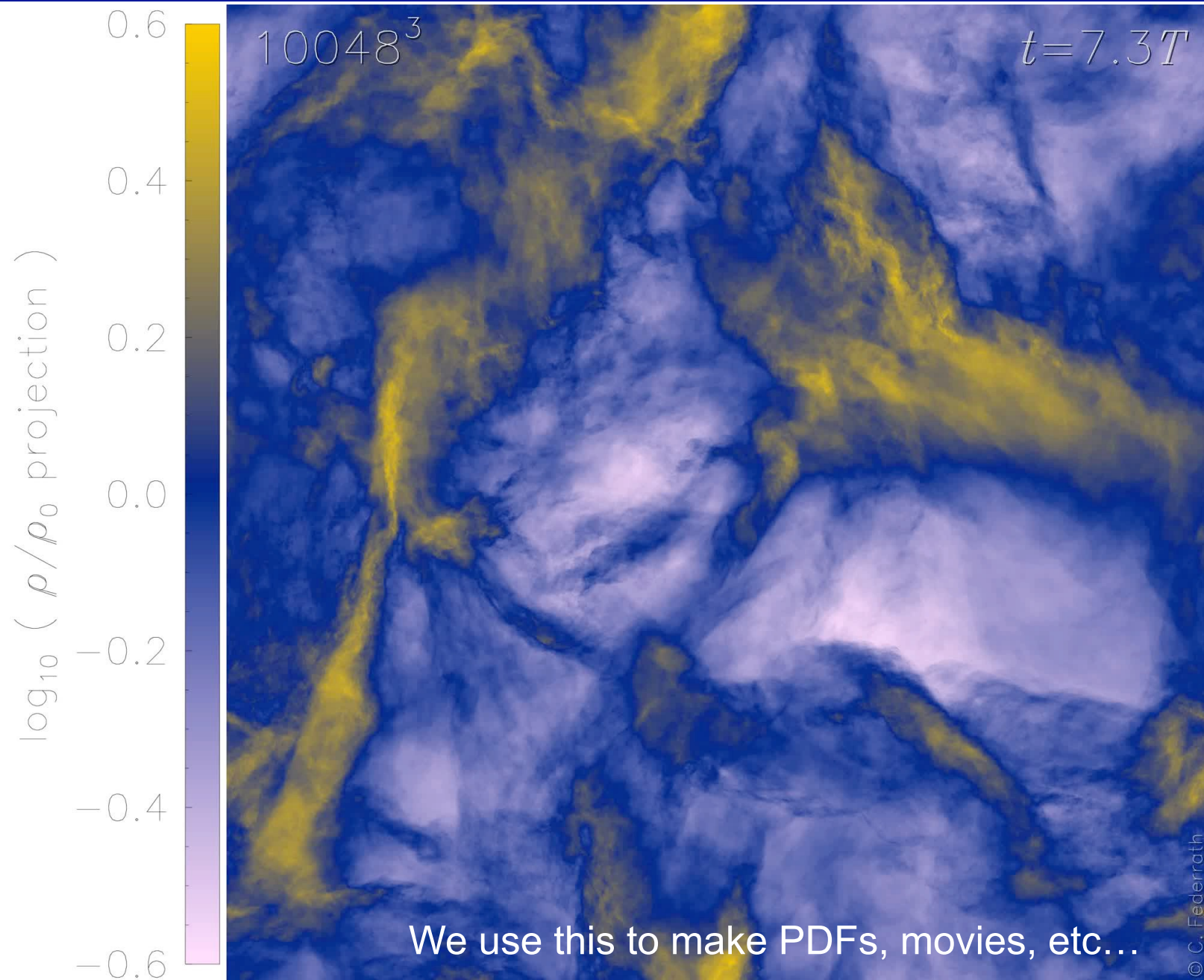


Overall changes to FLASH for this setup resulted in

- factor 3.6 higher speed
- factor 4.1 less memory

(Federrath et al. 2021,
Nature Astronomy;
Federrath & Offner 2026)

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



Turbulence is key for Star Formation

(Federrath & Klessen 2012)

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

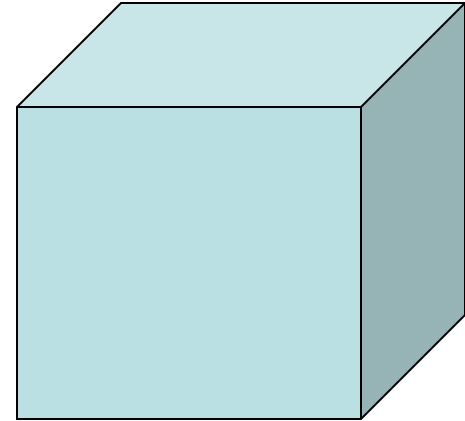
Solenoidal

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**

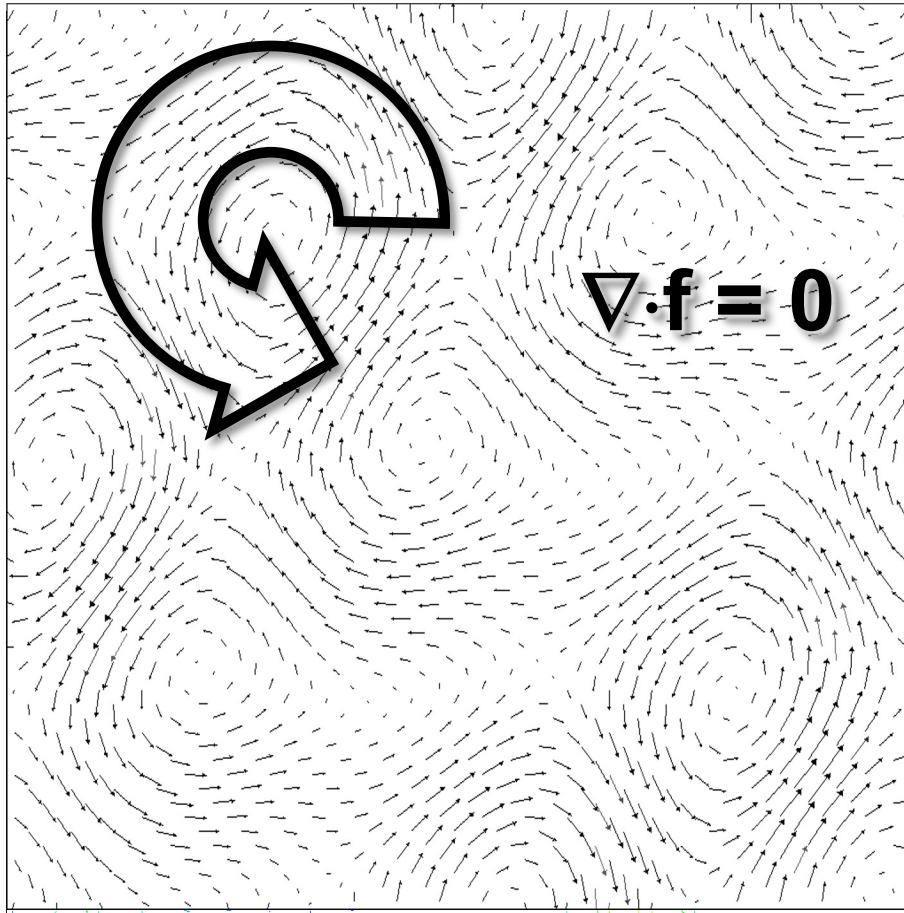


e.g., Vazquez 1994, Padoan+1997, Passot+1998, Stone+1998, Mac Low 1999, Klessen+2000, Ostriker+2001, Heitsch+2001, Cho+2002, Boldyrev+2002, Li+2003, Haugen+2004, Padoan+2004, Jappsen+2005, Ballesteros+2006, Mee+Brandenburg 2006, Kritsuk+2007, Kowal+2007, Dib+2008, Offner+2008, Schmidt+2009, Burkhart+2009,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

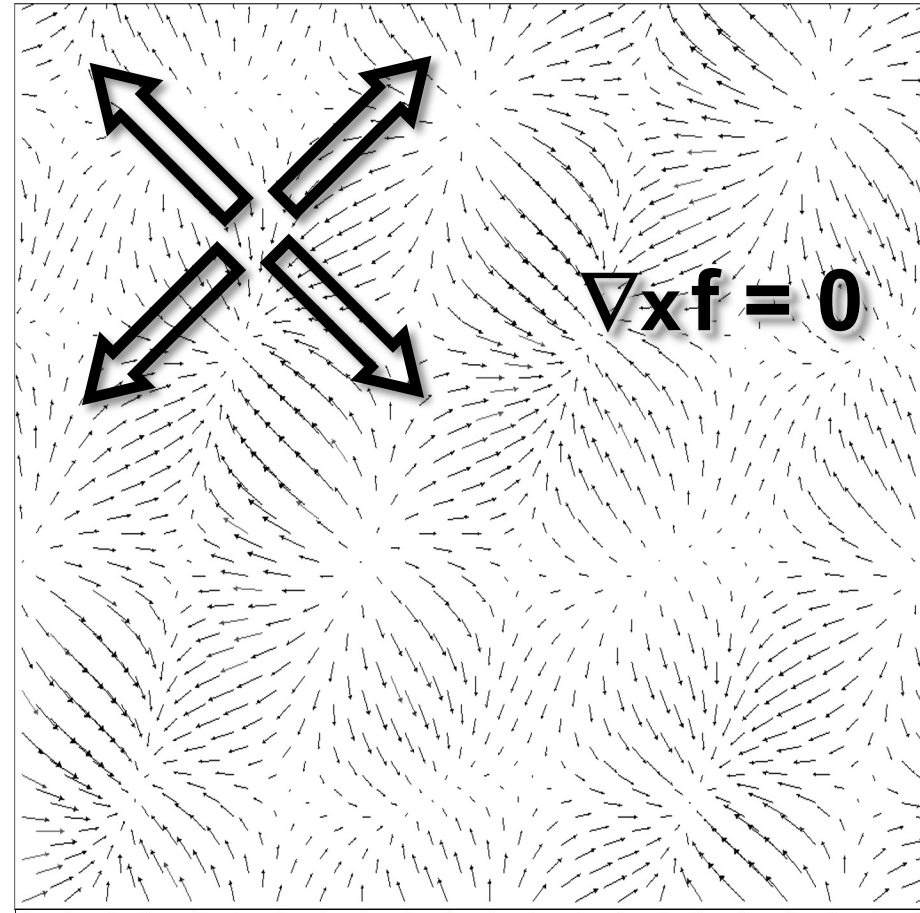
Turbulence forcing – solenoidal versus compressive

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

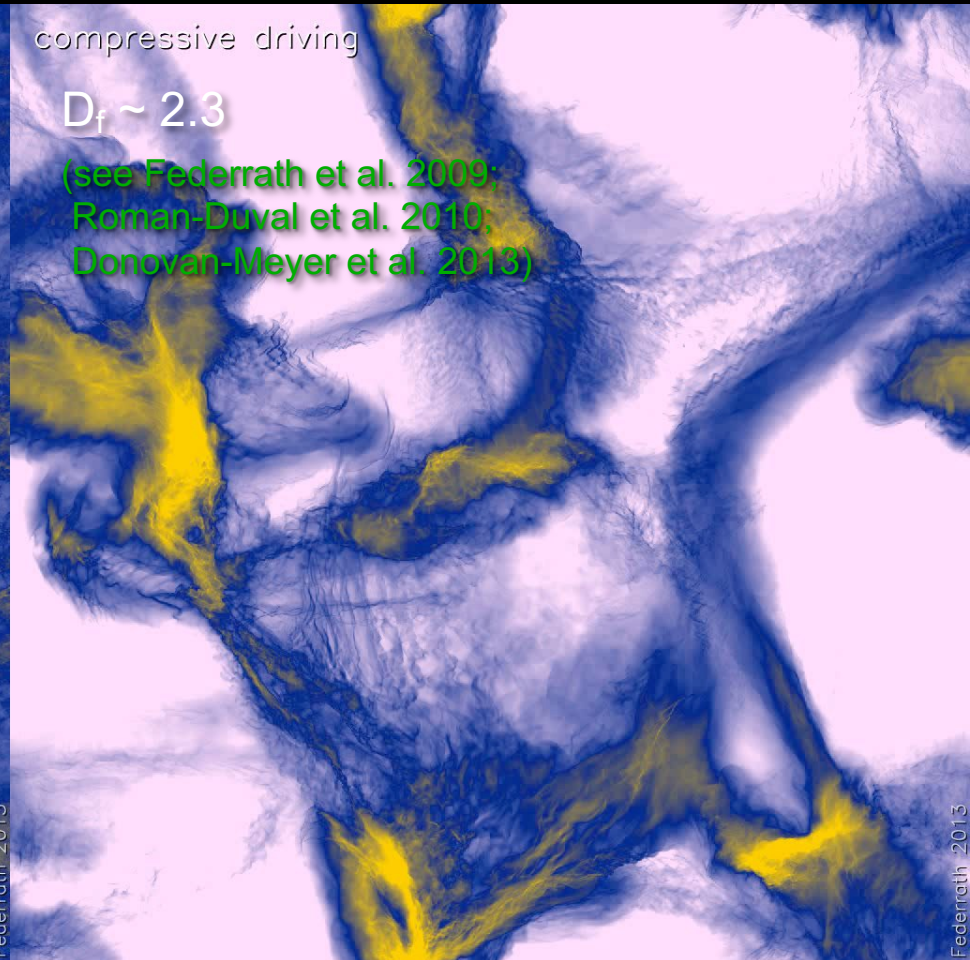
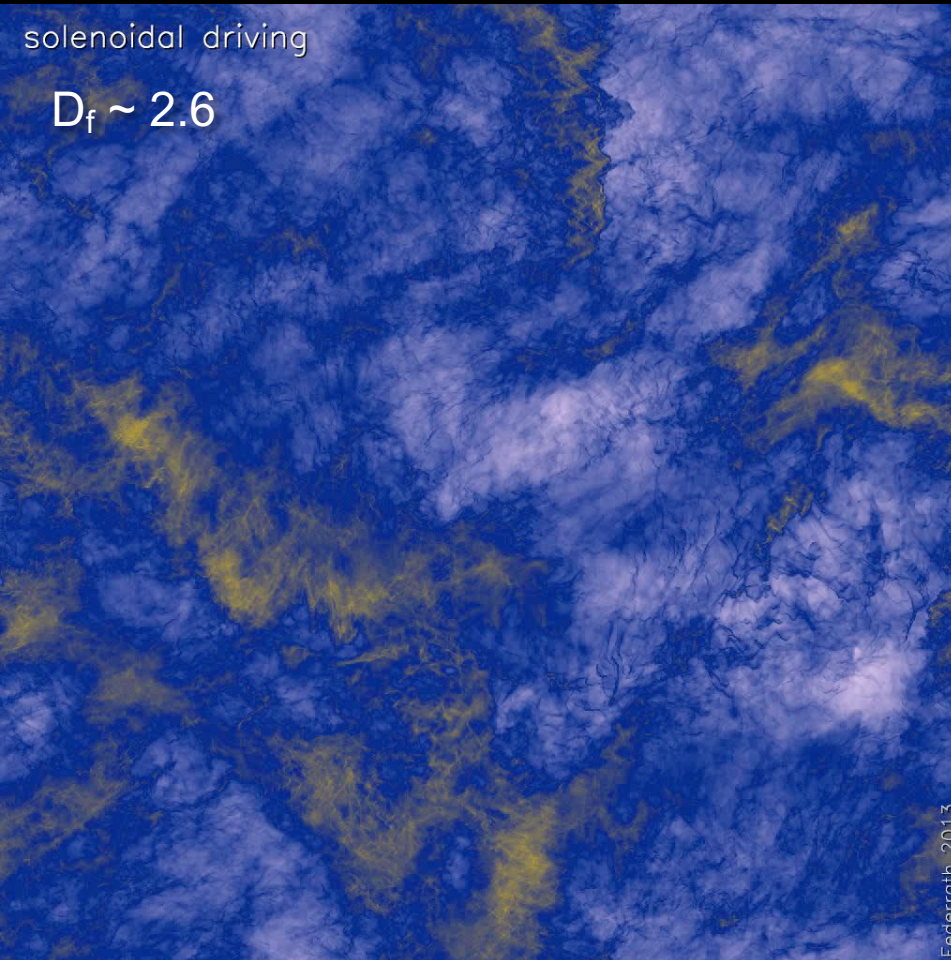


Turbulence driving – solenoidal versus compressive

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

solenoidal forcing

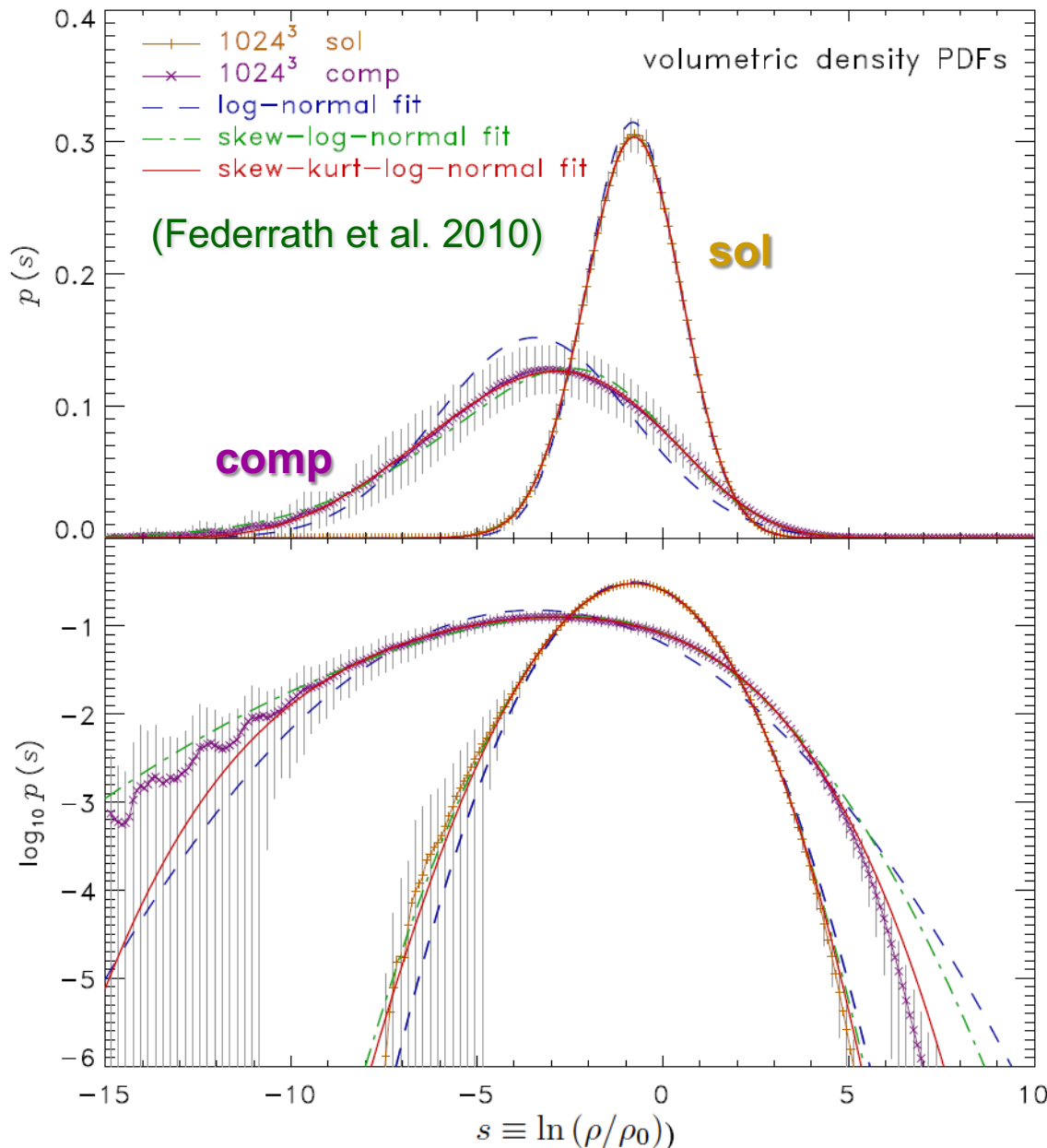
compressive forcing



Compressive driving produces much stronger density enhancements

(Federrath 2013, MNRAS 436, 1245: Supersonic turbulence @ 4096³ 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)

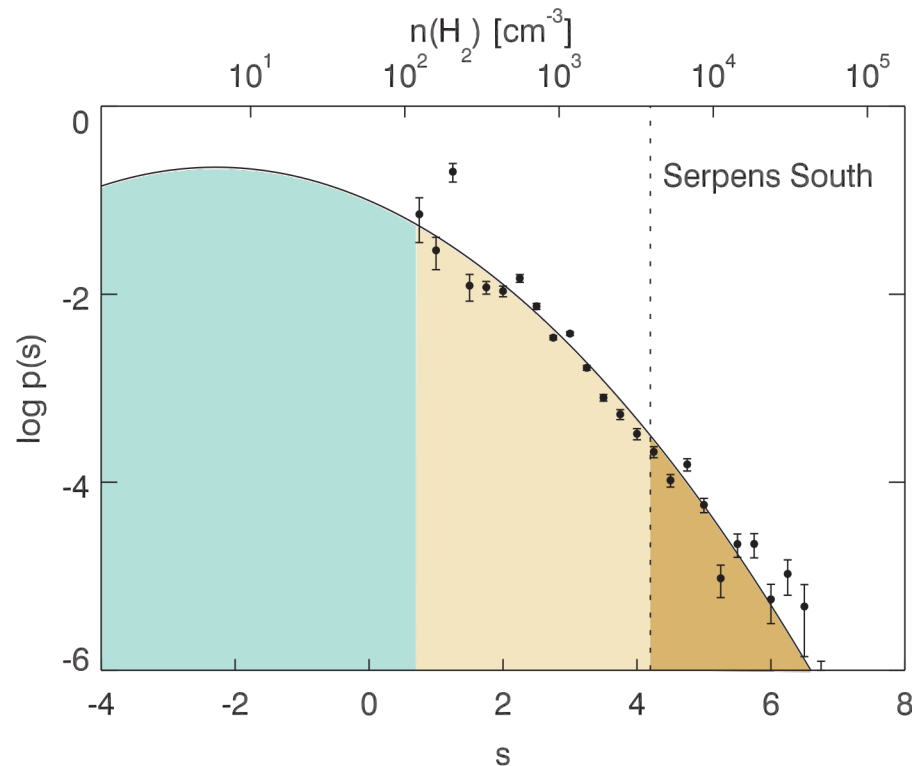
$$\sigma_s^2 = \ln(1 + b^2 \mathcal{M}^2)$$

$b = 1/3$ (sol)
 $b = 1$ (comp)

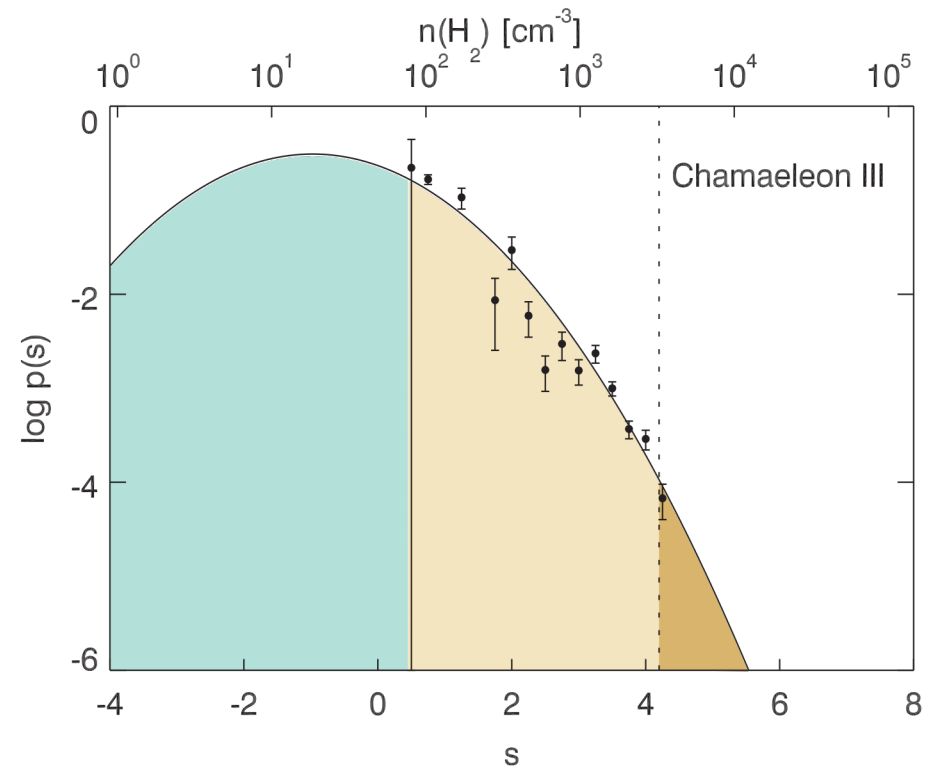
Federrath et al. (2008, 2010);
Price et al. (2011); Konstandin et al. (2012);
Molina et al. (2012); Federrath & Banerjee
(2015); Nolan et al. (2015)

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

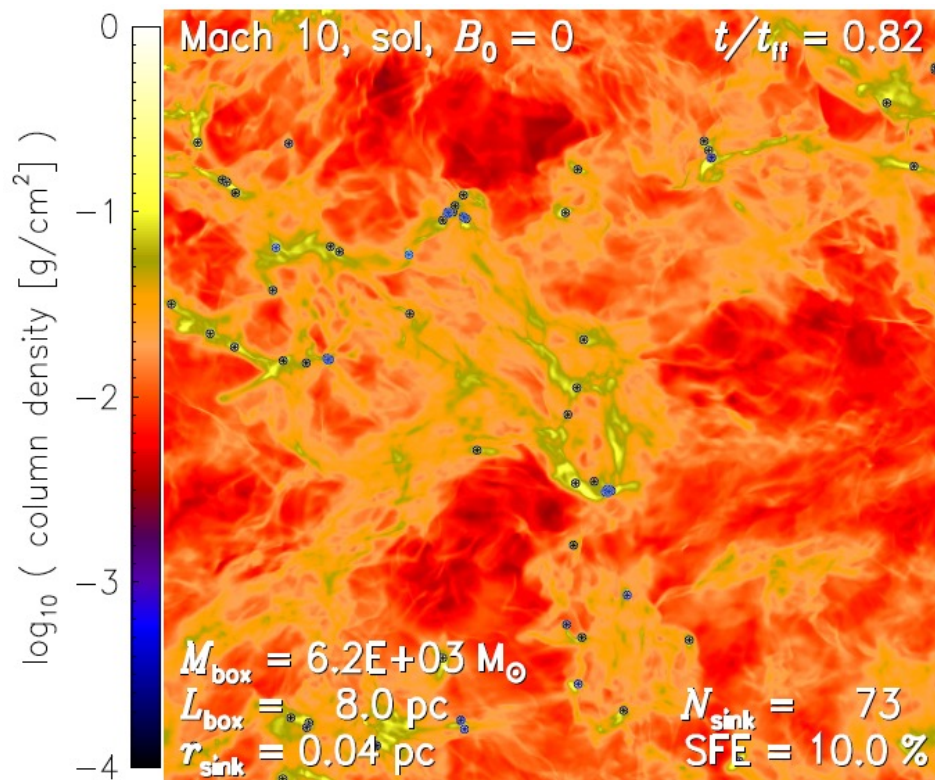
(Brunt et al. 2010a,b)

Density Distribution → Star Formation Rate

Numerical experiment for Mach 10

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

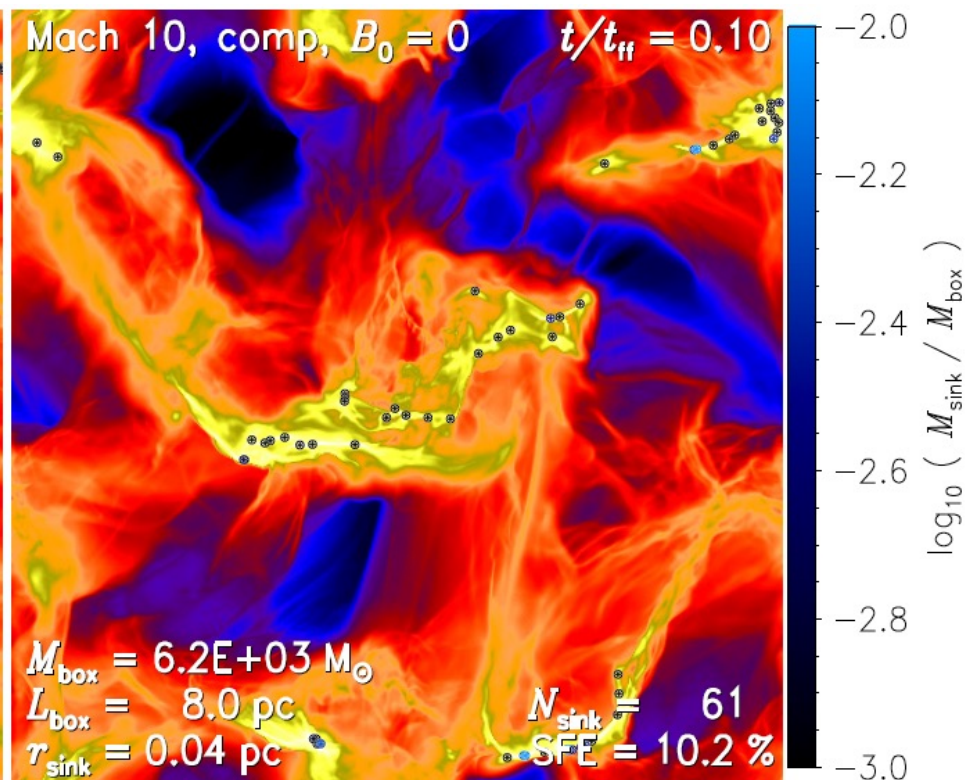
Solenoidal Driving ($b=1/3$)



$SFR_{ff}(\text{simulation}) = 0.14$

$SFR_{ff}(\text{theory}) = 0.15$

Compressive Driving ($b=1$)



$\times 20$

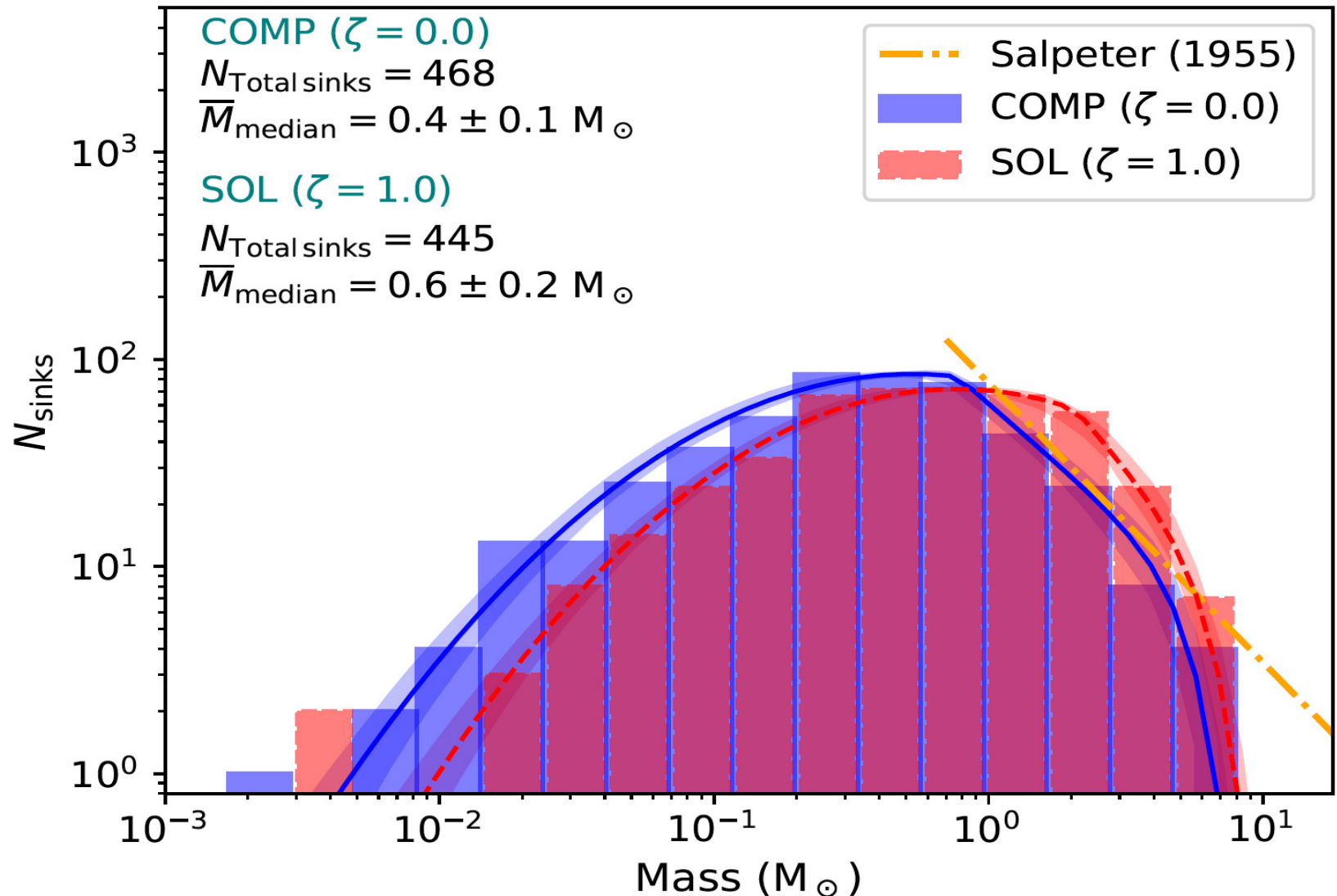
$\times 15$

$SFR_{ff}(\text{simulation}) = 2.8$

$SFR_{ff}(\text{theory}) = 2.3$

Turbulence driving is a key parameter for star formation!

Role of Turbulence Driving for Initial Mass Function



(Mathew et al. 2022)



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

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/>

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/>