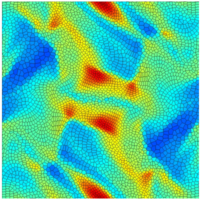
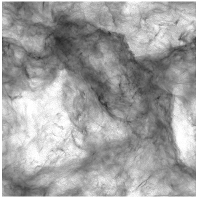
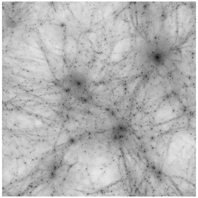
Moving mesh magnetohydrodynamics: the role of magneto–turbulence in star formation

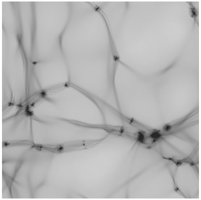
Philip Mocz

Princeton University









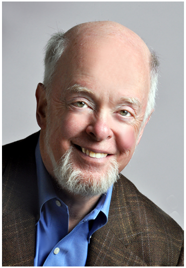
Einstein Symposium
Oct 12, 2017

Acknowledgements

Lars Hernquist
(Harvard)

Blakesley Burkhart
(Harvard)

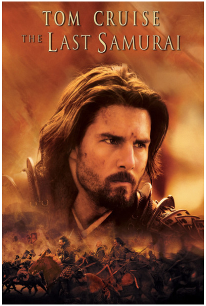
Chat Hull
(NAOJ Chile)

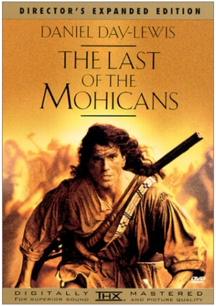


Chris McKee
(Berkeley)

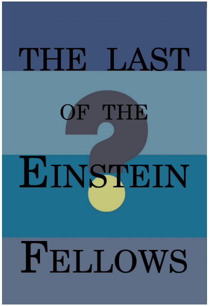
NASA Einstein Fellowship Program

The last…?


TOM CRUISE
THE LAST SAMURAI


DIRECTOR'S EXPANDED EDITION
DANIEL DAY-LEWIS
THE LAST OF THE MOHICANS
DIGITALLY THX MASTERED
FOR SUPERIOR SOUND
AND PICTURE QUALITY


STAR WARS
THE LAST JEDI
DECEMBER 15

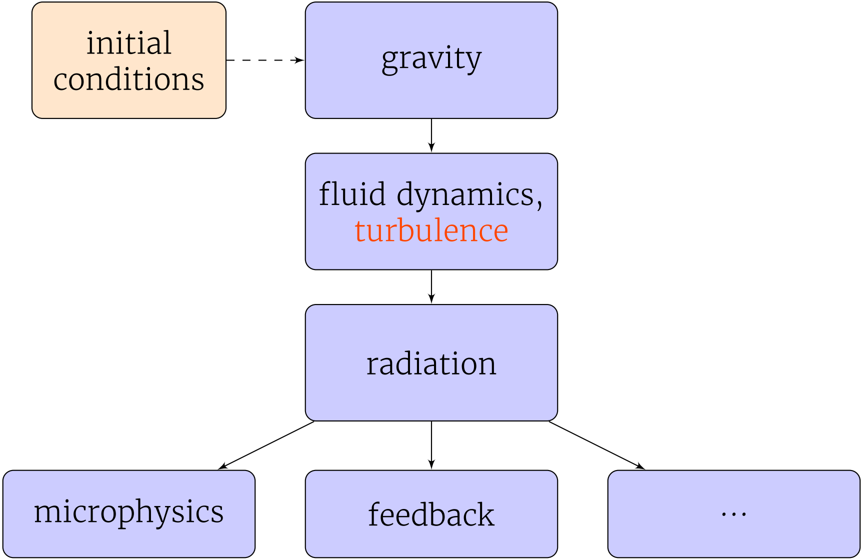

THE LAST
OF THE
EINSTEIN
FELLOWS

The New NASA Hubble Fellowship Program

How does the Universe work? – Einstein Fellows
How did we get here? – Hubble Fellows
Are we alone? – Sagan Fellows

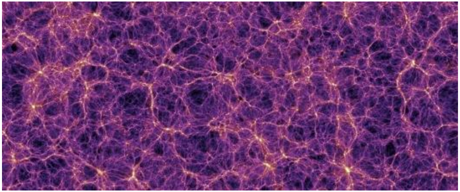
How does the Universe work?

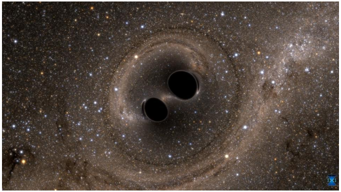
A hierarchy of physical processes...



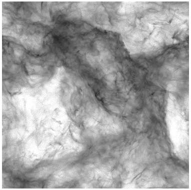
How does the Universe work?

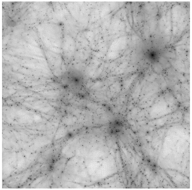
- 0^{th} order: gravity often is most important
  - Sometimes gravity wins on even the smallest scales…



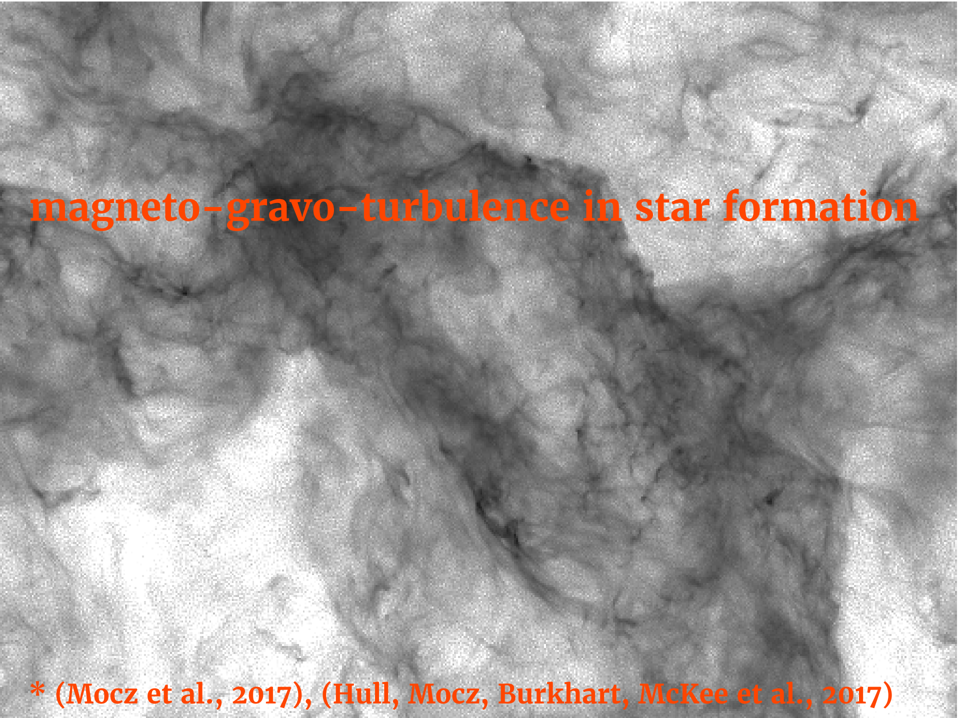


- 1^{st} order: is often fluid dynamics
  - study of fundamental physical processes *(How does the Universe work?)*
    - structure formation
    - turbulence
    - different regimes where qualitative behavior changes



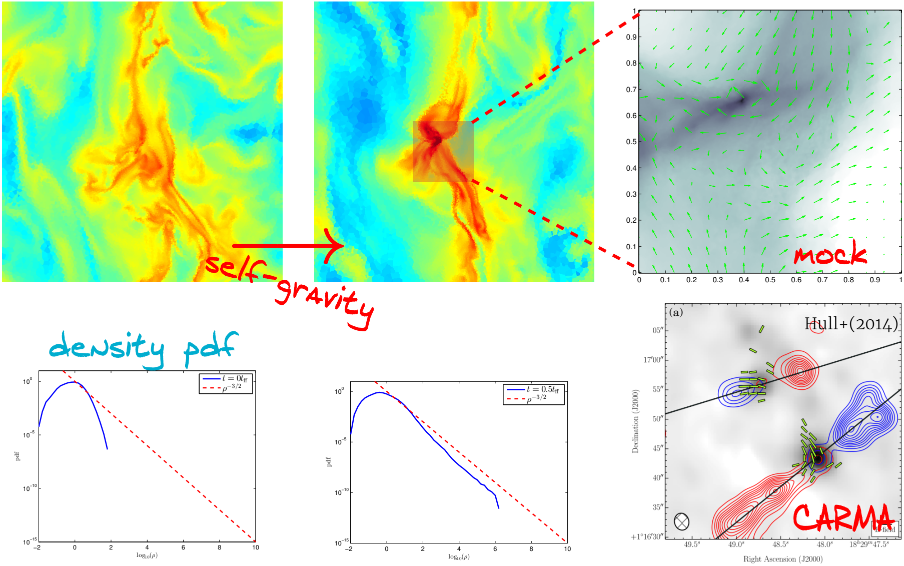


magneto-gravo-turbulence in star formation



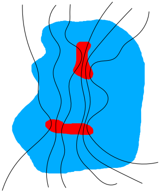
* (Mocz et al., 2017), (Hull, Mocz, Burkhart, McKee et al., 2017)

Overview

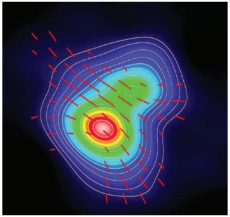


self-gravity
mock
density pdf
t = 0t_ff
ρ^{-3/2}
pdf
log10(ρ)
t = 0.5t_ff
ρ^{-3/2}
pdf
log10(ρ)
(a)
Hull+(2014)
CARMA
Declination (J2000)
Right Ascension (J2000)

Star formation background



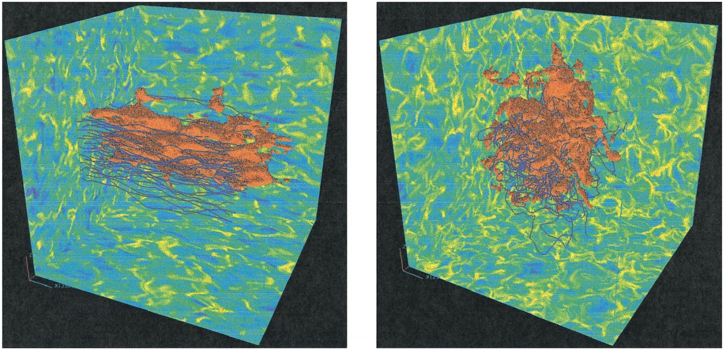
- competition between turbulence, self-gravity & B–field
- basic theory predicts cores collapse and form **hourglass** shaped magnetic fields
- sub– or super–Alfvénic turbulence?



NGC 1333
IRAS4A
(Girart, Rao, Marrone 2006)

Origin of magnetic field structure

- inherit strong field from large-scale medium
- amplify weak field via turbulence

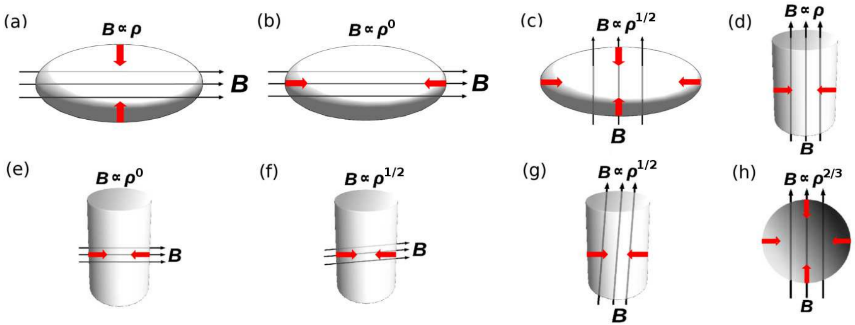


(Stone+1998)

- magnetic topology problem(McKee+1993): how does the magnetic field topology evolve as the ISM forms molecular clouds and cores contract to form stars?

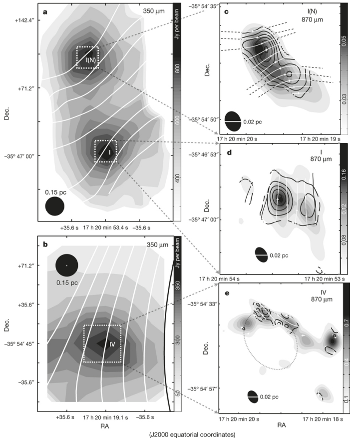
How does contraction of cores happen?

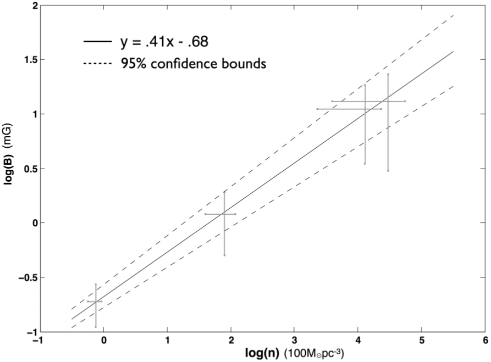
$B \propto \rho^{\alpha}$



(Tritsis+2015)

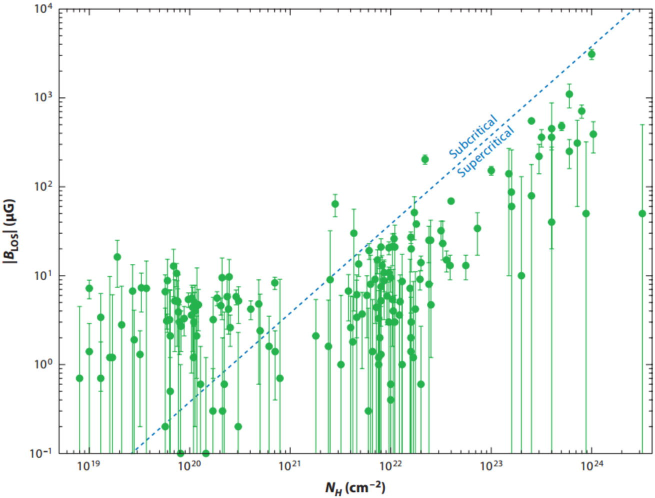
Is core-formation self-similar? (Li+2015)





- self-similar scaling $100 \rightarrow 0.1$ pc (SMA)
- dynamically important B-fields
- anisotropic contraction

Or not! Zeeman obs. of B–field in clouds

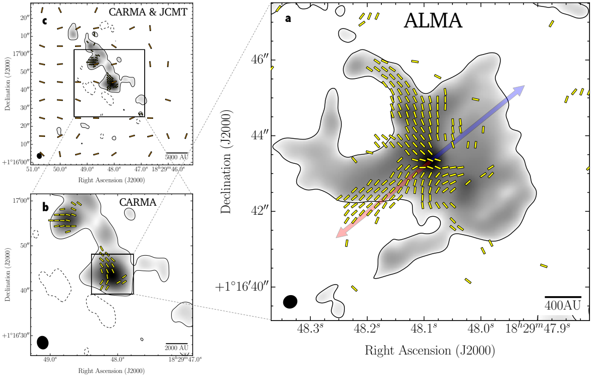


(Crutcher+2012)

- $B \propto \rho^{0.67}$, weak–field preferred
- Zeeman measurements are the gold standard for B–field

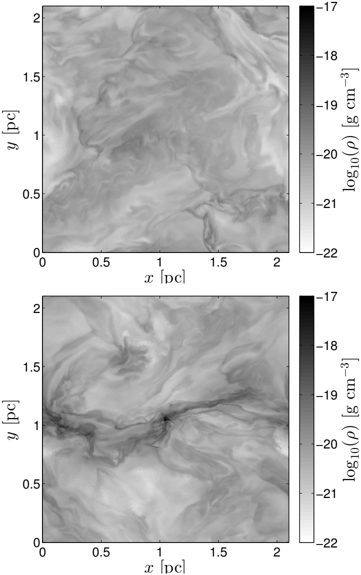
What about smaller scales? (Hull, **PM**+2016)

CARMA (0.1 pc) ⇒ ALMA (0.01 pc)



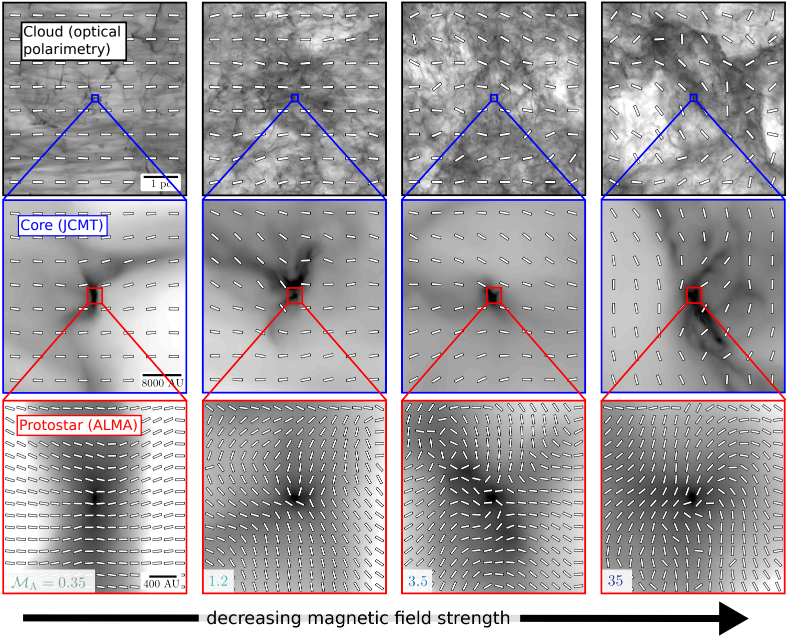
- new Ser-emb 8 Type 0 protostar ALMA observation
- pinches, filaments, clumps, **chaotic!**

What can simulations teach us?: Setup



- turbulent, magnetized, self-gravitating ISM cloud ($L_0 \sim 5$ pc)
- isothermal
- $\mathcal{M}_\mathrm{s} = \frac{v_\mathrm{rms}}{c_s} = 10$
- $\alpha_\mathrm{vir} = 5v_\mathrm{rms}^2(L/2)/(3GM_0) = 1/2$
- $\mathcal{M}_\mathrm{A} = \langle|\mathbf{v}|\rangle/\langle|\sqrt{B^2/4\pi\rho}|\rangle =$ $0.35, 1.2, 3.5, 35$

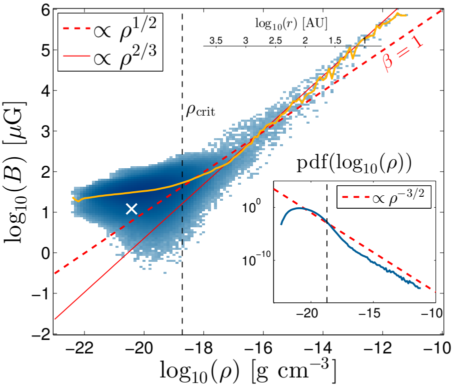
Simulations of star formation in turbulent ISM



B–ρ scaling

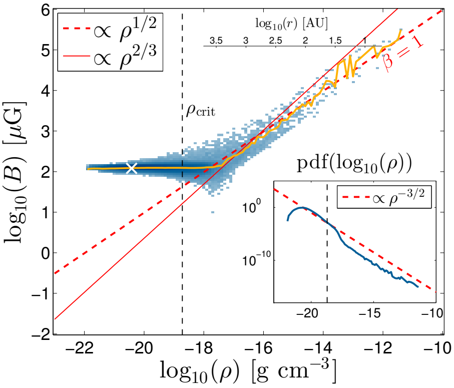
Weak-field

$\mathcal{M}_{\mathrm{A,mean-field}} = 3.5$



Strong-field

$\mathcal{M}_{\mathrm{A,mean-field}} = 0.35$

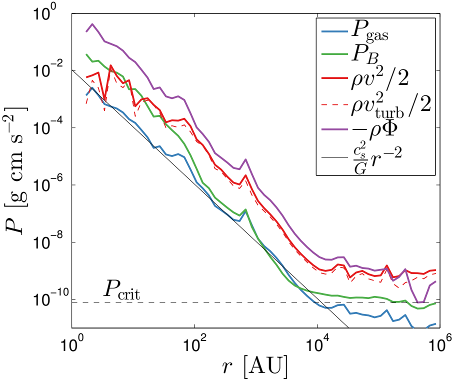


(transition at $\rho_{\mathrm{crit}} = \langle\rho\rangle\mathcal{M}_{\mathrm{s}}^2/3$)

Density-averaged radial profiles

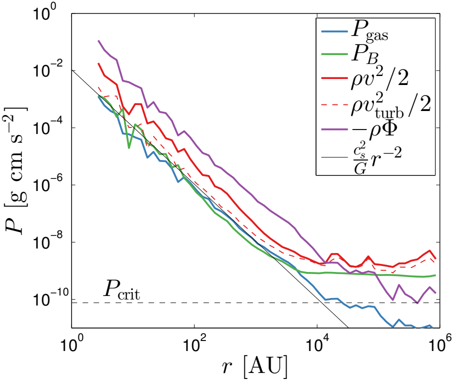
Weak-field

$\mathcal{M}_{\mathrm{A,mean-field}} = 3.5$



Strong-field

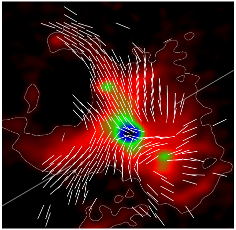
$\mathcal{M}_{\mathrm{A,mean-field}} = 0.35$



Conclusions – I

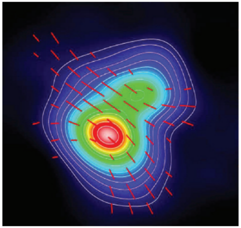
Weak-field

- $B \propto \rho^{2/3}$
- isotropic
- turbulent morphology
- **not** self-similar
- $\beta = 1$ @collapse outer-scale



Strong-field

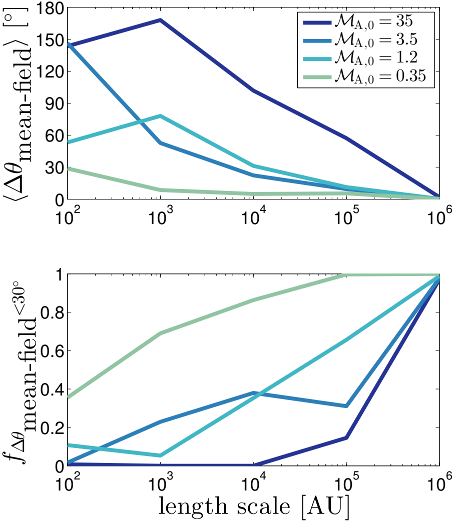
- $B \propto \rho^{1/2}$
- anisotropic
- hourglass morphology
- self-similar
- $\beta = 1$



Conclusions – II

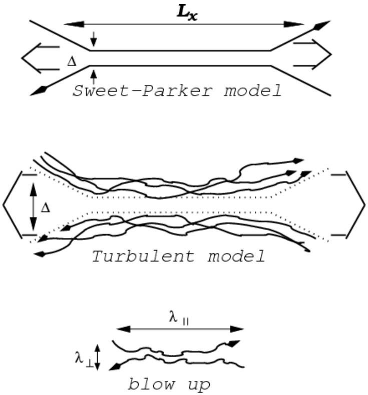
- $\mathcal{M}_\mathrm{A} \sim 1$ a good fiducial value for star formation
- Star formation may occur in **both** $\mathcal{M}_\mathrm{A} \gtrsim 1$ and $\mathcal{M}_\mathrm{A} \lesssim 1$ environments, very different consequences!
  - turbulent vs. hourglass morphology
  - different central magnetic field strengths
  - higher B leads to more massive stars, less fragmentation

B–field as function of scale



- despite core properties being similar, mean–field direction as function of length–scale strongly depends on the mean–field $\mathcal{M}_{A,0}$
- future ALMA observations of young proto–stellar systems can constrain $\mathcal{M}_{A,0}$

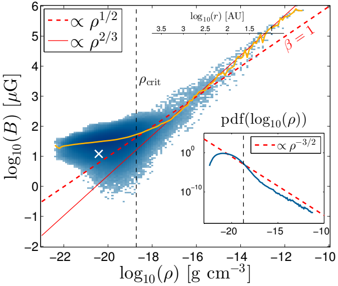
Turbulent reconnection diffusion

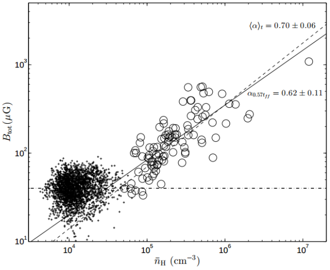


(Lazarian & Vishniac, 1999)

- evidence for turbulent-reconnection seen in our simulations
- Mass-to-flux ($\mu_{\Phi,0}$) in cores evolves during collapse as:
  - $\mu_{\Phi,0} = 80 \rightarrow 12.7$
  - $\mu_{\Phi,0} = 8 \rightarrow 16.5$
  - $\mu_{\Phi,0} = 2.7 \rightarrow 12.1$
  - $\mu_{\Phi,0} = 0.8 \rightarrow 5.8$

Density– vs Volume– averaged B–fields

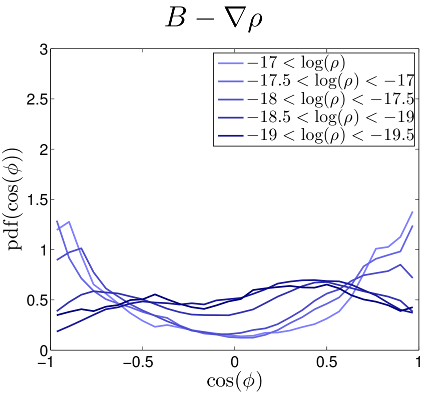




(Li, McKee, Klein, 2015)

- Crutcher+ (2012) Zeeman measurements recover *density*–averaged B–fields
- B–ρ scaling can be steeper with *density*– as opposed to *volume*–average
- Li, McKee, Klein (2015) find mass–to–flux is also affected by type of averaging
- demonstrates the importance of modeling all observational effects for interpretation of data

Self-gravitating turbulent box properties



- Histogram of Relative Orientations (Soler+2013)
- B–field & velocities tend to align, especially at low density
- $\nabla \cdot \mathbf{B} = 0$, shocks, prevent perfect alignment
- B–fields aligned with density gradient at high densities
- transition occurs at critical density ρ_{crit} (Chen,King,Li,2016)

Large-scale EE/BB modes

- *Planck* dust polarization maps of interstellar turbulence show EE/BB=2 (Caldwell, Hirata, Kamionkowski 2016)
- analytic theory predicts EE/BB=1 for turbulence
- My simulations confirm analytic theory EE/BB=1 for super-Alfvenic turbulence
- EE/BB=2 might indicate stirring-scale or strong B-fields