Possible high energy phenomena related to the stellar capture by the galactic supermassive black holes

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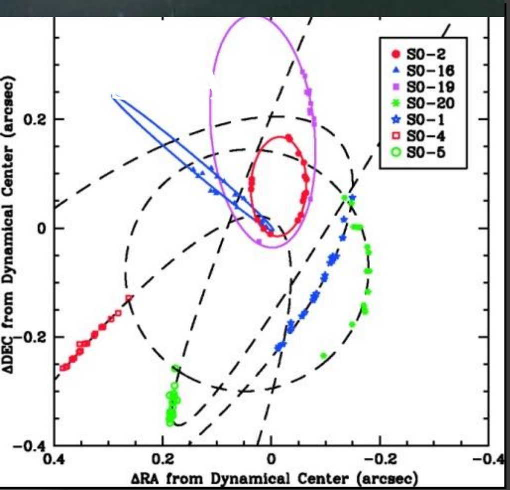
Outline

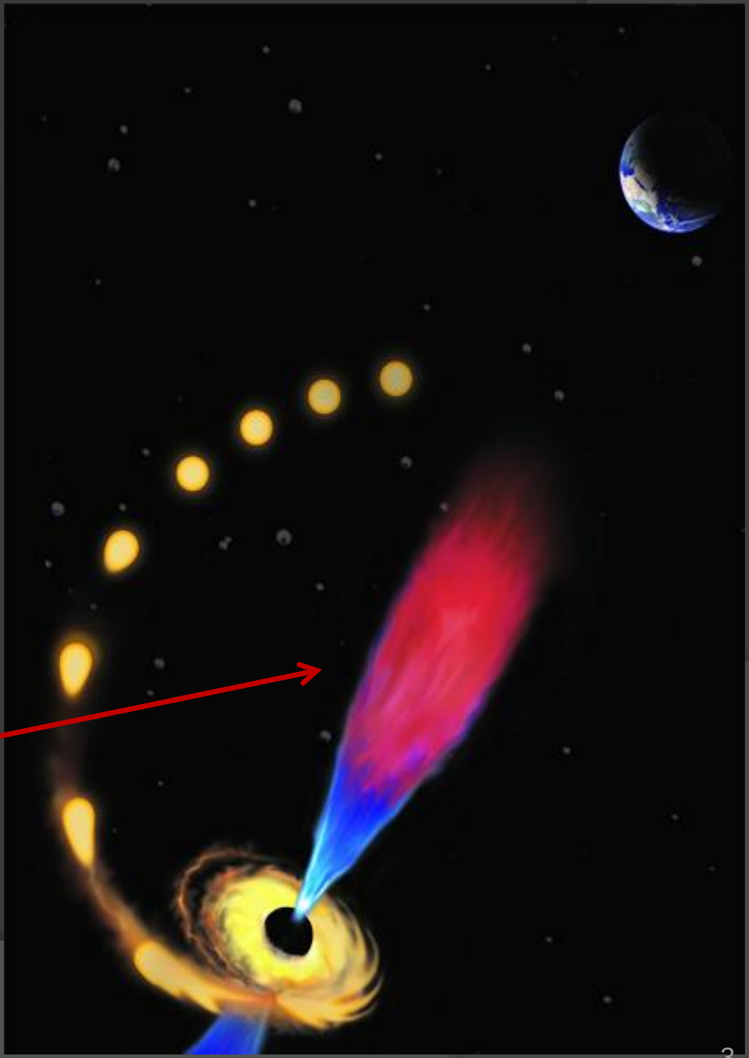
- Introduction
- Swift J1644+57
- Positron Annihilation in GC
- Fermi Bubbles
- Cosmic Rays with energy $>10^{15}$eV
- Summary

Galactic centers: some are active, most are dormant



Ghez et al. 2005

Tidal disruption event (TDE) can light dormant SMBH.
So TDE is promising tool to probe galactic center BHs.

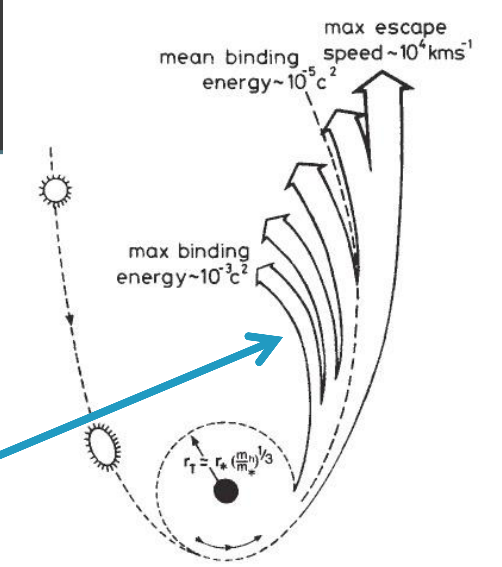


X-ray/UV flare produced by tidal disruption of stellar object (Rees 1988):

When a star's orbit in tidal radius (tidal force=self gravity)

$$R_t \sim \left(\frac{M_{\mathrm{BH}}}{\mathrm{M}_*}\right)^{1/3} R_*$$

Fallback time (most bound material): t_f ~ days to weeks.



Initially radiating with Eddintong luminosity:

$$L_{Edd} = 1.3\times10^{45}\left(\frac{M_\bullet}{10^7 M_\odot}\right) \text{ ergs/s}$$

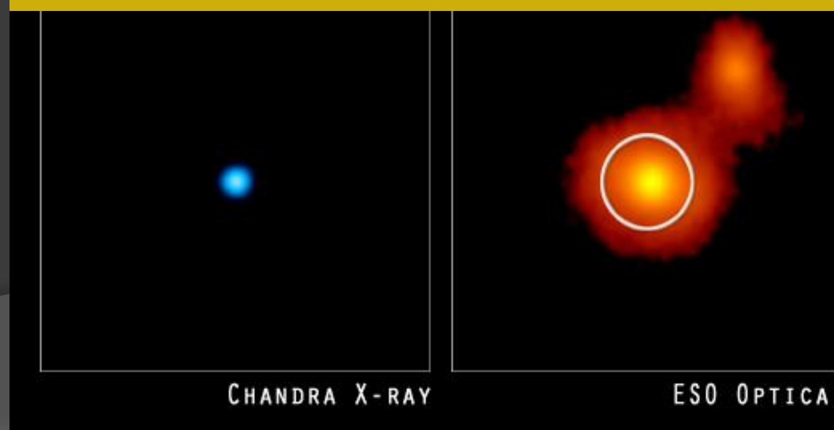
Thermal spectrum of effective temperature

$$T_{eff} \sim \left[\frac{L_{Edd}}{4\pi r_t^2 \sigma}\right]^{1/4} = 2.4\times10^5\left(\frac{r_*}{r_\odot}\right)^{-1/2}\left(\frac{m_*}{M_\odot}\right)^{1/6} M_8^{1/12}\ \mathrm{K}$$

Decaying after peak as power-law with time $f \propto \left(t/t_{flare}\right)^{-5/3}$

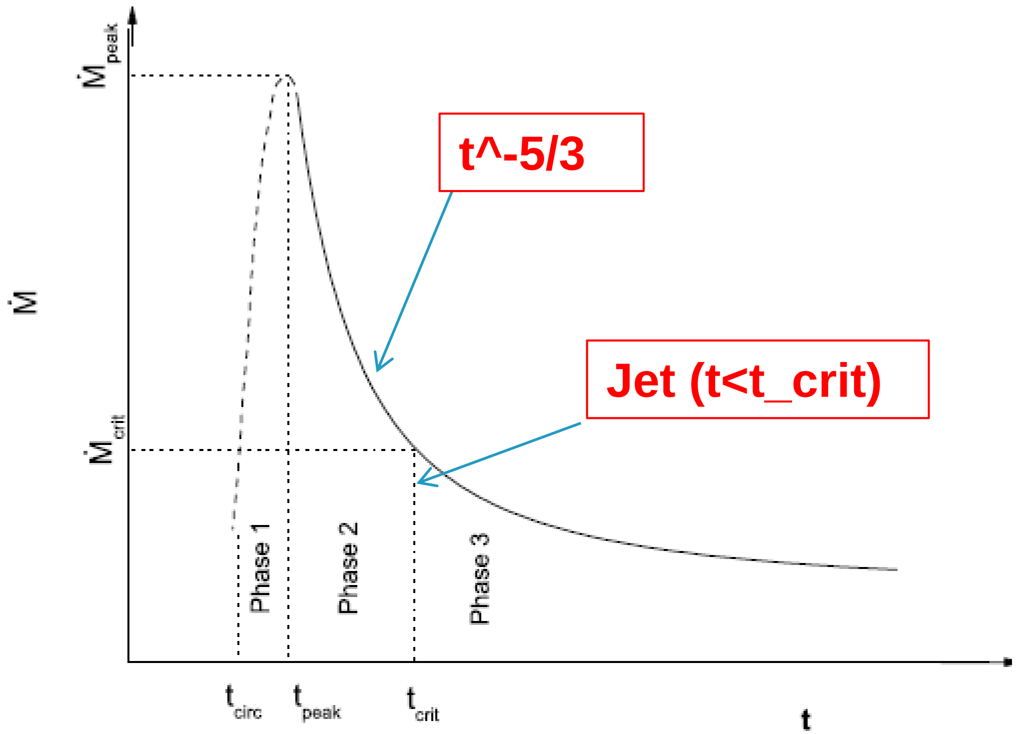
on a timescale: $t_{flare} \sim 1.1\mathrm{yr}\left(\frac{r_*}{r_\odot}\right)^{3/2}\left(\frac{m_*}{M_\odot}\right)^{-1} M_8^{1/2}$

RX J 1242.6-1119A (Komossa et al. 2004



Rate of TDEs~10^{-5}-10^{-3} yr^{-1}gal^{-1}
(e.g. Wang & Merritt 2004)

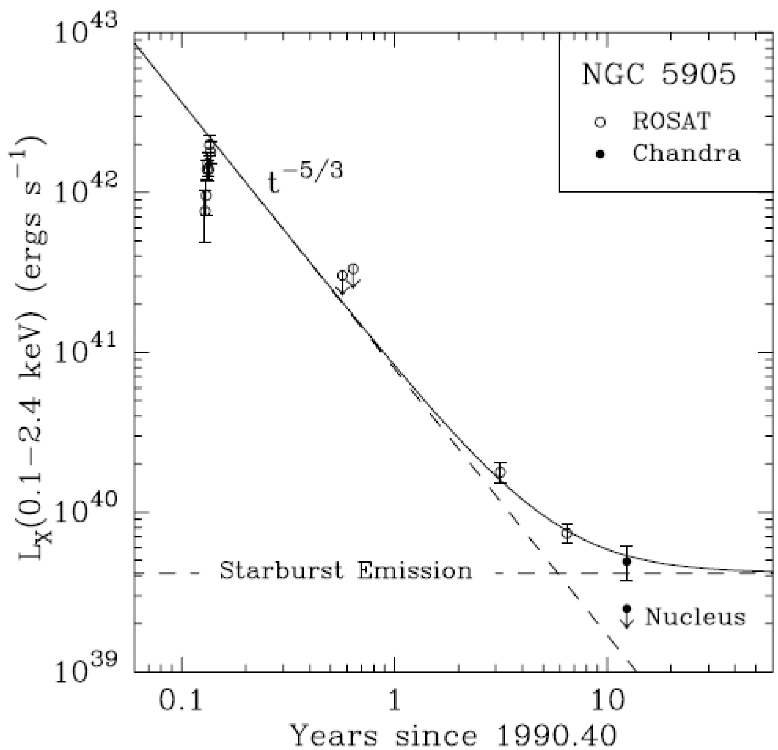
Extra-galactic Events – direct evidence



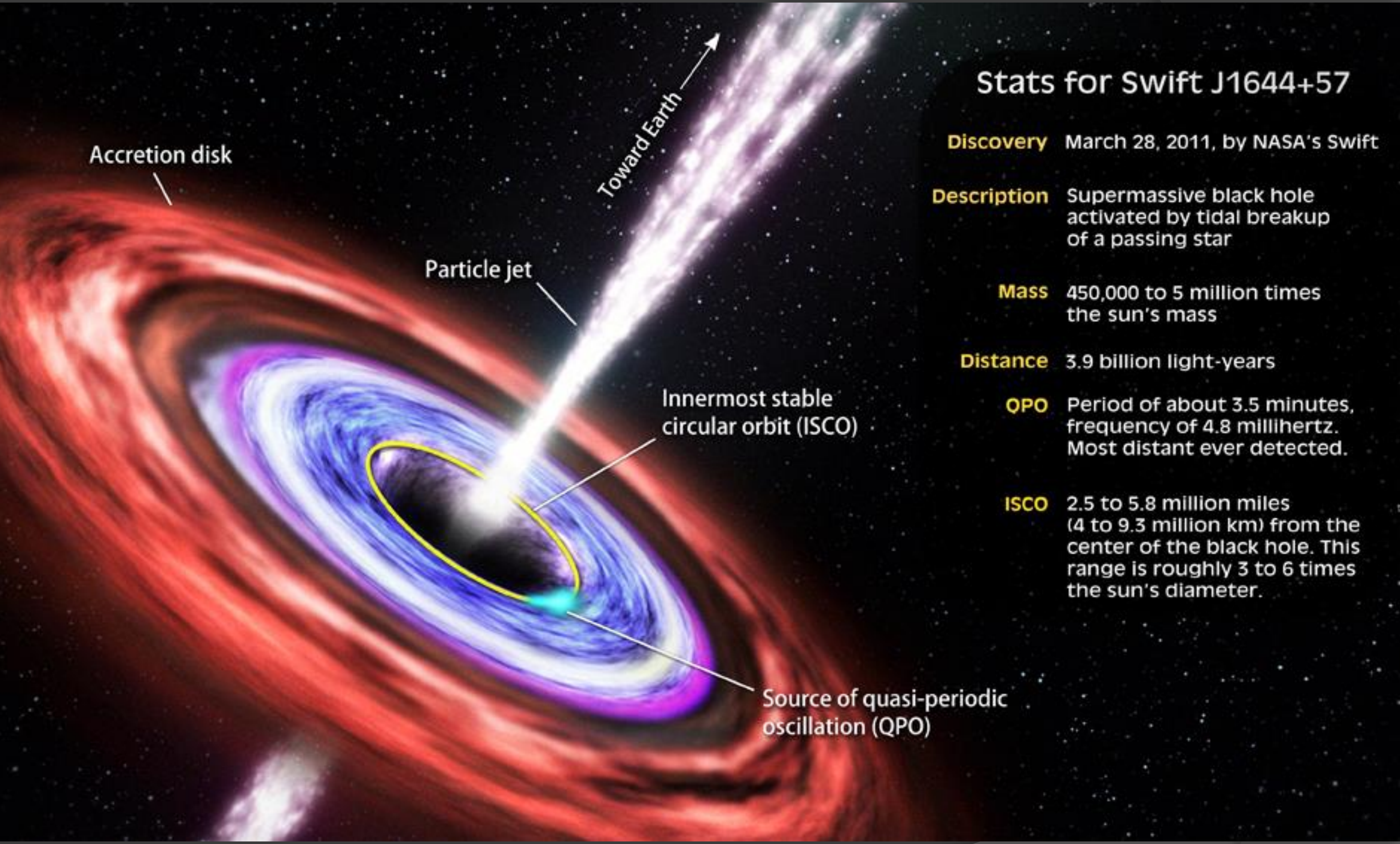
$$t_{cir} \sim 2 t_{peak}$$

$$t_{peak} \sim \frac{0.2\left(\frac{M_{BH}}{10^6}\right)^{\frac{1}{2}}}{\left(\frac{M}{M_s}\right)} yr$$

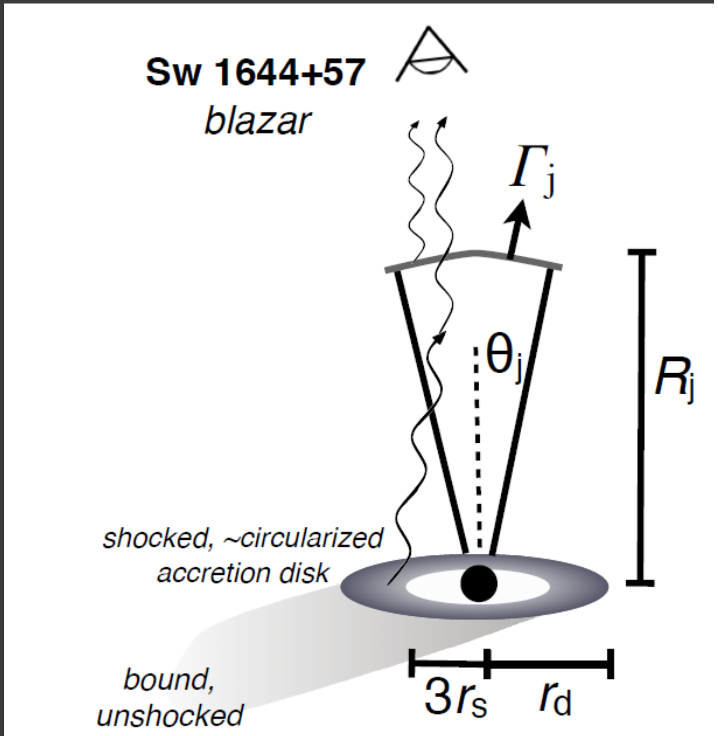
Galaxy	z	kT_{bb} [keV]	$L_{x,bb}$ [erg s^{-1}]	Photon Index
NGC 5905	0.011	0.06	3×10^{42}	–4.0
RX J1242.6-1119A	0.050	0.06	9×10^{43}	–5.1
RX J1624.9+7554	0.064	0.097	$\sim 10^{44}$	–3.3
RX J1420.4+5334	0.147*	0.04	8×10^{43}	–5.8
RX J1331.9-3243	0.051		$\sim 10^{44}$	–3.8

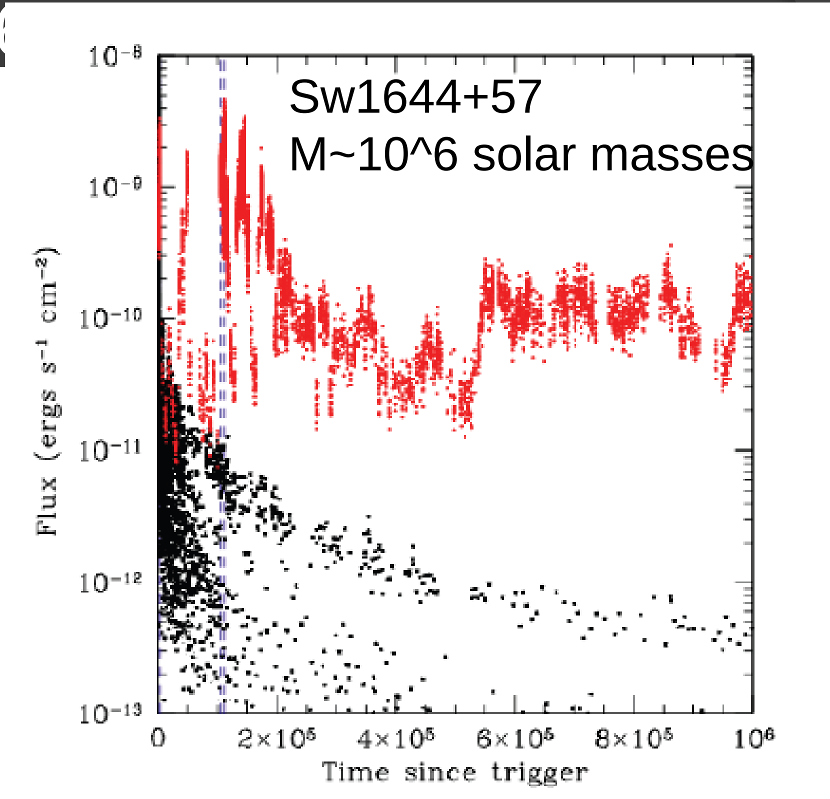


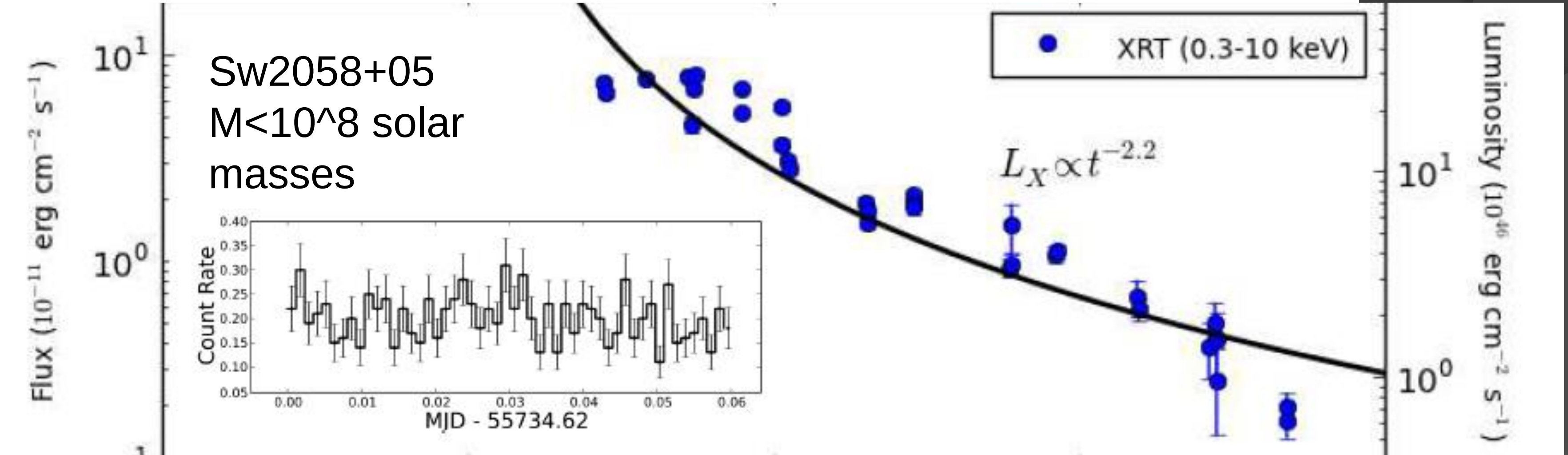
Halpern et al. 2004


Stats for Swift J1644+57
Discovery March 28, 2011, by NASA's Swift
Description Supermassive black hole activated by tidal breakup of a passing star
Mass 450,000 to 5 million times the sun's mass
Distance 3.9 billion light-years
QPO Period of about 3.5 minutes, frequency of 4.8 millihertz. Most distant ever detected.
ISCO 2.5 to 5.8 million miles (4 to 9.3 million km) from the center of the black hole. This range is roughly 3 to 6 times the sun's diameter.
Accretion disk
Toward Earth
Particle jet
Innermost stable circular orbit (ISCO)
Source of quasi-periodic oscillation (QPO)

Two recent super-Eddington events - Swift 1644+573 and Swift J2058.4 + 0516



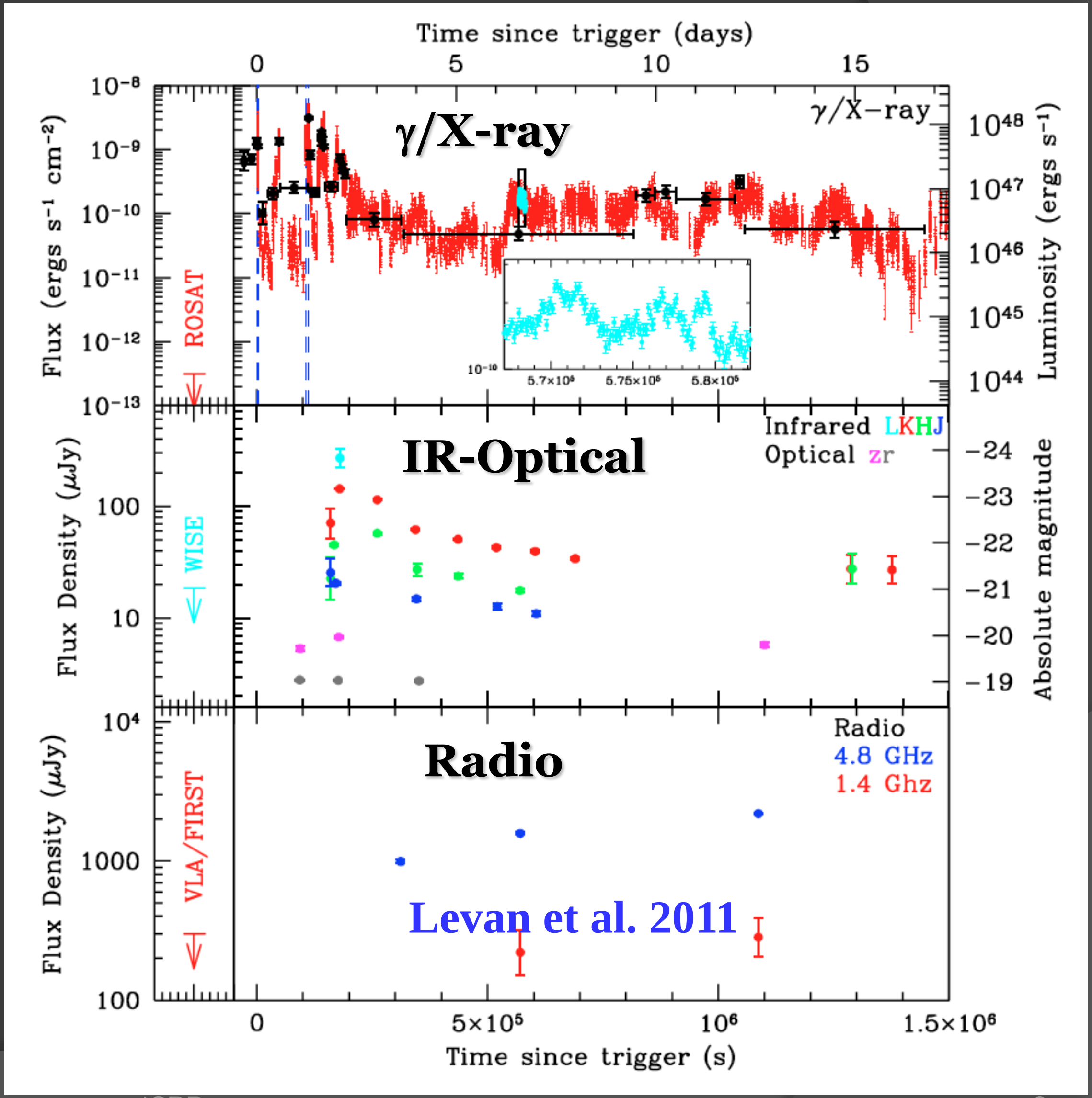




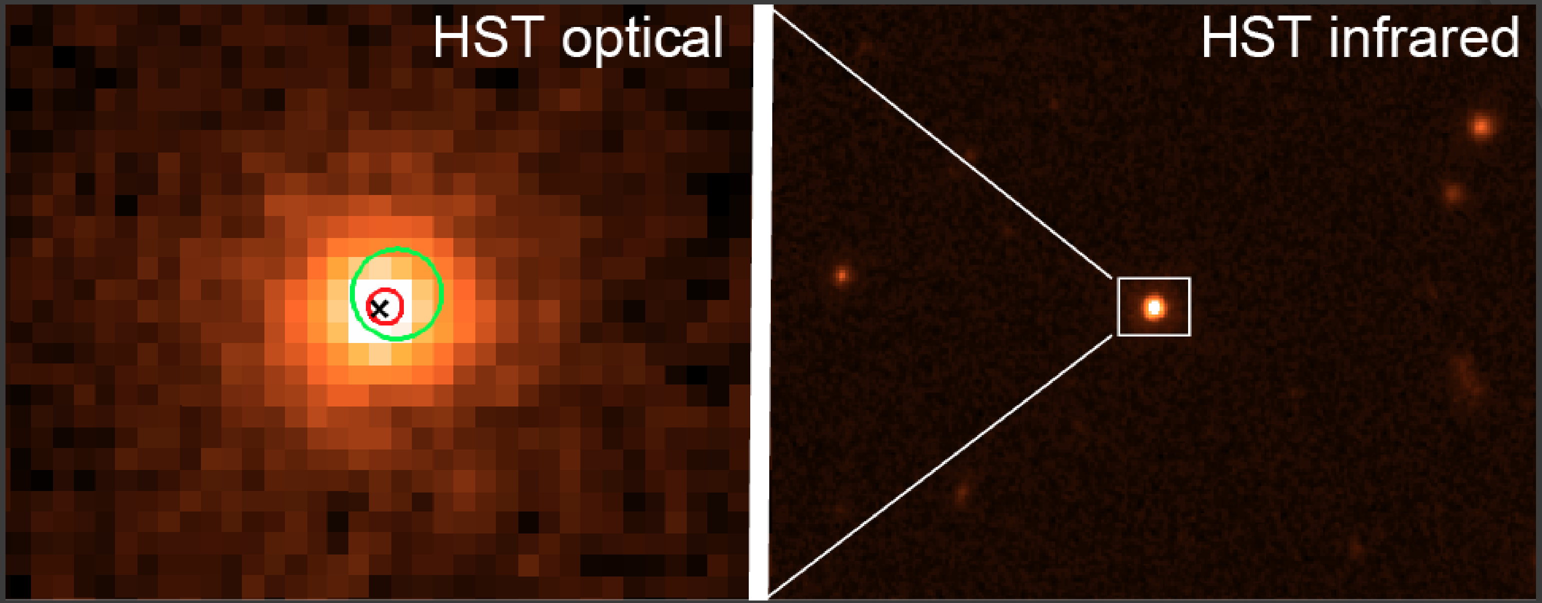
Swift J1644+57: first TDE with a jet

(Levan et al. 2011; Bloom et al. 2011; Burrows et al. 2011; Zauderder et al. 2011)

- Triggered *Swift* BAT on March 28, 2011
- Triggered BAT 3 more times over next few days
- Remains bright in X-rays
- IR and Radio Brightening
- Host galaxy at z = 0.35
- *NOT a (normal) GRB*
  - low luminosity
  - duration ~ months
- *NOT a normal AGN*
  - no evidence for AGN or past activity



Host Galaxy at z = 0.35

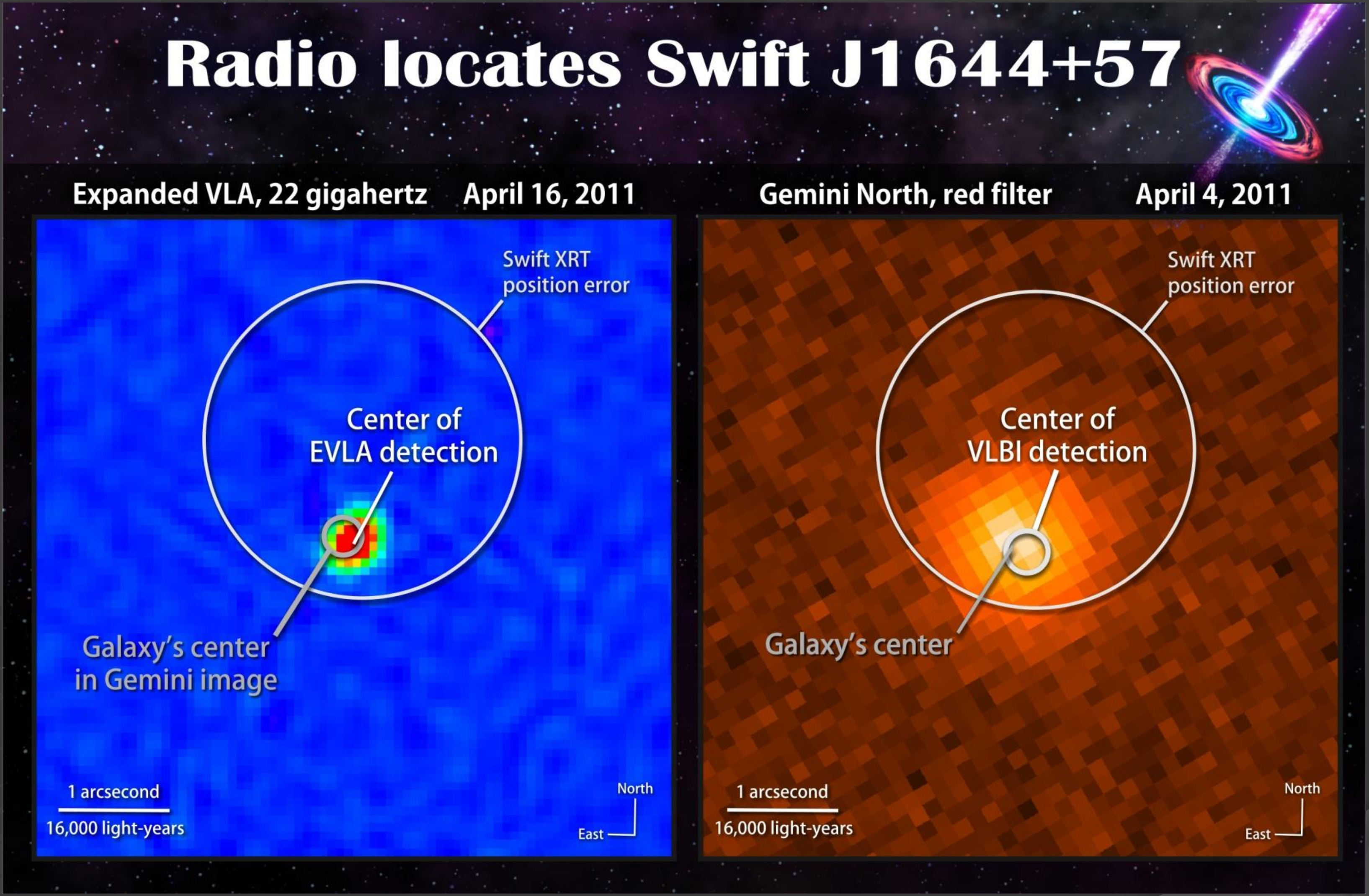


Levan et al. 2011

Not an AGN

- Within < 150 pc of galactic center
  $\Rightarrow$ SMBH origin

•$L_X > 10^{48}$ erg $s^{-1} > 10000\ L_{Edd}$ of $10^6 M_\odot$ black hole $\Rightarrow$ super-Edd accretion and/or beaming



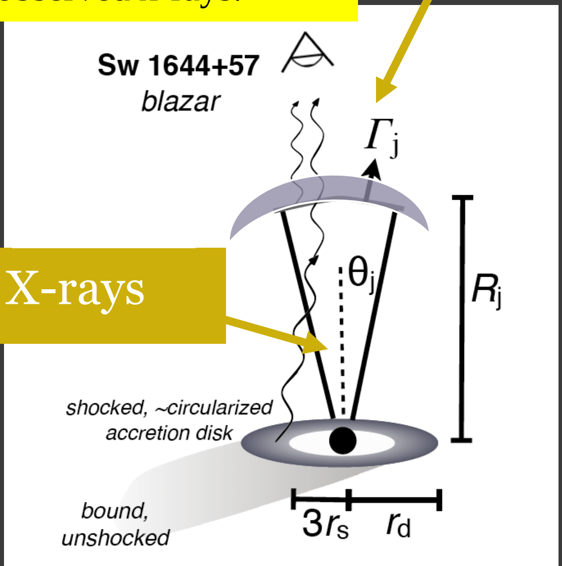
Zauderder et al. 2011

Blazar model for Swift J1644+57

Emission from the accretion disk is Compton-upscattered, giving rise to the observed x-rays.

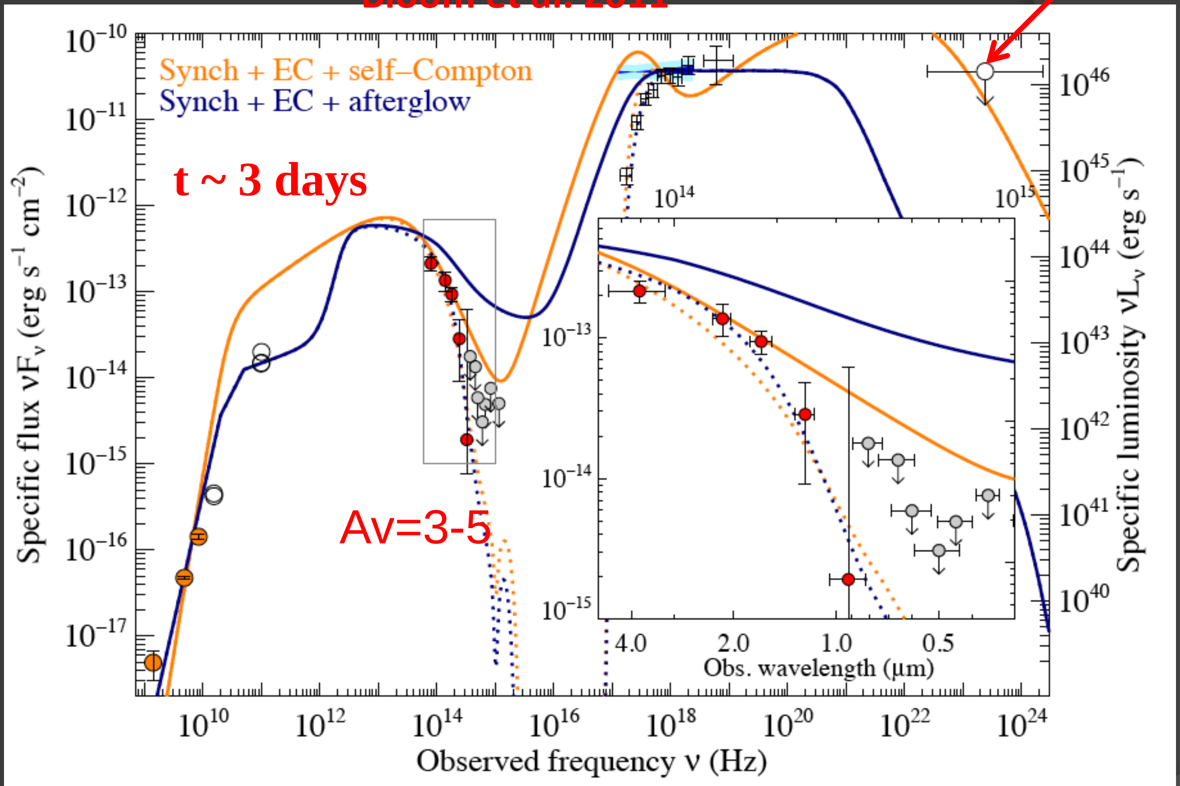
radio

X-rays



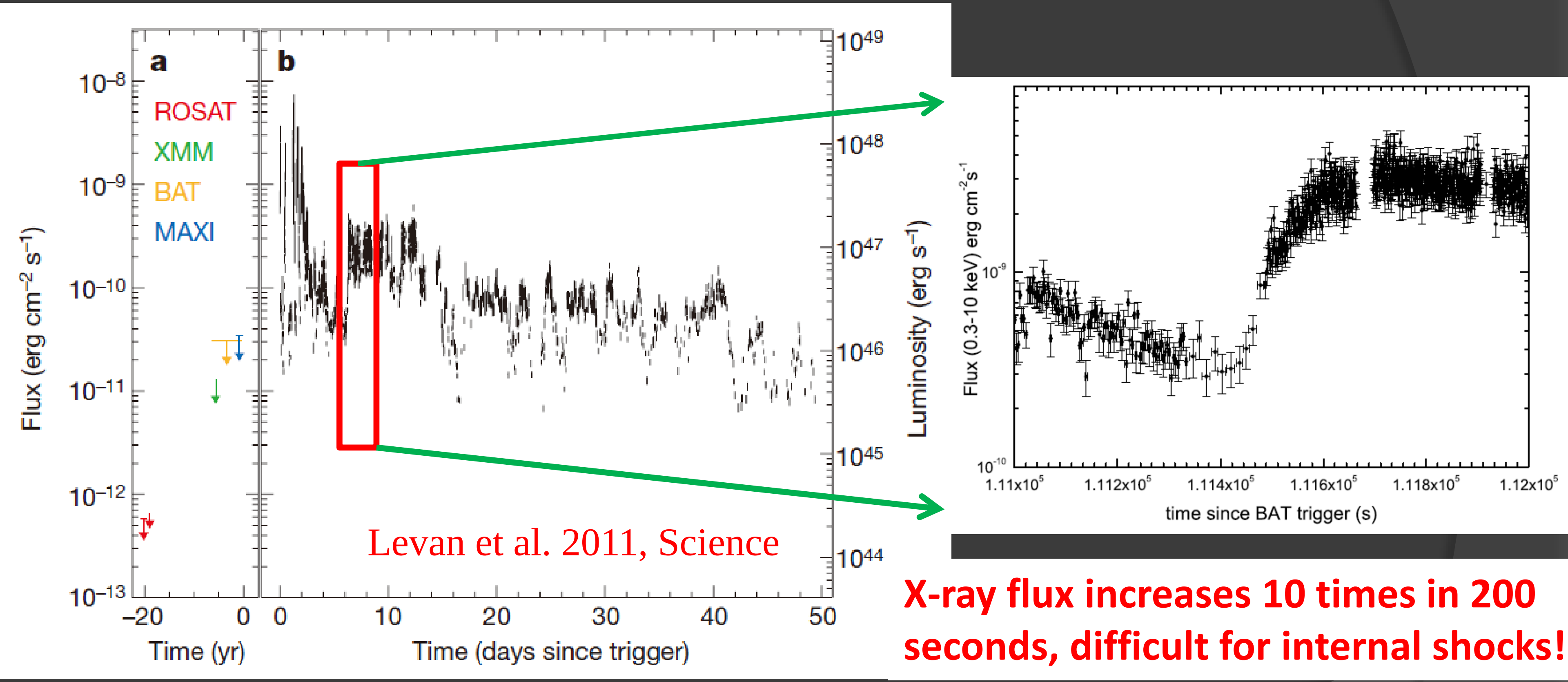
Bloom et al. 2011

Fermi LAT



- synchrotron self-absorption $\Rightarrow$ $R_{radio} > 10^{16}$ cm $\Rightarrow$ $\Gamma \sim 20$ $\Rightarrow$ external shock from ISM interaction (Giannios & Metzger 2011)
- X-ray variability $\Rightarrow$ $R_X \sim c\,\delta t_X\,\Gamma^2 \sim 3\times10^{14}\,(\Gamma/20)^2$ cm $\Rightarrow$ "internal" process (e.g. shocks, reconnection)

Internal model for X-ray flares

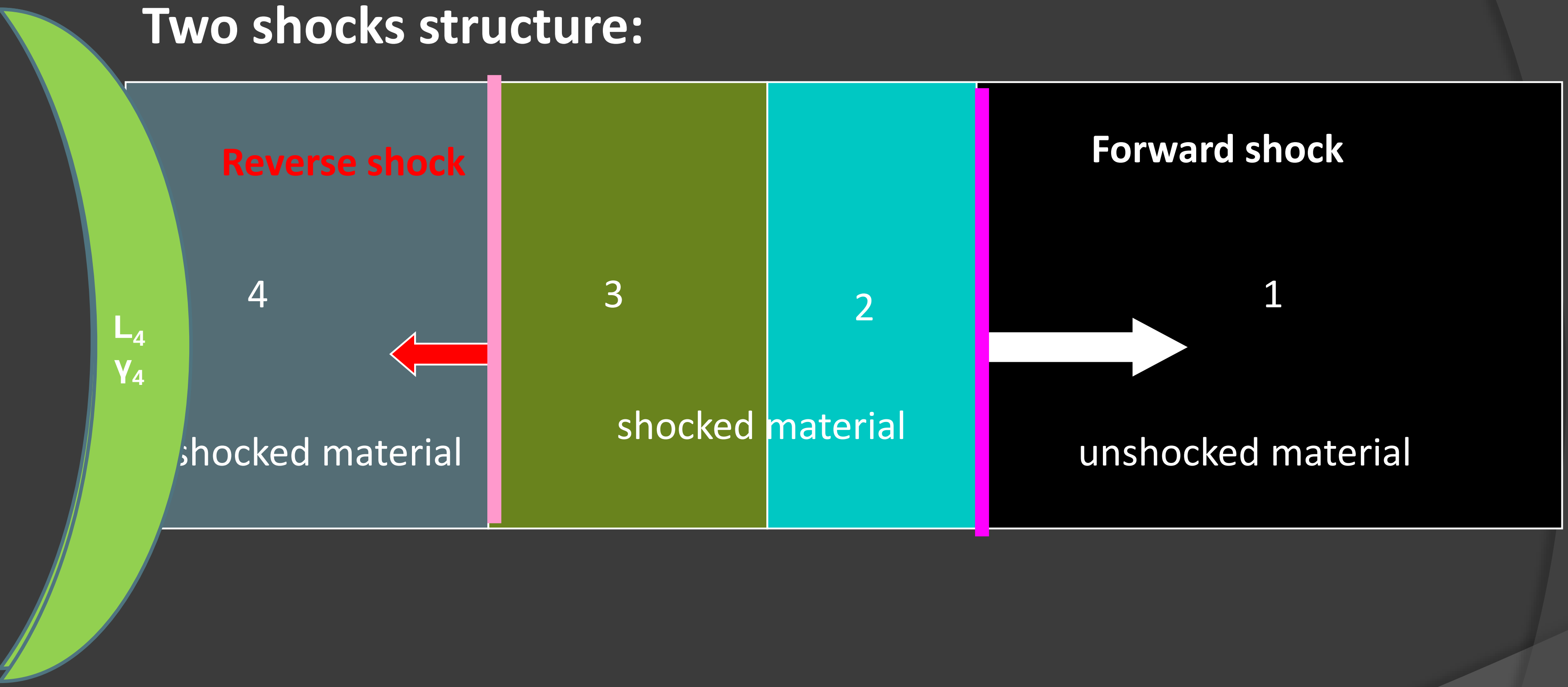


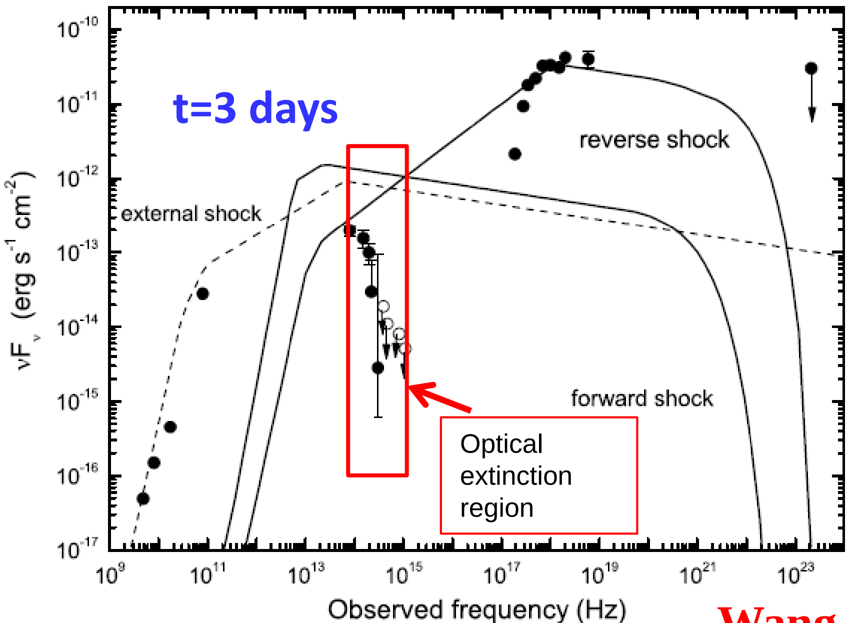
X-ray flux increases 10 times in 200 seconds, difficult for internal shocks!

Many flares in the X-ray band!

Internal-shock model for X-ray flares

Two shocks structure:





Wang & Cheng 2012

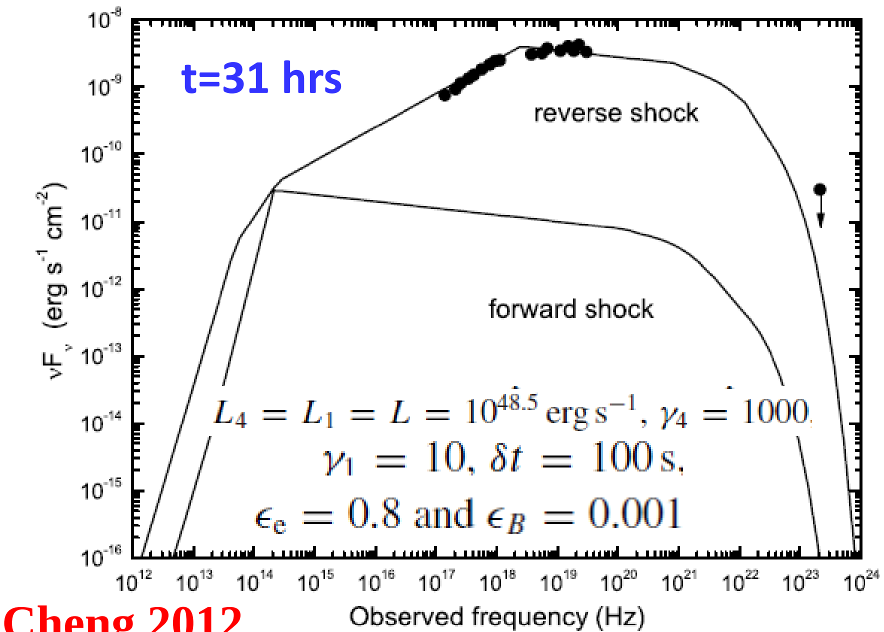


Figure 2. The broad-band spectral energy distribution of Swift J1644+57 at 2.9 d after the BAT trigger. The points show the observation data, which are taken from Bloom et al. (2011). The two solid lines represent the unabsorbed spectrum of the reverse and forward shocks, which are generated by the internal shock. The dashed line shows the spectrum of the external shock. In order to fit the spectrum, a moderate extinction ($A_V = 3$–5) is required.

Figure 3. The spectral energy distribution of Swift J1644+57 at 31 h after the BAT trigger. The points show the observation data, which are taken from Burrows et al. (2011). The two lines represent the unabsorbed spectrum of the reverse and forward shocks, which are generated by the internal shock. The parameters of the two shocks are given in the text.

reverse shock:

$$\nu_{m,3} \simeq 1.2 \times 10^{18}\ \mathrm{Hz}\ \epsilon_{e,-0.3}^2 \gamma_{4,3}^2 L_{47}^{1/2} \epsilon_{B,-1}^{1/2} \delta t_2^{-1} \gamma_{1,1}^{-4},$$

$$\nu_{c,3} \simeq 2.2 \times 10^{13}\ \mathrm{Hz}\ L_{47}^{-3/2} \epsilon_{B,-1}^{-3/2} \delta t_2 \gamma_{1,1}^{8},$$

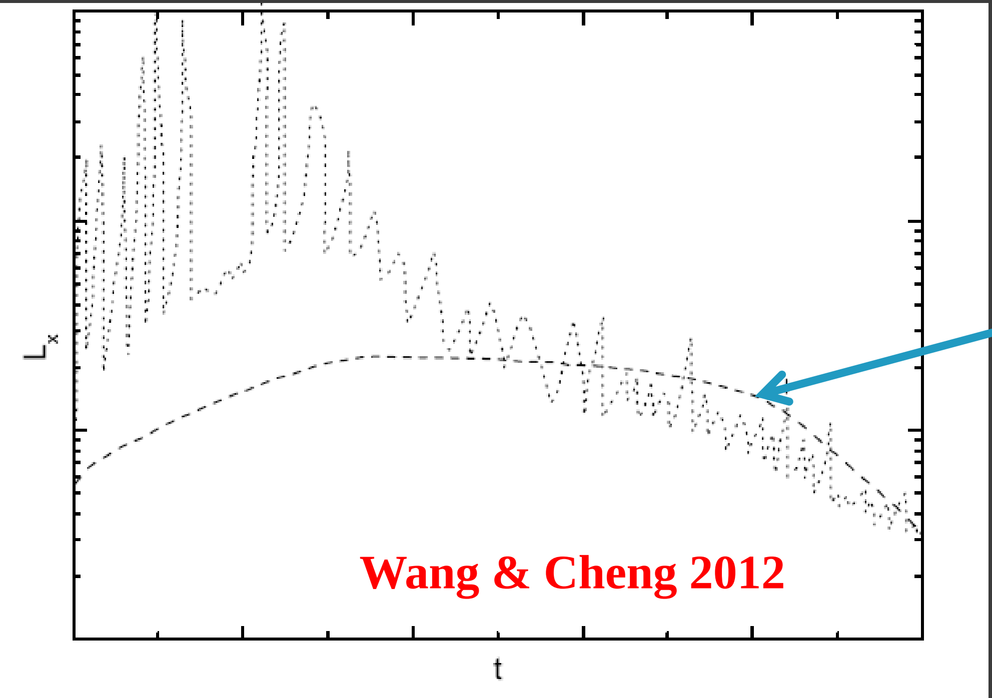
$$F_{\nu,\max,3} \simeq 0.9\ \mathrm{mJy}\ L_{47}^{3/2} \epsilon_{B,-1}^{1/2} \gamma_{1,1}^{-2} \gamma_{4,3}^{-1} d_{L,27.7}^{-2}.$$

For the forward shock, we obtain

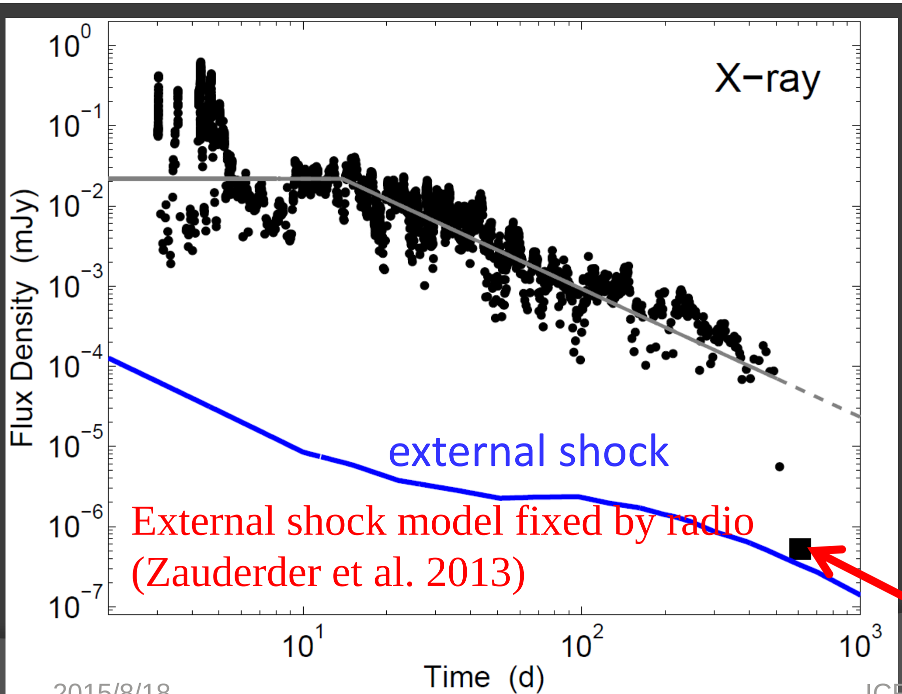
$$\nu_{m,2} \simeq 3.5 \times 10^{11}\ \mathrm{Hz}\ \epsilon_{e,-0.3}^2 L_{47}^{1/2} \epsilon_{B,-1}^{1/2} \delta t_2^{-1} \gamma_{1,1}^{-2},$$

$$\nu_{c,2} \simeq 2.2 \times 10^{13}\ \mathrm{Hz}\ L_{47}^{-3/2} \epsilon_{B,-1}^{-3/2} \delta t_2 \gamma_{1,1}^{8},$$

$$F_{\nu,\max,2} \simeq 15\ \mathrm{mJy}\ L_{47}^{3/2} \epsilon_{B,-1}^{1/2} \gamma_{1,1}^{-3} d_{L,27.7}^{-2}.$$

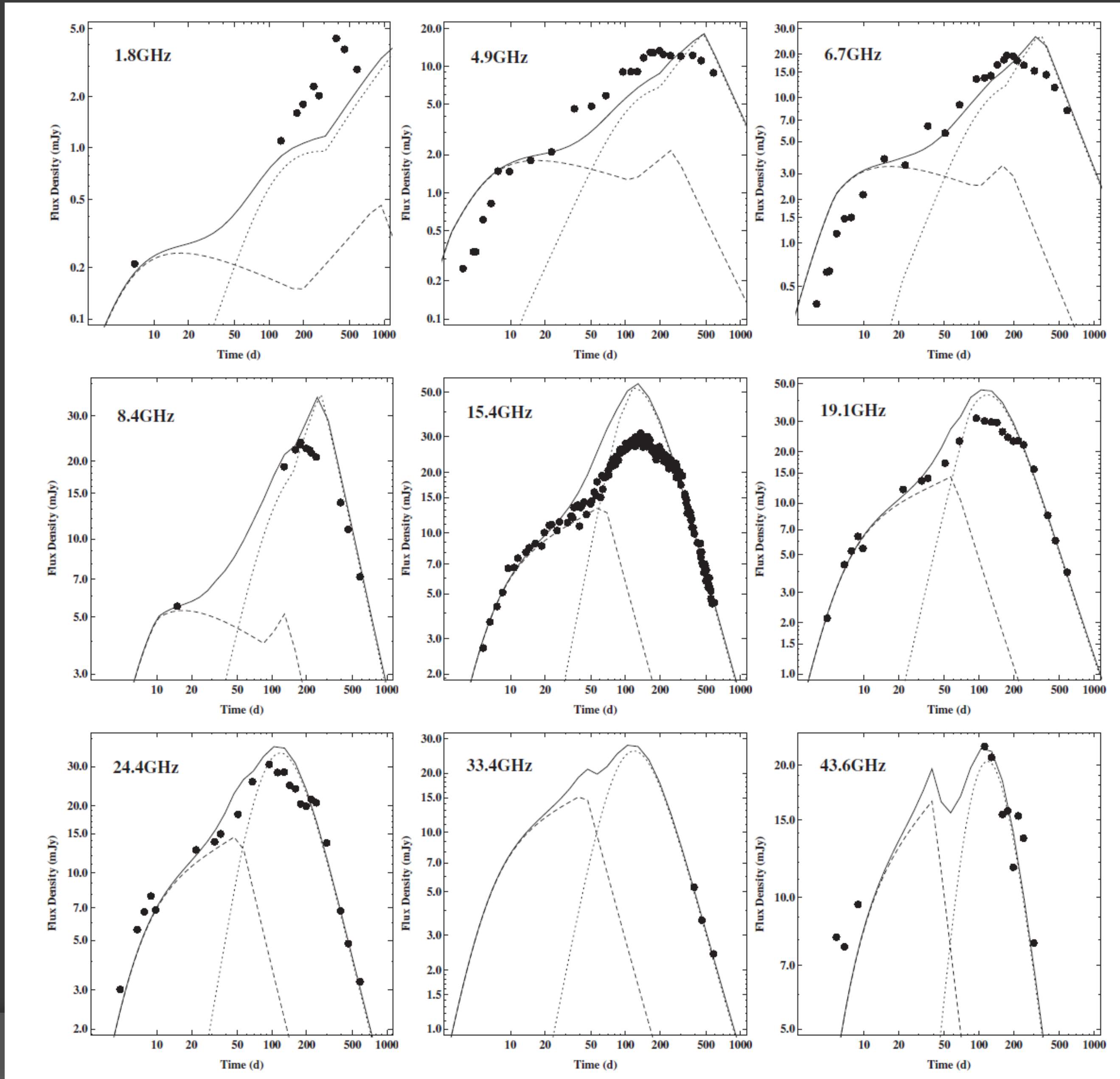


Our model predicts that the external shock (dashed line) will dominate the X-ray emission when the internal shock has ended, i.e. no more ejecta coming out from the BH.

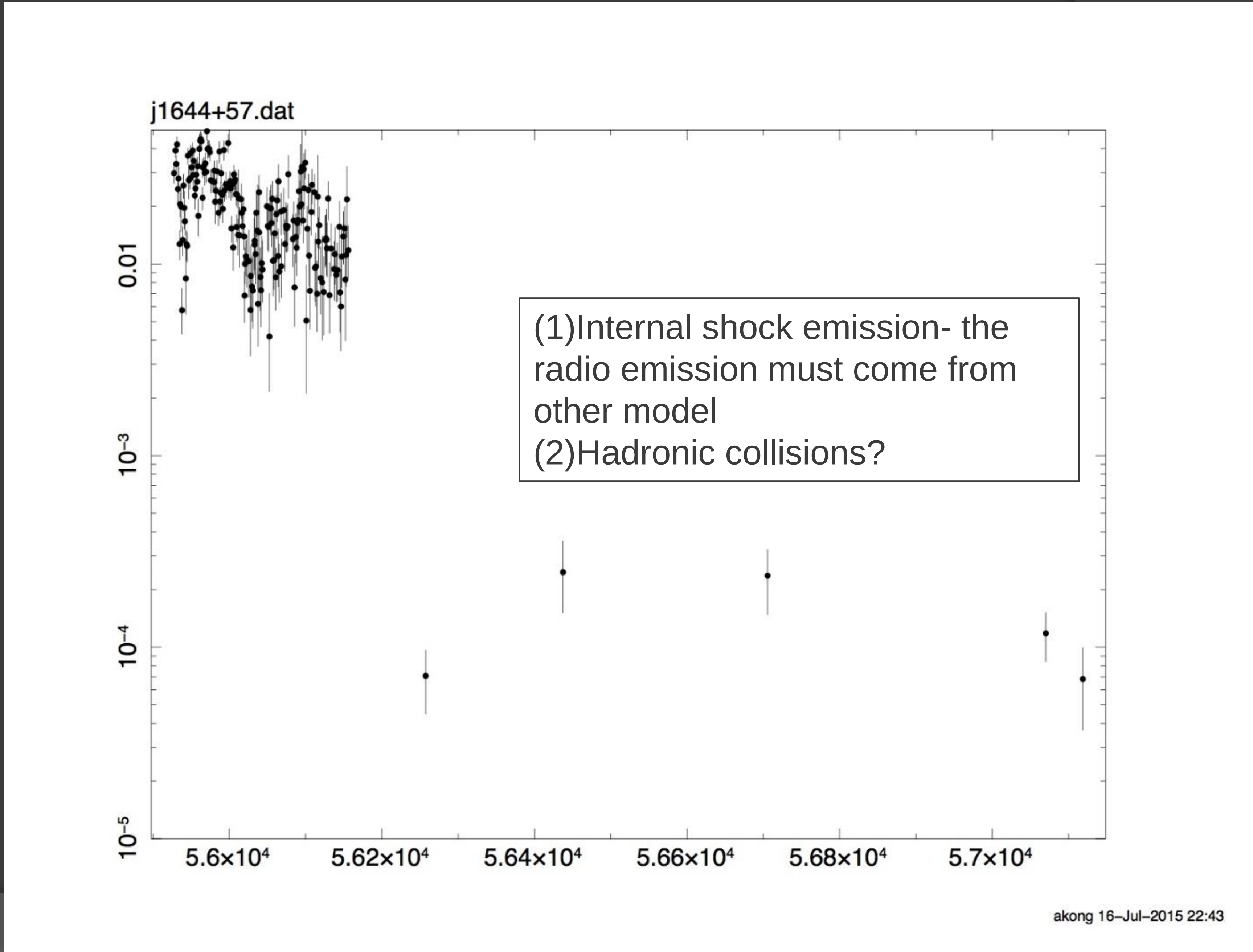


Chandra observation at 630 days

Radio fitting with external shock model (Wang et al. 2014)

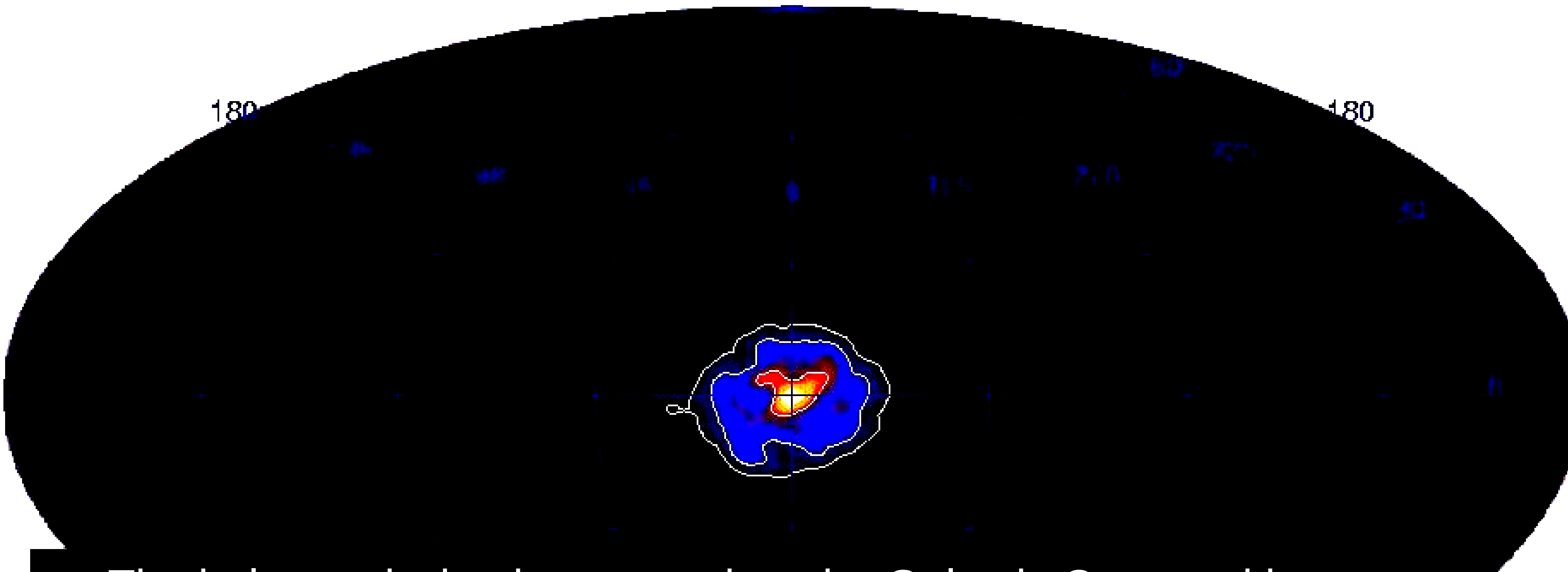


Surprise ! Recent X-ray observations by Swift and Chandra



(1)Internal shock emission- the radio emission must come from other model
(2)Hadronic collisions?

An all-sky image of 511 keV emission



- The bulge emission is centered on the Galactic Center with an extension of ~6 ° - 8° (FWHM)
- Emissions appears to be diffuse. No evidence were found for significant emission from point sources in the Galactic Center

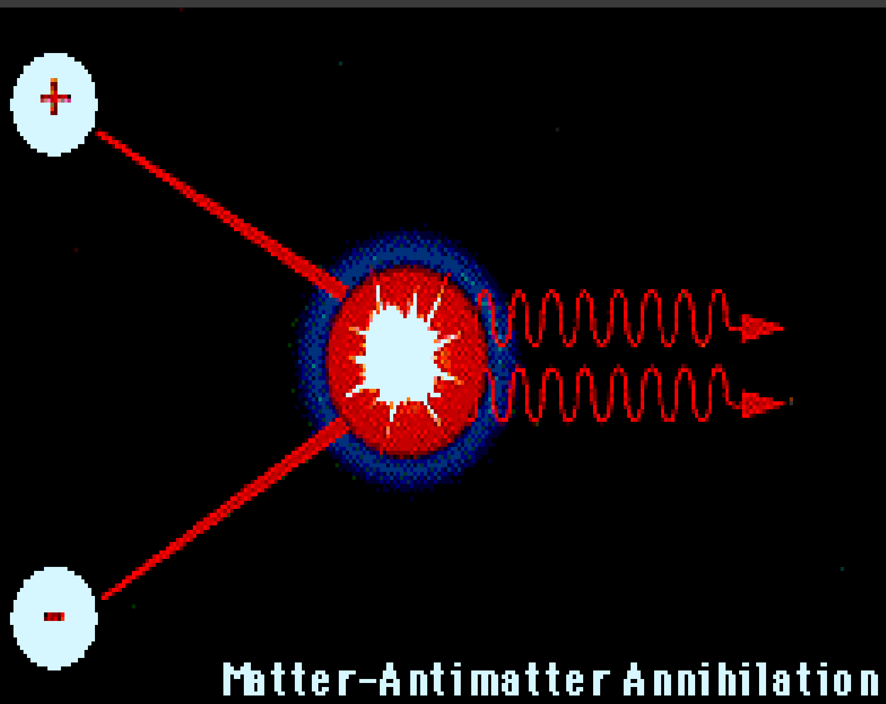
- Iteration 17 of accelerated Richardson-Lucy algorithm
- 5° x 5° boxcar smoothing
- Integrated 511 keV flux : 1.4×10^{-3} ph cm^{-2} s^{-1}

e^+/e^- 511 keV Line from the Galactic Center Region

- First reported more than 30 years ago as a 476 keV feature (Jonhson et al. 1972)
- Identified with a narrow 511 keV line in 1978 (Leventhal et al. 1978)
- Observed by SMM, OSSE, INTEGRAL etc.
- The brightest gamma-ray line in the Galaxy(~ 10^{-3} ph/s/cm^2) is indeed from the GC

$$\Phi_{511keV} \approx 10^{37} erg/s \Rightarrow F_{e^+} \approx 10^{43} e^+/s$$

Positron Annihilation



Processes in hydrogen plasma (dust free)

- Positrons born hot - at least few hundred keV
- Direct annihilation $\sigma \mathrm{v} \sim \sigma_T c$
  Bound electrons, free electrons => 2 photons
- Deceleration of positrons:
  Ionization, Excitation, Coulomb losses
- Radiative recombination (if ionized, T - low)
- Charge exchange (if neutral, E>6.8 eV) $\sigma \sim \pi r_0^2$
  Positronium formation => 2 or 3 photons

Bussard, Ramaty & Drachman 1979

Interstellar cloud properties and e+/e- annihilation lines

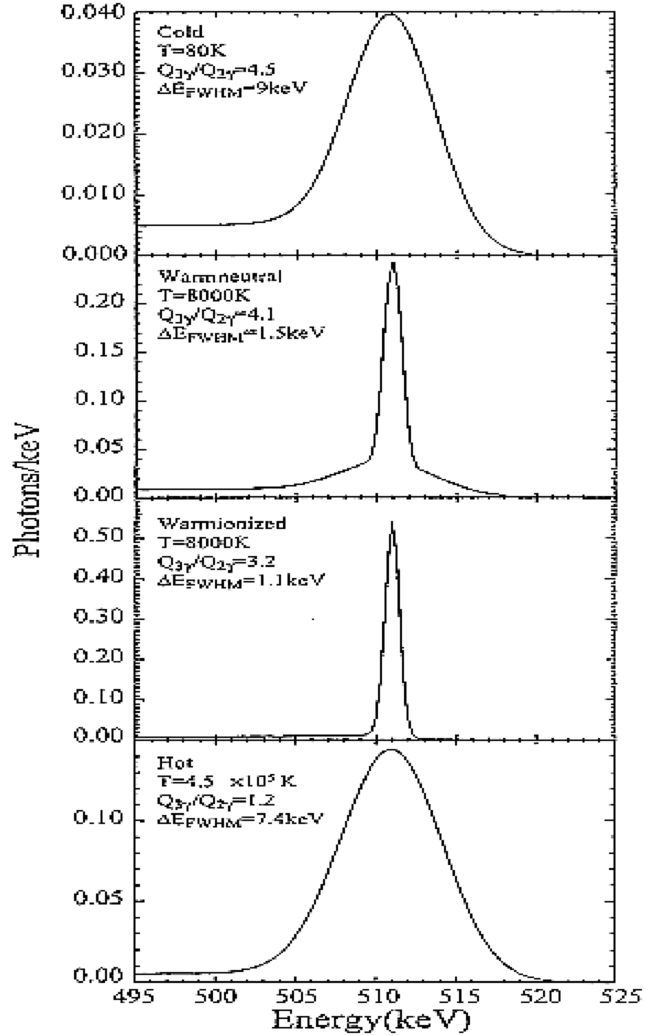
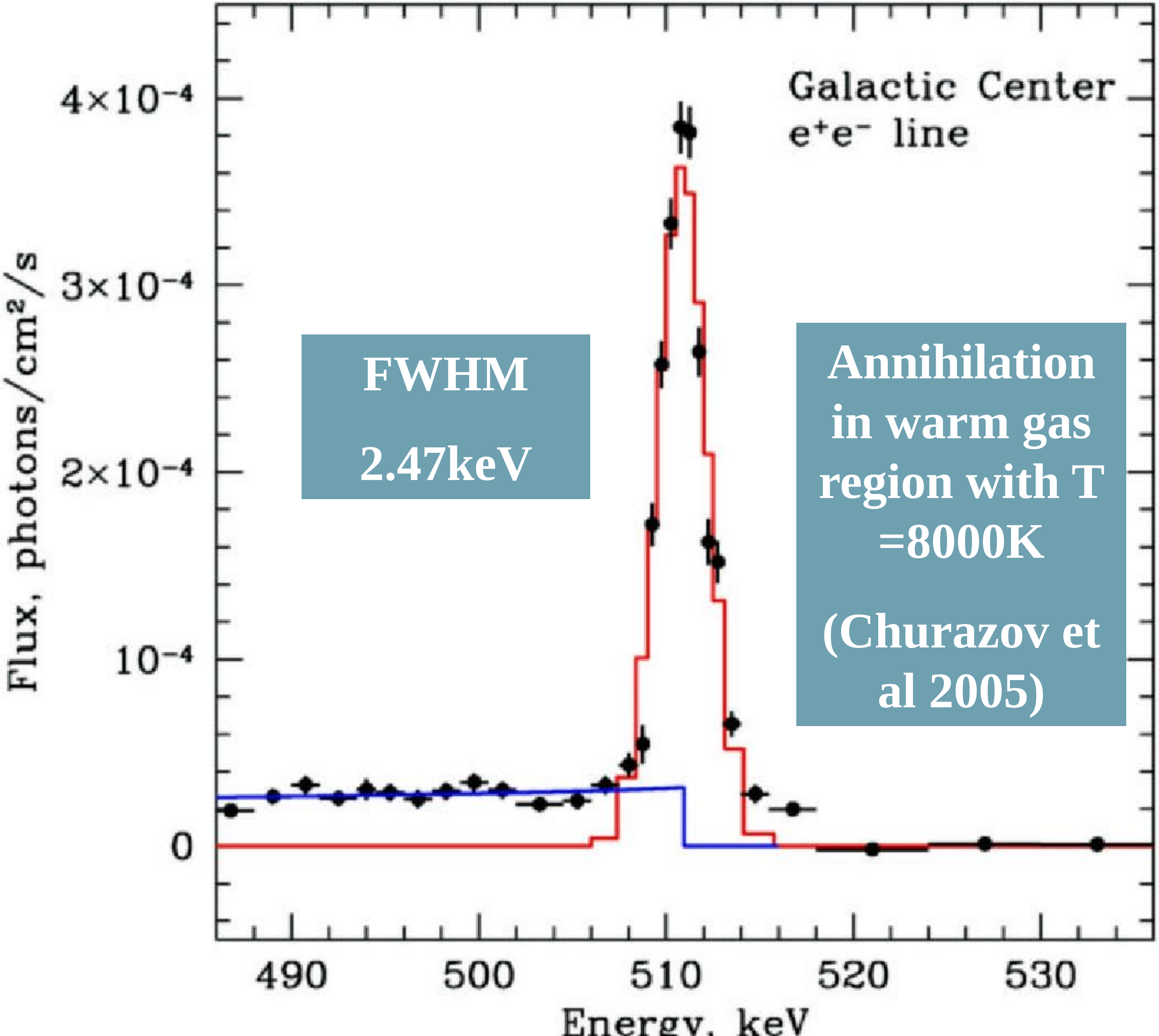


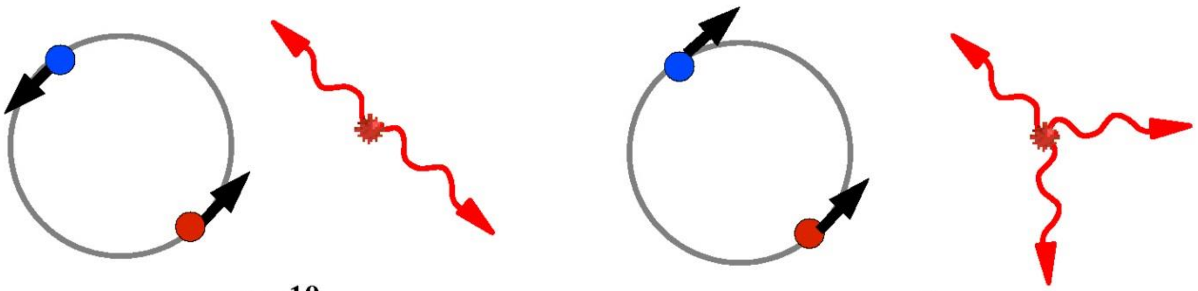
Figure 2. *Calculations of annihilation line and Ps continuum from the injection of MeV positrons into regions with different temperatures and ionization fractions.*



Galactic Center
e+e- line
Flux, photons/cm²/s
4×10⁻⁴
3×10⁻⁴
2×10⁻⁴
10⁻⁴
0
490
500
510
520
530
Energy, keV
FWHM
2.47keV
Annihilation in warm gas region with T =8000K
(Churazov et al 2005)

Observations indicate that the intensity ratio between continuous component and the line component is 3.65+/-0.82 for a free background

$$\mathrm{CE} + \mathrm{RR} = \begin{cases} \text{Para-positronium,} & \frac{1}{4} & 2\gamma \\ \text{Ortho-positronium,} & \frac{3}{4} & 3\gamma \end{cases}$$

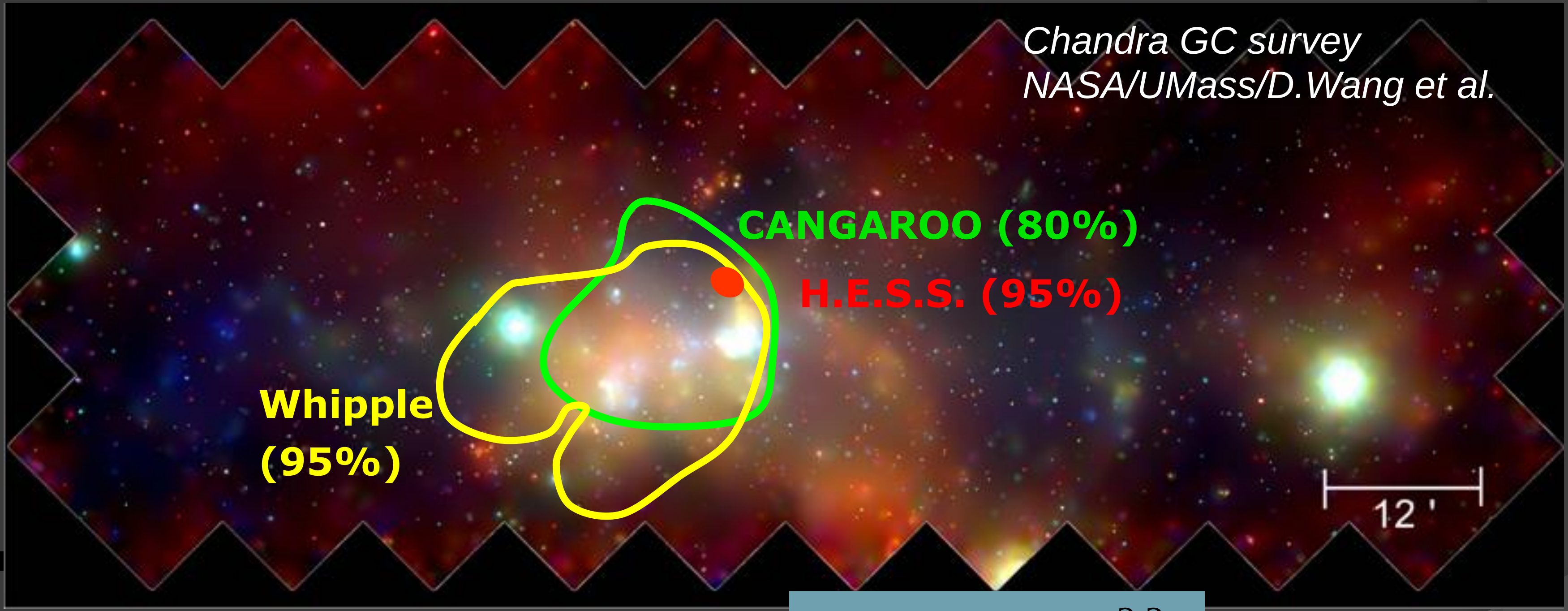


$10^{-10}\,\mathrm{s}$ $\quad$ $10^{-7}\,\mathrm{s}$

$$\frac{F_{3\gamma}}{F_{2\gamma}} = \frac{\frac{3}{4}\times 3}{\frac{1}{4}\times 2} = 4.5 \qquad \text{Deviations from } 4.5 \rightarrow \frac{\text{Direct annihilation}}{\mathrm{CE+RR}}$$

This suggests that most annihilation photons are mainly produced via formation of Positroniums.

TeV Gamma-Ray Emission from the Galactic Center (Aharonian et al., 2004)



Contours from Hooper et al. 2004

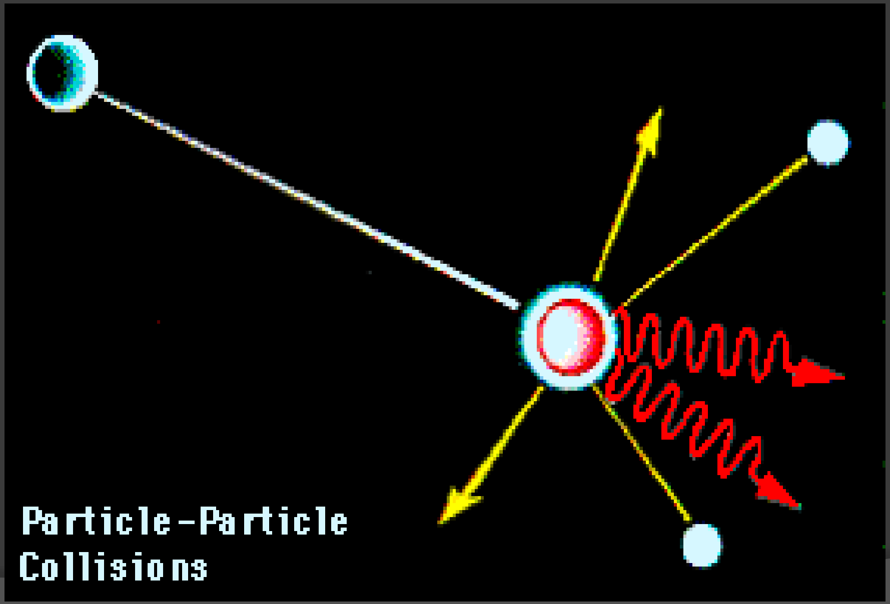
$$F(E_\gamma) \sim E_\gamma^{-2.2}$$

$$Q_\gamma \approx 10^{35} erg/s$$

$$\sim 10\,pc$$

Implications of annihilation data

- It is important to notice that the implied input energy for e^+ is huge if they are produced by proton-proton collisions. Because it takes at least 1GeV to produce positron and the implied input power is $\sim 10^{40}$ erg/s. However, p-p collisions also produce gamma-rays via the decay of neutral pions and the observed gamma-rays should be $\sim 3\times10^{38}$ erg/s, which is much higher than the current observed value. Furthermore, if protons are ejected by a source, it takes 10^7 years to diffuse to 500pc region and the implied total input energy is 10^{54} erg!



$$p + p \Rightarrow \pi^0, \pi^\pm$$

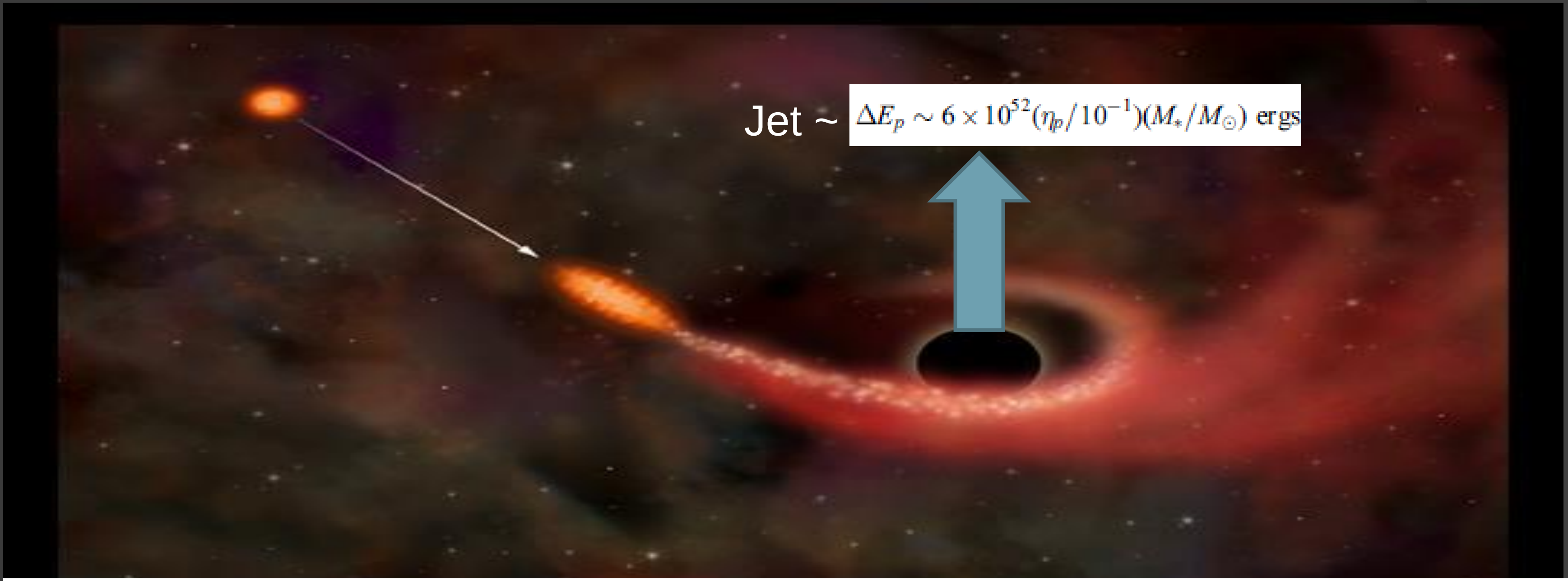
$$\pi^0 \Rightarrow 2\gamma$$

$$\pi^\pm \Rightarrow e^\pm$$

Models of positron production (Prantzos et al. 2011)

- Radioactivity from stellar nucleosynthesis – e.g. ^{56}Co in SNIa, ^{26}Al and ^{44}Ti from massive star explosions (Hypernovae/gamma-ray bursts)
- High energy processes in cosmic rays and compact objects – e.g. p-p collisions (energy sources could be pulsars, MSPs, magnetars etc.
- Positron production by the Galactic black hole – e.g. Tidal disruption of nearby stars and subsequent accretion of their material
- Dark matter and ”non-standard” models

Tidal Stellar Capture as Energy Input



We suggest that the periodic tidal disruption events taken place in the galactic center could be the energy injection for the positrons. In each capture event roughly >10^52 ergs accretion energy can be carried away by relativistic protons. The subsequent hadronic collision processes can produce positrons.

Quasi-Stationary model

- Main assumption: the positron flux from the Bulge (~ $10^{43}\ e^{+}/s$) and the gamma-ray flux (< $2\cdot 10^{37}\ erg/s$) are produced in the same eruption event, also assuming positrons annihilate once they are produced
- Result: The maximum production of thermal positrons is only $2\cdot 10^{41}\ e^{+}/s$ because each neutral pion has energy ~100MeV
- Conclusion: The model fails to explain these observed fluxes

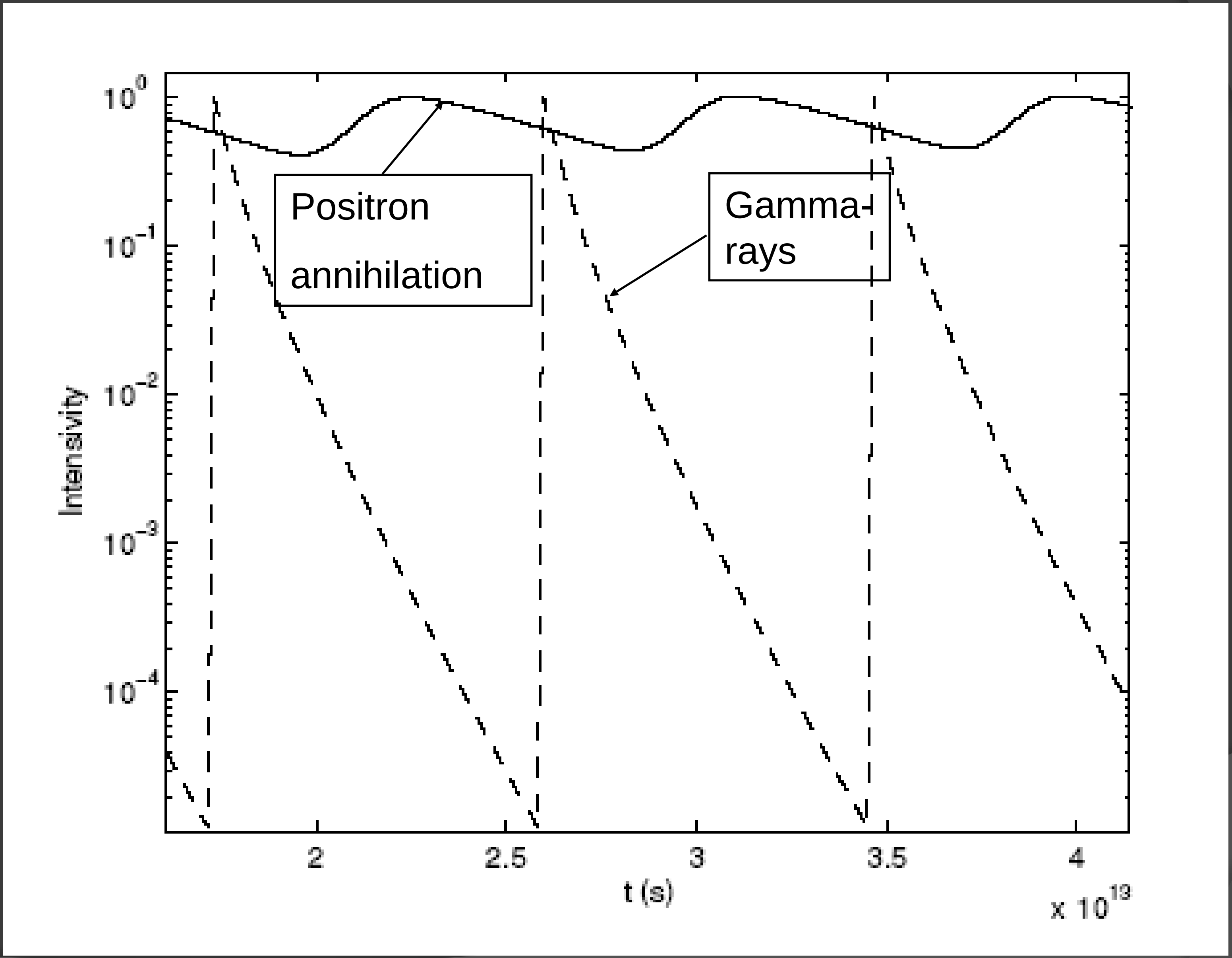
Repeated capture model

- Main assumption:

  $\tau_{cool} > \tau_{capture} > \tau_{collision}$

  Stellar capture takes place in a time scale less than the positron cooling time scale τ_{cool} ~10^{13}s (E/100MeV)/(n/10cm^{-3}). If this assumption is satisfied, the gamma-ray flux must decrease substantially between two capture events, which implies the p-p collision time scale ($\tau_{collision}$ ~10^{12}s /(n/10^3cm^{-3}) must be shorter than the capture time scale. This implies that the gas density for p-p collision and e^+ thermalization must be different! (we will see the justification later)
- Result: The production of thermal positrons is almost constant and gamma-ray intensity will be only about 2-3 order of magnitude smaller than that implied by the annihilation intensity.
- Conclusion: The energy input of primary protons per capture is only ~10^{52} ergs

Repeated Stellar Capture model (n_p =1000 cm^{-3})

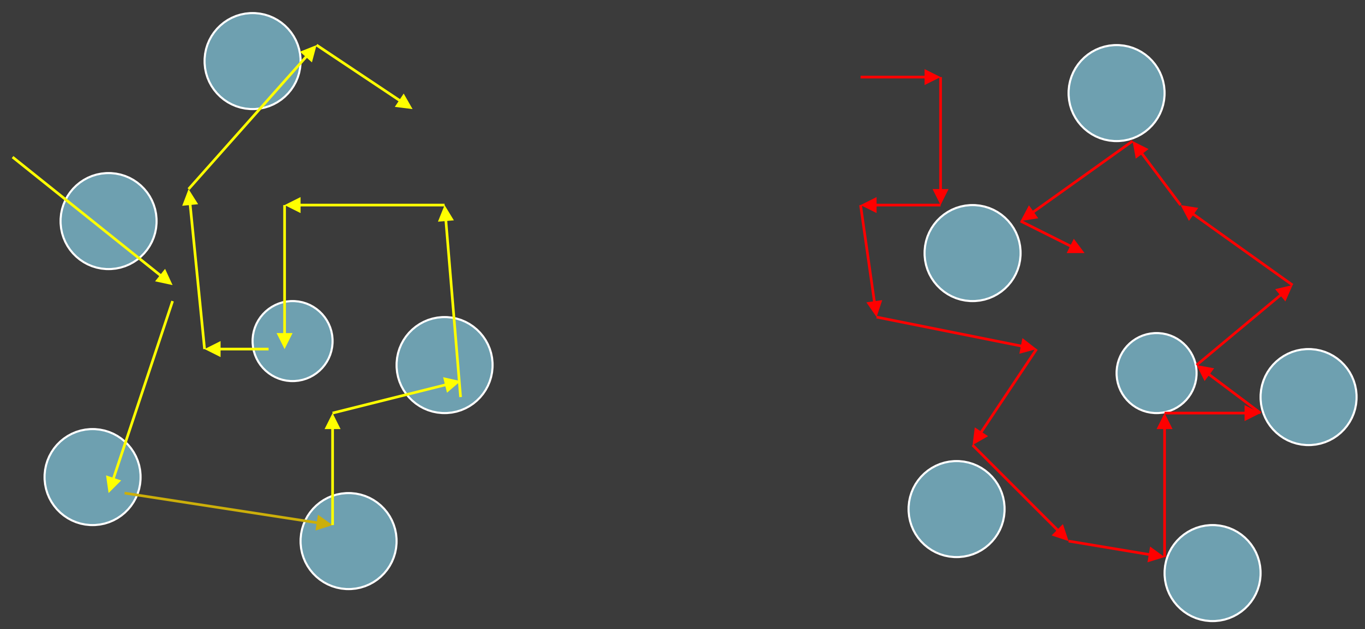


Parameters of the Interstellar Medium in the Galactic Bulge Region (Jean et al. 2005)

- The budge (region inside the radius ~230 pc and height 45 pc) contains $7 \cdot 10^{7} M_{\otimes}$
- 90% of this mass is trapped in small high density clouds (as high as 10^{3} cm^{-3})while the remaining 10% is homogeneously distributed with the average density ~10 cm^{-3}.
- The HI mass is about $4 \cdot 10^{7} M_{\otimes}$ and it is equally distribute between cold and warm neutral gas
- The remaining mass is in warm and hot ionized gas: about 90% of this mass is in the warm phase and 10% is in the hot phase.

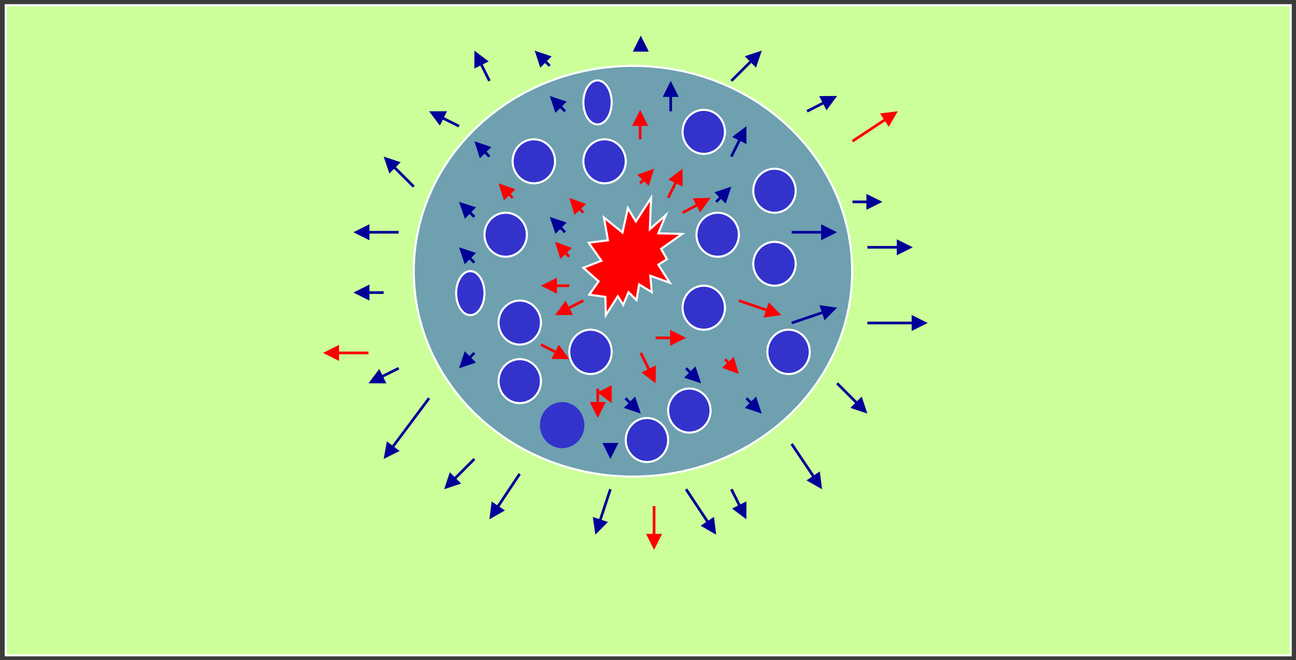
Propagation of

> GeV protons and Tens MeV positrons



Morfill’s model (1982)

Particle escape from the Central region



Central region filled by molecular gas

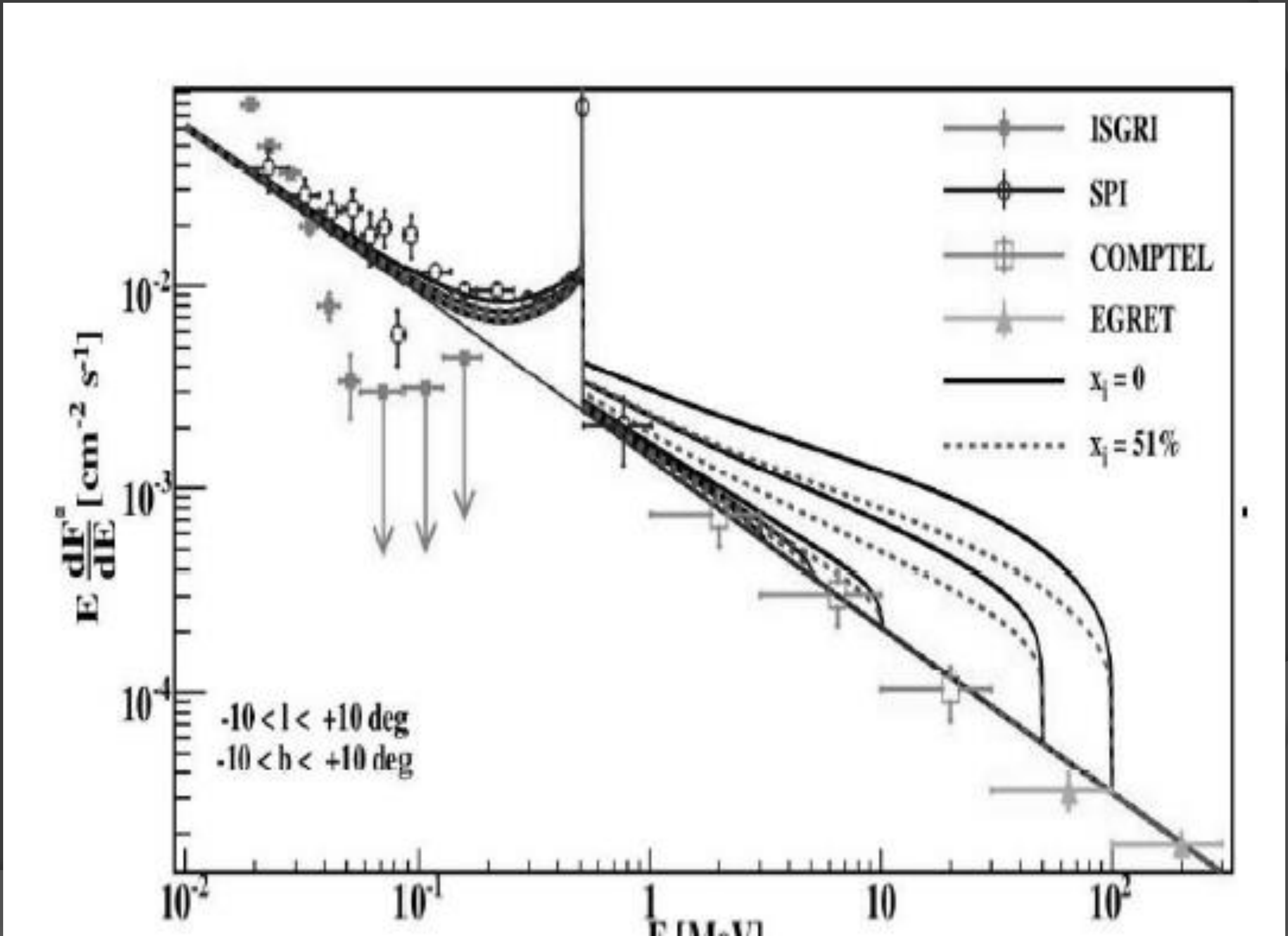
Dense clouds

Surrounding region filled by warm neutral and ionized fractions of the interstellar gas

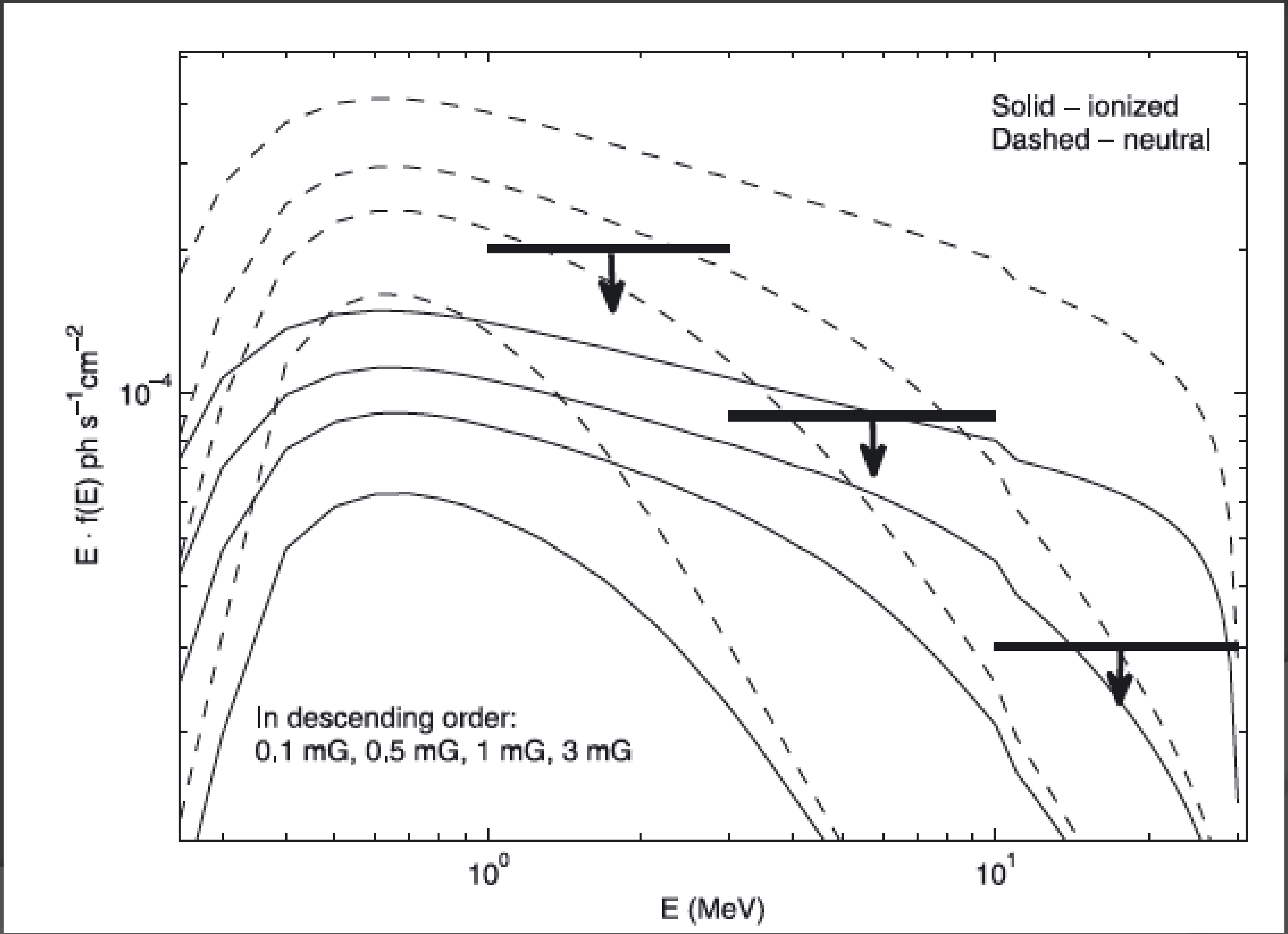
Flux of relativistic protons

Flux of tens MeV positrons

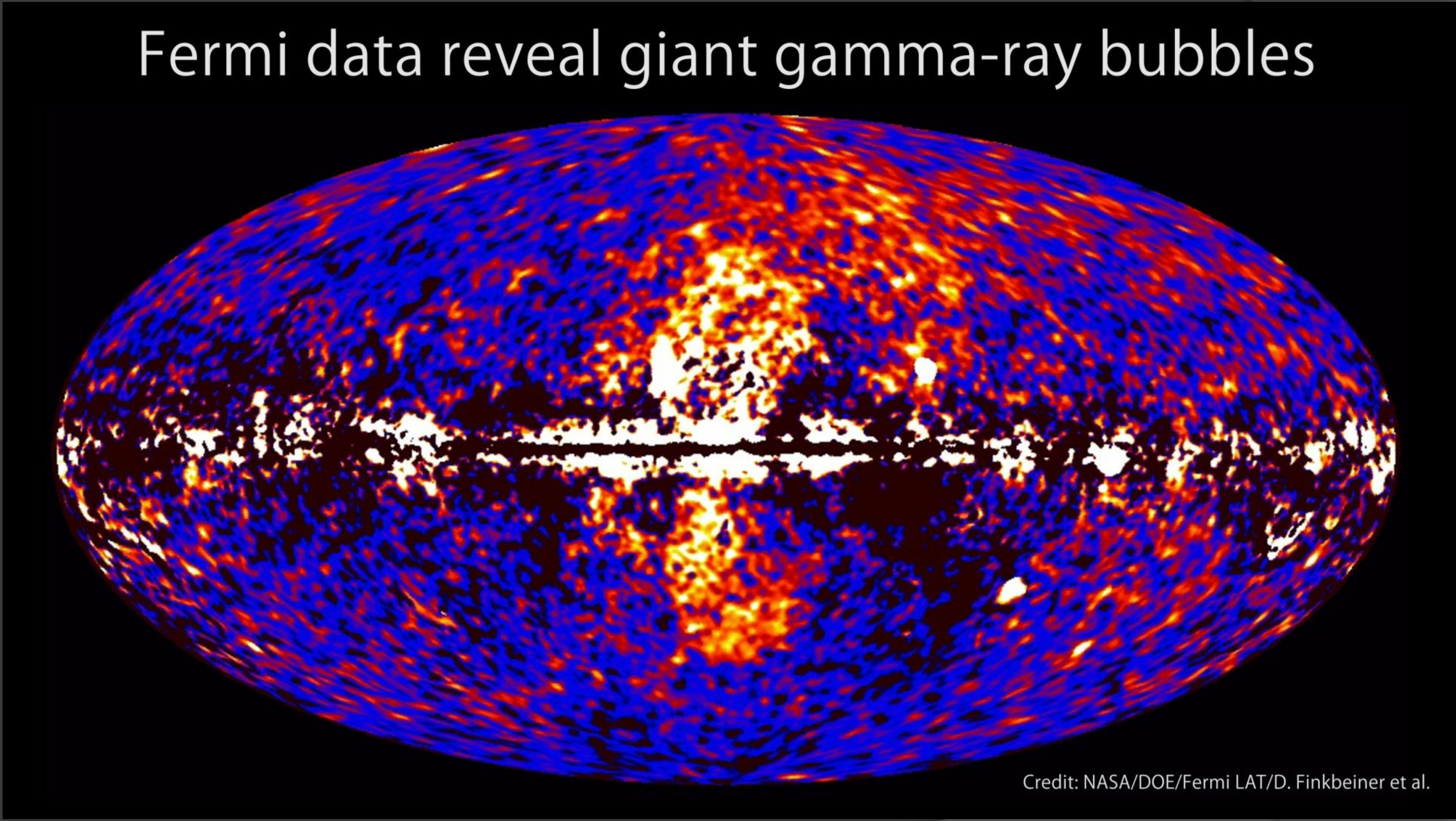
Over-production of gamma-rays in tens MeV range (Beacom and Yüksel 2006)



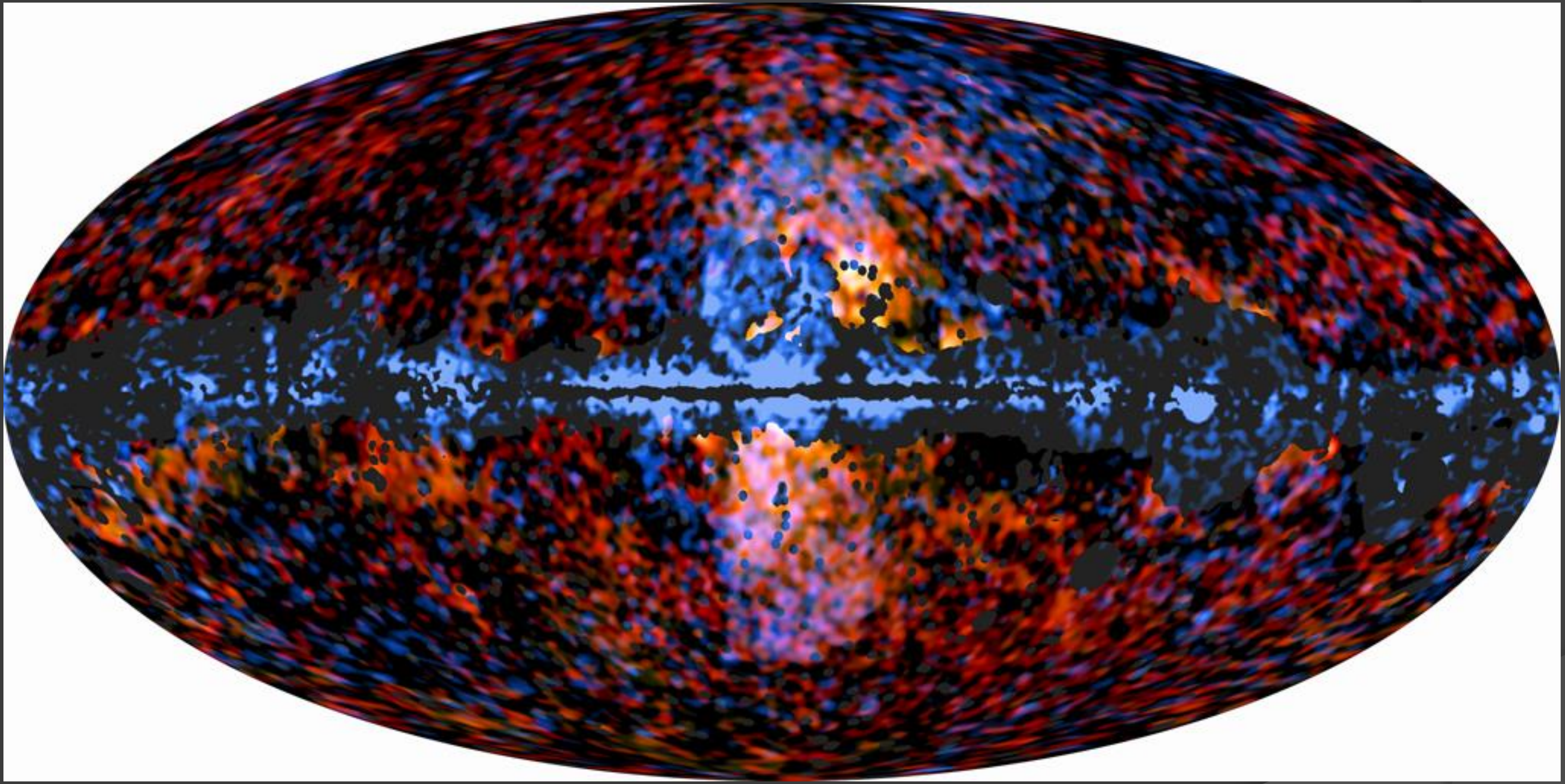
Rapid cooling by magnetic field? (Chernyshov et al. 2010)



(Su et al. 2010;Dobler et al. 2010)



Planck intermediate results



30 -44 GHz.
Good correlation between radio and gamma-rays
Spectrum is harder than in the Galaxy (⇔ -2.1)

Ade et al, 2013

Multi-wavelength Observations of Fermi Bubble

- 1997 - the ROSAT All-Sky Survey at 1.5 keV (Snowden et al. 1997) revealed a biconical X-ray structure over the inner tens of degrees around the Galactic center (GC). This requires 10^55 ergs injection energy in a time scale of 10Myrs.
- 2004 - A microwave residual excess (named “the microwave haze”) with spherical (non-disklike) morphology about ~ 4 kpc in radius toward the GC (Finkbeiner 2004)
- 2010 – A pair of giant gamma-ray bubble in GeV was found
- The injected power to maintain these radiations ~10^40-10^41 erg/s is required.

Fermi Observations

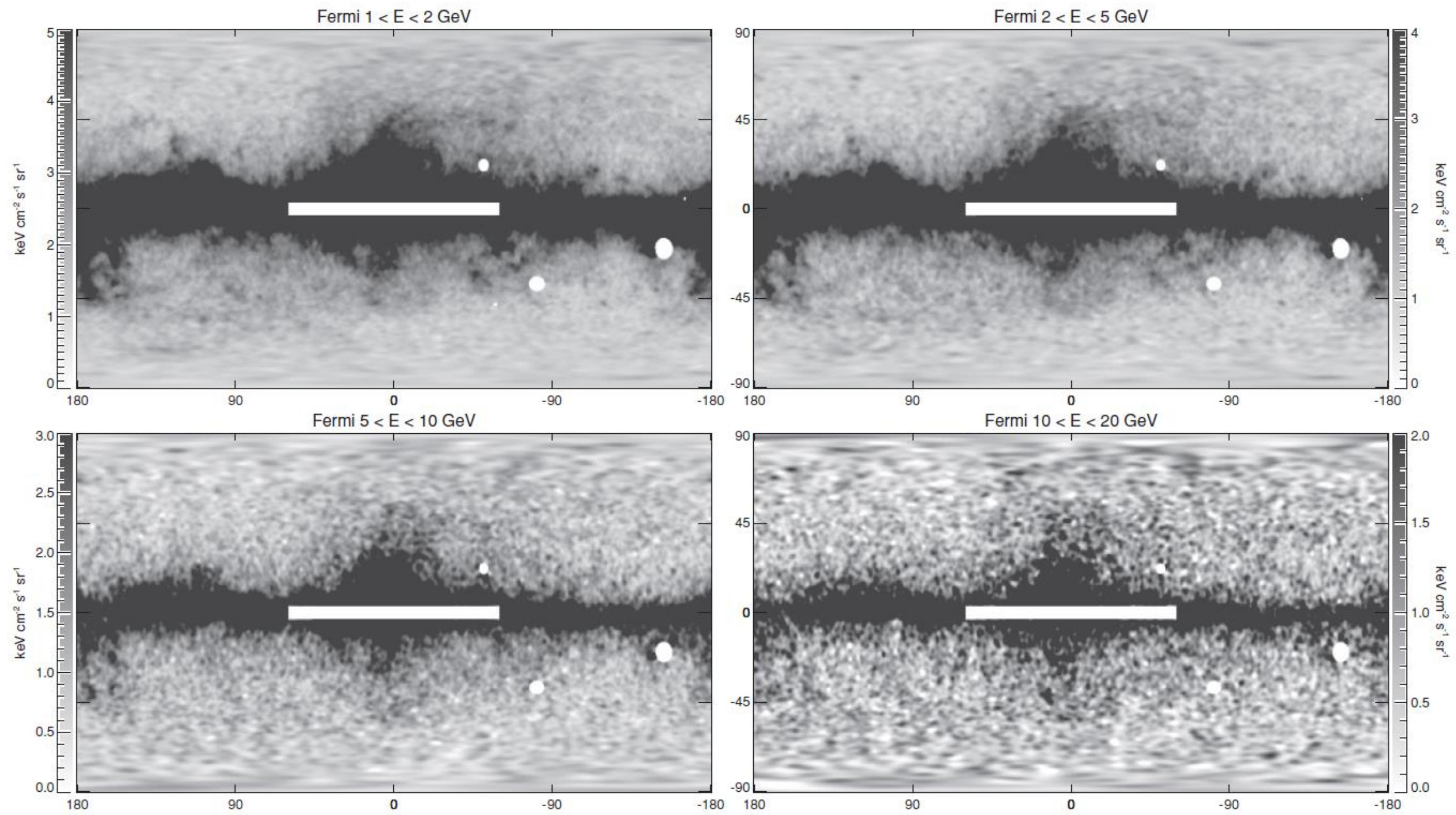


Figure 1. All-sky *Fermi*-LAT 1.6 year maps in four energy bins. Point sources have been subtracted, and large sources, including the inner disk ($-2° < b <$

After the background subtraction

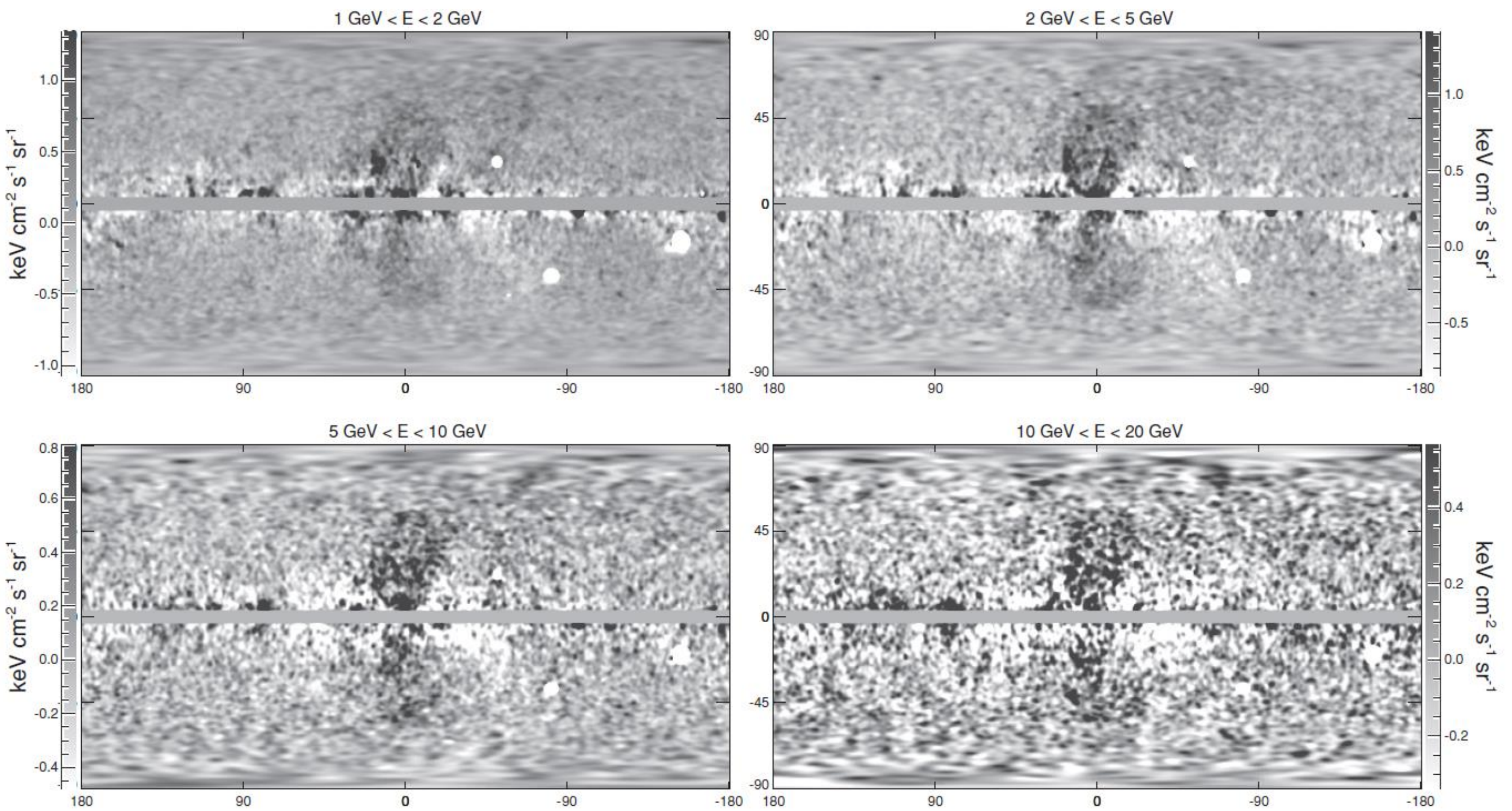
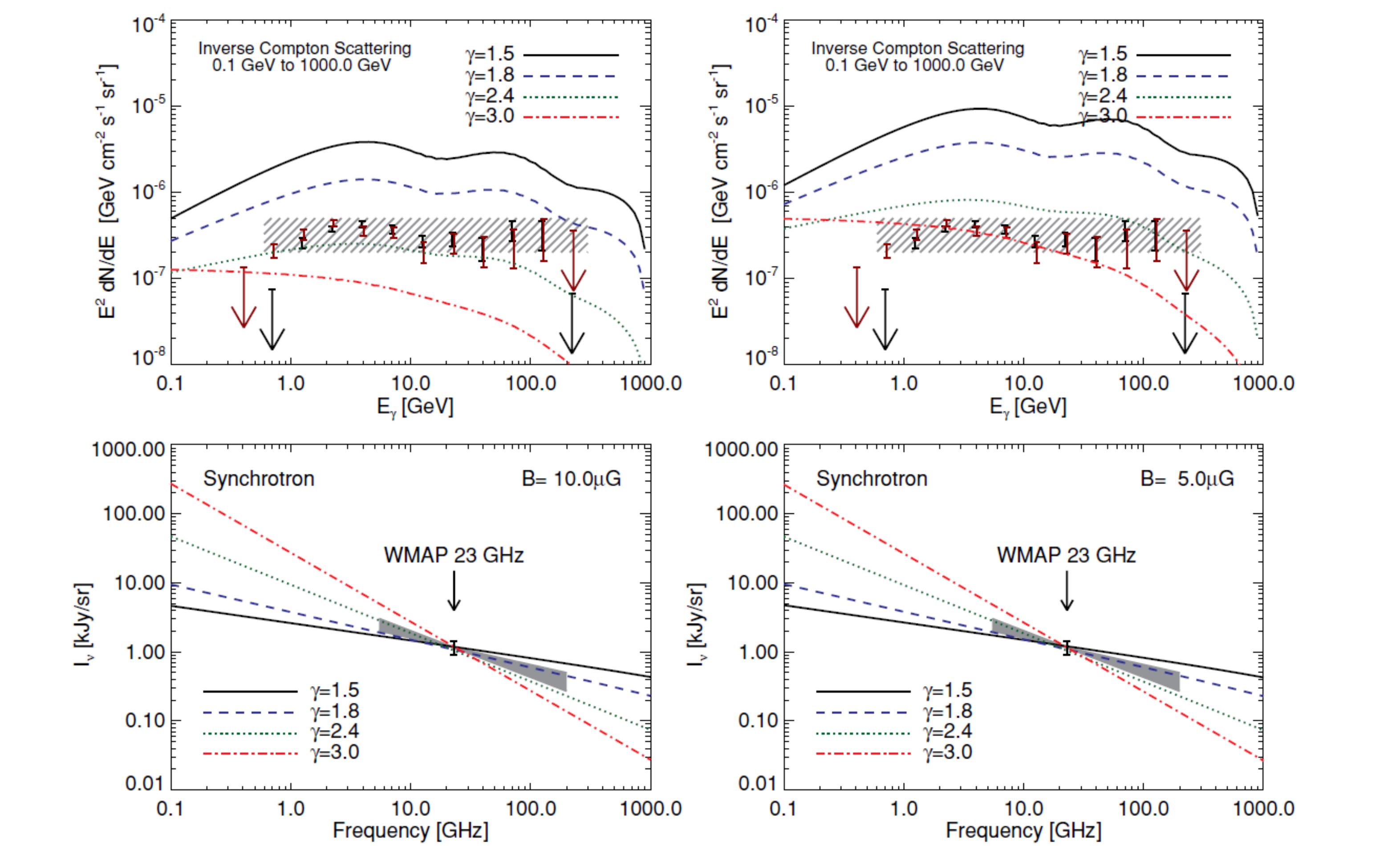


Figure 2. All-sky residual maps after subtracting the *Fermi* diffuse Galactic model from the LAT 1.6 year maps in four energy bins (see Section 3.1.1). Two bubble structures extending to $b \pm 50°$ appear above and below the GC, symmetric about the Galactic plane.

Spectra (Su et al. 2010)

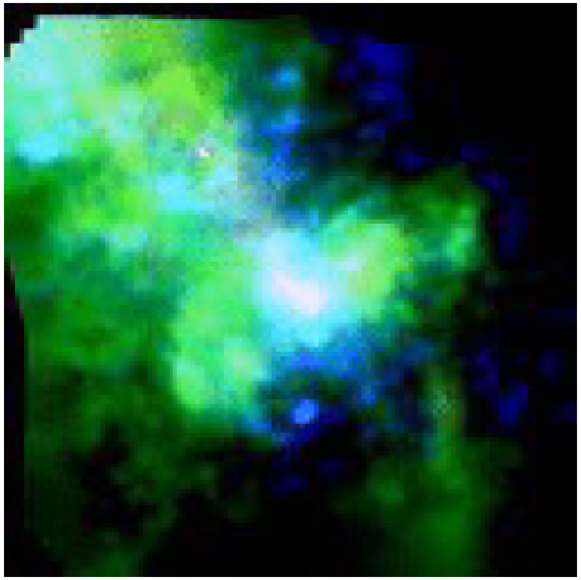


Origin of the bubble?

- Since this pair of bubbles are located symmetrically around the GC, it must relate to activities around GC
- Other activities in GC – electron/positron annihilation lines, diffuse gamma-rays, several TeV sources, SNe etc.
- Most important- hot plasma with kT~10KeV is found in GC, which cannot be confined in GC and has to be maintained by constant injected rate into halo of >10^40 erg/s

GC Thermal Emission
(Koyama, 1996-2009, Muno, 2004)

- $T \sim 10^8$ K
- $L_{2\text{-}10} \sim 2\text{x}10^{36}$ergs/s
- Size ~ 50pc x 30pc
- $n_{ave} \sim 0.1\text{cm}^{-3}$
- $n_{peak} \sim 0.4\text{cm}^{-3}$
- $E_{gas} \sim 3\text{x}10^{52}$ergs



- The energy input needed to heat the gas up to T~10 keV is about 10^{41} erg/s. This energy supply cannot be produced by SN explosions. Other more powerful sources of energy are required to support the energy balance there (Sunyaev et al. 1993; Koyama et al. 1996; Muno et al. 2004).

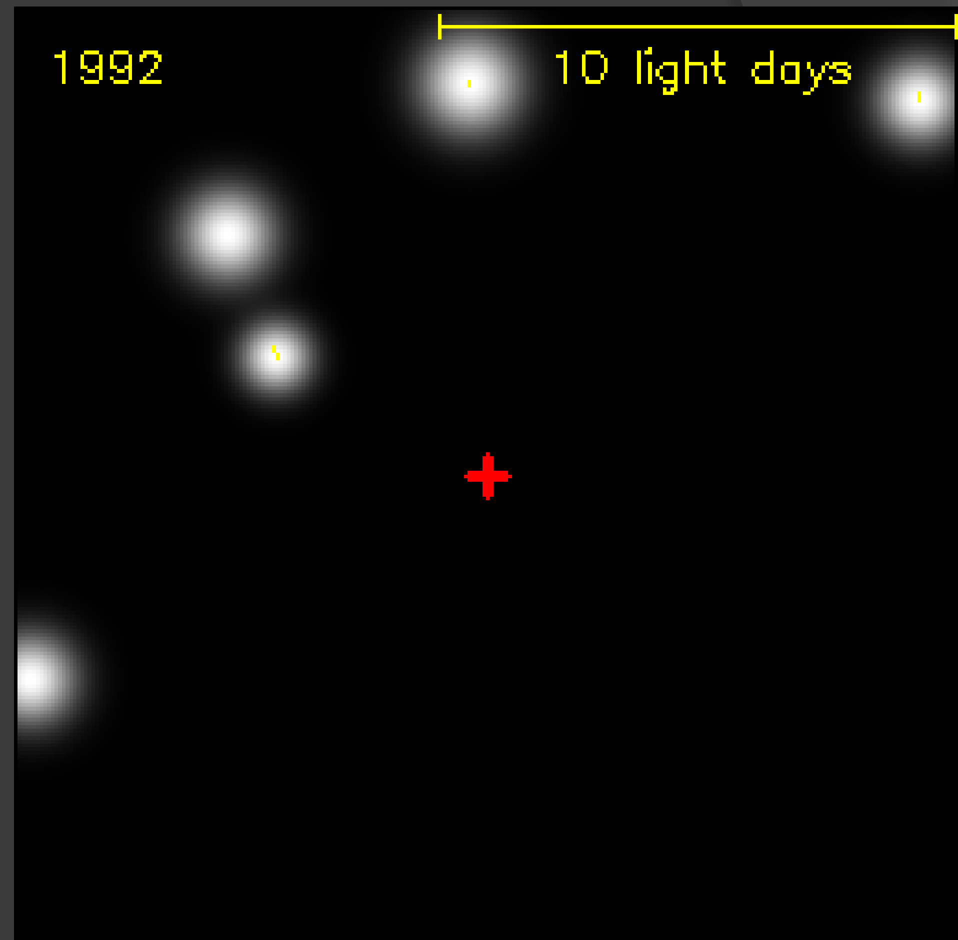
The source of energy with an output ~10^{41}erg/s is required!!!

This injected energy is similar to that to maintain the radiation in FB

Possible sources of energy injection for FB

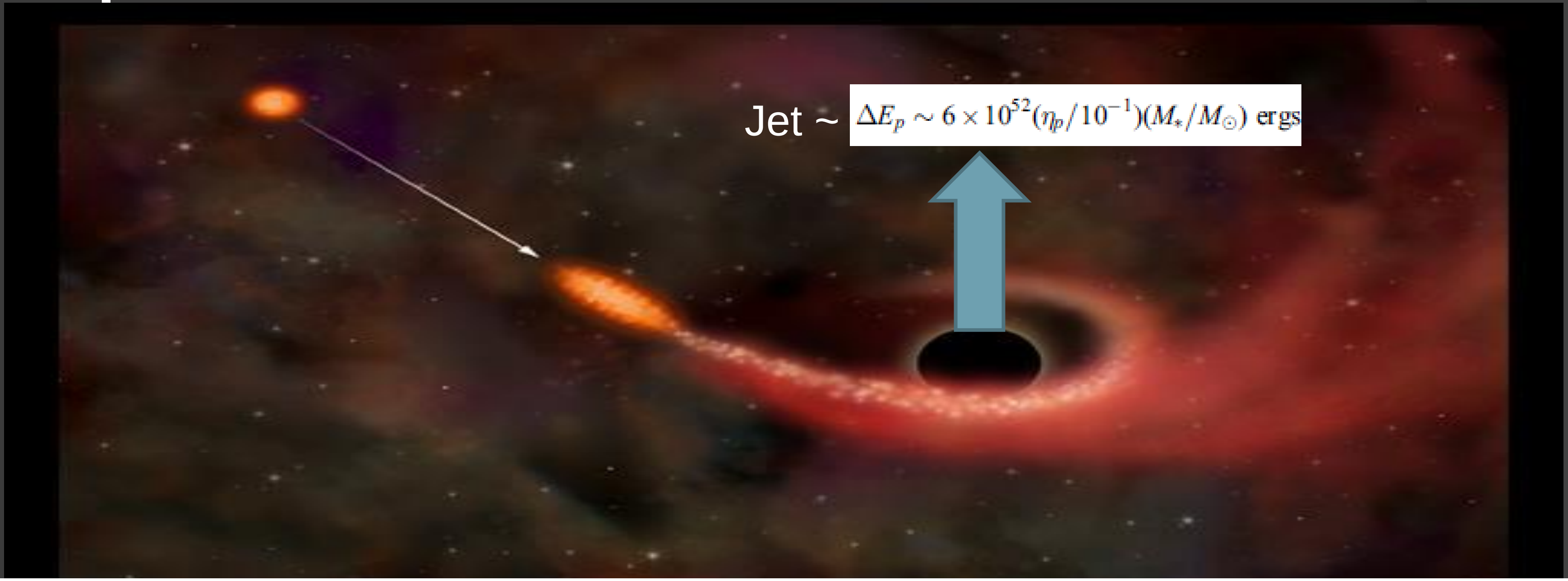
- Exceptional frequent SNe rate in GC in past 10^7 yr – but the line emission of radioactive 26^Al is missing
- Past accretion events onto the central supermassive black hole (SMBH) in the last ~ *10 Myr* similar to NGC3081
- Annihilation of dark matter – the bubble up to 4-8kpc. It is unclear why the dark matter distributes like a pair of bubbles
- In next few slides I offer our view about the origin of FB, which could be wrong !!!!!!!

Black Hole at the center of Milky Way with Mass 3.7×10^6 solar masses!



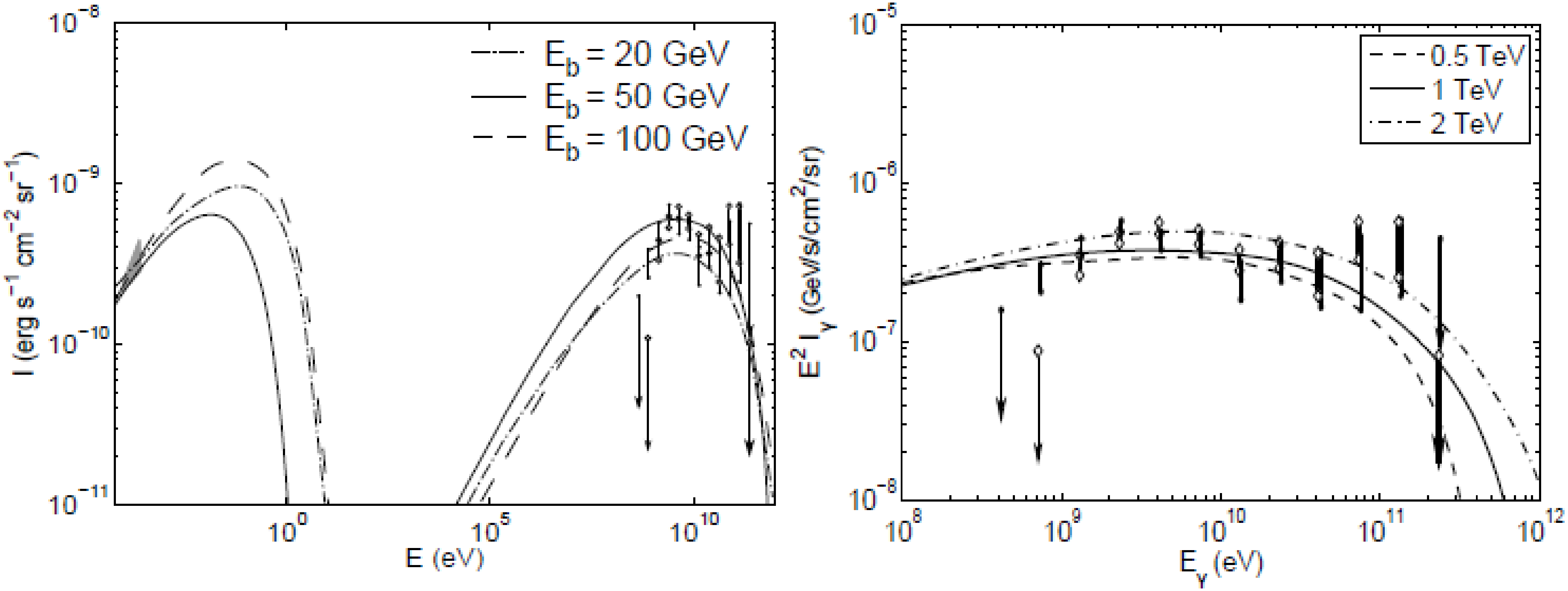
MPE / R. Genzel et al.

Tidal Stellar Capture as Energy Input



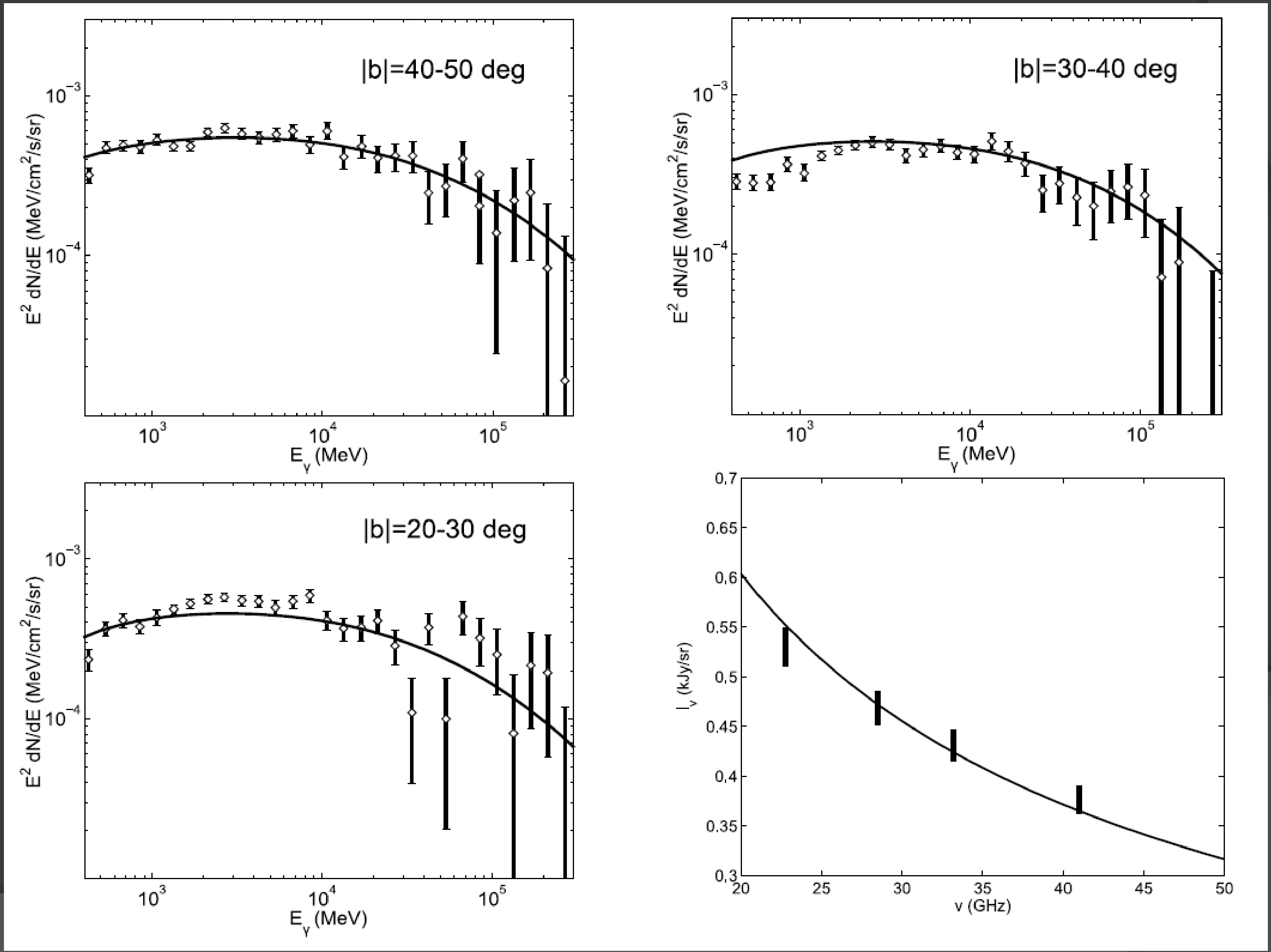
The periodic tidal disruption events taken place in the galactic center could be energy injection to the FB. In each capture event roughly >10^52 ergs can be released via relativistic and non-relativistic particles, which can heat up the gas in the GC. This hot gas can expand to the galactic halo with velocity ~10^8cm/s, which is faster than the local sound speed in the halo, therefore strong shock can be formed and accelerate electrons in the halo to relativistic energies. The subsequent IC and synchrotron radiation processes produce the observed gamma-rays and radio waves respectively.

Model fitting



Injected spectrum from the shock front is E^-2, then evolves according to Flokker-Planck eq. with maximum energy determined by the balance between acceleration and cooling and the energy break due to diffusion loss. The actual spectrum is nearly -3. Here 50GeV is the break energy in the electron spectrum, which corresponds to the escape time scale of 10Myr

Numerical model with adiabatic losses

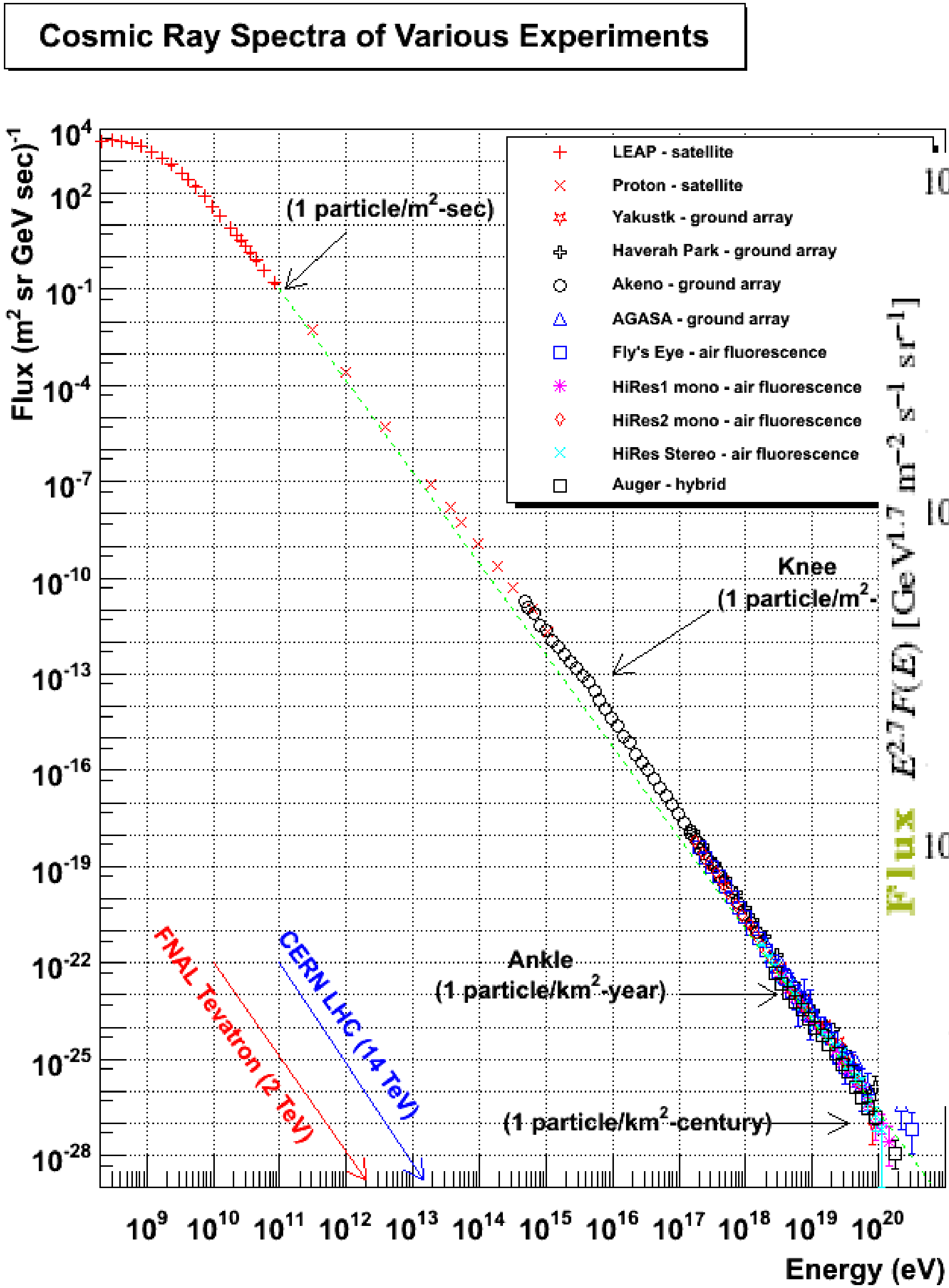


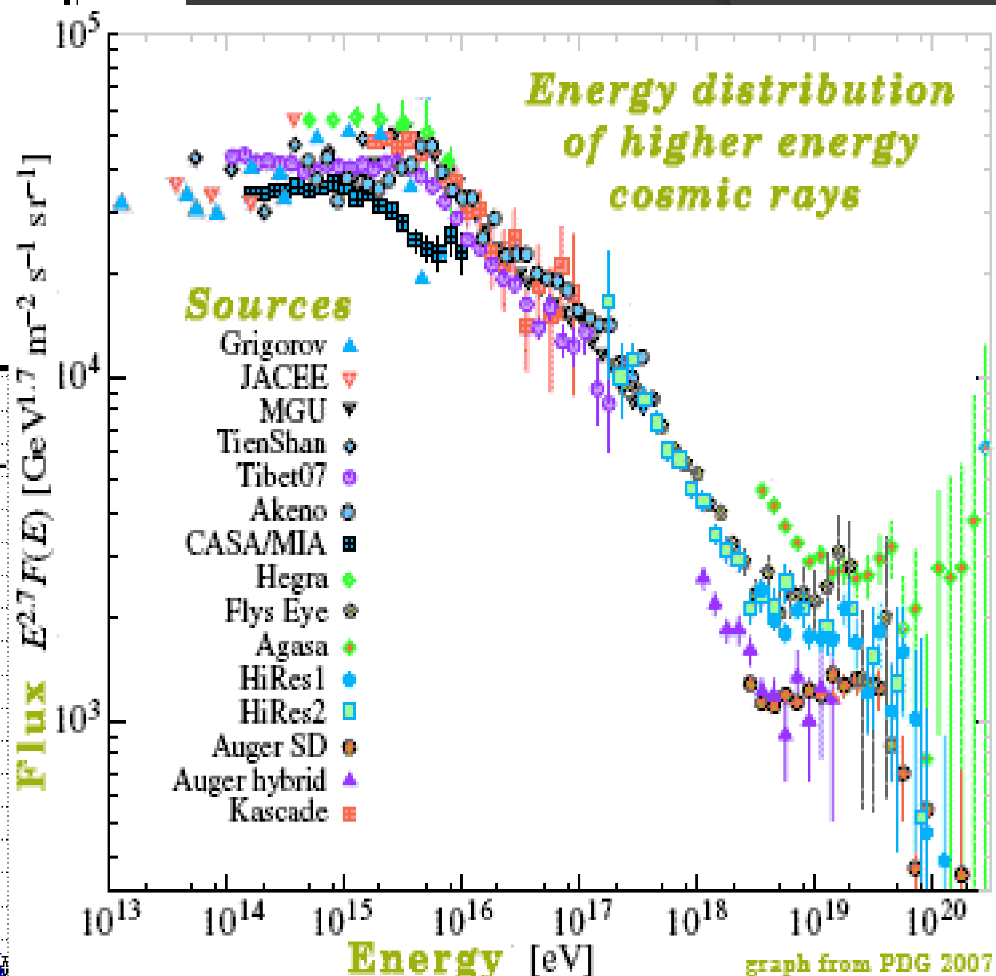
Models for Fermi Bubble

Hadronic	Leptonic
$p + p \to 2\gamma + e^{\pm}$	IC: $e + \gamma \to \gamma' + e'$
- Lifetime in the Bubbles ~10^{10}yr. Can be produced anywhere in the Galaxy. - But how to confine them in the Bubbles? - Spectrum of secondary electrons is steeper than follows from the Planck data	- Are confined in the Galaxy (< 1 Myr) - Should be produced in-situ
A) Crocker & Aharonian, 2011 **Crocker et al., 2014, Yang et al., 2014** 1) 0.04 SN/cen inside 1.5º of the GC=> 10^{40} erg/s (F_γ~4x10^{37} erg/s) 2) "magnetic walls" (Jones et al 2012) **B) Fujita et al. (2013, 2014)** –shock **C) Thoudam (2013)** – injection +compression	**A) Su et al., 2010** Starburst или jet => giant shock from 10^{56}erg energy release **B) Guo & Mathews, 2011; Yang et al., 2012** Jet – electron propagation (almost) without scattering **C) Mertsch & Sarkar, 2011** Stochastic Acceleration (Fermi II) **D) Lacki 2013 –** starburst wind, termination shock **E) Cheng et al., 2011** Star captures=> shock wave acceleration

Could we find Fermi Bubble-like cases in other galaxies?

- Fermi bubbles are FAINT structures (signal << background)
- It is difficult to observe the exact copy of them from other distance galaxies except the local group (3Mpc in diameter)
- The angular resolution of gamma-rays is low (GAMMA-400 ~0.01º (E_γ > 100 GeV))


Cosmic Ray Spectra of Various Experiments
Flux (m^2 sr GeV sec)$^{-1}$
(1 particle/m^2-sec)
LEAP - satellite
Proton - satellite
Yakustk - ground array
Haverah Park - ground array
Akeno - ground array
AGASA - ground array
Fly's Eye - air fluorescence
HiRes1 mono - air fluorescence
HiRes2 mono - air fluorescence
HiRes Stereo - air fluorescence
Auger - hybrid
Knee
(1 particle/m^2-
FNAL Tevatron (2 TeV)
CERN LHC (14 TeV)
Ankle
(1 particle/km^2-year)
(1 particle/km^2-century)
Energy (eV)


Energy distribution of higher energy cosmic rays
Flux $E^{2.7} F(E)$ [GeV$^{1.7}$ m^{-2} s^{-1} sr^{-1}]
Sources
Grigorov
JACEE
MGU
TienShan
Tibet07
Akeno
CASA/MIA
Hegra
Flys Eye
Agasa
HiRes1
HiRes2
Auger SD
Auger hybrid
Kascade
Energy [eV]
graph from PDG 2007

Maximum energy of the accelerated particle

- The SNRs has a limited age and particle acc. Time is

$$\tau_{acc}(E) \sim D(E)/u_{sh}^2$$

- Equating these two time scales and in the Bohm approximation $E_{max} \sim 10^{14} - 10^{15}$ eV

- Magnetic field amplification in young SNRs?
- Multiple acceleration?
- More long-lived objects?

Acceleration in FB using SNe particles as injected spectrum

$$-D\frac{\partial^2 f}{\partial z^2}-\frac{1}{\rho}\frac{\partial}{\partial\rho}\left(\rho D\frac{\partial f}{\partial\rho}\right)-\frac{1}{p^2}\frac{\partial}{\partial p}\left(\kappa p^4\frac{\partial f}{\partial p}\right)=Q(p,\rho,z)$$

$$\kappa=\kappa_B\theta(\rho_B-\rho)$$

$$Q(p,\rho,z)=N_{SN}(\rho)\exp\left(-\frac{z^2}{z_d^2}\right)p^{-4.7}\exp\left(-\frac{p}{p_k}\right)$$

$$D(\rho)=D_B\,\theta(\rho_B-\rho)+D_G\,\theta(\rho-\rho_B)$$

$$D_B=2.08\times10^{30}\ \mathrm{cm^2\ s^{-1}}$$

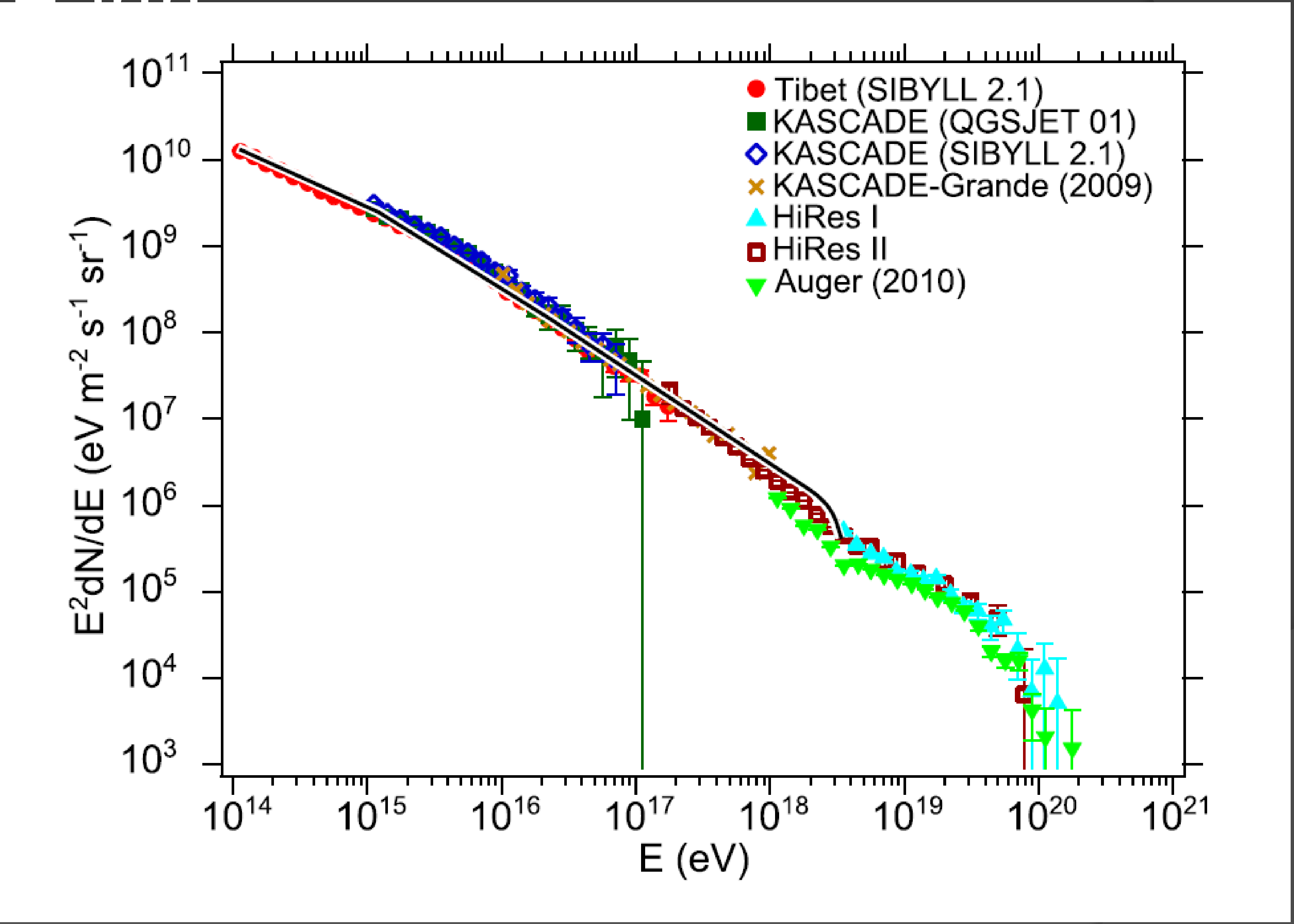
$$D_G=6.2\times10^{28}(\mathrm{pc}/4\,\mathrm{GeV})^{0.6}\ \mathrm{cm^2\ s^{-1}}$$

$$\kappa(\rho,p)=\kappa_B\,p^2\theta(\rho_B-\rho)\,,$$

$$\kappa_B\sim u^2/D_B$$

- Particles injected in disk according to SNR density and p_k ~10^15eV/c
- Acceleration is only inside the bubble

The CR spectrum near the Earth



Ultra-high energy neutrinos produced by cosmic rays accelerated by FB

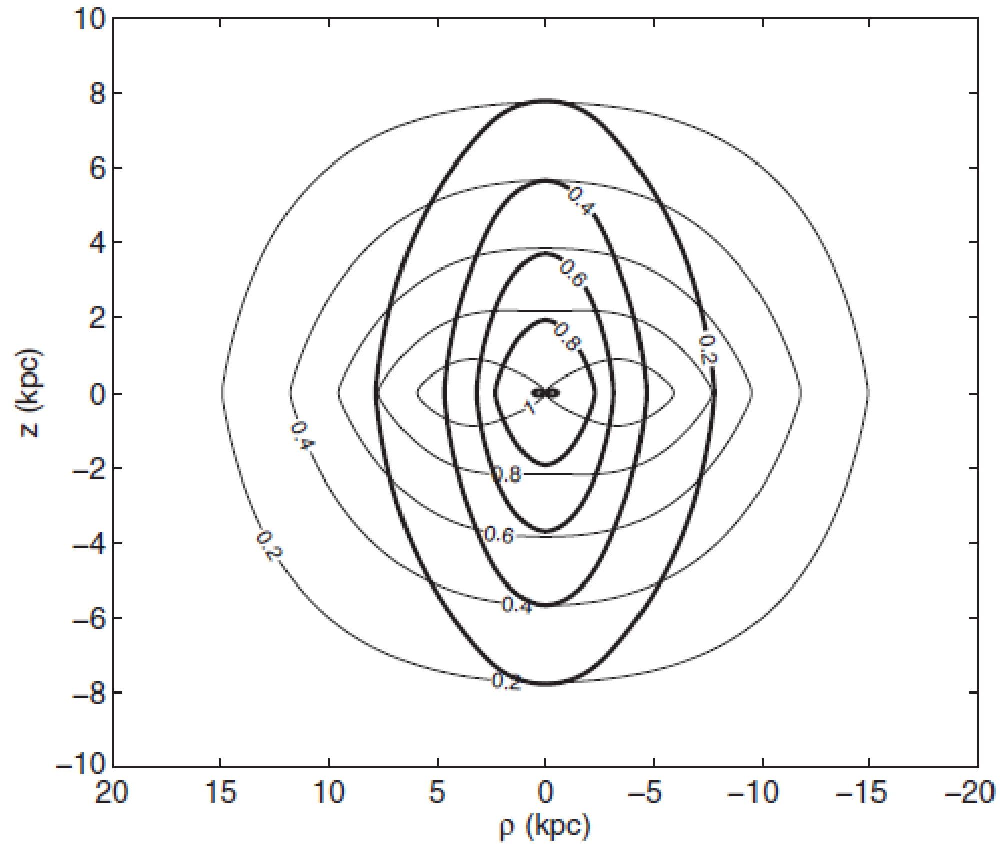


Figure 8. Contour of the relative number density distribution of the re-accelerated CRs ($E > 3 \times 10^{15}$ eV) in the halo (thick lines). The seed for the re-accelerated CRs comes from SNRs in the Galactic plane (thin lines).

Icecube has detected 4-5 out of 28 events above 30TeV, which may originate from cosmic rays with energies >10^15eV from FB (Lunardini et al. 2014). However the spatial distribution of CRs with energies >10^15eV does not show any concentration in the direction of FB!

Summary

- Although the tidal stellar capture rate is low ~10^{-3} yr^{-1} to 10^{-5} yr^{-1} , these processes are common in other normal galaxies, e g. Swift 1644+57.
- But each of these capture events can release ~10^{52} ergs. Perhaps these tidal captures may be responsible for many high energy phenomena around GC including positron annihilation, FB and Cosmic rays with energy >10^{15} eV etc.
- However all these phenomena are indirect evidence of tidal capture events and there are alternative explanations
- In our models there are still a lot of short falls needed to be fixed. For examples how to avoid over-production of tens MeV gamma-rays, how the jet energy produced by accretion can be efficiently transferred to heat up the gas in tens pc region. It is unclear whether successive star captures produce only a single shock at the border of expending envelope of hot plasma or series of shocks going one after other. The Cosmic ray model requires too many fine tune parameters etc.
- More careful studies are necessary!