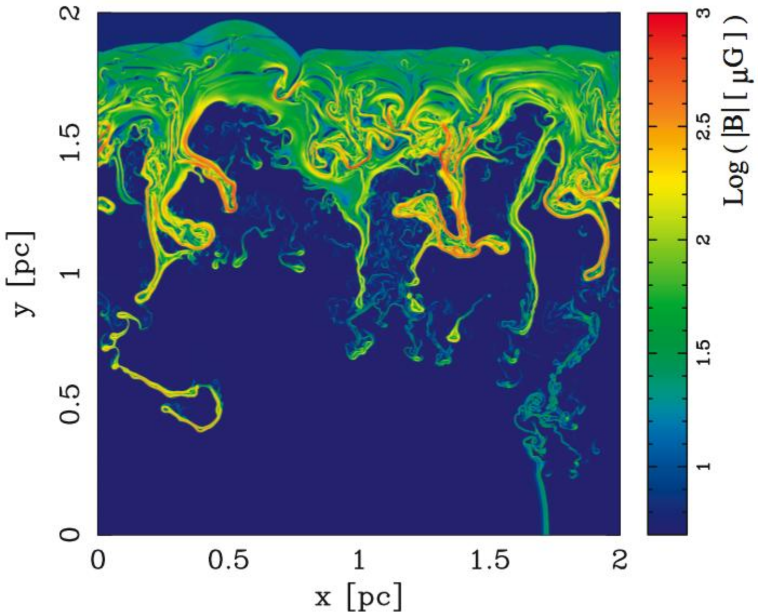
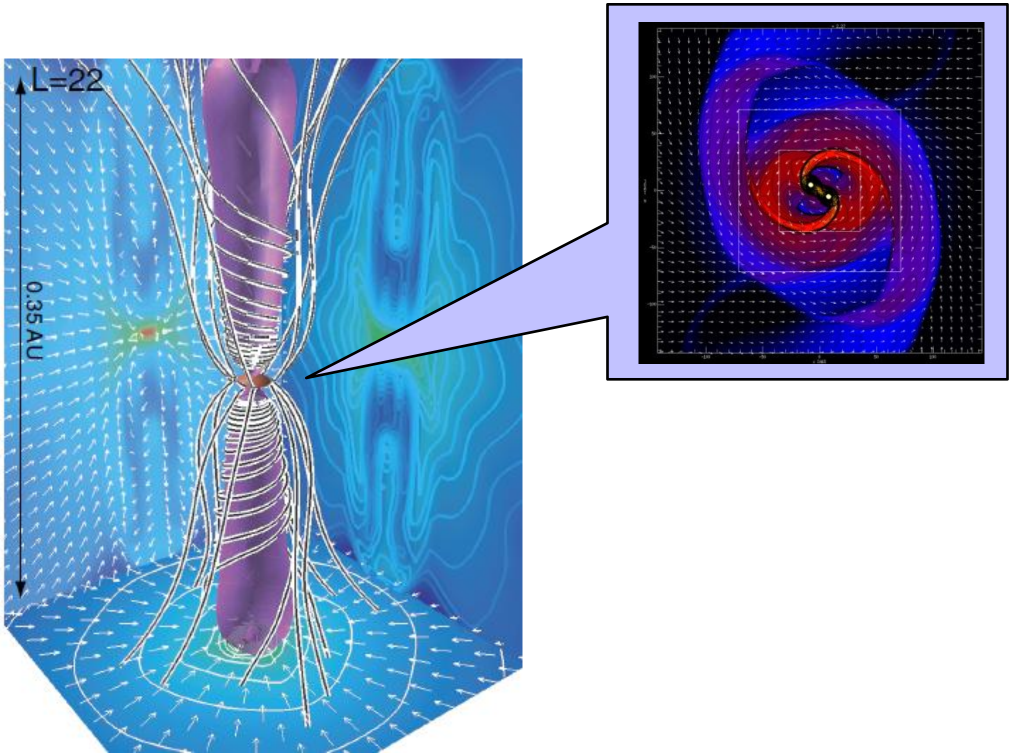
Subaru-Gemini Meeting

Recent Progress in Theory of ISM & Star Formation

Shu-ichiro Inutsuka (Kyoto Univ. ➔ Nagoya Univ.)





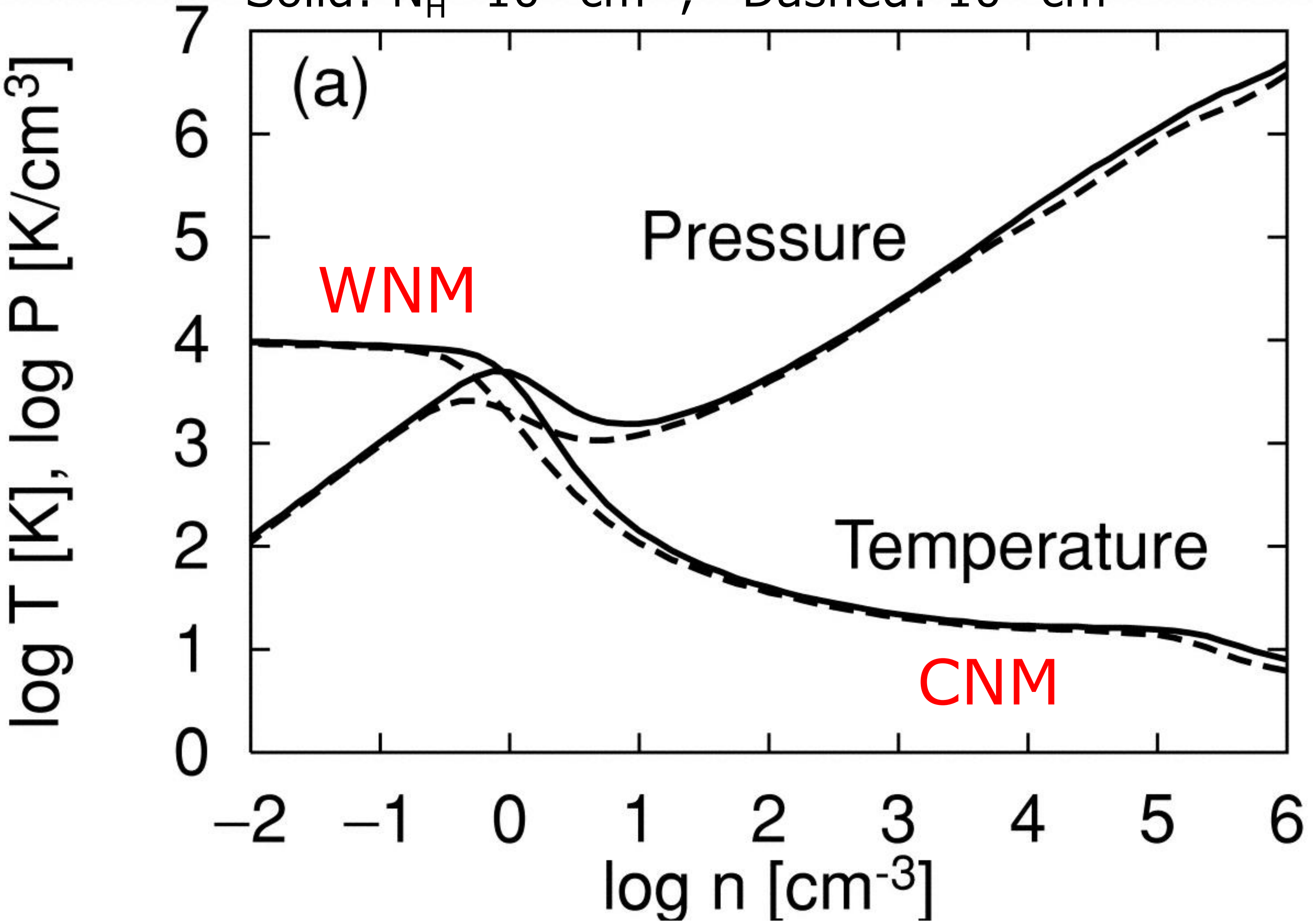
May 21, 2009 @Kyoto

Outline

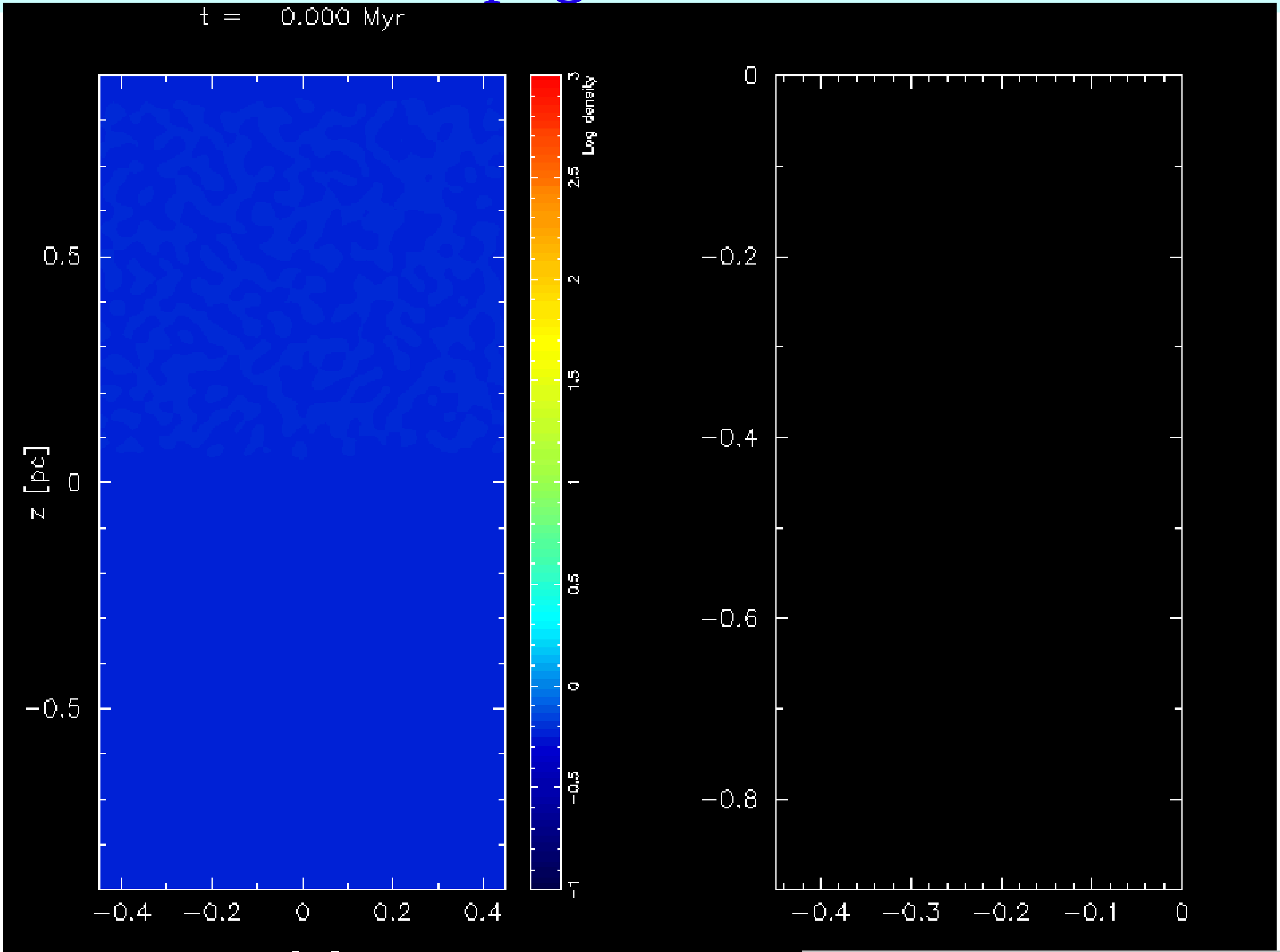
- Dynamics of Multi-Phase ISM
  - Magnetic Field Amplification & CRs
- Expanding HII Region
- Formation & Evolution of Protostars
  - Outflows and Jets
  - Hybrid Scenario for Planet Formation

Radiative Equilibrium

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



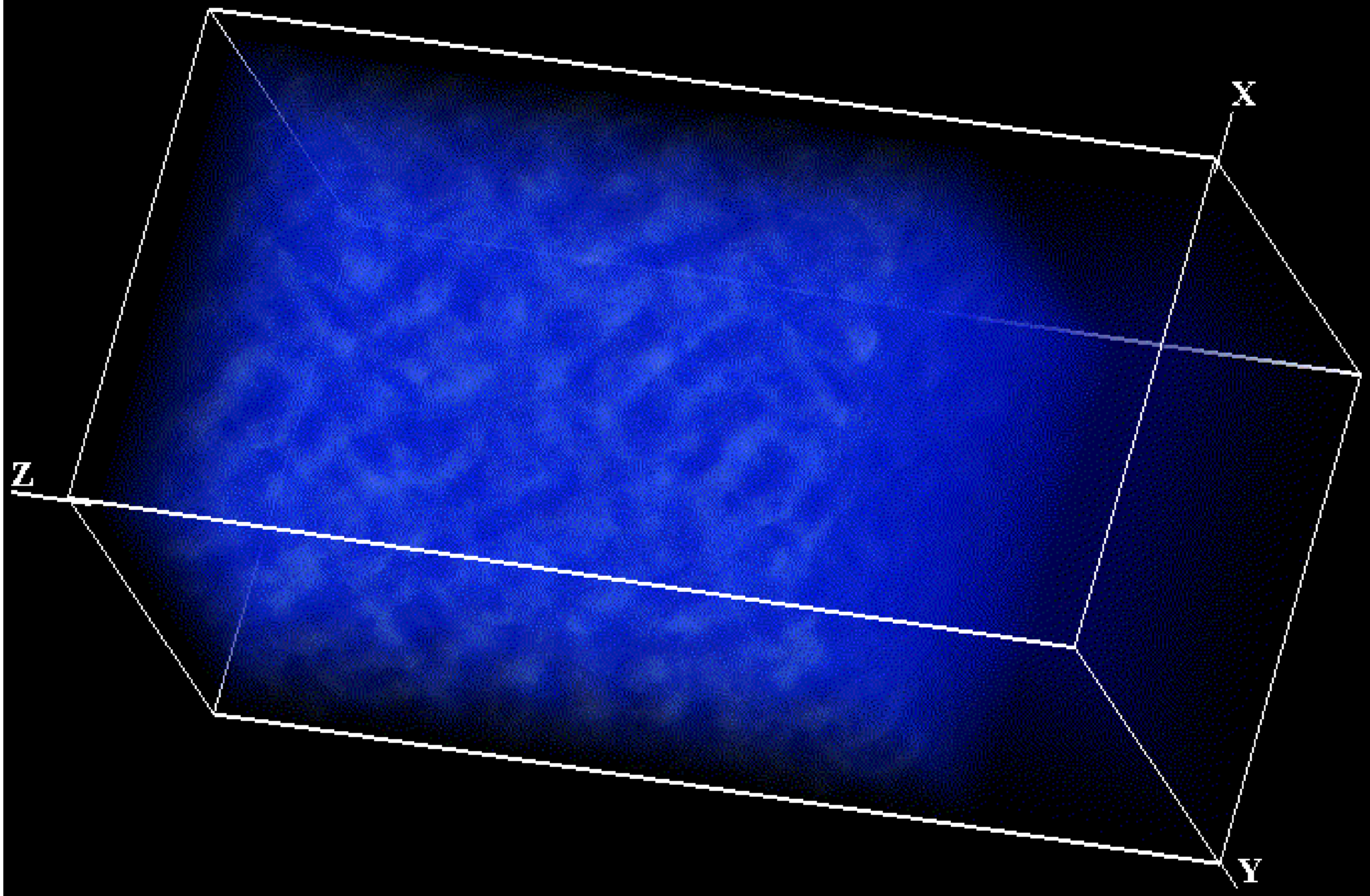
Shock Propagation into WNM



Koyama & SI (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 The Propagation of Shock Wave into WNM

  via Thermal Instability

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

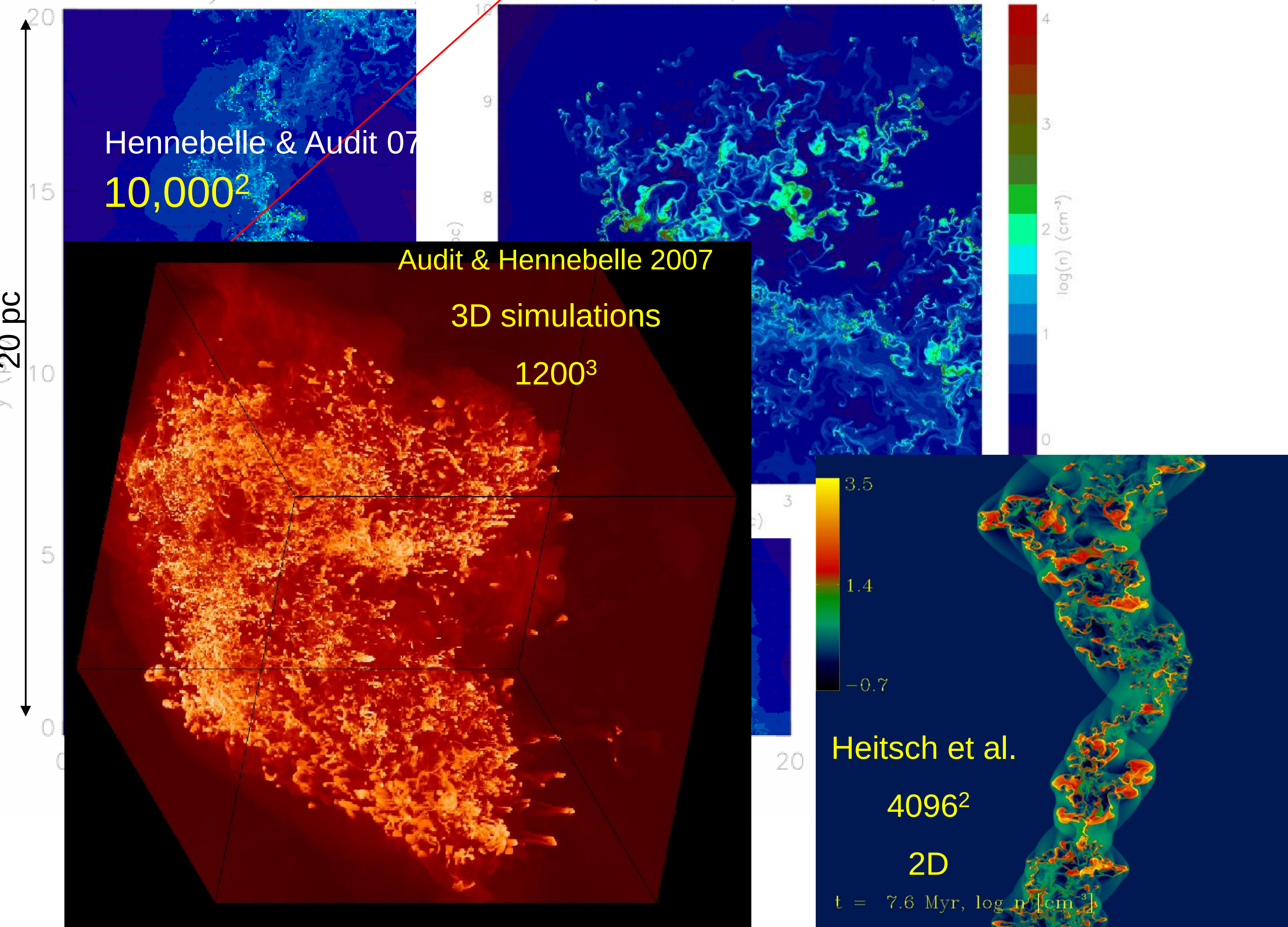
1D: Shock $\Rightarrow E_{th} \Rightarrow E_{rad}$

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

$$\delta v \sim \text{a few km/s} < C_{S,WNM}$$

Koyama & SI (2002) ApJ 564, L97

xels



Hennebelle & Audit 07

$10{,}000^2$

Audit & Hennebelle 2007

3D simulations

1200^3

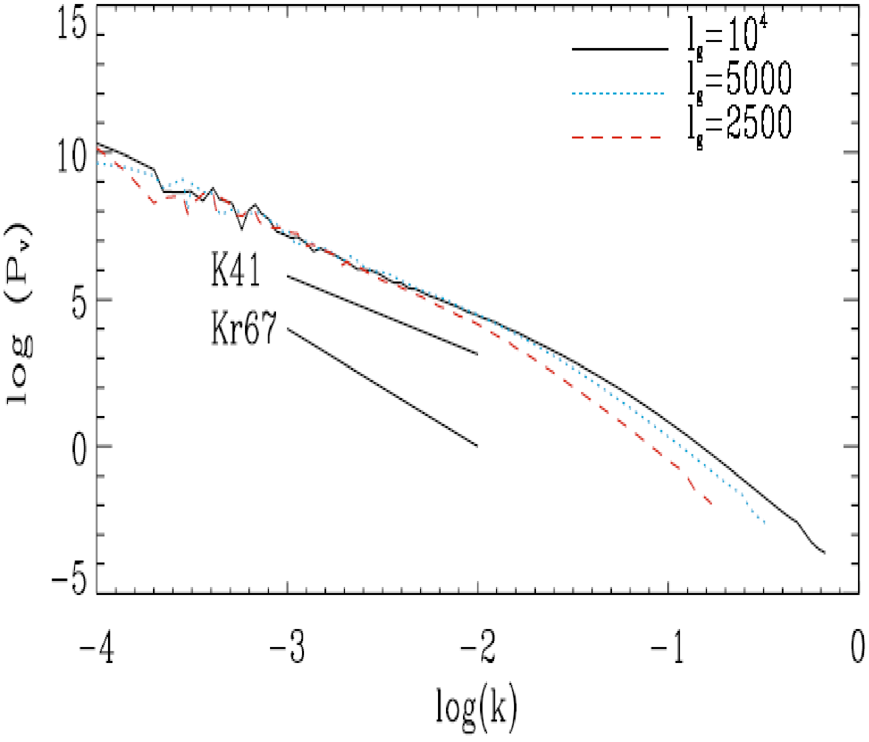
Heitsch et al.

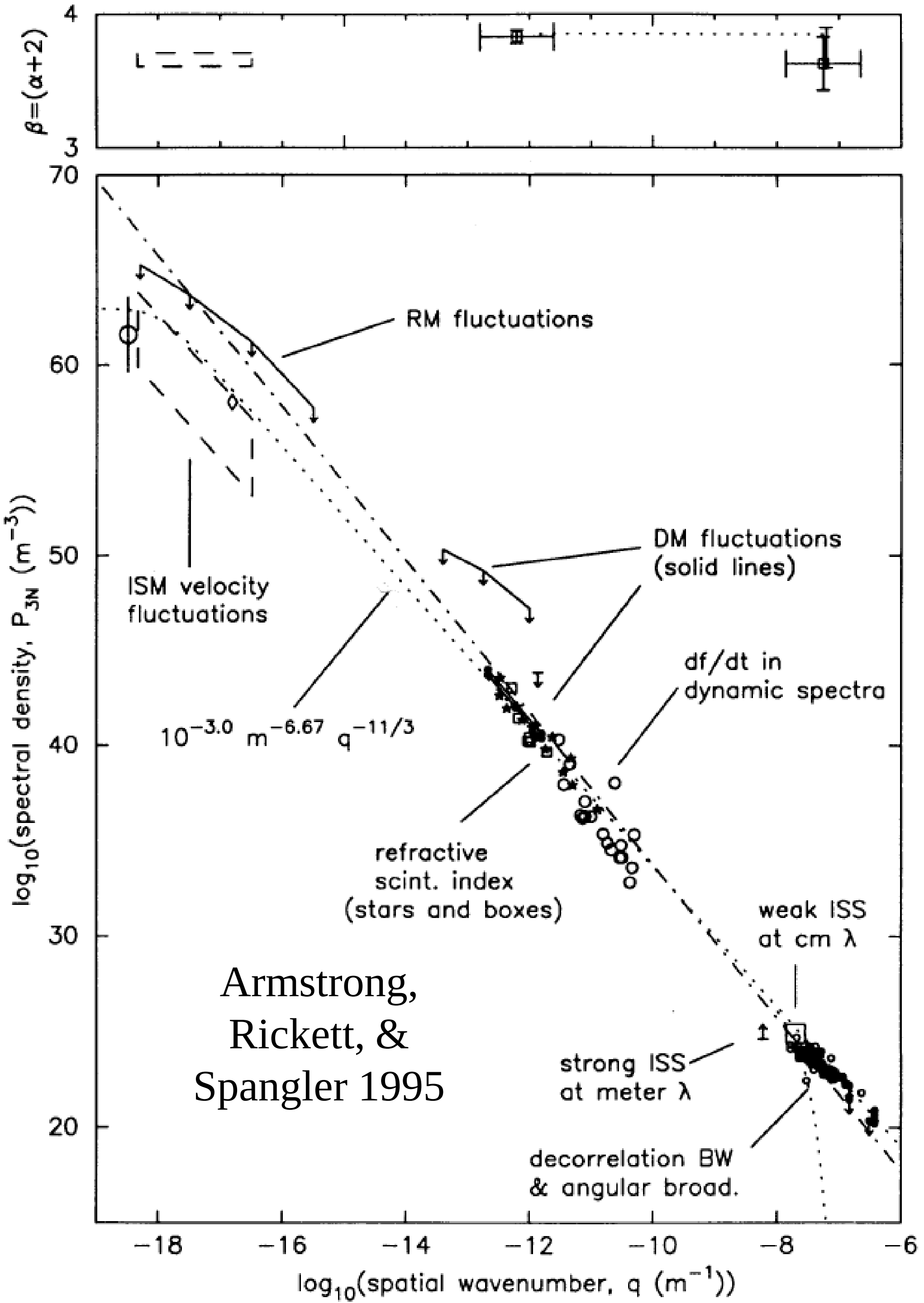
4096^2

2D

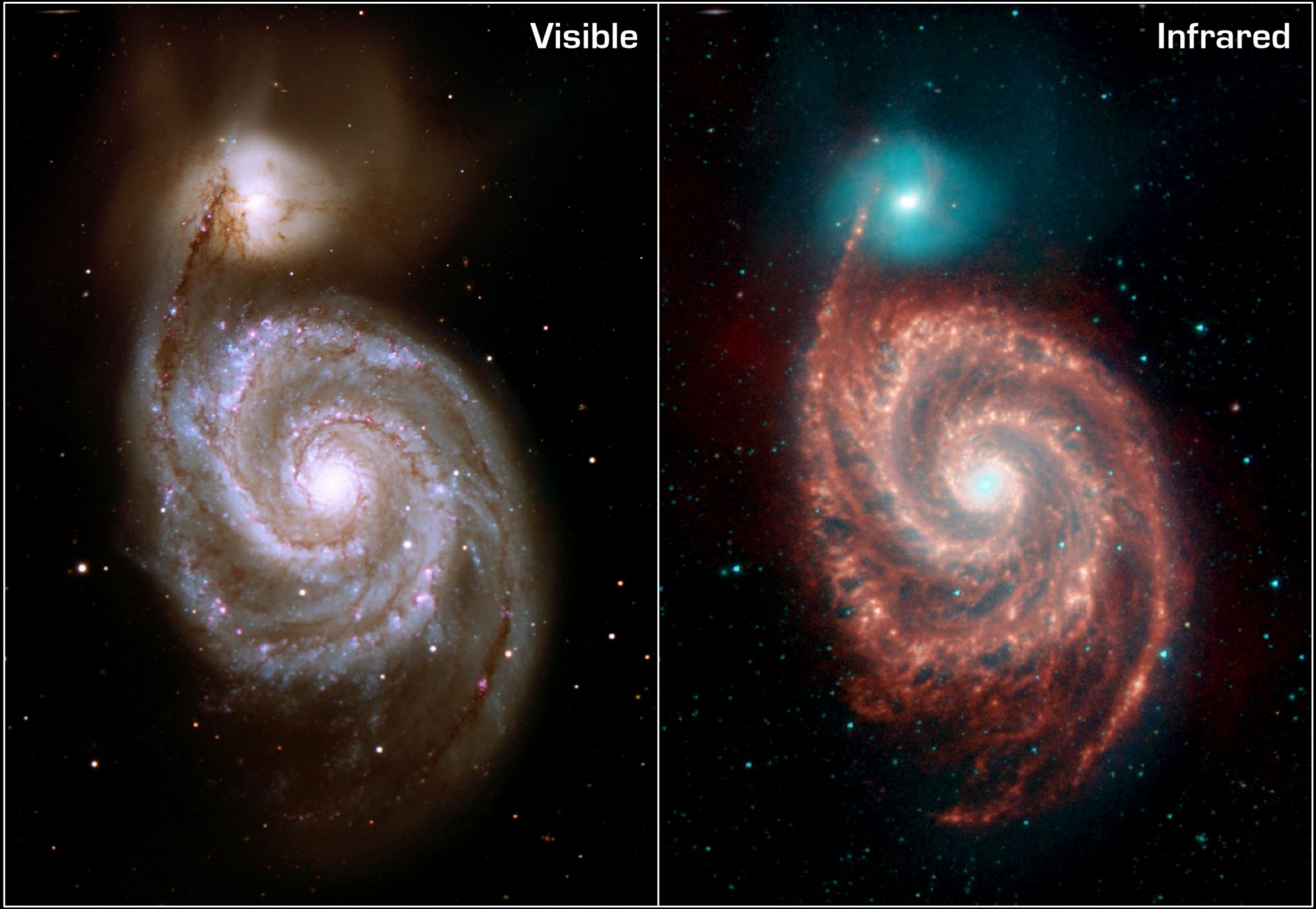
Property of "Turbulence"

Hennebelle & Audit 2007




Armstrong, Rickett, & Spangler 1995

$\delta v < C_{S,WNM}$ ⟷ Kolmogorov-like Spectrum

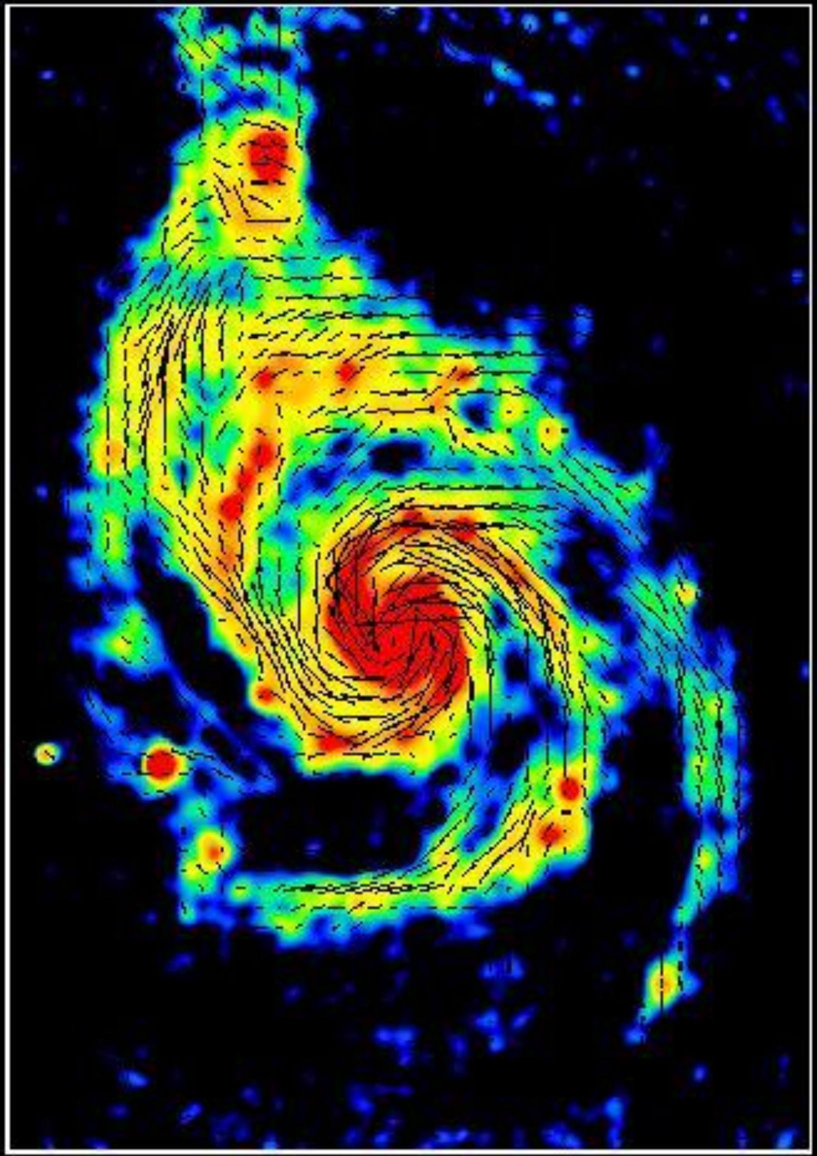


Spiral Galaxy M51 ("Whirlpool Galaxy") Spitzer Space Telescope • IRAC

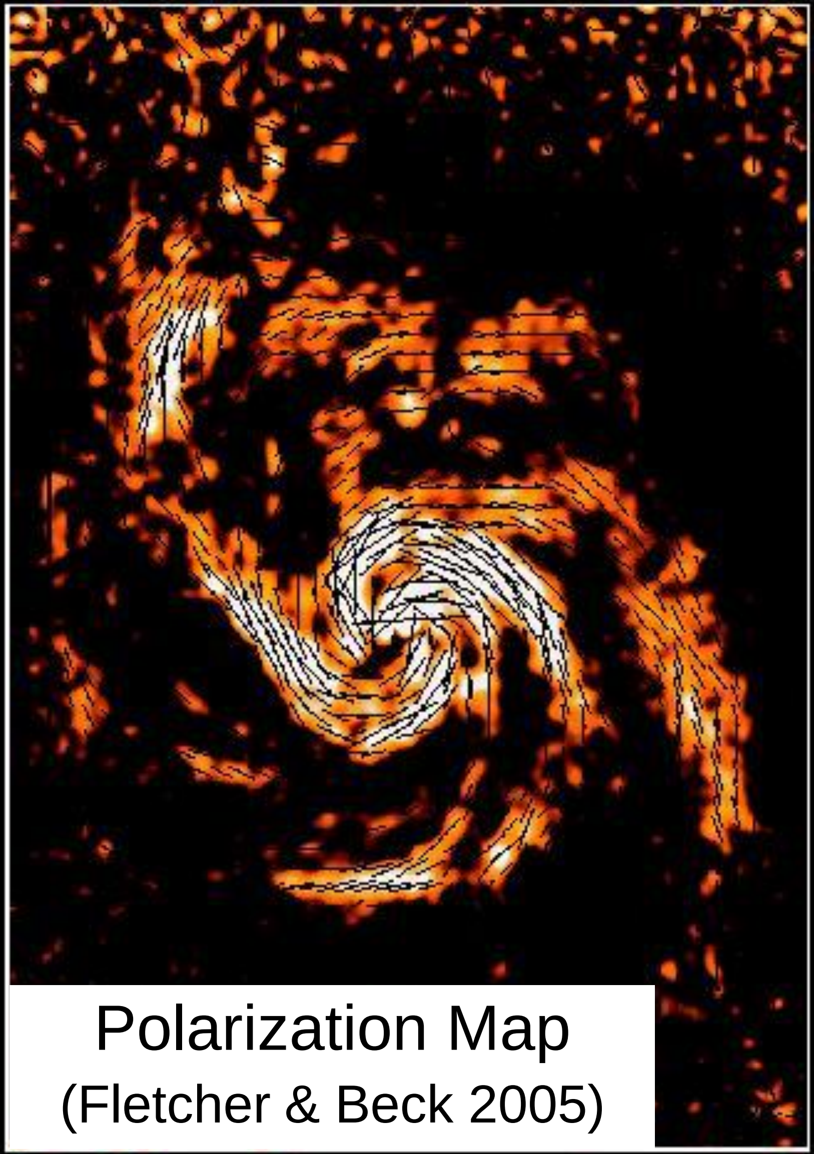
NASA / JPL-Caltech / R. Kennicutt (Univ. of Arizona) ssc2004-19a

M51 Synchrotron

M51 6cm Tot.Int.+B-Vectors (VLA+Effelsberg)



M51 6cm Pol.Int.+B-Vectors (VLA+Effelsberg)

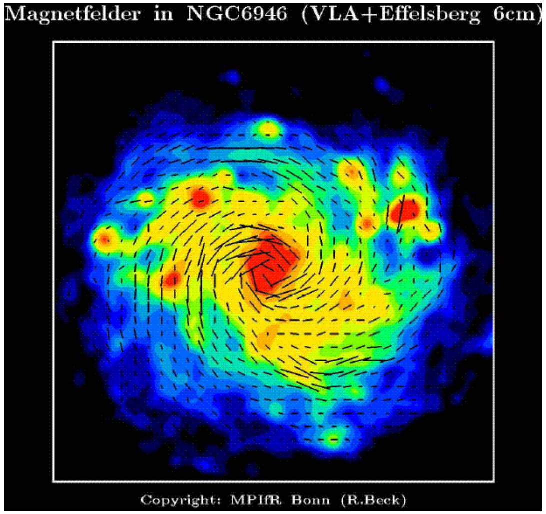


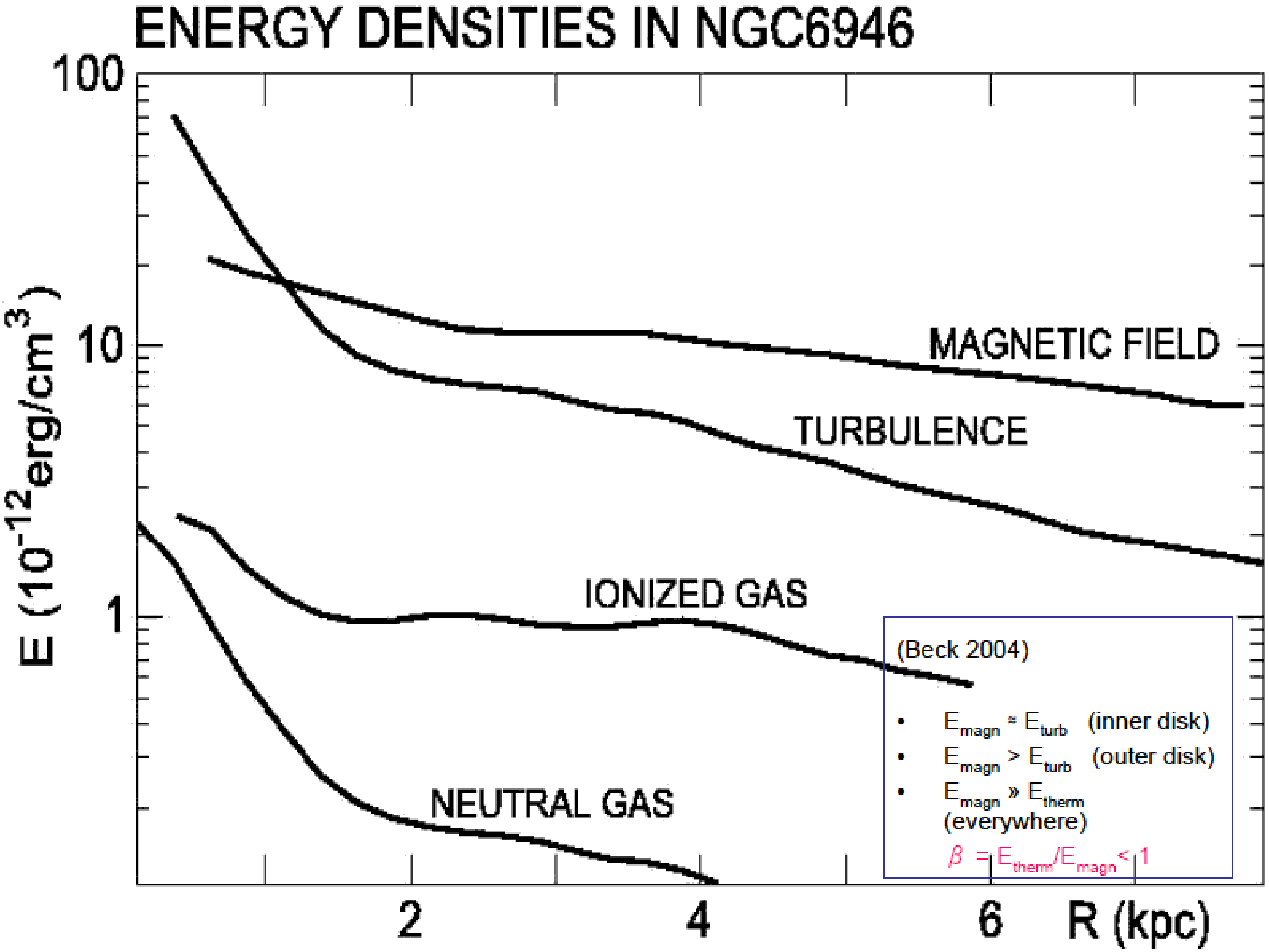
Polarization Map

(Fletcher & Beck 2005)

Energy Density of Magnetic Field

NGC6946





(Beck 2004)

- $E_{magn} \approx E_{turb}$ (inner disk)
- $E_{magn} > E_{turb}$ (outer disk)
- $E_{magn} \gg E_{therm}$ (everywhere)

$\beta = E_{therm}/E_{magn} < 1$

This cannot be explained simply by MRI!

R. Beck (2004)

Dynamics of ISM

Major Components:

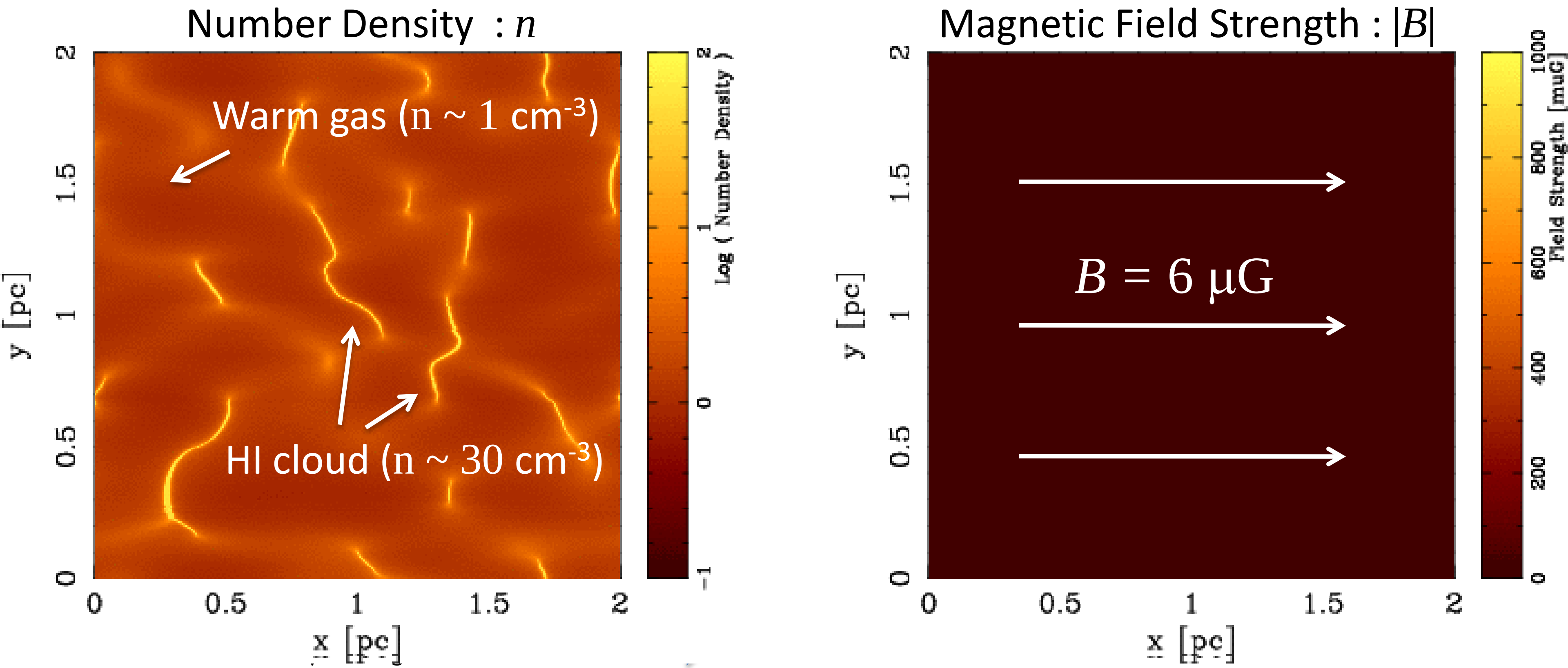
- Hot Gas + Warm Gas + Cold Gas
- Magnetic Field
- CRs

Timescales: Spiral Wave (10^8yr)

> SNe (10^6yr)

> Expanding HII Region

Supernova Shock in Multi-Phase ISM



Number Density : n

Warm gas ($n \sim 1\ \mathrm{cm}^{-3}$)

HI cloud ($n \sim 30\ \mathrm{cm}^{-3}$)

Magnetic Field Strength : $|B|$

$B = 6\ \mu\mathrm{G}$

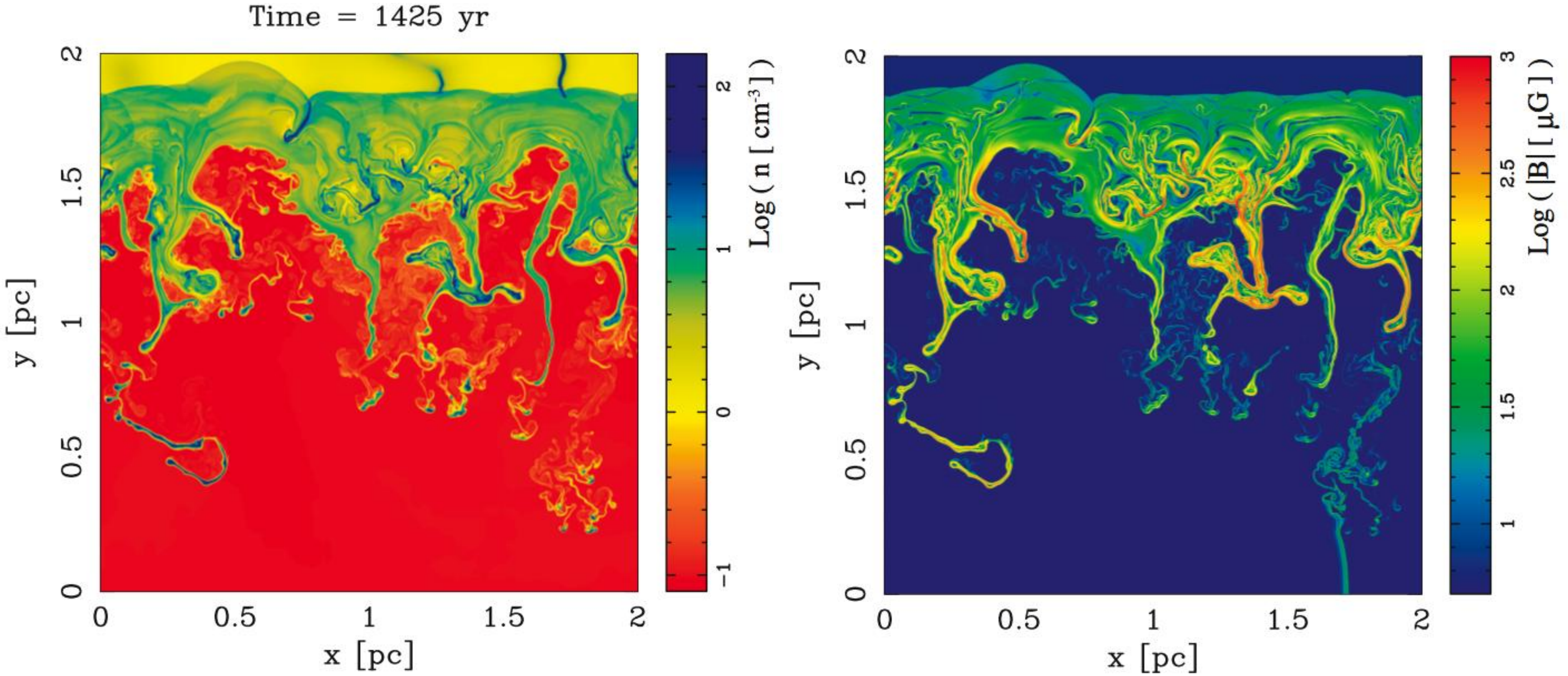
$\nabla\rho \times \nabla p \neq 0 \rightarrow$ Vorticity Creation ($\delta v \sim c_s$)

Magnetic Field Amplification via Turbulent Dynamo

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

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

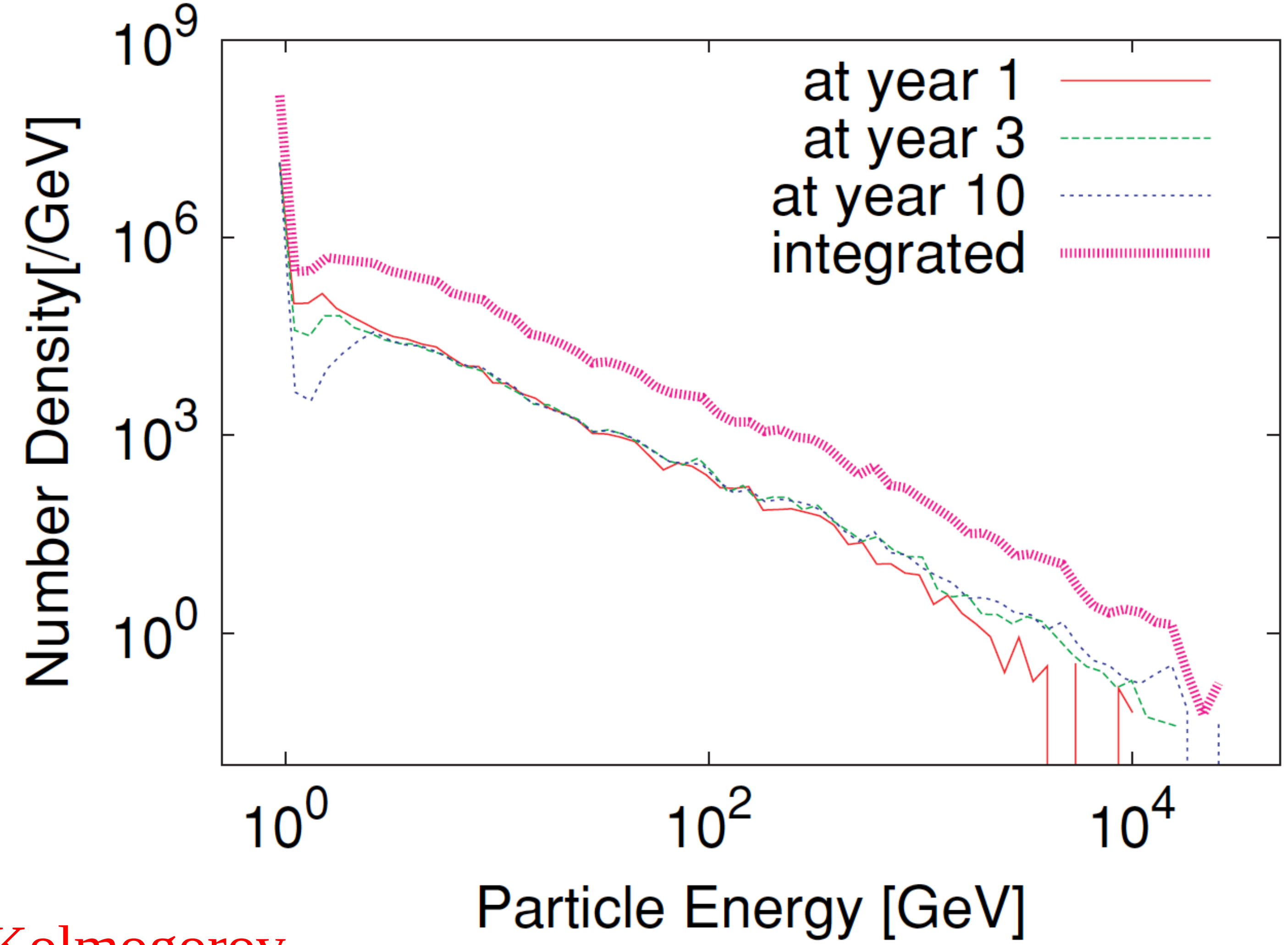
Result



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

$B \sim 1$mG (Bamba+2002, Uchiyama+ 2008, etc.)

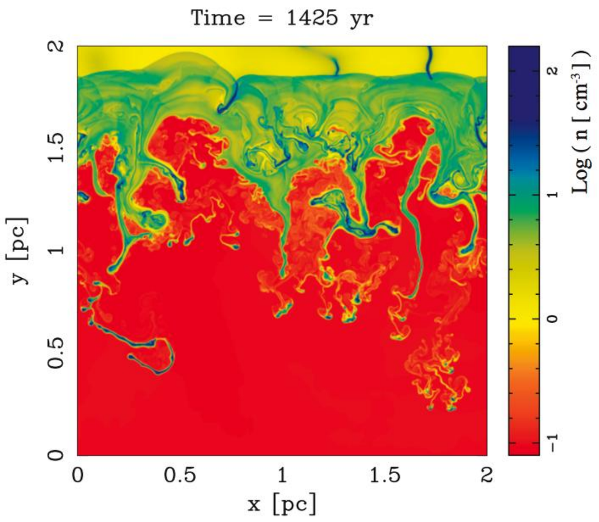
1st Order Fermi Acceleration

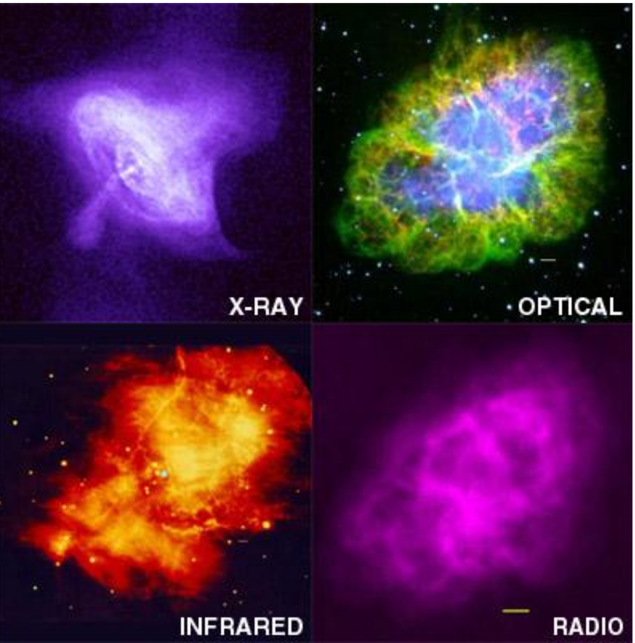


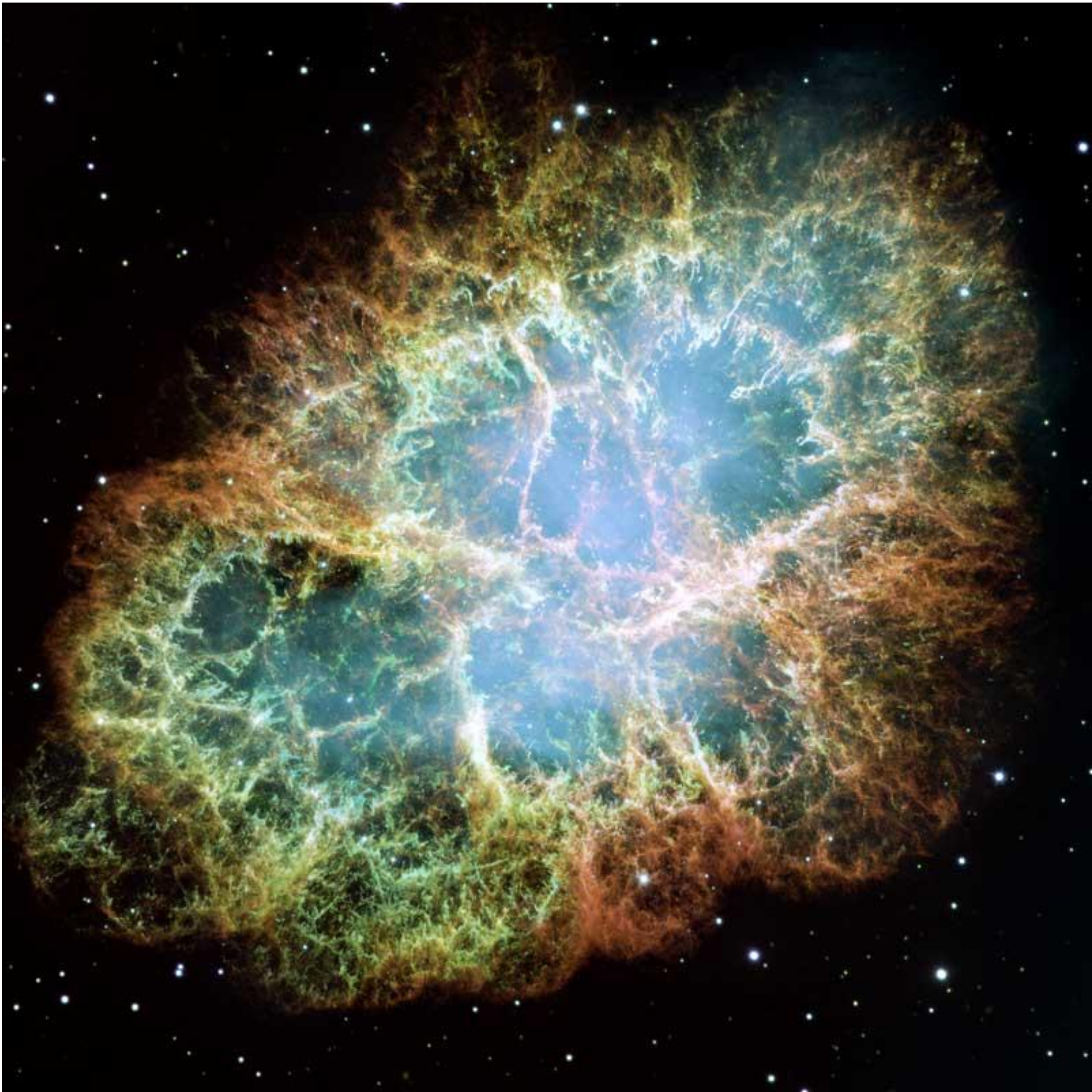
Kolmogorov
Background Turbulence

Muranushi & SI (2009) ApJL **691**, L24

Explosions in Multi-Phase ISM

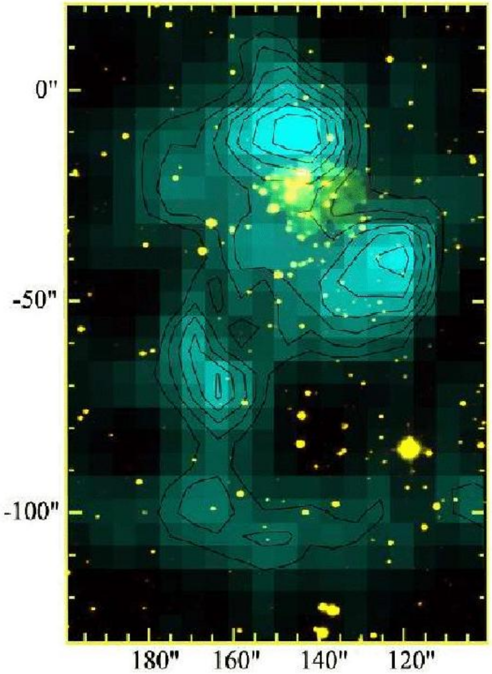


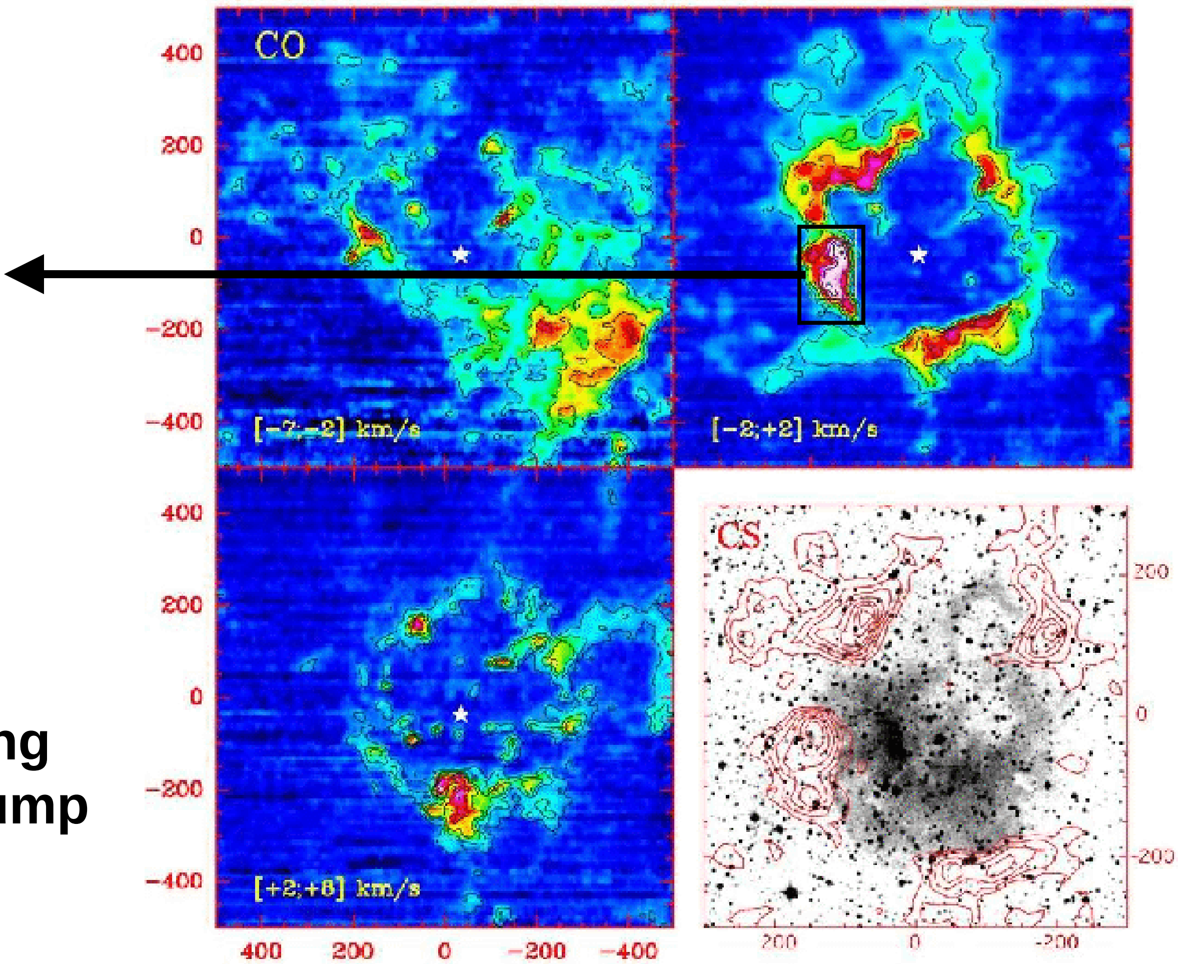




Expanding HII Region

Sh104 classical HII region, $R \approx 4$pc





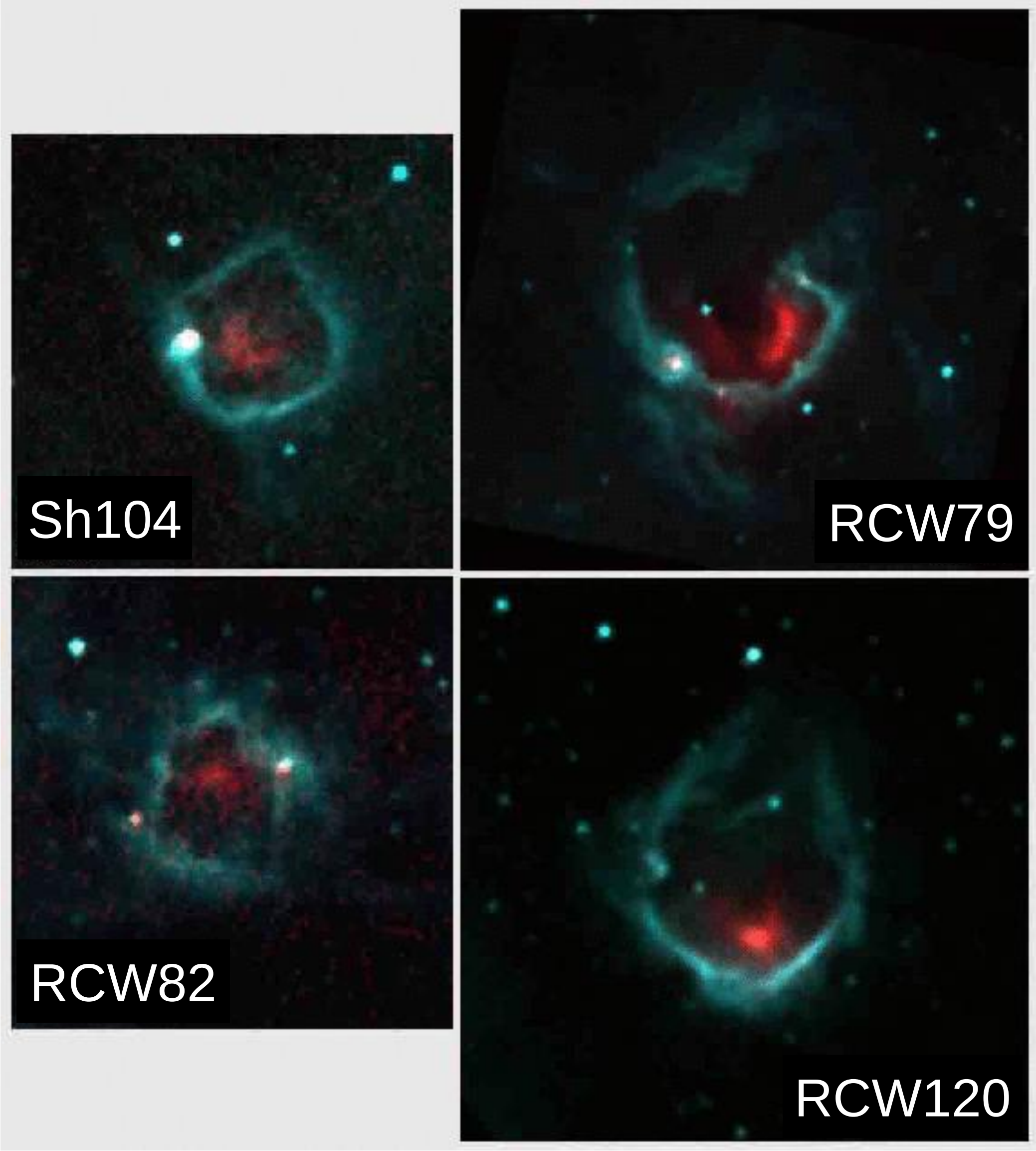
embedded young cluster in one clump

Deharveng et al. (2003) A&A, 408, L25

Direct Evidence of Collect and Collapse Scenario? Possible?

Other Similar Regions

Deharveng, Zavagno & Caplan (2005) , A&A, 433, 565



Dust emission

red : 21.3μm (grains)

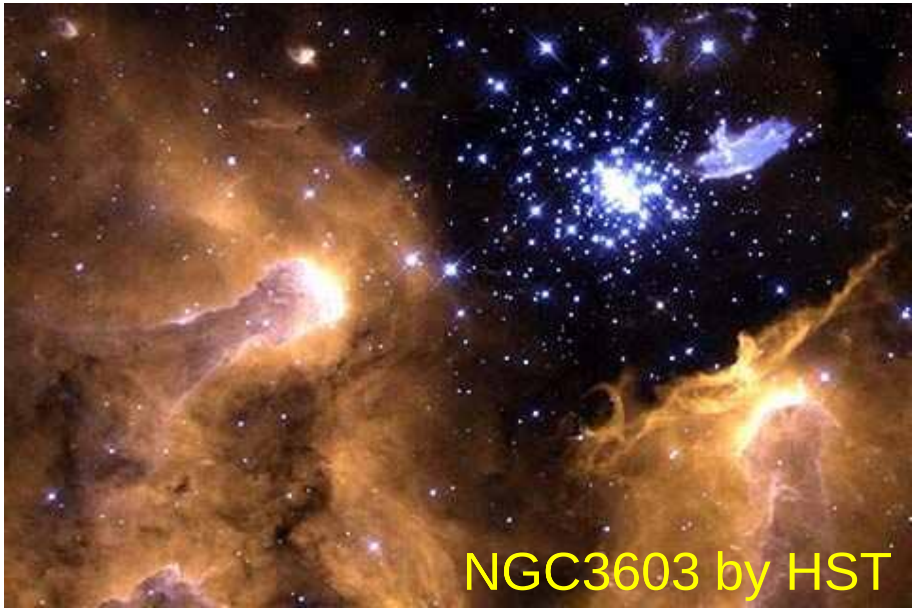
green: 8.3μm (PAHs)

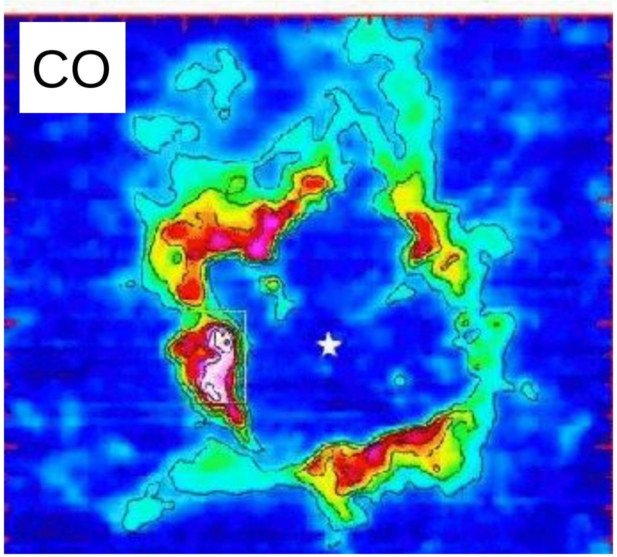
Many Similar Regions

Dust ring around HII regions

+ embedded point sources

Radiative Feedback for Molecular Cloud





Sh104 ; Deharveng et al. (2003)

- Ionizing photons ($h\nu > 13.6\mathrm{eV}$)
- Dissociating photons

($11.0\mathrm{eV} < h\nu < 13.6\mathrm{eV}$)

Negative Feedback

destroy molecular cloud and

suppress star formation
(H2 → HI → HII)
(e.g., Whitworth 1979)

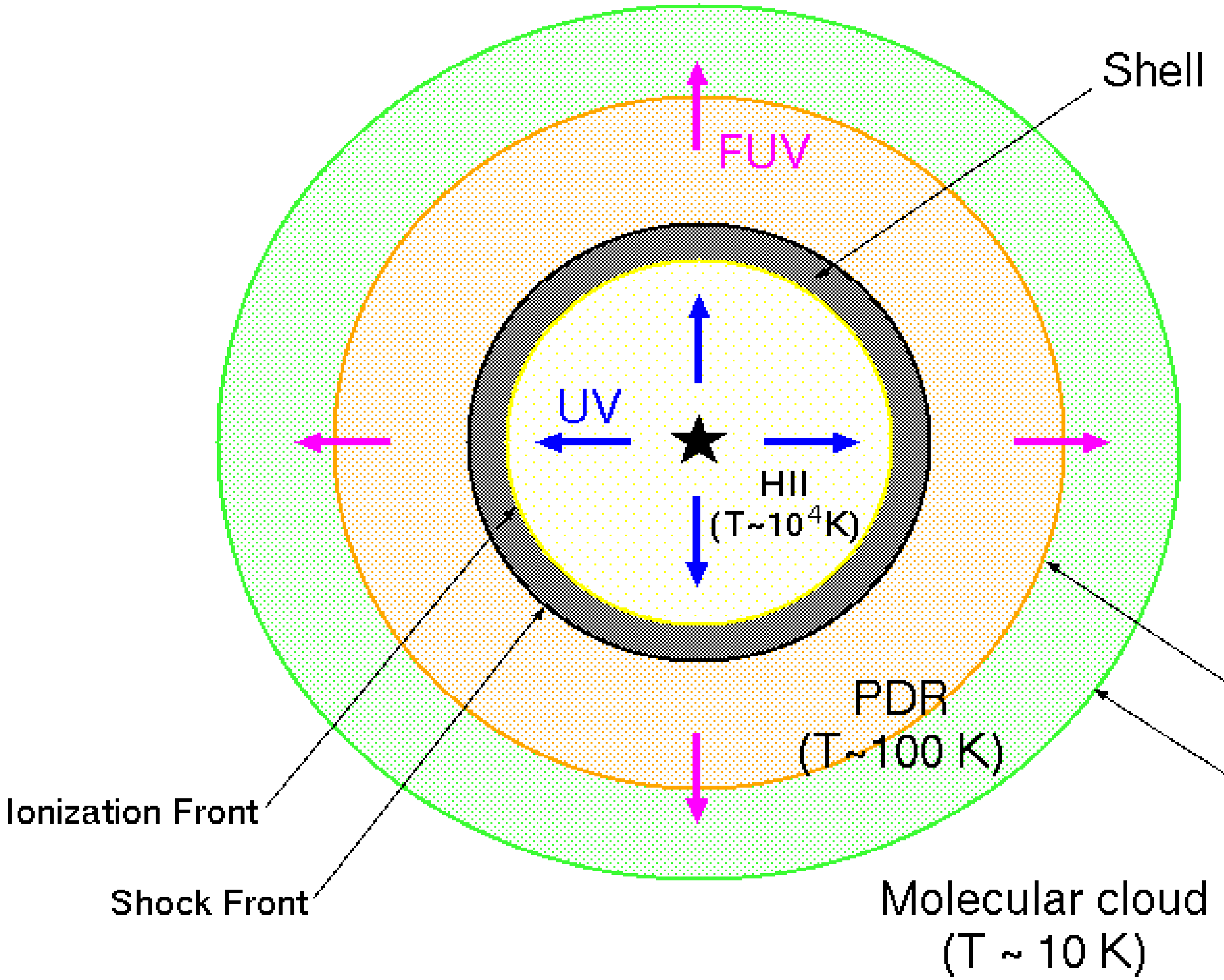
V.S

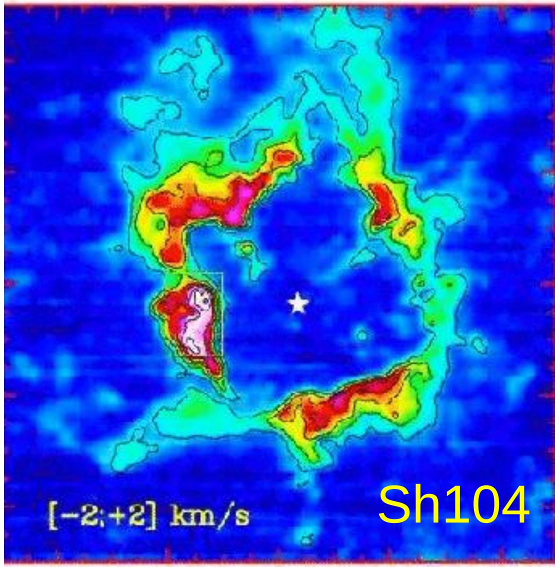
Positive Feedback

shock front sweeps up ISM

to trigger star formation
(compression of H2)
(e.g., Elmegreen & Lada 1977)

Expansion in Molecular Cloud





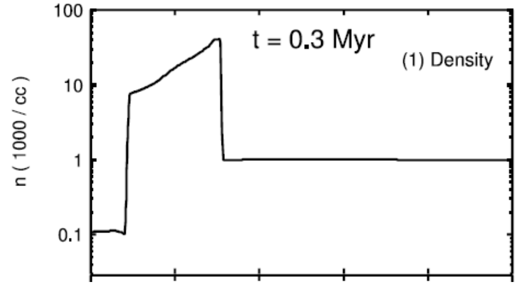
- study the physical/chemical structure of the shell
- Does molecular gas accumulates in the shell shielding FUV photons?

Gas Dynamics

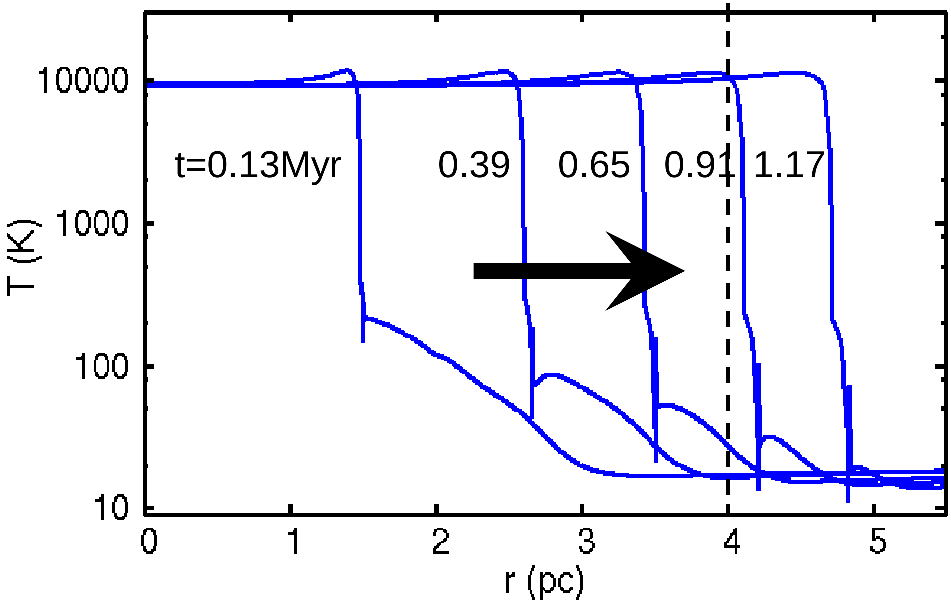
Central Star : $41M_{sun}$

Ambient Medium: homogeneous molecular gas

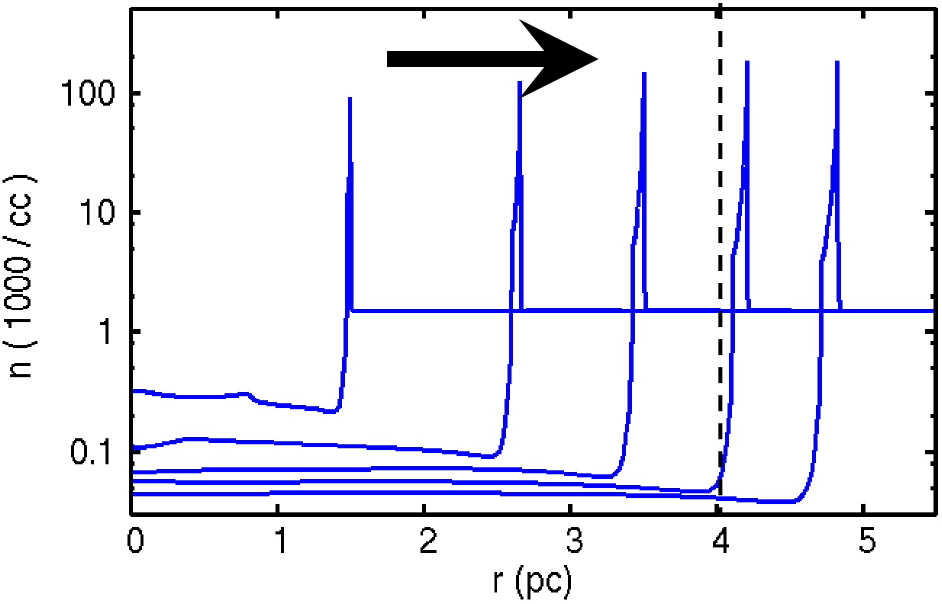
($n = 1.5 \times 10^3$ /cc)



Temperature



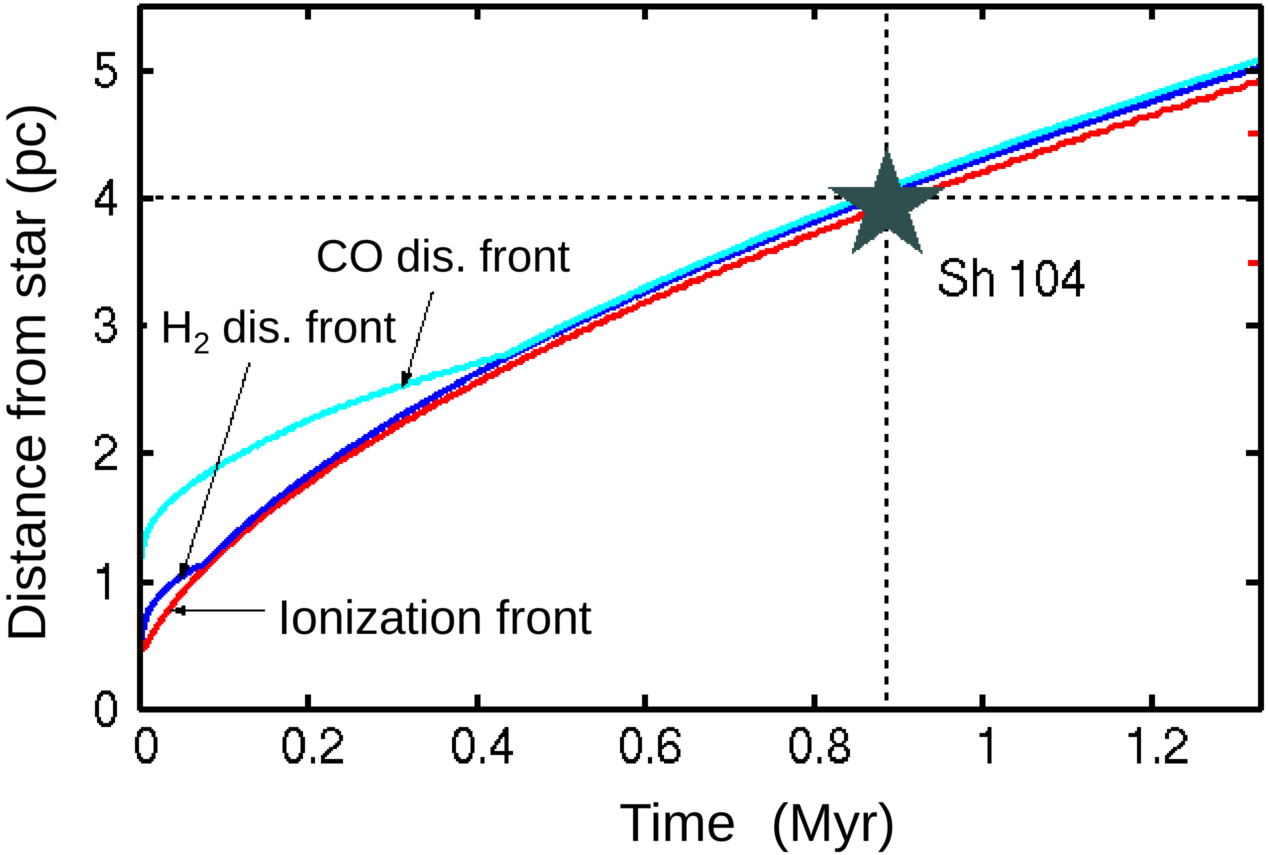
density



T~10^4K→HII region, T~100K→PDR, T~10K→molecular cloud

PDR is gradually trappeded in the shell

Front-Overtaking

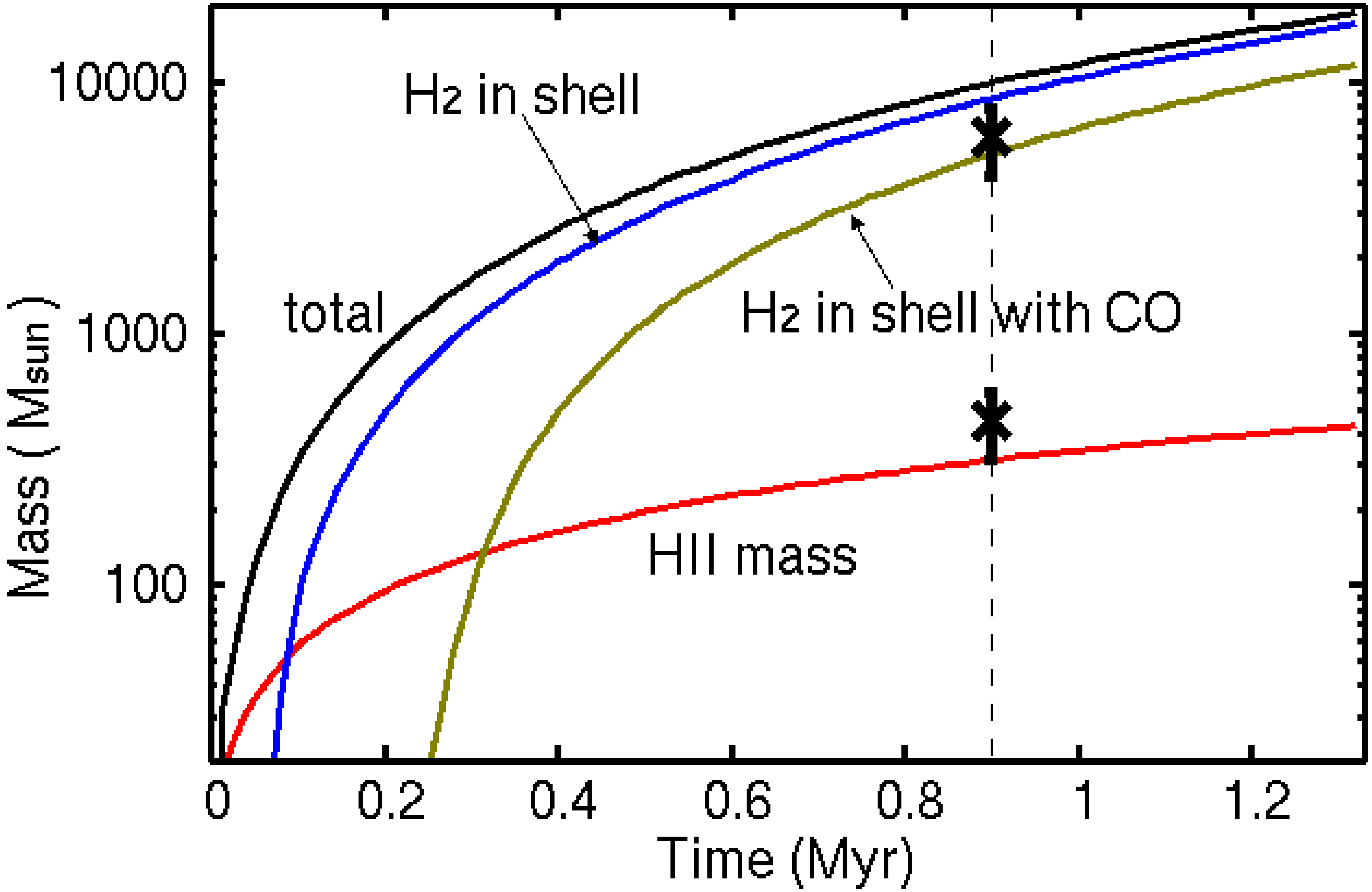


Ionization front and shock front gradually overtake the

preceding dissociation fronts.

The PDR is taken in the shell by the time when the HII region expands to the observed radius of Sh104.

Mass Evolution



Sh104 obs.

Mass of HII region: ~ 450 $M_\odot$

H_2 Mass of the shell : ~ 6000 $M_\odot$

Excellent agreement

Most of the swept-up gas remains in the shell as molecular gas → ***Positive feedback***

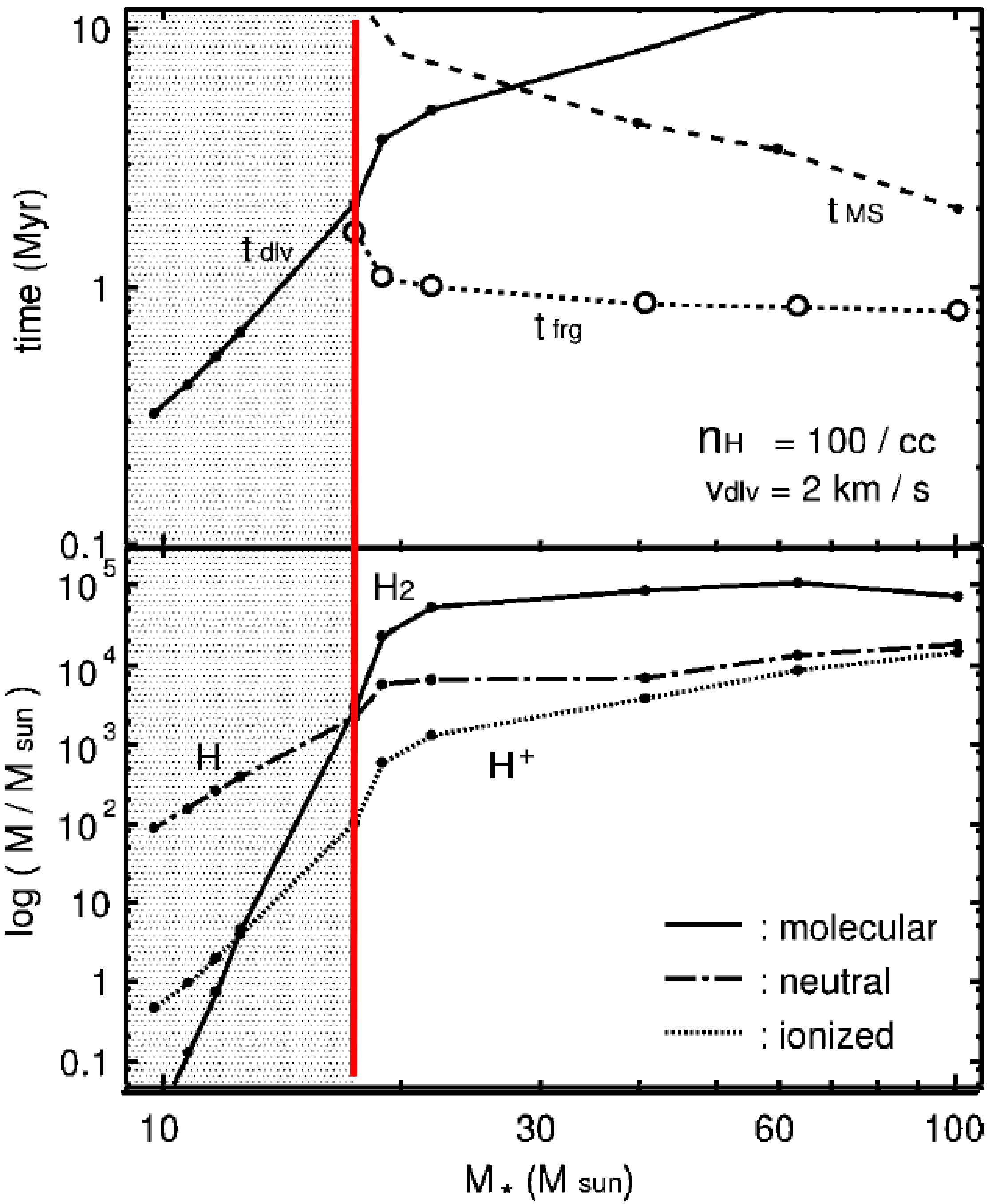
Condition for Star Burst

If $M_* > 20M_o$,

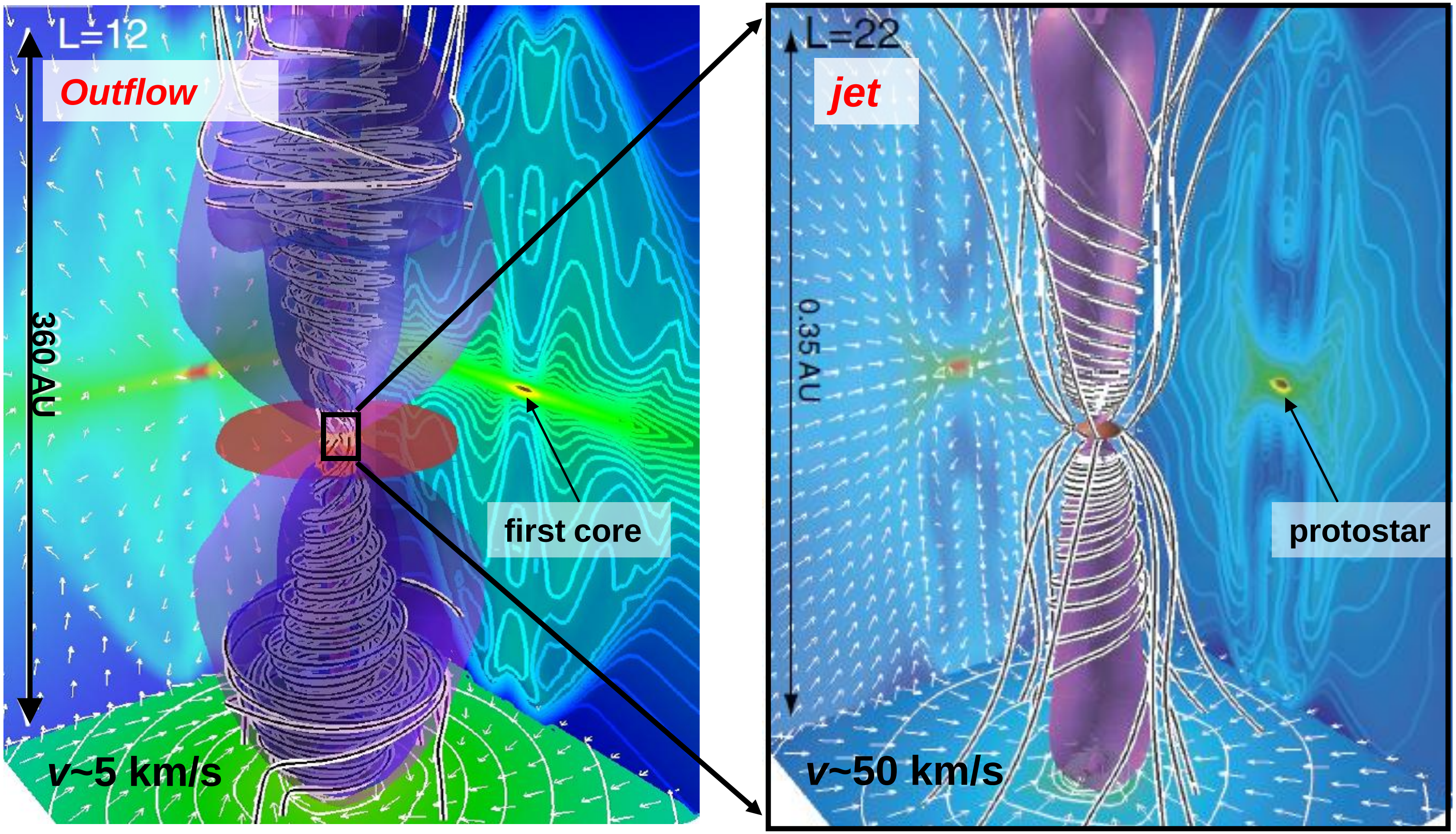
then number of massive stars increases exponetially.

Hosokawa & SI (2006)

ApJ **648**, L131



Early Phase of Protostar



Machida et al. (2006, 2007, 2008, 2009)

Dynamic Range: 10^9cm < Length < 10^{17}cm

We have good understanding upto $M = 0.1\ M_\odot$!

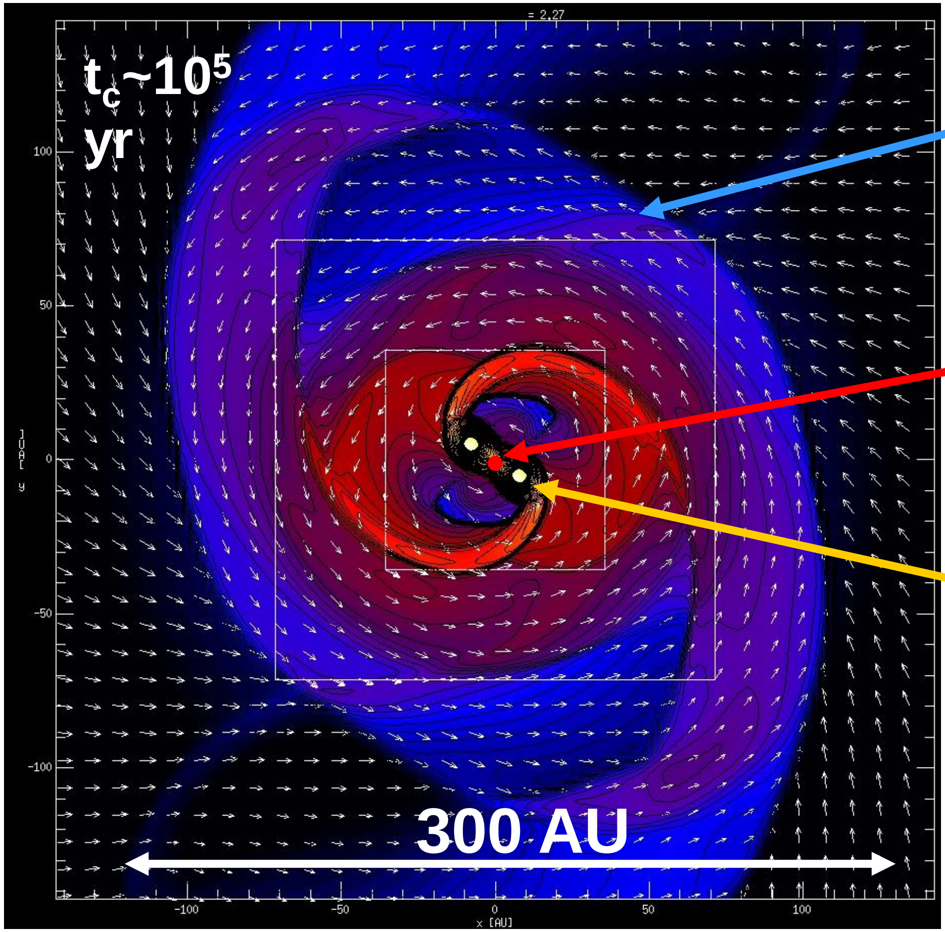
Star Formation Theory Extended

Rapid Progress in Our Understanding of Formation of Protostars

➔ Further Evolution to Formation/Evolution of Protoplanetary Disks

➔ Star formation process determines Initial Condition of Planet Formation!

Formation of Planetary Mass Companions in Protoplanetary Disk



Protoplanetary Disk

Protostar

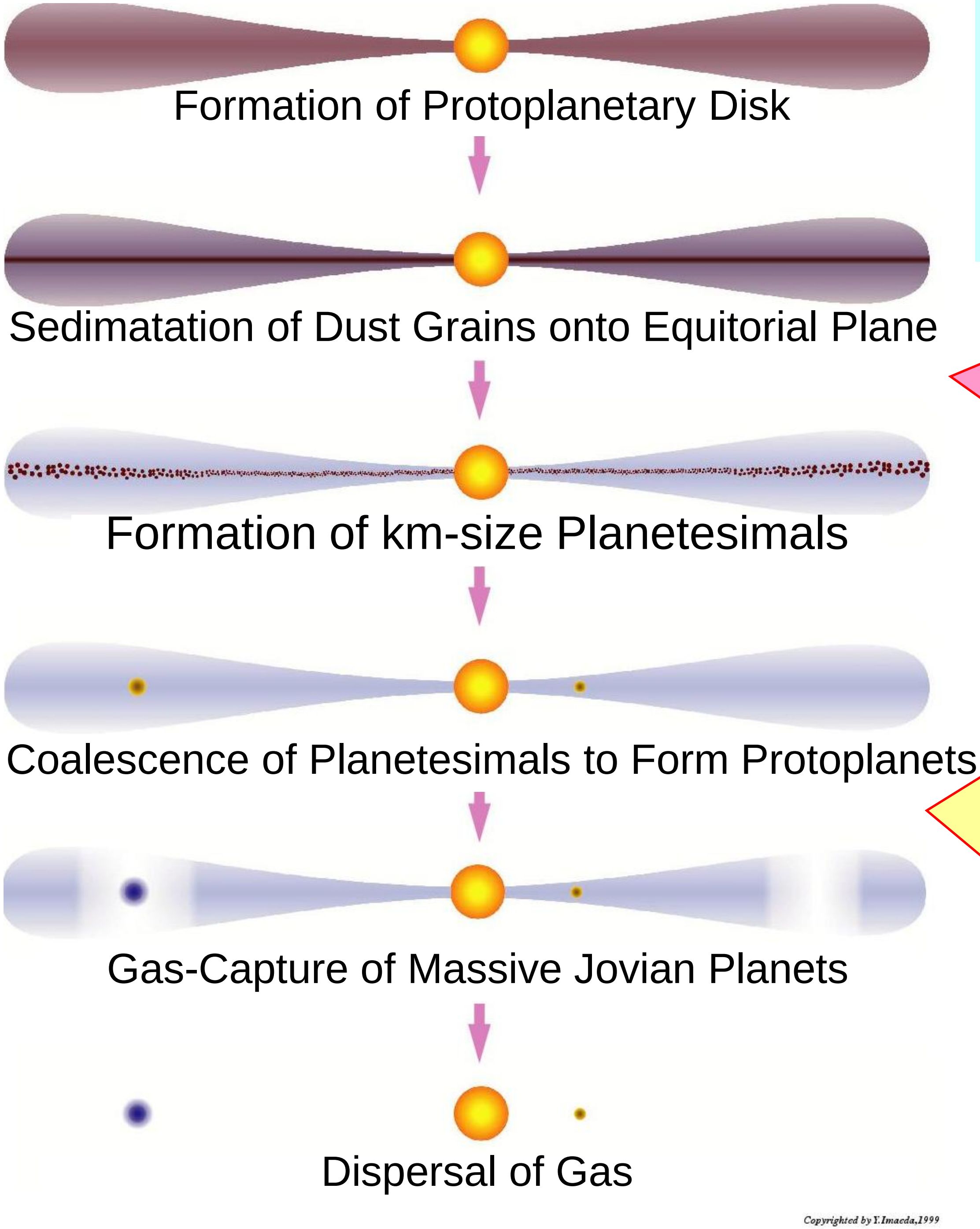
- ~0.1 M_{sun}

Protoplanet

- M~8 M_{Jup}
- R_{sep}～10-20 AU

Machida, SI, & Matsumoto 2009

Two Problems in Standard Model of Planet Formation



Formation of Protoplanetary Disk

Sedimatation of Dust Grains onto Equitorial Plane

Formation of km-size Planetesimals

Coalescence of Planetesimals to Form Protoplanets

Gas-Capture of Massive Jovian Planets

Dispersal of Gas

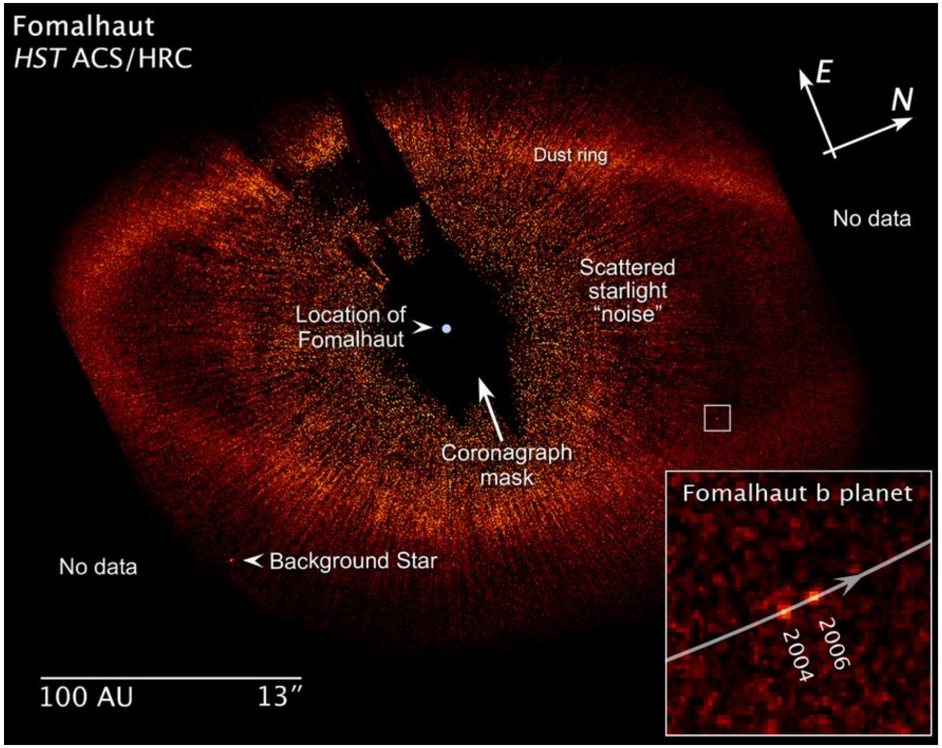
Copyrighted by Y.Imaeda,1999

Problem 1: Kelvin-Helmholz instability hinders sedimentation!

Problem 2: Gravitational interaction between planet and gas disk leads to planet migration onto the central star!

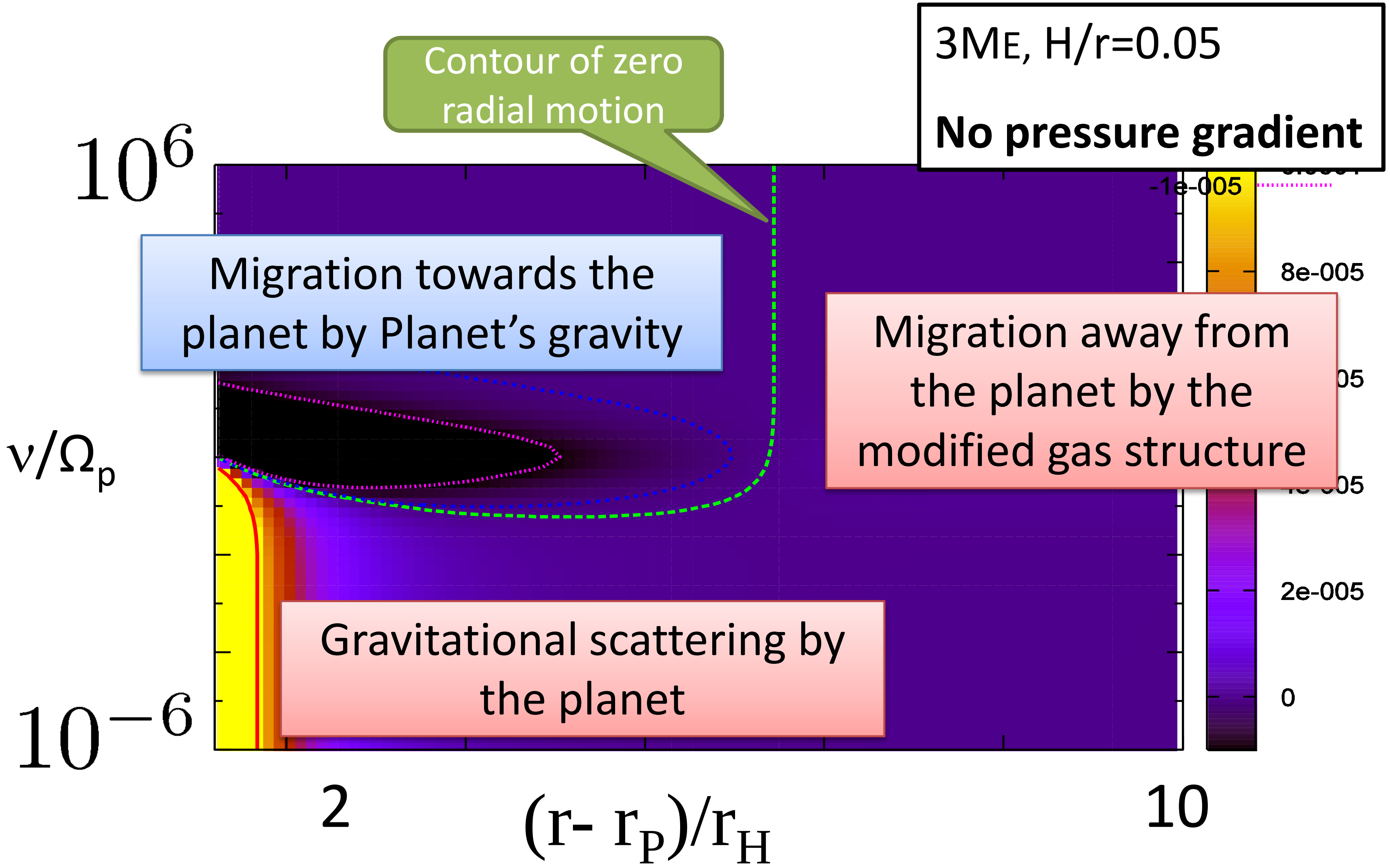
Discovery of Far-Away Planets

- Kalas et al. (2008)
  - R=98AU
- Marois et al. (2008)
  - R=68AU
- Lagrange et al. (2008)
  - R=8AU



Something wrong with standard core accretion scenario!

Shepherding for Dust Grains



Contour of zero radial motion

3ME, H/r=0.05

No pressure gradient

Migration towards the planet by Planet's gravity

Migration away from the planet by the modified gas structure

Gravitational scattering by the planet

Muto & SI (2008) ApJ 695, 1132

“Hybrid Scenario”

Scenario 1: Giant planets fall onto the central star.

➔ Remnant Planetesimals may proceed to (classical) core accretion scenario.

Scenario 2: Giant planets survive gas dispersal.

➔ Giant planets (no core) and rocky planets

NB: This can be a formation scenario even for our solar system if M_{core} of Jupiter is very small.

Gap in Mass Distribution?

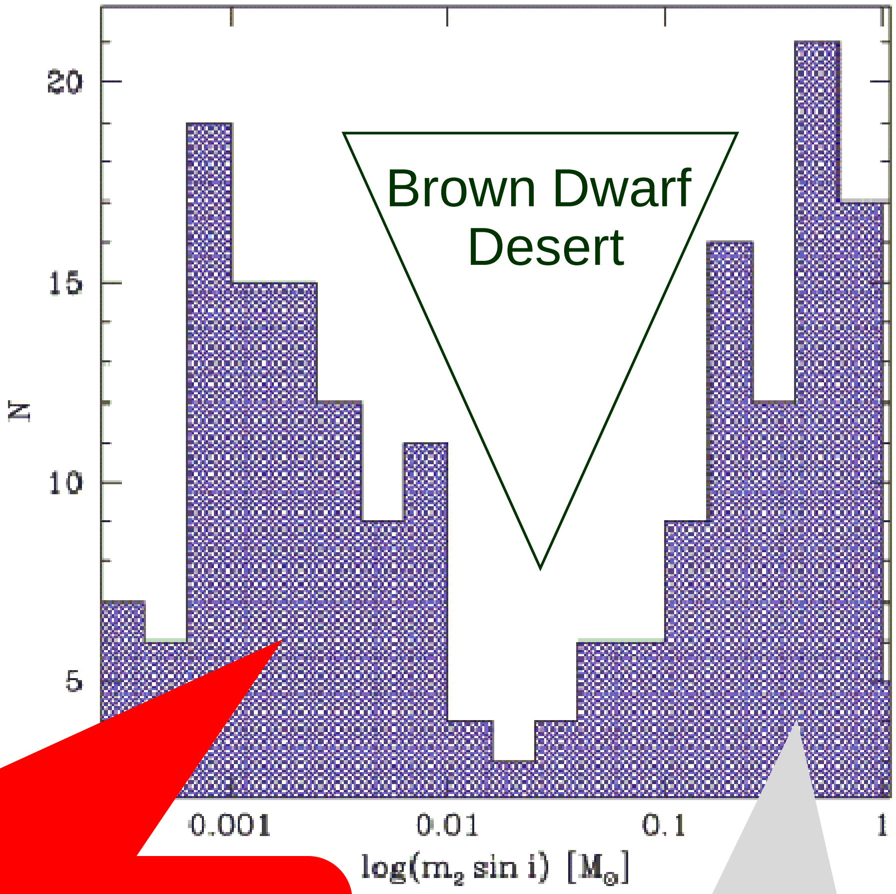
Brown Dwarf Desert:

$M \sin(i) < 0.01\,M_\odot$

$M \sin(i) > 0.01\,M_\odot$

➔ different formation mechanism?

➔ Smaller mass objects are formed by <u>core accretion model?</u>



Mass Function of Companions

Fragmentation in Protoplanetary disk

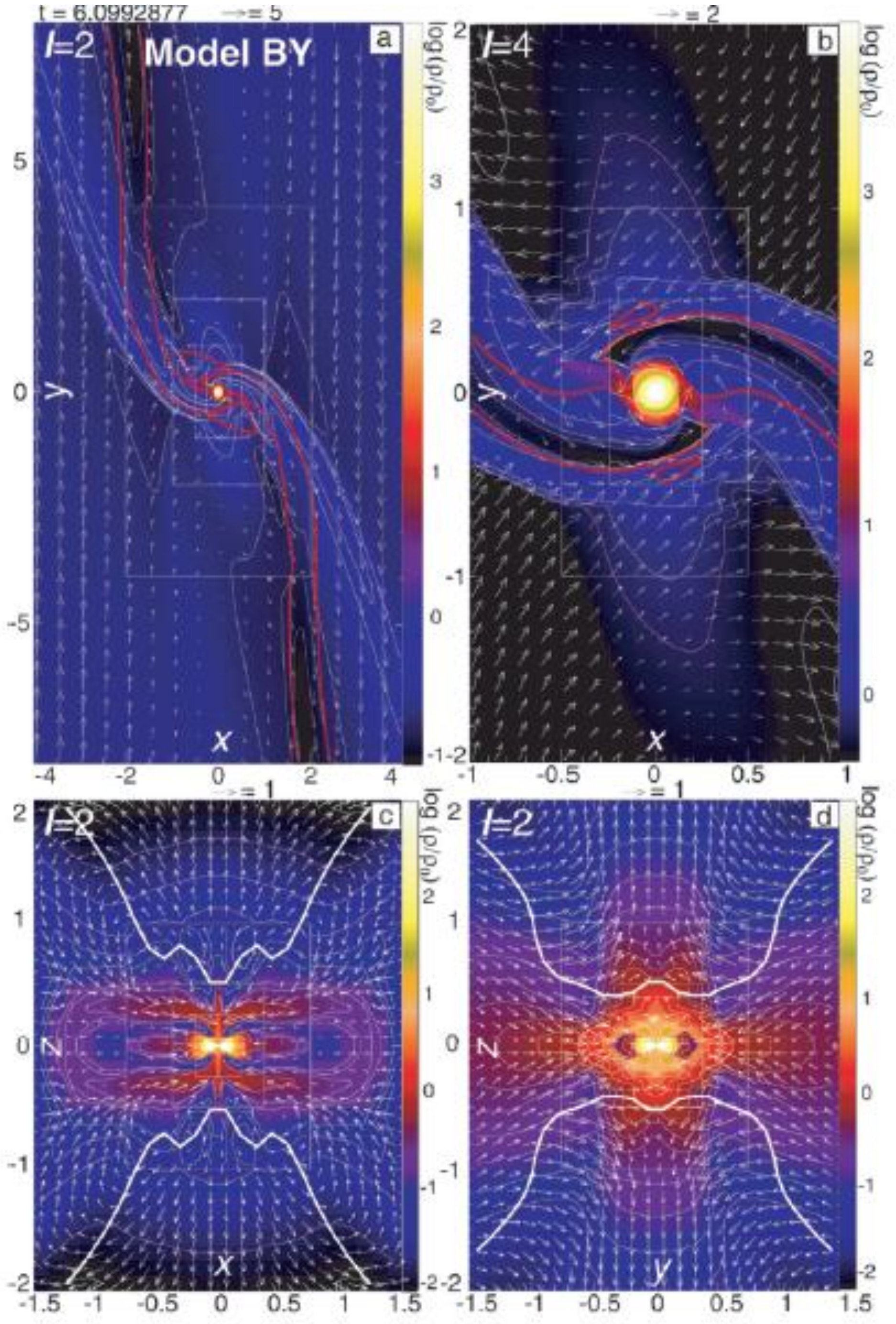
Fragmentation

Theoretical Discovery

Formation of Gaseous Giant Planet

in MHD

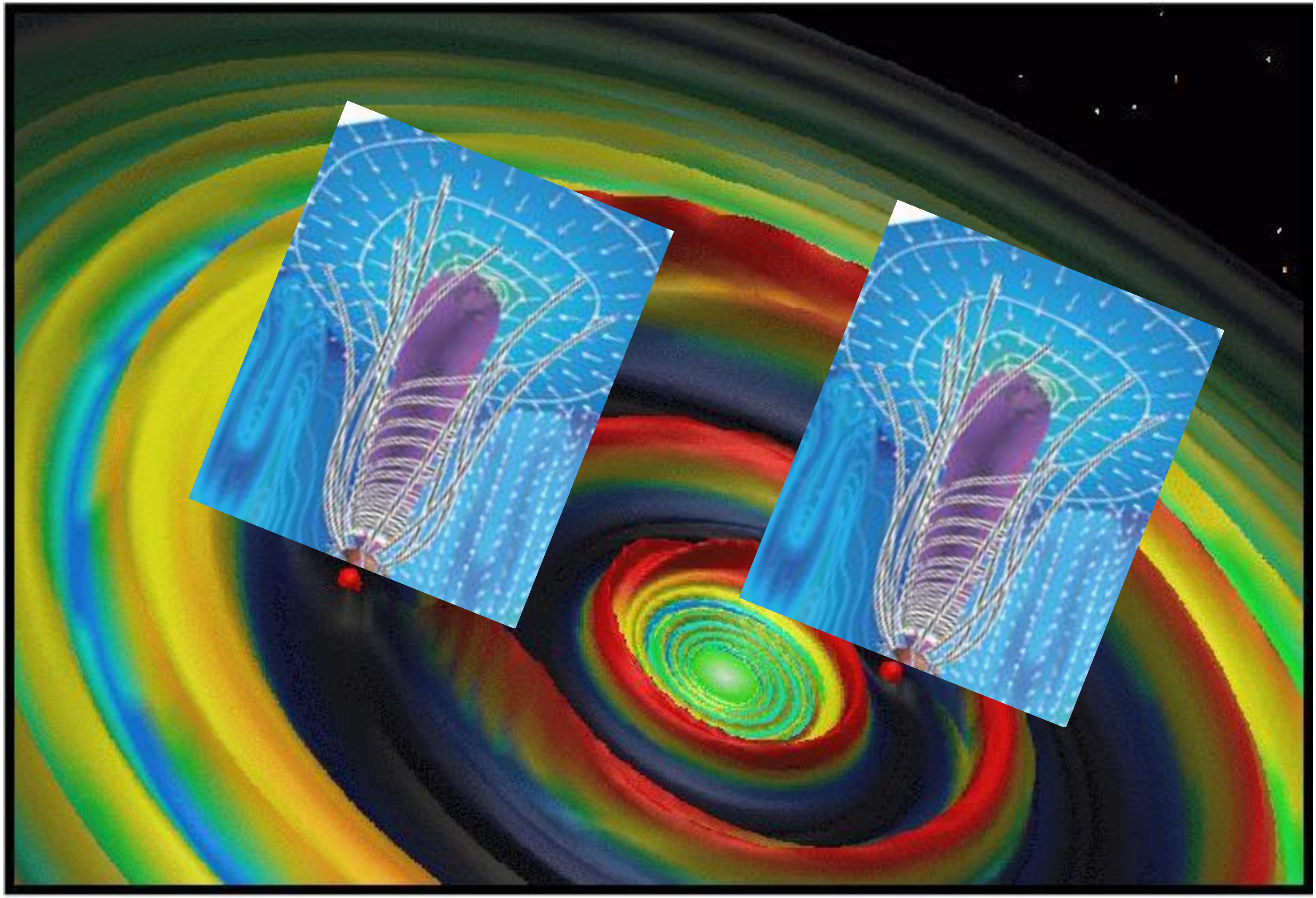
➔ Driving of Outflow!



Machida, SI, & Matsumoto

(2006) ApJ **649**, L129

Discover Forming Planets!



Artwork by G. Bryden

Summary

Dynamics of Multi-Phase ISM

Kolmogorov Turbulence, mG Mag. Field, …

Expanding HII Region

Feedback depends on M_* of Central Star!

Quenching or Star Burst

Recent Theory on Protostellar Collapse

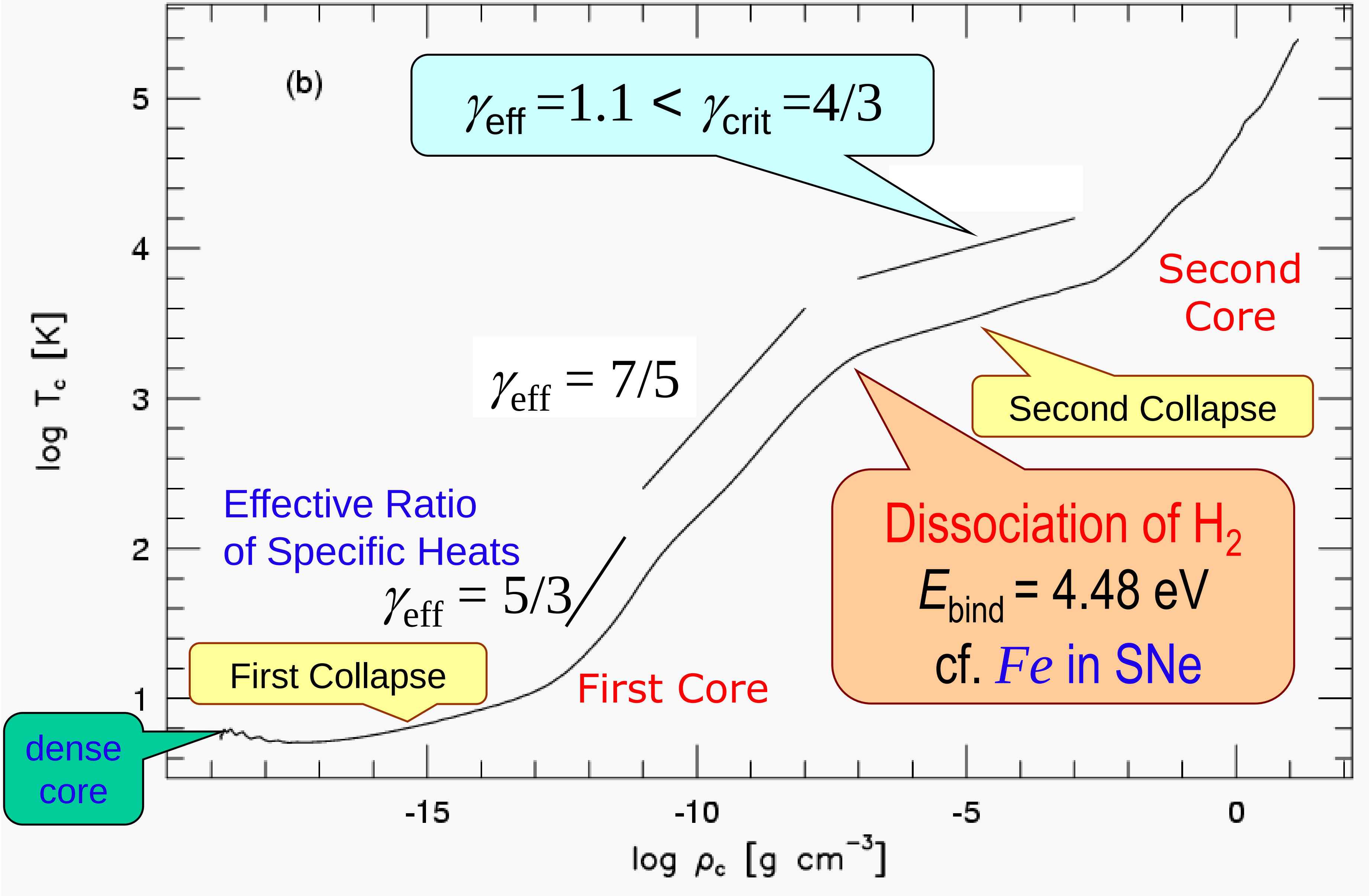
➔ Natural “*Hybrid Scenario*”

Planetary Mass Companions in PP Disks

Shepherding of Dust Grains

➔ Formation of Planetesimals

Temperature Evolution at Center



$\gamma_{\rm eff} = 1.1 < \gamma_{\rm crit} = 4/3$

$\gamma_{\rm eff} = 7/5$

Effective Ratio of Specific Heats

$\gamma_{\rm eff} = 5/3$

First Collapse

dense core

First Core

Second Core

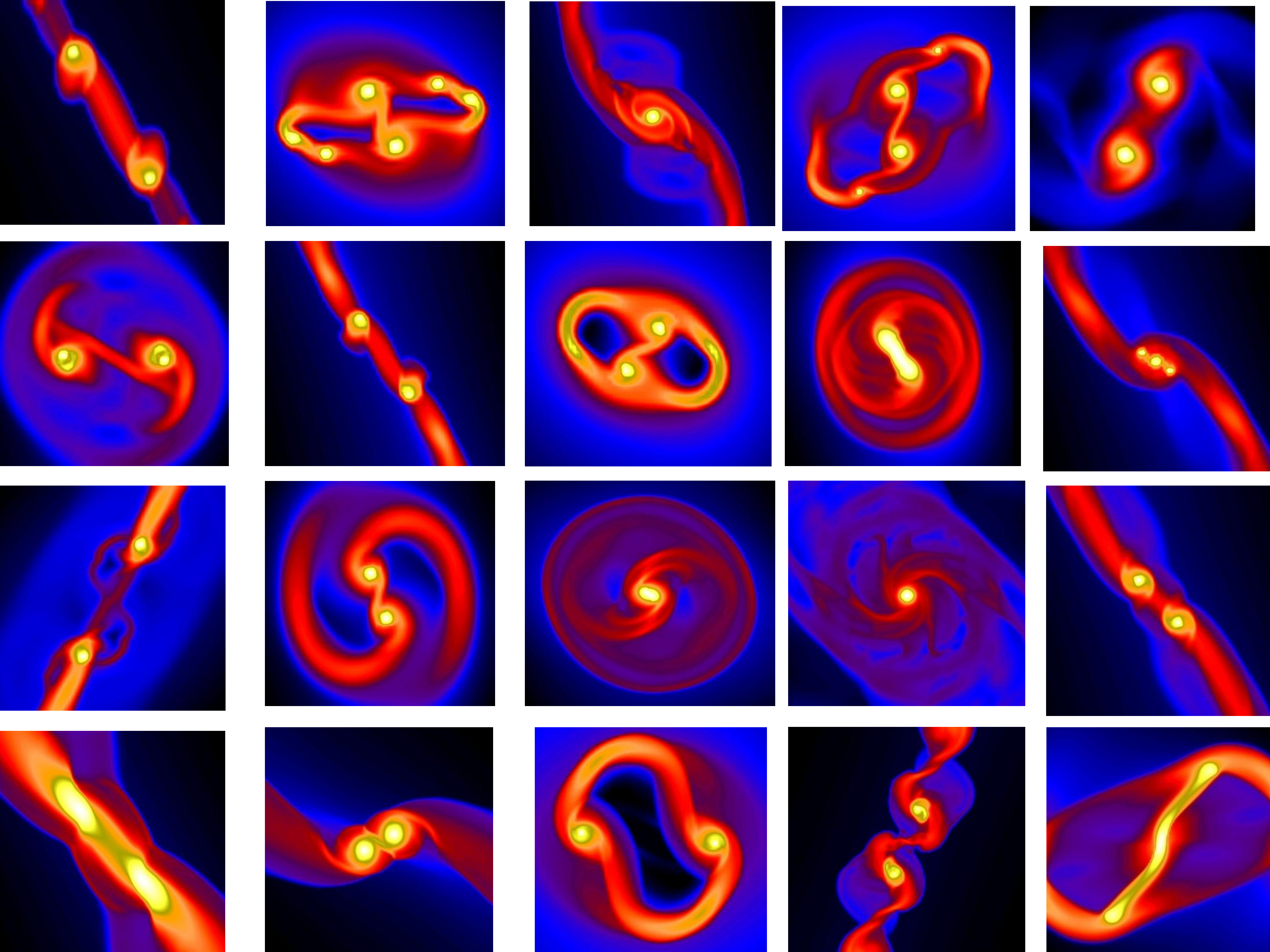
Second Collapse

Dissociation of H_2

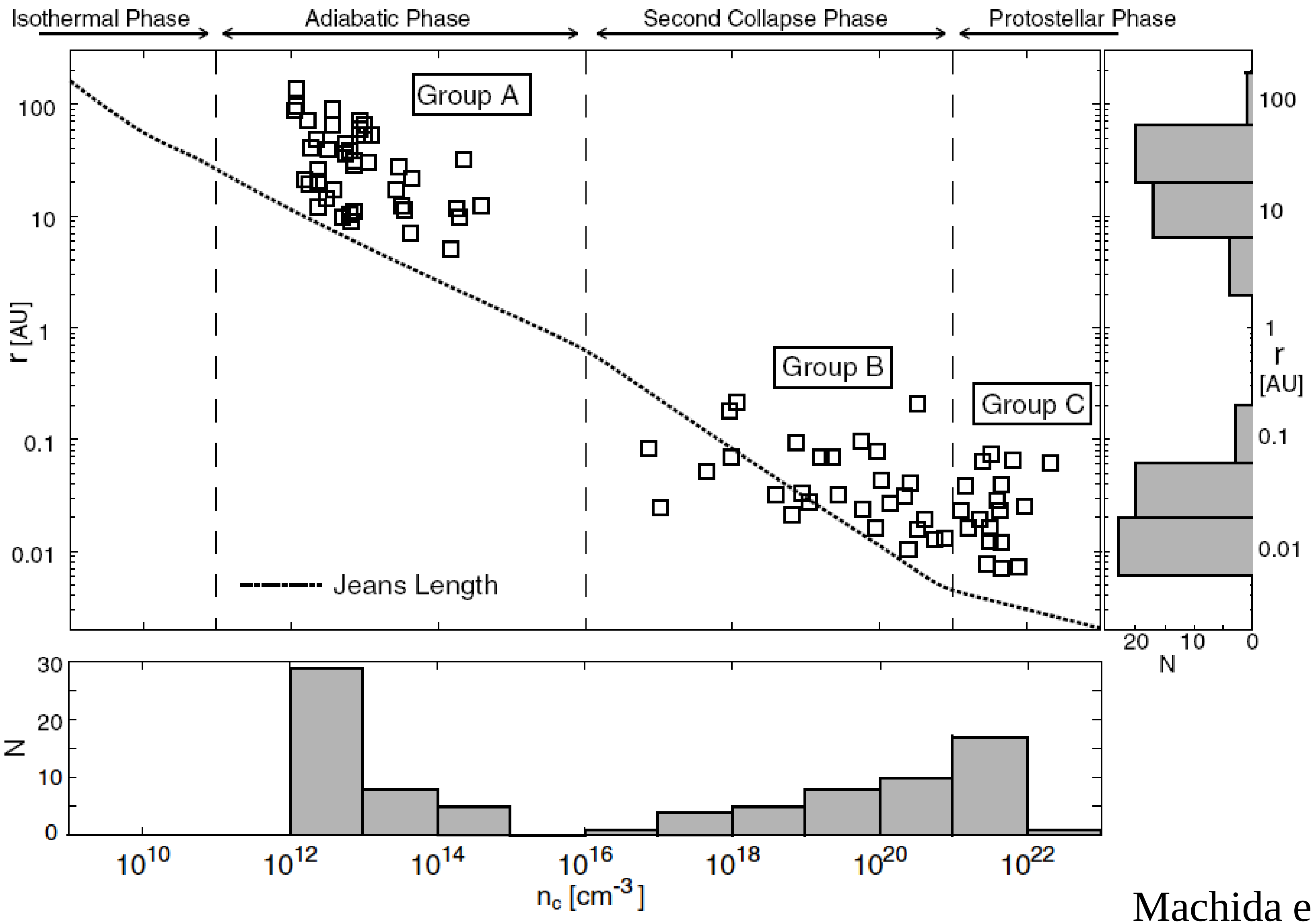
$E_{\rm bind} = 4.48$ eV

cf. *Fe* in SNe

Masunaga & SI 2000, ApJ **531**, 350



Bimodal Binary Formation



distance from primary star

Machida et al. (2008)
ApJ **677**, 327

Std Model of Protoplanetary Disks

$$\Sigma_e(r) = 1.7\times10^3 f_\Sigma \left(\frac{r}{1\mathrm{AU}}\right)^{\frac{3}{2}} \frac{\mathrm{g}}{\mathrm{cm}^2}$$

$$T(r) = 280\left(\frac{r}{1\mathrm{AU}}\right)^{\frac{1}{2}} \mathrm{K}$$

$$\mathrm{C_S}(r) \approx 10^5 \left(\frac{r}{1\mathrm{AU}}\right)^{-\frac{1}{4}} \left(\frac{\mu}{2.34}\right)^{-\frac{1}{2}} \frac{\mathrm{cm}}{\mathrm{s}}$$

$$\rho(r,z) \approx 1.4\times10^{-9} f_\Sigma \left(\frac{r}{1\mathrm{AU}}\right)^{-\frac{11}{4}} \left(\frac{M_*}{M_\odot}\right)^{\frac{1}{2}} \left(\frac{\mu}{2.34}\right)^{\frac{1}{2}} \mathrm{g/cm^3}$$

$$\mathrm{B}(r) \approx 1.9 f_\Sigma{}^{\frac{1}{2}} \left(\frac{r}{1\mathrm{AU}}\right)^{-\frac{13}{8}} \left(\frac{\beta_c}{100}\right)^{-\frac{1}{2}} \mathrm{G}, \quad \beta_c \equiv \left(\frac{2\mathrm{C_S}^2}{\mathrm{v_A}^2}\right)$$

Ionization Degree in PP Disks

neutral gas + ionized gas
+ dust grains

$\zeta_{CR} = 10^{-17}\ \mathrm{s}^{-1}$

cosmic ray ionization
$\Rightarrow$ resistivity

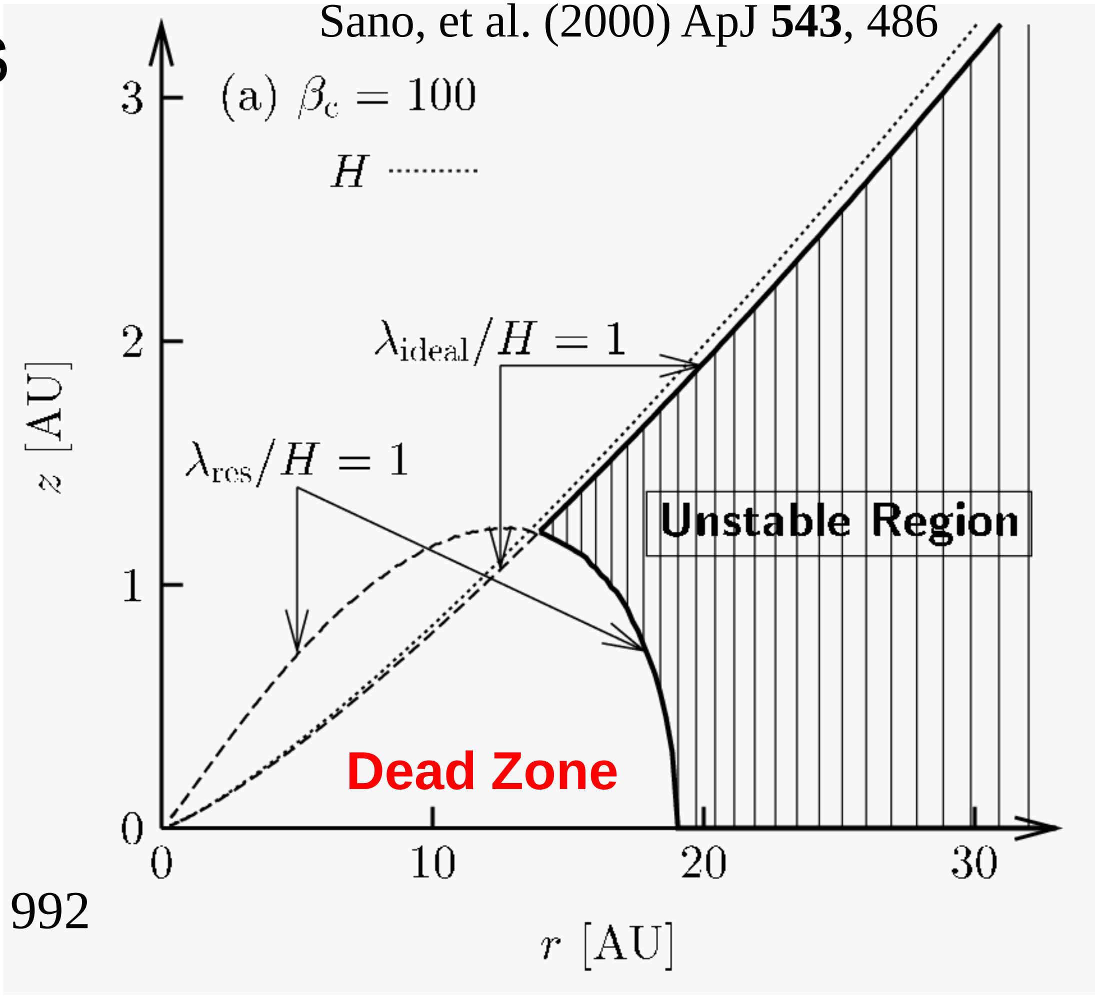
Classical Models:

Sano et al. 2000, ApJ **543**, 486

Glassgold et al. 2000, PPIV

Fromang et al. 2002, MN **329**, 18

Salmeron & Wardle 2003, MN **345**, 992



Sano, et al. (2000) ApJ **543**, 486

"Dead Zone" can be removed by self-sustained ionization!

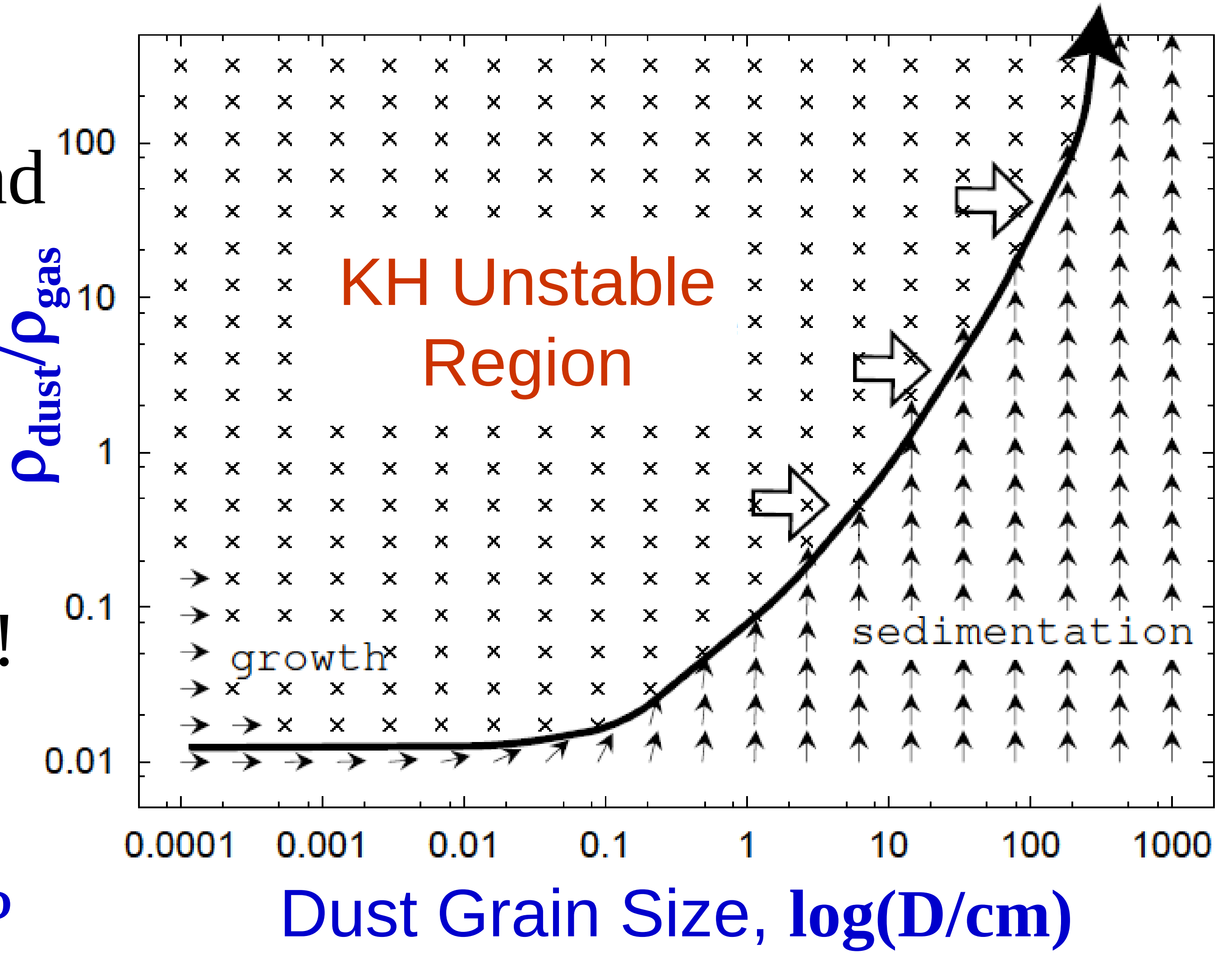
SI & Sano (2005) ApJ **628**, L155

A Possible Path Toward Gravitational Instability to Form Planetesimals

Big Grains Avoid KHI and Enable Gravitational Instability to Form Planetesimals!

➔ small κ_{dust}

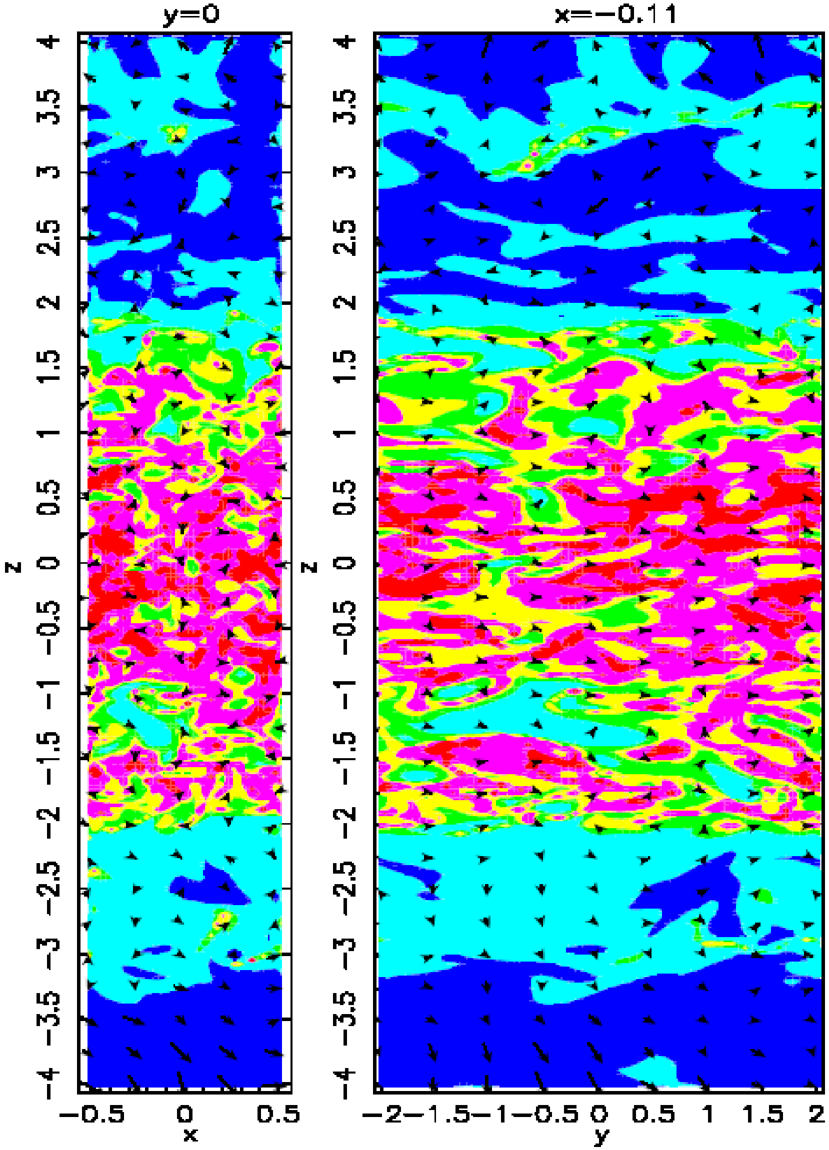
observable?

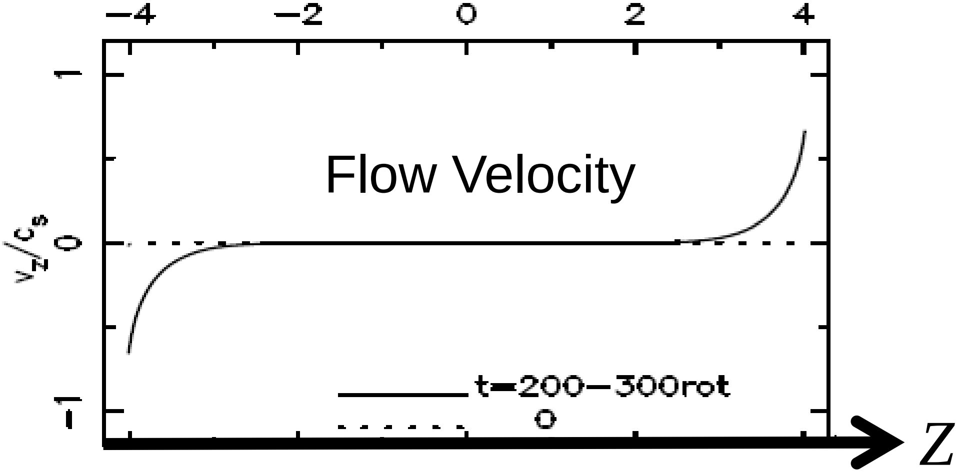


Michikoshi & SI (2006) ApJ **641**, 1131

Effect of MRI on Planet Formation

after 210 rotations





Powerful MHD Wind from Disk

Just Like Solar Wind

Dispersal Timescale ~ 4000yr (locally)

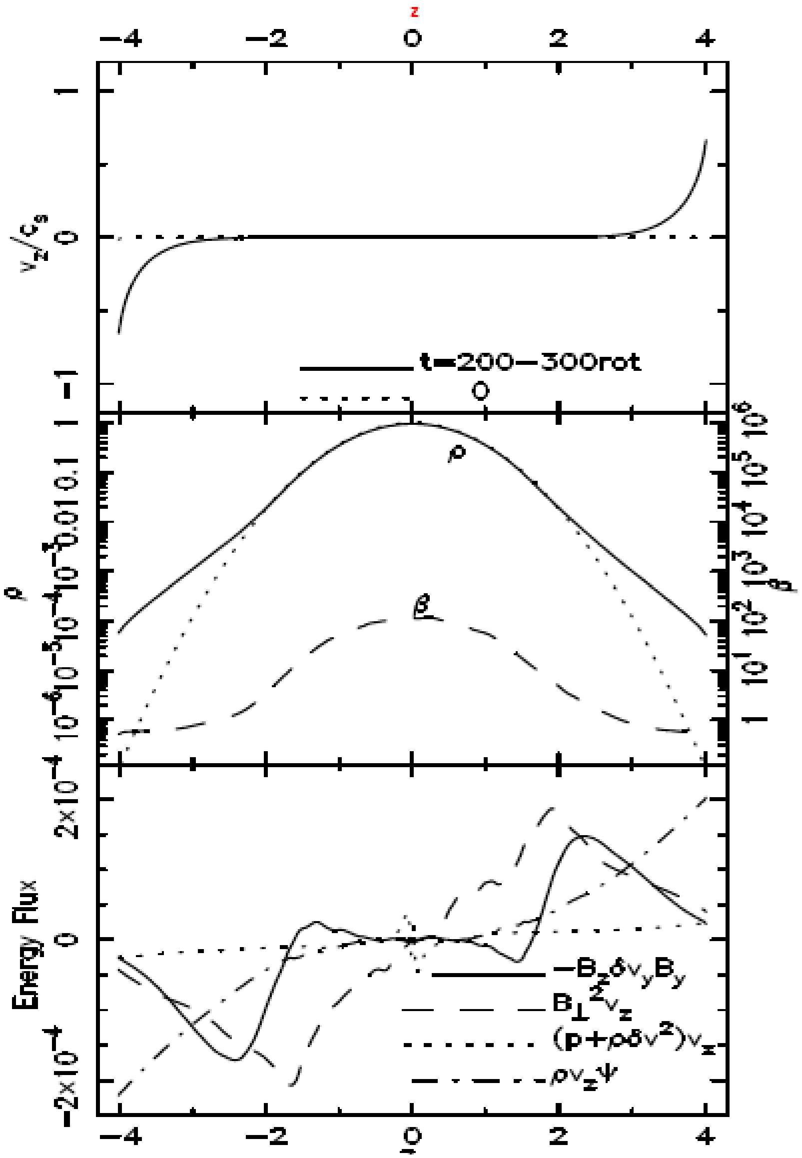
~ a few Myr for typical disk models

in Ideal MHD

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

See Poster by T. K. Suzuki

Quasi-Steady Disk Wind



Distance from Midplane, Z

Dispersal Timescale

~ 4000yr (locally)

~ a few Myr for typical disk models

in Ideal MHD

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