Consequences of the Interaction of Cosmic Rays with Molecular Clouds near the Galactic Center

F. Yusef-Zadeh
Northwestern University

- **Large Scale: The inner 200pc of the Galaxy**

1. H_3^+ absorption lines (diffuse high temperature gas)
2. Synchrotron radio emission (e^-)

$$\zeta = \frac{1.6 \times 10^{-13}\, \mathrm{I}_\nu\, \nu^{(\mathrm{p}-1)/2}}{(p-1)\, L\, \mathrm{B}^{(\mathrm{p}+1)/2}}\ \mathrm{s}^{-1}\,\mathrm{H}^{-1}$$

3. Warm molecular gas

$$\frac{\Gamma}{n_{\mathrm{H}}} = 4.0 \times 10^{-26} \left(\frac{\zeta_{\mathrm{H}}}{10^{-15}\,\mathrm{s}^{-1}\,\mathrm{H}^{-1}}\right)\ \mathrm{erg\,s}^{-1}\,\mathrm{H}^{-1}$$

4. GeV γ-ray emission

$$F_\gamma \approx \frac{3.3 \times 10^{-13}}{p-1} \left(\frac{S_\nu}{\mathrm{Jy}}\right) \left(\frac{\nu}{\mathrm{GHz}}\right)^{\alpha} \left(\frac{B}{100\,\mu\mathrm{G}}\right)^{-(1+\alpha)} \left(\frac{n_{\mathrm{H}}}{\mathrm{cm}^{-3}}\right) \times \left(\frac{E_\gamma}{1\ \mathrm{GeV}}\right)^{-p} \mathrm{photons\,cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{GeV}^{-1},$$

5. FeI Kα 6.4KeV emission

$$I_{\mathrm{K}\alpha} = \frac{40.1\mathrm{eV} \times \zeta \times \mathrm{N_H} \times \mathrm{q}}{4\pi}\ \mathrm{ph\ s}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{sr}^{-1}$$

6. Chemistry

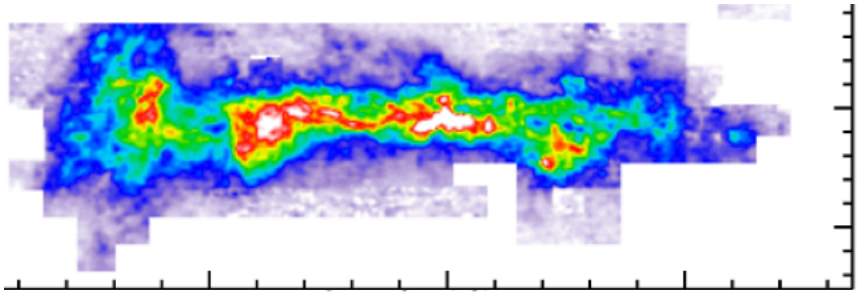
Collaborators: M. Wardle, E. Chambers, S. Viti, B. Cotton & J. Hewitt

Interacting Molecular and Relativistic Components

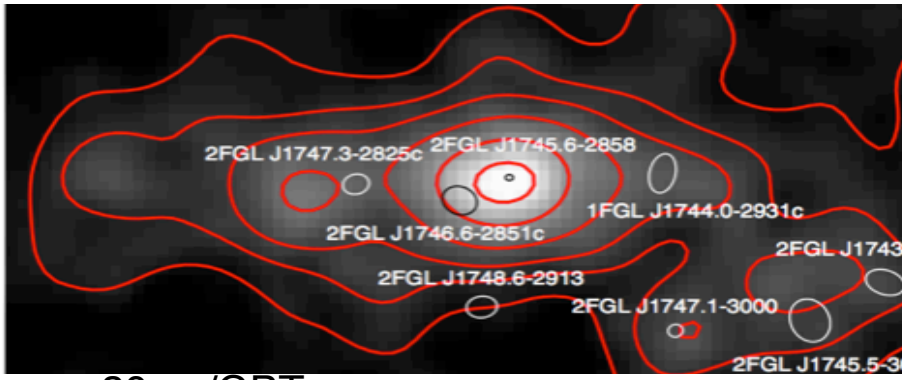
4. Relativistic Bremsstrahlung Radiation

- Spatially similar: radio/γ-rays/molecular emission
- Consider synchrotron emitting electrons interact with the gas
- A fraction of the energy gets transferred from CRs to photons

Sgr B2 B1 Arc **Sgr A*** Sgr C



CS (1-0)/NRO



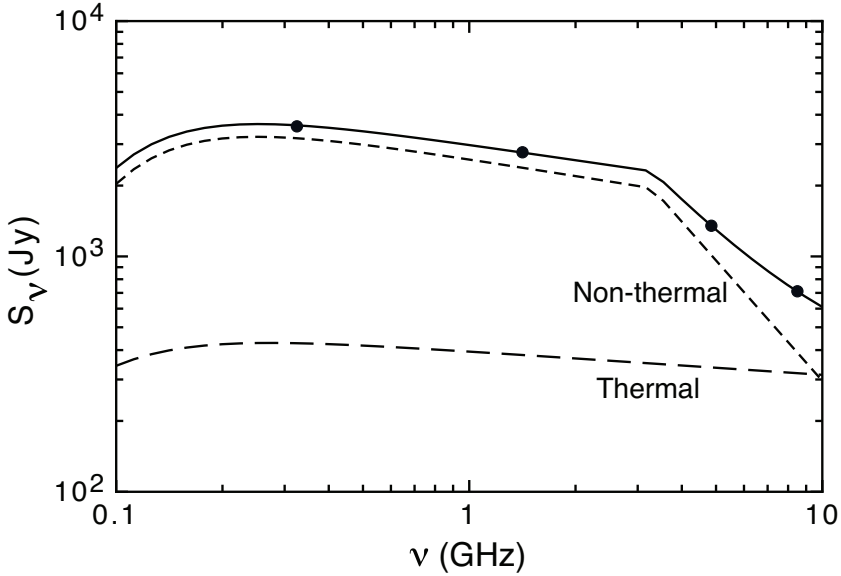
20cm/GBT

GeV/Fermi

Interacting Molecular and Relativistic Components

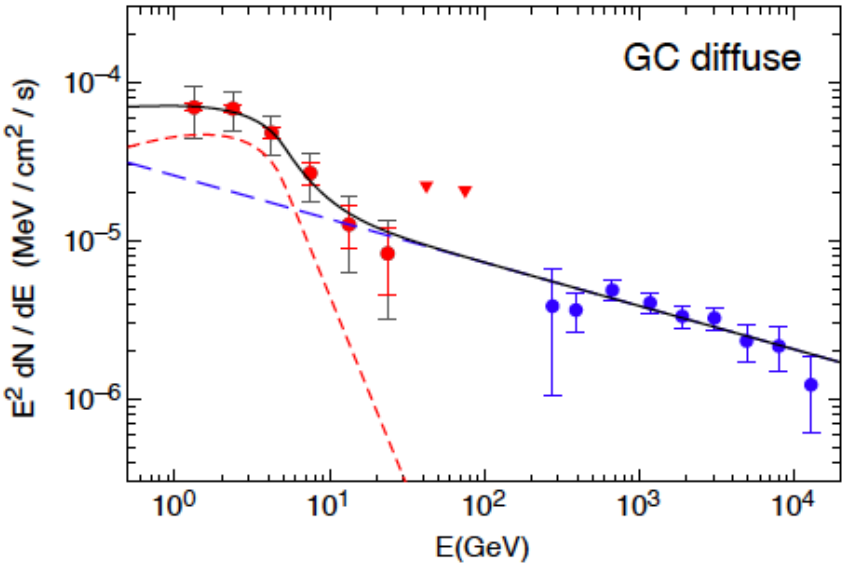
4. Relativistic Bremsstrahlung Radiation

- The photon spectrum of diffuse γ-ray
- Predicted model from radio spectrum
- A break in radio and γ-ray spectrum
- Bremsstrahlung γ-ray flux



$$F_\gamma \approx \frac{3.3\times10^{-13}}{p-1}\left(\frac{S_\nu}{\mathrm{Jy}}\right)\left(\frac{\nu}{\mathrm{GHz}}\right)^{\alpha}\left(\frac{B}{100\,\mu\mathrm{G}}\right)^{-(1+\alpha)}\left(\frac{n_\mathrm{H}}{\mathrm{cm}^{-3}}\right) \times\left(\frac{E_\gamma}{1\,\mathrm{GeV}}\right)^{-p}\ \mathrm{photons\,cm^{-2}\,s^{-1}\,GeV^{-1}}, \quad (8)$$

Source	B (μG)	n_H (cm^{-3})	F_{325MHz} (Jy)	p1	p2	ν_{break} (GHz)
GC diffuse	8	12.5	508	1.5	4.4	3.3



FYZ et al. 2013

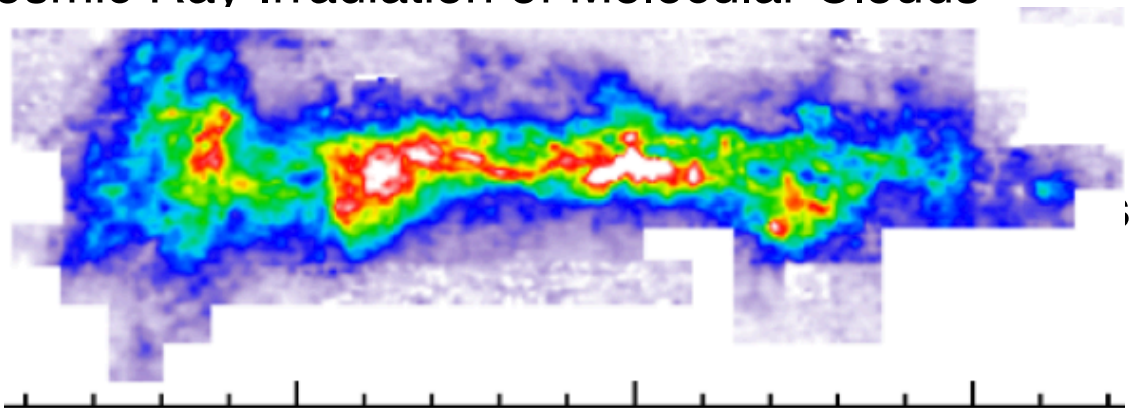
Interacting Molecular and Relativistic Components
4. Relativistic Bremsstrahlung Radiation

- Excess γ-ray emission

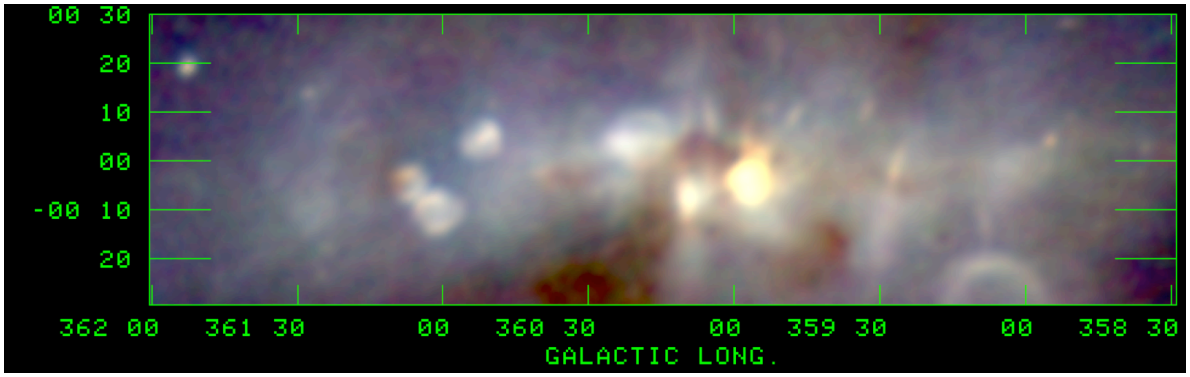
1. Emission from ~1000 millisecond pulsars
2. Byproduct of annihilating DM particles
3. Alternative: nonthermal Bremsstrahlung

Interacting Molecular and Relativistic Components

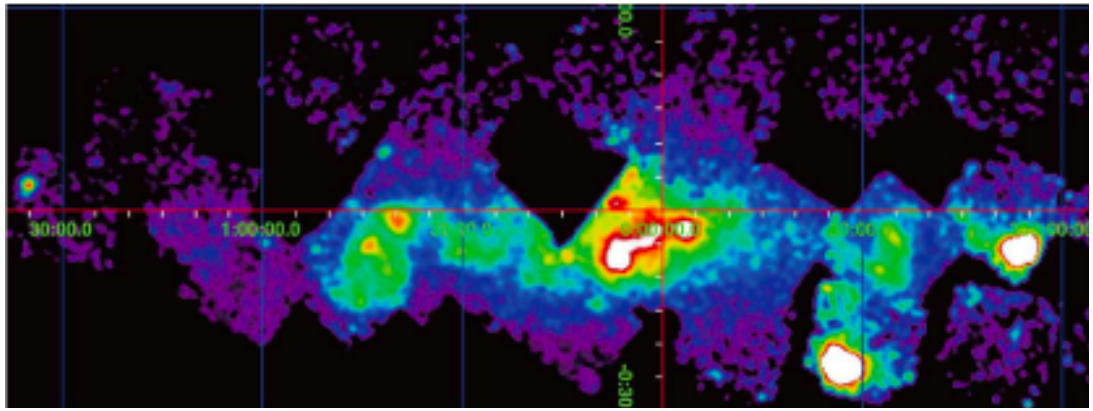
5. Cosmic Ray Irradiation of Molecular Clouds



CS (1-0)



180/150/100 MHz
(MWA)

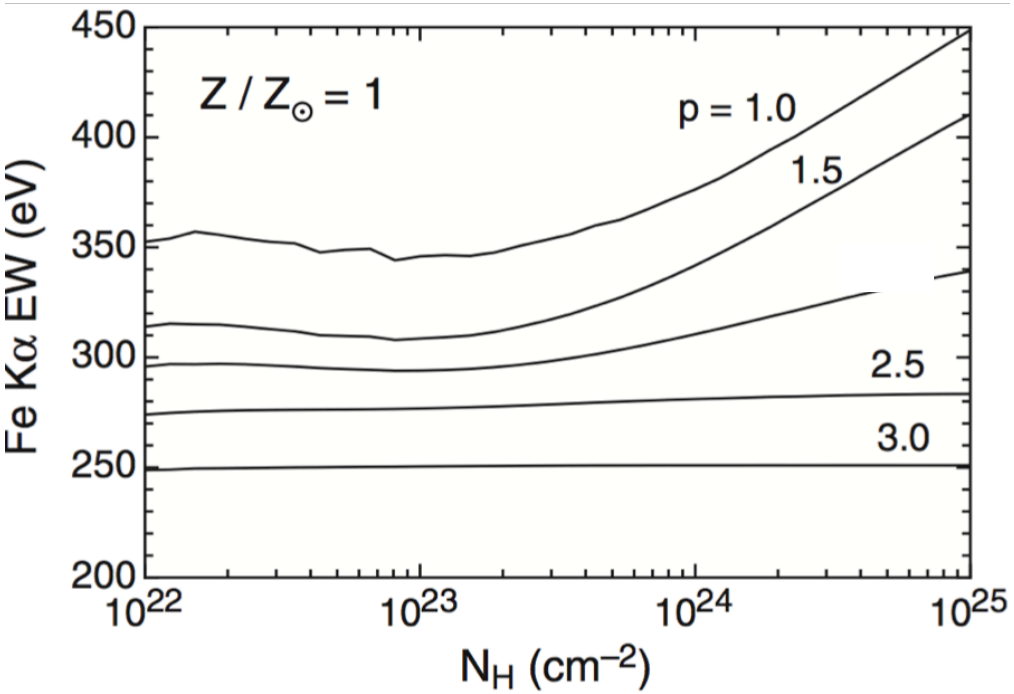


FeI 6.4 keV
(Suzaku)

Interacting Molecular and Relativistic Components

5. Cosmic Ray Irradiation of Molecular Clouds: Impact of LECRe

- Efficiency of 6.4 keV production
- 200 Fe Ka production per erg of electrons



$$I_{K\alpha} = \frac{40.1\mathrm{eV} \times \zeta \times N_H \times q}{4\pi} \ \mathrm{ph\ s^{-1}\ cm^{-2}\ sr^{-1}}$$

$N_H = 3 \times 10^{23}$ cm^{-2}
gives
$\zeta = 3 \times 10^{-15}$ s^{-1}
Metalicity ~2-3 is needed

- Enhanced 6.4 keV emission toward interacting SNRs (Suzaku)

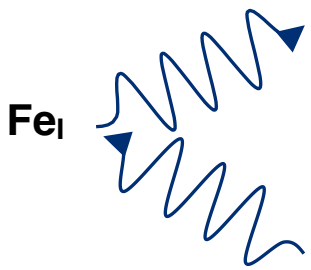
Interacting Molecular and Relativistic Components

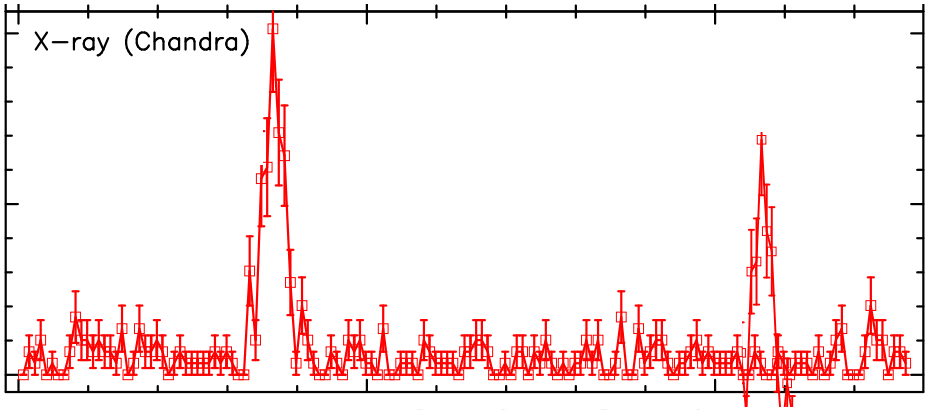
5. Alternative Model: X-ray Flash

- Equivalent Width (EW) ~700-1000eV

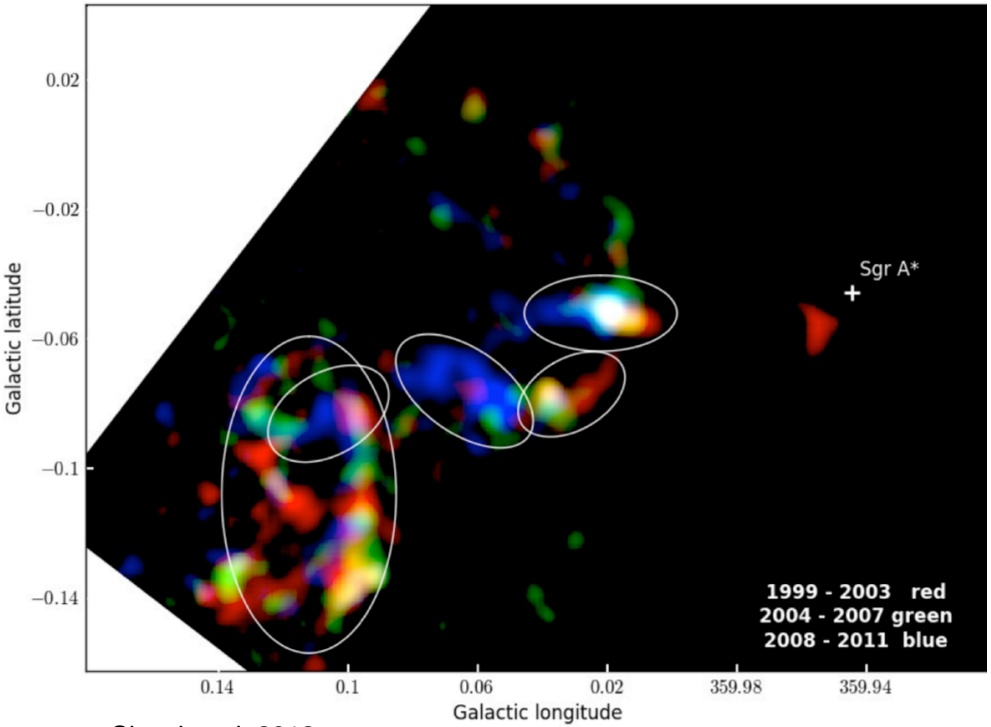
Irradiation by X-rays

Murakami+00





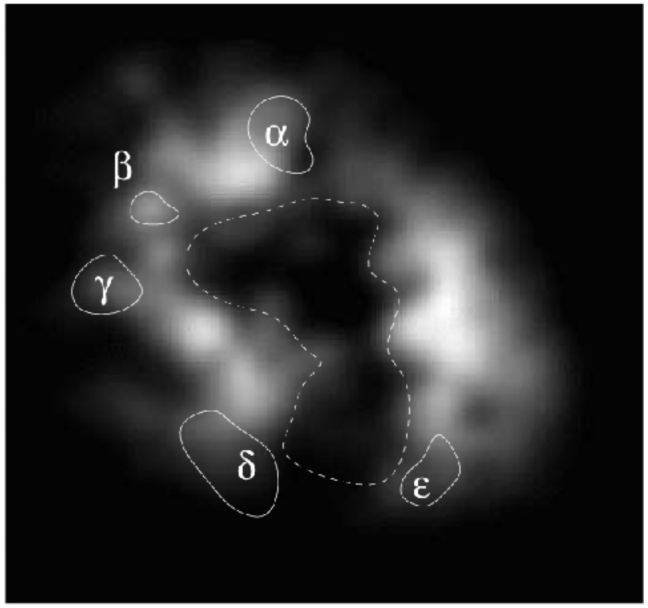
- Sgr A* or nearby variable X-ray sources
- Variable 6.4 keV line emission
- Echo of few 10^{39} erg/s flare from Sgr A*
- ~300 and ~100 years ago (Ponti et al. 2010)
- Duration of 10 and 2 years



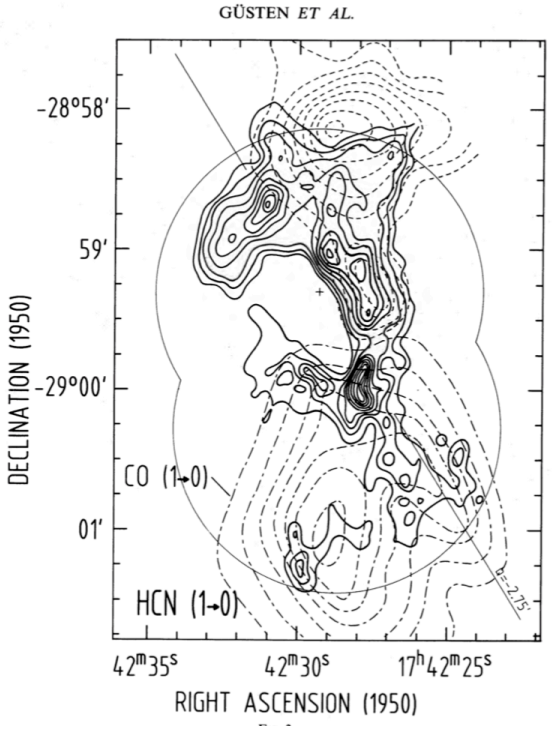
Clavel et al. 2013

Interacting Molecular and Relativistic Components

5. Alternative Model: X-ray Flash



Mossoux & Eckart 2018

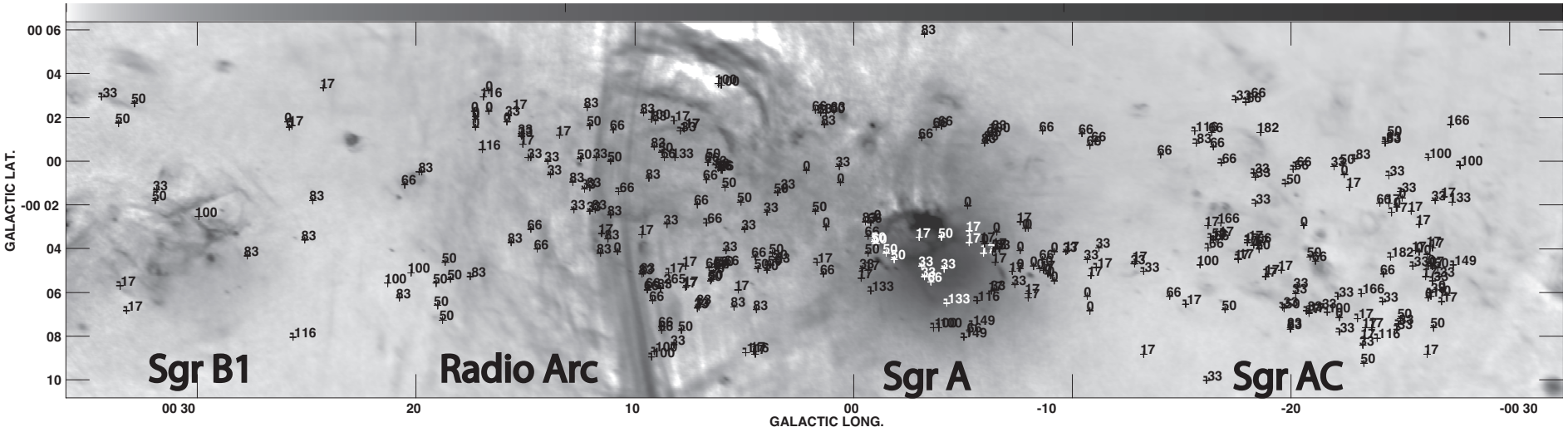


- Circumnuclear Molecular Ring
- n~ few 10^6 cm^{-3}
- M ~ few 10^4 solar mass
- N_H ~ few x10^{24} cm^{-2}
- Attenuation at 10 keV:

Exp-(σ N_H) with $N_H > 10^{24}$ cm^{-2} (Morrison & McCammon 1983)

Interacting Molecular and Relativistic Components
6. Chemistry

- Collisionally excited CH_3OH masers at 36.2 GHz



1. 6.4 keV line vs

HCN/HCO^+ line ratio

:Anti-correlation

2. High CH3OH abundance

- **Summary**

- **The inner 200pc of the Galaxy**
  - ❑ **Relativistic, thermal and magnetized cold and hot plasmas**
  - ❑ **Interaction of cosmic rays and molecular gas**
    1. **H^+_3 studies**
    2. **high ζ and high ionization fraction and CR driven chemistry**
    3. **warm gas**
    4. **Relativistic Bremsstrahlung γ radiation: Excess γ-ray emission**
    5. **6.4 keV Fe I line emission**
    6. **Chemistry**