The world's highest-resolution simulation of Turbulence

...and why it matters for Star Formation

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MHD Turbulence $\rightarrow$ Stars $\rightarrow$ Feedback

(Federrath & Klessen 2012; Federrath 2018)

Magnetic Fields

Mac Low & Klessen (2004)
McKee & Ostriker (2007)
Padoan et al. (2014)
Star Formation is inefficient

Turbulence  Magnetic Fields  Feedback
Star Formation is Inefficient  (Federrath 2015 MNRAS; 2018 Physics Today)


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Jet/Outflow Feedback


Turbulence

- Reynolds numbers $> 1000$
- Kinetic energy cascade

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

Incompressible

Mach $< 1$

Kolmogorov (1941)
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

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

![Diagram showing energy cascade](image)

\[ E(k) \sim k^{-2} \]

- Shock-dominated
- Mach > 1

\[ E(k) \sim k^{-5/3} \]

- Subsonic
- Mach < 1

Kolmogorov (1941)
- Reynolds numbers > 1000
- Kinetic energy cascade

Interstellar Turbulence
Towards resolving the sonic scale: Turbulence @ 10048³

Technical specifications:
- Resolution: 10048³ grid cells (10¹² 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 the FLASH code for this setup resulted in
- factor 3.6 higher speed
- factor 4.1 less memory requirement

(Federrath et al., submitted)
Modelling turbulence at extreme resolution \((10k)^3\)

Scaling test

![Graph showing scaling test results](image)

FLASH (v4, Federrath mods) on SuperMUC–NG

MHD turbulence (double-precision, public version)

MHD turbulence (hybrid-precision, optimized)

HD turbulence (hybrid-precision, optimized)

(Federrath et al., submitted)
Structure function $\rightarrow$ sonic scale

(Federrath et al., submitted)
Structure function \rightarrow sonic scale

Federrath et al., submitted
Structure function $\Rightarrow$ sonic scale

Federrath et al., submitted

(Federrath et al., submitted)
Structure function $\rightarrow$ sonic scale

Federrath et al., submitted

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Structure function $\rightarrow$ sonic scale

Federrath et al., submitted

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Sonic scale → Filament width distribution:

Filament width ≈ Sonic scale:  
\[ \lambda_{\text{sonic}} = L \left( \frac{c_s}{\sigma_v} (1 + \beta^{-1})^{1/2} \right)^2 \]

Observation (Arzoumanian et al. 2011)

(Federrath et al., submitted)

Sonic-scale Theory

(Federrath 2016)
Sonic scale $\rightarrow$ Critical density for star formation:

$$\ell_s = \ell_{\text{Jeans}} \rightarrow \rho_{\text{critical}}$$

(Turbulence = Gravity)

(Krumholz & McKee 2005; Federrath & Klessen 2012)

By measuring the sonic scale directly, we find:

$$\ell_{\text{Jeans}} = 13^{+7}_{-4}\ell_s$$

$\rightarrow$ Critical density for star formation

on 10 times larger scales than $\ell_s = \ell_{\text{Jeans}}$

(Federrath et al., submitted)
Turbulence driven by:
- Shear
- Jets / Outflows
- Cloud-cloud collisions
- Winds / Ionization fronts
- Spiral-arm compression
- Supernova explosions
- Gravity / Accretion

Magnetic Fields

Solenoidal

Compressive

Dynamics (shear)

Turbulence → Stars → Feedback

(Federrath & Klessen 2012; Federrath 2018)
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**
\[ \nabla \cdot f = 0 \]

**Compressive forcing**
\[ \nabla \times f = 0 \]
Turbulence driving – solenoidal versus compressive

Compressive forcing produces much stronger density enhancements

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


solenoidal driving

compressive driving

\( D_f \sim 2.6 \)

\( D_f \sim 2.3 \)

(see Federrath et al. 2009; Roman-Duval et al. 2010; Donovan-Meyer et al. 2013)
Solenoidal Driving ($b=1/3$) vs. Compressive Driving ($b=1$)

**Density Distribution → Star Formation Rate**

**Numerical experiment for Mach 10**

SFR$_{ff}$ (simulation) = 0.14  
SFR$_{ff}$ (theory) = 0.15  

*SFR$_{ff}$ (simulation) = 2.8  
SFR$_{ff}$ (theory) = 2.3*

Turbulence driving is a key parameter for star formation!

Federrath & Klessen (2012)


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Driving of turbulence in different galactic environments

Determine the driving in Galactic Centre (Federrath et al. 2016) vs. Galactic Disc

→ Recently applied to SAMI galaxy survey (Federrath et al. 2017; Zhou et al. 2017)
  …also plans to apply to DYNAMO (Fischer, Glazebrook)

(see also work by Salim et al. 2015; 2019 and Sharda et al. 2018)
**The Star Formation Rate – Magnetic fields**

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


- $B=0$ ($M_A = \infty$, $\beta = \infty$)
- $B=3\mu G$ ($M_A = 2.7$, $\beta = 0.2$)

![Simulation images](image-url)

<table>
<thead>
<tr>
<th>Condition</th>
<th>SFR$_{ff}$ (simulation)</th>
<th>SFR$_{ff}$ (theory)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B=0$</td>
<td>0.46 x 0.63</td>
<td>0.29</td>
</tr>
<tr>
<td>$B=3\mu G$</td>
<td>0.29 x 0.40</td>
<td>0.18</td>
</tr>
</tbody>
</table>

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

Federrath & Klessen (2012)
The role of magnetic field structure

Serpens SMM1

ALMA

Hull et al. (2017)
The role of magnetic field structure

Uniform Magnetic Field  Partially Turbulent Field  Fully Turbulent Field

Gerrard et al. (2019)
The role of magnetic field structure

Gerrard et al. (2019)

Density (g cm$^{-3}$)

- $2 \times 10^{-17}$
- $2 \times 10^{-16}$
- $2 \times 10^{-15}$
- $2 \times 10^{-14}$
- $2 \times 10^{-13}$
- $2 \times 10^{-12}$

See also Hodapp & Chini (2018) on dual jet/outflow components launched in Serpens South

→ Need ordered magnetic field component for jet launching (Blandford & Payne 1982)
Built-up of circum-binary disks

Turbulence makes bigger disks \( \rightarrow \) relevant for planet formation

Magnetic field structure is key for outflow/jet launching


Kuruwita & Federrath (2019)
1) **Star Formation is inefficient** →
   Only the combination of
   
   Turbulence + Magnetic Fields + Feedback
   
   gives realistic (observed) Star Formation Rates

2) **Resolved the transition from supersonic to subsonic turbulence**
   The **sonic scale in (10k)^3 turbulence simulation**

3) **Observations and simulations** are beginning to reveal the complex
   magnetic field structures in dense star-forming cores and disks
   → Disk Winds, Jets, Dynamos

4) **The Formation of the First Stars in the Universe**
   - **magnetic fields** → jets from First Stars, **IMF**

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