

**Dynamos on galactic scales,
or
Dynamos around us.**
Part I. Galaxies and galaxy clusters

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1. Introduction: basic facts and parameters

2. Spiral galaxies

2.1. Rotation

2.2. Hydrostatic equilibrium of the gas layer

2.3. Interstellar gas and its multi-phase structure

2.4. Interstellar turbulence

3. Elliptical galaxies

4. Galaxy clusters

Warning

❑ cgs units will be used, $1 \text{ G} = 10^{-4} \text{ T}$, $1 \mu\text{G} = 10^{-6} \text{ G} = 0.1 \text{ nT}$.

❑ $G \approx 6.67 \times 10^{-8} \text{ cm}^3 \text{ g}^{-1} \text{ s}^{-2}$; $k \approx 1.38 \times 10^{-16} \text{ erg K}^{-1}$;
 $m_p \approx 1.7 \times 10^{-24} \text{ g}$, $1 \text{ year} \approx 3 \times 10^7 \text{ s}$; $1 \text{ eV} \approx 1.6 \times 10^{-12} \text{ erg}$.

❑ $1 \text{ parsec} \approx 3 \times 10^{18} \text{ cm} \approx 3.26 \text{ light years}$,
 $1 \text{ kpc} = 10^3 \text{ pc}$; $c \approx 3 \times 10^{10} \text{ cm s}^{-1}$
(1 parsec distance: Earth orbit's parallax = 1 second of arc).

❑ Solar mass, radius and luminosity:
 $M_{\odot} \approx 2 \times 10^{33} \text{ g}$; $R_{\odot} \approx 7 \times 10^{10} \text{ cm}$; $L_{\odot} \approx 4 \times 10^{33} \text{ erg s}^{-1}$.

❑ **Notation:** HI = neutral hydrogen, HII = p^+ = ionized hydrogen,
CIV = triply ionized carbon, etc.

Further reading

- ❑ R. G. Tayler, *Galaxies: Structures and Evolution*, Cambridge Univ. Press, 1993 (a high-level scientific popular book on galactic astrophysics, entertaining and informative, very well written).
- ❑ J.E Dyson and D.A Williams, *The Physics of the Interstellar Medium*, Second Edition (The Graduate Series in Astronomy), IOP, 1997 (a good textbook on interstellar medium, presents appropriate equations and their solutions together with clear qualitative arguments and explanations and order of magnitude estimates).
- ❑ A. Shukurov & Dmitry Sokoloff, *Astrophysical dynamos*. In: Ph. Cardin, L.F. Cugliandolo, editors, *Les Houches, Session LXXXVIII, 2007, Dynamos*, Amsterdam: Elsevier, 2008, pp. 251-299

1. Introduction: basic facts and parameters

Galaxies:

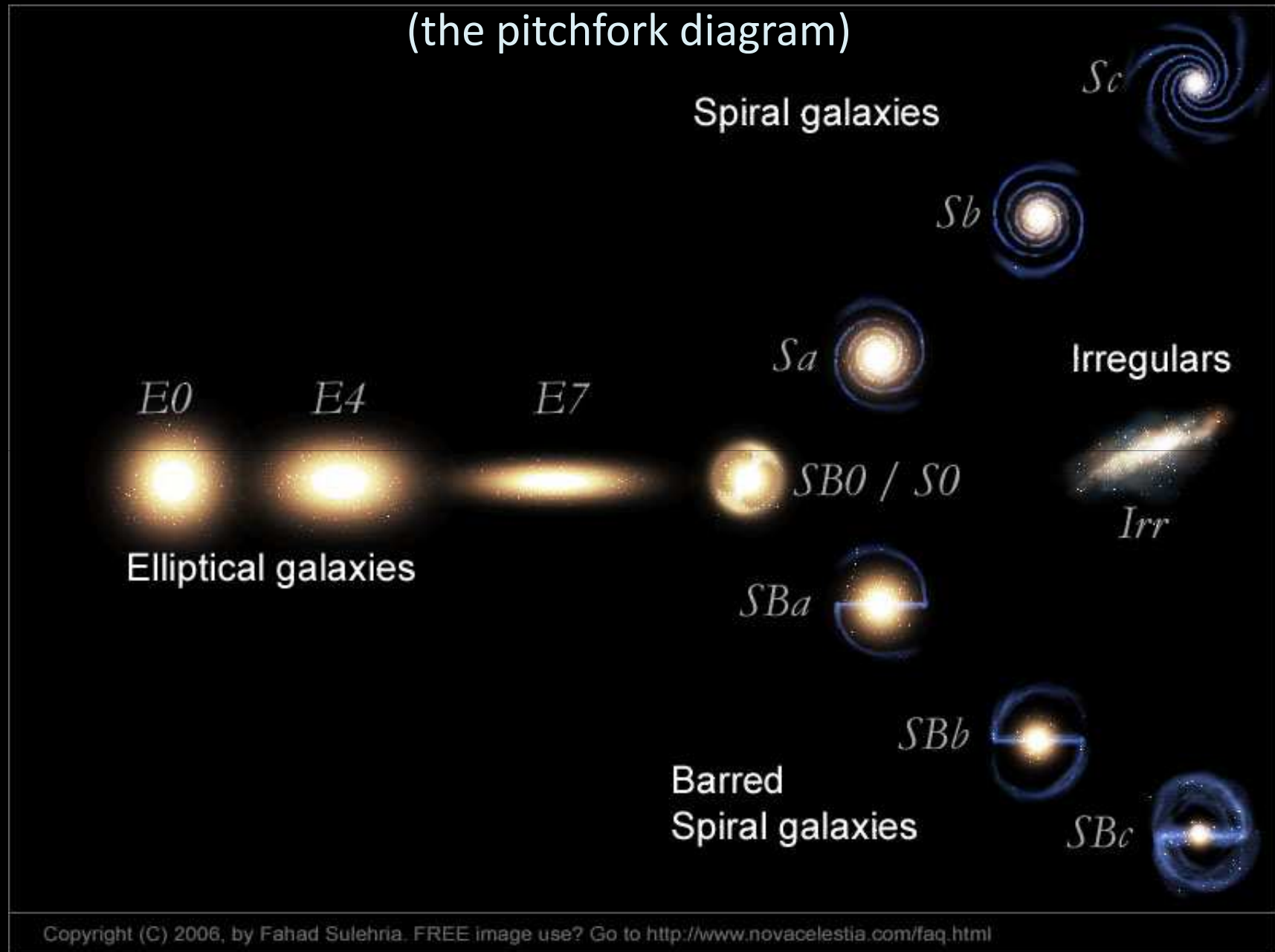
- ☐ stars,
- ☐ interstellar gas,
- ☐ cosmic rays (relativistic charged particles, mainly protons and electrons),
- ☐ dust

Clusters of galaxies – the largest gravitationally bound objects in the Universe:

- ☐ collections of galaxies (elliptical near the centre, spirals at the outskirts),
- ☐ intracluster gas

Galaxies: Hubble's morphological classification

(the pitchfork diagram)



The structure of a spiral galaxy

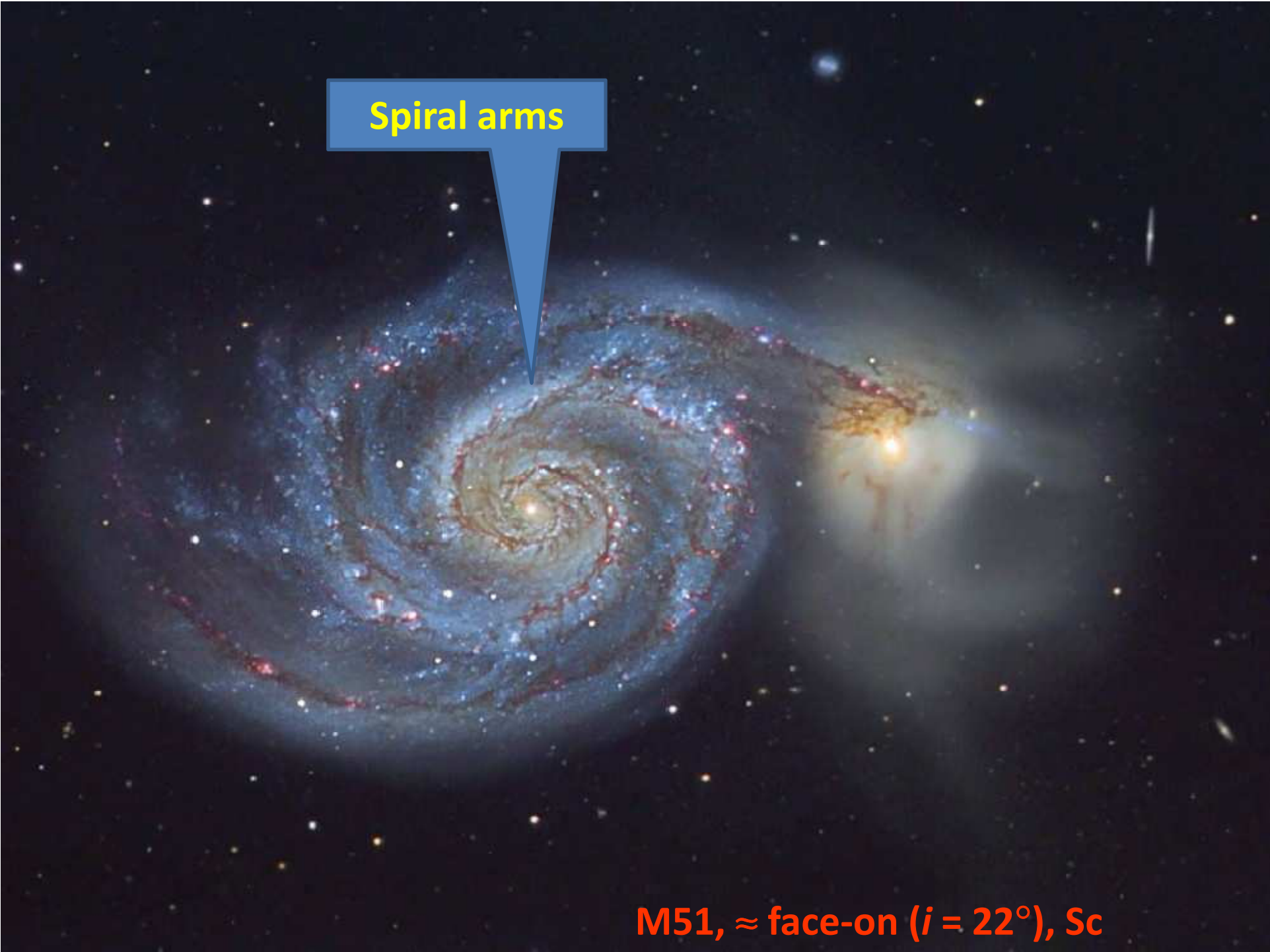
Spheroidal **stellar halo**,
old stars

Dark matter halo,
only felt via gravity

Stellar **bulge**, quasi-spherical, similar to an elliptical galaxy is Sa and consisting of younger stars in Sc

Rotating **stellar disc**,
young stars; light absorbed by dust

NGC891, edge-on ($i = 89^\circ$), Sb

A face-on view of the spiral galaxy M51, also known as the Whirlpool Galaxy. The galaxy is shown in a deep blue color, with its spiral arms clearly visible. A blue callout box with a pointer indicates the spiral arms. The galaxy is surrounded by a field of stars and other celestial objects. The background is a dark, star-filled space.

Spiral arms

M51, $\approx$ face-on ($i = 22^\circ$), Sc



Galaxy characteristics are uniquely related to Hubble's classification

	E0-E7	S0	Sa	Sb	Sc	Irr
Nuclear Bulge	"All Bulge" No disk	Bulge & Disk	Large		Small	None
Spiral Arms	None	None	Tight/smooth		Open/clumpy	Occasional traces
Gas	Almost none	Almost none	$\cong 1\%$	2–5%	5–10%	10–50%
Young Stars, HII Regions	None	None	Traces		Lots	Dominate appearance
Stars	All old ($\cong 10^{10}$ yr)	Old	Some young			Mostly(?) young (but some very old)
Spectral Type	G–K	G–K	G–K	F–K	A–F	A–F
Color	Red	Red				Blue
Mass ($M_{\odot}$)	10^8 – 10^{13}	(More) $\rightarrow 10^{12}$ – $10^9 \rightarrow$ (Less)				10^8 – 10^{11}
Luminosity ($L_{\odot}$)	10^6 – 10^{11}	(More) $\rightarrow 10^{11}$ – $10^8 \rightarrow$ (Less)				10^8 – 10^{11}

2. Spiral galaxies

M51 (Sc)

NGC 253 (Sc)

NGC891 (Sb)

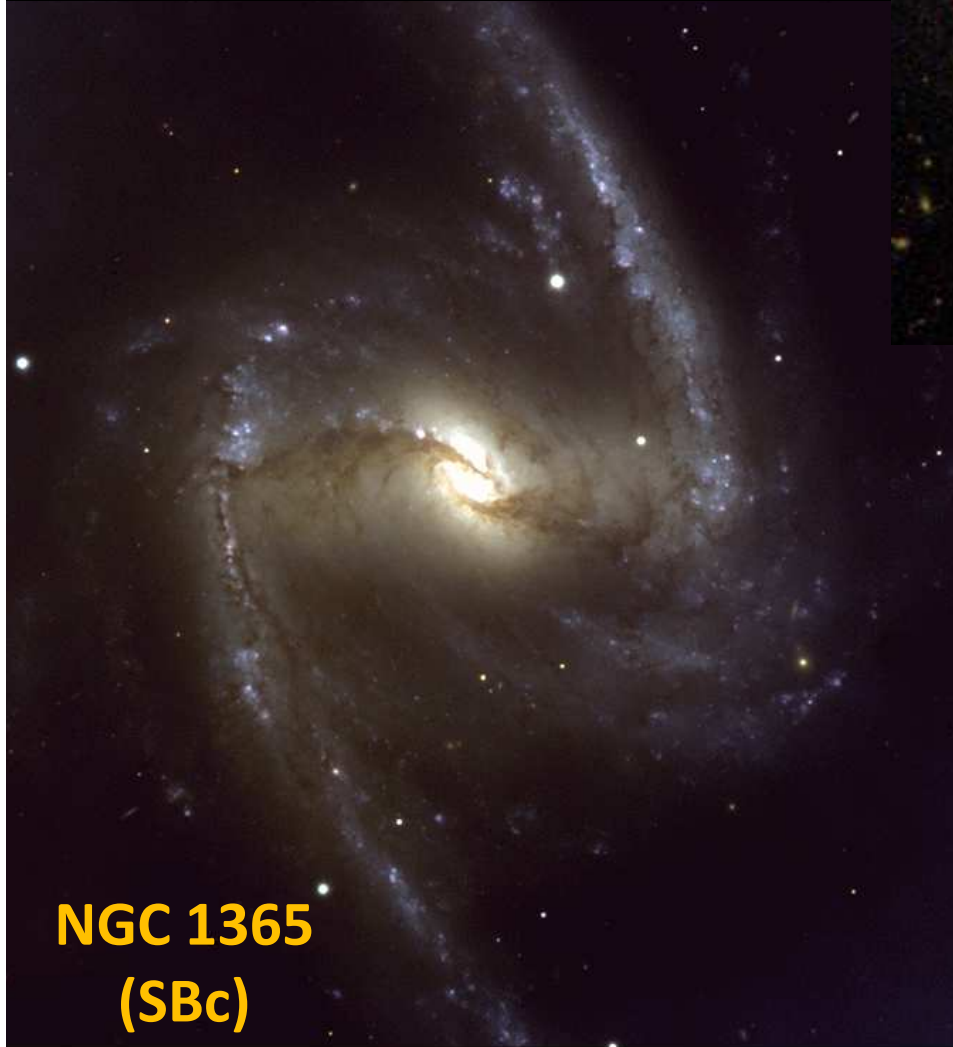
M33 (Sc)

Barred spiral galaxies

NGC 3992
(SBa)



NGC 1365
(SBc)

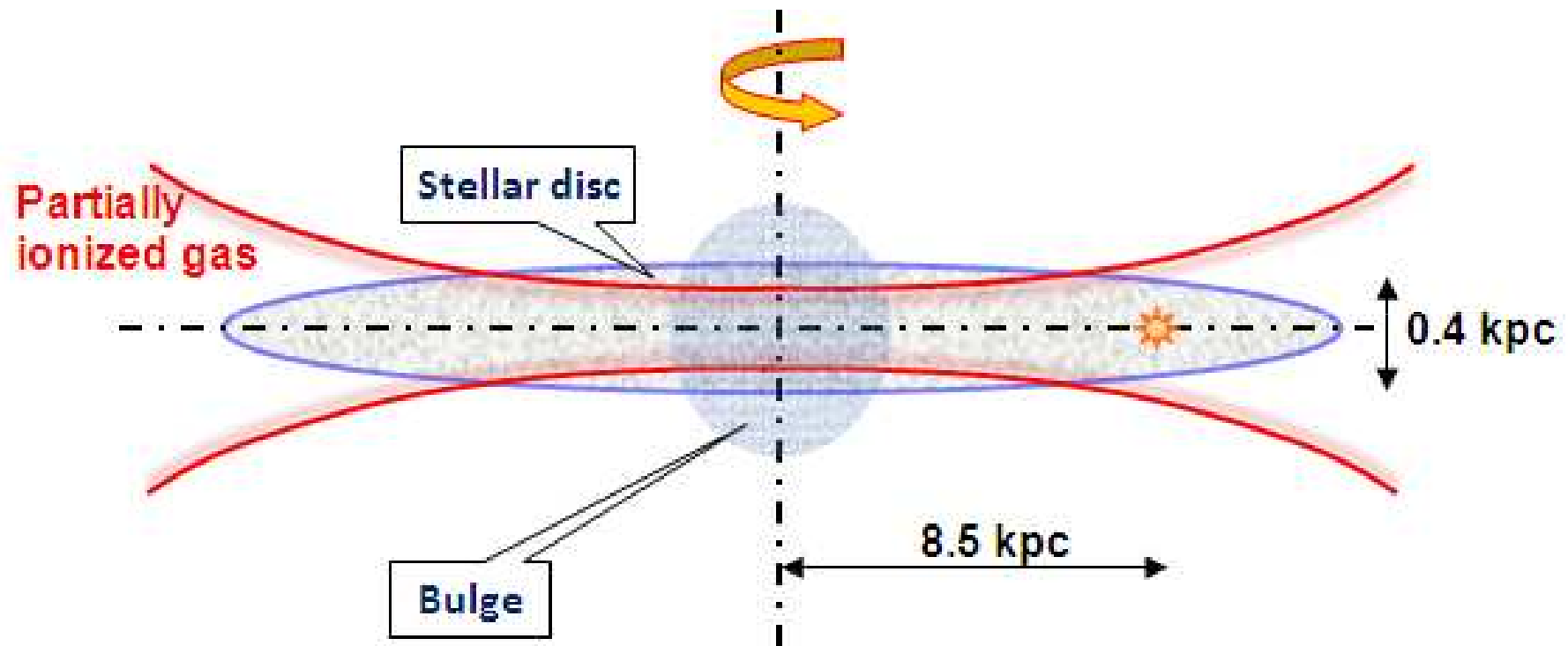


NGC 1300
(SBb)



Spiral galaxies:

thin rotating discs of $\cong 10^{11}$ stars (90% of the visible mass)
and interstellar gas (10%)
+ dark matter



Interstellar gas: $\langle n \rangle \cong 1 \text{ cm}^{-3}$, $\langle T \rangle \cong 10^4 \text{ K}$,
 $10^{-3} < n < 10^3 \text{ cm}^{-3}$, $10 < T < 10^6 \text{ K}$

Milky Way parameters, Sbc

Diameter		30 kpc
Average thickness (stellar disc)		0.3 kpc
Bulge radius		2 kpc
Visible mass		$1.4 \times 10^{11} M_{\odot}$
Rotation period (near the Sun)		2.5×10^8 yr
Rotational velocity (near the Sun)	V_0	220 km/s
Radius of the Solar orbit	R_0	8.5 kpc
Age		1.2×10^{10} yr
Mean interstellar gas number density	n_0	1 cm^{-3}
Mean gas temperature	T_0	10^4 K
Mean speed of sound	c_s	10 km/s
Thickness of the diffuse gas layer near the Sun	$2h_0$	1 kpc
Pitch angle of the spiral arms (trailing spiral)	p_0	$\cong -10^\circ$

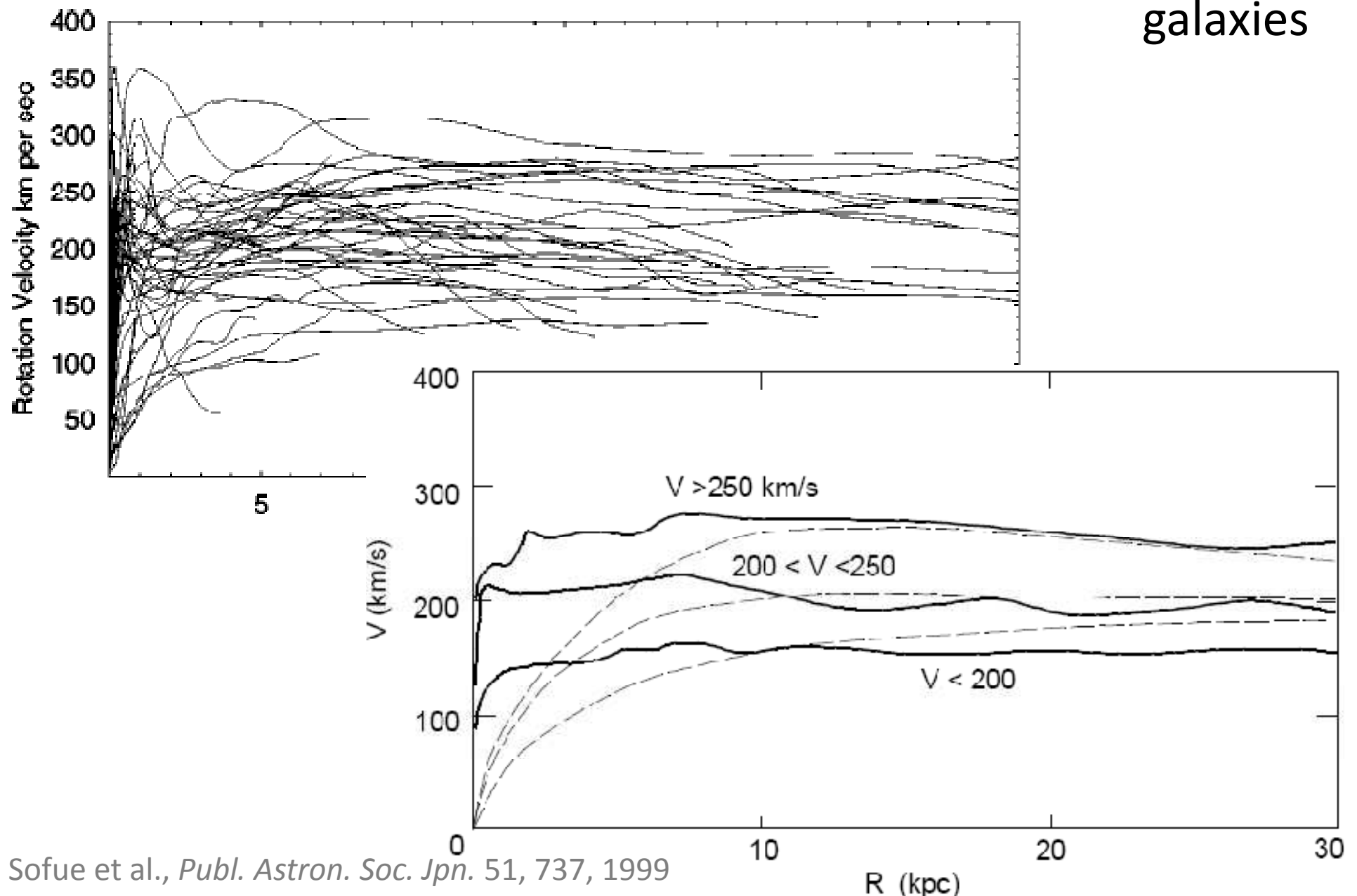
DIRBE 1.25, 2.2, 3.5 μm Composite



The near-infrared sky (COBE, false-colour image):
stars in the Milky Way (thin disk and the central bulge)

http://lambda.gsfc.nasa.gov/product/cobe/slide_captions.cfm

2.1. Rotation: $V(r)$ (*rotation curve*) measured for 1000's of galaxies



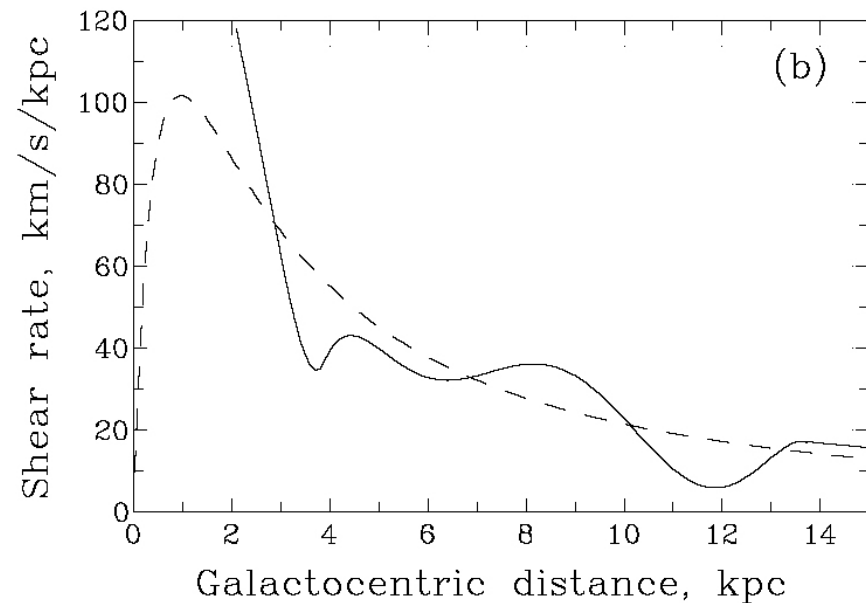
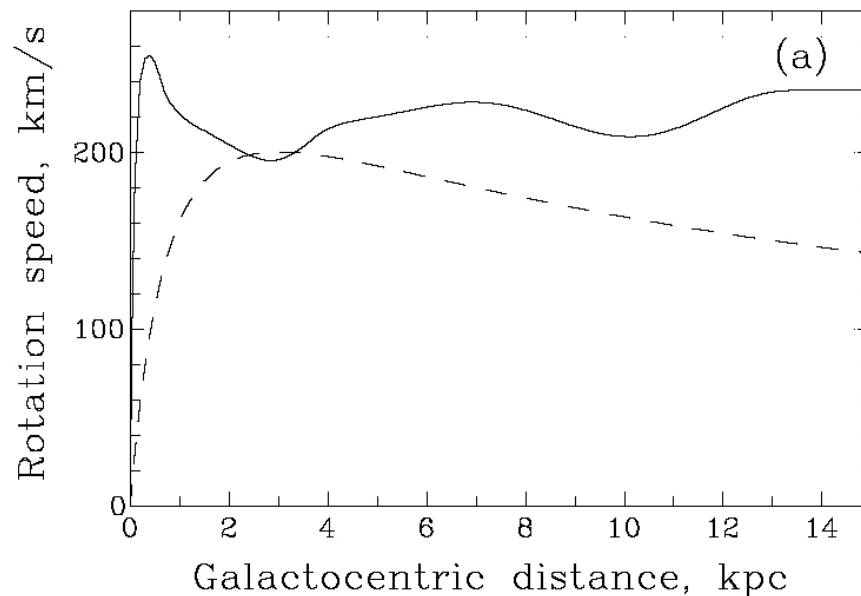
□ Differential rotation:

angular velocity varying with position.

□ Flat rotation curves at large radii (dark matter halo):

$$V = r\Omega \cong 200 \text{ km/s} \cong \text{const}; \quad \Omega \propto 1/r .$$

Rotational shear rate: $G = r \, d\Omega/dr \cong -\Omega$.



Rotation curve and shear: Milky Way (solid) and a generic galaxy (dashed)

Rotation curve $V(r)$: balance of the centrifugal force and gravity due to mass density $\rho_g(\vec{r})$ (neglecting pressure contributions from gas, magnetic fields, etc.):

$$\frac{V^2}{r} = \frac{\partial \Phi}{\partial r}, \quad \nabla^2 \Phi = 4\pi G \rho_g(\vec{r}).$$

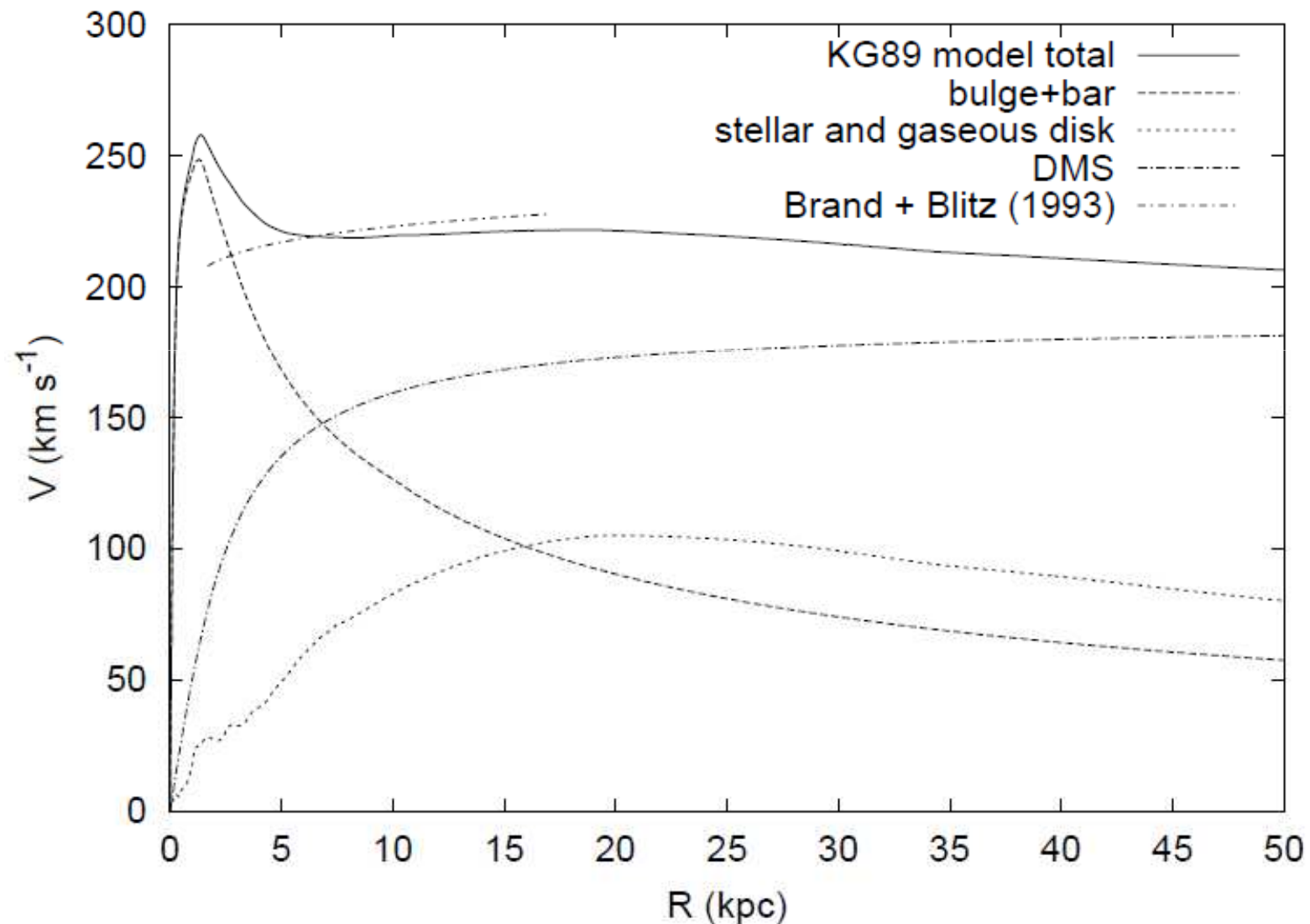
For a point-like mass distribution, $\Phi = -GM/r$,

$$\frac{V^2}{r} = \frac{GM}{r^2} \Rightarrow V = \sqrt{\frac{GM}{r}}, \quad \text{Kepler's rotation law}$$

Φ = gravitational potential, r = spherical radius,
applied in a thin disc $z \approx 0$ ($\theta \approx \pi/2$).

Observed rotation curve $V(r) \Rightarrow$ galactic gravitating mass model $\rho(r)$

Rotation curve of the Milky Way, with contributions of various mass components (Kalberla, ApJ 588, 805, 2003)



2.2. Hydrostatic equilibrium of the gas layer

A crude but physically realistic and useful description of the background gas distribution:

$$\underbrace{\frac{d}{dz} (P_{\text{th}} + P_{\text{turb}} + P_{\text{mag}} + P_{\text{c.r.}})}_{\text{pressure support}} = \underbrace{\rho g_z}_{\text{gravity}},$$

$P_{\text{th}} = nkT$, thermal pressure, $P_{\text{turb}} = \frac{1}{3}\rho v_0^2$, turbulent pressure,
 $P_{\text{th}} = B^2/8\pi$, magnetic pressure, $P_{\text{c.r.}}$, cosmic ray pressure.

Vertical gravitational acceleration near the Sun (**disc**+**dark halo**):

$$g_z = - \left[a_1 \frac{z}{\sqrt{z^2 + H_1^2}} + a_2 \frac{z}{H_2} \right],$$

with $a_1 = 4.4 \times 10^{-9} \text{ cm s}^{-2}$, $a_2 = 1.7 \times 10^{-9} \text{ cm s}^{-2}$,
 $H_1 = 0.2 \text{ kpc}$ and **$H_2 = 1 \text{ kpc}$** (Ferrière 1998).

Assumptions:

□ Energy (pressure) **equipartition**:

$$P_{\text{th}} = P_{\text{turb}} = P_{\text{mag}} = P_{\text{c.r.}}$$

□ An **isothermal** atmosphere:

$$T(z) = \text{const} \Rightarrow c_{\text{sound}} = \text{const} \Rightarrow v_0 = \text{const.}$$

□ For **$g_z = \text{const}$** ,

$$\rho \propto \exp(-z/h), \quad h = \left(\frac{8v_0^2 H_2}{3|g_z|} \right)^{1/2} \simeq 200 \text{ pc},$$

c_{sound} = speed of sound, v_0 = turbulent velocity,

h = density **scale height**.

Hydrostatic equilibrium at various radii: a flared gas disc

$$\frac{d}{dz}P = \rho g_z, \quad g_z = -\frac{\partial\Phi}{\partial z}, \quad \nabla^2\Phi = 4\pi G\rho_g(r, z).$$

(ρ_g = gravitating mass density)

Oort (BAN, 15, 45, 1960):

$$\frac{\partial^2\Phi(r, z)}{\partial z^2} = 4\pi G\rho_g(r, z) + \frac{1}{r} \frac{\partial}{\partial r}(r g_r),$$

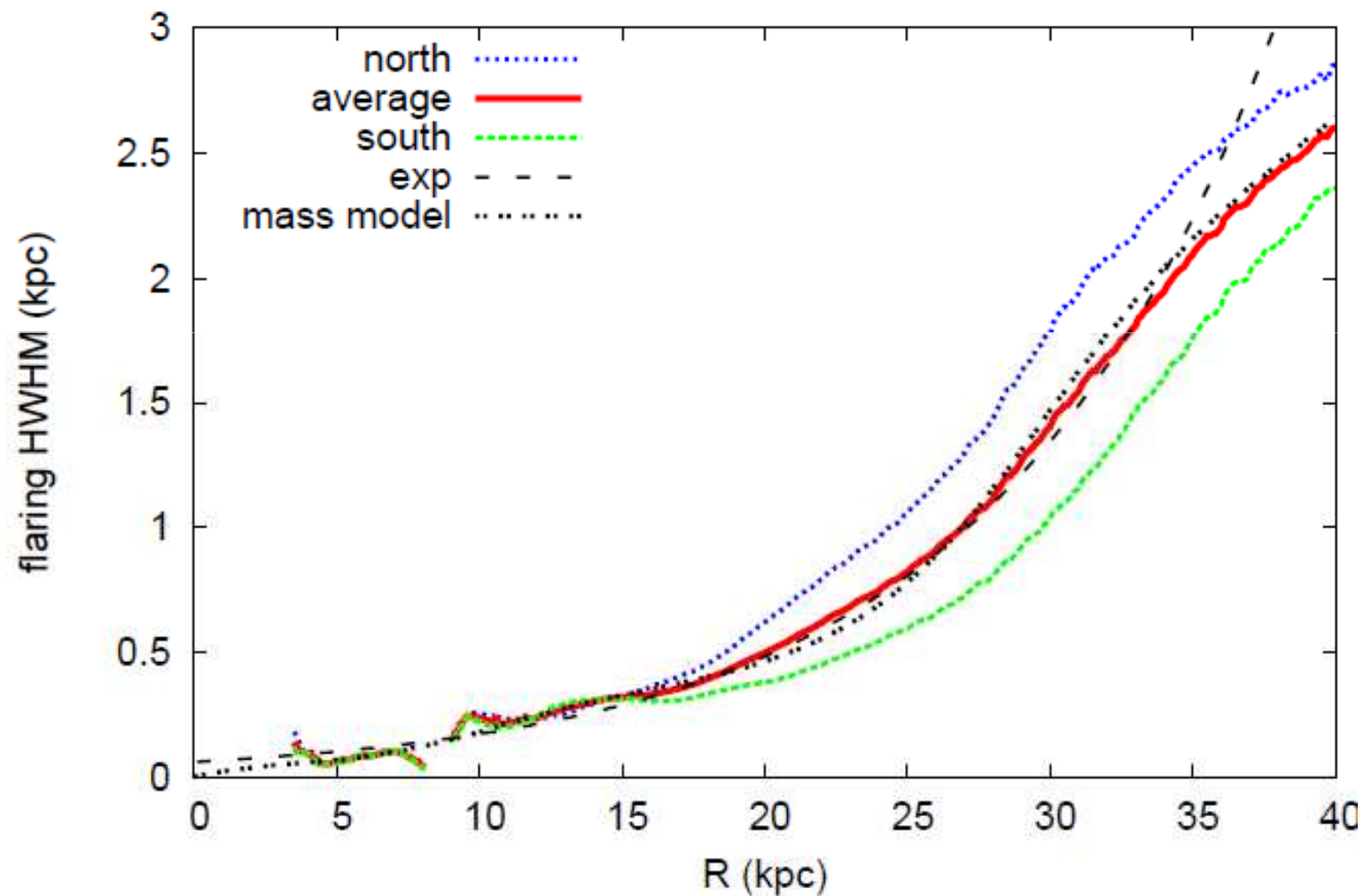
$$g_r = -\frac{\partial\Phi}{\partial r} = \frac{V^2(r, z)}{r} \propto \frac{1}{r} \quad \left(\begin{array}{l} \text{centrifugal balance} \\ + \text{ flat rotation curve} \end{array} \right)$$

$$g_z(r, z) = -4\pi G \left\{ \int_0^z \rho_g(r, z') dz' + \int_0^z \left[\frac{\partial g_r(r, z')}{\partial r} + \frac{g_r(r, z')}{r} \right] dz' \right\}$$

- $\frac{4}{3}v_0^2 \frac{d}{dz} \rho = \rho g_z.$
- $$g_z(r, z) = -4\pi G \left\{ \int_0^z \rho_g(r, z') dz' + \int_0^z \left[\frac{\partial g_r(r, z')}{\partial r} + \frac{g_r(r, z')}{r} \right] dz' \right\}.$$
- $g_r = -\frac{V^2}{r} \Rightarrow \frac{\partial g_r(r, z')}{\partial r} + \frac{g_r(r, z')}{r} = 0.$
- $\rho_g = \rho_0(z) \exp(-k_g r) \Rightarrow g_z \propto \exp(-k_g r), \quad k_g^{-1} = 3\text{--}5 \text{ kpc}$
- $$h = \left(\frac{8v_0^2 H_2}{3|g_z|} \right)^{1/2} \Rightarrow h \propto \exp(k_g r/2),$$
- h grows with r , a **flared** gas layer.

Observations of the HI layer in the Milky Way

(Kalberla & Dedes, A&A, 487, 951, 2008)



2.3. Interstellar gas and its multi-phase structure

- Supernova explosions → hot, tenuous gas → slow cooling → pervasive hot regions
- Supernovae (SNe) → transonic turbulence → compression → cooling → cool clouds
- Gravitational & thermal instabilities → cold, dense clouds → star formation → supernovae

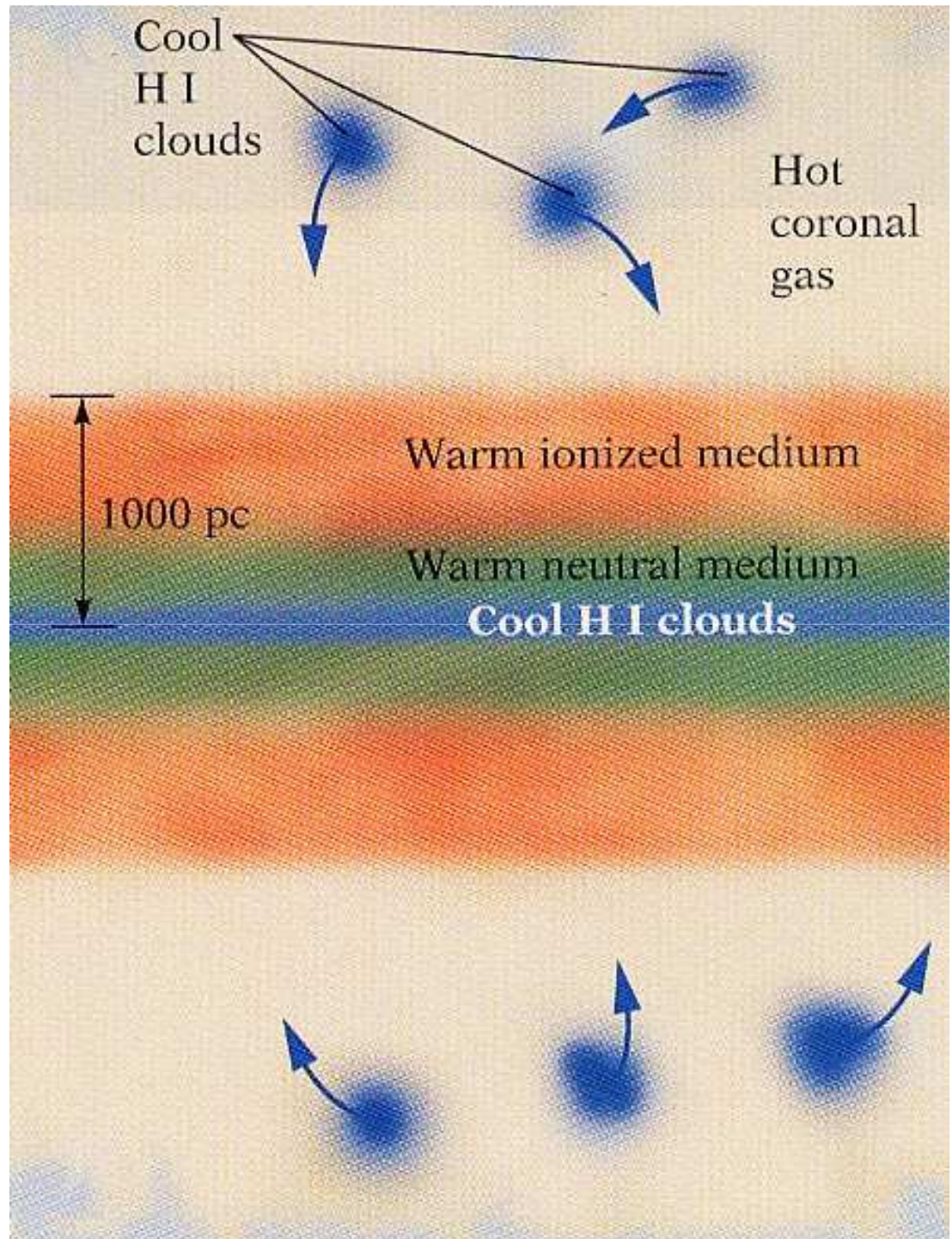
Phase	Origin	Density [cm ⁻³]	Temperature [K]	Size [pc]	Volume fraction, %
Molecular clouds	Gravity, thermal instability	10 ³	10	10	0.1
Hydrogen clouds	Compression	20	100	100	2
Diffuse warm gas		0.1	10 ⁴	—	60
Hot gas	Supernovae	10 ⁻³	10 ⁶	100–1000	38

The multi-layered interstellar medium (ISM):

The warmer is the component of the ISM, the more it expands away from the Galactic midplane.

Galactic fountain:

Hot gas rises to the halo, cools, and returns to the disc in $\approx 10^9$ yr



Galactic gaseous halos:

turbulent, rotating, hot,
ionised, quasi-spherical
gas envelopes of galactic
discs,

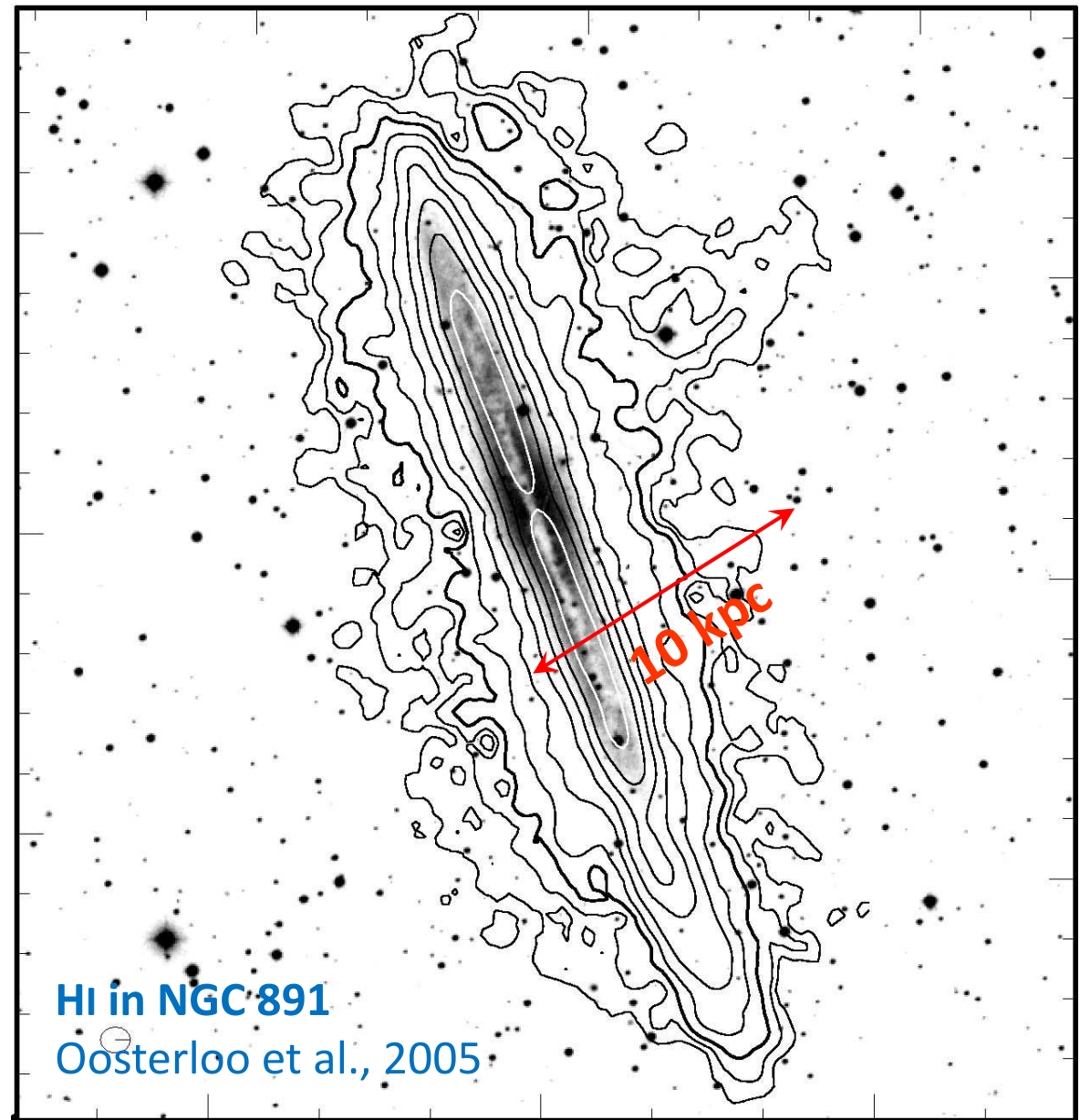
$$n \cong 10^{-3} \text{ cm}^{-3},$$

$$T \cong 10^6 \text{ K},$$

$$c_s \cong 100 \text{ km/s},$$

$$v_0 \simeq 60 \text{ km/s},$$

$$H \cong \text{several kpc}$$

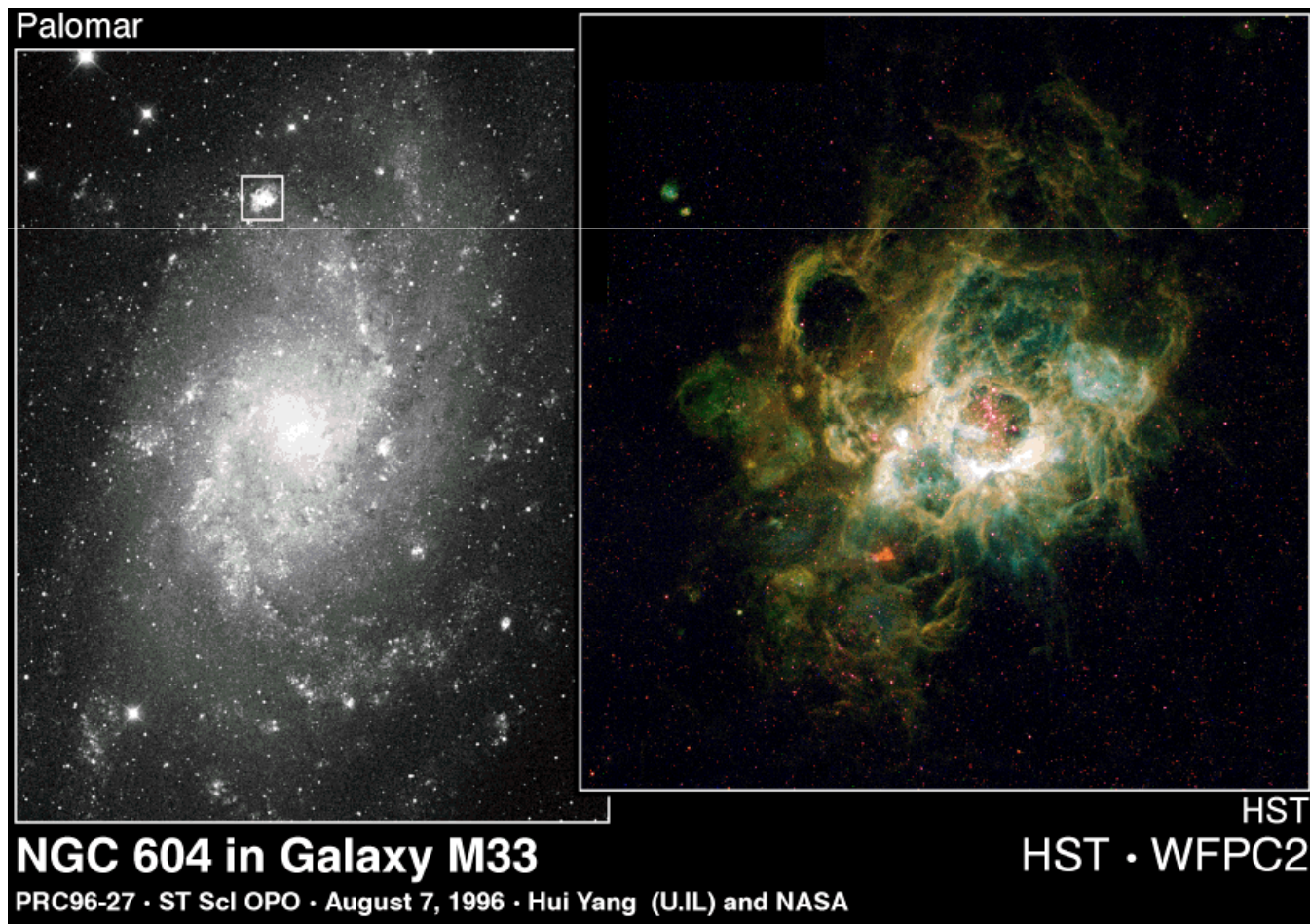


2.4. Interstellar turbulence: driven mainly by SN explosions,
30% isolated, 70% in clusters (*OB associations*)

Smaller contributions ($\cong 25\%$): stellar winds and galactic differential rotation

Starburst region NGC 604 in M33:

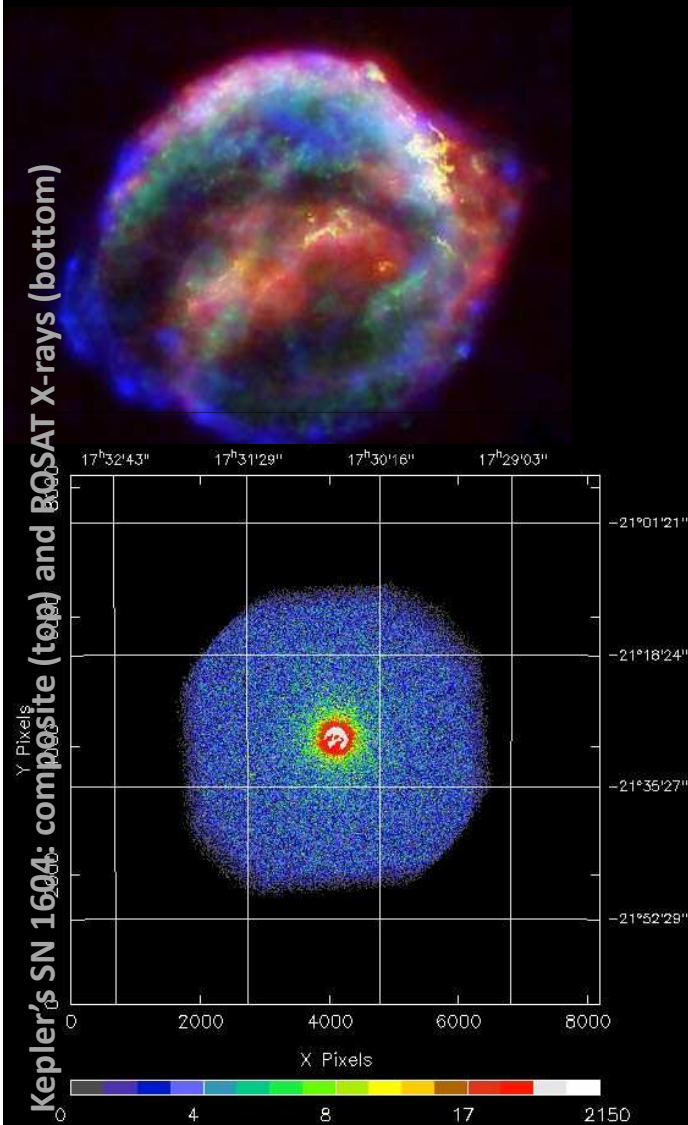
200 young massive stars ($15\text{--}60 M_{\odot}$) in a region 300 pc across



Supernova (SN): explosion of a massive star,

$M_* > 16 M_\odot$, energy released $E \simeq 10^{51}$ erg

$\Rightarrow$ a hot gas bubble expanding supersonically $\Rightarrow$ spherical shock wave

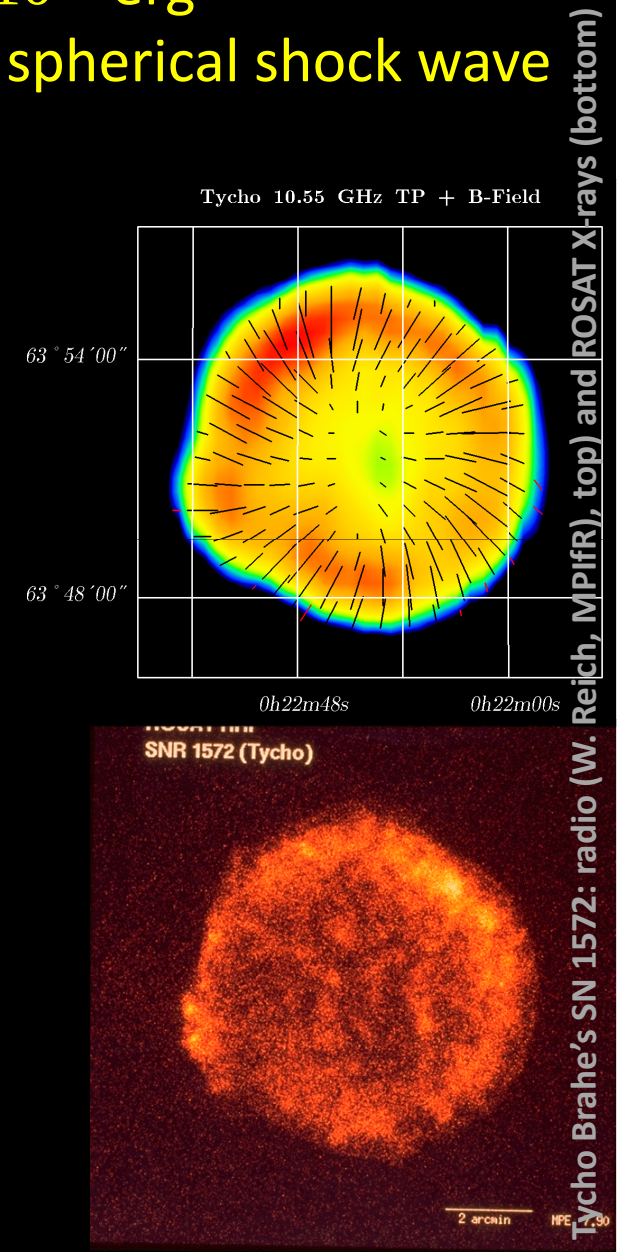


SN remnant (SNR):

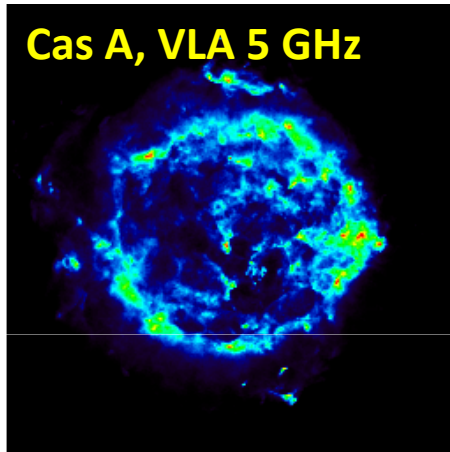
a hot, expanding gas, X-ray emitting bubble (mostly heated interstellar gas),

□ separated from the ISM by a dense shell of swept-up, shocked interstellar gas;

□ a site of cosmic ray acceleration.



Stages of SNS expansion

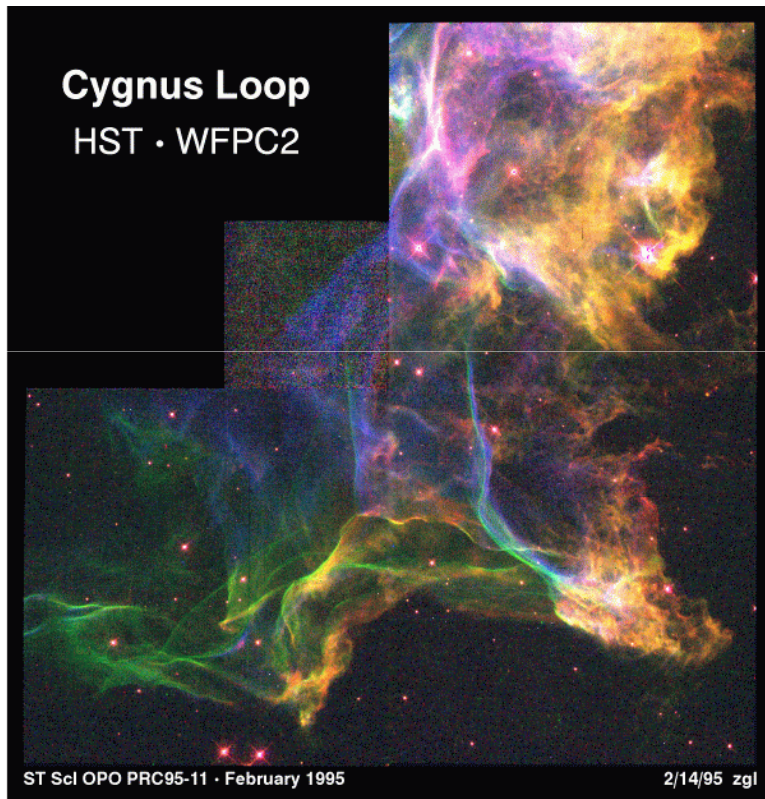


1. **Free expansion:** the ejected mass ($\cong 4M_{\odot}$) dominates the swept-up mass, constant expansion velocity, lasts $\cong 200$ yrs.
2. **Sedov–Taylor (adiabatic) phase:** the swept-up ISM mass dominates, lasts 10,000 - 20,000 yrs. Ambient pressure is still negligible, radiative cooling time is long, so energy is conserved:

$$R = \left(\frac{25}{3\pi} \right)^{1/5} \left(\frac{Et^2}{\rho_0} \right)^{1/5}, \quad V = \dot{R} \propto t^{-3/5},$$

R = SN remnant (SNR) radius, E = explosion energy,
 ρ_0 = ambient gas density, t = time.

3. **Momentum-conserving (snowplough) phase:** $T < 10^6$ K, lasts for 10^5 yr, remnant's age $\cong$ radiative cooling time near the shock, expansion energy is no longer conserved but radial momentum remains conserved:



$$R = R_0 \left[1 + 4 \frac{V_0}{R_0} (t - t_0) \right]^{1/4}, \quad V = \dot{R}.$$

$$t_0 = 3.5 \times 10^4 \left(\frac{E}{10^{51} \text{ erg}} \right)^{4/17} n_0^{-9/17} \text{ yr},$$

$$V_0 = 230 \left(\frac{E}{10^{51} \text{ erg}} \right)^{1/17} n_0^{2/17} \frac{\text{km}}{\text{s}},$$

$n_0 \simeq 0.1 \text{ cm}^{-3}$, ambient gas number density.

4. **Dissipation of the remnant** and merger with the ISM: expansion velocity drops below the local speed of sound, $V < c_{\text{sound}}$, $t > 10^6$ yr.

Numerical estimates

$$E = 10^{51} \text{ erg}, \quad n_0 = 1 \text{ cm}^{-3}.$$

Sedov–Taylor phase:

$$\frac{R}{1 \text{ pc}} \approx 0.35 \left(\frac{t}{1 \text{ yr}} \right)^{2/5}, \quad \frac{\dot{R}}{1 \text{ km/s}} \approx 1.4 \times 10^5 \left(\frac{t}{1 \text{ yr}} \right)^{-3/5},$$

Transition to the snowplough phase:

$$R_0 \approx 24 \text{ pc}, \quad \dot{R} \approx 250 \text{ km/s}, \quad t \approx 3.4 \times 10^4 \text{ yr},$$

$$\text{shell mass } M_{0,\text{shell}} \approx 1.4 \times 10^3 M_{\odot}.$$

Expanding SN shells → random ISM motions → turbulence

Turbulent scale:

$l = 50\text{--}100\text{ pc}$

$\cong$ SN shell @ pressure balance

Turbulent velocity:

$v \simeq 10\text{ km/s} \approx c_s$

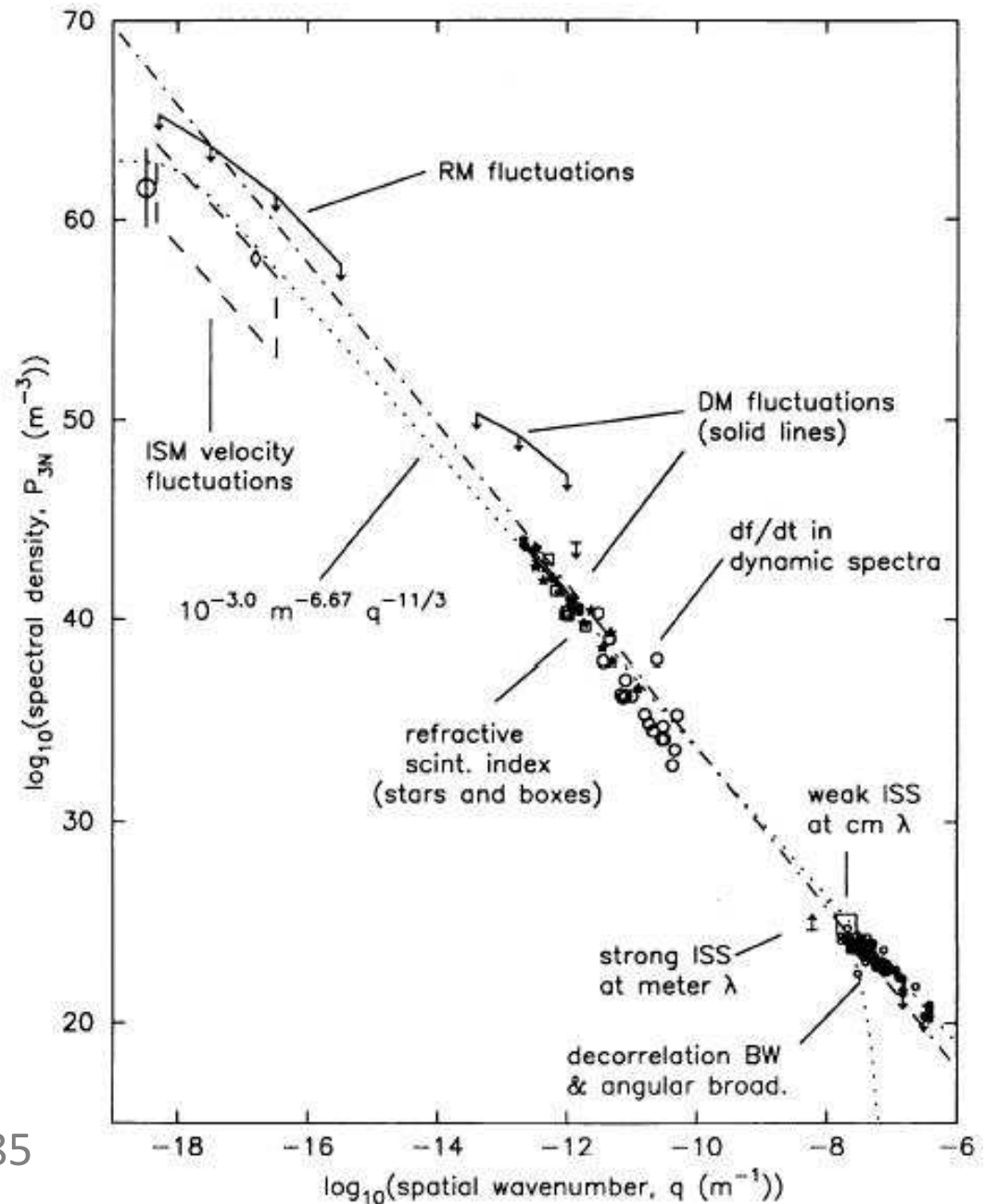
Kolmogorov spectrum,

$$v_l \propto l^{1/3},$$

wide range of scales,

$$10^{10} < l < 10^{20}\text{ cm.}$$

Armstrong et al., ApJ, 443, 209, 1985



Interstellar medium in spiral galaxies:

- ❑ rotating,
- ❑ stratified,
- ❑ randomly stirred by SNe & stellar winds,
- ❑ electrically conducting fluid (plasma)

➔ perfect environment for turbulence & various dynamos

3. Elliptical galaxies (10% of all galaxies)

M89 (E0)

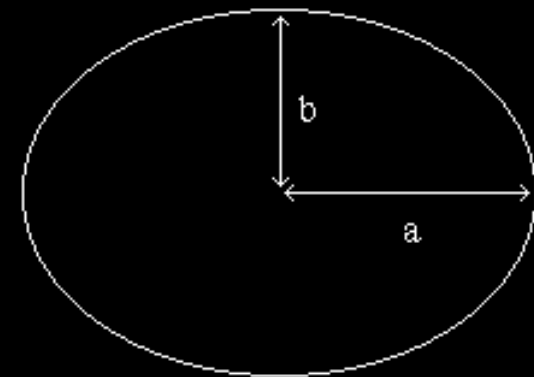
M49 (E4)

M84 (E3)

M87 (E1)

M59 (E5)

Defining the class of elliptical galaxy



$$n = 10 \times (1 - \frac{b}{a})$$

E_n

❑ **Structureless**, triaxial ellipsoids of old stars, no star formation, stellar density monotonously decreases outwards.

❑ **Wide range in size and mass:**

0 from giants (diameter a few Mpc, a few times $10^{12} M_{\odot}$, many have active nucleus, jet, are bright in radio, etc.)

0 to dwarves (a kpc in diameter, $10^6 M_{\odot}$).

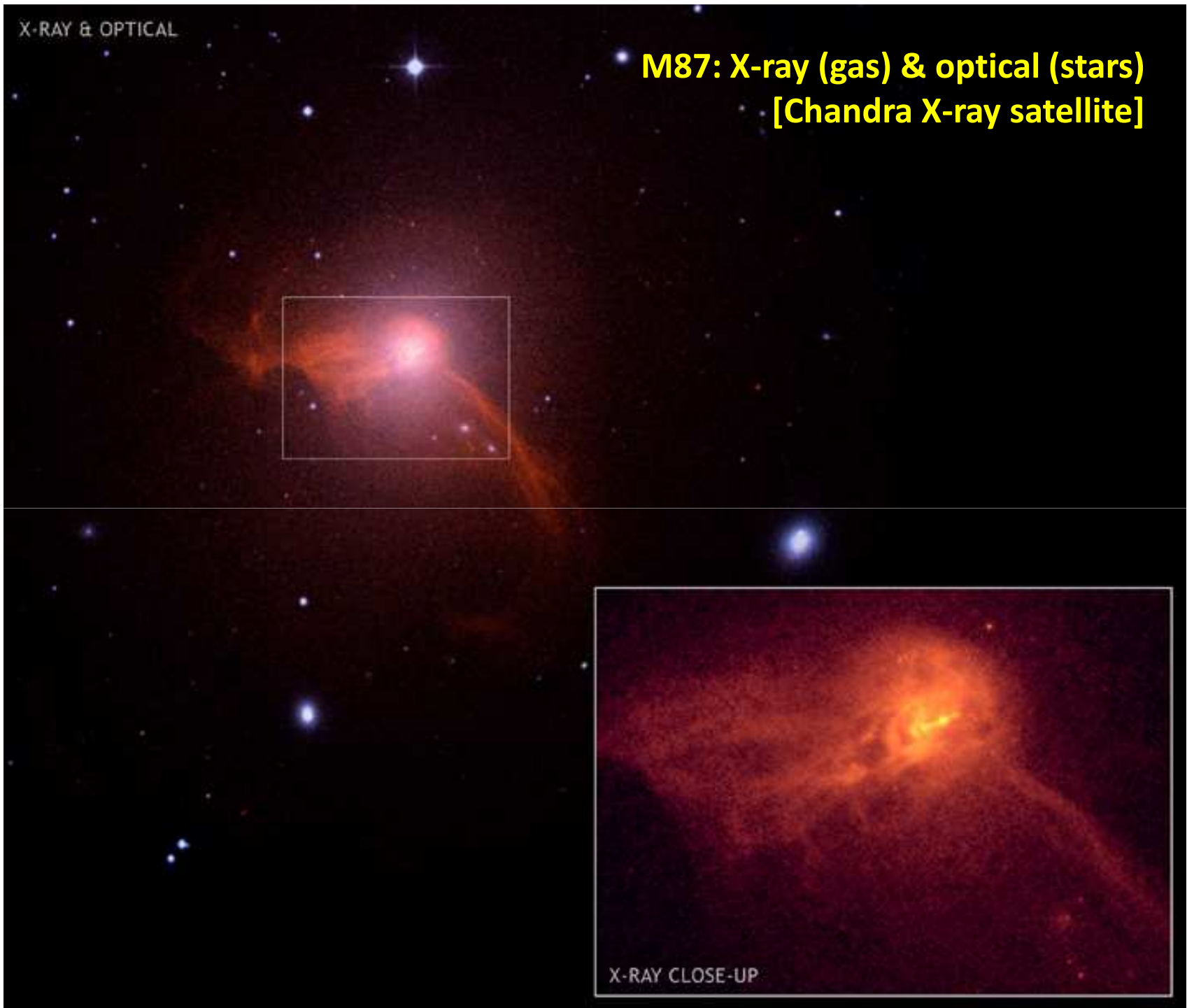
❑ **No overall rotation**: randomly oriented stellar orbits, stellar velocity dispersion $\sigma_* \cong 300$ km/s.

Interstellar gas in ellipticals

- ❑ Hot, $T \cong 10^7$ K, detected in X-rays;
- ❑ tenuous, $n \cong 10^{-3} \text{ cm}^{-3}$ (10^{-2} cm^{-3} near the centre);
- ❑ total gas mass $10^9 M_{\odot} \cong 1\%$ of the stellar mass;
- ❑ radius of the gas distribution $\cong 50 \text{ kpc} \cong$ radius of the stellar distribution;
- ❑ no or weak spectral line emission $\Rightarrow$ little is known about gas motions.

X-RAY & OPTICAL

M87: X-ray (gas) & optical (stars)
[Chandra X-ray satellite]



NGC 1132: optical



**NGC 1132: X-rays
[Chandra]**



**NGC 4649: X-ray (purple),
optical (blue) [Chandra]**

4. Galaxy clusters

- ❑ The largest gravitationally bound objects in the Universe
- ❑ No overall rotation
- ❑ Visible mass 10^{14} – $10^{15} M_{\odot}$ ($\cong$ a few 10^3 galaxies)
- ❑ Core radius 500 kpc
- ❑ Velocity dispersion of galaxies 10^3 km/s
- ❑ Intergalactic gas: hot, $T \cong 10^7$ – 10^8 K,
dilute $n \cong 10^{-3}$ cm, extended $R \cong 500$ kpc
- ❑ Most clusters are **not** relaxed, steady-state systems: evidence of merger, continuing formation process

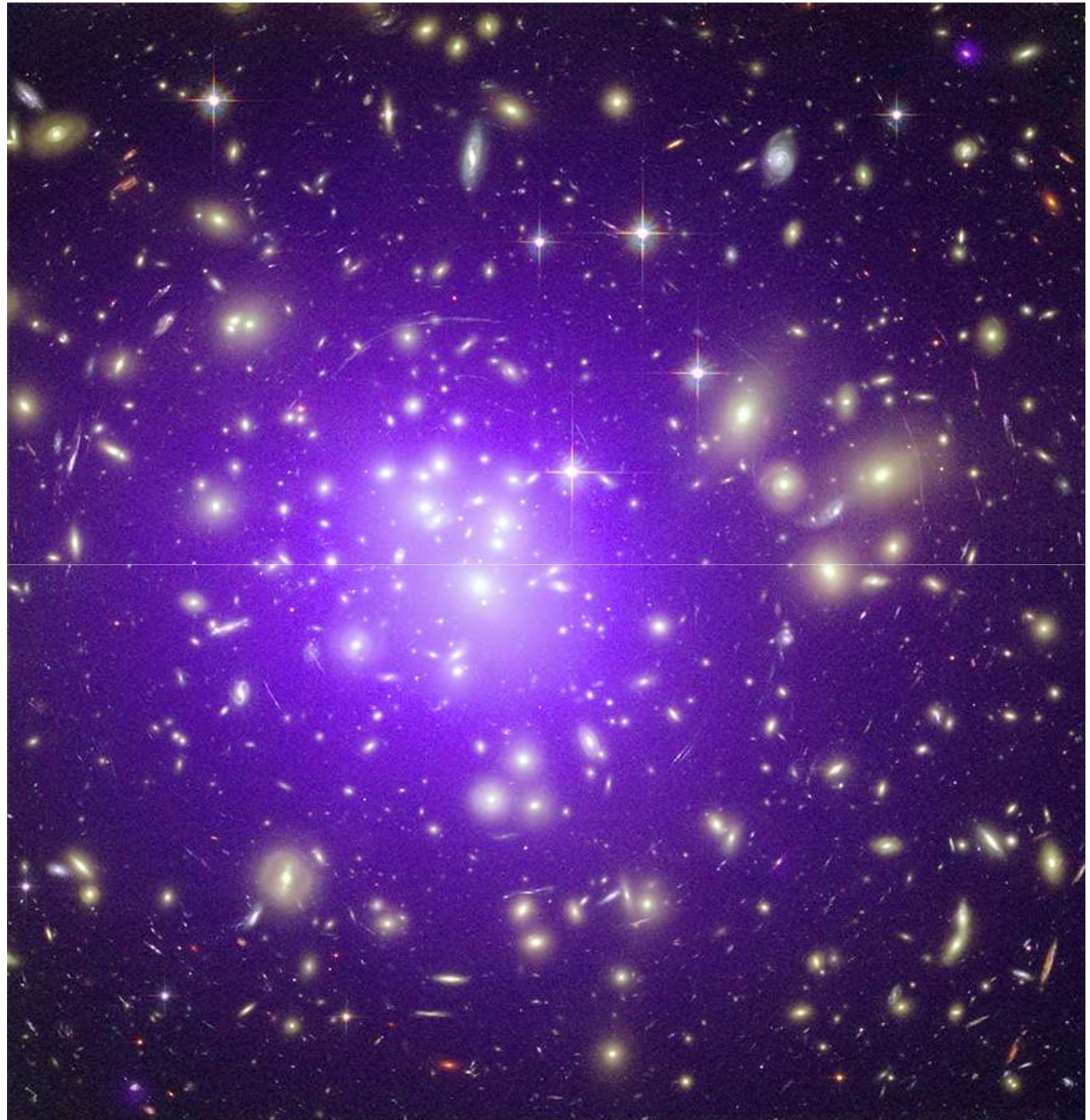
❑ **Abell 1689:**
a massive cluster.

❑ **Hot gas** in X-rays
[purple, Chandra],
visible galaxies from
HST (yellow).

❑ Evidence for **recent
merger** from gas
temperature
distribution.

❑ Long optical arcs:
gravitational lensing
of background
galaxies, probe of the
gravitating mass.

<http://chandra.harvard.edu/photo/2008/a1689/>





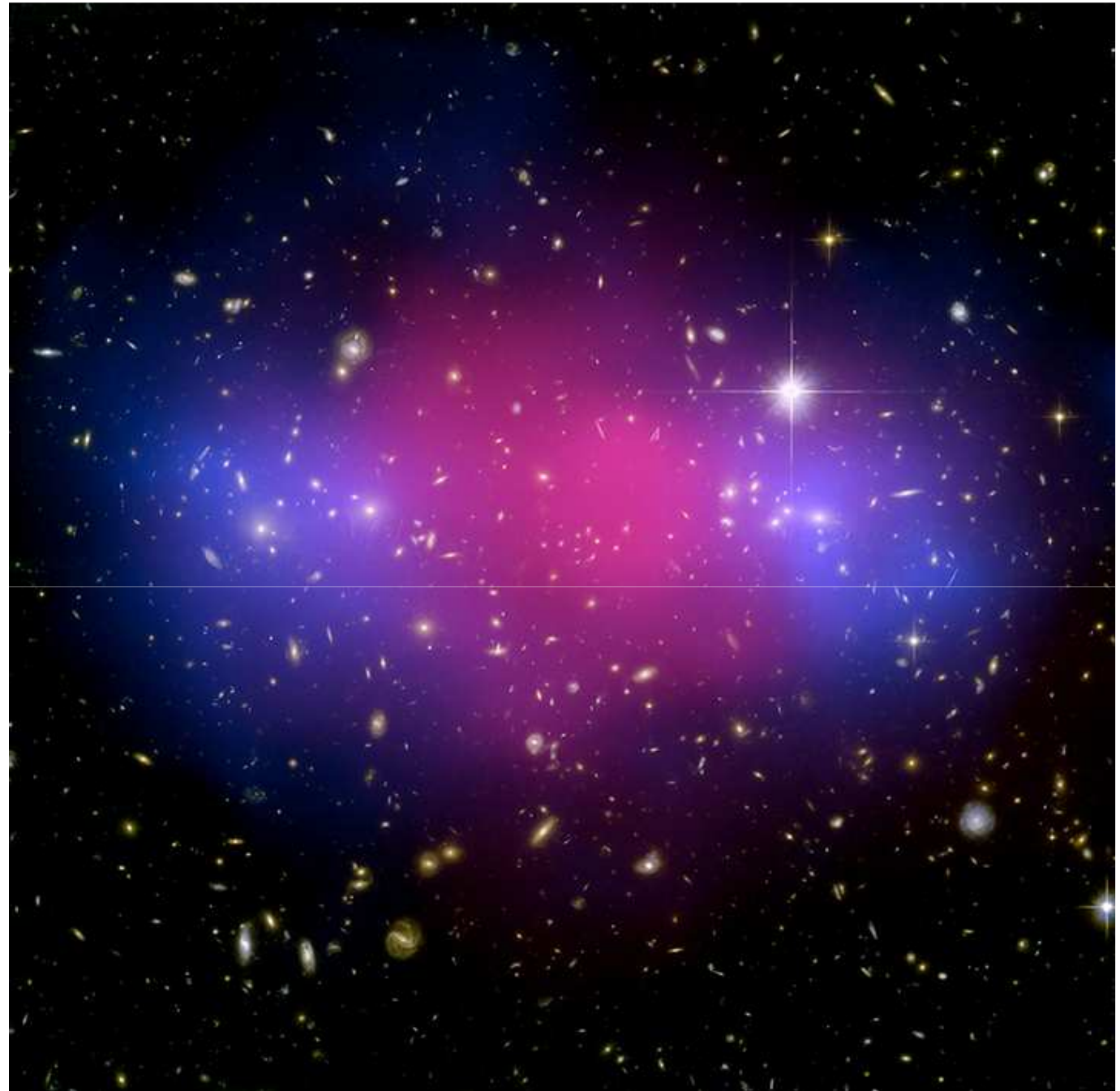
Watch the movie at http://chandra.harvard.edu/photo/2008/a1689/a1689_wwt_lg_web.mov

❑ **MACS J0025.4-1222:**

merger of 2 large clusters $\approx$ in the sky plane, separation of dark and visible matter

❑ **hot gas** in X-rays (pink, Chandra), **dark & visible matter** from gravitational lensing using HST images (lensing: blue; optical: yellow & cyan).

❑ Gas stopped in the collision, but dark matter keeps moving.



A simulation of the merger of two galaxy clusters



Watch the movie at http://chandra.harvard.edu/resources/animations/cluster_merger_lg_web.mpg