清華大學天文系
Department of Astronomy, Tsinghua University

Physics of the Interstellar Medium

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Department of Astronomy

Tsinghua University

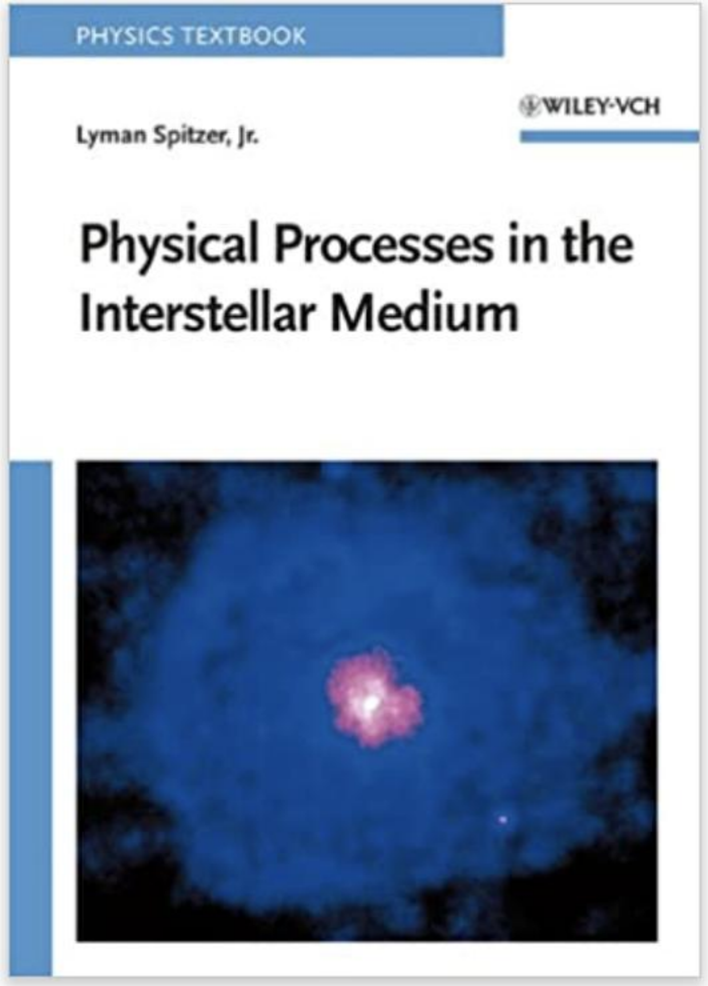
Syllabus

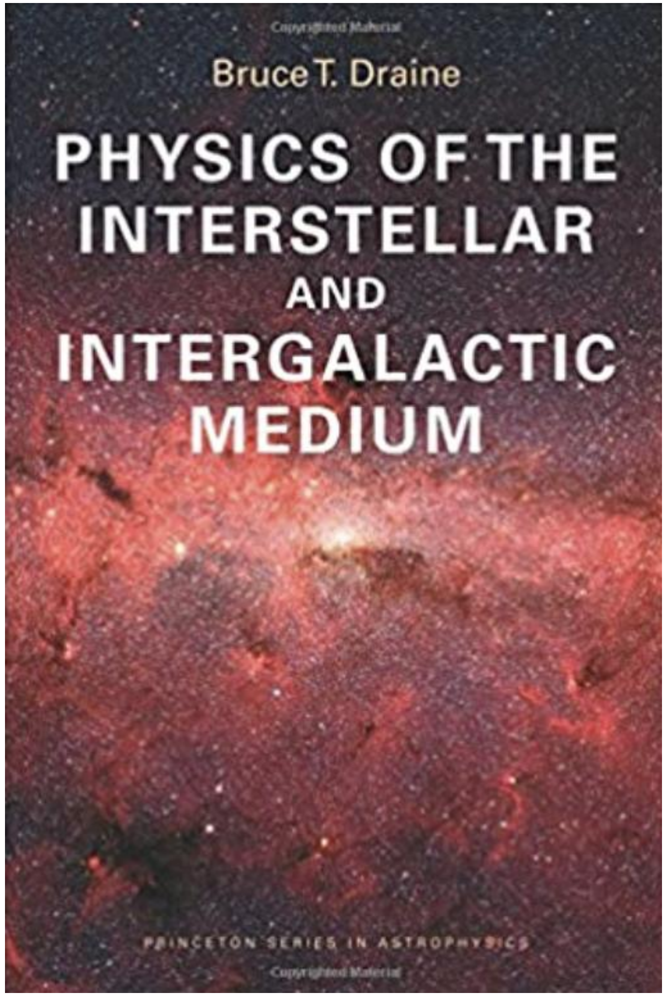
- 第一周：星际介质简述
- 第二周：微观物理过程：碰撞与统计力学基础
- 第三周：量子力学、原子物理基础
- 第四周：中性冷介质
- 第五周：中性温介质
- 第六周：光致电离介质
- 第七周：碰撞电离热介质
- 第八周：尘埃对观测的影响
- 第九周：尘埃物理
- 第十周：星际介质动力学
- 第十一周：其他非热成分
- 第十二周：前沿专题：恒星形成
- 第十三周：前沿专题：星风泡、超新星遗迹和超风泡
- 第十四周：前沿专题：星系生态系统
- 第十五周：团队项目汇报

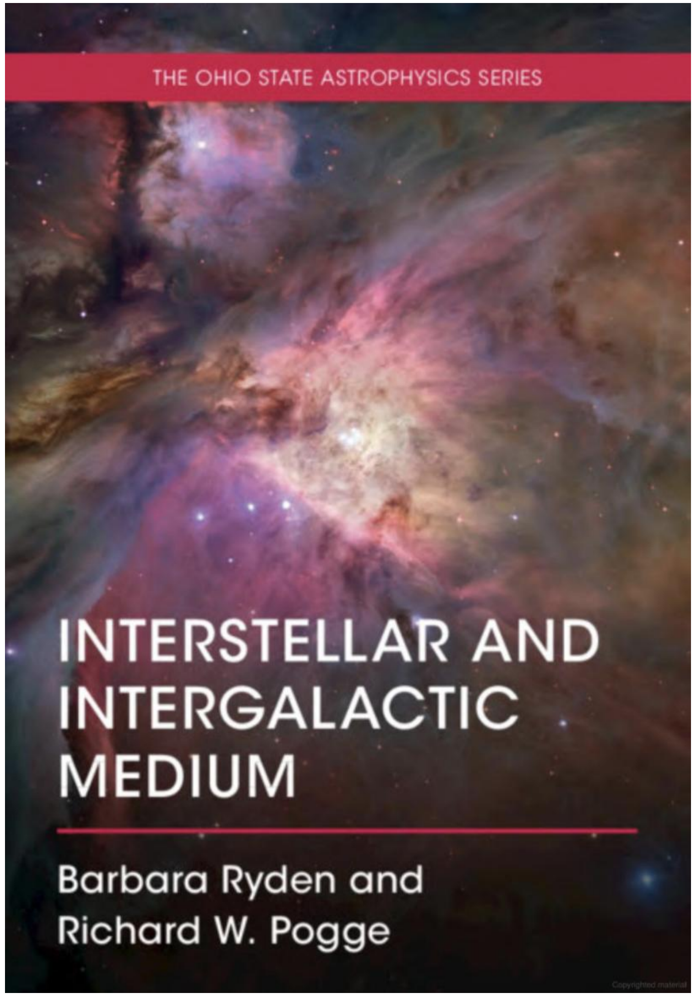
Prerequisites

- Intro to astronomy: stellar structure, spectrum, galaxies, etc.
- Thermodynamics and Atomic physics: heat transfer, detailed balance, ideal gas, Boltzmann distribution, adiabatic process, phase, blackbody radiation, atomic structure, energy levels, spin-orbit coupling, LS-coupling, Zeeman effect, hyperfine structure.
- Fluid dynamics*: Euler equation, thermal conduction, viscosity, turbulence.
- Let’s do a survey of background knowledge!

Reference books







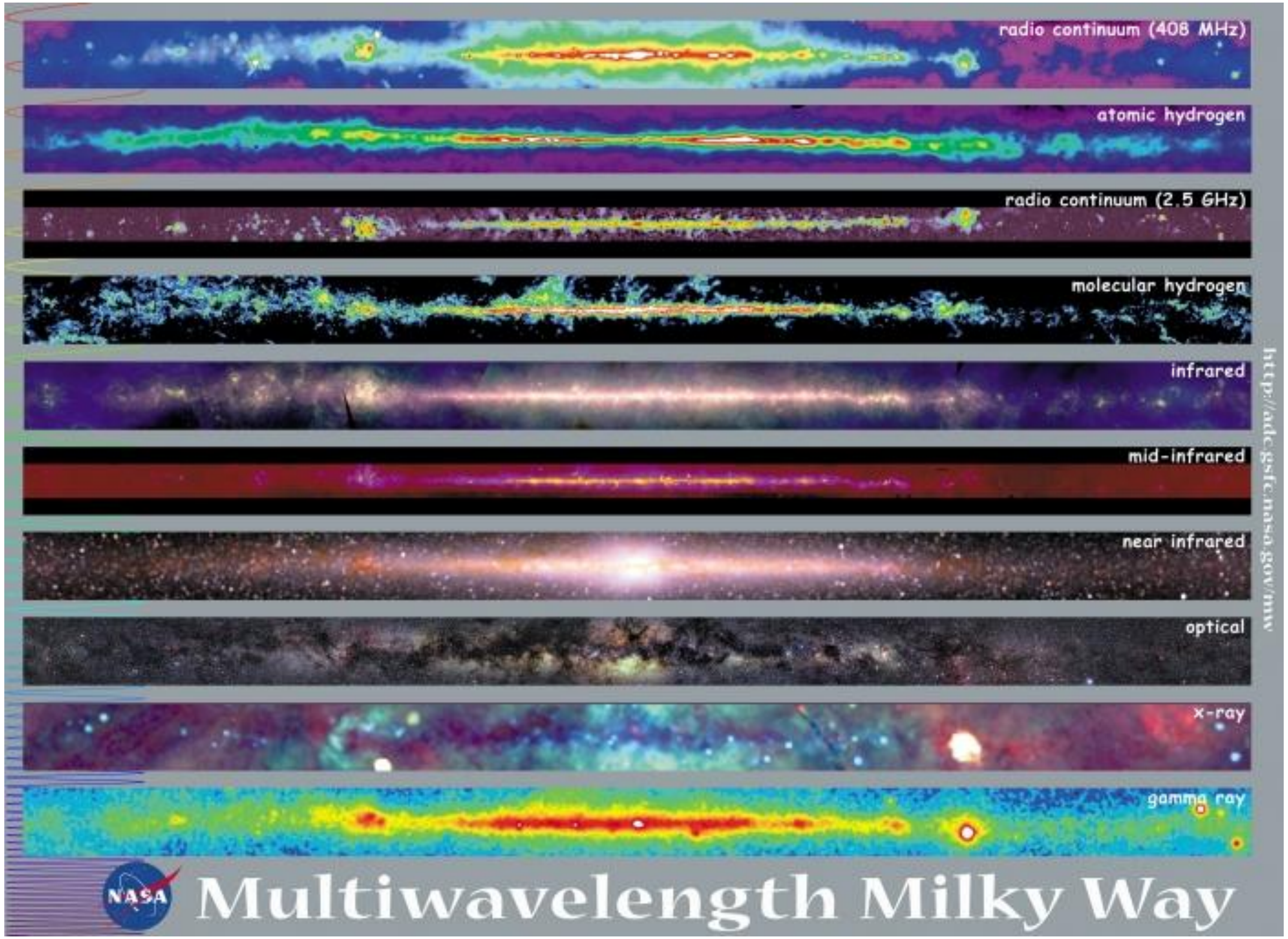
Notes

- Chinese with English terminology and slides.
- ISM is a very broad topic and can be taught in completely different ways. I can only share my own view of the topic, a theoretical view.
- The first time ISM is taught in the department. My first time teaching ISM. My first time teaching.
- More discussion is encouraged. Do not follow the syllabus strictly.

Course evaluation

- Homework: 5 (?) assignments, in total 40%.
- Mid-term exam: close book, written, 30%.
- Final project: group projects with written report and presentation, 30%.
  - Make your group
  - Select your project
  - Divide your project and distribute efforts to group members
  - Keep on making progress from the very beginning

“The Interstellar medium is anything not in stars” ---Donald Osterbrock



History of ISM studies: a journal full of surprises and excitements

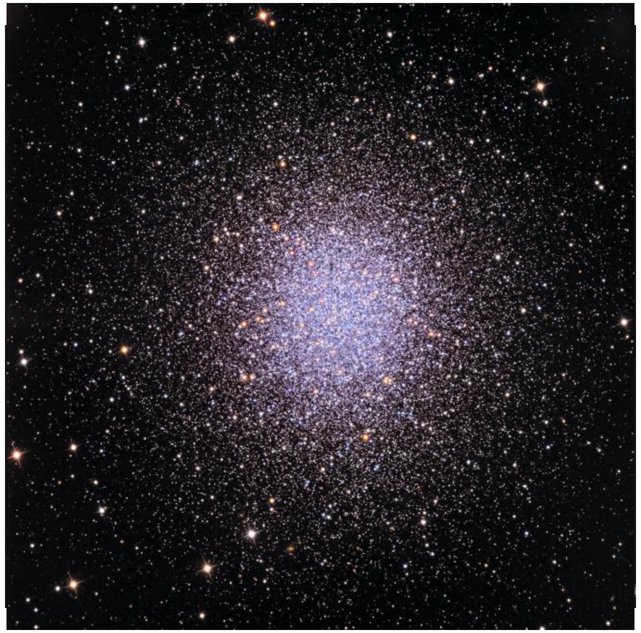
Exploring the nature of bright nebulae

- Nicolas Louis de Lacaille at Cape of Good Hope in South Africa (1750-1754) observed many nebulae.
- In 1774, Charles Messier published a list of relatively bright, deep-sky, diffuse objects: e.g. M 15, M 23, M 31, M42, M57

Bright Nebulae: the most beautiful fireworks in the Universe!

- Definition of bright nebula? LMC can be seen by naked eyes and therefore observations of bright nebulae is as ancient as humanity.

M31

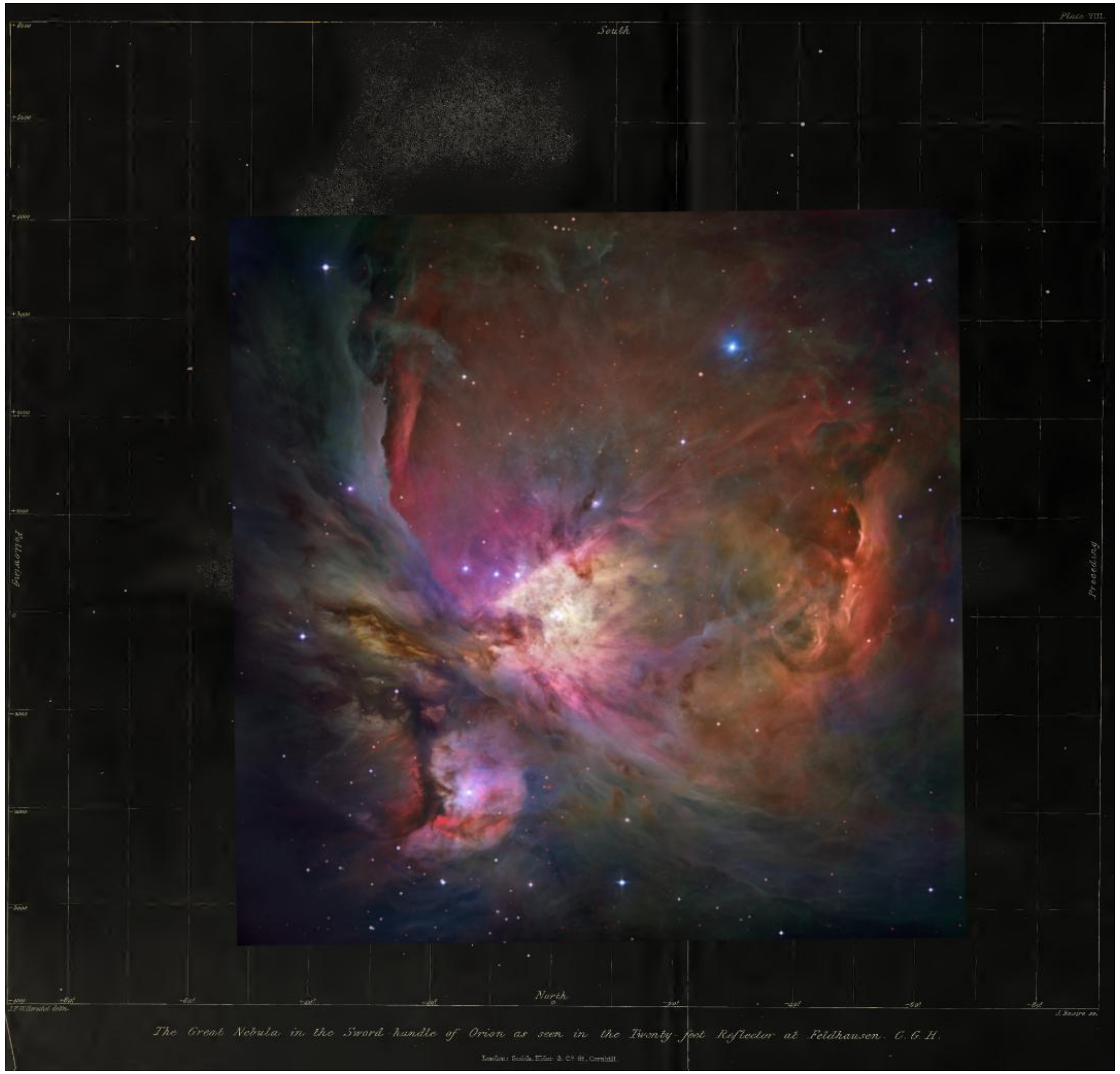


M13

Pleiades

Orion Nebula

Herschel's drawing of the Orion nebula can be considered as the milestone of the quantitative study of the ISM!

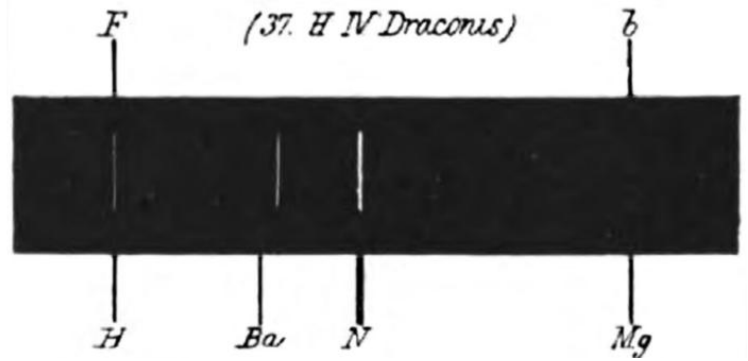


- Frederick William Herschel later observed a few thousand of nebulae.
- He later realized/concluded that there exists nonstellar nebulae, "bright fluids", whose properties were uncertain.
- He then speculated that young stars are formed from the "bright fluids" in the early 19th century.
- By the end of 19th century, around 10,000 nebulae were known, half of which were discovered by the Herschels.

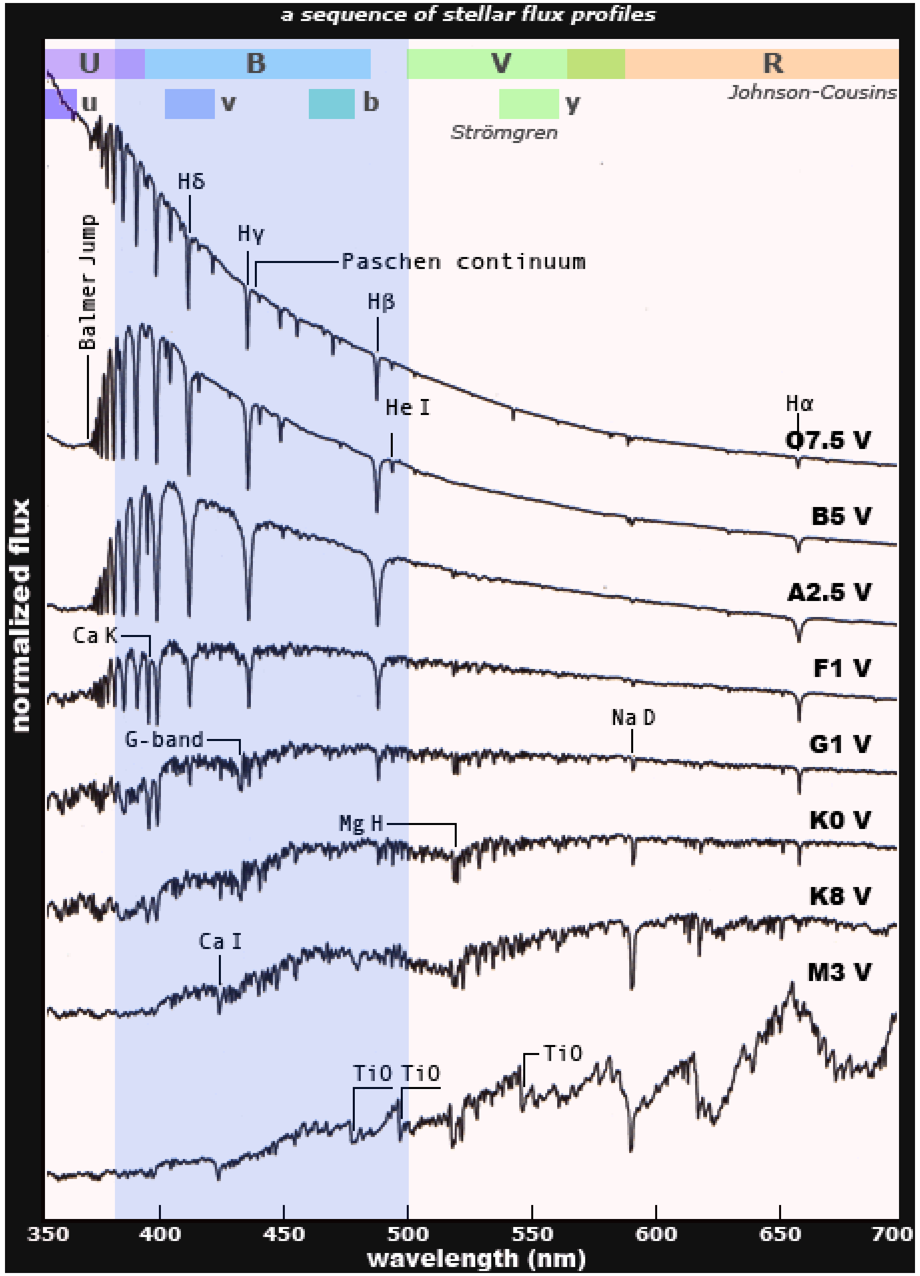
Spectral analysis of nebulae

- In 1864, William Huggins obtained the first spectra of the nebula, Cat's Eye Nebula, with three prominent emission lines!

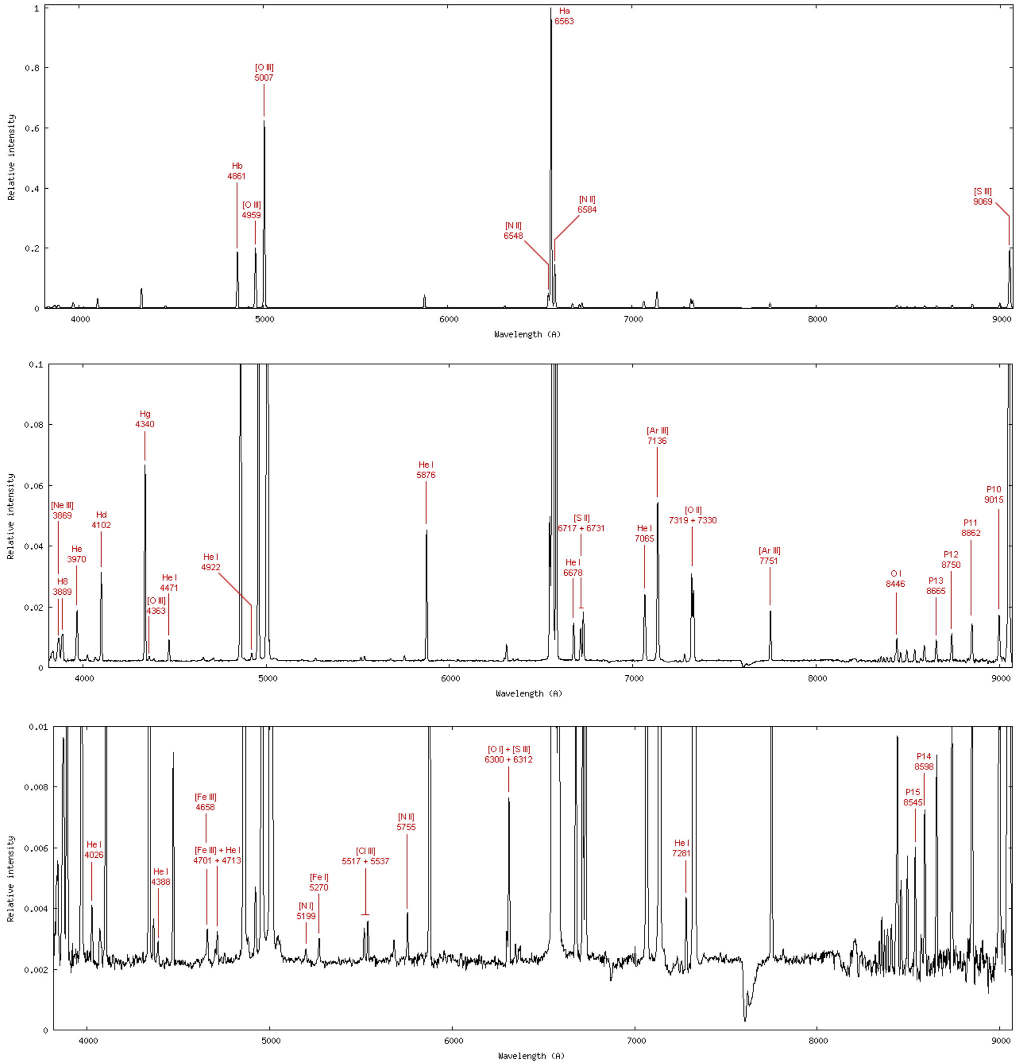
Balmer beta line

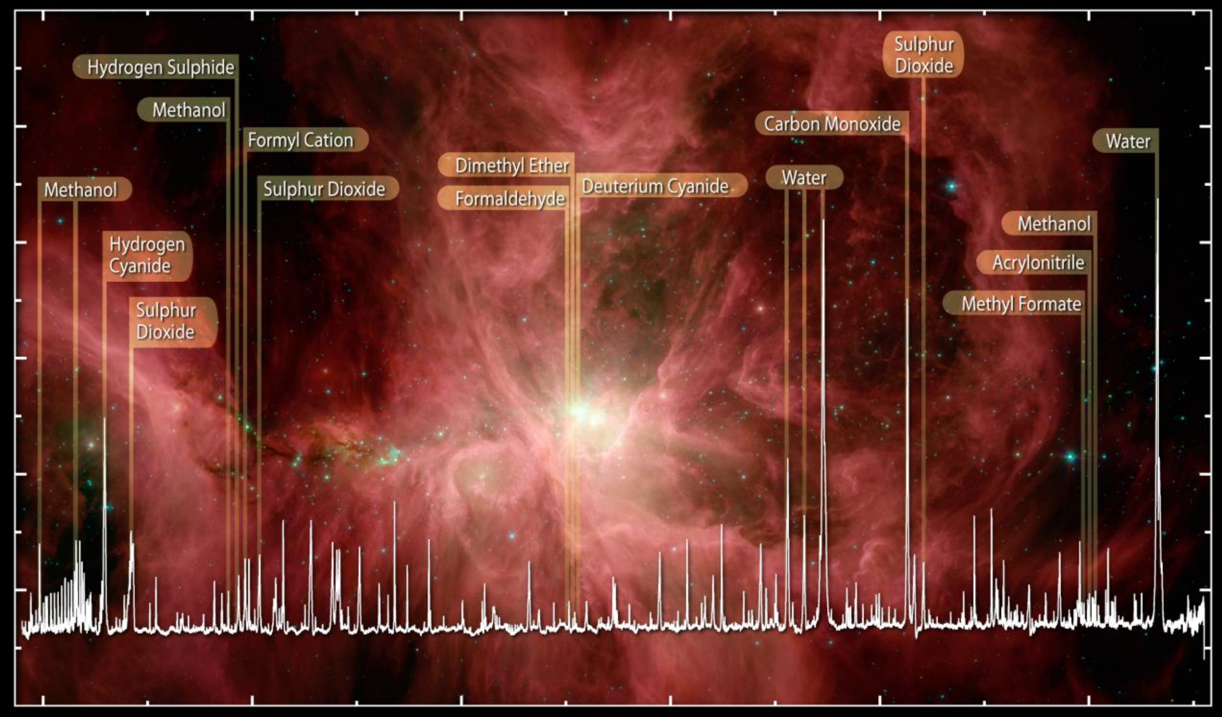


Unknown element nebulium?
It was actually [OIII]!



Spectra of Orion Nebula



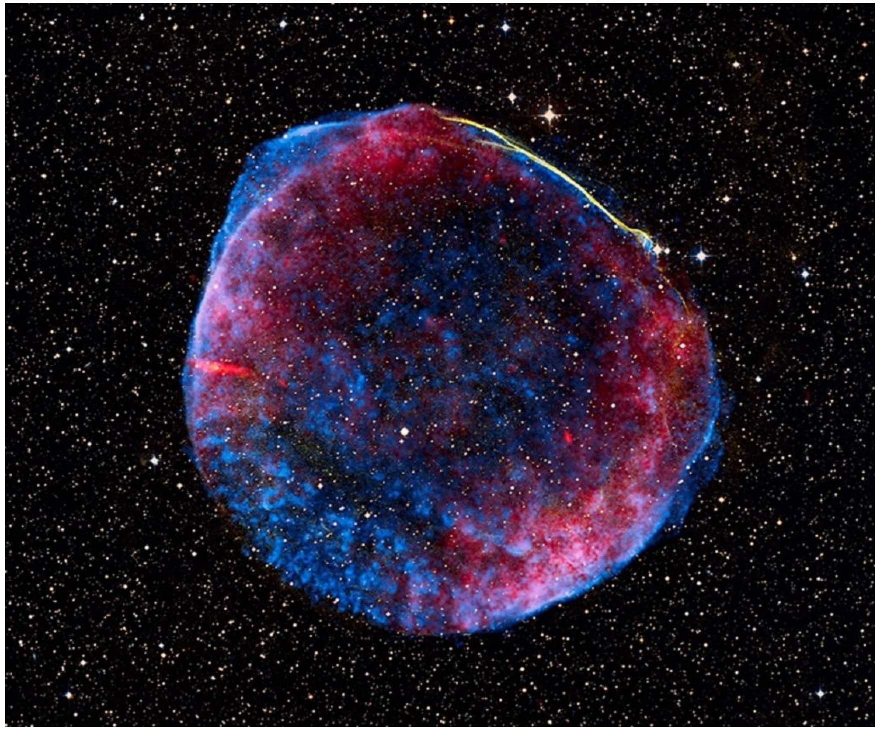


HIFI Spectrum of Water and Organics in the Orion Nebula

Stromgren sphere

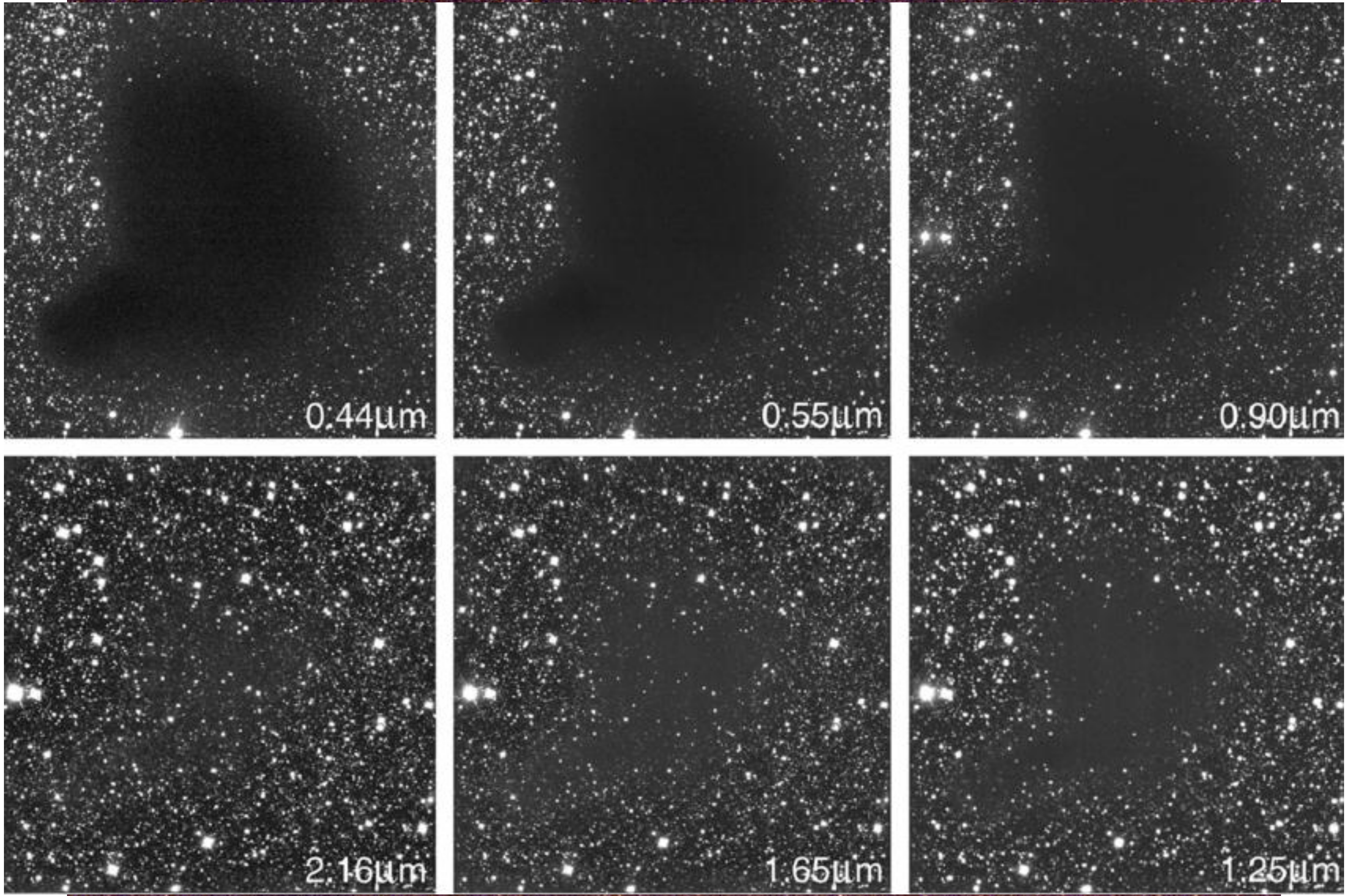
- In 1939, Bengt Stromgren developed the idea the bright nebulae with strong emission line spectra are regions of photo-ionized gas, surrounding a hot star or other ionizing sources.
- One of the most important concept of the ISM, "Stromgren sphere", had been established.
- Three Types of bright ionized nebulae: HII regions; Planetary nebulae; Supernova remnants





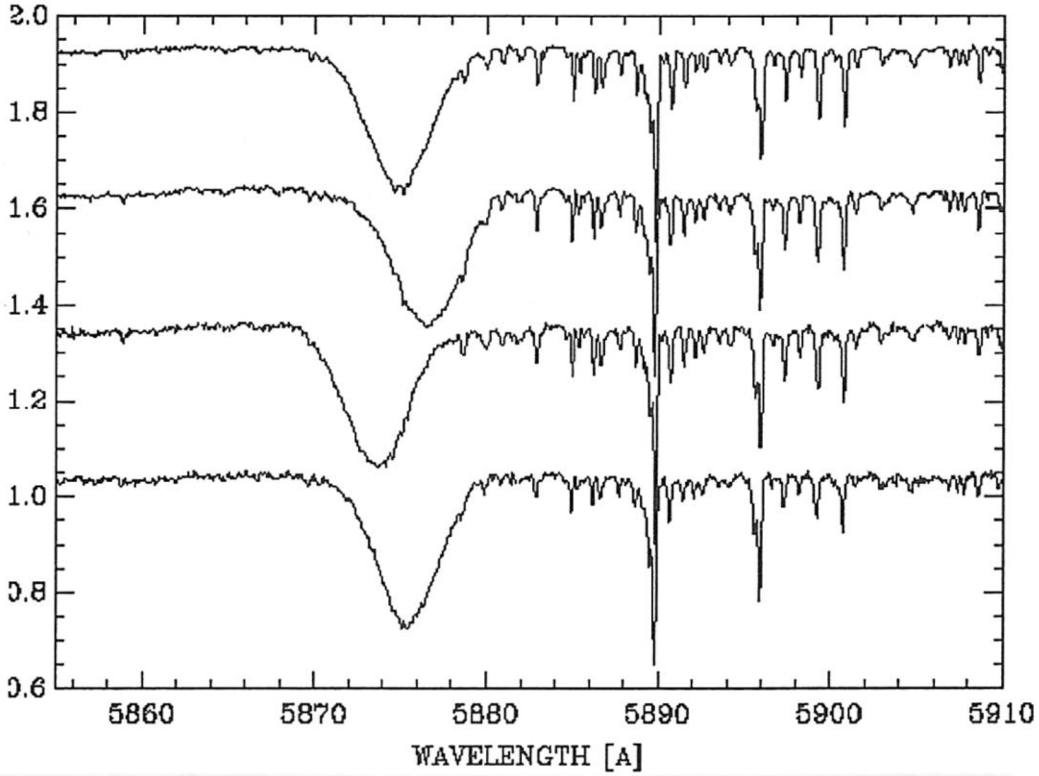
Revealing the dark side of the ISM

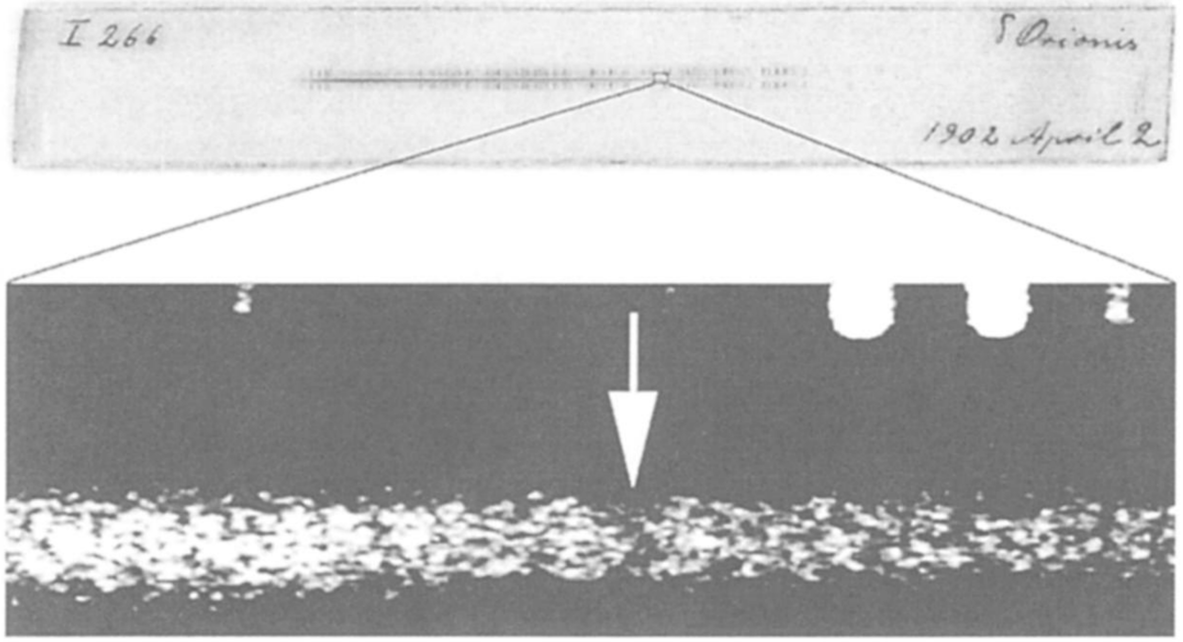
Barnard 68



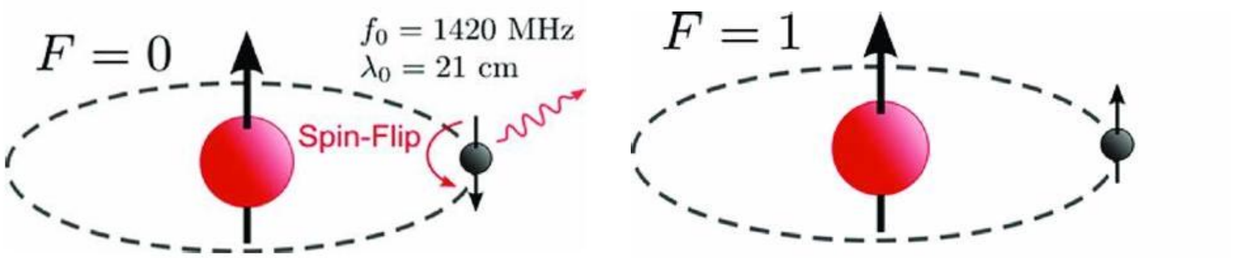
Diffuse Interstellar Gas

- First evidence dates back to Johannes Franz Hartmann (1865–1936), whose observations of δ Orionis in 1904, a spectroscopic binary, revealed the presence of Ca II absorption lines that did not show the orbital motion of the stars around each other. Hartmann concluded on the existence of a calcium cloud in the line of sight of δ Orionis, which produced the absorption and was moving away with a radial velocity of 16 km/s.
- The lines were all narrow.
- More distant stars showed stronger stationary lines.

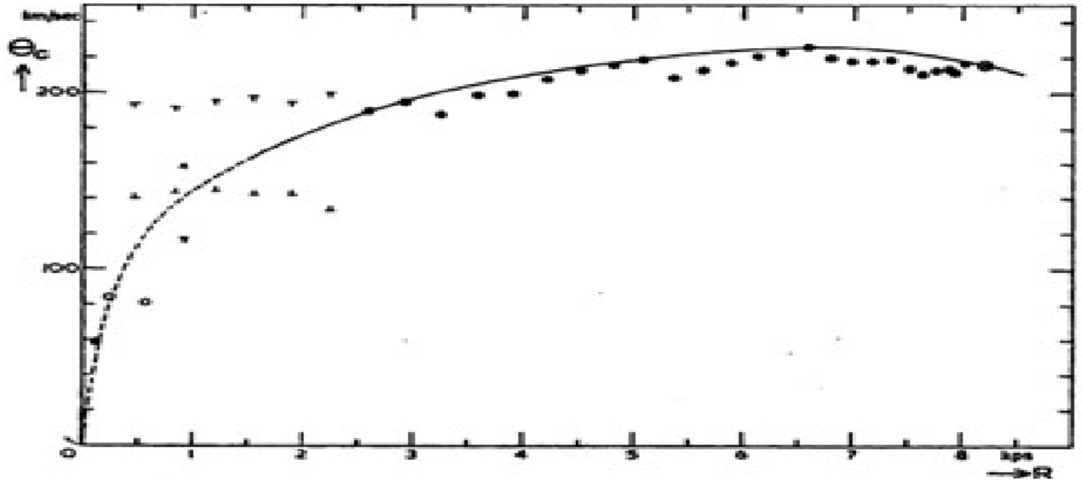




Diffuse Interstellar Gas



- Arthur Eddington in 1926 initiated the first theoretical studies of the physical properties of the ISM, e.g. kinetic temperature and ionization states.
- Hendrik Christoffel van de Hulst in 1945 made s theoretical prevision of the possibility of observing the 21 cm radiation of neutral H. This radiation was detected by Ewen & Purcell 1951!



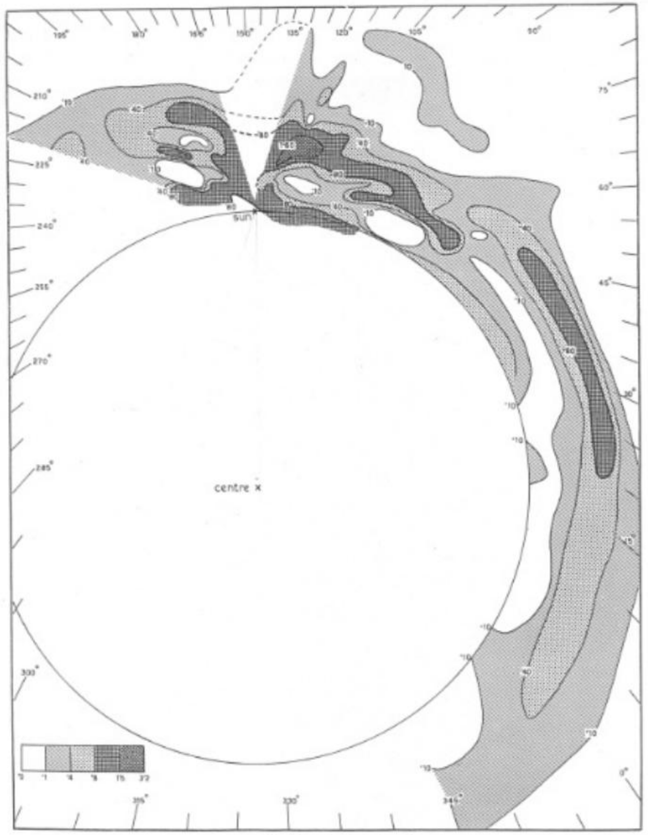
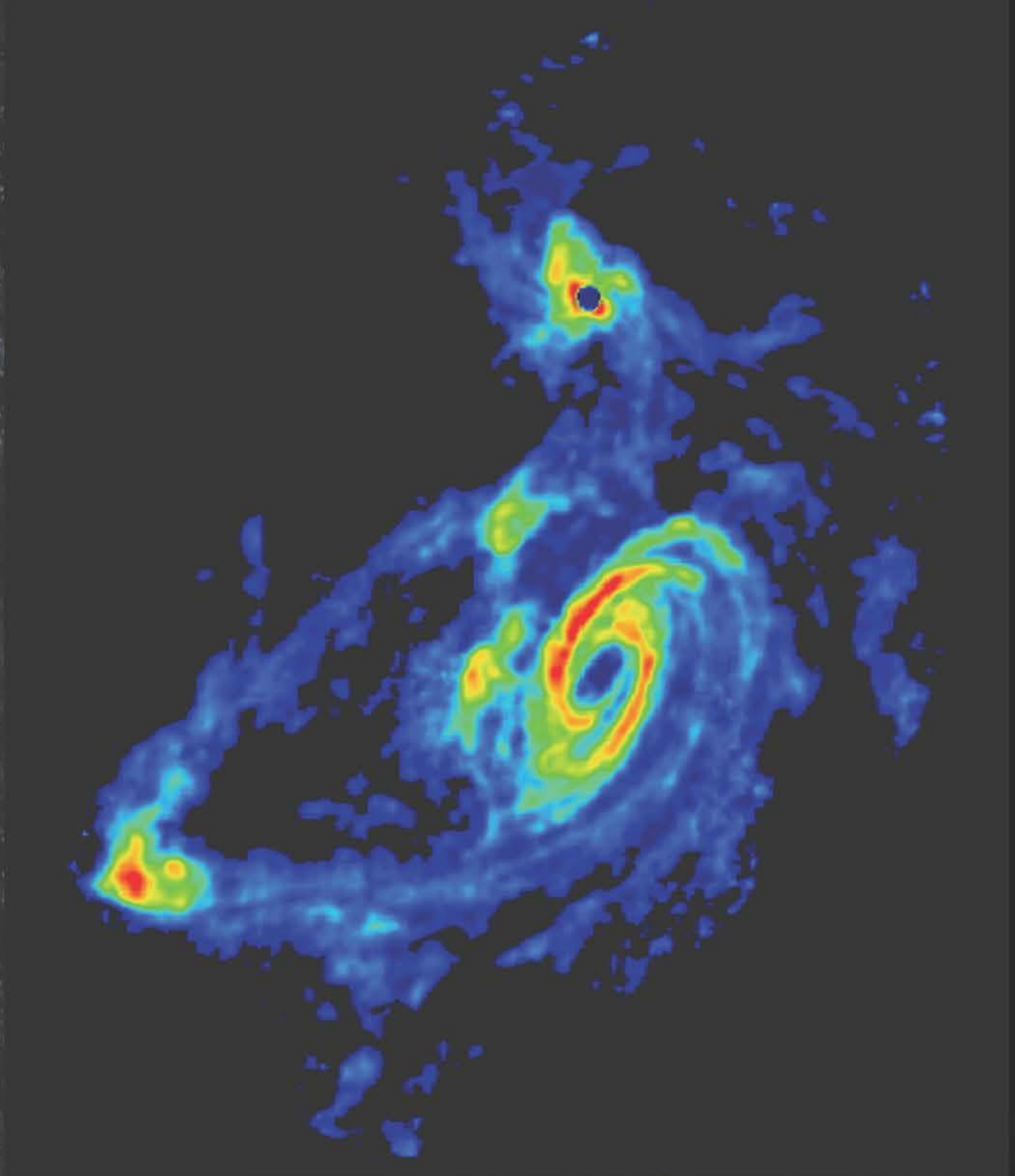


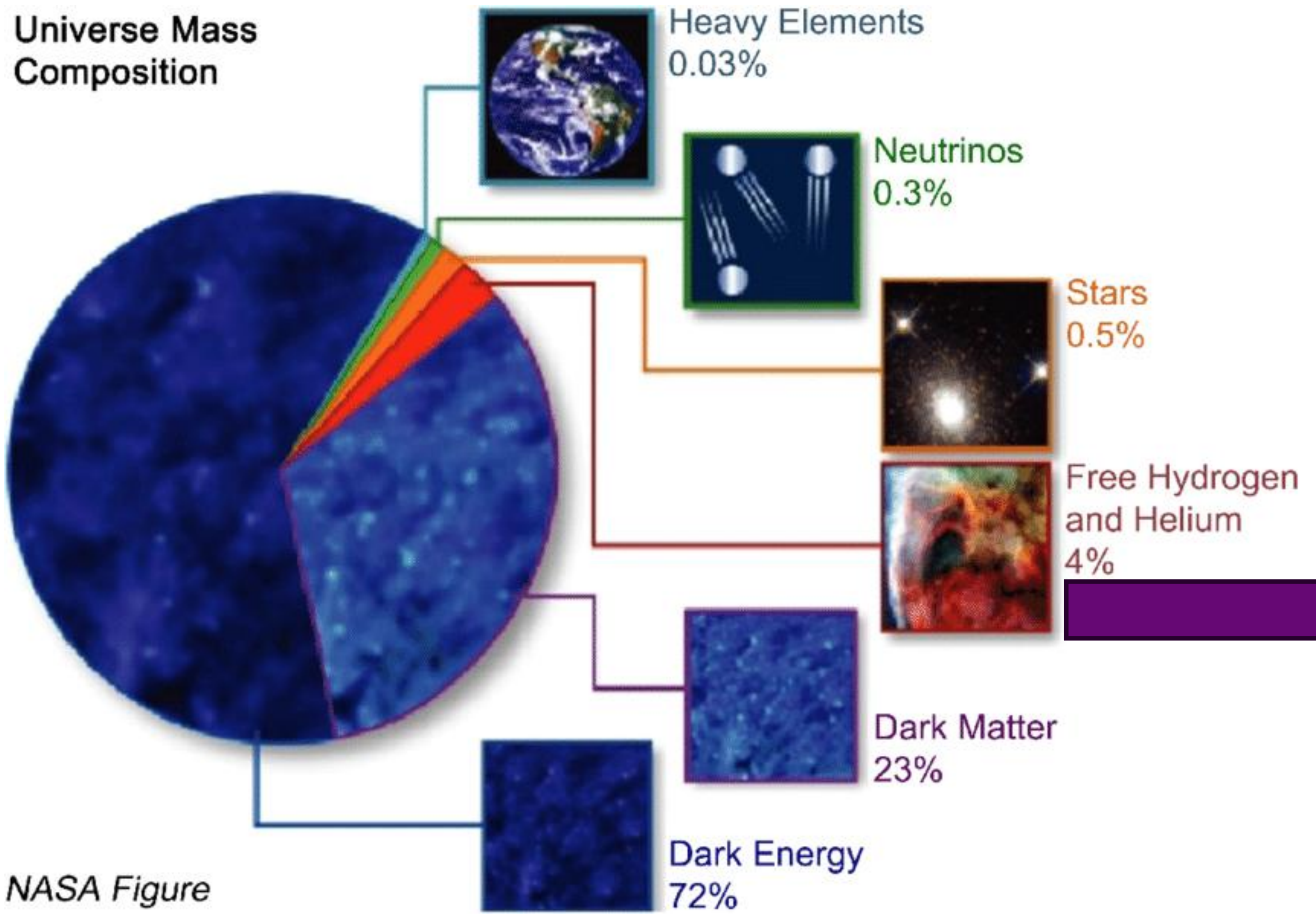
Figure 9: The first HI map of the Galaxy outside of the solar circle, showing spiral structure, with contour shading to indicate "points of equal density" (after Van de Hulst et al., 1954: 146).

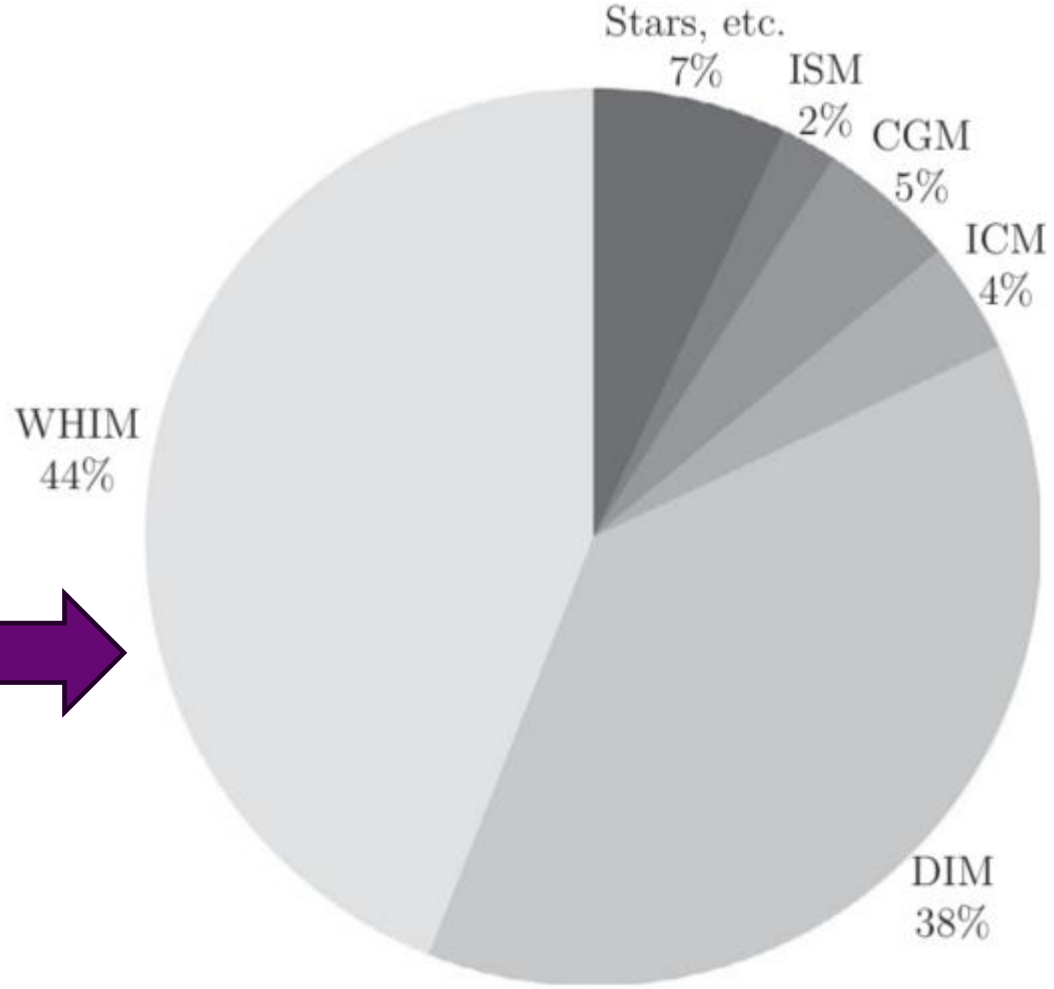


Introduction: Why study the ISM?

- The formation of stars from the interstellar medium is the fundamental process that determines the properties of galaxies *and* the structure of planet forming disks.
- The ISM provides unique tracers to study the physical processes of different astronomical objects.

An overview of the ISM: mass/energy division of different components.





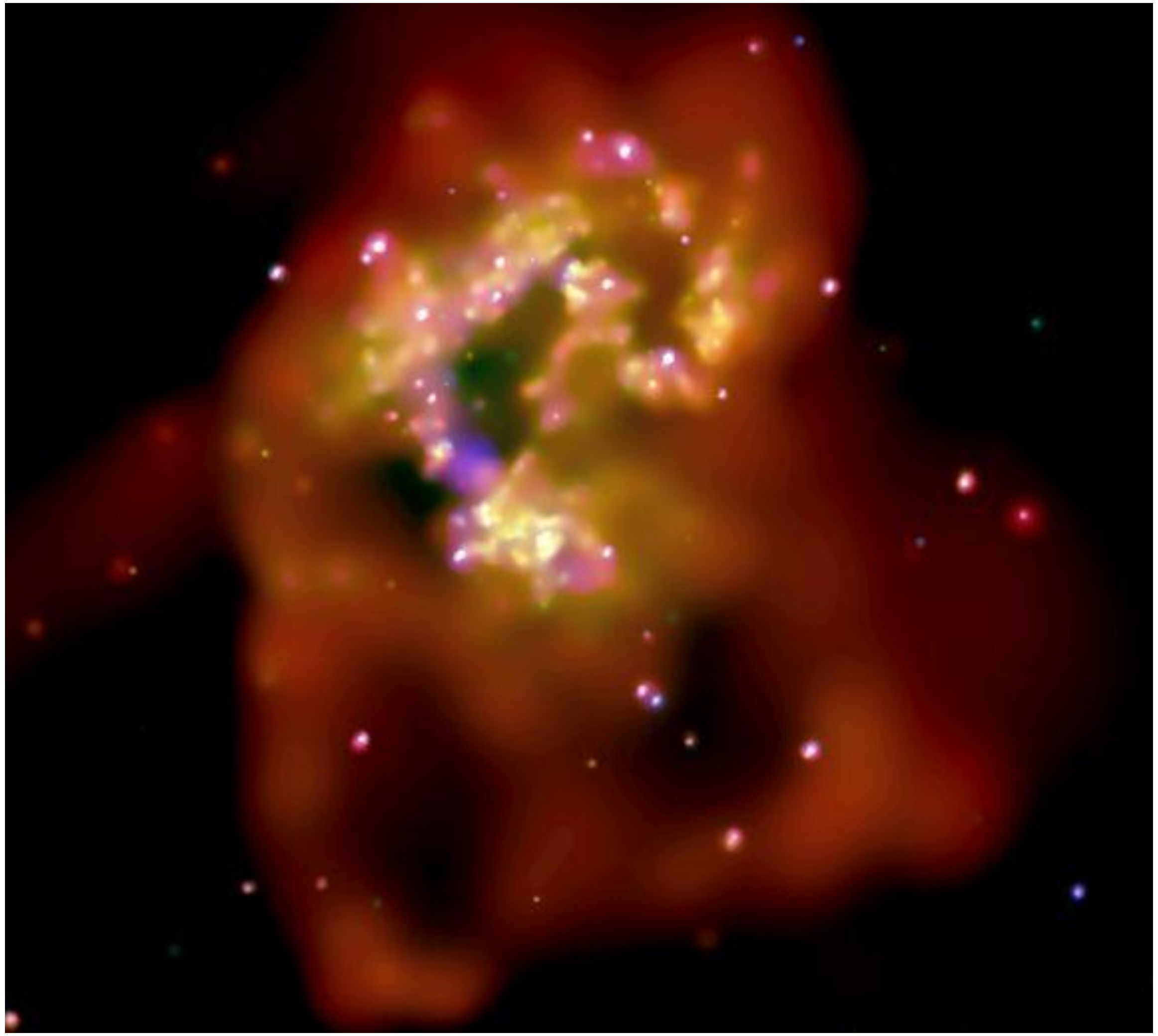
Phases of the ISM (on the order of temperature)

- Coronal gas (HIM)
- HII gas (WIM)
- Warm HI gas (WNM)
- Cold HI gas (CNM)
- Molecular gas

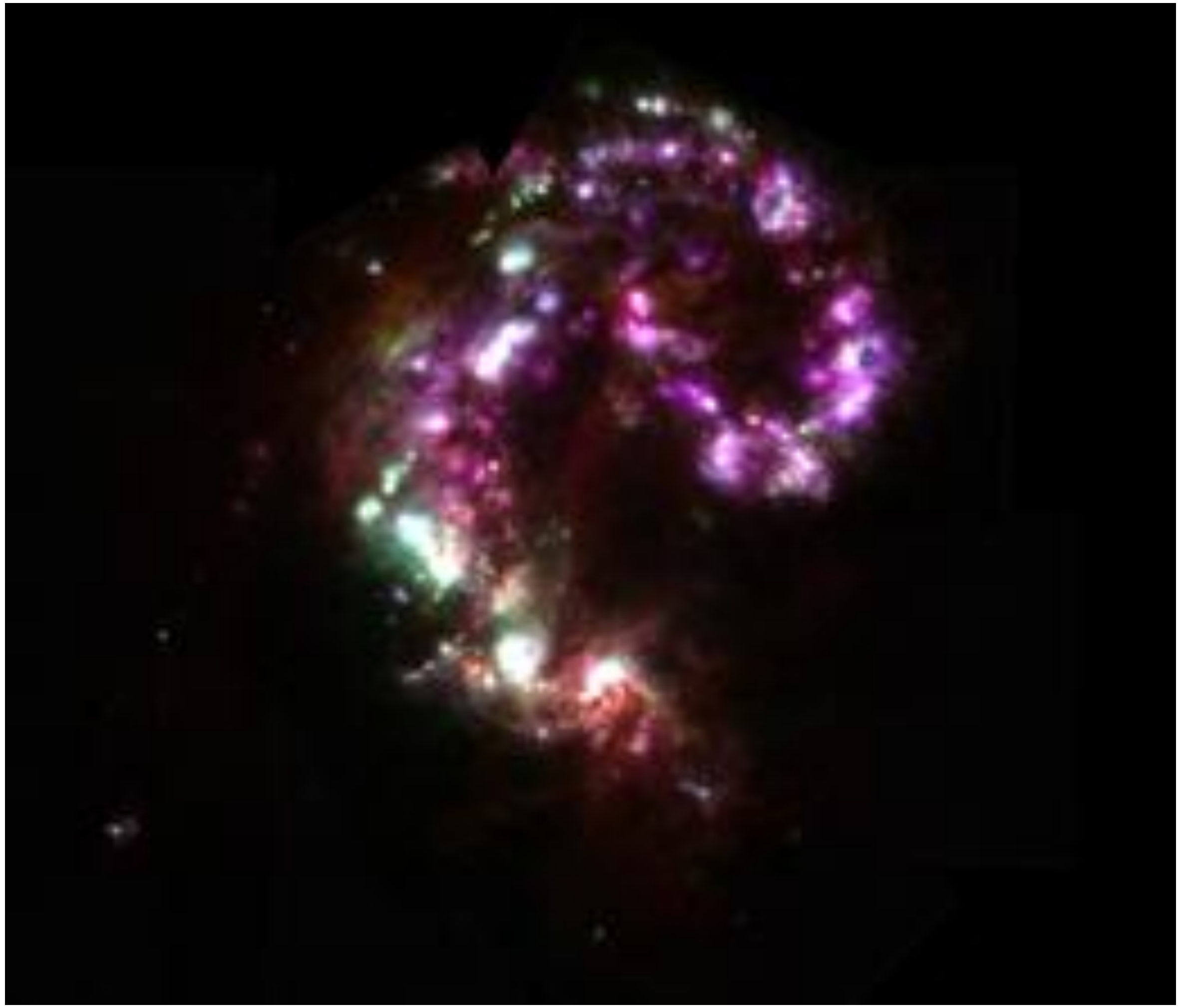
- I'm using Antennae galaxies, an interacting system, as an example to demonstrate the ISM in different phases.

Antennae galaxies

Coronal gas

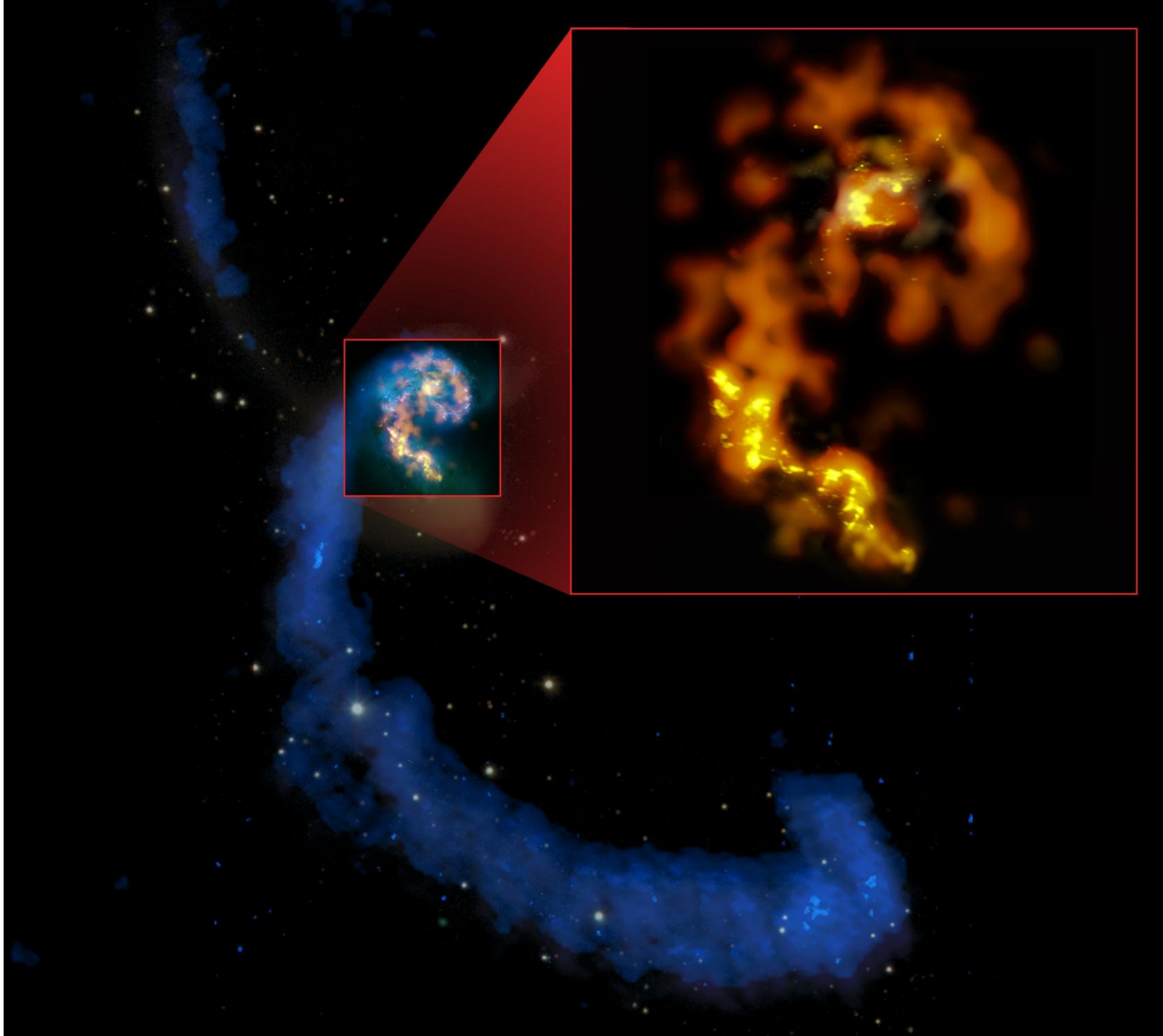


HII gas: bright nebulae and diffuse ionized gas



[SII], [OIII], Hbeta line emission with MUSE

HI and molecular gas



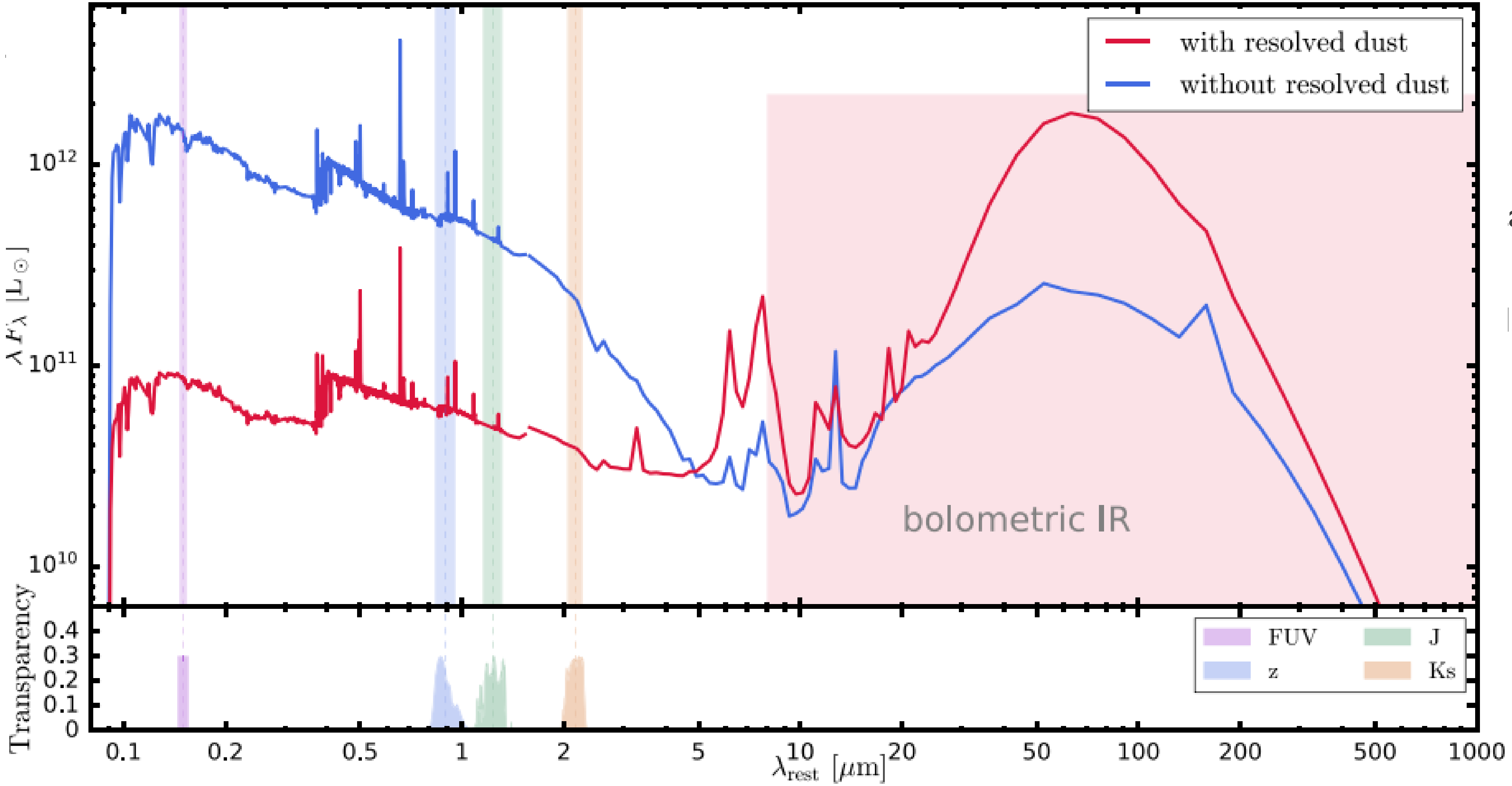
Phases of the ISM (on the order of temperature)

Phase	$T(\mathrm{K})$	$n_{\mathrm{H}}(\mathrm{cm}^{-3})$	Comments
Coronal gas (HIM) $f_V \approx 0.5?$ $\langle n_{\mathrm{H}} \rangle f_V \approx 0.002\,\mathrm{cm}^{-3}$ ($f_V \equiv$ volume filling factor)	$\gtrsim 10^{5.5}$	~ 0.004	Shock-heated Collisionally ionized Either expanding or in pressure equilibrium Cooling by: ◇ Adiabatic expansion ◇ X ray emission Observed by: • UV and x ray emission • Radio synchrotron emission
H II gas $f_V \approx 0.1$ $\langle n_{\mathrm{H}} \rangle f_V \approx 0.02\,\mathrm{cm}^{-3}$	10^4	$0.3 - 10^4$	Heating by photoelectrons from H, He Photoionized Either expanding or in pressure equilibrium Cooling by: ◇ Optical line emission ◇ Free–free emission ◇ Fine-structure line emission Observed by: • Optical line emission • Thermal radio continuum
Warm H I (WNM) $f_V \approx 0.4$ $n_{\mathrm{H}} f_V \approx 0.2\,\mathrm{cm}^{-3}$	$\sim$5000	0.6	Heating by photoelectrons from dust Ionization by starlight, cosmic rays Pressure equilibrium Cooling by: ◇ Optical line emission ◇ Fine structure line emission Observed by: • H I 21 cm emission, absorption • Optical, UV absorption lines
Cool H I (CNM) $f_V \approx 0.01$ $n_{\mathrm{H}} f_V \approx 0.3\,\mathrm{cm}^{-3}$	~ 100	30	Heating by photoelectrons from dust Ionization by starlight, cosmic rays Cooling by: ◇ Fine structure line emission Observed by: • H I 21-cm emission, absorption • Optical, UV absorption lines
Diffuse H_2 $f_V \approx 0.001$ $n_{\mathrm{H}} f_V \approx 0.1\,\mathrm{cm}^{-3}$	$\sim 50\,\mathrm{K}$	~ 100	Heating by photoelectrons from dust Ionization by starlight, cosmic rays Cooling by: ◇ Fine structure line emission Observed by: • H I 21-cm emission, absorption • CO 2.6-mm emission • optical, UV absorption lines
Dense H_2 $f_V \approx 10^{-4}$ $\langle n_{\mathrm{H}} \rangle f_V \approx 0.2\,\mathrm{cm}^{-3}$	$10 - 50$	$10^3 - 10^6$	Heating by photoelectrons from dust Ionization and heating by cosmic rays Self-gravitating: $p > p(\text{ambient ISM})$ Cooling by: ◇ CO line emission ◇ C I fine structure line emission Observed by: • CO 2.6-mm emission • dust FIR emission
Cool stellar outflows	$50 - 10^3$	$1 - 10^6$	Observed by: • Optical, UV absorption lines • Dust IR emission • H I, CO, OH radio emission

Energy partition in the local ISM

Component		$u(\mathrm{eV\,cm^{-3}})$	Note
Cosmic microwave background	$(T_{\mathrm{CMB}} = 2.725\,\mathrm{K})$	0.265	a
Far-infrared radiation from dust		0.31	b
Starlight ($h\nu < 13.6\,\mathrm{eV}$)		0.54	c
Thermal kinetic energy $(3/2)nkT$		0.49	d
Turbulent kinetic energy $(1/2)\rho v^2$		0.22	e
Magnetic energy $B^2/8\pi$		0.89	f
Cosmic rays		1.39	g

Non-thermal components of the ISM: dusts



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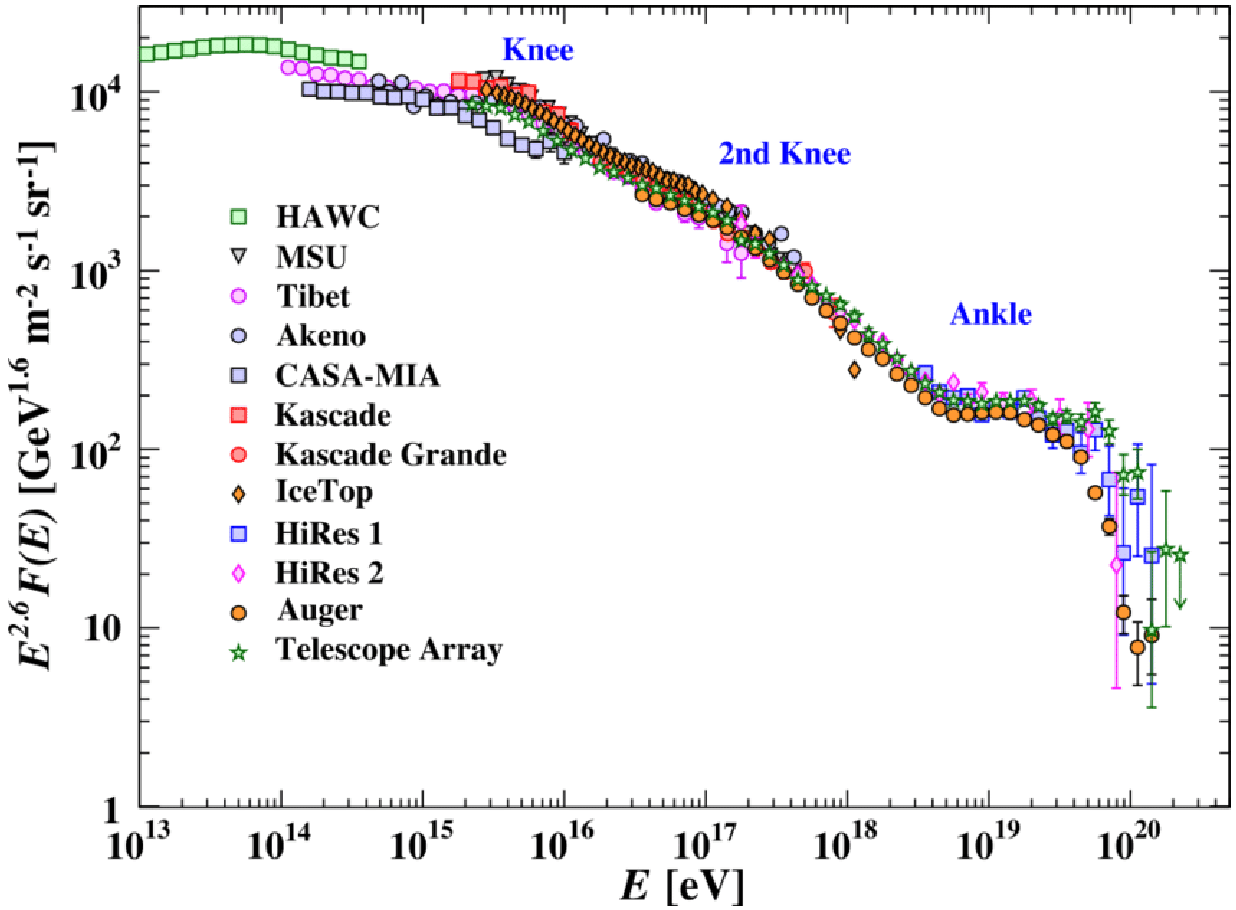
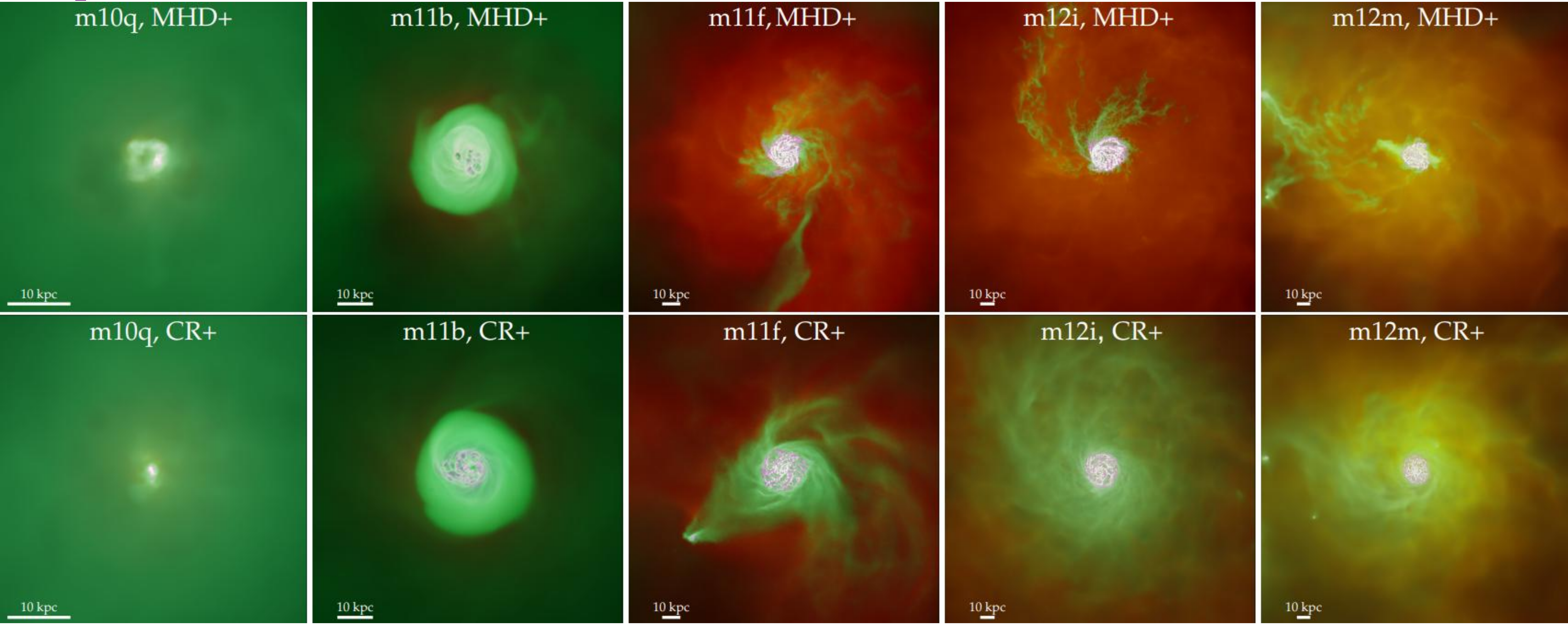
Non-thermal components of the ISM: cosmic rays

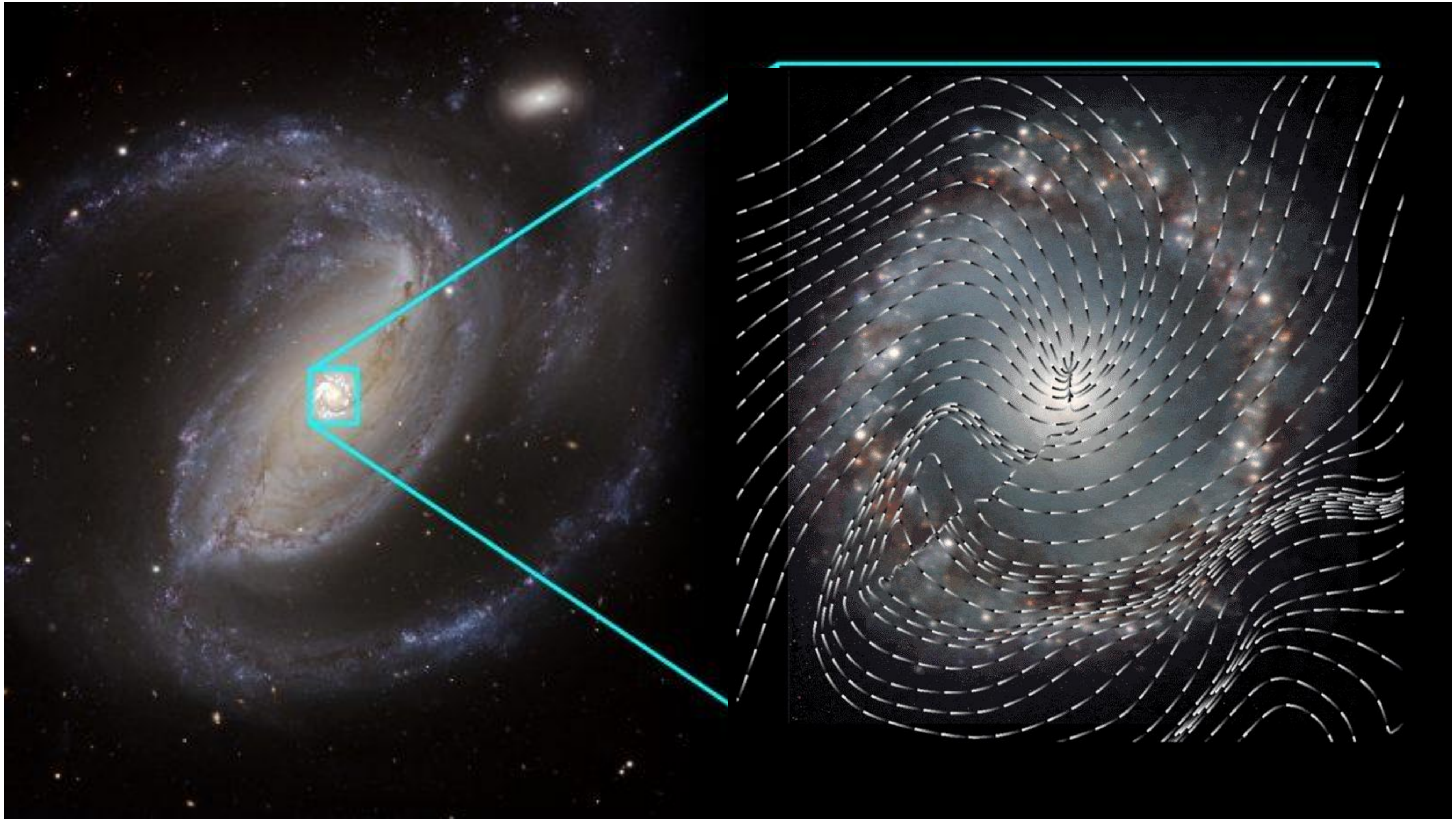
- Relativistic particles with energy that can reach the energy of macroscopic objects!



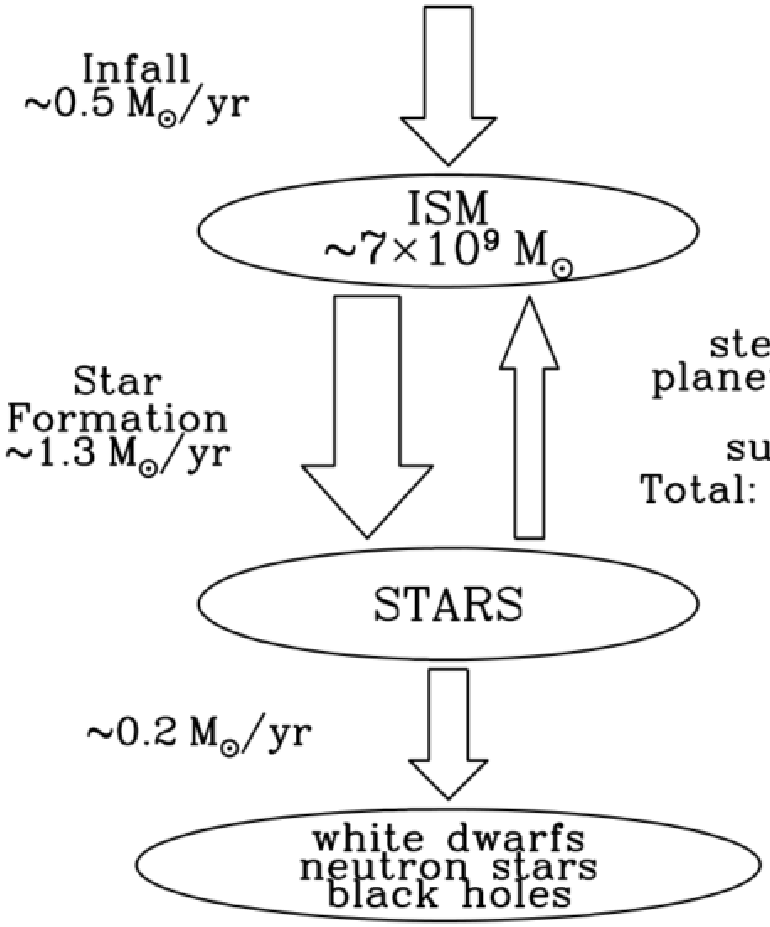
Non-thermal components of the ISM: cosmic rays



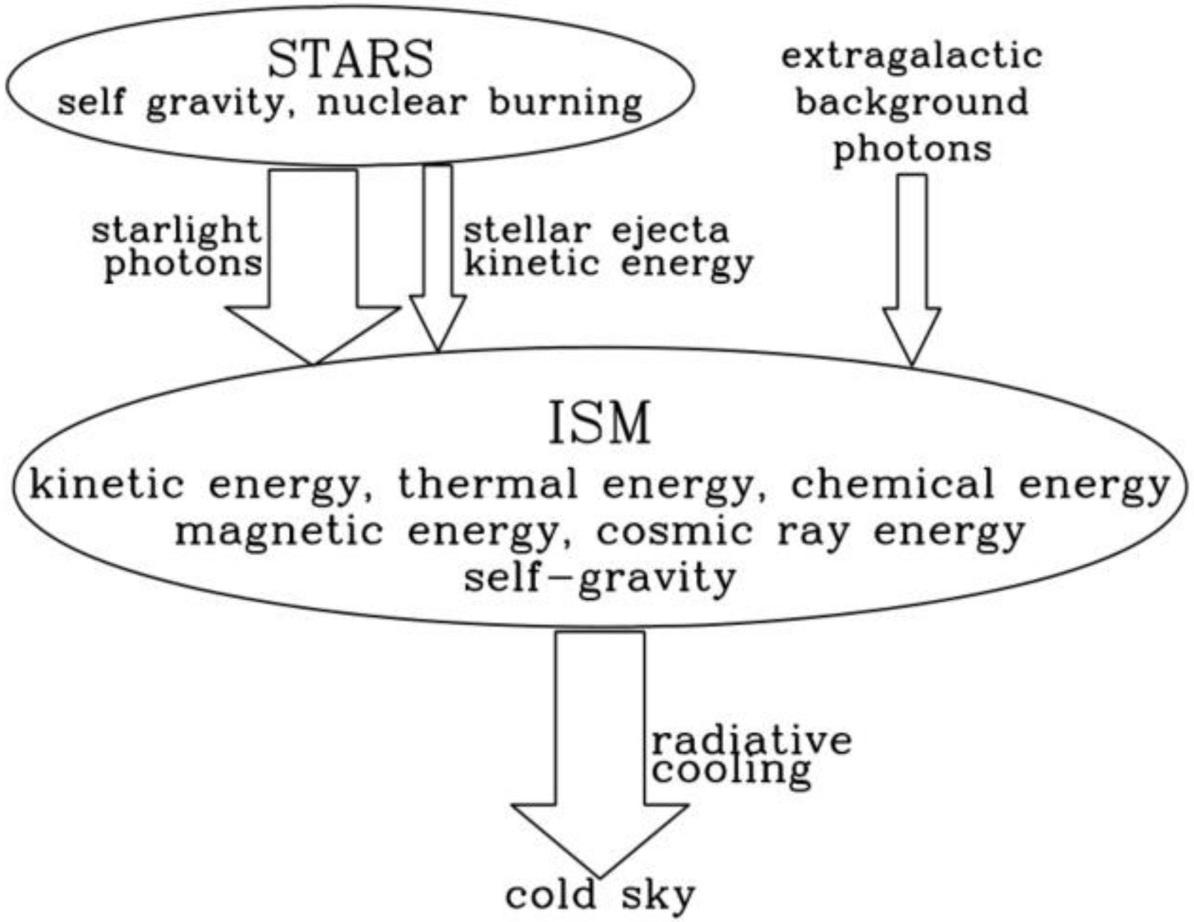
Non-thermal components of the ISM: magnetic fields



Baryonic cycles in the galaxies



Mass flow



Energy flow