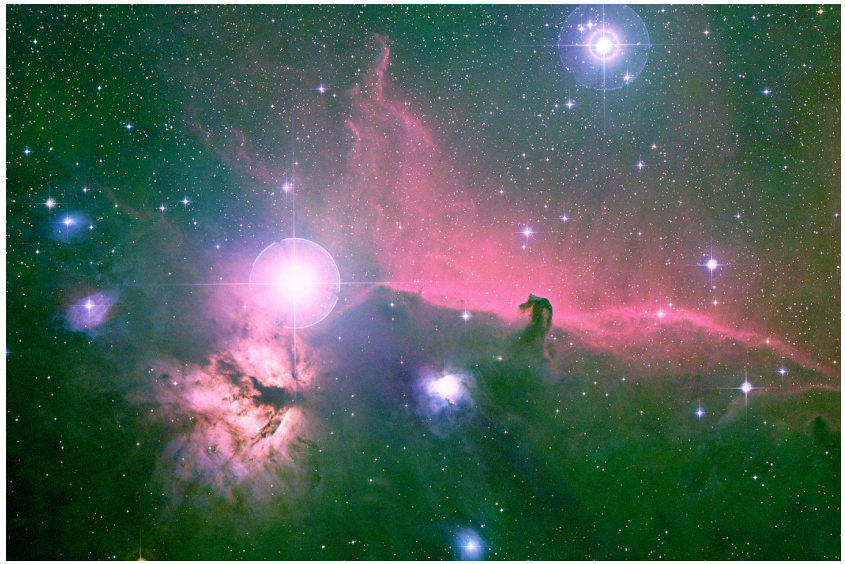


Our Galaxy: gas, dust and surveys

Michael Burton

ARMAGH OBSERVATORY & PLANETARIUM

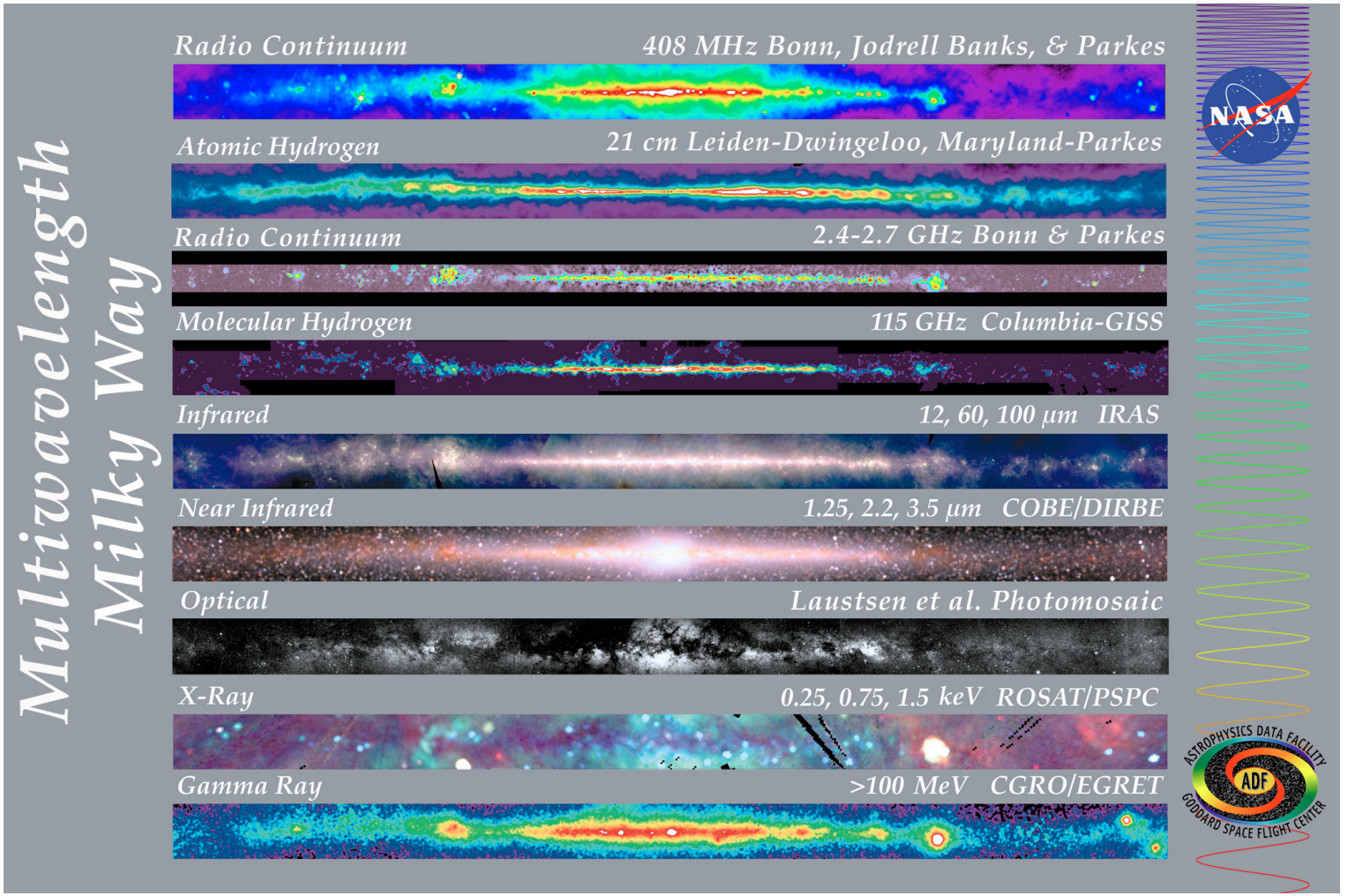
EXPLORING THE COSMOS SINCE 1790

Synopsis

- The multi-wavelength Milky Way
  - Viewing the ISM
- Overview of the ISM
  - Molecular Gas and Star Formation
  - Putting it together: the Galactic Ecosystem
- TeV-energy Gamma Rays and the CTA
- Mopra Southern Galactic Plane CO Survey
- Our Galaxy seen through Stellarium

A nearby spiral galaxy like our own

The multi-wavelength Milky Way

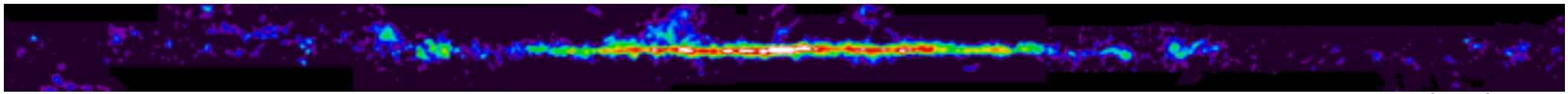


Optical: Stars obscured by dust

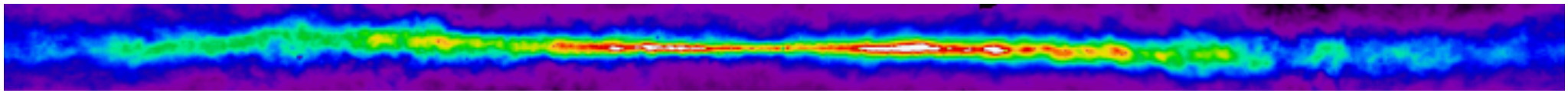
Near-infrared: Stars through the dust

Far-infrared: Warm Dust

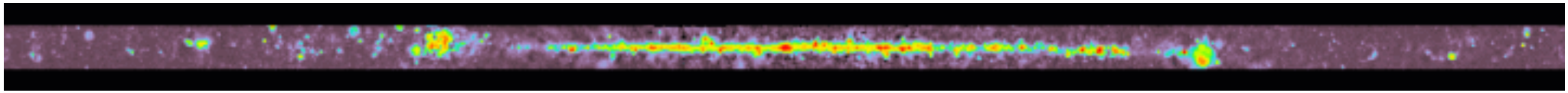
Millimetre line: Molecular Clouds



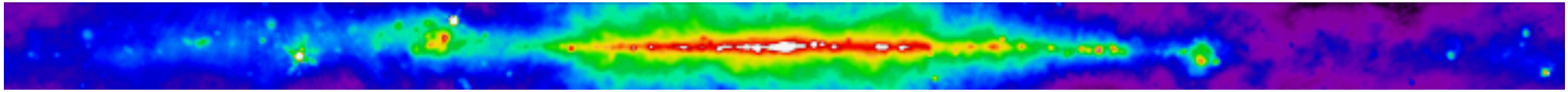
Centimetre Line: Atomic Clouds



Centimetre: Ionized Gas (HII)

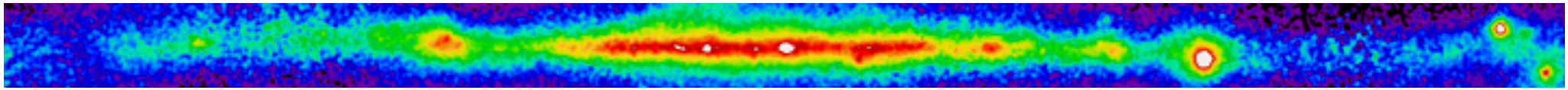


Decimetre: Synchrotron Gas (SNRs)



X-rays: Hot, shocked sources

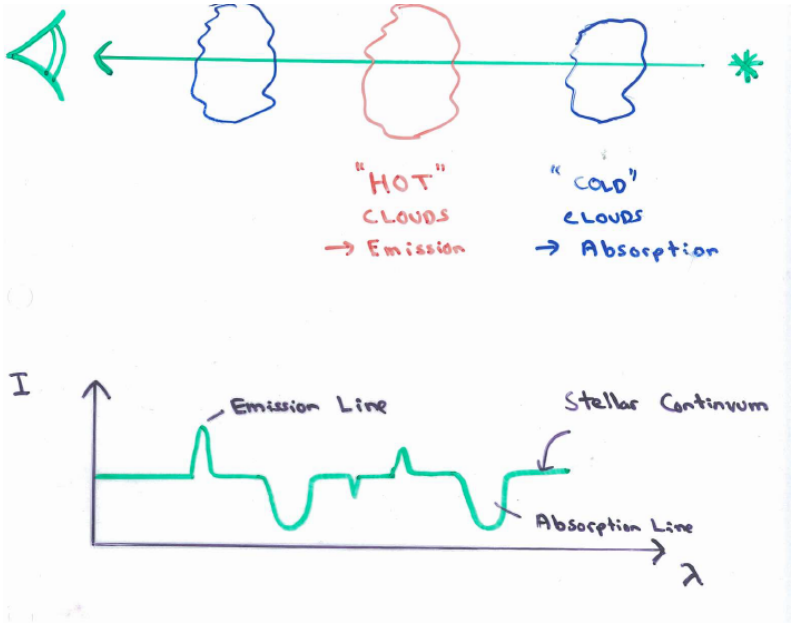
Gamma Rays: Cosmic Rays inc. pulsars



Components of the ISM

Component	Nature
Gas	Ions + Atoms + Molecules ~70% H, ~30% He, ~1% Trace elements, by mass ~1 particle per cm^{-3}, ~0.025 $M_\odot/pc^3$
Dust	Silicates ('sand' coated with 'ice'), size ~0.1µm ~0.0002 $M_\odot/pc^3$, 1% of Mass of ISM
Cosmic Rays	~0.5 eV/cm^3 High speed atomic nuclei; accelerated in SN??
Magnetic Fields	B~1 µG, E ~0.2 eV/cm^3 All pervading
Starlight	E ~0.5 eV/cm^3
Other energy sources:	Rotation of Galactic Disk Turbulence CMBR

Characteristics of ISM

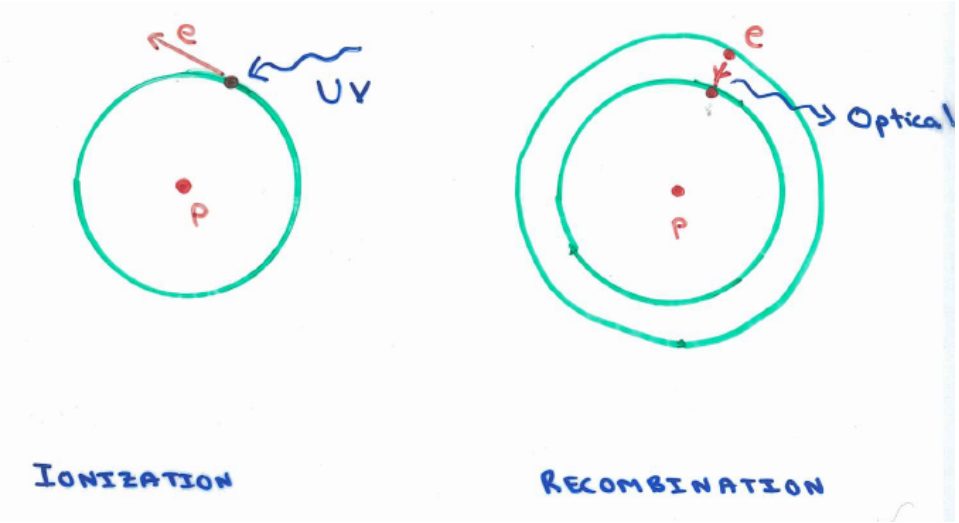


- T from 10 to 10^6 K
- n from 10^{-3} to 10^6 cm^{-3}
- Non-static
  - Energy & Matter in continuous interchange
  - *Clouds are ephemeral*
- Nuclear reaction play no role
  - Atomic & molecular processes dominate
- Hot gas in Emission, i.e. *nebulae*
- Cold gas in Absorption, i.e. *clouds*

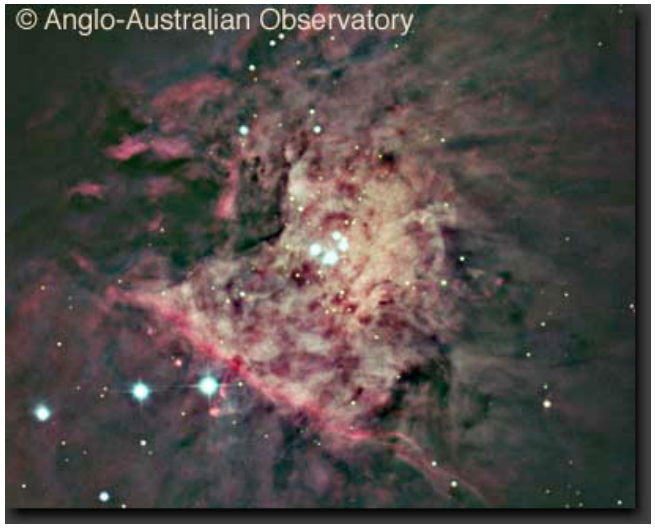
The Interstellar Gas

Ionized, Neutral and Molecular forms

	Component	Temp (K)	Density (cm^{-3})	Description	Vol. Frac.	Mass $10^9 M_\odot$
Pressure Balance – the "three phase" medium	Cold Atomic Medium	50 – 100	20 – 50	H-atoms (neutral) Galactic Plane	1-5%	3
	Warm Atomic Medium	6,000 – 10,000	0.2 – 0.5	H-atoms (neutral) Galactic Plane	10-20%	0.2
	Hot Ionized Medium	$10^6 – 10^7$	$10^{-4}–10^{-2}$	H^+ (+ highly ionized "metals"). Halo	30-70% [?]	0.003
Violently expanding	HII Regions	8,000	10^{2-4}	H^+ (ionized) Near Hot Stars	< 1%	
Gravitation-ally bound [?]	Molecular Clouds	10 – 20	10^{3-6}	H_2 (molecules) Galactic Plane ☞ Star Formation	< 1%	3
	Warm Ionized Medium	8,000	0.2 – 0.5	H^+ (ionized) Galactic Plane + Halo	~20% [?]	0.05



HII Regions



- Ionized Hydrogen (H^+)
- Located near hot stars
  - ~40,000K, O (+B)-type, ionizing UV radiation λ<912Å

➢ Ionizes all H within cavity centred on star

➢ Recombination radiation p+e ⇒ H^* ⇒ H + emission line

  ➢ e.g. Balmer series with n ⇒ 2, such as n=3-2 Hα 6563Å

➢ Heating via collisions with electrons $T \sim 10^4$ K

➢ Cooling via line emission $n \sim 10^4$ cm^{-3}

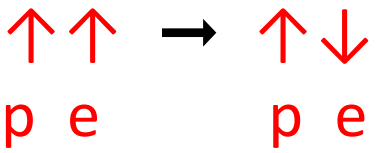
  ➢ "Forbidden" lines from metastable levels of ions

    ➢ e.g. [OII] 3727Å, [OIII] 4959Å

➢ <u>Not</u> in pressure equilibrium with surroundings

HI Clouds
The Cold and Warm Neutral Mediums

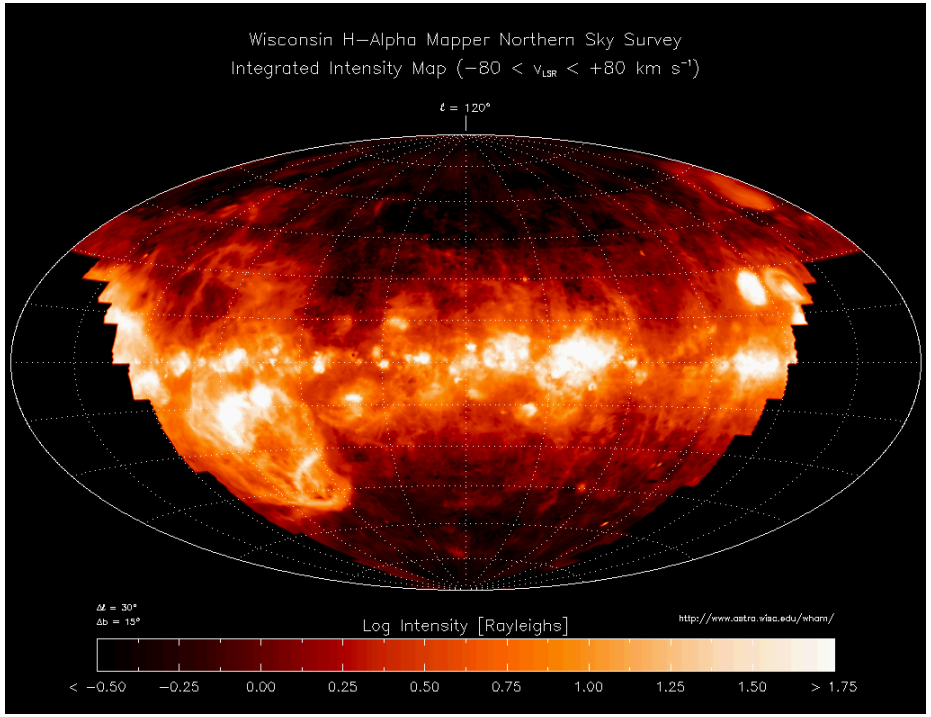
- Most abundant form of hydrogen



- Found <u>away</u> from hot stars
- Seen through 21cm spin-flip; τ~10^7 years
- Confined to thin disk in Plane, z~100 pc
  - Cold Clouds: CNM
    - T~50-100K, n~20-50 cm^{-3}, d~1-10pc, M~1-1,000 $M_\odot$
  - Warm Clouds: WNM
    - T~8,000K, n~0.2-0.5 cm^{-3}

Warm Ionized Medium

- Hot gas with H as H^+ ($H\alpha$)
- Temperature ~8,000K, Density ~0.2 cm^{-3}, f~20%
- Extends around the Galactic plane

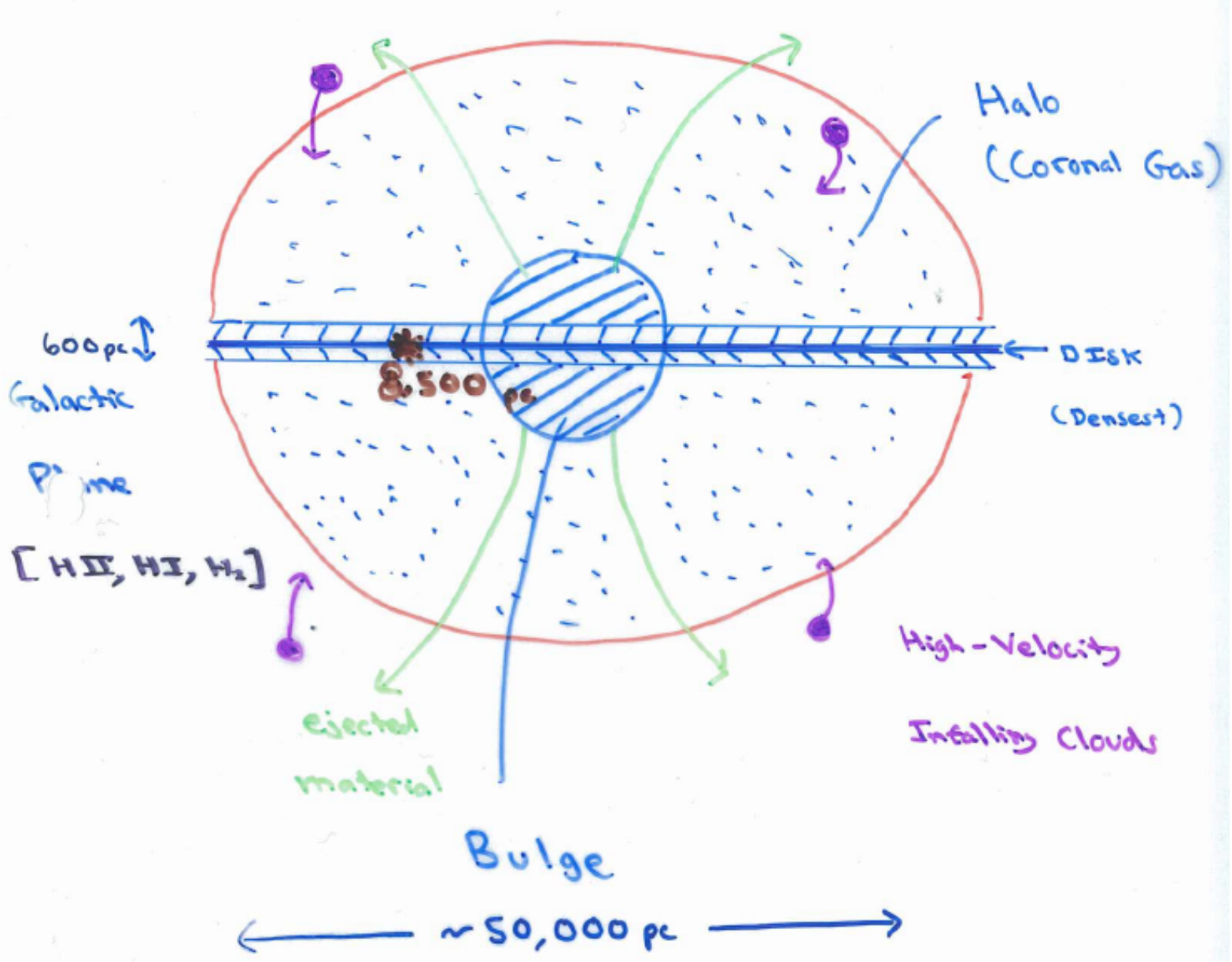


WHAM
$H\alpha$

Hot Ionized Medium
Coronal Gas

- Diffuse, extends to Halo
  - $T \sim 10^{6\text{-}7}$K, $n \sim 10^{-4} - 10^{-2}$ cm^{-3}
- Matter ejected from SN (Novae, WR stars) to Halo
- Completely ionized $\Longrightarrow$ X-ray emission (thermal)
  - i.e. all H is in H^+, all He in He^{++}
  - plus UV lines of highly ionized atomic species
    - e.g. [CIV], [OVI], [NIV]
- HI clouds + Warm Ionized Medium + Coronal Gas $\Longrightarrow$ Diffuse Component of the ISM

The Galactic Interstellar Medium

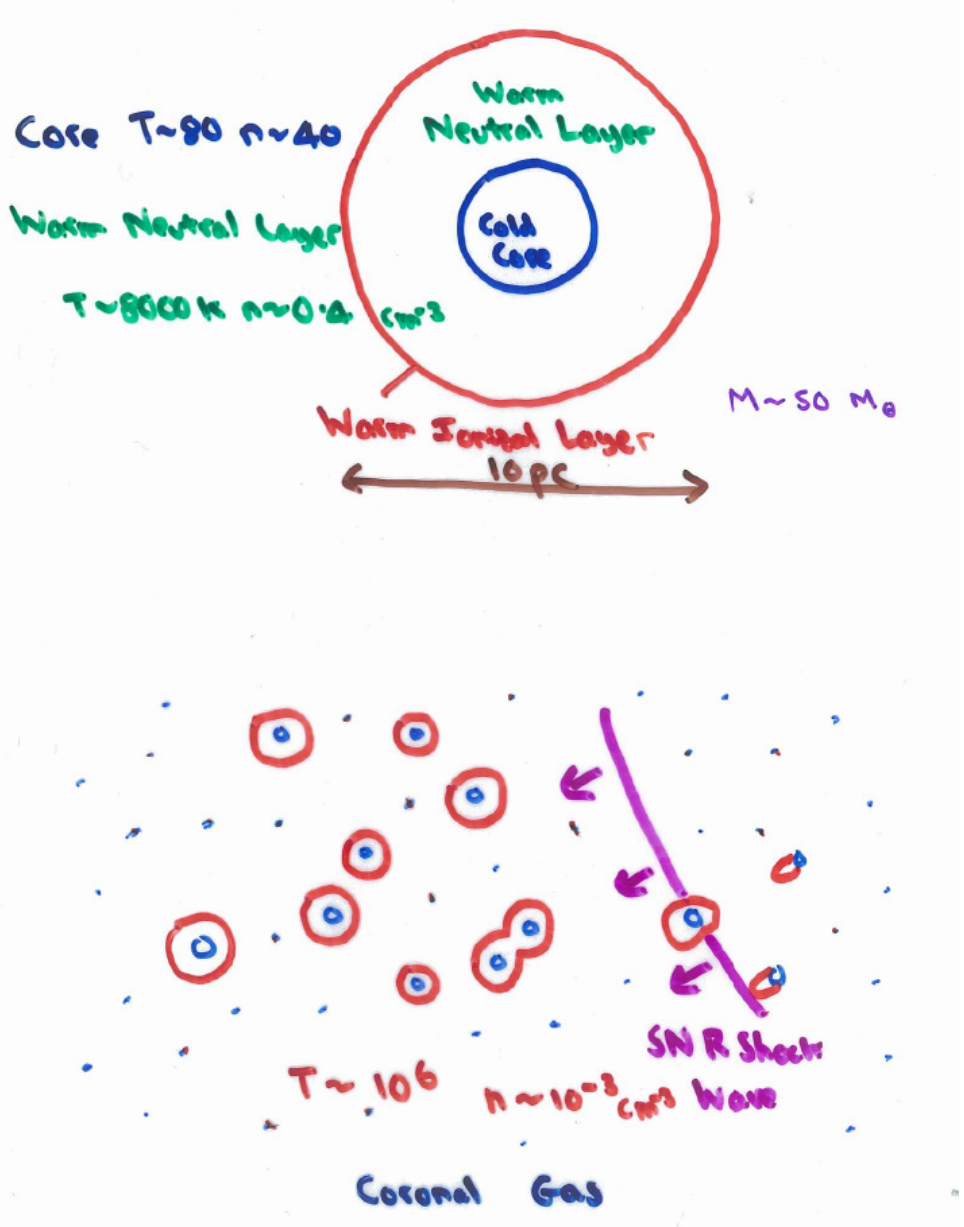


Three Phase Model
CNM + WNM + Coronal Gas

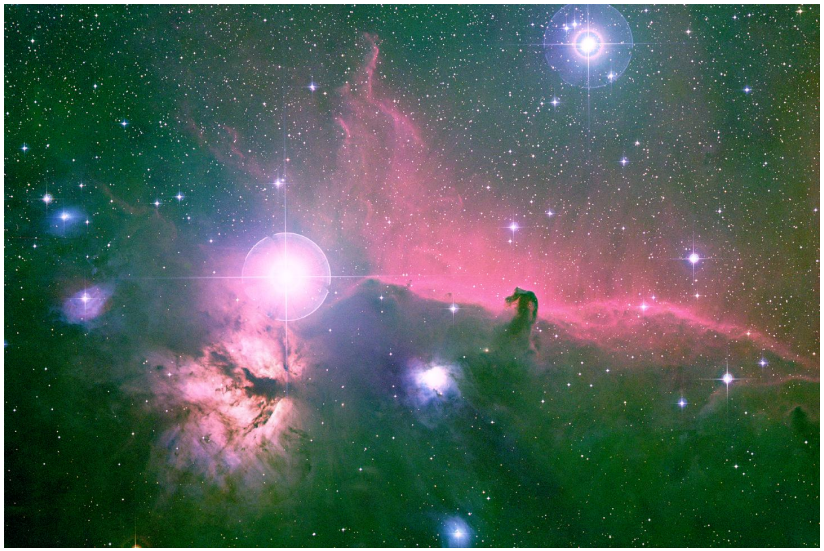
- Approximate pressure equilibrium between phases
- *P=nkT* so that

$$\frac{n(cloud)}{n(intercloud)} =$$

$$\frac{T(intercloud)}{T(cloud)}$$



Molecular Clouds
Star Forming Regions



- Composed primarily of H_2 with:
  - M ~ 10^2 to 10^6 $M_\odot$
    - the most massive individual objects in the Galaxy
  - n ~ 10^3 to 10^6 cm^{-3}
  - D ~ 15 – 60 pc
  - T ~ 10 – 20K (up to 100K in “hot molecular cores”)
- Molecules shielded from UV radiation by dust
  - over 120 species known
  - Interesting (organic) chemistry!
- Very hard to observe! H_2 v=0-0 S(0) line at 28μm
  - Atmosphere opaque, line weak against strong continuum
- Must observe trace species (CO/H_2 ~10^{-4})
  - e.g. CO J=1-0 at 2.6mm ≡ 115 GHz, E_{upper}=5K

Molecular Clouds

- Trace molecules are very efficient coolants
- Molecular clouds are [?] self-gravitating objects
  - Equilibrium between
    gravity vs. centrifugal + turbulent + magnetic support
  - Ephemeral
- Not in pressure balance with external medium
- Trigger $\Longrightarrow$ Collapse to Star Formation
  - Loss of magnetic flux through ambipolar diffusion
  - Compression from passing spiral density waves
  - SN blast waves
  - Winds from massive stars
  - ???

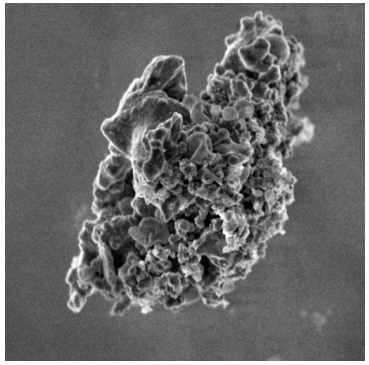
Molecular Aggregates

Three principal forms

	GMCs	"Clumps"	"Cores"
Mass ($M_\odot$)	$10^{5\text{-}6}$	10^2	1–10
Size (pc)	20–100	0.2–4	0.1–0.4
Density (cm^{-3})	$10^{3\text{-}4}$	$10^{4\text{-}5}$	$10^{5\text{-}6}$
Temperature (K)	15–40	7–15	10
Magnetic Field (μG)	1–10	3–30	10–50
Line Width (km/s)	6–15	0.5–4	0.2–0.4
Dynamical Life (yrs.) (R/ΔV)	$3x10^6$	10^6	$6x10^5$

Cold, Dense, Massive, Non-static, Thermal, Turbulent and Transient

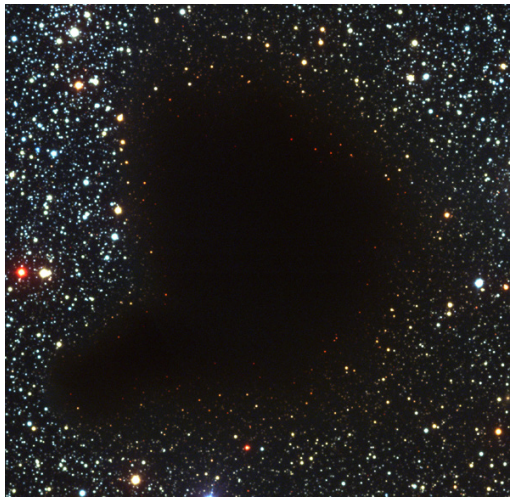
Proceeds towards Star Formation



Interstellar Dust

~1% of mass of the ISM

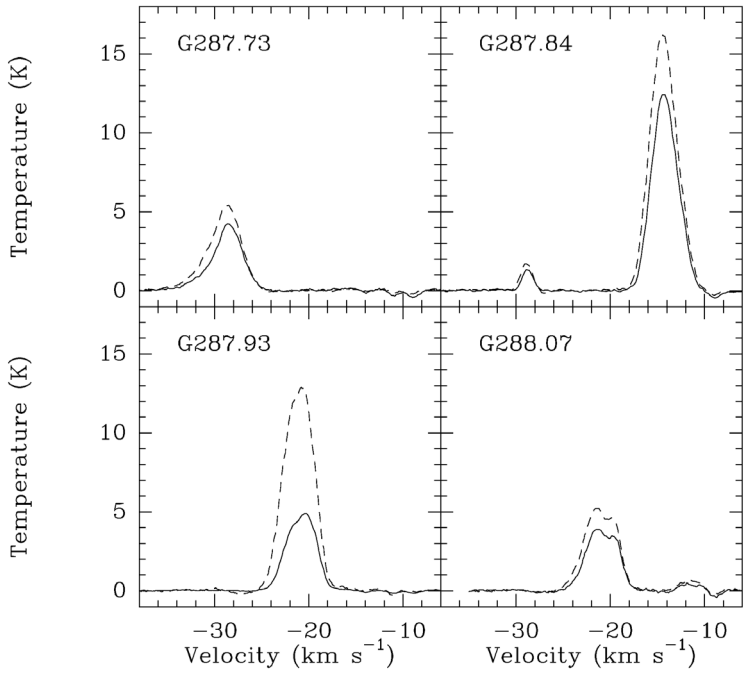
- Dark Nebulae [= molecular clouds]
  - Where visible light absorbed by dust
  - Re-radiates IR as thermal emission at ~20-500K
  - Reddened
- Reflection Nebulae
  - Scattering of starlight
  - Blue $I_\lambda \propto \lambda^{-4}$
- Solid Particles, not gas
    - Grains ~0.1 μm, $10^{7\text{-}9}$ atoms per grain
    - Core + Mantle
      - Silicates 9.7µm, Ices: H_2O (3.1µm), NH_3, CH_4, CH_3OH
- Formed in Red Giant envelopes
  - Ejected into ISM
  - Condensation sites for organic molecules



What can you measure with Molecules?

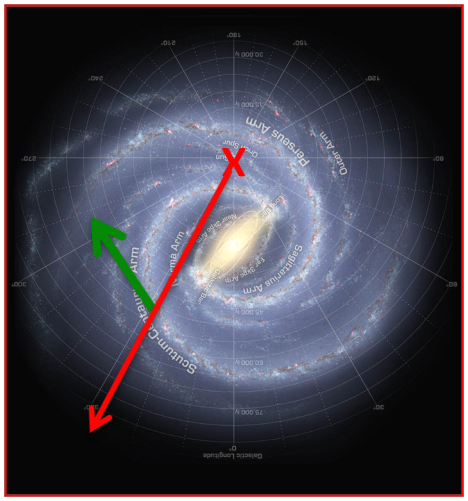
Boltzmann Eqn: $\frac{N_i}{N_X} \propto g_i \, e^{-\frac{E_i}{kT}}$

- Velocities
  - Line widths, Centres, Shapes
- Gas Temperature
- Abundances
- Gas Density
- Optical Depth
- Column Density
- Gas Mass



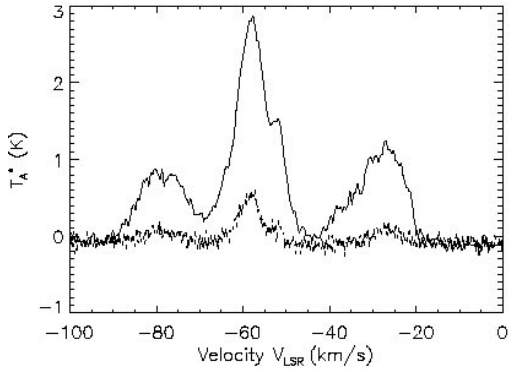
Provide hard numbers to constrain your physics!

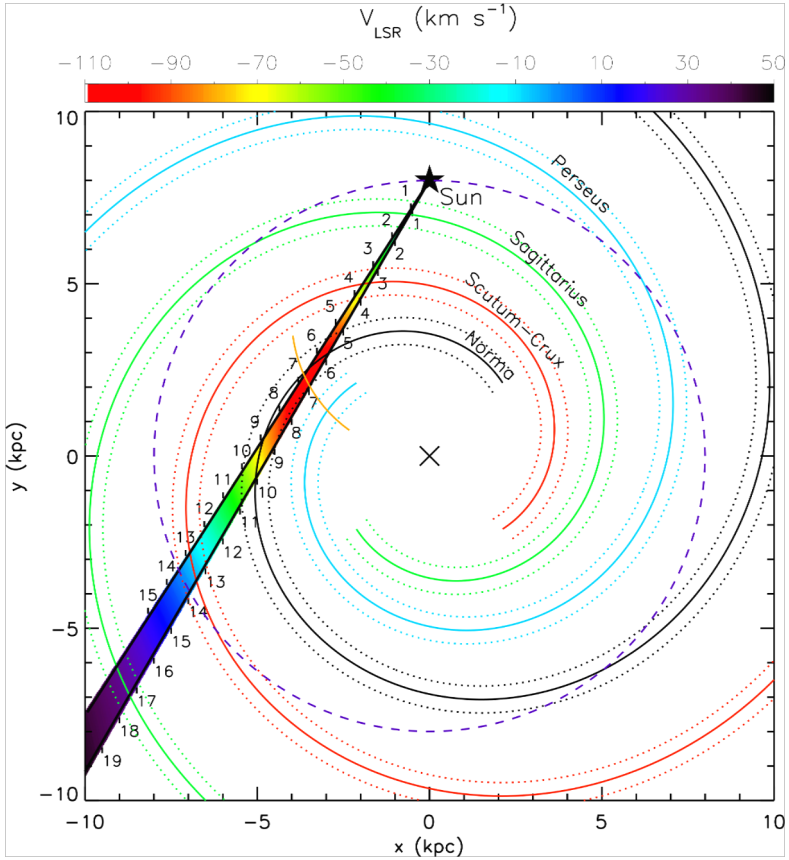
CO Lines yield: Source Distance + Column Density



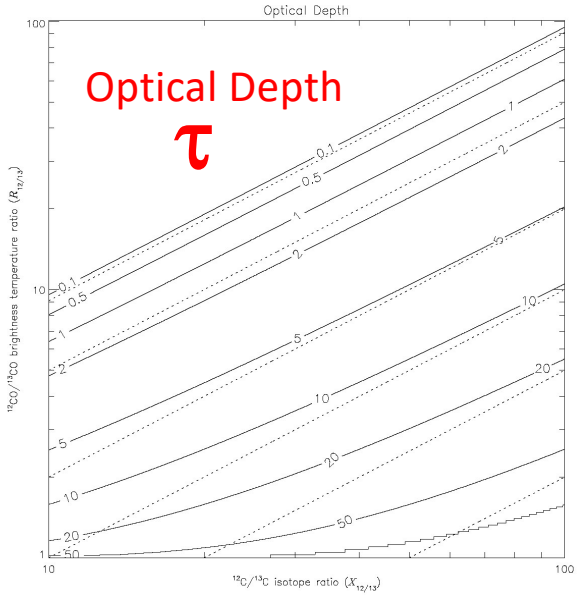
$$N \propto \text{Flux}\ \frac{\tau}{1 - e^{-\tau}}$$

^{12}CO +^{13}CO
Line Profiles





$[^{12}CO/^{13}CO]$
Measured

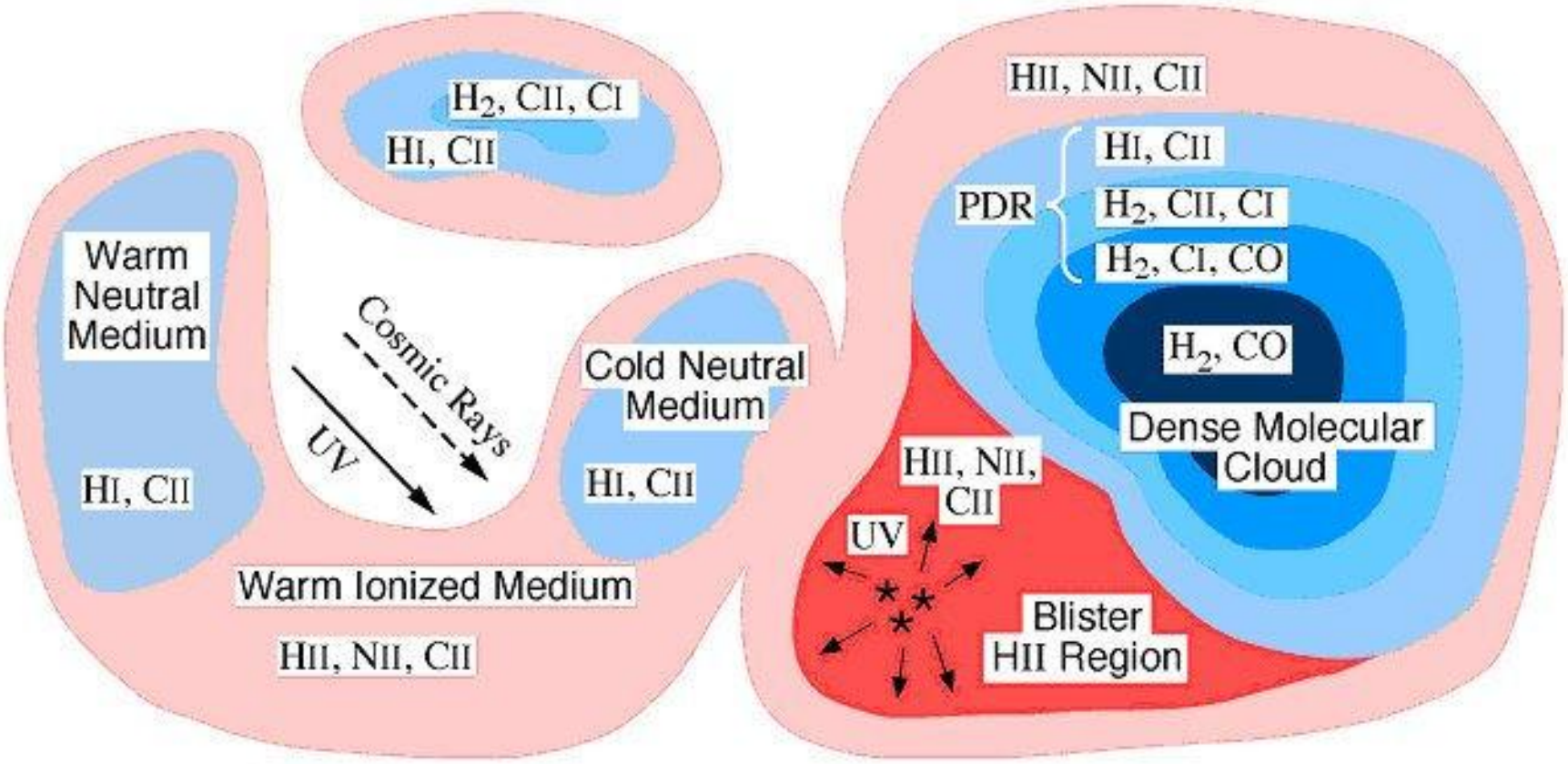


Optical Depth
τ

$[^{12}C/^{13}C]$
Intrinsic Isotope Ratio

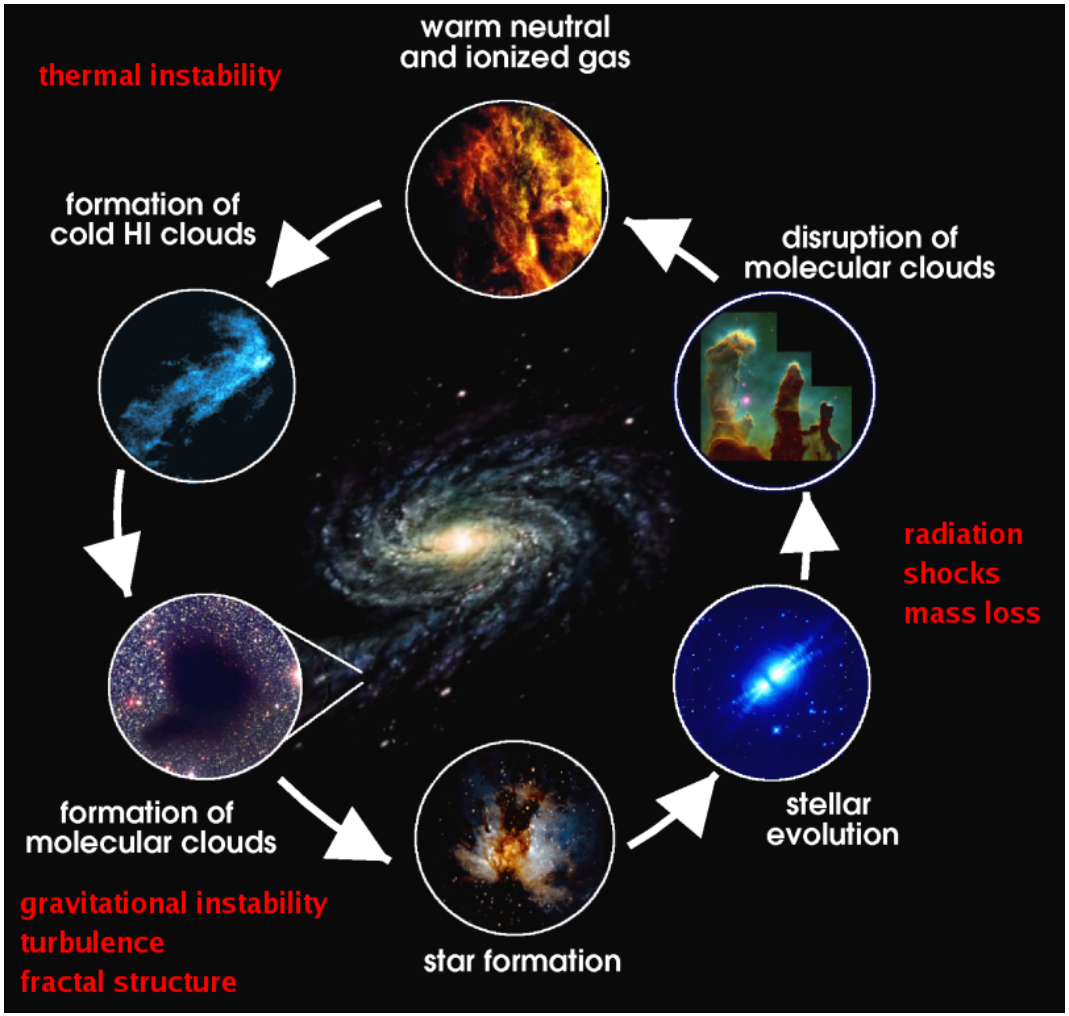
The Galactic Ecosystem

Schematic of the multi-phase ISM and its diagnostic tracers



Follow the Carbon Trail: C^+ → C → CO

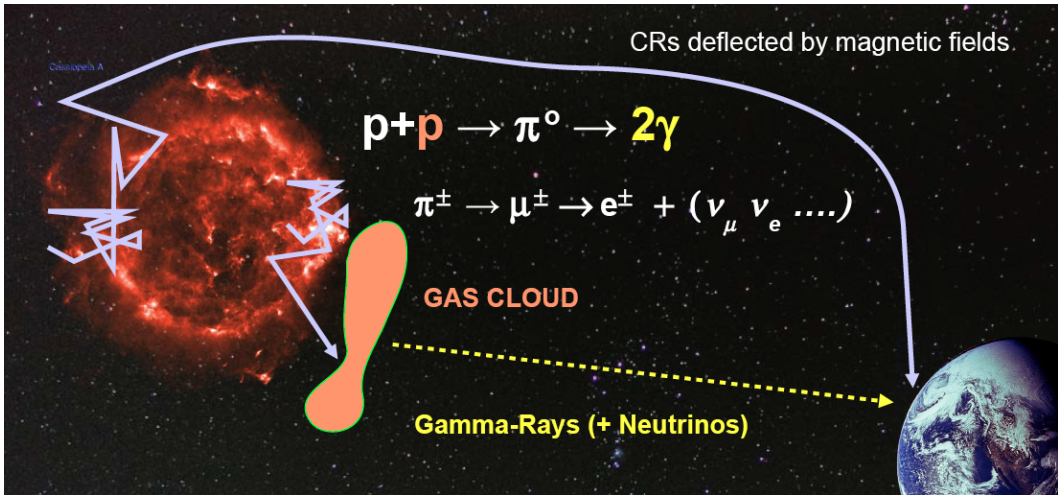
Galactic Evolution:
the life cycle of the interstellar medium



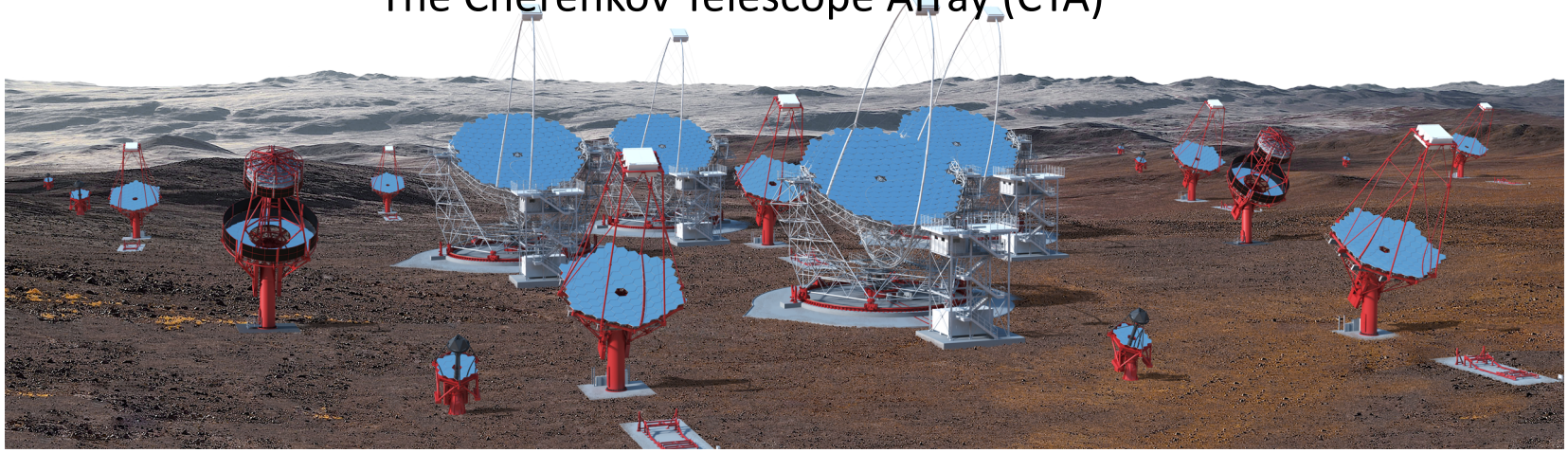
TeV Gamma Rays

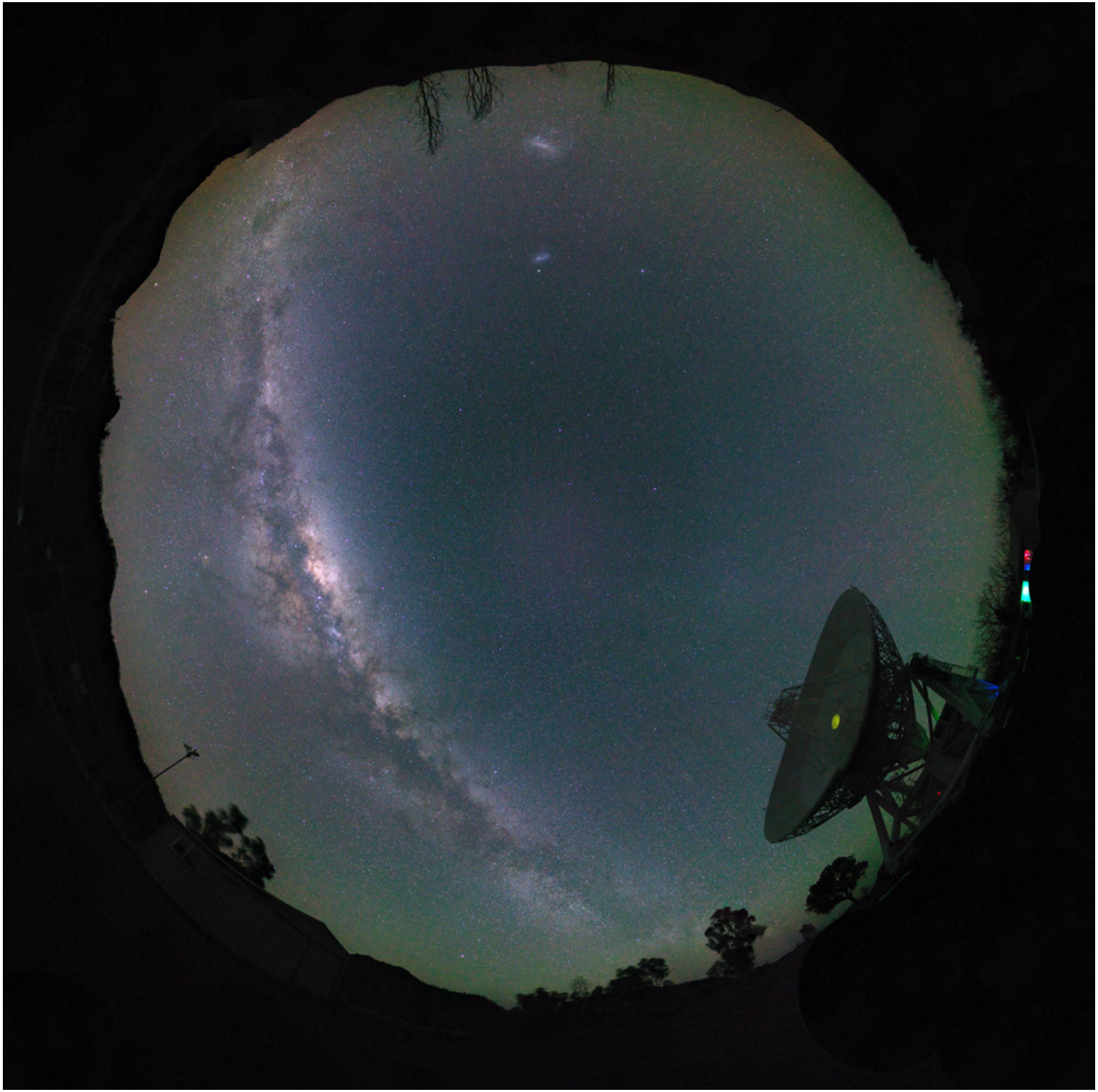
Galactic Plane in TeV gamma rays

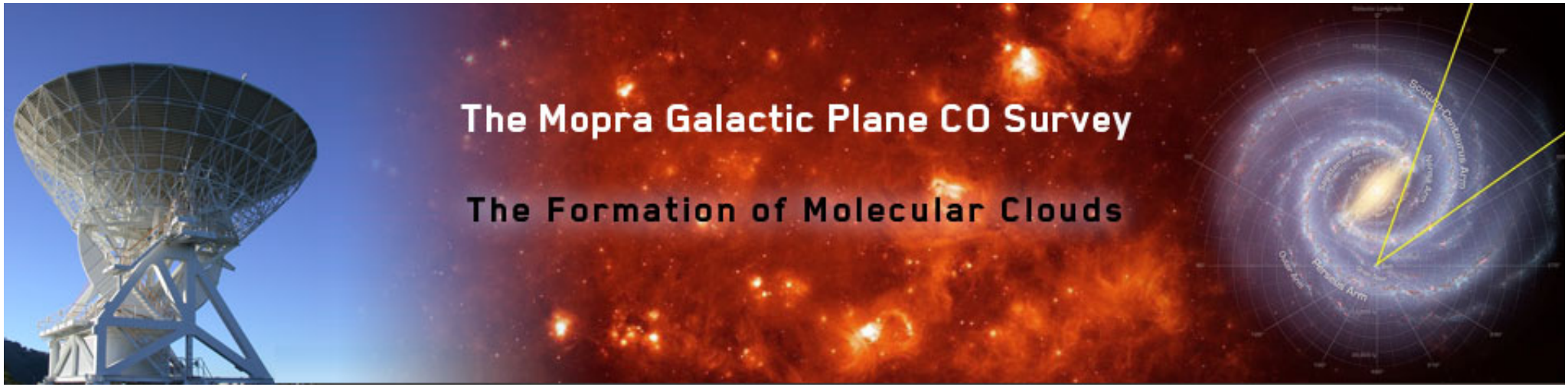
Need to know the distribution of the molecular gas!



The Cherenkov Telescope Array (CTA)







Michael Burton, Gavin Rowell, Catherine Braiding, Nigel Maxted,
Graeme Wong, Rebecca Blackwell, David Rebolledo, Kerem Cubuk

M. Filipovic, M. Freeman , C. Glueck, P. Goldsmith, J. Hawkes, D. J. Hollenbach, B. Indermuehle, E. Istiqomah, C. Kulesa, J. Lau, C. L. Martin, J. L. Pineda, S. Pointon, D. Romano, R. Simon, C. Snoswell, A. A. Stark, J. Stutzki, N. J. H. Tothill, J. S. Urquhart, F. Voisin, C. Walker, A. J. Walsh, P. de Wilt, M. Wolfire.

Also #TeamMopra backers.

#TeamMopra

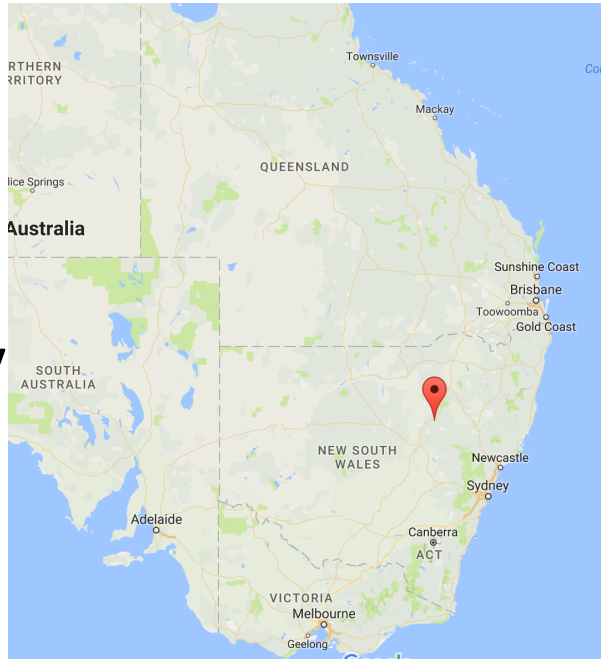
UNSW, University of Adelaide, Western Sydney University and others.

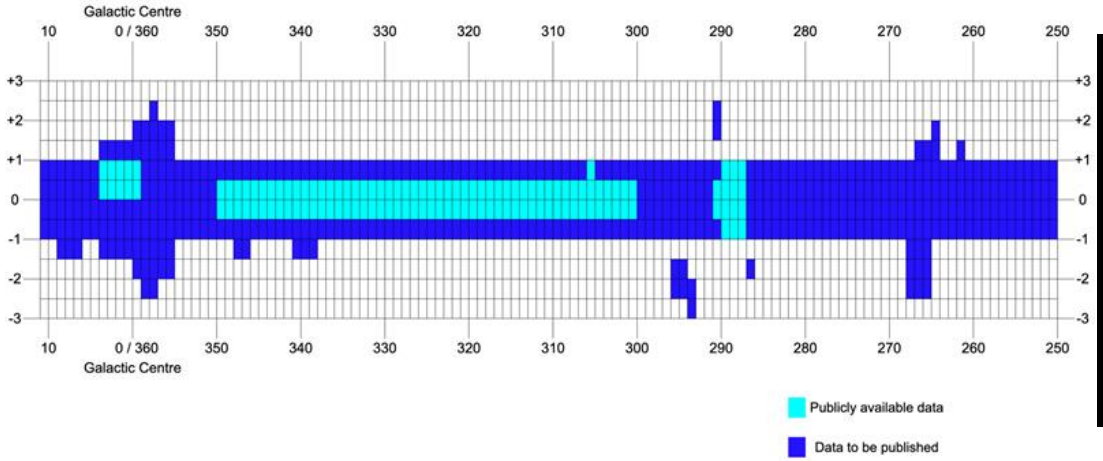
Burton et al. 2013, Braiding et al, 2015, 2018, Rebolledo et al. 2016, Blackwell et al., Cubuk et al 2021…..

Mopra

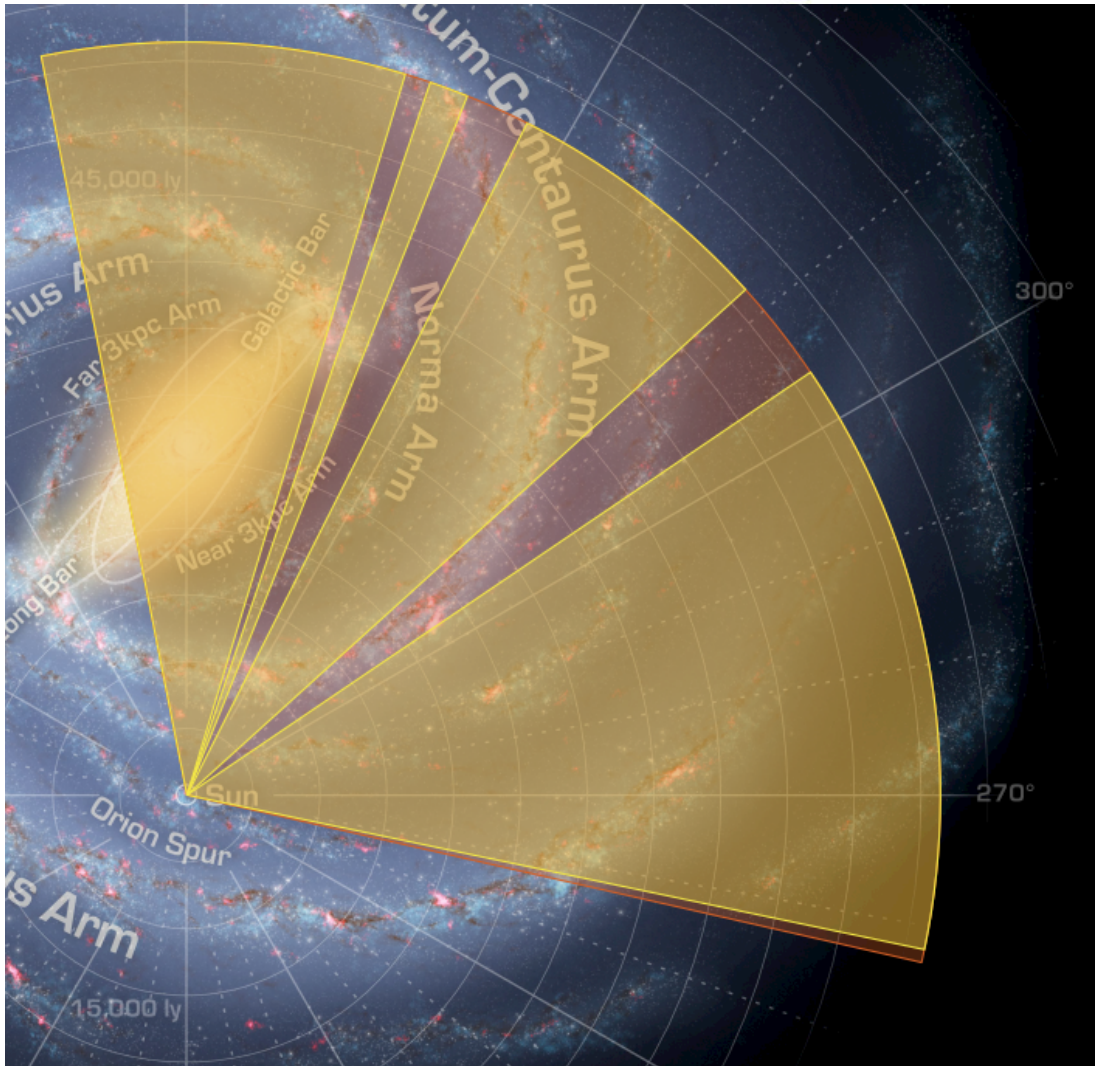
- 22m telescope for long-wave mm astronomy
  - 3mm + 7mm + 12mm receivers
  - 0.6 arcmin beam @ 3mm
- 8 GHz UNSW-MOPS correlator
  - Broadband
    - 0.8 km/s resolution over 32,000 channels
  - Zoom modes
    - 0.1 km/s resolution over 4,096 channels
- Surprisingly bushfire resistant!
  - See YouTube

    youtube.com/watch?v=WlHP9J1UPrs

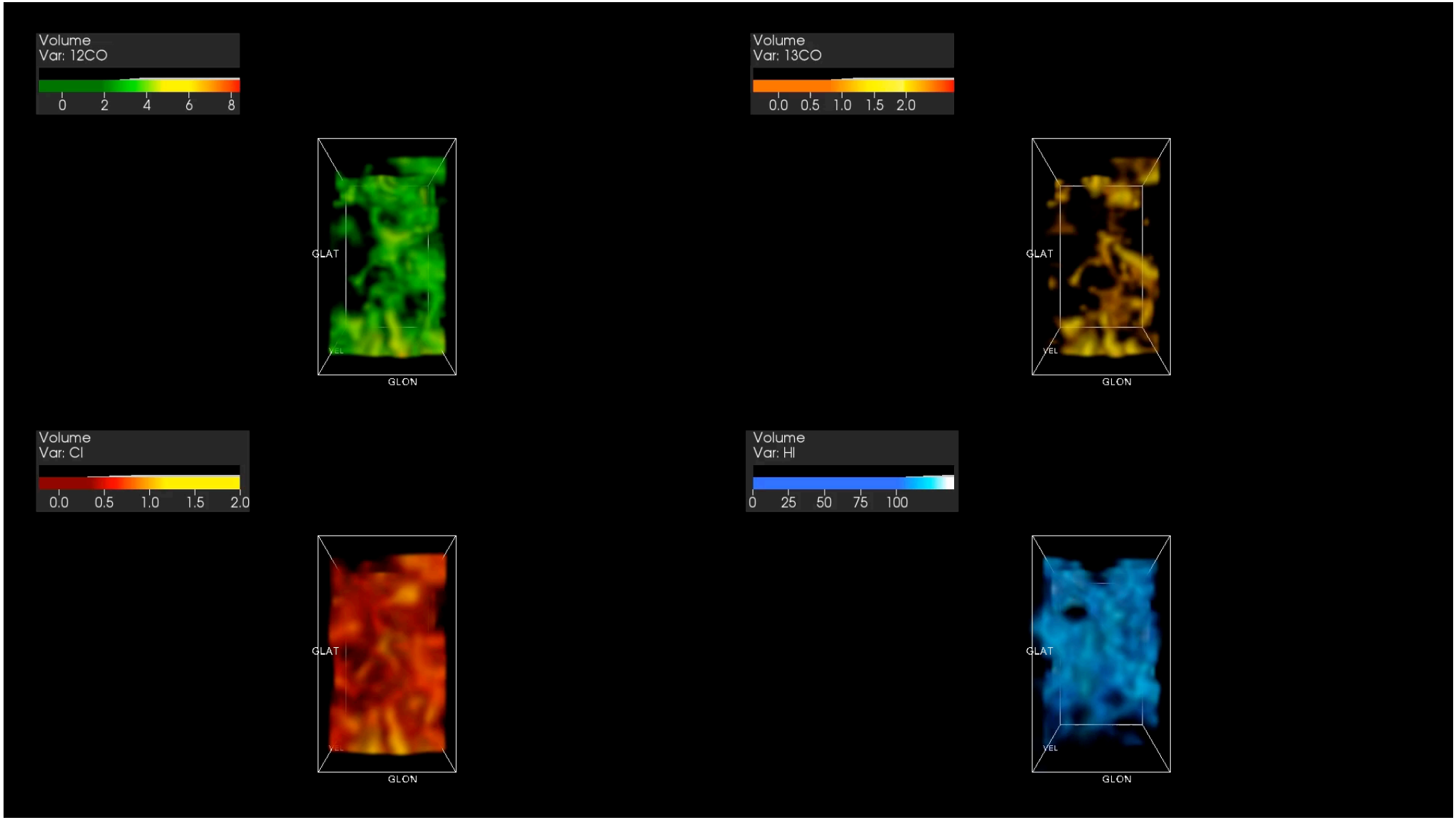


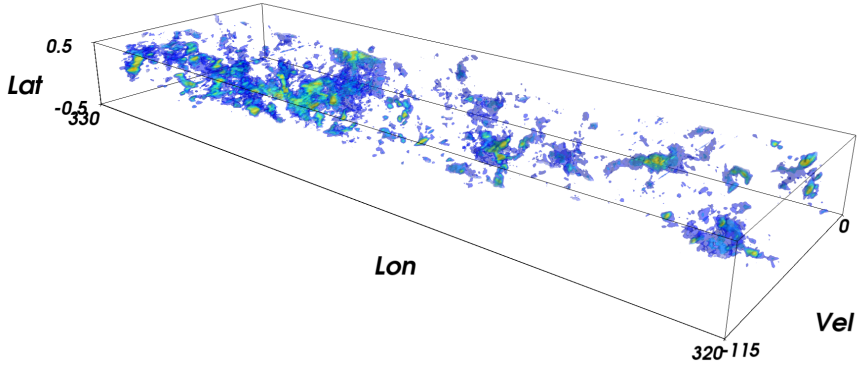


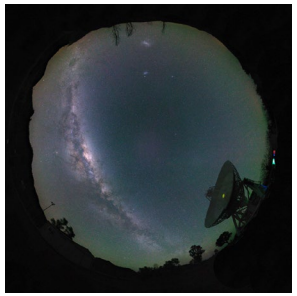
Mopra Southern Galactic Plane CO Survey



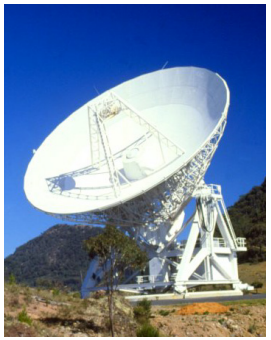
- ^{12}CO, ^{13}CO, $C^{18}O$ and $C^{17}O$ J = 1-0
- l = 250° to +11°
- $|b| < 1.0^{o}$.
- 0.6’ Beam @ 0.1 km/s resolution
- www.phys.unsw.edu.au/MopraCO/

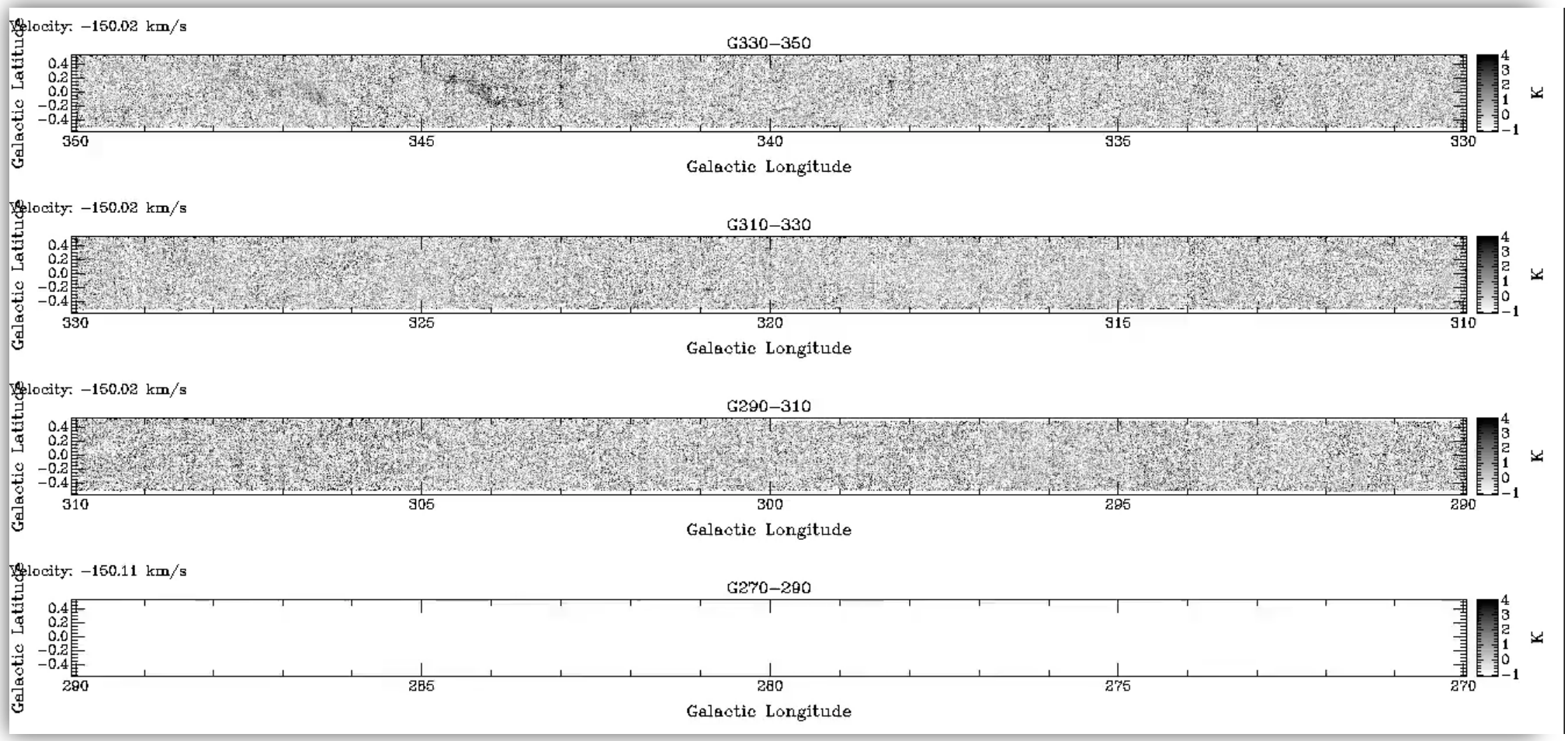

Volume
Var: 12CO
0 2 4 6 8
GLAT
VEL
GLON
Volume
Var: 13CO
0.0 0.5 1.0 1.5 2.0
GLAT
VEL
GLON
Volume
Var: CI
0.0 0.5 1.0 1.5 2.0
GLAT
VEL
GLON
Volume
Var: HI
0 25 50 75 100
GLAT
VEL
GLON


0.5
Lat
-0.5
330
Lon
0
Vel
320
-115



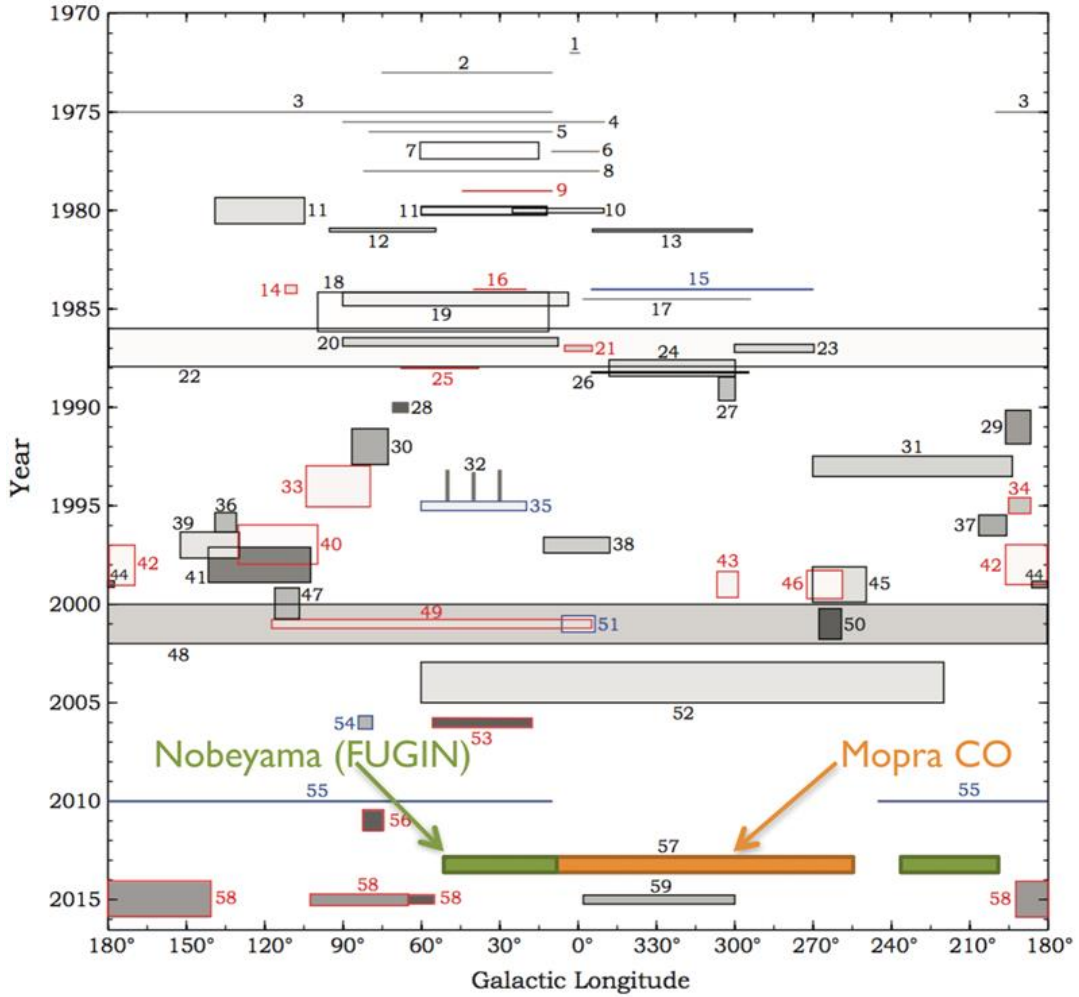
Galactic Plane: *l*=270° – 350°





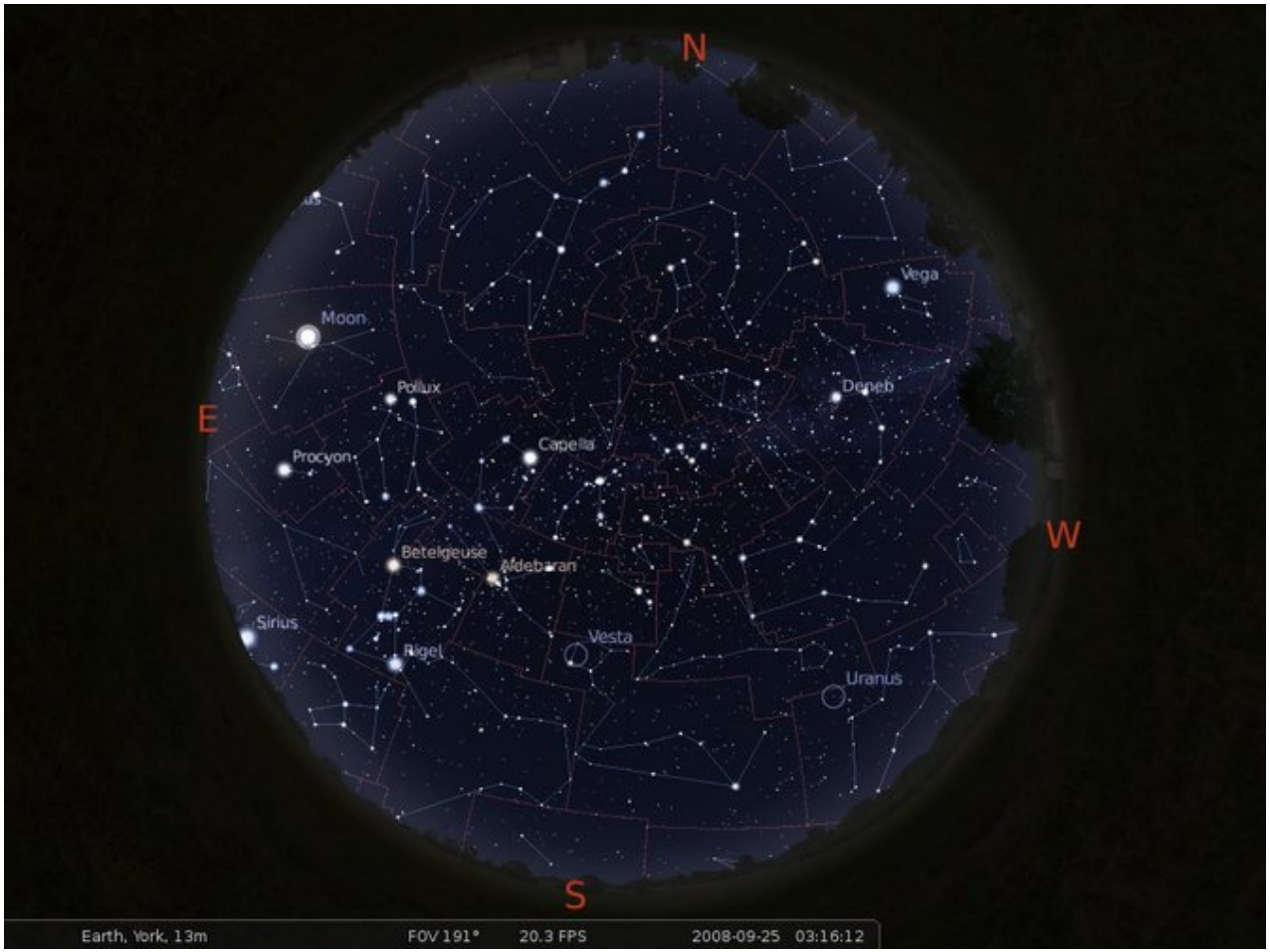
CO Galactic Plane Surveys

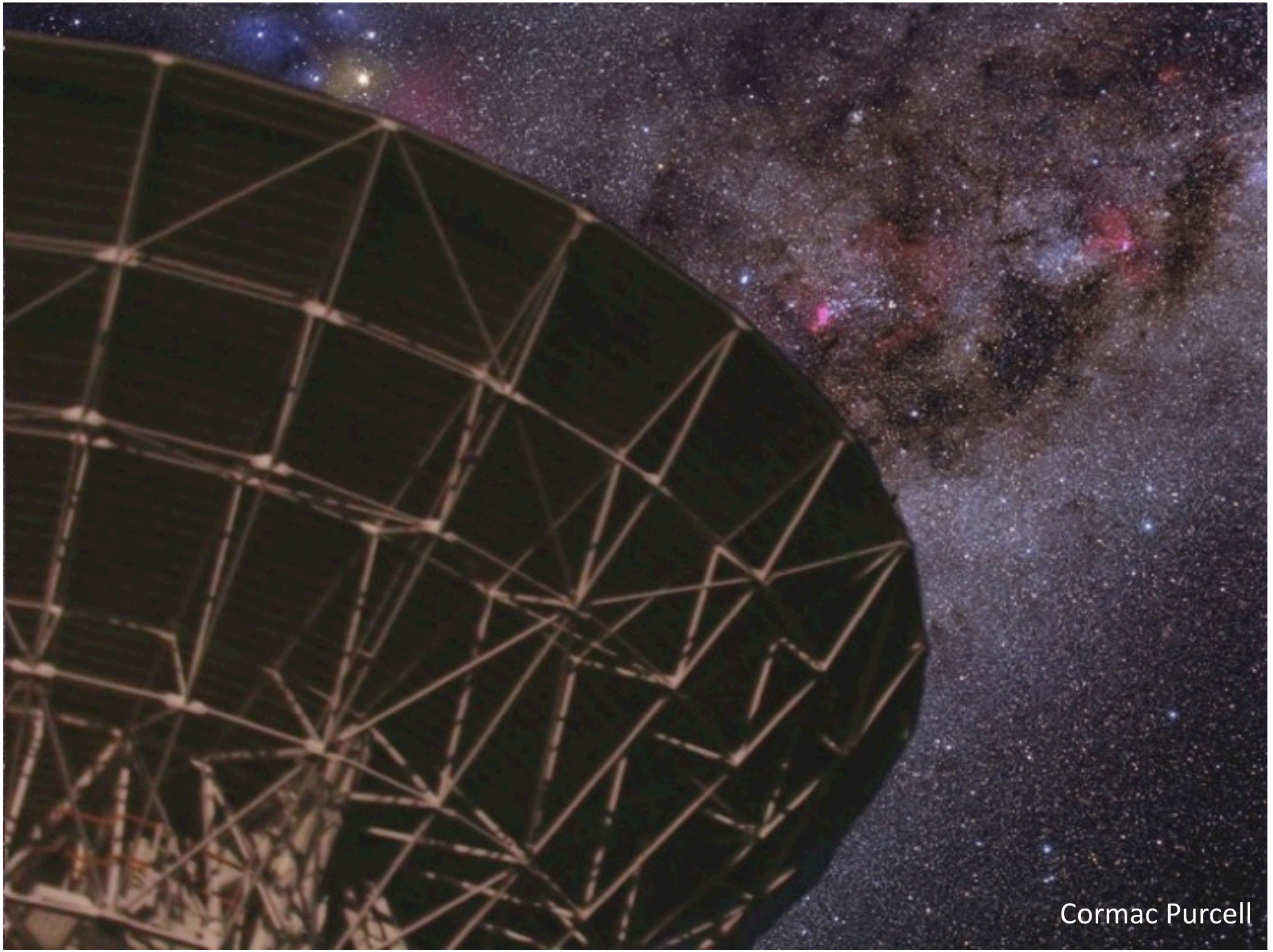
Height
=
Latitude
Coverage



The Night Sky and the Galaxy with Stellarium

stellarium.org




Cormac Purcell