Fermi
Gamma-ray
Space Telescope

The Galactic Center and GeV gamma-rays

"Jack" J.W. Hewitt
NASA Goddard / UMBC

member of LAT collaboration since 2012

Overview

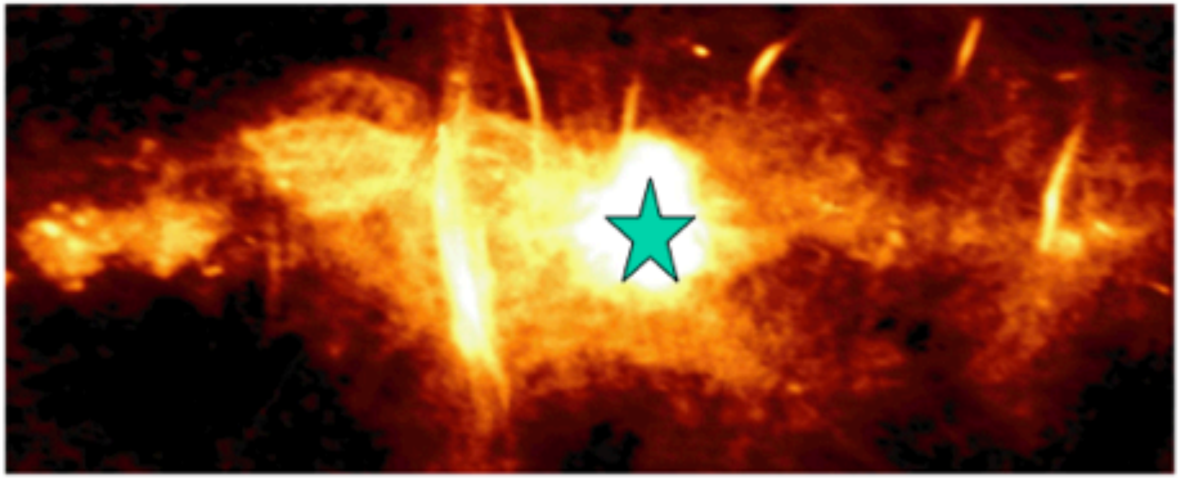
- 1. Tour of the Galactic Center (GC)
  - Multi-wavelength overview: physical conditions and past activity

- 2. GeV emission with Fermi-LAT and a few highlights
  - Origin of diffuse GeV emission?
  - Emission from the central source: Sgr A*?
  - Dark Matter?

Overview of the GC

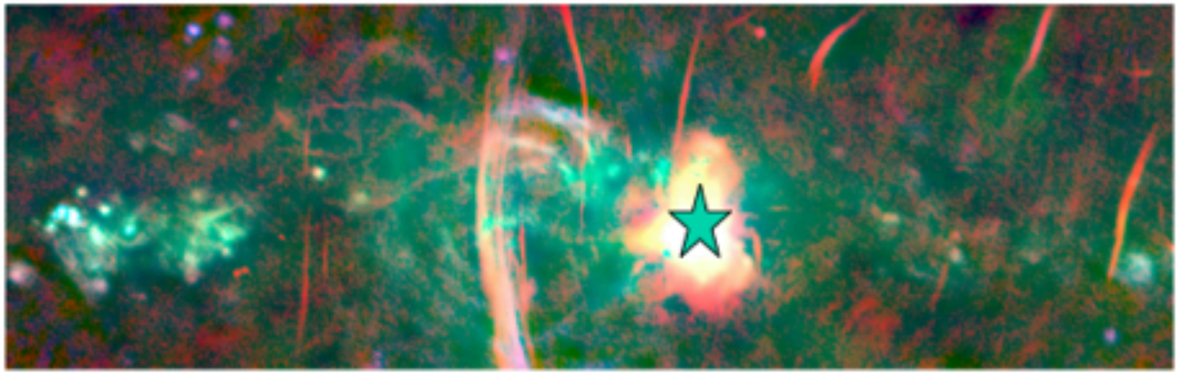
Mixture of thermal and non-thermal emission

- Nonthermal 90cm emission: ~ Gev particles



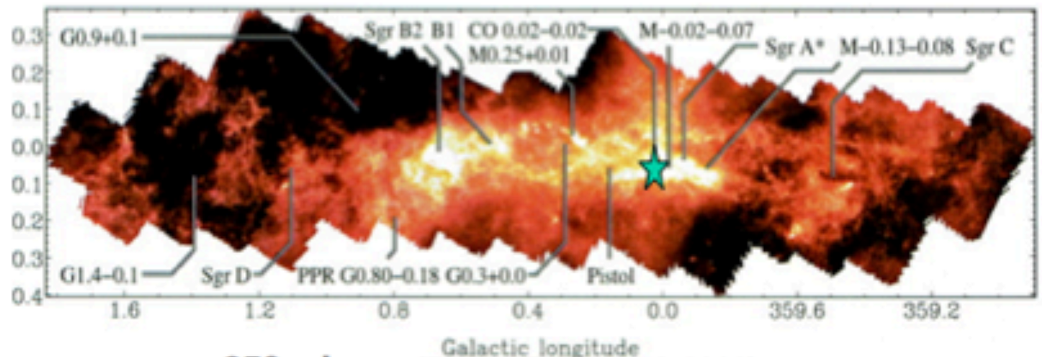
Sgr B2 Sgr B1 Arc Sgr A* Sgr C

- Thermal Emission
  - Compact HII regions
  - Evolved HII regions
- Nonthermal Emission
  - SNRs,
  - Nonthermal filaments
  - Diffuse background
  - Colliding winds

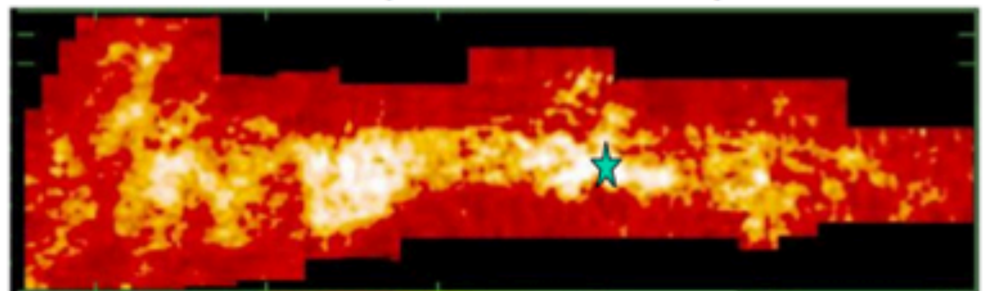


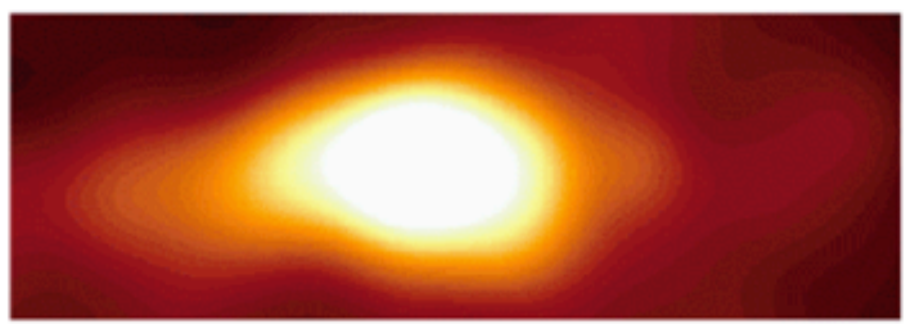
Overview of the GC

- Molecular layer: 450 x 50 pc
- Velocity Dispersion Δv ~15 km/s
- Scatter broadening: turbulent medium
- Multi-temperature gas T ~ 30-100K,
- T_{dust} ~ 30K
- Molecular gas density n ~ 10^2 cm^{-3} (uncertain)
- Mass ~10^7 to 10^8 solar mass (uncertain)
- **H3+ line emission indicates CR ionization rate ~10^{-15} s^{-1} H^{-1} (~2 orders of magnitude higher than locally observed)**

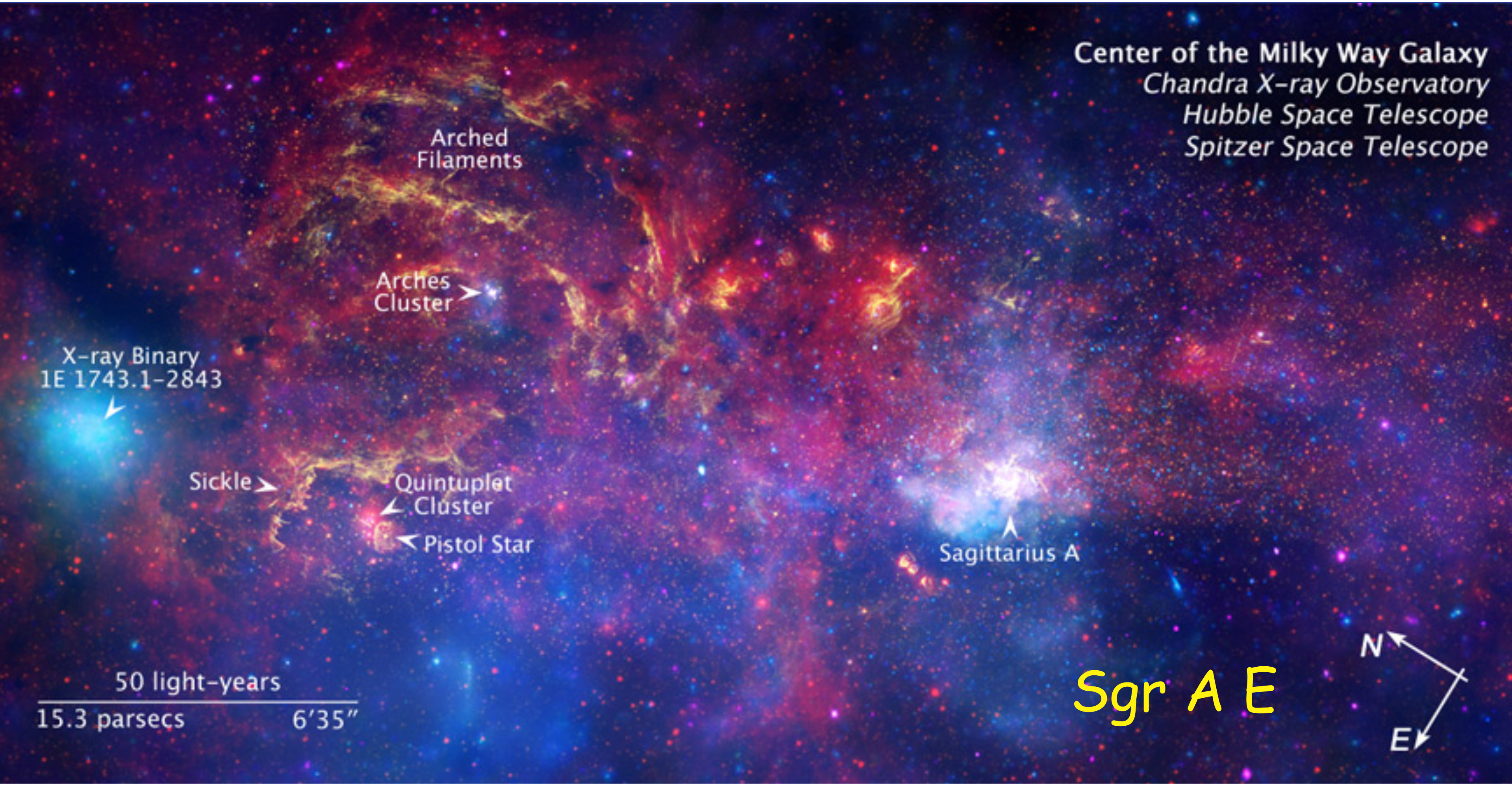


850 micron (Pierce-Price et al. 2000)


CS (2-1) (Oka et al. 2004)


90cm (LaRosa et al. 2005)

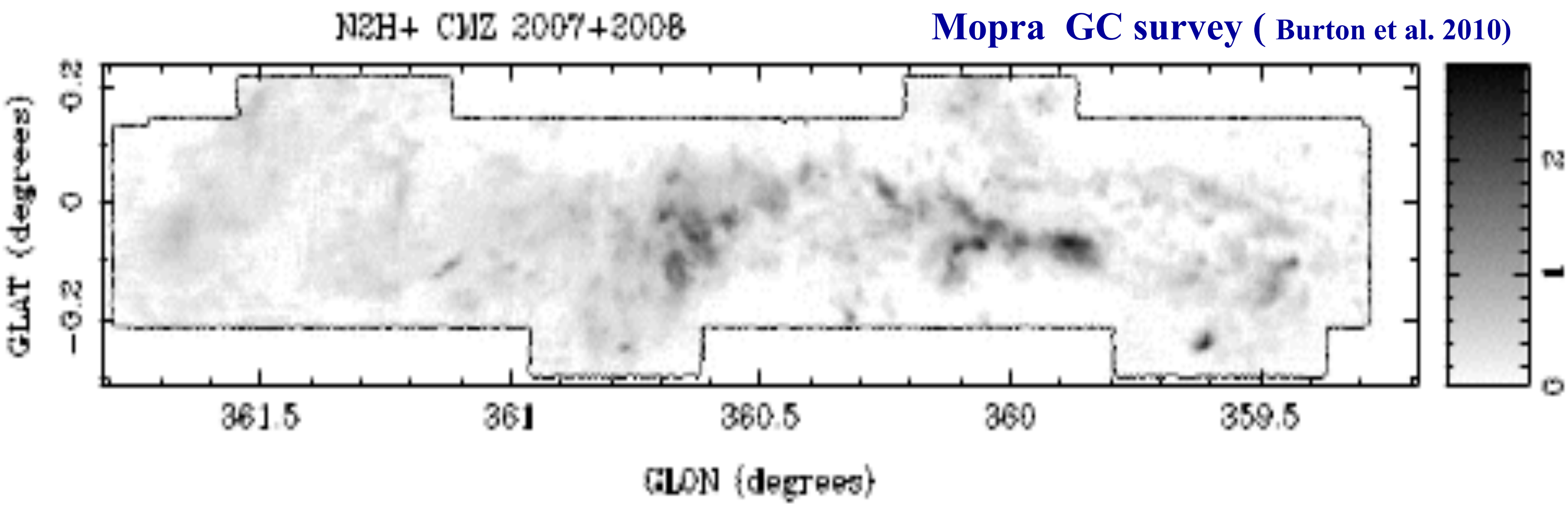
A view from the Great observatories



Central Molecular Zone (CMZ)

- The inner 500 pc with ~10^8 M_{sol} of mostly molecular gas

Mopra GC survey (Burton et al. 2010)

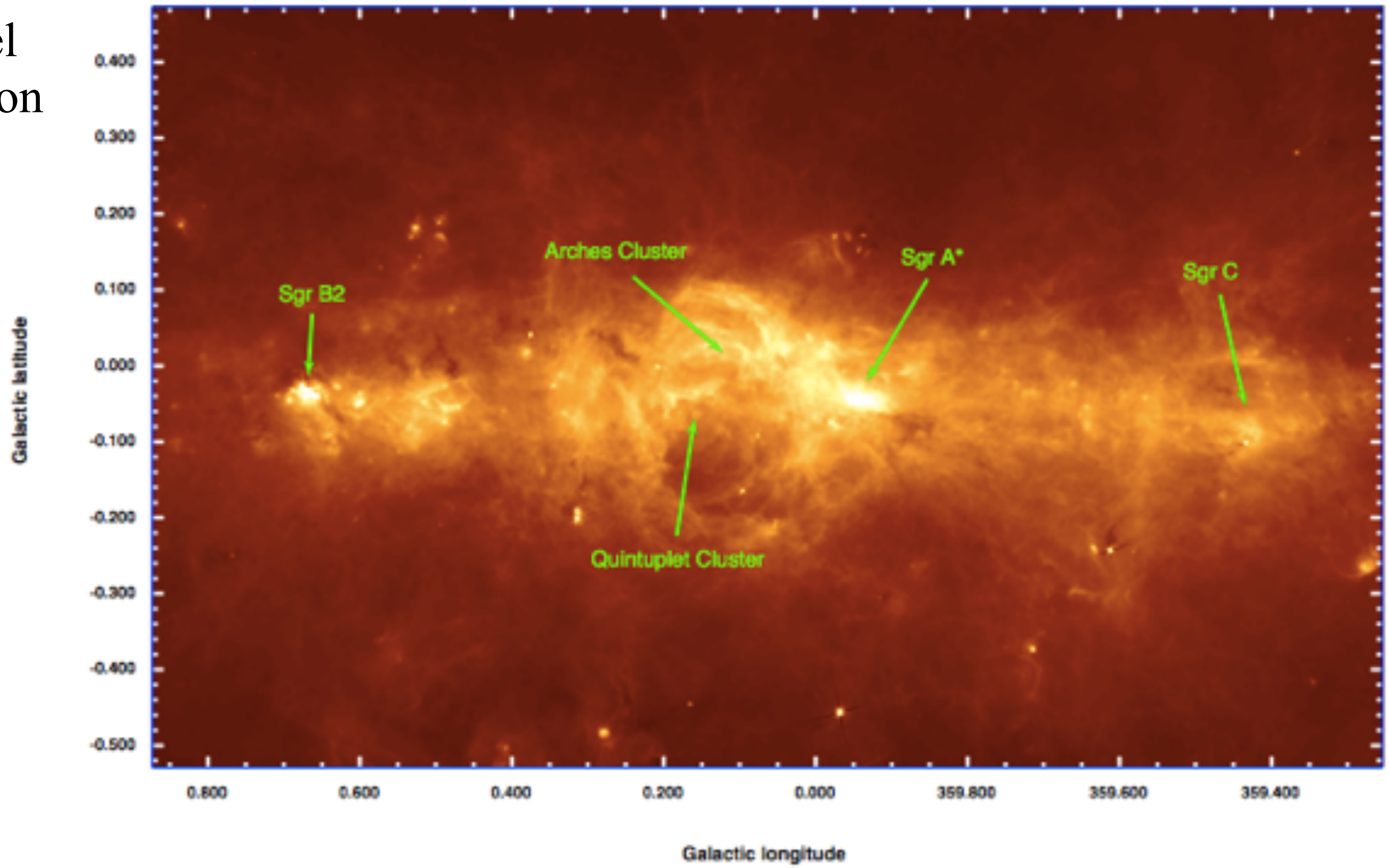


Average gas density: 100 cm^{-3} 100 times that of the Disk
Star Formation Rate: ~0.5M⊙ yr^{-1} verus 5 M⊙ yr^{-1} in the Disk
Efficiency: 5 10^{-9} similar to that in the Disk

CMZ as the Molinari Ring

- **~100x60 pc twisted ring of cold dust observed by Herschel with a total mass of ~3x10^7 Msol**

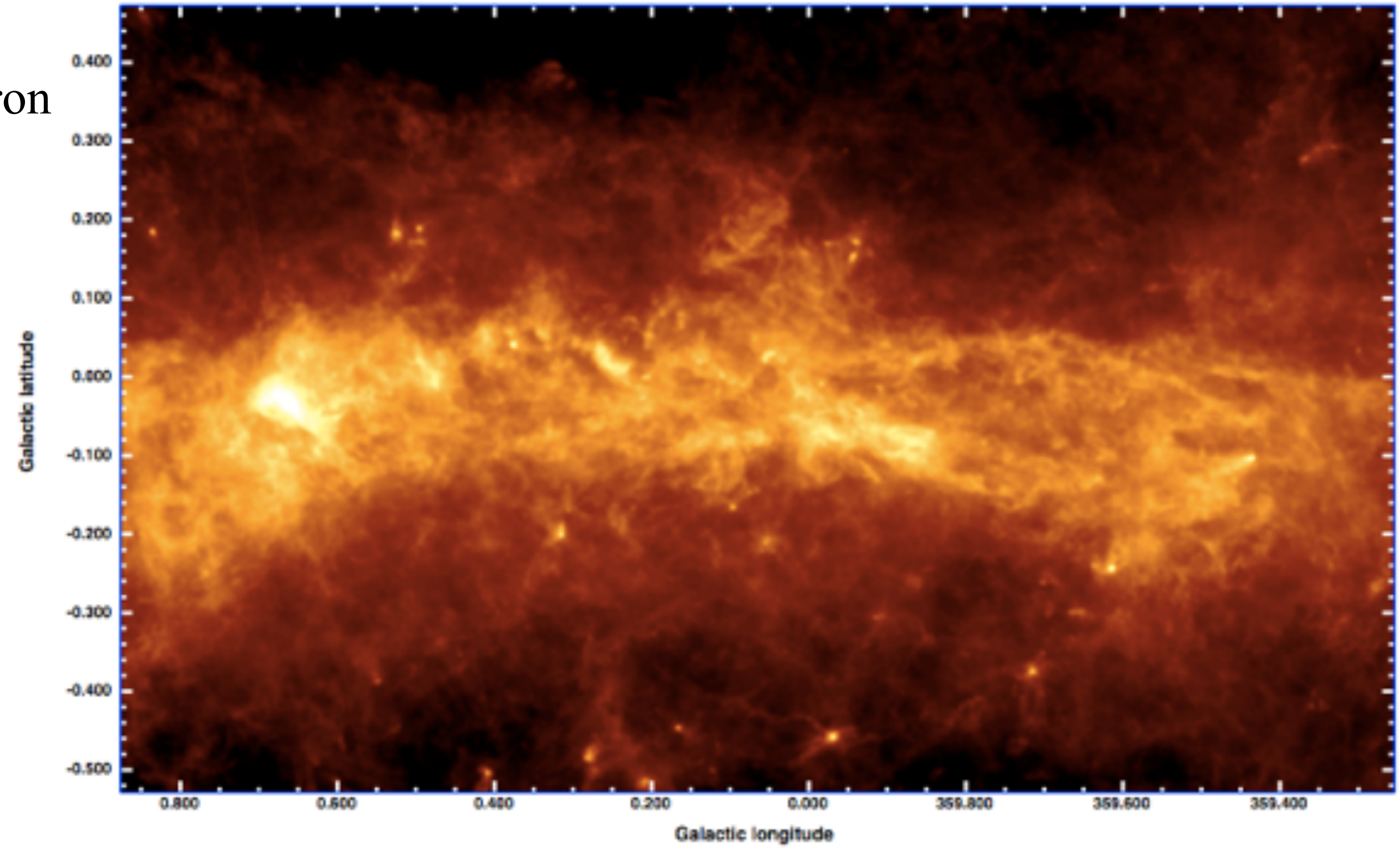
Herschel
70 micron



CMZ as the Molinari Ring

- **~100x60 pc twisted ring of cold dust observed by Herschel with a total mass of ~3x10^7 Msol**

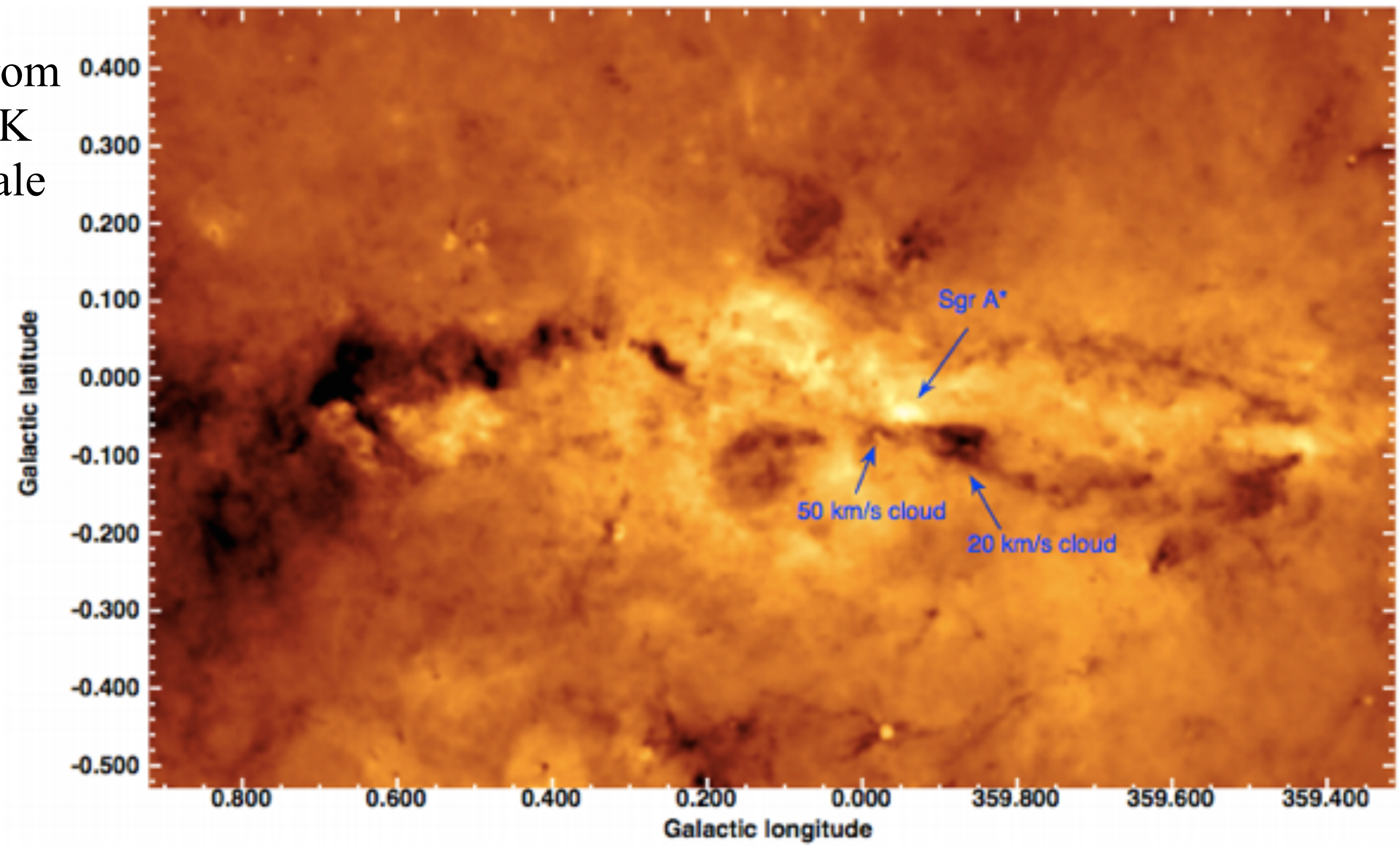
Herschel
250 micron



CMZ as the Molinari Ring

- **~100x60 pc twisted ring of cold dust observed by Herschel with a total mass of ~3x10^7 Msol**

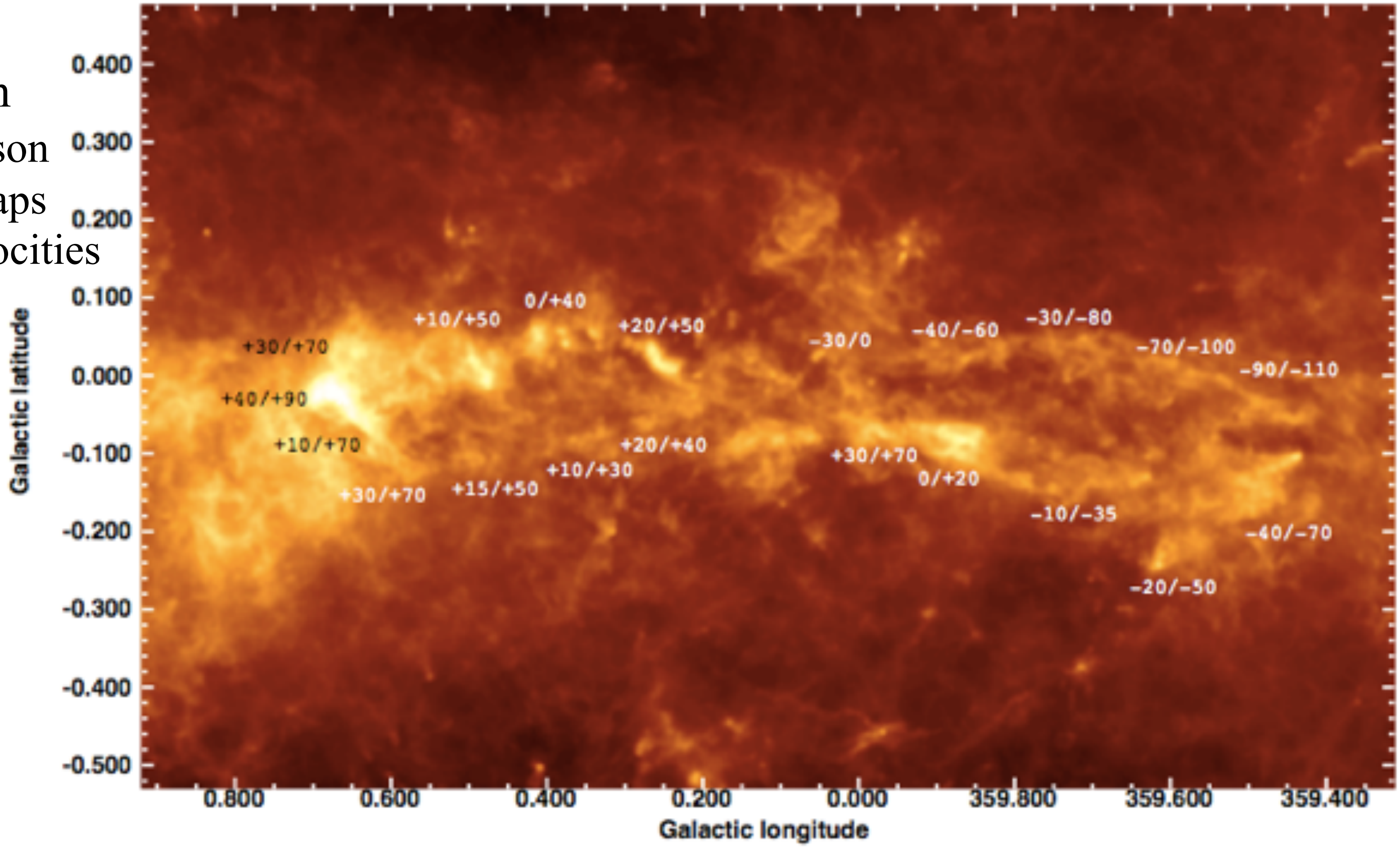
T_{dust} from 15-40 K log-scale



CMZ as the Molinari Ring

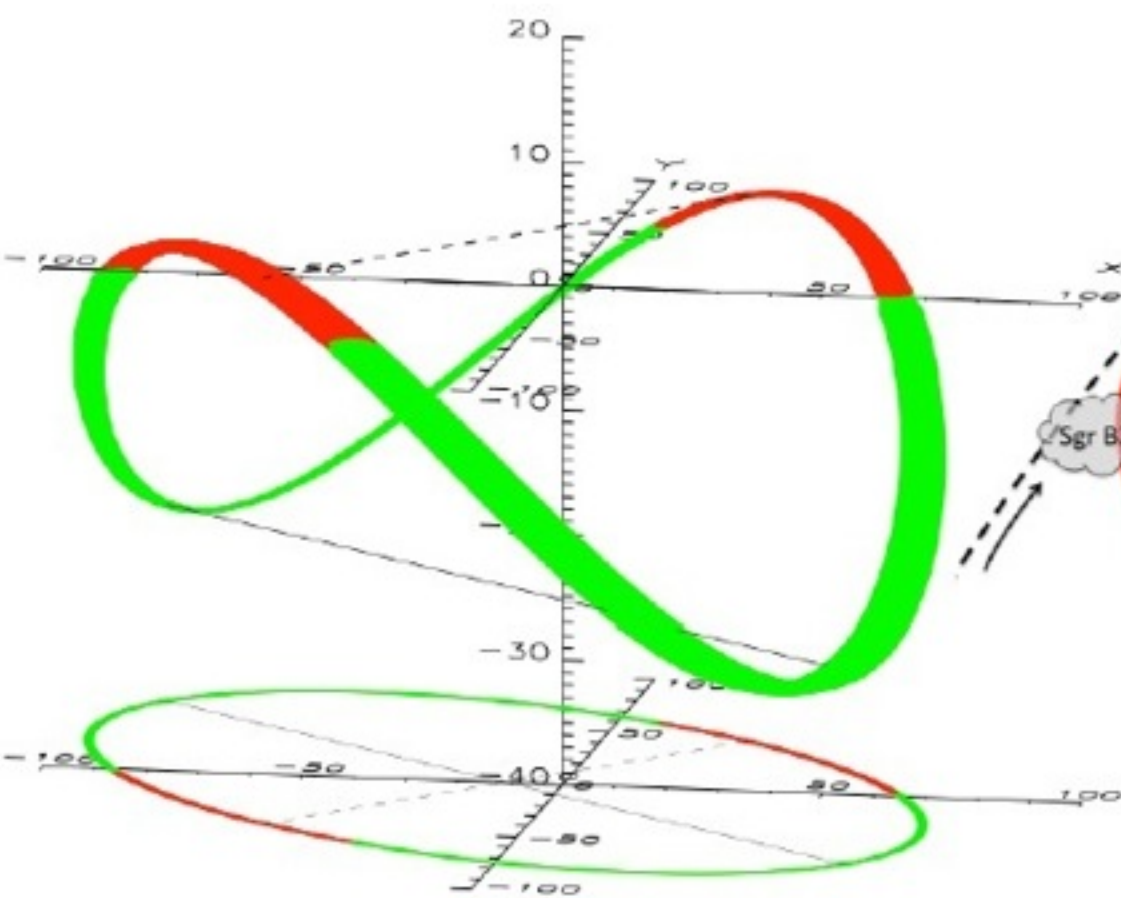
- **~100x60 pc twisted ring of cold dust observed by Herschel with a total mass of ~3x10^7 Msol**

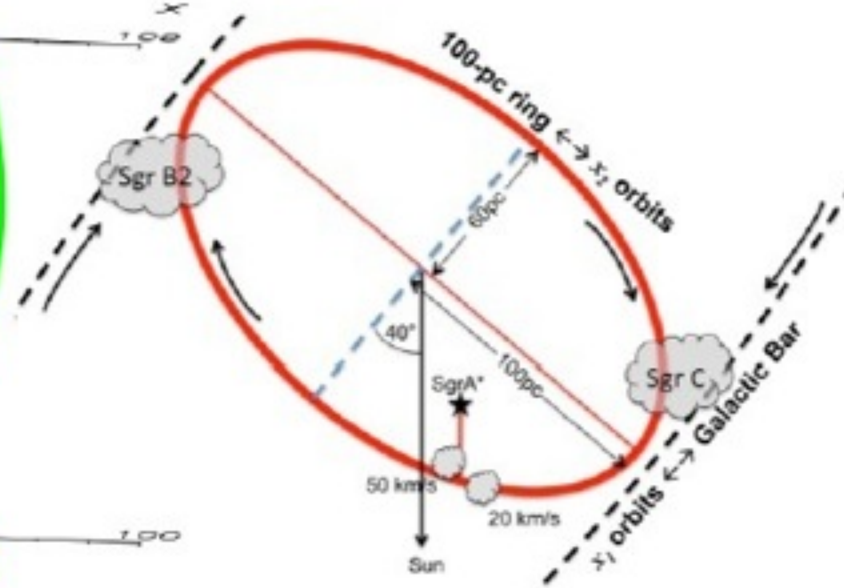
N_H from comparison to CS maps with velocities



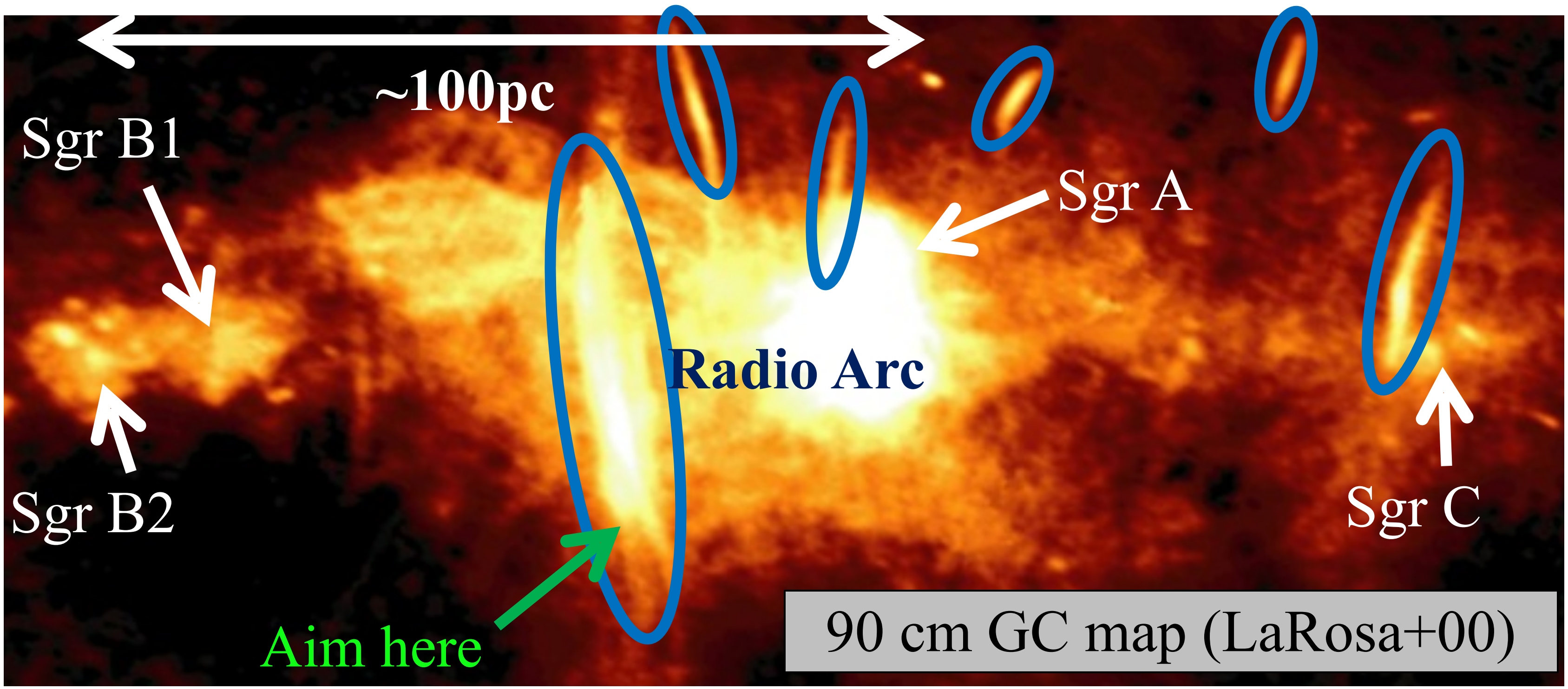
CMZ as the Molinari Ring

- **~100x60 pc twisted ring of cold dust observed by Herschel with a total mass of ~3x10^7 Msol**





Cosmic Rays in the GC

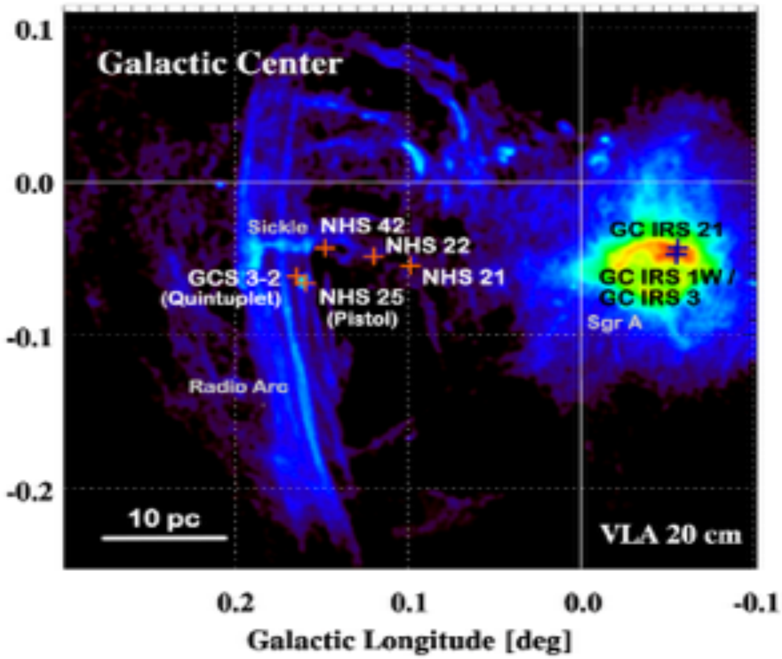


Radio Arc (e.g. Yusef-Zadeh+ 84)

- Largest-scale non-thermal filaments plentiful throughout GC
- Indicates a strong (or turbulent?) magnetic field
- Relativistic electrons (~1 GeV) are abundant

Cosmic Rays in the GC

- H_3^+ absorption line studies of bright stars in the GC provide constraint on ζL : CR ionization rate * path length (Oka et al.)



$$\zeta L = 2k_e N(\mathrm{H}_3^+) \left(\frac{n_\mathrm{C}}{n_\mathrm{H}}\right)_\mathrm{SV} \frac{R_{\mathrm{C/H}}}{f(\mathrm{H}_2)}$$

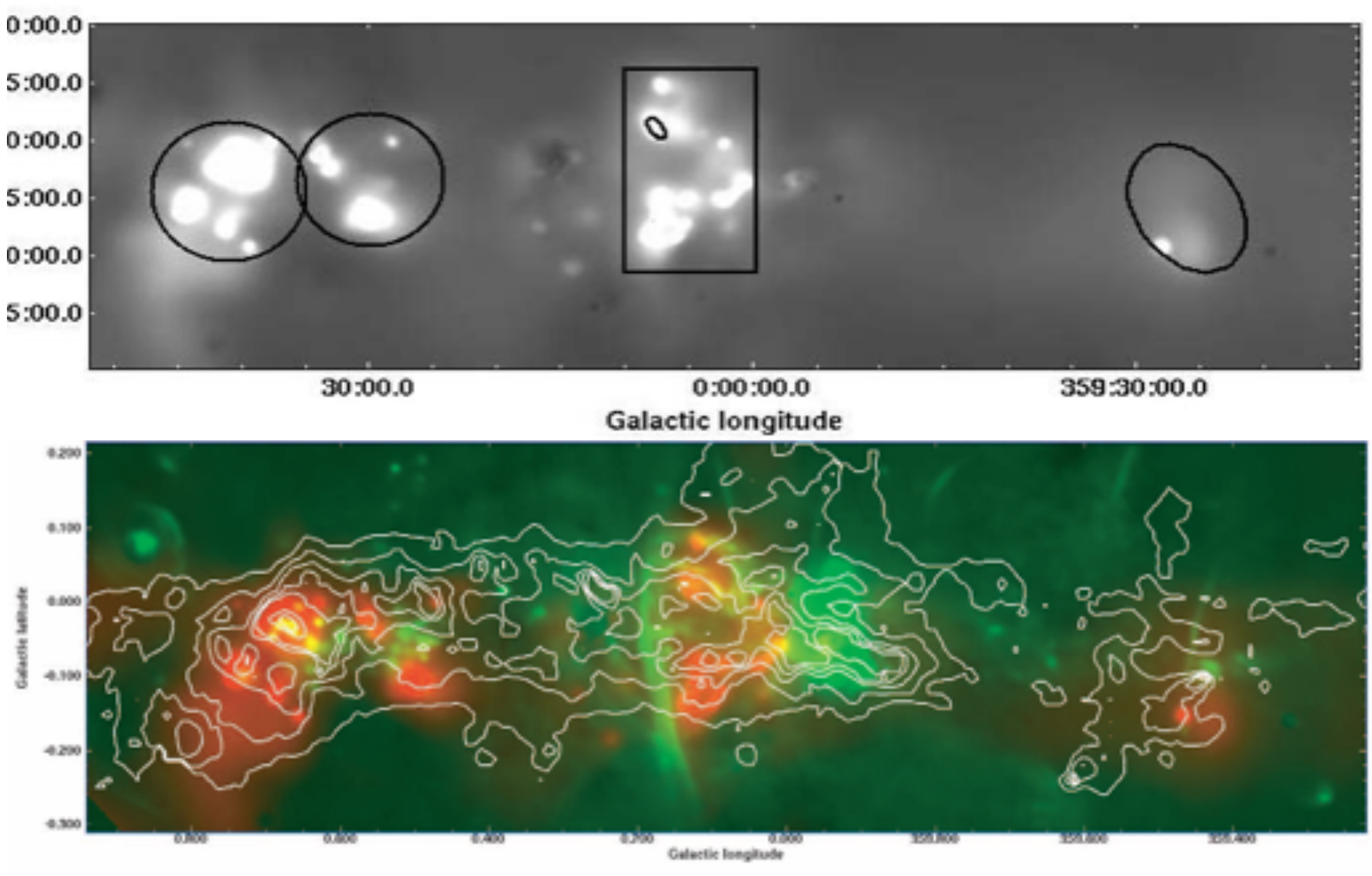
For $\zeta \sim 3\times 10^{-15}\ \mathrm{s}^{-1}$ $L \sim 15 - 50$ pc

Note: these assume solar interstellar C; for constant ζ, L increases as C increases

- Evidence for abundant low-energy (ionizing) Cosmic Rays filling $n_H \sim 100\ \mathrm{cm}^{-3}$ gas at Galactic center

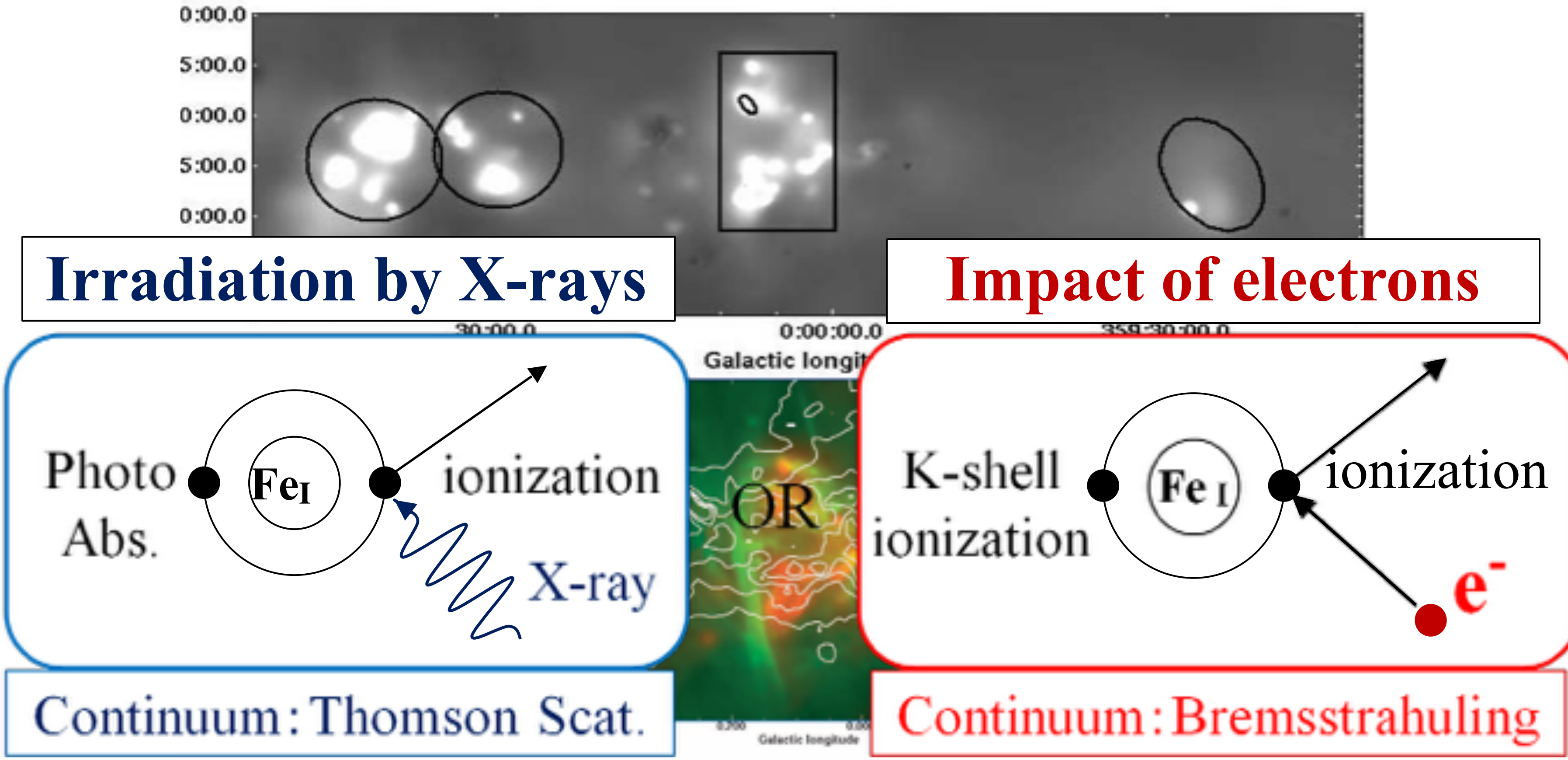
Fe 6.4 keV line emission

- **Dense, neutral gas is observed to correlate with 6.4 keV line emission observed in X-rays (Chandra, XMM, Suzaku, Integral)**



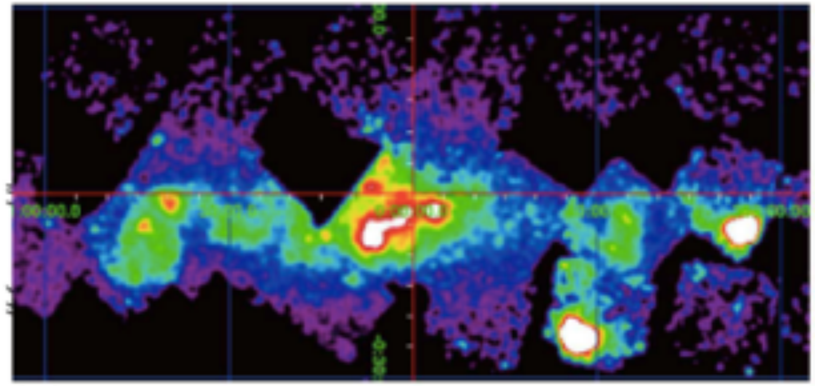
Fe 6.4 keV line emission

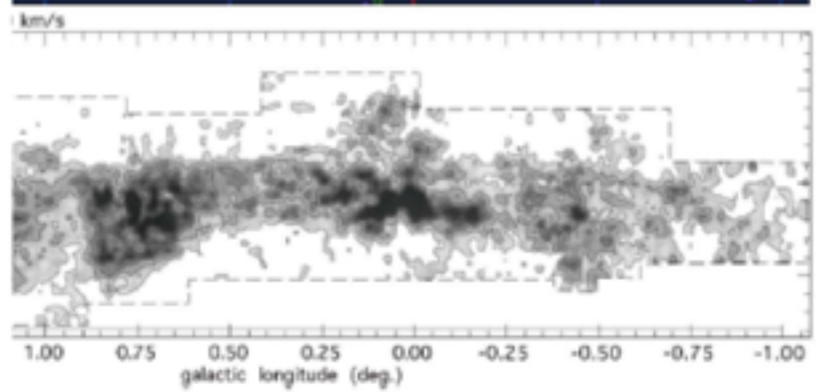
- **Dense, neutral gas is observed to correlate with 6.4 keV line emission observed in X-rays (Chandra, XMM, Suzaku, Integral)**



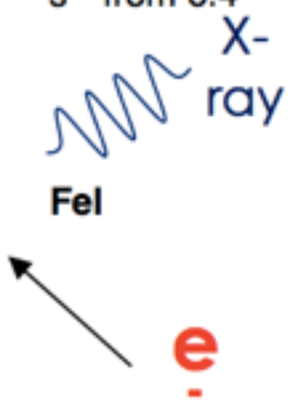
Diffuse Radio, X-ray and ɣ-rays

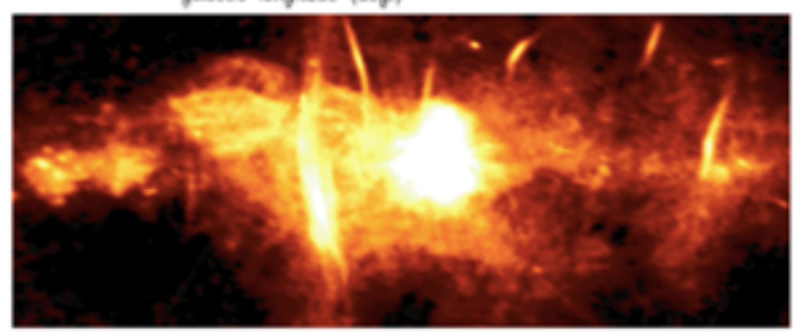
- Enhanced nonthermal radio emission
- X-ray irradiation of molecular clouds
- Enhanced H_3^+ Absorption lines
- Warm molecular gas
- Diffus γ-ray emission (Fermi)
- Chemisty of the gas (SiO, CH_3OH)





- CR ionization rate:
- z = 10^{-14} to fewx10^{-15} s^{-1} from 6.4 keV line

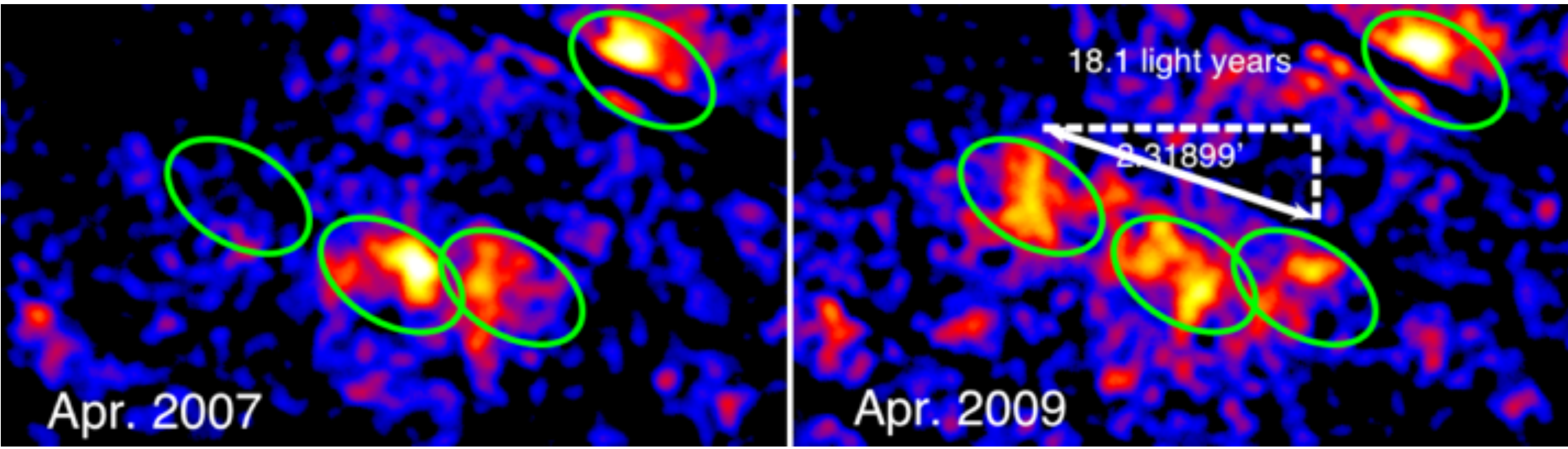




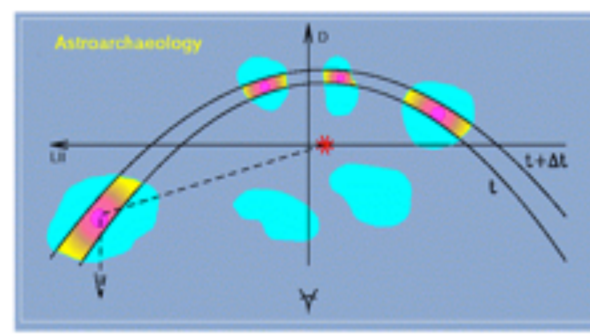
Continuum : Bremsstrahuling

Past activity from Sgr A*

- **XMM observes brightening and dimming of Fe 6.4 keV lines => super-luminal motion consistent with X-ray light echo.**



Note: LECRs could still fit this scenario, but seem ad hoc. Coulomb lifetime ~ 1 yr.



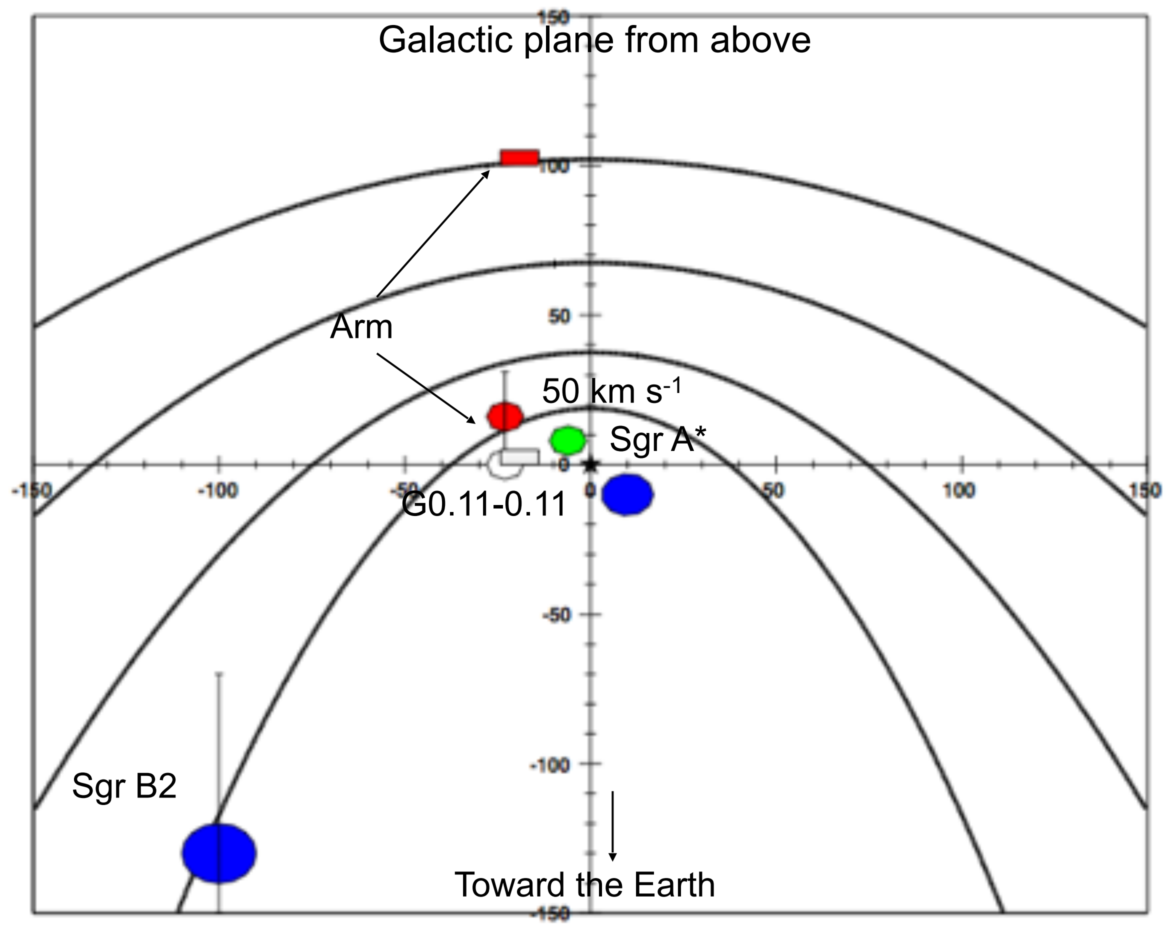
Past activity from Sgr A*

- **Multiple Fe 6.4 keV line regions fit by period of intense X-rays from Sgr A* that ended ~100 yr ago.**

from Arm region
$N_H = 2.7\times10^{23}$ cm^{-2}
$D_{proj} = 15$ pc
Radius=1.1 pc

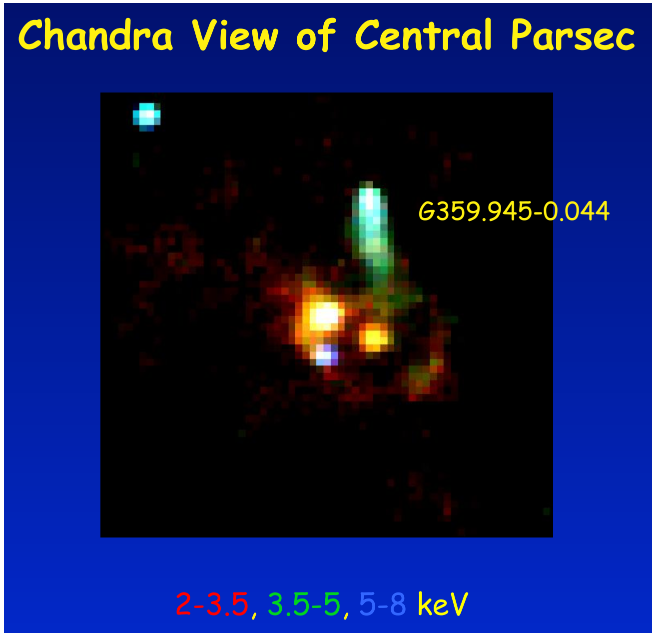
$L_{SgrA^*} > 3\times10^{37}$ erg s^{-1}

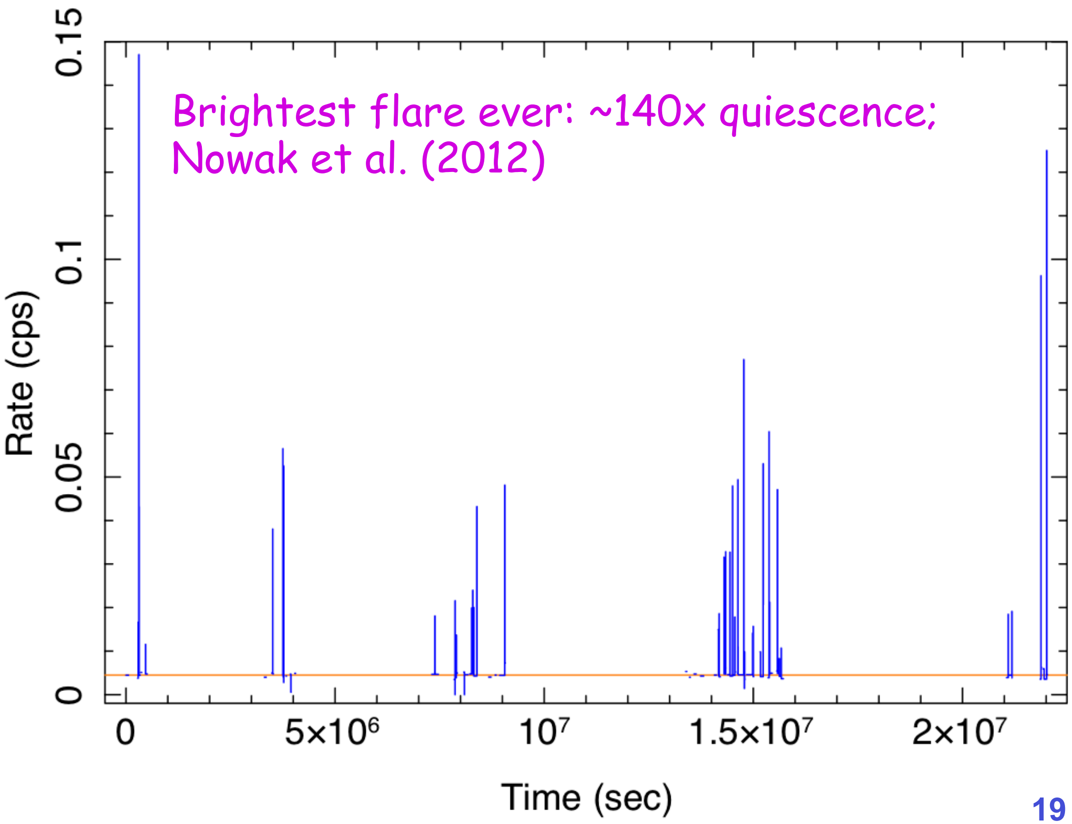
Assuming $L = 1.4\times10^{39}$ erg s^{-1}
100 pc
Sgr A* activity 500 yr



Current activity from Sgr A*

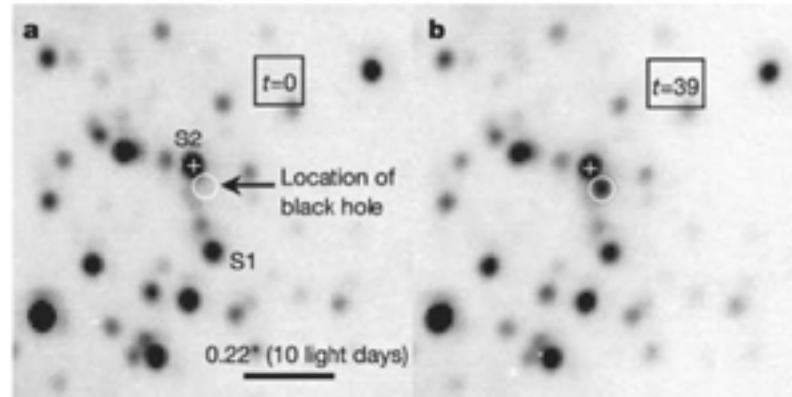
- Current X-ray flares observed ~3x10^{35} erg /s
- As short as 200s => ~20 Rs
- Average ~1 flare per day

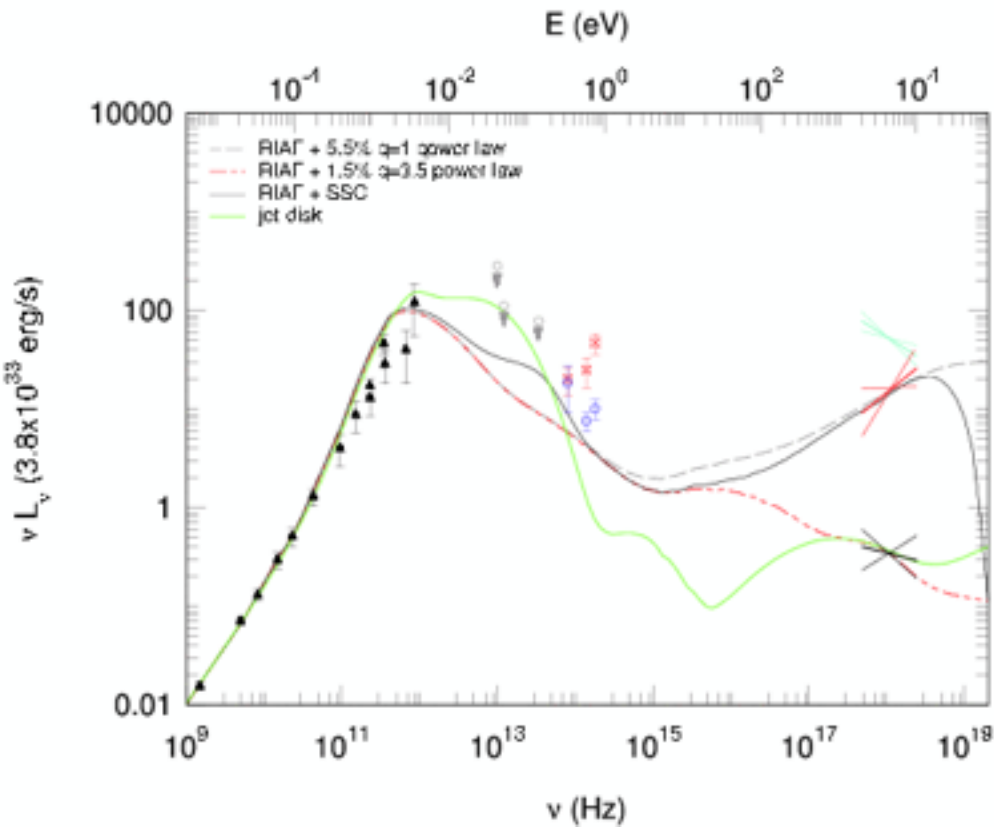




Current activity from Sgr A*

- **NIR and sub-mm flares observed**
- **Flares are polarized, with time-variable polarization angle.**

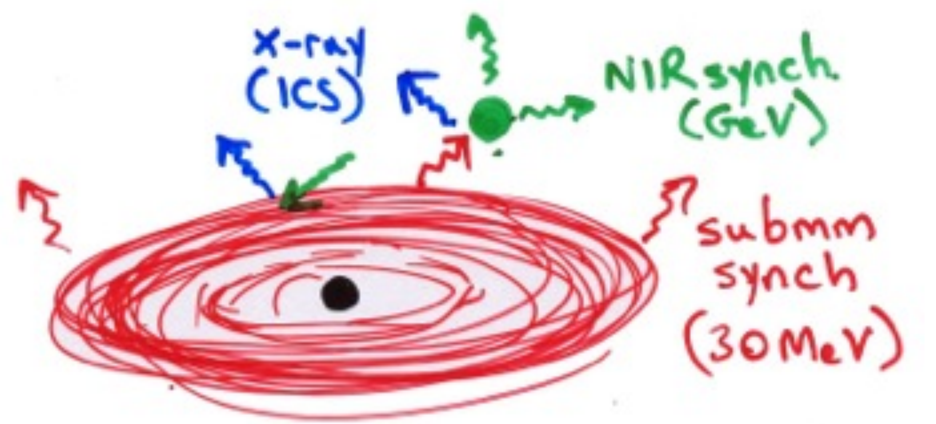




- **Broadband SED of flares from radio to X-rays**

Sgr A* Flares

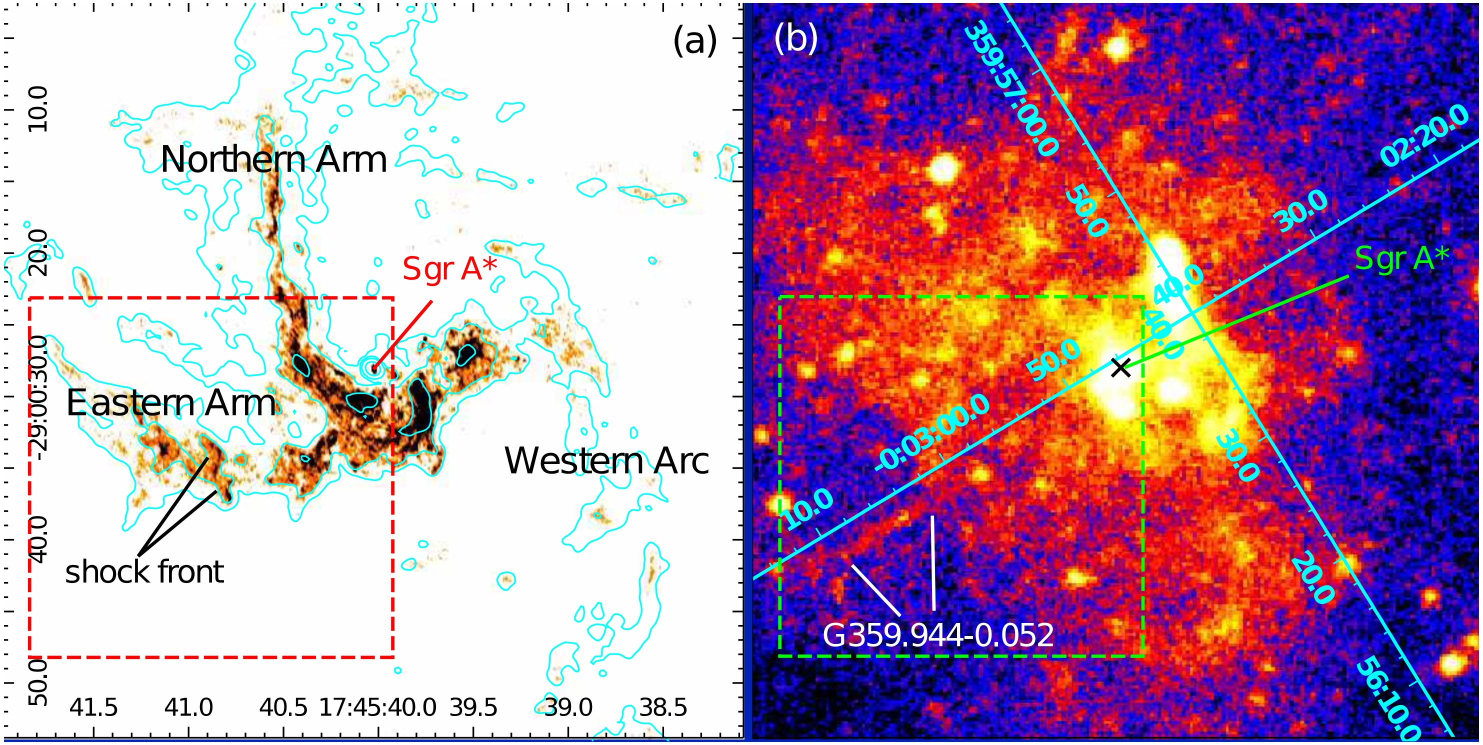
- X-ray flare emission mechanism is non-thermal but otherwise still undetermined:
  - Synchrotron with cooling break
  - External Compton
  - Synchrotron self-Compton (SSC)
- Origin of NIR/sub-mm flares is undetermined:
  - magnetic reconnection
  - stochastic acceleration?
  - shock in jet or inner accretion flow
  - infalling asteroids? (Zubovas et al. 2012)



X-rays via inverse Compton scattering

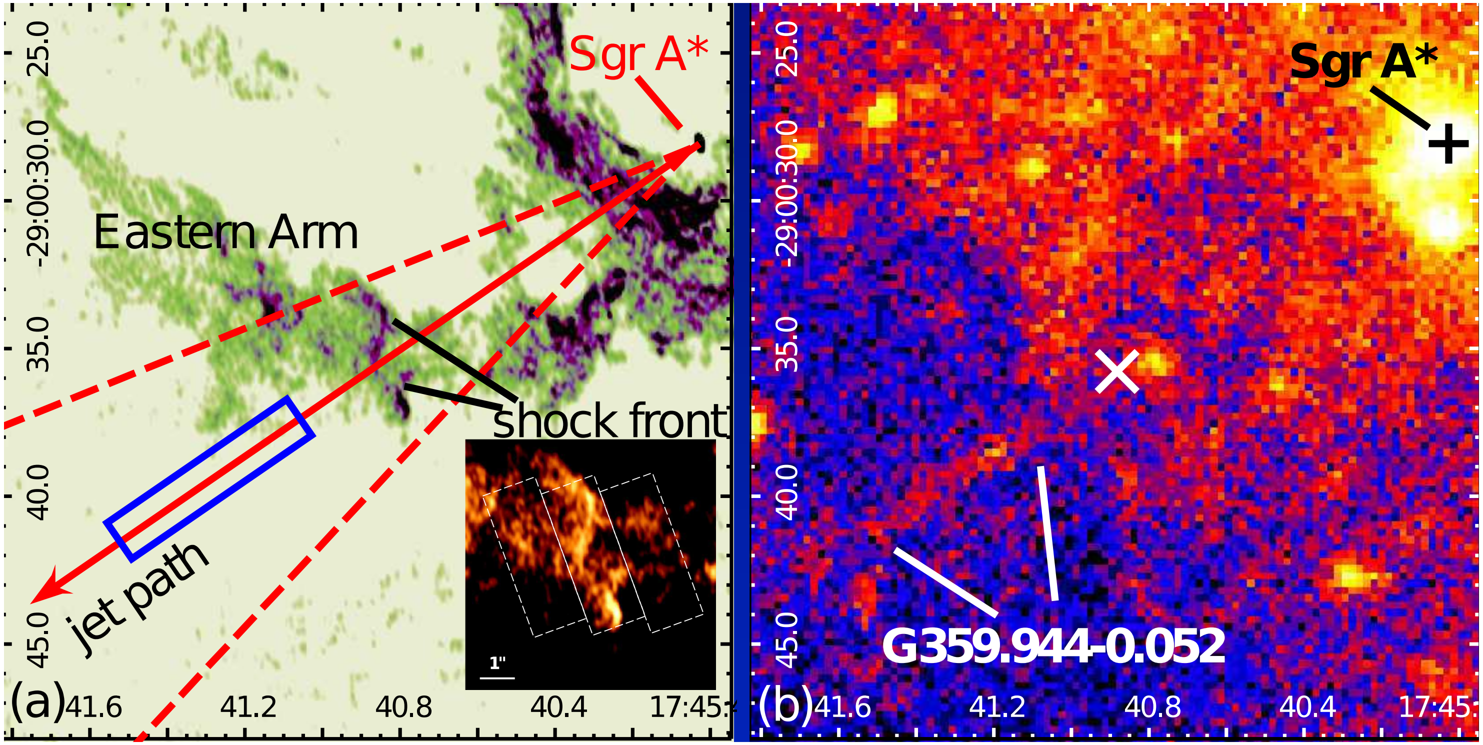
Does Sgr A* have a jet?

- **Parsec-scale, linear X-ray feature appears at the intersection with the Eastern arm of the "mini-spiral"** **(Li, Morris, Baganoff 2014)**



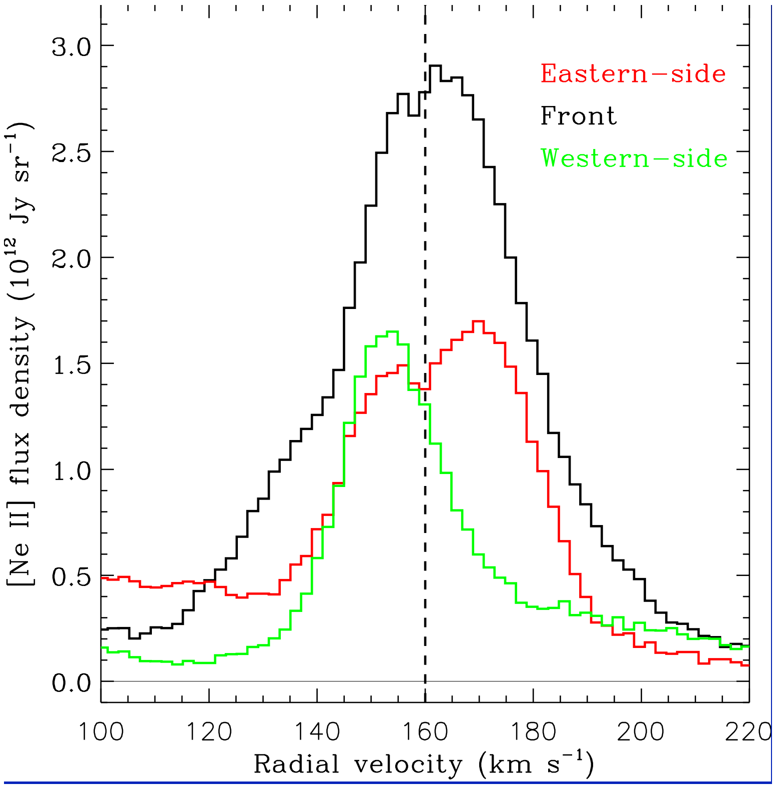
Does Sgr A* have a jet?

- **Parsec-scale, linear X-ray feature appears at the intersection with the Eastern arm of the "mini-spiral"** **(Li, Morris, Baganoff 2014)**
- **Bisects radio "shock front" in Eastern Arm**



Does Sgr A* have a jet?

- **Parsec-scale, linear X-ray feature appears at the intersection with the Eastern arm of the "mini-spiral" (Li, Morris, Baganoff 2014)**
- **Bisects radio "shock front" in Eastern Arm**
- **[Ne II] 12.8 micron flux density - velocity diagram shows flux drop at 160 km/s**
  => momentum impact on velocity field of E. Arm
- **Too many coincidences?**



- **Other authors have claimed evidence of a putative jet from Sgr A*, but with different inclination angles, extents**

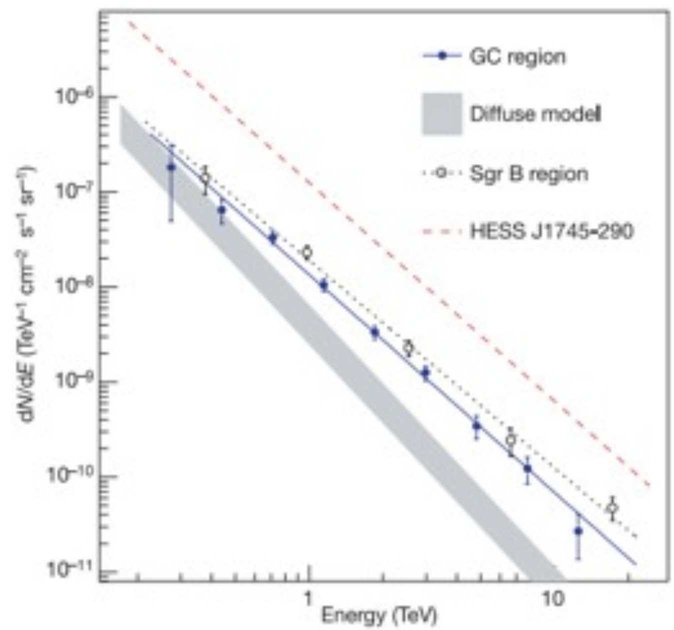
Overview of the GC

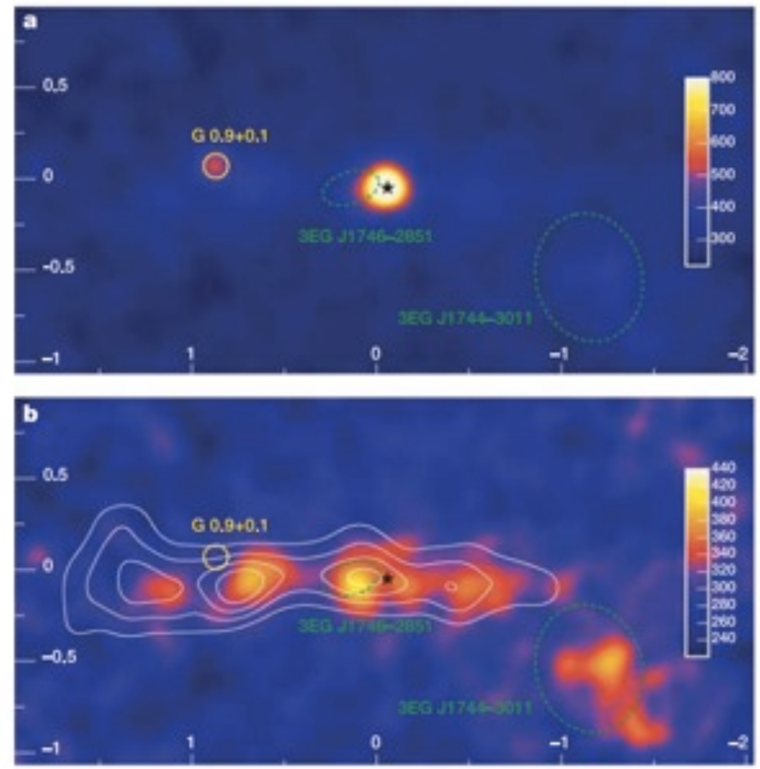
- ~10^8 M_{sol} reservoir of gas in inner 300 pc.
- Massive stellar clusters, compact objects, supernova remnants and pulsars (+ nebulae)
- Enhanced cosmic ray ionization rate
- Evidence for past/current activity from Sgr A*
  - May or may not have an existing jet
- All within inner 2x1 degrees (~300 pc)

GeV emission with Fermi-LAT

High energy activity in the GC

- HESS TeV detection of a “Galactic ridge” ~2ºx1º (Aharonian+ 2006)





- FeI Kα 6.4 keV line emission.
  - Evidence of past AGN-like activity from Sgr A*? (Sunyaev 1993;1998)
  - LECR bombardment? (Yusef-Zadeh+ 2007;Tatischeff+ 2012)

The GeV GC with Fermi

- **Fermi has brought a new era to GC studies**
- **Exposure, angular resolution, stability of response**
- **Never as much as you'd want, but a huge advance**

COS-B >300 MeV

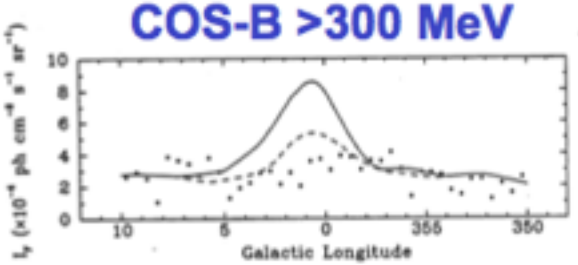
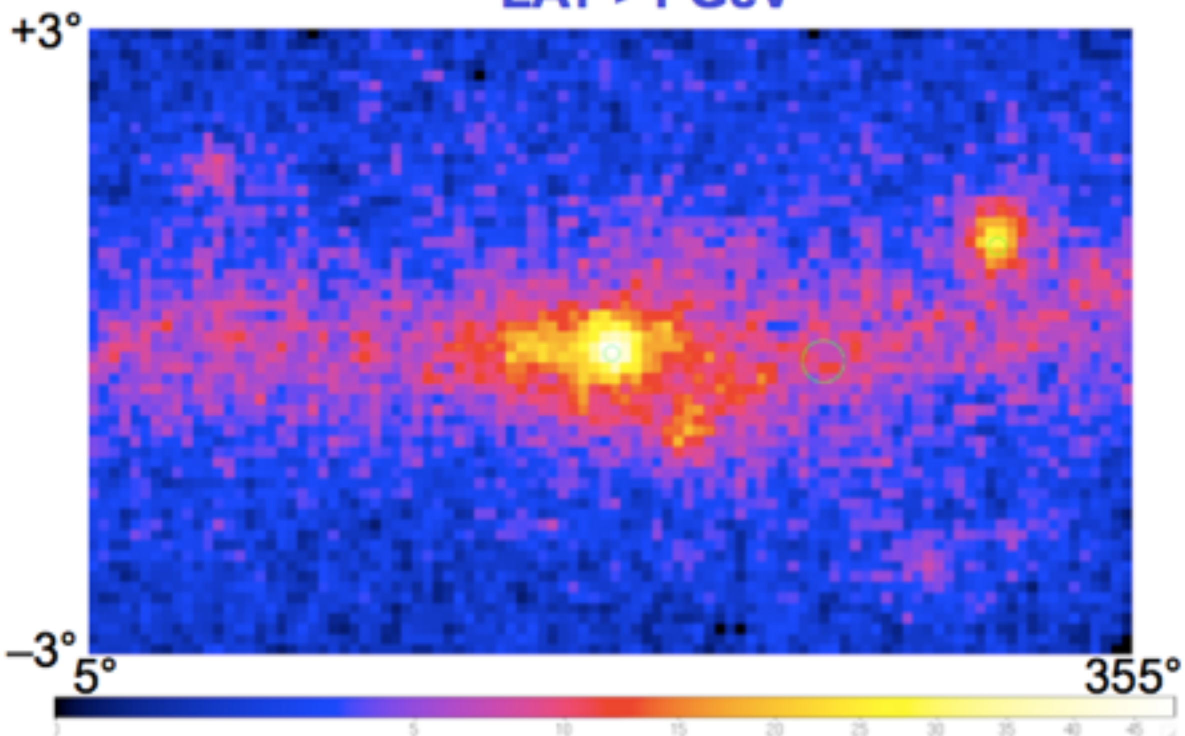


Figure 2. Profiles of observed and predicted γ-ray intensity in the Galactic center region, averaged over $|b| < 1°$. Points: observed COS-B γ-ray intensity (300–5000 MeV). Solid curve: predicted γ-ray intensity using the standard mass calibration ratio, N_{H_2}/W_{CO}, derived from Galactic disk observations. Dashed curve: predicted γ-ray intensity using the standard mass calibration ratio, but with the eight wide-line clouds indicated in Figure 1 removed from the analysis

Stacy, Dame, & Thaddeus (1987)

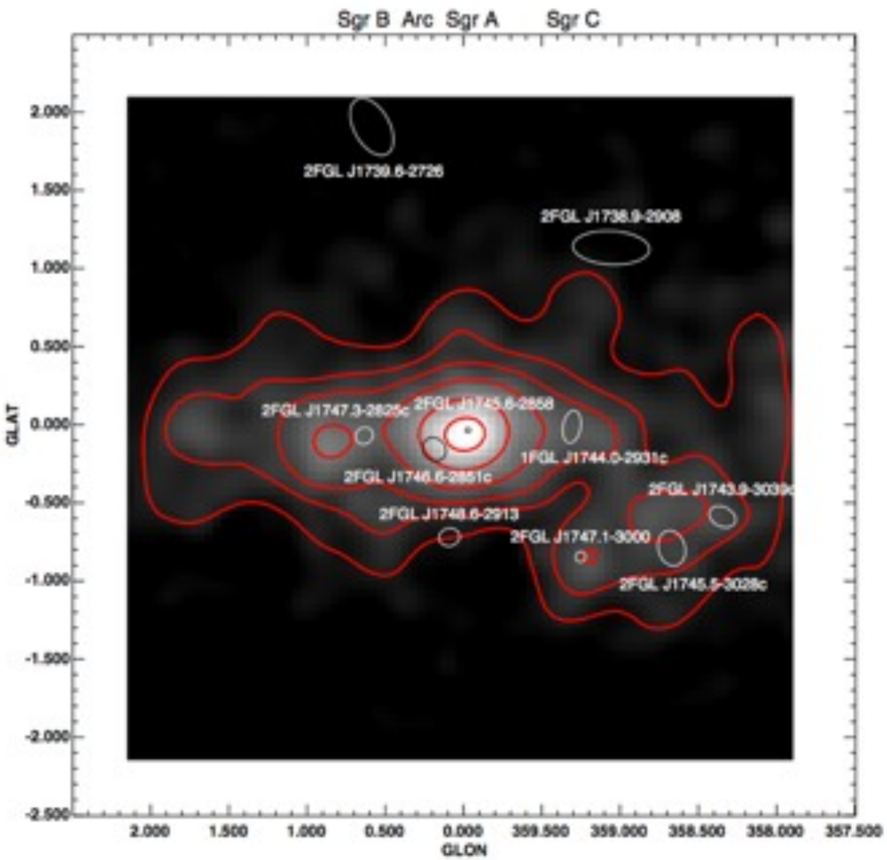
LAT >1 GeV



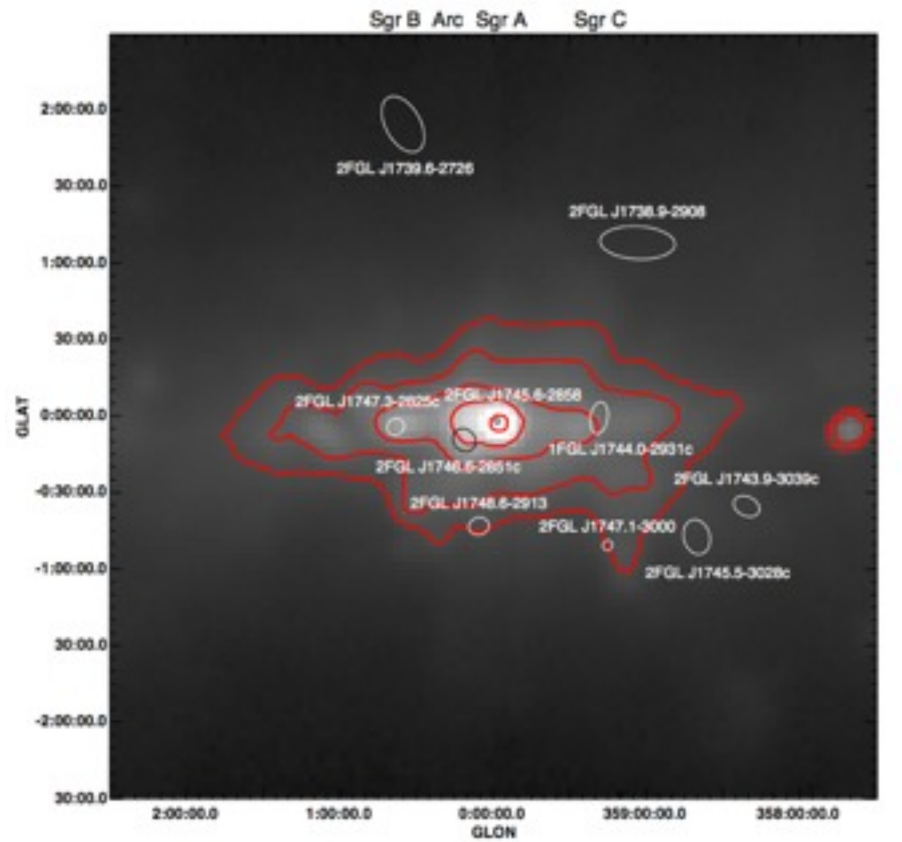
12-month data set, Diffuse class, **Front** only

LAT Analysis: Inner 2ºx1º Emission

- Both GeV and Radio emission appear to be extended along the Galactic ridge (inner ~2º x 0.85º)



smoothed >1GeV CMAP, background subtracted

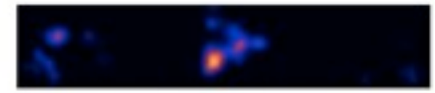


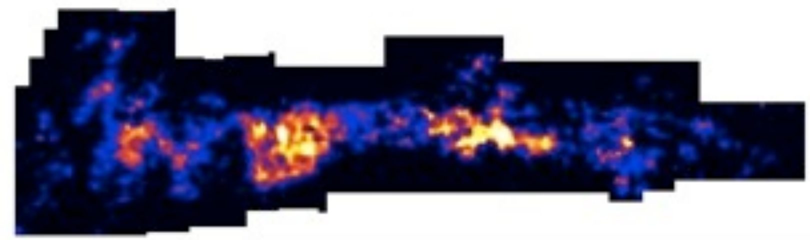
Diffuse 20cm Radio Map

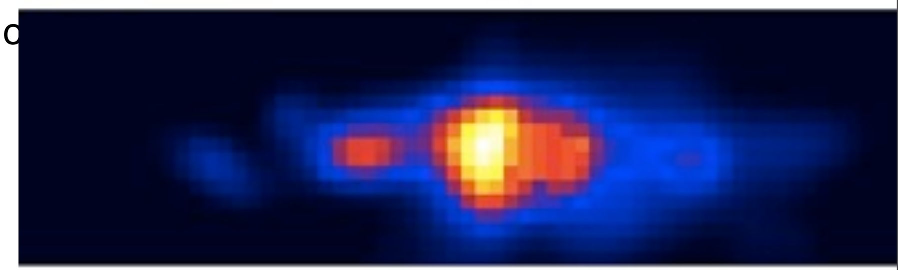
LAT Analysis: Spatial Template Fitting

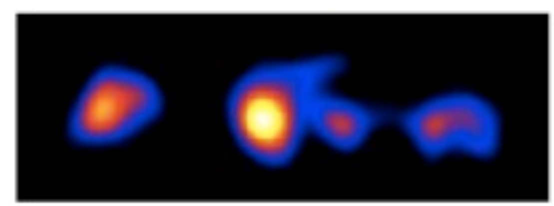
- Multi-wavelength Spatial Templates:
  - FeI Kα Line (X-rays)
  - CS 1-0 line (gas; optically thin)
  - 20cm GBT map (radio)*
  - HESS excess map (TeV)*

    *needed to remove Sgr A source







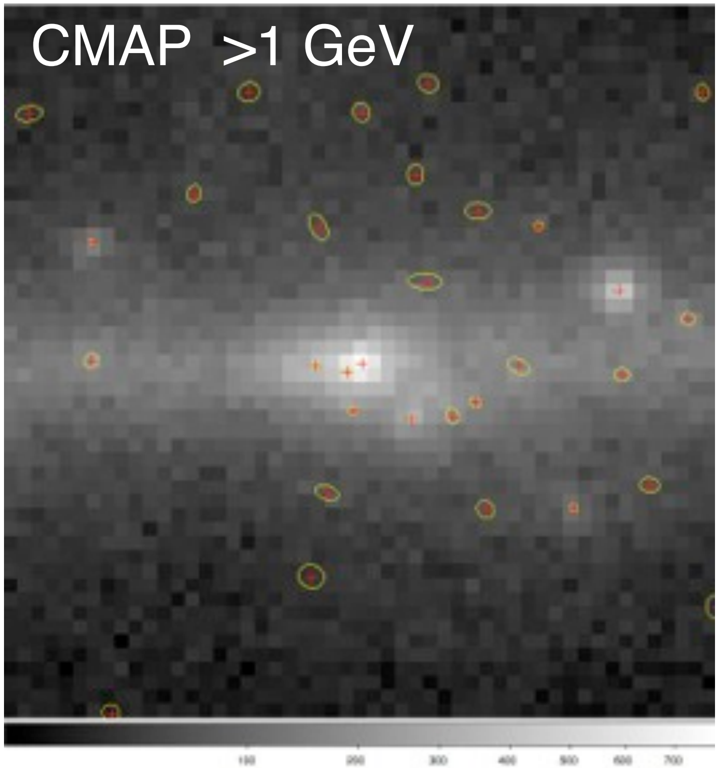


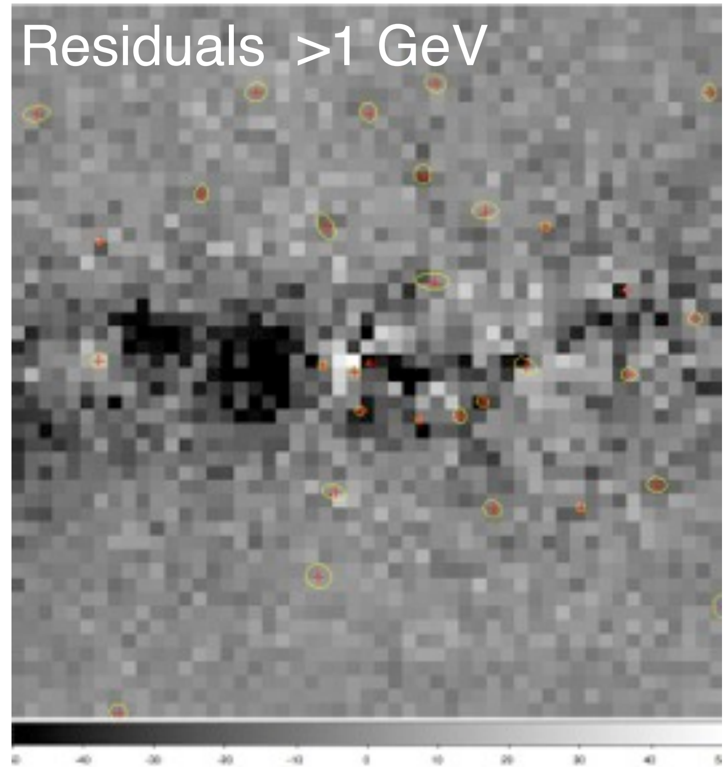
- Replace 2FGL sources in inner 2°x1° (Arc, Sgr B, Sgr C) with template.

- Likelihood improves for template fits -->

Model	$2\ \log(\mathcal{L}_1/\mathcal{L}_0)$
2FGL	0
2FGL refit	25.6
X-ray Fe Kα	33.9
HESS residual	50.6
20cm Radio big	60.6
CS gas	–51.4

LAT Analysis: Residuals

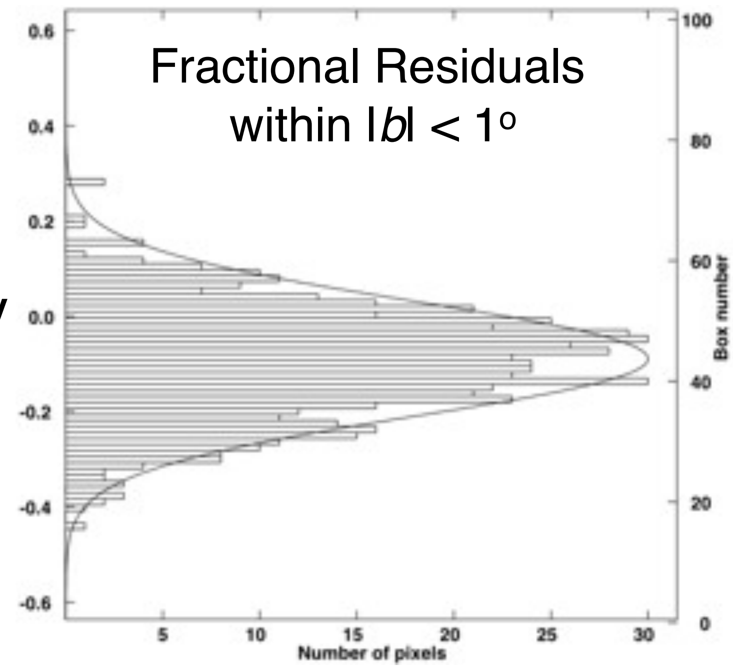




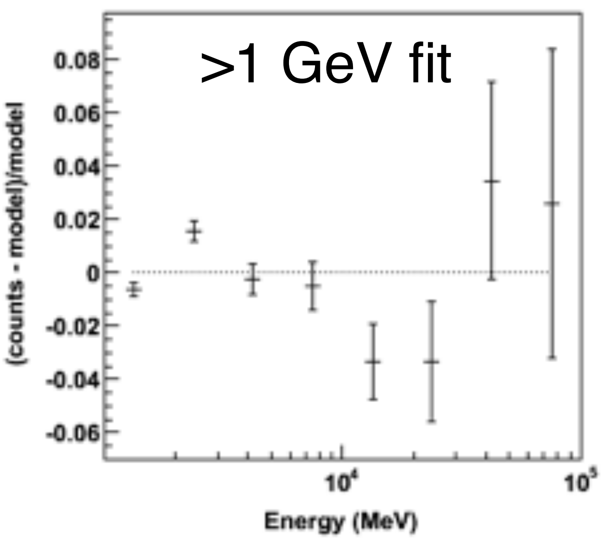
- See well-known negative residual from ring model.
  No sources fit in this region.
- CS gas map should trace residual emission due to gas in the GC, yet this gave the worst fit of all models.

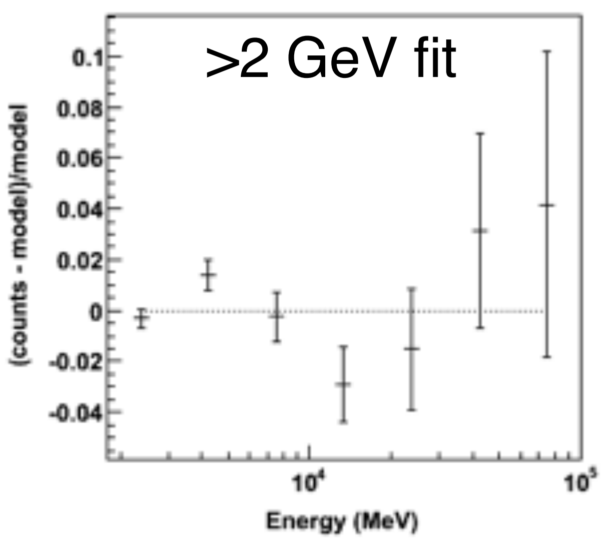
LAT Analysis: Systematic Errors

- Gaussian residuals from |*b*| < 1° show small offset due to negative structure at GLON~3°. Standard deviation = 0.12
- Therefore take the systematic uncertainty in the Galactic Normalization ~ 6%



- Even with GAL_v02 index free, still see residuals at ~6% level.





- Residuals still apparent with higher energy cut (2 vs 1 GeV)

SED Modeling (Radio + GeV + TeV)

- Radio synchrotron spectrum has a clear break at ~3 GHz
- Can Bremsstrahlung emission from these e- explain γ-rays?

$$F_\gamma \sim 10^{-14}\left(\frac{E_\gamma^{-p}\, f(p)\, \nu^{(p-1/2)}\, S_\nu\, n_H}{B^{(p+1)/2}}\right)\ \mathrm{ph\ cm^{-2}\ s^{-1}\ GeV^{-1}}$$

- GeV electrons can also explain Fe Kα line X-rays, and mol. gas heating rate due to enhanced ionizations (see text for details.)

Radio spectrum of Gal. Ridge

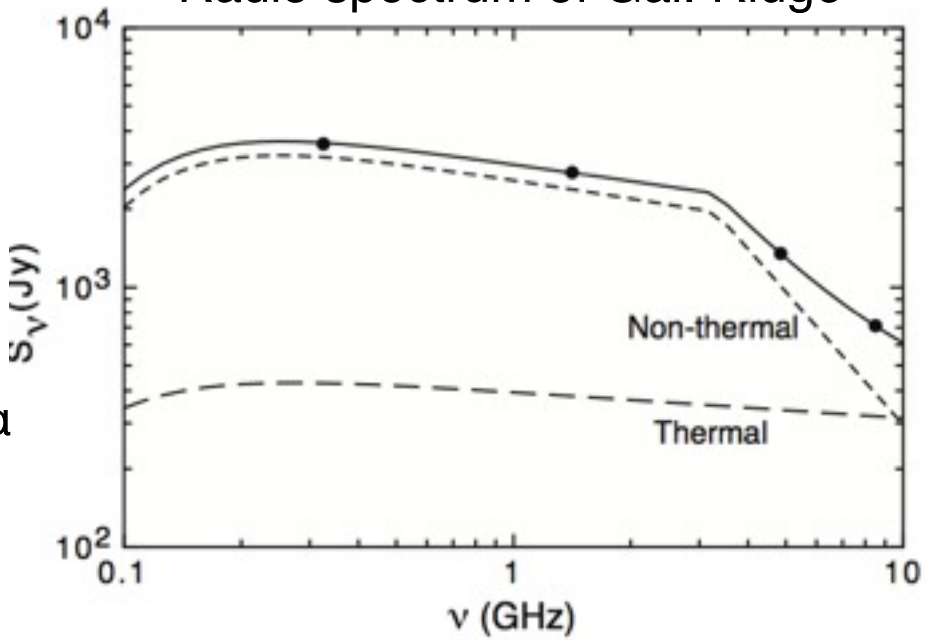
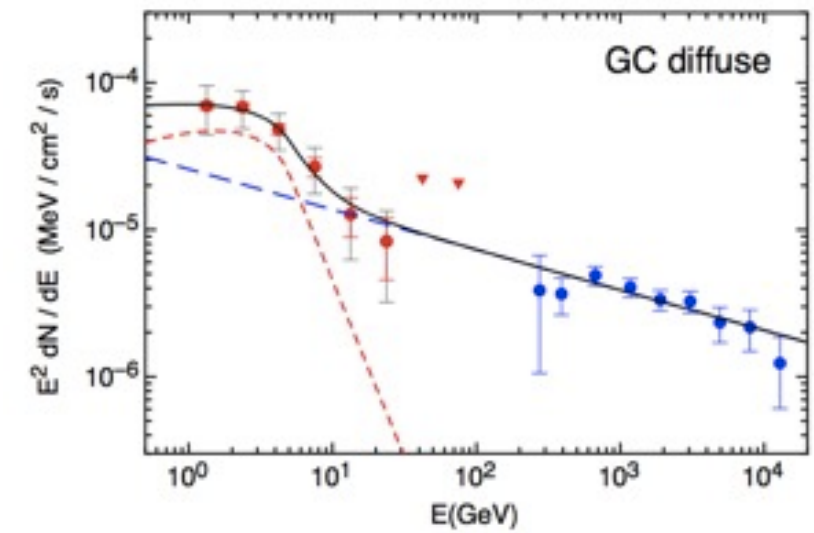


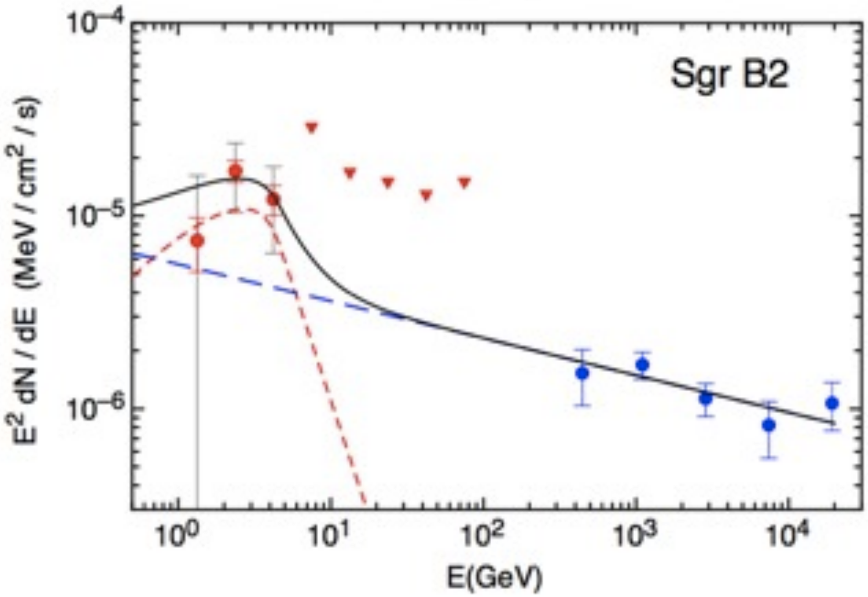
Table 4. Parameters of the fit to γ-ray sources using *Fermi* and HESS data

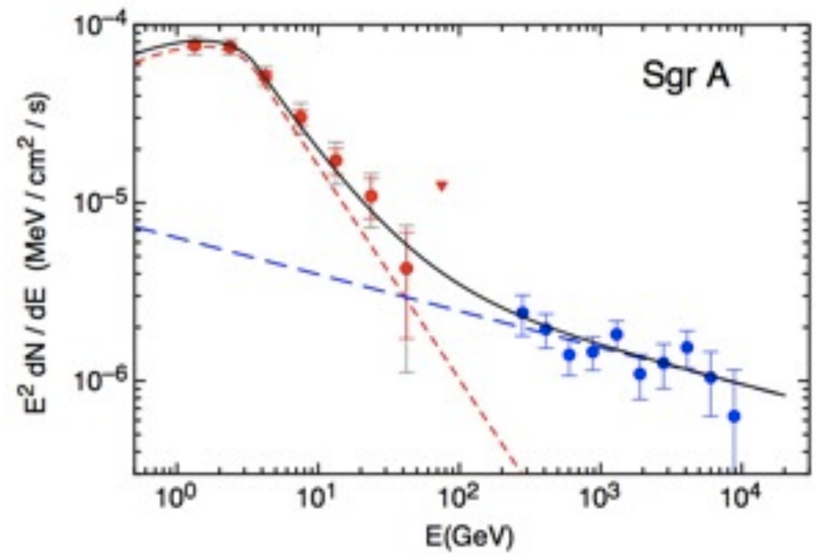
Source	B (μG)	n_H (cm^{-3})	F_{325MHz} (Jy)	p1	p2	ν_{break} (GHz)	Flux(HESS) ($MeV\ cm^{-2}\ s^{-1}$)	Γ(HESS)
GC diffuse	8	12.5	508	1.5	4.4	3.3	$(2.58\pm1.39)\times10^{-5}$	2.27±0.07
Sgr A	70	770	185	1.4	3.2	15	$(6.37\pm4.18)\times10^{-6}$	2.20±0.09
Sgr B2	30	2600	9	0.4	4.4	10	$(5.62\pm4.24)\times10^{-6}$	2.19±0.10
Radio Arc	40	450	156	2.4	2.8	20		

SED Modeling (Radio + GeV + TeV)

- Example SED fits for regions with published TeV spectra.
- TeV emission could arise from much young electron population which does not yet show break...
- Acceleration by X-ray/radio filaments? . . . expect X-ray synchrotron L~1-3x10^{38} erg /s



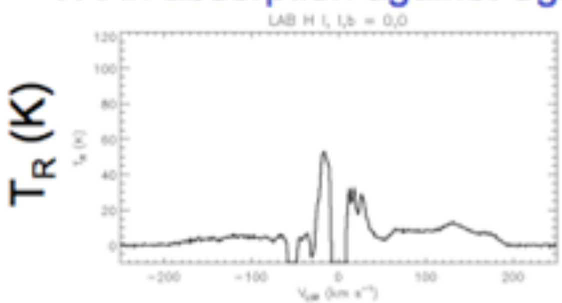




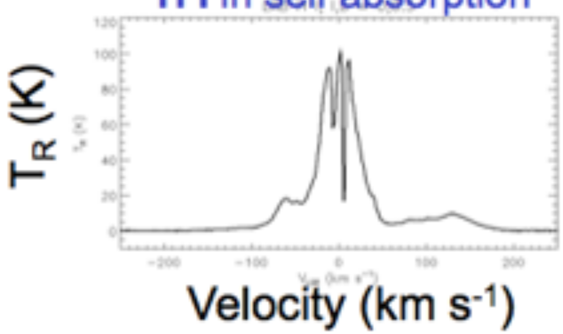
Modeling GeV Emission

- **A model invoking GeV (and TeV) electrons could explain a wide variety of observed physical conditions: ionization rate, mol. heating rate, FeI Kα lines, radio synchrotron spectrum and γ-ray emission (via Bremsstrahlung radiation).**
- **Hadronic models also viable.**
- **Challenges: conditions and kinematics**

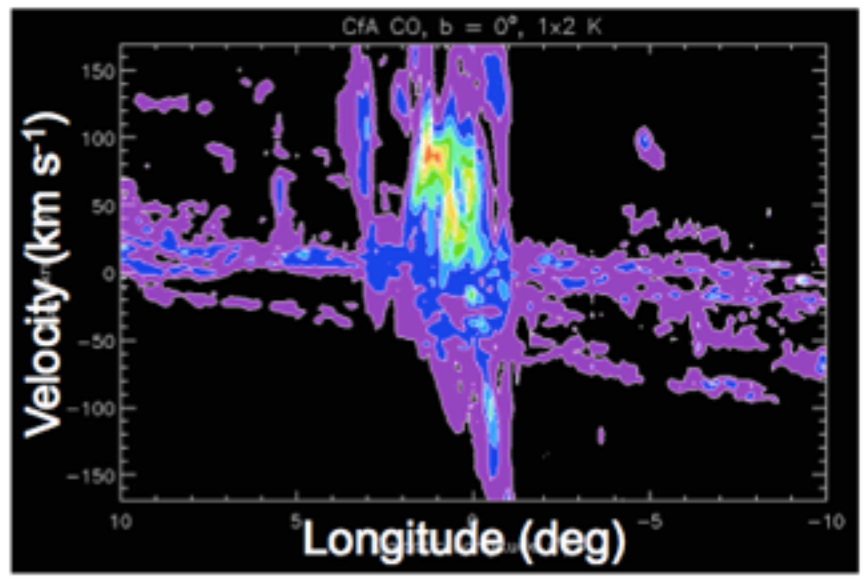
H I in absorption against Sgr A*



H I in self absorption



CO distribution in velocity and longitude

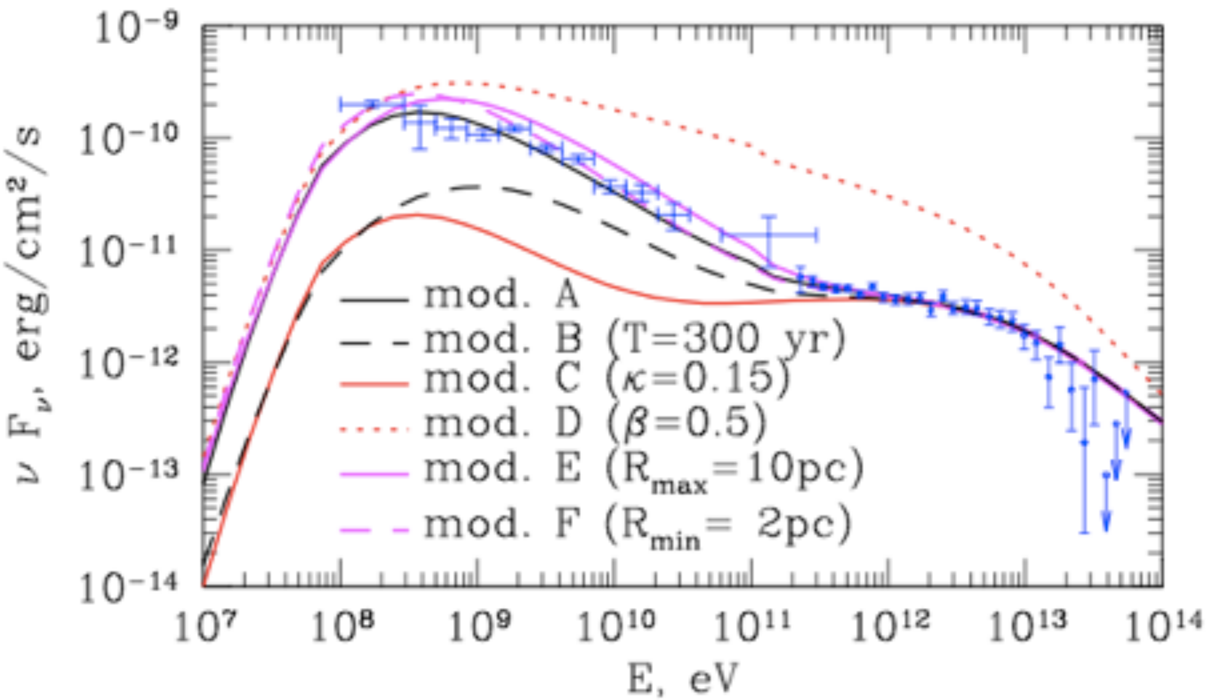


CfA CO (Dame et al.)

GeV emission from Sgr A*

Sgr A* as a gamma-ray source

- Sgr A* - the $4x10^6$ M_{sol} black hole at Gal. Center
  - Current activity: X-ray/IR flares (L_X~10^{35} erg/s)
  - Evidence of past activity: 6.4 keV Fe Kα lines X-ray light echo, ~300 yr ago: L_X ~ 10^{39} erg/s
- Unidentified GeV/TeV source

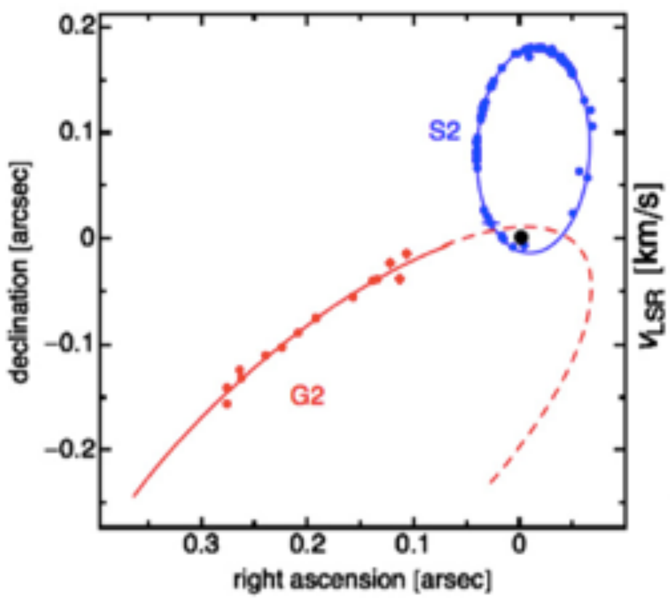


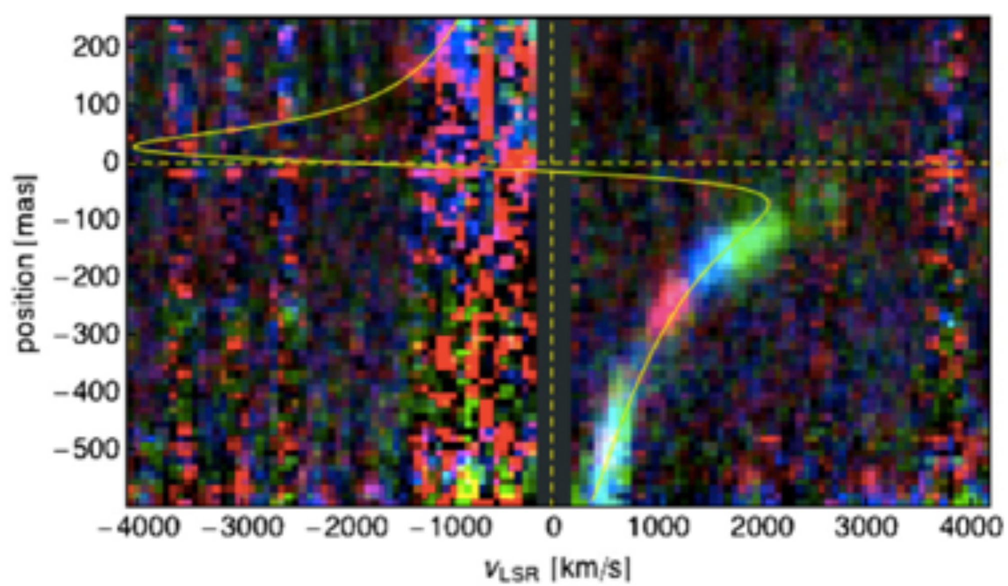
<u>One explanation:</u>
CR proton source flared ~300 or 10^4 yr ago, now diffused into surroundings (Chernyakova et al. 2011)

<u>One alternative:</u>
TeV PWN + Diffuse CRs

G2 cloud: A probe of AGN accretion?

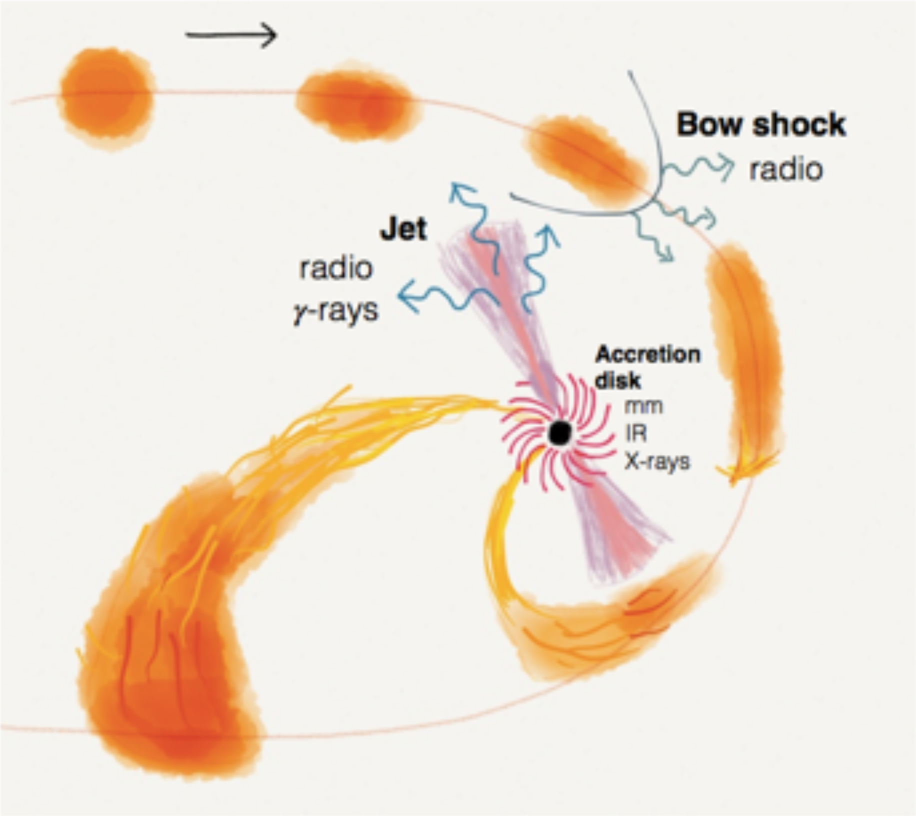
- ~3 Earth mass cloud (around star?) identified in Br-ɣ by Gillessen et al. (2012)
  - Pericenter of ~2000 R_S in ~2014.25
  - Close enough to probe accretion flow?
    Or be tidally disrupted and accreted?





What could Fermi say about G2 passage?

- **G2 has led to largest coordinated MW obs of Sgr A***
- **We attempted "cauldron free" estimates of activity**
  SR Gal. Center white paper: confluence.slac.stanford.edu/x/Zb__C
-

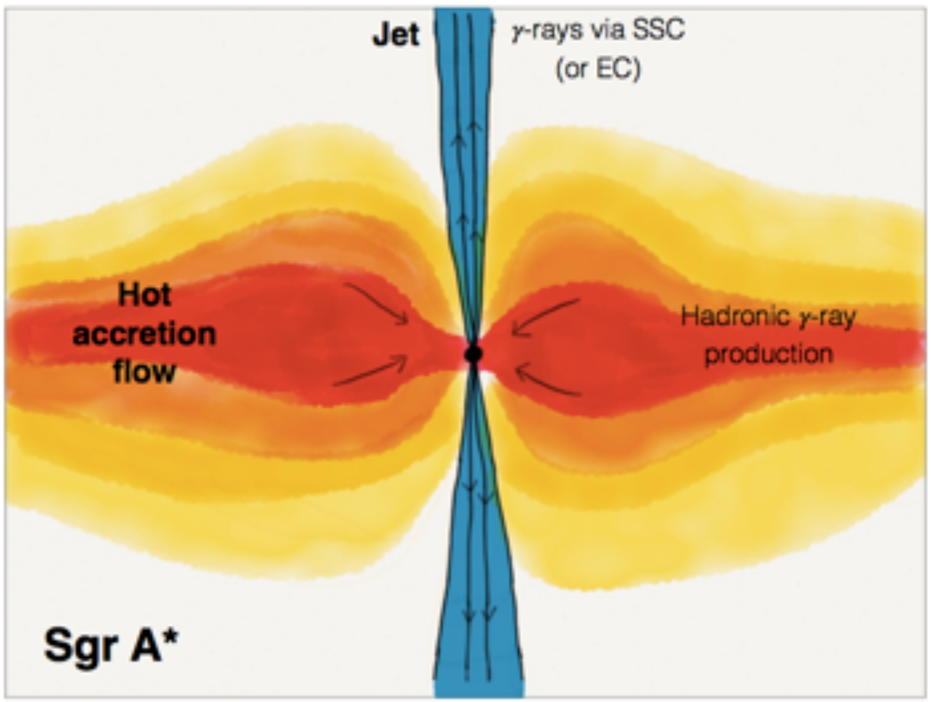


"Sgr A* Storm"

- Estimates for current Bondi accretion rate $M_B \sim 10^{-6}$ M_{sol}/yr
- Estimates range for G2: $M_{G2} \sim 10^{-8}$-10^{-5} M_{sol}/yr
- Consider ɣ-ray production in:
  - hot accretion flow
  - relativistic outflow (jet)
- Cannot exceed GeV source

What could Fermi say about G2 passage?

- **Detection of hot accretion flow (RIAF) *very unlikely***
- **Detection of relativistic outflow is *possible***



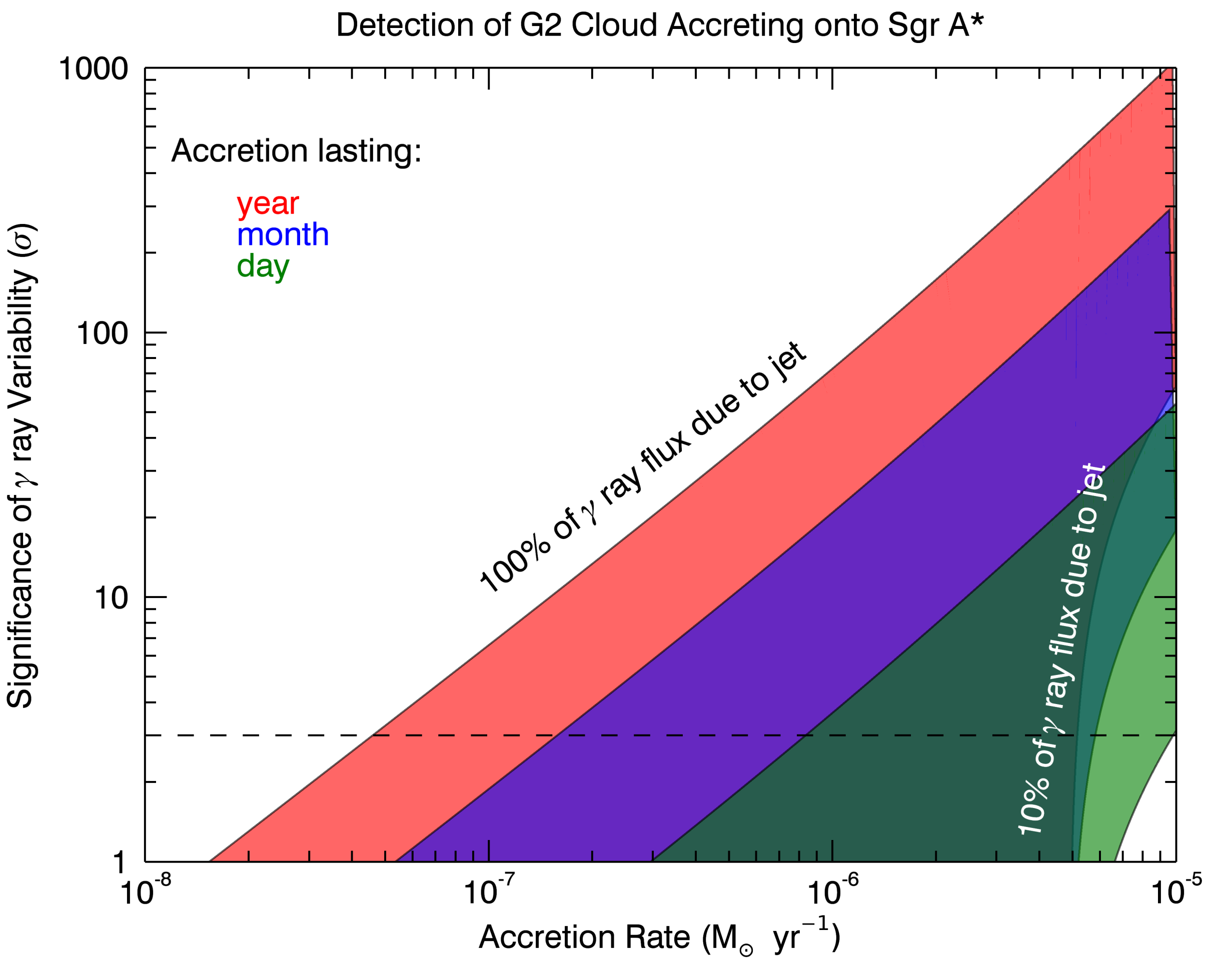
Required for Fermi-LAT

- Jet forms (or exists)
- $\gtrsim$10% current Sgr A* flux
- Accretion rate $\gtrsim 10^{-6}$ (~M_B) is sustained for ~week-month

$$F_\gamma = F_\gamma(\dot{M}, \Gamma, \theta, p, \epsilon_\gamma).$$

$$F_\gamma = f F_{\rm obs} \frac{P_{\rm jet}(\dot{M}_{\rm Bondi} + \dot{M}_{\rm G2})}{P_{\rm jet}(\dot{M}_{\rm Bondi})}.$$

Plausible scenarios for Fermi-LAT

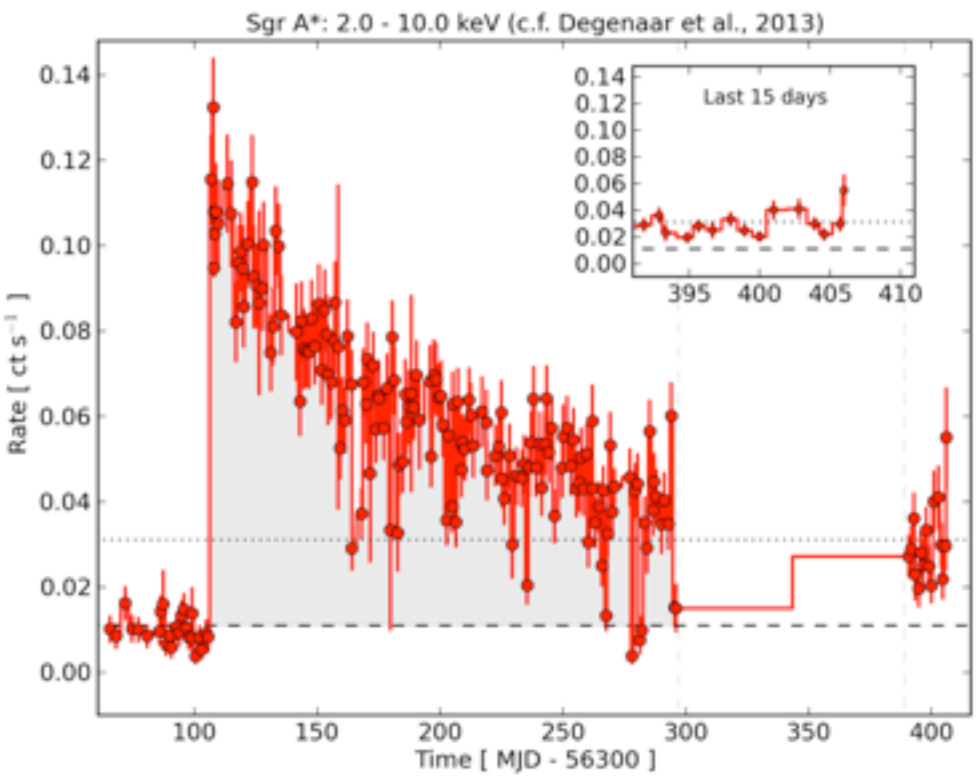


Detection depends on:

- Accretion rate induced by infall
- Timescale of infall (variability)
- Fraction of current LAT flux due to steady-state accretion onto Sgr A*

False Alarm: SGR J1745-29

- **25 Apr 2013: Swift monitoring observed 10-fold increase in Sgr A* flux => brightest flare ever? No.**
- **A new magnetar, confirmed by NuStar**



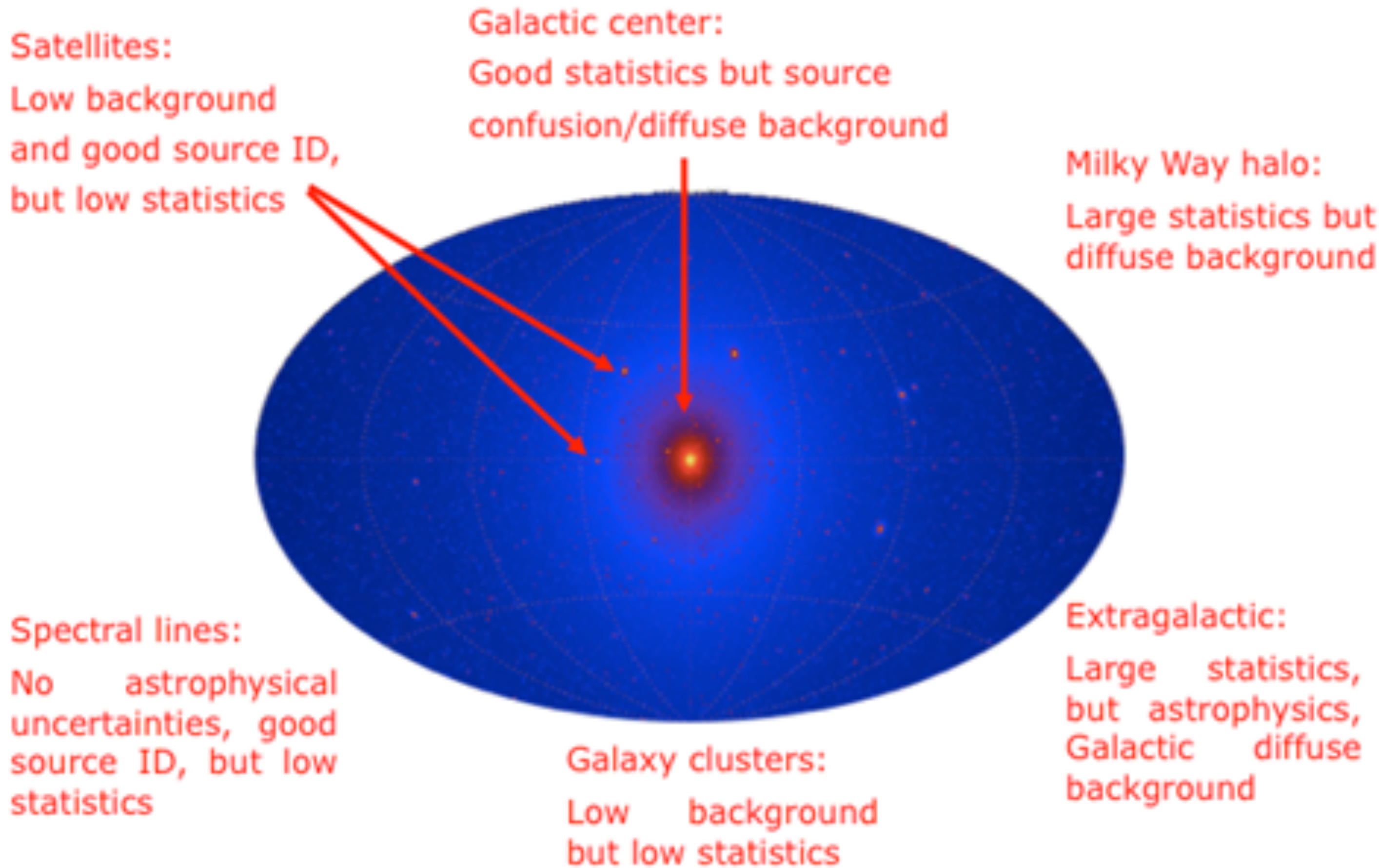
from: www.swift-sgra.com

- **Search for variability continues… expected ~ few months to 2 yr after G2 has been tidally disrupted.**

Dark Matter Signatures

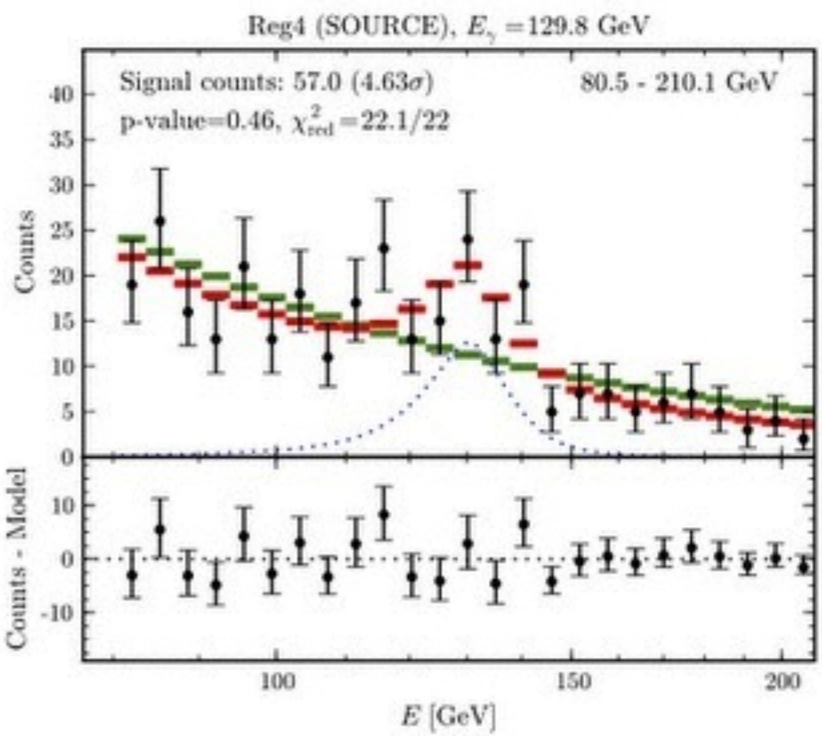
Dark Matter from the Galactic Center

- **The brightest astrophysical source of dark matter should be at the Galactic center.**

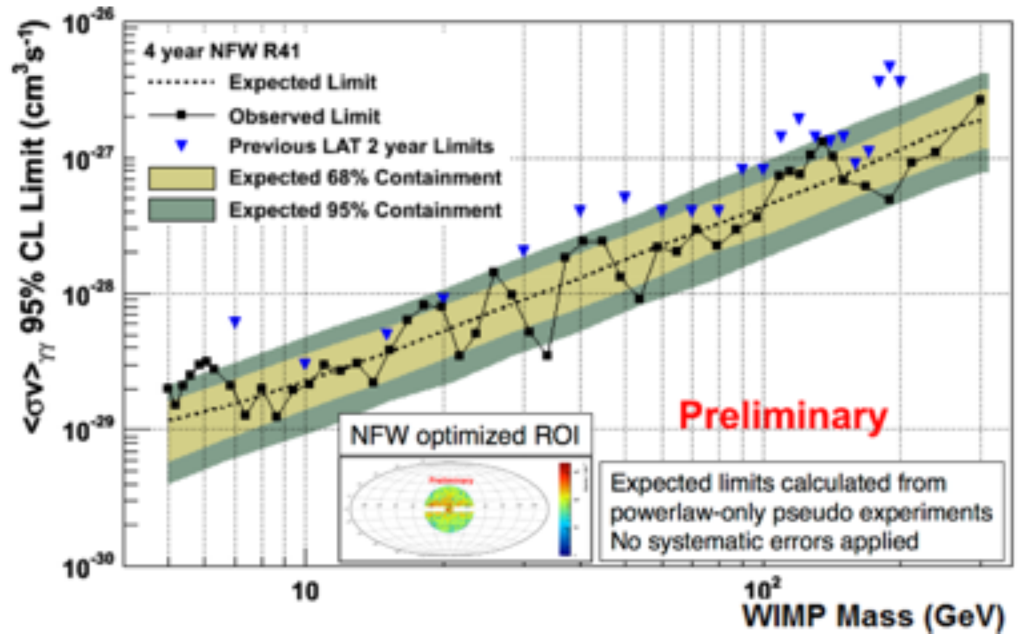


A 130 GeV dark matter line

- **Weniger (2012)**

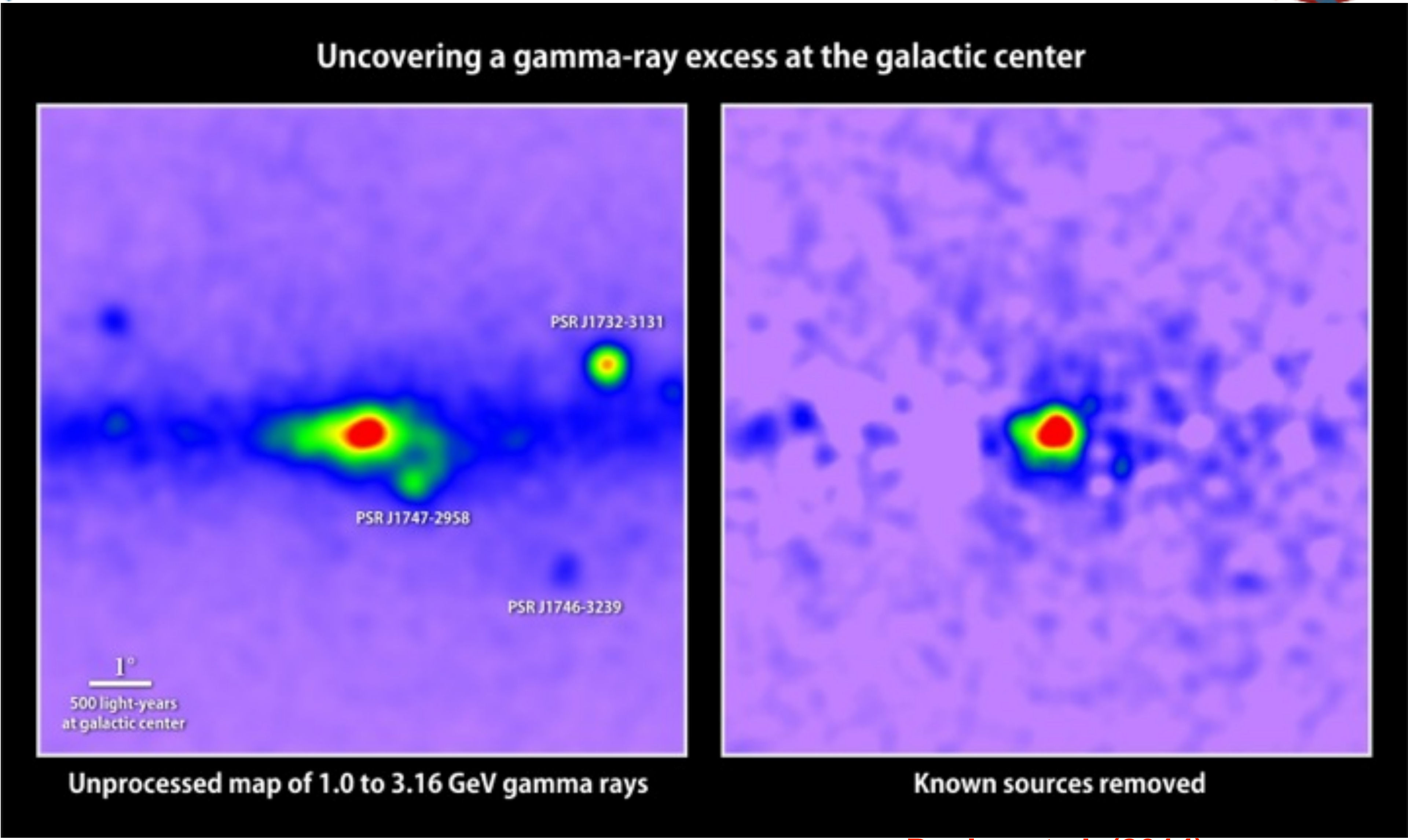


- **LAT collaboration**



- **Tantalizing signal, that faded with time.**

A GeV Excess?



Daylan et al. (2014)

Conclusions

- The GC is a complex region requiring detailed study, though some interesting initial conclusions have been drawn from GeV studies.

- GeV studies are particularly limited by resolution and an incomplete knowledge of Galactic diffuse foreground/background.

- The definitive study of GeV emission from the Galactic center has yet to be carried out with Fermi.