on the origin and source of the Fermi bubbles

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menu of the day

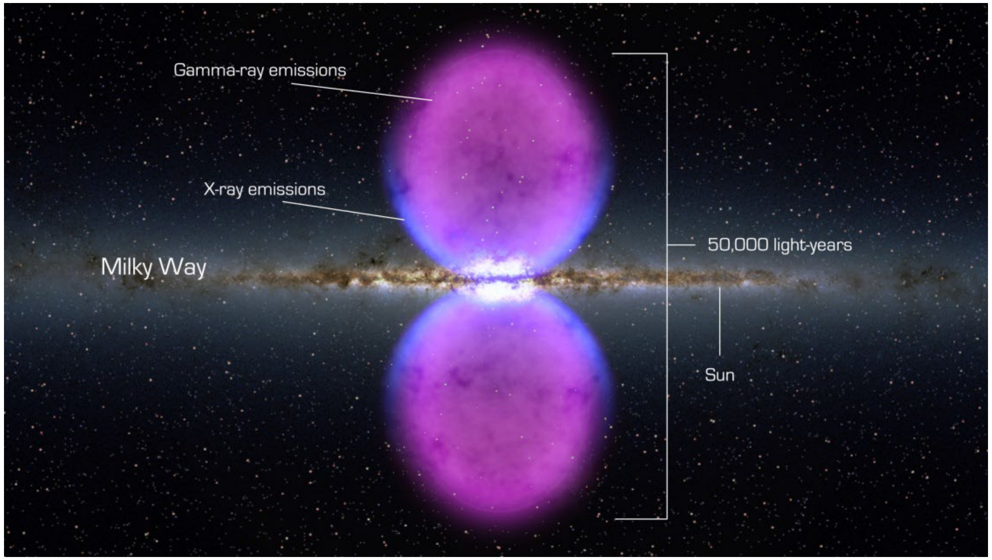
Fermi bubbles
origin
source
...

Fermi bubbles

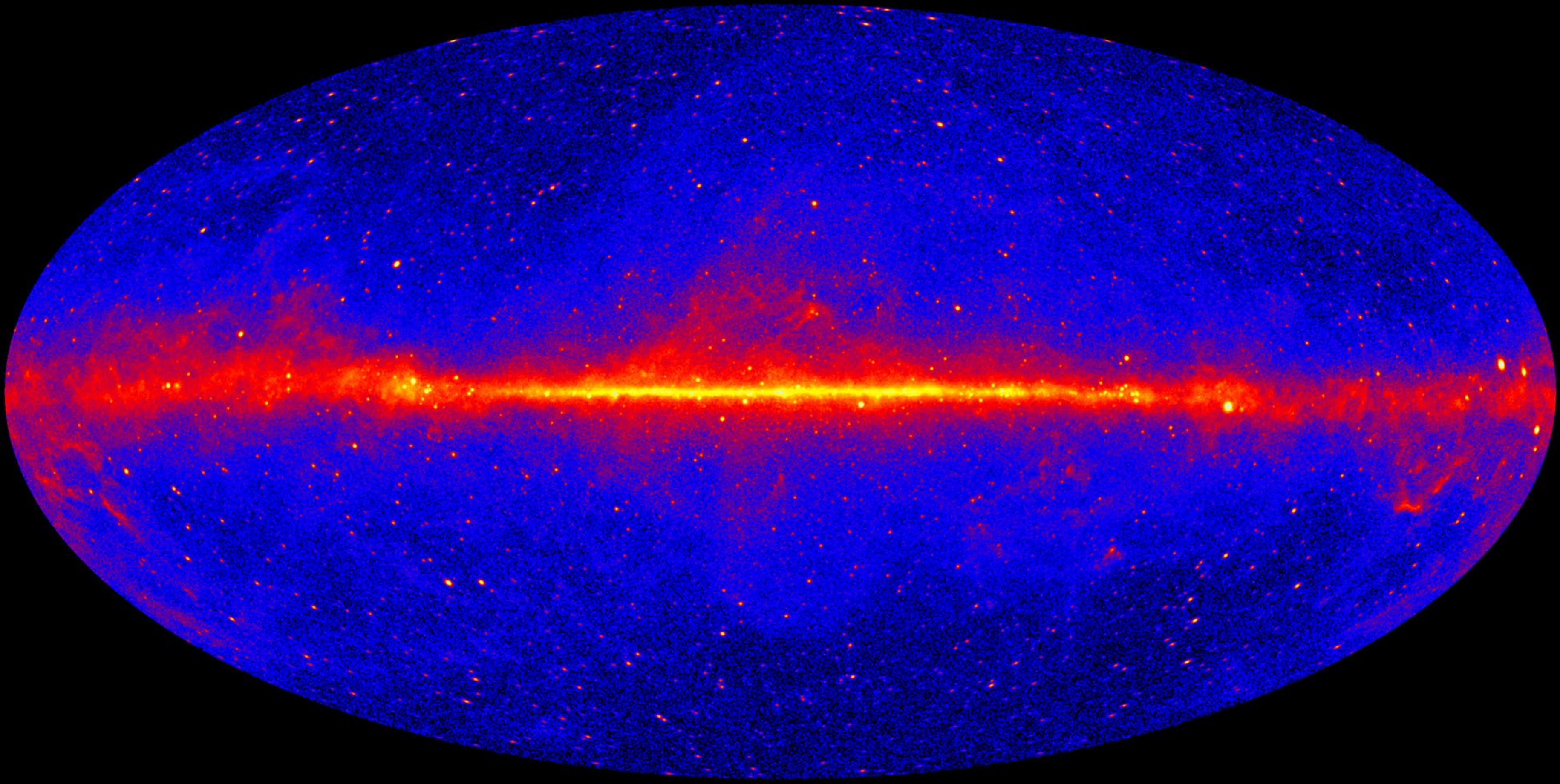
discovery

- in late 2010, two giant bubbles at the Galactic Centre (~ 6 kpc $\times$ 8 kpc) were discovered from the data of *Fermi* gamma ray telescope

credit: NASA/GSFC

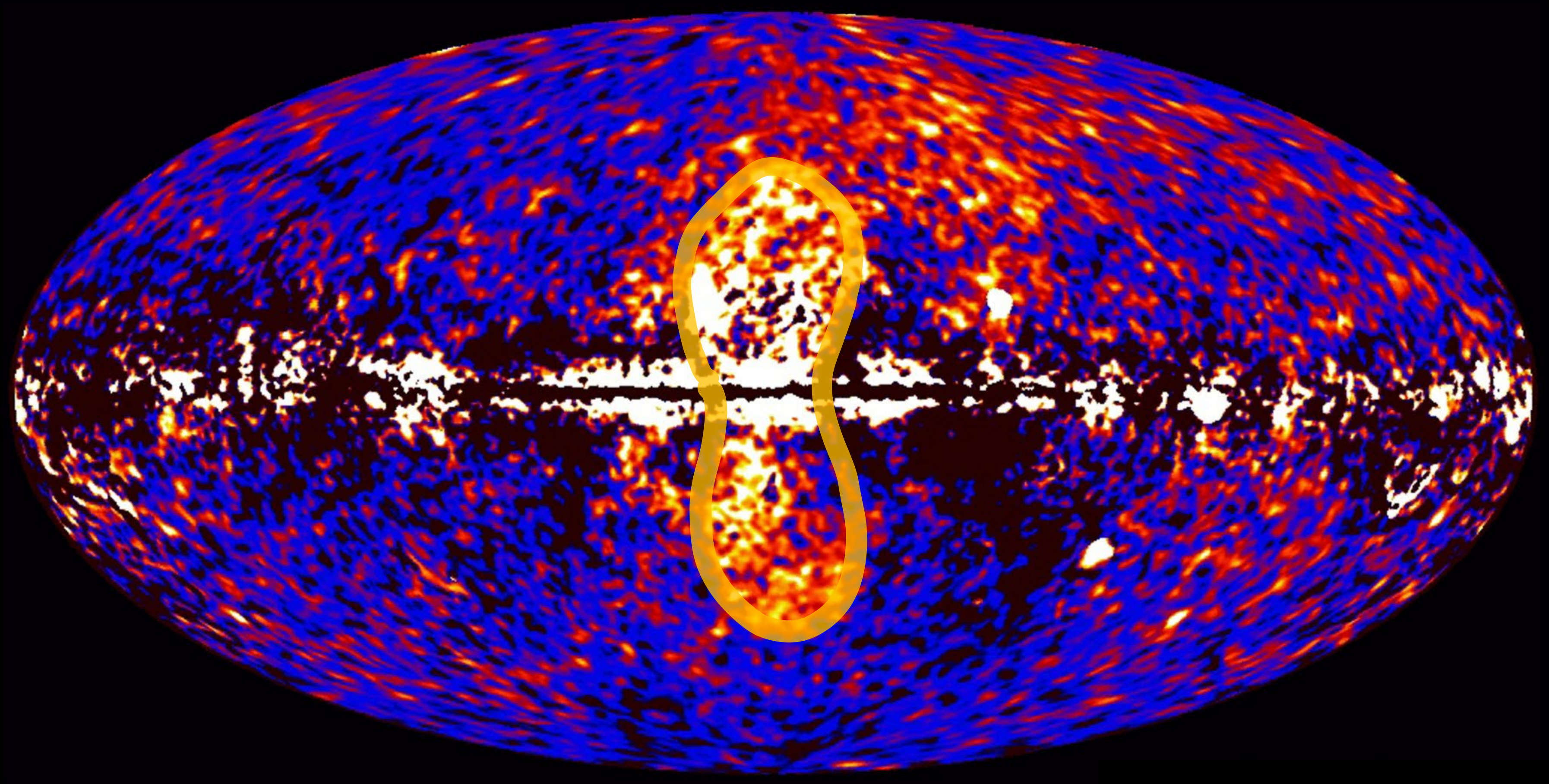


12-year view of the gamma-ray sky by *Fermi*



credit: NASA/DOE/Fermi LAT Collaboration

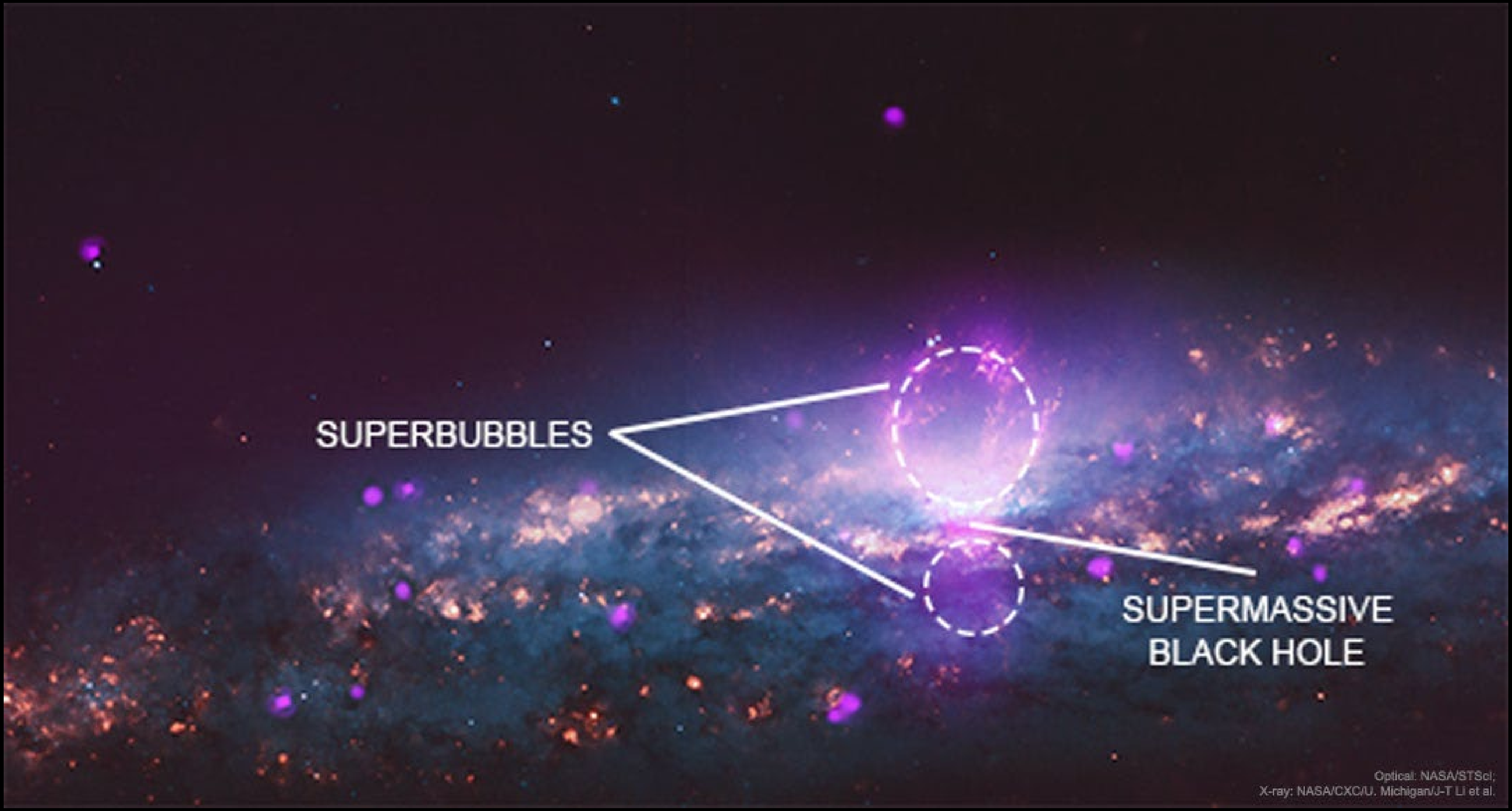
Fermi data reveal giant gamma-ray bubbles



credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.

x-ray superbubbles in galaxy ngc 3079

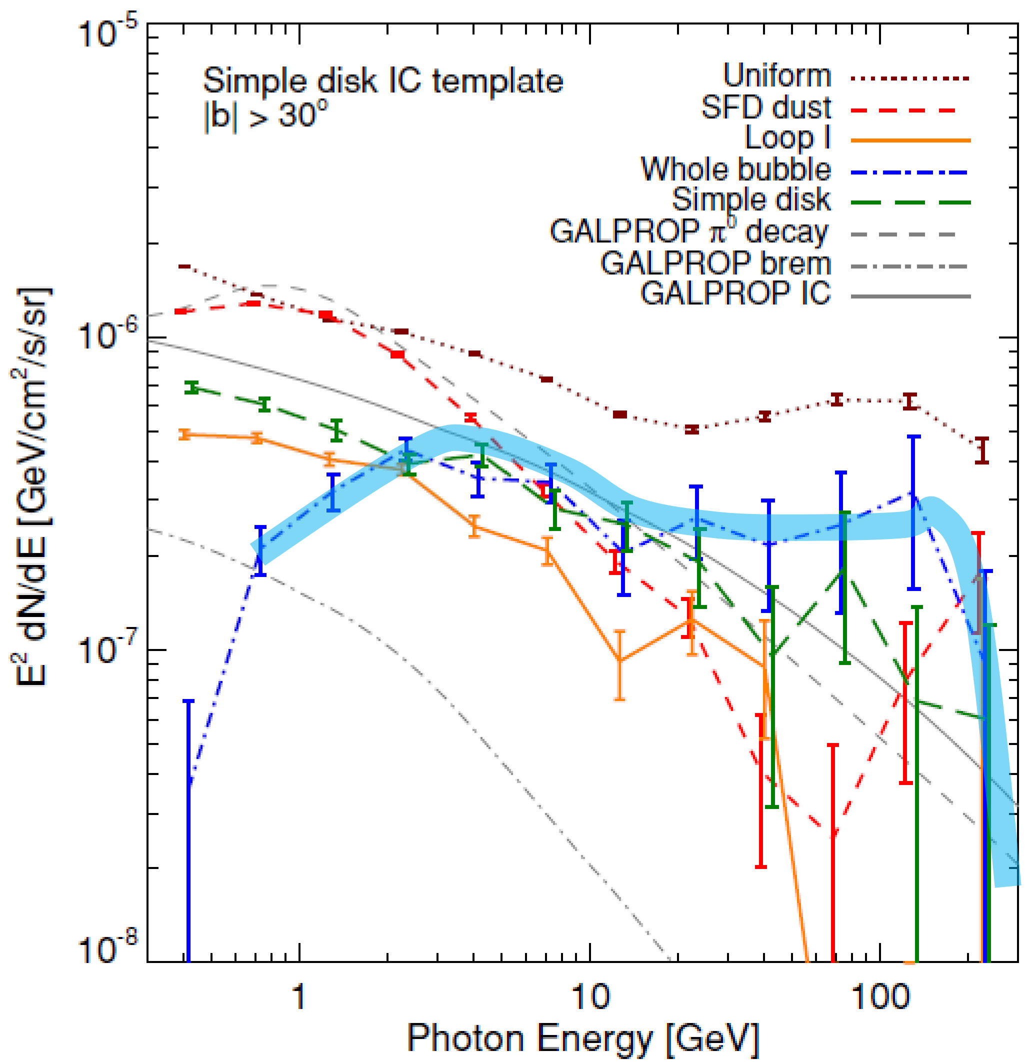
credit: X-ray: NASA, CXC, U. Michigan, J-T Li et al.; Optical: NASA, STScI



x-ray superbubbles in galaxy ngc 3079

credit: X-ray: NASA, CXC, U. Michigan, J-T Li et al.; Optical: NASA, STScI

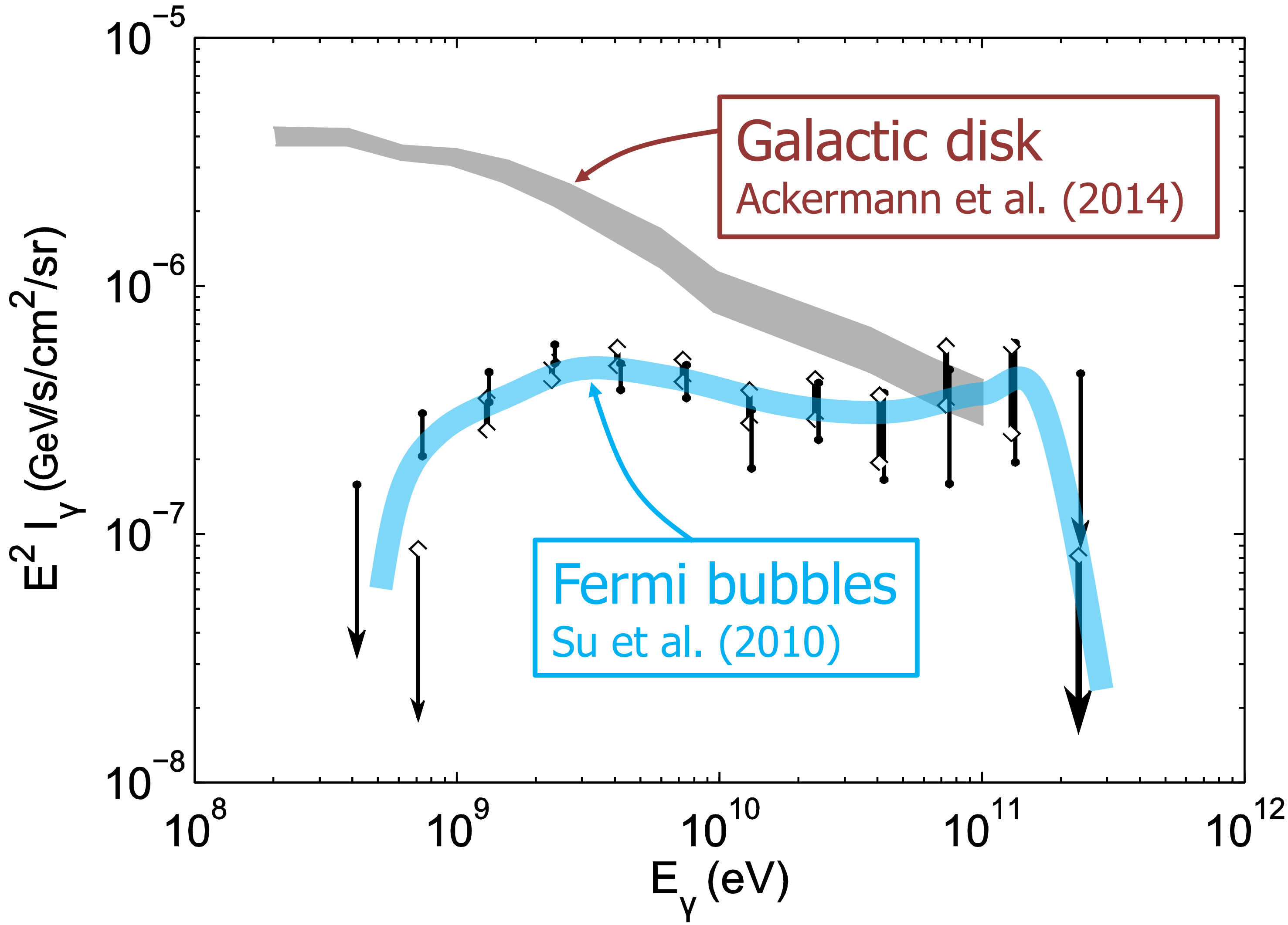
spectrum of various components



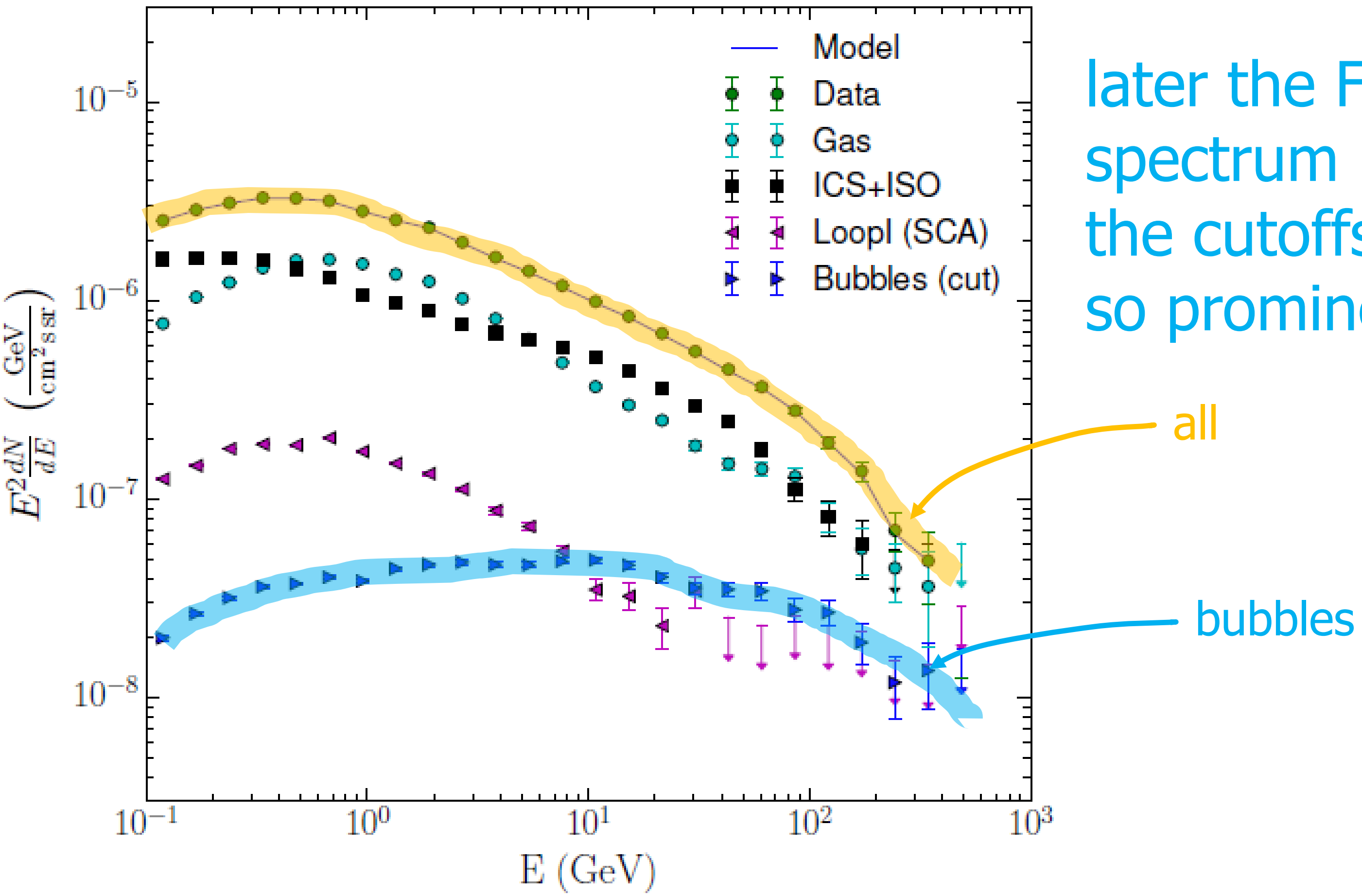
bubble spectrum is very hard and has a sharp cutoff around 100 GeV (the low energy cutoff may not be real), and intensity is relatively uniform spatially

Su et al., ApJ 724, 1044 (2010)

spectrum of the bubbles is hard



gamma-ray spectrum from Fermi (2014)



later the Fermi team: spectrum is hard but the cutoffs are not so prominent

Ackermann et al., ApJ 793, 64 (2014)

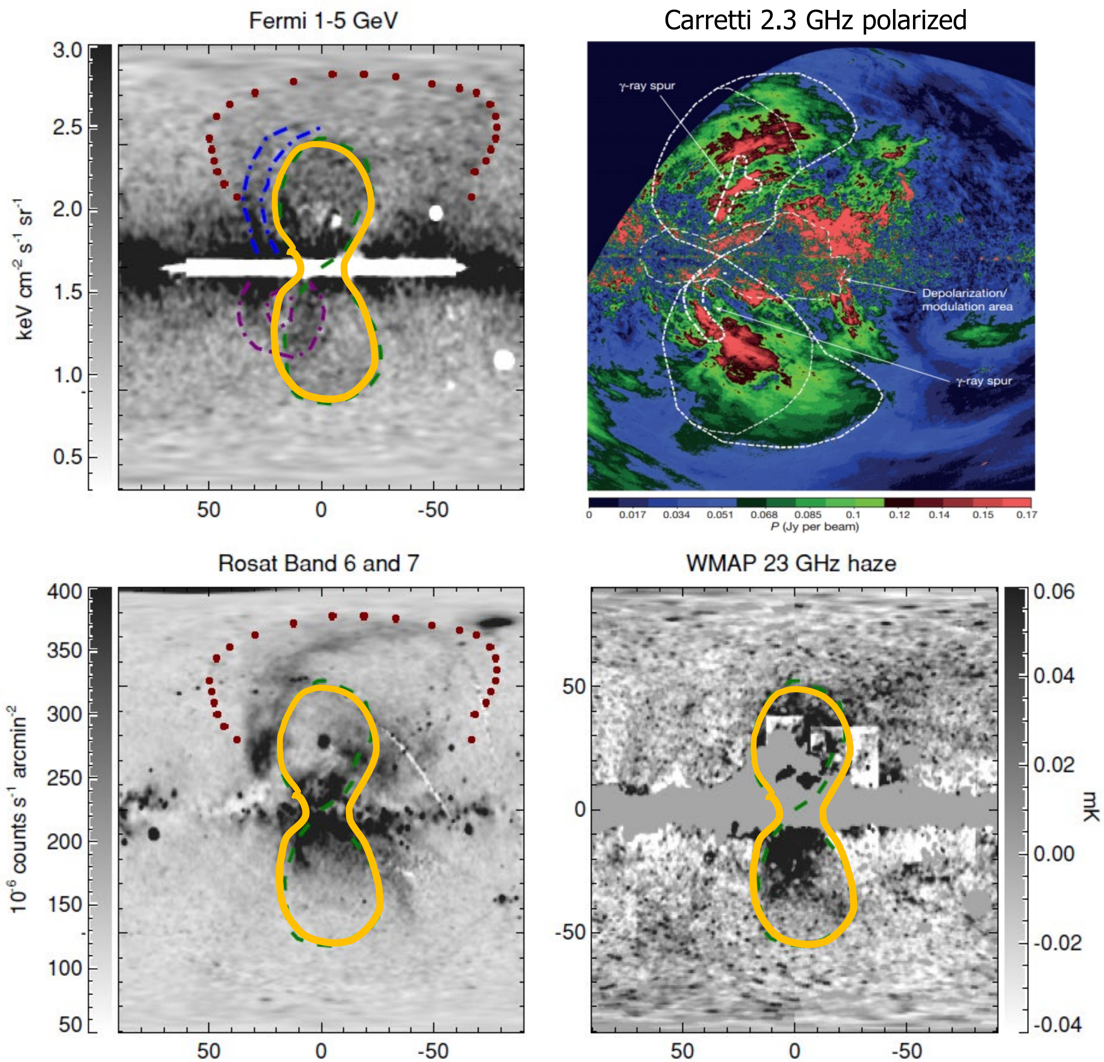
in hindsight?

- besides gamma ray emission, the bubbles are also emitting in other wavelengths
- x-ray, microwave, radio

in different wavelengths

gamma-ray
Su et al. (2010)

radio (?)
Carretti et al. (2013)



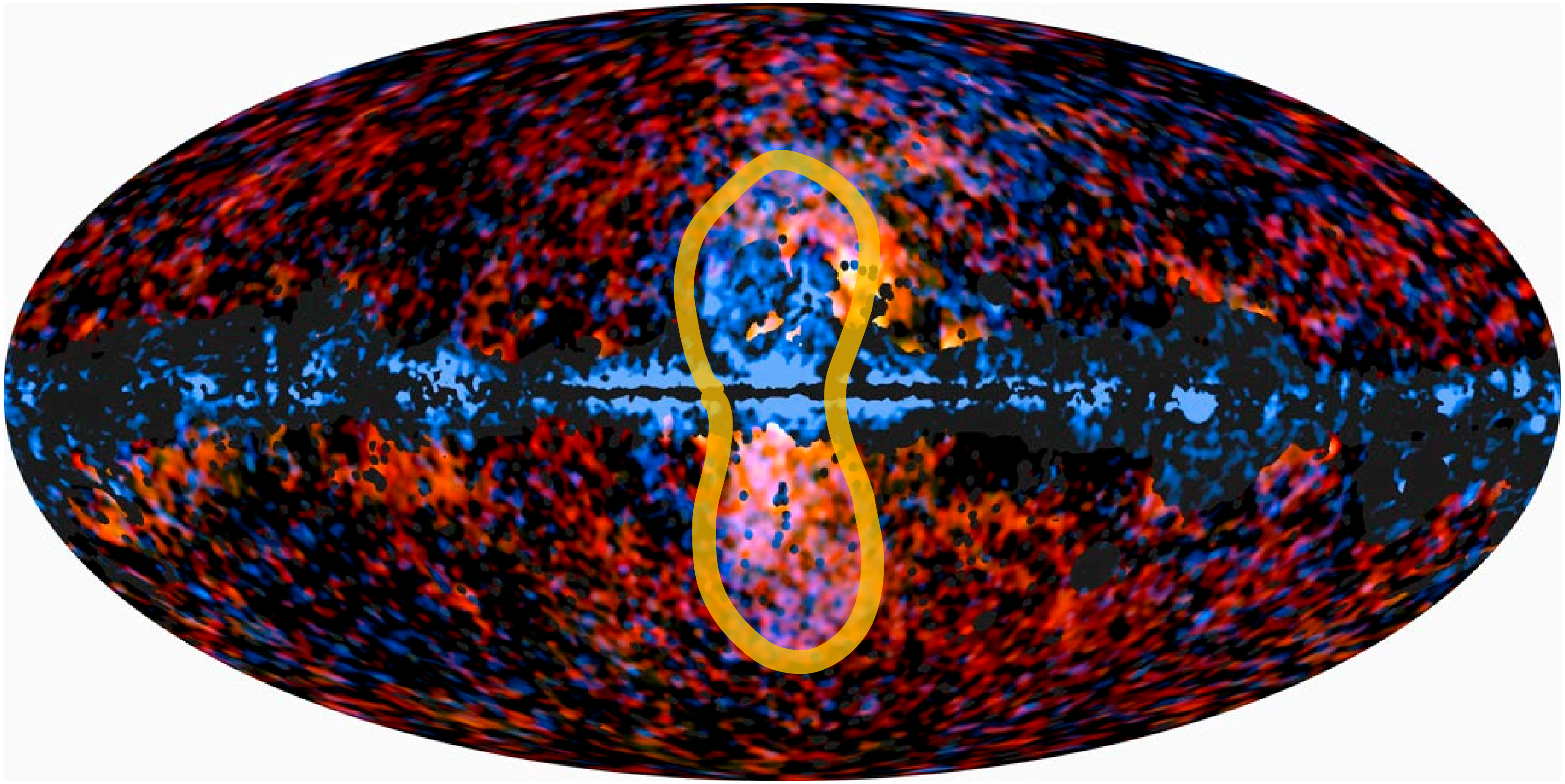
x-ray
Snowden et al. (1997)

microwave
Finkbeiner (2004)

Su et al., ApJ 724, 1044 (2010)

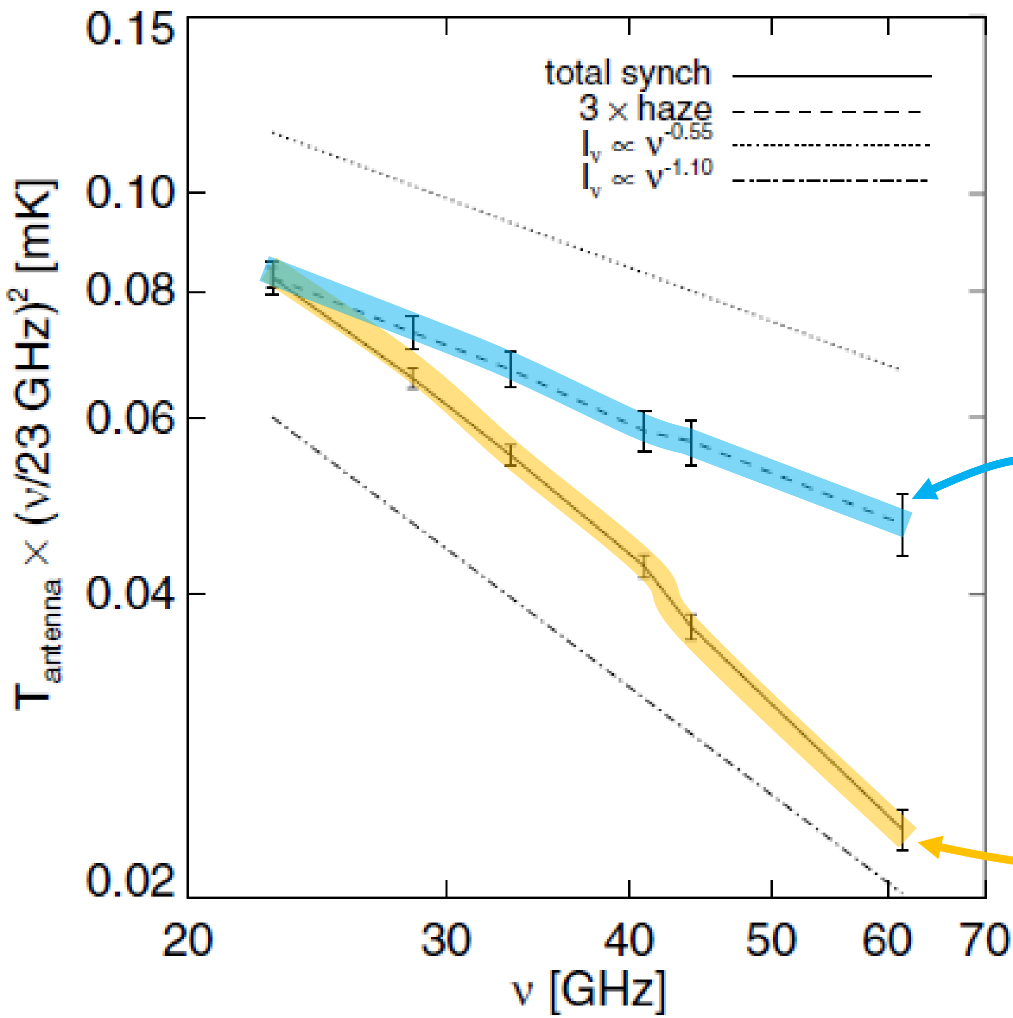
galactic haze and bubbles

red (and yellow): microwave
blue: gamma rays



credit: microwave: ESA/Planck Collaboration
gamma rays: NASA/DOE/Fermi/LAT/Finkbeiner et al.

Galactic haze from Planck



haze spectrum is harder than ambient

Ade et al. (Planck Collaboration), A&A 554, A139 (2013)

summary on observations of FBs

- they are 6 kpc wide and 8 kpc tall
- gamma-ray spectrum: E^{-2}
  - harder than the Galactic one
- spectrum does not change along the bubble
- almost uniform surface brightness
- gamma-ray flux is 4×10^{37} erg/s in $1 \sim 100$ GeV

- microwave counterpart
  - spectrum: $\nu^{-0.5}$
  - flux: 2×10^{36} erg/s in $20{\sim}60$ GHz
- radio counterpart
- X-ray counterpart
- morphology similarity and correlation between GHz and GeV implies the emissions have a common origin
- existence of a population of anomalously hard spectrum HE electrons above GC

questions in mind

- what is(are) the radiation mechanism(s)?
  – hadronic? leptonic?
- what and where is the source or engine?
  – SMBH at the GC? superbubble?
- how does the structure form?
  – outflows? jets?
- what is the nature?
  – one-time event? quasi-steady?

origin?

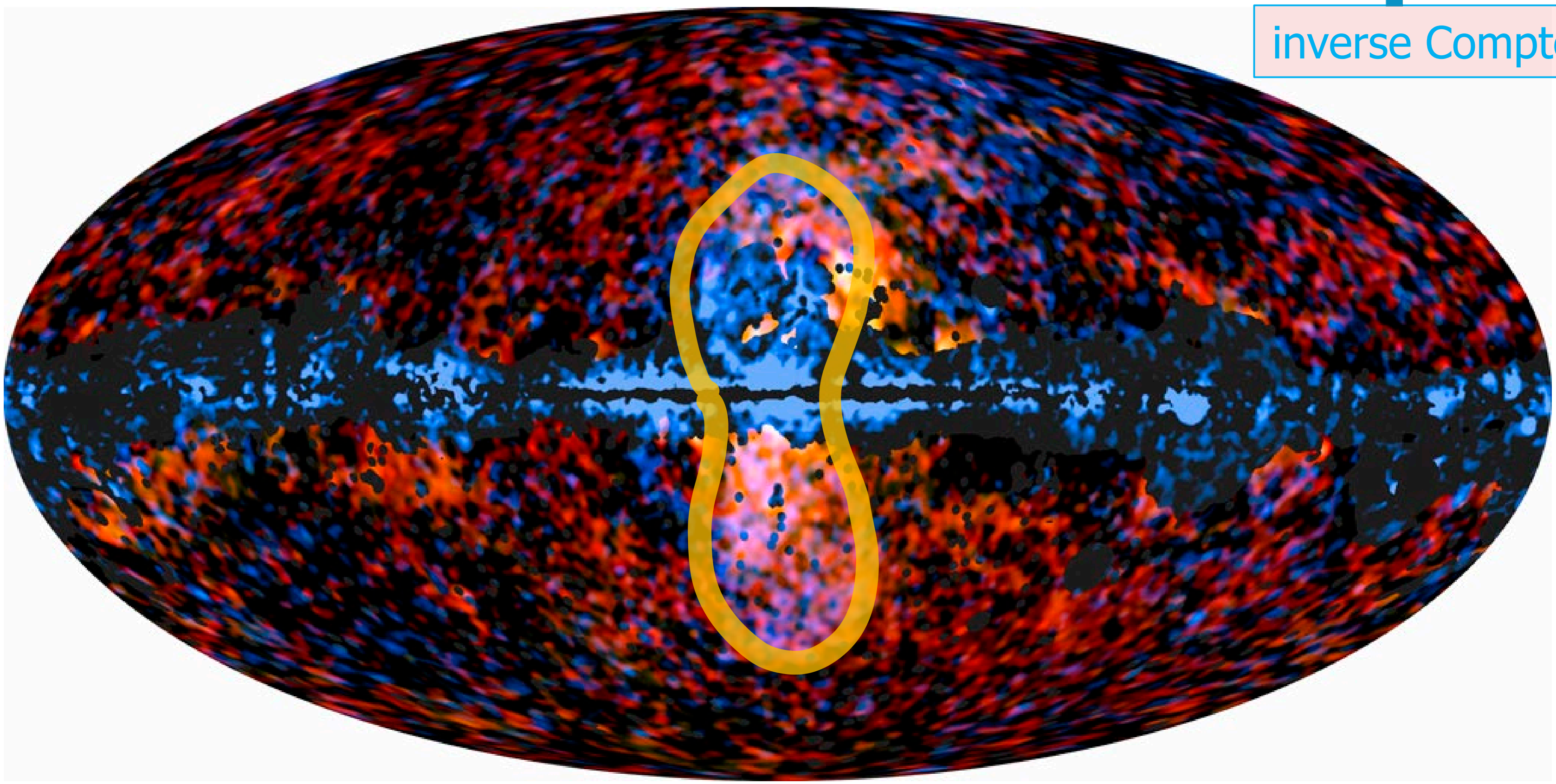
radiation origin?

galactic haze and bubbles

synchrotron?

red (and yellow): microwave
blue: gamma rays

inverse Compton?

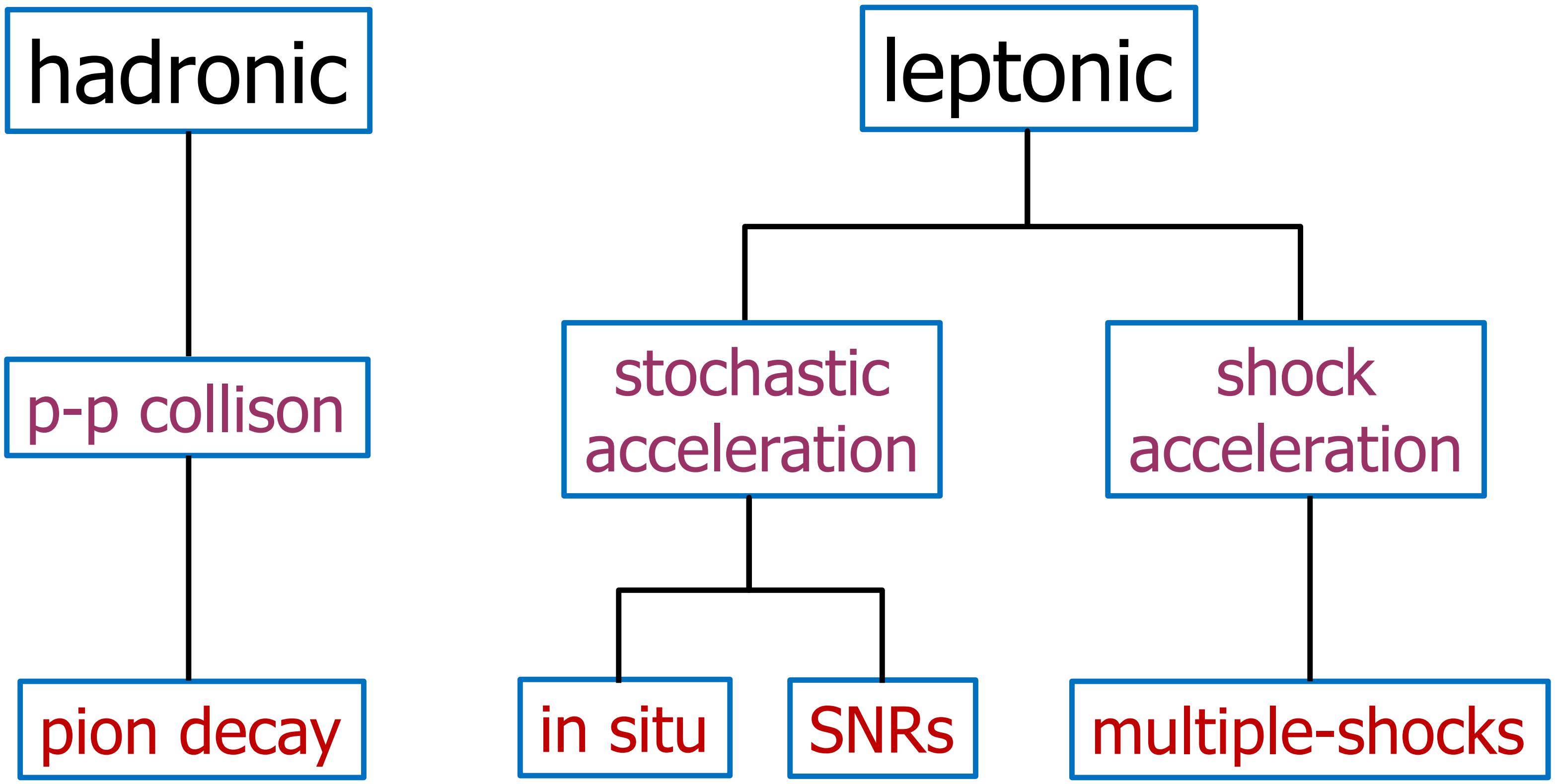


credit: microwave: ESA/Planck Collaboration
gamma rays: NASA/DOE/Fermi/LAT/Finkbeiner et al.

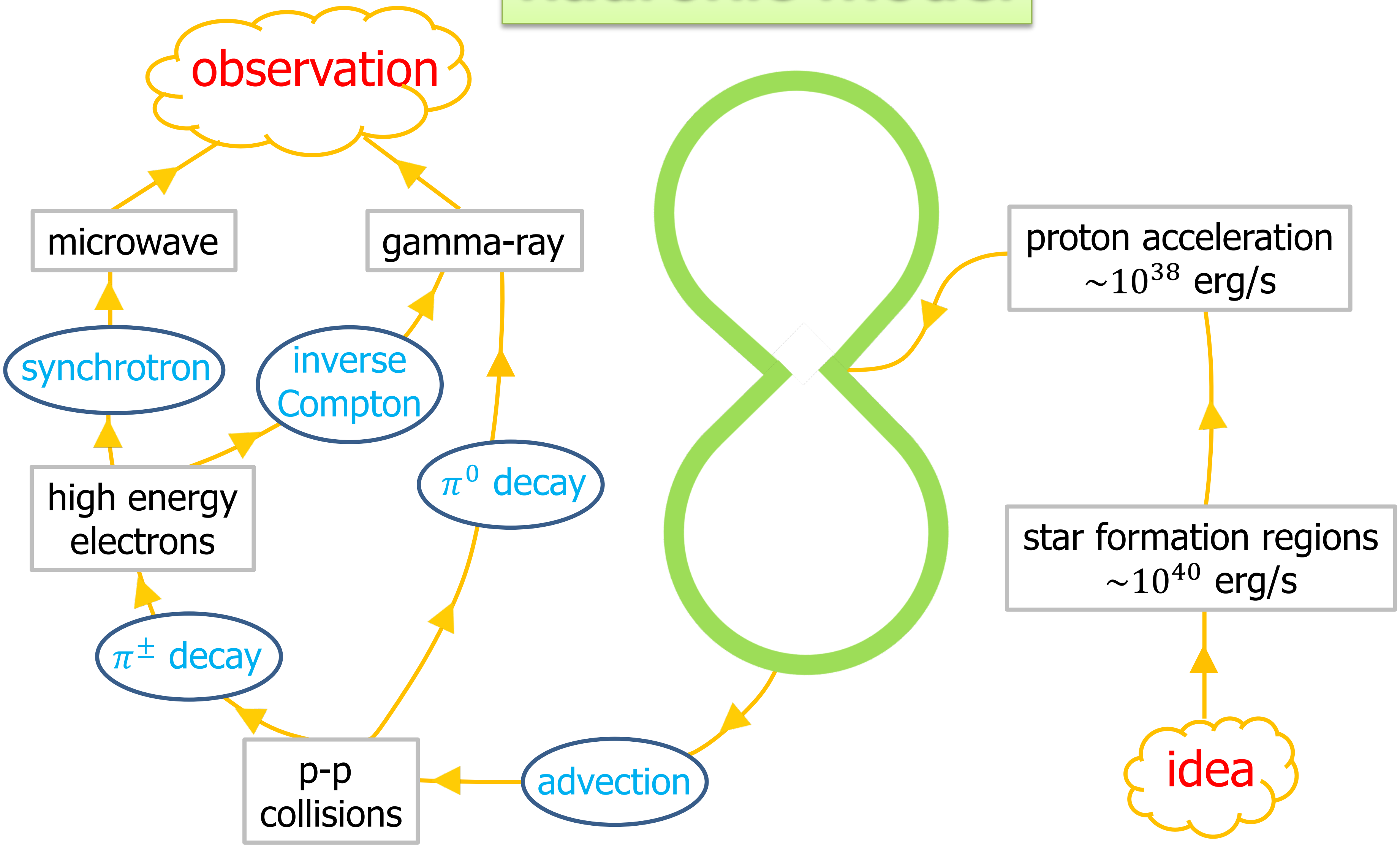
radiation

- need high energy particles
  - in particular, high energy electrons
- hadronic?
- leptonic?

possible models



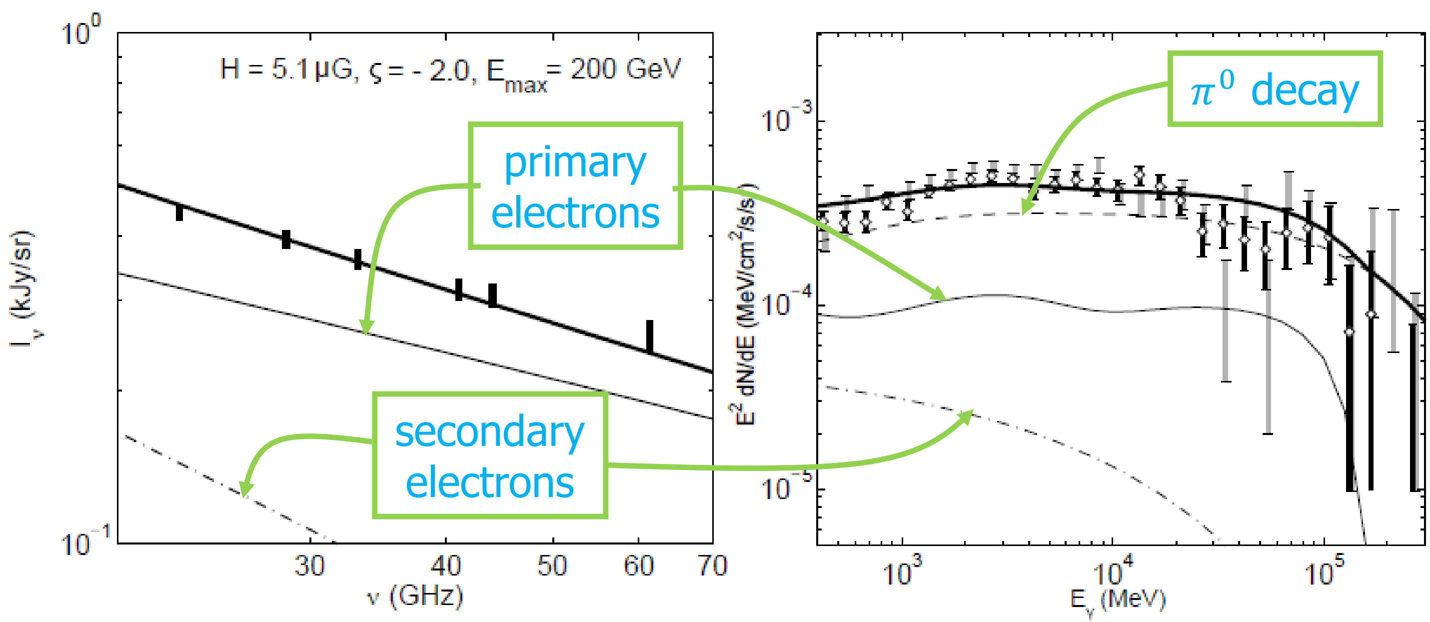
hadronic model



hadronic

- cosmic ray protons produced near the galactic centre are advected into the halo, and somehow confined in the Fermi bubbles
- p-p collisions produce pions
- π^0 decays to gamma rays
- $\pi^{\pm}$ decays to secondary electrons that produce radio emission
- problem: secondary electrons is too soft (E^{-3}) to produce the hard microwave spectrum ($\nu^{-0.5}$)

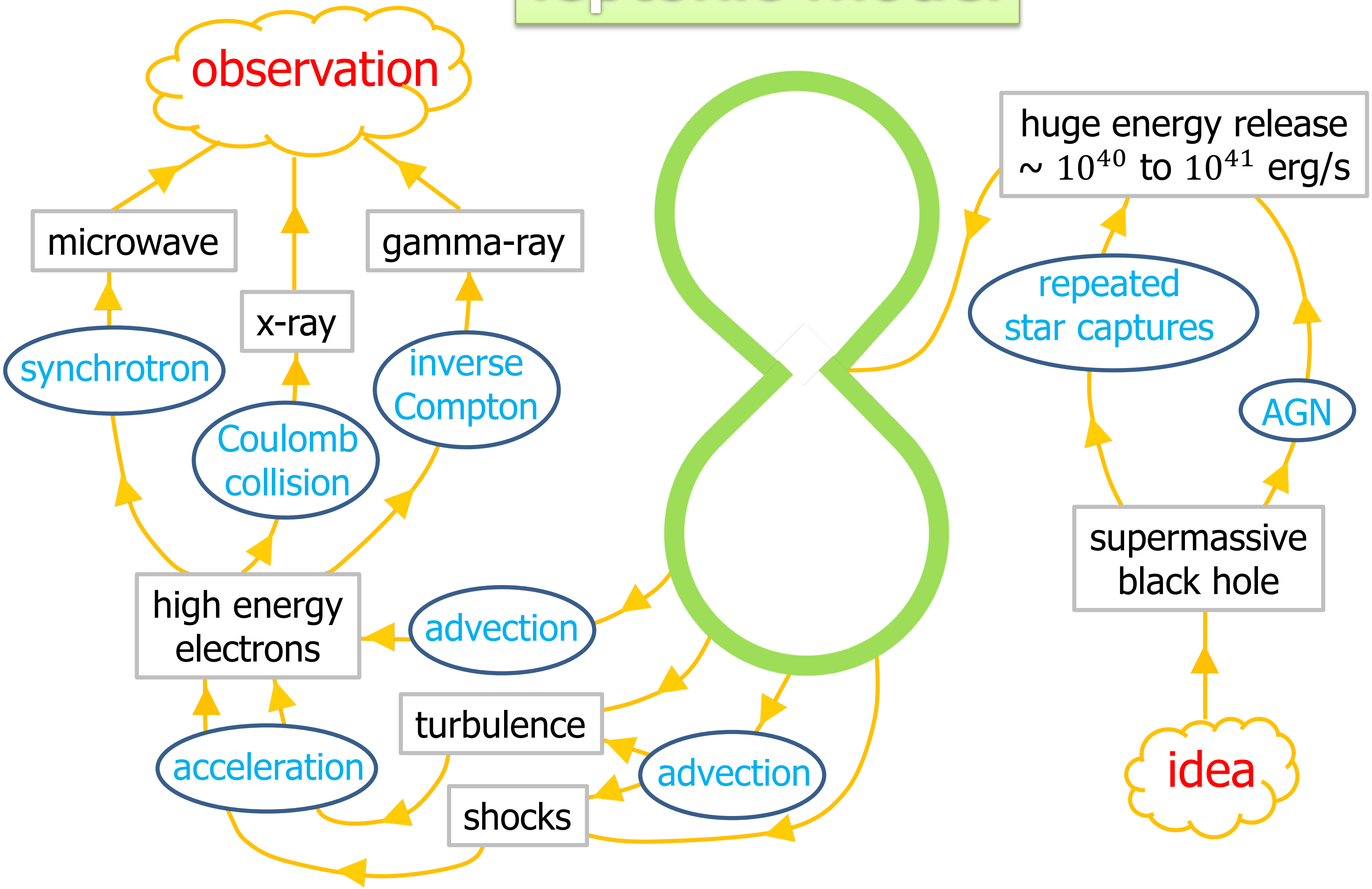
- remedy
  - another source of primary high energy electrons (with hard spectrum)
  - strong adiabatic loss (by expansion flow or wind)
- a mixture of hadronic and leptonic model can explain both spectra



primary electron E^{-2} with a cutoff at 200 GeV

- strong adiabatic loss can help pure hadronic models to produce correct gamma ray and microwave spectrum
  - require magnetic field strength in the FBs ($B \approx 10{\sim}100\ \mu$G) and
  - power of CR sources ($W \approx 10^{41}{\sim}10^{42}$ erg/s)
  - both are much larger than observations
- in our opinion all versions of pure hadronic model are problematic (Cheng et al. 2015a)

leptonic model



leptonic

- lifetime of relativistic electrons is quite short
- require in situ acceleration in the halo
(or very fast advection of high energy electrons into the halo)
- acceleration by turbulence or shocks
- shocks from tidal disruptions of stars at the supermassive black hole at the Galactic centre?

stochastic acceleration

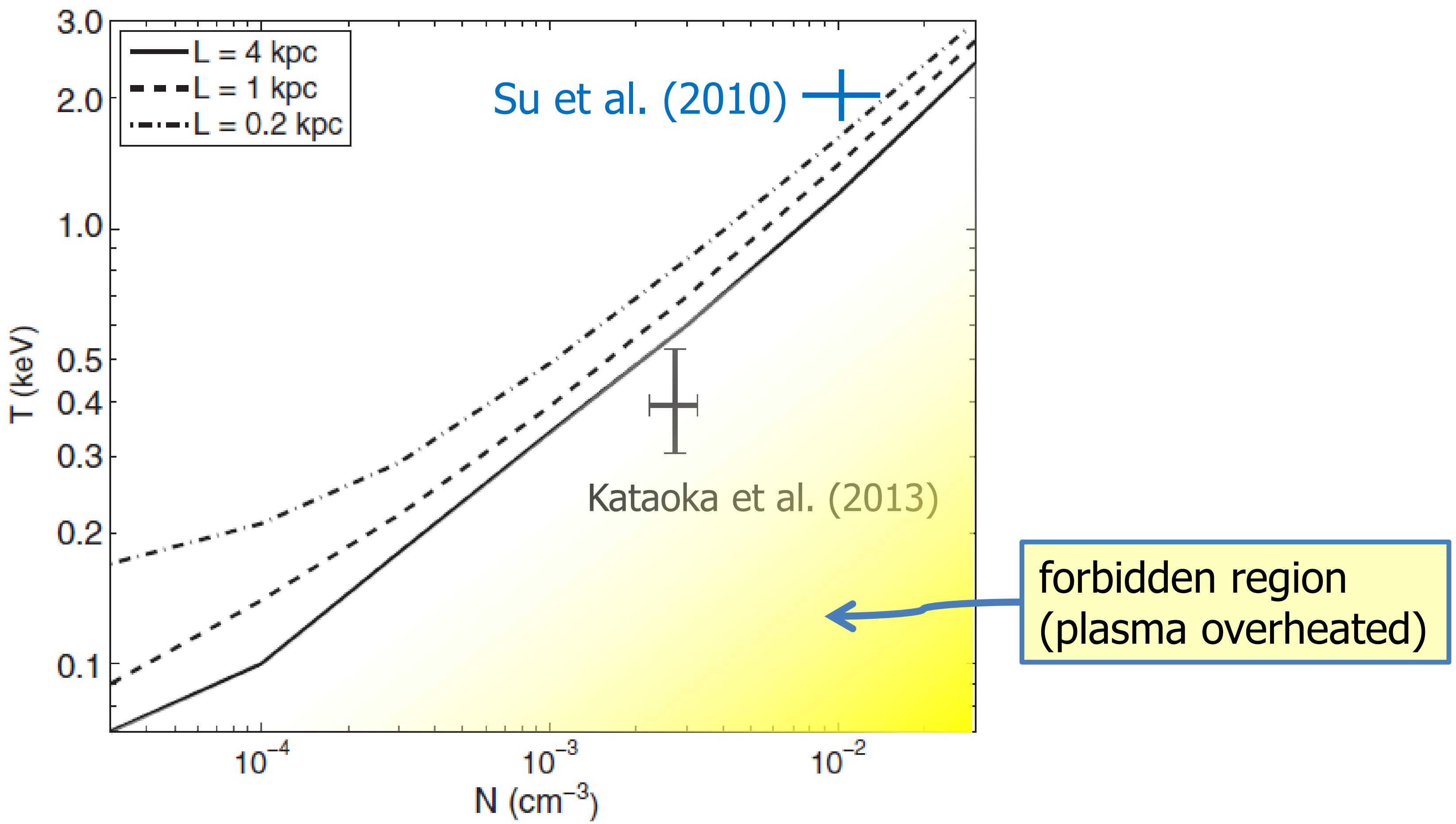
- high energy electrons (~ 100 GeV) responsible for both gamma-ray (inverse Compton) and microwave (synchrotron)
- seed for high energy electrons
  - acceleration of in situ thermal plasma: from $0.2 \sim 1$ keV to 300 GeV
  - re-acceleration of high energy electrons from SNRs in the Galactic plane: from 1 GeV to 300 GeV
- acceleration process
  - MHD turbulence
  - supersonic turbulence (multiple-shock acceleration)

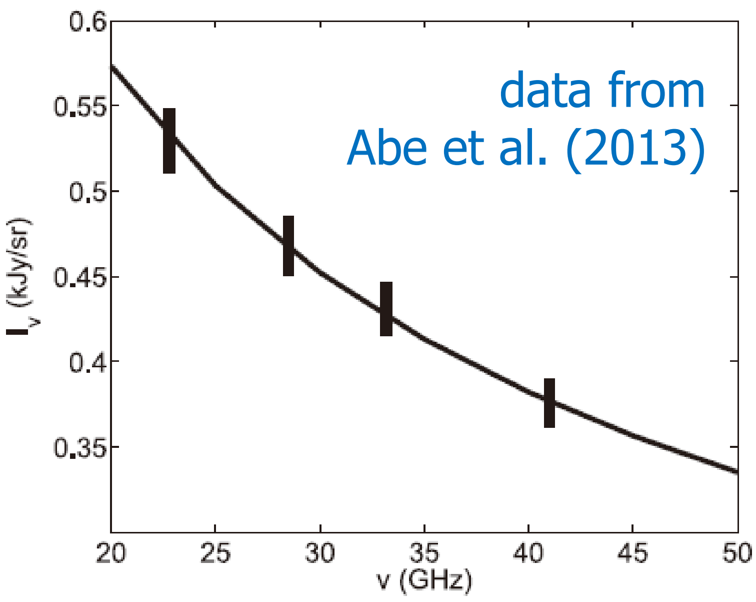
in situ thermal plasma

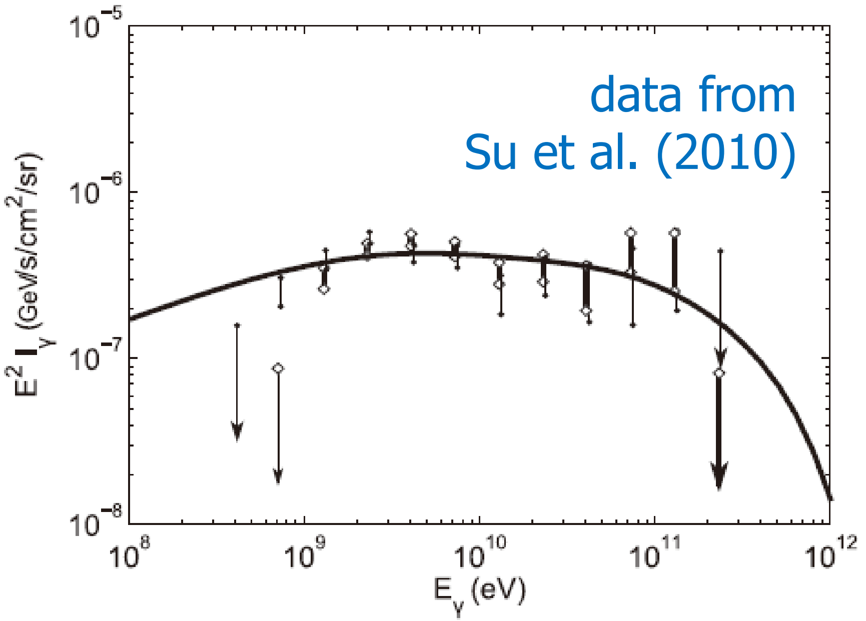
$$\frac{\partial f}{\partial t} + \frac{1}{p^2}\frac{\partial}{\partial p}p^2\left[\left(\frac{dp}{dt}\right)_C f - \{D_C(p) + D_F(p)\}\frac{\partial f}{\partial p}\right] + \frac{f}{\tau} = 0$$

- stochastic acceleration forms hard spectra with index close to `$-1$', but radio observations require index `-2'
  - remedy: escape of HE electrons to 'soften' spectrum
- acceleration range is large, number of thermal electrons accelerated to $E > 1$ GeV may not be high enough to produce observed flux

- plasma can be easily overheated
- to make acceleration efficient it should not be too cold or too dense





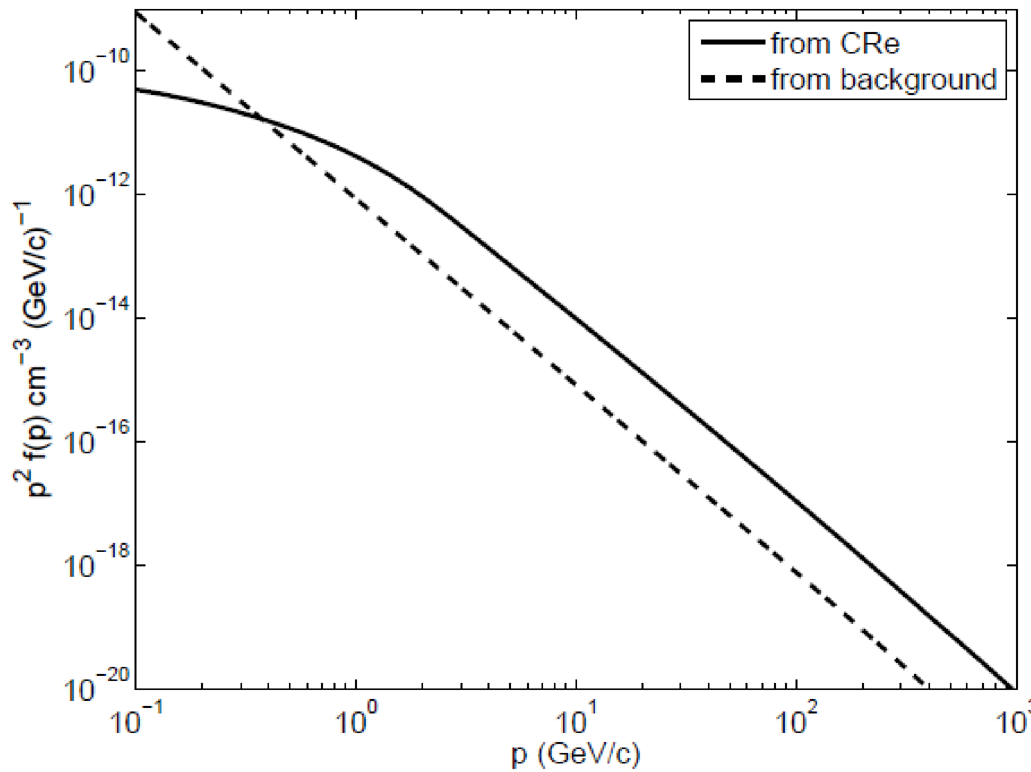


- we conclude that in situ acceleration from a thermal background plasma is possible, but the range of parameters of the FB model is strongly restricted (Chernyshov et al. 2012 and Cheng et al. 2014)

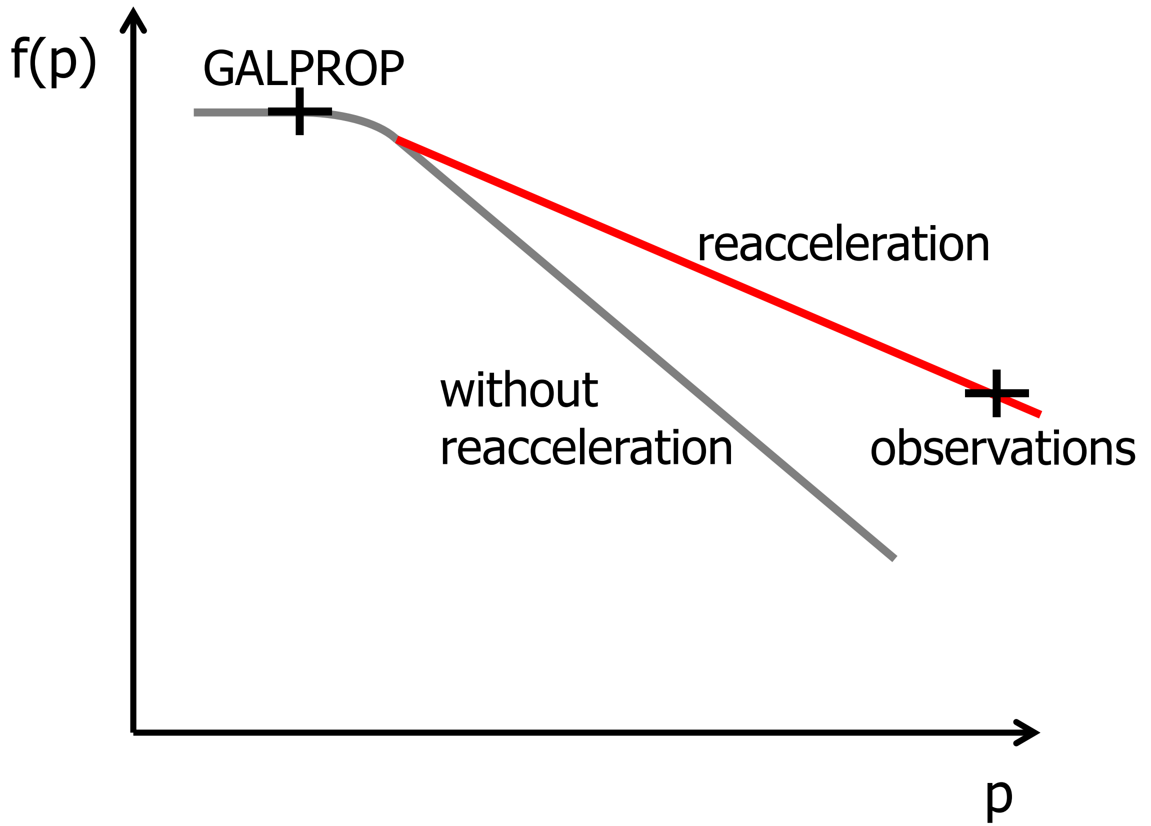
electrons from SNRs

$$-\nabla \cdot \left[\overleftrightarrow{\mathbf{D}}(r,z,p) \cdot \nabla f\right] + \frac{1}{p^2}\frac{\partial}{\partial p}\left\{p^2\left[\frac{\mathrm{d}p}{\mathrm{d}t}f - \kappa(r,z,p)\frac{\partial f}{\partial p}\right]\right\} = Q(r,p)\delta(z)$$

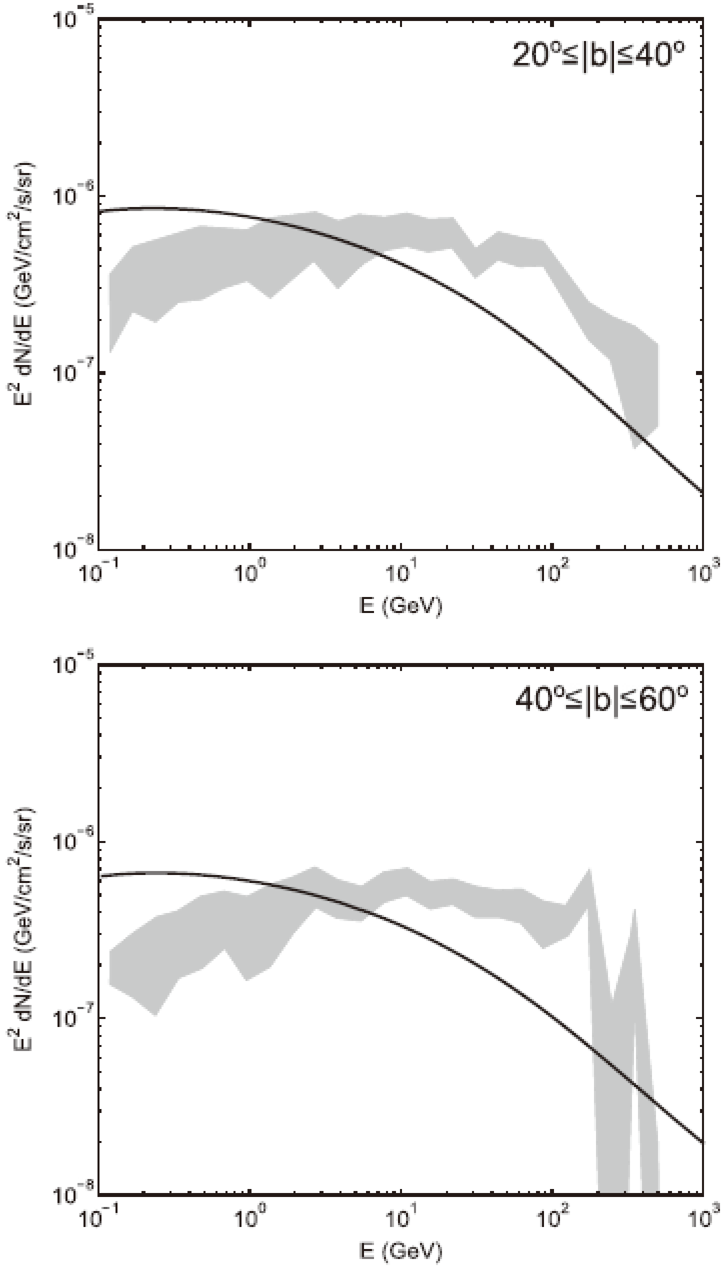
- more efficient than from thermal plasma
- but other shortcomings



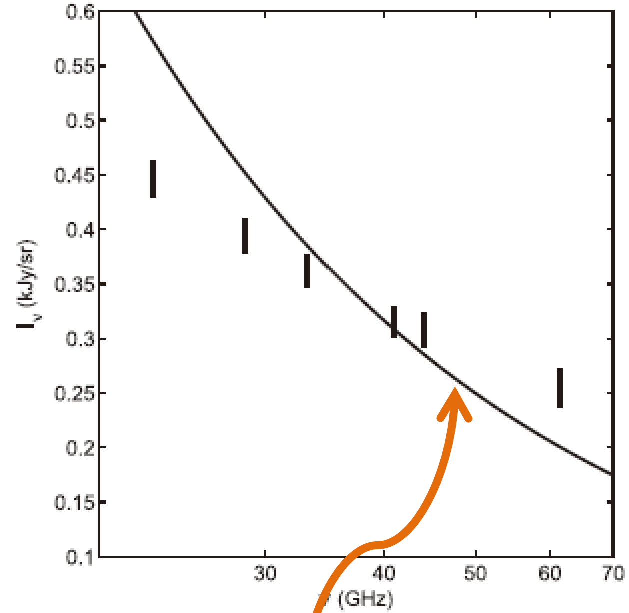
- density of cosmic ray electron is fixed
- reaccelerated spectrum is too steep



data from Ackermann et al. (2014)



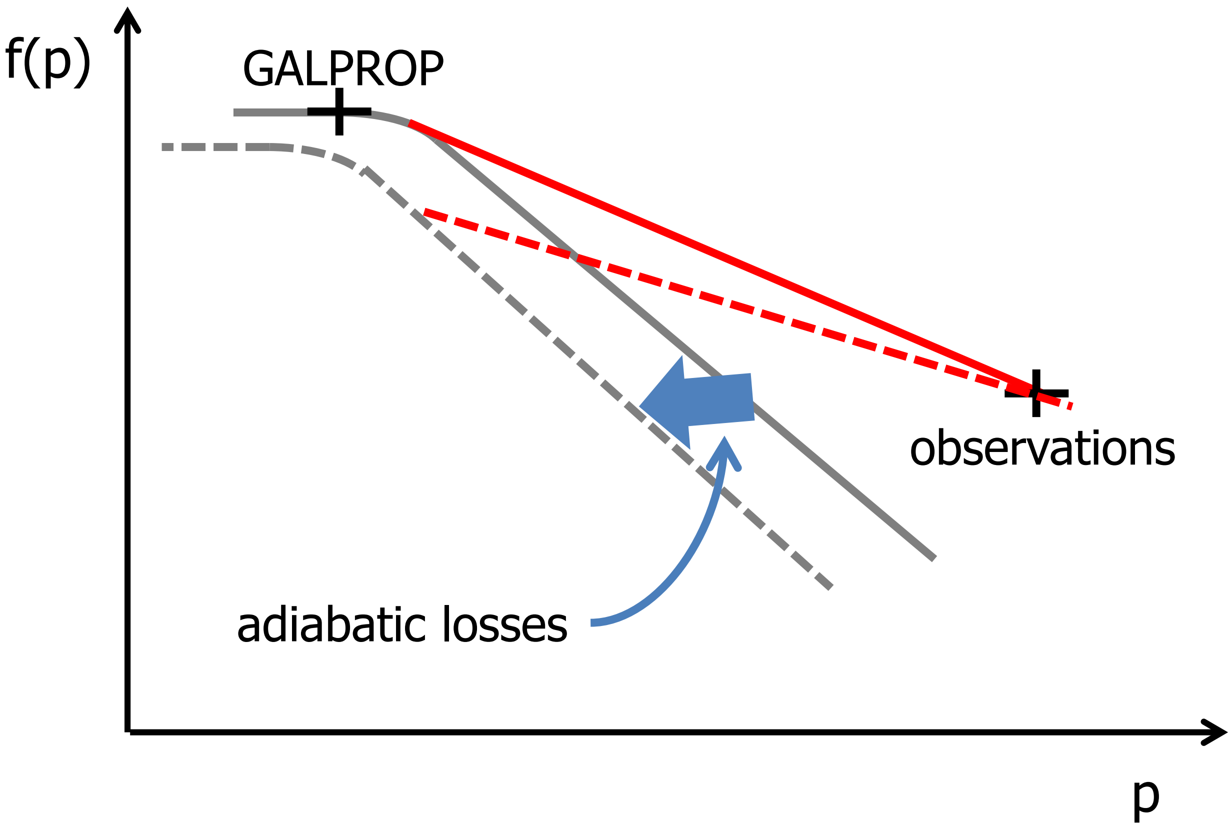
data from Abe et al. (2013)



model spectrum
is too steep!

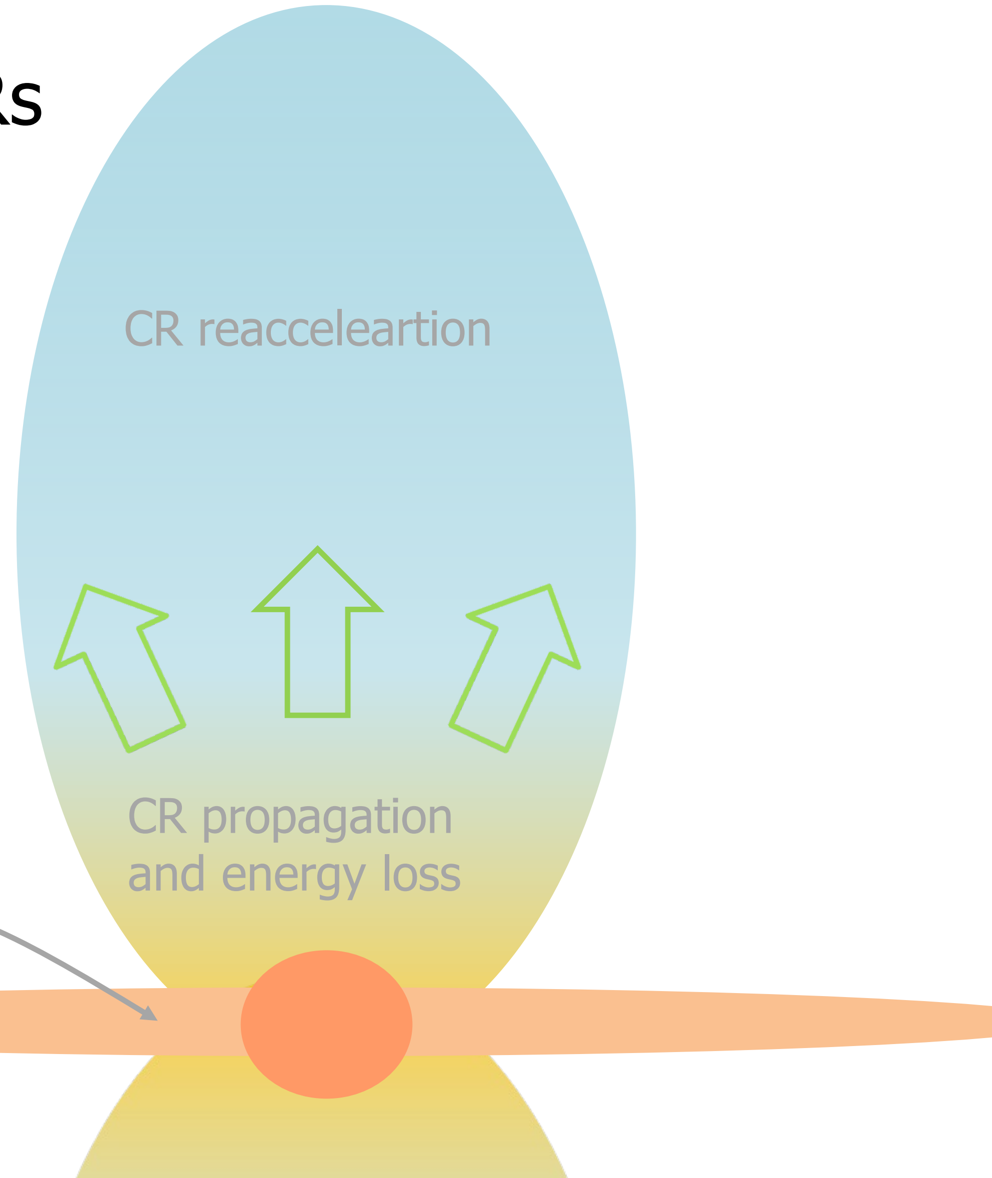
gamma-ray: Ackermann et al. (2014)
micro-wave: Ade et al. (2013)

- remedy: efficient adiabatic losses due to expansion flow (wind) within Fermi bubbles
- spectrum becomes harder

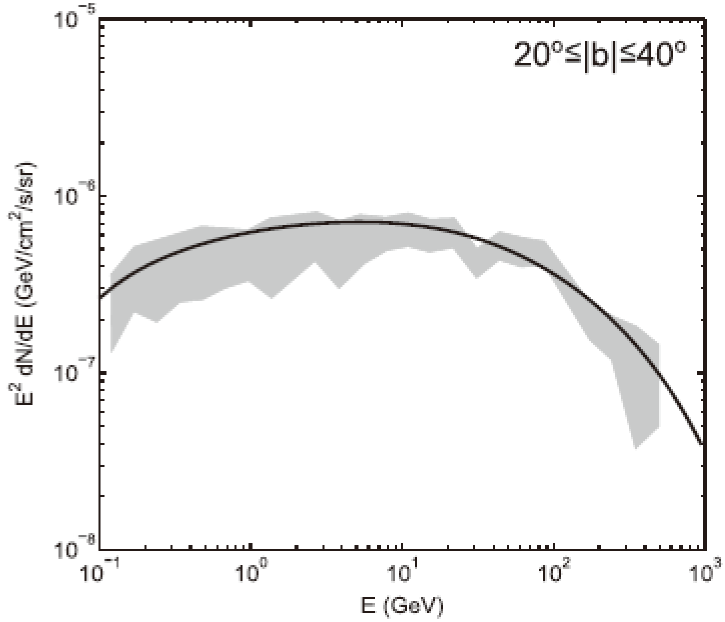


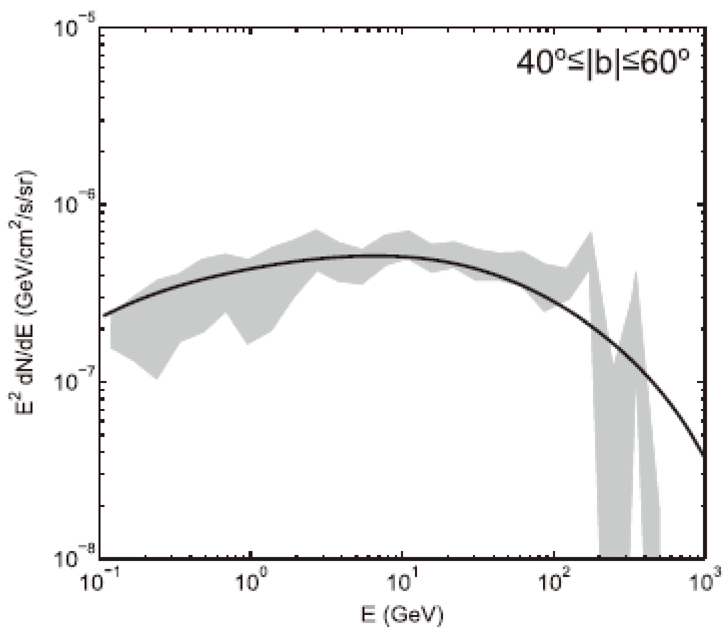
$$\nabla\cdot\left[\mathbf{u}(z)f - \overleftrightarrow{\mathbf{D}}(r,z,p)\cdot\nabla f\right] + \frac{1}{p^2}\frac{\partial}{\partial p}\left\{p^2\left[\left(\frac{\mathrm{d}p}{\mathrm{d}t} - \frac{p}{3}\nabla\cdot\mathbf{u}\right)f - \kappa(r,z,p)\frac{\partial f}{\partial p}\right]\right\} = Q(r,p)\delta(z)$$

- CR electrons from SNRs in the disk
- propagate to halo in an expansion flow
- reaccelerate in the bubbles

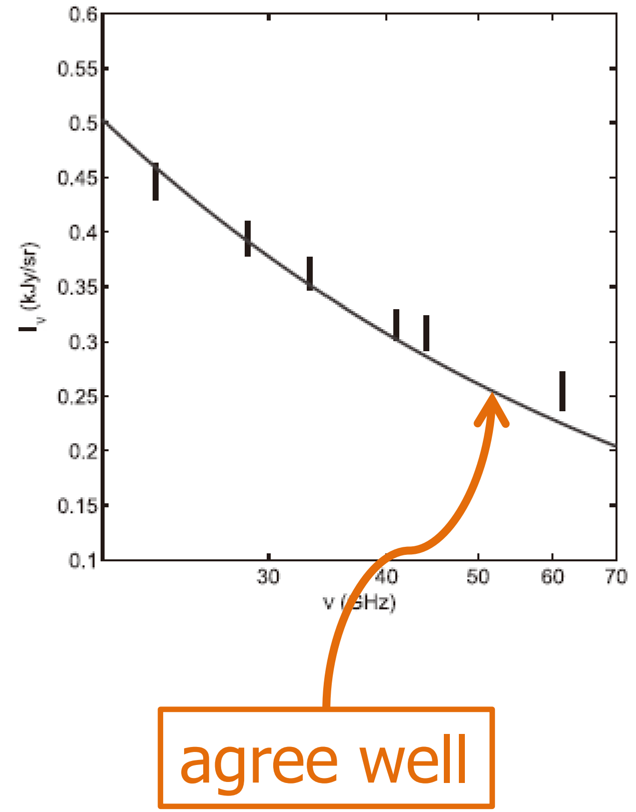


data from Ackermann et al. (2014)





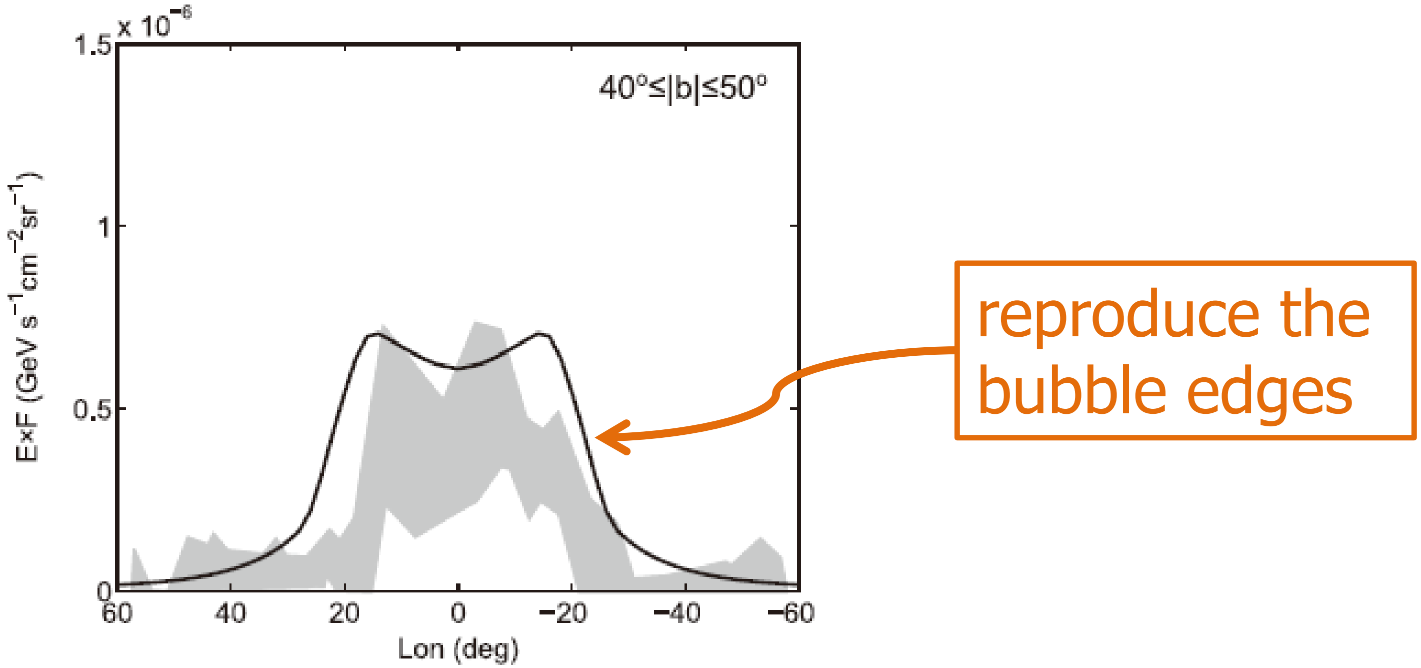
data from Abe et al. (2013)



gamma-ray: Ackermann et al. (2014)
micro-wave: Ade et al. (2013)

- the model is able to reproduce the gamma-ray and microwave emission from the FBs but only for an appropriate combination of acceleration and adiabatic losses
- our analysis shows that in order to produce the observed gamma-ray and microwave spectra
  - characteristic frequency of stochastic acceleration should be about 10^{-14} s^{-1}
  - characteristic frequency of adiabatic energy losses should be about 10^{-15} s^{-1}

data from Akermann et al. (2014)



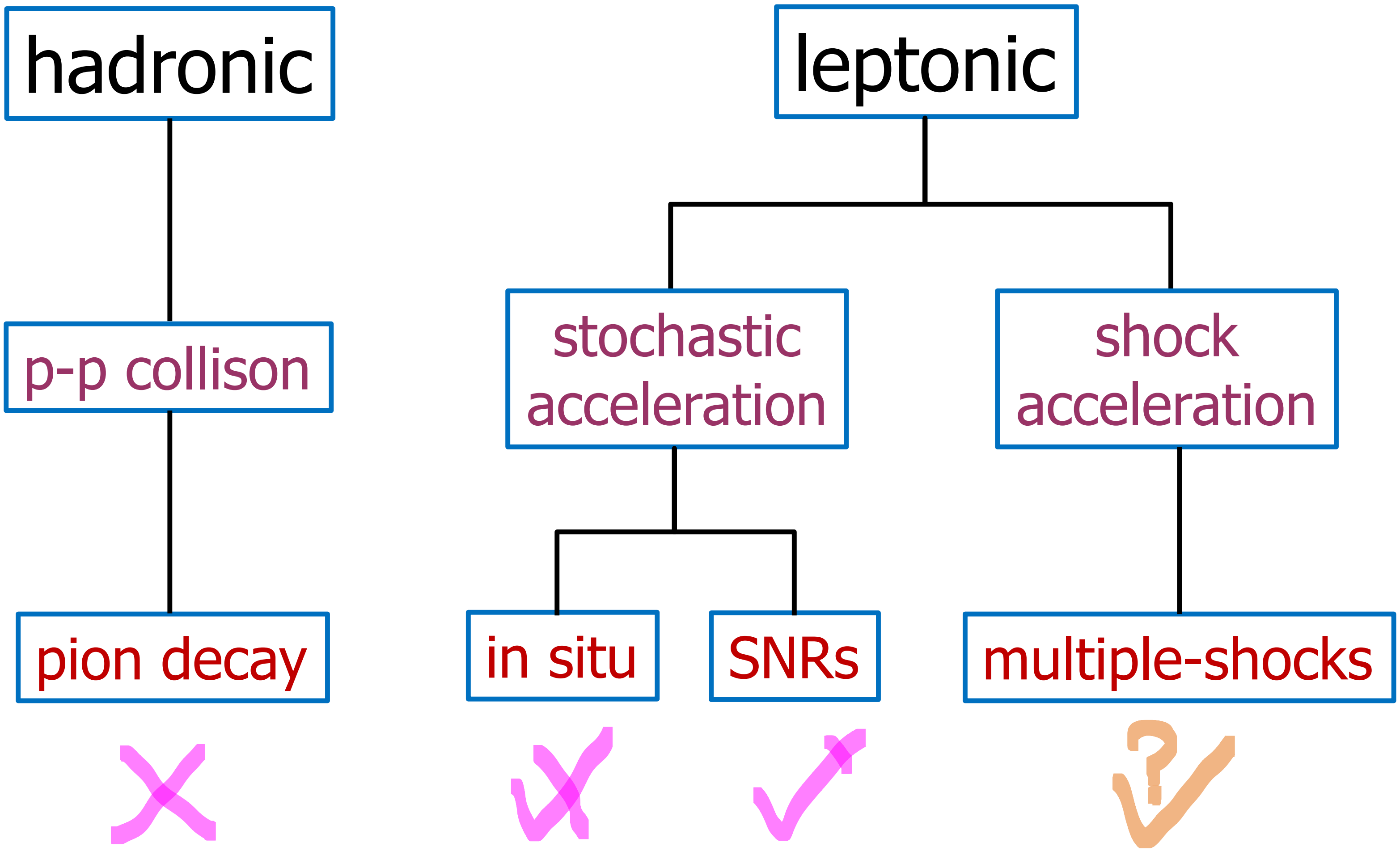
- reacceleration of SNR electrons from Galactic plane can reproduce the spectral and spatial parameters of emission from the Fermi bubbles, but for special conditions (Cheng et al. 2015b)

summary on radiation from FBs

- hadronic model is problematic as it is unable to produce the microwave spectrum from the FBs
- leptonic model for both gamma ray and microwave emissions from FBs
  - stochastic acceleration
  - shock acceleration

- two stochastic acceleration models
  - acceleration of in situ thermal plasma ($0.2\sim1$ keV)
  - re-acceleration of HE electrons from SNRs (~1 GeV)
  - both are plausible but with some shortcomings and require some fine tunings
- in any case, our favourite model is multiple shock acceleration in the bubbles
  - however, we haven't worked out the glory detail yet?!?

possible models



- of course, this is not the whole story
  - what about x-ray (and possibly radio)
- ask Karen Yang at NTHU
  - she has some stories, e.g., Yang et al. (2022)

source?

driving source?

what/where is the engine?

- one-time event
  - a burst of star forming activity near the central region of our Galaxy, say $\sim 10^7$ years ago, with energy release $\sim 10^{56}$ erg
  - an episode of AGN activity of the SMBH at GC (jet energy $> 10^{56}$ erg?)
- quasi-steady
  - continuous (low level) AGN activity at GC
  - regular/periodic tidal disruption events at GC

what/where is the engine?

- one-time event
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  - an episode of AGN activity of the SMBH at GC (jet energy $> 10^{56}$ erg?)
- quasi-steady
  - continuous (low level) AGN activity at GC
  - regular/periodic tidal disruption events at GC

a possible scenario

- a solar mass star captured by the SMBH at the GC (tidal disruption event, TDE)
  - half of the star is swallowed
  - half is ejected as energetic particles
  - energy release $10^{52}{\sim}10^{53}$ erg
- regular or periodic TDEs at the GC
  - once per $10^{4}{\sim}10^{5}$ yr
  - (magneto)hydrodynamical outflow forms FBs
  - turbulence (supersonic)

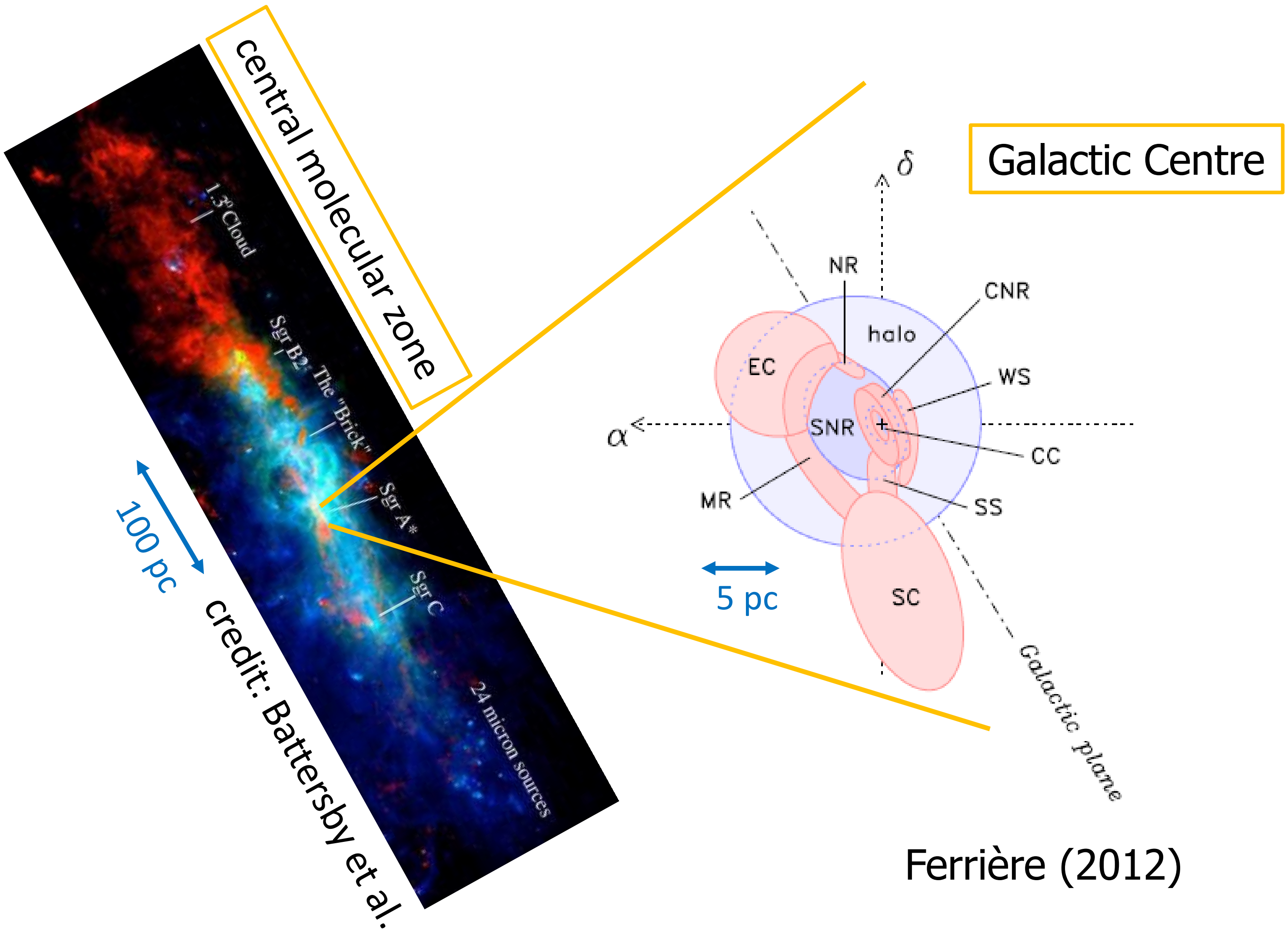
hurdles on the way to form FBs

- how does the TDE energy get out of the GC region, propagate through the galactic gas disk, and get into the galactic halo?
- can it form a shock-like boundary as the Fermi bubbles in the halo?

TDE energy to halo

- development of a TDE cavity is analogous to supernova remnant
- development of a series of TDEs can be modelled as interstellar wind cavity
- adiabatic stage: retains most of its input energy
- radiative stage: energy loss, and merge with ISM within some cooling or sound crossing times
- if the cavity can penetrate the galactic disk within its adiabatic stage, then most of the TDE energy can deposit into the halo

- regions near the Galactic Centre are very complicated and not well understood

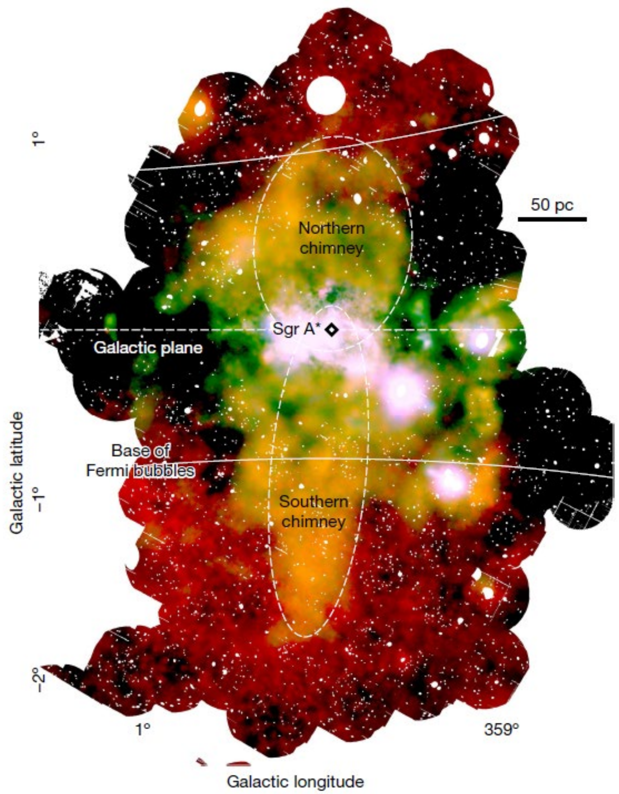


- “standard view” (e.g., Ferrière et al. 2007):
  - warm gas with a large filling factor, density $\sim 0.4\ \mathrm{cm}^{-3}$, scale height $\sim 100\ \mathrm{pc}$
- adiabatic stage (Sedov) for a single energy release:
  - $R_\mathrm{s} \approx 19.1 \times W_{51}^{5/17} n_\mathrm{H}^{-7/17} \mathrm{pc}$
- a TDE with energy $10^{52} \sim 10^{53}\ \mathrm{erg}$ can penetrate the disk and deposit the energy into the halo

- “new interpretation” (Oka et al. 2019):
  - density $\sim 50\ \mathrm{cm}^{-3}$, scale height $\sim 30\ \mathrm{pc}$
- a TDE with energy $10^{52} \sim 10^{53}\ \mathrm{erg}$ cannot penetrate the disk and energy will start to dissipate after some $10^{4}\ \mathrm{yr}$
- adiabatic stage for continuous energy release:
  - $R_{\mathrm{ad}} \approx 1.93 \times \dot{W}_{36}^{2/5} n_{\mathrm{H}}^{-3/5} \mathrm{pc}$
- a series of TDEs with an average power of $3 \times 10^{40} \sim 10^{41}\ \mathrm{erg\,s^{-1}}$ will do the trick

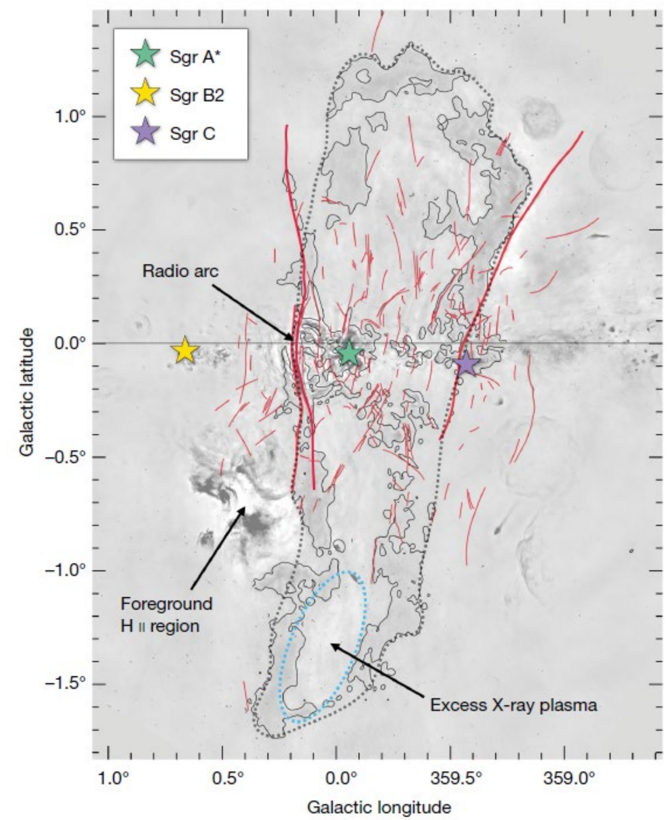
chimneys?

x-ray



Ponti et al. (2019)

radio

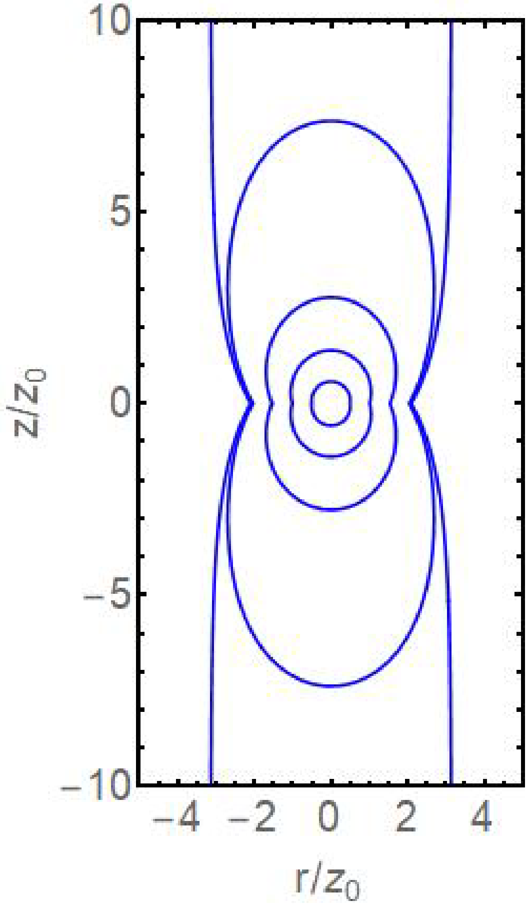


Heywood et al. (2019)

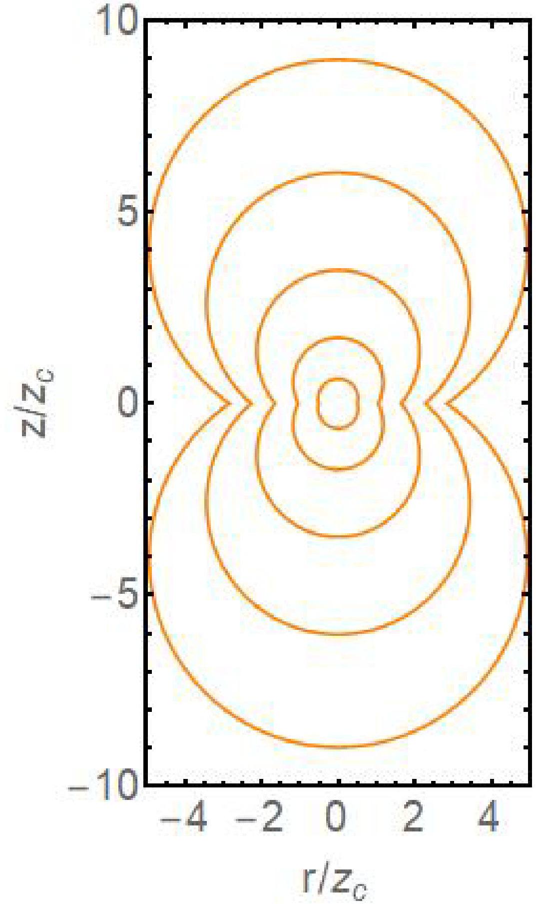
forming bubbles …

- gas distribution in the halo
  - exponential?
  - β-model? (power-law?)
- can the shock survive in the halo?

Kompaneets-type solutions



exponential: $\exp(-z/z_0)$



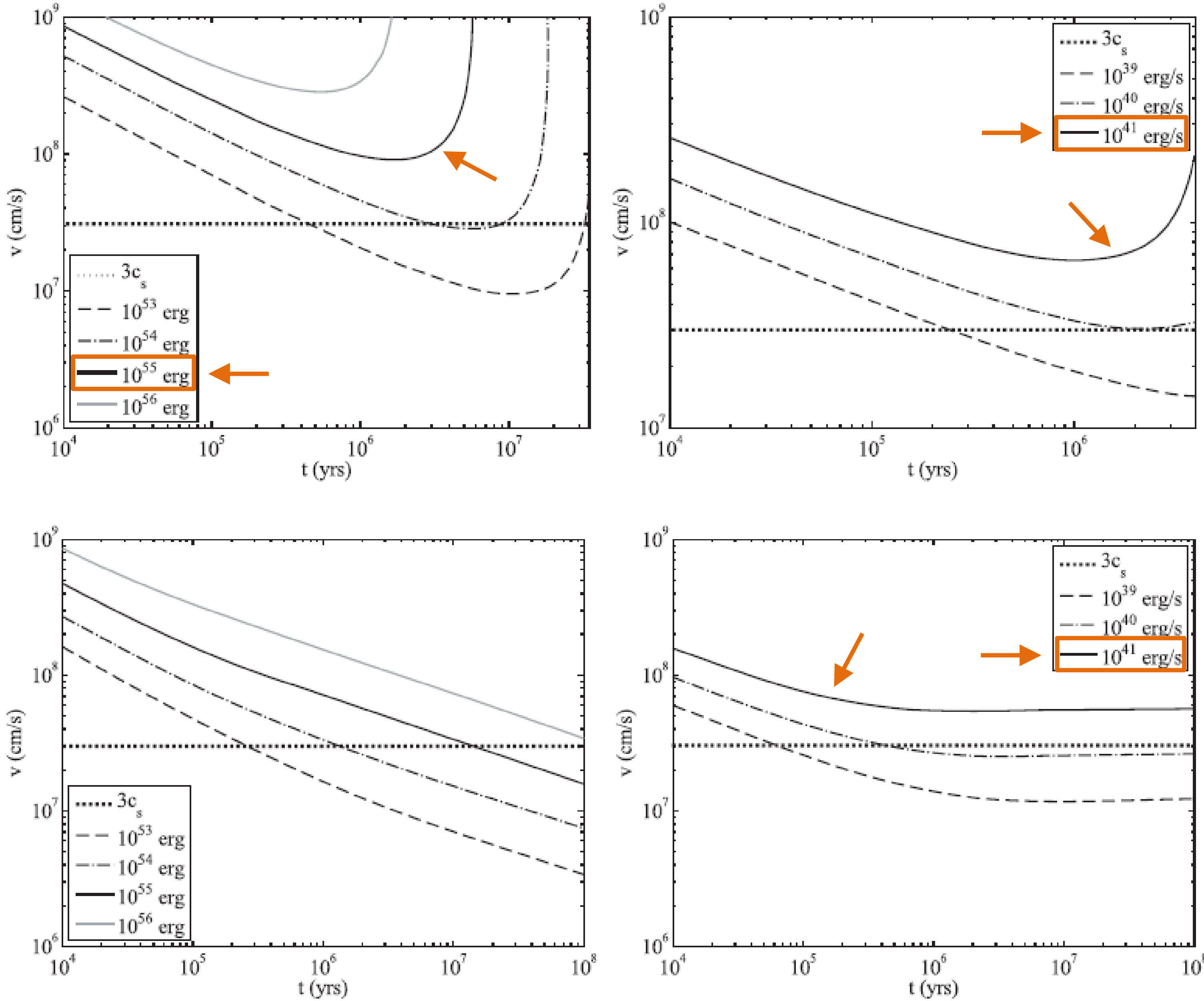
“power-law”: $(1 + z/z_c)^{-2}$

can the shock survive?

- to avoid fragmentation the shock velocity at the top of the bubble should be three times larger than the sound speed (Baumgartner & Breitschwerdt 2013) single energy release | continuous energy release

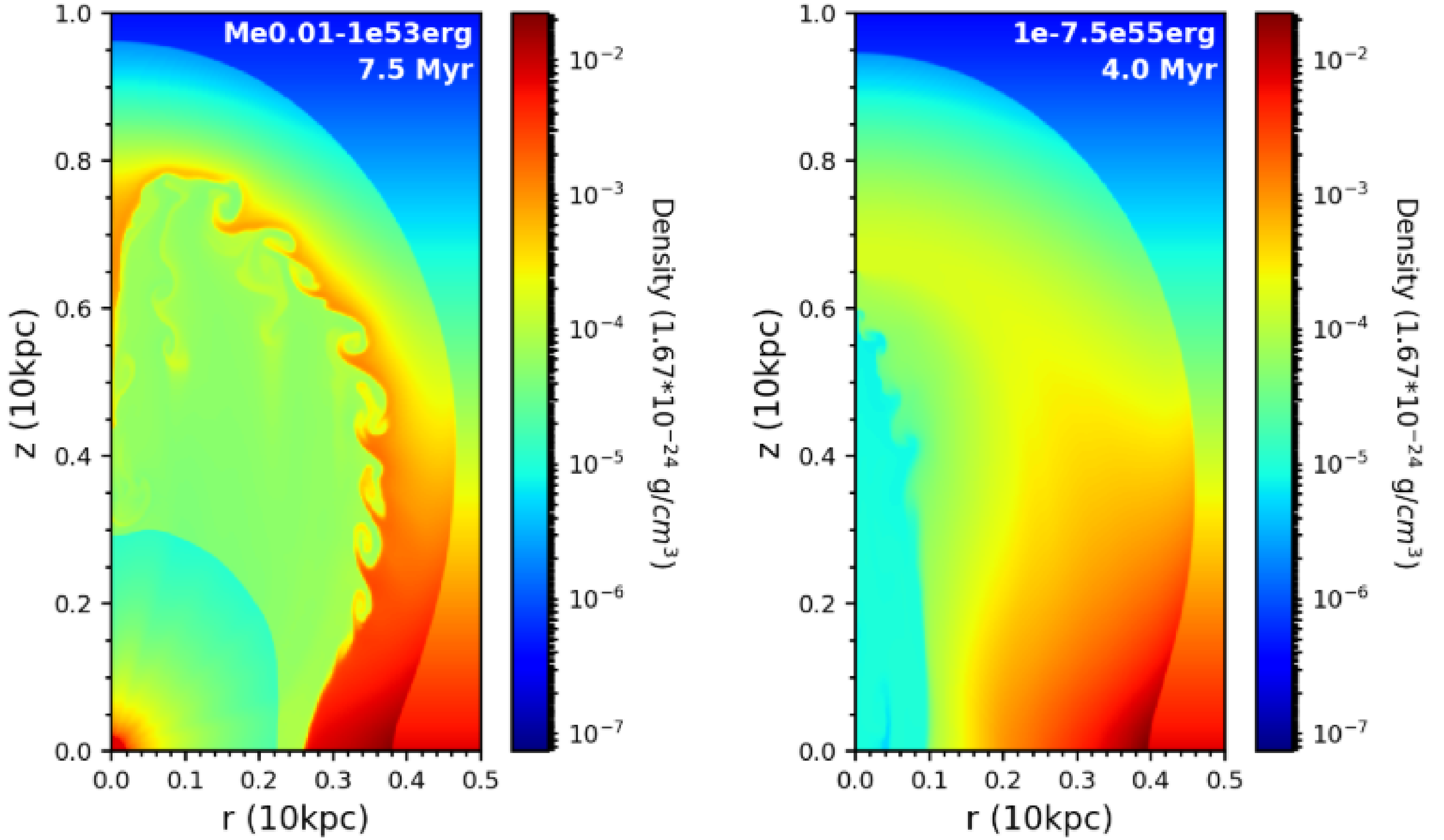
exponential: $\exp(-z/z_0)$

"power-law": $(1+z/z_c)^{-2}$



summary on the source of FBs

- our favourite model is regular or periodic tidal disruption events of stars by the supermassive black hole at the Galactic Centre
  - energy release by each event: $10^{52} \sim 10^{53}$ erg
  - rate of events: $10^{-5} \sim 10^{-4}$ yr^{-1}
  - gas distribution in the halo is exponential



- of course, this is not the only story
  – for more, ask Karen Yang at NTHU (again)