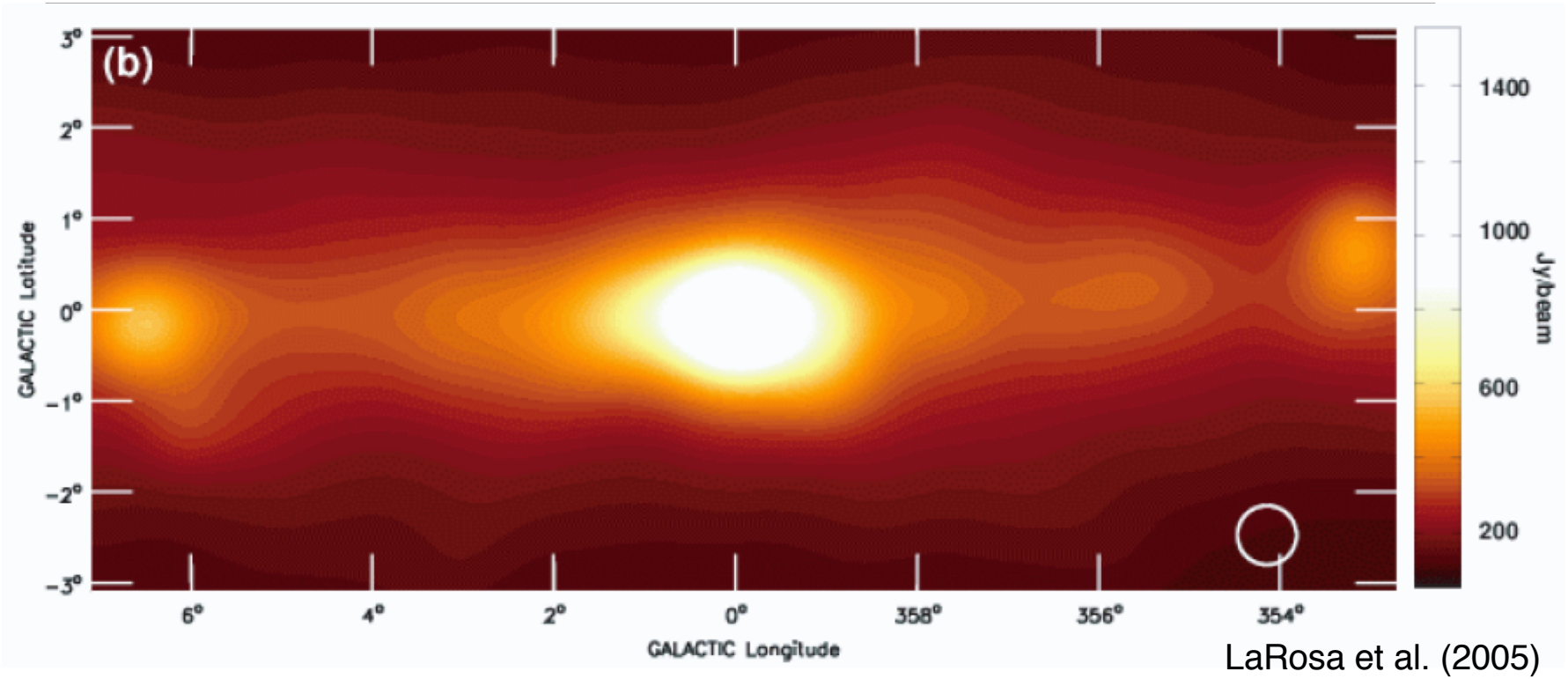
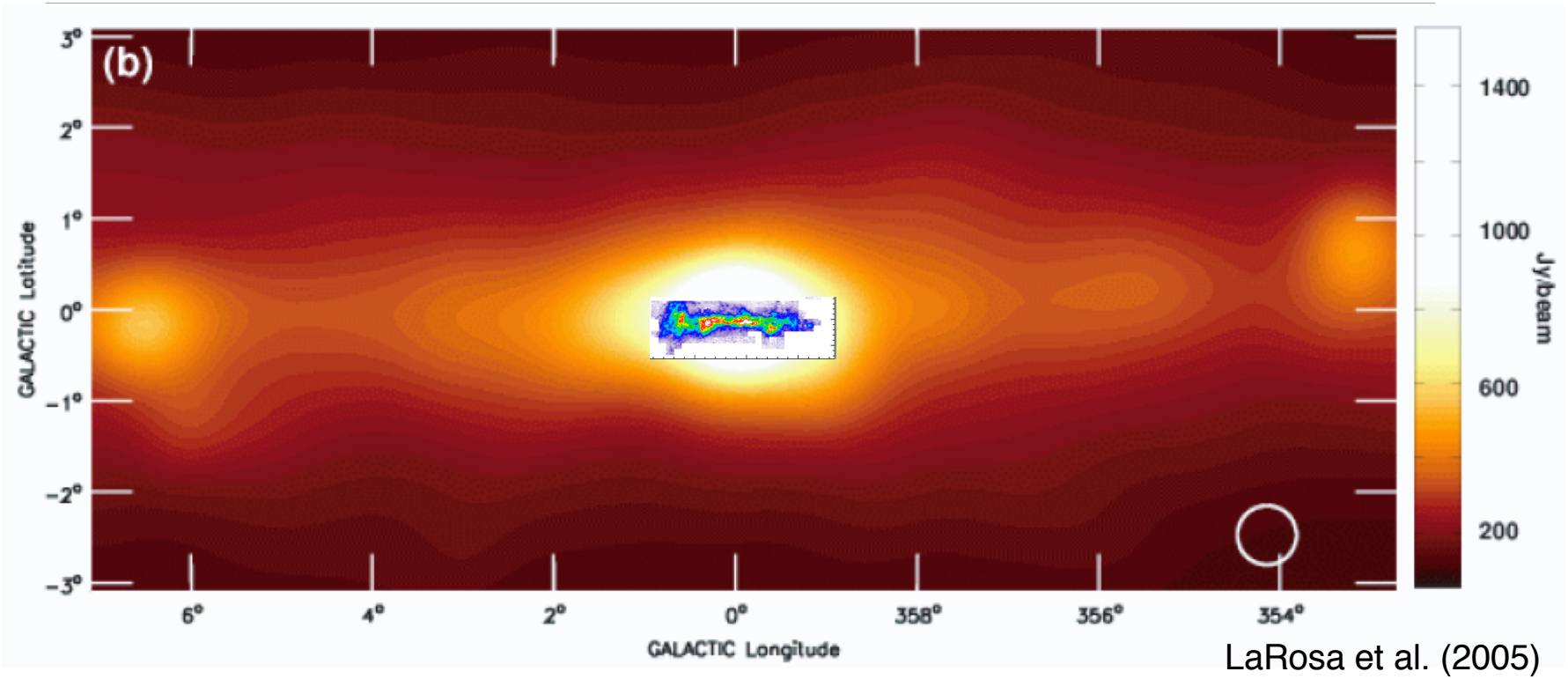
Consequences of the Interaction of Cosmic Rays with Molecular Clouds near the Galactic Center



LaRosa et al. (2005)

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



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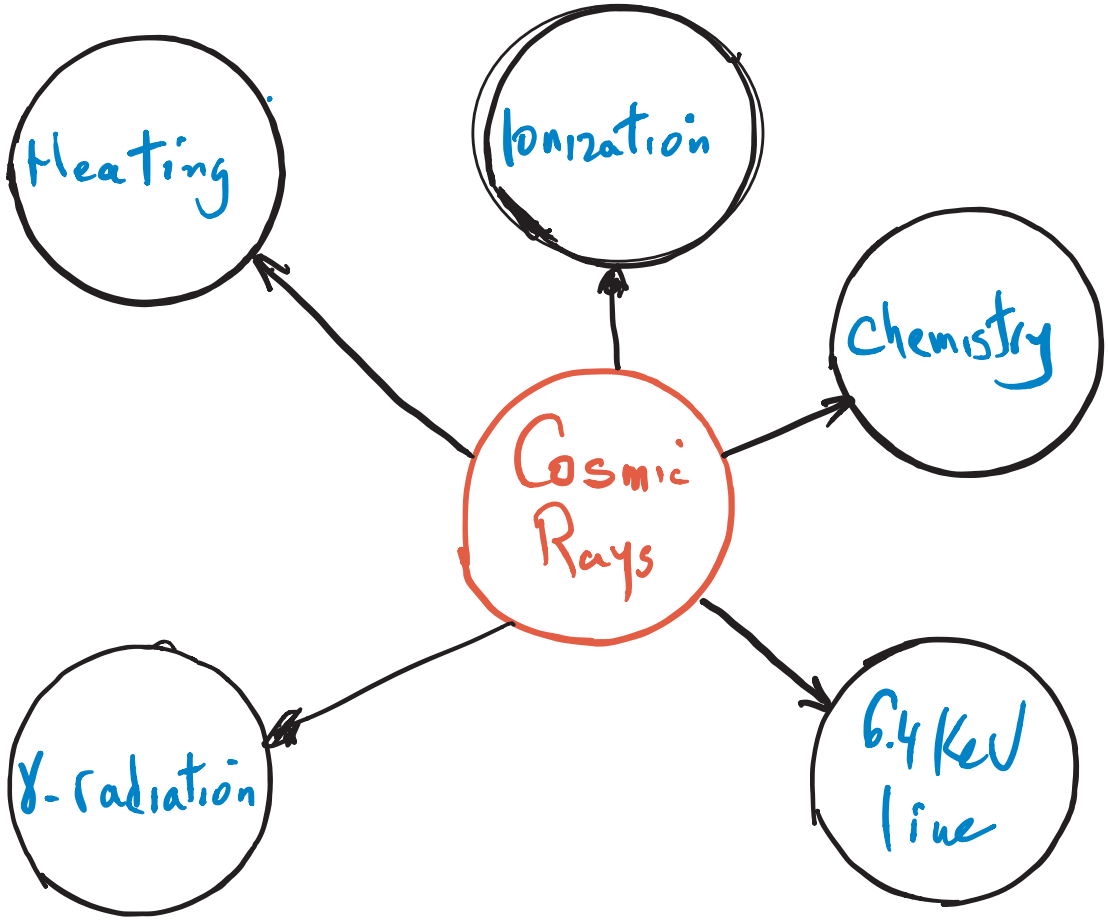
Consequences of the Interaction of Cosmic Rays with Molecular Clouds near the Galactic Center

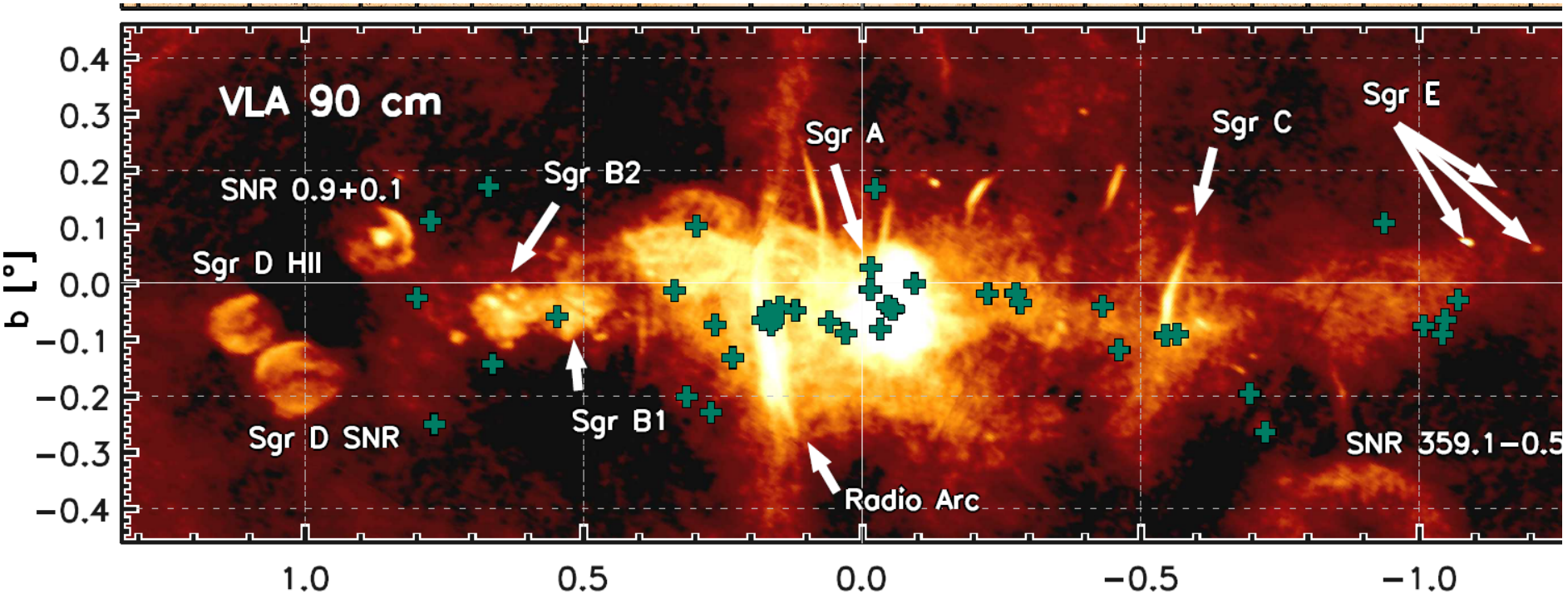
F. Yusef-Zadeh
Northwestern University



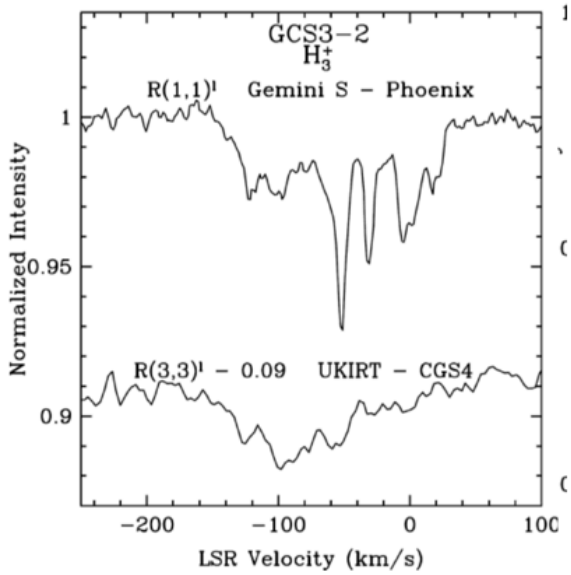
Collaborators: M. Wardle, E. Chambers, S. Viti, B. Cotton, J. Hewitt, & M. Royster

Interacting Molecular and Relativistic Components

1. Cosmic Ray Ionization Rate Using H_3^+



LaRosa et al. 2005

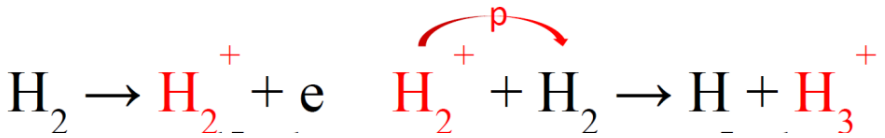


Oka et al. 2019

Interacting Molecular and Relativistic Components

1. Cosmic Ray Ionization Rate Using H_3^+

- Ubiquitous as long as H_2 exist. Dense and diffuse clouds
- Simple chemistry and straightforward



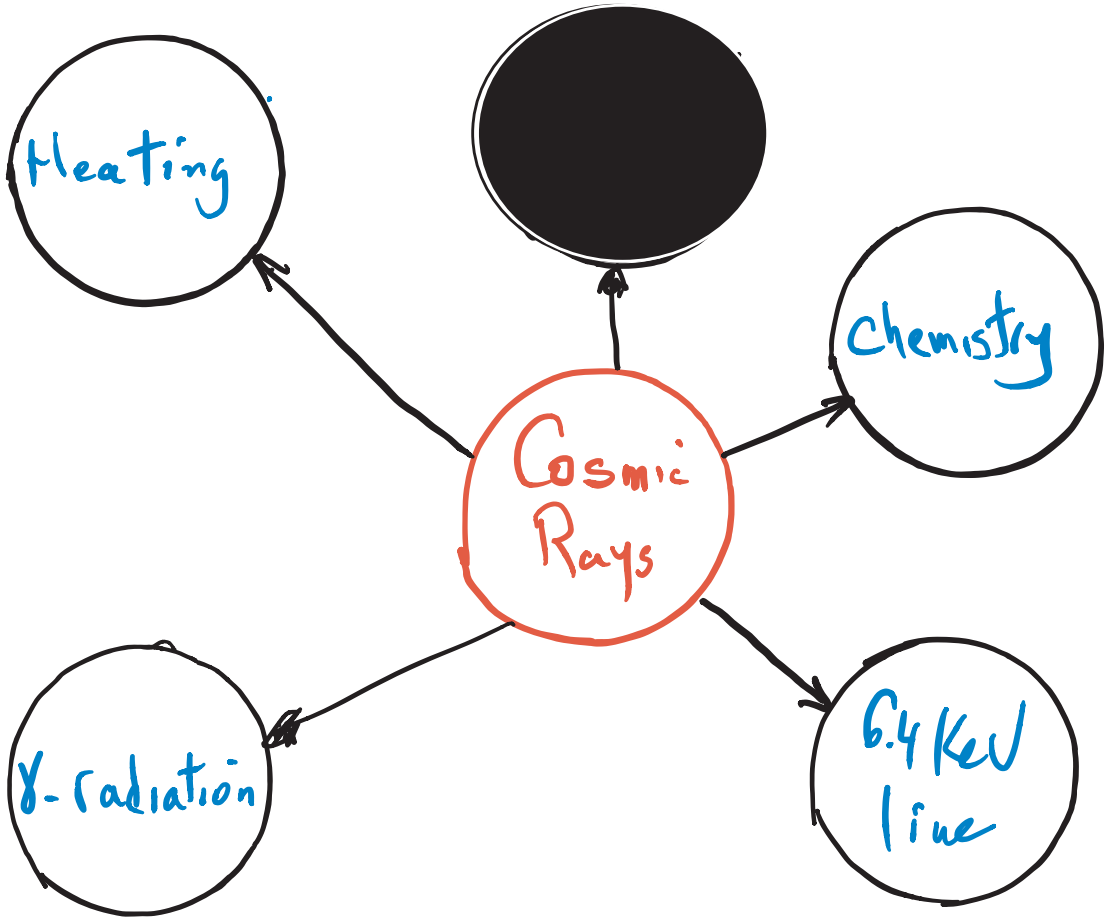
$$H_2 \rightarrow H_2^+ + e \qquad H_2^+ + H_2 \rightarrow H + H_3^+$$

- $\zeta \sim 2 \times 10^{-14}$ s^{-1} (Galactic center)
- Two to three orders of magnitude higher than in the Galactic disk

- gas temperature 200K
- gas density <200 cm^{-3}

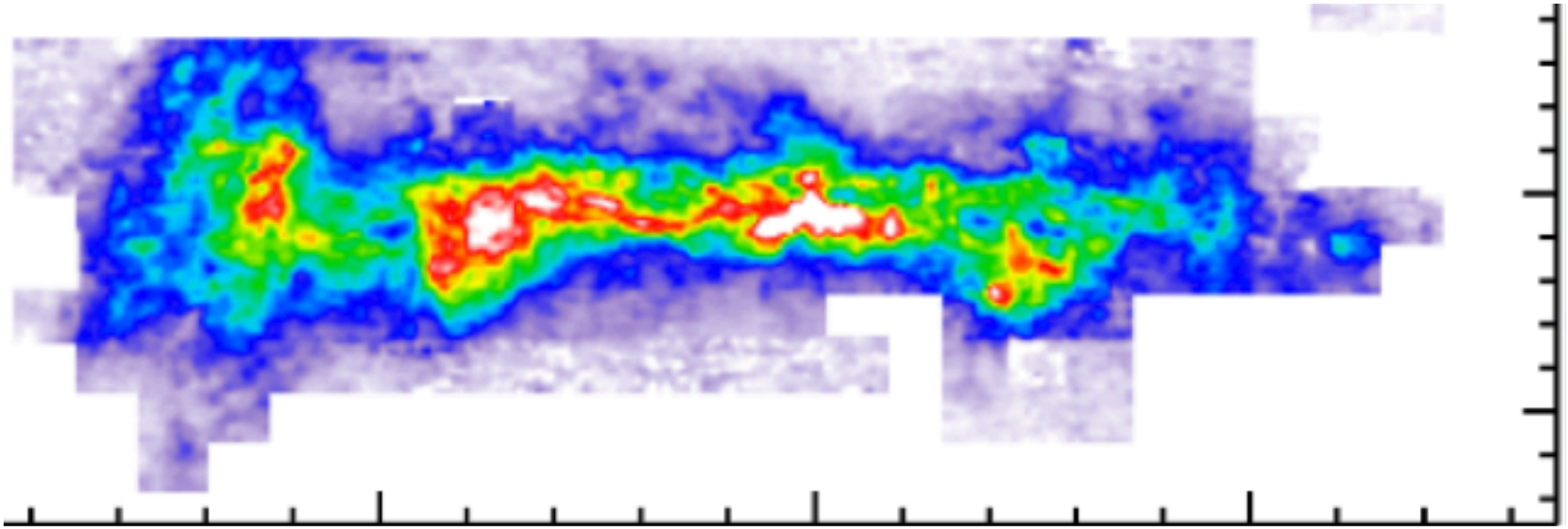
Oka et al. 2005, 2019
LePetit et al. 2016

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



Interacting Molecular and Relativistic Components

2. Cosmic Ray Heating Rate



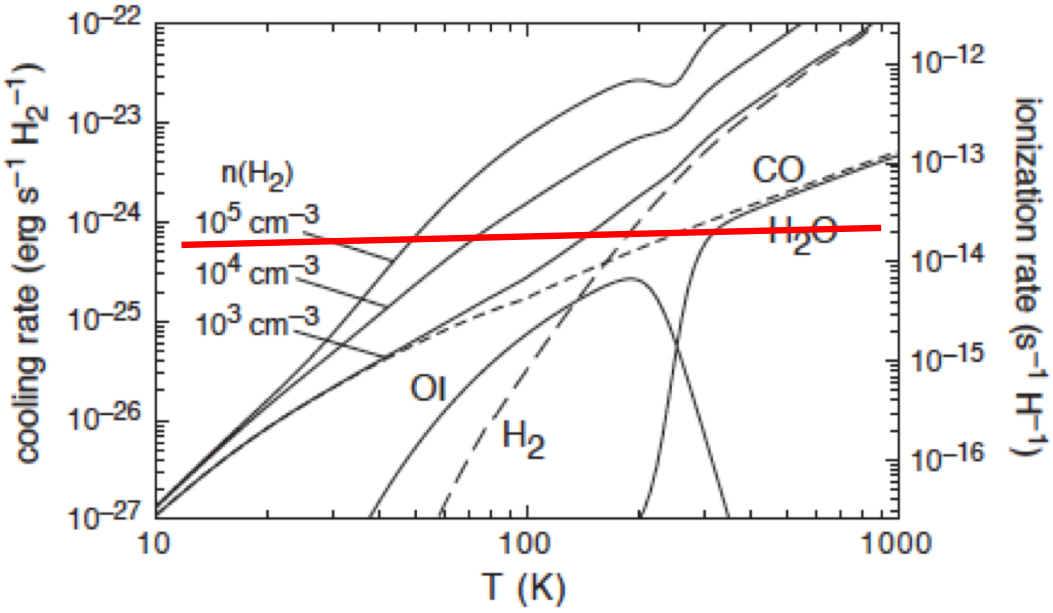
- High temperature molecular gas like NH_3 and and H_3^+
- T_{gas}~70-200K
- T_{dust}~25K
- Ubiquity of warm gas
- Heat the gas
- CRs or X-rays or shocks or turbulence

Interacting Molecular and Relativistic Components

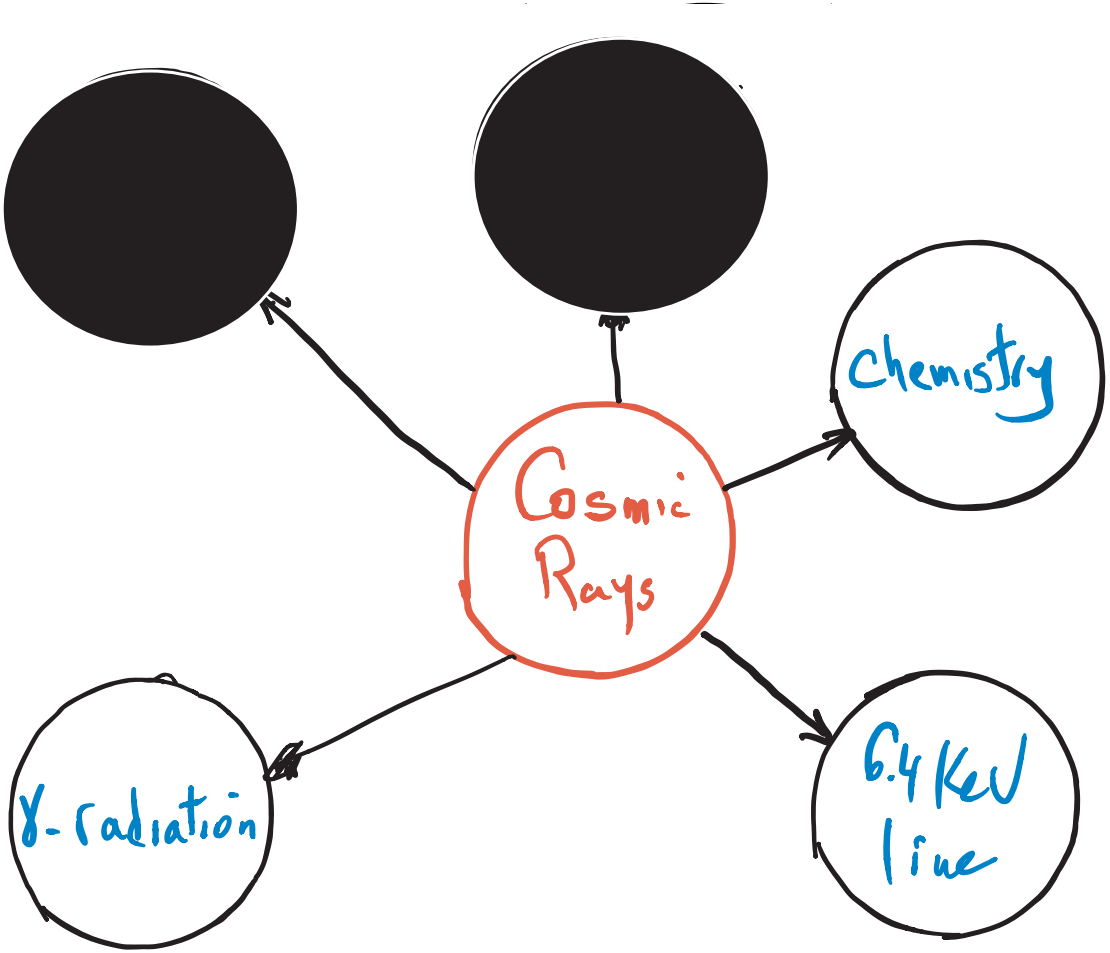
2. Cosmic Ray Heating Rate

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

- Heating rate ~ Cooling rate
- Total mass 2x10^{7} M_{solar}
- Total heating rate ~ 1-2x10^{39} erg/s
- ~ 3/2kT/Λ ~10^{7} yrs



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

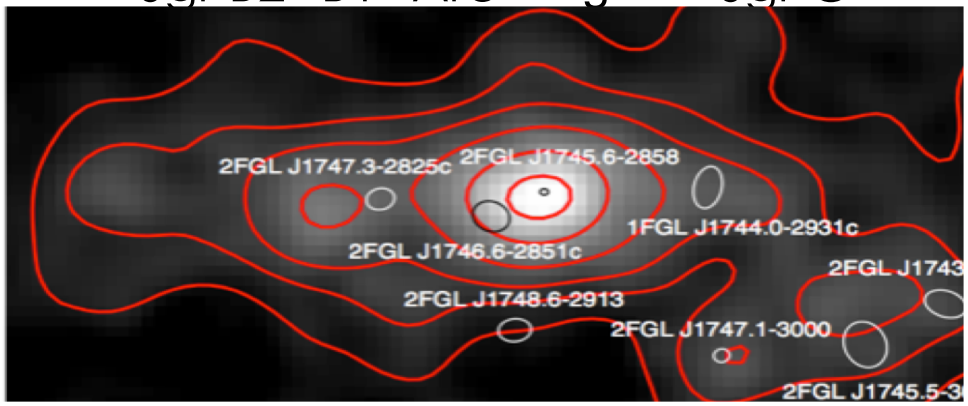


Interacting Molecular and Relativistic Components

3. Cosmic Ray Ionization Rate: NT Radio + γ–Rays

- 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



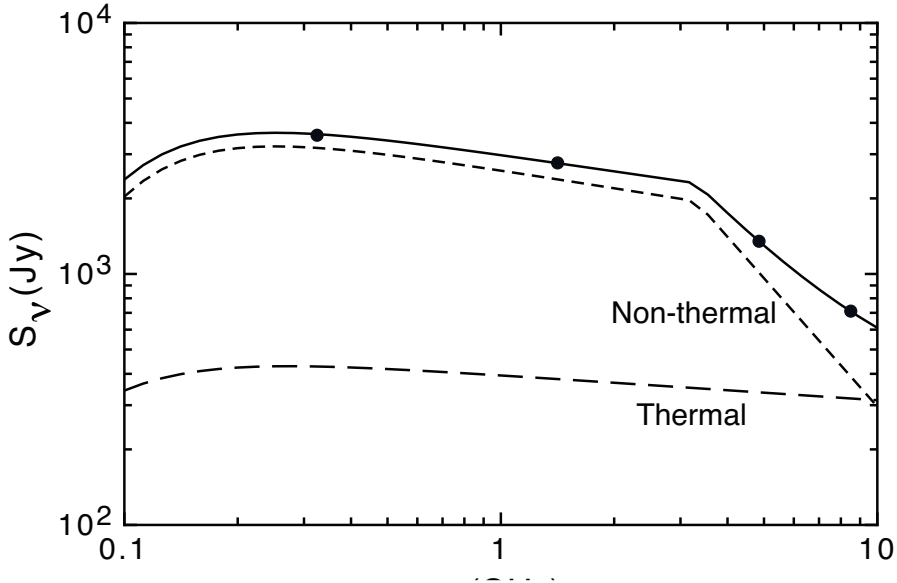
20cm/GBT

GeV/Fermi

Interacting Molecular and Relativistic Components

3. Cosmic Ray Ionization Rate: NT Radio + γ–Rays

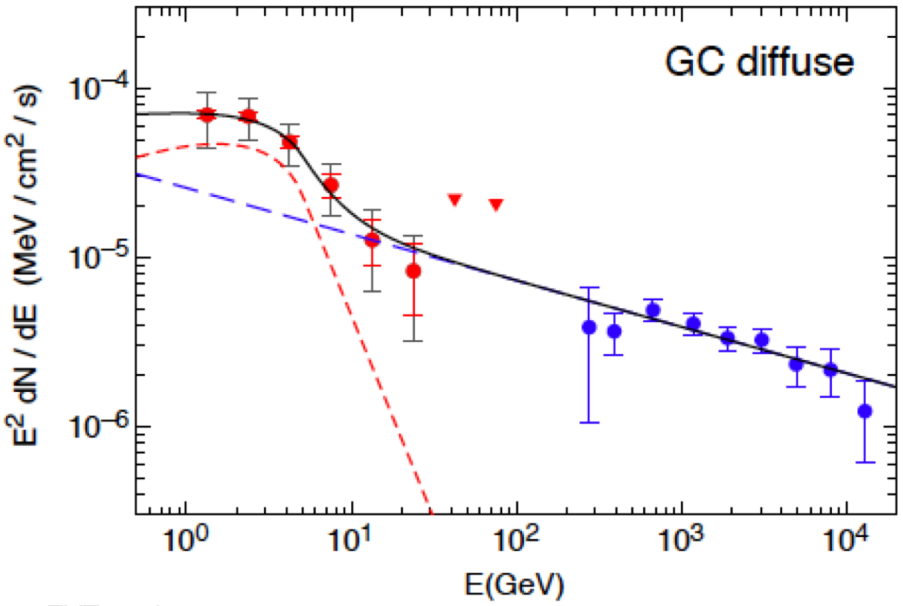
- A break in the radio spectrum over 2x1deg
- Account for thermal continuum emission



- Bremsstrahlung γ-ray flux

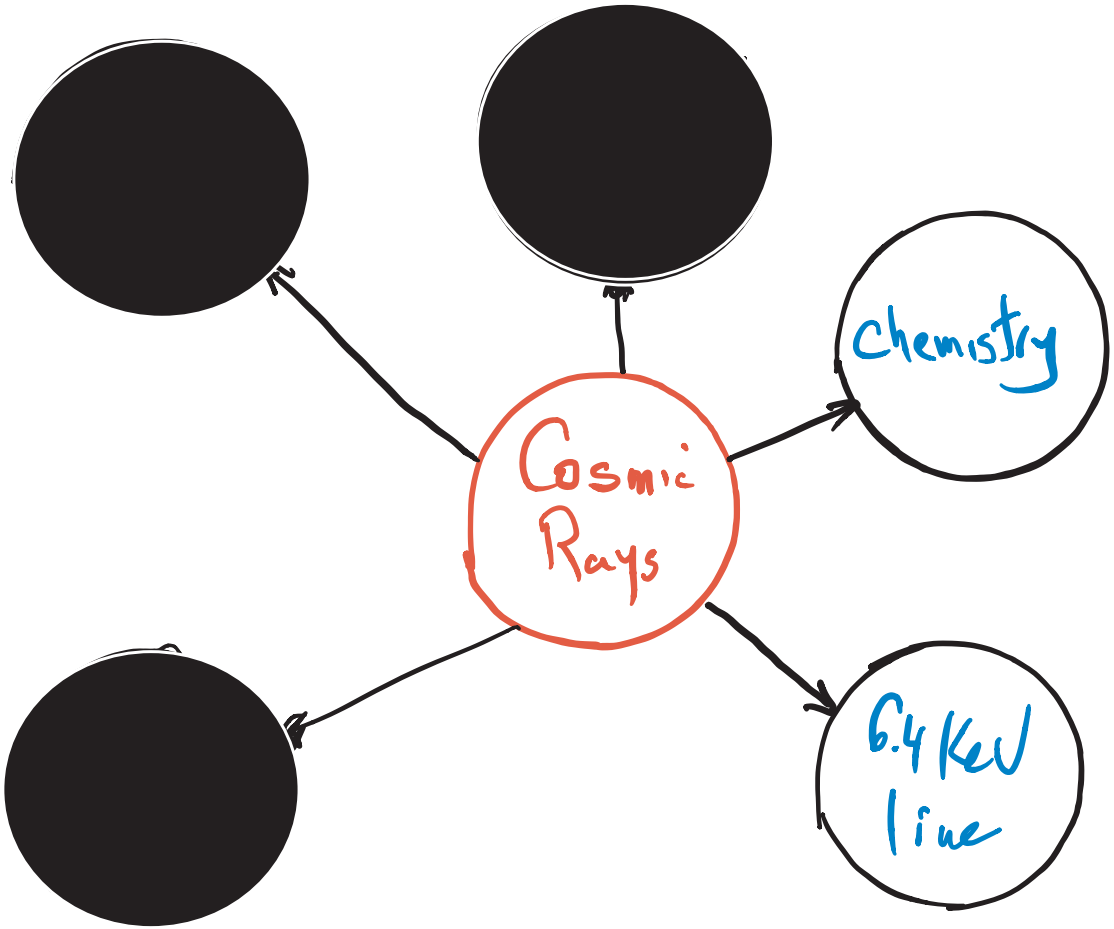
$$F_\gamma \approx \frac{3.3\times10^{-13}}{p-1}\left(\frac{S_\nu}{\mathrm{Jy}}\right)\left(\frac{\nu}{\mathrm{GHz}}\right)^{\alpha}\left(\frac{B}{100\,\mu\mathrm{G}}\right)^{-(1+\alpha)}\left(\frac{n_\mathrm{H}}{\mathrm{cm}^{-3}}\right) \times\left(\frac{E_\gamma}{1\,\mathrm{GeV}}\right)^{-p}\ \mathrm{photons\,cm^{-2}\,s^{-1}\,GeV^{-1}},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

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



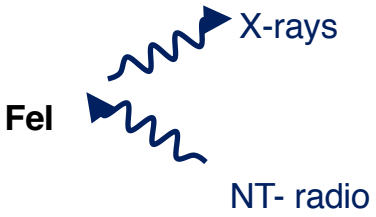
FYZ et al. 2013

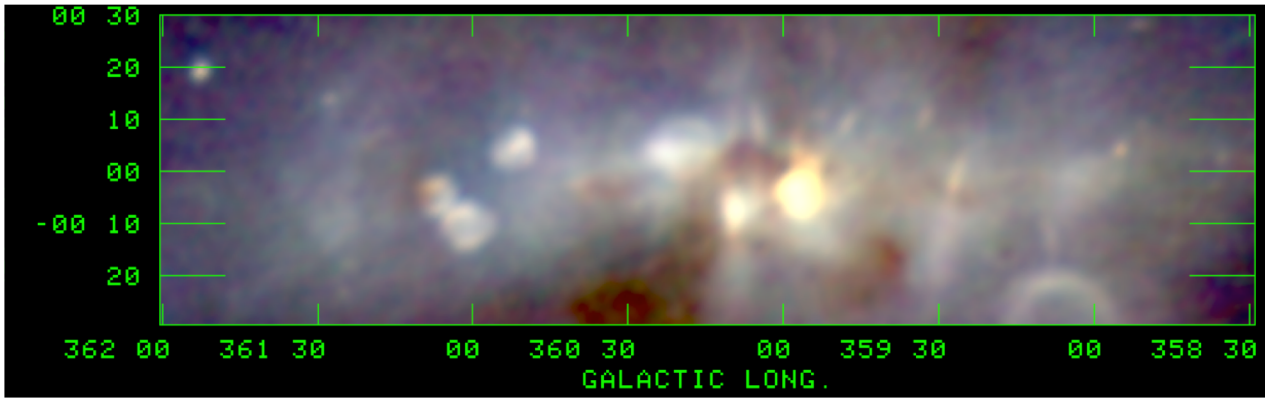
Consequences of the Interaction of Cosmic Rays with Molecular Clouds near the Galactic Center

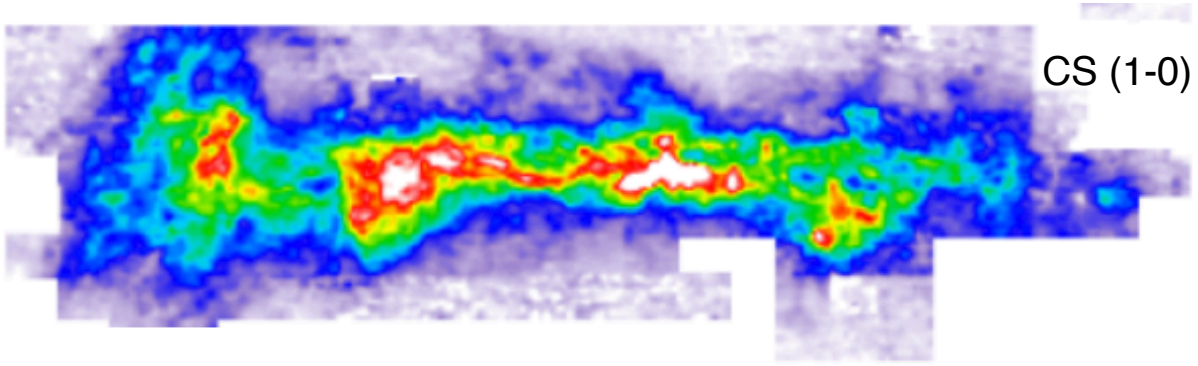


Interacting Molecular and Relativistic Components

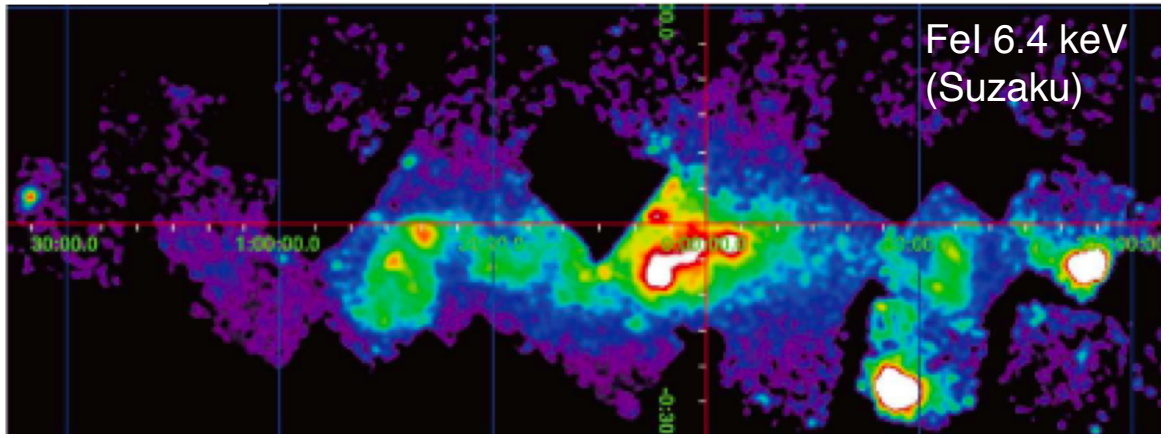
4. 6.4 keV Emission: Irradiation of Molecular Clouds







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



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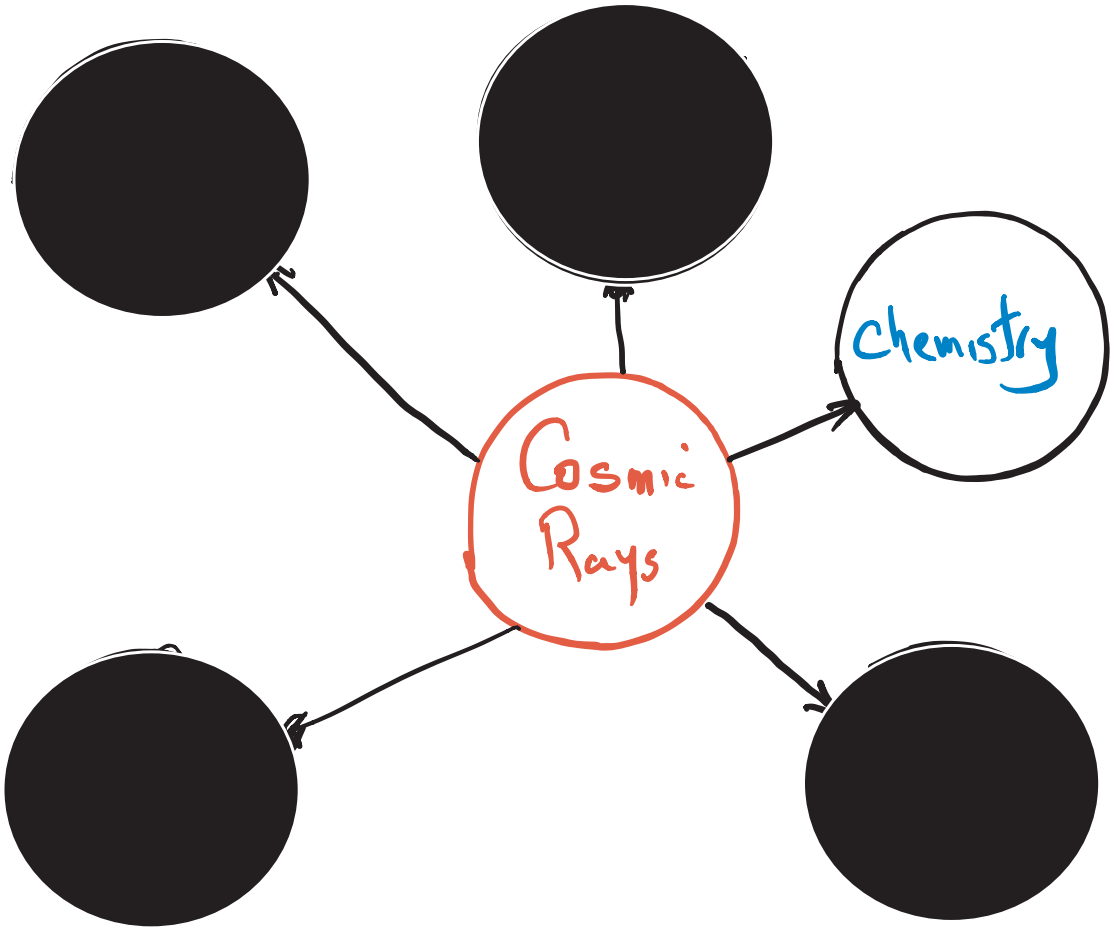
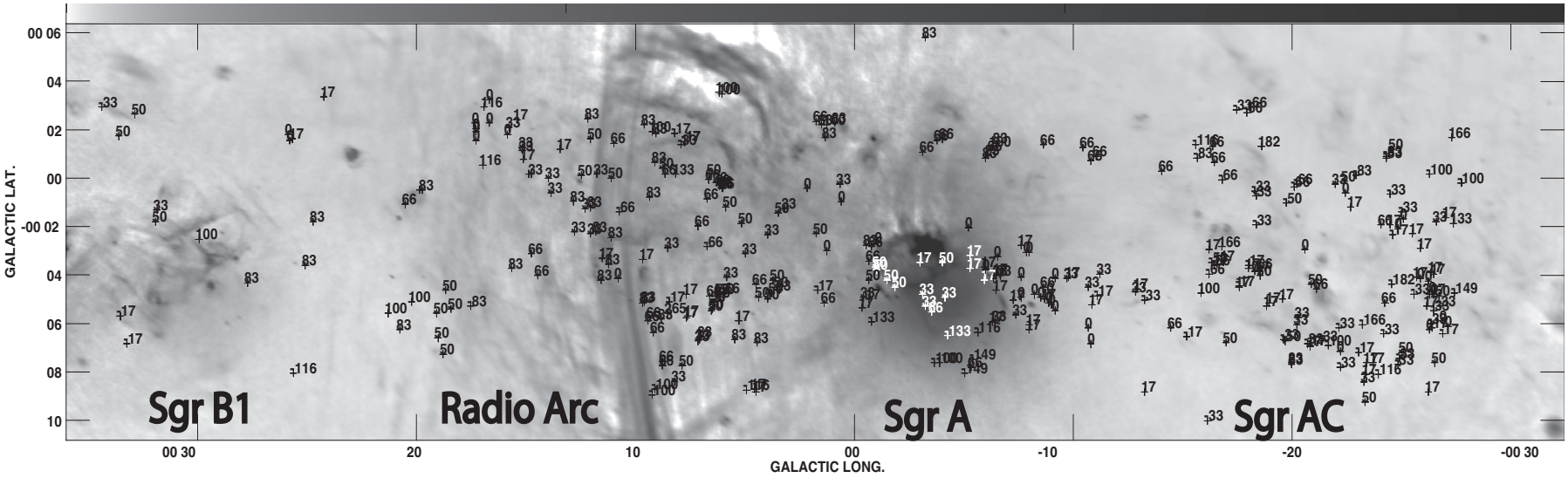


Interacting Molecular and Non-Relativistic Components

5. Chemistry

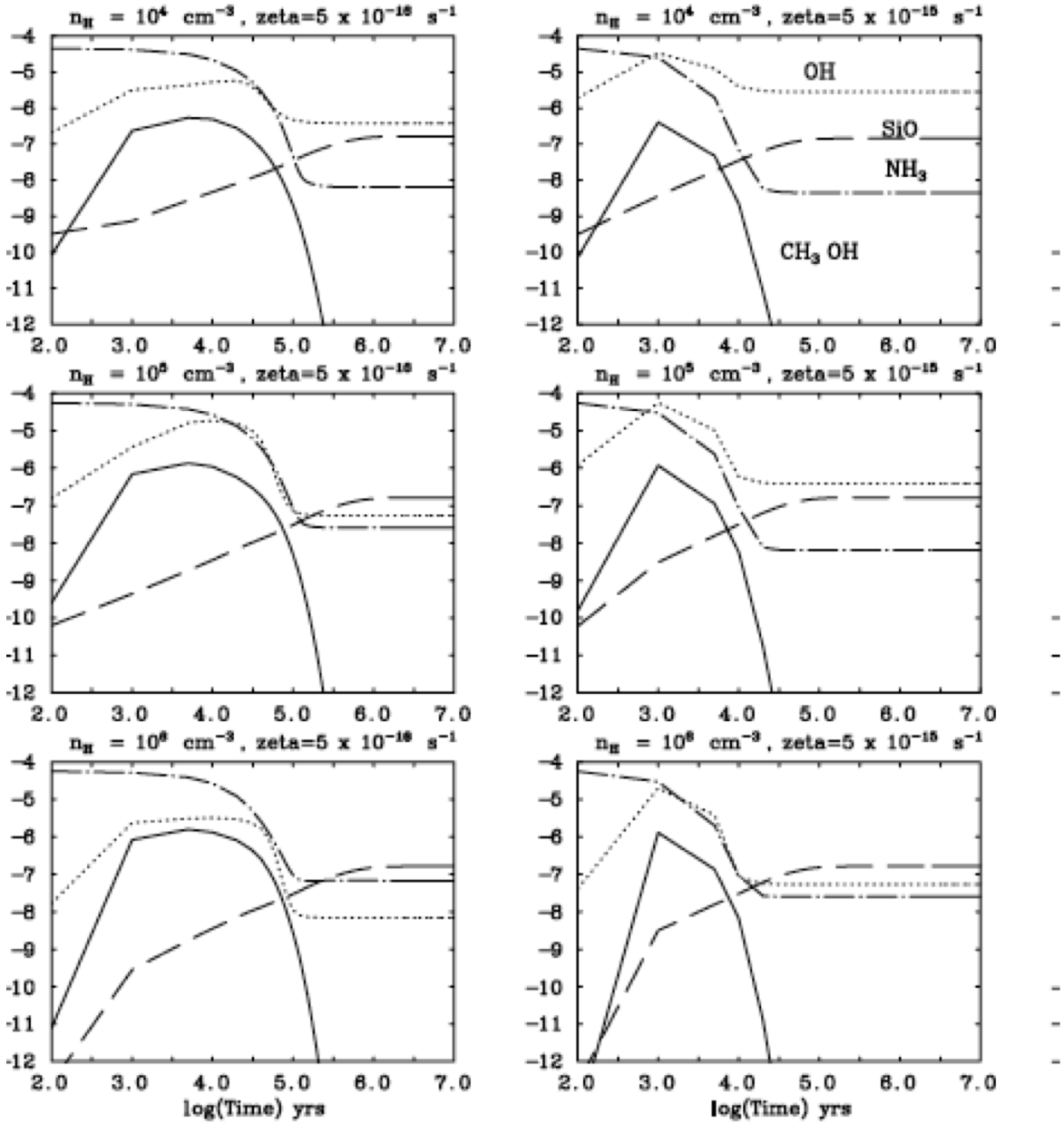
1. Collisionally excited CH_3OH masers at 36.2 GHz
2. High CH_3OH, SiO, NH_3 abundance and widespread
3. Grain surface chemistry



Grain Surface Chemistry

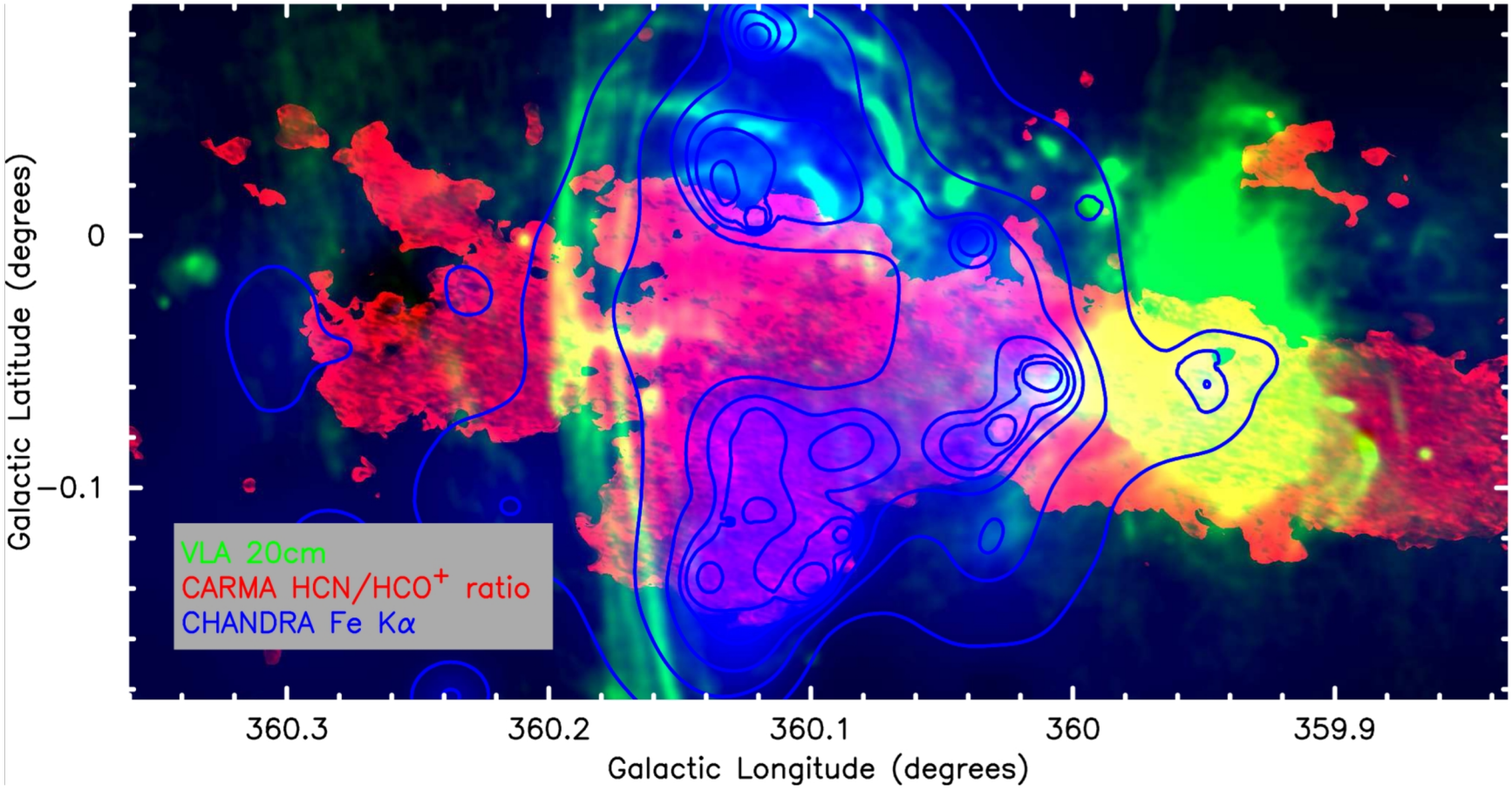
High Abundance of Methanol

SiO, NH3



Interacting Molecular and Non-Relativistic Components

5. Chemistry



- **Summary**

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