Sternentstehung - Star Formation

Winter term 2020/2021

Henrik Beuther, Thomas Henning & Sümeyye Suri

03.11 Today: Introduction & Overview	(Beuther)
10.11 Physical processes I	(Beuther)
17.11 Physcial processes II	(Beuther)
24.11 Molecular clouds as birth places of stars	(Suri)
01.12 Molecular clouds (cont.), Jeans Analysis	(Suri)
08.12 Collapse models I	(Henning)
15.12 Collapse models II	(Henning)
------------ Christmas break -------------	
12.01 Protostellar evolution	(Beuther)
19.01 Pre-main sequence evolution & outflows/jets	(Beuther)
26.01 Accretion disks I	(Henning)
02.02 Accretion disks II	(Henning)
09.02 High-mass star formation, clusters and the IMF	(Suri)
16.02 Extragalactic star formation	(Henning)
23.02 Examination week, no star formation lecture	

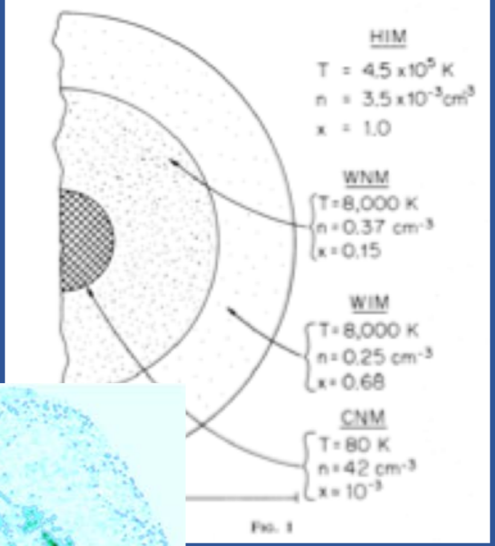
Book: Stahler & Palla: The Formation of Stars, Wileys

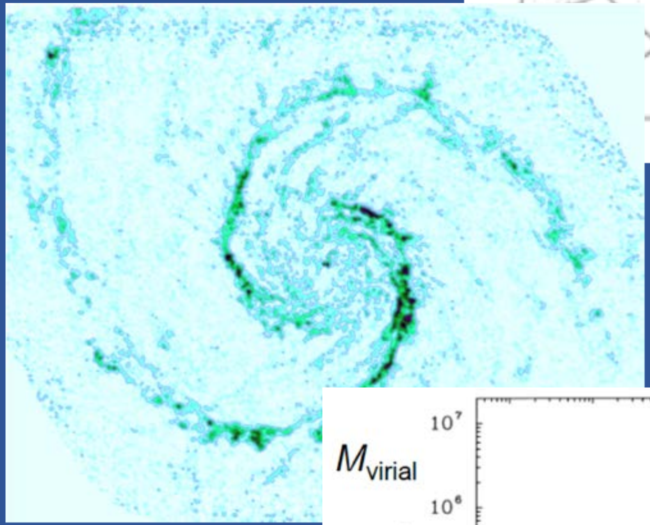
More Information and the current lecture files: http://www.mpia.de/homes/beuther/lecture_ws2021.html

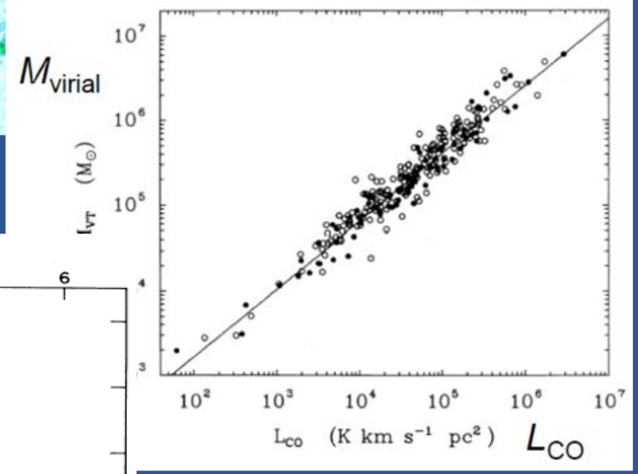
beuther@mpia.de, henning@mpia.de , suri@mpia.de

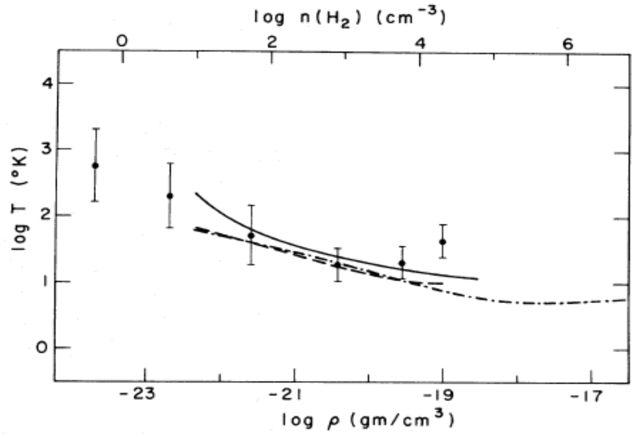
Last Week

- Different components of ISM
- Basic characteristics
- Important cloud relations
- Cloud fragmentation



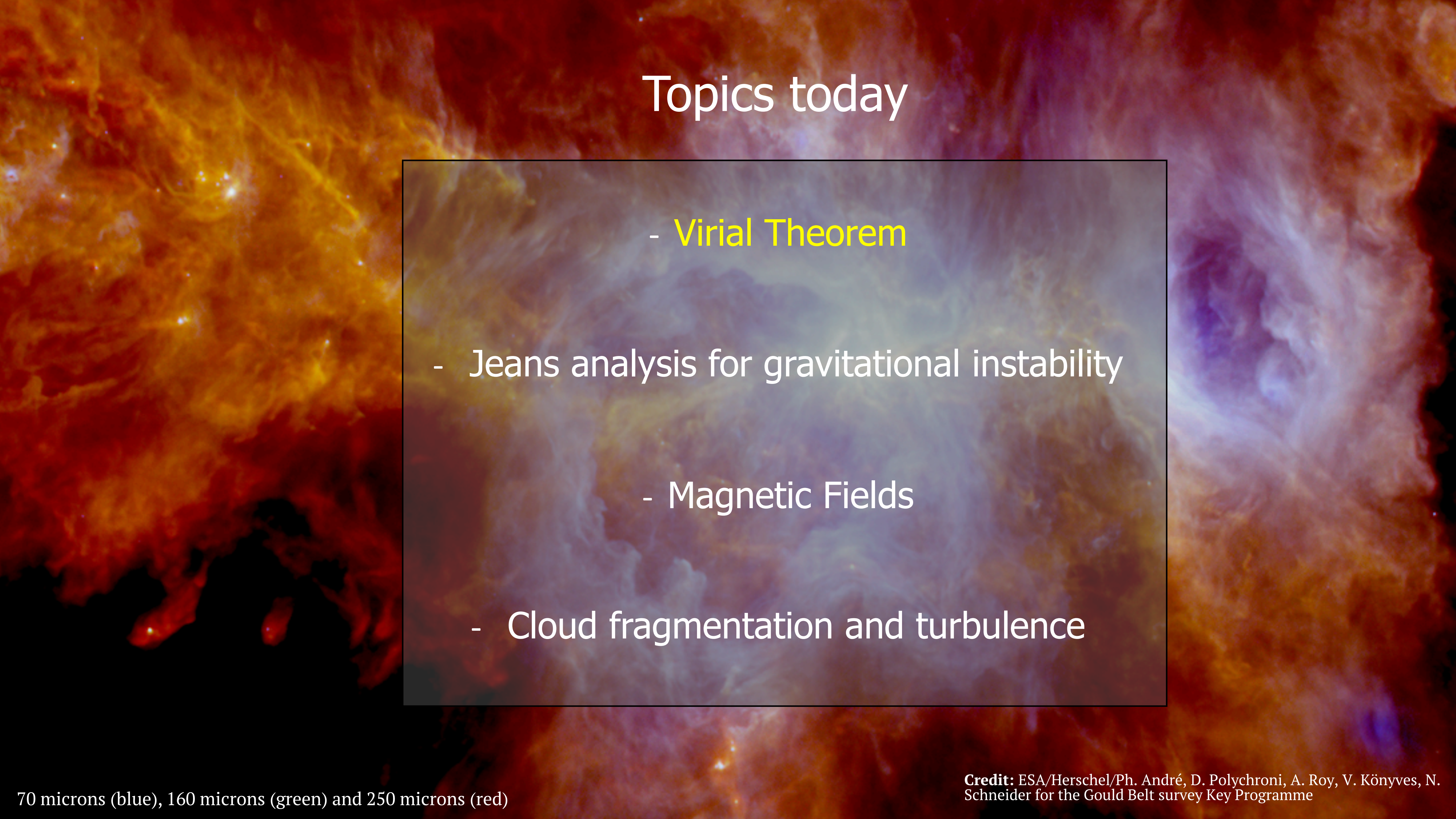






Topics today

- Virial Theorem
- Jeans analysis for gravitational instability
- Magnetic Fields
- Cloud fragmentation and turbulence



70 microns (blue), 160 microns (green) and 250 microns (red)

Credit: ESA/Herschel/Ph. André, D. Polychroni, A. Roy, V. Könyves, N. Schneider for the Gould Belt survey Key Programme

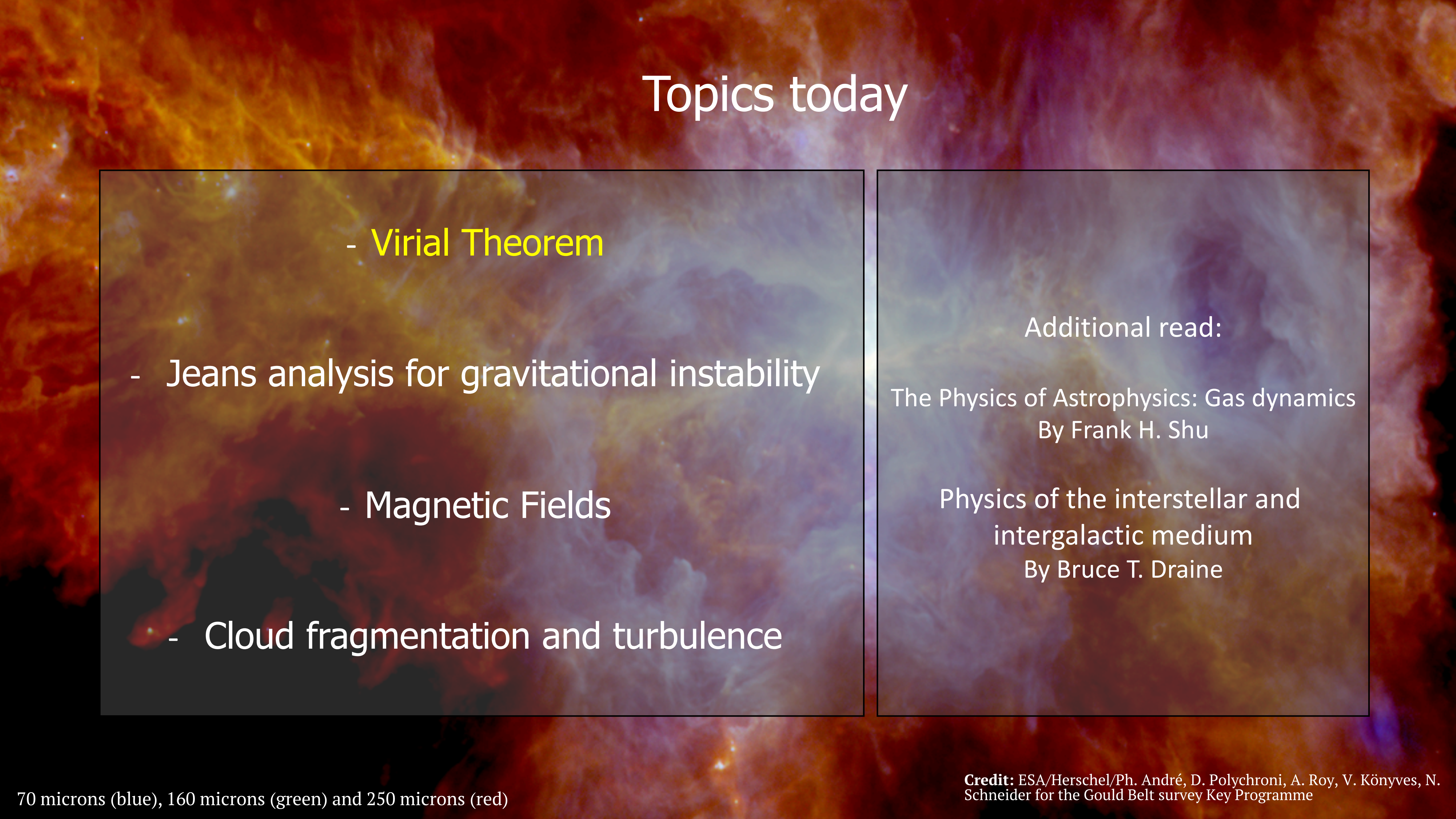
Topics today

- Virial Theorem
- Jeans analysis for gravitational instability
- Magnetic Fields
- Cloud fragmentation and turbulence

Additional read:

The Physics of Astrophysics: Gas dynamics
By Frank H. Shu

Physics of the interstellar and intergalactic medium
By Bruce T. Draine



70 microns (blue), 160 microns (green) and 250 microns (red)

Credit: ESA/Herschel/Ph. André, D. Polychroni, A. Roy, V. Könyves, N. Schneider for the Gould Belt survey Key Programme

Virial Analysis

Virial Analysis

We are going to assess the balance of forces:

Starting with the equation of momentum conservation:

$$\rho\, D\mathbf{v}/Dt = -\nabla P - \rho\, \nabla\Phi_g + 1/c\, \mathbf{j} \times \mathbf{B}$$

Virial Analysis

We are going to assess the balance of forces:

Starting with the equation of momentum conservation:

$$\rho \boxed{D\mathbf{v}/Dt} = - \nabla P - \rho \nabla \Phi_g + 1/c\, \mathbf{j} \times \mathbf{B}$$

Full time derivative of
v the fluid velocity

$$D\mathbf{v}/Dt = (\partial \mathbf{v}/\partial t)_x + (\mathbf{v} \cdot \nabla)\mathbf{v}$$

Virial Analysis

We are going to assess the balance of forces:

Starting with the equation of momentum conservation:

$$\rho \boxed{D\mathbf{v}/Dt} = - \nabla P - \rho \nabla \Phi_g + 1/c\, \mathbf{j} \times \mathbf{B}$$

Full time derivative of
v the fluid velocity

$$D\mathbf{v}/Dt = \boxed{(\partial \mathbf{v}/\partial t)_x} + (\mathbf{v} \cdot \nabla)\mathbf{v}$$

Rate of change at
position x

Virial Analysis

We are going to assess the balance of forces:

Starting with the equation of momentum conservation:

$$\rho \boxed{D\mathbf{v}/Dt} = -\nabla P - \rho \nabla \Phi_g + 1/c\, \mathbf{j} \times \mathbf{B}$$

Full time derivative of
v the fluid velocity

$$D\mathbf{v}/Dt = \boxed{(\partial \mathbf{v}/\partial t)_x} + \boxed{(\mathbf{v} \cdot \nabla)\mathbf{v}}$$

Change caused by moving
to a new location
with differing velocity

Rate of change at
position x

Virial Analysis

We are going to assess the balance of forces:

Starting with the equation of momentum conservation:

$$\rho \boxed{D\mathbf{v}/Dt} = -\nabla P - \rho \nabla \Phi_g + \boxed{1/c\, \mathbf{j} \times \mathbf{B}}$$

Magnetic force per unit volume
Acting on current density **j**

Full time derivative of
v the fluid velocity

$$D\mathbf{v}/Dt = \boxed{(\partial \mathbf{v}/\partial t)_x} + \boxed{(\mathbf{v} \cdot \nabla)\mathbf{v}}$$

Change caused by moving
to a new location
with differing velocity

Rate of change at
position x

Virial Analysis

We are going to assess the balance of forces:

Starting with the equation of momentum conservation:

$$\rho \boxed{D\mathbf{v}/Dt} = - \nabla P - \rho \nabla \Phi_g + \boxed{1/c\, \mathbf{j} \times \mathbf{B}}$$

Magnetic force per unit volume
Acting on current density **j**

Full time derivative of
v the fluid velocity

$$D\mathbf{v}/Dt = \boxed{(\partial \mathbf{v}/\partial t)_x} + \boxed{(\mathbf{v} \cdot \nabla)\mathbf{v}}$$

Change caused by moving
to a new location
with differing velocity

Rate of change at
position x

$$\nabla \times \mathbf{B} = (4\pi/c)\, \mathbf{j}$$

j and **B** are related through the Ampere's Law

Virial Analysis

We are going to assess the balance of forces:

Starting with the equation of momentum conservation:

$$\rho \boxed{D\mathbf{v}/Dt} = -\nabla P - \rho \nabla \Phi_g + \boxed{1/c\ \mathbf{j} \times \mathbf{B}}$$

Magnetic force per unit volume
Acting on current density **j**

Full time derivative of
v the fluid velocity

$$D\mathbf{v}/Dt = \boxed{(\partial \mathbf{v}/\partial t)_x} + \boxed{(\mathbf{v} \cdot \nabla)\mathbf{v}}$$

Change caused by moving
to a new location
with differing velocity

Rate of change at
position x

$$\nabla \times \mathbf{B} = (4\pi/c)\ \mathbf{j}$$

j and **B** are related through the Ampere's Law

$$\rho\ D\mathbf{v}/Dt = -\nabla P - \rho \nabla \Phi_g + 1/4\pi\ (\mathbf{B} \cdot \nabla)\mathbf{B} - 1/8\pi\ \nabla\ |\mathbf{B}|^2$$

Virial Analysis

We are going to assess the balance of forces:

$$\rho \, D\mathbf{v}/Dt = -\nabla P - \rho \, \nabla\Phi_g + 1/4\pi \, (\mathbf{B} \cdot \nabla)\mathbf{B} - 1/8\pi \, \nabla \, |\mathbf{B}|^2$$

Virial Analysis

We are going to assess the balance of forces:

$$\rho \, D\mathbf{v}/Dt = -\nabla P - \rho \nabla \Phi_g + \boxed{1/4\pi \, (\mathbf{B} \cdot \nabla)\mathbf{B}} - 1/8\pi \, \nabla \, |\mathbf{B}|^2$$

Tension associated with
Curved magnetic field lines

Virial Analysis

We are going to assess the balance of forces:

$$\rho\, D\mathbf{v}/Dt = -\nabla P - \rho\, \nabla\Phi_g + \boxed{1/4\pi\, (\mathbf{B} \cdot \nabla)\mathbf{B}} - \boxed{1/8\pi\, \nabla\, |\mathbf{B}|^2}$$

Gradient of magnetic pressure

Tension associated with
Curved magnetic field lines

Virial Analysis

We are going to assess the balance of forces:

$$\rho\, D\mathbf{v}/Dt = -\nabla P - \rho\, \nabla\Phi_g + \boxed{1/4\pi\, (\mathbf{B} \cdot \nabla)\mathbf{B}} - \boxed{1/8\pi\, \nabla\, |\mathbf{B}|^2}$$

Gradient of magnetic pressure

Tension associated with
Curved magnetic field lines

This is the local behavior of the fluid.
We need to integrate over volume to describe the global properties.

Virial Analysis

We are going to assess the balance of forces:

$$\rho\, D\mathbf{v}/Dt = -\nabla P - \rho\, \nabla\Phi_g + \boxed{1/4\pi\, (\mathbf{B}\cdot\nabla)\mathbf{B}} - \boxed{1/8\pi\, \nabla\, |\mathbf{B}|^2}$$

Gradient of magnetic pressure

Tension associated with
Curved magnetic field lines

This is the local behavior of the fluid.
We need to integrate over volume to describe the global properties.

Equation of mass continuity: $-(\partial\rho/\partial t)_x = \nabla\cdot(\rho\, \mathbf{v})$

Poisson equation: $\Delta\Phi_g = 4\pi G\rho$

Virial Analysis

We are going to assess the balance of forces:

$$\rho\, D\mathbf{v}/Dt = -\nabla P - \rho\, \nabla\Phi_g + \boxed{1/4\pi\, (\mathbf{B}\cdot\nabla)\mathbf{B}} - \boxed{1/8\pi\, \nabla\, |\mathbf{B}|^2}$$

Gradient of magnetic pressure

Tension associated with
Curved magnetic field lines

This is the local behavior of the fluid.
We need to integrate over volume to describe the global properties.

Equation of mass continuity: $-(\partial\rho/\partial t)_x = \nabla.(\rho\,\mathbf{v})$

Poisson equation: $\Delta\Phi_g = 4\pi G\rho$

Repeated surface integrals lead to the virial theorem:

$$1/2\,(\delta^2 I/\delta t^2) = 2T + 2U + W + \mathcal{M}$$

Virial Analysis

We are going to assess the balance of forces:

$$\rho\, D\mathbf{v}/Dt = -\nabla P - \rho\, \nabla\Phi_g + \boxed{1/4\pi\, (\mathbf{B}\, .\, \nabla)\mathbf{B}} - \boxed{1/8\pi\, \nabla\, |\mathbf{B}|^2}$$

Gradient of magnetic pressure

Tension associated with
Curved magnetic field lines

This is the local behavior of the fluid.
We need to integrate over volume to describe the global properties.

Equation of mass continuity: $-(\partial\rho/\partial t)_x = \nabla.(\rho\, \mathbf{v})$

Poisson equation: $\Delta\Phi_g = 4\pi G\rho$

The detailed derivation is in the appendix of the book!

Repeated surface integrals lead to the virial theorem:

$$1/2\, (\delta^2 I/\delta t^2) = 2T + 2U + W + \mathcal{M}$$

Virial Analysis

We are going to assess the balance of forces:

$$1/2\ \boxed{(\delta^2 I/\delta t^2)} = 2T + 2U + W + \mathcal{M}$$

I: Moment of inertia
Decreases during core collapse
($m*r^2$)

Virial Analysis

We are going to assess the balance of forces:

T: kinetic energy

$$\frac{1}{2}\boxed{\left(\frac{\delta^2 I}{\delta t^2}\right)} = \boxed{2T} + 2U + W + \mathcal{M}$$

I: Moment of inertia
Decreases during core collapse
$(m*r^2)$

Virial Analysis

We are going to assess the balance of forces:

T: kinetic energy

$$\frac{1}{2}\boxed{(\delta^2 I/\delta t^2)} = \boxed{2T} + \boxed{2U} + W + M$$

I: Moment of inertia
Decreases during core collapse
($m*r^2$)

U: thermal energy

Virial Analysis

We are going to assess the balance of forces:

T: kinetic energy

W: gravitational
potential energy

$$1/2\ \boxed{(\delta^2 I/\delta t^2)} = \boxed{2T} + \boxed{2U} + \boxed{W} + M$$

I: Moment of inertia
Decreases during core collapse
($m*r^2$)

U: thermal energy

Virial Analysis

We are going to assess the balance of forces:

T: kinetic energy

W: gravitational potential energy

$$1/2\ (\delta^2 I/\delta t^2) = 2T + 2U + W + \mathit{M}$$

I: Moment of inertia
Decreases during core collapse
($m*r^2$)

M: magnetic energy

U: thermal energy

Application of the Virial Theorem I

If all forces are too weak to match the gravitational energy, we get

$$1/2\ (\delta^2 I/\delta t^2) = W \sim Gm^2/r$$

Approximating further $I=mr^2$, the free-fall time is approximately

$$t_{ff} \sim \mathrm{sqrt}(r^3/Gm)$$

Since the density can be approximated by $\rho=m/r^3$, one can also write

$$t_{ff} \sim (G\rho)^{-1/2}$$

Or more exactly for a pressure-free 3D homogeneous sphere

$$t_{ff} = (3\pi/32G\rho)^{1/2}$$

For a giant molecular cloud, this corresponds to

$$t_{ff} \sim 7*10^6\ \mathrm{yr}\ (m/10^5 M_{sun})^{-1/2}\ (R/25\mathrm{pc})^{3/2}$$

For a dense core with $\rho \sim 10^5 \mathrm{cm}^{-3}$ the t_{ff} is approximately 10^5 yr.

However, no globally collapsing GMCs observed → add support!

Application of the Virial Theorem II

If the cloud complexes are in approximate force equilibrium, the moment of inertia actually does not change significantly and hence $1/2\ (\delta^2 I/\delta t^2)=0$

$$2T + 2U + W + \mathcal{M} = 0$$

This state is called VIRIAL EQUILIBRIUM. What balances gravitation W best?

Thermal Energy: Approximating U by $U \sim 3/2 N k_B T \sim m\mathcal{R}T/\mu$

$$U/|W| \sim m\mathcal{R}T/\mu\ (Gm^2/R)^{-1}$$

$$= 3*10^{-3}\ (m/10^5 M_{sun})^{-1}\ \ (R/25pc)\ \ (T/15K)$$

--> Clouds cannot be supported by thermal pressure alone!

Magnetic energy: Approximating $\mathcal{M}$ by $M \sim B^2 r^3/6$ (cloud approximated as sphere)

$$\mathcal{M}/|W| \sim B^2 r^3/6\ (Gm^2/R)^{-1}$$

$$= 0.3\ (B/20\mu G)^2\ \ (R/25pc)^4\ \ (m/10^5 M_{sun})^{-2}$$

--> Magnetic force is important for large-scale cloud stability!

Application of the Virial Theorem III

The last term to consider in $2T + 2U + W + \mathcal{M} = 0$ is the kinetic energy T

$$T/|W| \sim 1/2 m \Delta v^2 \, (Gm^2/R)^{-1}$$
$$= 0.5\ (\Delta v/4\mathrm{km/s})\ \ (M/10^5 M_{sun})^{-1}\ \ (R/25\mathrm{pc})$$

Since the shortest form of the virial theorem is $2T = -W$, the above numbers imply that a typical cloud with linewidth of a few km/s is in approximate virial equilibrium.

The other way round, one can derive an approximate relation between the observed line-width and the mass of the cloud:

$$2T = 2^*\ (1/2 m \Delta v^2) = -W = Gm^2/r$$
$$\rightarrow \text{ virial velocity: } v_{vir} = (Gm/r)^{1/2}$$
$$\rightarrow \text{ or virial mass: } m_{vir} = v^2 r/G$$

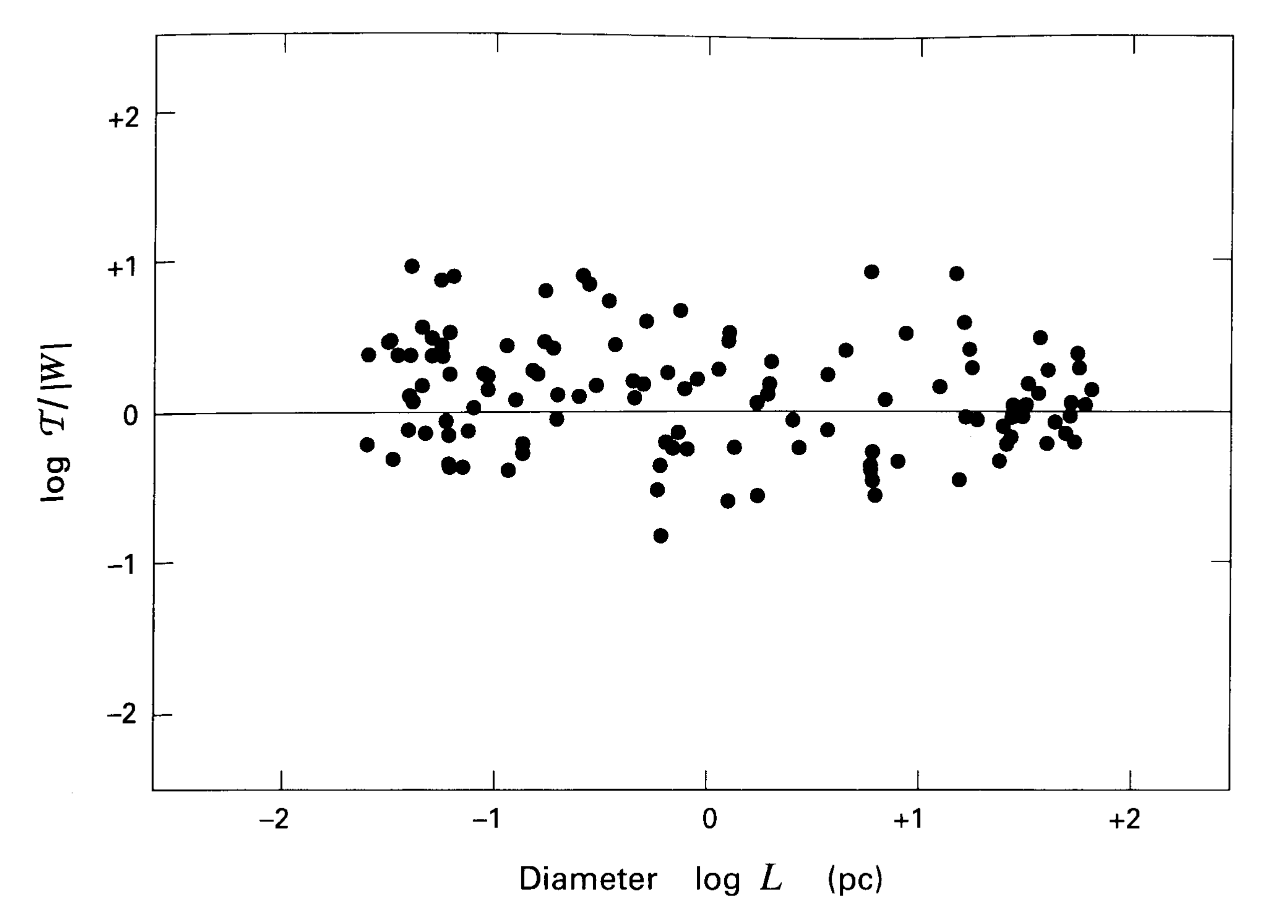
Application of the Virial Theorem III

The last ... ic energy T

(R/25pc)

Since the ... ove numbers
imply th... proximate

The othe... etween the



Topics today

- Virial Theorem
- Jeans analysis for gravitational instability
- Magnetic Fields
- Cloud fragmentation and turbulence

70 microns (blue), 160 microns (green) and 250 microns (red)

Credit: ESA/Herschel/Ph. André, D. Polychroni, A. Roy, V. Könyves, N. Schneider for the Gould Belt survey Key Programme

Jeans analysis I

Start again with equation of hydrodynamic equilibrium (without magn. Field):

Conservation of momentum: $\rho\, D\mathbf{v}/Dt = -\nabla P - \rho\, \nabla\Phi_g$

$$\rho\, (\partial\mathbf{v}/\partial t) + (\mathbf{v}\, .\, \nabla\,)\mathbf{v} = -\nabla P - \rho\, \nabla\Phi_g$$

Continuity equation: $(\partial\rho/\partial t) = -\nabla(\rho\mathbf{v})$

Poisson equation: $\Delta\Phi_g = 4\pi G\rho$

Jeans analysis I

Start again with equation of hydrodynamic equilibrium (without magn. Field):

Conservation of momentum: $\rho\, D\mathbf{v}/Dt = -\nabla P - \rho\, \nabla\Phi_g$

$\rho\, (\partial\mathbf{v}/\partial t) + (\mathbf{v}\, .\, \nabla\,)\mathbf{v} = -\nabla P - \rho\, \nabla\Phi_g$

Continuity equation: $(\partial\rho/\partial t) = -\nabla(\rho\mathbf{v})$

Poisson equation: $\Delta\Phi_g = 4\pi G\rho$

Static solution: $\rho = \rho_0 =$ const; $P = P_0 =$ const; $\mathbf{v} = \mathbf{v_0} =$ const; $\Phi_g = \Phi_0 =$ const

Jeans analysis I

Start again with equation of hydrodynamic equilibrium (without magn. Field):

Conservation of momentum: $\rho\, D\mathbf{v}/Dt = -\nabla P - \rho\, \nabla\Phi_g$

$$\rho\, (\partial\mathbf{v}/\partial t) + (\mathbf{v} \cdot \nabla)\mathbf{v} = -\nabla P - \rho\, \nabla\Phi_g$$

Continuity equation: $(\partial\rho/\partial t) = -\nabla(\rho\mathbf{v})$

Poisson equation: $\Delta\Phi_g = 4\pi G\rho$

Static solution: $\rho = \rho_0 = \text{const}$; $P = P_0 = \text{const}$; $\mathbf{v} = \mathbf{v_0} = \text{const}$; $\Phi_g = \Phi_0 = \text{const}$

Little pertubation: linear stability analysis:

$\rho = \rho_0 + \rho_1$; $P = P_0 + P_1$; $\mathbf{v} = \mathbf{v_0} + \mathbf{v_1}$; $\Phi_g = \Phi_0 + \Phi_1$

(with $|\rho_1| << \rho_0$ etc.)

Jeans analysis II

Considering only expressions of first order:

$\partial \mathbf{v_1}/\partial t = - 1/\rho_0 \, \nabla(P_1) - \nabla(\Phi_1)$ (Eq. 1)

$\partial \rho_1/\partial t = -\rho_0 \, \nabla(\mathbf{v_1})$ (Eq. 2)

$\Delta\Phi_1 = 4\pi G \rho_1$ (Eq. 3)

Using furthermore: $P_1 = c_s^2 \rho_1$ and $c_s = kT/(\mu \, m_H)$

(c_s sound speed; μ mean mass of particle; m_H mass of hydrogen)

Apply grad to Eq. 1: $\nabla(\partial \mathbf{v_1}/\partial t) = -\Delta \, (a_t^2 \rho_1 / \rho_0 + \Phi_1)$

Time derivative for Eq. 2: $\partial^2 \rho_1/\partial t^2 = -\rho_0 \, \nabla(\partial \mathbf{v_1}/\partial t)$

→ wave equation: $\partial^2 \rho_1/\partial t^2 = c_s^2 \Delta \rho_1 + 4\pi G \rho_0 \rho_1$

Jeans analysis III

$$\partial^2\rho_1/\partial t^2 = c_s^2\Delta\rho_1 + 4\pi G\rho_0\rho_1$$

A travelling wave in an isothermal gas can be described as:

$\rho_1 = \text{const} \exp[i(kx - \omega t)]$ with wave number $k=2\pi/\lambda$ and frequency ω

Then $\partial^2\rho_1/\partial t^2 = -\omega^2\rho_1$ and $\Delta\rho_1 = -k^2\rho_1$ (see equations 9.20a to 9.22 in the book)

Jeans analysis III

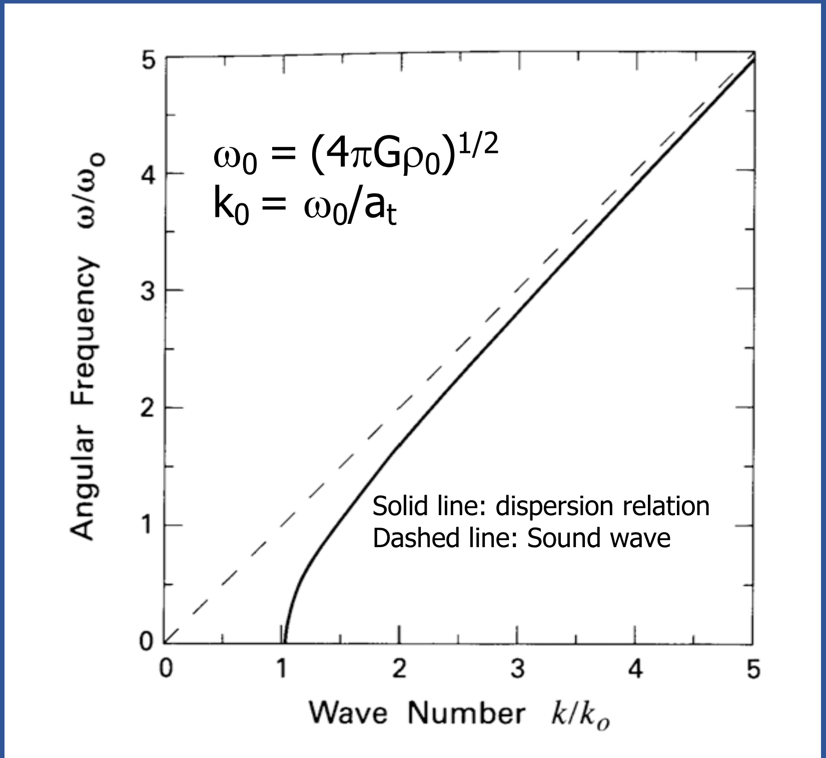
$$\partial^2\rho_1/\partial t^2 = c_s^2\Delta\rho_1 + 4\pi G\rho_0\rho_1$$

A travelling wave in an isothermal gas can be described as:

$\rho_1 = \text{const}\ \exp[i(kx - \omega t)]$ with wave number $k=2\pi/\lambda$ and frequency ω

Then $\partial^2\rho_1/\partial t^2 = -\omega^2\rho_1$ and $\Delta\rho_1 = -k^2\rho_1$ (see equations 9.20a to 9.22 in the book)

This results in *dispersion equation:* $\omega^2 = k^2c_s^2 - 4\pi G\rho_0$



Jeans analysis III

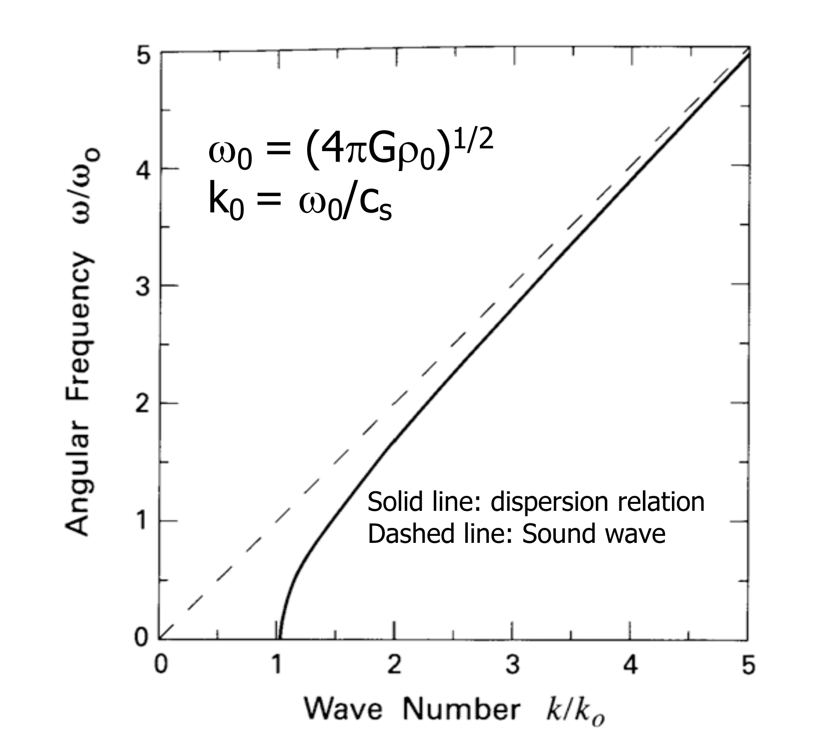
$\partial^2\rho_1/\partial t^2 = c_s^2\Delta\rho_1 + 4\pi G\rho_0\rho_1$

A travelling wave in an isothermal gas can be described as:

$\rho_1 = \text{const}\ \exp[i(kx - \omega t)]$ with wave number $k=2\pi/\lambda$ and frequency ω

Then $\partial^2\rho_1/\partial t^2 = -\omega^2\rho_1$ and $\Delta\rho_1 = -k^2\rho_1$ (see equations 9.20a to 9.22 in the book)

This results in *dispersion equation:* $\omega^2 = k^2c_s^2 - 4\pi G\rho_0$



Large k high-frequency disturbances

→ sound wave $\omega=kc_s$

→ isothermal sound speed of background

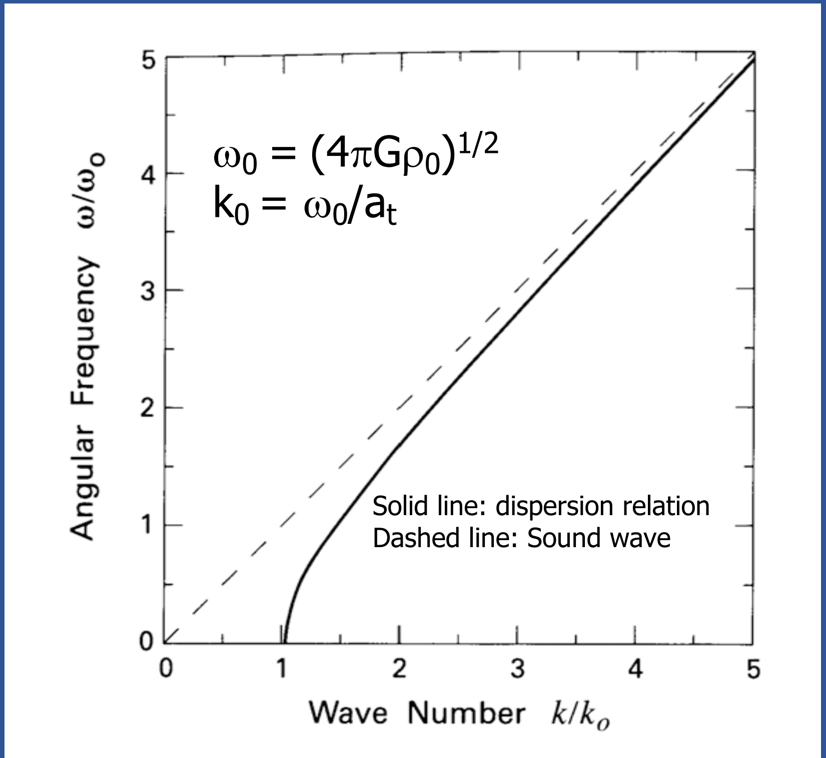
Jeans analysis III

- A travelling wave in an isothermal gas can be described as:

$\rho(x,t) = \rho_1 \exp[i(kx - \omega t)]$ wave number $k=2\pi/\lambda$ and frequency ω

Then: $\partial^2\rho_1/\partial t^2 = -\omega^2\rho_1$ and $\Delta\rho_1 = -k^2\rho_1$

- This results in *dispersion equation:* $\omega^2 = k^2 c_s^2 - 4\pi G\rho_0$



Large k high-frequency disturbances
→ sound wave $\omega=kc_s$
→ isothermal sound speed of background

Low k $(k<=k_0)$ ω^2 → 0.
→ Jeans-length: $\lambda_J = 2\pi/k_0 = (\pi c_s^2/G\rho_0)^{1/2}$

Perturbations larger λ_J have exponentially growing amplitudes → instable

Jeans analysis IV

This corresponds in physical units to Jeans-lengths of

$$\lambda_J = (\pi c_s^2/G\rho_0)^{1/2} = 0.19\mathrm{pc}\ (T/(10K))^{1/2}\ (n_{H2}/(10^4 cm^{-3})^{-1/2}$$

and Jeans-mass

$$M_J = 4\pi/3\ \rho_0(\lambda_J/2)^3 = 0.32 M_{sun}\ (T/(10K))^{3/2}\ (m_H/\mu)^{3/2}\ (n_H/(10^6 cm^{-3})^{-1/2}$$

→ Clouds larger λ_J or more massive than M_J may be prone to fragmentation.

→ Conversely, small or low-mass cloudlets could be stable if there is sufficient external pressure. Otherwise only transient objects.

Jeans analysis V

Examples:

Small HI cloud:

$T \sim 100K$; $n_H \sim 20\ cm^{-3}$; $L \sim 5pc$; $M \sim 20M_{sun}$

→ $L_J \sim 13pc$

→ Jeans stable

Giant Molecular Cloud (GMC)

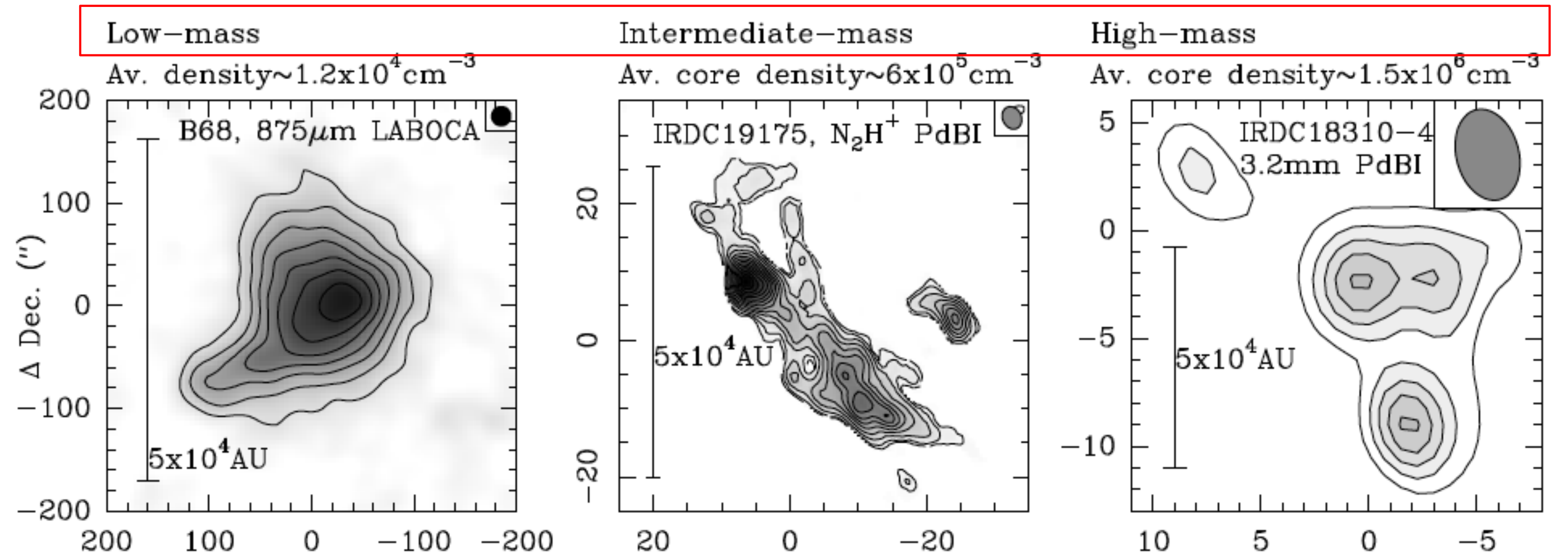
$T=10K$ and $n_{H2}=10^3 cm^{-3}$

→ $M_J = 3.2\ M_{sun}$

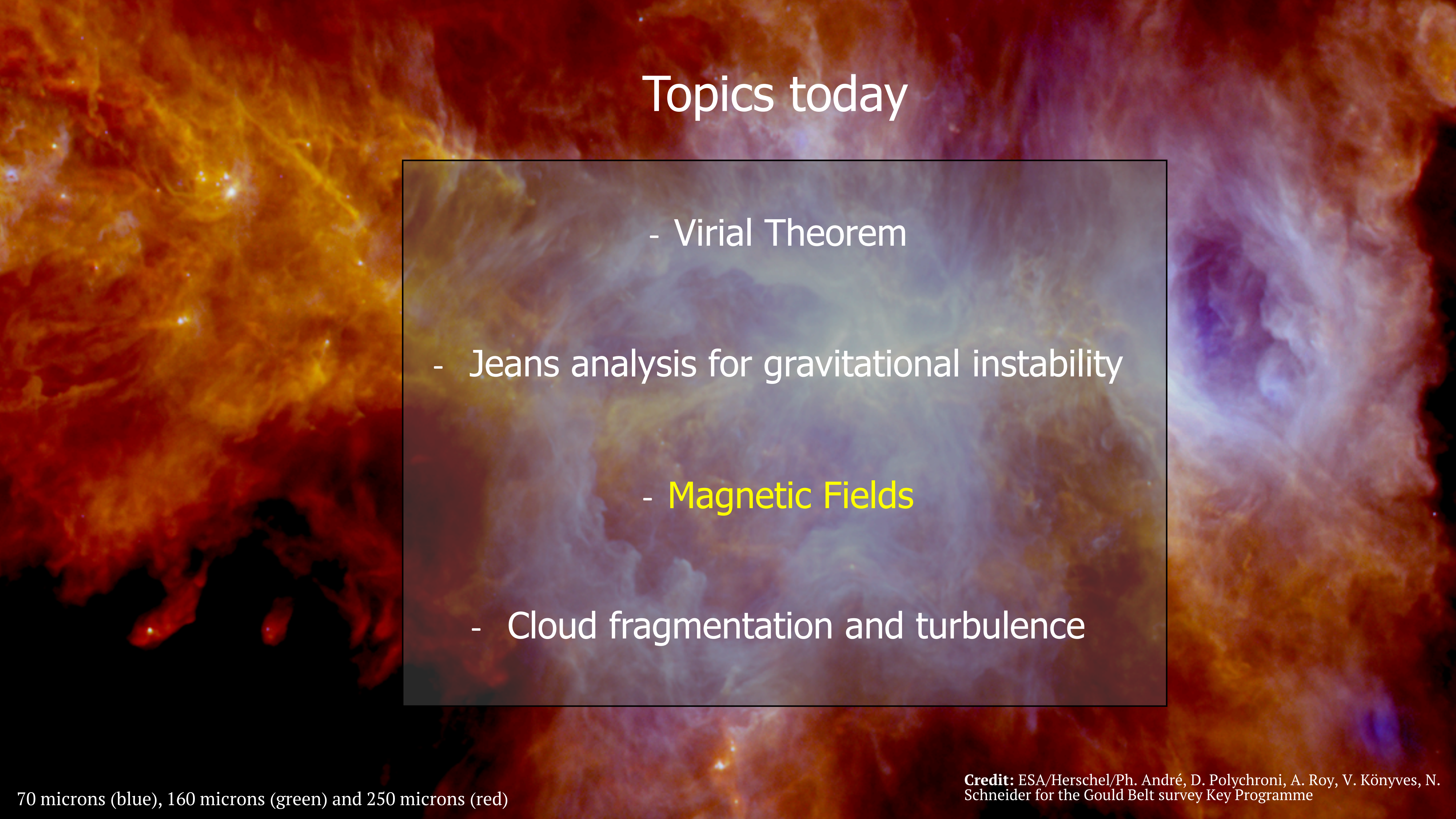
Orders of magnitide too low → Jeans instable

→ Additional support necessary, e.g., magnetic field, turbulence …

Jeans fragmentation in star formation



Beuther et al. 2013



Topics today

- Virial Theorem
- Jeans analysis for gravitational instability
- Magnetic Fields
- Cloud fragmentation and turbulence

70 microns (blue), 160 microns (green) and 250 microns (red)

Credit: ESA/Herschel/Ph. André, D. Polychroni, A. Roy, V. Könyves, N. Schneider for the Gould Belt survey Key Programme

Magnetic fields I

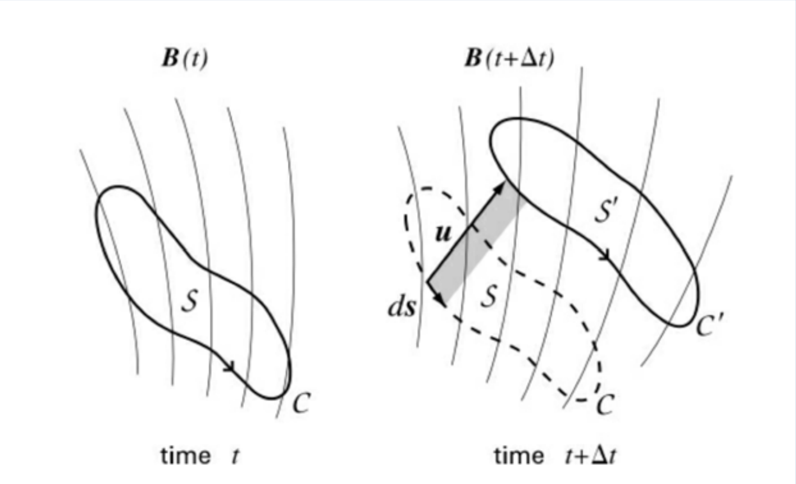
Object	Type	Diagnostic	$|B_{||}|$ [μG]
Ursa Major	Diffuse cloud	HI	10
NGC2024	GMC clump	OH	87
S106	HII region	OH	200
W75N	Maser	OH	3000

Increasing magnetic field strength with increasing density indicate “field-freezing” between B-field and gas

(B-field couples to ions and electrons, and these via collisons to neutral gas).

Magnetic fields II

This field freezing can be described by ideal MHD: $$\frac{d\mathrm{B}}{dt} = \nabla \times (\mathbf{u} \times \mathrm{B})$$ (Eq. 9.45)



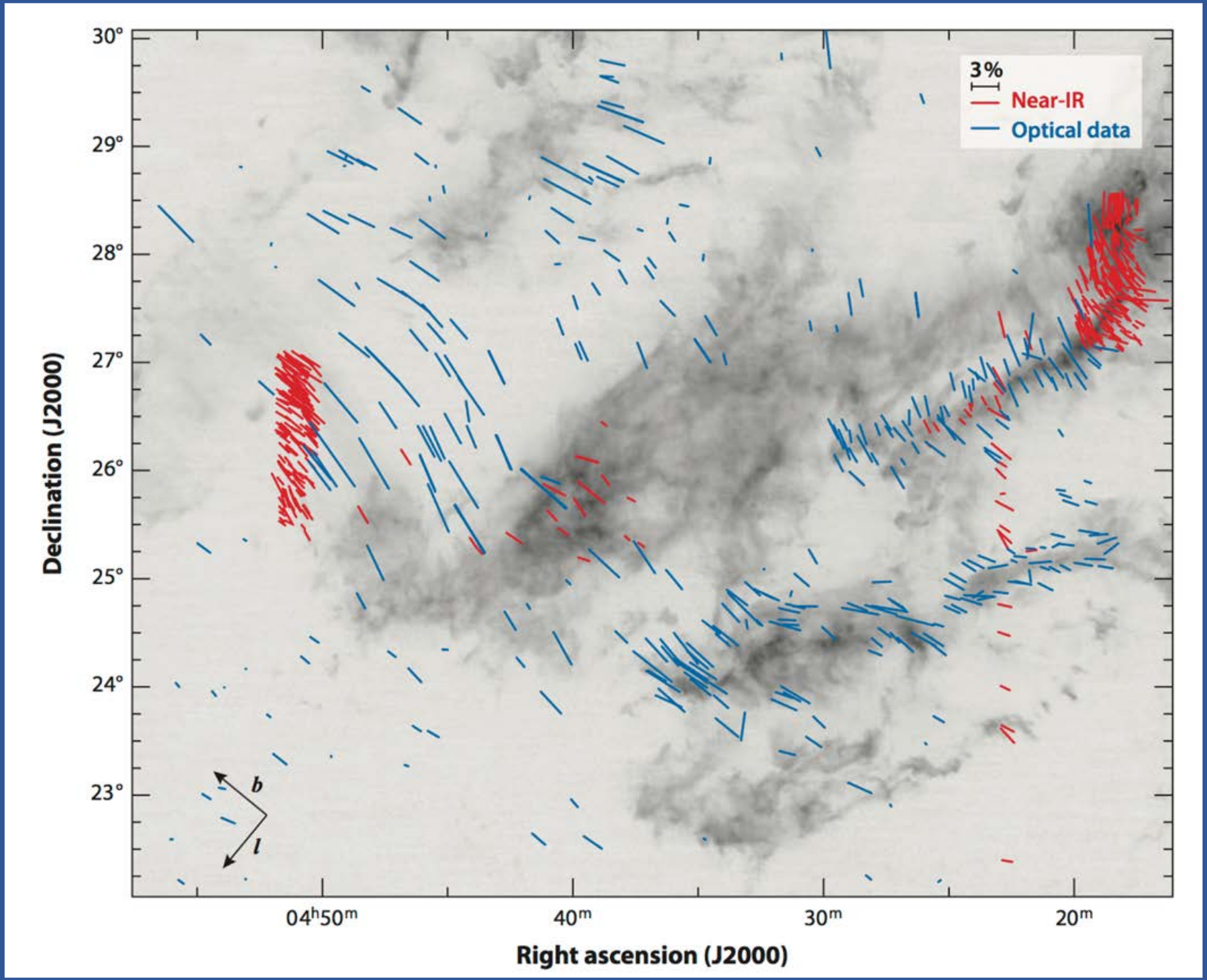
However, ideal MHD must break down at some point.

Dense core: $1M_{sun}$, R_0=0.07pc, B_0=30μG <u>*versus*</u> T Tauri star: $R_1=5R_{sun}$

If flux-freezing → magnetic flux $\Phi_M=\pi BR^2$ should remain constant:
→ $B_1=2\times10^7$ G, which exceeds observed values by orders of magnitude

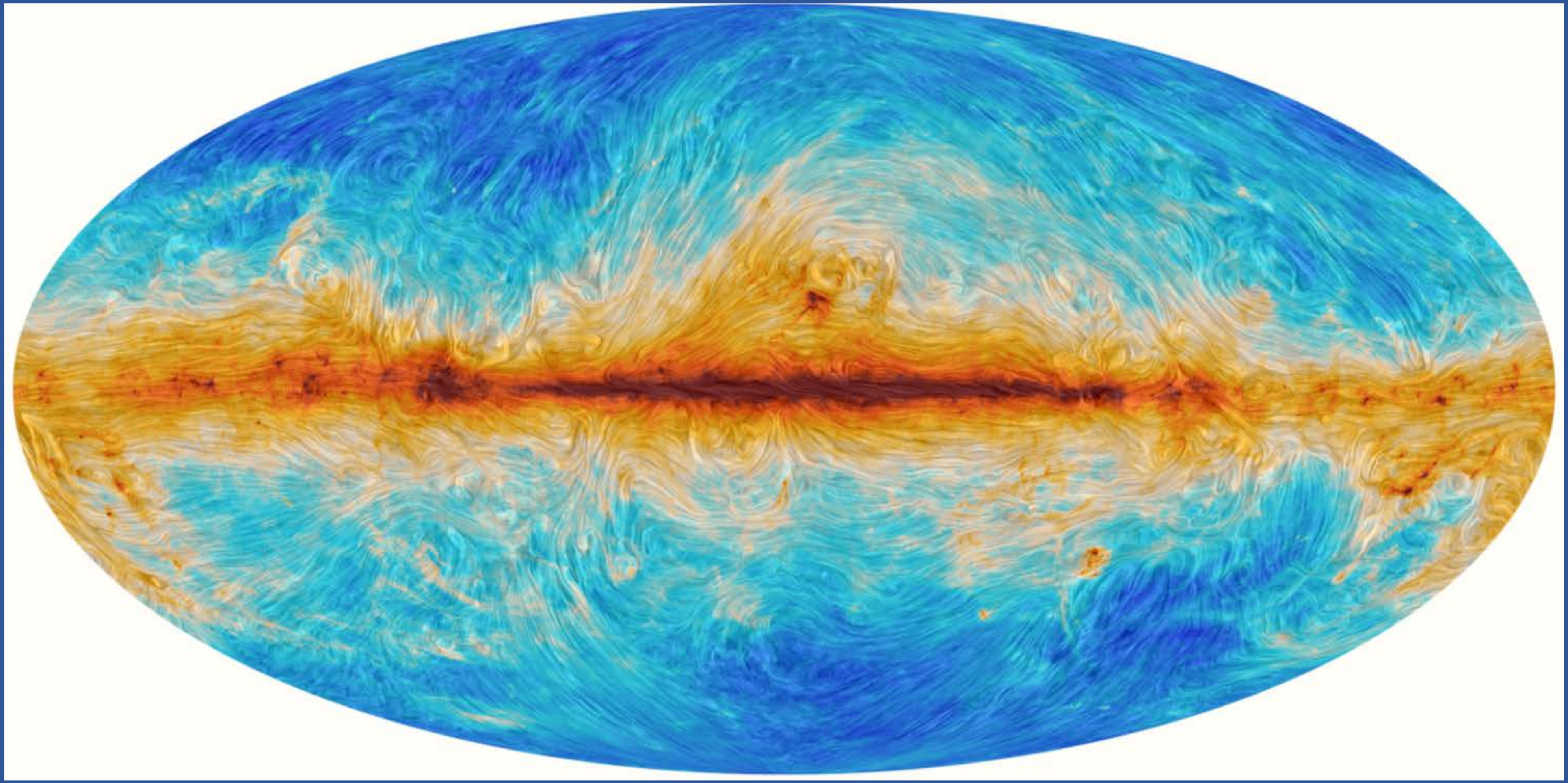
Ambipolar diffusion: neutral and ionized medium decouple, and neutral gas can sweep through during the gravitational collapse.

Magnetic fields morphology in Taurus



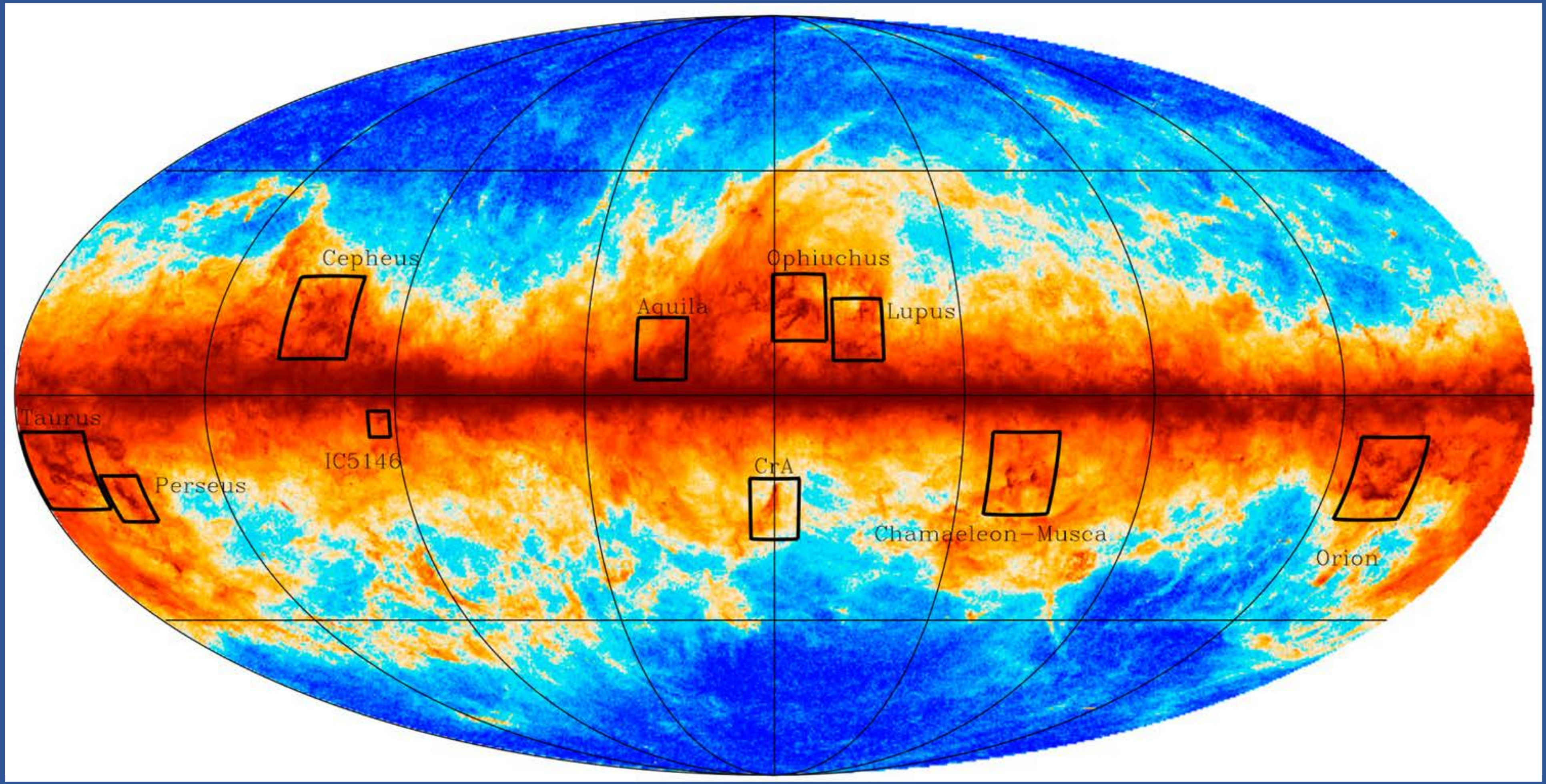
Grey: ^{13}CO; line segments: optical polarization *Chapman et al. 2011*

Planck and the magnetic field



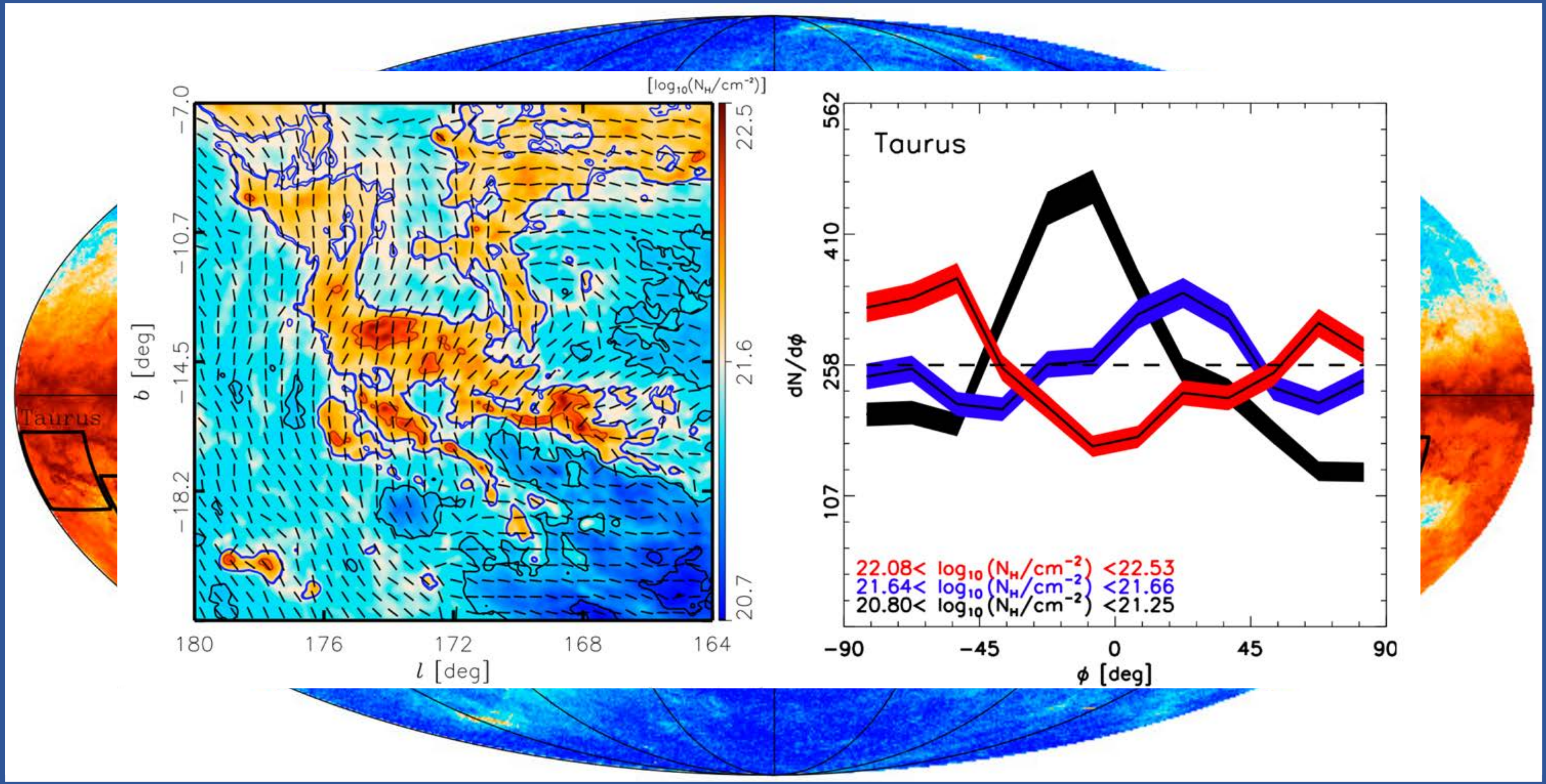
Soler et al. 2015

Planck and the magnetic field



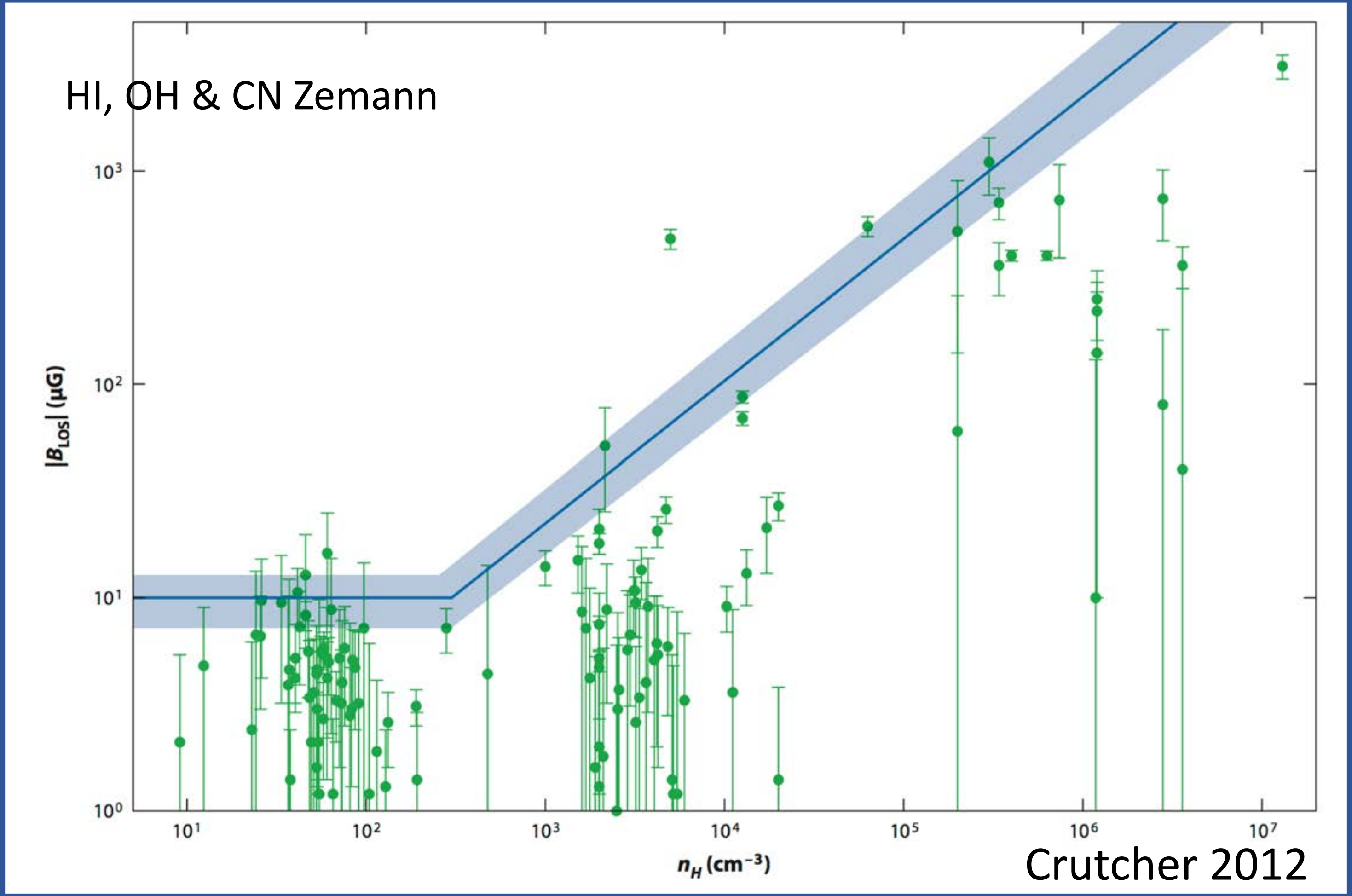
Soler et al. 2015

Planck and the magnetic field



Soler et al. 2015

Magnetic fields strength



Jeans-like analysis: $M_{cr} = 1000 M_{sun} (B/(30\mu G)) (R/(2pc)^2$

$M<M_{cr}$ magnetically subcritical; $M>M_{cr}$ magnetically supercritical

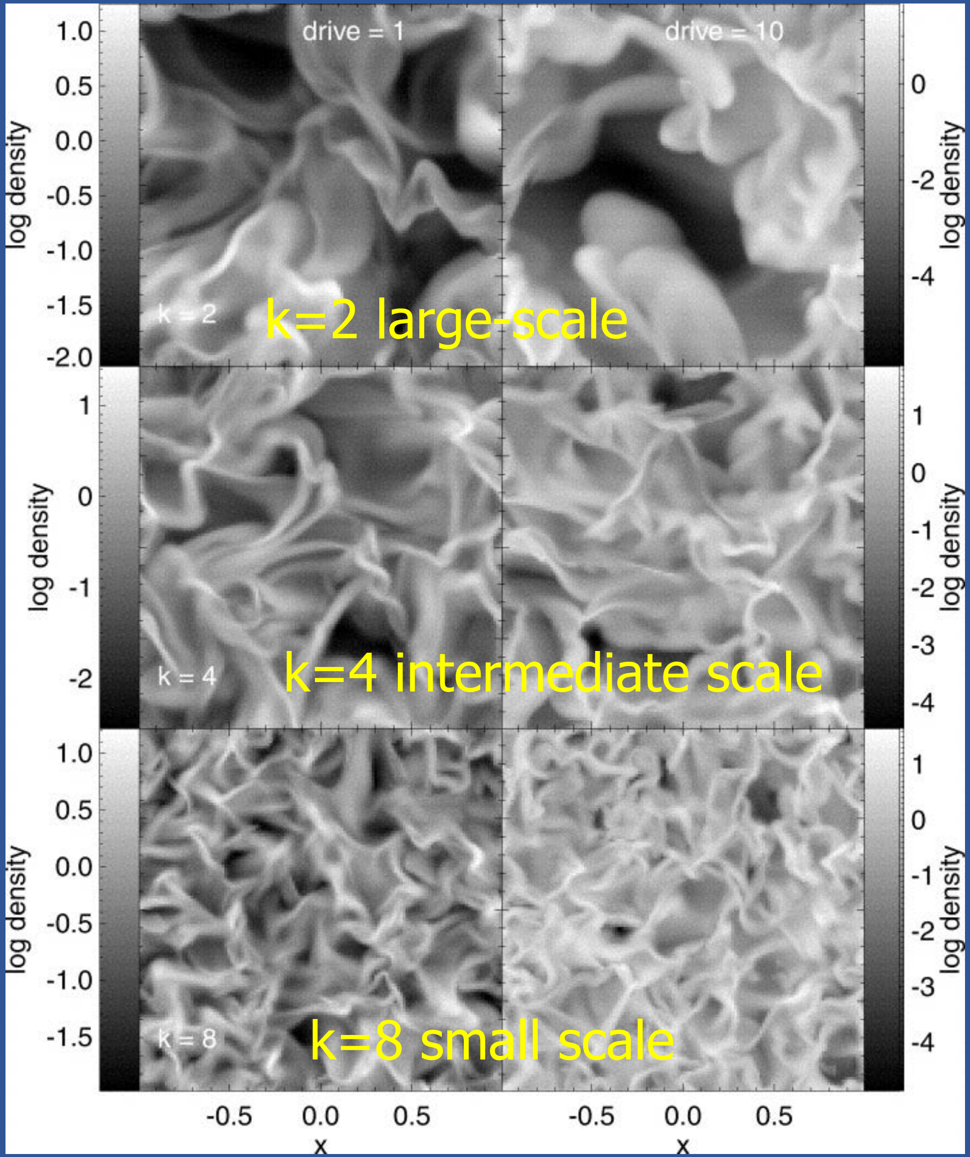
Topics today

- Virial Theorem
- Jeans analysis for gravitational instability
- Magnetic Fields
- Cloud fragmentation and turbulence

70 microns (blue), 160 microns (green) and 250 microns (red)

Credit: ESA/Herschel/Ph. André, D. Polychroni, A. Roy, V. Könyves, N. Schneider for the Gould Belt survey Key Programme

Interstellar Turbulence



MacLow 1999

- Supersonic → network of shocks

→ Density fluctuations $\delta\rho \propto \mathcal{M}^2$

- Decays on time-scales of order the free-fall time-scale

→ Needs continuous driving

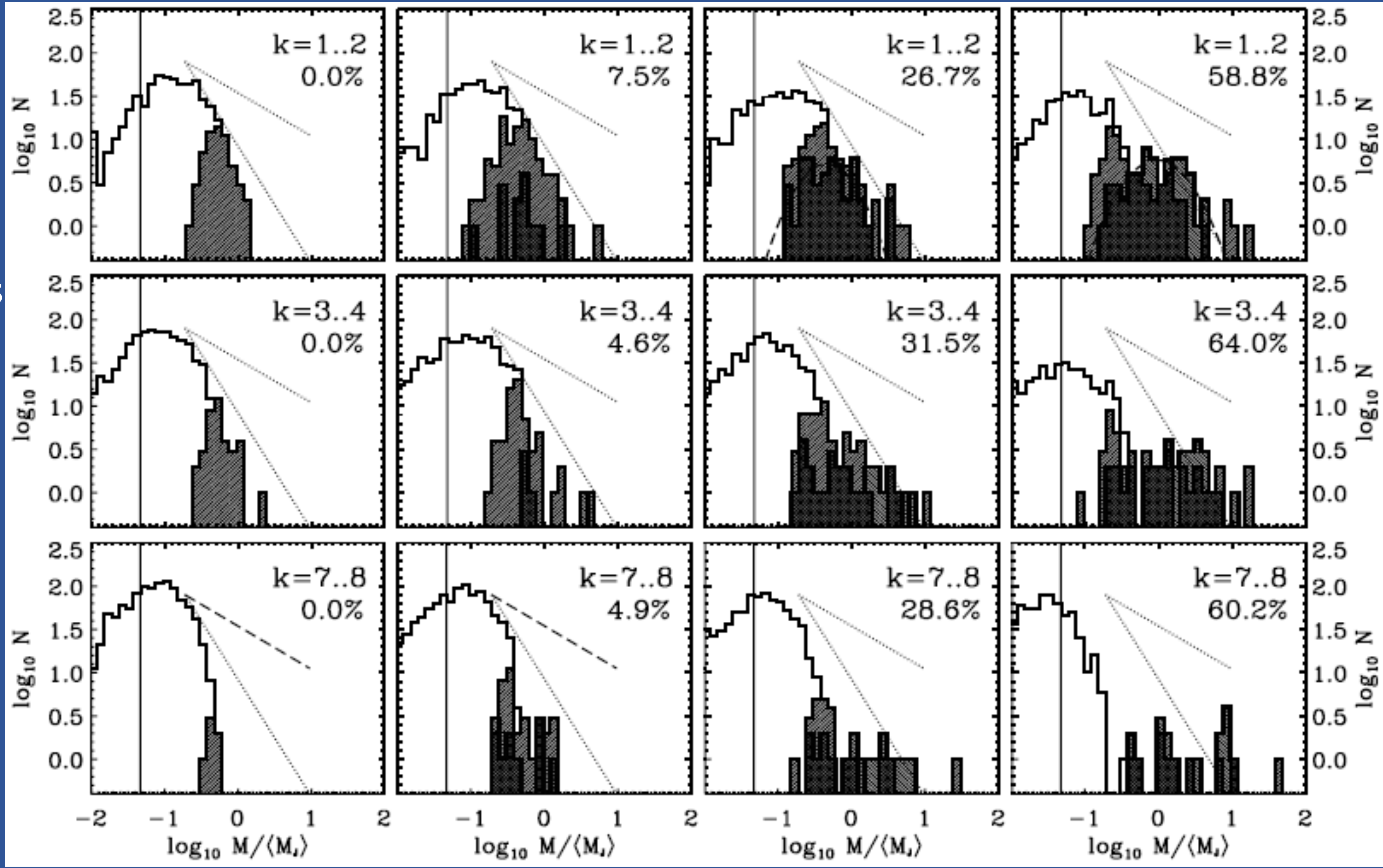
Candidates: Protostellar outflows,
radiation from massive stars,
supernovae explosions

(Gravo)-turbulent fragmentation

Histogram:
 Gas clumps
Grey:
 Jeans un-
 stable clumps
Dark:
 Collapsed
 core

Slopes: -1.5
 & -2.3

Klessen 2001

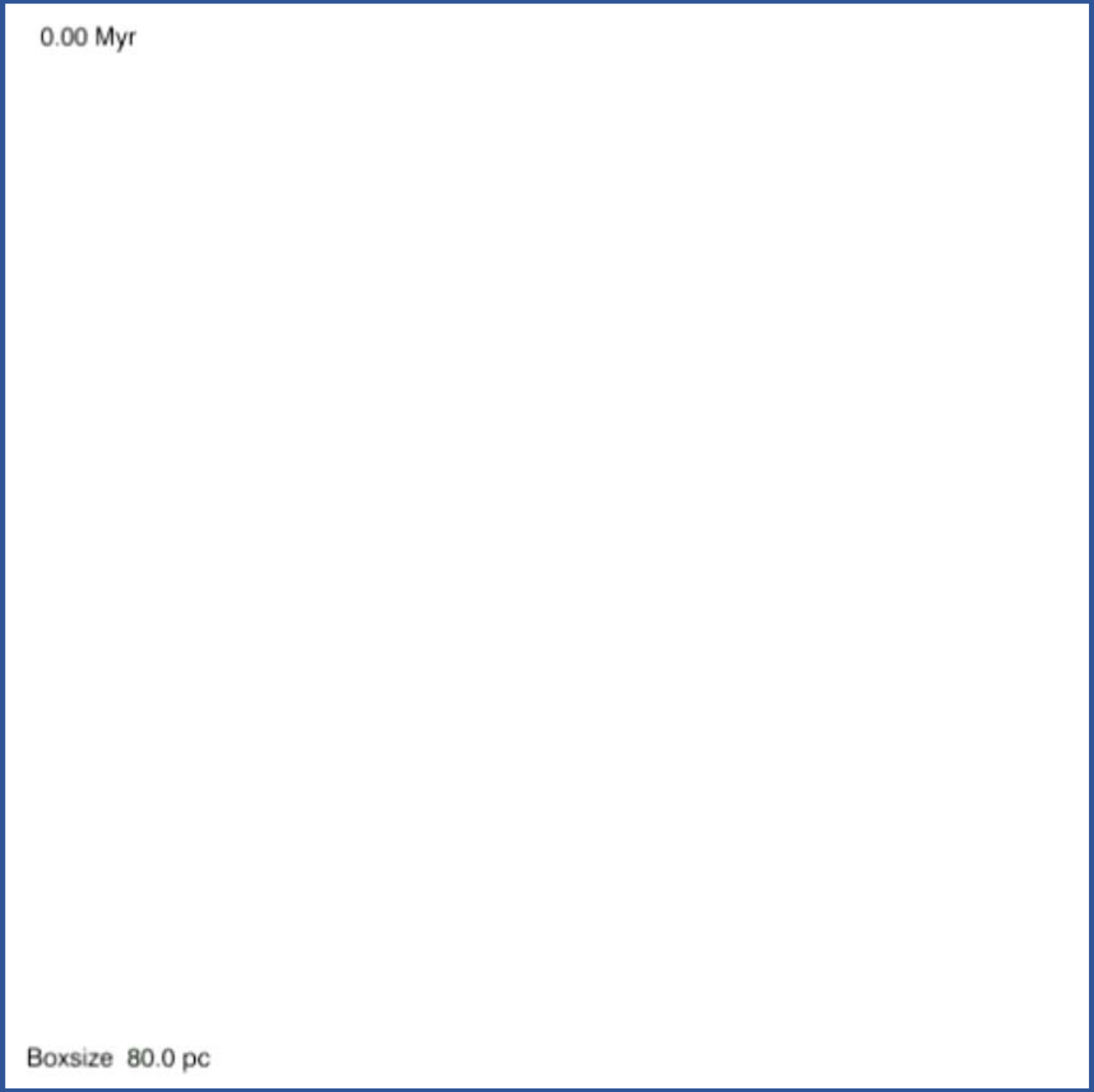


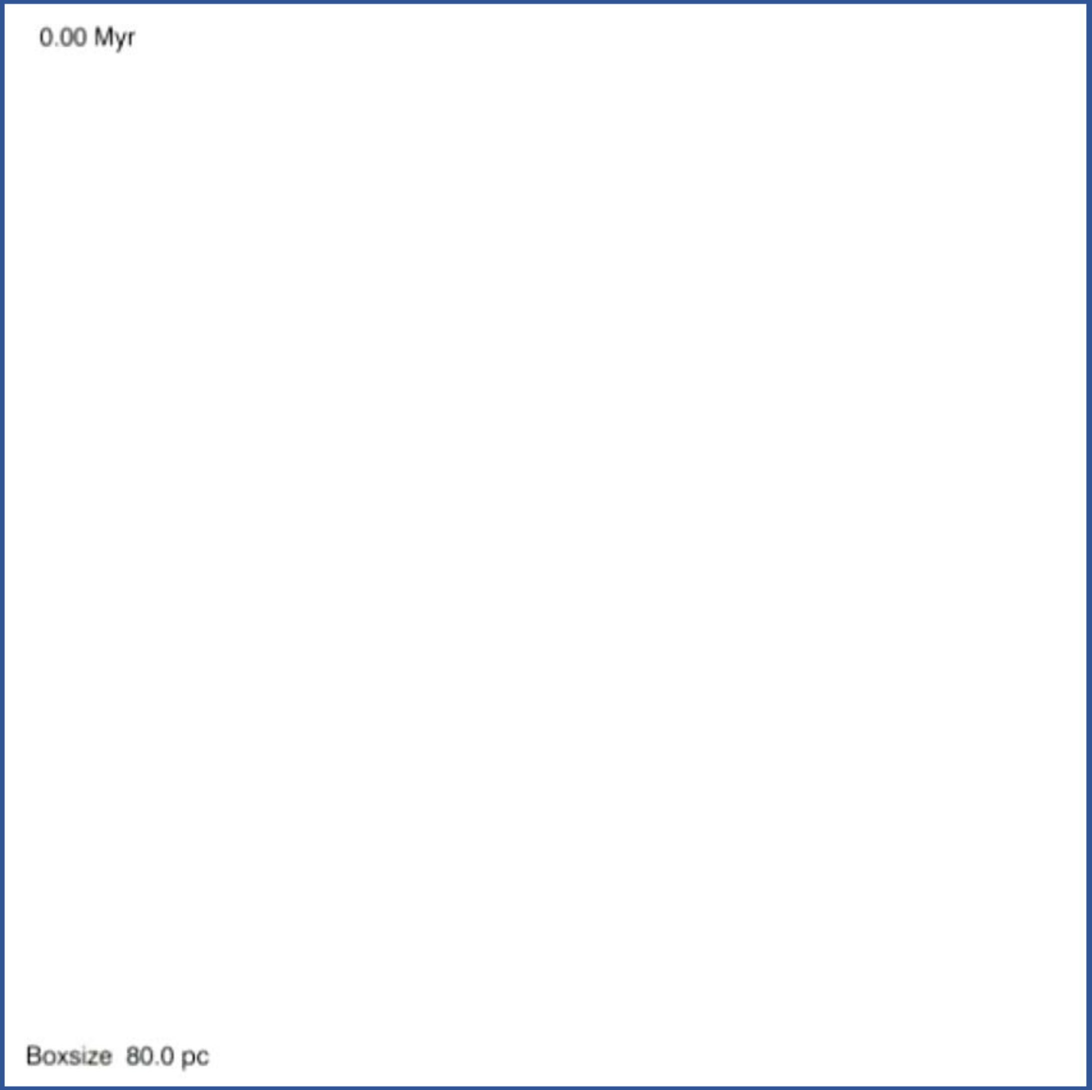
2 steps: 1.) Turbulent fragmentation → 2.) Collapse of individual core

- Large-scale driving reproduces shape of IMF.
- Discussion whether largest fragments remain stable or fragment further …

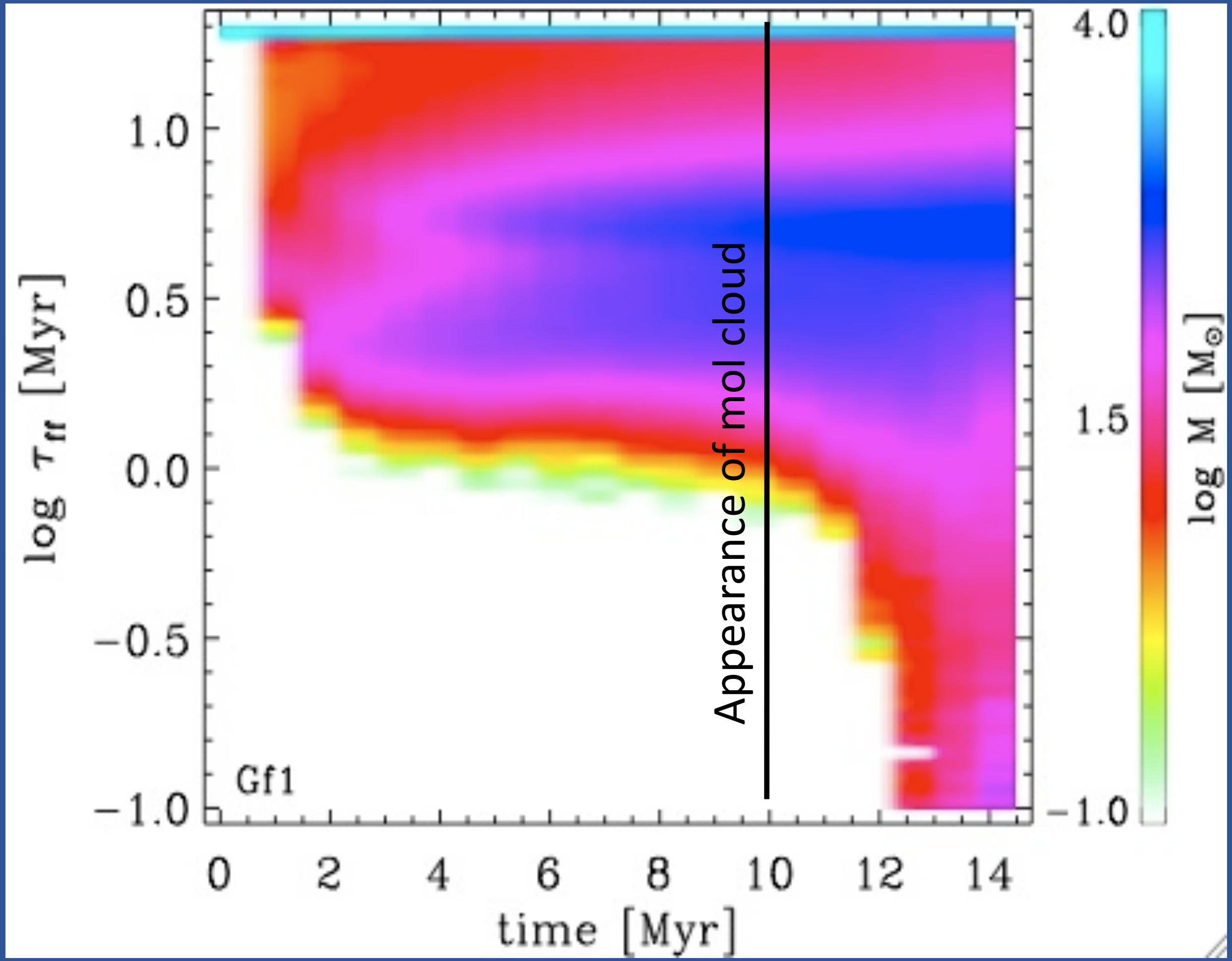
Simulations of colliding flows

Banerjee et al. 2009





Time scales

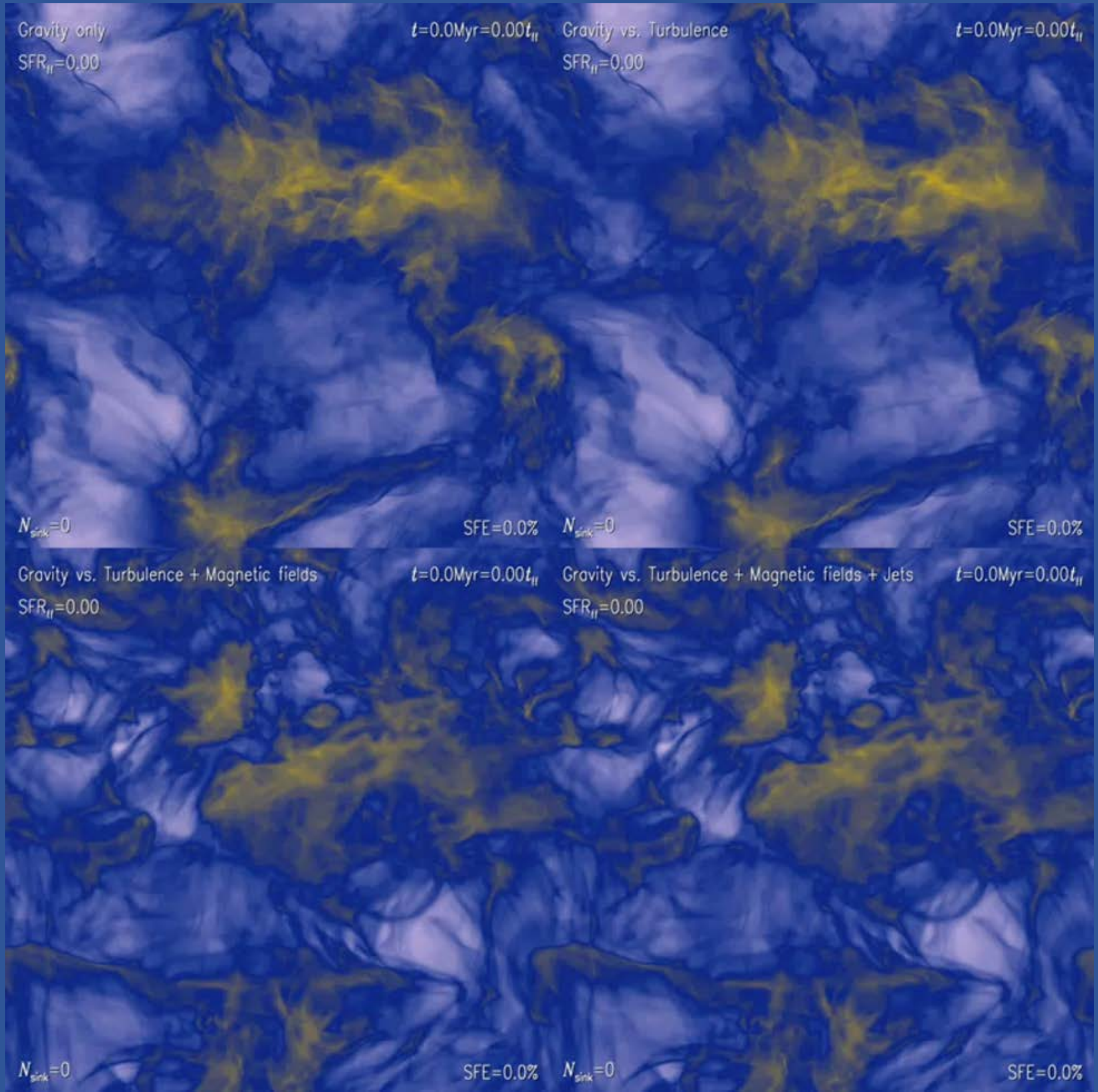


$$\tau_{ff} = \sqrt{\frac{3\pi}{32G\rho}}$$

→ Densest region have shortest free-fall time.

Heitsch & Hartmann 2008

Cloud and star formation with different physics



Federrath 2015

Summary

- Virial theorem and its application

- Jeans analysis and applications

- Magnetic fields in the interstellar medium

- Turbulence, cloud formation and time scales

Sternentstehung - Star Formation

Winter term 2020/2021

Henrik Beuther, Thomas Henning & Sümeyye Suri

03.11 Today: Introduction & Overview	(Beuther)
10.11 Physical processes I	(Beuther)
17.11 Physcial processes II	(Beuther)
24.11 Molecular clouds as birth places of stars	(Suri)
01.12 Molecular clouds (cont.), Jeans Analysis	**(Suri)**
08.12 Collapse models I	(Henning)
15.12 Collapse models II	(Henning)
------------ Christmas break -------------	
12.01 Protostellar evolution	(Beuther)
19.01 Pre-main sequence evolution & outflows/jets	(Beuther)
26.01 Accretion disks I	(Henning)
02.02 Accretion disks II	(Henning)
09.02 High-mass star formation, clusters and the IMF	(Suri)
16.02 Extragalactic star formation	(Henning)
23.02 Examination week, no star formation lecture	

Book: Stahler & Palla: The Formation of Stars, Wileys

More Information and the current lecture files: http://www.mpia.de/homes/beuther/lecture_ws2021.html

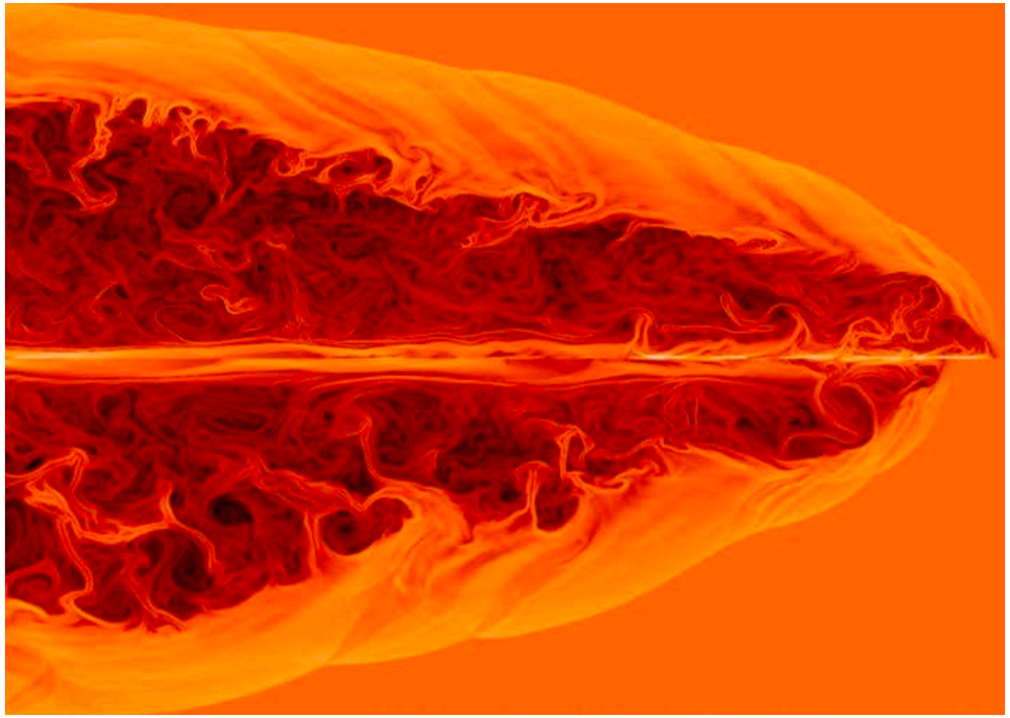
beuther@mpia.de, henning@mpia.de , suri@mpia.de

Heidelberg Joint Astronomy Colloquium

Winter Semester 2020/2021 — Tuesday, December 1, 16:00

Online through Zoom

Meeting ID: 971 4868 1900, passcode 69120



Magnetic field strength in a 2D axisymmetric relativistic magnetised jet
Credit: Mignone et al. 2009, MNRAS 393, 1141

Andrea Mignone
(University of Torino)

Frontiers of high-energy computational astrophysics: bridging gaps between large and small scales

High-energy non-thermal astrophysical environments - such as Active Galactic Nuclei, Pulsar Wind Nebulae and Gamma Ray burst - involve magnetized relativistic flows, whose energy flux can be partly converted, at dissipation sites, into random relativistic motion of particles that lose their energy through a variety of non-thermal processes and give rise to the observed radiation. Understanding of these extreme environments requires a detailed description of the highly nonlinear interactions between plasmas, non-thermal relativistic particles and radiation taking place on a wide range of spatial and temporal scales. This has forced practitioners in the field to take a sectorial approach. On the one hand, models at the large scale can be obtained through relativistic magnetohydrodynamical (RMHD) numerical simulations using a fluid model, albeit neglecting the relativistic particle component. On the other, Particle In Cell (PIC) codes allow a deeper comprehension of kinetic phenomena taking place at much smaller scales. As a consequence, the resulting picture is incomplete and fragmentary. In this talk, I will discuss some of the present and future computational perspectives which intend to bridge this gap. This task requires the coupling between large scale dynamics with a detailed treatment of the microphysics at dissipation sites, an extremely challenging task that only now is becoming feasible thanks to the advancements of high performance computing.