Astronomy 496/596:

Observational ISM and Star Formation

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http://eeyore.astro.uiuc.edu/~lwl/classes/astro596/spring07

This Class (Lecture 2):

ISM

Next Class:

Molecular Clouds

Music: *Fly Away* – Lenny Kravitz

Outline

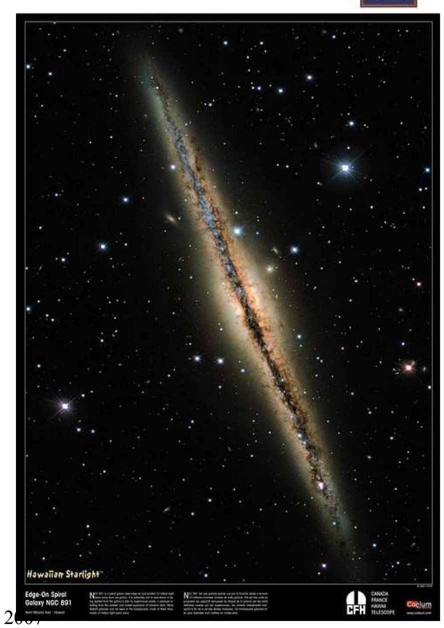
- ISM overview
- Technical diversion– radio astronomy
- HI and CO

ReCap

1. 20-30 min lecture that hopefully prepares everyone for the paper in the next class
2. Someone is chosen, randomly, to give a brief summary
   - Like you would explain the key results to a peer
   - Bullets of main points (not just from abstract)
3. Primary gives presentation on paper
   - Fit into large scale picture of star formation
   - Parse paper into the more salient points
4. Secondary, working with primary, chooses an important reference from paper and gives a brief summary
   - Fit into presentation
   - How it relates to topic at hand

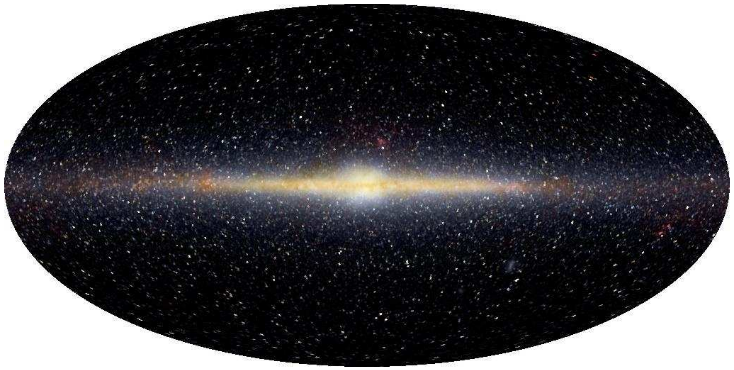
The ISM

- Makes beautiful dust lanes
  - Mostly confined to the disk, with a little gas in the halo
- In optical, only notice the extinction
  - Most of the ISM is either cold (< 100 K: IR) or very hot (> 10^6 K: x-ray)
  - Only in the last 50 years has the nature & importance of the ISM become evident
- Density can be vastly different ($n \sim 10^{-3}$ to 10^6 cm^{-3})
  - Still "ultra-high vacuum" (10^{-10} Torr is $n \approx 4 \times 10^6$ cm^{-3}, compare to air at STP $n \approx 3 \times 10^{19}$ cm^{-3})



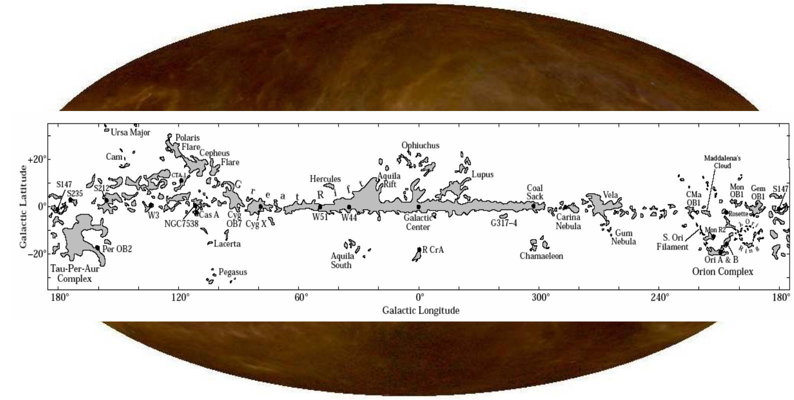
http://antwrp.gsfc.nasa.gov/apod/ap020703.html

Without the ISM

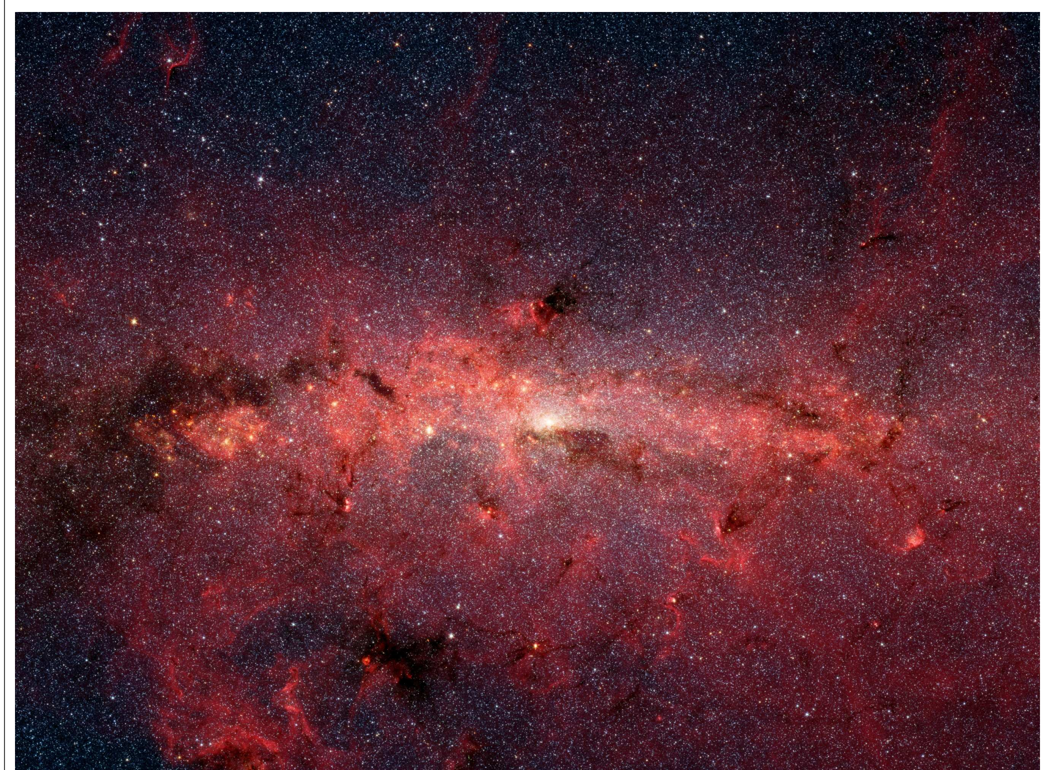


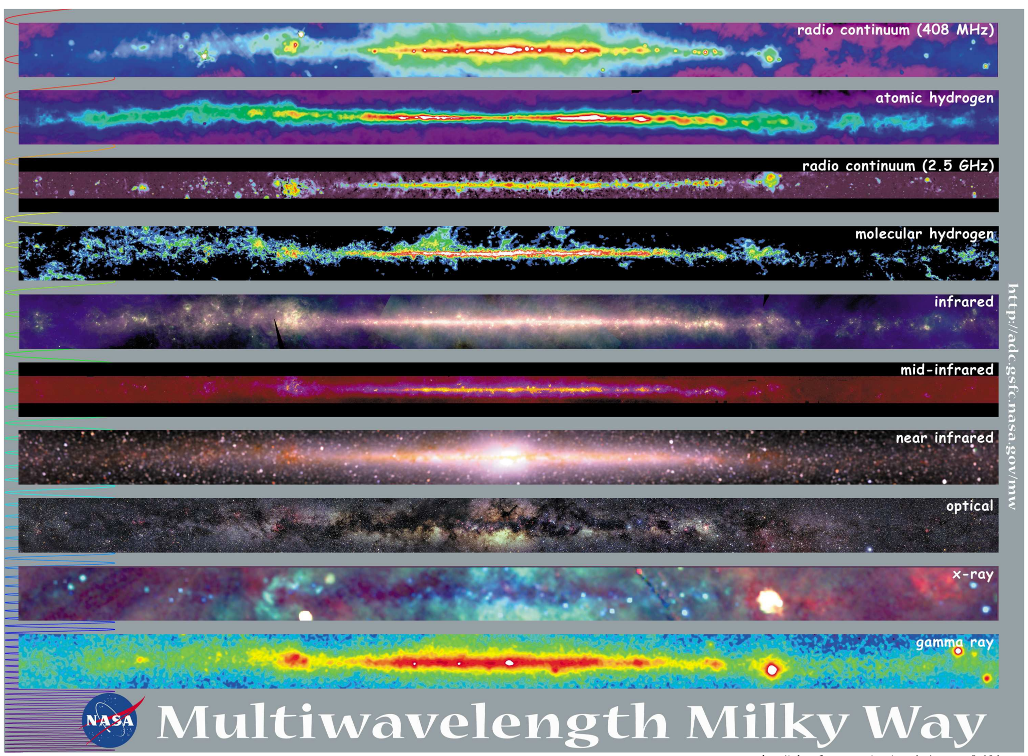
- A different picture of the sky emerges in the IR
  - COBE maps the sky between 1.3 µm and 4 µm
  - The near-IR (*J*, *K* & *L*) shows mostly stars & reduced ISM absorption
  - The disk-like nature of our Galaxy with its bulge is evident

ISM Only

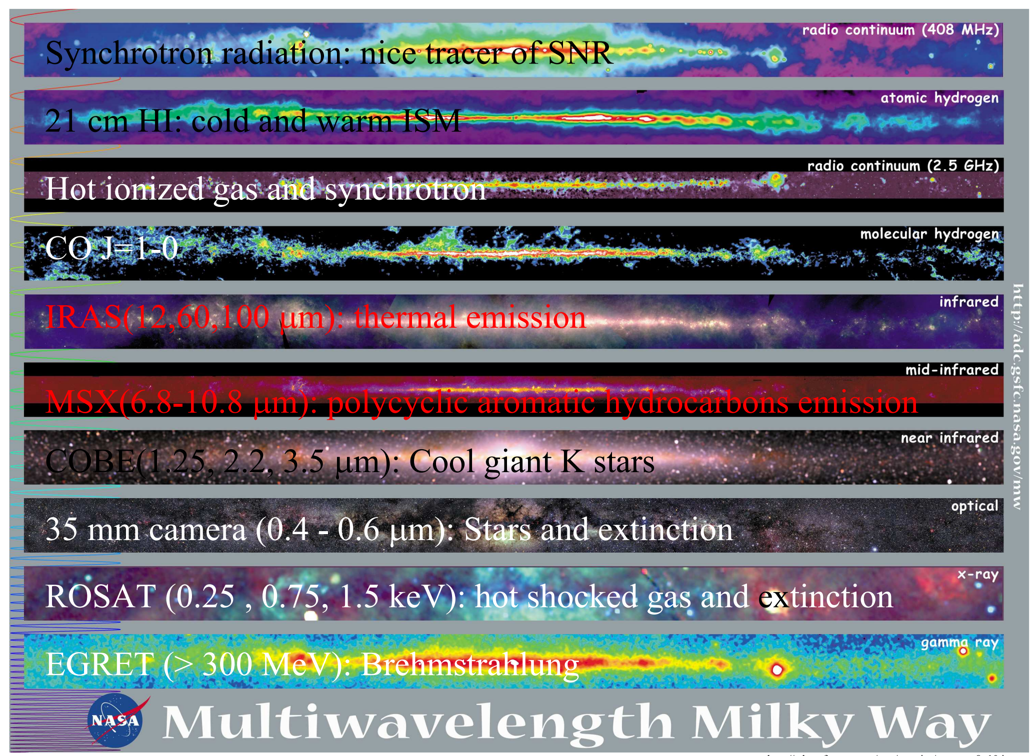


- COBE 100, 140 & 240 µm
  - No ordinary stars, only a few with circumstellar dust shells are weakly detected
  - The bulk majority of emission is from clouds of cool dust (≤ 20 K)





http://adc.gsfc.nasa.gov/mw/mwpics/mwmw_8x10.jpg



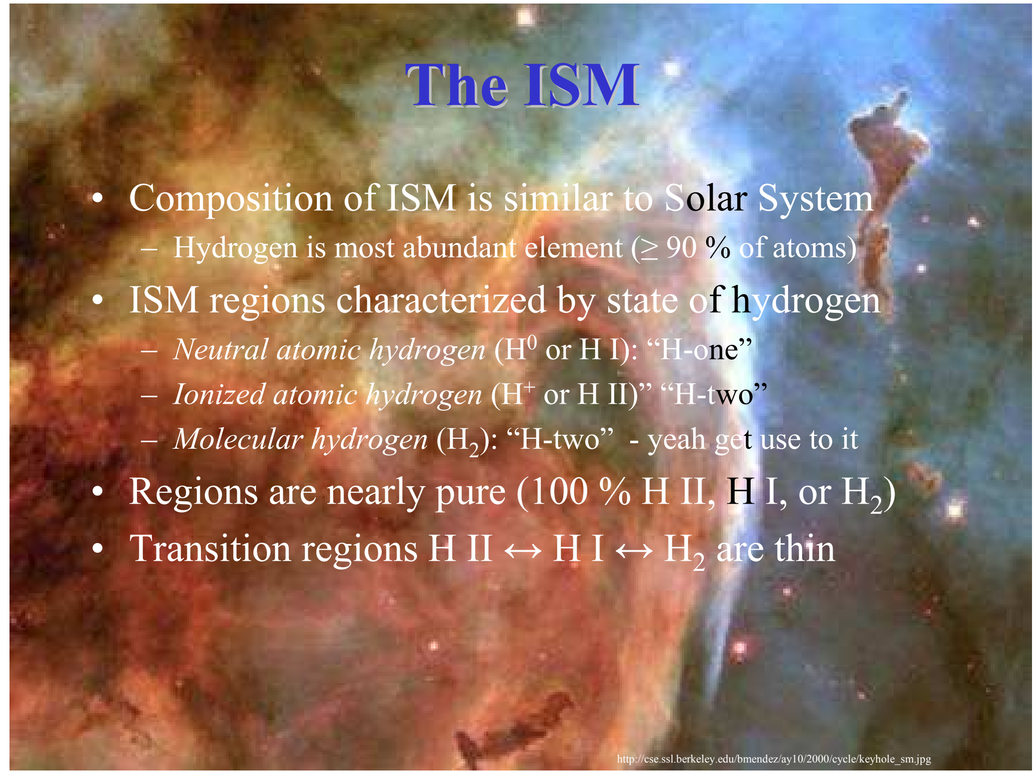
http://adc.gsfc.nasa.gov/mw/mwpics/mwmw_8x10.jpg

Solar Abundance

Element	N/N_H	Element	N/N_H
H	1.0	Mg	4.2×10^{-5}
He	0.096	Al	3.5×10^{-6}
C	2.9×10^{-4}	Si	4.1×10^{-5}
N	8.0×10^{-5}	S	1.8×10^{-5}
O	5.8×10^{-4}	Ca	2.6×10^{-6}
Na	2.4×10^{-6}	Fe	3.4×10^{-5}

From Lodders (2003): protosolar (corrected)

- Mass fractions
  X = 0.7110 (H), Y = 0.2741 (He), Z = 0.0149 (metals)
- Maybe very different in B stars (recent ISM values), e.g. higher C



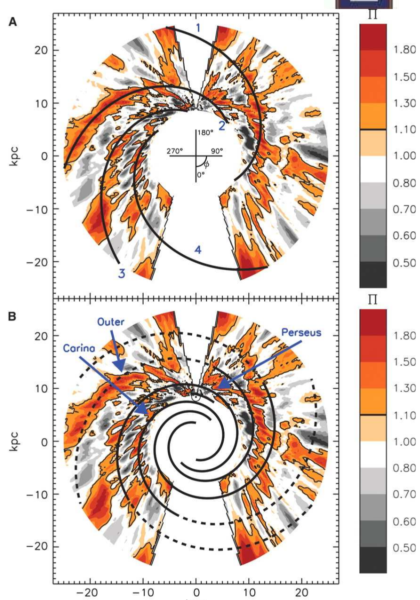
The ISM

- Composition of ISM is similar to Solar System
  - Hydrogen is most abundant element (≥ 90 % of atoms)
- ISM regions characterized by state of hydrogen
  - *Neutral atomic hydrogen* (H^0 or H I): "H-one"
  - *Ionized atomic hydrogen* (H^+ or H II)" "H-two"
  - *Molecular hydrogen* (H_2): "H-two" - yeah get use to it
- Regions are nearly pure (100 % H II, H I, or H_2)
- Transition regions H II ↔ H I ↔ H_2 are thin

http://cse.ssl.berkeley.edu/bmendez/ay10/2000/cycle/keyhole_sm.jpg

H I: Atomic Gas

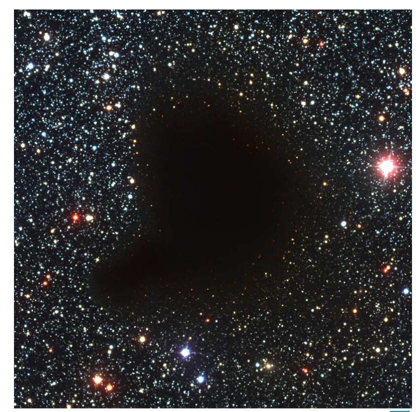
- "Cool" Clouds (CNM)
  - $T \approx 80$ K
  - $n \approx 1$ cm^{-3}
- Warm neutral gas (WNM)
  - $T \approx 6000$ K
  - $n \approx 0.05$ to 0.2 cm^{-3}



How many arms do we have?
Levine et al. 2006

H_2: Molecular Gas

- Cold dark clouds ($M \approx 10$ - $1000\ M_\odot$)
  - $T \geq 10$ K
  - $n \approx 10^2$ - 10^4 cm^{-3}
- Giant molecular clouds ($M \approx 10^3$ - $10^6\ M_\odot$)
  - $T \geq 20$ K
  - $n \approx 10^2$ - 10^4 cm^{-3}
- Molecular material exhibits complex structure including cores and clumps with $n \approx 10^5$ - 10^9 cm^{-3}
- Molecular clouds are the sites of star formation



The "Black Cloud" B68 (VLT ANTU + FORS1)

http://antwrp.gsfc.nasa.gov/apod/ap990511.html

H II: Ionized Gas

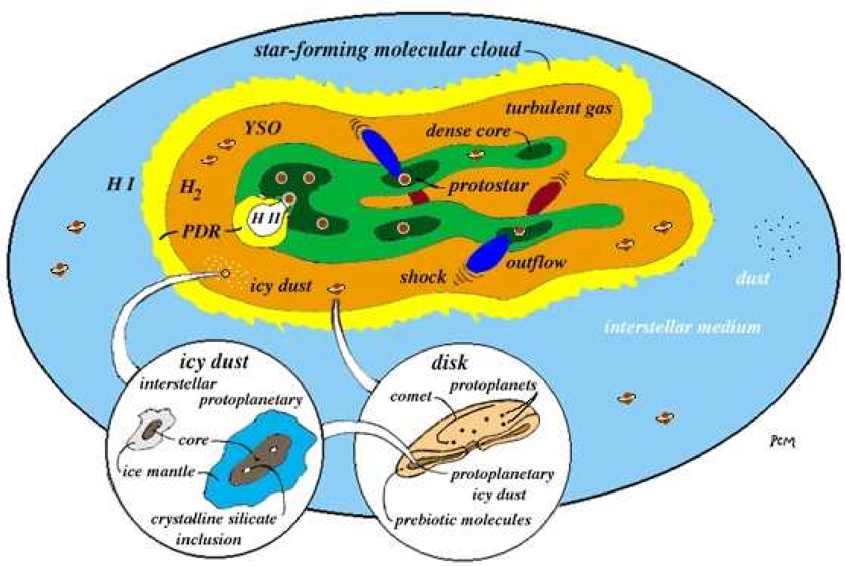
- H II regions surrounding early-type (OB) stars
  - Photoionized
  - $T \approx 10^4$ K
  - $n_e \approx 0.1$ to 10^4 cm^{-3}
  - Bright nebulae associated with regions of star formation & molecular clouds
- Warm Ionized Medium
  - $T \approx 8000$ K
  - $\langle n_e \rangle \approx 0.025$ cm^{-3}
- Hot Ionized Medium: tenuous gas pervading the ISM
  - Ionization by electron impact
  - $T \approx 4.5 \times 10^5$ K
  - $n \approx 0.0035$ cm^{-3}

http://astro.berkeley.edu/~ay216/06/NOTES/ay216_2006_01_Intro.pdf
http://antwrp.gsfc.nasa.gov/apod/ap060120.html

Other Stuff

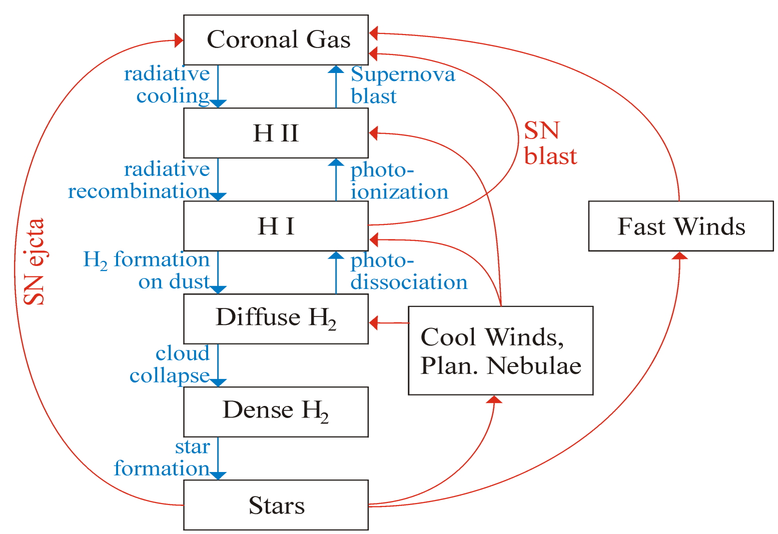
- Heavy elements
  - He (≈ 10 % by number)
  - C, N, O (≈ "cosmic" abundances)
  - Si, Ca, Fe (depleted onto grains)
  - Dust grains (≈ 0.1 μm size, silicates or carbonaceous material ≈ 1% by mass of ISM)
- Photons
  - CMB
  - Star light—average interstellar radiation field
  - X-rays—from hot gas & the extragalactic background
- Magnetic fields & cosmic rays

The Cycle?



http://astro.berkeley.edu/~ay216/06/NOTES/ay216_2006_01_Intro.pdf

The ISM: Moving Between Phases



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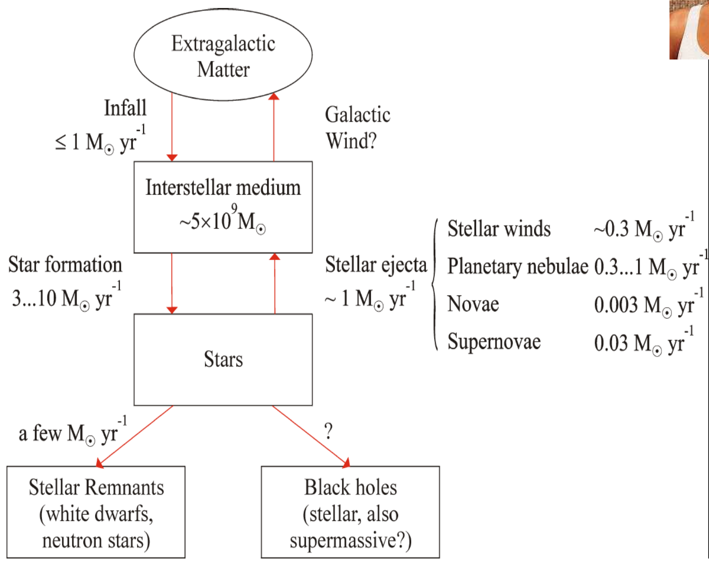
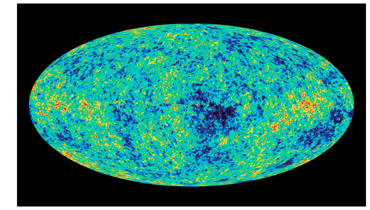
Baryons for Berry



http://www.strw.leidenuniv.nl/~dave/ISM/lecture1.pdf

Basic Questions

- How are baryons transformed into stars?
  - Subject to
    - Gravity (well understood)
    - Radiation pressure (small)
    - Magnetic fields
    - Turbulent stresses



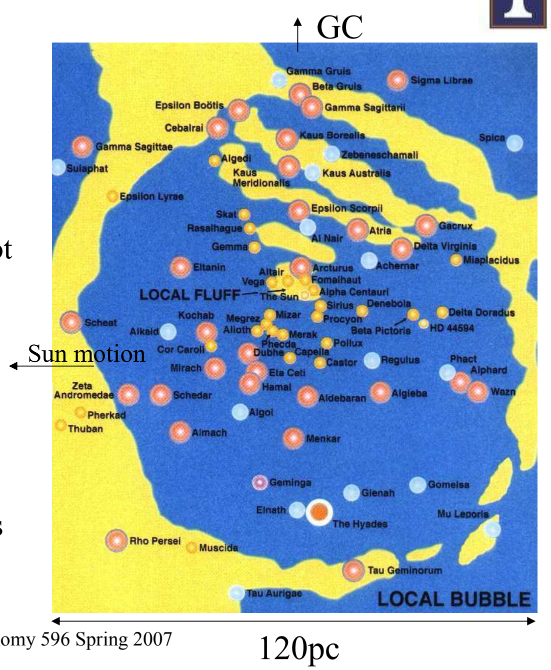
- Fundamental questions
  - Why does star formation occur mostly in spiral arms?
  - What triggers star formation?
  - What determines the star formation rate in different Hubble types?
  - What determines the initial mass function of stars?
  - Why do stars form in multiples?
  - How do planets form?

http://content.answers.com/main/content/wp/en/a/a5/WMAP.jpg

http://astro.berkeley.edu/~ay216/06/NOTES/ay216_2006_01_Intro.pdf

The Local ISM

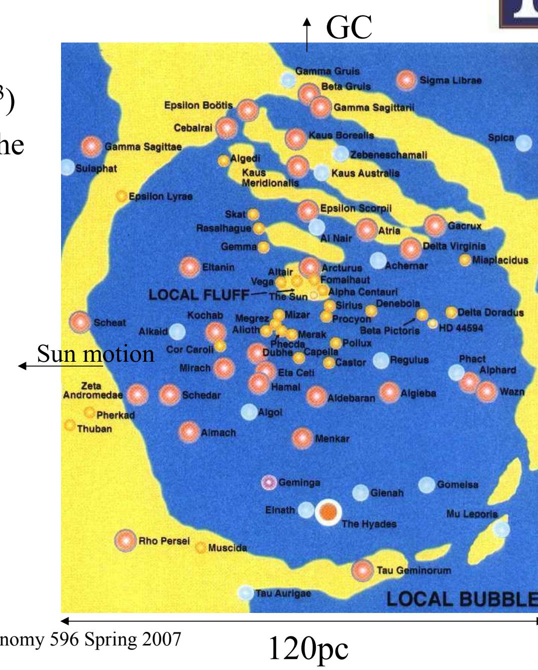
- Blue stars (OB), yellow (AFG), and orange (KM)
- Denser gas is yellow
  - Really shells of warm gas (~5000K)
  - Inside is low density but hot gas (~$10^{5\text{ to }6}$ K)
  - From supernovae or OB winds
- Local bubble
  - Not spherical
  - n ~ 0.05 to 0.07 cm^{-3}
  - "The Wall" above Arcturus probably from Sco-Cen associations



http://www.astronomycafe.net/qadir/q1372.html

The Local ISM

- Local fluff
  - A denser region (~0.1 cm^{-3})
  - Recently encountered by the Sun
  - Sun is moving ~20 km/s plowing through the local fluff
  - May be piece of the Wall
  - After millennia in low density region may encounter high density (effects?)



http://www.astronomycafe.net/qadir/q1372.html

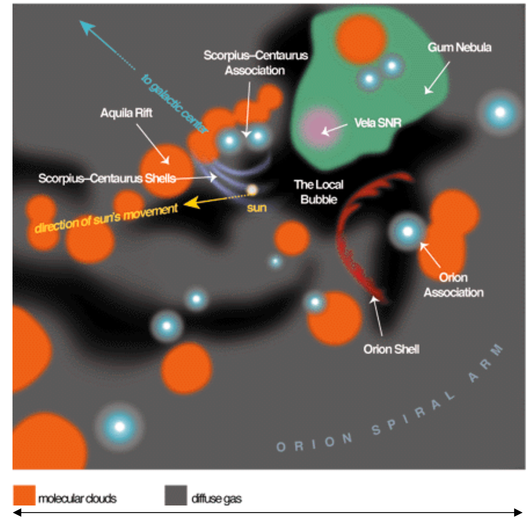
Zoom Out

- Sun and the brightest stars only
- Loop I is from the Cen-Sco associations
- Denser regions are darker orange: Taurus, Rho Ophiuchi, Chameleon

500 pc

http://astro.berkeley.edu/~ay216/06/NOTES/ay216_2006_01_Intro.pdf

Zoom Out

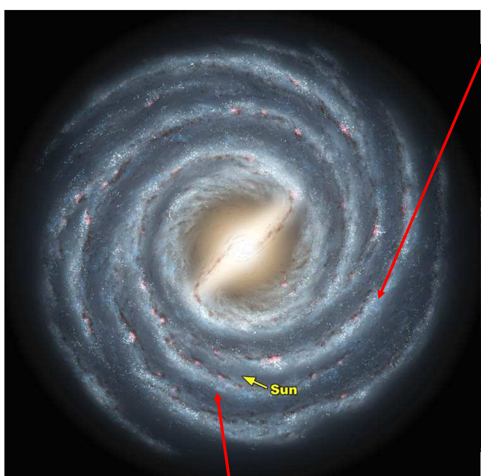


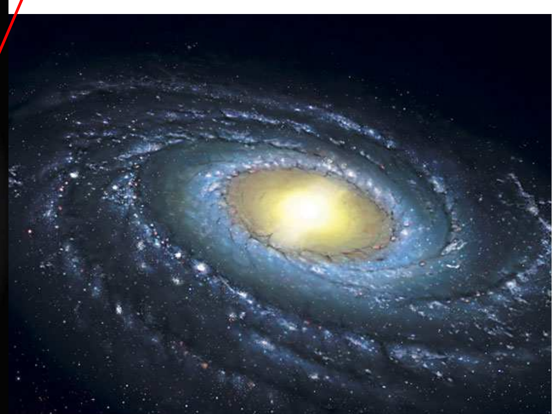
900 pc

http://antwrp.gsfc.nasa.gov/apod/ap020217.html

Zoomed Out

Sagittarius arm

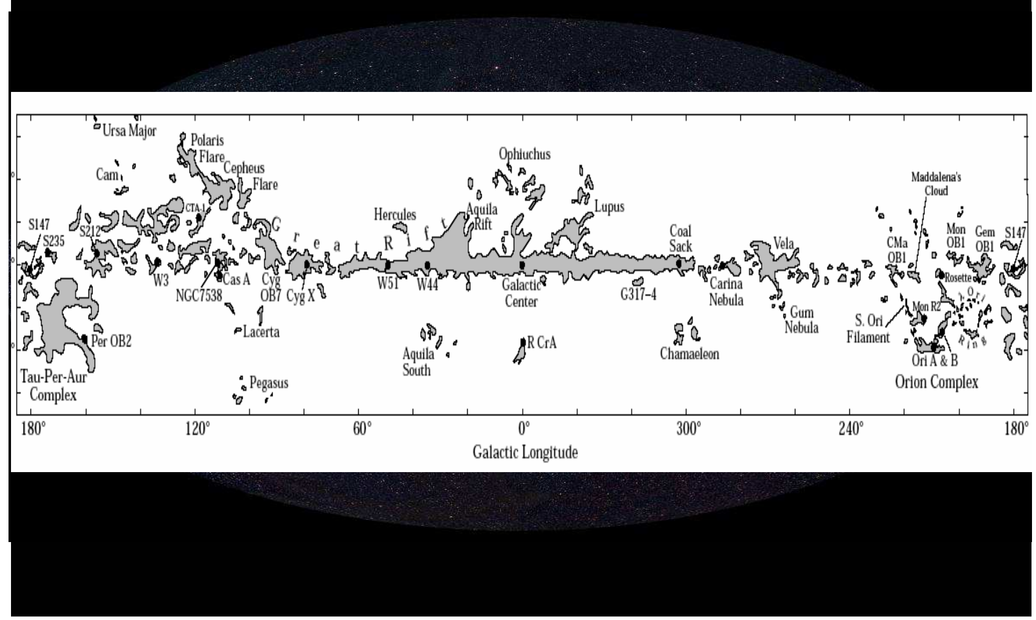




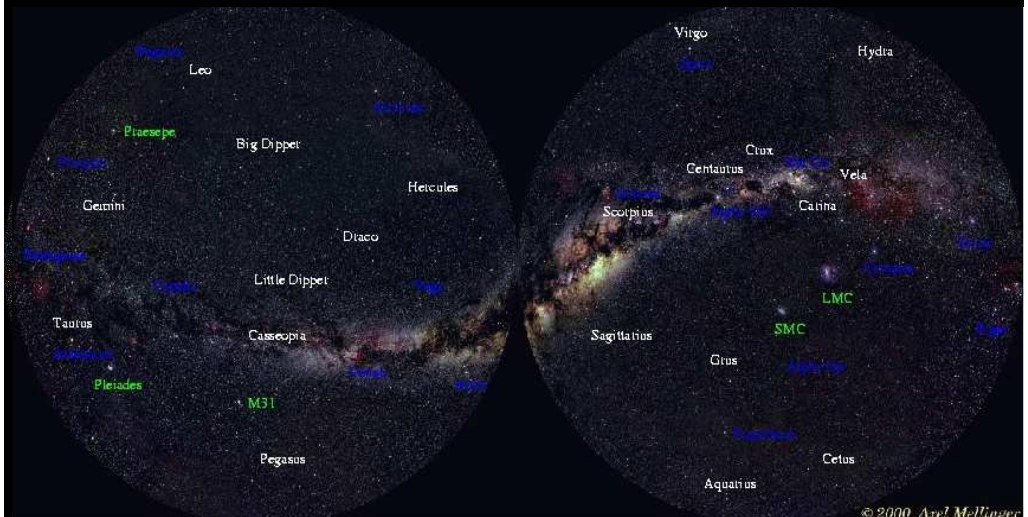
Orion arm

http://antwrp.gsfc.nasa.gov/apod/ap050104.html
http://www.wisconline.com/feature/milkyway.jpg

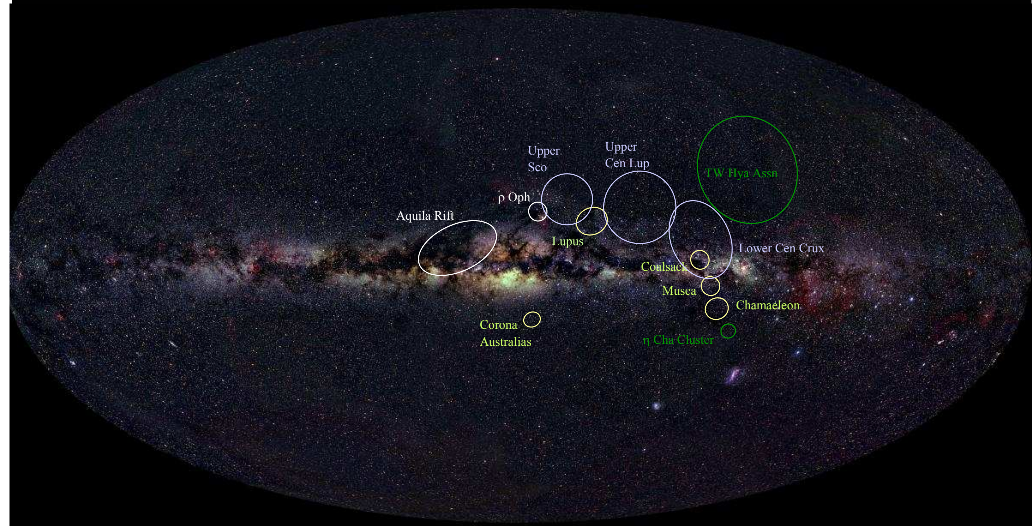
Perspective



Perspective

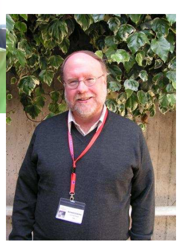


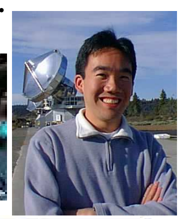
Local Star Formation Regions



Technical Diversion

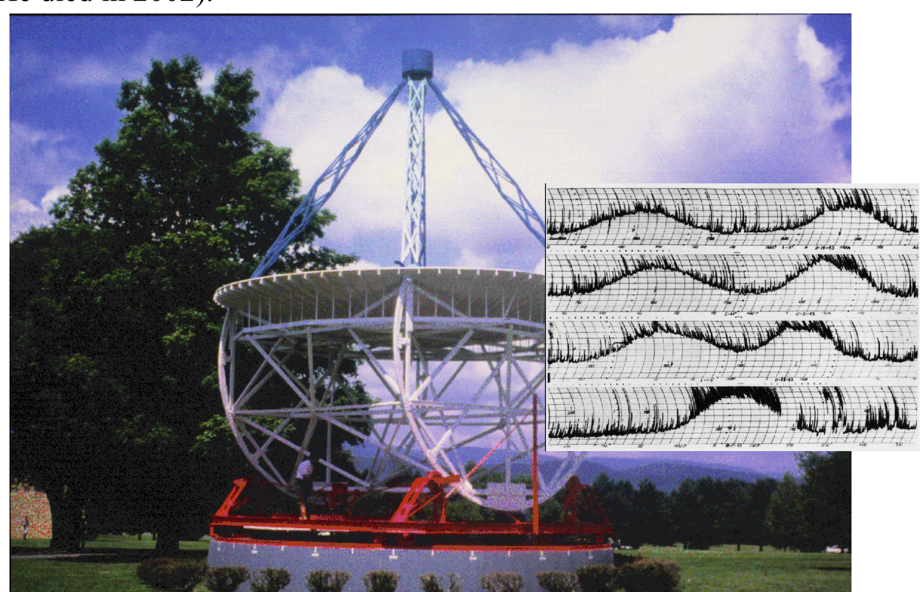
- We will now take a small digression to talk about how radio astronomers do business.
- On the whole they are a logical, but perverse, group, so hold you breath and let's proceed.


Origins of Radio Astronomy

Pioneering work by Grote Reber in back yard, Wheaton, Illinois. (He died in 2002).



Radio Astronomy

- Origins in Electrical Engineering
- Since radio telescope is basically a total power detector, convention was to compare to an equivalent temperature that would produce same power (in Rayleigh-Jeans limit)

$$P = G\frac{2k\nu^2 T}{c^2}\Omega_{beam}$$

- Where G is the Gain of the telescope (includes area, bandwidth, gain of amplifiers) and Ω_{beam} is solid angle of main beam of antenna

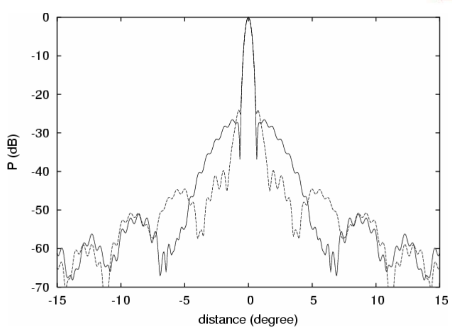
Radio Astronomy

- Can turn it around to defined the "antenna temperature", T_A

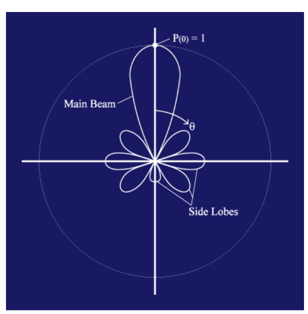
$$T_A = \frac{P}{G}\frac{c^2}{2k\nu^2\Omega_{beam}} = P_{cal}\frac{c^2}{2k\nu^2\Omega_{beam}}$$

- A nice unit
  - Linear with power (unlike magnitudes)
  - Can be related to the physical temperature in the dense ISM
- T_A^* is also regularly used, which is the emission above the atmosphere, i.e. corrected for atmospheric attenuation, radiative loss, and rearward scattering and spillover.

Antenna Pattern



- When you observe with a radio telescope, the data is averaged over the dish response, which is the same as the dish emission pattern.
- In the far-field (distance $\geq 2D^2/\lambda$), the beam shape is approximated as a Gaussian of width $\theta_{FWHM} = 1.22\ \lambda/D$ (radians) = $2.5 \times 10^5\ \lambda/D$ (arcsecs)



http://aanda.u-strasbg.fr:2002/components/com_imageProcess/read.php?url=articles/aa/full/2005/35/aa1863-04/img30.gif
http://www.ras.ucalgary.ca/grad_project_1996/frame-ca.html

Antenna Sensitivity

- Radiometer equation

$$\sigma_{RMS} \propto \frac{T_{sys}}{\sqrt{BW \times \tau}}$$

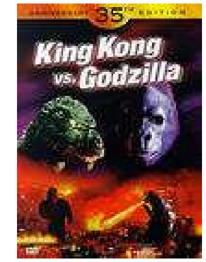
- BW is bandwidth (channel size typically) and τ is time.
- Tsys is the noise of the system (including sky), expressed in a power equivalent temperature.
- The units of σ depends on the amplitude scale being used, but we want it to be as small as possible.

RMS

- Noise is σ_{RMS}
- It is a good assumption that noise is Gaussian
- Need a simple statistic to maximize detections and minimize false positives
  – Most researchers use > 3σ as detection threshold
  – Some use > 7σ
  – Keep in mind that 3σ means that formally only 0.1% of the data (i.e. pixels/samples) will be false detections!

Which to Use: Telescopes

- The first paper will be single-dish observations.
- What are the advantages/disadvantages?
- It is not single-dish vs. interferometers
  – Which tool for the job?

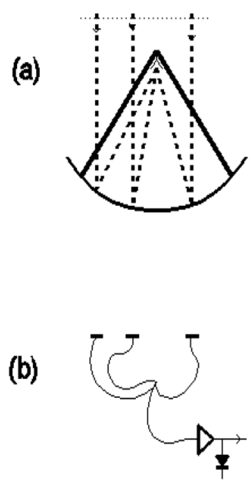


http://membres.lycos.fr/morbide666/godzilla/godzilla.htm

What's the Diff?

a) **Single dish:** Free space propagation & reflection to bring signals together in phase

b) **Phased Array:** Cables of just the right length, to bring all signals together in phase

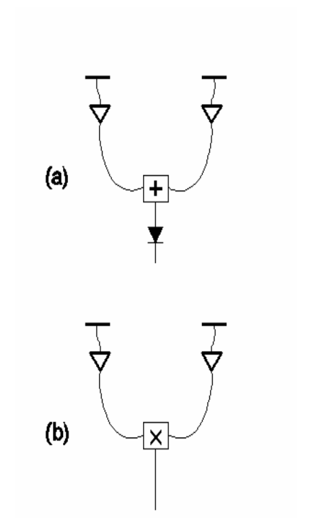


http://www.gb.nrao.edu/sd03/talks/whysd_r1.pdf

What's the Diff?

a) **Adding Interferometer or Phased Array:** A single dish with missing metal.

b) **Correlation or Multiplying interferometer:** All aperture synthesis radio telescopes are made up of multiple correlation interferometers



http://www.gb.nrao.edu/sd03/talks/whysd_r1.pdf

What's the Diff?

- **Single Dish, phased array, or adding interferometer:** The gain ***very*** susceptible to changes in receiver gain, and to changes in receiver noise temperature

- **Correlation interferometer:** nearly immune to receiver gain and noise changes

http://www.gb.nrao.edu/sd03/talks/whysd_r1.pdf

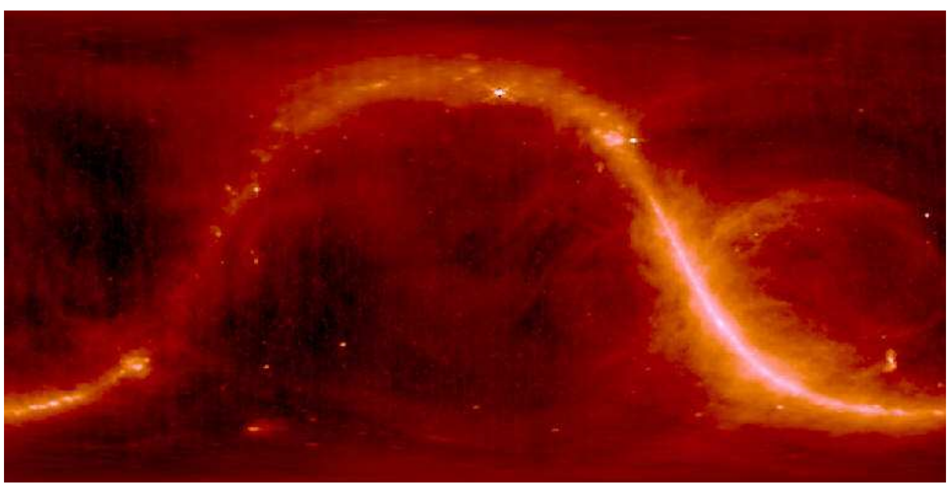
What's the Diff?

- **Single Dish, phased array, or adding interferometer:** resolution depends on size of dish, mechanical issues

- **Correlation interferometer:** resolution is separation of dishes, electronic issues

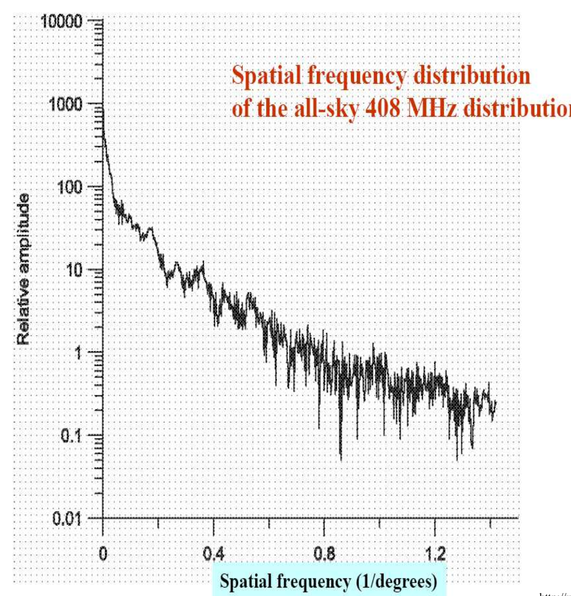
http://www.gb.nrao.edu/sd03/talks/whysd_r1.pdf

All Sky Map @ 408 MHz



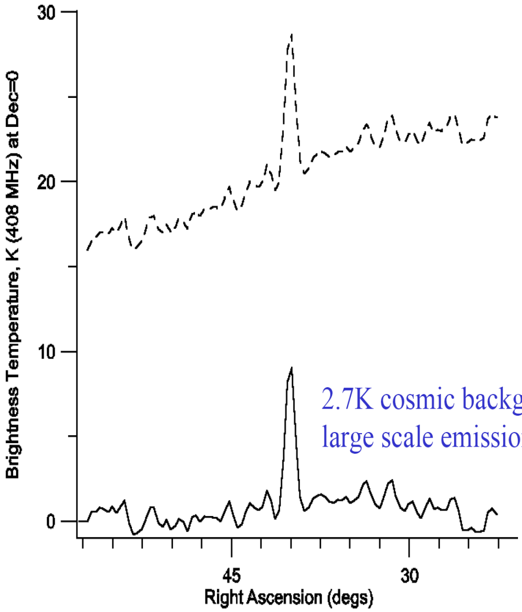
http://www.tuc.nrao.edu/~demerson/radiosky/radiosky.htm

Spatial Scale



http://www.gb.nrao.edu/sd03/talks/whysd_r1.pdf

Slice Through NGC 1068

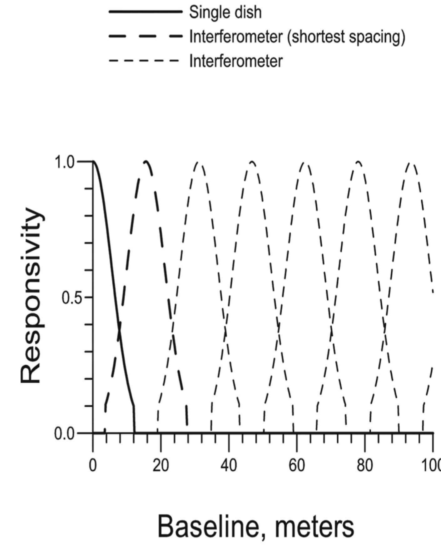


Complete data

2.7K cosmic background and other large scale emission features removed

http://www.gb.nrao.edu/sd03/talks/whysd_r1.pdf

Sensitivity Issues



http://www.gb.nrao.edu/sd03/talks/whysd_r1.pdf

*Angle on sky = (λ/**Baseline**) radians*

Bottom Line

- Single Dish resolution is limited by it's size (diffraction)
- Interferometer resolution is limited by antenna separation.

- Single Dish is sensitive to large-scale emission (low spatial frequencies)
- Interferometer is less sensitive to large-scale emission depending on the minimum antenna separation
  - Can never get smallest spatial frequencies
  - Sometimes, the interferometer low spatial frequency cut-off is a good thing.
  - Sometimes, it is a bad thing

Bottom Line

- Usually, Single Dish maps are analyzed in a way that removes the lowest spatial frequencies too.
  - don't normally want the 3 K cosmic background in the data

- The relative flux in low spatial frequencies is typically far greater than that at higher spatial frequencies
- For cases where we **DO** want large scale structure, we may **HAVE TO** use a Single Dish.

Last Point

- Amplitude calibration, i.e. absolute Temperature scale, between two telescopes
  - Tricky.. In the millimeter/submillimeter it can be 10-20% absolute uncertainty
  - Amplitude calibration often needs comparison of two known temperatures (sky temperature and ambient)