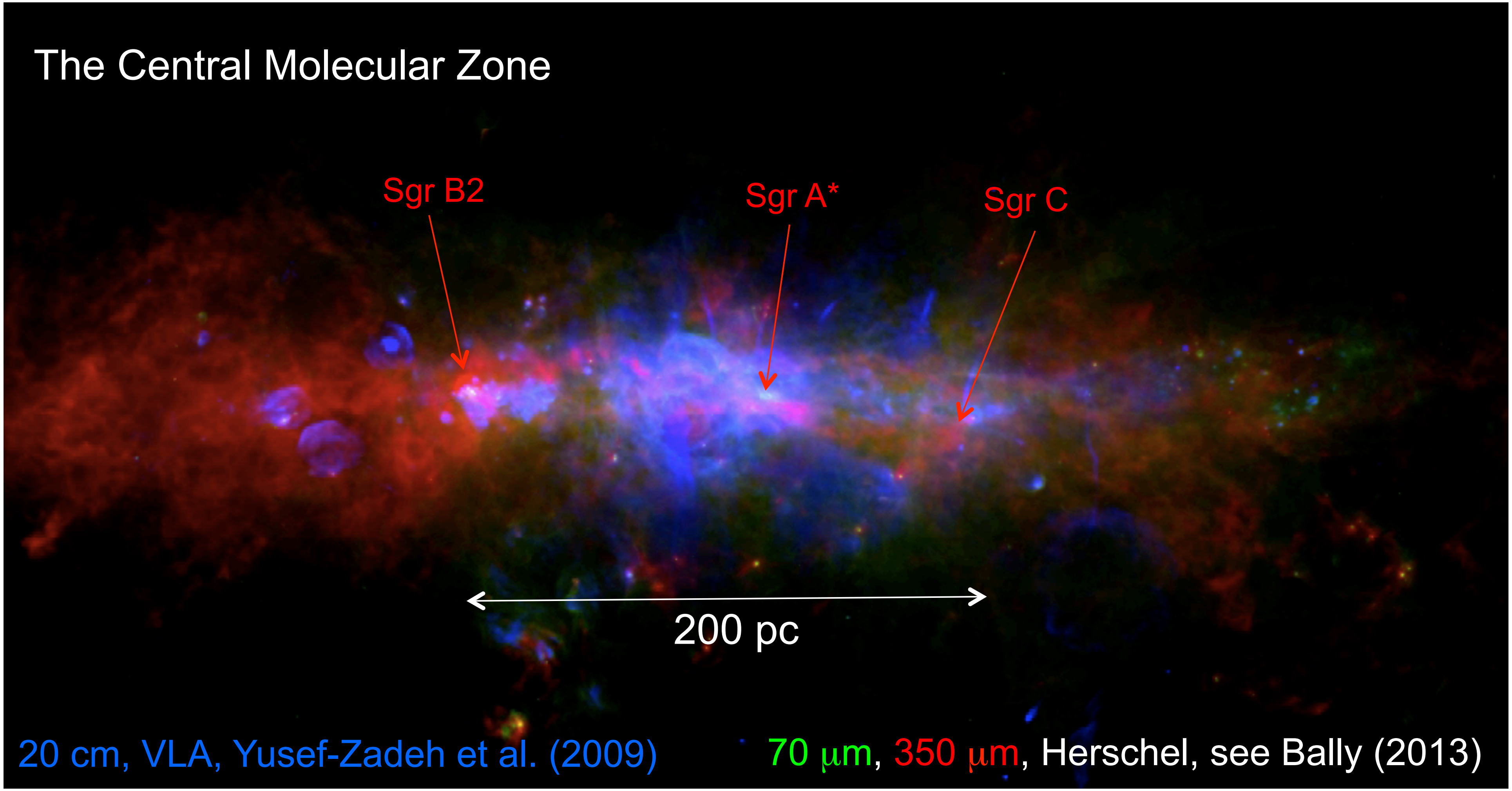
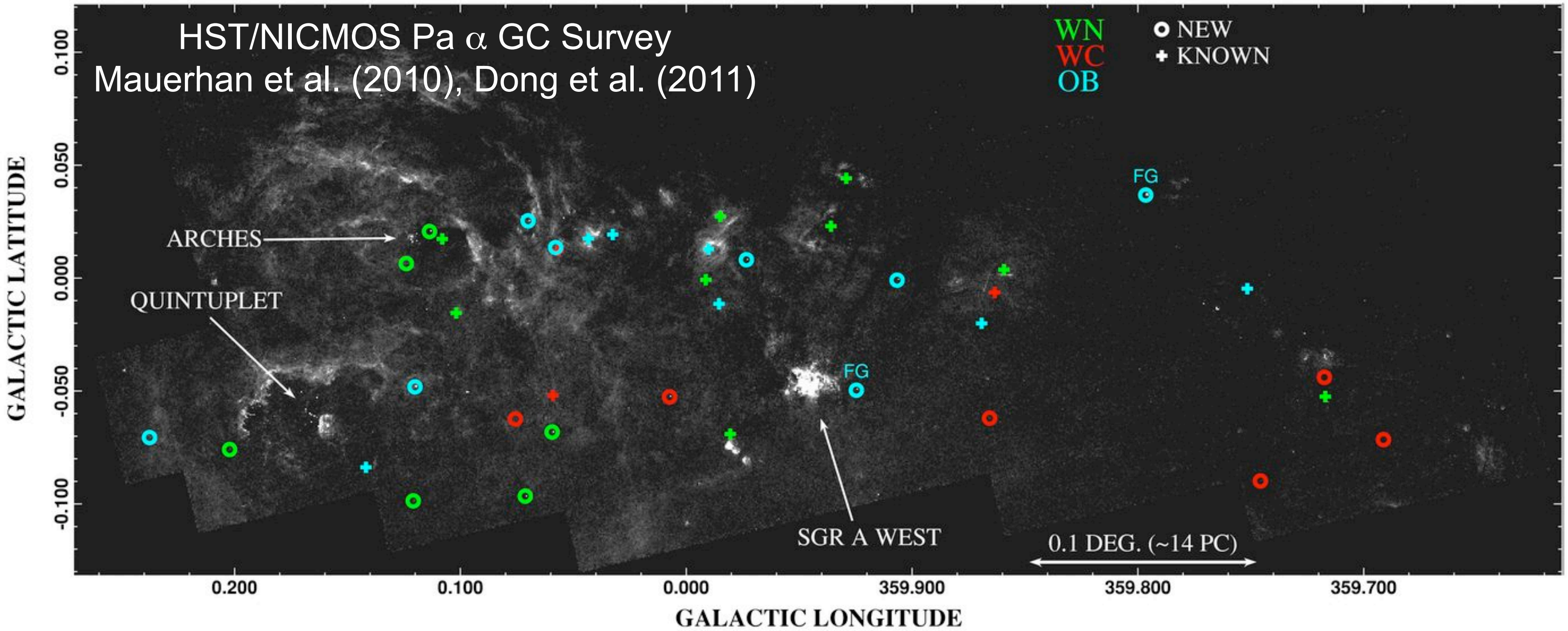
Low-Energy Cosmic Rays in the Galactic Center Region



Vincent Tatischeff, CRISM-2014, June 24-27, 2014

Energy sources in Central Molecular Zone



- Three extraordinary star clusters + several tens of isolated massive stars ⇒ 0.04 SN per century (2% of the Galactic rate in ~10^{-6} of the volume)

\+ Tidal disruption of stars, clouds (G2) etc. by Sgr A* (e.g. Dogiel et al. 2009)

\+ Proper motion of the Arches + Quintuplet clusters (Tatischeff et al. 2012)

\+ Gas turbulence, pulsars etc..

- Fermi bubbles: AGN event releasing ~ 10^{55} – 10^{57} erg about 1 – 3 Myr ago? (e.g. Guo & Mathews 2012; but see Crocker et al. 2011, 2014)

Cosmic-ray energetics

- With only "classical" sources (i.e. 0.04 SN per century):

$$P_{\mathrm{CR},p} \sim 1.3 \times 10^{39}\ \mathrm{erg\ s^{-1}}\quad \text{and}\quad P_{\mathrm{CR},e} \sim 2 \times 10^{37}\ \mathrm{erg\ s^{-1}}$$

(assuming the Galactic average $P_{\mathrm{CR},p}/P_{\mathrm{CR},e} \sim 70 \pm 20$, Strong et al. 2010)

- If these CRs deposit all their energy in the CMZ:

$$\varepsilon_{\mathrm{CR}} \sim \frac{P_{\mathrm{CR}} \times t_{pp}}{V_{\mathrm{CMZ}}} \sim \boxed{430\ \mathrm{eV\ cm^{-3}}}\qquad \text{with}\quad t_{pp} \approx 5\times 10^{5}\ \mathrm{yr}\left(\frac{n_{\mathrm{H}}}{100\ \mathrm{cm^{-3}}}\right)^{-1}$$

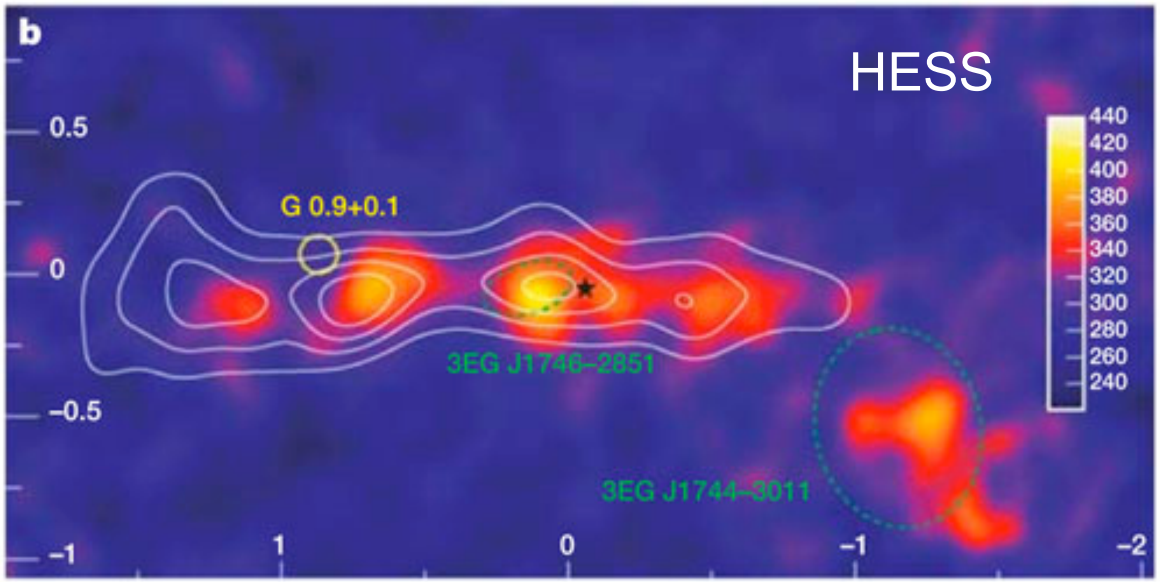
and $V_{\mathrm{CMZ}} \sim 3 \times 10^{61}\ \mathrm{cm}^3$

- CR energy to produce the diffuse TeV γ-ray emission:

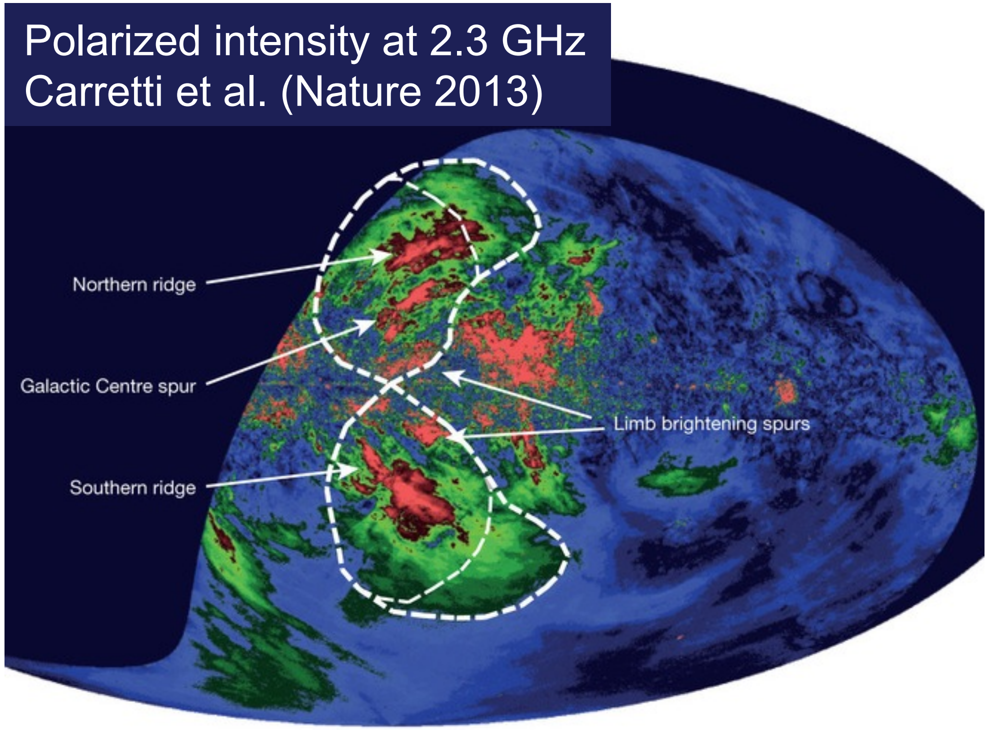
$\sim 10^{50}$ erg (in $10^9 - 10^{15}$ eV)

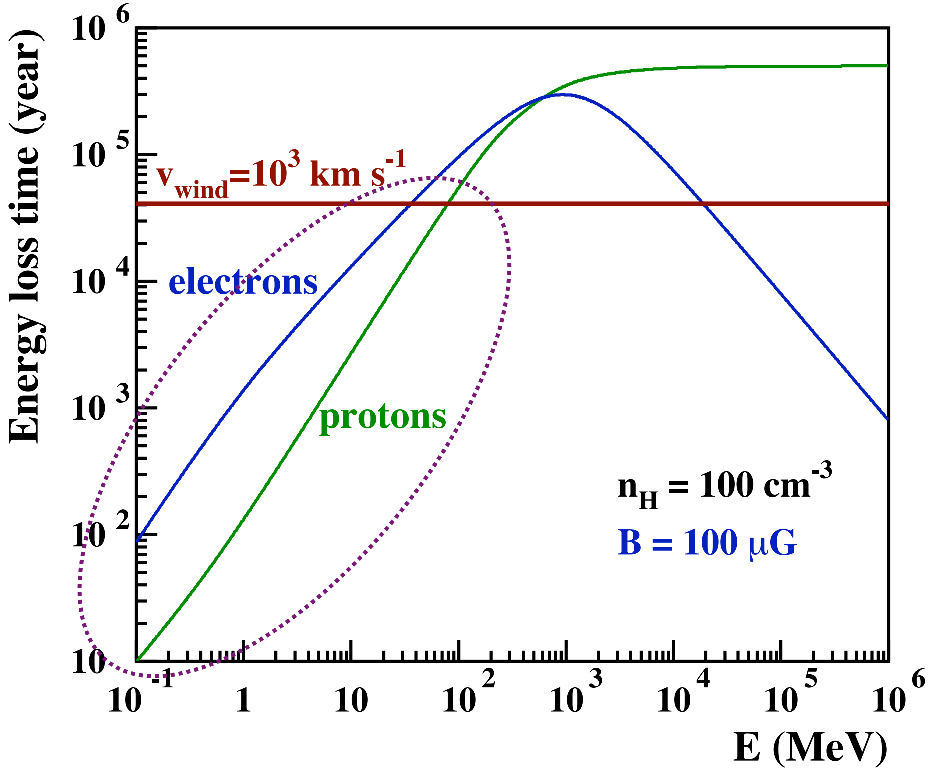
$\Rightarrow \varepsilon_{\mathrm{CR}} \sim \boxed{2\ \mathrm{eV\ cm^{-3}}}$

⇒ energy loss by advection



Cosmic-ray energy deposit in the CMZ





- Low-energy CRs ($E <$ a few tens of MeV) deposit their energy in the CMZ by ionization and heating of the ambient gas (⇒ chemistry)

✓ What is the deposited power (depends on the CR spectrum/sources)?

✓ Are SNe the only significant sources of CRs in the CMZ?

⇒ Two potential tracers: the H_3^+ molecule and the Fe Kα line at 6.4 keV

H_3^+ chemistry in diffuse gas of the CMZ

- Formation:

  $CR + H_2 \rightarrow H_2^+ + e^- + CR'$

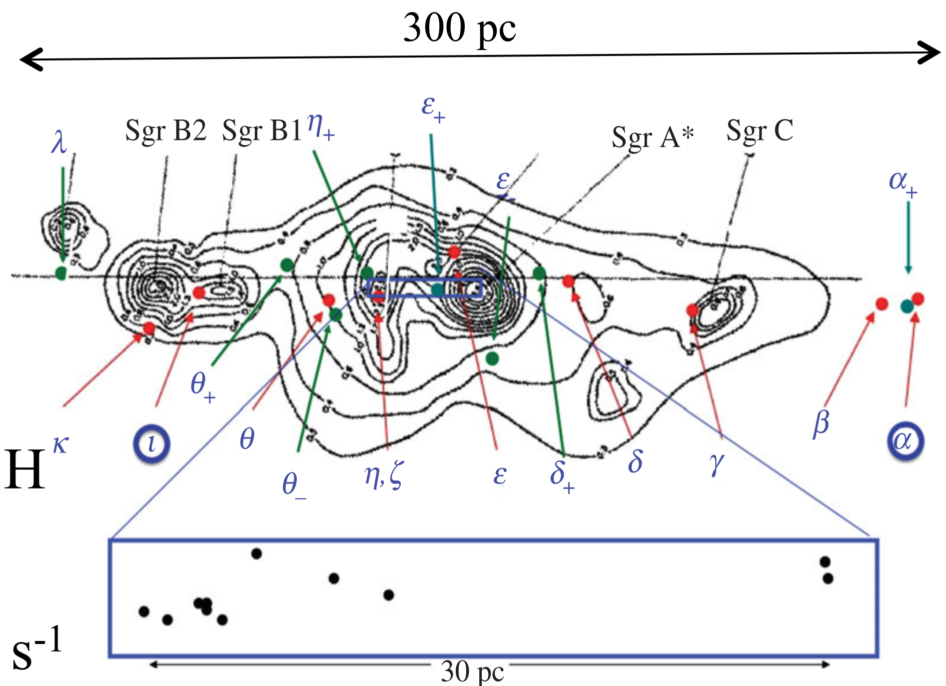
  $H_2^+ + H_2 \rightarrow H_3^+ + H$

- Destruction (in diffuse clouds):

  $H_3^+ + e^- \rightarrow H_2 + H$ or $H + H + H$

⇒ Assuming $N(H_3^+)$ increases linearly with ζ_2 (?), $\zeta_2 L = (1.3 - 4.5)\times 10^5$ cm s^{-1} (Goto et al. 2008)

⇒ With $L \sim 50$ pc, $\zeta_2 = (1 - 3)\times 10^{-15}$ s^{-1}

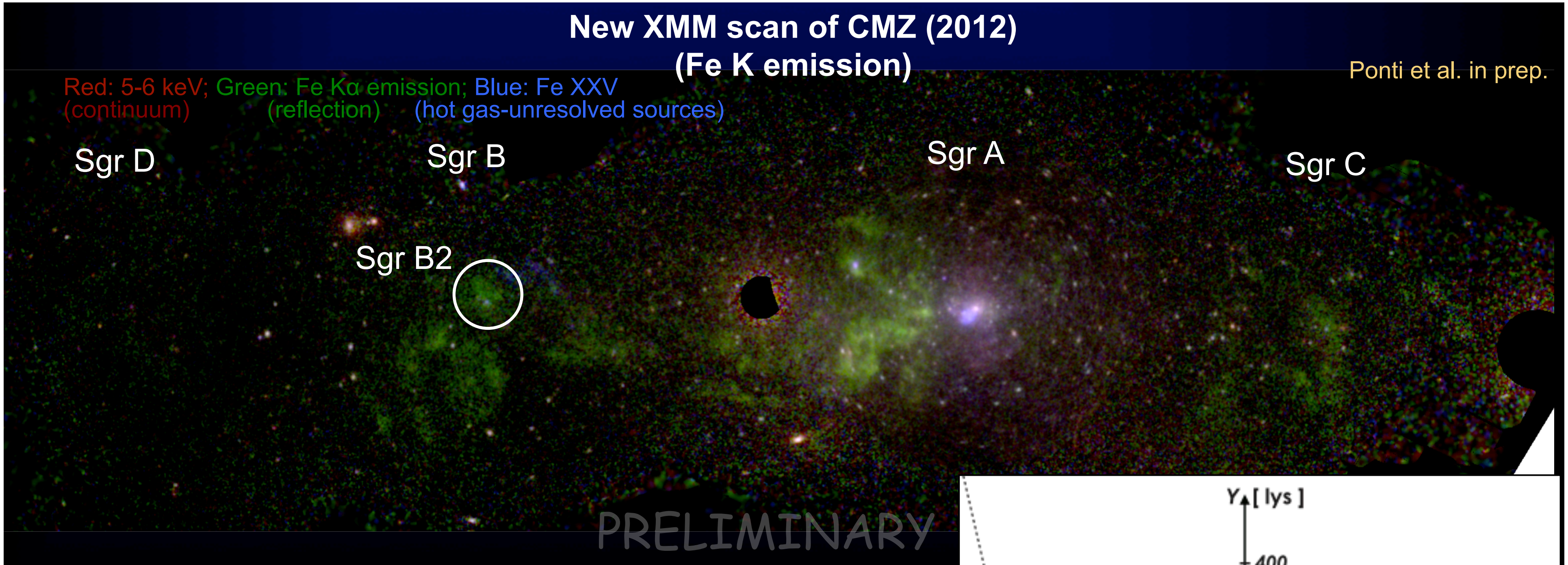


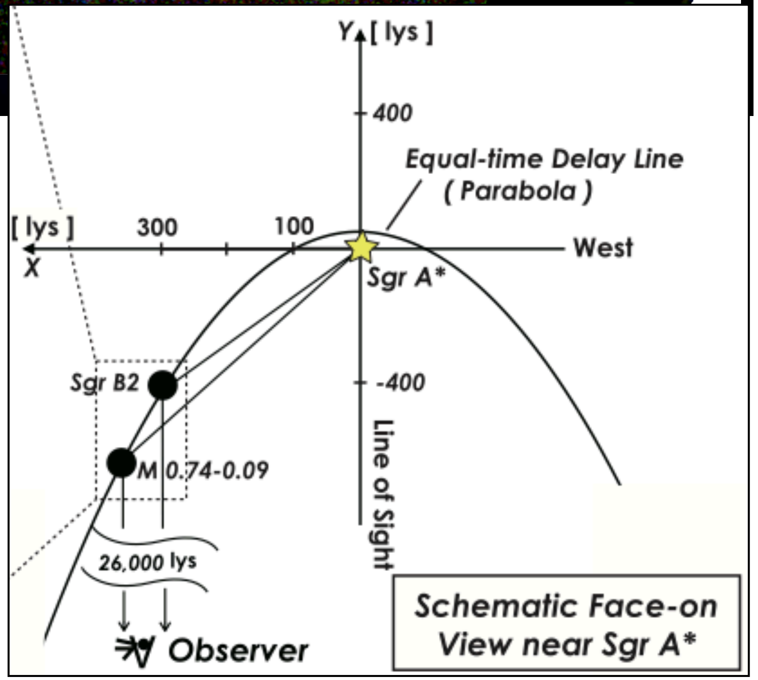
Background IR sources ~30 known sources in the CMZ (Geballe 2012)

⇒ H_3^+ line intensity ratios also provide the density and T° of the diffuse gas. In the GC $n = 50 - 200$ cm^{-3}, $T = 200 - 300$ K (Goto et al. 2008, 2011)

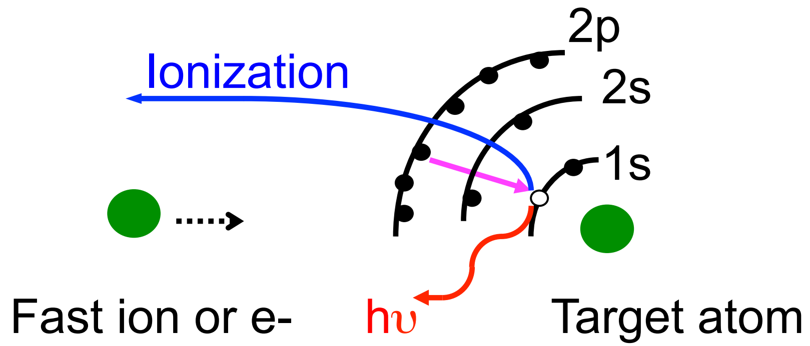
⇒ Diffuse molecular gas is pervasive in the CMZ. Filling factor: $f_V \sim 0.3$

Fe Kα line emission at 6.4 keV





Collisional ionization by CR electrons/ions or photoionization by hard X-rays?



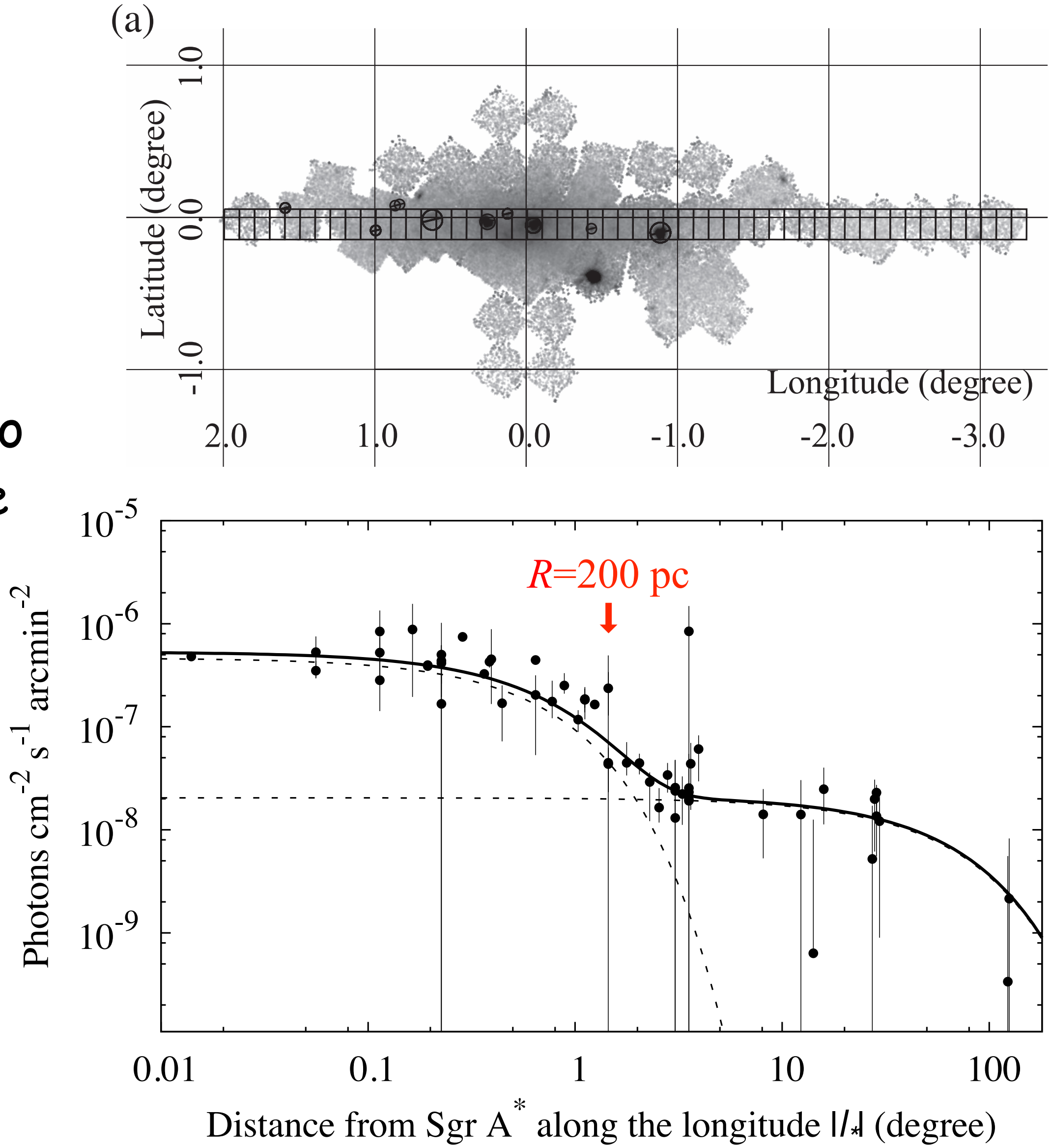
Diffuse 6.4 keV line emission

- Global distribution of the Fe I Kα line emission with *Suzaku* (Uchiyama et al. 2011, 2013)
- Bright diffuse and point sources were excluded
- The intensity profile shows two components: the Galactic ridge and GC X-ray emissions

⇒ A major contribution from unresolved sources, perhaps magnetic CVs (Heard & Warwick 2013)?

or

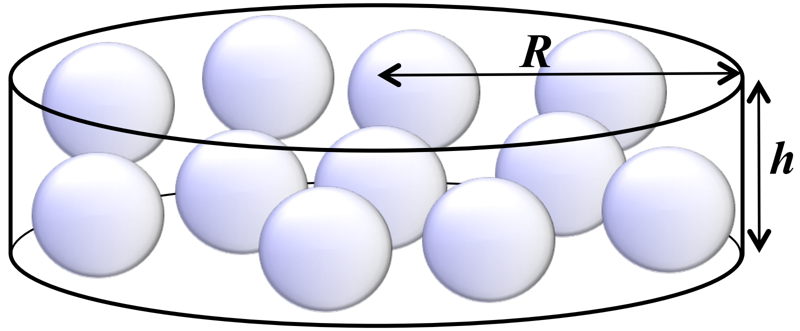
⇒ Widespread Fe ionization in the diffuse molecular gas



Observed 6.4 keV photon yield per H_2 ionization

- $$X_{6.4} = \frac{4\pi D^2 I_{6.4}\Omega}{V\langle n_{\mathrm{H_2}}\rangle \zeta_2}$$

  with $I_{6.4} = (7.3 \pm 0.7)$ ph cm^{-2} s^{-1} sr^{-1} (Uchiyama et al. 2013), $\Omega = 2Rh/D^2$ and $V = \pi R^2 h$ the solid angle at the observer position and volume of the thick disk, and $\langle n_{\mathrm{H_2}}\rangle = f_V n_{\mathrm{H_2}}$.



$$\Rightarrow \quad X_{6.4} = \frac{8 I_{6.4}}{\langle n_{\mathrm{H_2}}\rangle \zeta_2 R} = (0.6 - 1.9) \times 10^{-6} \times \left(\frac{\langle n_{\mathrm{H_2}}\rangle}{50\ \mathrm{cm^{-3}}}\right)^{-1} \left(\frac{R}{200\ \mathrm{pc}}\right)^{-1}$$

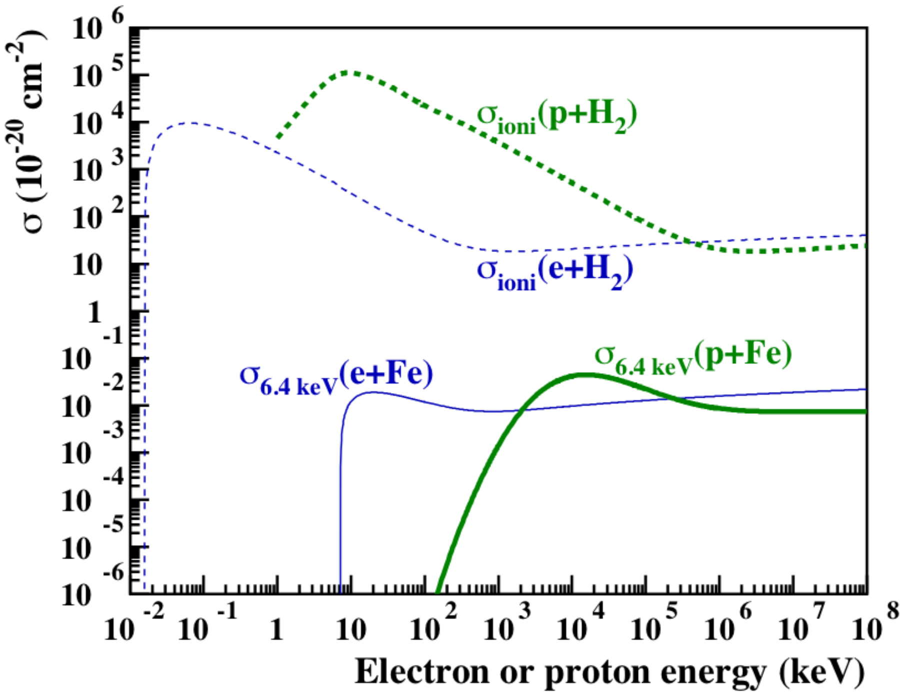
- Can $X_{6.4}$ be explained if Fe atoms and H_2 molecules of the diffuse gas are ionized by the same CR particles or photons?

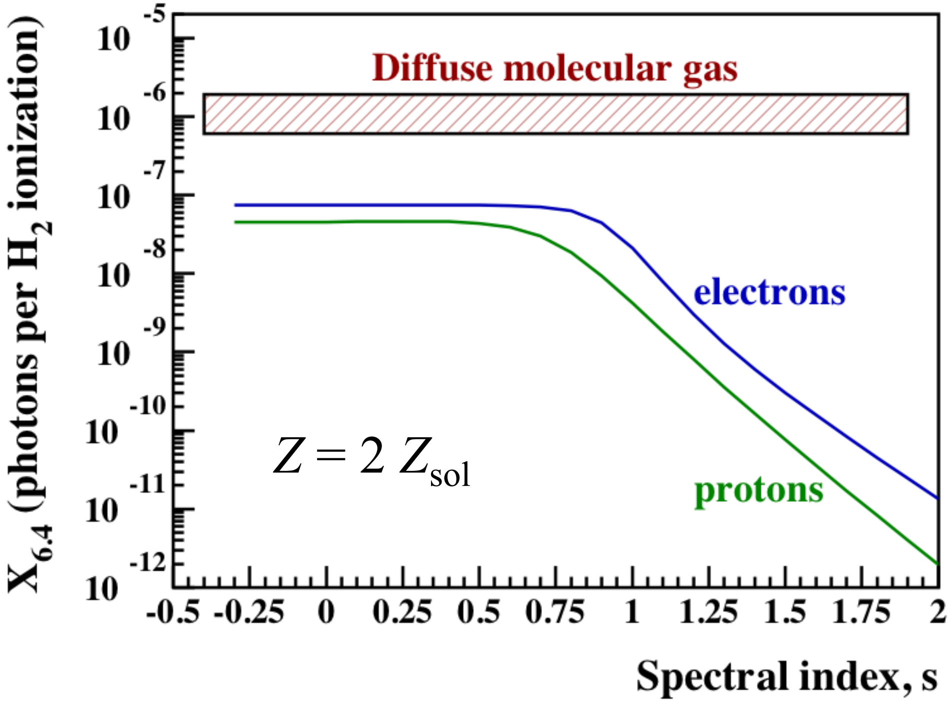
Theoretical 6.4 keV photon yield per H_2 ionization

- $X_{6.4}$ produced by CRs: $X_{6.4,i} \approx \frac{\eta_{\rm Fe}}{f_{\rm H_2}} \frac{\int_{I({\rm Fe\ K})}^{E_{\rm max}} N_i(E)\sigma_{i{\rm Fe}}^{{\rm K}\alpha}(E)v_i(E)dE}{\int_{I({\rm H_2})}^{E_{\rm max}} N_i(E)\sigma_{i{\rm H_2}}^{\rm ioni}(E)v_i(E)dE}$

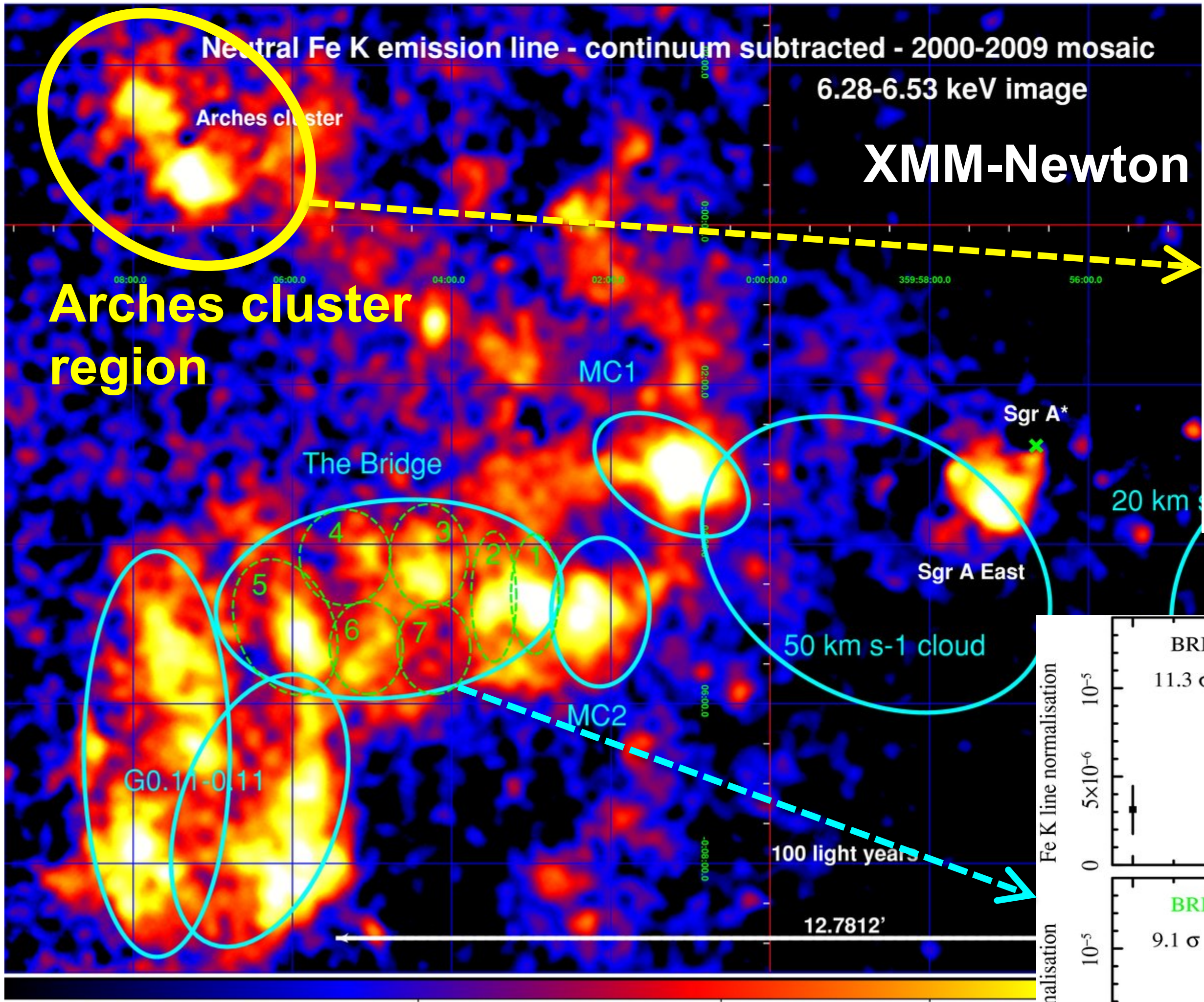
- H_2 ionization X-sections much higher than that for Fe Kα line production

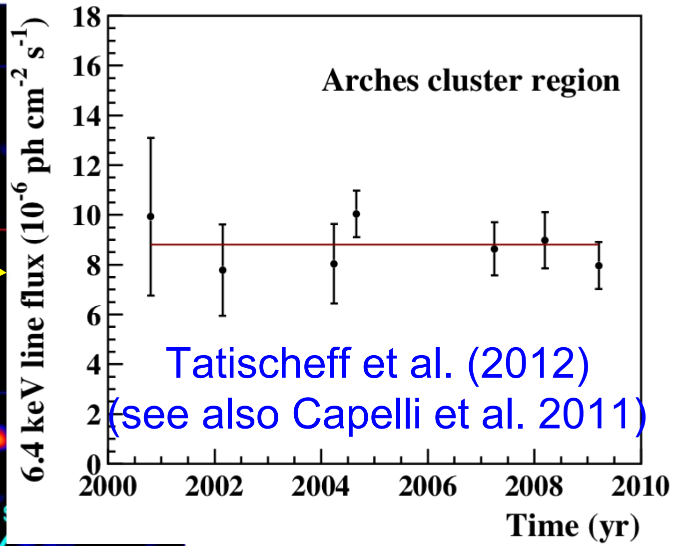
⇒ $X_{6.4} < 7 \times 10^{-8}$ independent of $N_i(E)$ ⇒ bulk of the diffuse 6.4 keV line emission not produced by CRs, but likely by hard X-rays emitted by Sgr A* hundreds of years ago (Dogiel et al. 2013)

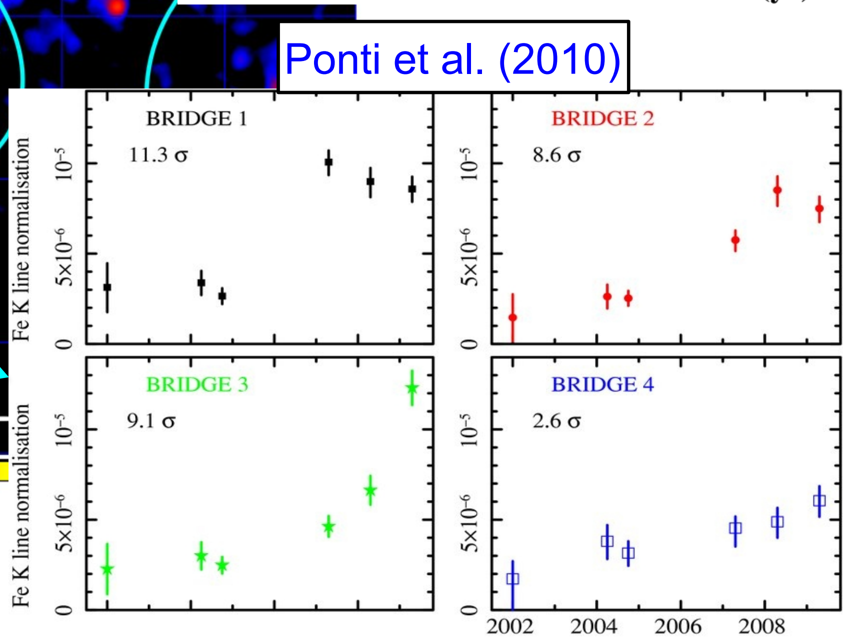




6.4 keV line emission from dense molecular clouds

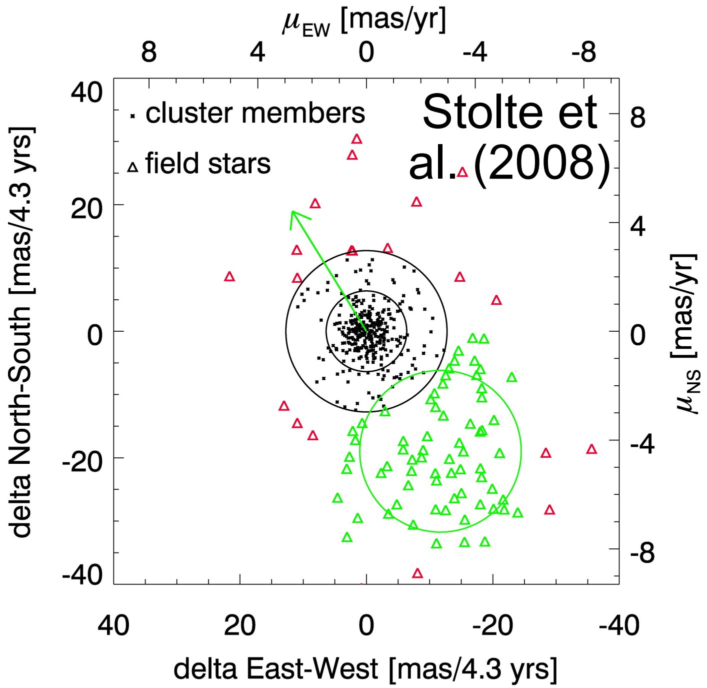


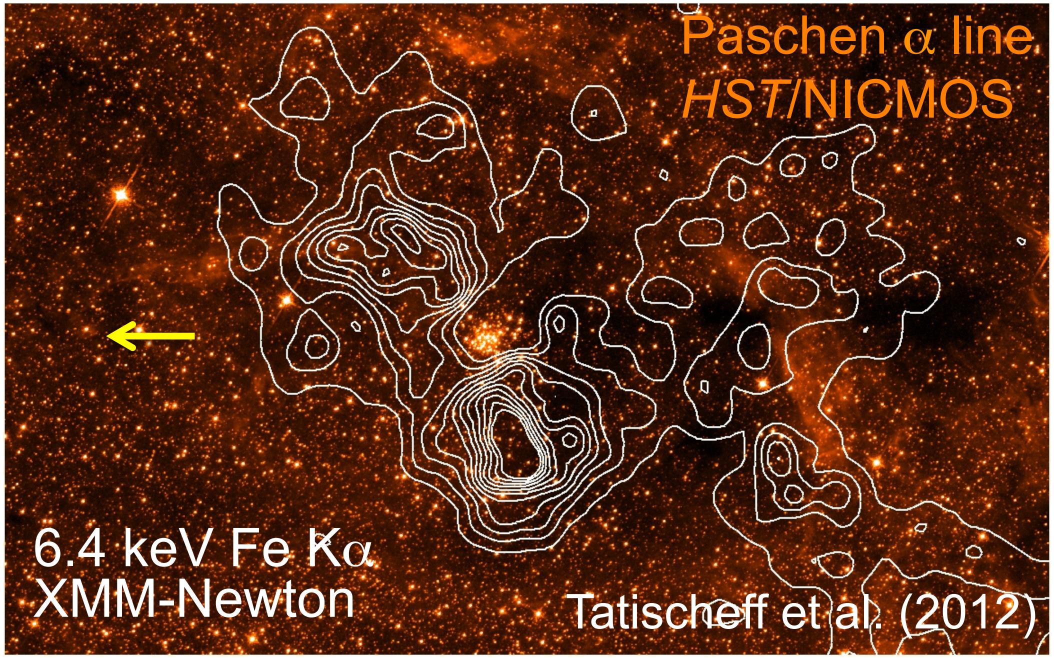




- Variable 6.4 keV emission: fluorescence excited by a past flaring activity of Sgr A*

The X-ray emission around the Arches cluster

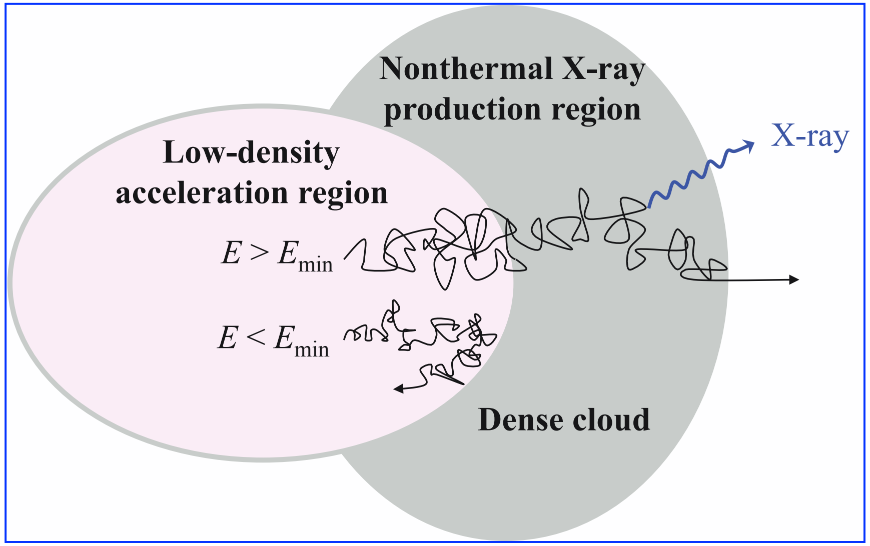




- Massive (a few 10^4 M_{sol}) and dense cluster of young (2.5 Myr) stars, with ~160 O-type stars (e.g. Figer et al. 2002)
- From star proper motions (Keck): $V_* \sim 200$ km s^{-1} (Clarkson et al. 2012)
- The bright 6.4 keV line emission remained constant over ~8.5 years of XMM-Newton observations (Capelli et al. 2011; Tatischeff et al. 2012)
- Not well correlated with the molecular gas (Chandra; Wang et al. 2006), but suggestive of a bow shock due to the cluster's supersonic motion

Nonthermal X-ray production models for XSPEC

- Generic, steady-state, slab models for CR electrons and protons (+ α particles)



- Differential equilibrium spectrum:

$$N_i(E) = \frac{1}{(dE/dt(E))_i} \int_E^{E_\Lambda^i(E)} \frac{dQ_i}{dt}(E')dE'$$

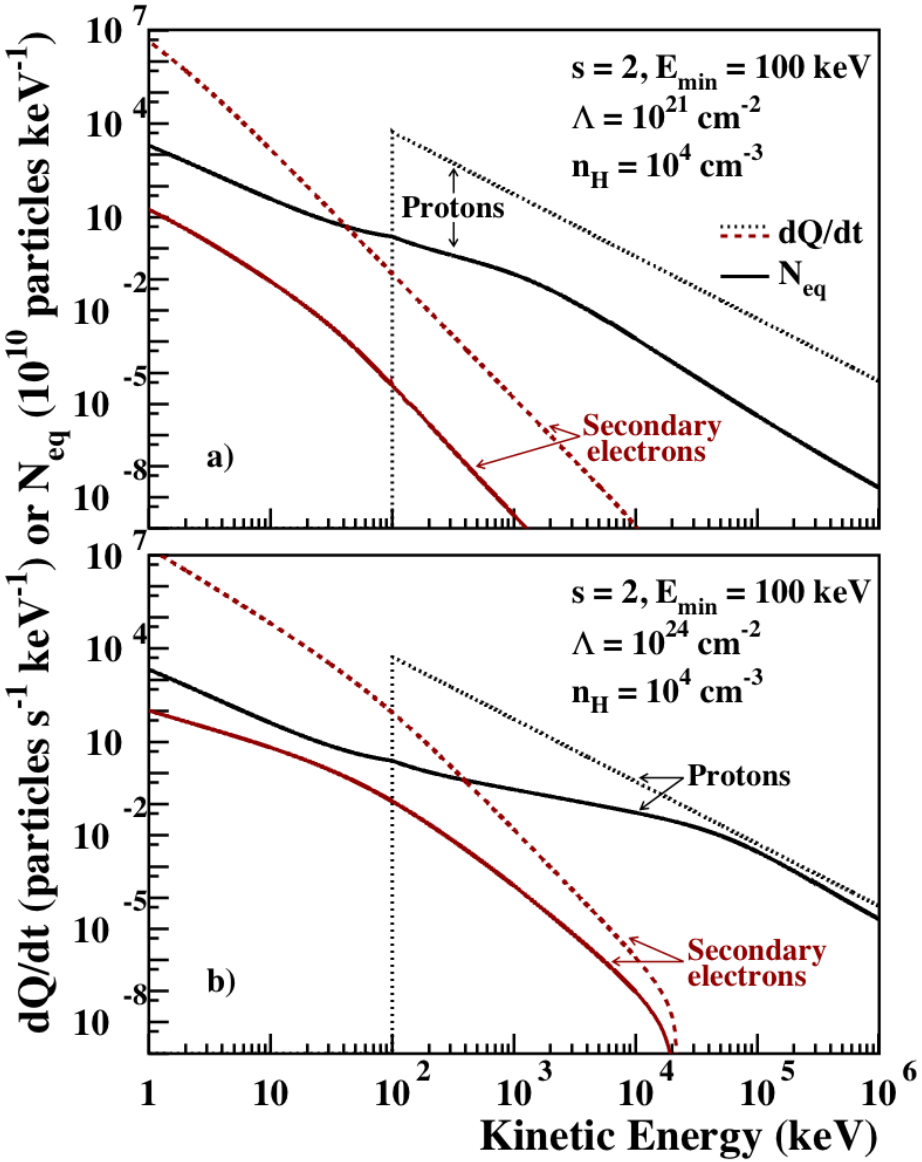
with a constant path length (in H cm^{-2})

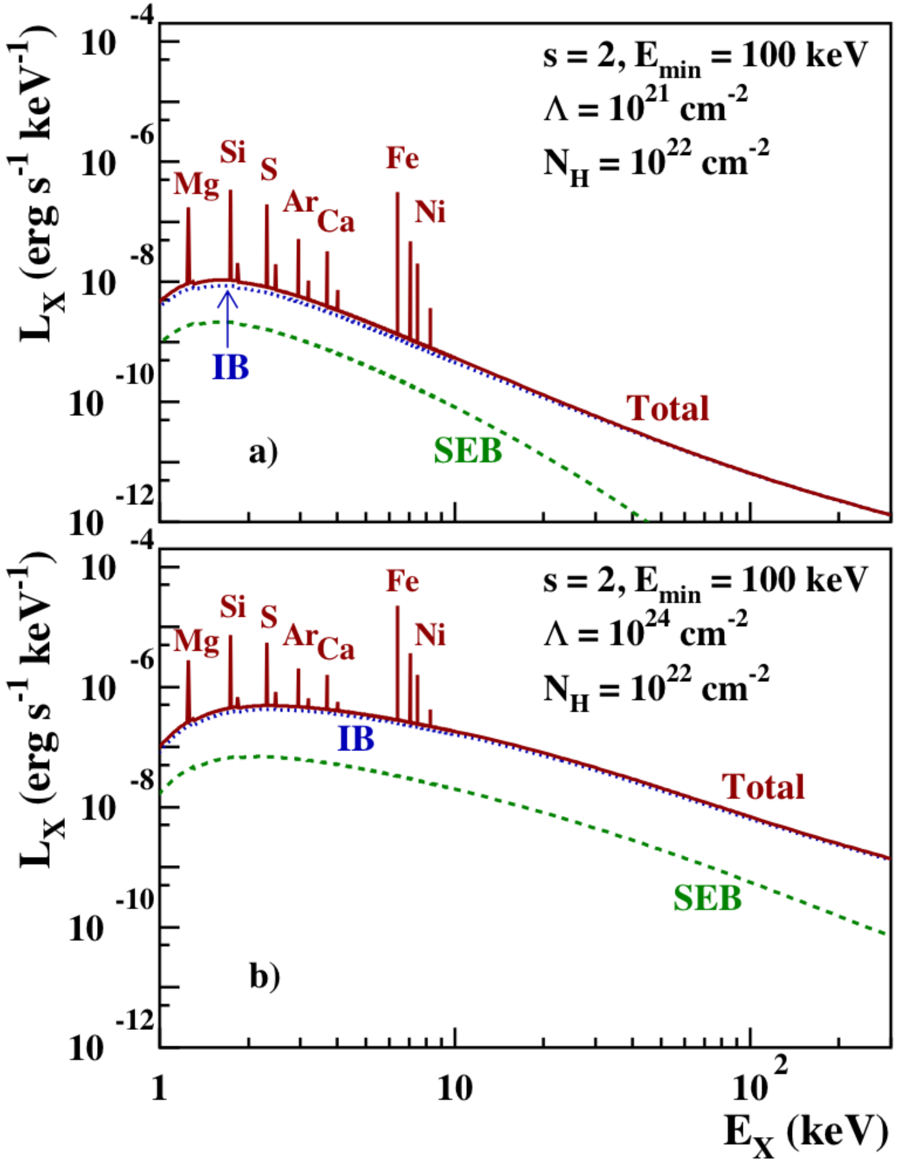
$$\Lambda = \int_E^{E_\Lambda^i(E)} \frac{dE'}{(dE/dN_H(E'))_i} \qquad \left(\text{with} \left(\frac{dE}{dN_H}\right)_i = \frac{1}{v_i n_H}\left(\frac{dE}{dt}\right)_i\right)$$

- Free parameters: E_{min}, index of the power-law source spectrum s, Λ and the ambient medium metallicity relative to solar $Z \Rightarrow$ XSPEC

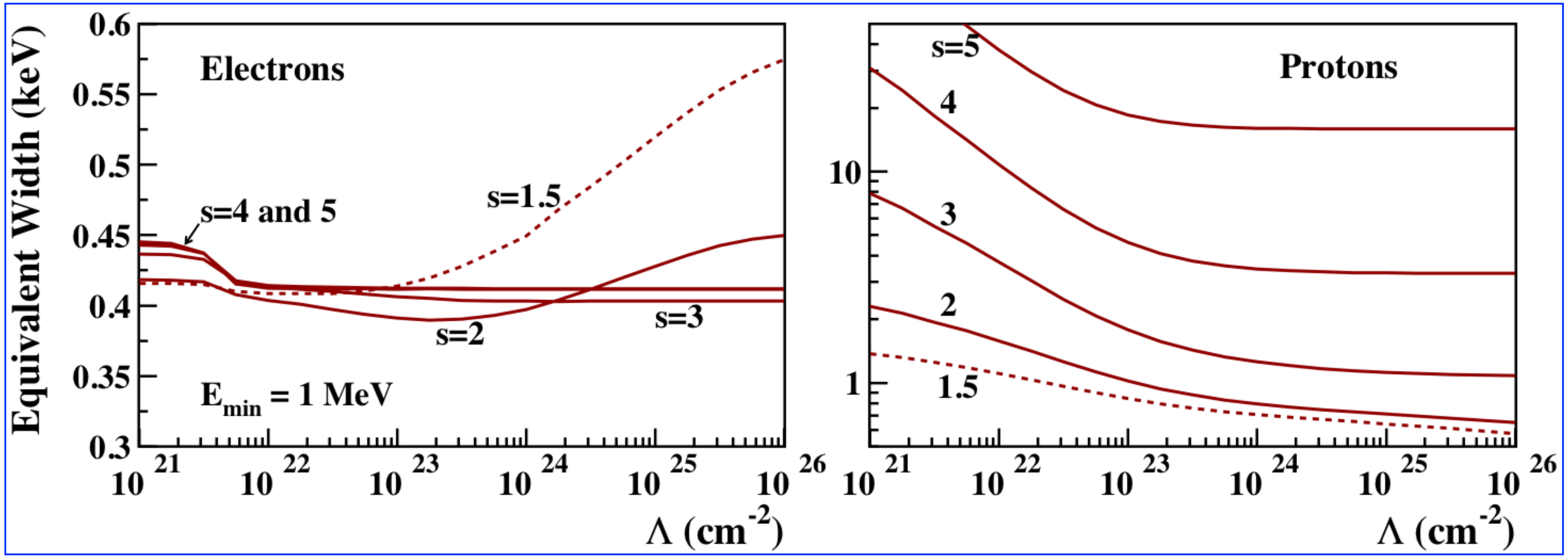
- 2nd set of models: with CR metals in variable proportions (i.e. with the broad lines from the fast ions)

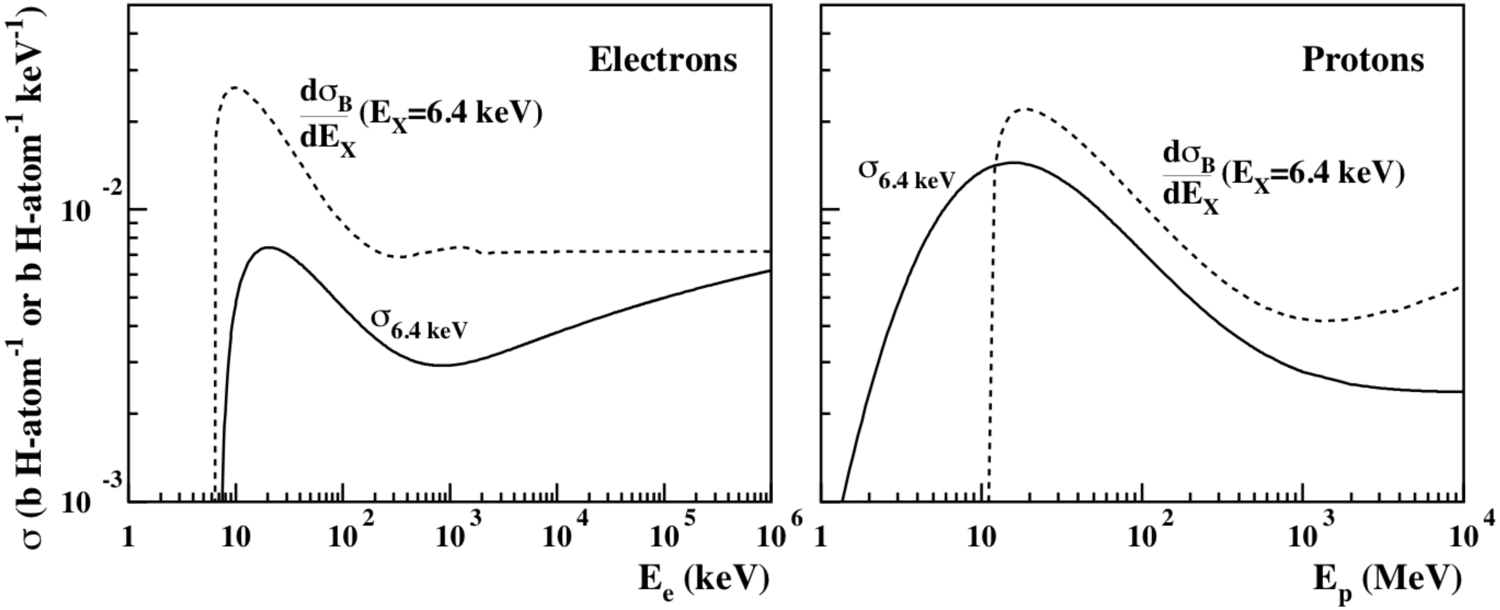
Examples of X-ray emissions from LECR protons





6.4 keV emission from LECR electrons / protons





Contrary to electrons, LECR protons can produced large EW of the 6.4 keV line for soft source spectra

Spectral analysis of the Arches cloud emission

LECR electrons

$N_H = (11.9^{+1.3}_{-1.4}) \times 10^{22}$ cm^{-2}

$kT = 1.9^{+0.6}_{-0.3}$ keV

$Z > 3.1\ Z_{sol}$ ⇐ not OK

$s(\text{LECRP}) > 2.5$

$E_{min} < 41$ keV ⇐ not OK

$\Lambda = 5 \times 10^{24}$ H cm^{-2} (fixed)

LECR ions

$N_H = (12.2^{+1.4}_{-1.6}) \times 10^{22}$ cm^{-2}

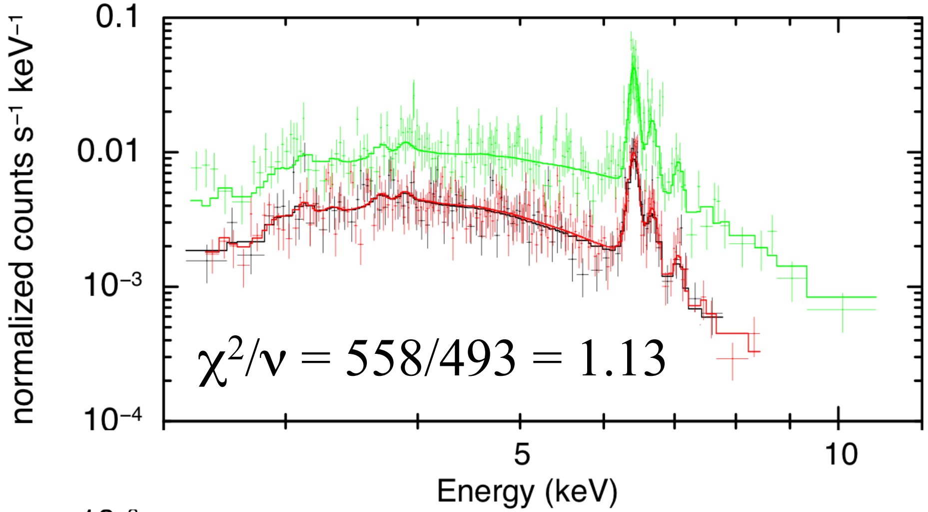
$kT = 2.0^{+0.7}_{-0.3}$ keV

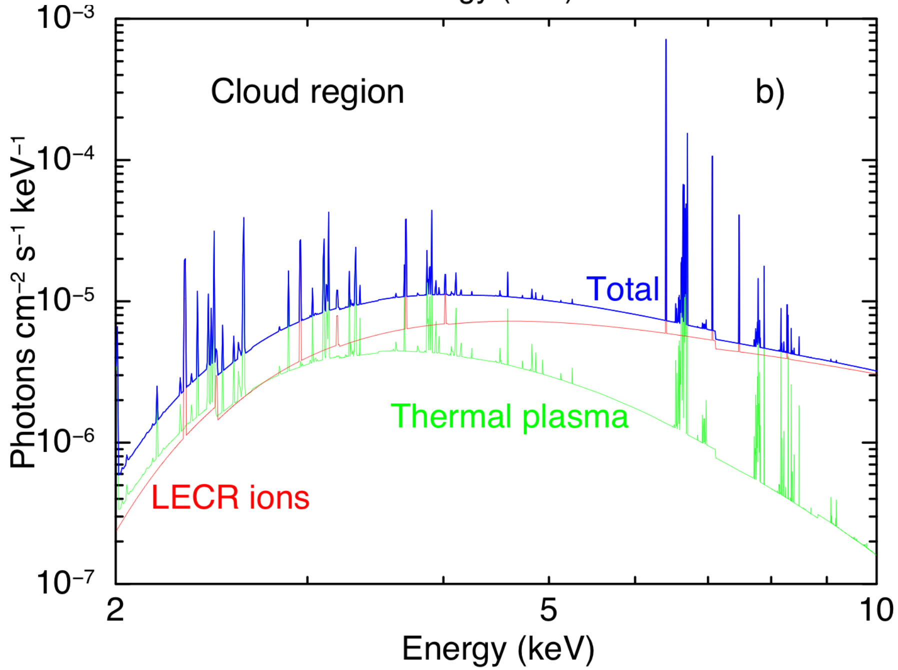
$Z = 1.7 \pm 0.2\ Z_{sol}$ ⇐ OK

$s(\text{LECRP}) = 1.9^{+0.5}_{-0.6}$ ⇐ OK

$E_{min} = 10$ MeV (fixed)

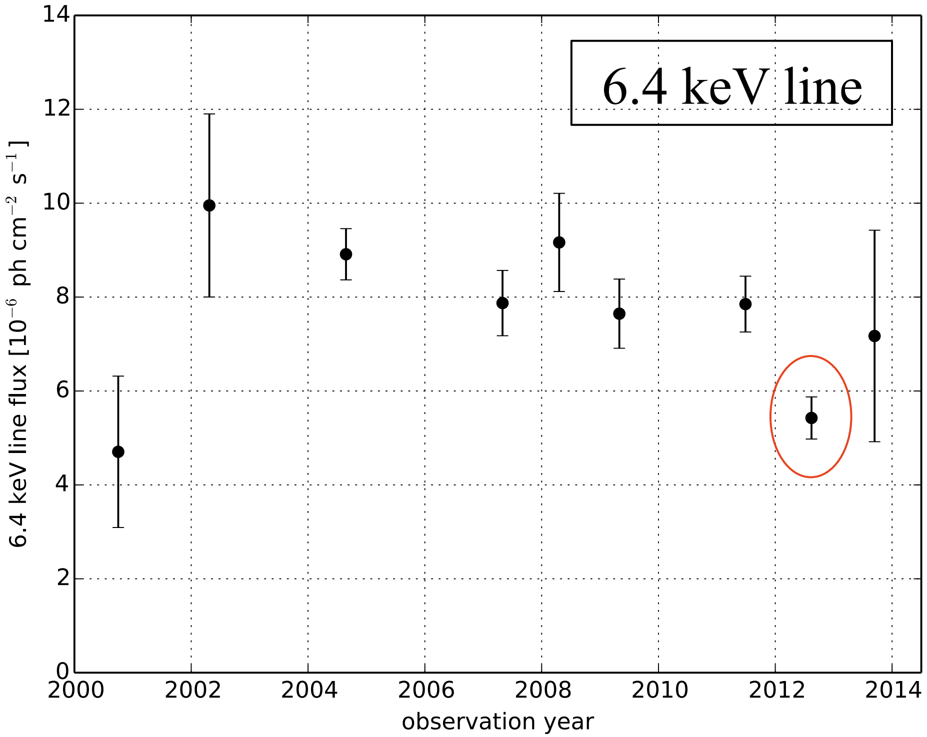
$\Lambda = 5 \times 10^{24}$ H cm^{-2} (fixed)

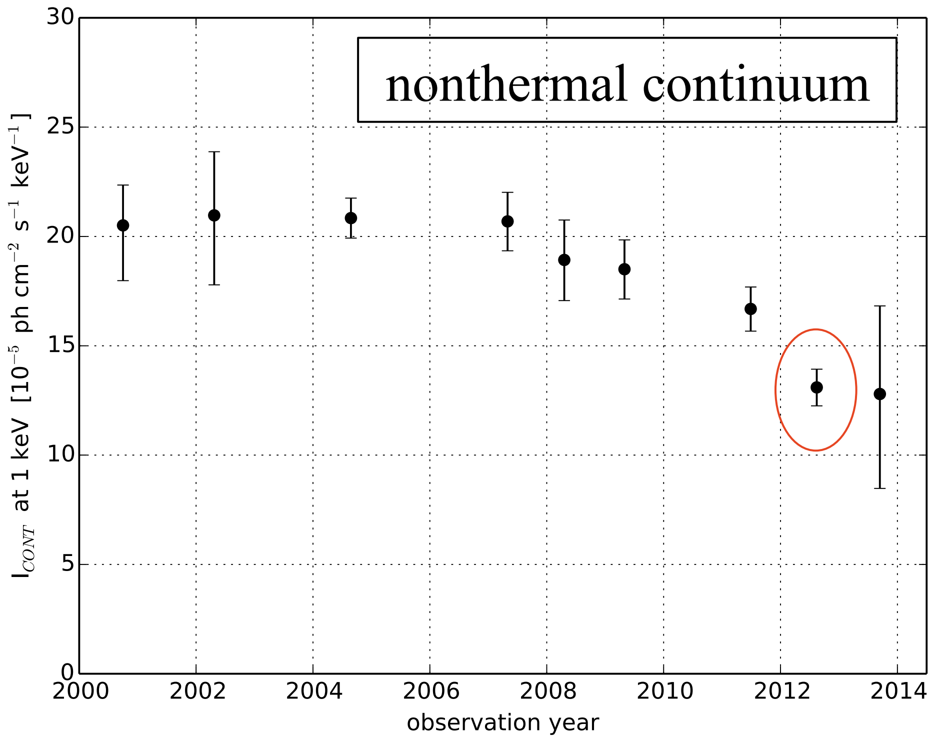




⇒ nonthermal X-rays possibly from LECR ions, but not electrons

Recent variation of the Arches cloud emission

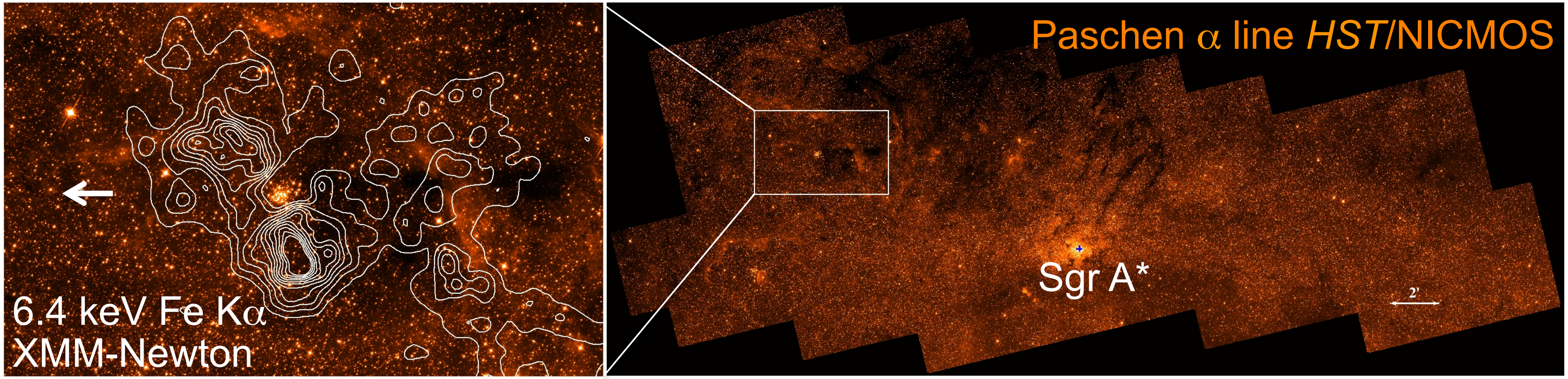




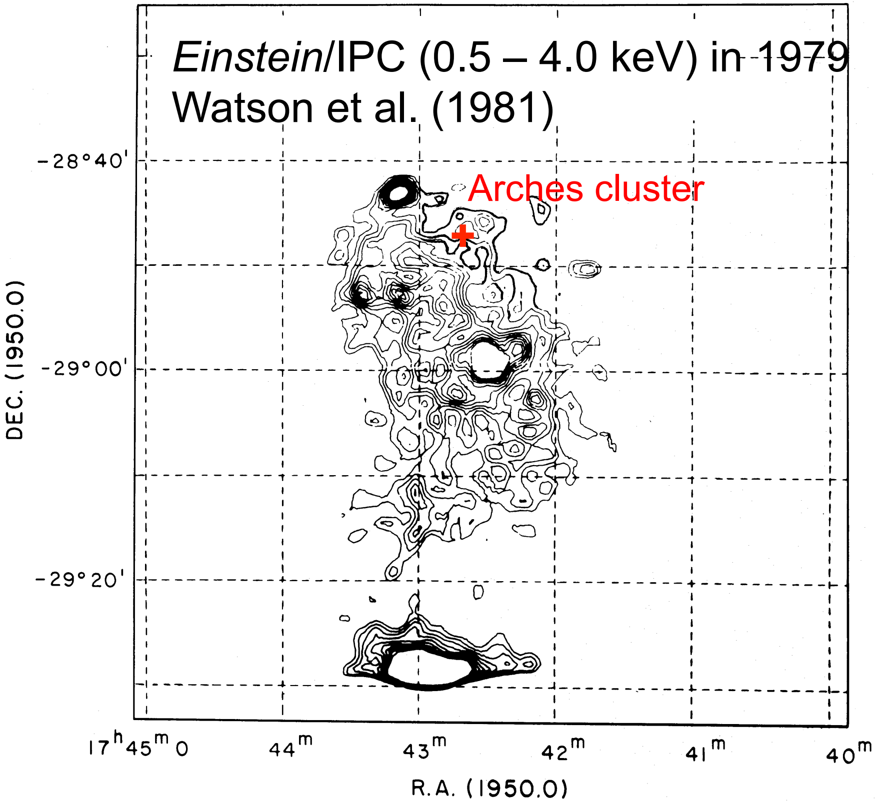
- 3 more years of XMM observations compared to Tatischeff et al. (2012)
- 30% flux drop in 2012 detected at more than 4σ for both the Fe Kα line and the associated continuum

⇒ A large fraction of the nonthermal emission is in fact due to the reflection of an X-ray transient source (Clavel et al. 2014)

On the variable emission from the Arches cloud



- The nonthermal X-ray emission seems to be related to the cluster itself, not to a distant source (Sgr A*)
- A transient source in the cluster should have a 4 – 12 keV luminosity of $\sim 10^{36}$ erg s^{-1}, whereas the cluster current luminosity is $\approx 5\times10^{33}$ erg s^{-1}
- A transient source in a long-lasting (>8.5 years) bright state some decades ago was not detected with *Einstein* and subsequent X-ray telescopes



Conclusions

- Most of the 6.4 keV line emission from both diffuse and dense molecular clouds in the GC is likely due to the past activity of Sgr A* (but see Yusef-Zadeh et al. 2007, 2013)
- More observations and work are needed on the origin of the variable, nonthermal X-ray emission from the Arches cluster region
- Assuming that $N(H_3^+)$ increases linearly with the cosmic-ray flux,

$$\zeta_2 = (1-3)\times 10^{-15}\ \mathrm{s}^{-1}$$

- The CR power needed to explain such an H_2 ionization rate is

$$P_{\mathrm{CR}} \sim \zeta_2 n_{H2} V W \sim \boxed{2\times 10^{39}\ \mathrm{erg\ s^{-1}}} \quad \text{with} \quad W \approx 40\ \mathrm{eV}$$

- This is comparable to the power supplied by SNe, but a large fraction of the latter ($>\sim 95\%$; Crocker et al. 2011) is advected by the GC outflow

⇒ Unconventional CR sources (other than SNe) may play a role in the GC