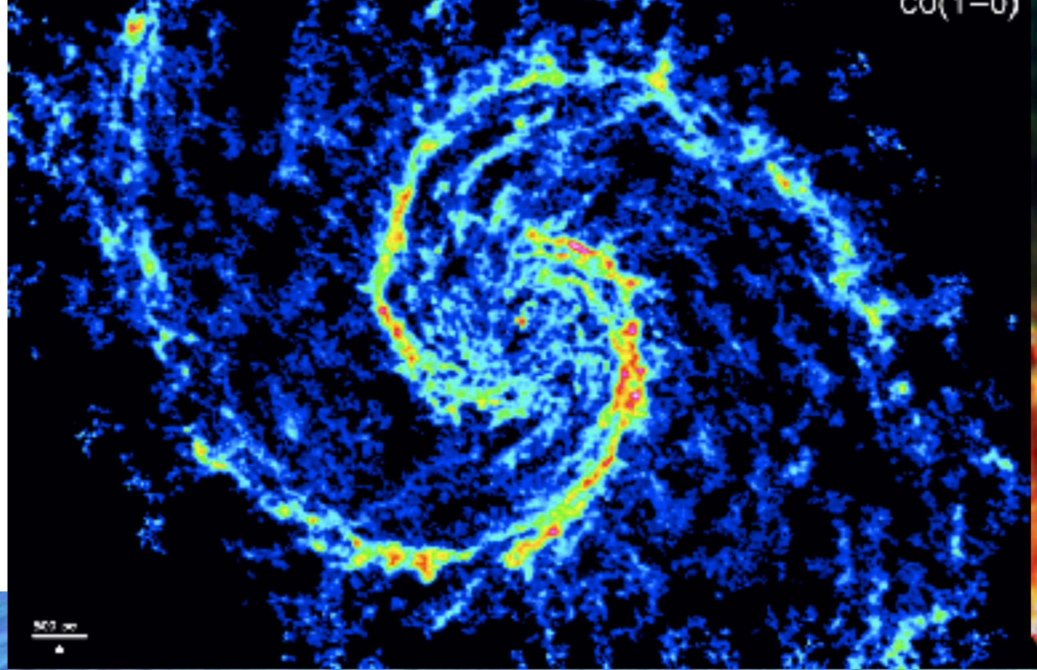
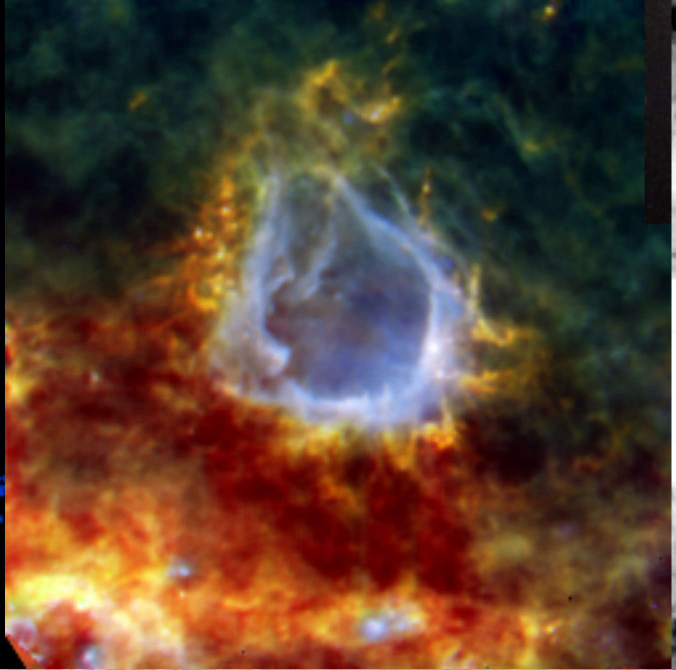
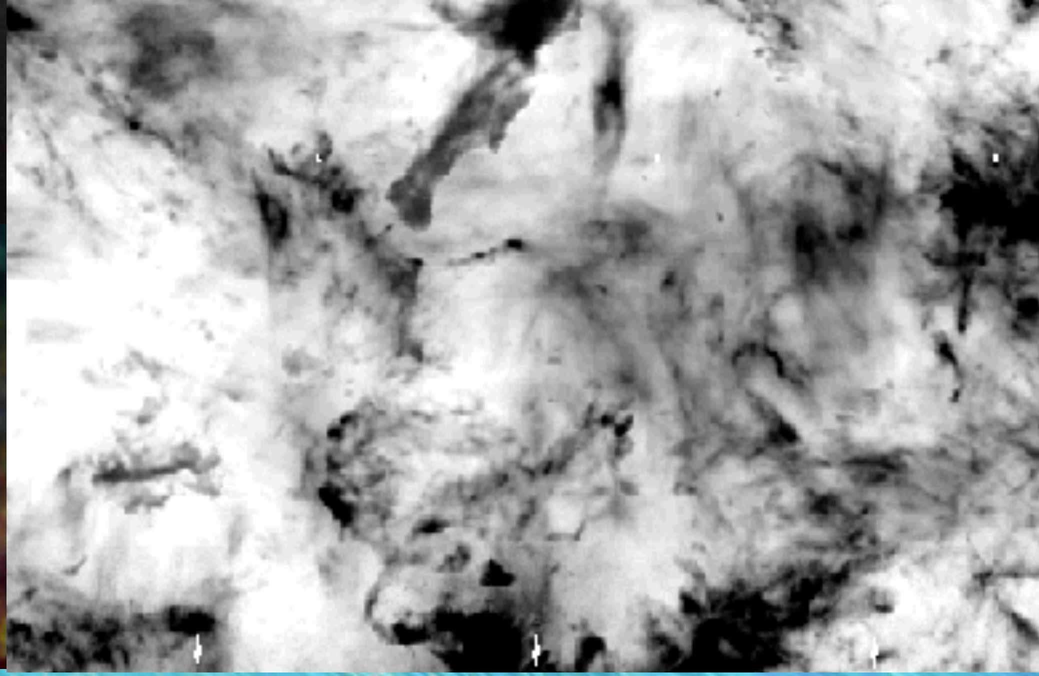
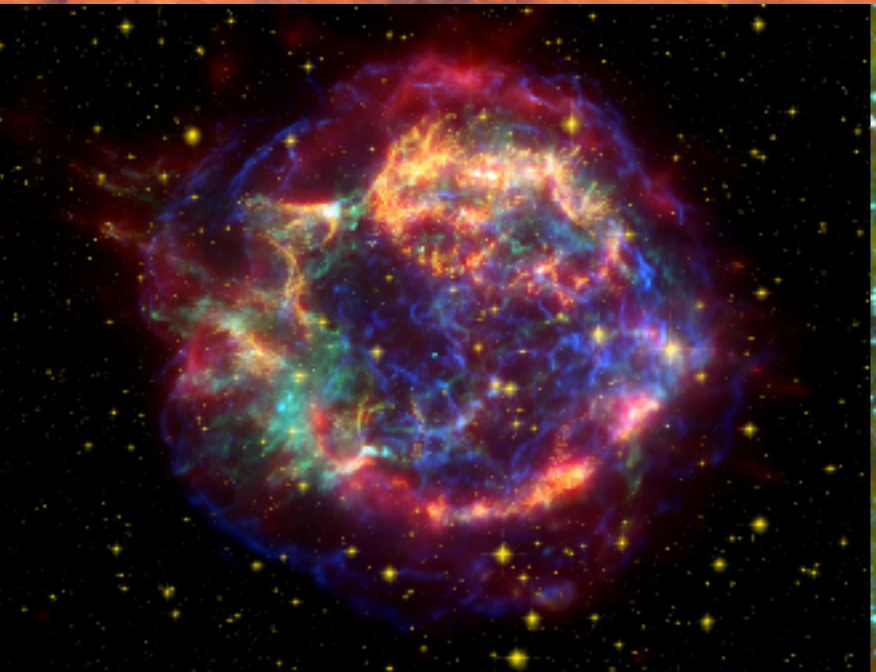
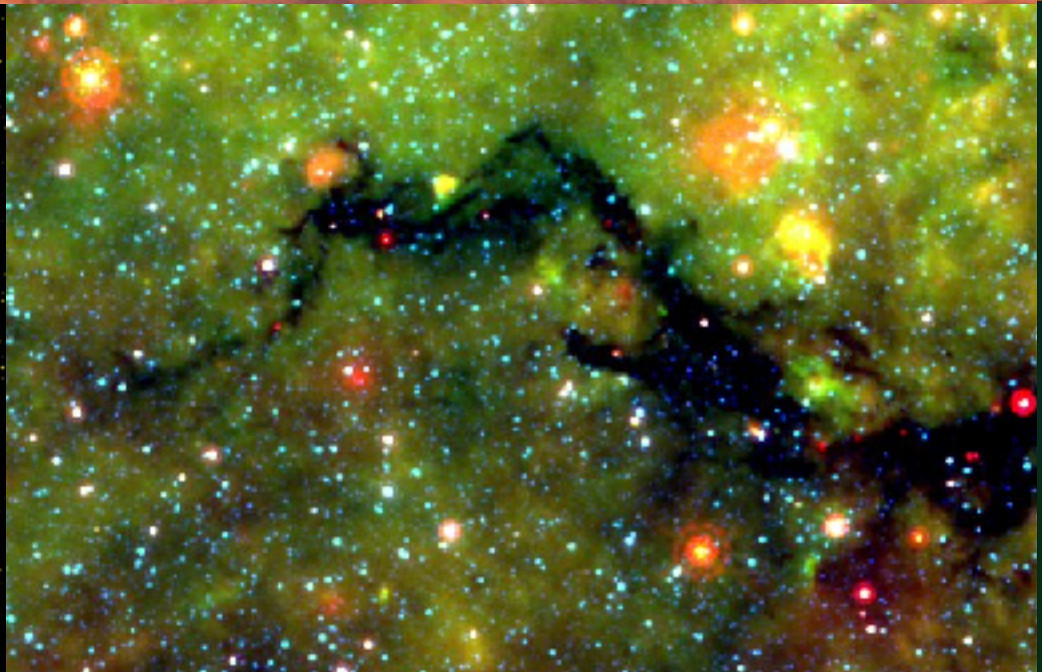
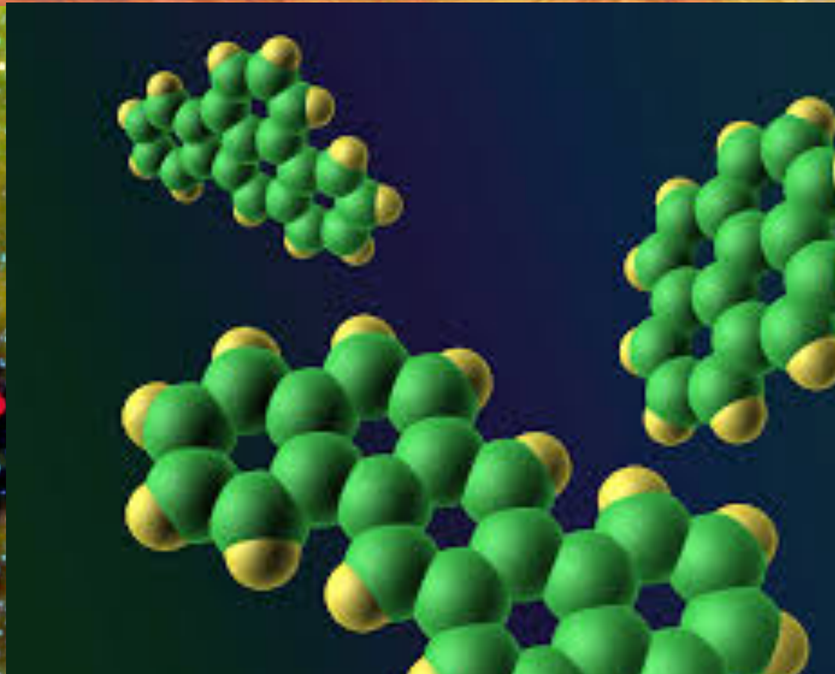




Physics 224
The Interstellar Medium

Outline

- Part I: About this class
- Part 2: Historical Perspective
- Part 3: An Overview of the ISM

Syllabus & Website

Course webpage:

http://karinsandstrom.github.io/w20_phys224.html

Syllabus is on the webpage - subject to change!

My Goals for this Class

- I want you to leave this class familiar with the big picture of the interstellar medium, the unsolved problems, & techniques for studying it.

- I intend to make the assigned work for this class serve as training for actual skills you will need in your research career: presentations, proposals, dealing with data, reading literature, etc.

About this class

- MWF 11-11:50am meetings
  - most weeks: lecture MW and discussion of papers on Friday
  - some weeks Friday will be a presentation on other aspects of astronomy careers
- Next two Fridays will be normal lectures
- I will post lecture slides on the website.

Homework

~4 homework assignments throughout the class

Homework should be turned in as a typeset pdf, LaTeX is recommended, but not required.

Free online LaTeX editors:
www.sharelatex.com or www.overleaf.com

Homework

You are encouraged to work together on the homework if you would like, but *each person must turn in their own individual write up!*

Use standard practice in our field for citing literature and relevant sources you used in your work.

If you do not feel like you know the standard practice yet, no problem - just ask and we can talk about it.

Homework

Some of the homework will require making plots or dealing with data & making measurements.

I recommend doing this in **python**, but any programming language you'd prefer is fine (IDL, matlab, etc).

You will have to read in fits files (typical data storage format for astronomy). I will post some links about fits files in python to the class webpage.

If some of you would like to learn python (recommended) we can arrange for a workshop!

Reading

The required textbook is:
The Physics of the Interstellar and Intergalactic Medium
by Bruce Draine

We will not cover everything in the book.
Suggested reading for each lecture is listed in the syllabus.

Try to read through the suggested chapters before lecture.

Paper Presentation

One of the key aspects of our research careers is *reading scientific literature.*

On 5 Fridays during the class we will have discussions of 12 classic papers from the ISM literature (2 per Friday). *Each of you will lead one of the discussions.*

Please sign up for leading a discussion at the link on the course webpage by the end of the week!

Paper Presentation

You will be expected to read the paper and put together a ~15 minute presentation about it that highlights:

- big picture context of the paper
- technical approach
- key findings
- impact on subsequent work in the field (cite a recent paper that builds on this work)*

* for those unfamiliar with NASA ADS for finding astro literature, I can give you a tutorial

Paper Presentation

Everyone else in the class will be expected to read the papers and submit substantive comments or questions for discussion by 5pm on the Thursday afternoon before the discussion.

This will be done via google form linked from the class webpage. I will send a link prior to the first discussion.

These are not easy reads! Some tips:

Start reading early. Google often. Take notes. Discussion leaders will most likely need to read their paper more than once.

"<u>Lean in" to confusion!</u> It is perfectly fine to be confused, try to understand specifically what you find confusing. Feeling confused is a big part of research!

Don't take things for granted - some of the stuff in these papers is old and may have been superseded. Dig deeper into the literature to understand the landscape.

Read critically, note the flaws, but also try to understand why these papers are classics - they all made a big impact on the field.

I am happy to chat with you about the papers beforehand - just set up an appointment.

Final Project

50% of your grade is based on a final proposal project submitted in the last week of class.

You will be expected to write a proposal, following standard practices in the field, asking for observations, supercomputer time, funding or other resources addressing a question about the ISM.

After the proposals are due, we will hold a review panel meeting to evaluate the proposals (although I get final say on grades :-)

Final Project

On Jan 17, we will have a more detailed discussion of proposals, going over some of the options.

Note, if you get into this project deeply - you could actually submit your proposal!

Final Project

Some key dates:

Jan 17: discussion in class of proposal & formats
Feb 14: submit proposal abstract & bibliography
Mar 9: full proposal deadline
Mar 13: presentations

I am available to talk about this throughout the quarter, just email to set up an appointment.

Grades

Your grade is based on:

15% paper presentation
10% participation in paper discussions
25% homework
50% final proposal project

Any Questions?

The History of Studying the ISM

Our conception of the ISM is closely tied to how we are able to observe it.

Time ↓

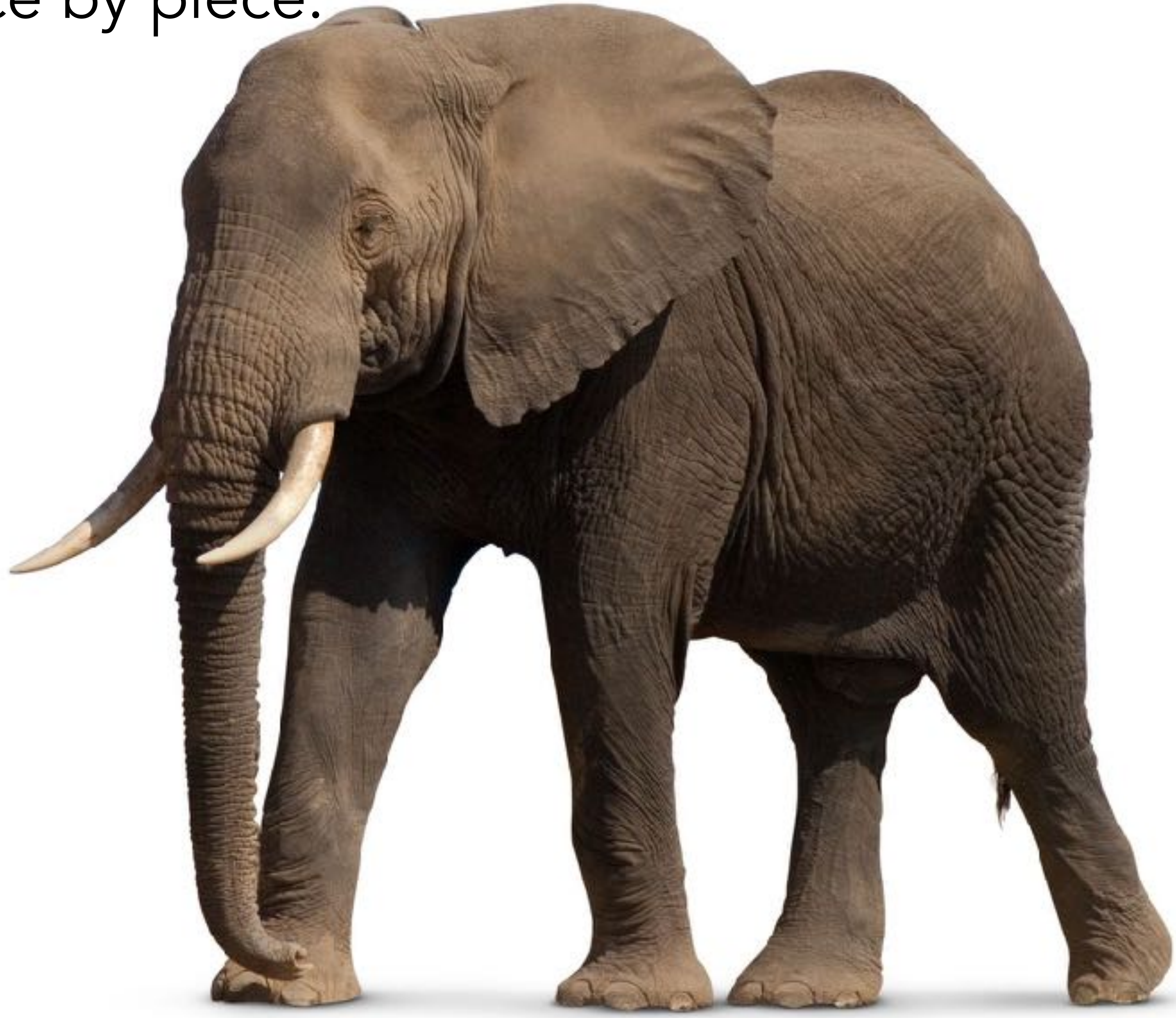
- Optical - Naked Eye
- Optical - Photographic Plates & Imaging
- Optical - Spectroscopy
- Radio
- UV/X-ray/Infrared
- mm

The ISM is a pretty uniform, wrinkly gray patch.

The ISM is very spiky
and made of hard stuff.

The ISM is mostly big tree trunk like patches of wrinkly gray stuff.

The ISM is a giant complex system that is hard to study piece by piece.



Around the start of the 20th century, astronomers started to recognize that there was material between the stars in the Milky Way

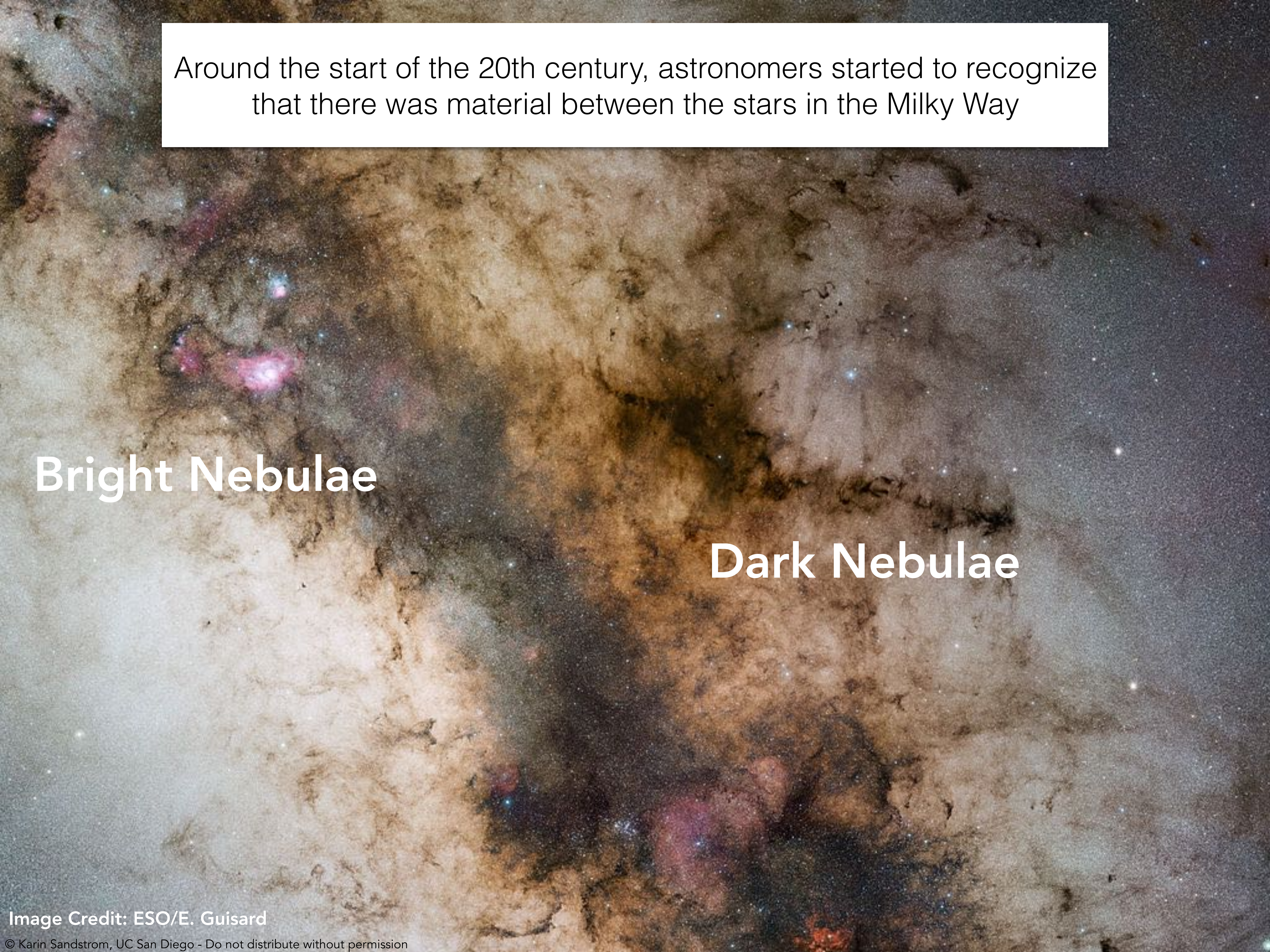


Image Credit: ESO/E. Guisard

“Hier ist wahrhaftig ein Loch im Himmel!”

“Here is truly a hole in Heaven.”

William and Caroline Herschel cataloged dark clouds or “holes” with the **naked eye**.

The Scientific Papers of Sir William Herschel, (London: The Royal Society & Royal Astronomical Society),1912 Vol II, pg 712.

712 STAR-GAGES FROM THE 358TH TO THE 1111TH SWEEP

VACANT PLACES

[*Extracted from the Sweeps. Places for the Year of Observation.*]

Sweep.	R.A.	P.D.	Stars.	
383 Mar. 10 1785	16 5 22	109 25	0	
	16 6 22	109 20	0	
	16 6 32	109 31	0	
	16 7 22	109 49	0	
	16 7 42	109 12	0	
	16 11 52	110 17	0	
	16 12 22	109 11	0	
	16 12 40	110 25	0	
	16 13 0	111 29	2	
485 Dec. 7 1785	4 17 37	65 29		Upper border of a vacancy, but it is a very irregular one.
	4 18 30	65 27		Do.
	4 19 17	65 29		Do.
	4 21 35	64 31	0	
	4 22 26	64 22	0	
	4 23 53	64 4	0	and many such in the neighbourhood.
	4 25 17	..		There is a vacancy between the bright row of stars in the direction of Orion's belt and the Bull's head, Perseus' body and the Milky Way, and I am now in that vacancy.
	4 27 26	65 4	0	Intermixed with places that have many stars.
	4 28 6	64 10	0	
	4 28 42	65 11	0	
	4 29 24	65 15	0	
	4 30 54	65 16	0	
	4 37 51	65 16	0	
	4 39 16	..		The straggling stars of the Milky Way seem now to come on gradually, most small.
	4 43 20	..		They begin now to be intermixed with some larger ones.
516 Jan. 30	5 32 16	98 30	0	
	5 32 42	100 21	0	Vacant spaces picked out, between stars

Optical Photographic **Spectroscopy** demonstrates some nebula have **emission line spectra** indicating "gaseity".

II. "On the Spectrum of the Great Nebula in the Sword-handle of Orion." By WILLIAM HUGGINS, F.R.A.S. Communicated by the Treasurer. Received January 11, 1865.

In a paper recently presented to the Royal Society*, I gave the results of the application of prismatic analysis to some of the objects in the heavens known as nebulæ. Eight of the nebulæ examined gave a spectrum indicating gaseity, and, of these, six belong to the class of small and comparatively bright objects which it is convenient to distinguish still by the name of planetary. These nebulæ present little indication of probable resolvability into discrete points, even with the greatest optical power which has yet been brought to bear upon them.

Spectrum of some nebulae shows a stellar spectrum, light is reflected off of small particles.

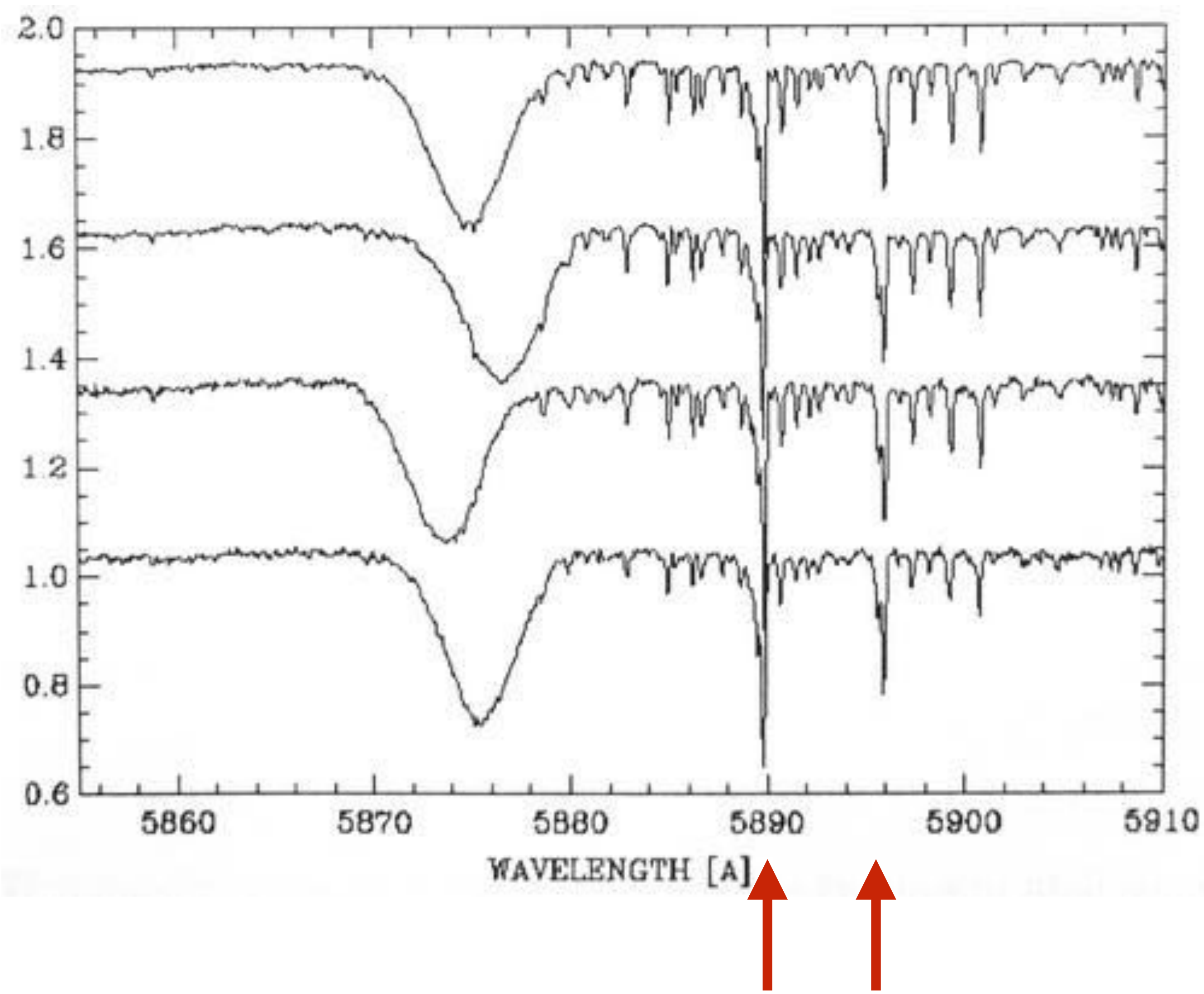
V. M. Slipher
Lowell Observatory
Bulletin 1912,
vol. 2, pp.26-27

by the star light to be visible, and thus there seems to be support for the conclusion that the Pleiades nebula shines by reflected light.

This observation of the nebula in the Pleiades has suggested to me that the Andromeda Nebula and similar spiral nebulæ might consist of a central star enveloped and beclouded by fragmentary and disintegrated matter which shines by light supplied by the central sun. This conception is in keeping with spectrograms of the Andromeda Nebula made here and with Bohlin's value for its parallax.

V. M. Slipher.

Hartmann 1904 shows narrow, stationary absorption lines in the spectrum of binary star δ Orionis - velocity different than the stars.

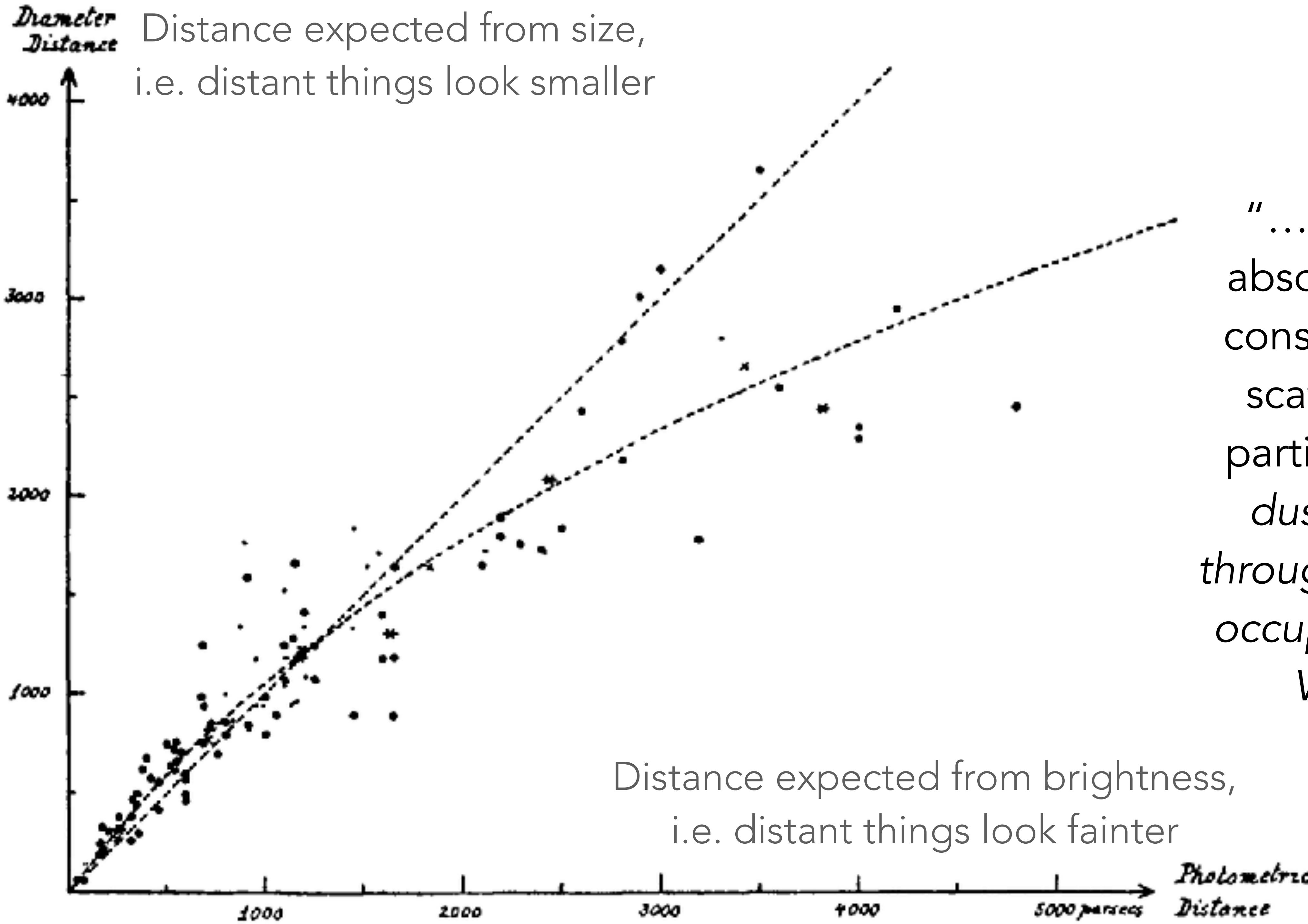


These lines turn out to be CaII H & K (3933 and 3968 Å) .

Similar measurements (left) show the "stationary" NaI D doublet (5890 and 5896 Å)

Lines are very narrow (i.e. from cold gas), strength of the line correlates with distance to the star.

In the 1930s, Robert Trumpler's observations of star clusters suggested the presence of dust in the ISM.



"…interstellar light absorption may be a consequence of light scattering by small particles, *fine cosmic dust, thinly spread through the vast spaces occupied by our Milky Way system.*"

ISM Paradigm Pre-1930's

Diffuse material, absorption from small particles, constant density, velocity.

Advances in high resolution spectroscopy show this isn't the case! Narrow NaI and CaII lines resolve into multiple velocity components.

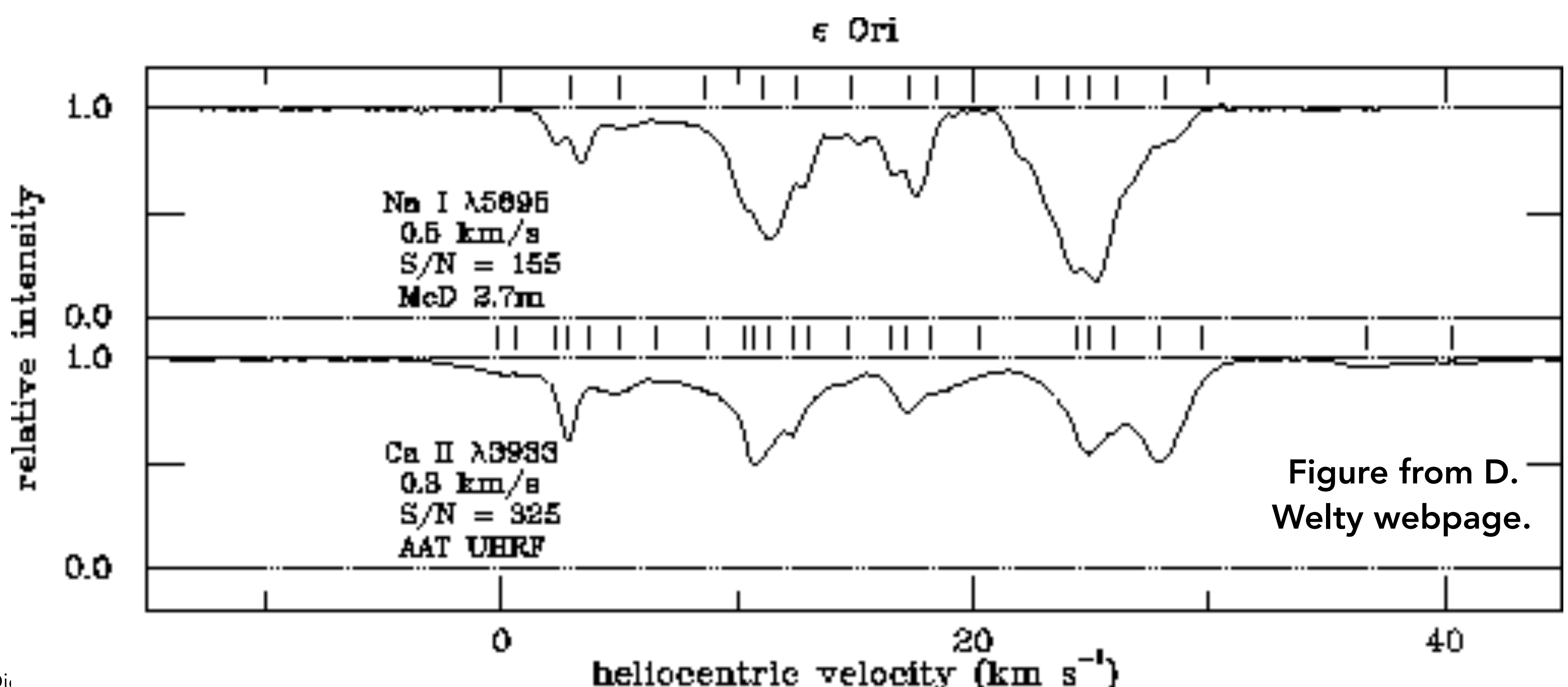


Figure from D. Welty webpage.

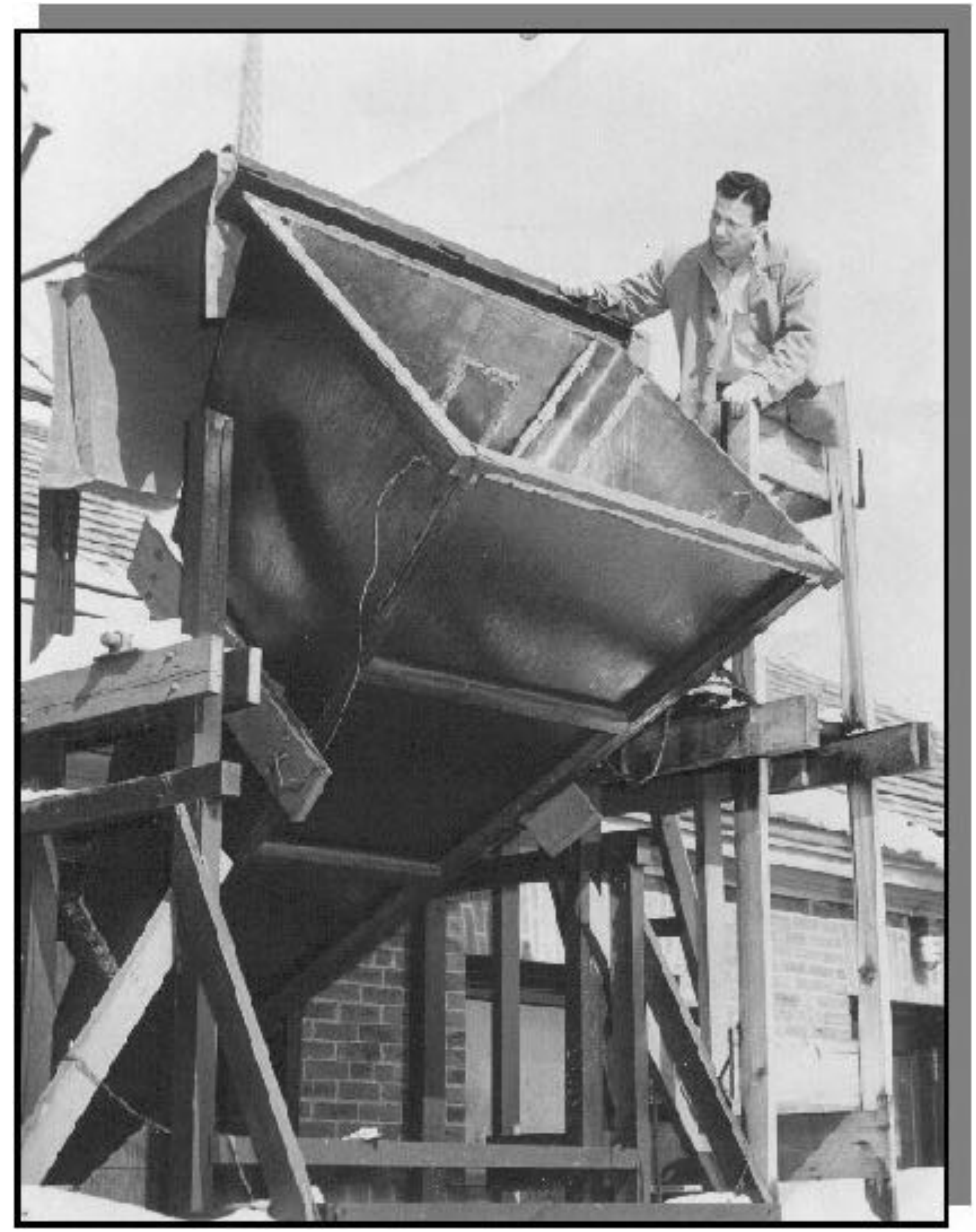
Cosmic Rays

- 1912: V. Hess balloon flights over 5km in altitude, finds some form of ionizing radiation which increases with altitude. 1912 flight during solar eclipse argues for interstellar origin. Nobel prize!

- 1927-34: Clay, Bothe, Kohlörster & Alvarez, cosmic rays are high energy charged particles not γ rays

Radio Astronomy & The 21-cm Line

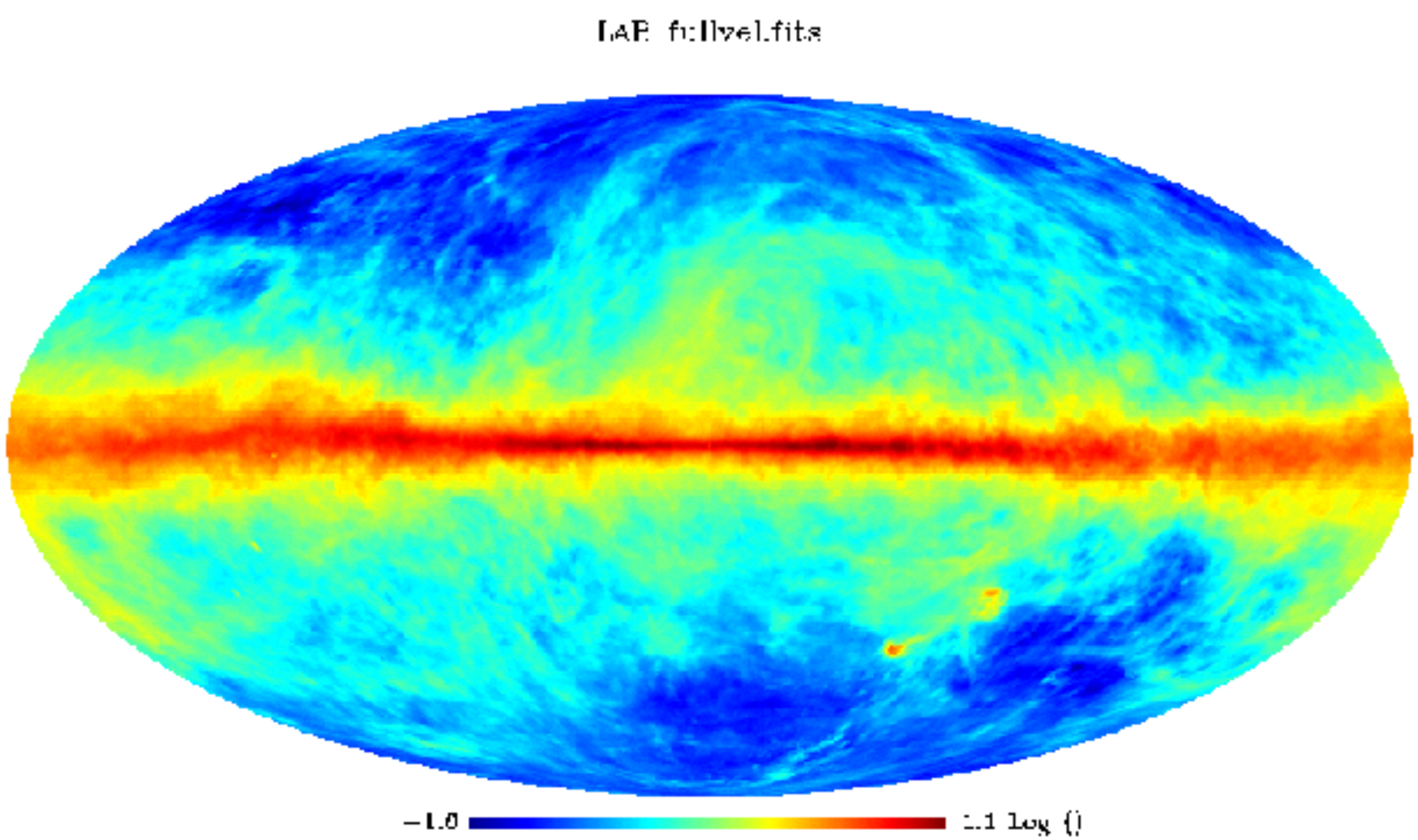
- 1944: Hendrik van de Hulst predicts the existence of the HI 21-cm hyperfine spin-flip transition.
- During WWII, development of radio astronomy parallels radar technology - lots of interesting history.
- 1951: Ewen & Purcell at Harvard (6 weeks later Muller & Oort in the Netherlands) measure the 21-cm line from the ISM.



http://www.nrao.edu/whatisra/hist_ewenpurcell.shtml

Radio Astronomy & The 21-cm Line

Cold HI emitting at 21-cm makes up most of the mass of ISM gas in the Milky Way, so being able to observe this **directly** was a revolution in how we understood the ISM.

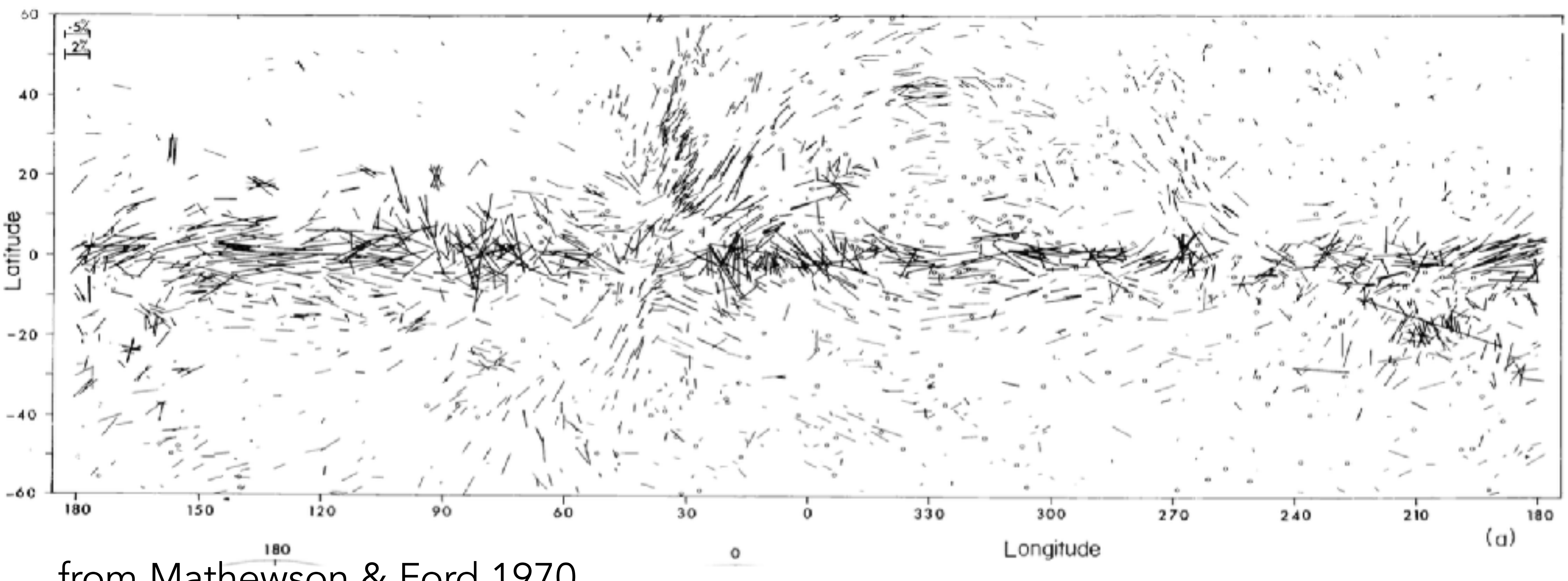


ISM is clumpy, turbulent, highly non uniform.

http://irsa.ipac.caltech.edu/data/Planck/release_1/external-data/external_maps.html

Magnetic Fields

1949: Hall & Hiltner show polarization of starlight correlated with reddening.

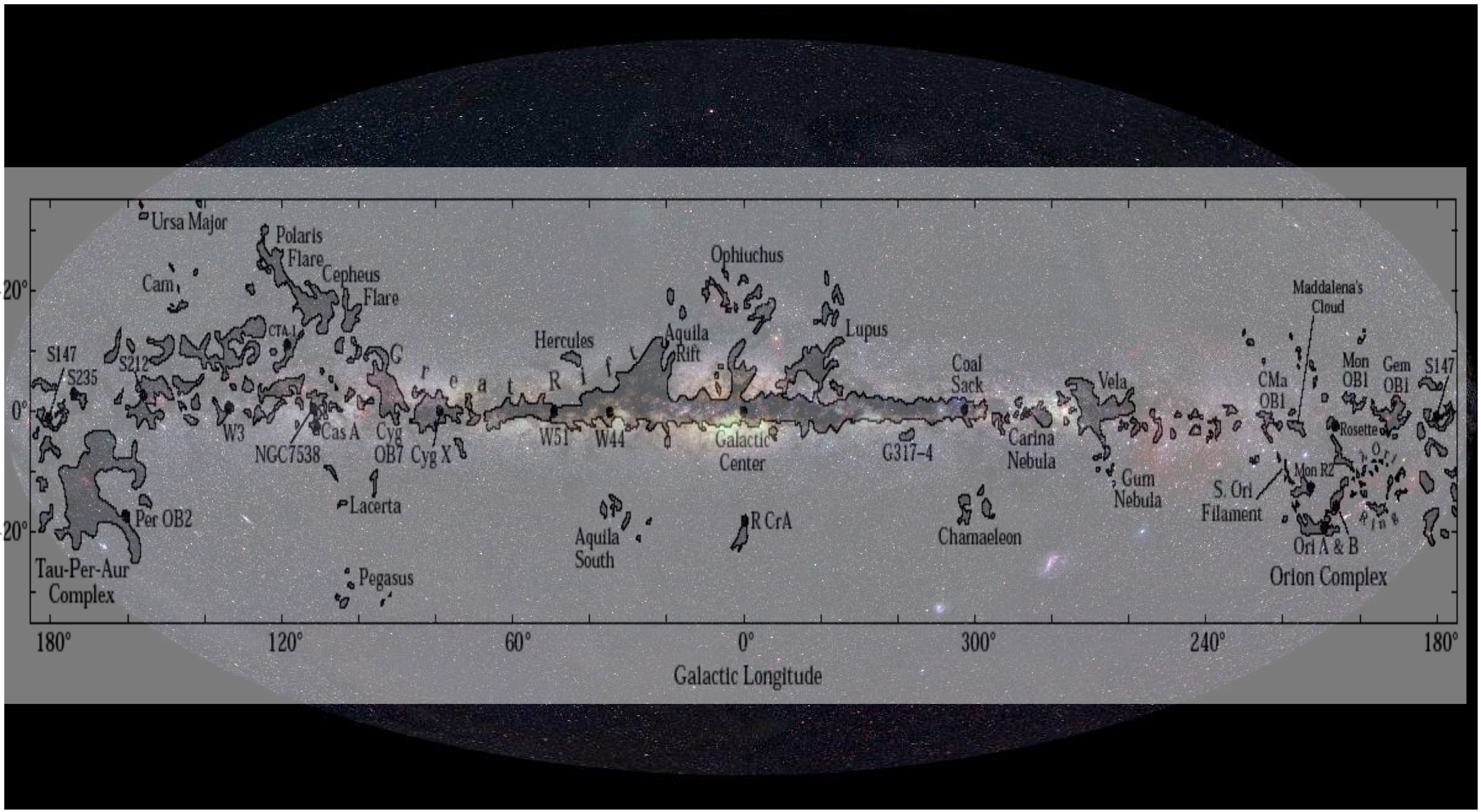


from Mathewson & Ford 1970

mm Astronomy & molecules

- 1937-40: optical absorption lines demonstrate there is interstellar diatomic molecules CH, CH^+, CN.
- 1963: radio observations of OH by Townes et al.
- 1968: NH_3 (ammonia) and H_2CO (formaldehyde) observed towards individual clouds.
- 1970: Wilson, Jefferts, & Penzias observe 2.6mm rotational line of the CO molecule.
- 1980s-now: many more & more complex molecules are observed in the ISM.

mm Astronomy & molecules



mm Astronomy & molecules

CO shows there are cold, dense regions of gas associated with star formation.

Reveals interstellar chemistry to be important & complex!

Sensitivity of mm telescopes initially shows only the densest regions - “cloud” paradigm.

Space Astronomy (1980s-now)

- γ-rays: high energy particles interacting with ISM gas
- X-ray: there's lots of hot (10^5-10^6 K) gas!
- Ultraviolet: H_2 absorption, UV extinction curve of dust
- Infrared: warm dust everywhere, H_2 rotational lines, far-infrared fine structure lines of carbon, oxygen, etc reveal cooling of ISM gas, small/hot dust grains

The Contents of the ISM

- Gas
- Dust
- Photons
- Cosmic Rays
- Magnetic Fields

Note: ISM resides in the gravitational potential set by dark matter and stellar mass of a galaxy (sometimes gas mass matters too).

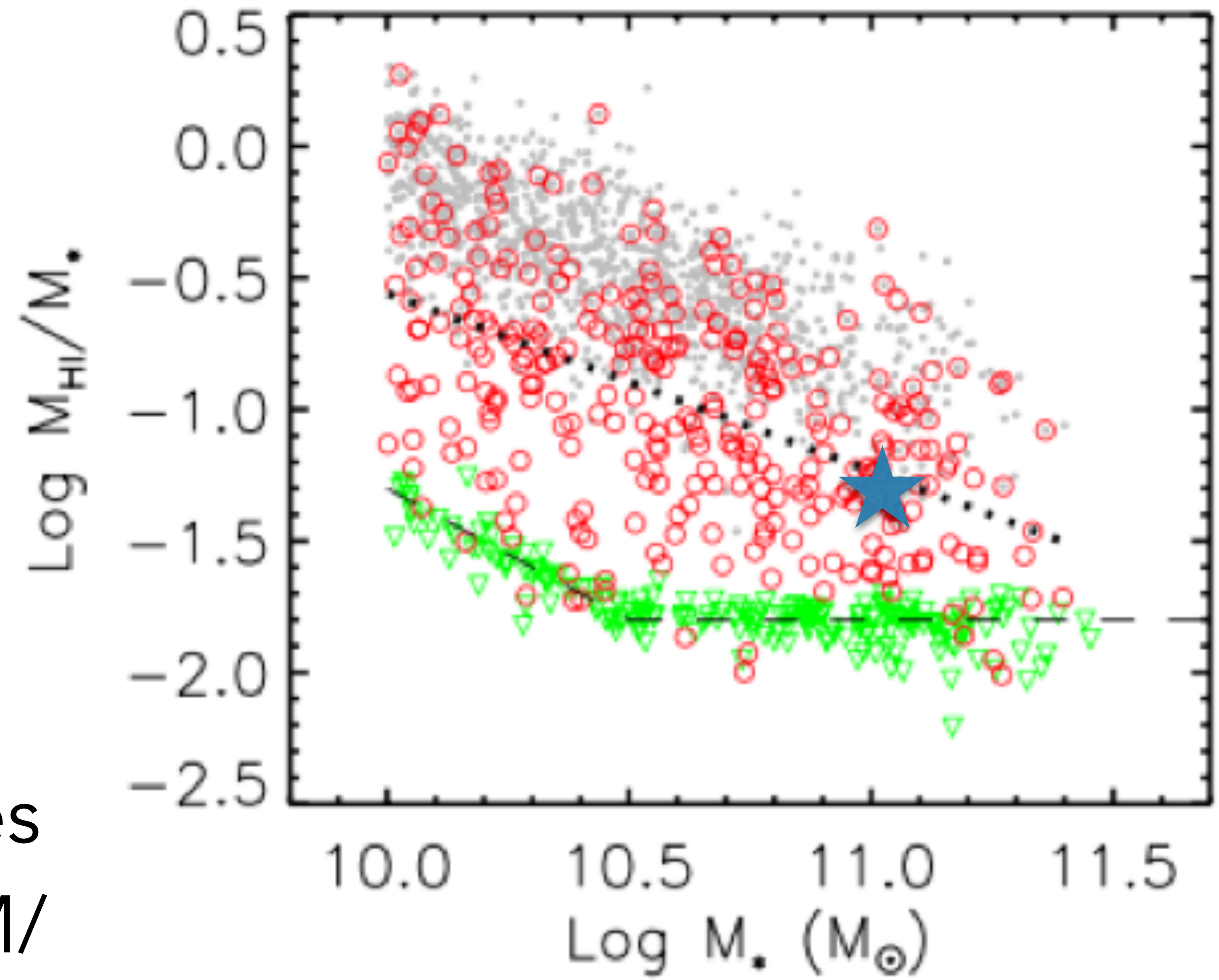
The Milky Way

Dark Matter: ~10^{12} $M_\odot$

Stellar Mass: ~10^{11} $M_\odot$

ISM Mass: ~$6x10^9$ $M_\odot$

Not the same in all galaxies — some have different ISM/ stellar mass ratios.



GASS Survey (Catinella et al. 2012)
gray = shallower ALFALFA survey
red = HI detected, green = not detected

ISM Gas

in MW, approx. 23% ionized, 60% neutral, 17% molecular

characterized by "phases"

Name	T (K)	Ionization	frac of volume	density (cm^{-3})	P ~ nT (cm^{-3} K)
hot ionized medium	10^6	H^+	0.5(?)	0.004	4000
ionized gas (HII & WIM)	10^4	H^+	0.1	0.2-10^4	2000 - 10^8
warm neutral medium	5000	H^0	0.4	0.6	3000
cold neutral medium	100	H^0	0.01	30	3000
diffuse molecular	50	H_2	0.001	100	5000
dense molecular	10-50	H_2	10^{-4}	10^3-10^6	10^5 - 10^7

ISM Dust

Gas & dust are well correlated in the disk of the Milky Way, but gas/dust ratio can & does vary.

Element	Abundance	*A*	M/M_H
C*	2×10^{-4}	12	0.00252
O*	1.5×10^{-4}	16	0.00246
Fe	3.5×10^{-5}	56	0.00196
Si	3.4×10^{-5}	28	0.00095
Mg	4×10^{-5}	24	0.00094
N,Al,S,Ca, Ni			0.00027
Total			**0.0091**

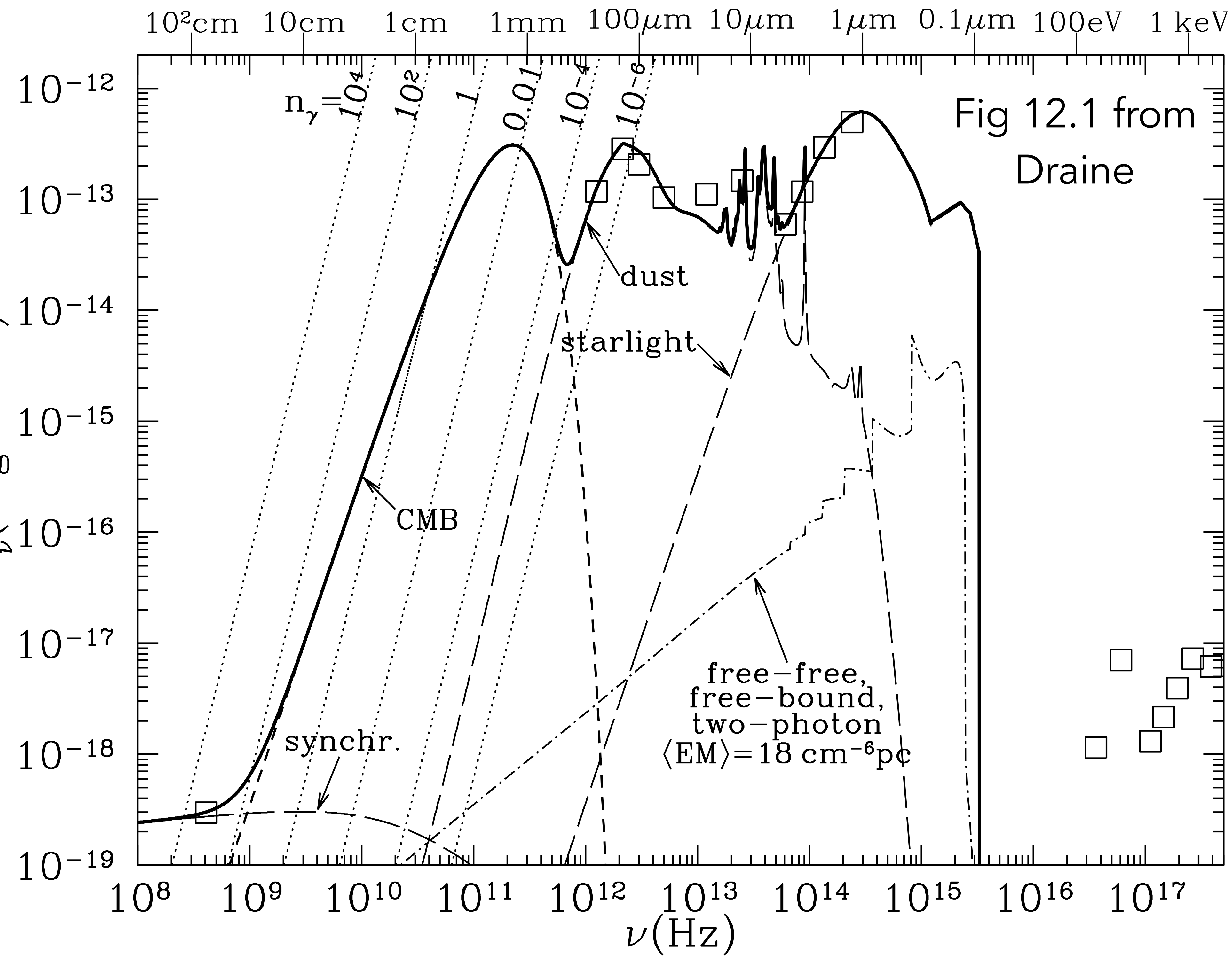
* uncertainty on oxygen depletion and carbon oscillator strength - see Draine

Dust is mainly composed of C, Mg, Fe, Si, and O.

MW Dust-to-H Ratio ~0.009

Small sub-μm size grains (can tell from reddening)

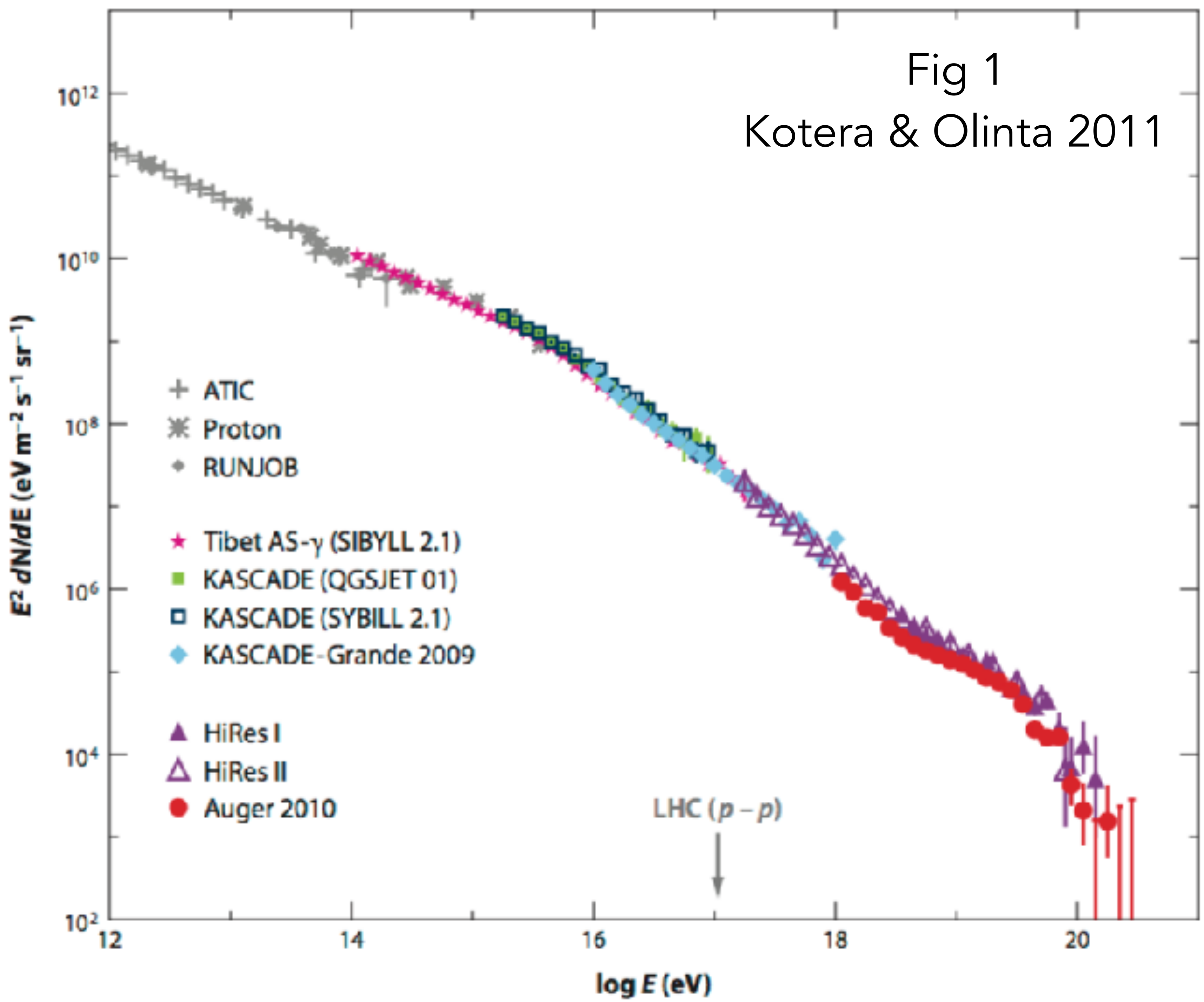
ISM Radiation Field



Average Interstellar Radiation Field

varies from place to place depending on local processes

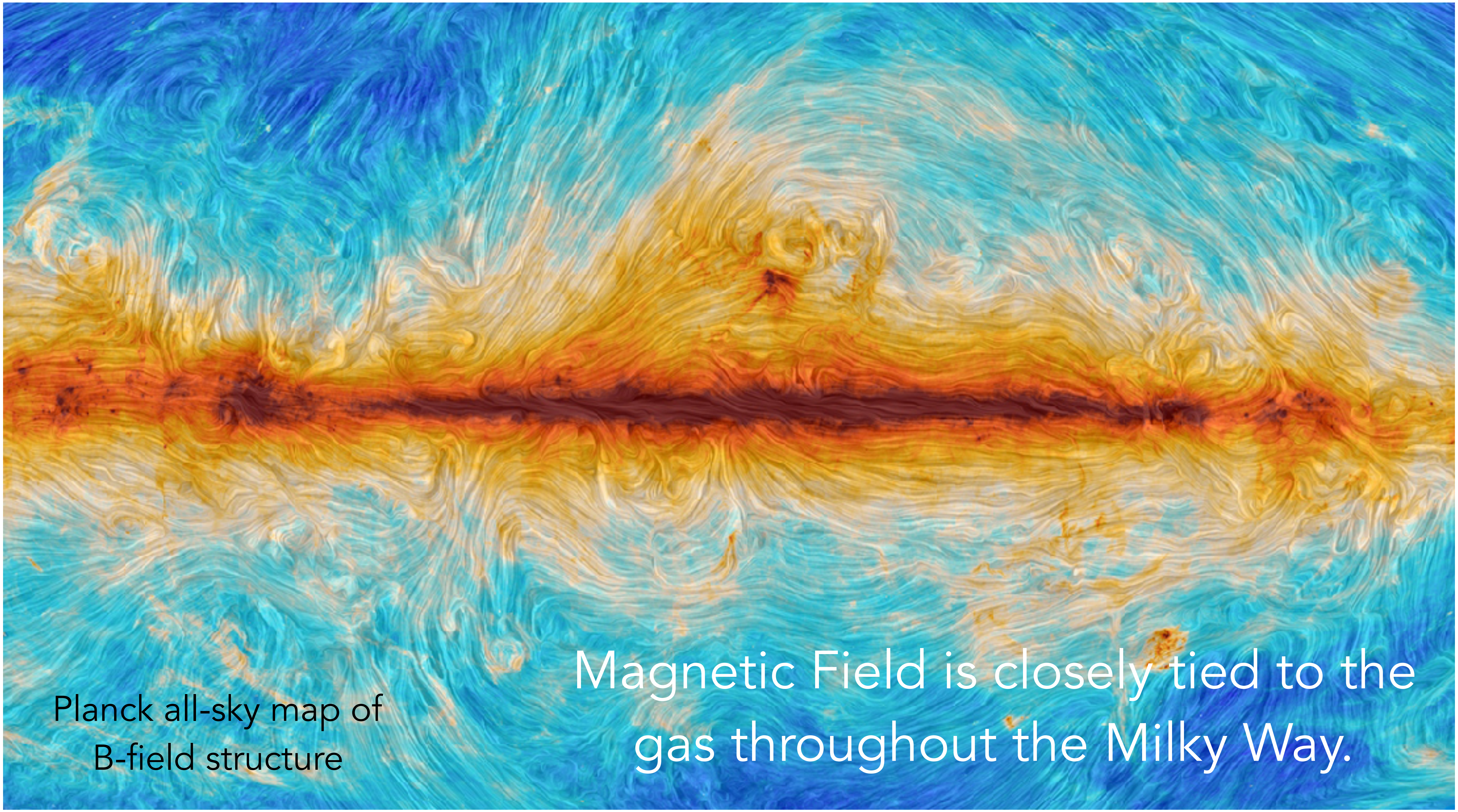
Cosmic Rays



Very energetic particles pervading the ISM.

Dominated by protons, but also includes other nuclei and e-.

Magnetic Fields



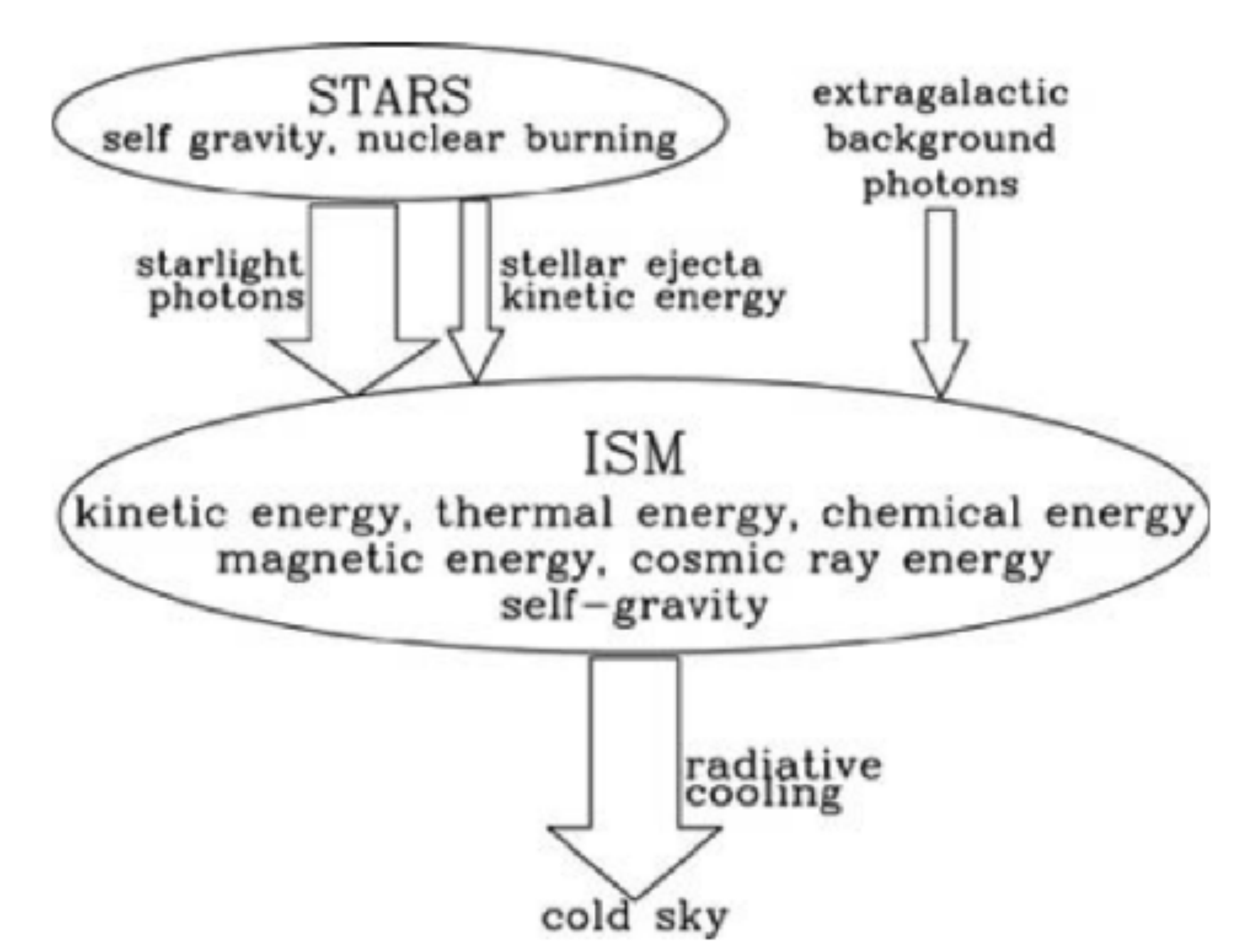
ISM Energy Density

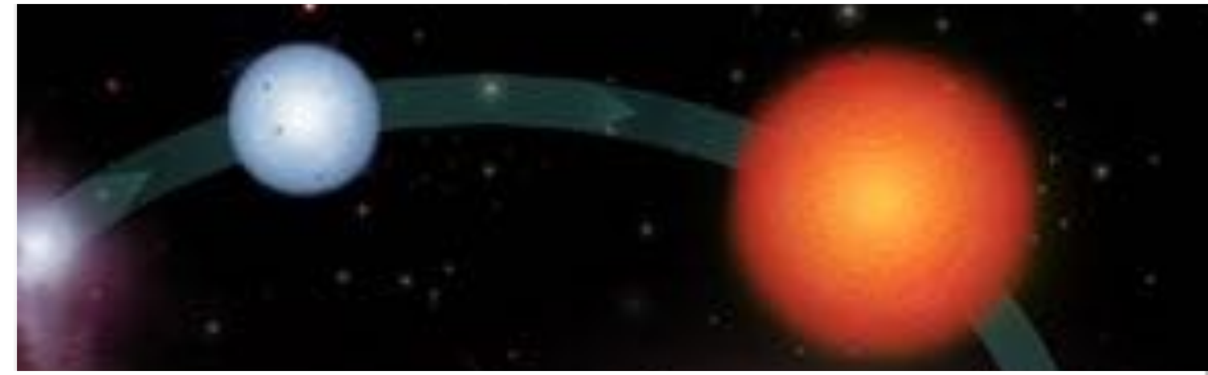
Component	*u* (eV cm^{-3})
Cosmic Microwave Background	0.25 (T_{CMB} = 2.725 K)
Gas Thermal Energy	0.49 (for nT = 3800 cm^{-3} K)
Gas Turbulent Kinetic Energy	0.22 (for n = 1 cm^{-3}, v_{turb} = 1 km/s)
B-Field	0.89 (for 6 μGauss)
Cosmic Rays	1.39 (see Draine ch 13)
Starlight	0.54 (for hν < 13.6 eV)

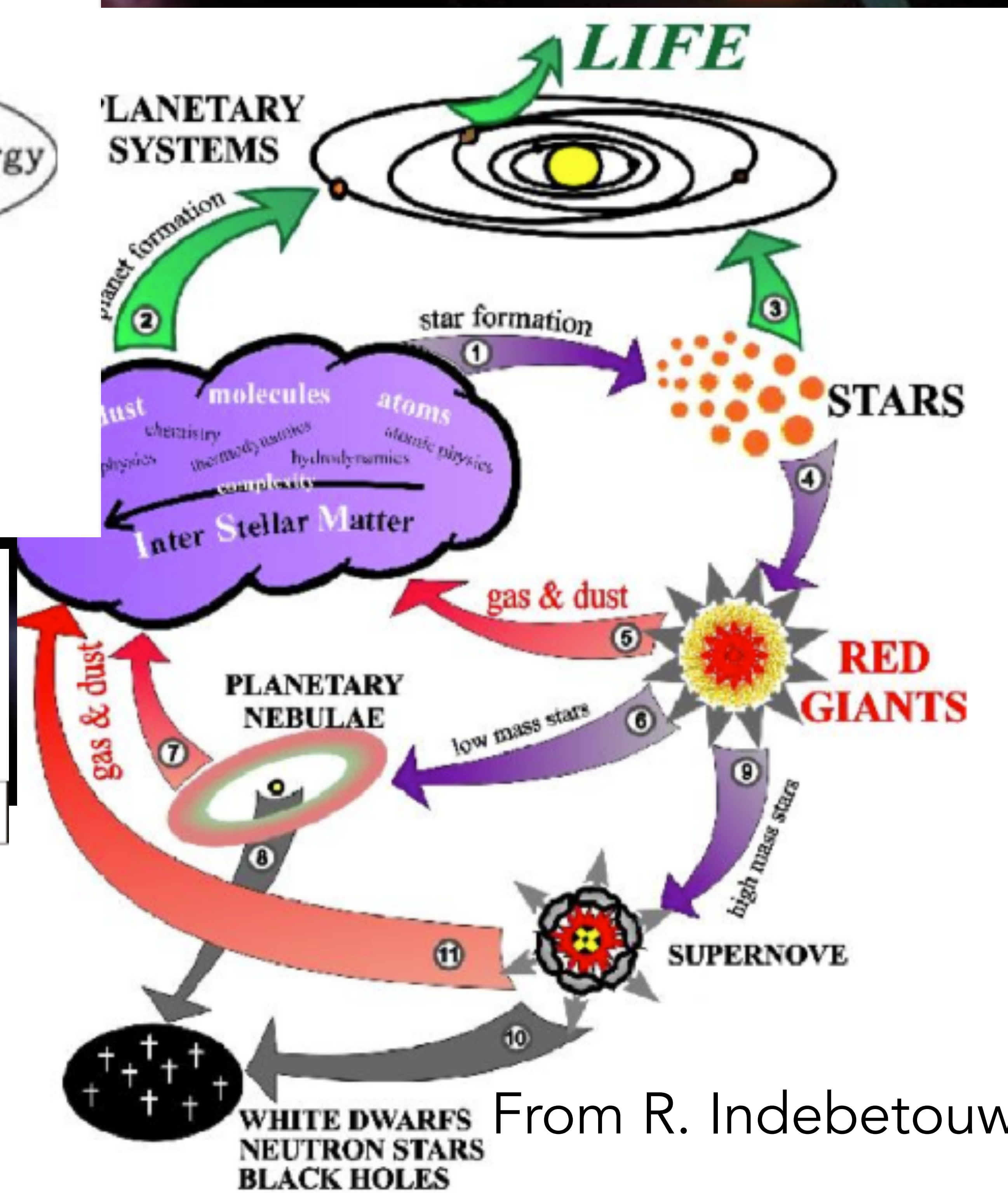
All the same order of magnitude! - Why?

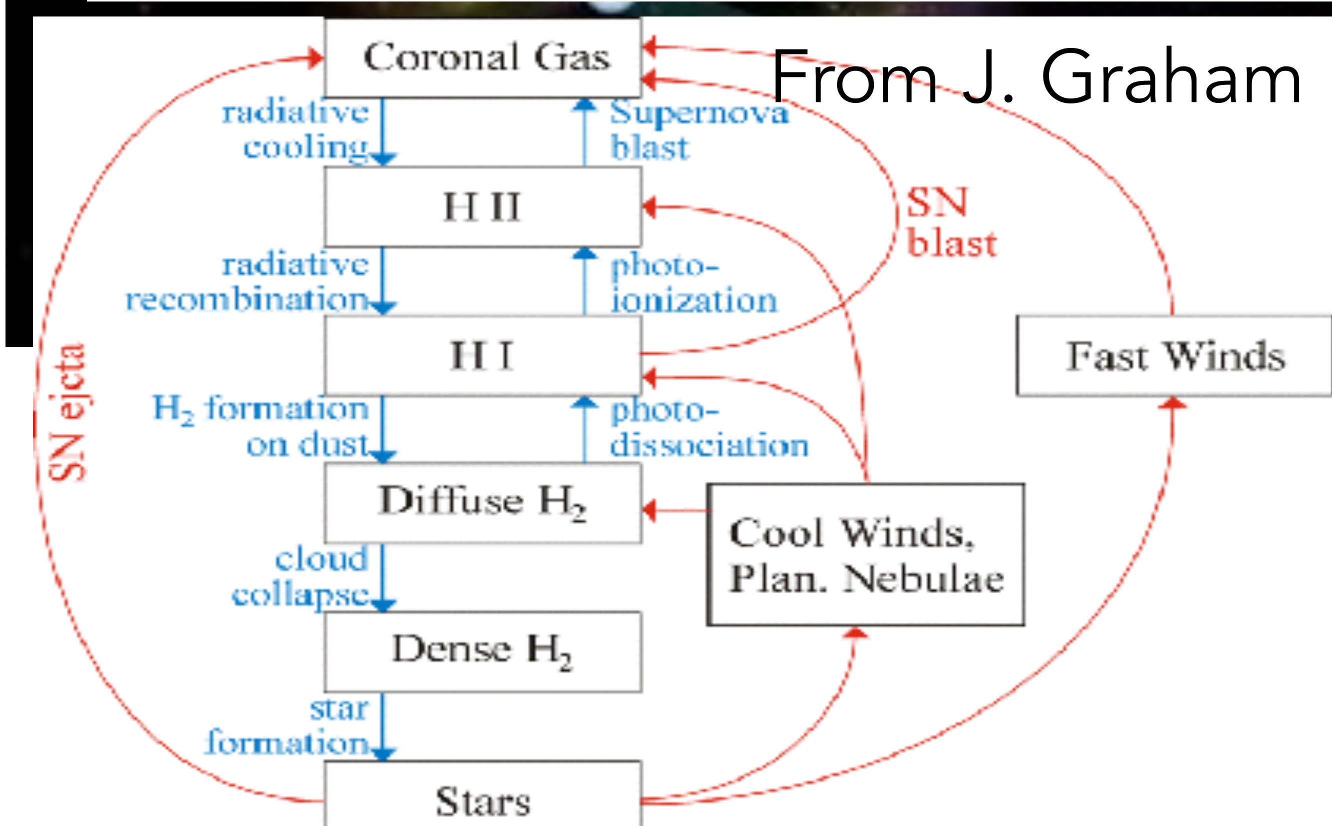
The ISM is Complex

- Huge dynamic ranges in density, temperature.
- Very dense regions of the ISM are “ultra-high” vacuum
  - ISM conditions are tough to reproduce in a lab.
- Most processes are not in thermodynamic equilibrium
  - low density means long equilibrium timescales.
- Processes are interconnected in feedback loops.









From J. Graham

From R. Indebetouw

How does THIS affect THIS	Gravitational Potential	Gas	Dust	Radiation Field	Cosmic Rays	Magnetic Fields	Stars
Gravitational Potential	———	hydrostatic pressure, dynamics, spiral arms, large scale gas stability	2nd order	2nd order	pressure confinement, dynamical influence (e.g. spiral arms)	gas dynamics, pressure arrange B-field	sets stellar mass distribution, 2nd order hydrostatic pressure -> SF
Gas	self-gravity in dense gas clouds	gas dynamics, collisional excitation, self gravity	dust growth in dense gas, collisional heating/cooling, charging, dust destruction in shocks	alters radiation field (H2 shielding, ionizing photons absorbed)	creation (shocks accelerate), collisions (CR + p+ -> γ ray), confinement (B-field)	dynamically, MHD turbulence, dynamos create/ amplify B-field	star formation
Dust	2nd order	heating/cooling gas, shielding, chemistry, metal abundance (grain sputtering)	grain-grain collisions, shielding small grains from UV	extinction (absorption & scattering)	2nd order	ionization of grains and gas, keeps B-field tied to gas	key role in SF
Radiation Field	2nd order	heating of gas, ionization, photoelectric effect	heating dust, charging grains (PE effect), destruction of small grains	———	2nd order	ionization of gas, keeps B-field tied to gas	key role in SF
Cosmic Rays	2nd order	ionization in dense gas, connection to B-field	2nd order	2nd order	———	tied closely to B-field, equipartition?	heats dense gas that forms stars
Magnetic Fields	2nd order	dynamically, MHD turbulence	grain alignment, charged grains coupled to B-field	2nd order	tied closely to B-field, equipartition?	? reconnection & dissipation	dynamically important in collapse -> SF
Stars	large part of the overall mass that sets the grav potential	SNe/winds - dynamics, nucleosynthesis (metals), radiation field generation	create & destroy dust, generate radiation field that heats dust	directly produce it	SNe shocks -> CR	2nd order	feedback shuts off SF