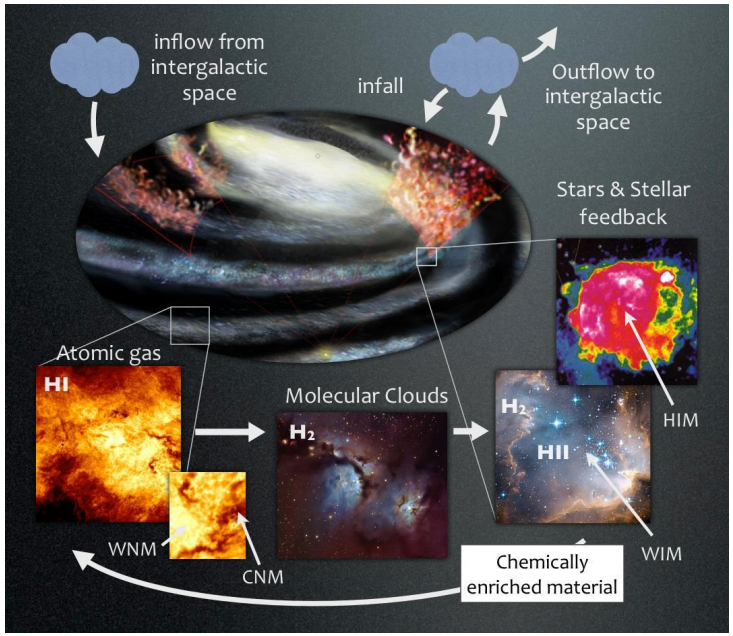
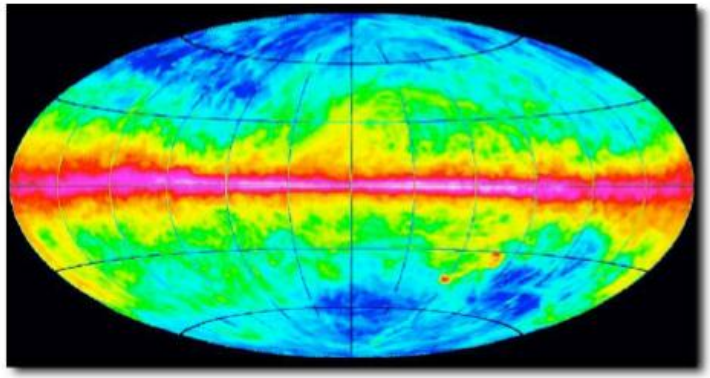
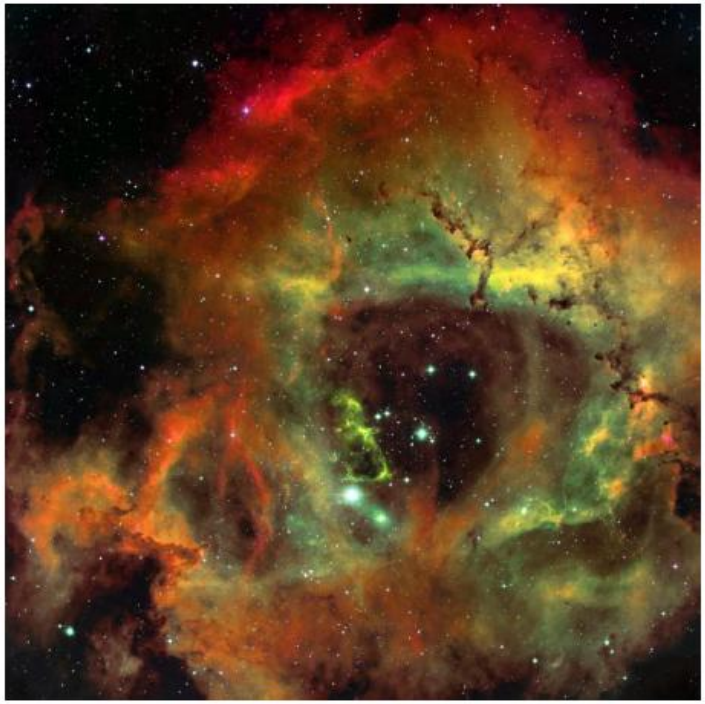
2.4 Interstellar Gas

- 星际介质：恒星之间存在的星际气体和星际尘埃等
- 星系中气体的质量少于恒星质量的10%，尘埃质量比例更小（~1%）
- 气体（温度10^6-10K、密度$10^{-3}\sim10^6\ \mathrm{cm}^{-3}$）为恒星形成提供原料；决定了星系的特性和星系演化



Gas in ISM





Atomic gas (HI = neutral H)

$n_H = 1\text{-}10^2\ cm^{-3}$
T = 80 - 8000 K

21cm line, [CII] 157μm line
optical absorption lines (equiv

Ionized gas (HII = H^+)
OB stars
⇒ recent star formation

$n_H = 10\text{-}10^4\ cm^{-3}$
T = 8000 K

The Stromgren sphere

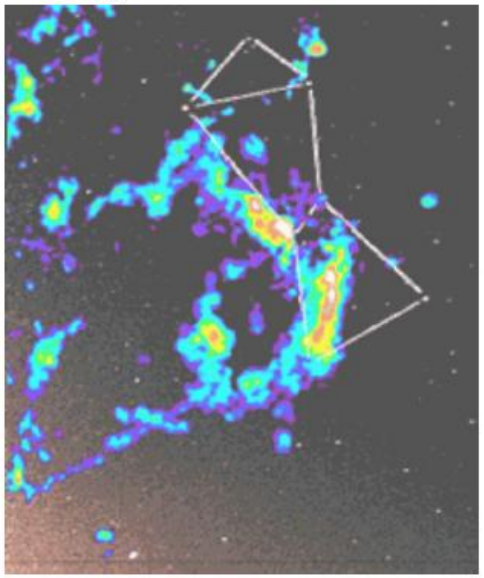
Optical recombination and collisional lines, infrared dust emission, radio free-free emission

Measuring densities, temperatures, abundances

Molecular clouds are the densest parts of the ISM and the sites of star formation

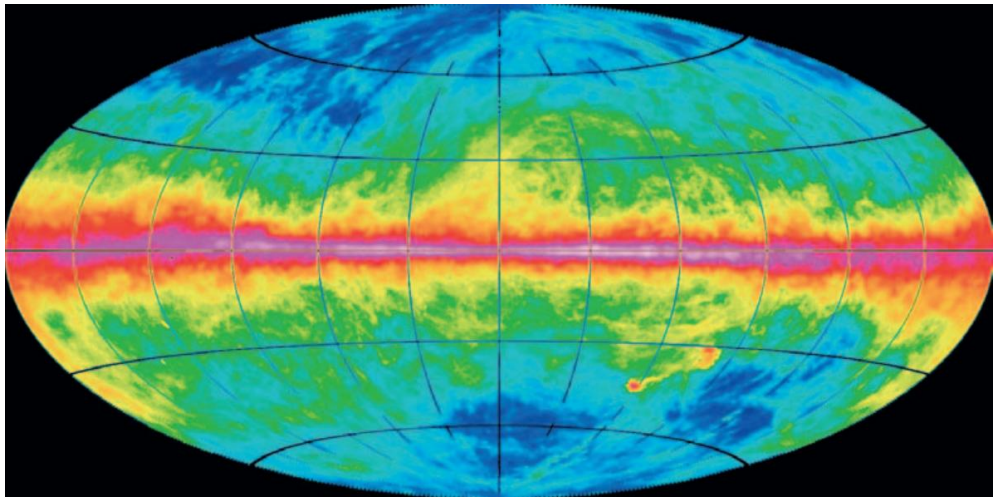
$n_H = 1\text{-}10^6\ cm^{-3}$
T = 10 - 1000 K

- Molecular vibrational and rotational lines
- Astrochemistry
- PDRs
- Extragalactic context



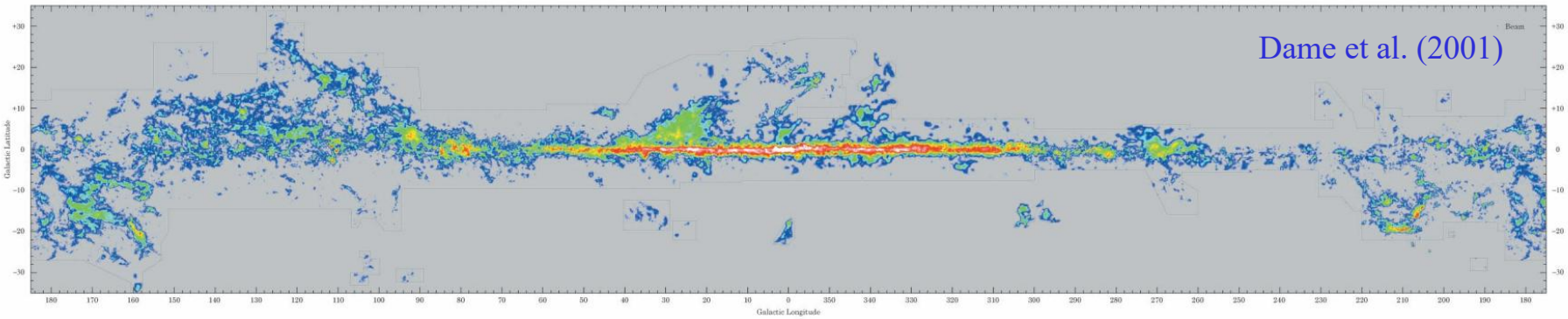
2.4.1 Mapping the gas layer

- 中性氢(HI) 利用射电21厘米谱线示踪



Kalberla et al. (2005)

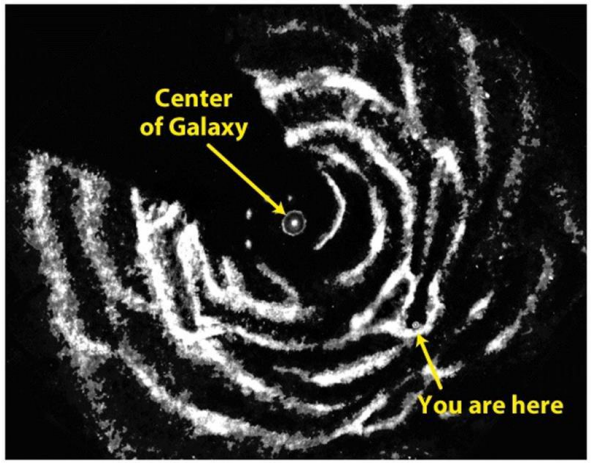
- 分子氢(H_2)是对称分子，分子利用CO谱线来示踪



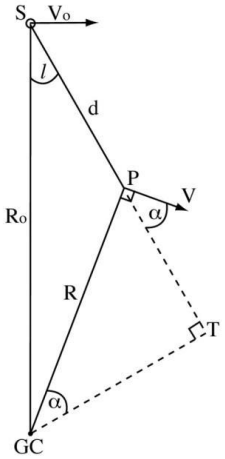
Dame et al. (2001)

Mapping the gas layer

气体所处的位置?



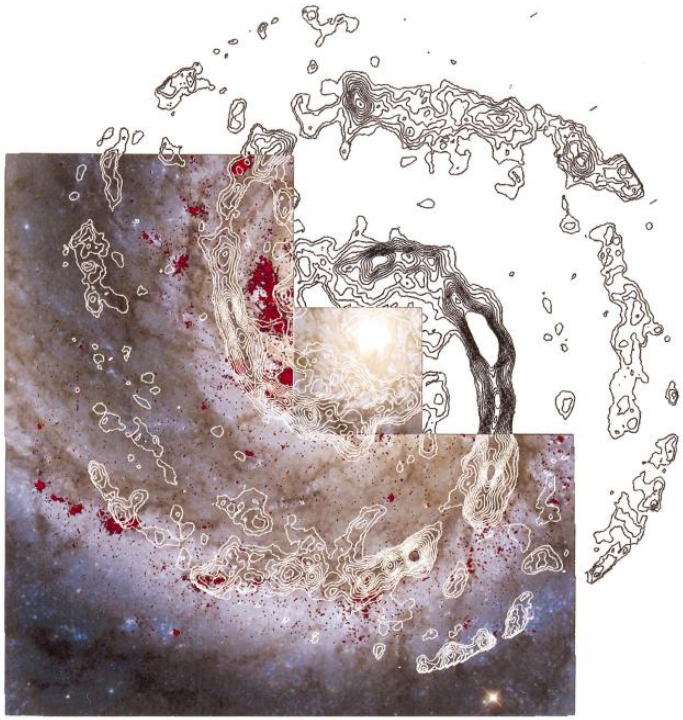
- 运动学距离
  - 在银盘内做圆轨道运动的气体，由其谱线发射，可求得在银经*l*方向有多少气体在以视向速度V_r运动
  - V_0、R_0已知，利用转动曲线V(R)，可以估计气体的距离：$V_r = R_0 \cdot \sin l \cdot (V/R - V_0/R_0)$ --> R
  - 测得银河系中不同位置气体的强度，可以构建银河系气体分布的图像

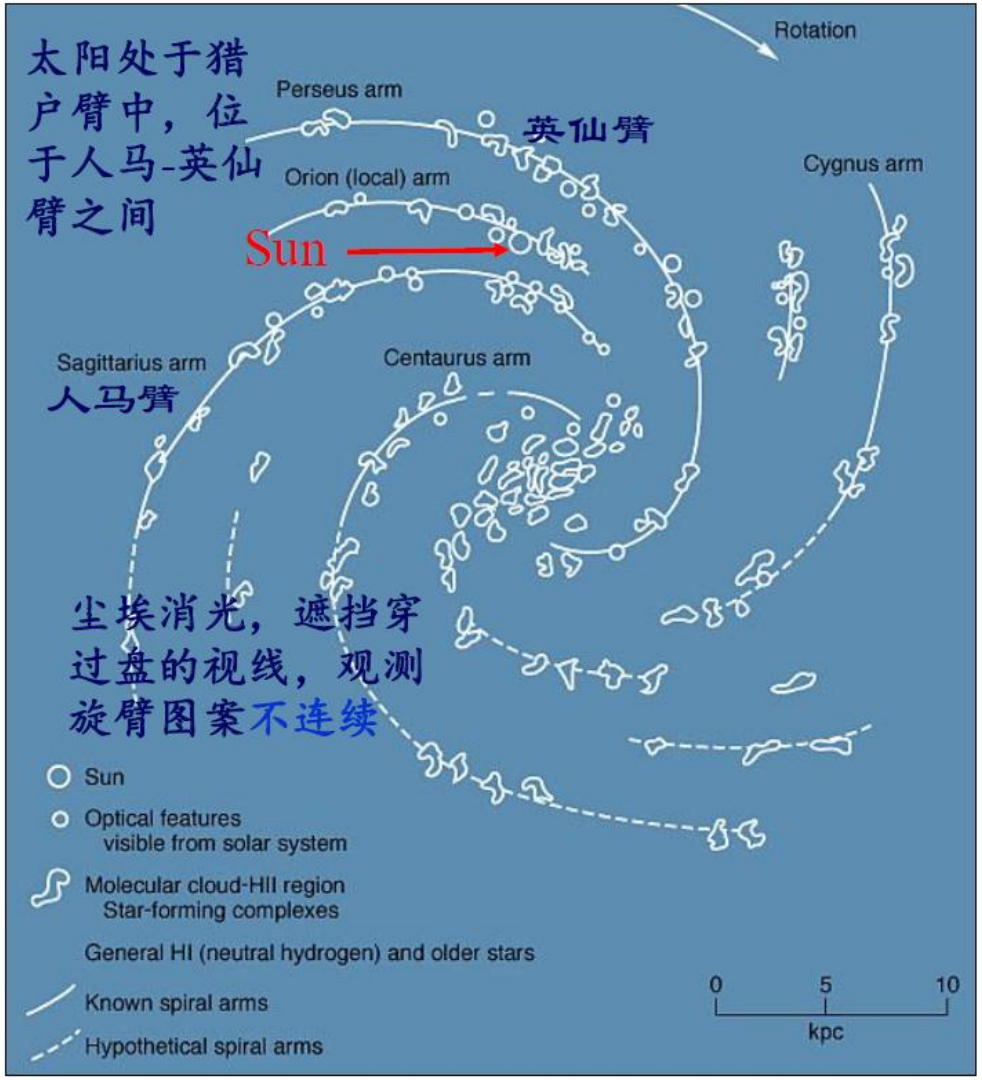


Mapping the gas layer

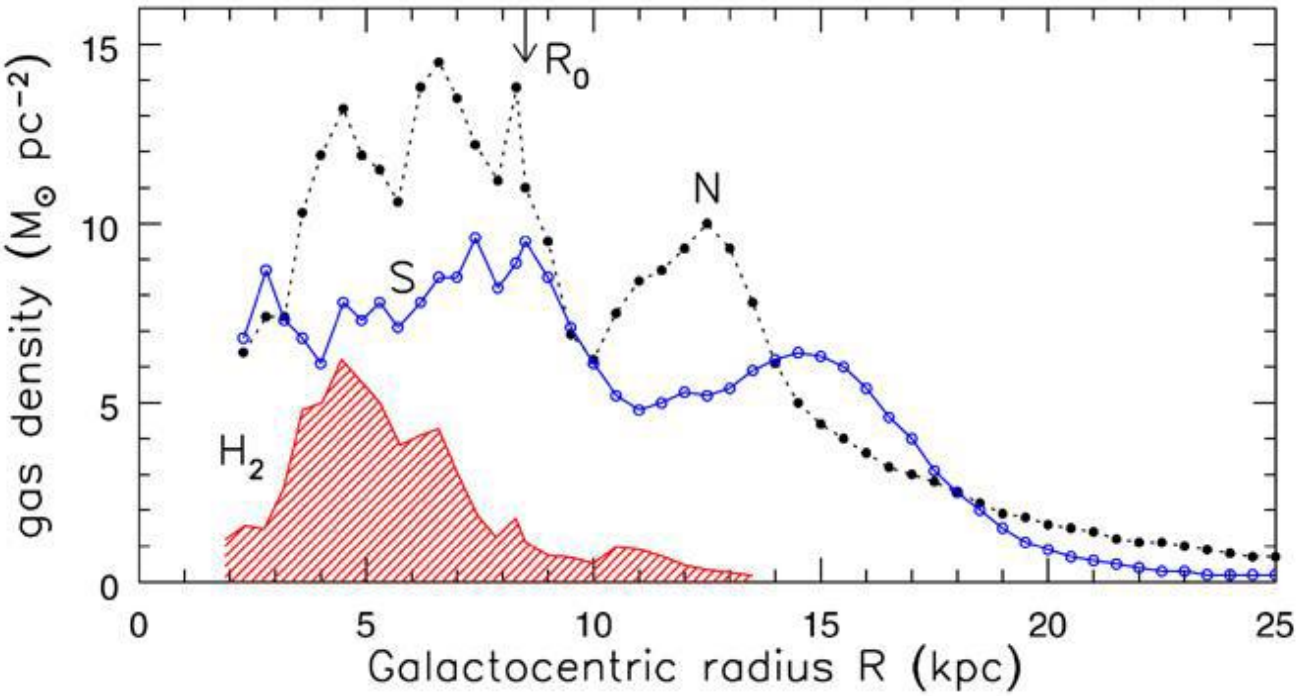
- 旋涡星系中，致密分子气体、尘埃和年轻恒星主要集中在星系的旋臂区域

M51, Aalto et al. (1999)



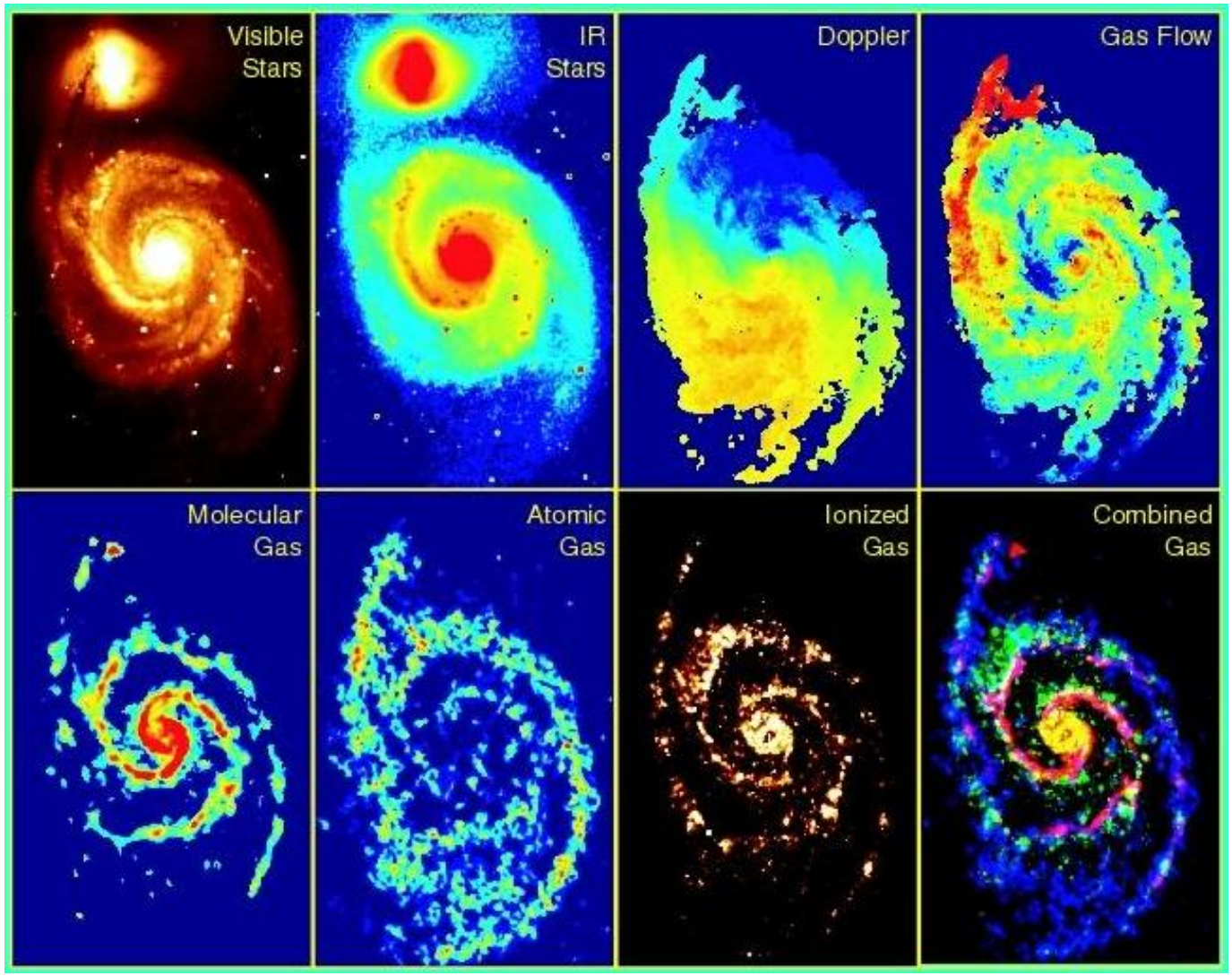


银河系HI和H_2的面密度

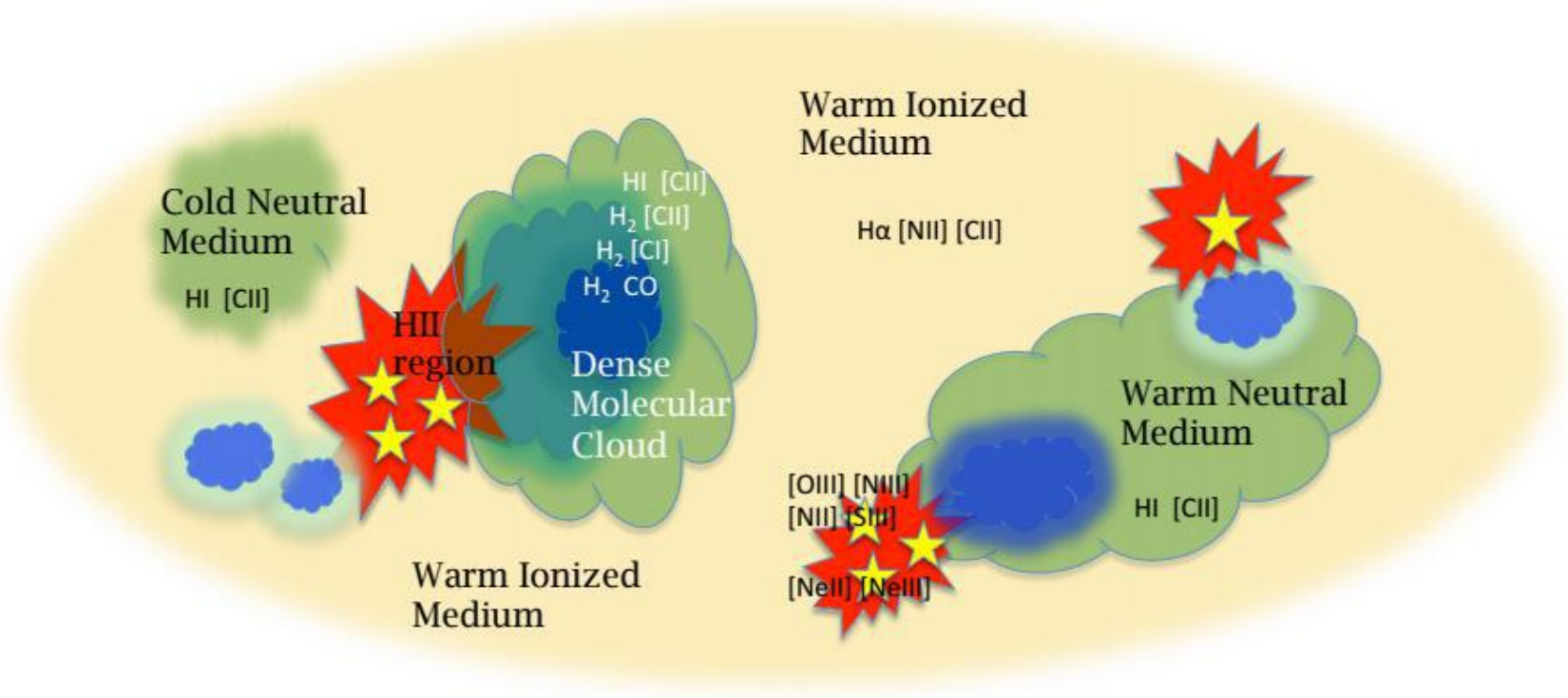


- 银河系中性氢(HI)的质量$M_{HI}\sim(4-8)\times10^9M_\odot$；分子氢质量$M_{H_2}\sim0.5M_{HI}$
- 分子氢（H_2）主要分布在$R < R_0$区域，但在星系中心几百pc内无HI和H_2
- HI比H_2分布在更大区域，HI也比恒星分布的更延伸，垂直盘方向HI比H_2分布在更厚的层

银河系HI 和 H_2 的面密度



2.4.2 A Physical Picture



2.4.2 A Physical Picture

- What is the volume filling factor（填充因子）of the hot ISM?
- What is the distribution of the temperature, density, and velocity?
- What are typical scales in the ISM and why?
- What is the effect of turbulence, magnetic fields and cosmic rays?
- What causes density and pressure inhomogeneities in the evolution of the ISM?
- How is the ISM related to star formation?

ISM Phases

- **Molecular Medium (MM): T ~ 20 K, n > 10^3 cm^{-3}, f < 1%**
  - MM is mostly cold dense molecular clouds which are gravitationally bound.
  - this phase contains ~as much mass as the atomic hydrogen, but occupies only a very small fraction of the ISM.
- **Cold Neutral Medium (CNM): T ~ 100 K, n ~ 20 cm^{-3}, f = 2 - 4%.**
  - The CNM is distributed in rather dense filaments or sheets, occupying a minor fraction of the ISM.
  - The CNM is most readily traced by HI measured in absorption.
- **Warm Neutral Medium (WNM): T ~ 6000 K, n ~ 0.3 cm^{-3}, f ~ 30%.**
  - This phase provides the bulk of the HI seen in emission line surveys.
- **Warm Ionized Medium (WIM): T ~ 8000 K, n ~ 0.3 cm^{-3}, f ~ 15%.**
  - associated with HII regions, but a considerable fraction of the ISM
  - outside of HII regions is also filled with ionized gas.
- **Hot Ionized Medium (HIM): T ~ 10^6 K, n ~ 10^{-3} cm^{-3} , f ~ 50%.**
  - The hot gas produced by supernova explosions
  - In spirals, the ISM is filled with this component.

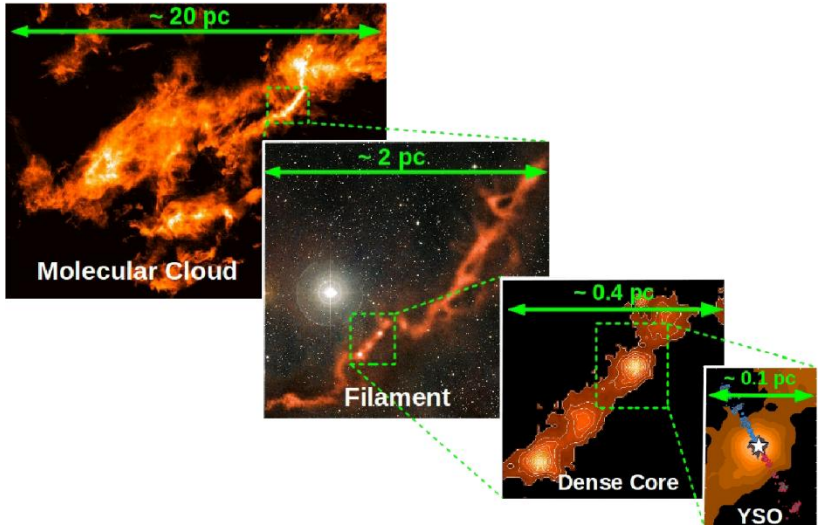
- Hot ionized medium (e.g. X-rays)
- Warm ionized medium HII region(e.g. Hα)
- Warm neutral medium (e.g. HI emission)
- Cold neutral medium (e.g. HI absorption)
- Molecular medium (e.g. CO)

分子云 Molecular clouds

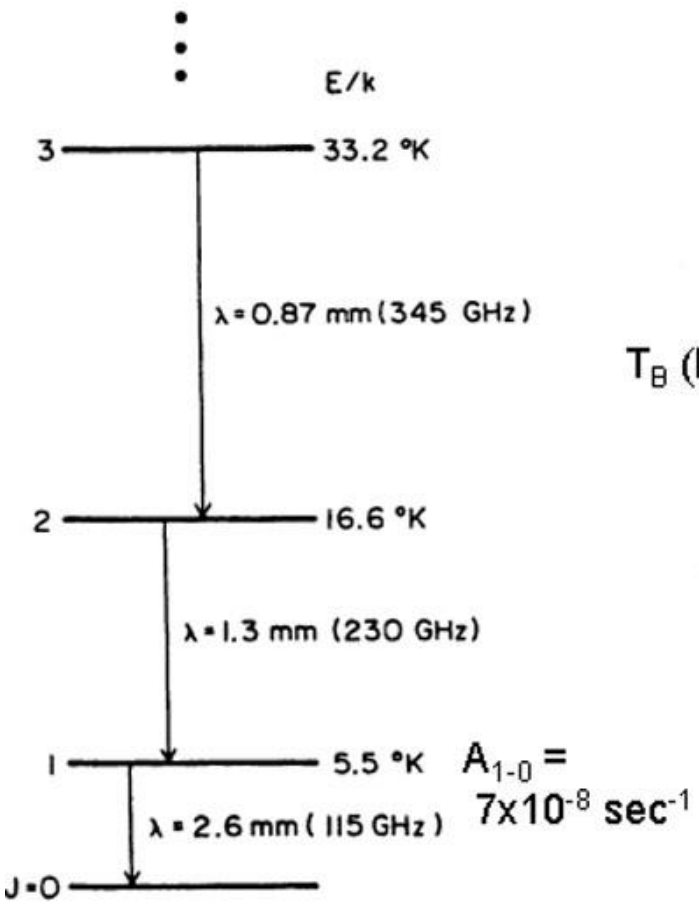
Table 2.4 A 'zeroth-order' summary of the Milky Way's interstellar medium (after J. Lequeux)

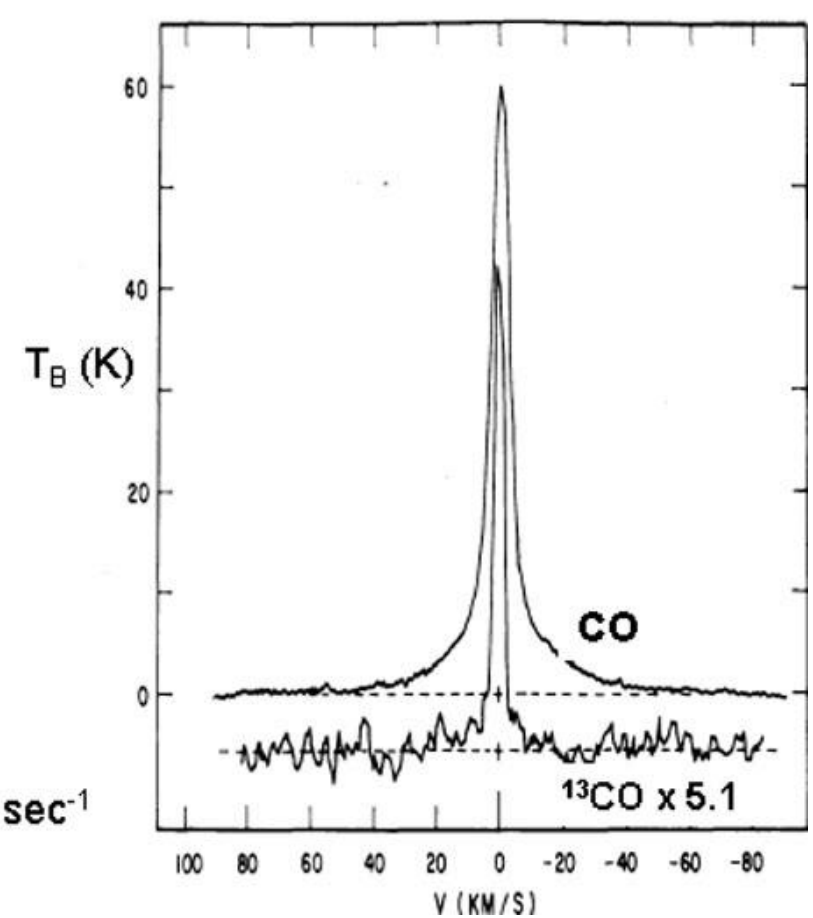
Component	*Description*	*Density* (cm^{-3})	*Temperature* (K)	*Pressure* (p/k_B)	*Vertical extent*	*Mass* ($\mathcal{M}_\odot$)	*Filling factor*
Cold clumpy gas	Molecular: H_2	>200	<100	Big	80 pc	$(2) \times 10^9$	<0.1%
	Atomic: HI	25	50–100	2 500	100 pc	3×10^9	2%–3%
Warm diffuse gas	Atomic: HI	0.3	8 000	2 500	250 pc	2×10^9	35%
	Ionized: HII	0.15	8 000	2 500	1 kpc	10^9	20%
HII regions	Ionized: HII	$1–10^4$	~10 000	Big	80 pc	5×10^7	Tiny
Hot diffuse gas	Ionized: HII	~0.002	$\sim 10^6$	2 500	~5 kpc	(10^8)	45%

- The coldest objects in the Universe
- Self-gravitating, dense, and neutral
- Sites of all star formation



Molecular Emission





Formation of Molecules

- **H_2 is symmetric and has no dipole moment: H_2 cannot form by two H coming together**
  - **They cannot radiate away their binding energy.**
  - **Something else must be involved.**

- **Grains act as a catalyst by allowing a reaction to take place without being chemically altered (by absorbing the reaction energy).**

Fraction of H atoms that stick: s

…… move across and find another H: ξ

…….... react: ζ

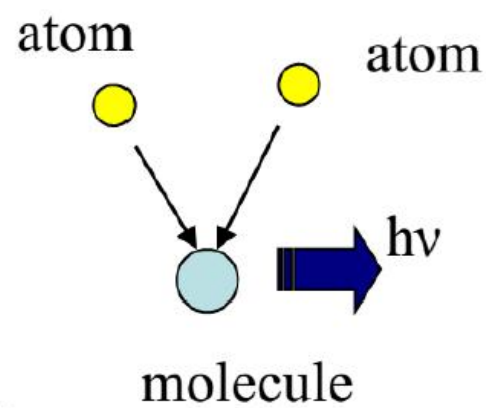
……. come off the grains: η

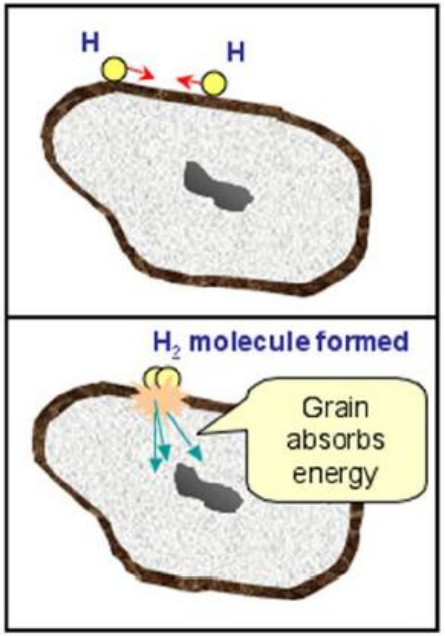
Overall, rate γ: fraction that hit and then make an H_2

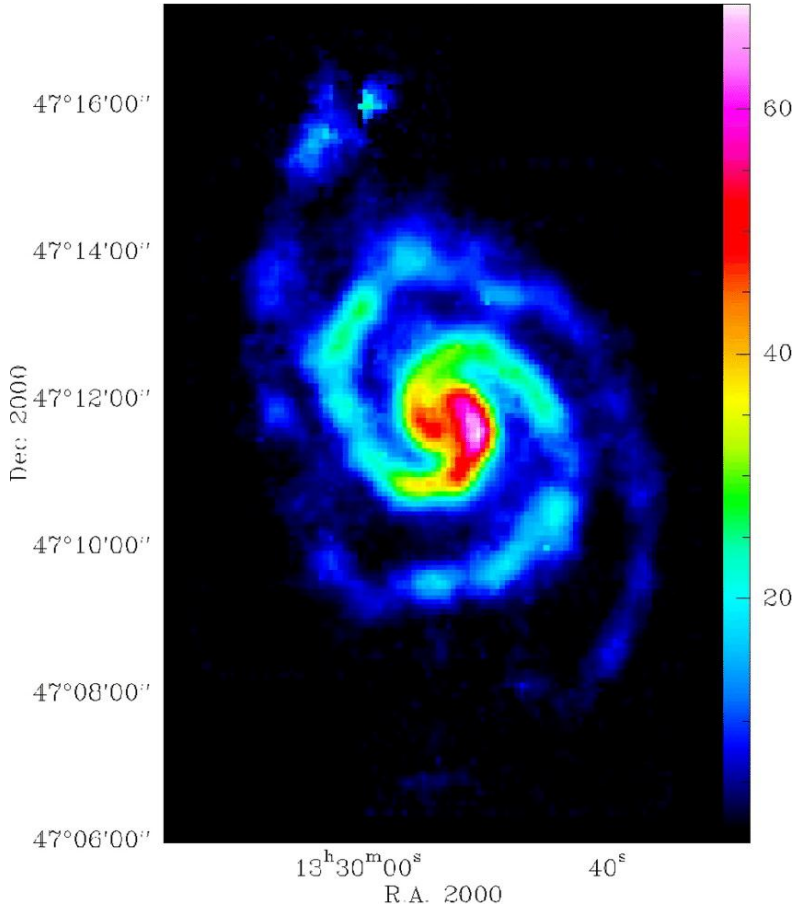
$$\gamma = s\,\xi\,\zeta\eta$$

In the lab, $s \sim 1/3$, and for H, ξ, ζ, η all ~ 1

Grains catalyzes (催化) the reactions between atoms which otherwise do not meet together (Gould & Salpeter 1963).






47°16'00"
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47°12'00"
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47°08'00"
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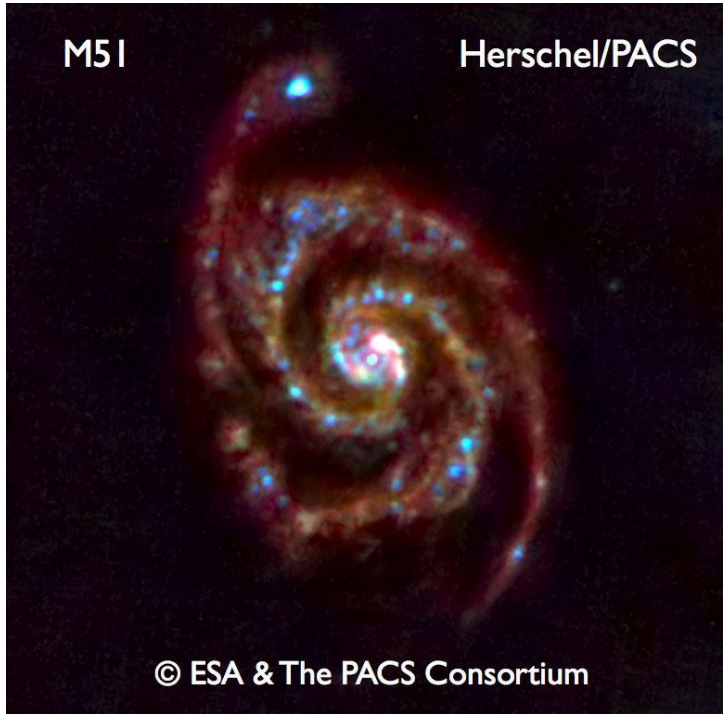
R.A. 2000
60
40
20


M51
Herschel/PACS
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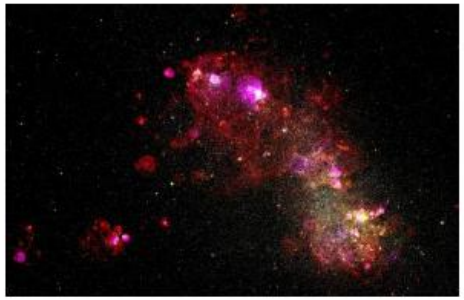
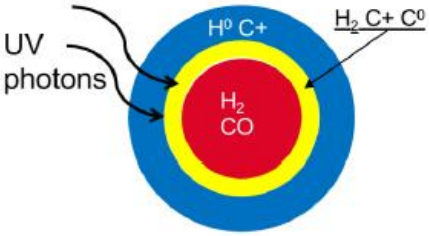
Different Metallicity

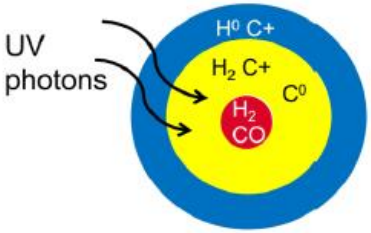
Solar metallicity



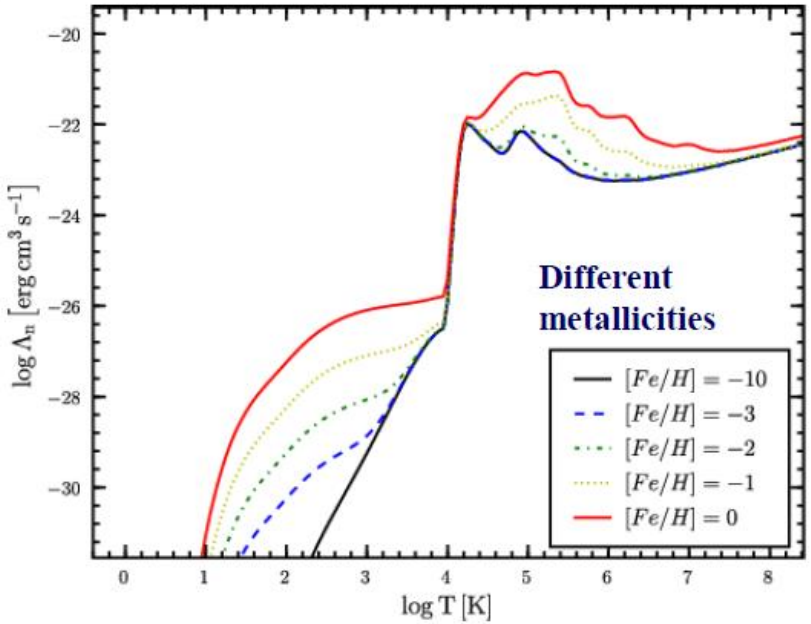
Low metallicity

- **Metals** account for 1% of the baryonic mass, but they dominate most of the important **chemistry**, **ionization**, and **heating/cooling** processes.





金属丰度较高的区域：能够破坏H_2分子的紫外光子，不能穿透较大的深度

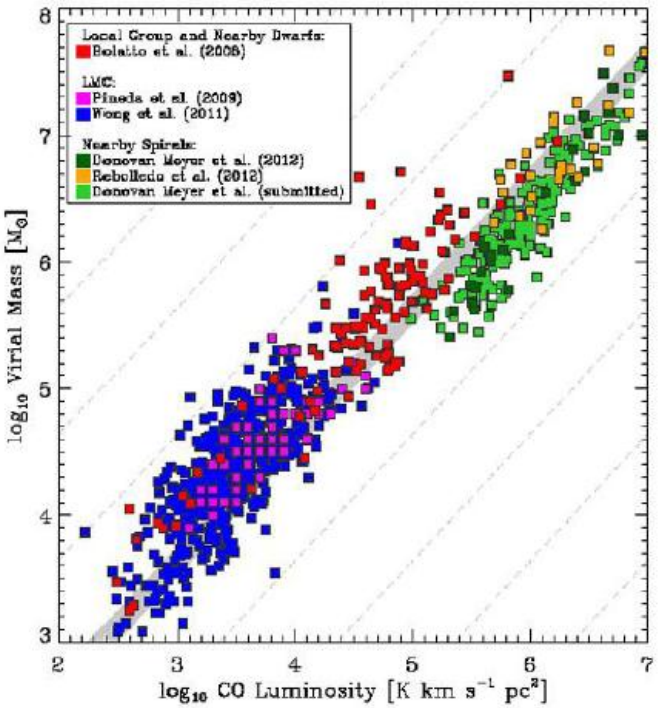


Cooling function 冷却速率（Λ）：Λ(T)依赖于气体温度和金属丰度；高温气体，冷却的更快；高金属丰度，冷却的更快。

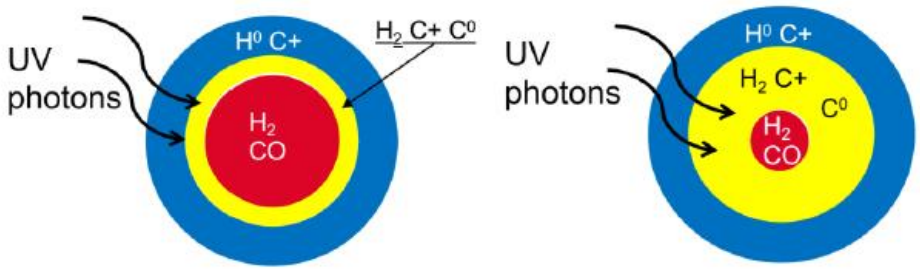
The X factor

- Empirically, it is found that the **integrated line intensity** of CO, W_{CO}, is directly **proportional to** the H_2 column density, $N(H_2)$ on cloud scales.

- It's a **very useful** relation as long as you know the constant of proportionality, **$X = N(H_2) / W_{CO} = 2\times10^{20}$ mol/cm^2/(K km/s)** in the solar neighborhood (Bolatto et al. 2013)



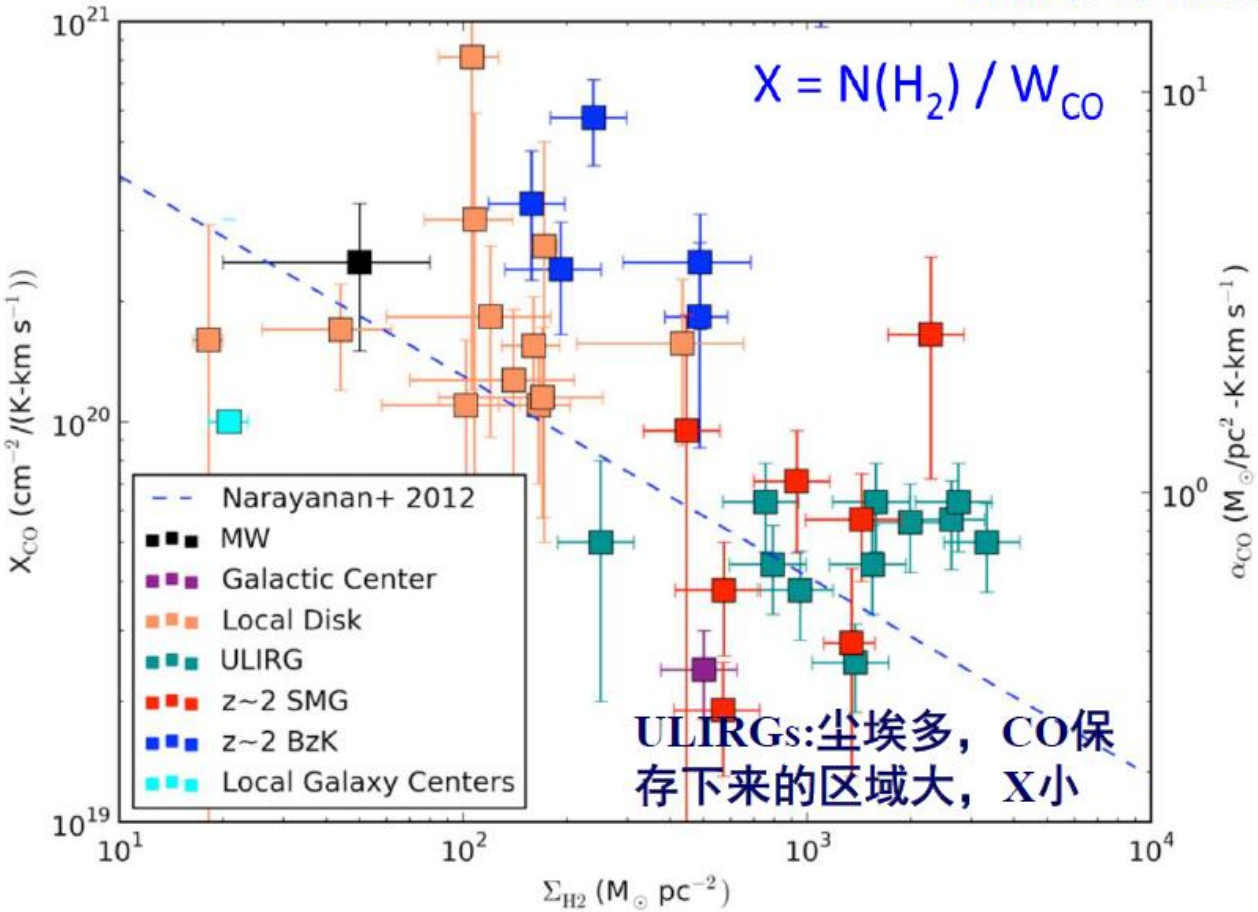
$X = N(H_2) / W_{CO}$



$$\left(\frac{M_{H_2}}{M_\odot}\right) = 1.18\times10^4 \times \left(\frac{D}{\mathrm{Mpc}}\right)^2 \left(\frac{S_{CO(1-0)}}{\mathrm{Jy\ km\ s^{-1}}}\right) \times \left[\frac{X}{3.0\times10^{20}\ \mathrm{cm^{-2}\ (K\ km\ s^{-1})^{-1}}}\right]$$

The X factor

Effect of metallicity on CO and H_2



金属丰度降低

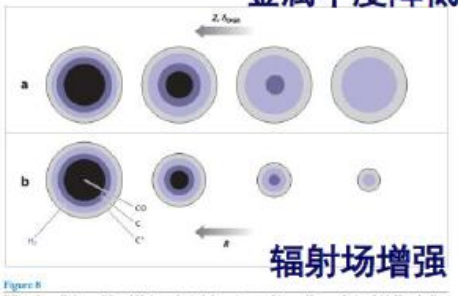


Figure 8
Effect of metallicity on CO and H_2 in a spherical clump immersed in a uniform radiation field. Blue shading indicates the region where the gas is molecular, according to Equation 25. Increasingly darker shading shows the regions where carbon is found as C^+, C, or CO. Panel *a* illustrates the effect of decreasing metallicity and dust-to-gas ratio on the distribution of C^+, CO, and H_2. Mostly because of the increase in N_{H} required to attain a given A_V, the CO-emitting region is pushed further into the clump and, for a fixed cloud size, it disappears at low enough metallicities. Panel *b* illustrates the effect of changing the clump size or column density at a fixed metallicity (adapted from Bolatto, Jackson & Ingalls 1999, Wolfire, Hollenbach & McKee 2010).

Destroying CO

Reaction
Cosmic Ray Reactions [s^{-1} molecule^{-1}]:
$cr + H \rightarrow H^+ + e$
$cr + H_2 \rightarrow H_3^+ + e + H + cr$
$cr + He \rightarrow He^+ + e + cr$
Photoreactions [s^{-1} molecule^{-1}]:
$\gamma + H_2 \rightarrow 2\,H$
$\gamma + CO \rightarrow C + O$
$\gamma + C \rightarrow C^+ + e$
$\gamma + CH_x \rightarrow C + H$
$\gamma + OH_x \rightarrow O + H$
$\gamma + M \rightarrow M^+ + e$
$\gamma + HCO^+ \rightarrow CO + H$

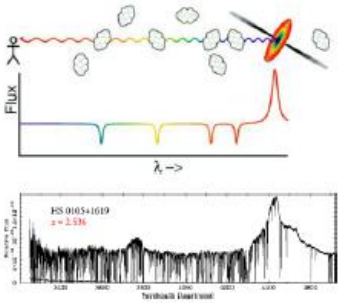
- Be careful when applying in other parts of the Galaxy or to other galaxies…

原子氢 (HI)

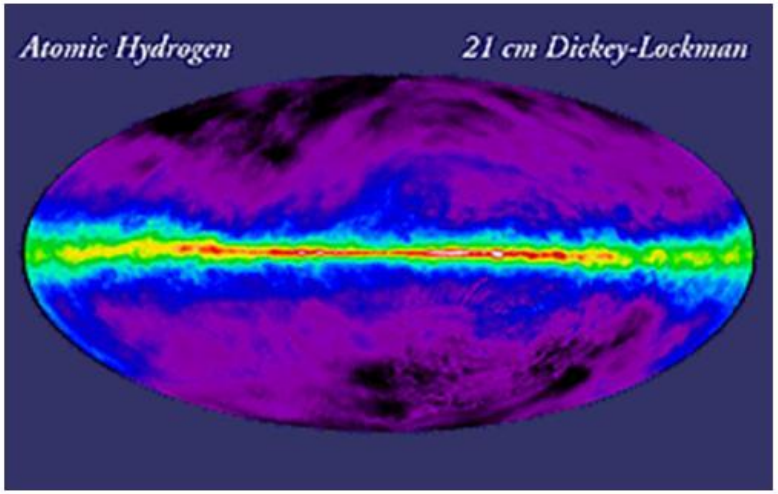
Table 2.4 A 'zeroth-order' summary of the Milky Way's interstellar medium (after J. Lequeux)

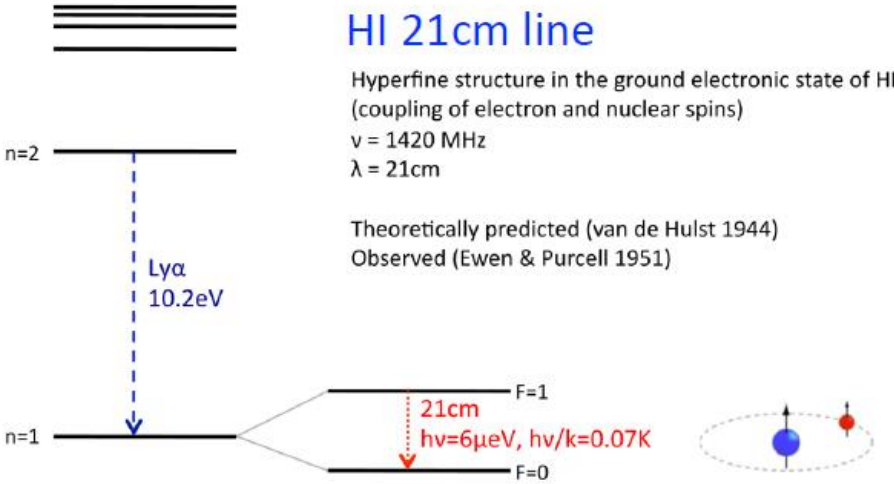
Component	*Description*	*Density* (cm^{-3})	*Temperature* (K)	*Pressure* (p/k_B)	*Vertical extent*	*Mass* ($\mathcal{M}_\odot$)	*Filling factor*
Cold clumpy gas	Molecular: H_2	> 200	< 100	Big	80 pc	$(2) \times 10^9$	<0.1%
	Atomic: HI	25	50–100	2 500	100 pc	3×10^9	2%–3%
Warm diffuse gas	Atomic: HI	0.3	8 000	2 500	250 pc	2×10^9	35%
	Ionized: HII	0.15	8 000	2 500	1 kpc	10^9	20%
HII regions	Ionized: HII	$1–10^4$	~10 000	Big	80 pc	5×10^7	Tiny
Hot diffuse gas	Ionized: HII	~0.002	$\sim 10^6$	2 500	~5 kpc	(10^8)	45%

Lyman Alpha Forest



HI密度和温度范围宽：低温$n_H \sim 25cm^{-3}$，$T \leq 80K$；高温$T \sim 8000K$，$n_H \sim 0.3cm^{-3}$





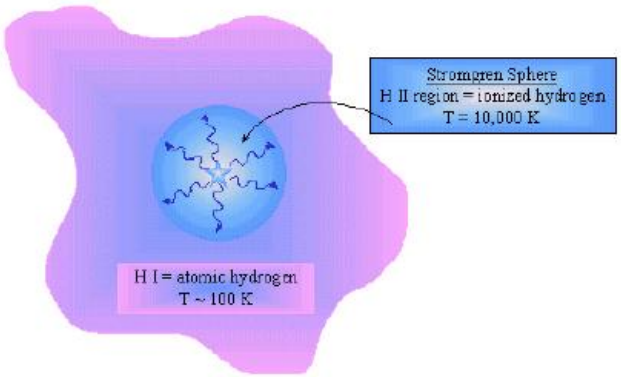
HI 21cm line

Hyperfine structure in the ground electronic state of HI (coupling of electron and nuclear spins)
ν = 1420 MHz
λ = 21cm

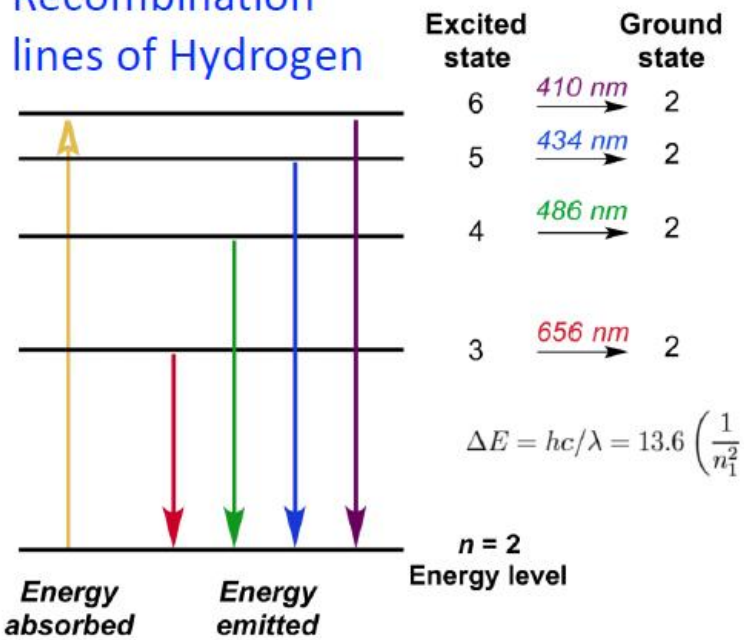
Theoretically predicted (van de Hulst 1944)
Observed (Ewen & Purcell 1951)

电离氢（HII）

- O、B等年轻恒星产生大量紫外光子（E > 13.6eV），将周围的氢分子（H_2）裂解为原子氢。
- 紫外光子又将原子气体光致电离，产生一个光致离解区，即HII区。



Recombination lines of Hydrogen



$$\Delta E = hc/\lambda = 13.6\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)\text{eV}$$

斯特龙根球：是年轻的O、B型星周围存在的电离氢区。

$$R_S = \left(\frac{3N_{\rm Lyc}}{4\pi\alpha_2 n_e^2}\right)^{1/3}$$

$$\simeq 70\left(\frac{N_{\rm Lyc}}{10^{49}{\rm s}^{-1}}\right)^{1/3}\left(\frac{T_e}{10^4{\rm K}}\right)^{0.28}\left(\frac{n_e}{1{\rm cm}^{-3}}\right)^{-2/3}\ {\rm pc}.$$

$$M_{\rm HII} = \frac{4}{3}\pi R_S^3 n_p m_p$$

$$= N_{\rm Lyc}/\alpha_2 n_e$$

$$= 3.2\times10^4\left(\frac{N_{\rm Lyc}}{10^{49}{\rm s}^{-1}}\right)\left(\frac{T_e}{10^4{\rm K}}\right)^{0.85}\left(\frac{n_e}{1{\rm cm}^{-3}}\right)^{-1} M_\odot$$

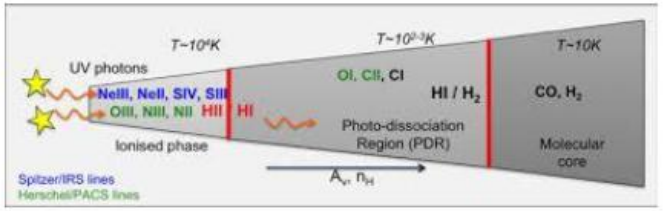
OB stars have an enormous impact on the ISM

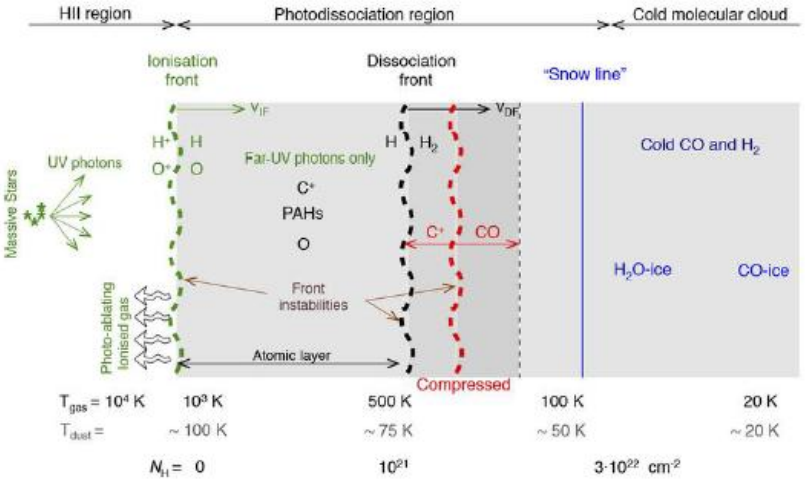
Photodissociation regions (PDR)

- Evolution of an H II region
  - An H II region is formed around a very hot star.
  - Original H I, T ~ 100 K; now H II, T ↑ ↑ (T ~ 10^4 K)
  - Ionization produces free electrons, so n ↑, hence pressure ↑ ↑
  - H II region expands, v ~ sound speed of the hot gas ~ 10 km/s
  - Sound speed in H I ~ 1 km/s, the H II expansion is highly supersonic → a shock front
  - H II continues to expand (n ↓) until pressure equilibrium with the H I region: all H II regions are expanding!

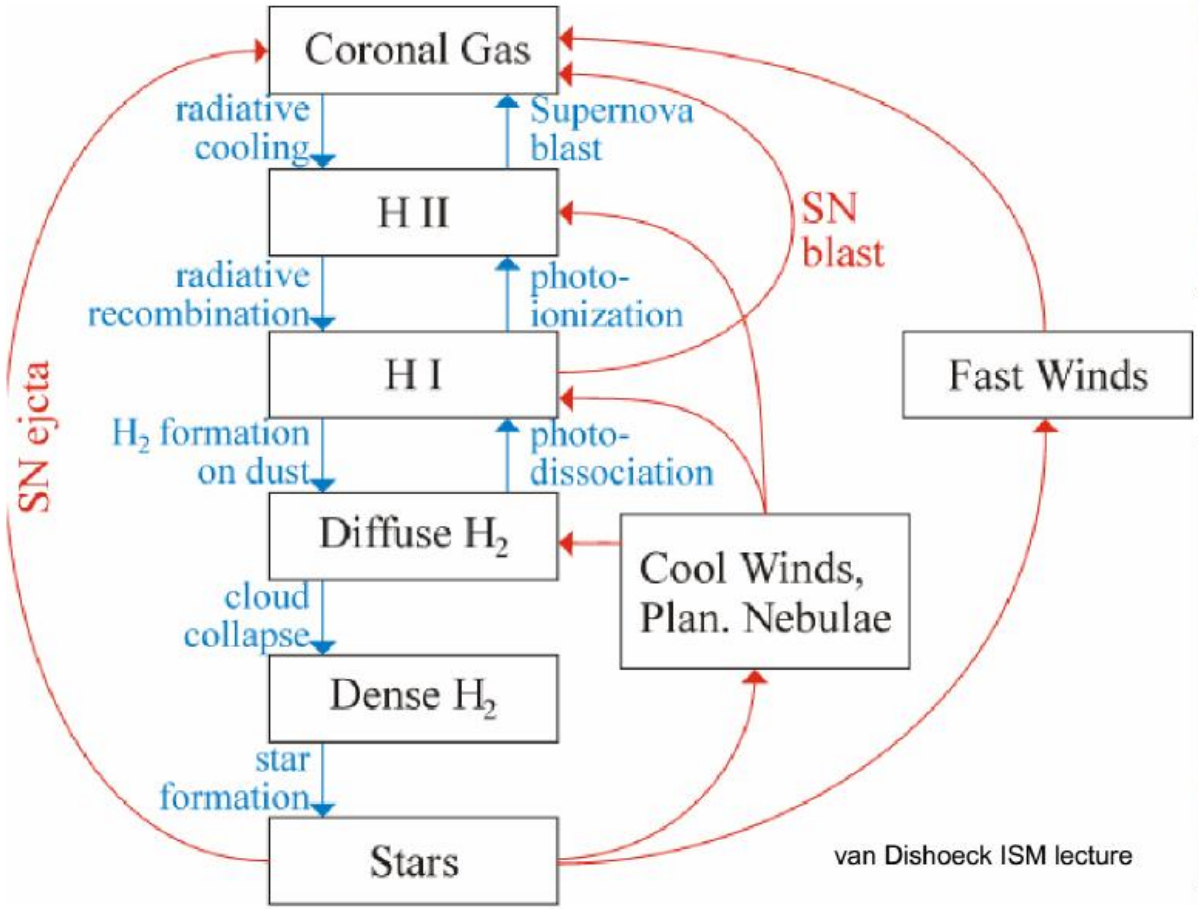
Most of the ISM (by mass) is a PDR!

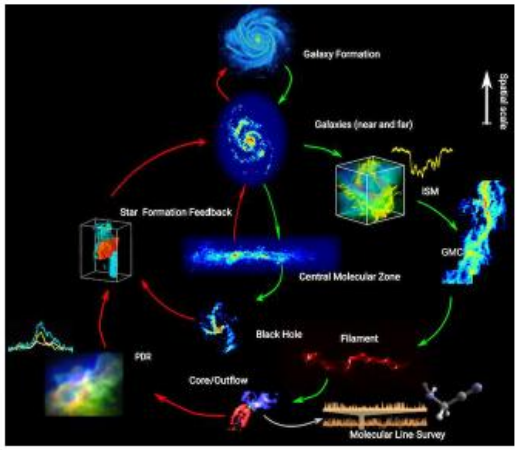
- PDR are predominantly neutral regions of the interstellar medium
- The physical and chemical structure of a PDR depends on the FUV flux density and density of the gas.





The ISM in Spirals is DYNAMIC



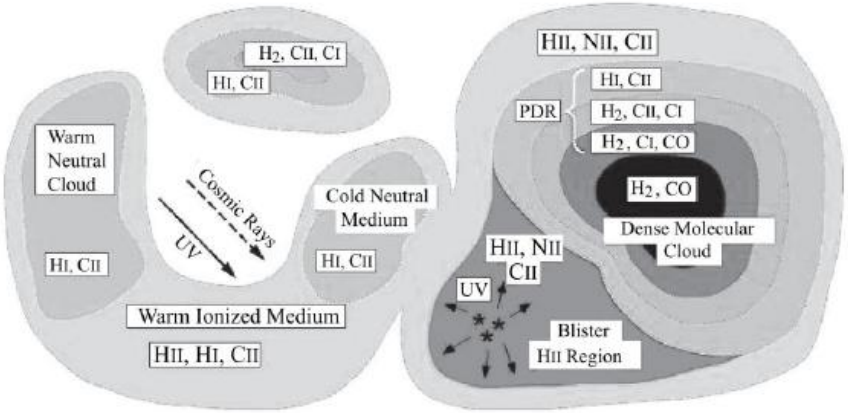


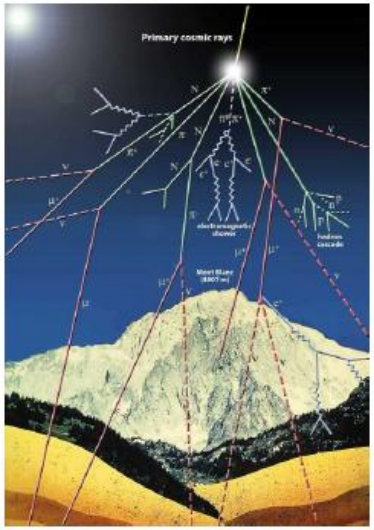
There is strong interaction between the different phases of the ISM and feedback between star formation and the rest of the ISM.

Heating and Cooling of ISM

Heating:

- Heating by low-energy cosmic-rays
  - Dense molecular clouds
- Photoelectric heating by grains
  - Dense molecular clouds, supernova remnants
- Photoelectric heating by the photo-ionization of atoms and molecules
  - HII regions
- photoelectric heating by soft X-rays
  - Warm diffuse interstellar medium, cold interstellar medium
- Chemical heating
  - Dense molecular clouds
- Heating by grain-gas thermal exchange
  - Dense molecular cloud
- Hydrodynamic and magneto-hydrodynamic heating
  - Large- and small-scale shocks, supernova remnants
- Interstellar shocks
  - Large- and small scales, supernova remnants





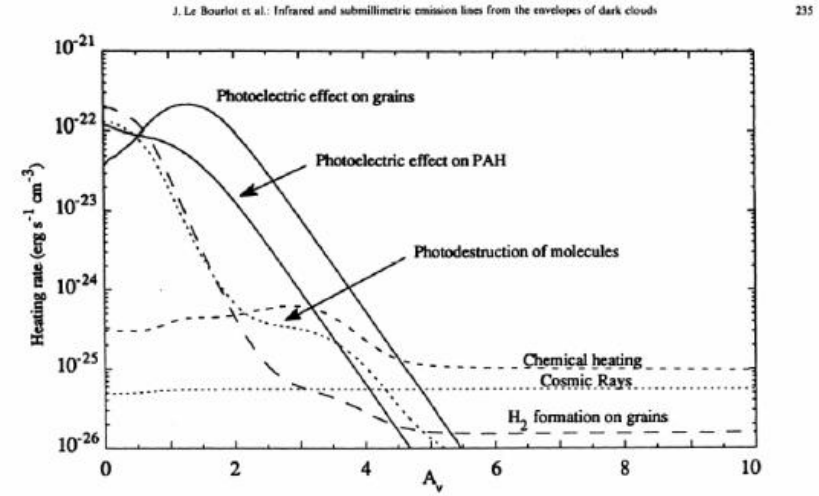


Fig. 1a. Contributions to the rate of heating of the gas for an isochoric model in which $n_H = 10^3$ cm^{-3} and $\chi = 1000$. The fractional elemental abundances of C and O are C/H = 3.62 10^{-5} and O/H = 8.53 10^{-5} (see text, Sect. 2.3)

Heating and Cooling of ISM

- **Cooling:**
  - $T \geq 10^7$K：气体完全电离，冷却主要通过自由电子的韧致辐射
  - 10^4K<T<10^6K：包括不同的激发和退激发过程
    - 电子与离子复合，辐射光子
    - 原子（or离子）与其他粒子碰撞激发，后退激发到基态
    - 不同的原子有不同的激发能，冷却效率与气体化学组成相关
  - T<10^4K：中性H和分子氢，碰撞激发（弱）、分子转动、振动谱

- **Requirements for cooling**
  - High frequency of collisions (depends on the chemical composition of the gas)
  - The amount of exchanged energy is less than the thermal (kinetic) energy of the gas
  - The excitation energy is transported via photons
  - The photons are emitted by the excited atom/ion before the next particle collision happens
  - The photons leave the gas distribution without any photoelectric absorption event along the path

Table 2.5 Main processes that cool the interstellar gas

Temperature	*Cooling process*	*Spectral region*
$>10^7$ K	Free–free	X-ray
10^7 K $< T <$ 10^8 K	Iron resonance lines	X-ray
10^5 K $< T <$ 10^7 K	Metal resonance lines	UV, soft X-ray
8000 K $< T <$ 10^5 K	C, N, O, Ne forbidden lines	IR, optical
Warm neutral gas: ~8000 K	Lyman-α, [OI]	1216 Å, 6300 Å
100 K $< T <$ 1000 K	[OI], [CII], H_2	Far IR: 63 μm, 158 μm
$T \sim 10-50$ K	CO rotational transitions	Millimeter-wave

气体冷却：星系形成极为重要过程，冷却效率与温度和密度有关

气体的复合和冷却

- 星际气体需要连续的能量供应：否则将迅速冷却，云的随机运动逐渐减小，并最终耗散掉
- 复合时间：

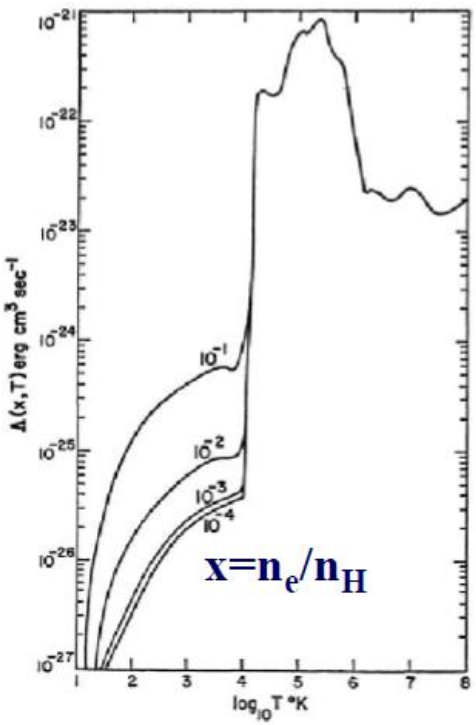
$$p^+ + e^- \leftrightarrow \mathrm{H}(1s) + \text{photons}.$$

$$t_{\rm rec} = \frac{n_{\rm e}}{|{\rm d}n_{\rm e}/{\rm d}t|} = \frac{1}{n_{\rm e}\alpha(T_{\rm e})} \approx 1500\,{\rm yr} \times \left(\frac{T_{\rm e}}{10^4\,{\rm K}}\right)^{3/4} \left(\frac{100\,{\rm cm}^{-3}}{n_{\rm e}}\right)$$

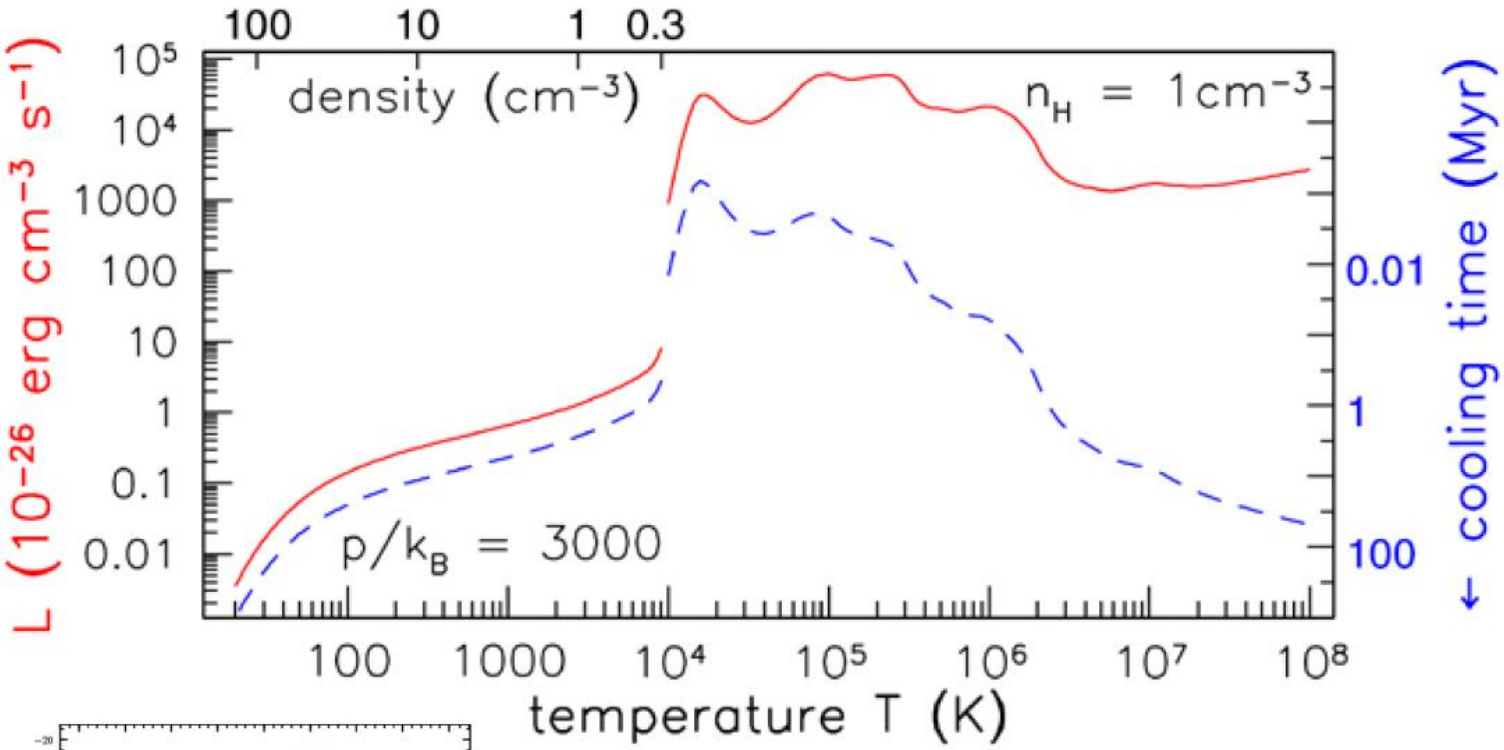
当气体较热时，电子和质子碰撞比较频繁但粘合在一起的可能性较小，所以t_{rec}较长

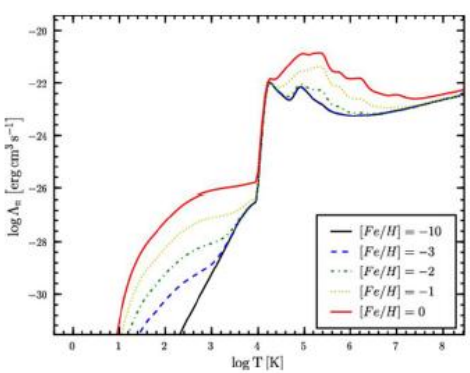
在HII区内，t_{rec}只有几千年。当恒星不再提供紫外光子，电离气体便迅速复合。温度越高，密度越小，复合时间越长。

- 冷却时间t_{cool}：表征气体辐射掉它的热能效率
- 原子数密度为n/cm^3，单位体积的能量正比于nT；辐射光度为L，则有$t_{cool} \sim nT/L$
- 光学薄气体的辐射能量的冷却速率（Λ）和光度有 $L = n^2\Lambda(T)$，则有$t_{cool} \sim T/[n\,\Lambda(T)]$
- Λ(T) 依赖于温度和金属丰度，致密气体（密度n大时），冷却的更快



气体的复合和冷却





$L = n^2\Lambda(T)$,

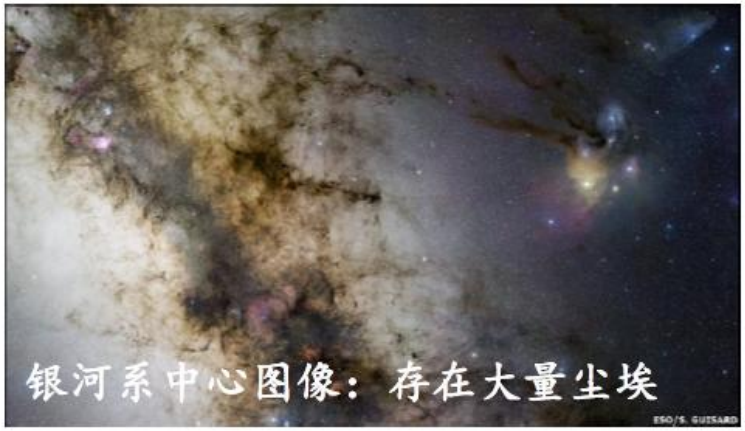
$t_{cool} \sim T/[n\,\Lambda(T)]$

元素丰度和太阳成分一样的气体：每立方厘米的光度L（实线）和冷却时间t_{cool}（虚线）与温度的关系

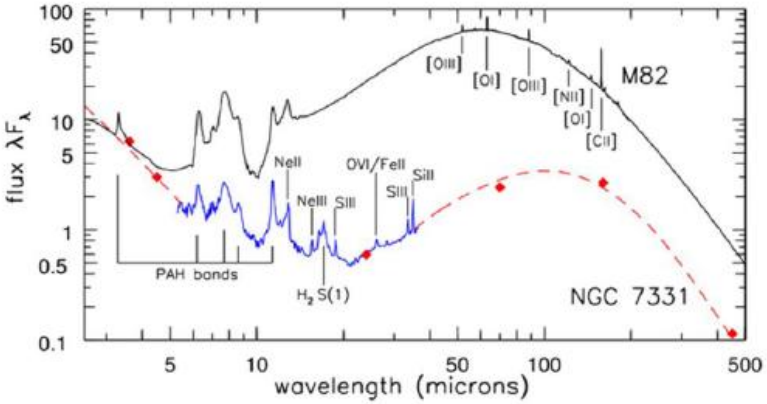
T> 10000K，令$n_H = 1\ cm^{-3}$；
T< 10000K，热压强p/kB＝3000

银河系尘埃

- $M_{dust}/M_{gas} \approx 1\%$
- L_{dust}/L_{bol} (MW) ≈ 30%



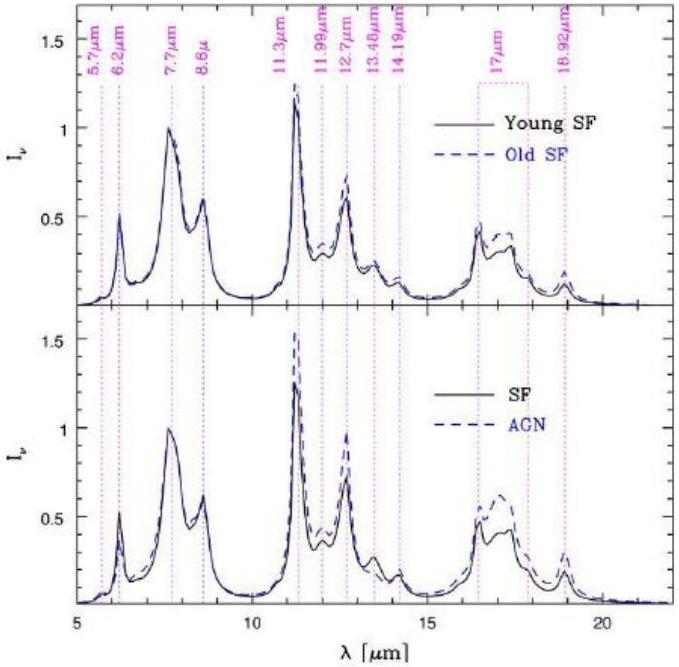
- 尘埃粒子小：尘埃能最有效地吸收波长小于尘埃颗粒尺度的光，对紫外吸收有效→大多数尘粒尺度 $r \leq 0.3\mu m$
- 尘埃再辐射：尘埃吸收了银河系紫外和光学波段的星光，又将吸收的能量在红外波段进行辐射
- 尘粒有不同尺寸：
  - 大尘粒（温度T～30K）产生峰值在100 μm的辐射。
  - T ≥ 100K的较热的颗粒辐射峰值在30 μm附近
  - 小尘埃粒子（PAHs）辐射短于30 μm

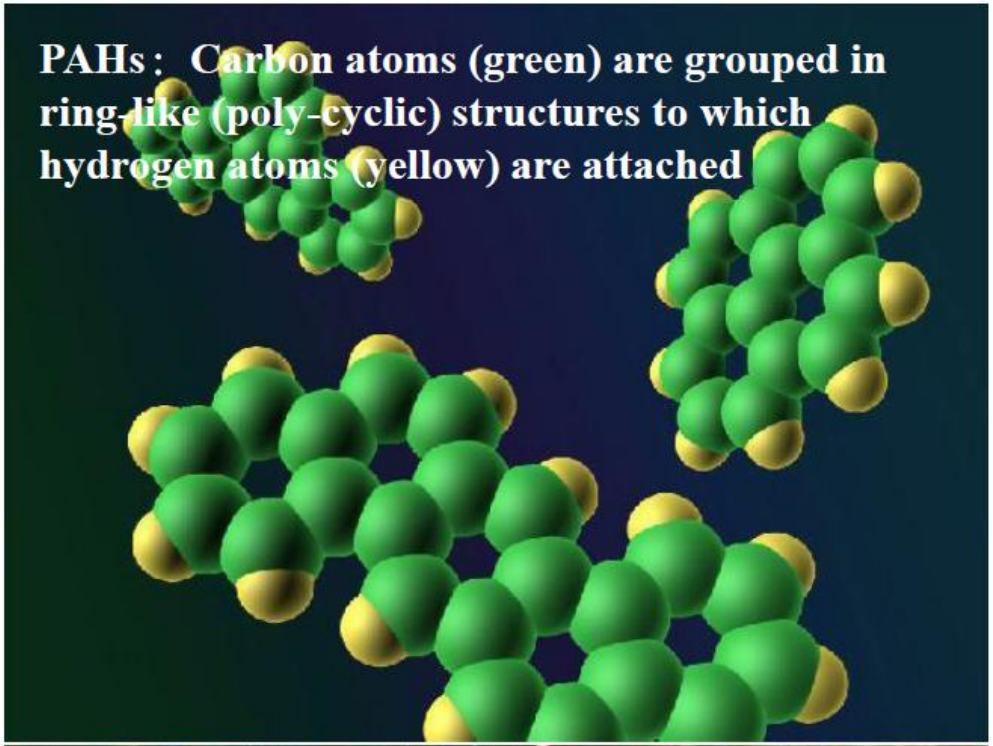


Sb旋涡星系NGC 7331和星暴星系M82（富尘埃）的红外光谱

Polycyclic Aromatic Hydrocarbons (PAHs)

- 星际尘埃质量的10%—20%可能在最小的粒子中，如多环芳香烃（PAHs）
- 多环芳香烃：只有 100 个或更少碳原子排列成环状扁片；性质更像一个大的分子





Definition of extinction A(λ)

Because of interstellar dust, the spectrum we observe from a galaxy is not the original stellar spectrum. Such extinction must be taken into account when interpreting an observed spectrum in terms of stellar populations. In general, the strength of dust extinction along a given line-of-sight can be described by the optical depth τ_λ:

$$I_\lambda = I_{\lambda 0} e^{-\tau_\lambda}, \tag{10.99}$$

where $I_{\lambda 0}$ is the intensity at the wavelength λ that would be observed in the absence of extinction, and I_λ is the observed intensity. Conventionally, dust extinction is expressed in terms of an empirical extinction law,

$$k(\lambda) \equiv \frac{A_\lambda}{E(B-V)} \equiv R_V \frac{A_\lambda}{A_V}, \tag{10.100}$$

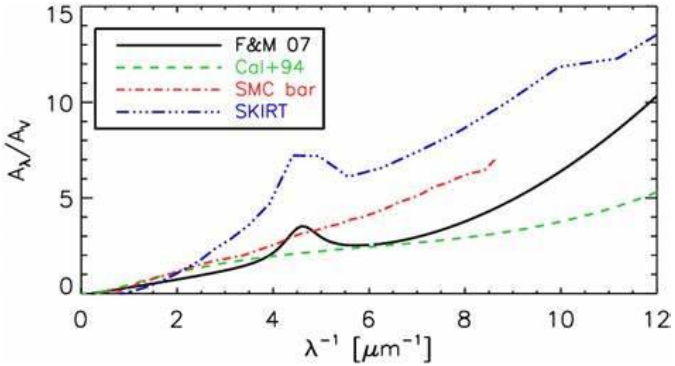
where $A_\lambda = (2.5 \log e)\tau_\lambda$ is the change in magnitude at wavelength λ due to extinction, $E(B-V) \equiv A_B - A_V$ is the color excess measured between the B and V bands, and $R_V \equiv A_V / E(B-V)$.

Extinction: $m(\lambda) = M(\lambda) + 5\log_{10}\left(\frac{d}{10\,\mathrm{pc}}\right) + A(\lambda)$

Intrinsic SED

Color excess $E(B\text{-}V) = (B\text{-}V)_{obs} - (B\text{-}V)_{int} = A_B\text{-}A_V$

Observed SED

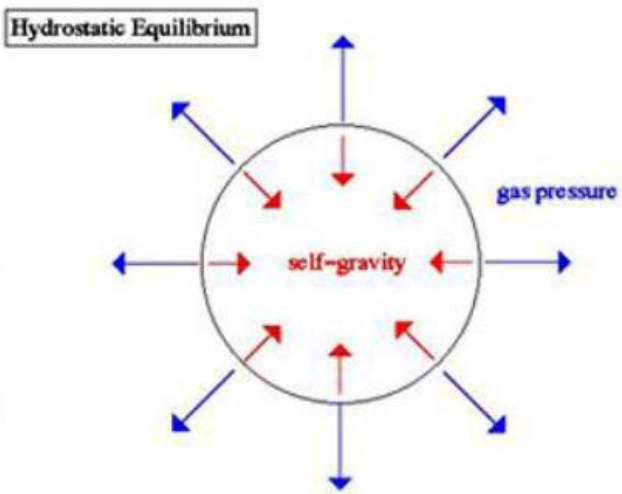


Hydrostatic Equilibrium (HE)

- Pressure vs. Gravity :
  - if gravity < pressure → 膨胀
  - if gravity > pressure → 收缩
- In order to get the highest gravity, we need lots of mass (density)
- In order to get the lowest gas pressure, we need the lowest T.
- Stars are born in very cold clouds (T ~ 10 - 100 K): cold dense regions
- JEANS' MASS (M_J):

$$\mathcal{M}_J \equiv \frac{\pi}{6}\lambda_J^3\rho = \left(\frac{1}{\mu m_H}\right)^2\left(\frac{k_B T}{G}\right)^{3/2}\left(\frac{4\pi n}{3}\right)^{-1/2}\frac{\pi^3}{3\sqrt{3}}$$
$$\approx 20\left(\frac{T}{10\,\mathrm{K}}\right)^{3/2}\left(\frac{100\,\mathrm{cm}^{-3}}{n}\right)^{1/2}\mathcal{M}_\odot.$$

金斯质量：当分子云的质量大于金斯质量时，分子云会发生引力塌缩。



GRAVITY (inward) = PRESSURE (outward)

For typical GMC: $M_J = 10^5\ M_\odot$

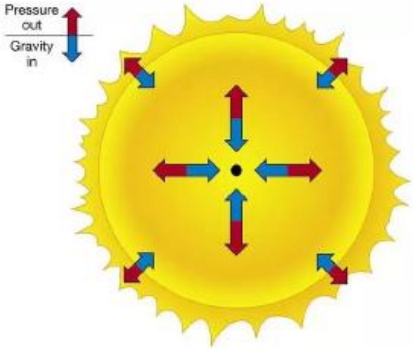
BUT: Typical stellar masses are only 1–10 $M_\odot$

As cloud collapses, ρ↑and the smaller the minimum mass, M_J, becomes.

自由—自由时间：$t_{ff} = \sqrt{\frac{1}{G\rho}} \approx \frac{10^8}{\sqrt{n_H}}\,\mathrm{yr}.$

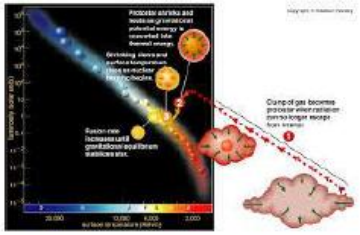
Jeans' Instability

- 分子云内部，存在引力和因分子热运动产生的热压力
  - Gravity pulls matter in; Pressure pushes it back out.
  - When pressure wins → oscillations (sound waves).
  - Cooling lowers pressure, when gravity wins → collapse.



- 当热压力足够高时，微小的密度涨落能够被热压力所克服，不能塌缩

- 当分子云的热压力不足以抵抗引力时，分子云会在引力的作用下发生塌缩：称为金斯不稳定性
  - Applies to both Star Formation and Galaxy Formation.



- 简单理论推导：均匀、球对称分子云（密度ρ、温度T，N个质量为m分子）

$$K = \frac{3}{2}Nk_{\mathrm{B}}T = \frac{3}{2}Mc_{\mathrm{s}}^2 \qquad c_{\mathrm{s}}^2 = (\partial P/\partial\rho)_{\mathrm{S}} = k_{\mathrm{B}}T/(\mu m_{\mathrm{H}})$$

$$W = -\frac{3}{5}\frac{GM^2}{a} \qquad \rho = 3M/4\pi a^3$$

金斯长度：分子云塌缩的临界尺度。如果扰动区域的长度大于金斯长度时，会发生引力塌缩。

- The collapse condition for MC based on virial theorem :

$$\lambda_{\mathrm{J}} = c_{\mathrm{s}}\sqrt{\frac{\pi}{G\rho}};$$

$$2K + W < 0$$

$$\mathcal{M}_{\mathrm{J}} \equiv \frac{\pi}{6}\lambda_{\mathrm{J}}^3\rho = \left(\frac{1}{\mu m_{\mathrm{H}}}\right)^2\left(\frac{k_{\mathrm{B}}T}{G}\right)^{3/2}\left(\frac{4\pi n}{3}\right)^{-1/2}\frac{\pi^3}{3\sqrt{3}}$$

金斯质量

Jeans Mass and Length

$$\lambda_J \equiv c_s\sqrt{\frac{\pi}{G\rho}} = \sqrt{\frac{\pi k_B T}{G\rho\mu m_H}} \qquad M_J \equiv \frac{\pi}{6}\lambda_J^3\rho \approx 30\left(\frac{T}{10K}\right)^{3/2}\left(\frac{100\mathrm{cm}^{-3}}{n}\right)^{1/2} M_\odot$$

- Today: T = 2.73K; $\rho = 10^{-28}$ kg/m^3
- 宇宙膨胀：$\rho \sim R^{-3} \sim T^3$ → T=3000K时；$\rho = 1.4 * 10^{-19}$ kg m^{-3} $\sim 2\ M_\odot$ pc^{-3}
- T=3000K: λ_J = 50 pc; $M_J = 3*10^5\ M_\odot$, More than a star, less than a galaxy, close to a globular cluster mass （形成的早，年老）.
- At decoupling (T=3000K):
  - Collapse timescale: $t_G = t_{ff}$ = sqrt(1/Gρ) = 10^7yr
  - Expect first "galaxies" ($M > 3*10^5\ M_\odot$) to form ~10^7 yr after decoupling.
- Over-dense regions collapse after decoupling (T = 3000 K)
  - IF large enough i.e. $\lambda > \lambda_J$; $M > M_J$
  - Large mass → Giant Elliptical; Smaller mass → Dwarf Galaxy
  - Smallest that collapse: globular clusters; Tiny regions stable: can't form stars.

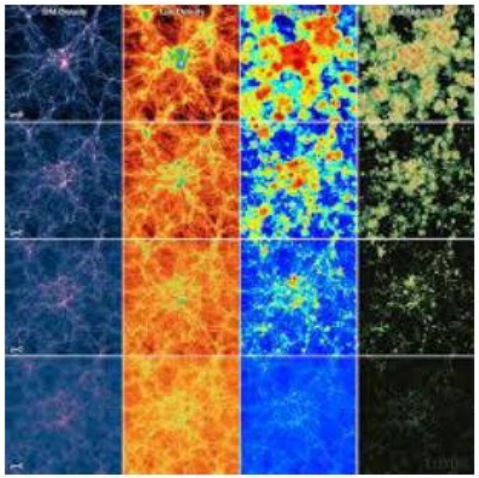
Star Formation Law

- **What is a SF law?**

A relation connecting Σ_{SFR} to Σ_{gas}: $\boxed{\Sigma_{SFR} = A \bullet \Sigma_{gas}^{N}}$

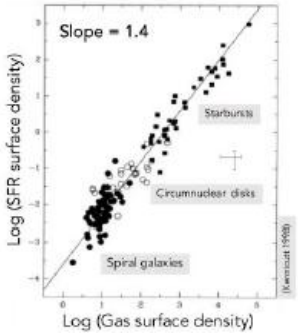
(going back to Schmidt 1959)

- **Why SF law?**
  - **Derive physical insight into what drives SF (e.g. by comparing empirical relations to predictions from theory)**
  - **SPH modeling of galaxy formation**
  - **Predictive power: measure the gas (surface) density and estimate the SFR (surface) density**

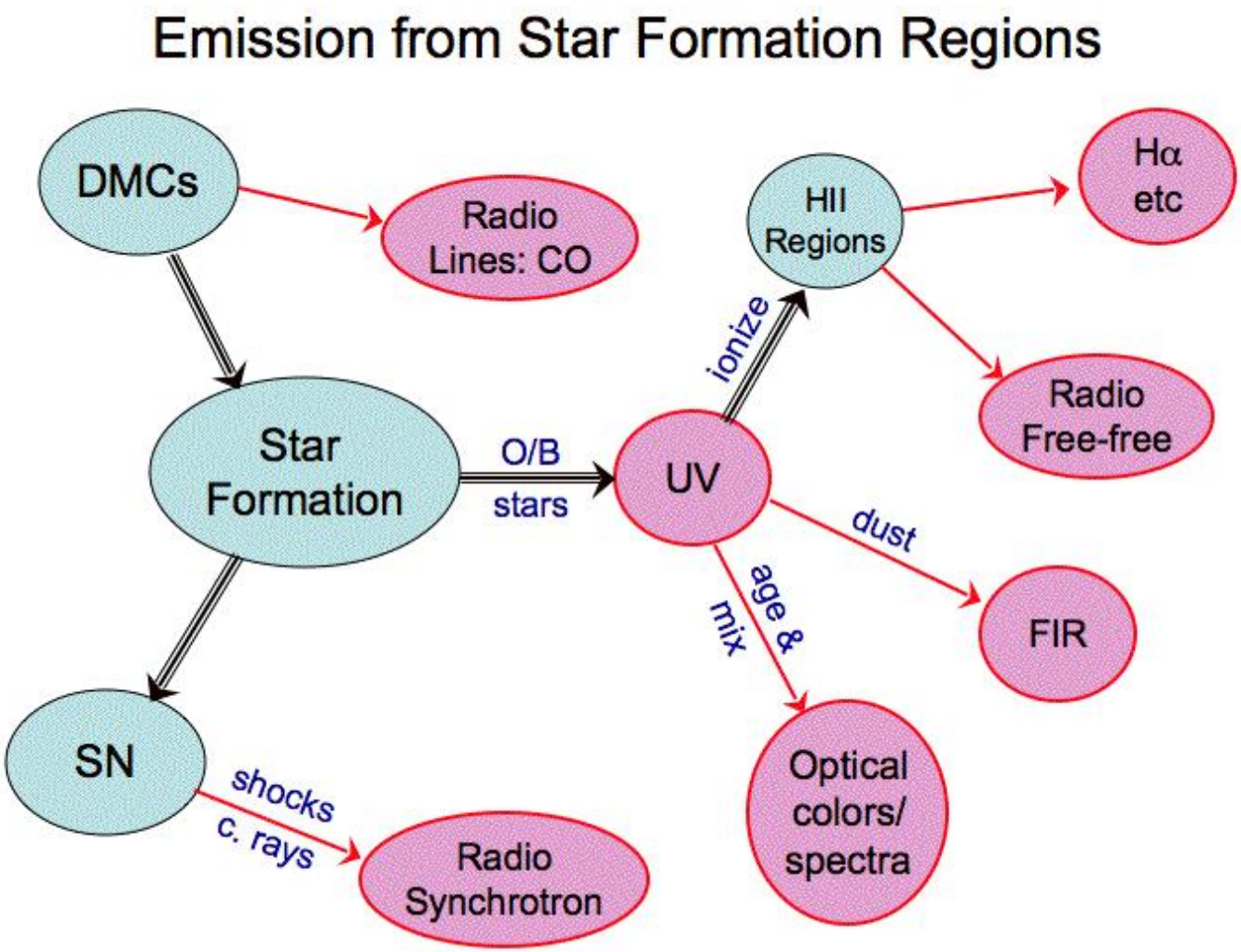


Previous studies include e.g.

- Schmidt (1959): N≈2 (Milky Way)
- Kennicutt (1989,1998): N≈1.4 (sample of ~90 nearby galaxies)
- Wong & Blitz (2002): N=1.2-2.1 (6 nearby spiral galaxies)
- Boissier et al. (2003), Heyer et al. (2004): N≈2 (16 galaxies) and N≈3.3 (M33)



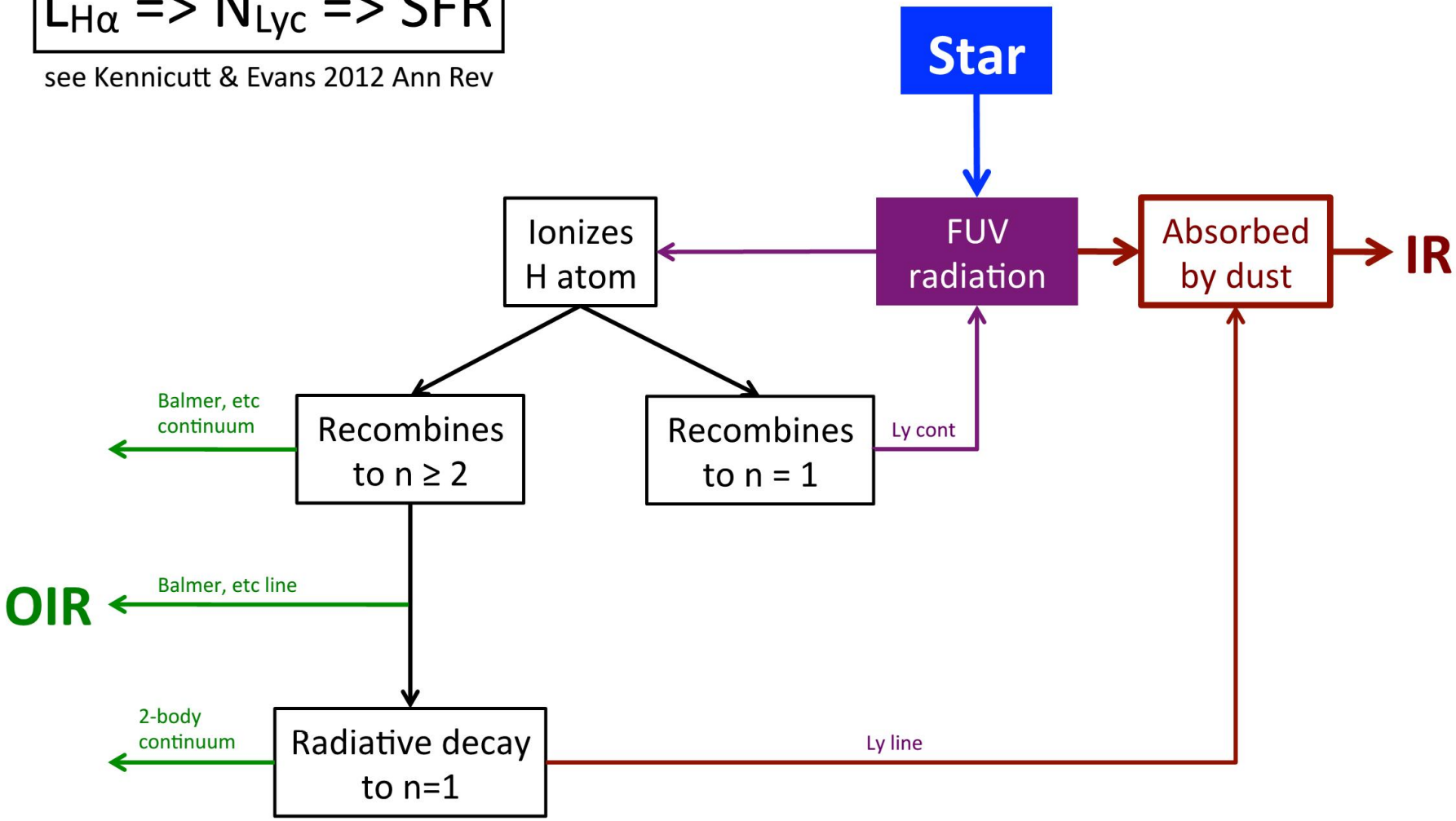
Relevant Observables



SFR indicators

$L_{H\alpha}$ => N_{Lyc} => SFR

see Kennicutt & Evans 2012 Ann Rev



Calibrating SFRs

- **SFR indicators**
  - **SFR indicators are defined from the X–ray to the radio**
  - **All probe the MASSIVE stars formation rate**
  - **IMF and population synthesis model assumed**
  - **Other wavelength calibrated against "unbiased" indicators**
    - **Pα (λ=1.876μm) corrected for extinction using Hα/Pα ratio**

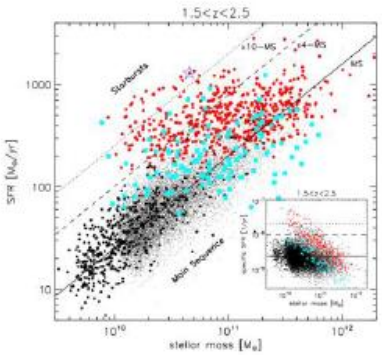


Table 1.1. **Model-based luminosity-to-SFR calibrations**

Luminosity[a]	C^b	Assumptions[c] Assumptions for mass range of the stellar IMF
L(UV)	$3.0\times10^{-47}\lambda$	0.1–100 $M_\odot$, $\tau \geq 100$ Myr
L(UV)	$4.2\times10^{-47}\lambda$	0.1–30 $M_\odot$, $\tau \geq 100$ Myr
L(UV)	$4.3\times10^{-47}\lambda$	0.1–100 $M_\odot$, $\tau=10$ Myr
L(UV)	$1.0\times10^{-46}\lambda$	0.1–100 $M_\odot$, $\tau=2$ Myr
L(TIR)	1.6×10^{-44}	0.1–100 $M_\odot$, $\tau=10$ Gyr
L(TIR)	2.8×10^{-44}	0.1–100 $M_\odot$, $\tau=100$ Myr
L(TIR)	4.1×10^{-44}	0.1–30 $M_\odot$, $\tau=100$ Myr
L(TIR)	3.7×10^{-44}	0.1–100 $M_\odot$, $\tau=10$ Myr
L(TIR)	8.3×10^{-44}	0.1–100 $M_\odot$, $\tau=2$ Myr
L(Hα)	5.5×10^{-42}	0.1–100 $M_\odot$, $\tau \geq 6$ Myr, $T_e=10^4$ k, $n_e=100\,\mathrm{cm}^{-3}$
L(Hα)	3.1×10^{-41}	0.1–30 $M_\odot$, $\tau \geq 10$ Myr, $T_e=10^4$ k, $n_e=100\,\mathrm{cm}^{-3}$
L(Brγ)	5.7×10^{-40}	0.1–100 $M_\odot$, $\tau \geq 6$ Myr, $T_e=10^4$ k, $n_e=100\,\mathrm{cm}^{-3}$

$\mathrm{SFR(H\alpha)} = 5.5 \cdot 10^{-42} L(\mathrm{H\alpha})$

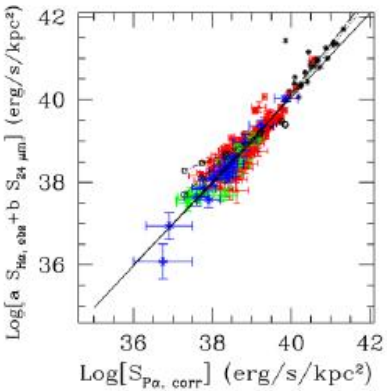
[a] Luminosity in erg s^{-1}. Stellar and dust continuum luminosities are given as $\nu L(\nu)$; total IR=TIR is assumed to be equal to the stellar population bolometric luminosity.

[b] The constant C appears in the calibration as: $\mathrm{SFR}(\lambda)= CL(\lambda)$, where SFR is in units of $M_\odot\,\mathrm{yr}^{-1}$. The constant is derived from stellar population models, with constant star formation and solar metallicity (Starburst99, Leitherer *et al.* 1999). For SFR(UV), the numerical value is multiplied by the wavelength λ in Å. the timescale τ over which star formation

Table 1.2. **Mixed processes-based SFR calibrations**[a]

λ_1^b	λ_2^b	$C_{\lambda_1}^c$	$a^d_{\lambda_2,\mathrm{Type}}$	Type[d]
FUV (0.153 μm)	24 μm	4.6×10^{-44}	6.0	local
FUV (0.153 μm)	25 μm	4.6×10^{-44}	3.89	global
FUV (0.153 μm)	TIR	4.6×10^{-44}	0.46	global
Hα	24 μm	5.5×10^{-42}	0.031	local
Hα	25 μm	5.5×10^{-42}	0.020	global
Hα	TIR	5.5×10^{-42}	0.0024	global

The calibrations are expressed as: $\mathrm{SFR}(\lambda_1,\lambda_2) = C(\lambda_1)[L(\lambda_1)_{\mathrm{obs}} + a_{\lambda_2,\mathrm{Type}} L(\lambda_2)_{\mathrm{obs}}]$

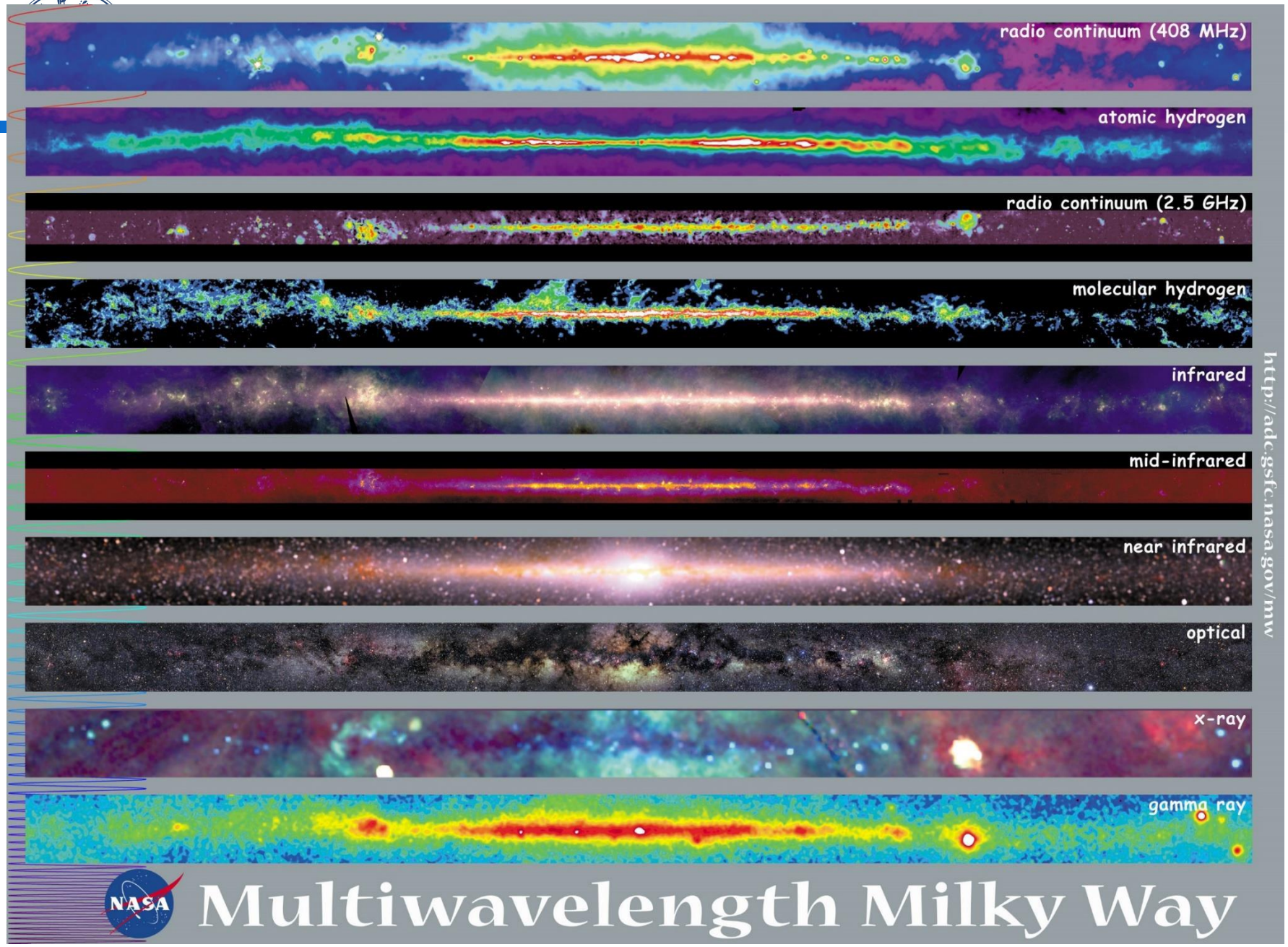


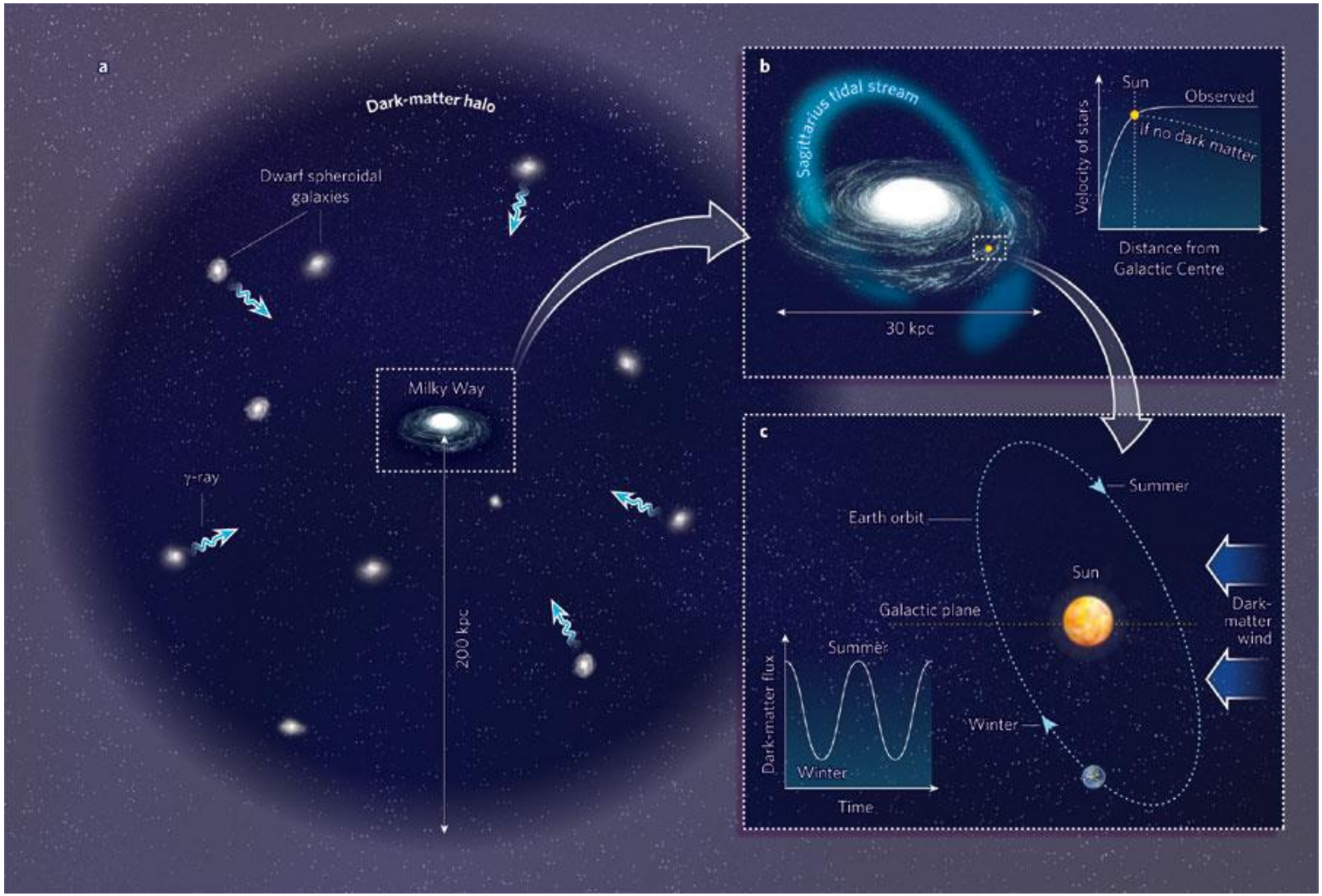
银河系星际介质总结

Table 2.4 A 'zeroth-order' summary of the Milky Way's interstellar medium (after J. Lequeux)

Component	*Description*	*Density* (cm^{-3})	*Temperature* (K)	*Pressure* (p/k_B)	*Vertical extent*	*Mass* ($\mathcal{M}_\odot$)	*Filling factor*
Dust grains						10^7–10^8	Tiny
large $\lesssim 1\ \mu m$	Silicates, soot		~20		150 pc		
small ~ 100 Å	Graphitic C		30–100				
PAH < 100 atoms	Big molecules				80 pc		
Cold clumpy gas	Molecular: H_2	> 200	< 100	Big	80 pc	$(2) \times 10^9$	<0.1%
	Atomic: HI	25	50–100	2 500	100 pc	3×10^9	2%–3%
Warm diffuse gas	Atomic: HI	0.3	8 000	2 500	250 pc	2×10^9	35%
	Ionized: HII	0.15	8 000	2 500	1 kpc	10^9	20%
HII regions	Ionized: HII	1–10^4	~10 000	Big	80 pc	5×10^7	Tiny
Hot diffuse gas	Ionized: HII	~0.002	~10^6	2 500	~5 kpc	(10^8)	45%
Gas motions	$\frac{3}{2}\langle\rho_{HI}\rangle\sigma_r^2$	$\langle n_H\rangle \sim 0.5$	$10\ km\ s^{-1}$	8 000			
Cosmic rays	Relativistic	$1\ eV\ cm^{-3}$		8 000	~3 kpc	Tiny	
Magnetic field	$B \sim 5\ \mu G$	$1\ eV\ cm^{-3}$		8 000	~3 kpc		
Starlight	$\langle \nu h_P\rangle \sim 1\ eV$	$1\ eV\ cm^{-3}$			~500 pc		
UV starlight	11–13.6 eV	$0.01\ eV\ cm^{-3}$					

Note: ( ) denotes a very uncertain value. Pressures and filling factors refer to the disk midplane near the Sun; notice that the pressures from cosmic rays, in magnetic fields, and the turbulent motions of gas clouds are roughly equal.


radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
http://adc.gsfc.nasa.gov/mw
NASA
Multiwavelength Milky Way


a
Dark-matter halo
Dwarf spheroidal galaxies
Milky Way
γ-ray
200 kpc
b
Sagittarius tidal stream
30 kpc
Sun
Observed
If no dark matter
Velocity of stars
Distance from Galactic Centre
c
Summer
Earth orbit
Sun
Galactic plane
Dark-matter wind
Summer
Winter
Winter
Dark-matter flux
Time