Star cluster formation triggered by giant molecular cloud collisions

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Wu, B., Tan, J. C., Nakamura, F., Van, L. S., Christie, D., & Collins, D. 2017a, ApJ, 835, 137
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Li, Q., Tan, J. C., Christie, D., Bistbas, T., & Wu, B. 2017, ApJ, sub. (arXiv:1706.03764)
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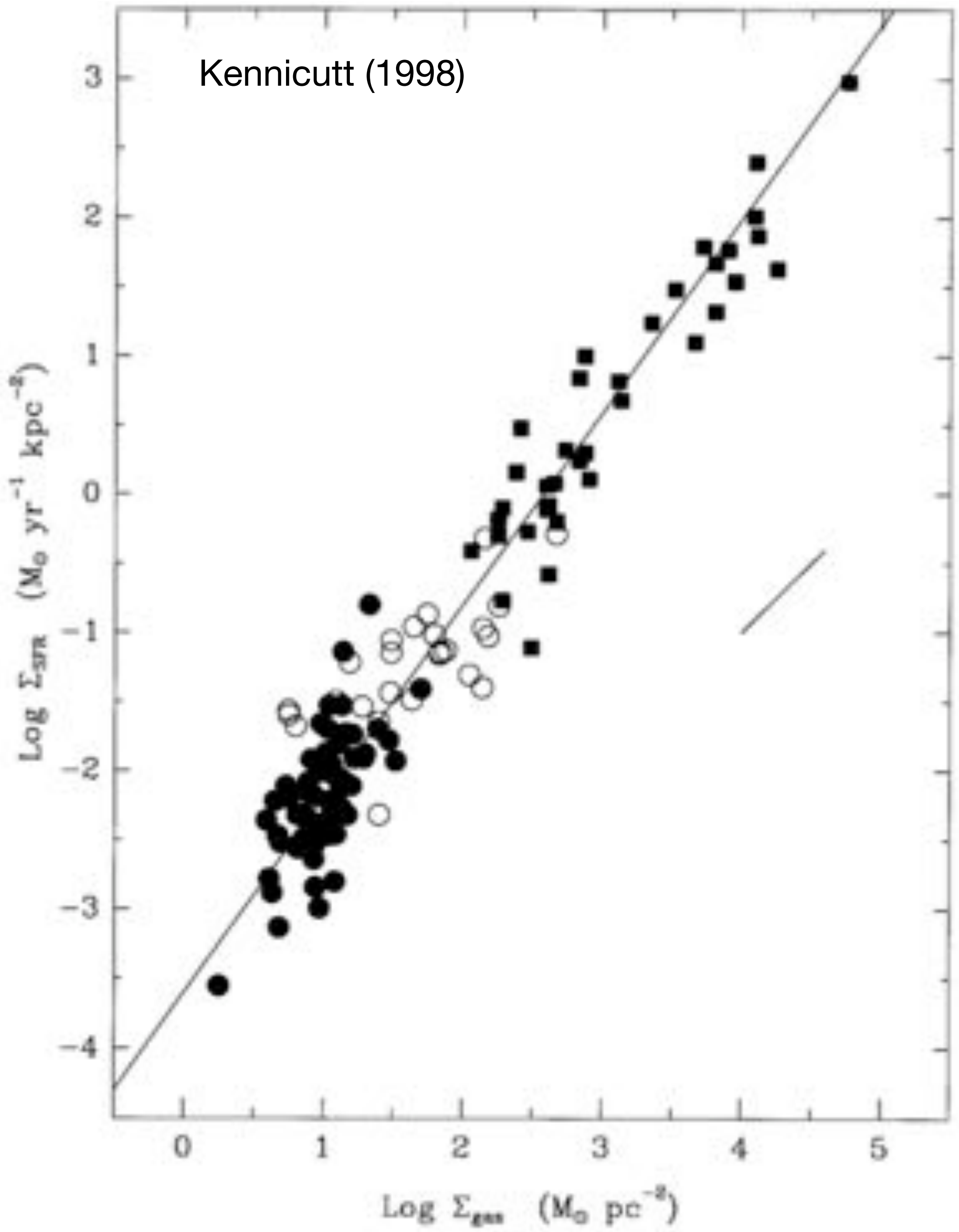
Global Galactic Scales

- Kennicutt-Schmidt Relation
- Empirical correlation between:
  star formation rate (SFR) surface density (Σ_{SFR})
  and
  gas mass surface density (Σ_{gas})

Schmidt (1959); Wong+Blitz (2002); Boissier+ (2003), Gao+Solomon (2004); Kennicutt+(2007); Leroy+(2008); Bigiel+(2008); Genzel+(2010);

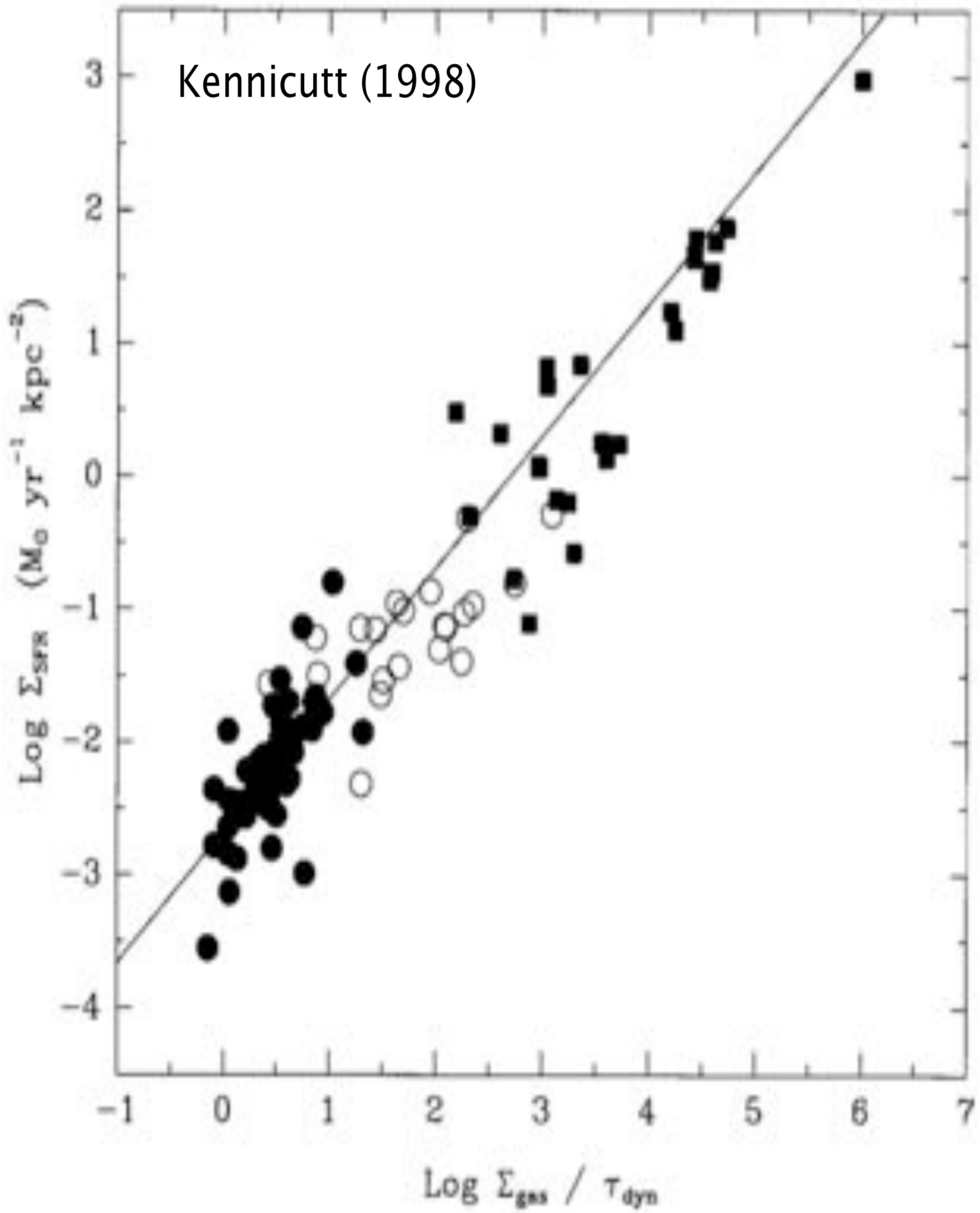


Global Galactic Scales

- Dynamical Kennicutt-Schmidt Relation

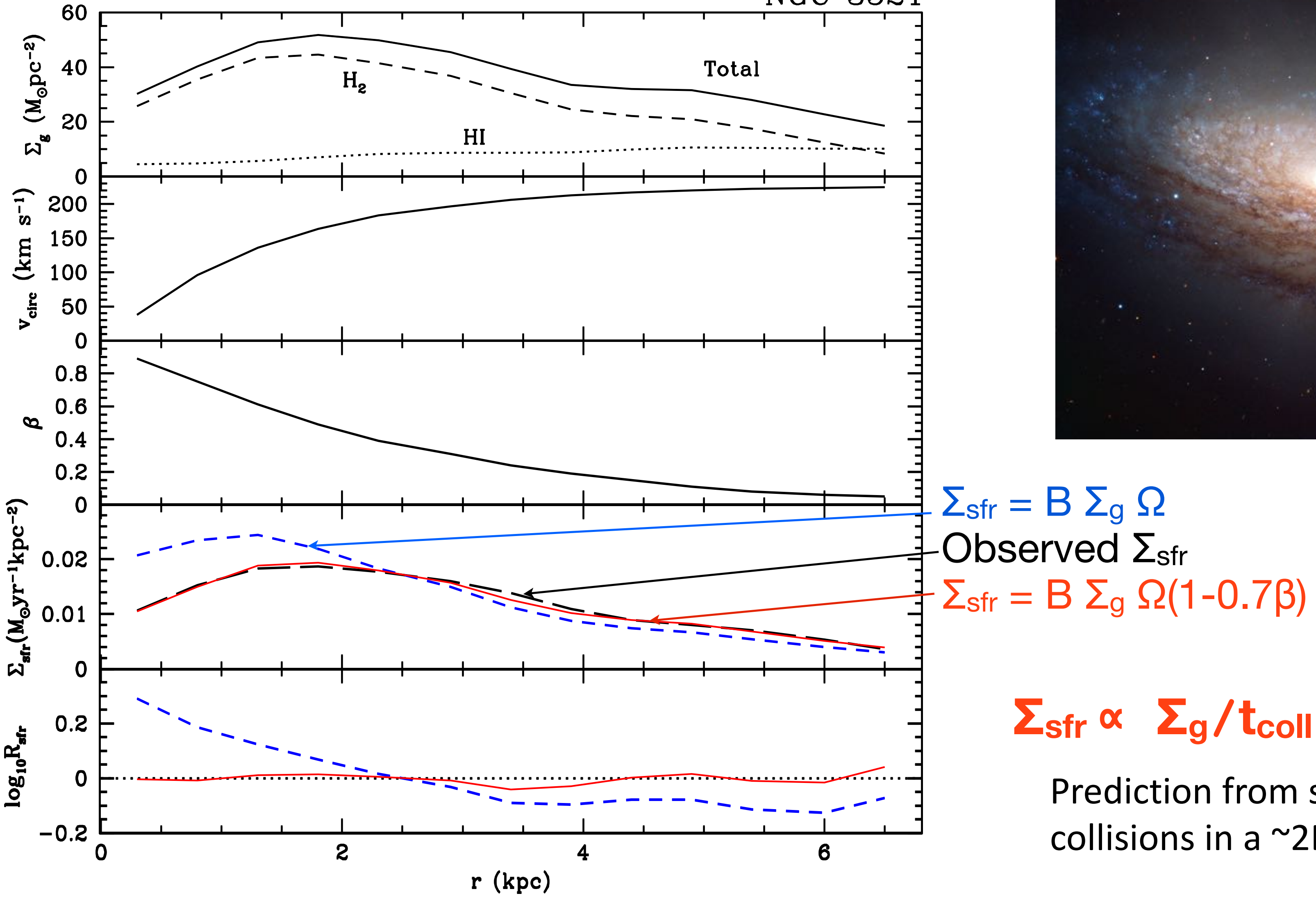
$$\Sigma_{\text{SFR}} = \frac{\varepsilon_{\text{orbit}}\Sigma_{\text{gas}}}{t_{\text{orbit}}} \propto \Sigma_{\text{gas}}\Omega$$

$$\Sigma_{\text{SFR}} = 0.017\Sigma_{\text{gas}}\Omega_{\text{gas}}$$



Effect of Shear on Σ_{SFR}

Leroy et al. (2008)



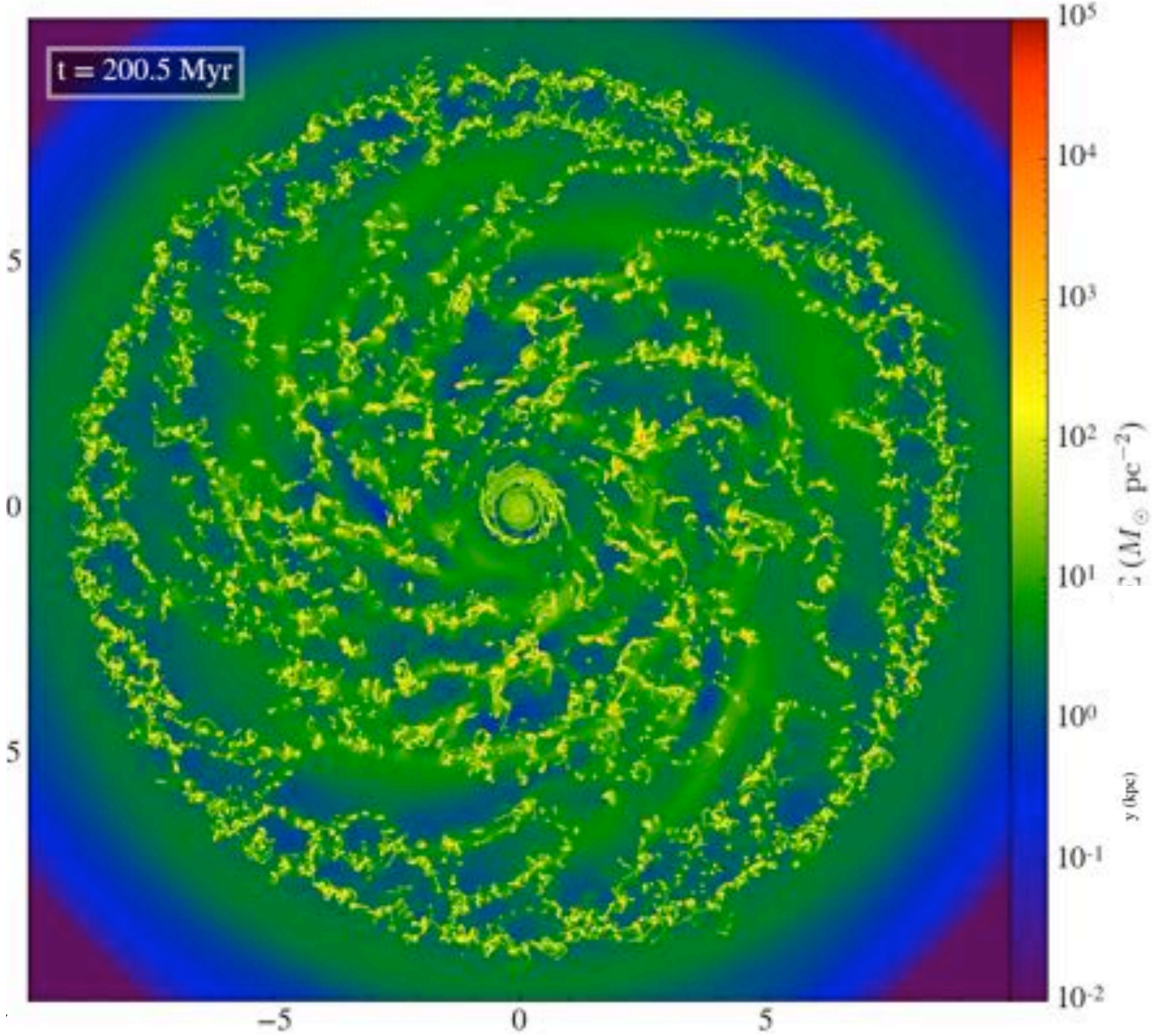
Tan (2000)

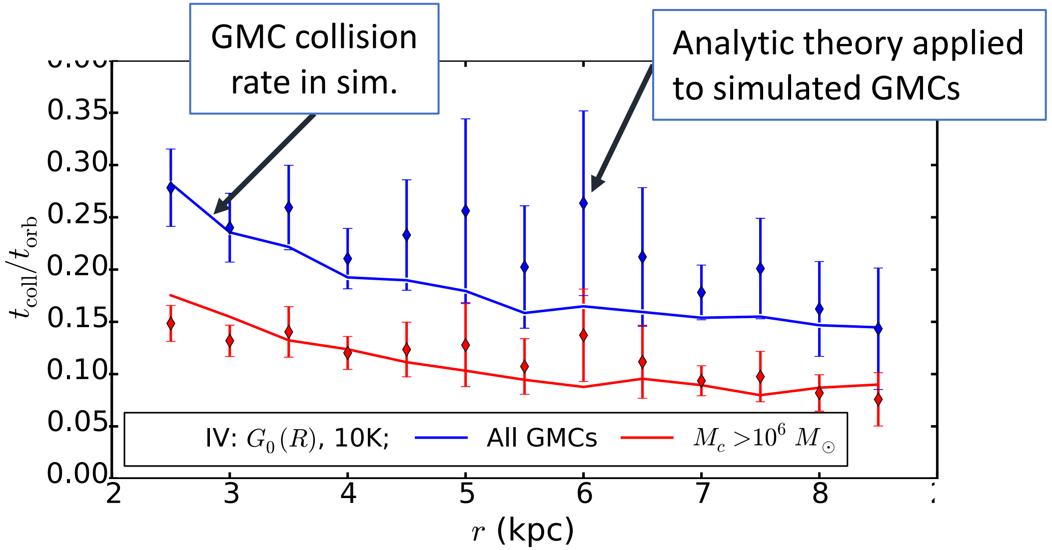
$\Sigma_{sfr} \propto\ \Sigma_g / t_{coll} \rightarrow B\ \Sigma_g\ \Omega(1-0.7\beta)$

Prediction from shear-driven collisions in a ~2D monolayer of GMCs

GMC Collision Timescales

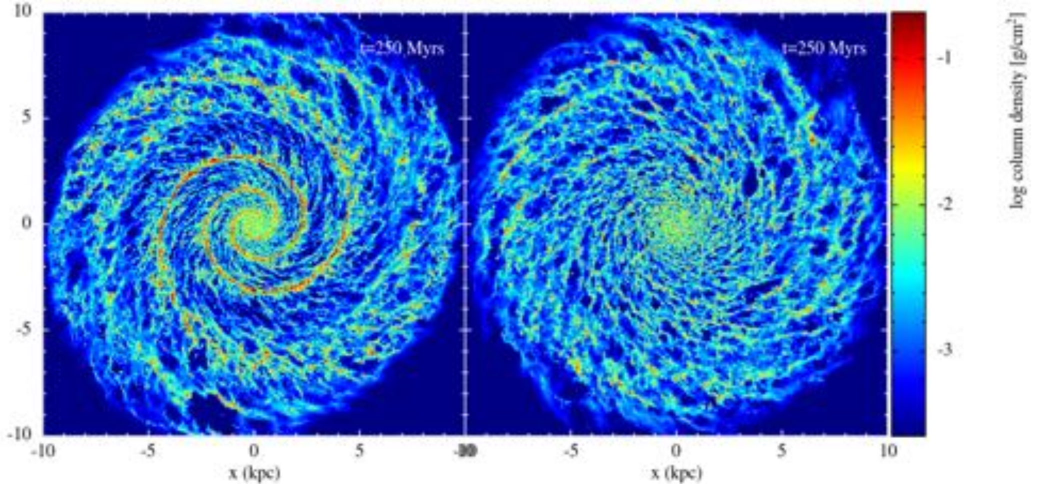
20 kpc



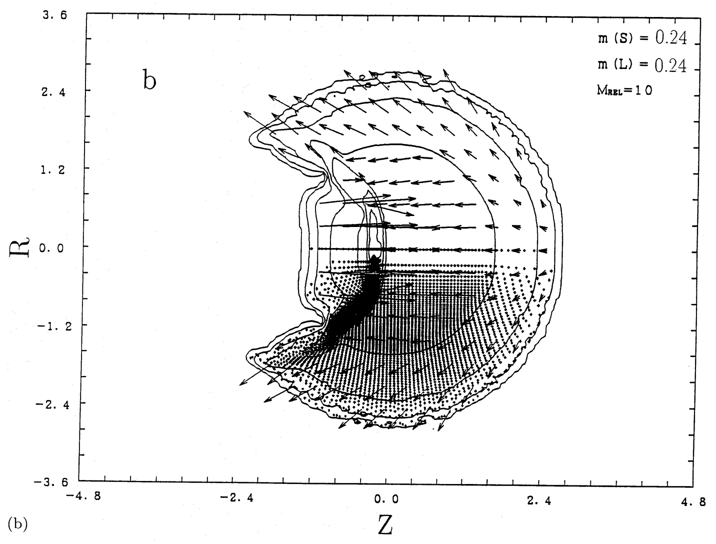


Li+ (2017); Tasker+Tan (2009)
$t_{coll}/t_{orb} \sim 1/5$ (20-30 Myr w/in R_0)

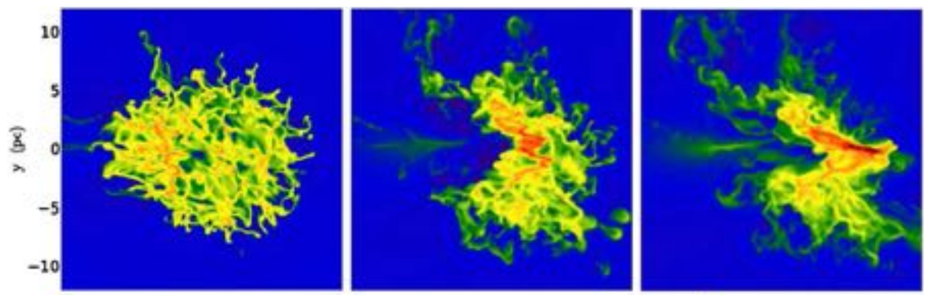
Dobbs+ (2014)
$t_{coll}/t_{orb} \sim 1/4$ (28 Myr), no spiral arms
$t_{coll}/t_{orb} \sim 1/15$ (8-10 Myr), spiral arms



Cloud Collision Simulations



- Bow shocks, compression, gravitational instabilities (Habe+Ohta 1992)
- Bending mode instabilities (Klein+Woods 1998)
- Thin shell & Kelvin-Helmholtz instabilities (Anathpindika 2009)
- Enhanced turbulence & B-fields (Inoue+Fukui 2013)
- Gravitationally unstable cores (Takahira+2014)
- Filament Formation (Balfour+2015)
- "Broad Bridge" feature in p-v (Haworth+2016a,b)
- Enhanced ^{12}CO, ^{13}CO high-to-low *J* ratios (Wu+ 2015)



Cloud Collision Candidates


- NGC1333 (Loren 1976)
- Dr21/W75 (Dickel+ 1978)
- GR110-13(Odenwald+ 1992)
- Sgr B2 (Hasegawa+ 1994; Sato+ 2000)
- Westerlund2 (Furukawa+ 2009; Ohama+ 2010)
- M20 (Torii+ 2011)
- NGC3603 (Fukui+ 2014)
- Cygnus OB7 (Dobashi+ 2014)
- RCW120 (Torii+ 2015)
- Galactic center 50 km/s molecular cloud (Tsuboi+ 2015)
- N159W and N159E (Fukui+ 2015; Saigo+ 2016)
- RCW38 (Fukui+ 2016)
- N37 (Baug+ 2016)
- G35.20-0.74 (Dewangan 2017)
- L1188 (Gong+ 2017)
- R136 (Fukui+ 2017a)
- M42 and M43 (Fukui+ 2017b)
- GM 24 (Fukui+ 2017c)
- M16 (Nishimura+ 2017)
- RCW34 (Hayashi+ 2017)
- RCW36 (Sano+ 2017)
- NGC2024 (Ohama+ 2017a)
- RCW166 (Ohama+ 2017b)
- W51 (Fujita+ 2017(arXiv))
- W33 (Kohno+ 2017(arXiv))
- DBS[2003]179 (Kuwahara+ 2017(arXiv))
- M17 (Nishimura+ 2017(arXiv))
- Sh2-48 (Torii+ 2017(arXiv))
- N44 (Tsuge+ 2017(arXiv))
- NGC6334 and NGC6357 (Fukui+ 2017(arXiv))

Two velocity components (CO spectra)

Morphology

Proximity to young massive stars

Features in p-v space

Giant Molecular Cloud Collisions

Scoville+ 1986
Gammie+ 1991
Tan 2000

- Giant molecular cloud (GMC) collisions (i.e., converging molecular flows) may be a dominant mode of star formation
- Self-gravitating GMCs supported by turbulent and magnetic pressure
- Undergo supersonic collisions driven by galactic shear
- Creates shock-compressed material, magnetically supercritical clumps, high mass surface density (Σ) gas prone to gravitational instability

Develop detailed numerical model to understand GMC collisions on the cloud-scale and make predictive observational diagnostics

→ Triggers formation of dense clumps and star clusters ?

ENZO code (Bryan+2014)
Adaptive Mesh Refinement (AMR)
Magnetohydrodynamics (MHD)
N-body

Numerical Model

Magnetohydrodynamics + PDR-based heating/cooling + Ambipolar Diffusion

+ self-gravity
+ cosmological expansion
($a = 1$; $\dot{a} = 0$)

Conservation of Mass

(1) $$\frac{\partial \rho}{\partial t} + \frac{1}{a}\nabla \cdot (\rho \mathbf{v}) = 0$$

Conservation of Momentum

(2) $$\frac{\partial \rho \mathbf{v}}{\partial t} + \frac{1}{a}\nabla \cdot \left(\rho \mathbf{v}\mathbf{v} + \mathbf{I}p^{*} - \frac{\mathbf{B}\mathbf{B}}{a}\right) = -\frac{\dot{a}}{a}\rho \mathbf{v} - \frac{1}{a}\rho \nabla \phi$$

Conservation of Total Energy (Kinetic + Magnetic + Thermal)

(3) $$\frac{\partial E}{\partial t} + \frac{1}{a}\nabla \cdot \left[(E + p^{*})\mathbf{v} - \frac{1}{a}\mathbf{B}(\mathbf{B}\cdot \mathbf{v})\right] = -\frac{\dot{a}}{a}\left(2E - \frac{B^2}{2a}\right) - \frac{\rho}{a}\mathbf{v}\cdot \nabla \phi - \Lambda + \Gamma + \frac{1}{a^2}\nabla \cdot \mathbf{F}_{\mathrm{cond}}$$

Heating
Cooling

PDR-models
(A_V, n_H, T)

Magnetic Induction

(4) $$\frac{\partial \mathbf{B}}{\partial t} - \frac{1}{a}\nabla \times (\mathbf{v} \times \mathbf{B}) = 0$$

$$\frac{\partial \boldsymbol{B}}{\partial t} - \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) = -\nabla \times \left(D_{\mathrm{AD}}\,(\nabla \times \boldsymbol{B}) \times \boldsymbol{b} \times \boldsymbol{b}\right) \qquad D_{\mathrm{AD}} = c^2 \eta_{\mathrm{AD}}/4\pi$$

Energy Density

$$E = e + \frac{\rho v^2}{2} + \frac{B^2}{2a}$$ (5)

Pressure

$$p^{*} = p + \frac{B^2}{2a}$$ (6)

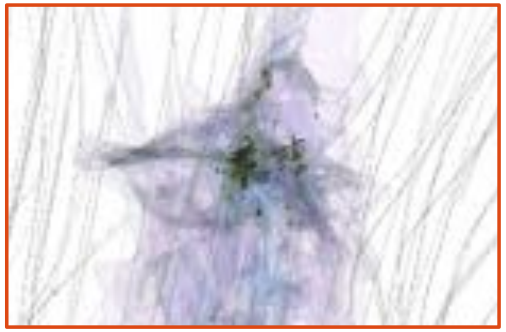
Equation of State

$$e = \frac{p}{(\gamma - 1)}$$ (7)

Poisson Equation for Gravitational Potential

$$\nabla^2 \phi = \frac{4\pi G}{a}(\rho_{\mathrm{total}} - \rho_0)$$ (8)

Star Formation Models



Simulate star particles using collisionless N-body dynamics

Star Formation (SF) Criteria

Density-Regulated SF

1(a). $n_H > n_{H,sf}$

Magnetically-Regulated SF

1(b) Use dimensionless mass-to-flux ratio in each cell:

$$\mu = \frac{\rho \Delta x \sqrt{G}}{B c_1}$$

$\mu > 1$: supercritical
$\mu < 1$: subcritical

$$\left(\frac{M}{\Phi}\right)_{\text{crit}} = \frac{c_1}{\sqrt{G}}$$

c_1 : geometric factor
$(1/63)^{1/2}$ for isolated sphere

(Mouschovias+Spitzer 1976)

n_H threshold determined by μ

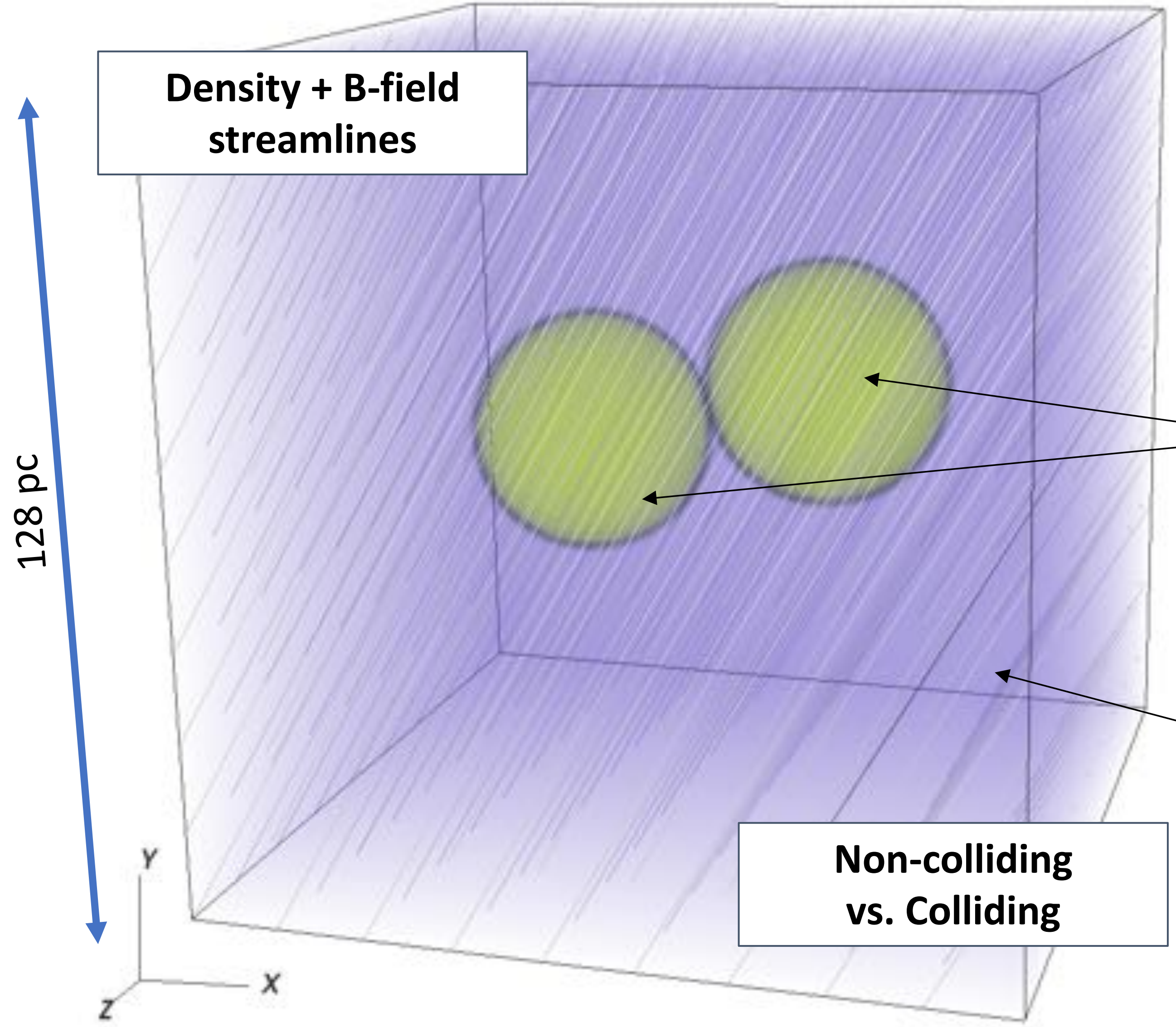
2. Finest level of AMR
3. T < 3000 K
4. Then, form star with:

$$M_\star = \epsilon_{\rm ff} \frac{\rho \Delta x^3}{t_{\rm ff}} \Delta t$$

ϵ_{ff} = 0.02 ("SF efficiency")
Δx^3 : cell volume
$t_{ff} = (3\pi/32G\rho)^{1/2}$ ("free-fall time")

If $M_* < M_{*,min}$, a $M_*/M_{*,min}$ probability to form a star with M_*

Initial Conditions



Global

Domain: $(128\text{pc})^3$
$v_{\text{bulk}} = 0$ (or $\pm 5\text{km/s}$)
$B = 10\mu\text{G}$
$\theta = 60°$

(effective) Resolution:

1024^3; 2048^3
0.125 pc; 0.0625pc

GMCs

$R_{\text{GMC}} = 20\text{pc}$
$n_{\text{H,GMC}} = 100\text{cm}^{-3}$
$M_{\text{GMC}} \sim 10^5 \text{M}_\odot$
$T_{\text{GMC}} \sim 15\text{K}$
$b = 0.5 R_{\text{GMC}}$

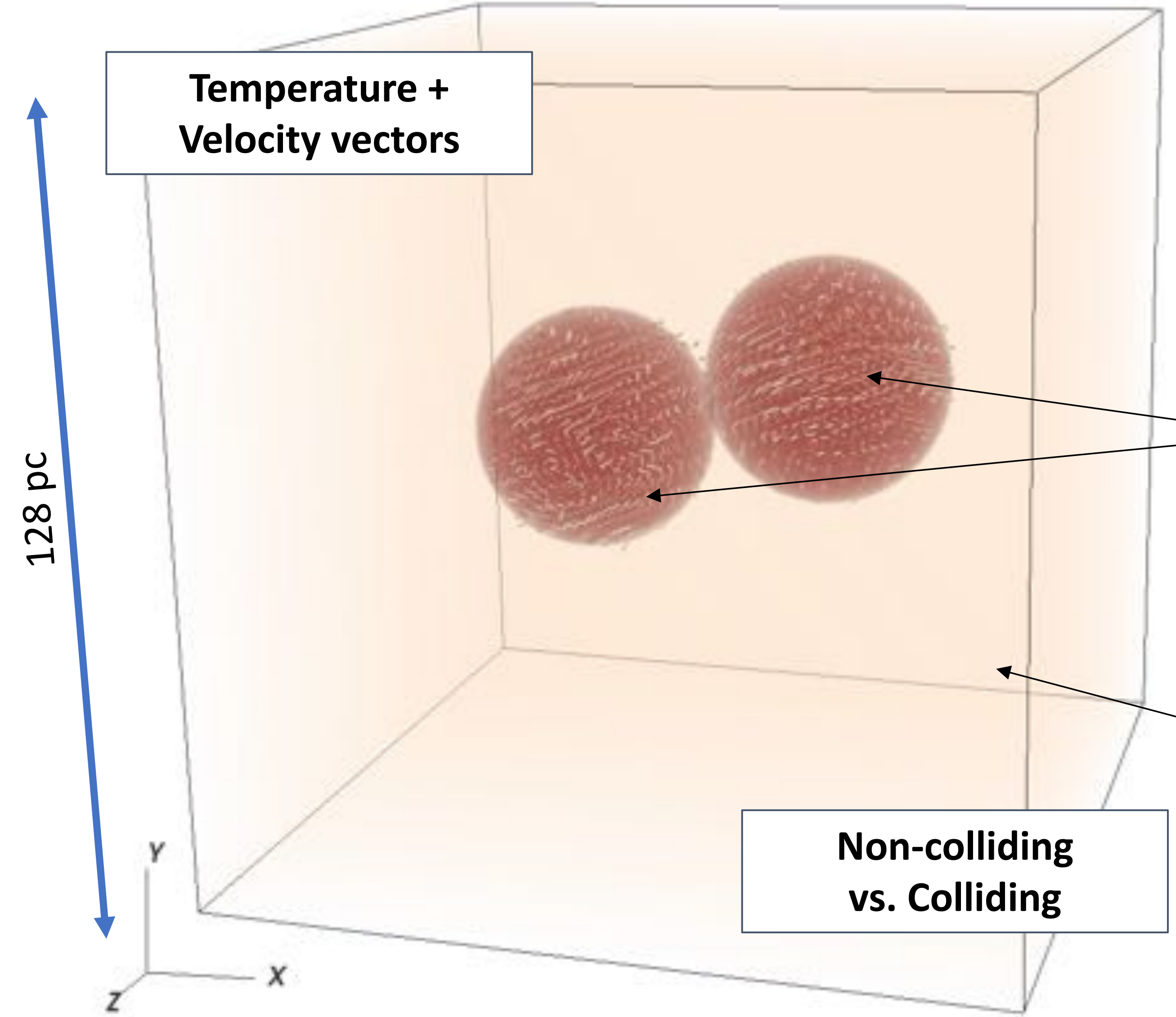
Turbulence

solenoidal
decaying
$M_s \sim 20$
$v^2 \propto k^{-4}$
$\{k_1, k_2\} = \{2, 20\}$

GMC envelope

$n_{\text{H,0}} = 10\text{cm}^{-3}$
$T_0 \sim 150\text{K}$

Initial Conditions



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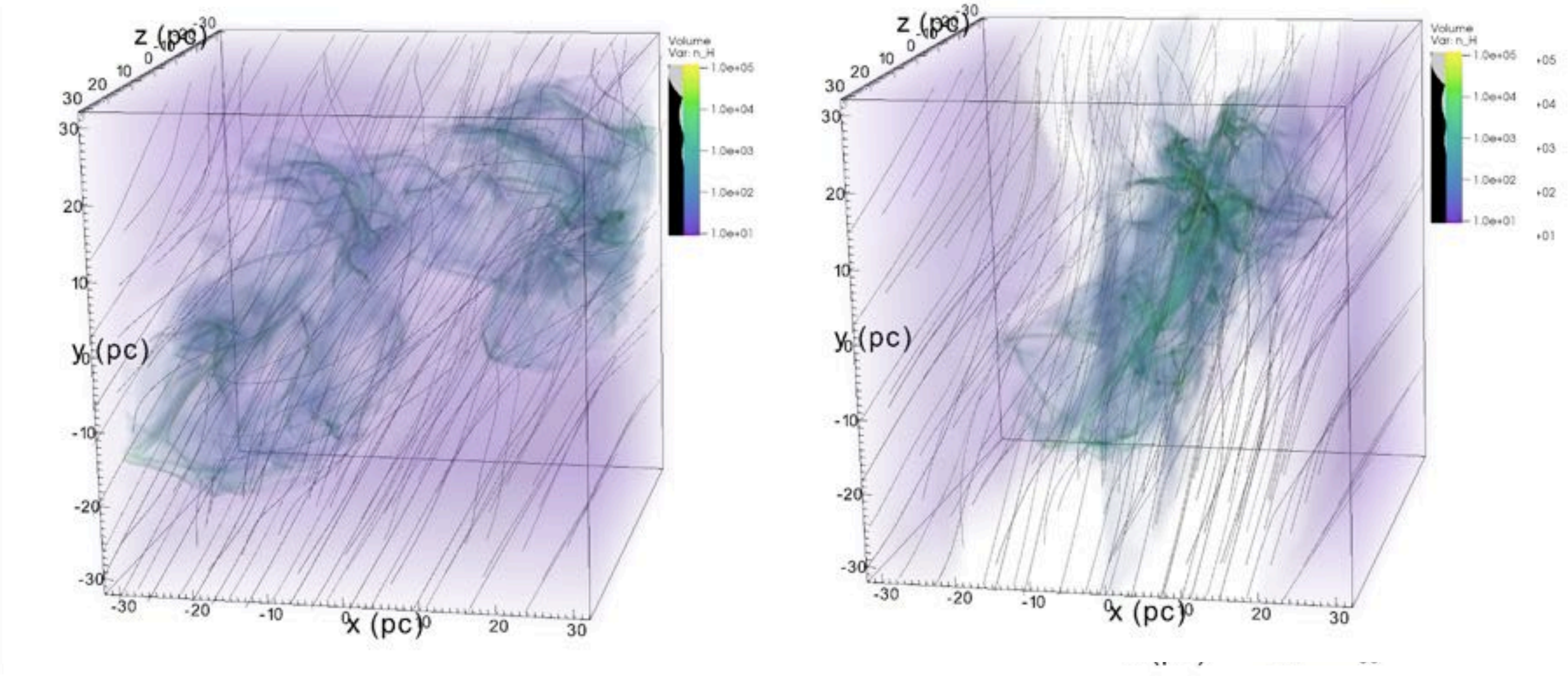
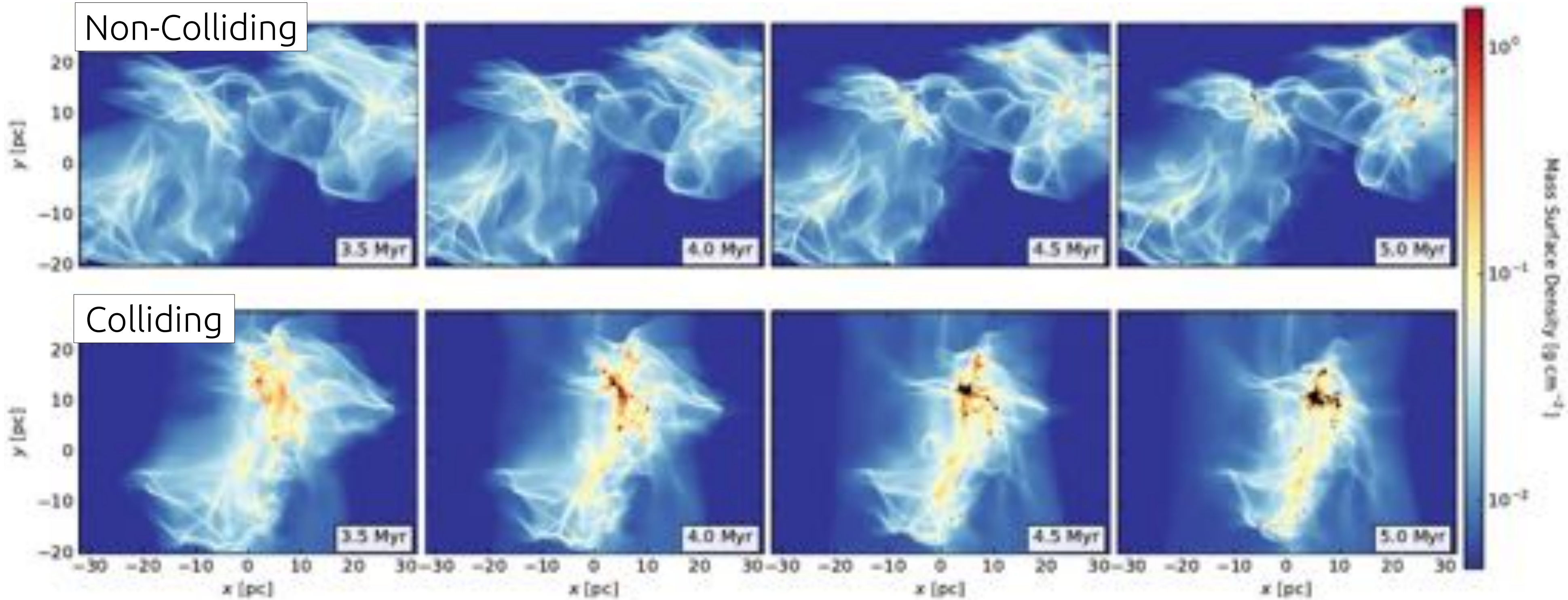
Time Evolution



Gas and Star Morphology



<u>Non-Colliding:</u>

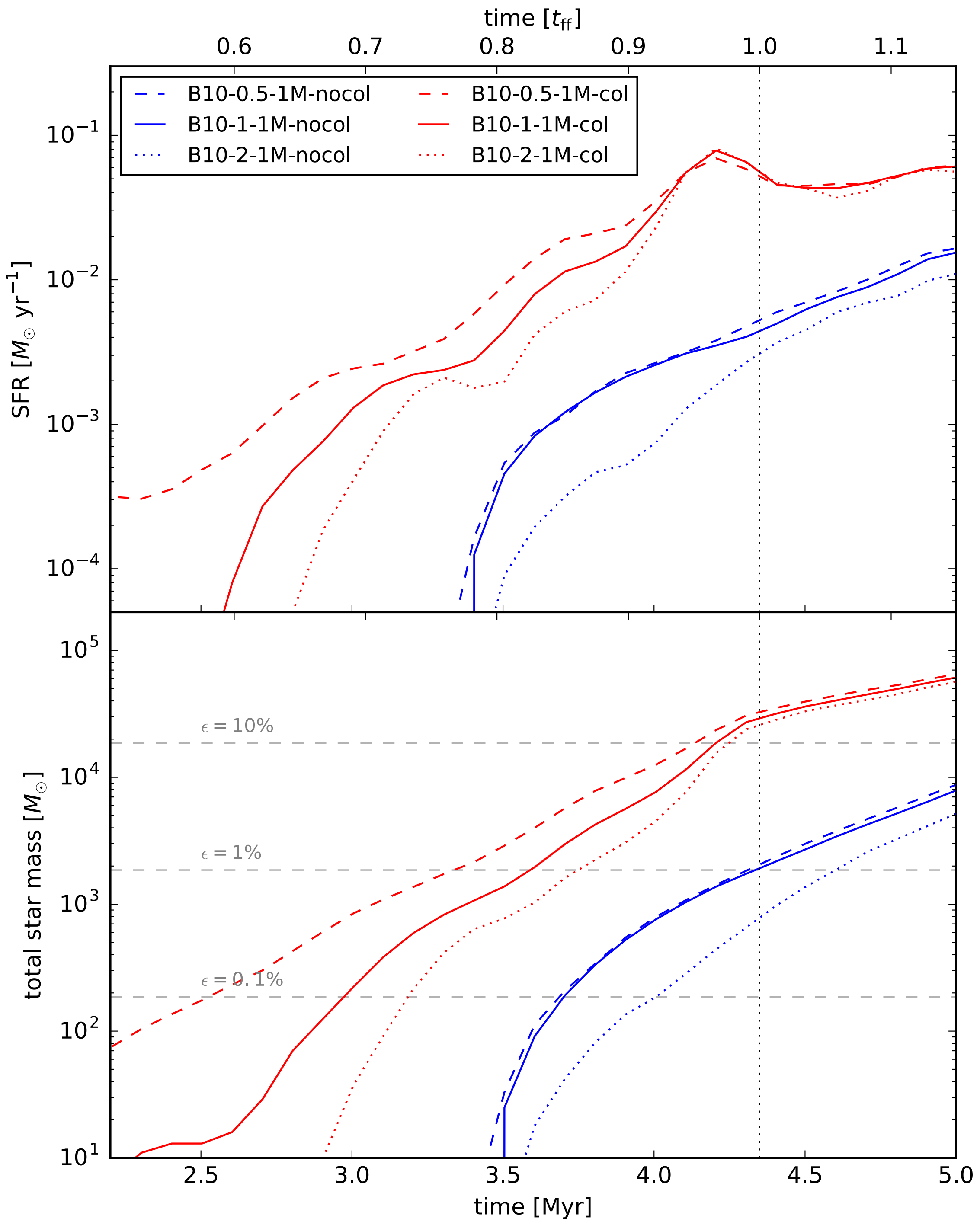
- Network of slower growing filaments
- High-Σ regions form later; develop from existing filaments
- SF initiated at late stages
- Scattered SF, in dense filaments

<u>Colliding:</u>

- Forms high density filamentary sheet/hub
- $\Sigma > 0.5$ g/cm^2 regions created earlier; clustered near collision region
- SF triggered earlier, in colliding region
- Many clusters form in proximity, coalesce into main central cluster

SFR and Efficiency

- Earlier onset of SF (~t_ff/2)
- ~10x higher SFR
- ~10x higher SFE per freefall time
  - Colliding: >10%
  - Non-colliding ~1%
  - Expect both decrease w/ feedback



B-field Polarization

Lee+Draine 1985; Fiege+Pudritz 2000
Kataoka+ 2012; Chen+ 2016

Stokes Parameters (q, u)

- Projection of (linear) polarization

$$q = \int n \cos 2\psi \cos^2 \gamma ds$$
$$u = \int n \sin 2\psi \cos^2 \gamma ds$$

→

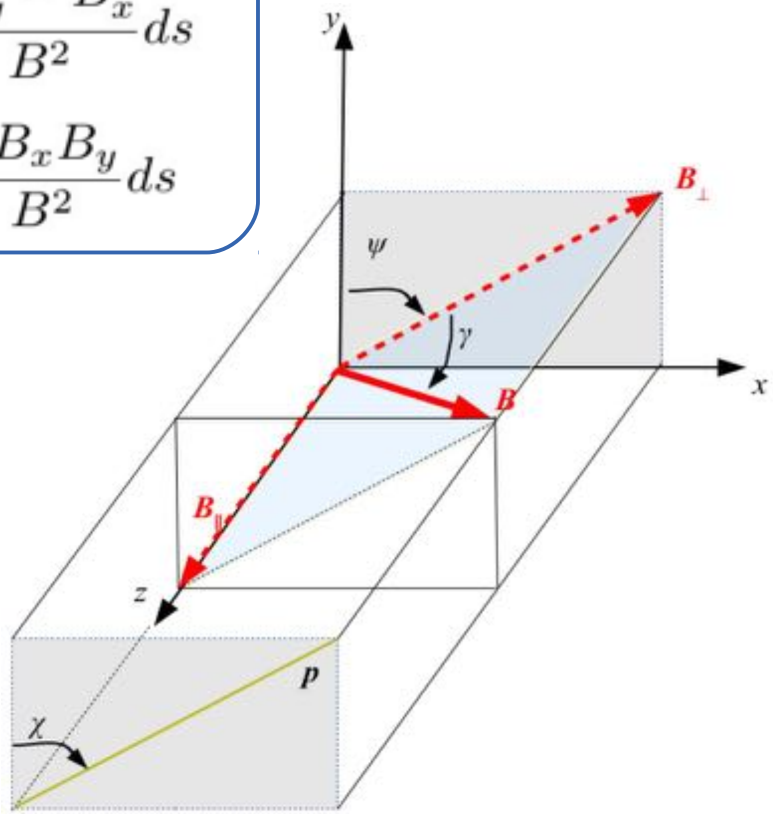
$$q = \int n \frac{B_y^2 - B_x^2}{B^2} ds$$
$$u = \int n \frac{2B_x B_y}{B^2} ds$$

- Inferred polarization angle

$$\chi = \frac{1}{2} \arctan 2(u, q)$$

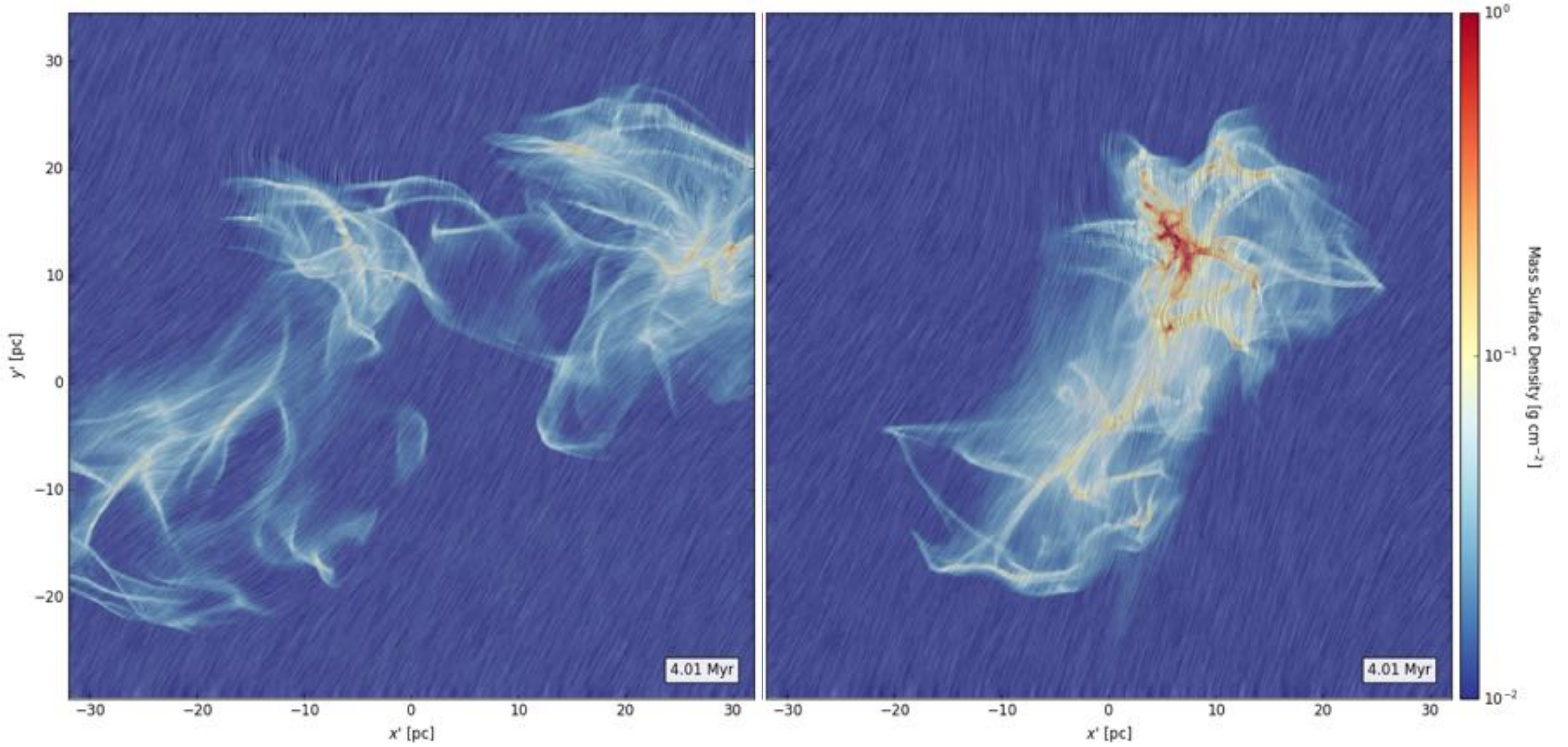
- *p* : polarization pseudo-vector

$$\boldsymbol{p} = (p \sin \chi)\hat{\boldsymbol{x}} + (p \cos \chi)\hat{\boldsymbol{y}}$$

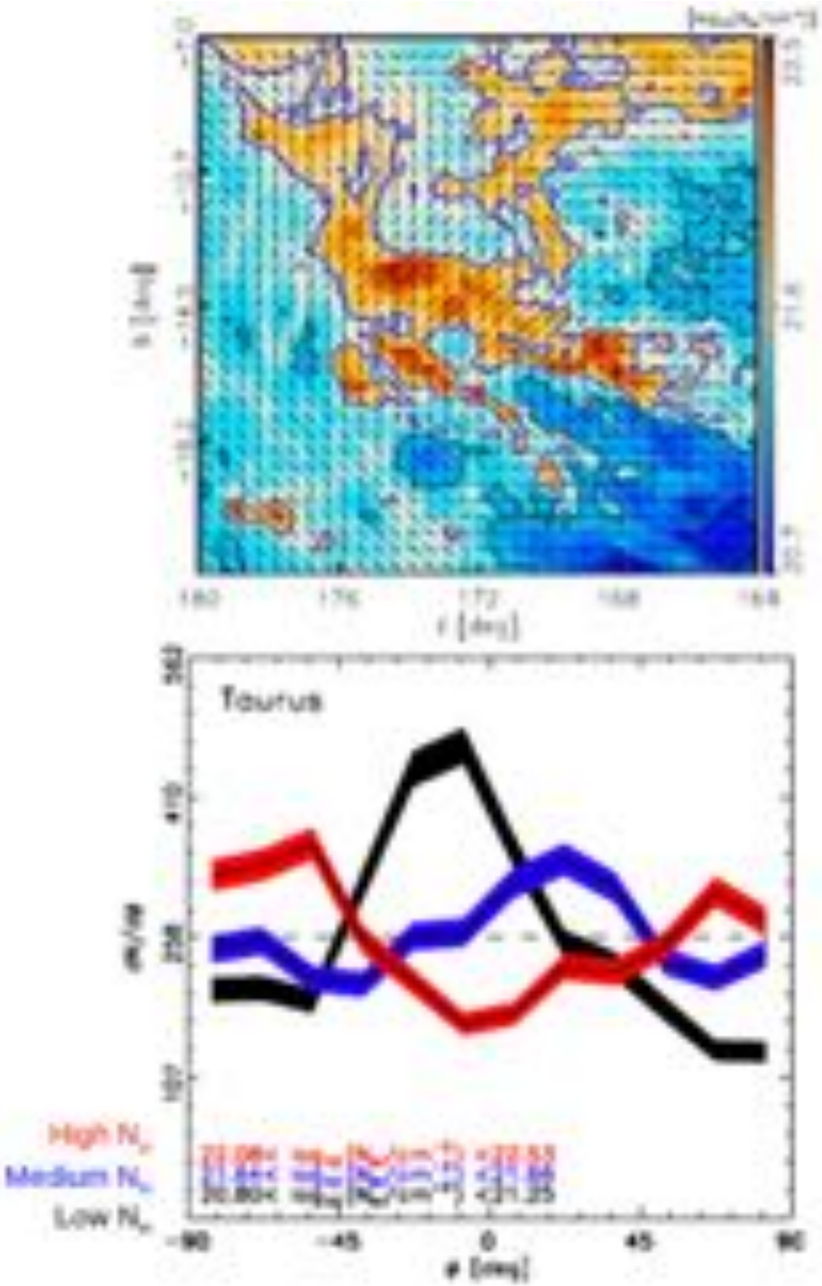


Synthetic Polarization Maps

Colormap: Mass surface density
Line Integral Convolution: B-pol
(Cabral+Leedom 1993)



Soler+ 2015
Planck Collab. XXXV 2016



Histogram of Relative Orientations

HRO: Quantitative relationship between B-field and filamentary structure orientation at different N_H

For each pixel, calculate:

$$\phi = \arctan\left(\frac{\nabla N_{\rm H} \cdot \boldsymbol{p}}{|\nabla N_{\rm H} \times \boldsymbol{p}|}\right)$$

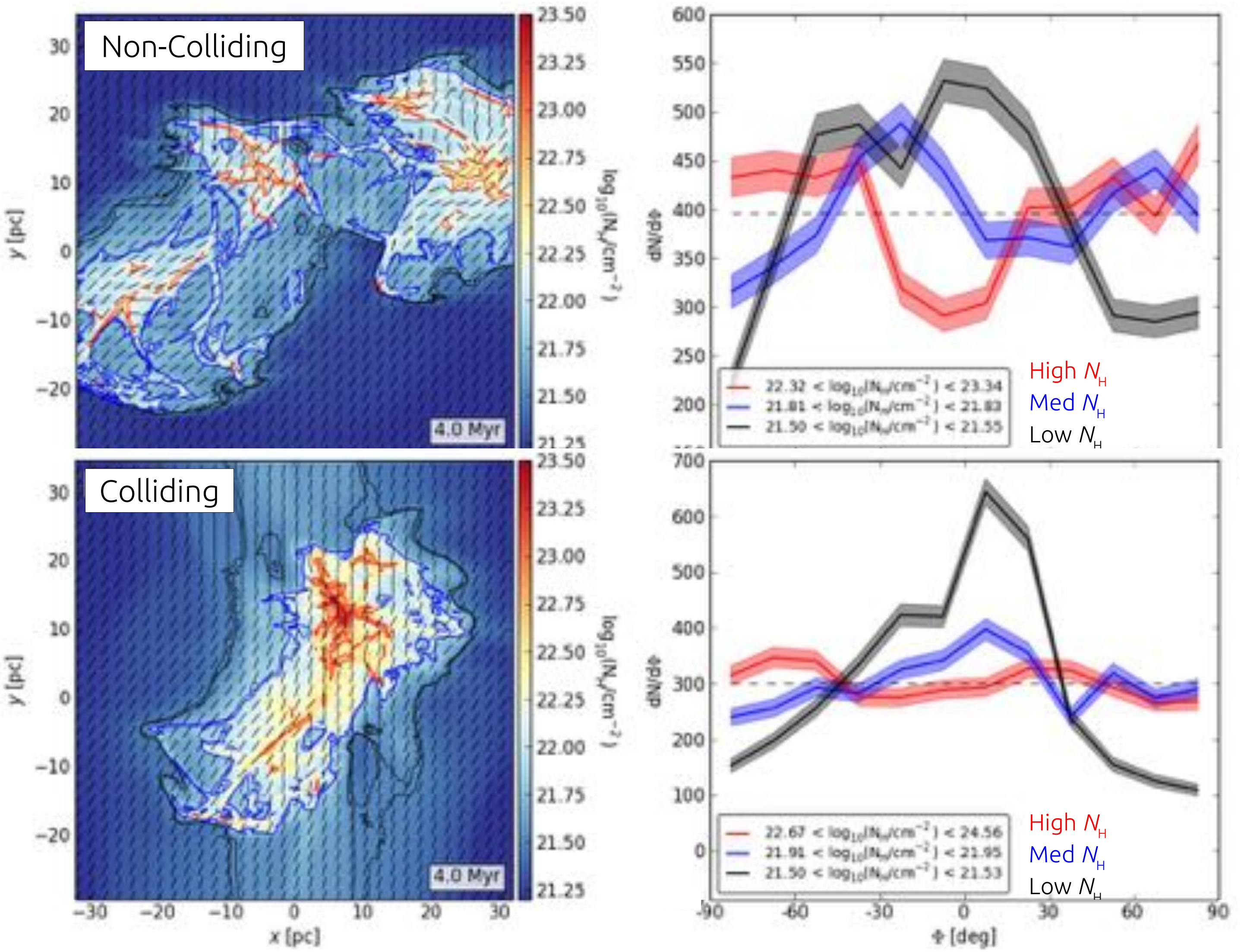
p : projected polarization pseudo-vector
Φ : angle between p and N_H iso-contours

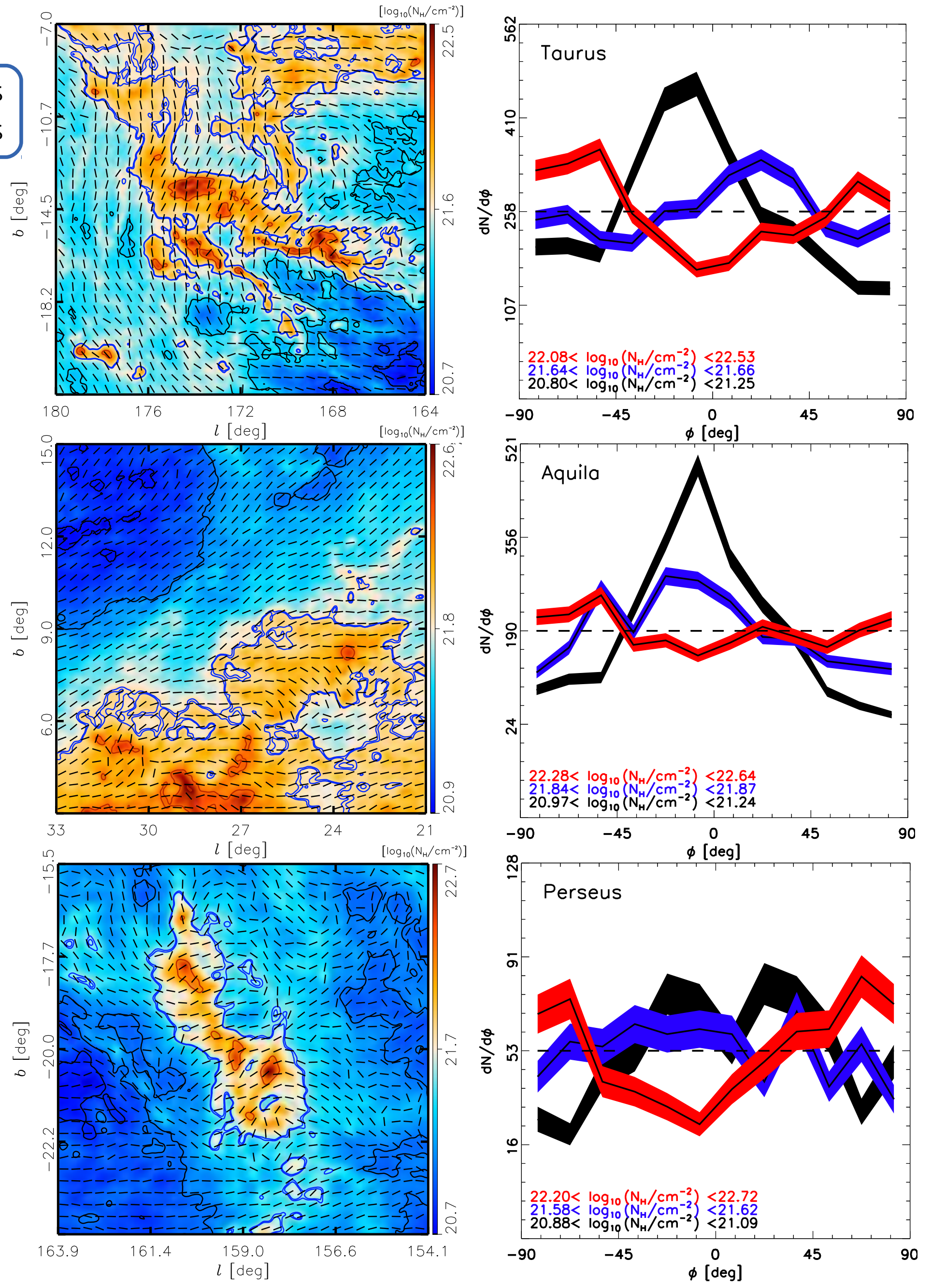
- $\Phi = 0°$: $B_\perp$ parallel to filaments
- $\Phi = \pm 90°$: $B_\perp$ perpendicular to filaments

Do relative orientations change with density?

B-fields vs. Filaments

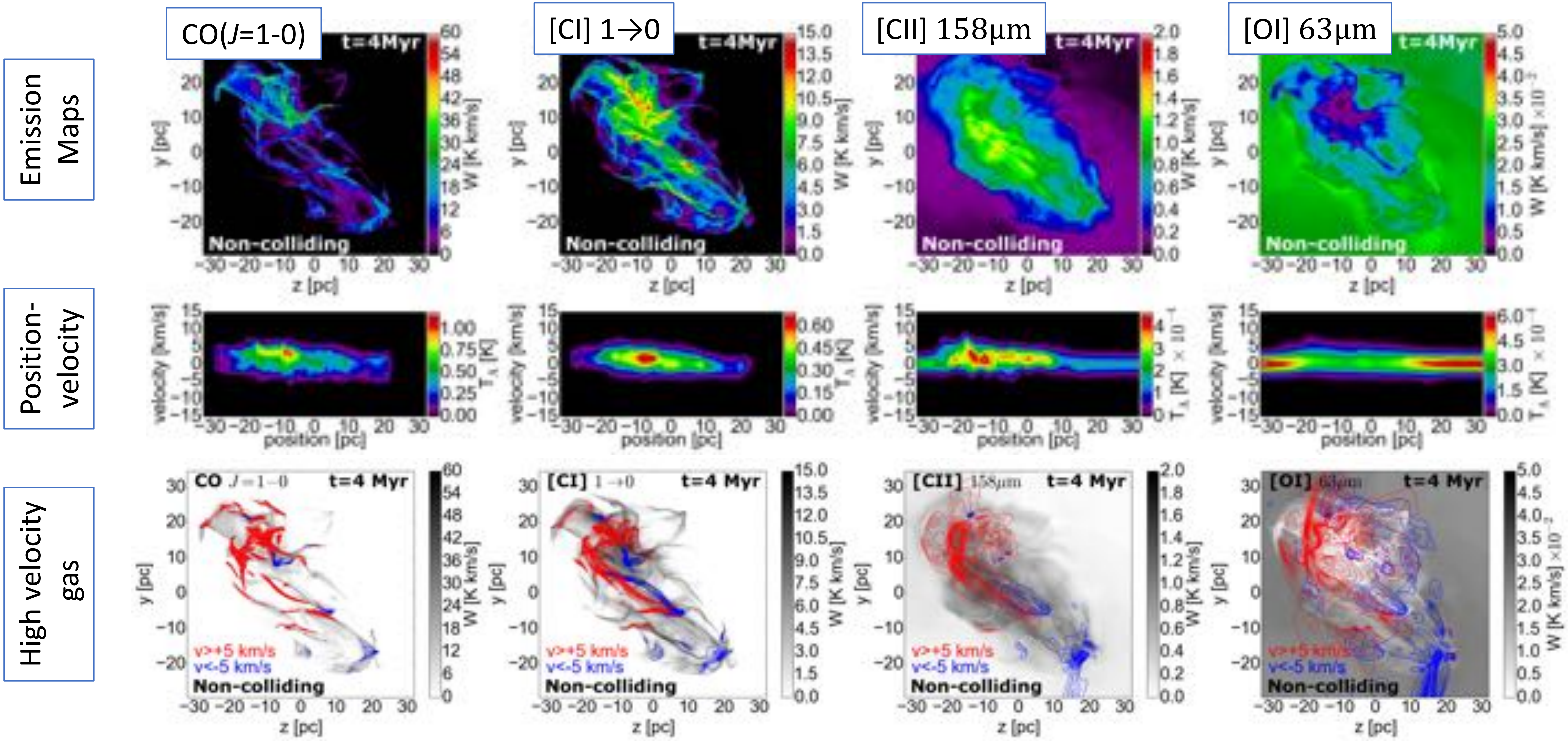
$\Phi = 0°$: $B_\perp$ || filaments
$\Phi = \pm 90°$: $B_\perp \perp$ filaments





Line Diagnostics

Non-Colliding

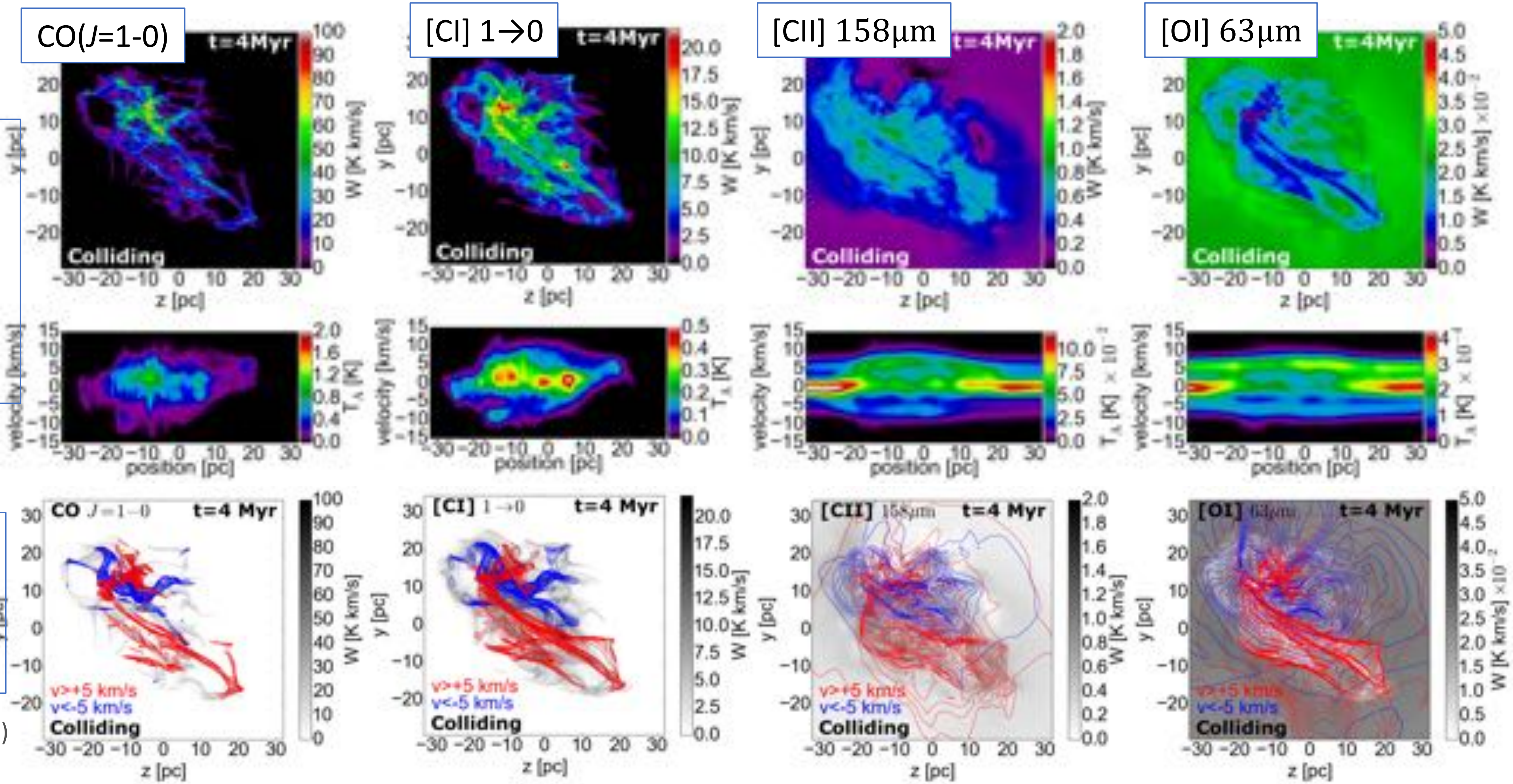


Line Diagnostics

Colliding

$\frac{dv}{ds}$: 3-4x
σ_{gas} : 2x
σ_* : 5x

$\overline{v_{gas}}$ vs. $\overline{v_*}$ offset

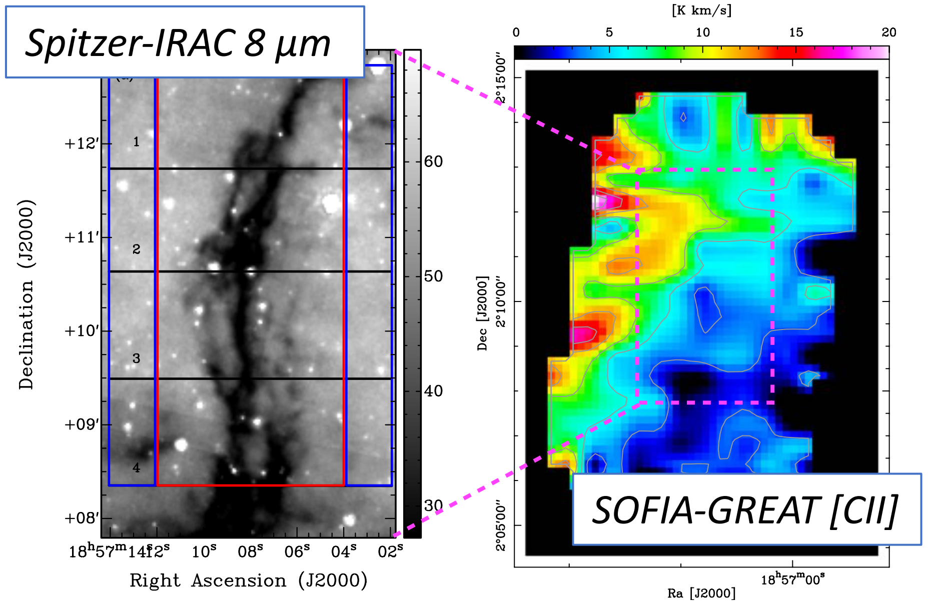


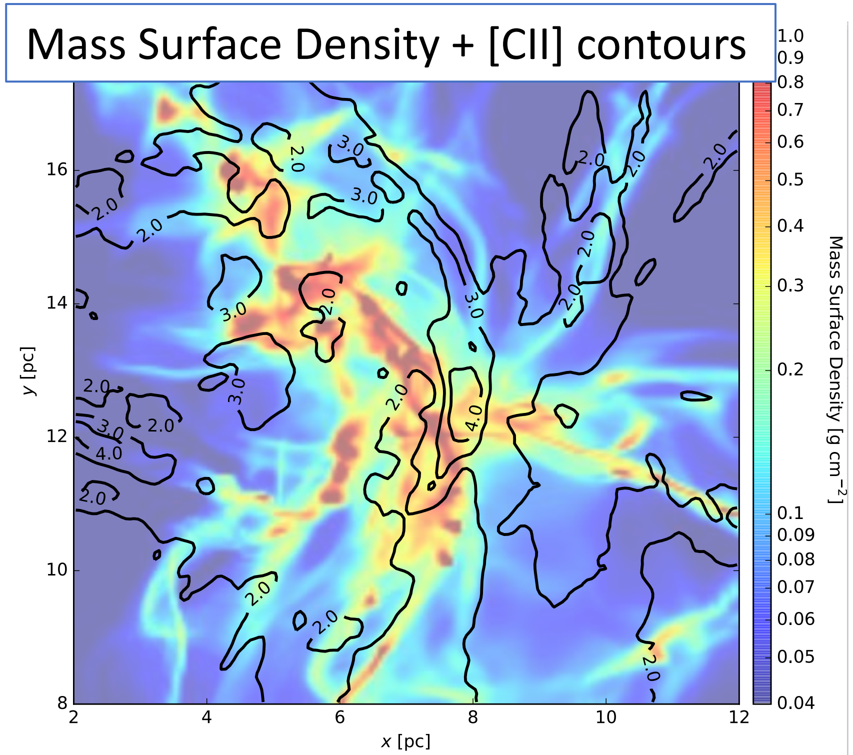
some IRDCs observed to have high σ_{gas}~4-7 km/s

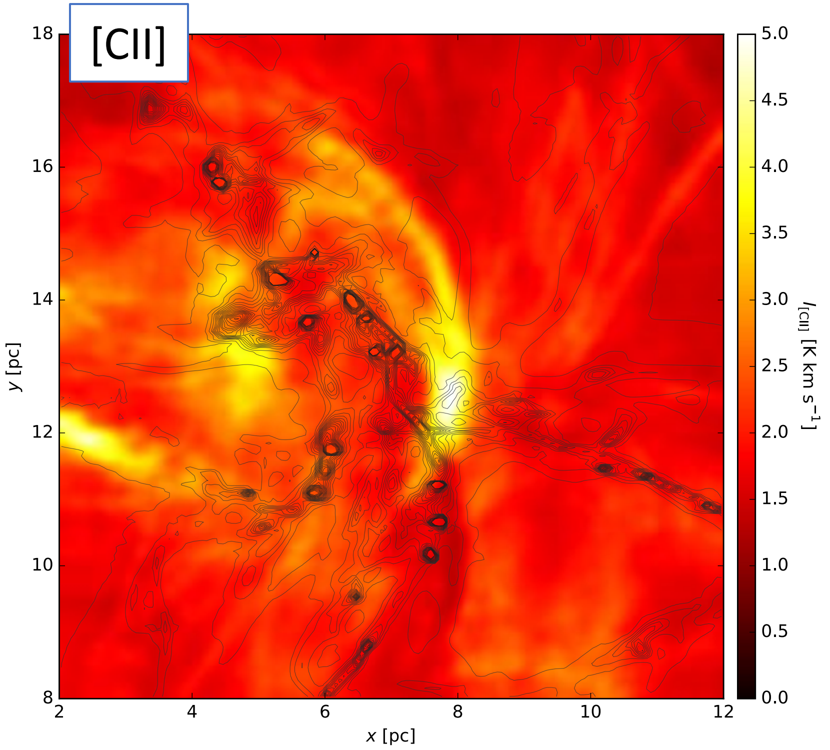
Hernandez+Tan (2015)

Line Diagnostics

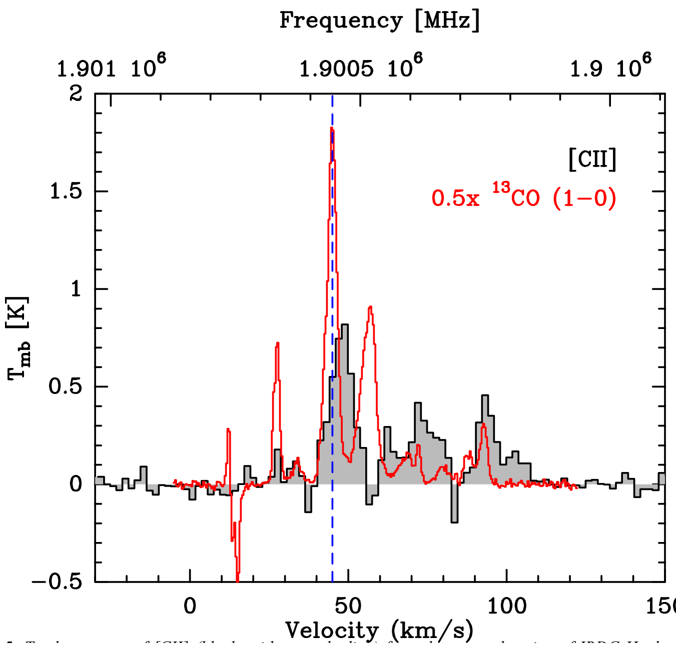
- Potential [CII] signature
    - Spatial and velocity offset from dense gas (and star cluster)







"IRDC H" (Kainulainen+Tan 2013)



Conclusions

- GMC-GMC collisions
  - May be frequent -- typical merger every ~0.2 orbital times (~20-30 Myr within r_0)
  - Naturally links ~pc-scale star cluster formation to global galactic dynamics
  - Difficult to confirm observationally, but list of candidates is growing rapidly
- Created numerical model of collisions on the GMC scale:
  - Includes realistic PDR-based heating/cooling, B-fields, turbulence
  - Magnetically regulated SF, ambipolar diffusion, 3D radiative transfer (post-process)
- Physical effects:
  - triggers formation of filamentary complexes w/ high density, high |B|, high velocity dispersion, star clusters w/ high SFE
- New Observational Diagnostics:
  - Polarization vs. filaments?
  - Spatial & velocity offset in [CII] emission?