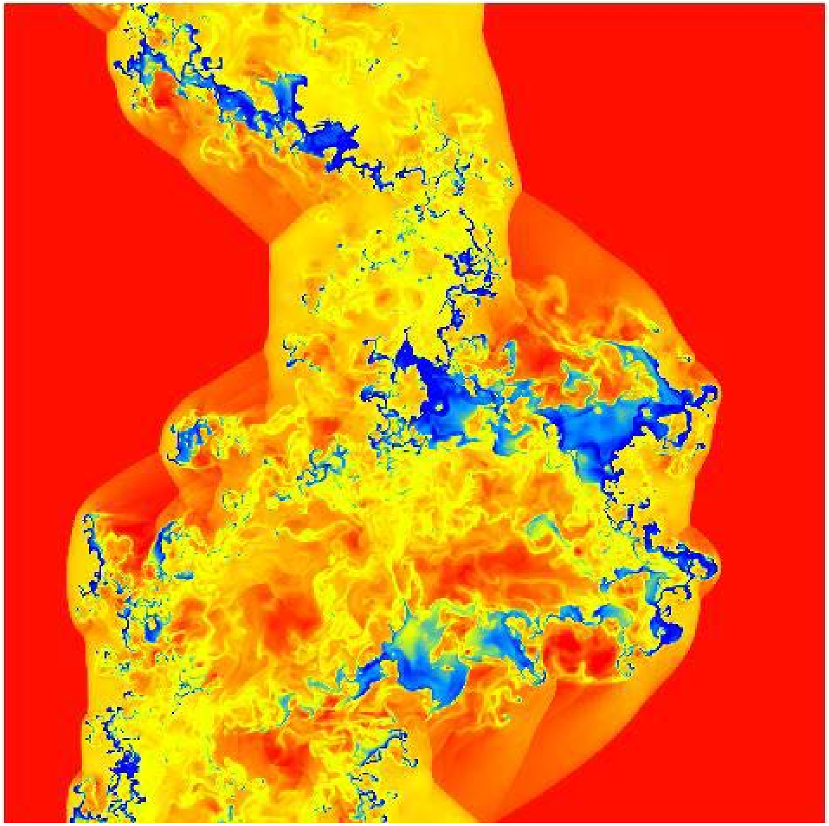
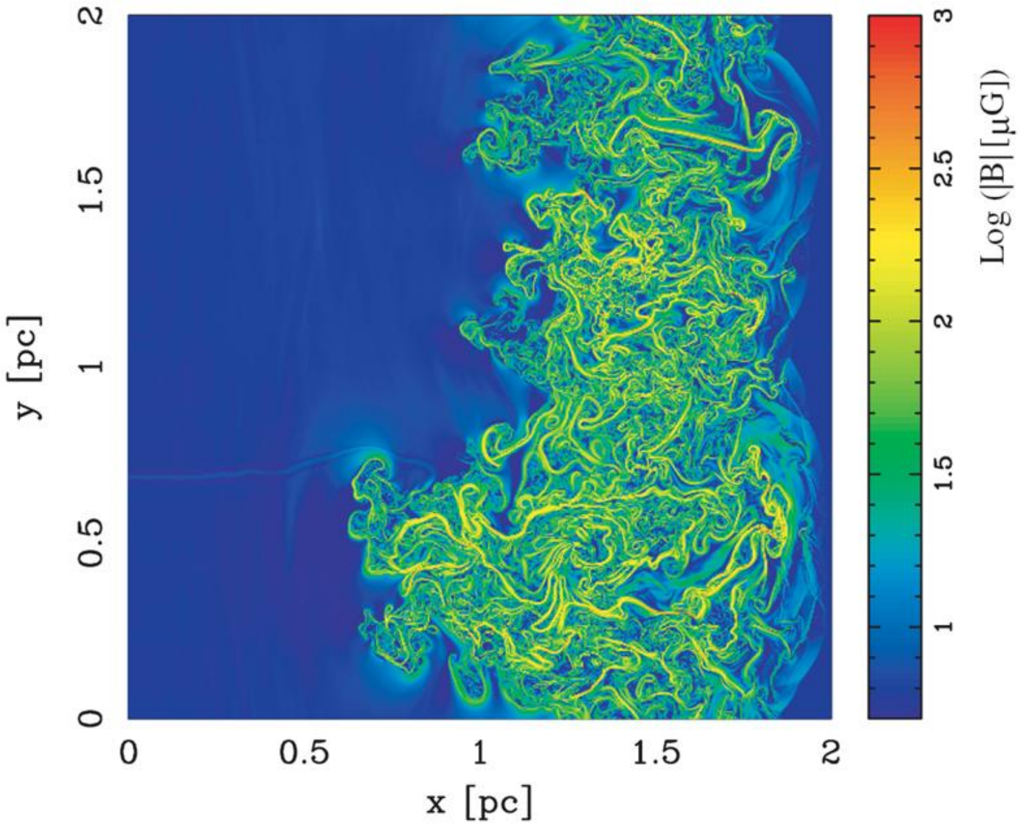
星形成･星間媒質研究の視点から
Physics of ISM & Star Formation

Shu-ichiro Inutsuka (Nagoya Univ.)



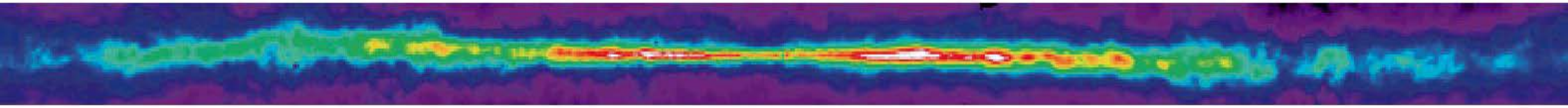


Outline

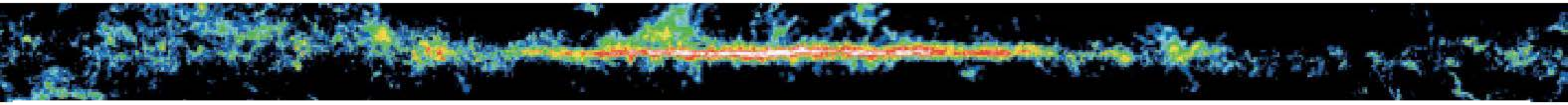
- Galactic Structure of Interstellar Medium
  - Phase Transition ➔ Turbulence
  - Formation of HI Clouds & Molecular Clouds
- Filaments & Star Formation
  - Star Formation Threshold, Star Formation Rate
  - IMF
- High Energy Astrophysics

Galactic Disk in Various Wavelengths

HI 21cm ➔ ISM ($T=10^2$-10^4K)

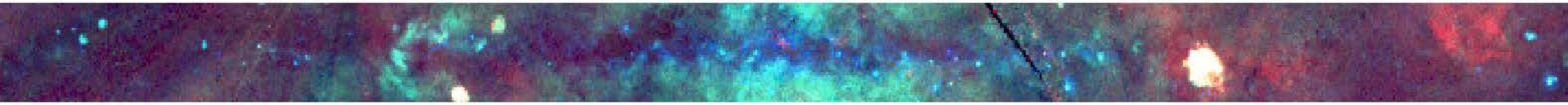


CO(J=1-0) ➔ Molecular Molecular Clouds (T~10K)

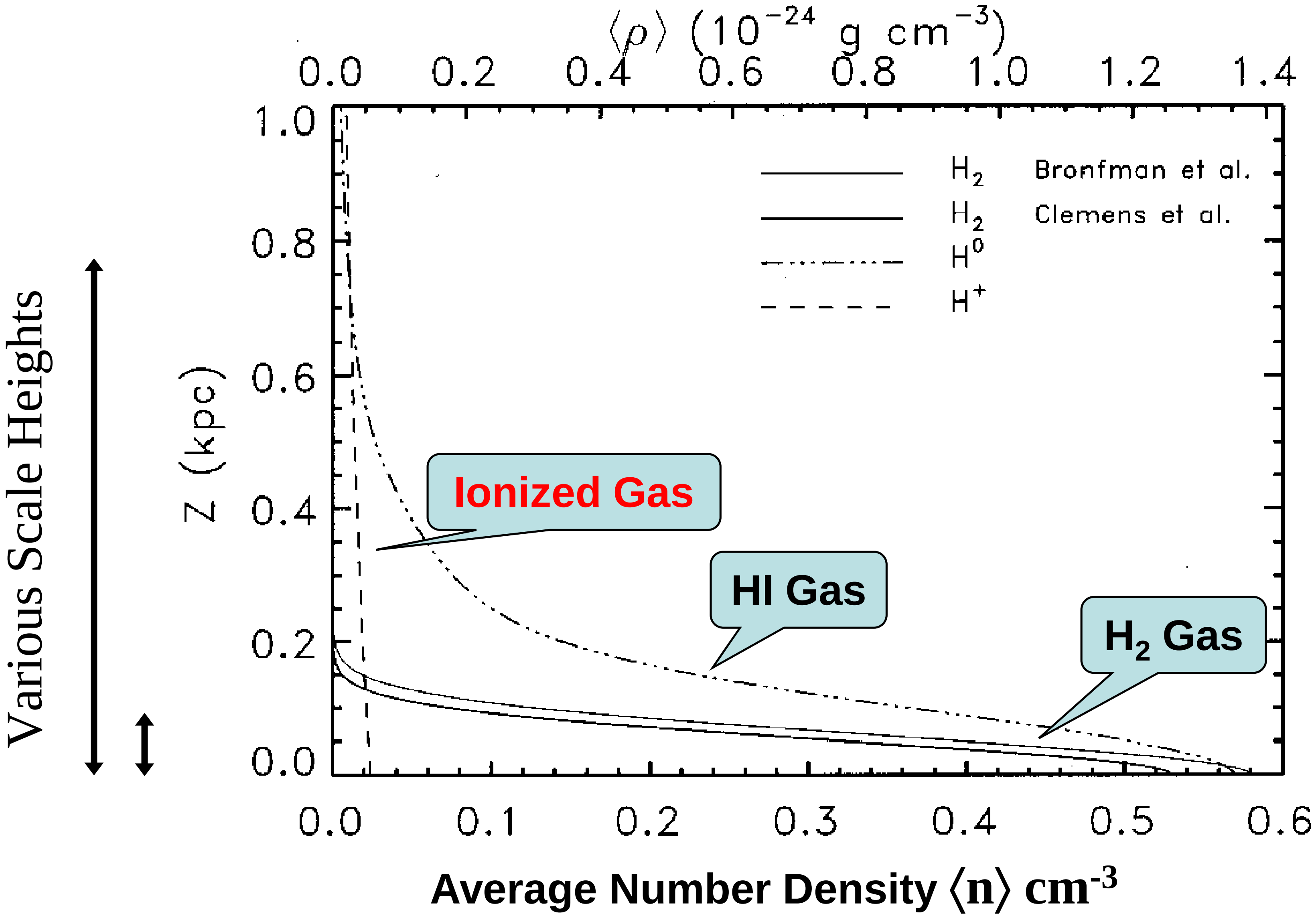


NIR (DIRBE) ➔ mainly K-Giants

X-Ray (ROSAT) ➔ Hot Gas ($T=10^6$K)



Galactic Latitude Distribution: n(z)



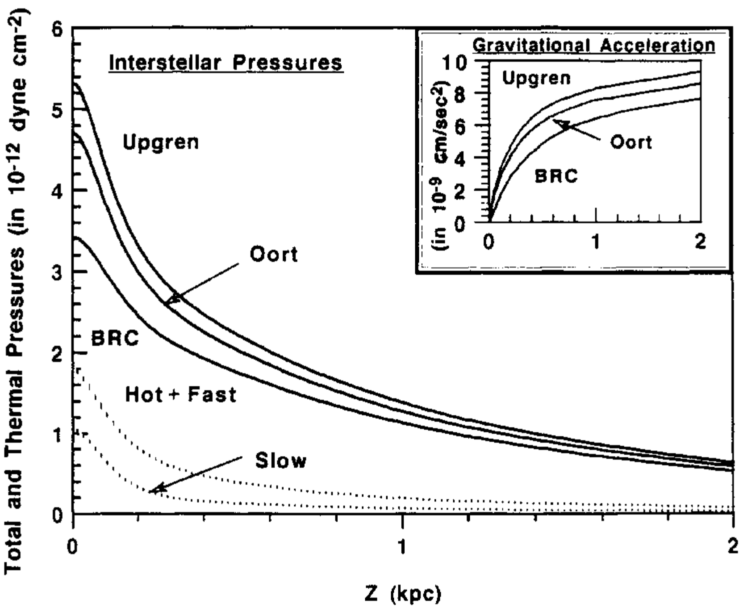
Ferrière 2001, Rev.Mod.Phys. **73**, 1031

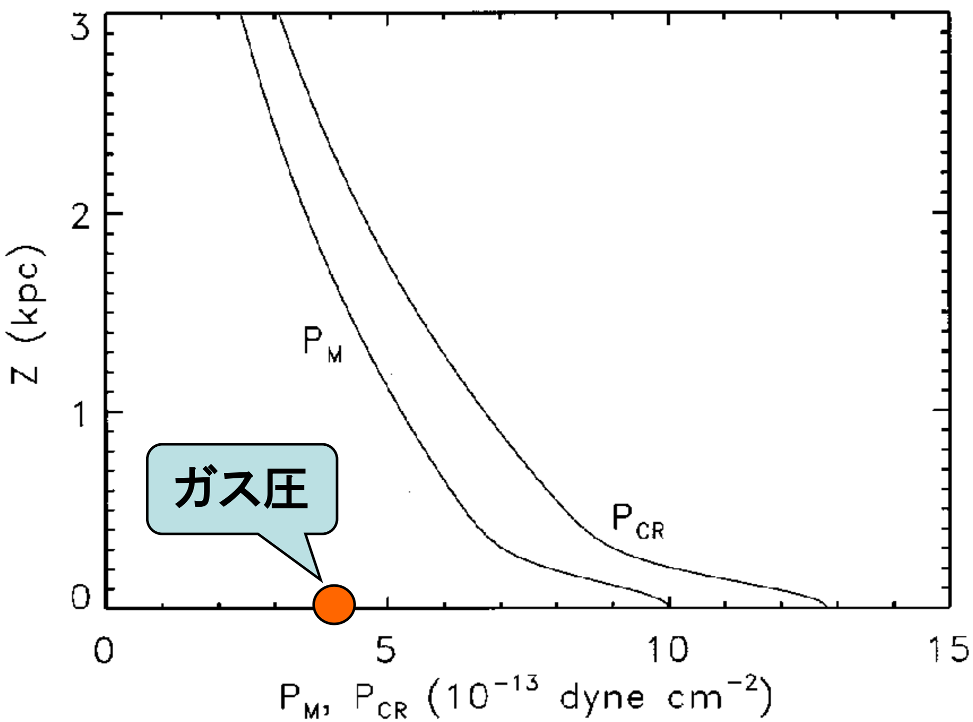
銀河面からの高さ(z)方向の静水圧平衡

種々の重力場モデルに対する静水圧平衡圧力分布の見積もり

Boulares & Cox 1990, ApJ **365**, 544

Ferrière 2001, Rev.Mod.Phys. **73**, 1031 によるレビュー論文から

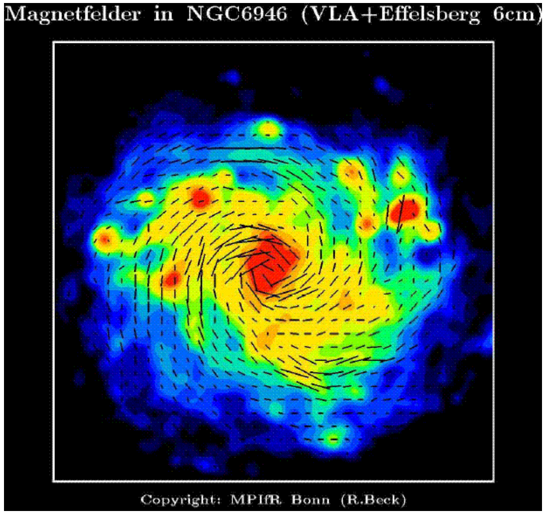


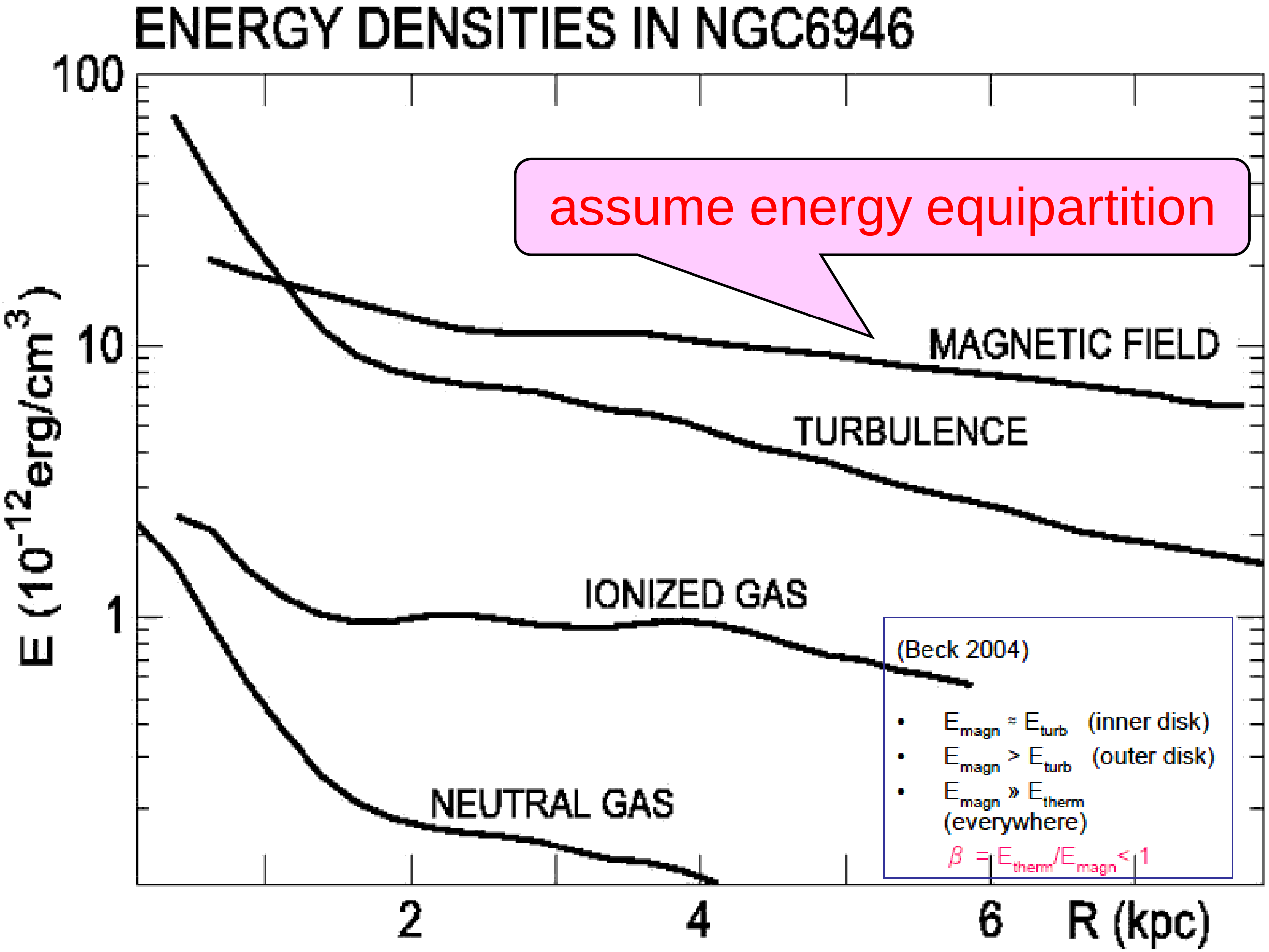


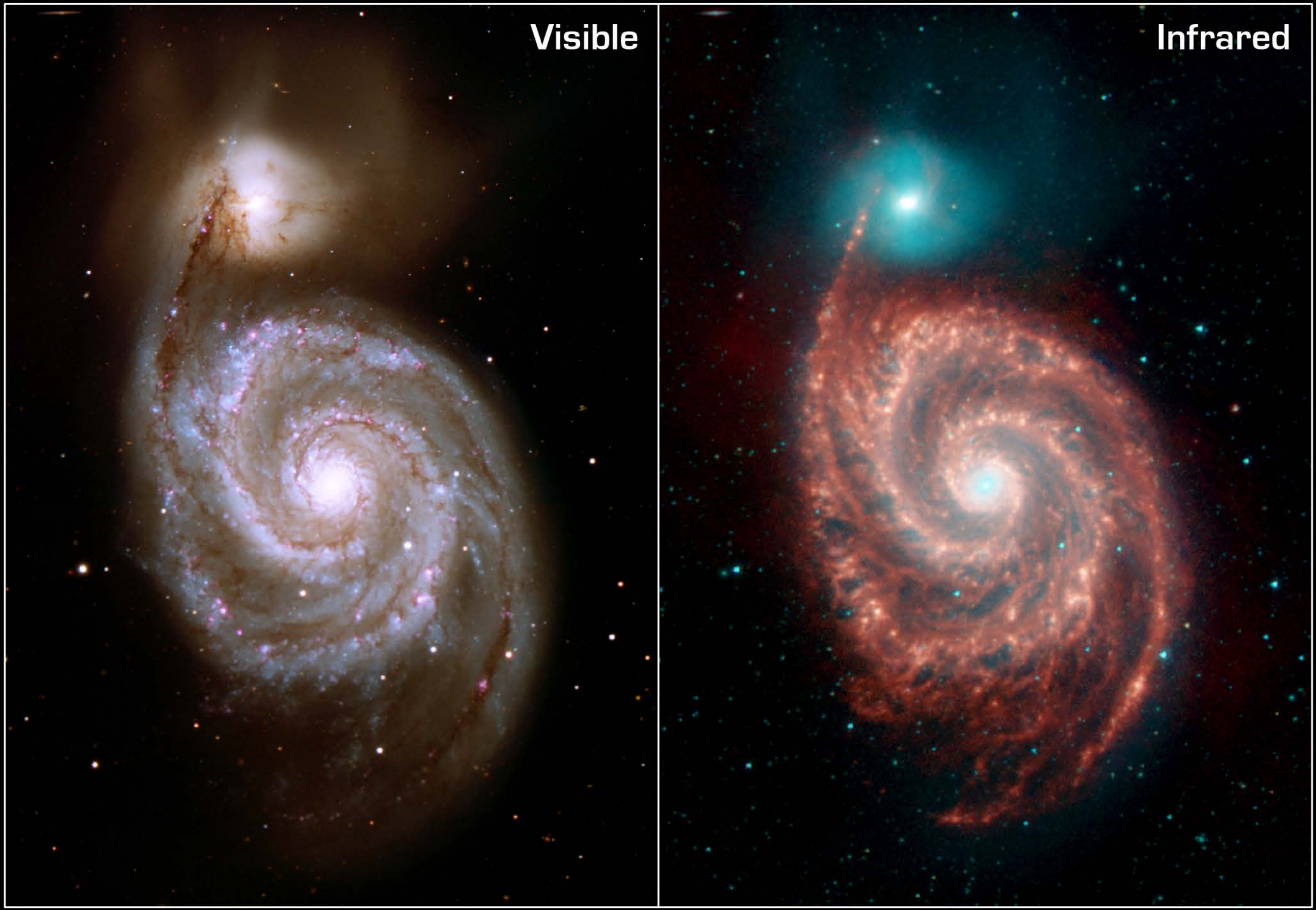
現状では，z方向の（準）静水圧平衡において，ガス圧よりも，磁場圧や宇宙線に起因する圧力が効いていると結論されている．???

Radial Distribution of Various Energy

NGC6946



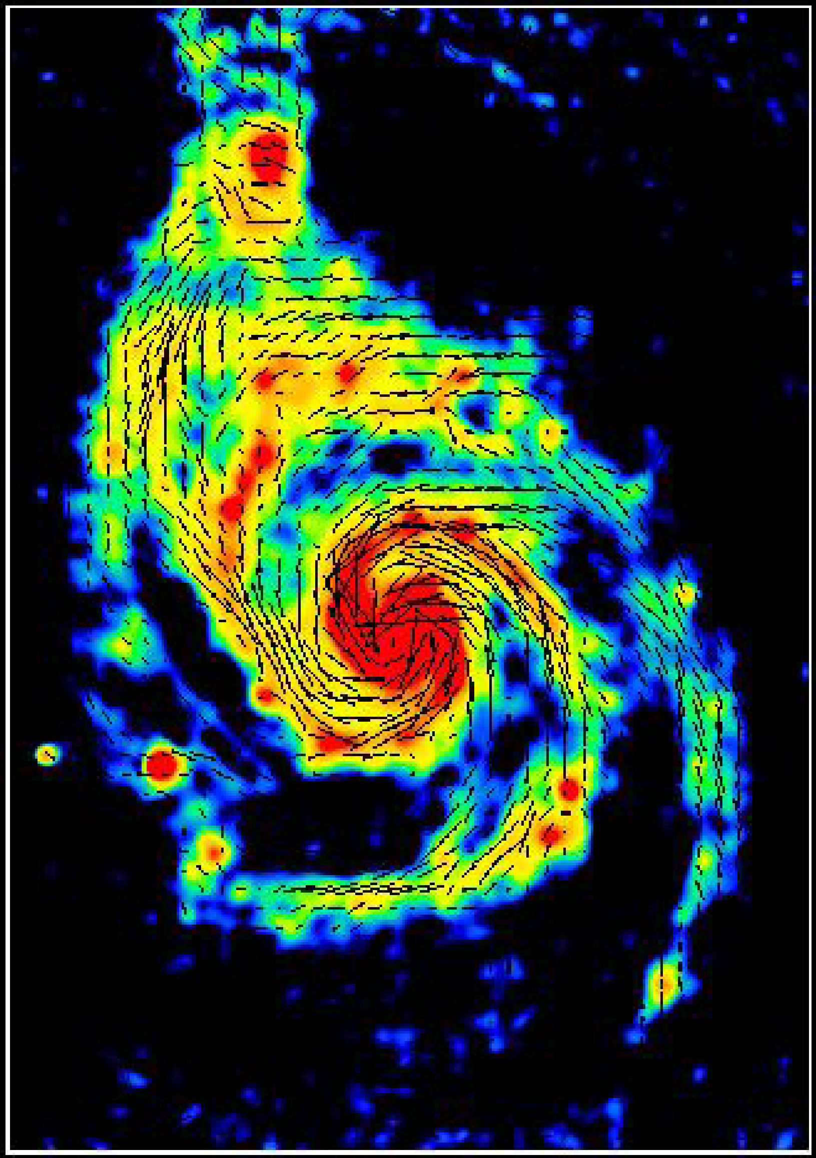


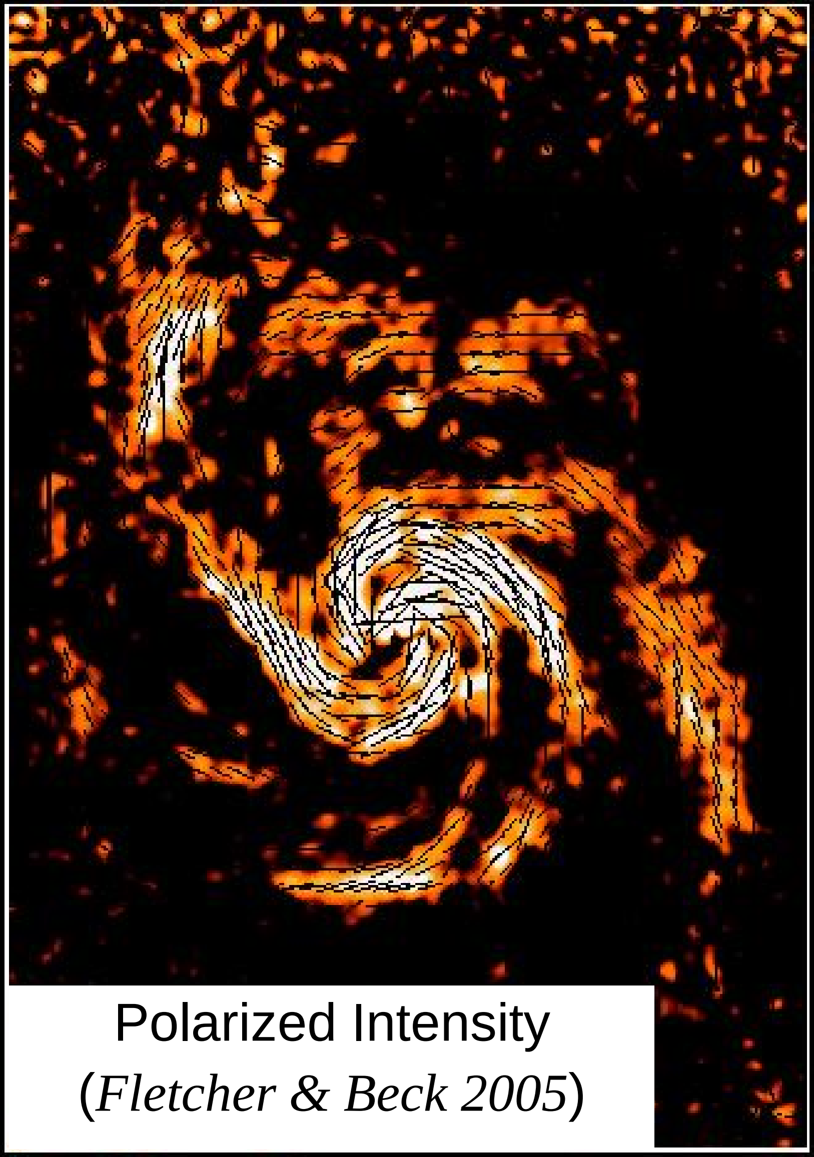


Spiral Galaxy M51 ("Whirlpool Galaxy") Spitzer Space Telescope • IRAC

NASA / JPL-Caltech / R. Kennicutt (Univ. of Arizona) ssc2004-19a

M51 Synchrotron

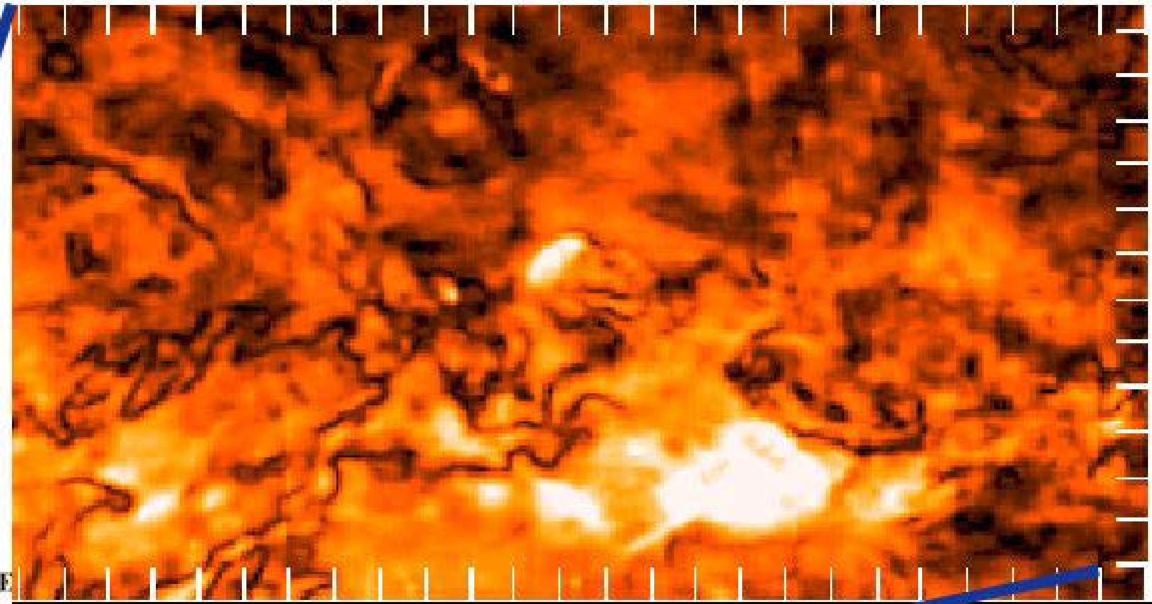


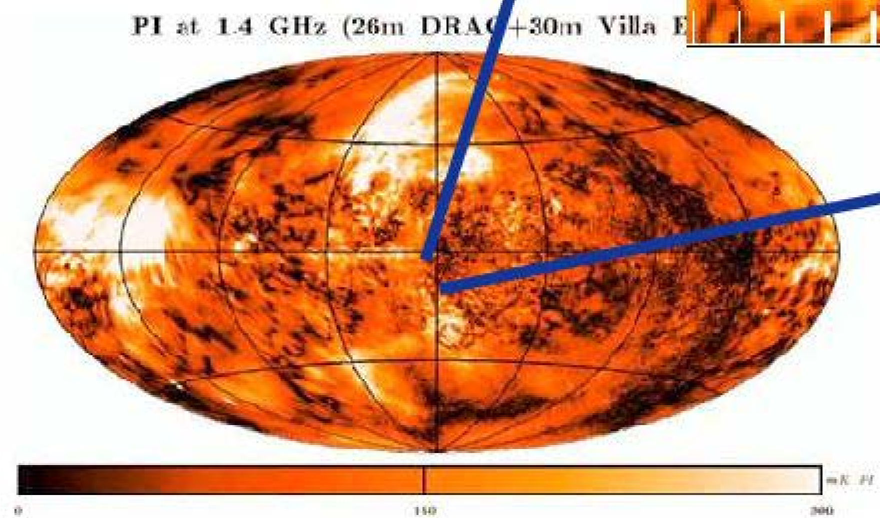


Polarized Intensity
(*Fletcher & Beck 2005*)

シンクロトロン偏波成分の詳細マップ

まだ，理論的説明は無い！

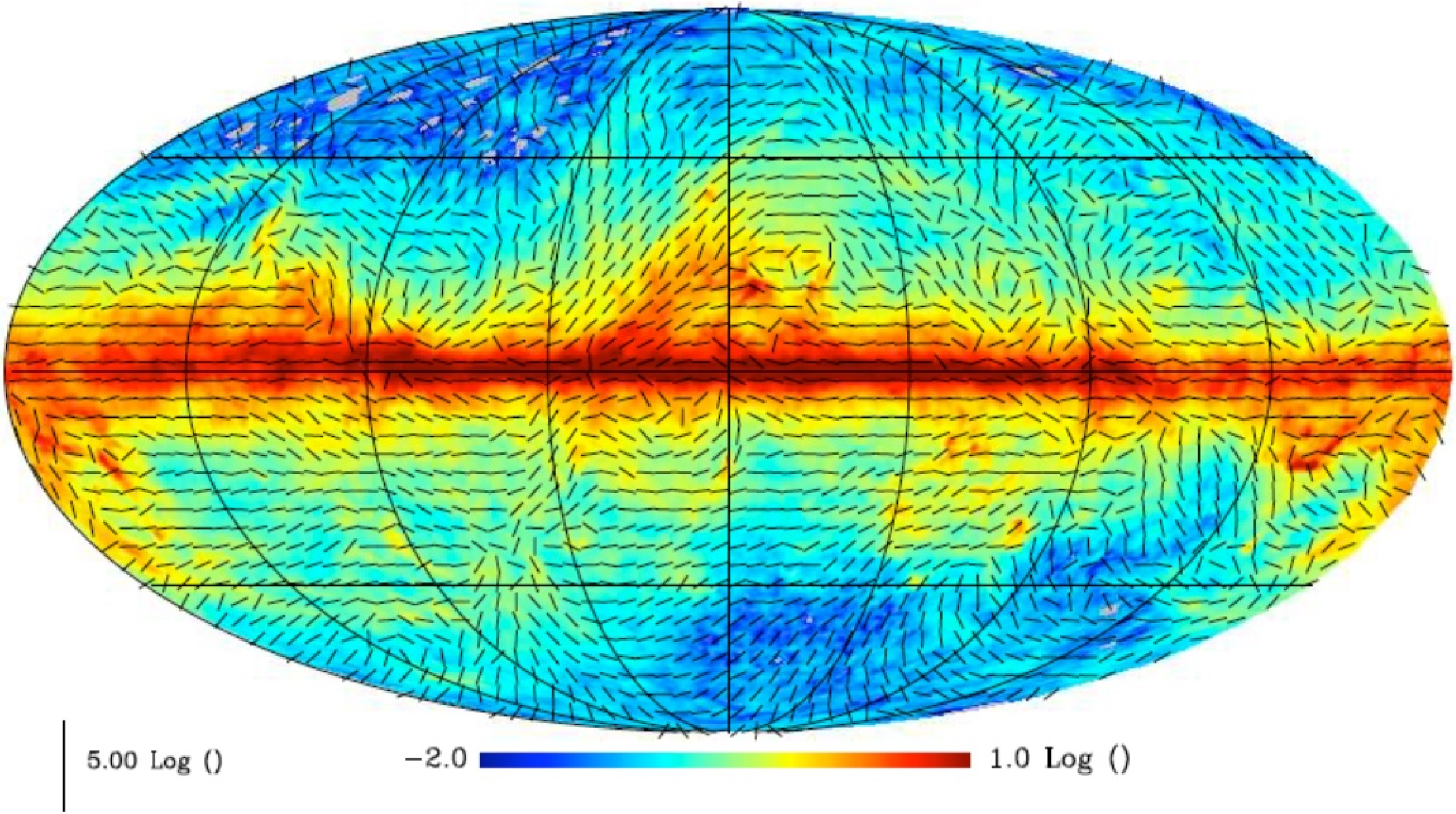




偏光が無い部分がCanal状の構造を作っている.

21cm DRAO+ Villa Elisa all-sky polarization survey
(Wolleben et al. 2004)

Waiting for Planck Paper



第1部

- 相転移のダイナミックス
  - 超新星爆発，電離領域膨張
  - 熱的不安定性➔乱流
  - 長さ:Field Length, 時間:Cooling Timescale

Observed "Turbulence" in ISM

Observation of Molecular Clouds

line-width $\delta v > C_S$

Universal Supersonic Velocity Dispersion

even in the clouds without star formation activity

➔ should not be due to star formation activity

What is the Origin of "Supersonic Turbulence" in Molecular Clouds?

Dynamical Timescale of ISM

Dynamical Three Phase Medium

– e.g., McKee & Ostriker 1977

- SN Explosion Rate in Galaxy… 1/(100yr)
- Expansion Time…1Myr
- Expansion Radius… 100pc

$(10^2 \text{kpc})^2 \times 100\text{pc}$

$$(10^{-2}\,\text{yr}^{-1}) \times (10^{6}\,\text{yr}) \times (100\text{pc})^{3} = 10^{10}\,\text{pc}^{3} \sim V_{\text{Gal.Disk}}$$

Dynamical Timescale of ISM ~ 1Myr

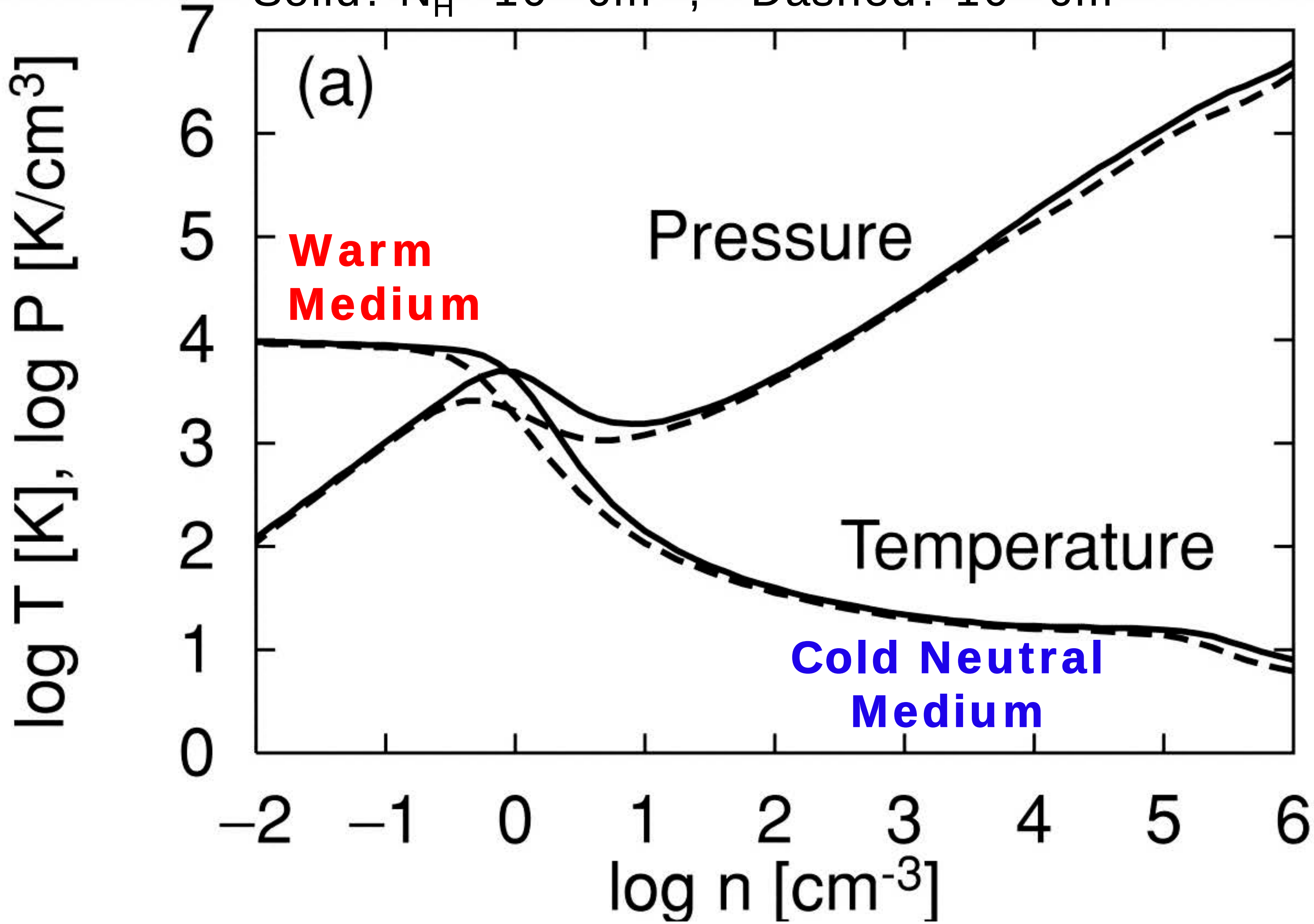
« Timescale of Galactic Density Wave ~ 100Myr

Expanding HII regions also important

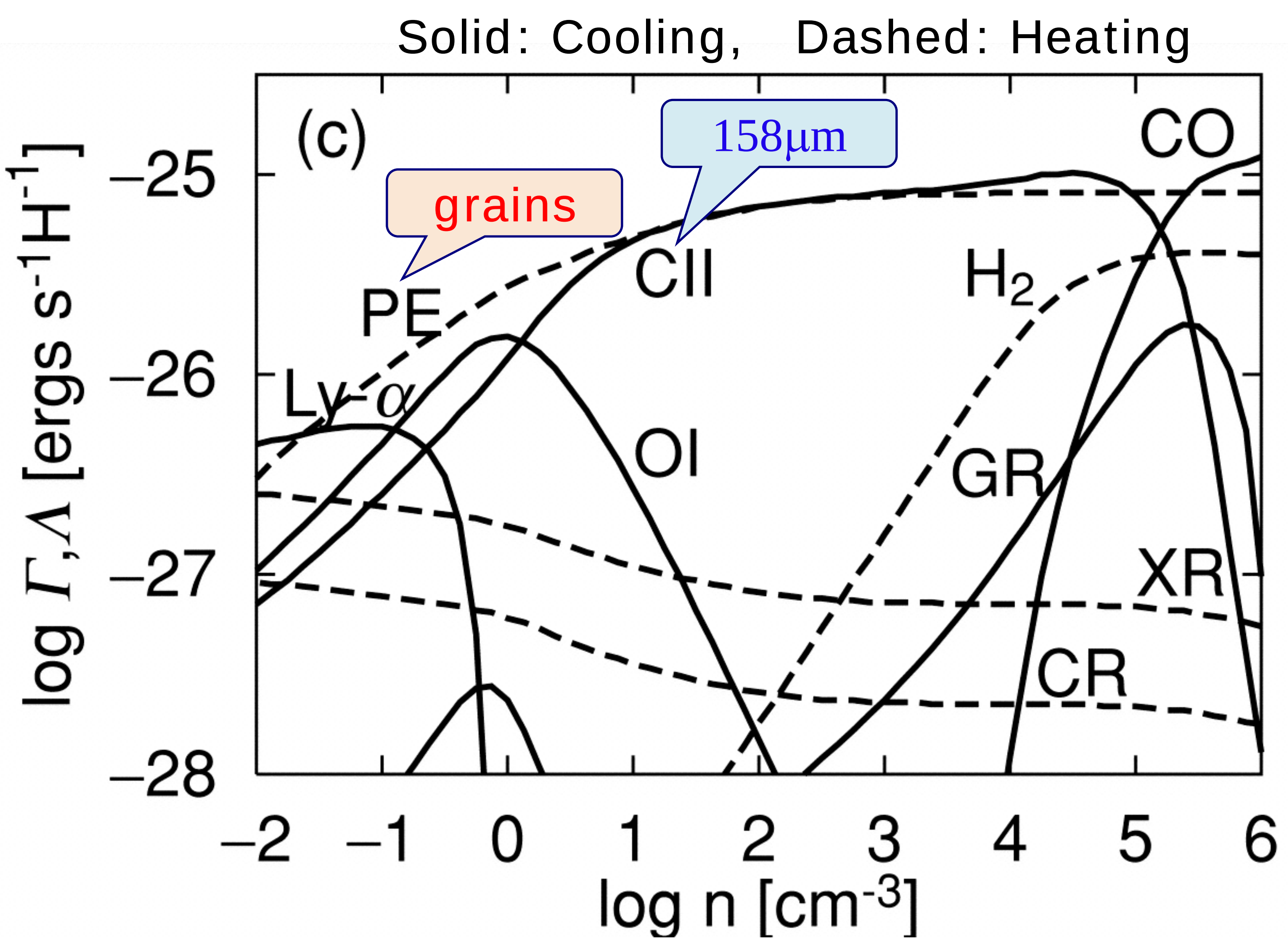
Energetics Argument ➔ SNe

Radiative Equilibrium for a given density

Solid: $N_H = 10^{19} cm^{-2}$, Dashed: $10^{20} cm^{-2}$

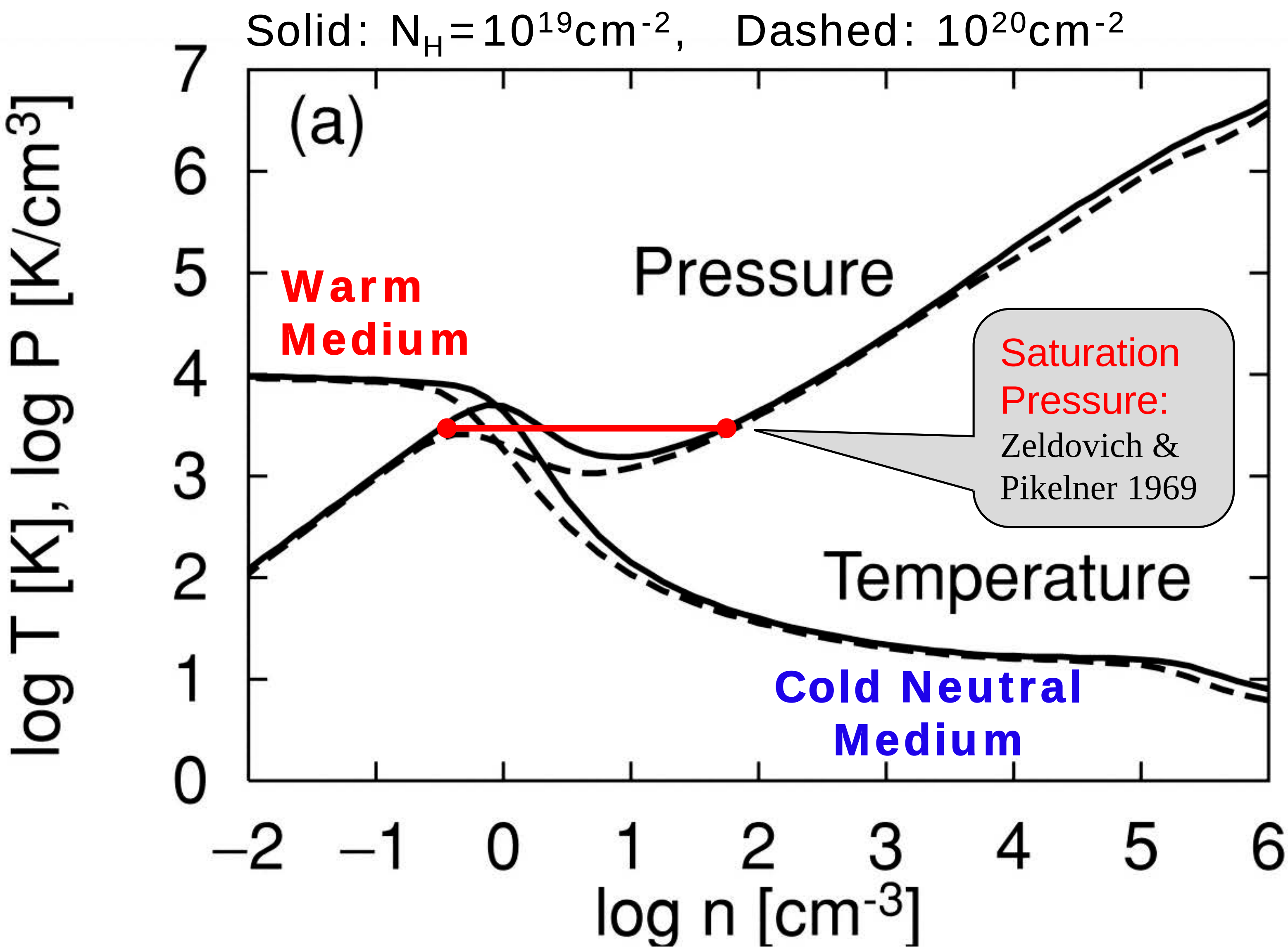


Radiative Cooling & Heating

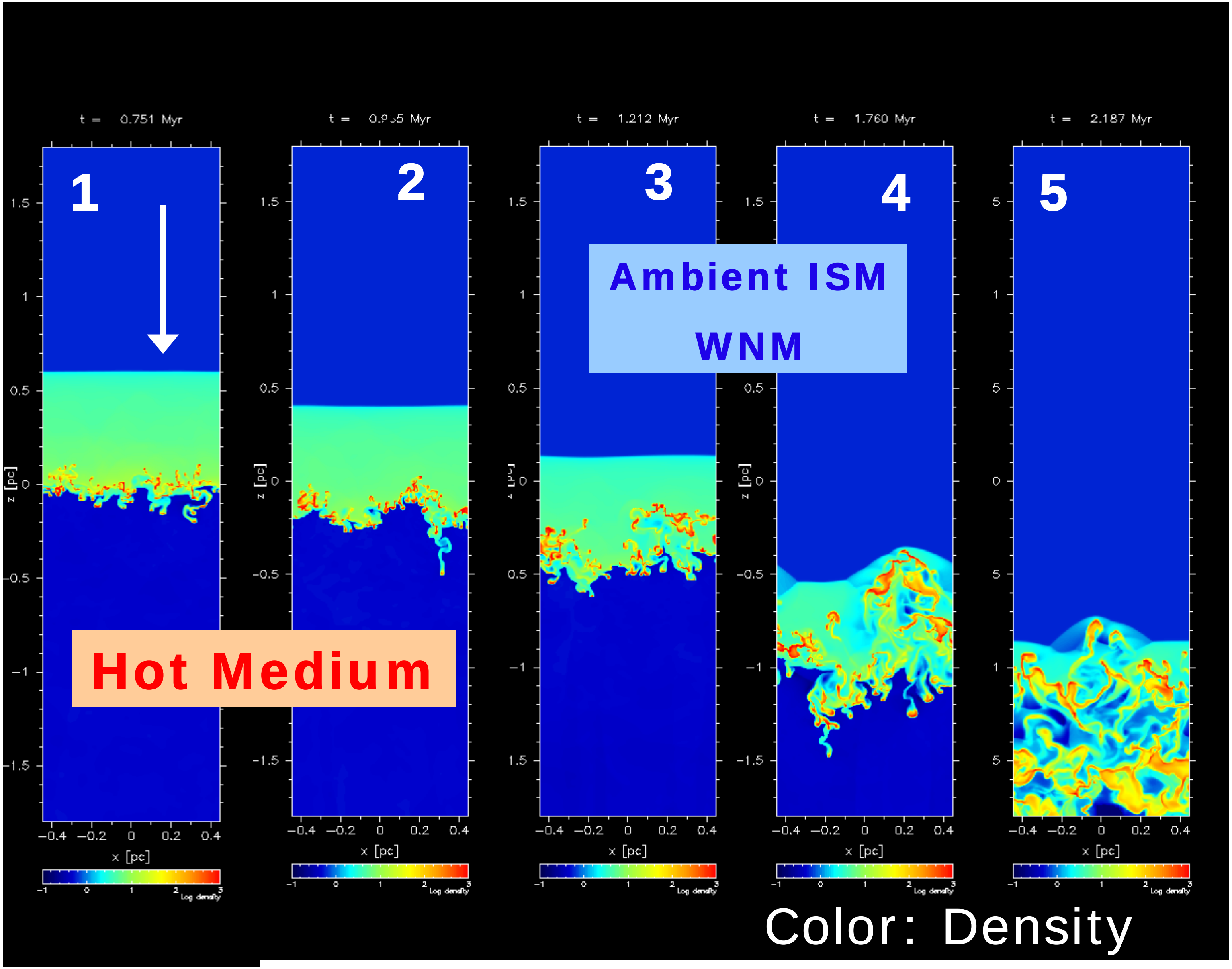


Koyama & SI (2000) ApJ **532**, 980 , (adding CO to Wolfire et al. 1995)

2 Phase in Equilibrium

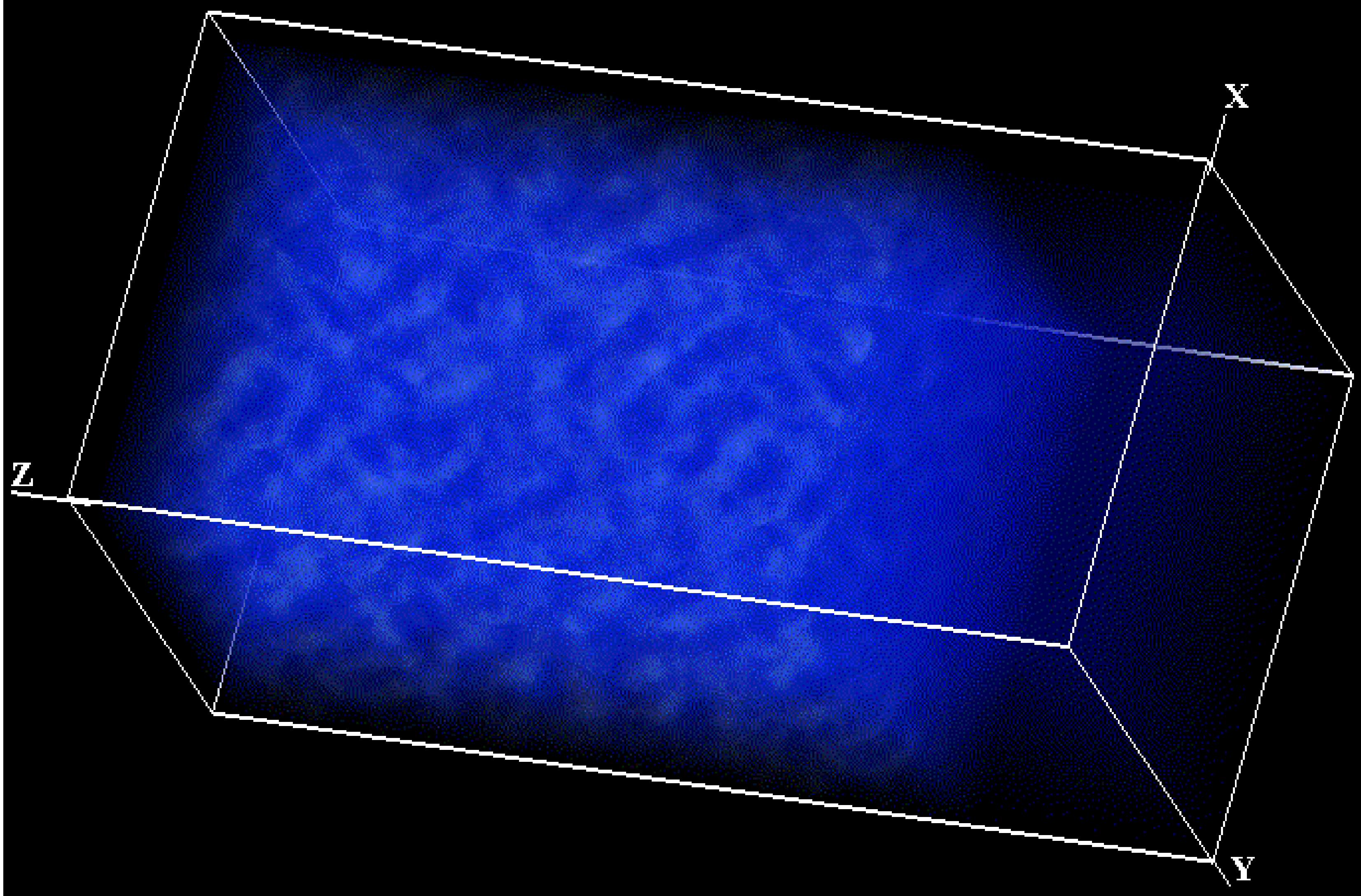


Shock Propagation into WNM



Koyama & Inutsuka (2002) ApJ 564, L97

WNM Swept-Up by 14.4km/s Shock (3D)
Koyama & Inutsuka 2002



Summary of TI-Driven Turbulence

- 2D/3D Calculation of Propagation of Shock Wave into WNM via Thermal Instability

➔ fragmentation of cold layer into cold clumps with long-sustained supersonic velocity dispersion (~ km/s)

"Field length" : $\lambda_F \equiv \sqrt{\dfrac{\kappa T}{\rho^2 \Lambda}} \rightarrow 10^{-2}\,\mathrm{pc}$

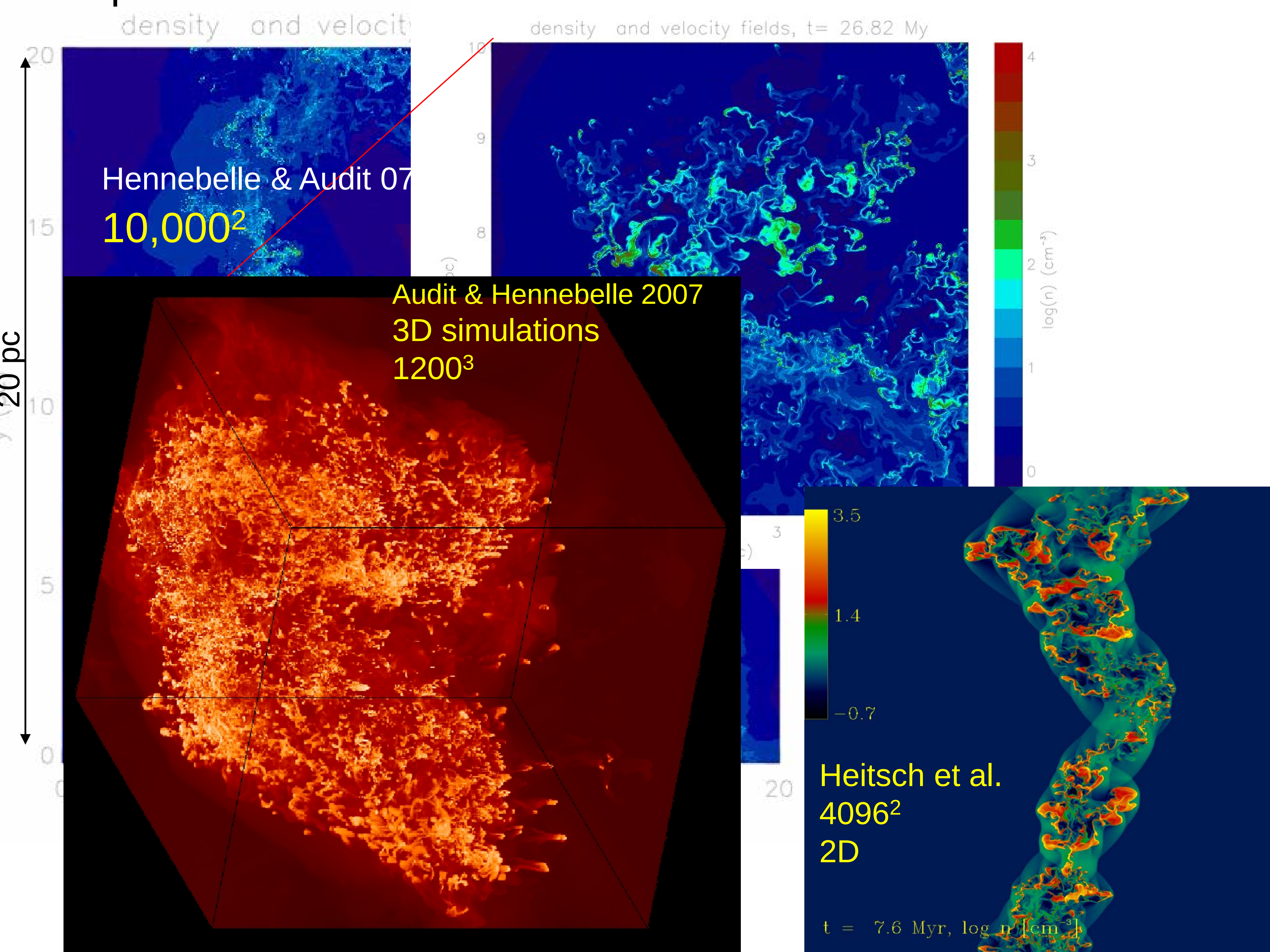
1D: Shock $\Rightarrow E_{th} \Rightarrow E_{rad}$

2D&3D: Shock $\Rightarrow E_{th} \Rightarrow E_{rad} + E_{kin}$

δv ~ a few km/s < $C_{S,WNM}$ =10km/s

🡐 10^4K due to Lyα line: Universality?

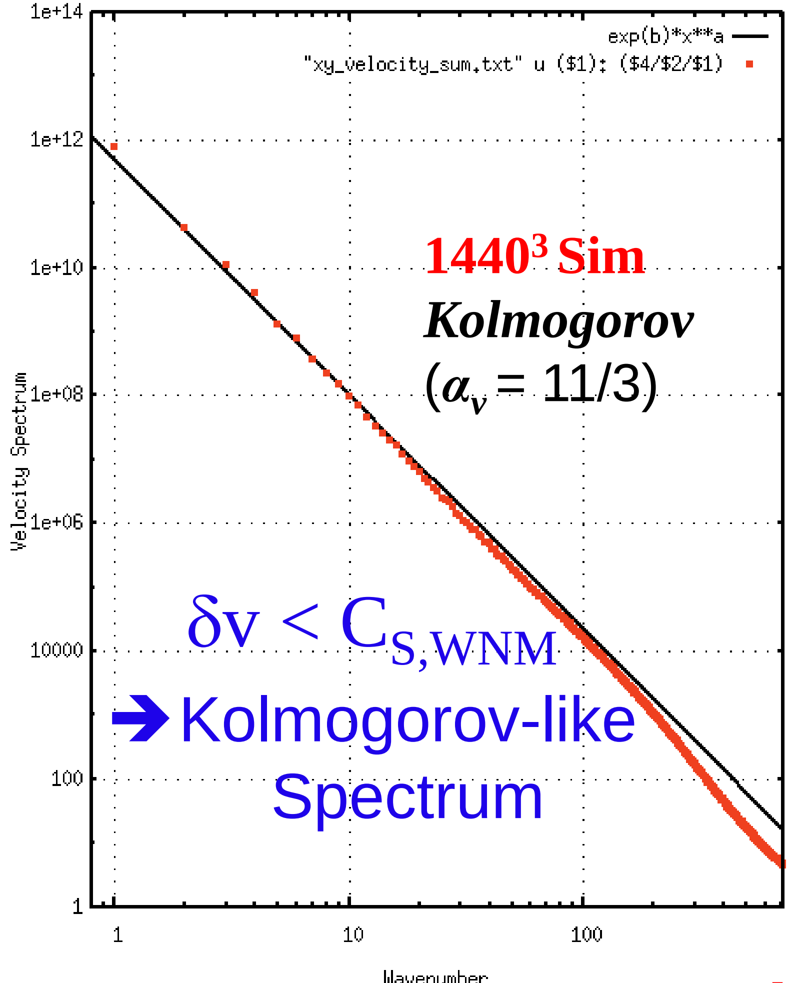
Koyama & SI (2002) ApJ 564, L97

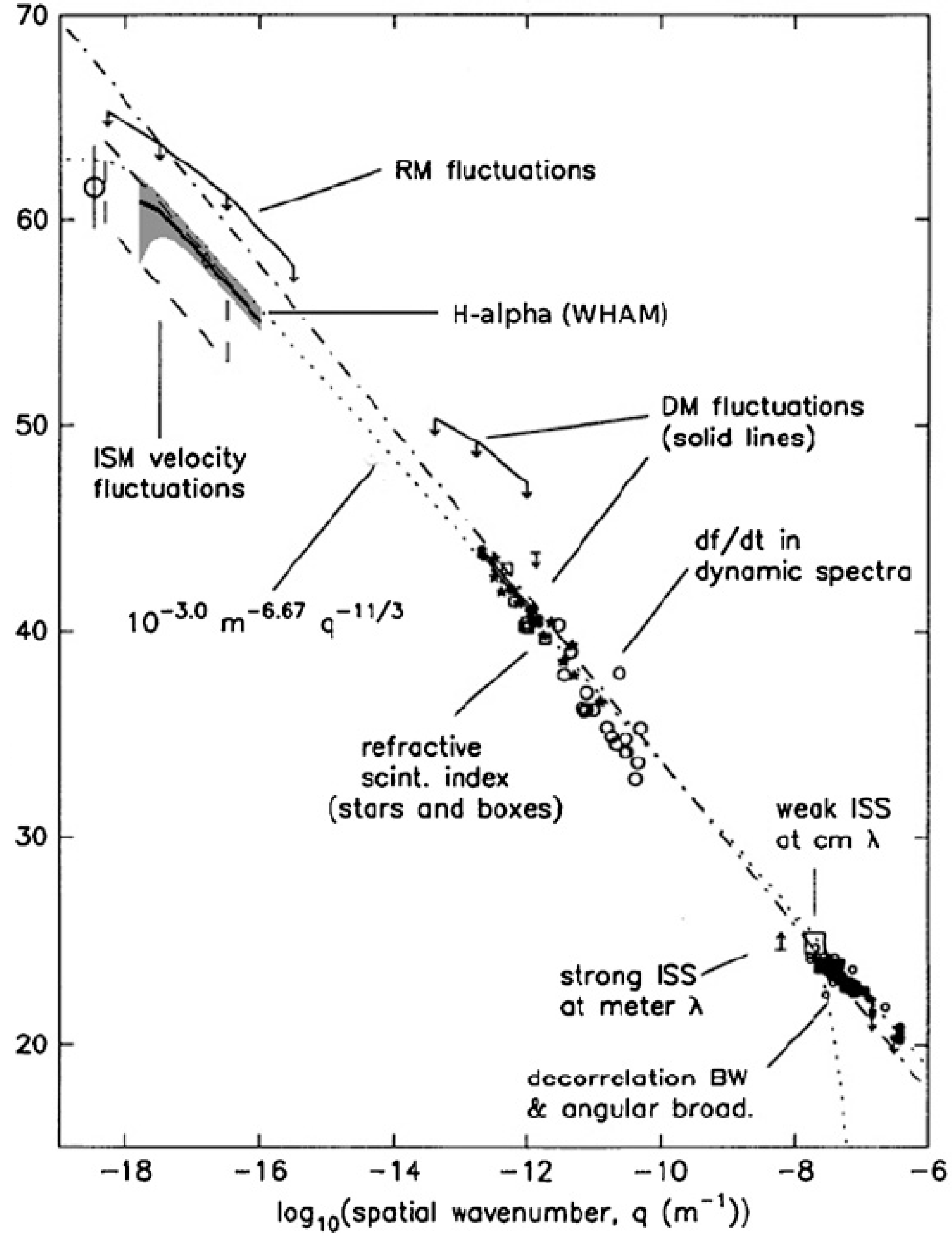


density and velocit
density and velocity fields, t= 26.82 My
20 pc
Hennebelle & Audit 07
10,000²
Audit & Hennebelle 2007
3D simulations
1200³
log(n) (cm⁻³)
Heitsch et al.
4096²
2D
3.5
1.4
−0.7
t = 7.6 Myr, log n [cm⁻³]

Property of 3D "Turbulence"

Muranushi, Inoue & SI 2014 in prep.





Good Agreement!

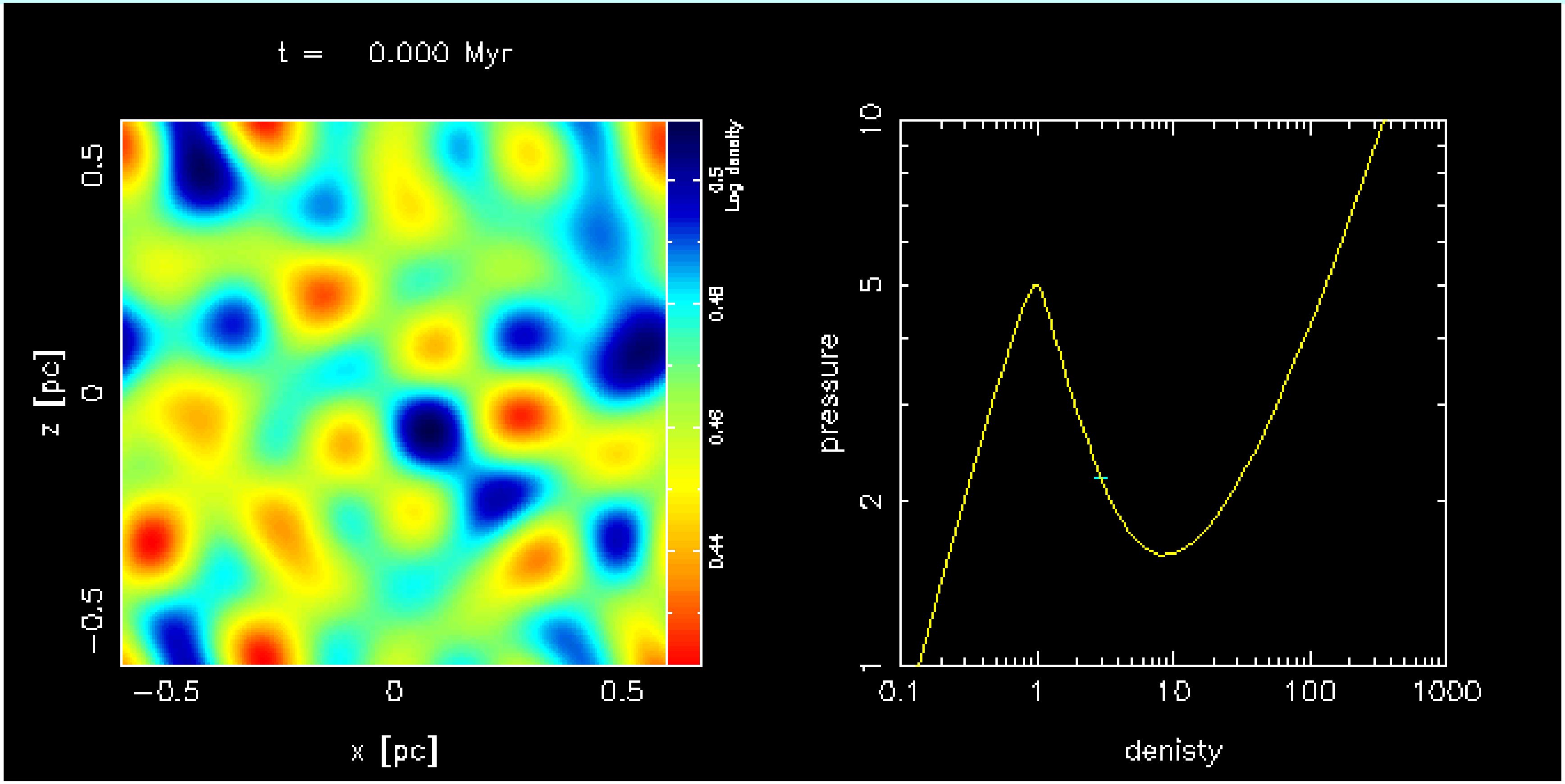
Chepurnov & Lazarian 2010
Armstrong et al. 1995

FAQ

衝撃波が無い場合は，乱流は減衰するか？

答えはNO!

Sustained “Turbulence” in Periodic Box



Periodic Box Evolution <u>without Shock Driving</u>

With Cooling/Heating and Thermal Conduction

Without Physical Viscosity (*Prandtl #* = 0)

Iwasaki & SI (2013)

磁気雲の形成過程

磁化したWNMを圧縮して分子雲はできるか？

Ref.

Inoue & SI (2008) ApJ **687**, 303

Inoue & SI (2009) ApJ **704**, 161

Inoue & SI (2012) ApJ **759**, 35

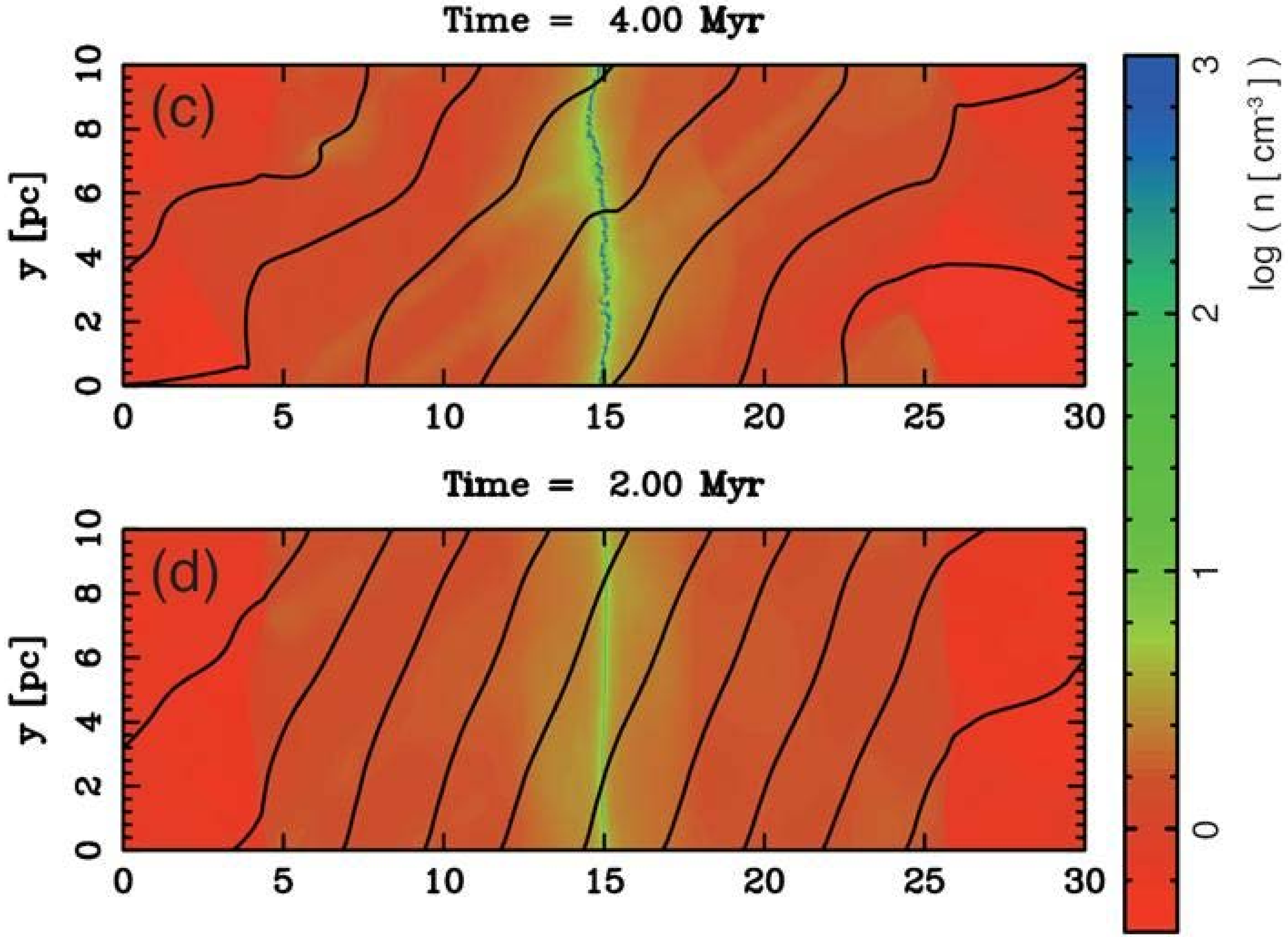
Colliding WNM with B_0=3μG

v=10km/s

B=3μG

(a) 15deg

(b) 40 deg



2-Fluid MHD Simulation (AD included)

Colliding WNM with B_0=3μG

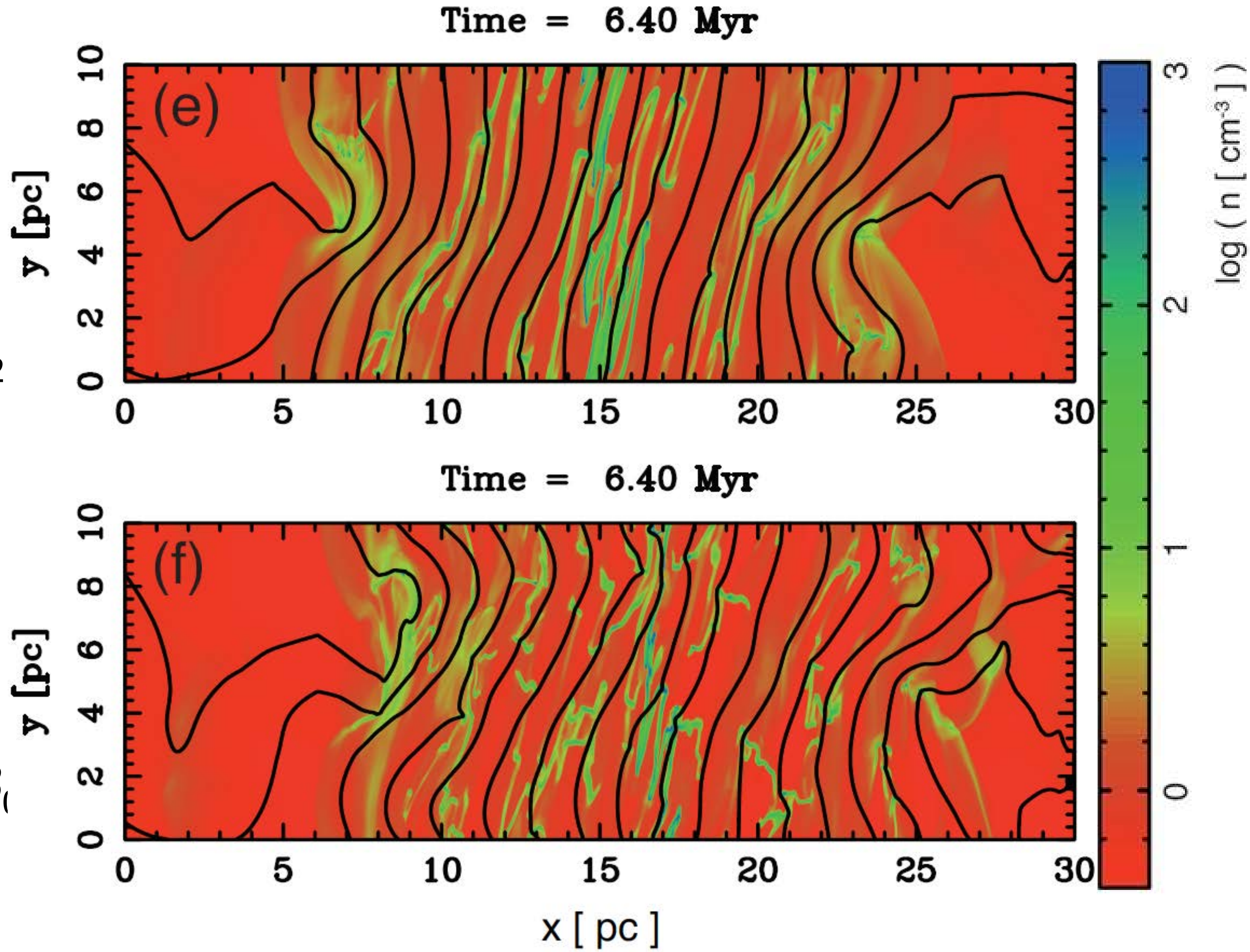
v=10km/s

(a) 15deg

$<\delta B^2>_{init} = B_0^2$

(a) 40 deg

$<\delta B^2>_{init} = 4B_0^2$



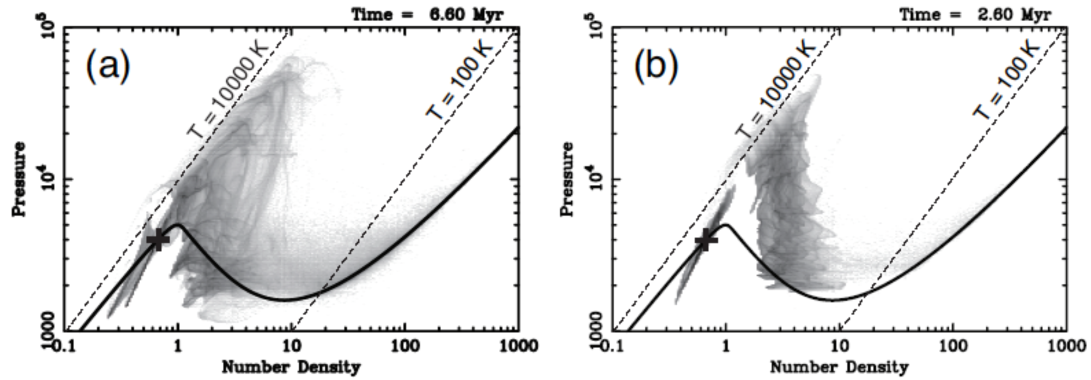
2-Fluid MHD Simulation (AD included)

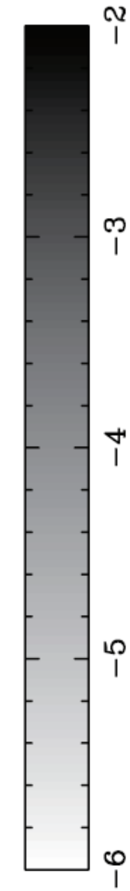
Colliding WNM with B_0=3μG

v=20km/s

(a) 15deg

(b) 40 deg

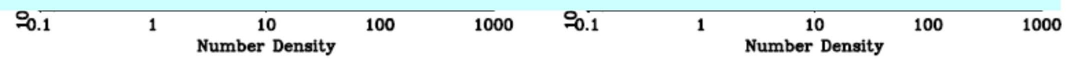




Significant Fraction of Gas in

Thermally Unstable State

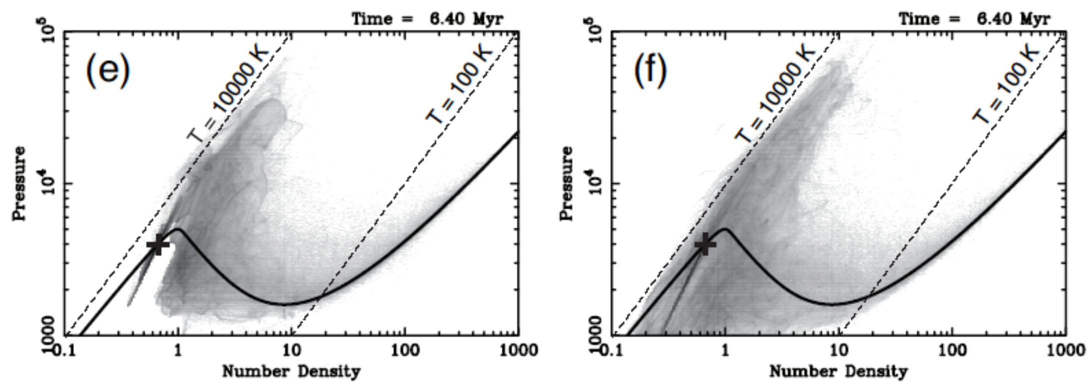
➔ Observable in HI (Heiles 2001)



v=20km/s

(e) $<\delta B^2>_{init} = B_0^2$

(f) $<\delta B^2>_{init} = 4B_0^2$



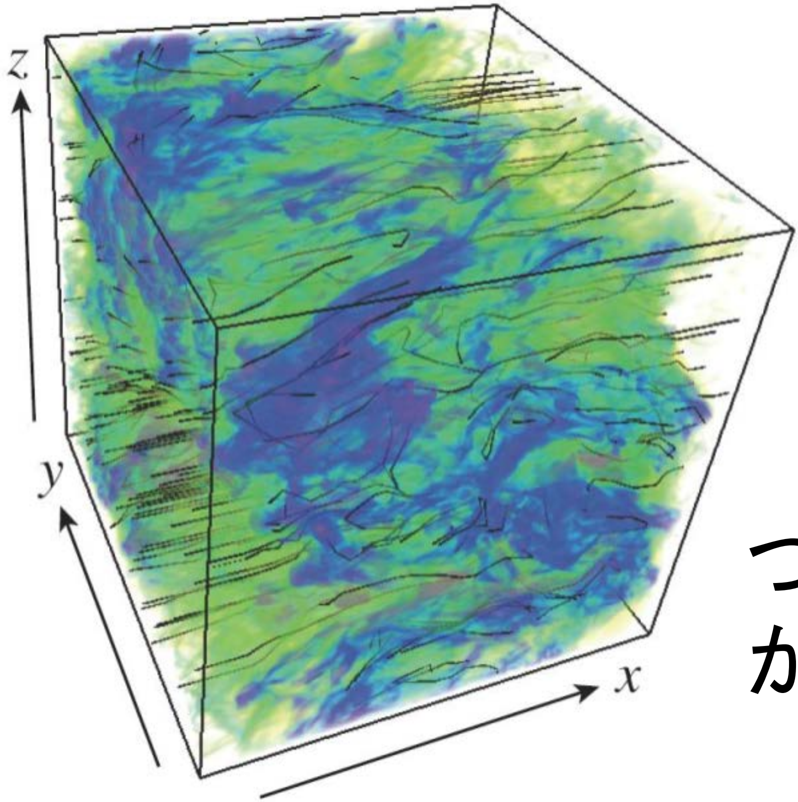
分子雲形成の現実的シナリオ

磁化したWNMを圧縮してもHI雲しかできない

Inoue & SI (2008) ApJ **687**, 303; Inoue & SI (2009) ApJ **704**, 161

HI雲を圧縮する必要がある➔

multiple episodes of compression.



Converging Flow into 2-Phase Medium

blue: 10^2/cc < n < 10^3/cc

magenta: dense clumps n > 10^3/cc

Inoue & SI (2012) ApJ **759**, 35

つまり，分子雲形成は時間がかかる！

Timescales for Phase Transition

- Warm Medium

10^6yr

- HI Clouds

10^7yr?

- Molecular Clouds

$10^{5\text{-}6}$yr?

- New-Born Stars

c.f. t_{MC}~20Myr in LMC (*Fukui & Kawamura 2010*)

HI Clouds vs Molecular Clouds

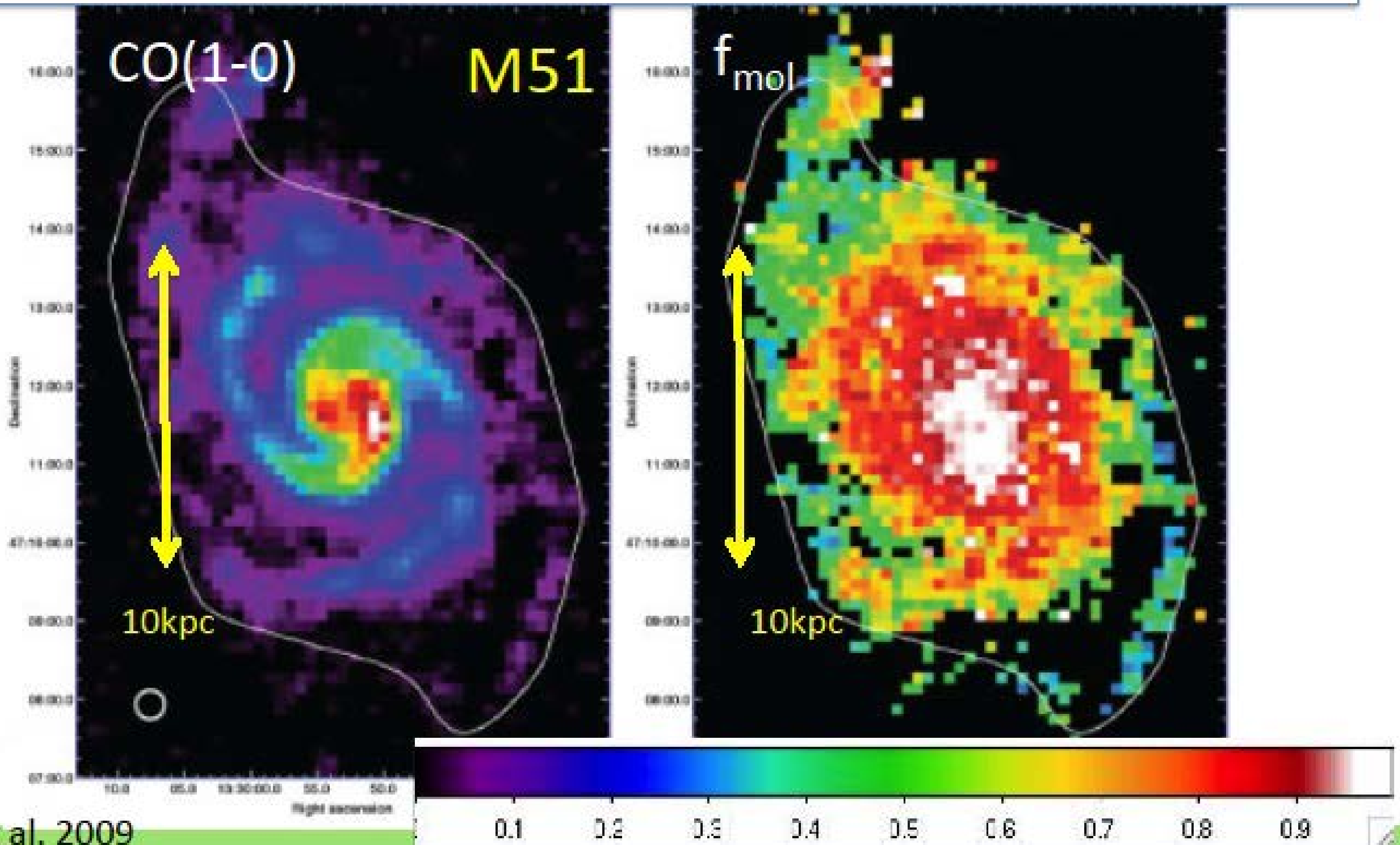
f_{mol}: Molecular Fraction

©J. Koda

$$f_{mol} = \frac{\Sigma_{H_2}}{\Sigma_{H_2} + \Sigma_{HI}}$$

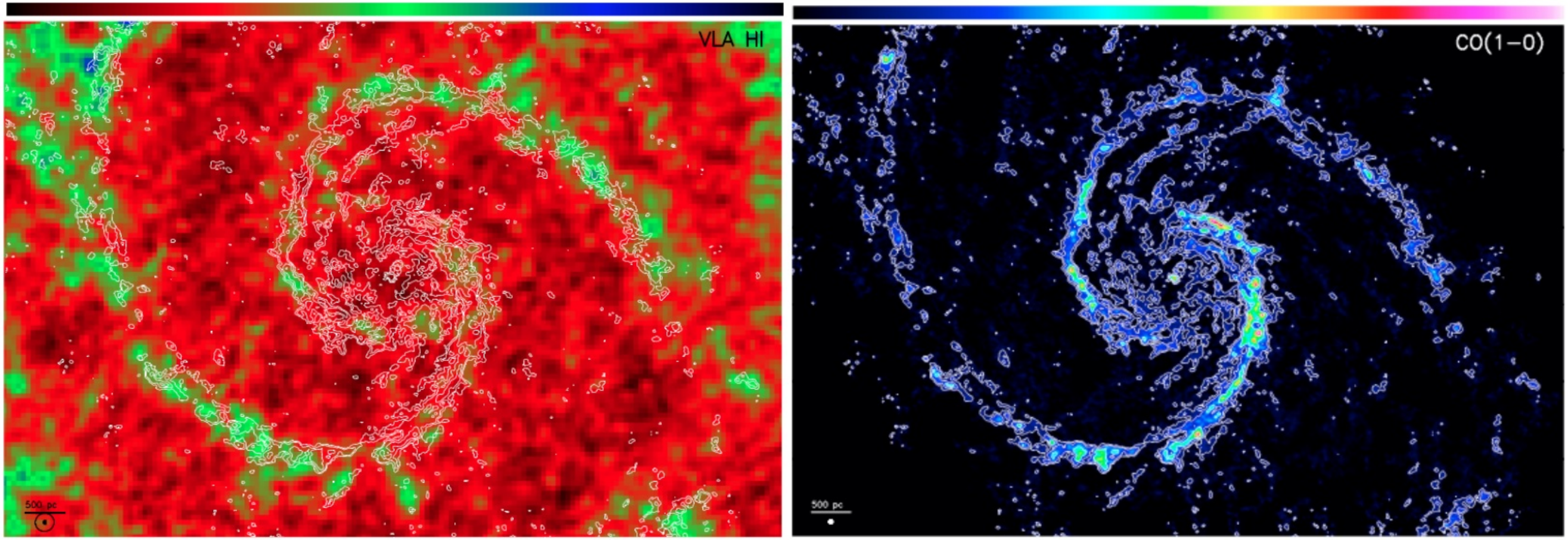
> 70-80%

Large radial change
Little azimuthal change



Koda et al. 2009

HI Clouds vs Molecular Clouds



M51 in PAWS   Schinnerer+ (2013)

Summary

- Shock waves in ISM create
  turbulent CNM embedded in WNM.
- TI-driven Turbulence in Multi-Phase ISM
  - Evaporation/Condensation of CNM clouds
  - Instabilities in Phase Transition Front
  - Agree with Observed Kolmogorov Law
- Multiple Compressions of Magnetized 2-Phase Medium ➔ Molecular Clouds

第2部

Filaments, Filaments, Filaments…

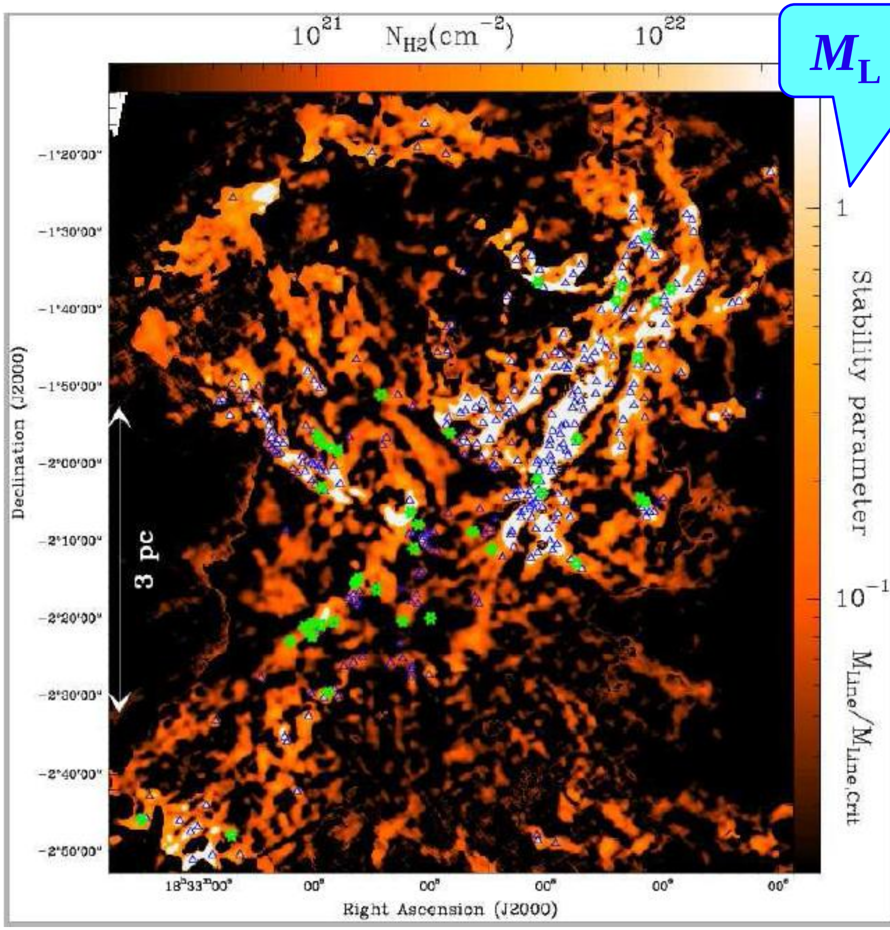
- Star Formation Threshold
- Star Formation Rate
- IMF

“The Milky Way in the Herschel Era”

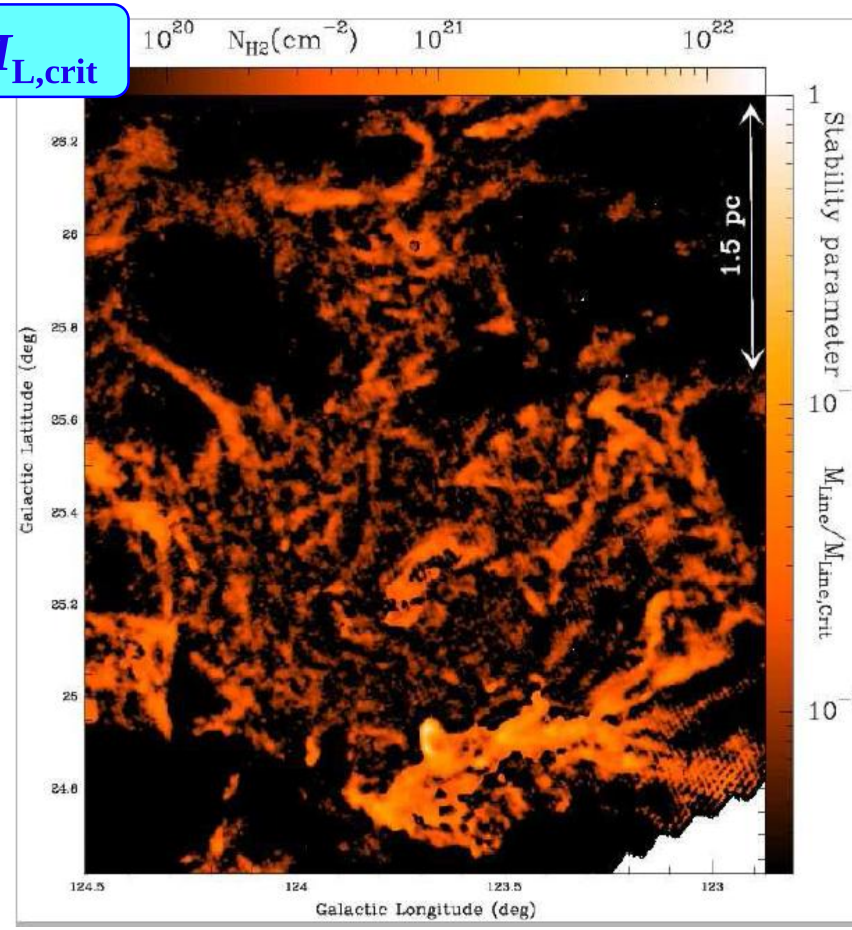
Sep 19-23, 2011@Rome, Italy

Herschel Satellite Telescope found ubiquitous filaments.

$\boldsymbol{M_L = M_{L,crit}}$



Aquila



Polaris

$M_L > M_{L,crit} = 2Cs^2/G$のフィラメントでは星形成

Ref. André et al. 2010

Character of Self-Gravity of Filaments

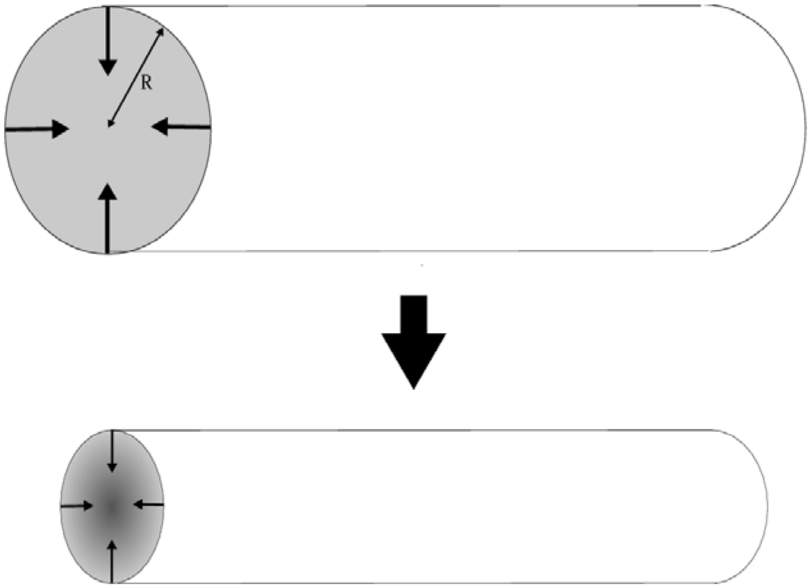
<u>Cylindrical Symmetry</u>

$$\frac{1}{R}\frac{\partial}{\partial R}R\frac{\partial \Phi}{\partial R} = 4\pi G\rho \Rightarrow \frac{\partial}{\partial R}R\frac{\partial \Phi}{\partial R} = 2\cdot 2\pi G\rho R$$

$$-\frac{\partial \Phi}{\partial R} \propto \frac{2GM_{\rm L}}{R},\ M_{\rm L} = 2\pi\int \rho R dR$$

Mass per Unit Length

$$-\frac{1}{\rho}\frac{\partial P}{\partial R} \propto \frac{C_{\rm S}^2}{R}$$



No <u>isothermal</u> pressure support against collapse ➔ γ_{crit}=1 for cylinder

⇐⇒ γ_{crit}=4/3 for sphere, γ_{crit}=0 for sheet

Critical Line-Mass for Filaments

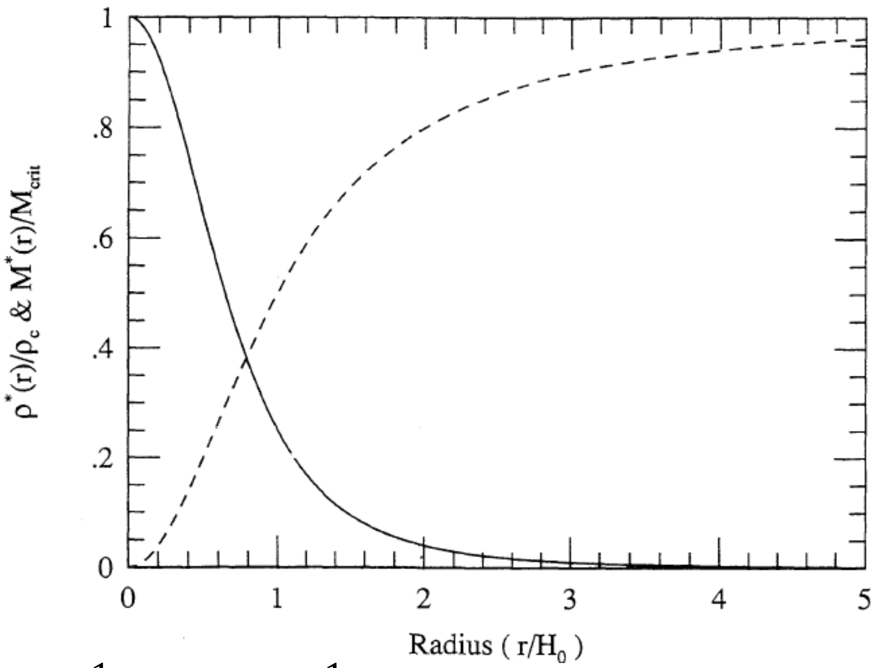
Isothermal Equilibrium Filament

(Stodolkiewicz 1963; Ostriker 1964)

$$\rho_{eq}(r) = \rho_c \left[1 + \left(\frac{r}{H_0} \right)^2 \right]^{-2} ,$$

where H_0 is the scale height and is defined by

$$H_0 \equiv \sqrt{\frac{2C_s^2}{\pi G \rho_c}} .$$



$$M_{L,crit} \equiv 2\pi \int_0^\infty \rho_{eq}(r) r dr = \frac{2C_S^2}{G} \approx 2\times 10^1 M_\odot \text{ pc}^{-1}$$

If $M_L < M_{L,crit}$, isothermal filament can be pressure-confined.

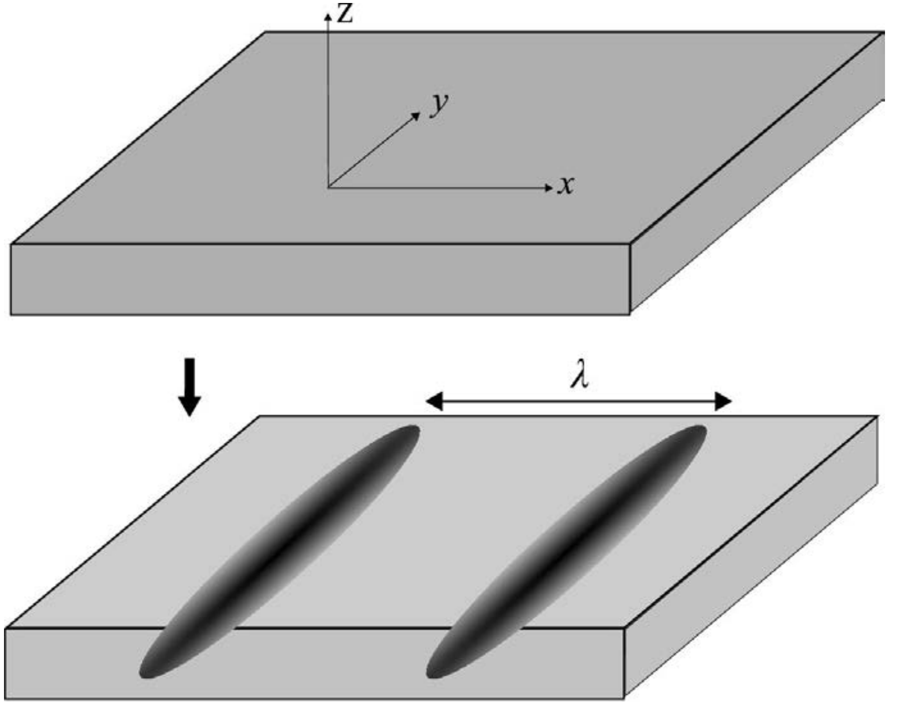
If $M_L > M_{L,crit}$, isothermal filament collapses indefinitely!

➔ **Self-gravity is essential for filament with $M_L \approx M_{L,crit}$.**

(SI & Miyama 1992, 1997)

What is the resultant line-mass?

Fragmentation of Isothermal Sheet-Like Cloud



Linear Analysis➔

$$\lambda_{fastest} \approx 4\pi H = 4C_s^2/(G\Sigma)$$

$$\Rightarrow M_L \approx \Sigma\lambda_{fastest} = 4C_s^2/G = 2\, M_{L,crit}$$

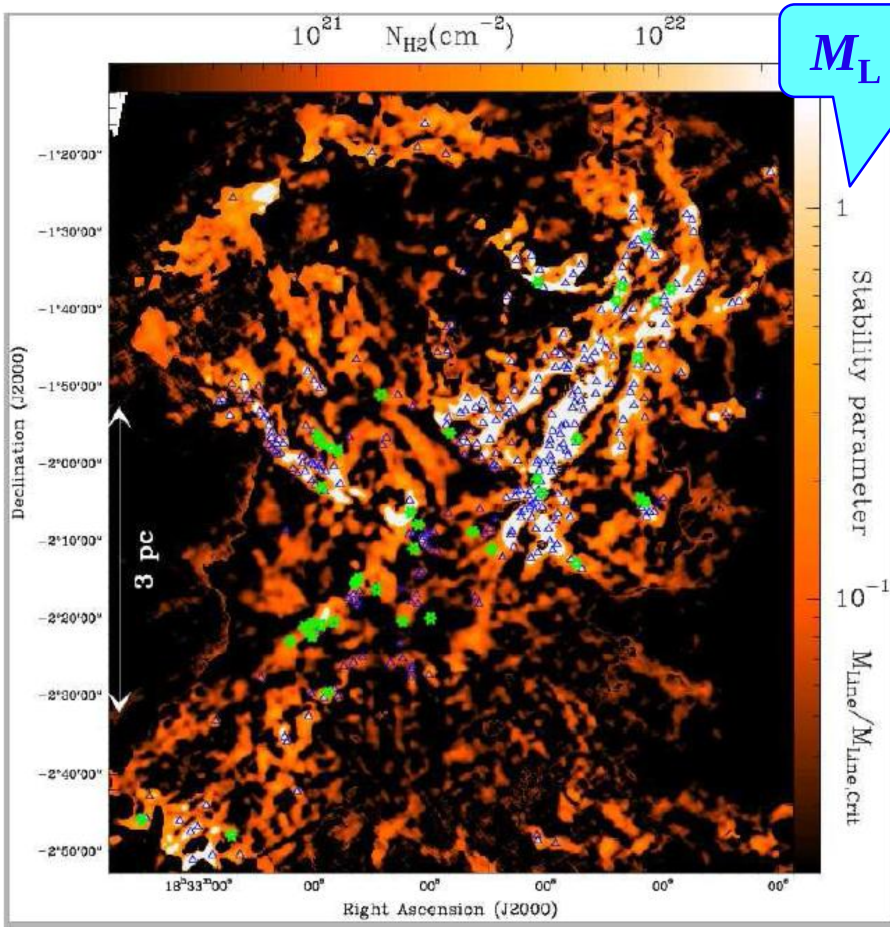
Nagai, SI, & Miyama 1998

“The Milky Way in the Herschel Era”

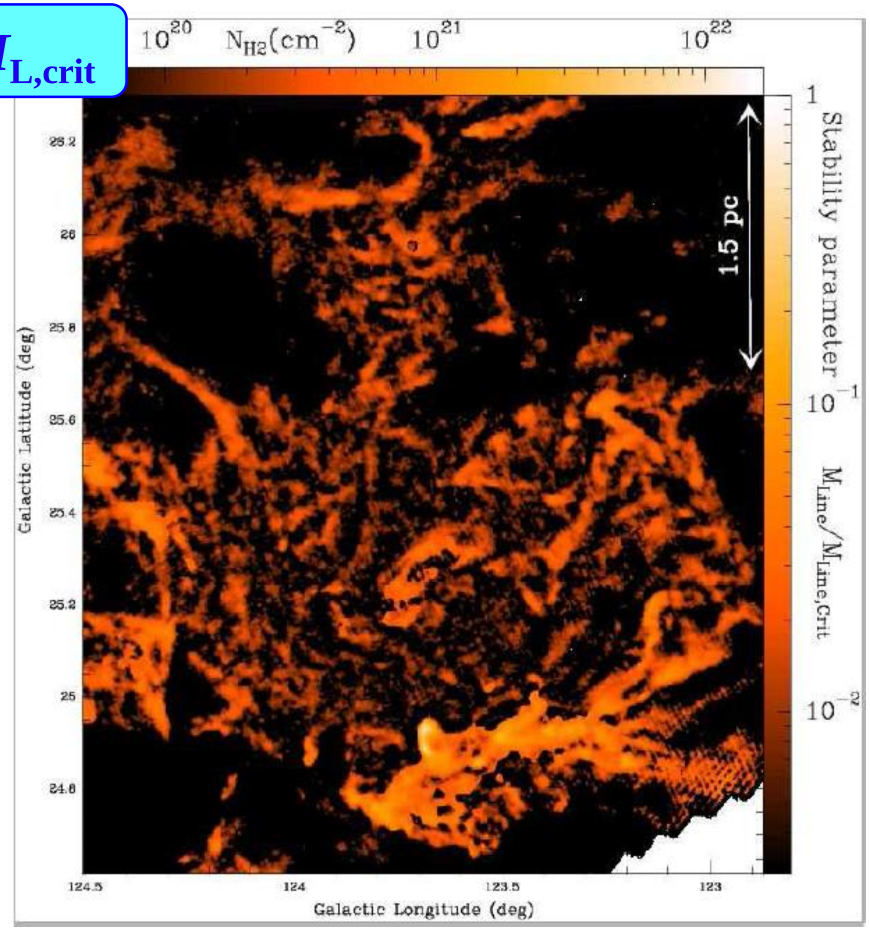
Sep 19-23, 2011@Rome, Italy

Herschel Satellite Telescope found ubiquitous filaments.

$M_L = M_{L,crit}$



Aquila



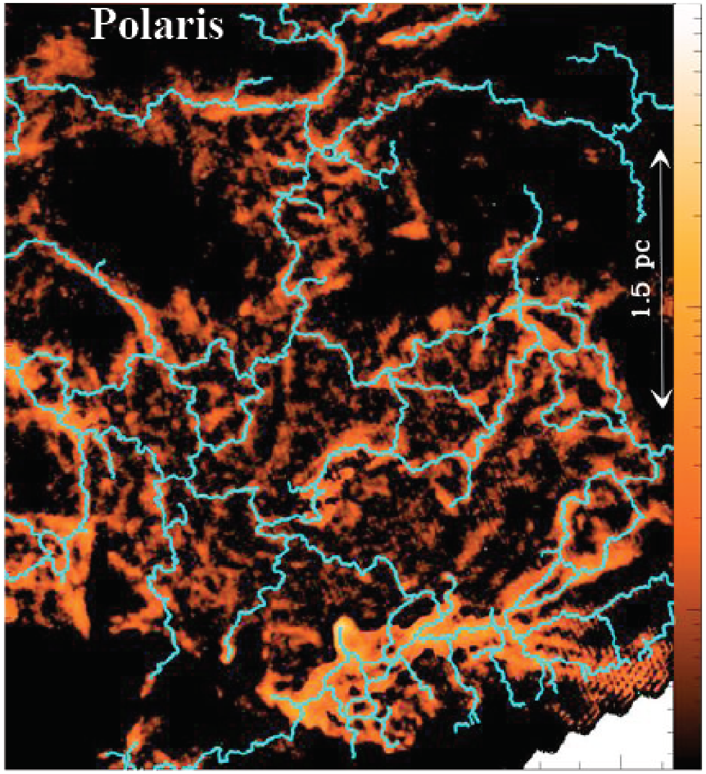
Polaris

$M_L > M_{L,crit}$=2Cs^2/Gのフィラメントでは星形成

Ref. André et al. 2010

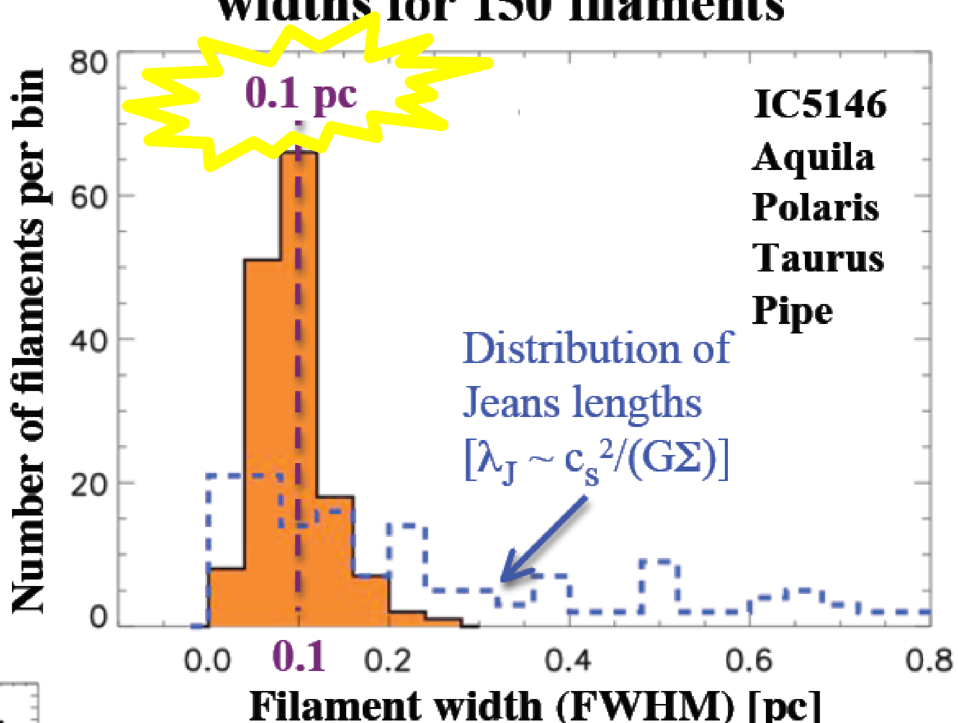
From Ph. André's Slide @Another Conference

Filaments have a characteristic width ~ 0.1 pc

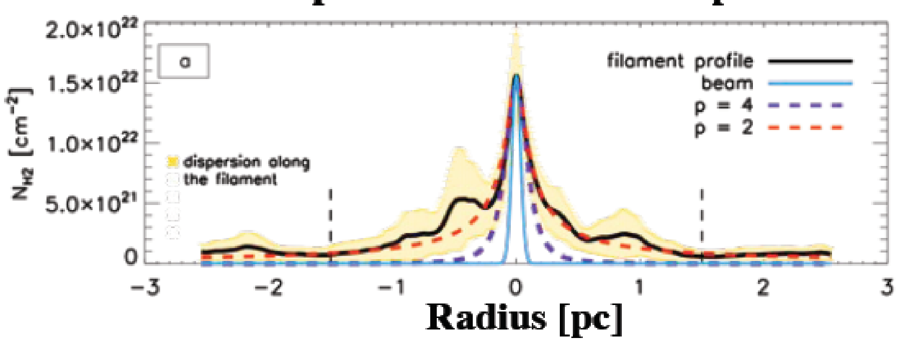


D. Arzoumanian et al. 2011, A&A, 529, L6

Statistical distribution of widths for 150 filaments



Example of a filament radial profile

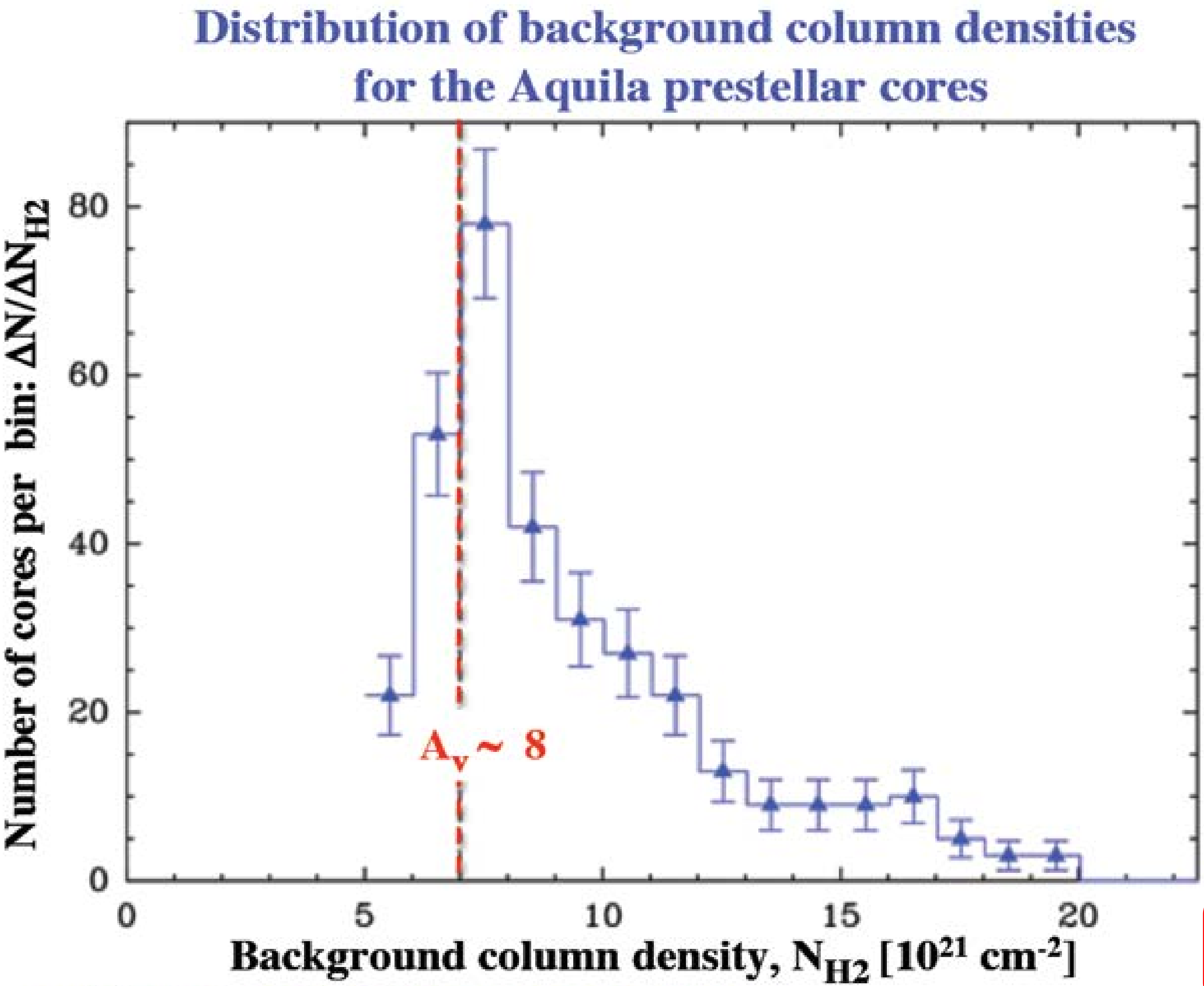


予想外の驚き

観測バイアスではない
(Juvela+2012)

From Ph. André's Slide

Confirmation of an extinction "threshold" for the formation of prestellar cores



André et al. IAU270, Könyves et al. in prep

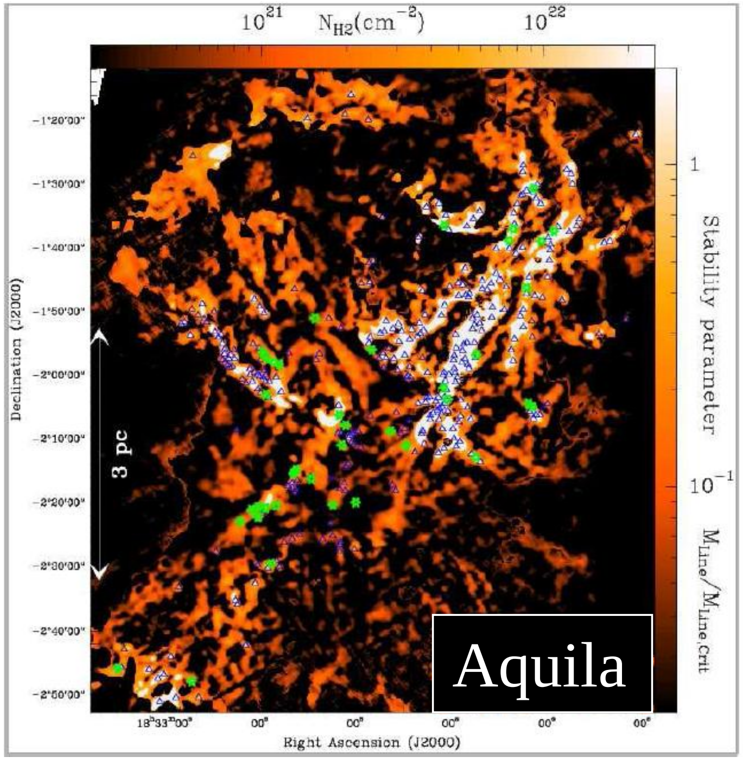
In Aquila, ~90% of the prestellar cores identified with *Herschel* are found above $A_v \sim 8 \Leftrightarrow \Sigma \sim 130\, M_\odot\, pc^{-2}$

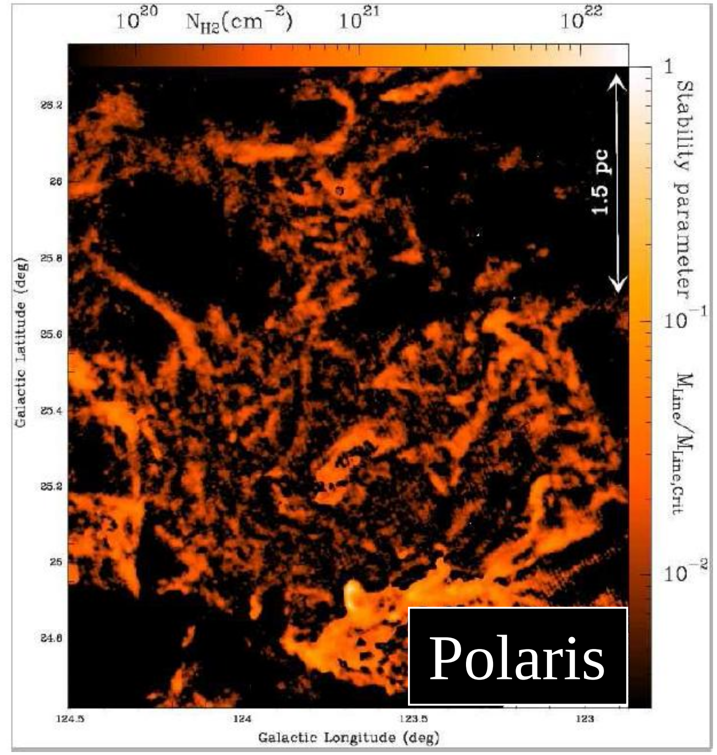
cf. Onishi et al. 1998
Johnstone et al. 2004

See also (for YSOs): Heiderman, Evans et al. 2010

Lada, Lombardi, Alves 2010

Which is determinant, N_H or Filament-Width?





Herschel filaments have almost the same radii!

Aquila: 2R=0.1pc & $M_L = 2C_s^2/G$ → $N_H \approx 10^{22}cm^{-2}$ (A_v= several)

Polaris: 2R=0.1pc & $M_L < 2C_s^2/G$ → $N_H < 10^{22}cm^{-2}$ (A_v< several)

"Column Density Threshold" is a consequence?

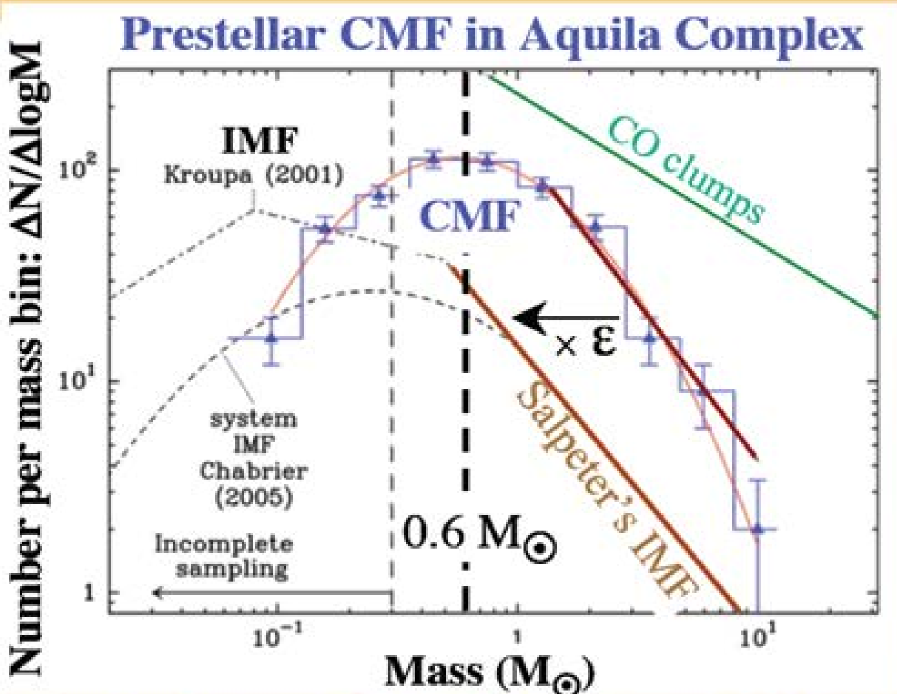
Onishi+, Lada+, etc.

From Ph. André's Slide

Filament fragmentation produces the prestellar CMF and accounts for the « base » of the IMF

Jeans/Bonnor-Ebert mass:

$M_{BE} \sim 0.6\ M_\odot \times (T/10\ K)^2 \times (\Sigma/150\ M_\odot pc^{-2})^{-1}$



André et al. 2010, Könyves et al. 2010
A&A Vol. 518

➤ The Jeans/Bonnor-Ebert mass at T ~ 10 K within marginally critical filaments with $\Sigma = \Sigma_{th} \sim 150\ M_\odot pc^{-2}$ is $M_{BE} \sim 0.6\ M_\odot$
→ characteristic stellar system mass $M_* = \varepsilon\ M_{core} \sim 0.2\ M_\odot$ for a typical efficiency $\varepsilon \sim 0.3$

(cf. Larson 1985's interpretation of the peak of the IMF)

Mass Function of Cores in a Filament

SI 2001, ApJ **559**, L149

Perturbation of Line-Mass of a Filamentary Cloud using Press-Schechter Formalism

Power Spectrum

$$P(k) \propto k^{-n}$$

Mass Function

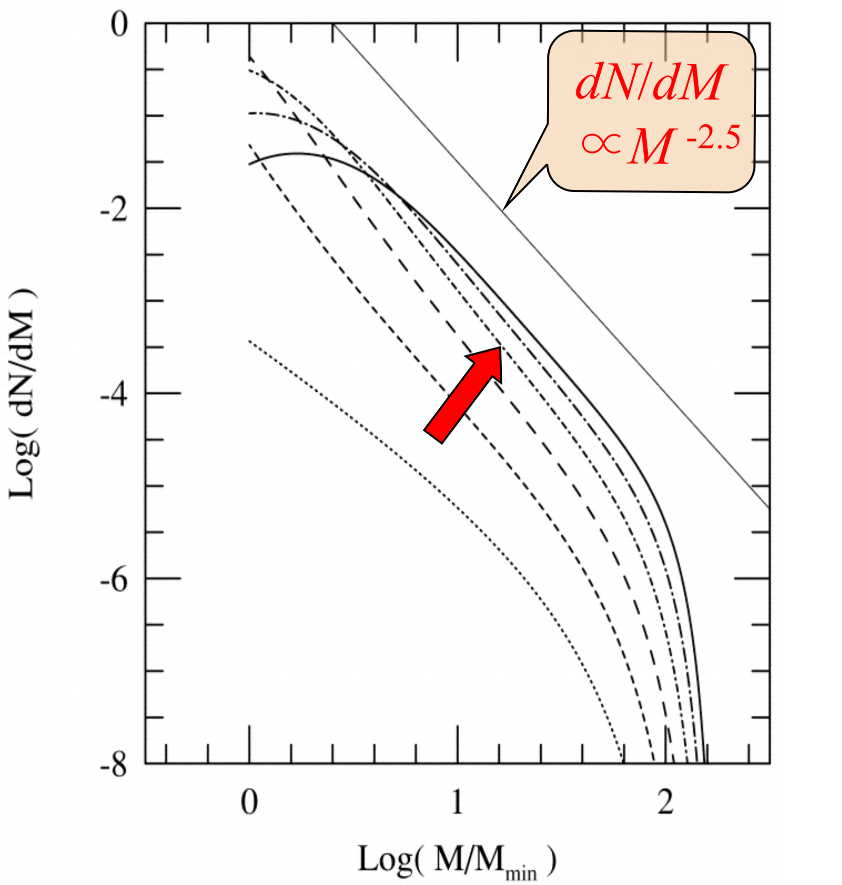
$$\frac{dN}{dM} = -2\frac{M_{\rm line}}{M}\frac{df(M,\ \delta > \delta_c)}{dM}$$

$$= -\frac{M_{\rm line}}{M}\frac{\delta_c}{\sqrt{\pi}}\exp\left(-\frac{\delta_c^2}{2\sigma_M^2}\right)\frac{1}{\sigma_M^3}\frac{d\sigma_M^2}{dM}$$

Observation of Both Perturbation Spectrum and Mass Function

➔direct test !

cf. Hennbelle & Chabrier Theory

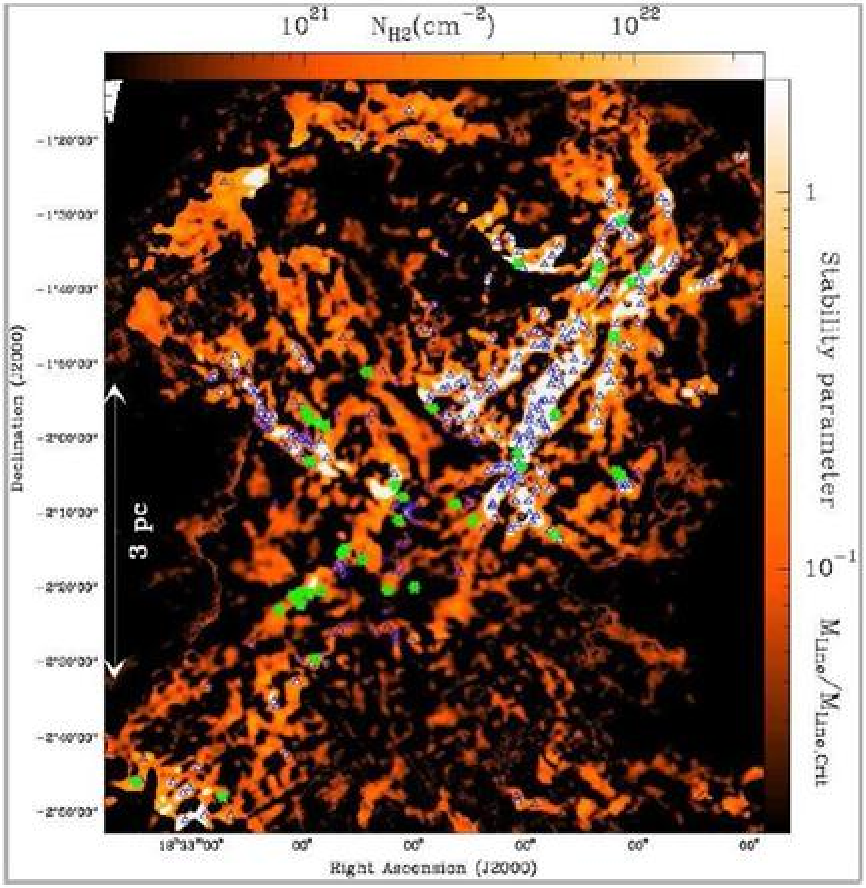


$P(k) \propto k^{-1.5}$

t/t_{ff} = 0 (dotted) , 2, 4, 6, 8, 10 (solid)

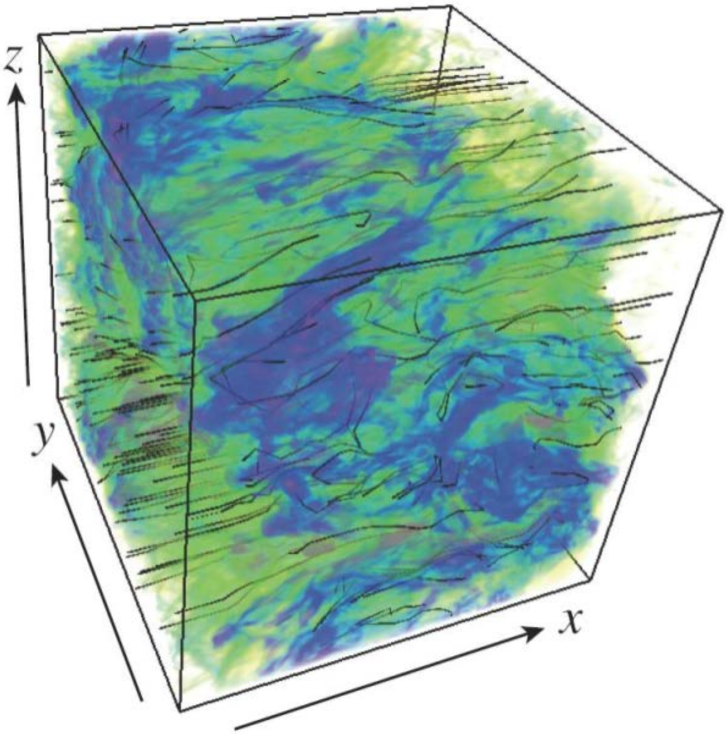
Observation shows $P(k) \sim k^{-1.6}$ (Andre+2013, PPVI)

What is missing?



$M_{\mathrm{filament}} << M_{\mathrm{envelope}}$

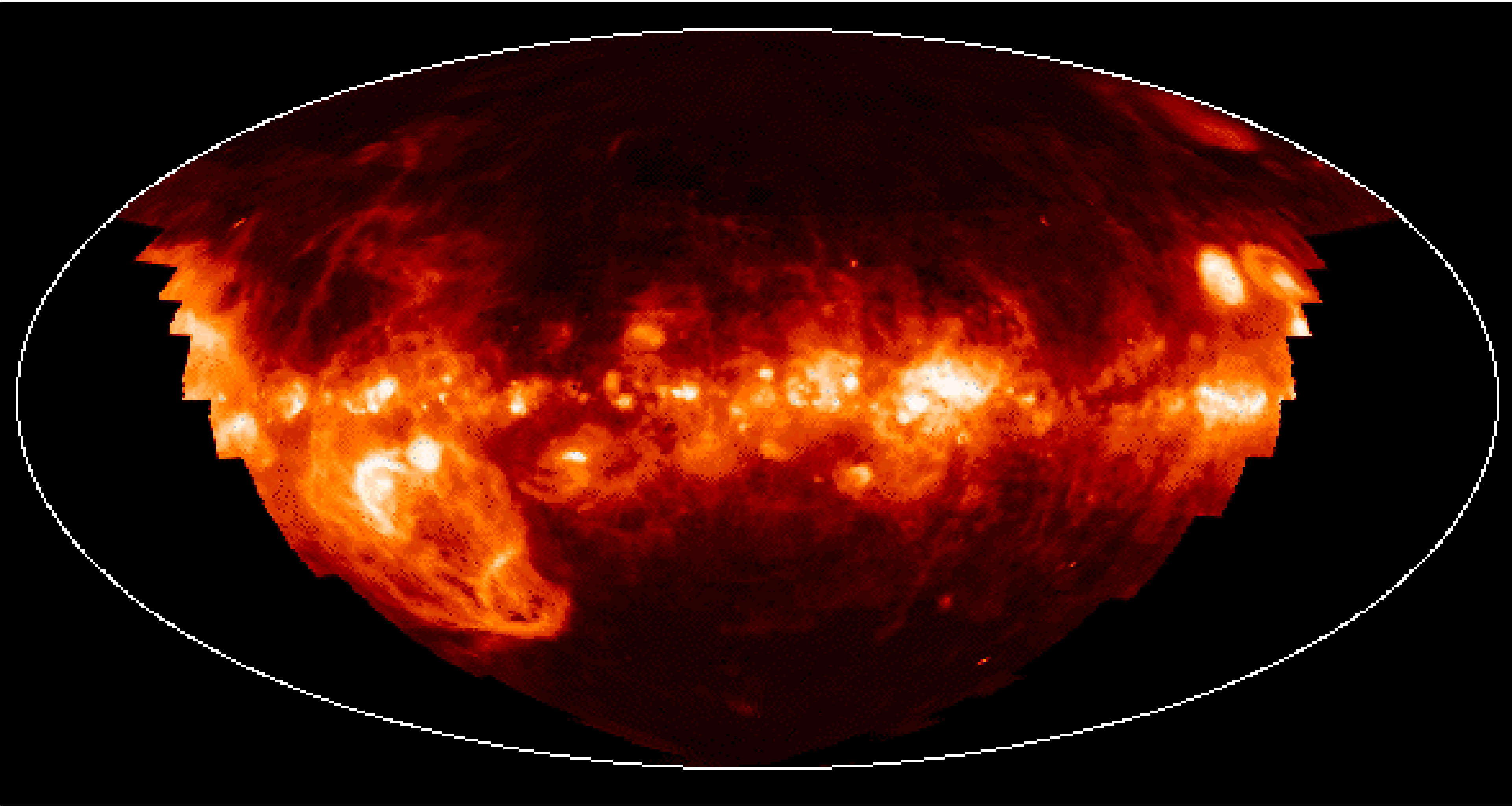
Formation of Molecular Clouds



Converging Flow into 2-Phase Medium

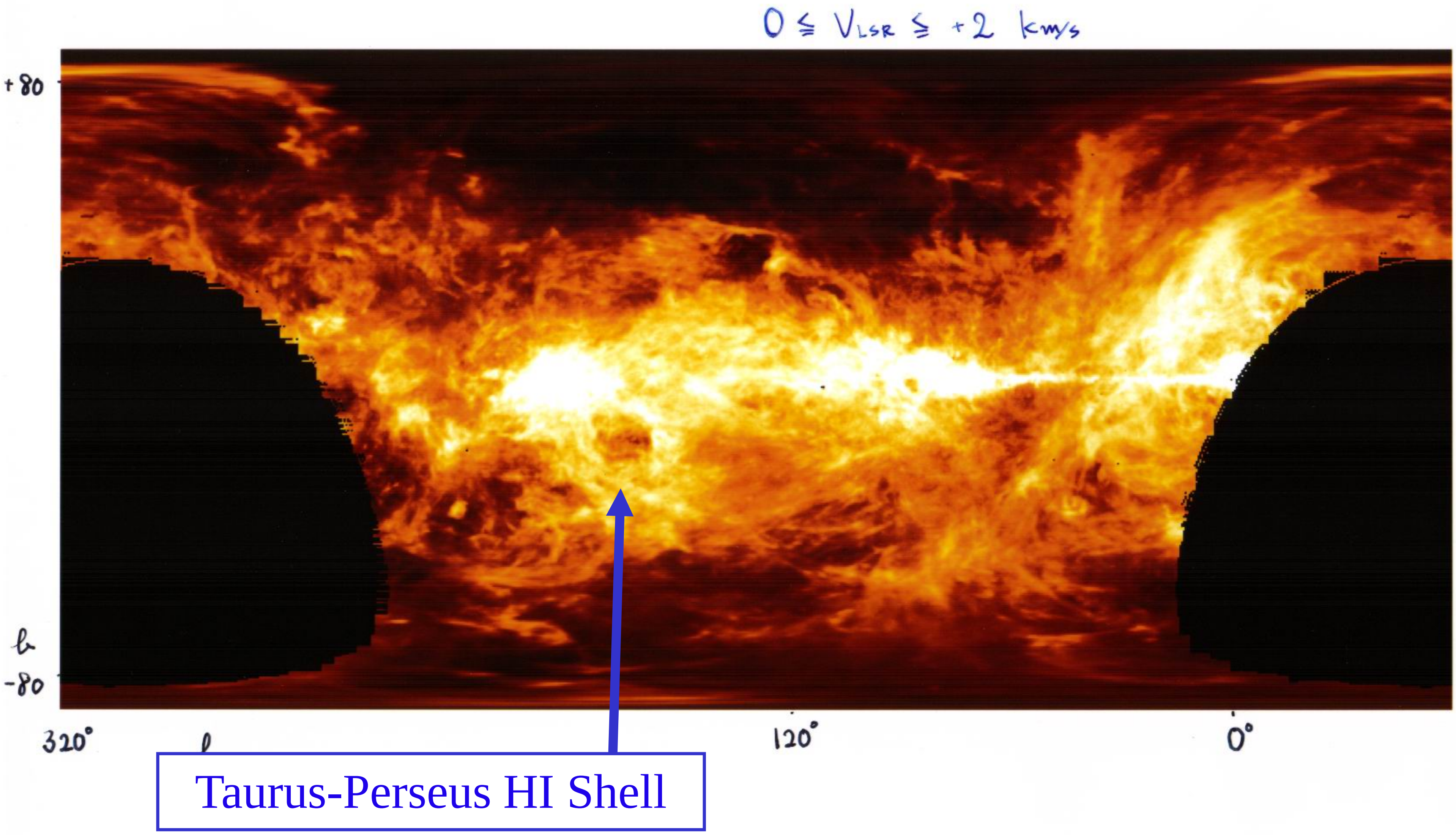
Inoue & SI (2012)

Hα View of Our Galaxy



Wisconsin H-alpha Mapper (WHAM) ; Haffner et al. (2003)

銀河内での中性水素原子の分布

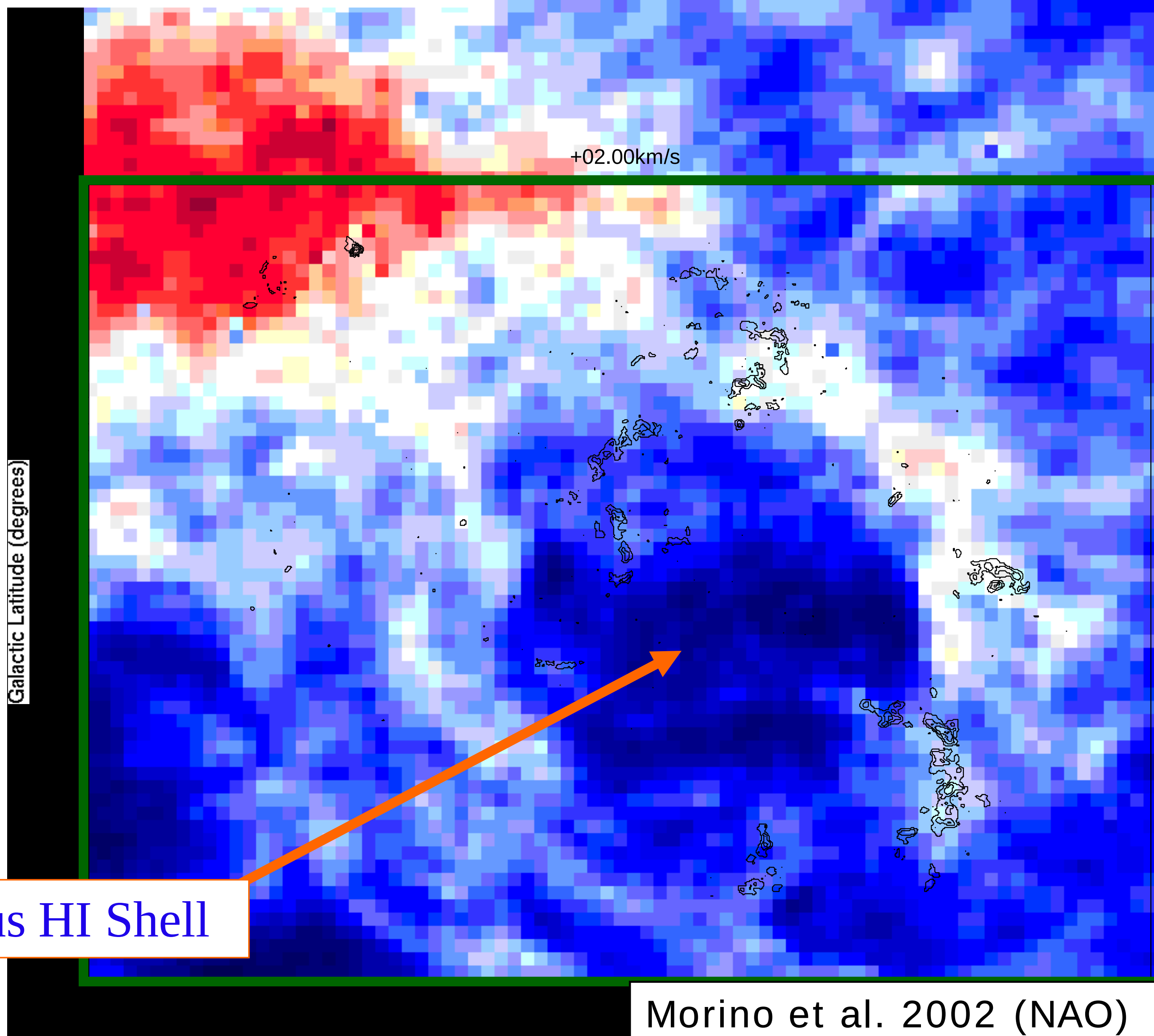


Hartmann & Burton 1997

中性水素ガス雲と分子雲

+2 km/sの成分

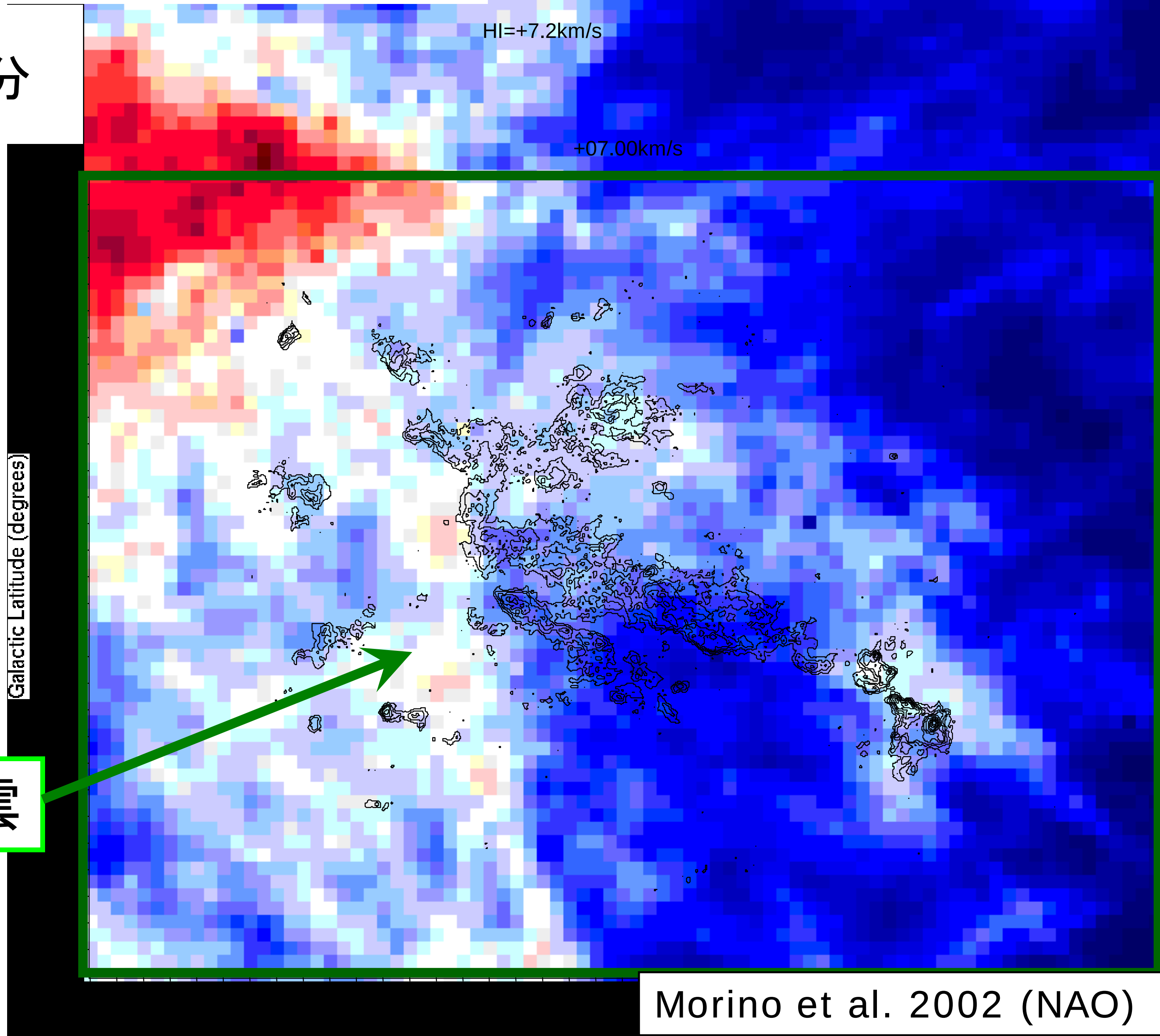
HIで直径15度の穴が存在。その周囲にCOガスが分布する。



中性水素ガス雲と分子雲

+7 km/sの成分

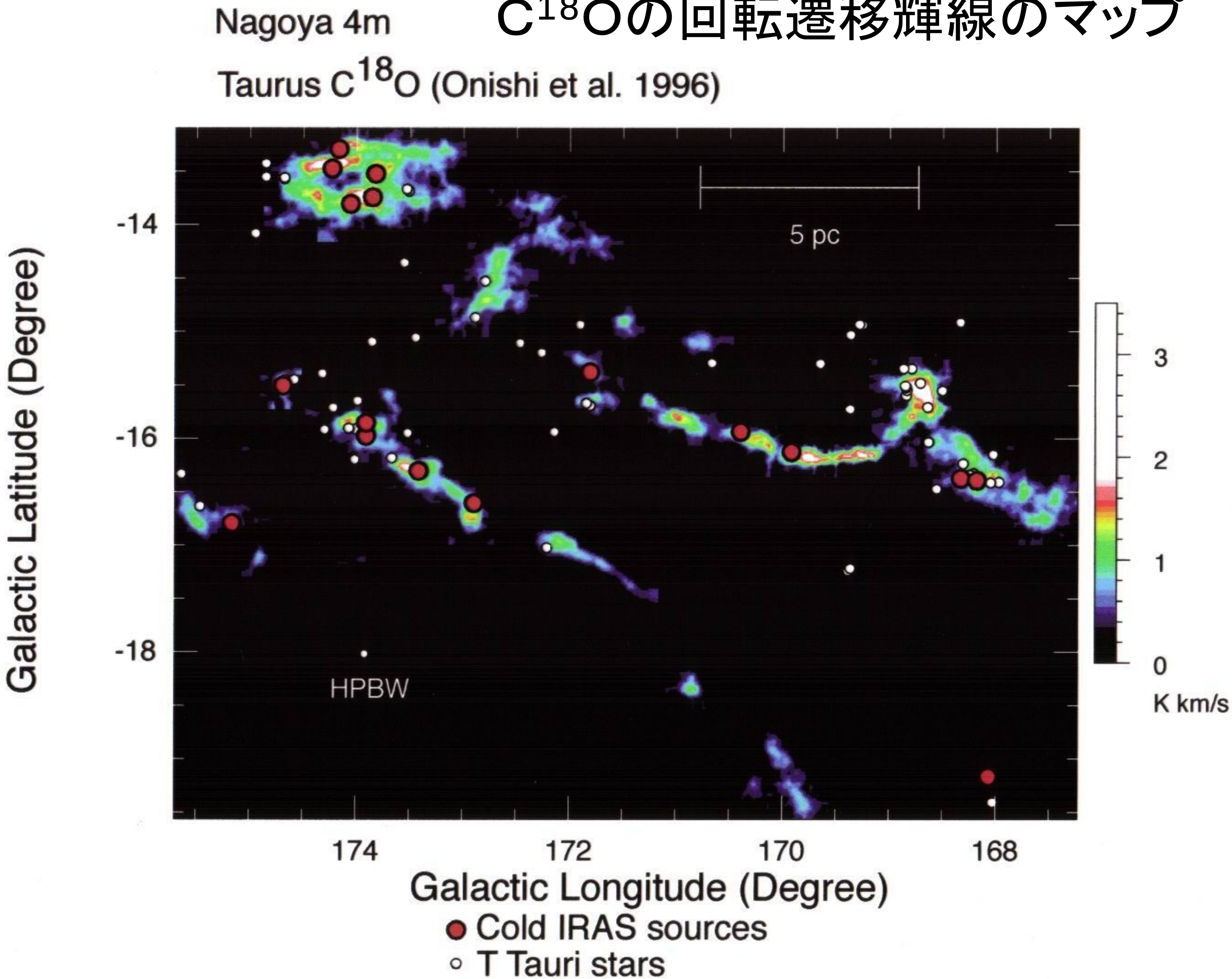
等高線はCOの回転遷移輝線のマップ



牡牛座分子雲

Morino et al. 2002 (NAO)

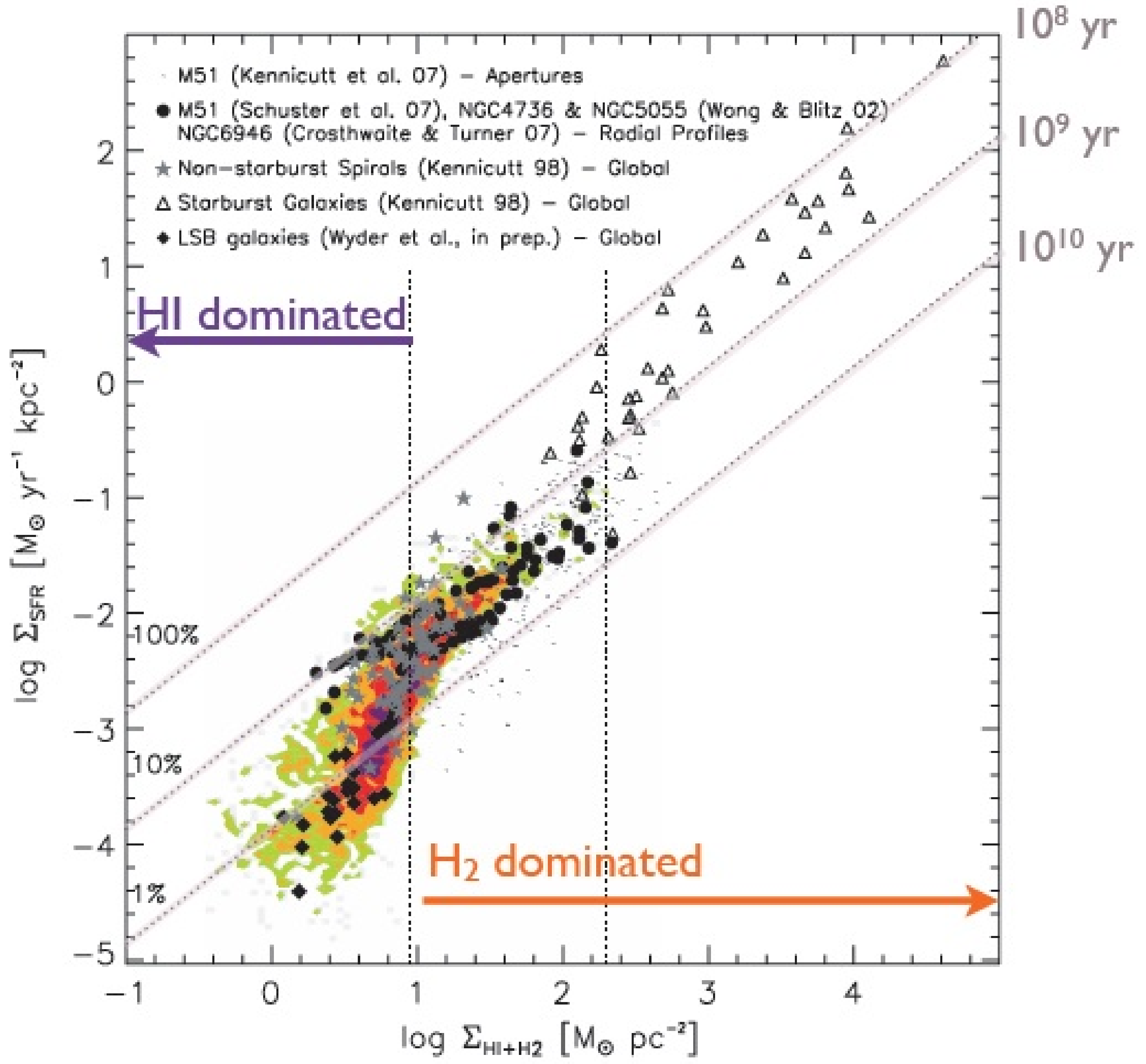
$C^{18}O$の回転遷移輝線のマップ



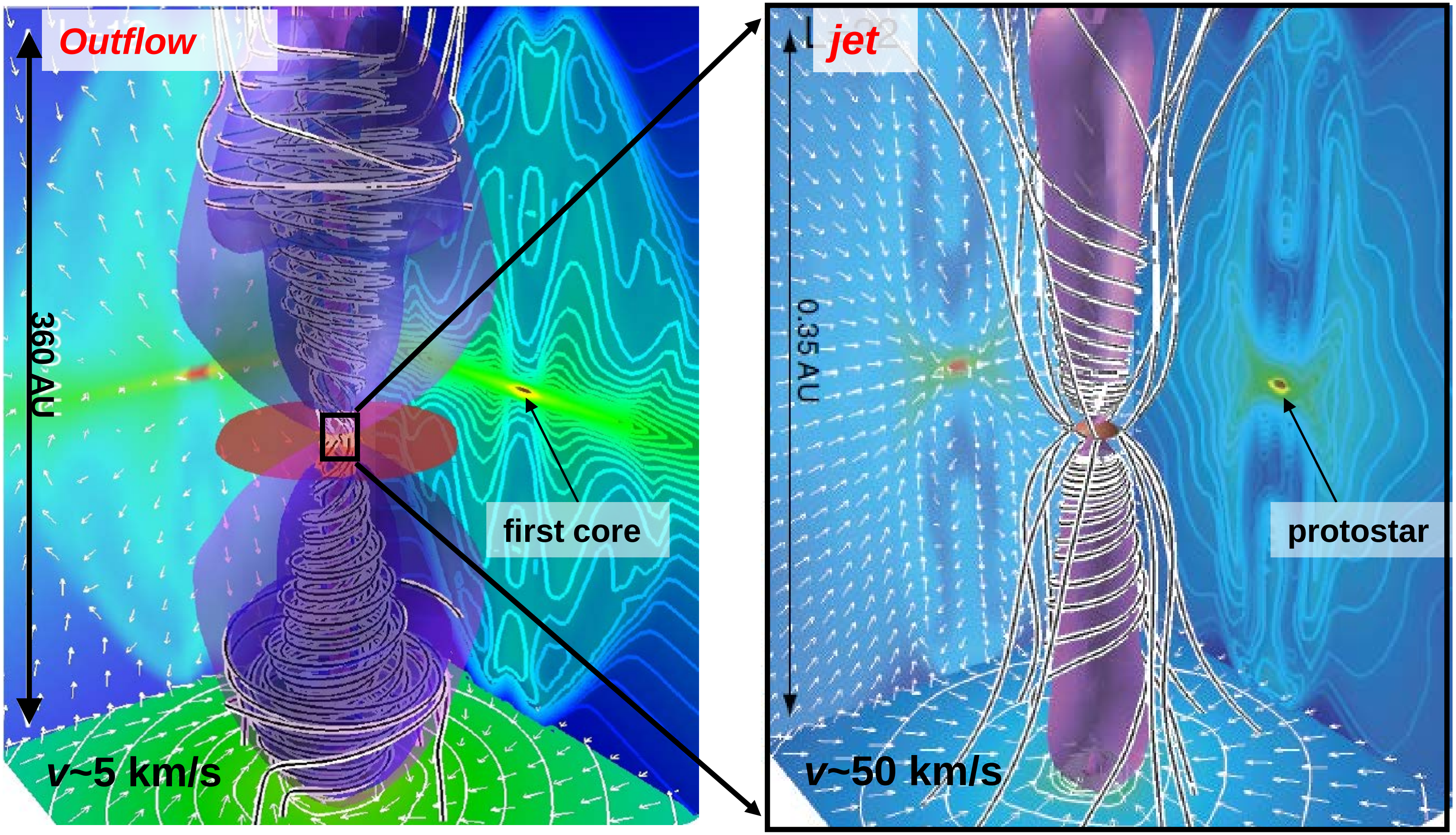
Column Density Threshold?

Bigiel+2008

AJ **136**, 2846



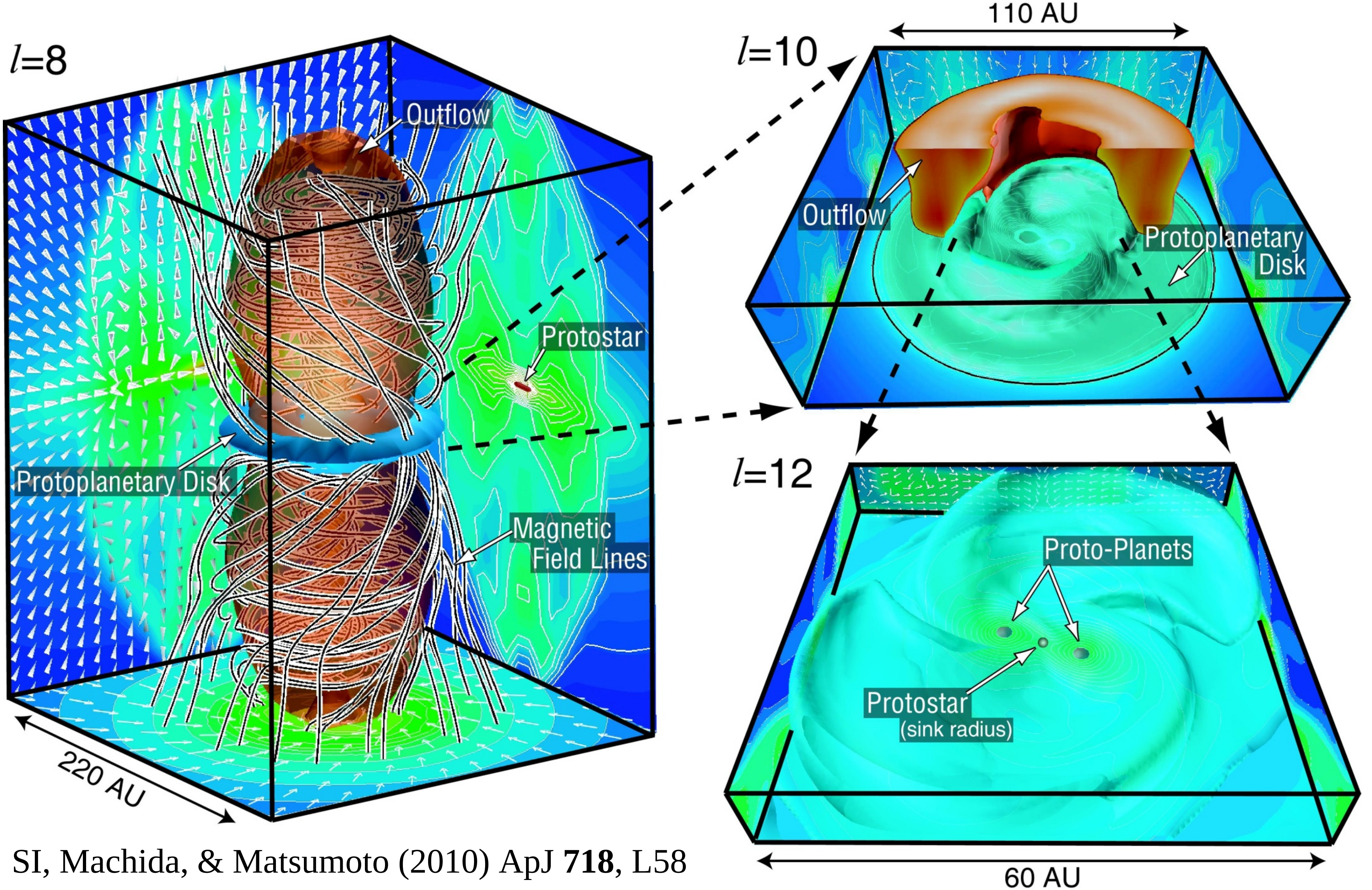
Part 1: Protostellar Collapse Phase



Machida et al. (2006-2009), Banerjee & Pudritz (2006), Hennebelle & Fromang (2008)

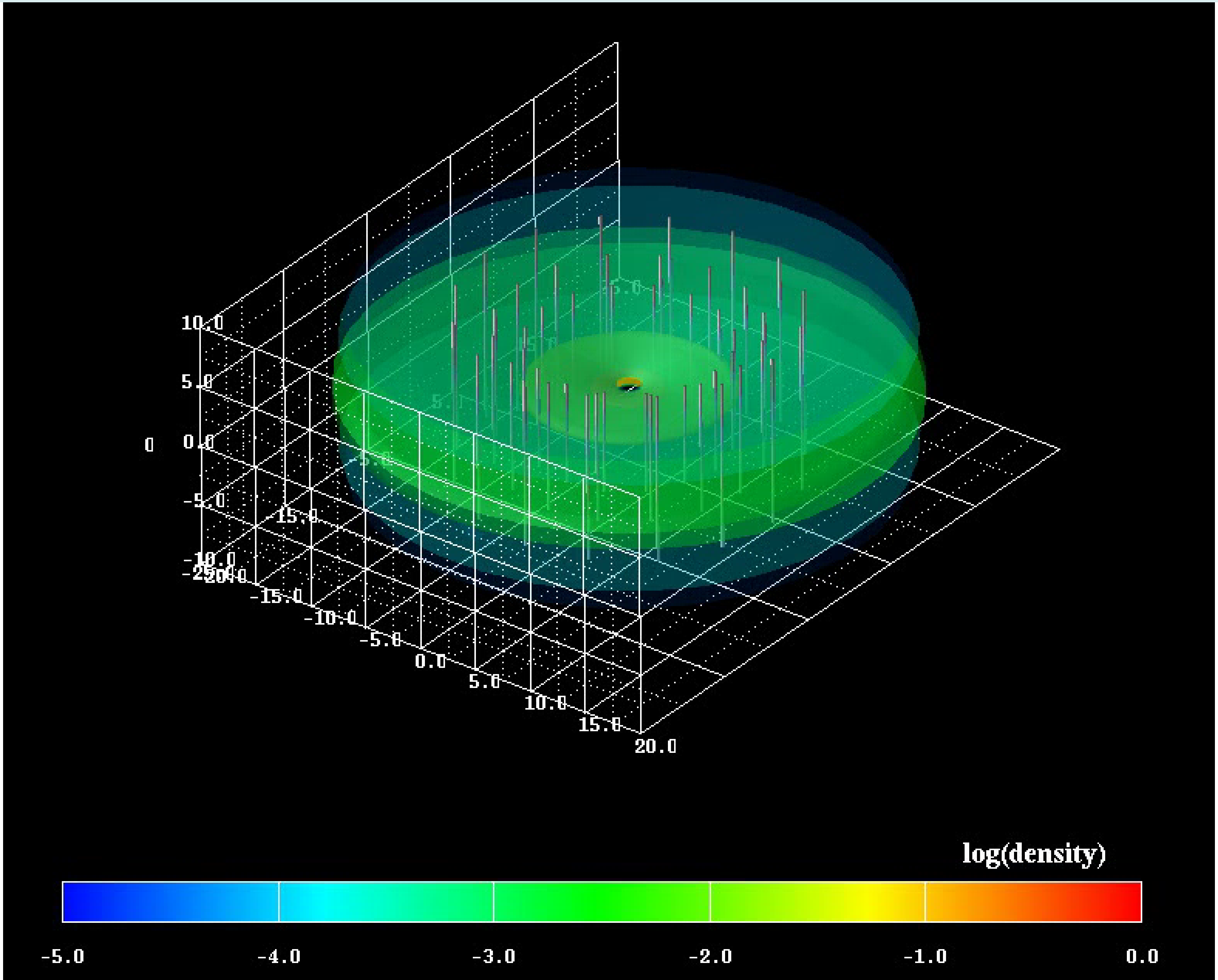
Outflows & Jets are Natural By-Products!

Resistive MHD Calc. 分子雲コアから惑星へ



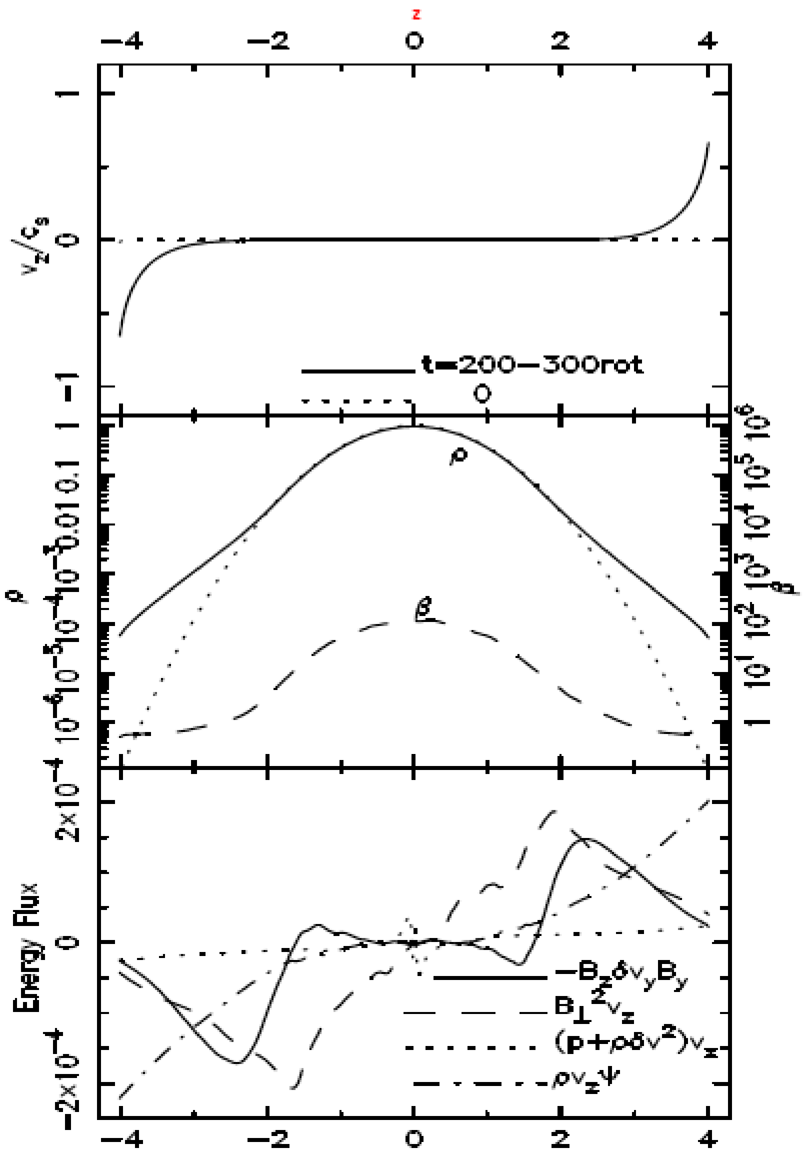
SI, Machida, & Matsumoto (2010) ApJ **718**, L58

Global Disk Simulation

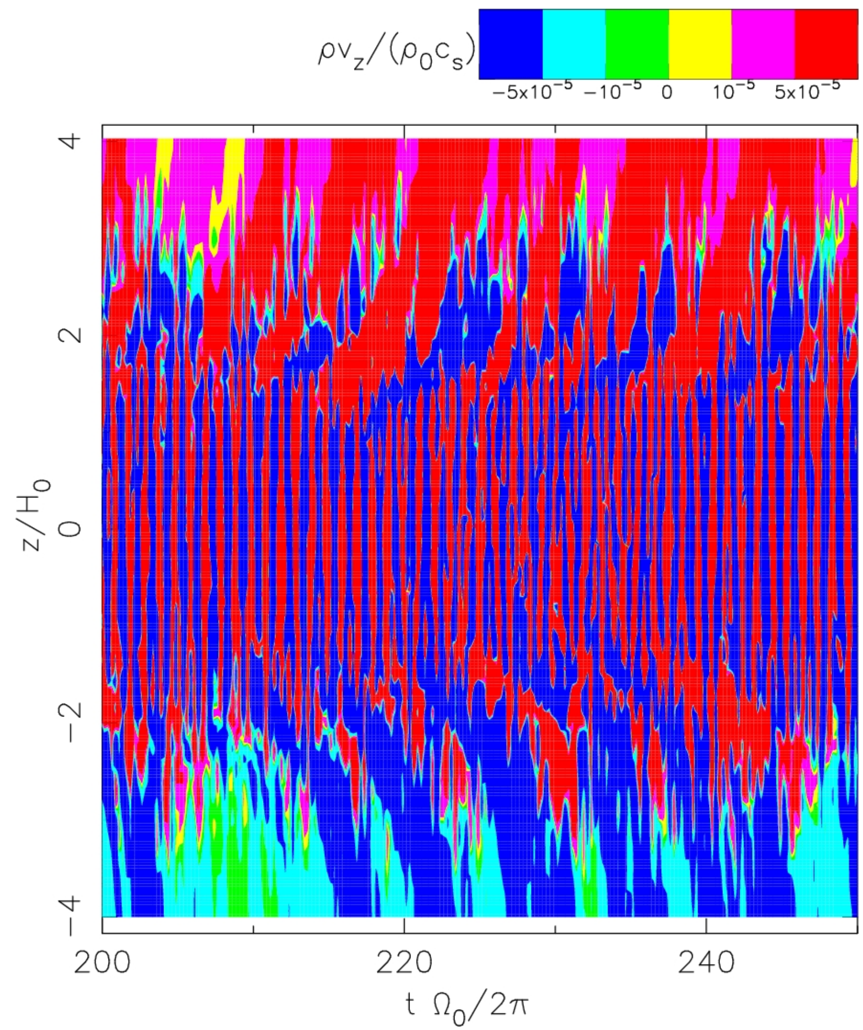


Global Calculation by T. K. Suzuki (2010)

円盤風のz軸方向プロファイル



Distance from Midplane, Z



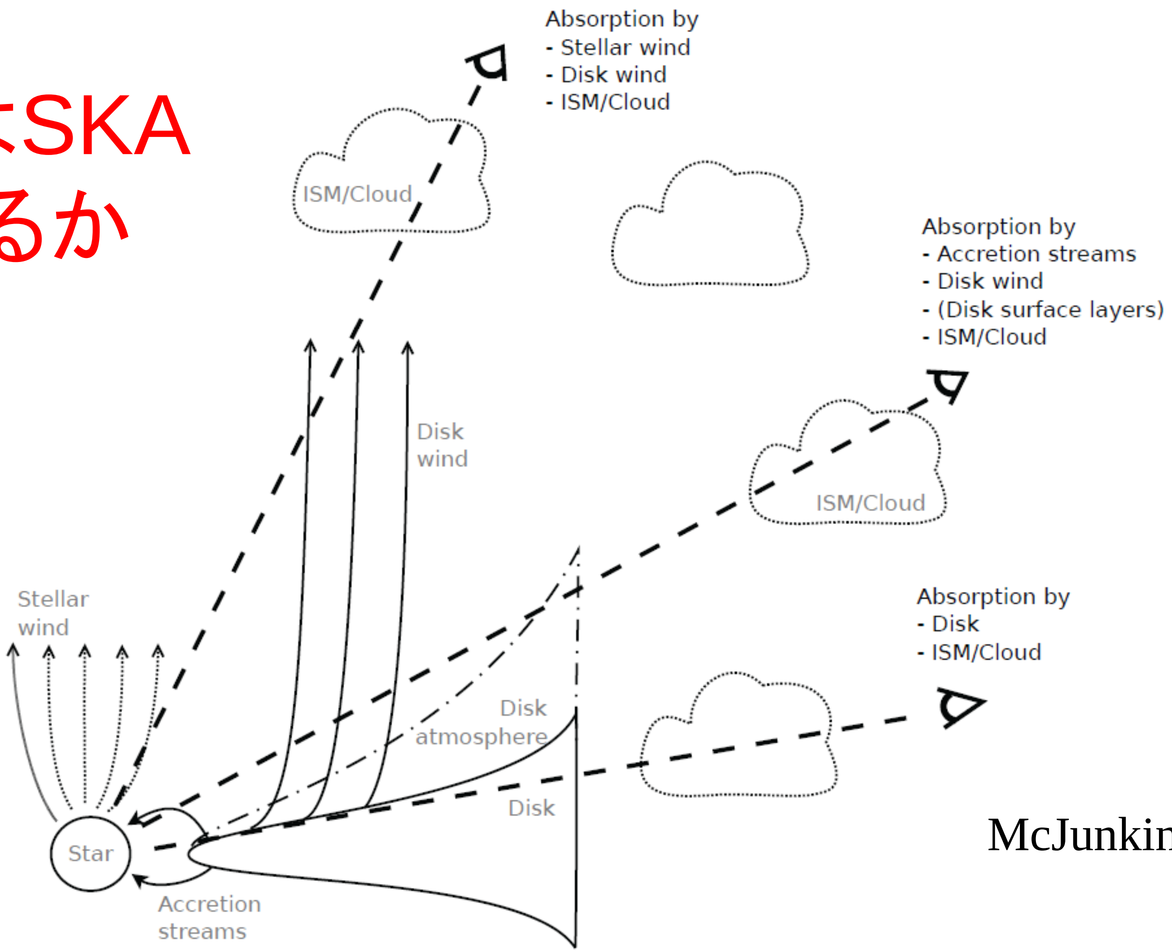
Suzuki & Inutsuka (2009) ApJ **691**, L49

惑星形成の最終段階:Disk Dispersal

Disk Windではガスだけが消失する

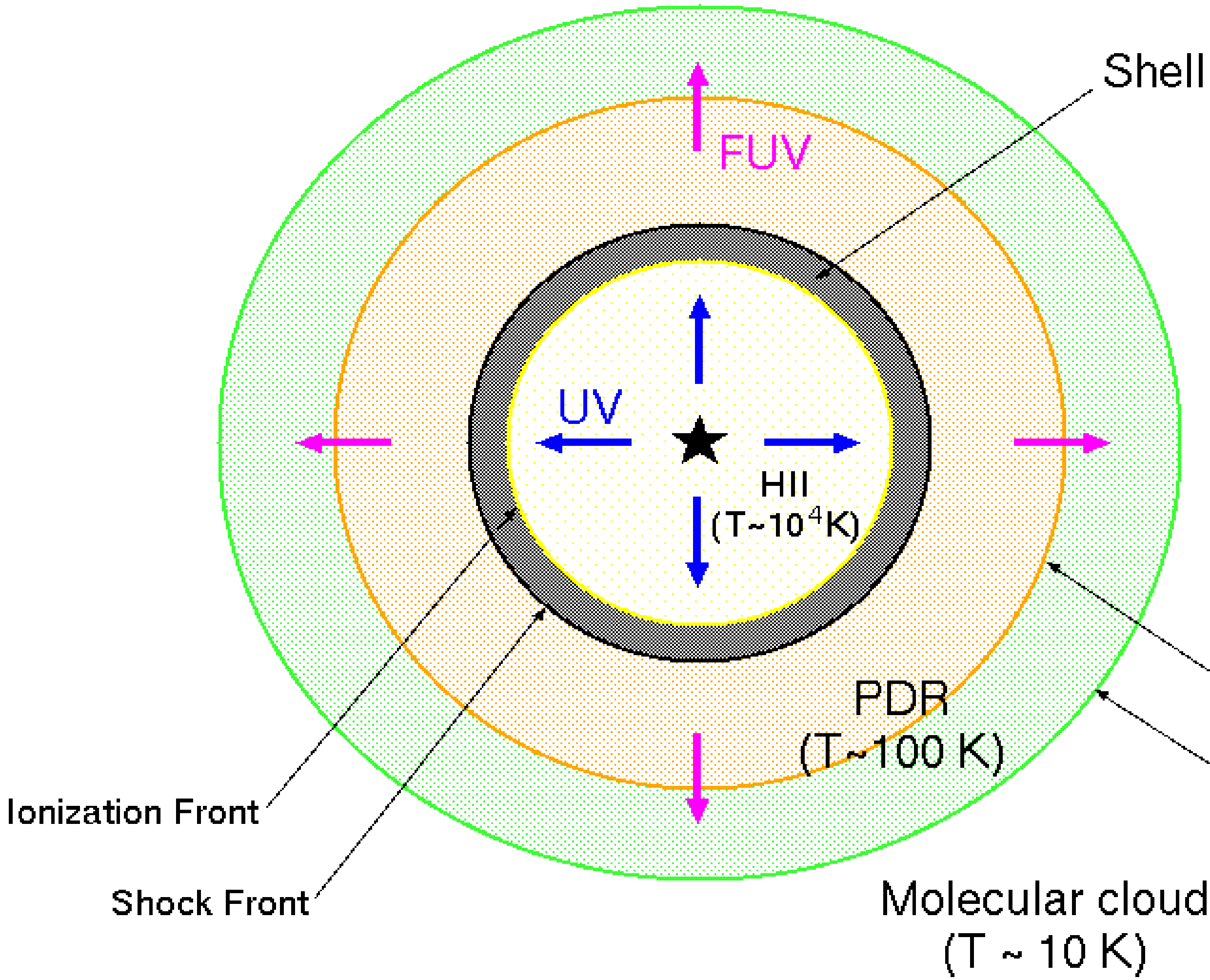
Suzuki, Muto & SI (2010) ApJ **718** 1289

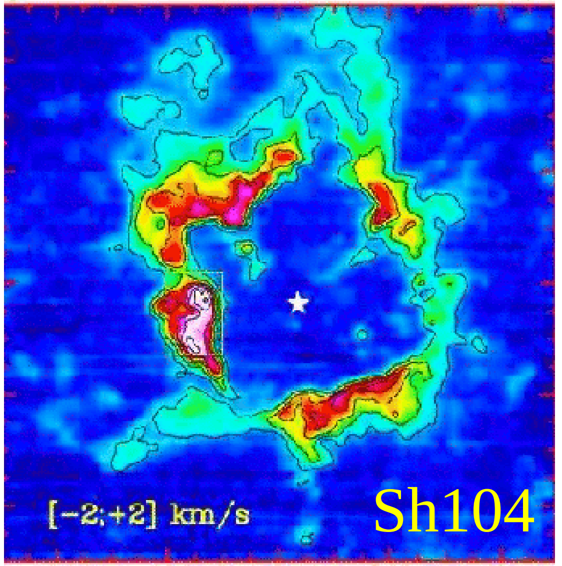
HI輝線はSKA
で見えるか



McJunkin, France+ (2014)
arXiv:1312.1650

HII Region in Molecular Cloud





- study the physical/chemical structure of the shell
- Does molecular gas accumulates in the shell shielding FUV photons?

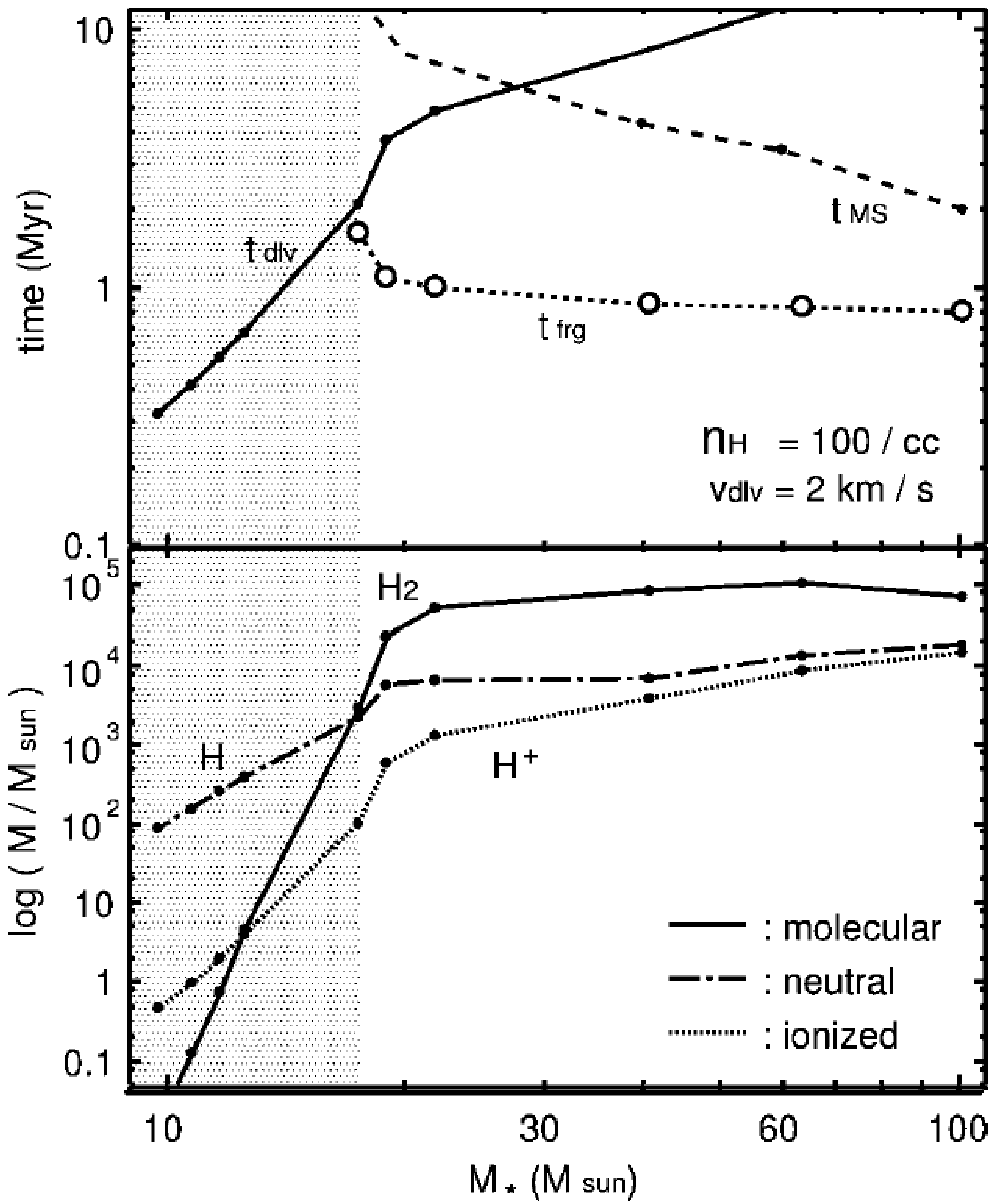
星形成の終焉 周りはHIに

If $M_* > 20 M_o$,

then number of massive stars increases exponetially.

➔ Star Burst

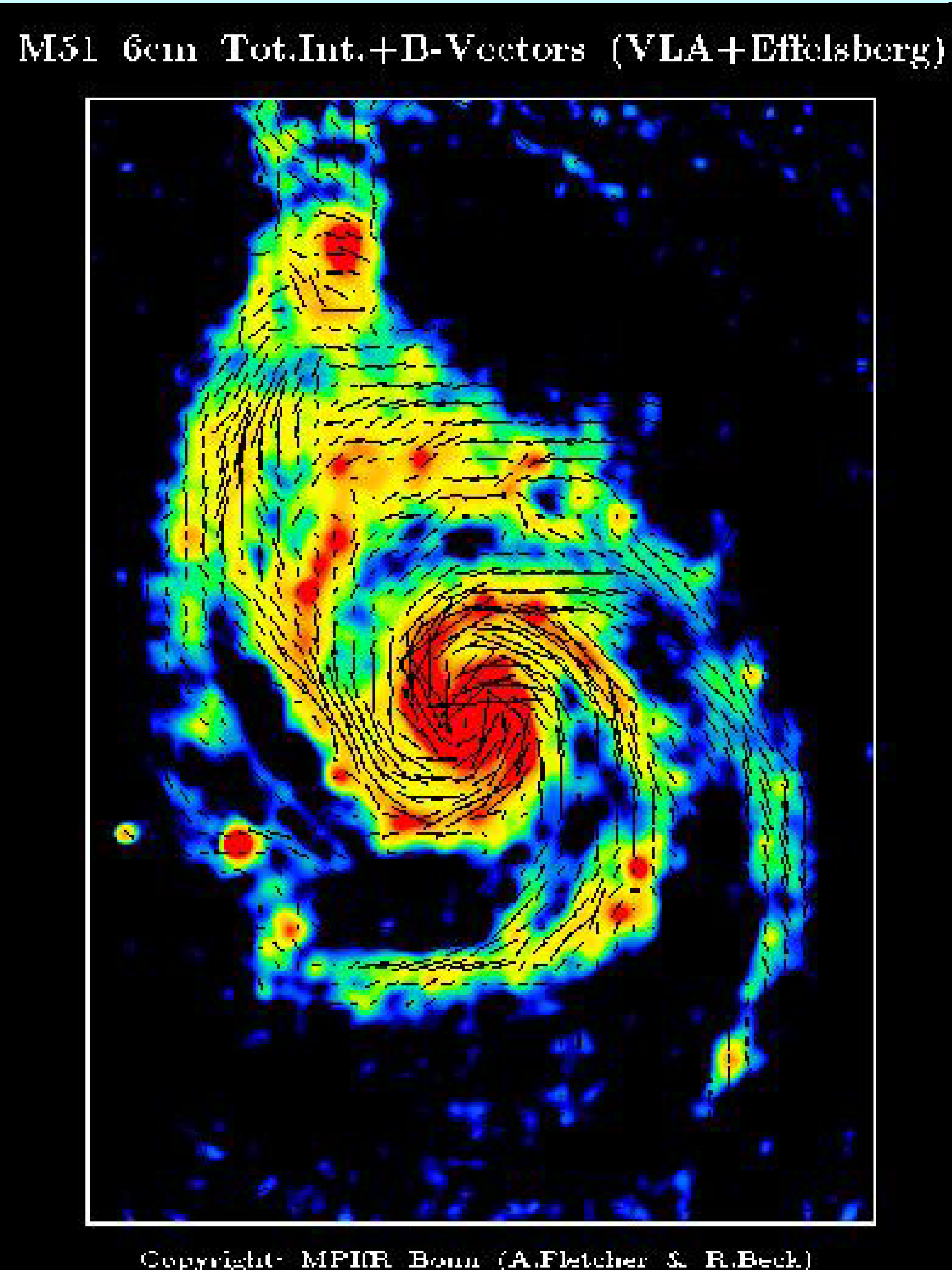
Hosokawa & SI (2006) ApJ **648**, L131

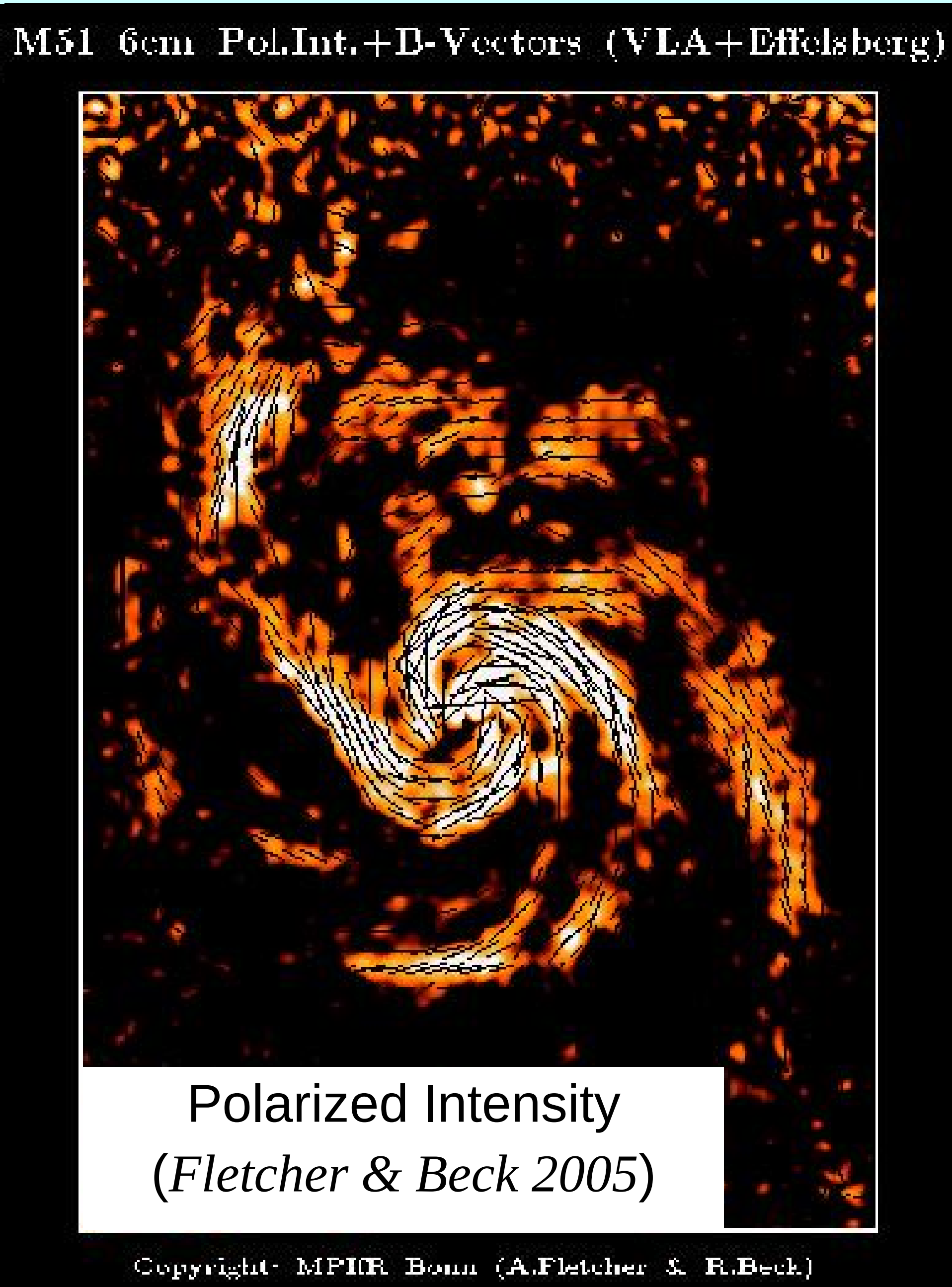


第3部

- 高エネルギー天体物理との接点
  - 超新星残骸
  - 粒子加速

M51 Synchrotron

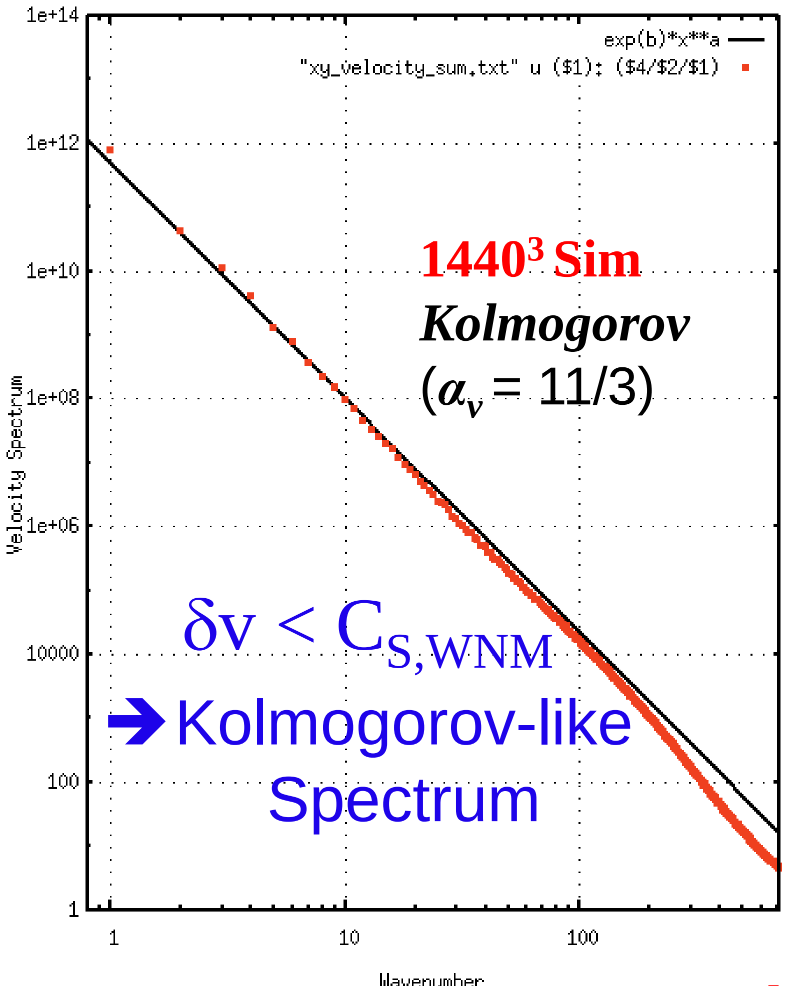


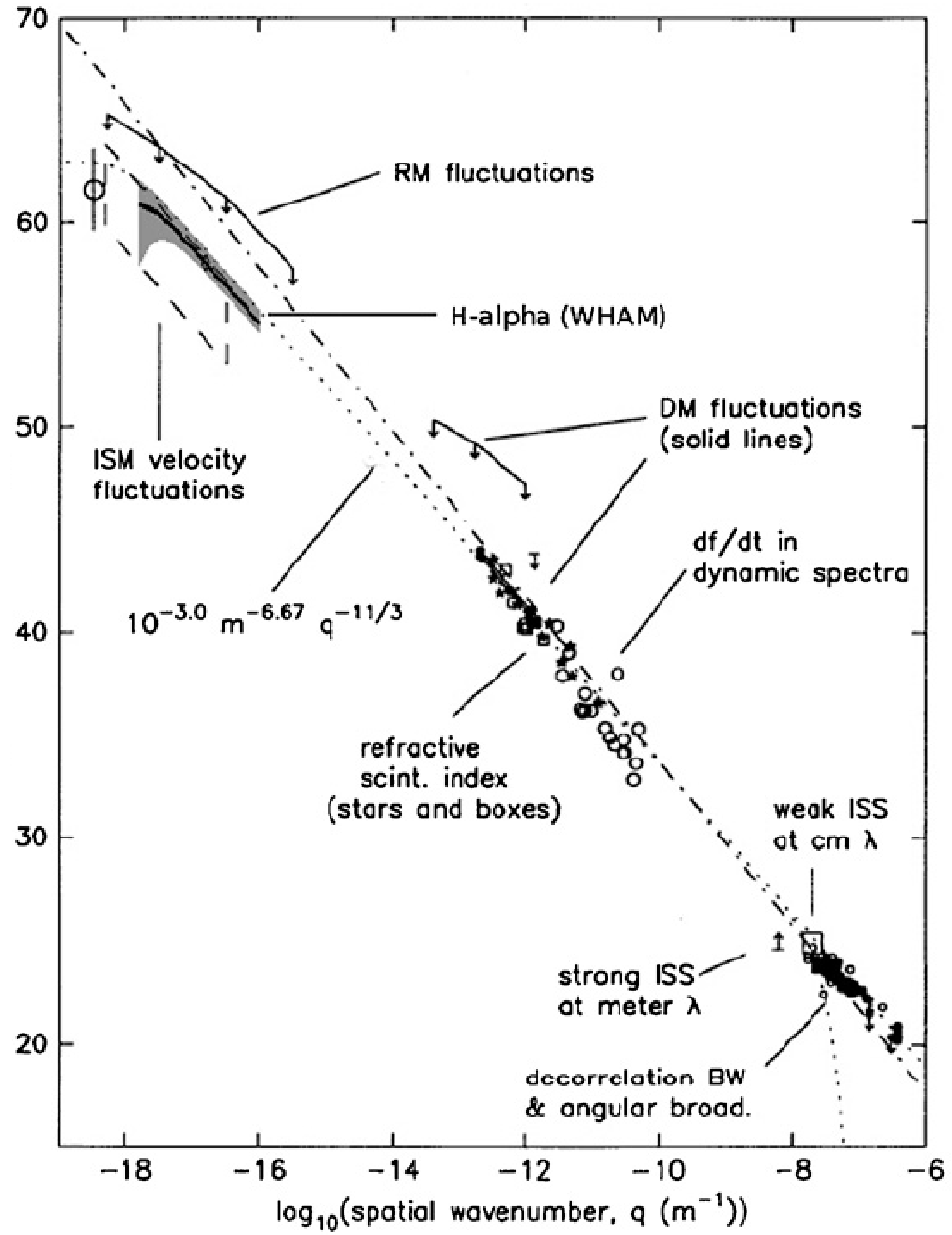


Polarized Intensity
(*Fletcher & Beck 2005*)

Property of 3D "Turbulence"

Muranushi, Inoue & SI 2014 in prep.





Good Agreement!

Chepurnov & Lazarian 2010
Armstrong et al. 1995

Mystery: Energy Equipartition?

銀河系の中のエネルギー分布

– 銀河系内の（単位体積当り）星起源の輻射場のエネルギーは, $E_{\gamma,\mathrm{stellar}} \sim 10^0$ eV/cc

$$E_{\gamma,\,星} \sim E_{\mathrm{th,\,gas}} \sim E_{乱流} \sim E_{宇宙線} \sim E_{磁場} \gtrsim E_{\mathrm{CMB}}$$

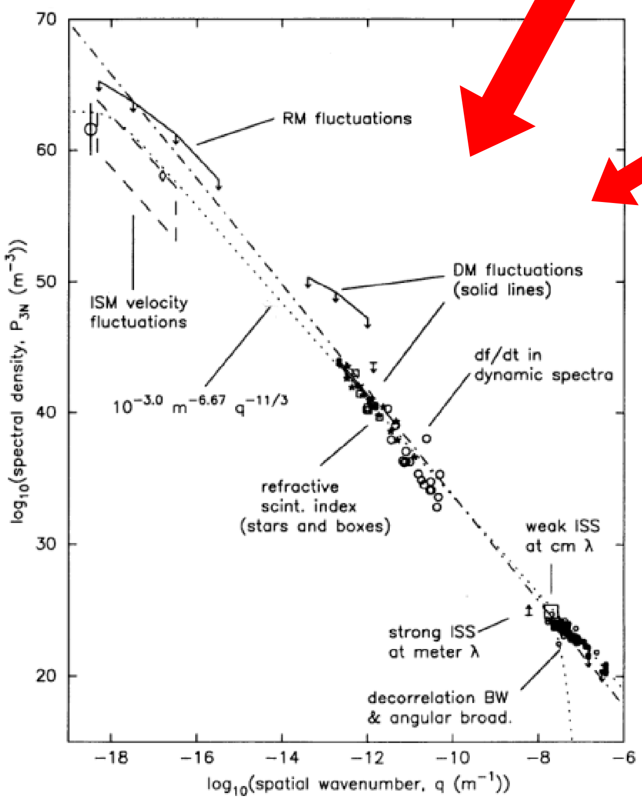
「～」の意味は±１桁程度の精度で… 理由は不明？

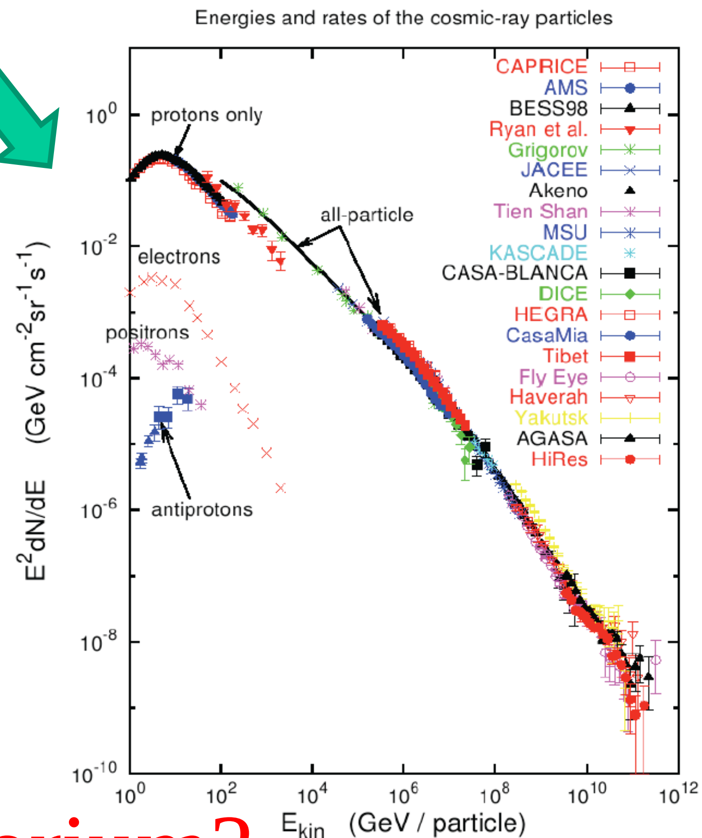
Overall Equilibrium???

Spectrum of Various Components

Every component has energy density ~ 10^0 eV/cc .

$$E_{\gamma,\,\mathrm{stellar}} \sim E_{\mathrm{th,\,gas}} \sim E_{\mathrm{turb}} \sim E_{\mathrm{CR}} \sim E_{\mathrm{mag}} \gtrsim E_{\mathrm{CMB}}$$





A New Type of Quasi-Equilibrium?

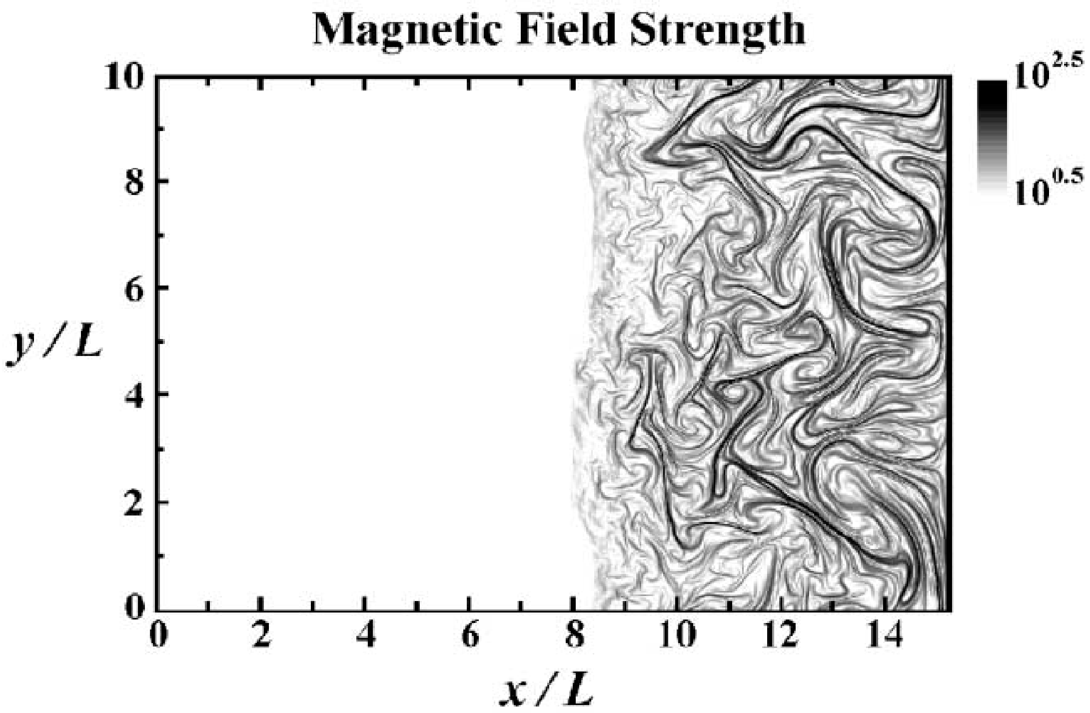
Supernova Explosion in Multi-Phase ISM

Shock waves can create turbulence in inhomogeneous pre-shock gas even without cooling!

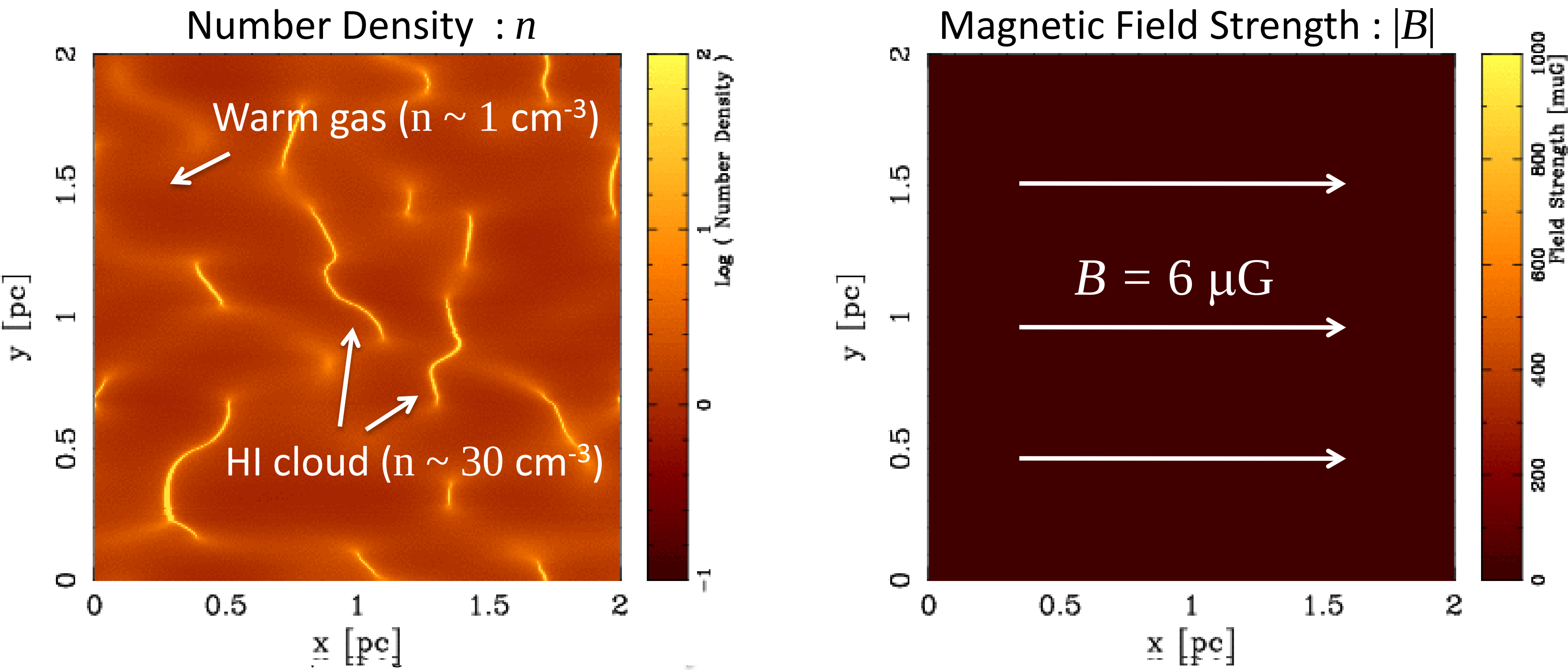
Giacalone & Jokipii 2007

$t_{\text{growth}} < t_{\text{cooling}}$

輻射冷却は
無視できる



Supernova Shock in Multi-Phase ISM



$$\nabla \rho \times \nabla p \neq 0 \rightarrow \text{Vorticity Creation } (\delta v \sim c_s)$$

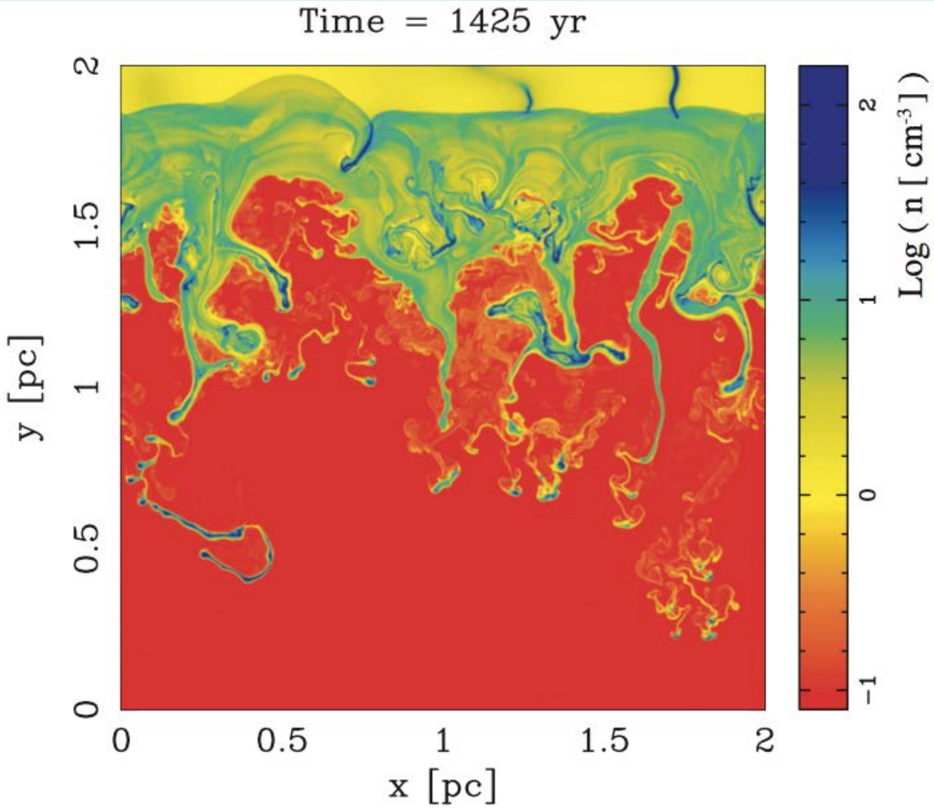
Magnetic Field Amplification via Turbulent Dynamo

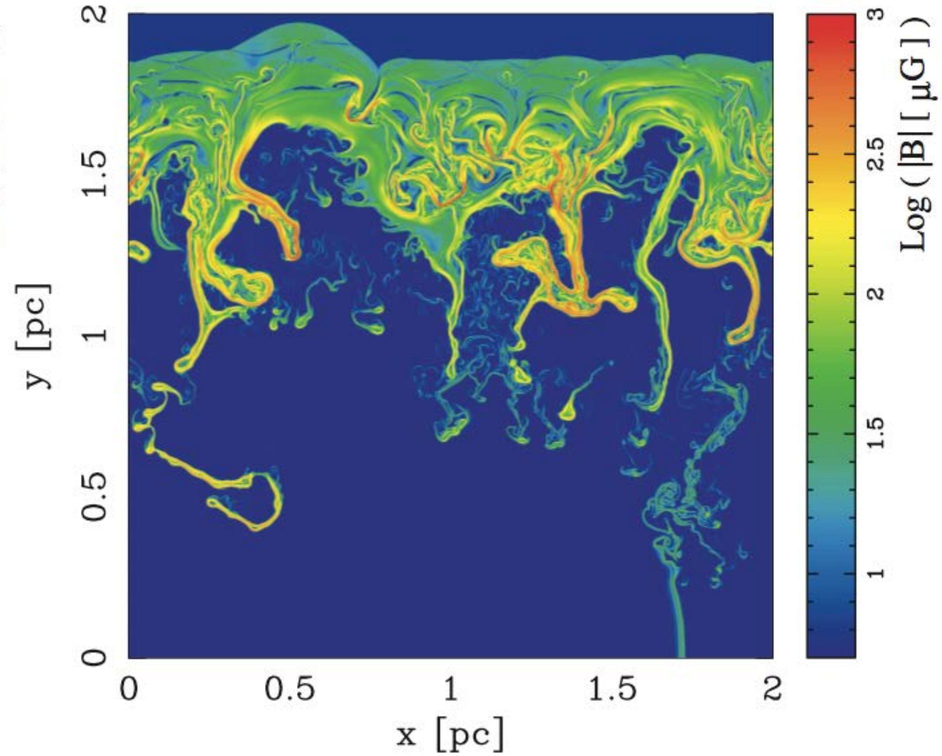
$$B_{max} \sim 1\text{mG} \quad (\beta \sim 1 \text{ @post shock})$$

Mach # > 10^4

Inoue, Yamazaki, & SI (2009) ApJ 695, 825

B~mG important for CRs





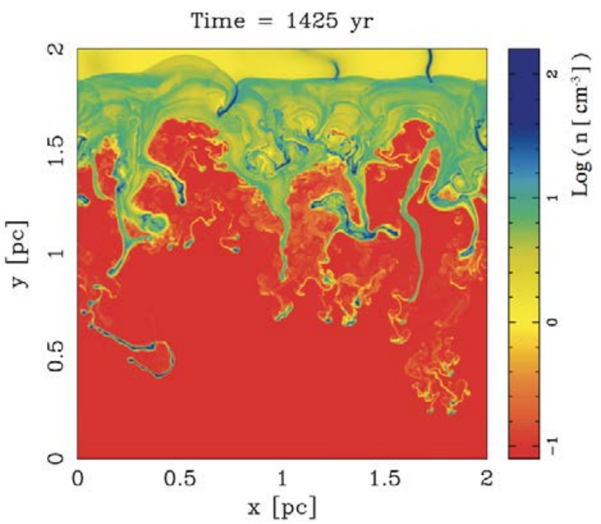
Inoue, Yamazaki, & SI (2009) ApJ 695, 825; (2010) ApJ 723, L108

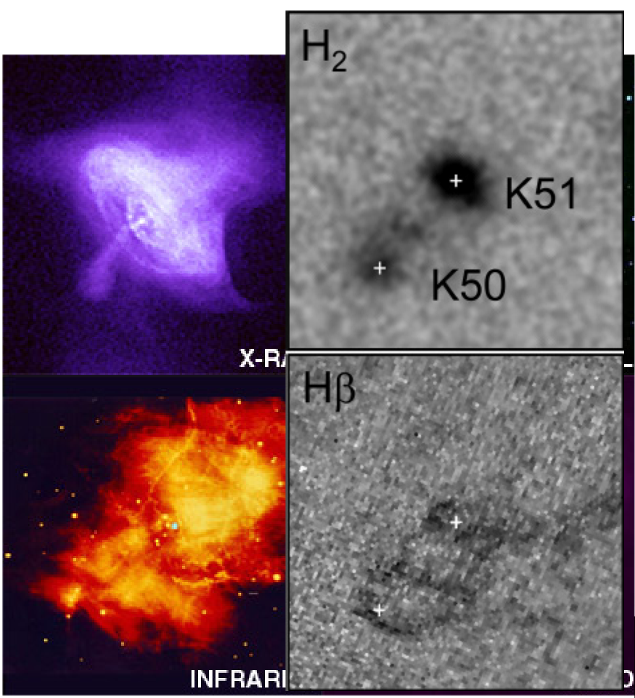
➔X-ray Observations of Supernova@age~10^3yr

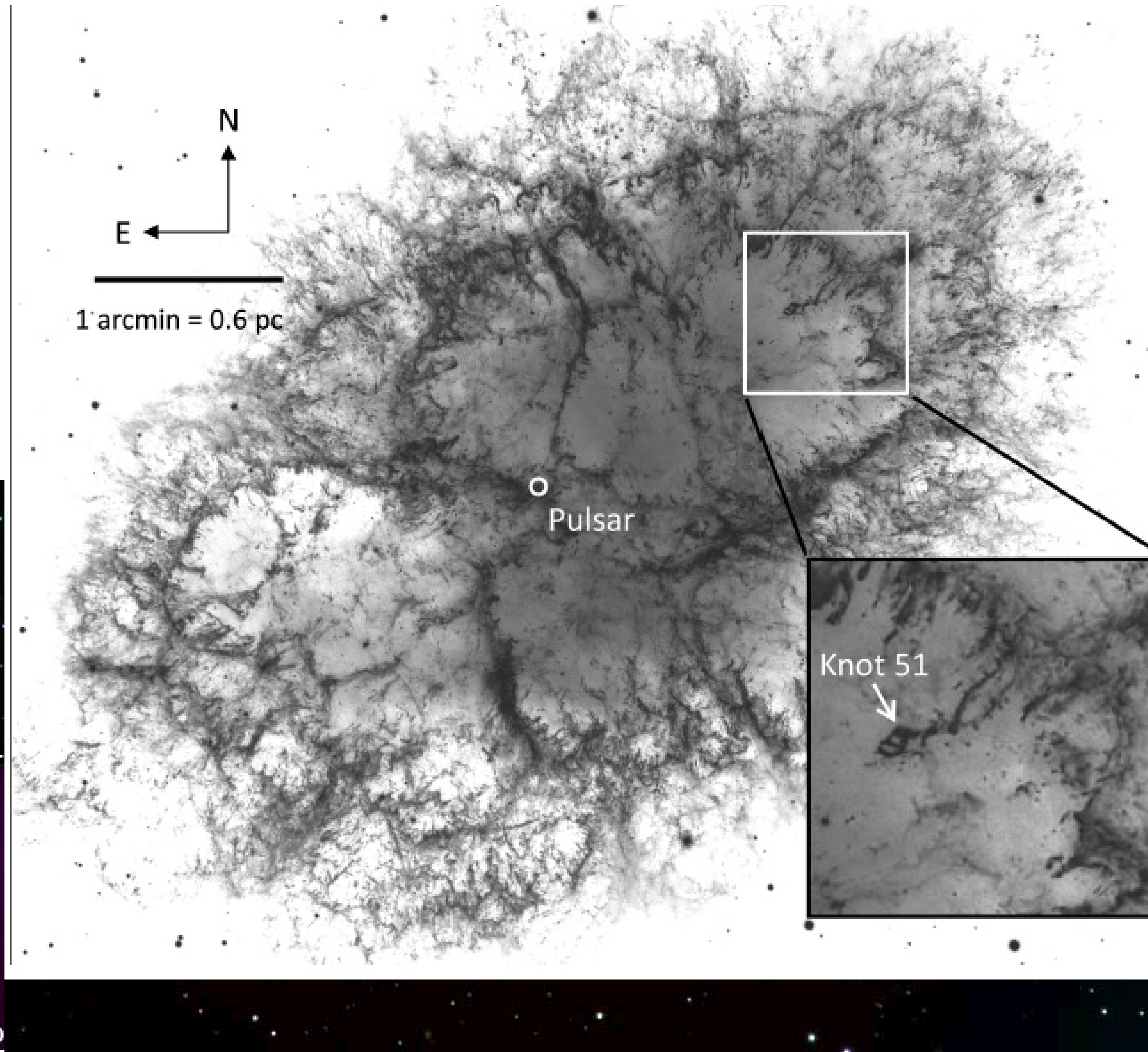
B ~ 1mG (Bamba+2002, Uchiyama+ 2008, etc.)

Crab Nebula in Multi-Phase ISM

Richardson+2013







Summary

- Phase Transition Dynamics
  - Transition Layer Width = λ_F
  - MC Formation Timescale $\sim 10^7$yr?
    - Observable as Spiral Structures
- Filaments & Star Formation
  - Star Formation Threshold
    - Various Environments... Observable
  - Planet Formation
- High Energy Astrophysics
  - SN Explosion in Multi-Phase ISM
  - CR acceleration Observable