On the effects of Cosmic rays on Galactic center molecular clouds

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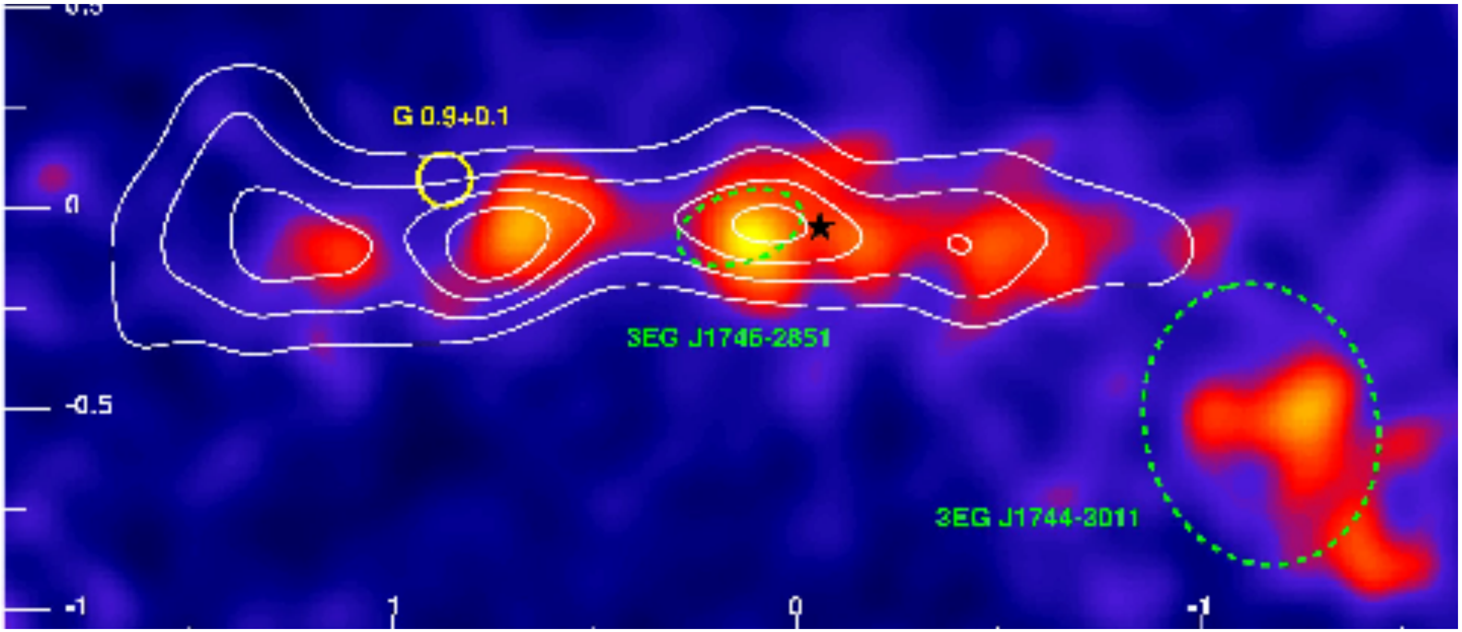


Outline

- Cosmic Ray Dominated Regions (CRDRs)
- Galactic center. Central Molecular Zone –CMZ-
- Tracers of CRDRs
- CMZ thermal balance (cooling lines and dust)
- CMZ ionization
- Summary
- Future prospects

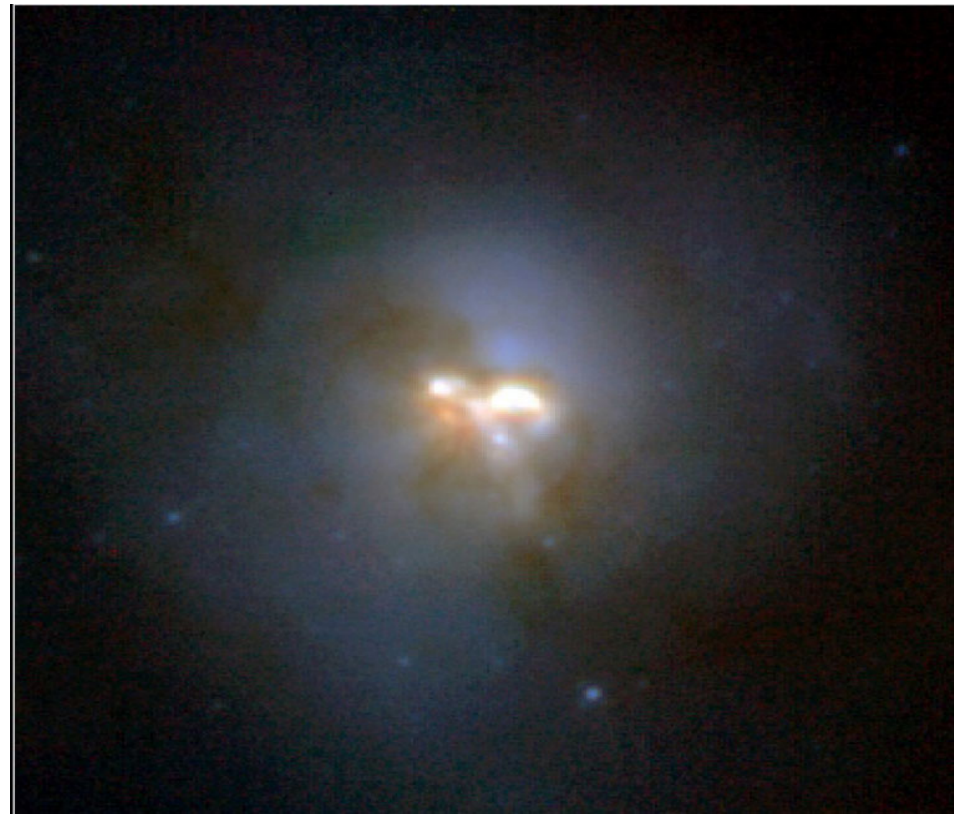
Cosmic Ray Dominated Regions (CRDRs)

Arp 220 Merger: 2 10^{12} Lo

- Forming stars a rate of >10^3 Msun/year
- Time scale is a short time of 10^5 years
- Shows an extremely high SN rate: 4/years
- Very obscured Av > 10^3 magnitudes
- Large ionization rates (>10^3) from high density

- Resembles the star formation at high redshift (z>2)

A scale version of local starbursts like M82



Cosmic Ray Dominated Regions (CRDRs)

CRs are expected to play an important role in dense regions (Av>5 mag) creating a CRDR and regulating :

- Thermal state (10 MeV≤E(CR)≤100 MeV)
- Ionization (chemistry and ambipolar diffusion)
- CRs feedback (talk by P. Girichidis)
- Initial conditions for star formation setting the IMF
  - Top heavy (less stars < 8 Msun)

Galactic center allows to study the importance of CRDRs in setting the initial conditions for star formation in the environment of galactic nuclei

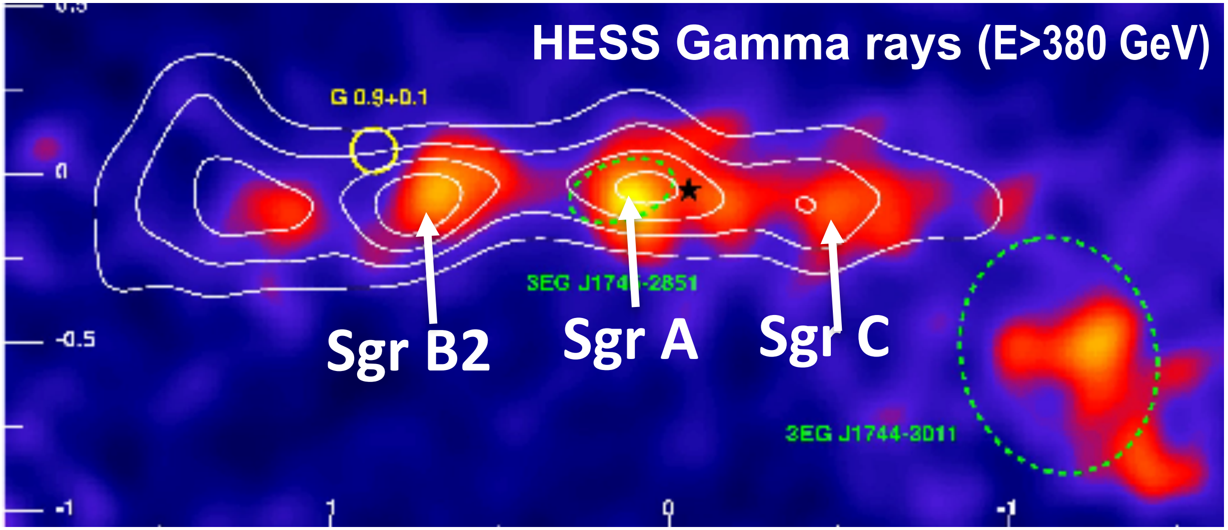
The Central Molecular Zone

The CMZ covering the inner 300 pc shows:

•Strong emission in all tracers of high energy activity

•Strong nonthermal (synchrotron) emission associated with SNRs

•Gamma ray emission: interaction of energetic Cosmic rays with molecular clouds **–CRDRs-**



Aharonian et al (2006)

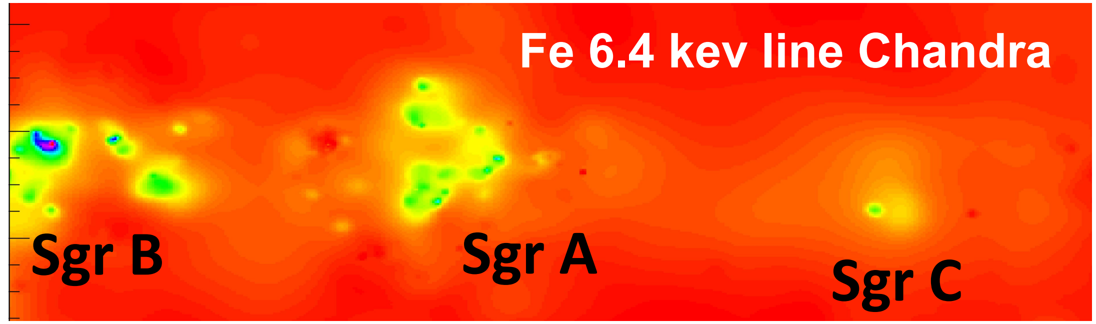
Dense Molecular Clouds ~10^8 M⊙

Tsuboi et al.(1999)

BUT ALSO:

The Central Molecular Zone

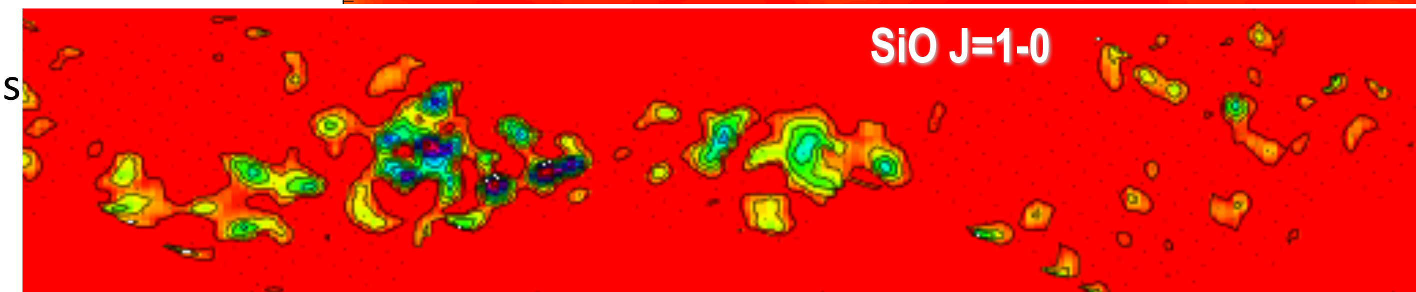
Strong emission of X-rays (Fe 6.4 keV) **XDRs**



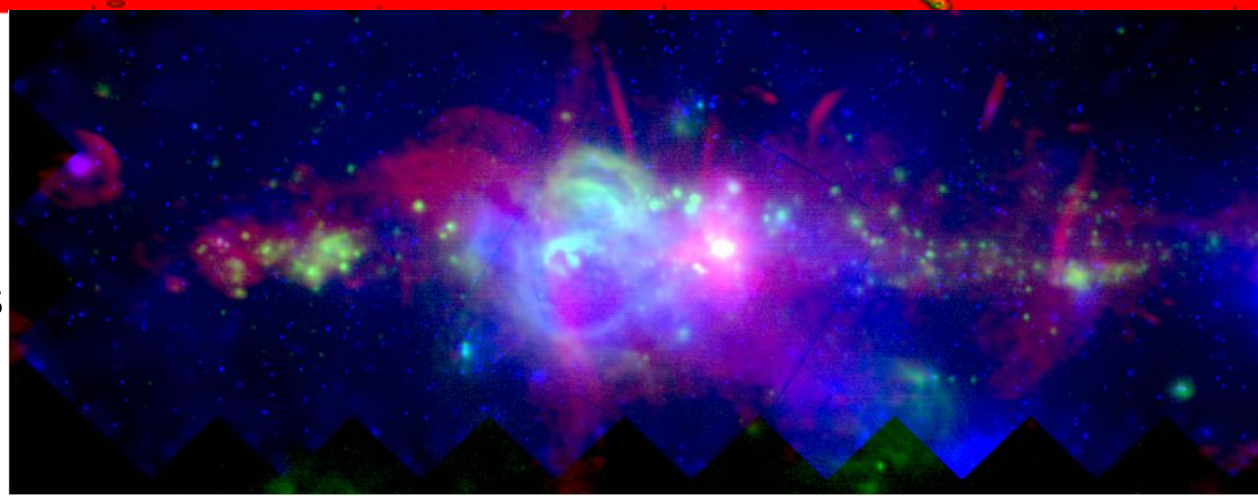
Huge kinematic activity:

- Bar potential
- Cloud collisions
- Turbulence..

➡ **Shocks**
MDRs



Star formation



Large **PDRs** illuminated by clusters of massive stars.

The Central Molecular Zone

- Strong emission of X-rays (Fe 6.4 keV) (**XDRs**)
- Large **PDRs** illuminated by clusters of massive stars
- Star formation throughout the region (clusters & protoclusters)
- Huge kinematic activity: Bar potential, disk-halo interactions, large turbulent motions (Mechanical Dominated Regions (**MDRs**)
- A massive black hole with past activity

The GC dense molecular clouds provides a unique laboratory for understanding the **relevance of enhanced Cosmic rays in star formation** in the nuclei of galaxies

Tracers of CRDRs

Thermal balance:

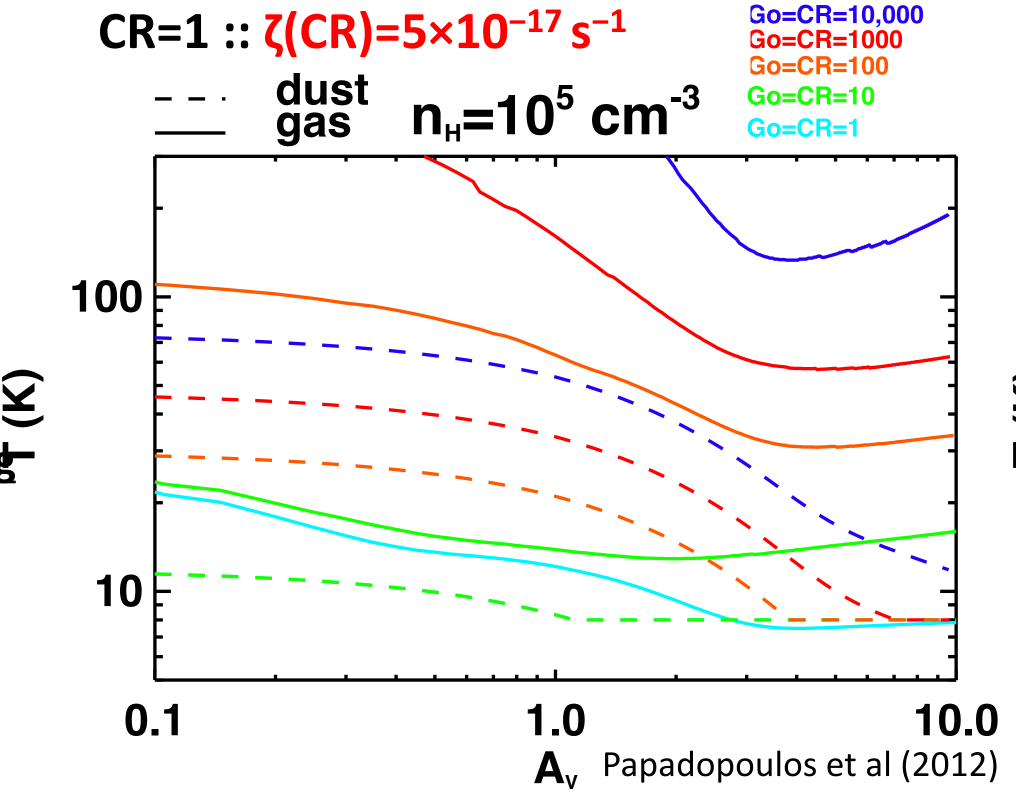
Heating (Γ) = Cooling (Λ)

Γ(CR) = Λ(Lines) + Λ(g−d)

- **Gas kinetic temperature d**
- **Strong dust-gas thermal decoupling**

Λ(lines):

- **Fine structure lines:**
  - OI, C+, ..
- **H_2**
- **CO**



Papadopoulos et al (2012)

Tracers of CRDRs

Ionization rates :

$x(e) \propto (\zeta(CR)/n(H2))^{-1/2}$

$n(H2)=10^5\ cm^{-3}$: $x(e)Gal \sim 2.4\times10^{-8}$. $\zeta(CR)=100$: $x(e)=8.4\times10^{-7}$

CRDR: 1,10, 10^2,10^3,10^4
PDR: Go =10^5

Chemistry:

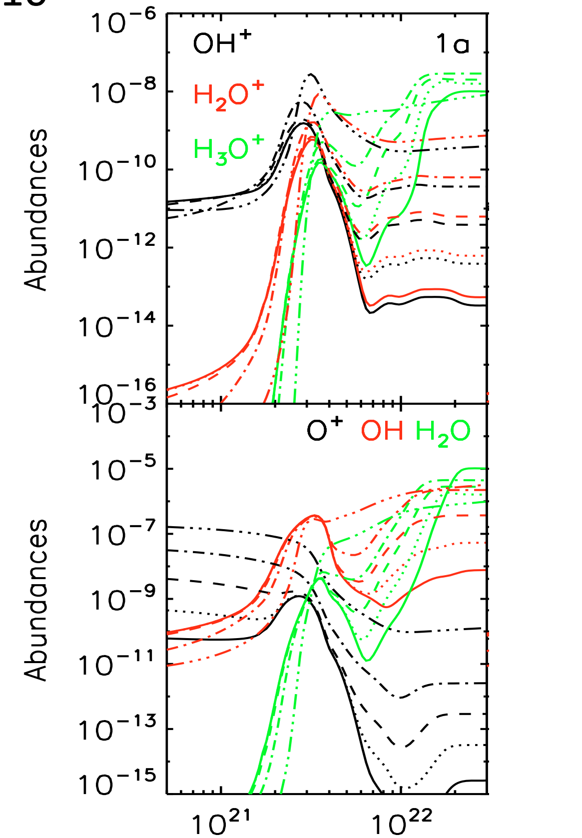
Ion-neutral gas phase reactions:

- Hydrogen: H3+ (ionization of H2 by CR/X-rays)
  (Geballe & Oka 1996)

- Oxygen: OH^+, $H2O^+$ and $H3O^+$
  (Ossenkopf et al. 2010 ; Gerin et al. 2010)

Icy mantle grain chemistry

Talks in session 2-a, 2-b and by S. Zeng



Meijerink et al (2011)

CMZ thermal balance

Decoupling Tk and Td: CR heating

Güsten et al. (1981)

(Morris et al.1983, Huttermesiter et.al. 1993)

Tk = 50-120 K

Tdust= 20-30 K

Heating by CRs

ζ(CR) ~ 10^{-15} s^{-1}

R. Güsten et al.: Ammonia in the Galactic Center

SGR A

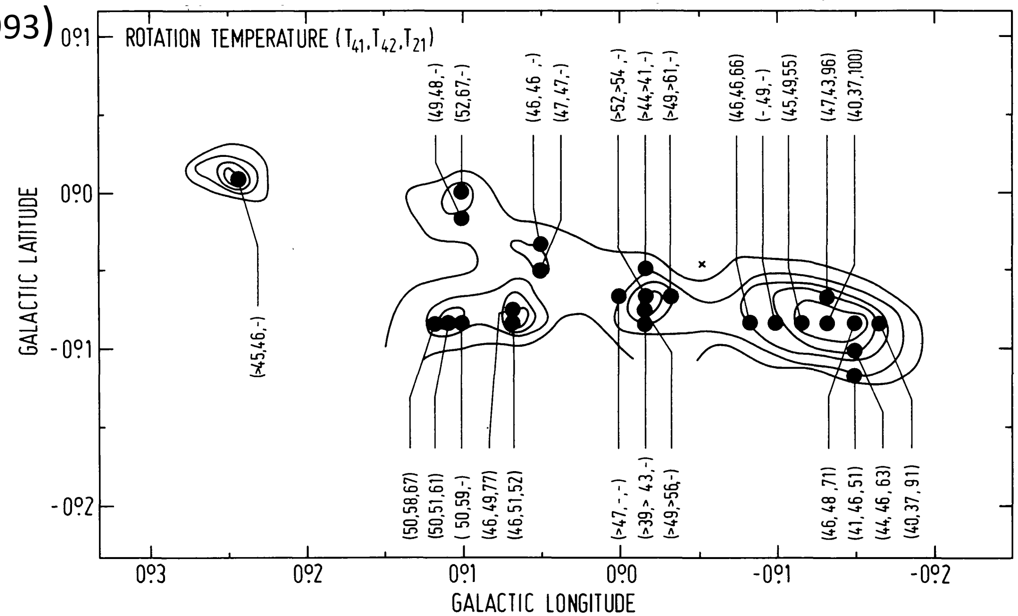


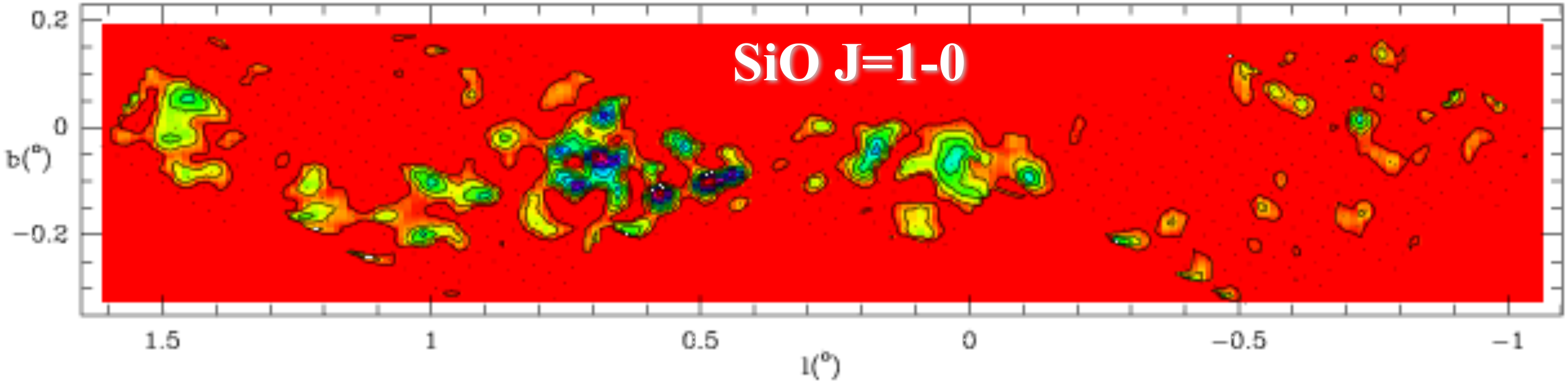
Fig. 3. The distribution of the rotation temperatures T_{41}, T_{42}, and T_{21} over the galactic center clouds

Consistent with the Gamma ray emission

CMZ thermal balance

Decoupling Tk and Td: Mechanical heating

Martin-Pintado et al. (1997) , (2000) and Hüttemeister et al. (1998)



SiO is one of the best tracers of shocks

In the CMZ, **large SiO widespread abundance** $>10^{-8}$

Widespread shocks with supersonic velocities (Td < Tk)

Origin of shocks?

Bar potential dynamics (cloud-cloud collisions, turbulence, expanding shells:

300 shells in the CO survey by Hasegawa et al. (1998), Oka et al. (1997),...

CMZ thermal balance

Fine structure lines and H_2: PDRs

Rodriguez-Fernandez et al.(2000), (2001) and (2004)

ISO + Spitzer

H2:

Gas temperature of ~150-500 K (>30% total)

Fine structure lines

Large PDR consistent with ionization

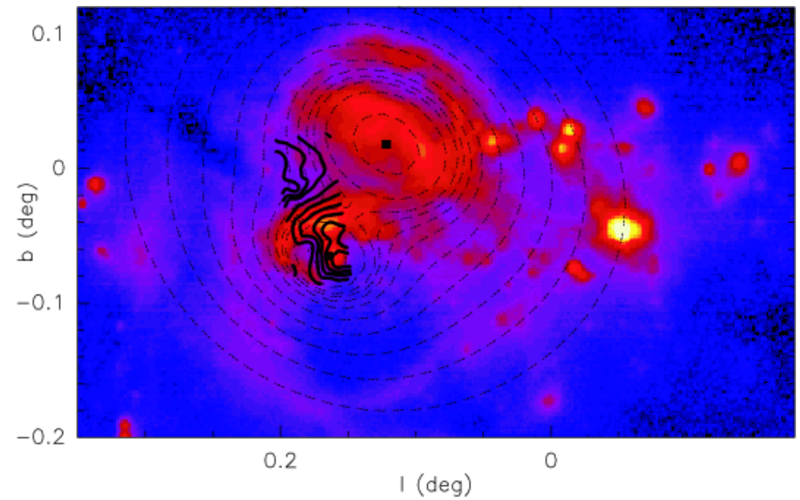
PDR/ C-shocks can explain the temperatures

PDRs : (n~10^3 cm^{-3}, FUV~10^3 Go)

But not the intensities

Several PDRs and/or C-shocks **and /or CRs?**

Quintuplet and Arches ionization

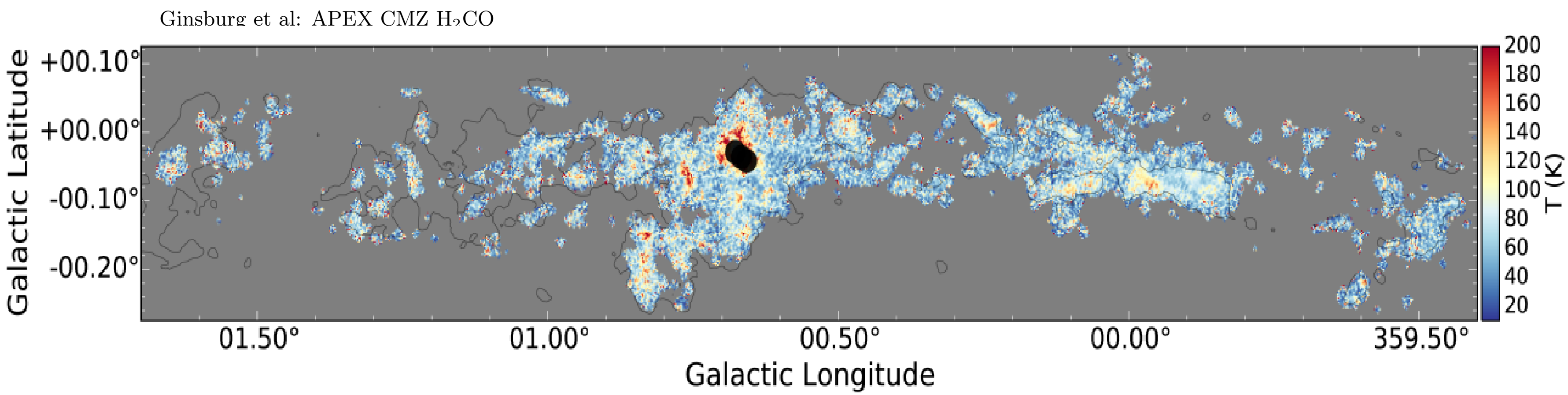


C-Shock from Draine et al. (1983)

J-Shock from Hollenbach & McKee (1989)

CMZ thermal balance

Large scale temperature variations



Ao et al (2013) & Ginsburg et al. (2015)

Multiline analysis of H_2CO to derive the temperature over the CMZ :

- Large temperature gradients from 60 to 120 K
- Modeling indicates that CRs are not the dominant heating in the CMZ
- Limits for ionization rates $<10^{-14}\ s^{-1}$
- Preferred mechanical heating

Heating by UV photons and X-rays were neglected.

CMZ thermal balance

CO Spectral Line Energy Distributions

Requena-Torres (2012), Goicoechea et al. (2013), Etxaluze (2013)

Herschel+SOFIA (CO J up to 24)

Sgr A* and Sgr B2 complexes:

Tk >300 K

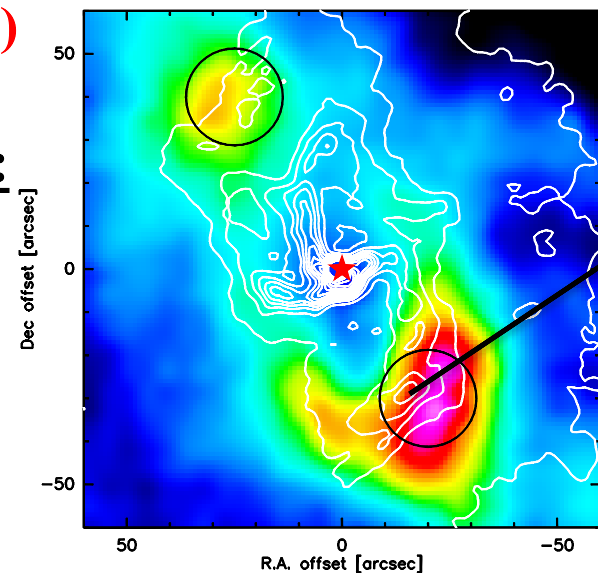
Sgr B2 :

PDRs+shocks in cores

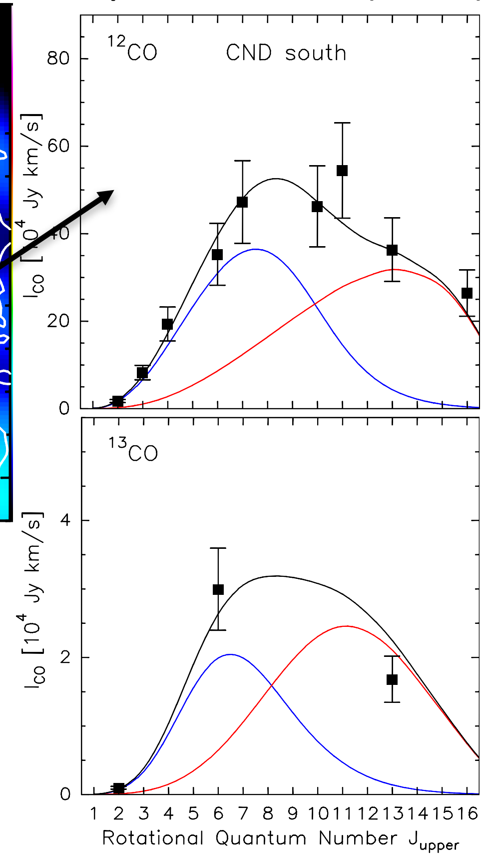
Sgr A* :

High-J CO lines can only be excited by shocks

Goicoechea et al. (2013) ruled out CR heating



Requena-Torres (2012)



CMZ ionization

$H3^{+}$

Oka et al. (2005); Goto et al. (2008); Goto et al. (2014)

<u>Diffuse foreground components</u>

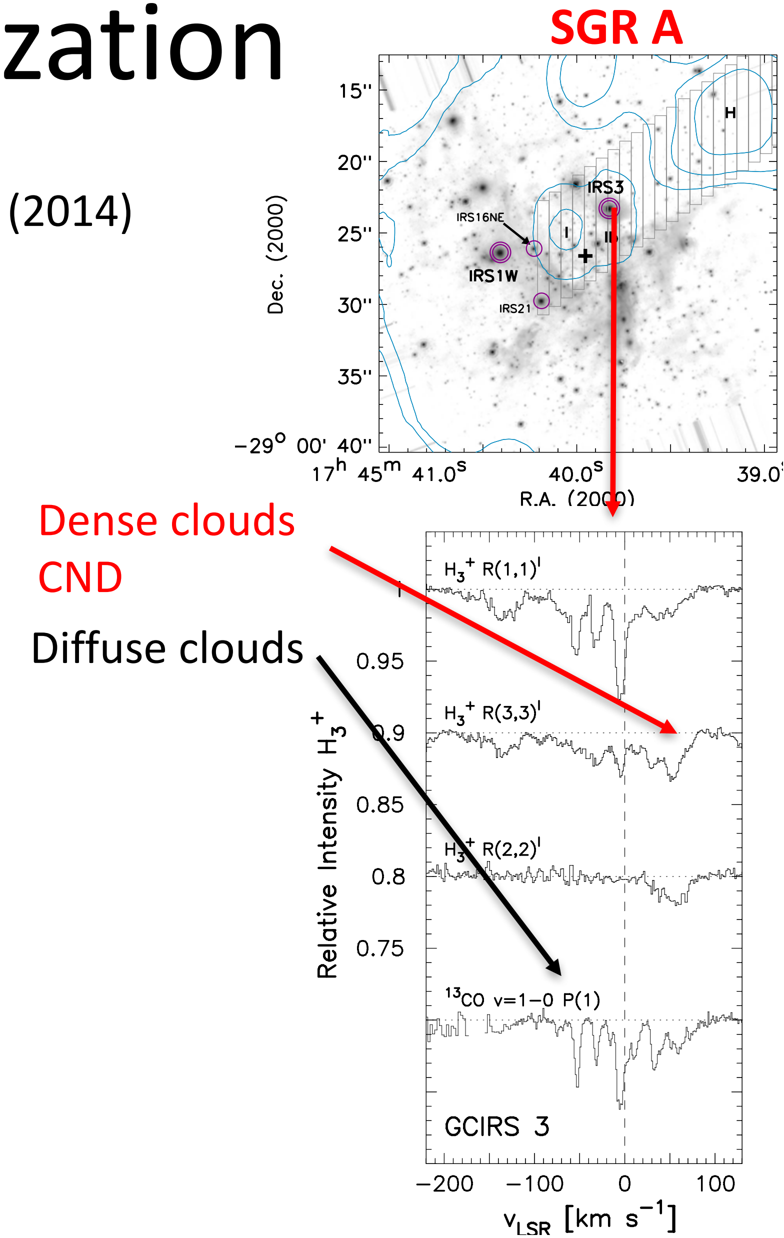
Density of 100 cm^{-3}

Temperature T ~ 250 K

Ionization rate, ζ(CR) ~ 10^{-14} -10^{-15} s^{-1}

Large filling factors

Small H_2 fractions



CMZ ionization

OH^+, $H2O^+$, $H3O^+$, H2O

Herschel (OH^+, $H2O^+$, $H3O^+$): Indriolo et al. (2015)

Sgr A* and Sgr B2 complexes:

Very complex line profiles. Foreground absorption.

Two type of clouds: Diffuse and dense clouds

Diffuse :

Large ionization rates of **~ 10^{-14} s^{-1}**

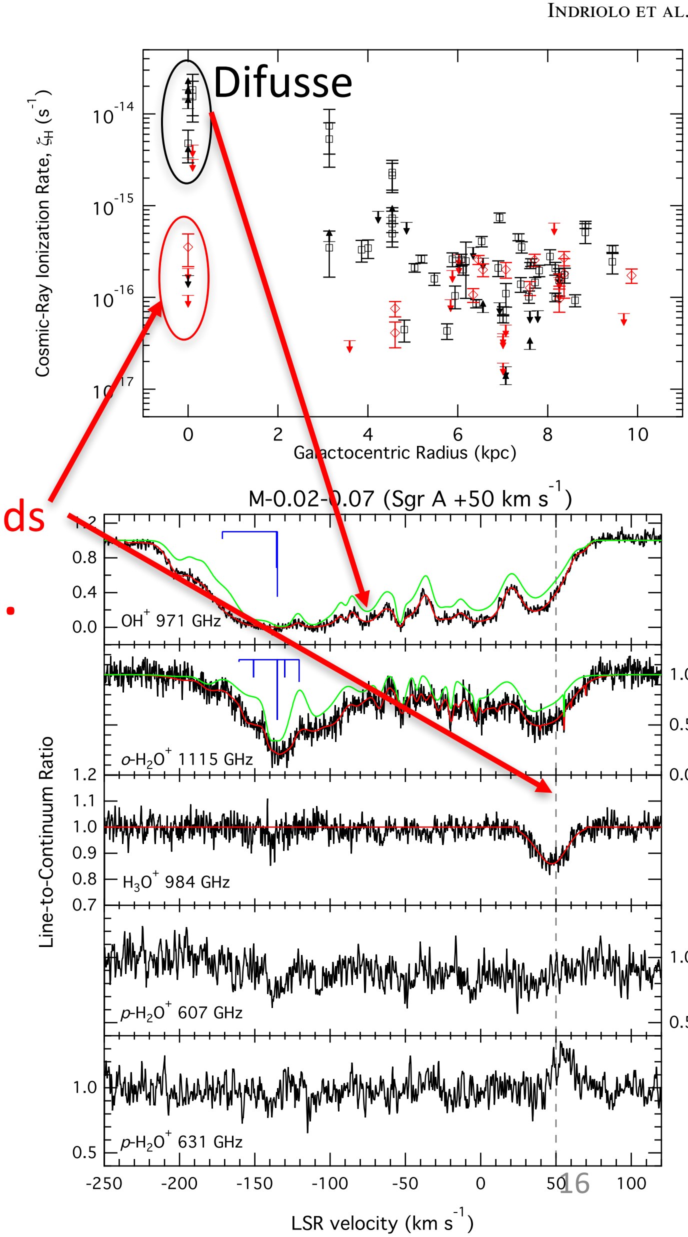
Dense clouds:

Similar ionization rates to those in the disk, **~ 10^{-16} s^{-1} .**

APEX: Van der Tak et al. (2006)

Confirm from H_3O^+/H_2O ratio the **ζ(CR) ~ 4 10^{-16} s^{-1}.**

The difference in the ionization rates between diffuse and dense cores is due to the propagation/spectrum of low energy CRs (Padovani et al 2009). This will also have a strong impact in the thermal balance.



Summary

- CRs does not seem to dominate the global heating of the bulk of molecular clouds in the CMZ at scales >0.5 pc.
- Mechanical heating seems to be the global dominant mechanism. PDR/XDRs also play an important role locally. So far, it is unclear the contribution of CRs heating.
- The **diffuse** component shows enhanced ζ(CR) by factors of $10\text{-}10^3$ with respect to that in the disk.
- The **dense component , however, only show a moderate enhancement** (factor of < 10) of the ζ(CR) with respect to the disk.

Future prospects

- The high angular resolution provided by ALMA and JWST will allow to look at the thermal balance with enough spatial resolution to disentangle the dominant heating mechanism at the relevant scales for star formation.
- Herschel, ALMA, APEX, SOFIA would allow to look at key species like H_2O, OH^+ and H_3O^+ to better establish the ionization rates , and its dependence on the H_2 column density of the clouds in the GC.
- The thermal balance and the ionization rates in the molecular clouds in the GC need to be properly modeled by considering the propagation of low energy CRs from the diffuse envelopes to the dense cores. Prediction of line fluxes of the main cooling lines is crucial to compare with observations.