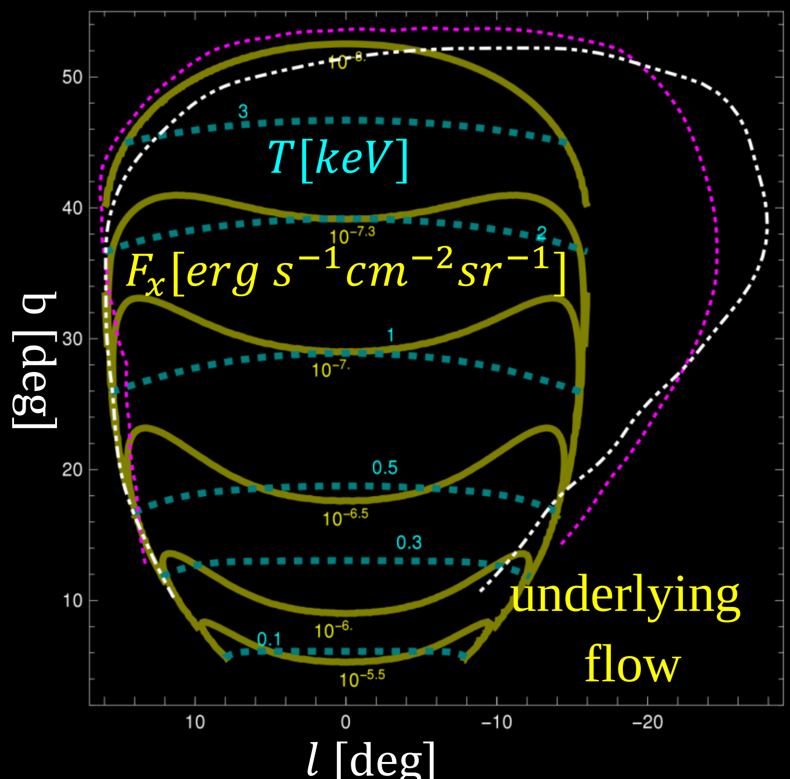
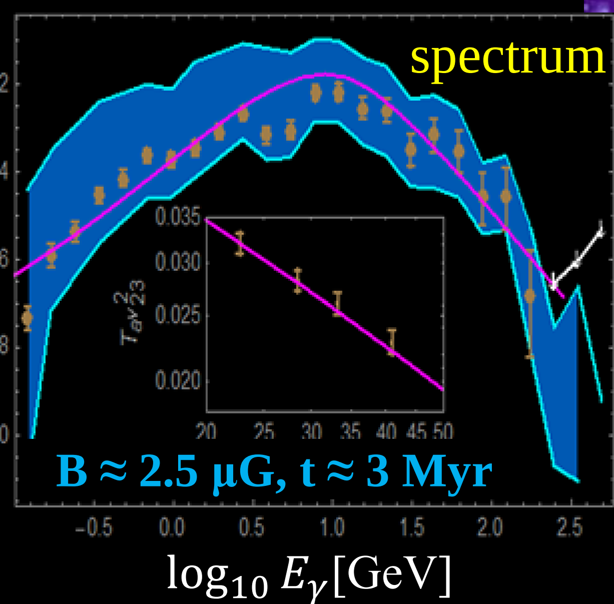
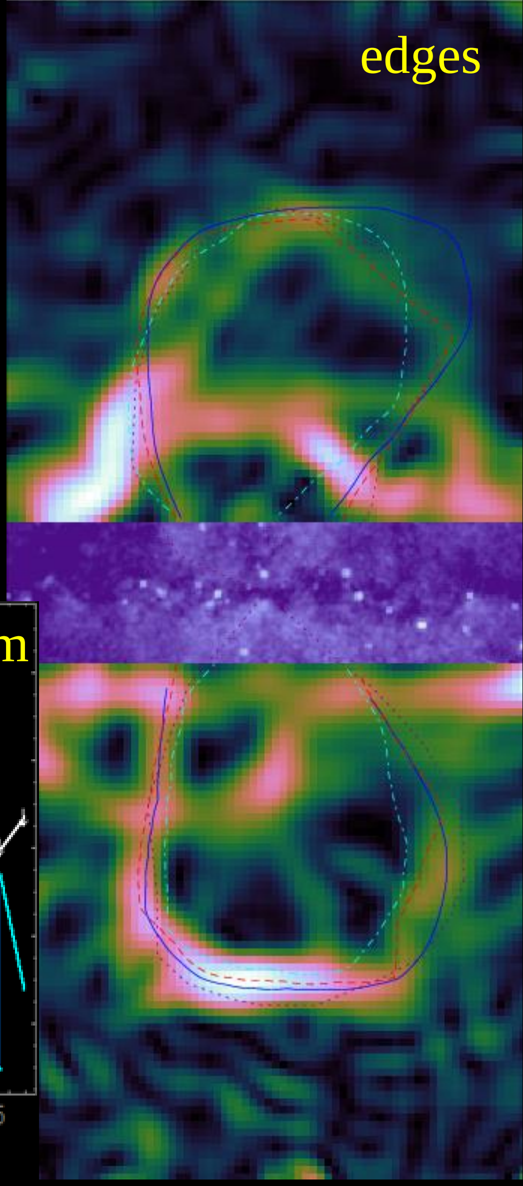
Fermi bubbles in X-rays and γ-rays: supersonic expanding shell







Uri Keshet / BGU

Ilya Gurwich / NRCN

ISF-UGC project

arXiv 1611.04190, 1704.05070, 1705.06665

Outline:

- Fermi bubbles (FB) & haze: mini-introduction
- Spectrum: STArlight Basked LEptons
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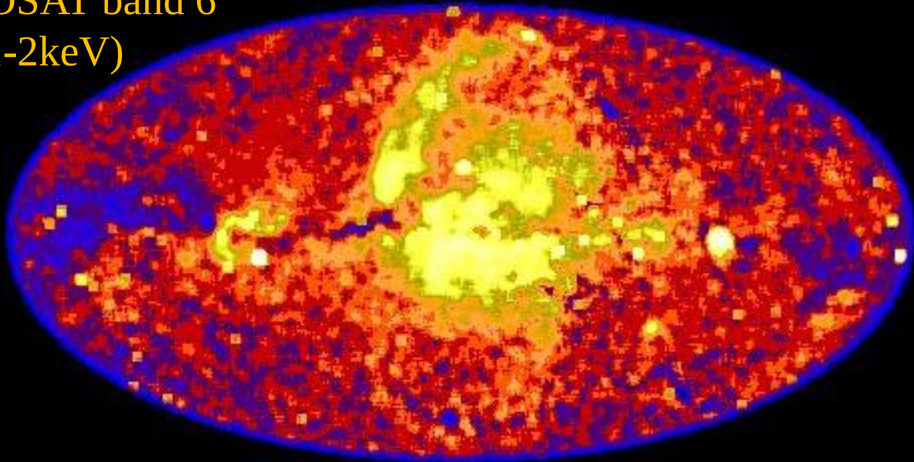
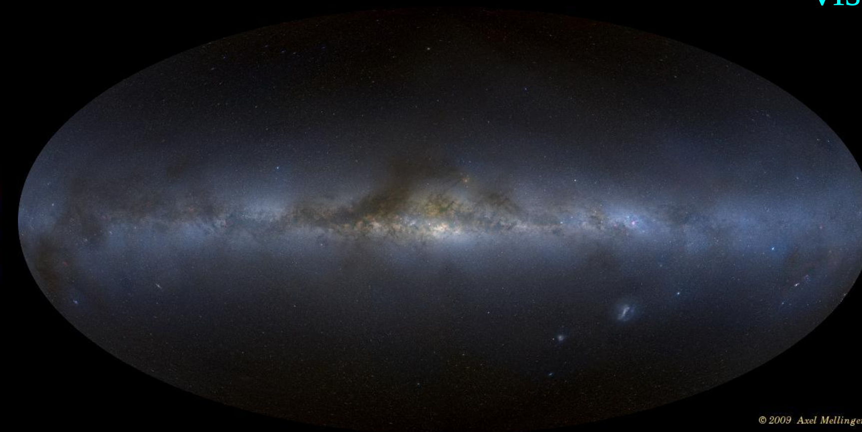
- Summary

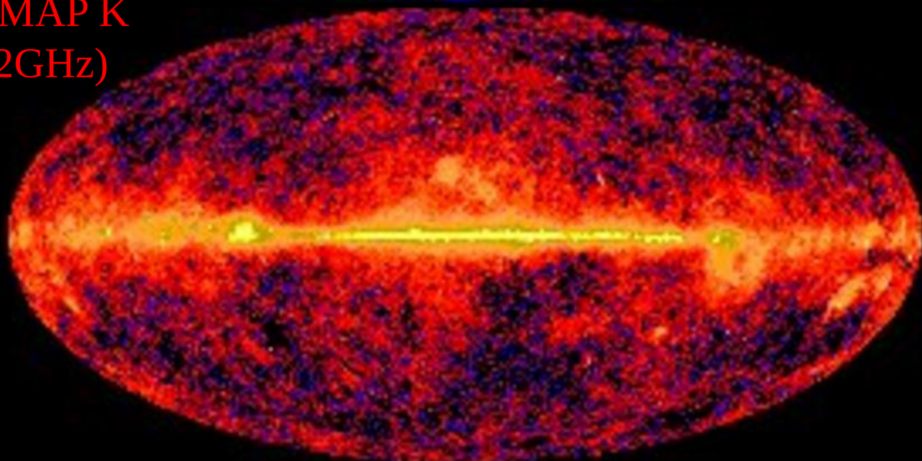
ROSAT band 6
(1-2keV)



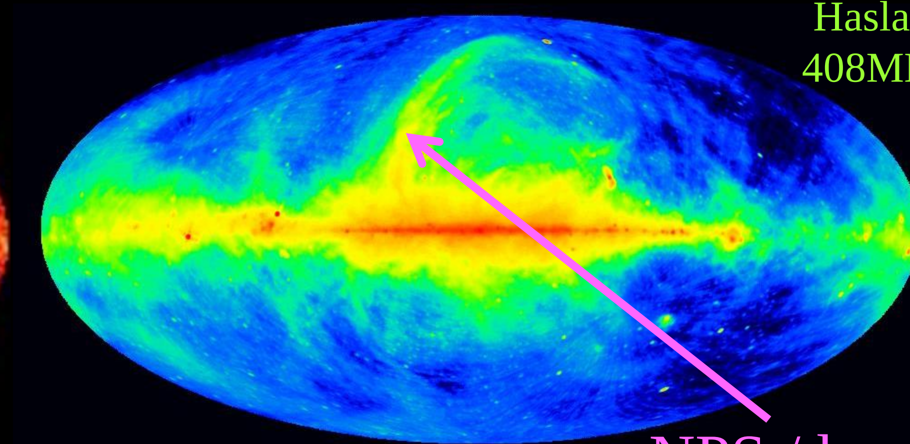
visible



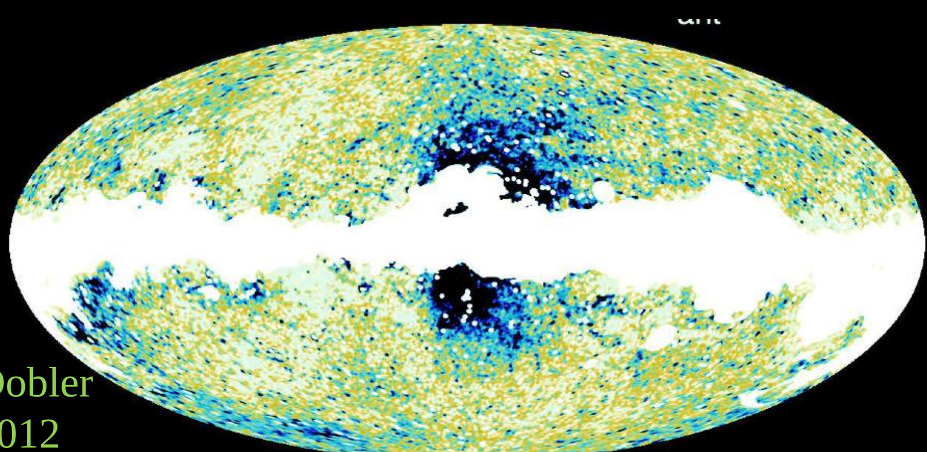
WMAP K
(22GHz)



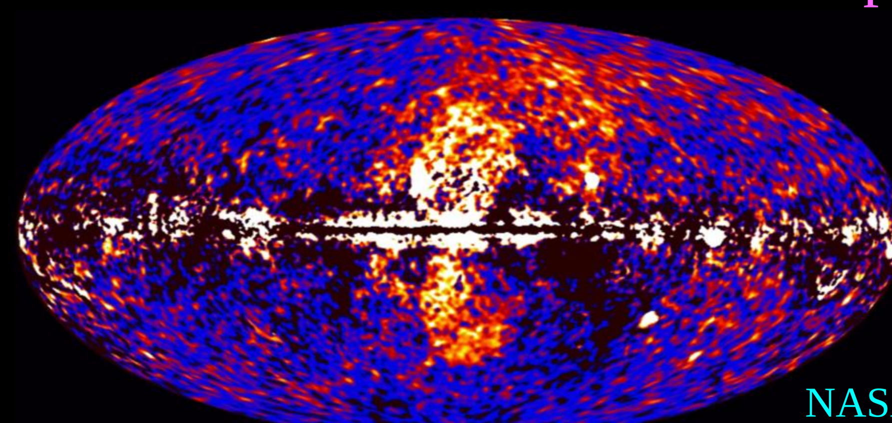
Haslam
408MHz



NPS / loop I



Dobler
2012



NASA

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

Fermi bubbles - some models

Radiation:

- **leptonic**: Su+ 2010; …
- **hadronic**: Su+ 2010; Aharonian & Crocker (2011); …

FB edge:

- **forward shock**: Su+ 2010, …
- **termination shock**: Su+ 2010; Lacki 2014; Mou+ 2014; Mou+ 2015
- **contact discont.**: Sarkar+ 2015; Guo & Mathews 2012; Guo+ 2012

Engine:

- **starburst**: Su+ 2010; Crocker 2012; Lacki 2014; Sarkar+ 2015
- **AGN jet**: Su+ 2010; Guo & Mathews 2012; Yang+ 2012; Guo+ 2012; Mou+ 2014
- **others**: Su+ 2010 (buoyant bubble)

CR injection:

- **1st order Fermi**: Su+ 2010, …
- **2nd order Fermi**: Mertsch & Sarkar 2011; Chernyshov+ 2014; Cheng+ 2015
- **others**: injection at GC (Guo & Mathews 2012; Guo+ 2012; Yang+ 2014); Galactic CR losses (Thoudam 2013);

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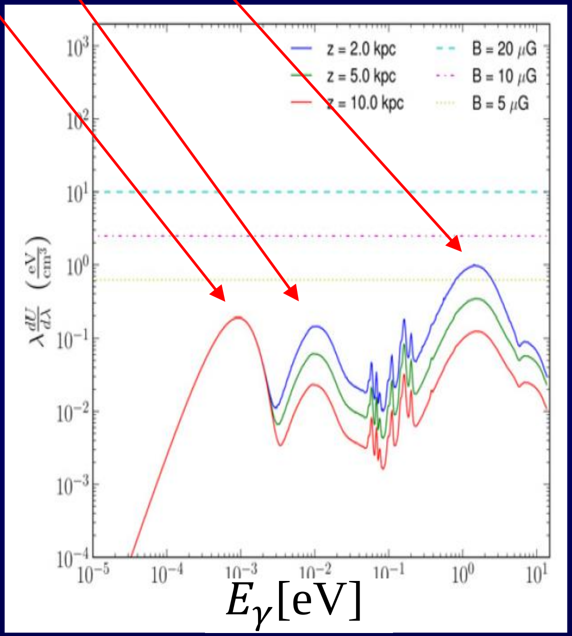
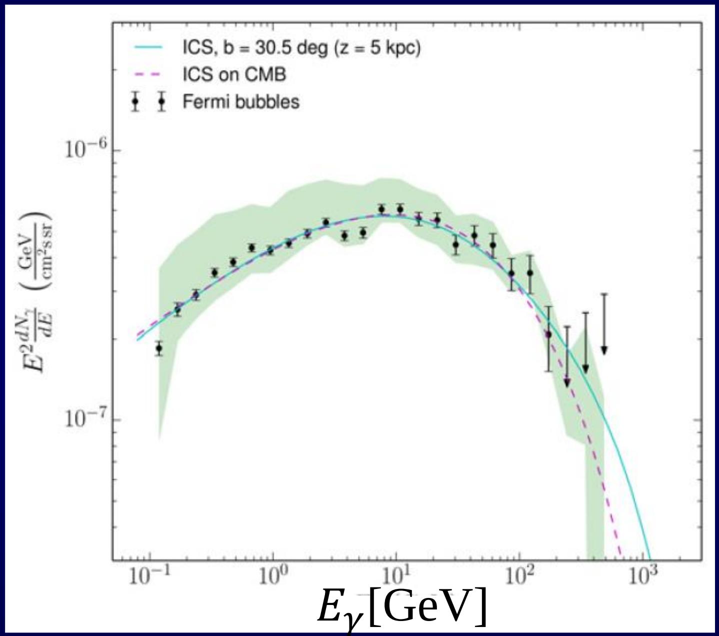
Fermi bubble γ-ray spectrum - leptonic model

See for example: Su et al. 2010 & Ackermann et al. 2014

- Inverse Compton of the radiation field above the Galactic plane (CMB, IR and SL) via CREs gives an excellent fit to the observed spectrum

(CRE = cosmic-ray electron)





Ackermann et al. 2014

Overall ISRF of 1.5 eV/cm^3

Magnetic field of 5-20 μG

$U_{cre}(> GeV) \simeq 10^{52}$erg

However, only if an unnaturally high cutoff (~1.3 Tev) on CREs is invoked

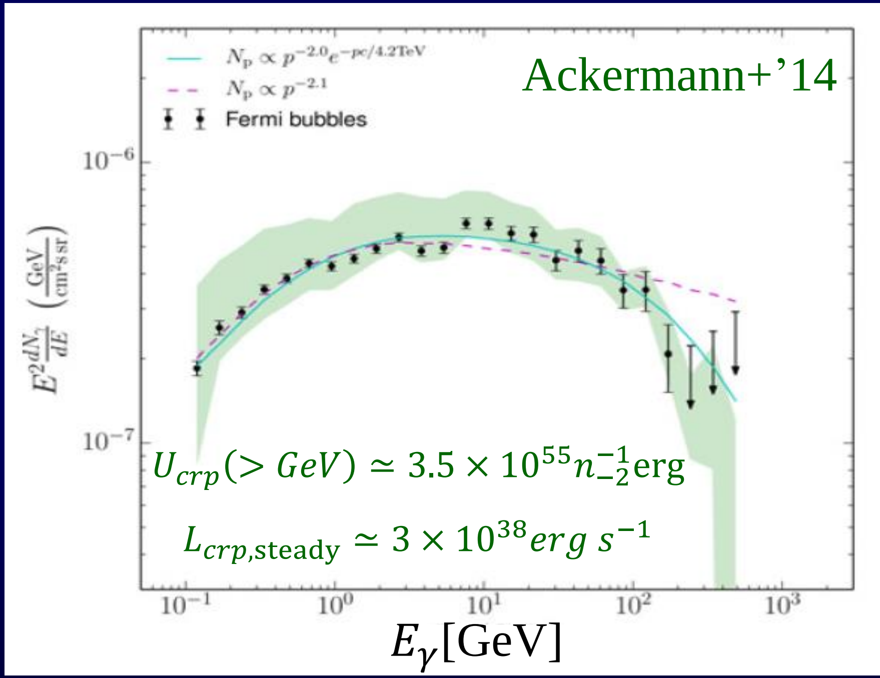
For example, CREs at this energy would cool **via IC and synchrotron over ~10^5 years**. If the bubbles were this young, they would be relativistic, requiring an incredibly energetic source.

Gurwich & Keshet 2015, in prep.

Fermi bubble γ-ray spectrum - hadronic model

See for example: Crocker & Aharonian 2011

Assuming π decay as the only source – gives a good fit to the flat $\frac{dN_\gamma}{dE} \sim E^{-2}$ region,
Seemingly fails to reproduce both the low-energy and high-energy parts of the spectrum



To fit the spectrum below 1 GeV, one must include the secondary electron IC component to soften the hadronic spectrum

Ackermann et al. 2014

Even then, the synchrotron does not match the haze (a general hadronic problem).

To fit the spectral break above 50 GeV, an arbitrary cutoff must be invoked (~4 TeV)

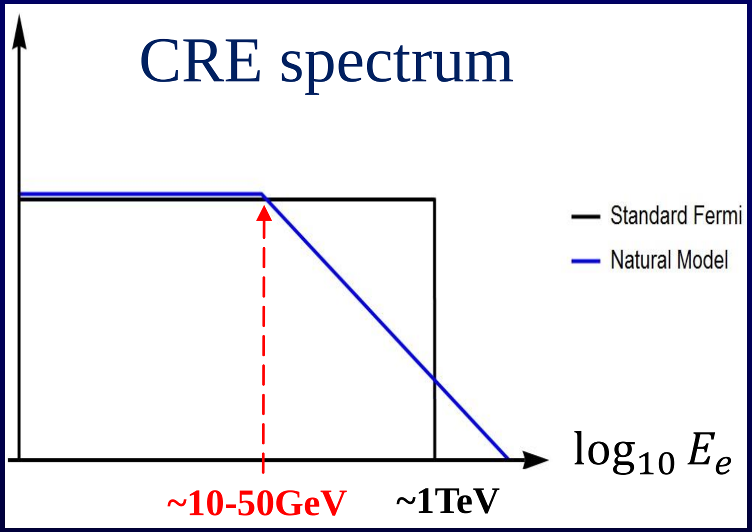
Ackermann et al. 2014

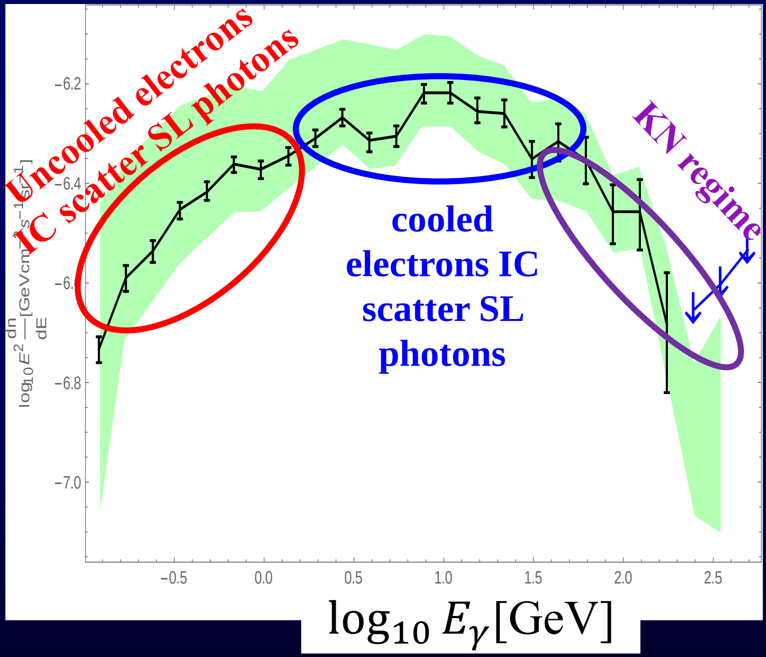
This cutoff is unnaturally low.

Gurwich & Keshet 2015, in prep.

Natural leptonic model

- Various evidence: FB edges are a shock continuously injecting CRs.
- Cooling break energy $E_C = \frac{3m_e^2c^3}{4\sigma_T(U_B+U_R)t}$ ~10 GeV for t~few Myr

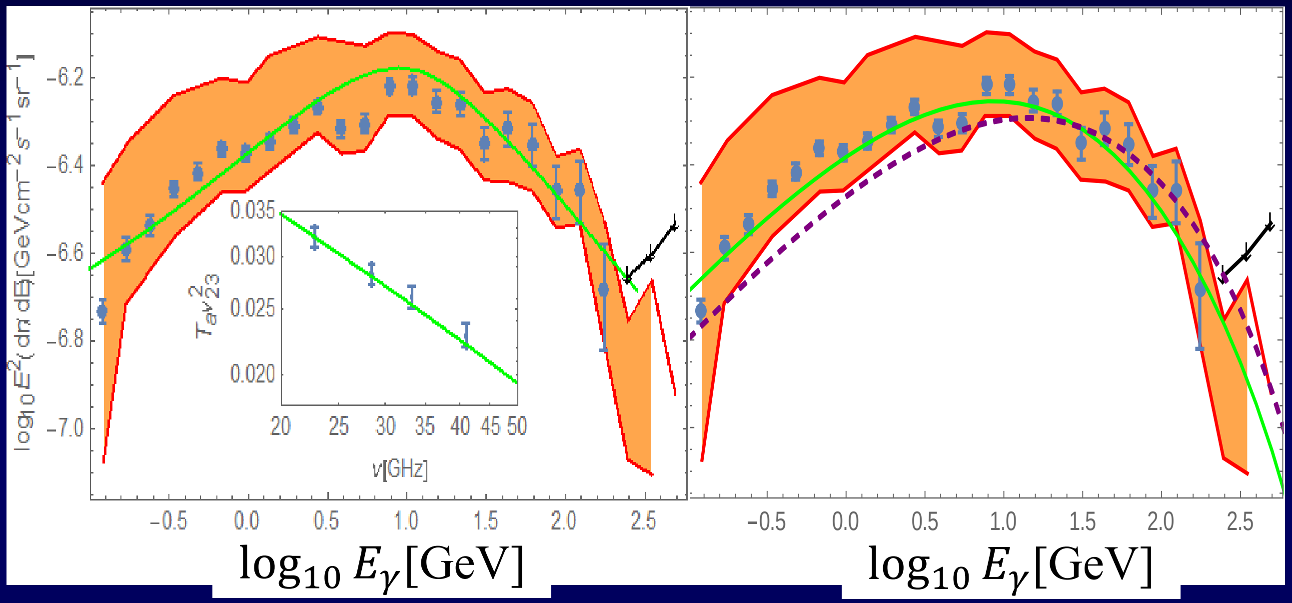




Gurwich & Keshet 2015, in prep.

Natural leptonic model

The model fits both γ-rays and microwave haze:



Uniform FB emissivity: CREs reach inner bubble before cooling

So diffusion $$D(E) \gtrsim 3 \times 10^{28} \left(\frac{U_R}{3eV/cm^3}\right)\left(\frac{E_{CRE}}{10GeV}\right) cm^2 s^{-1}$$

Gurwich & Keshet 2015, in prep.

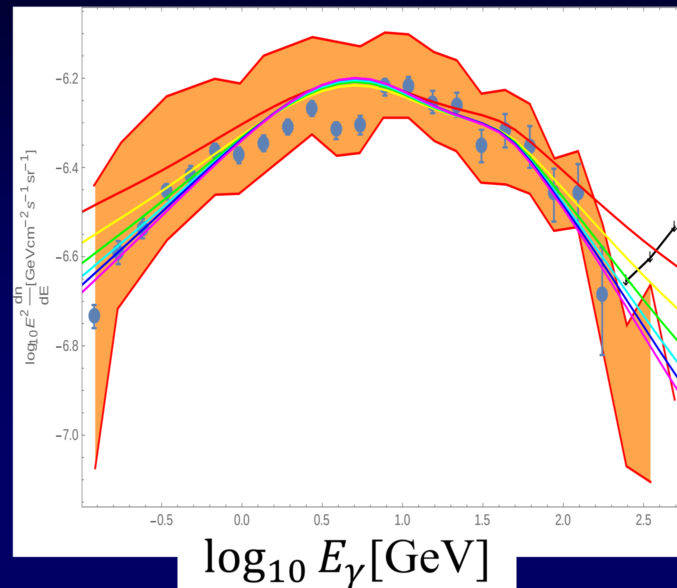
Natural model: STArlight-Basked LEptons (STABLE)

Requirement: Starlight component must dominate the radiation field.

(Otherwise, CMB+IR soften below 1GeV and harden above KN.)

For nominal values of IR radiation,

this means $U_R > 3$ eV/cm^3.



$\frac{U_{SL}}{U_R} \approx 0.83$

$\frac{U_{SL}}{U_R} \approx 0.88$

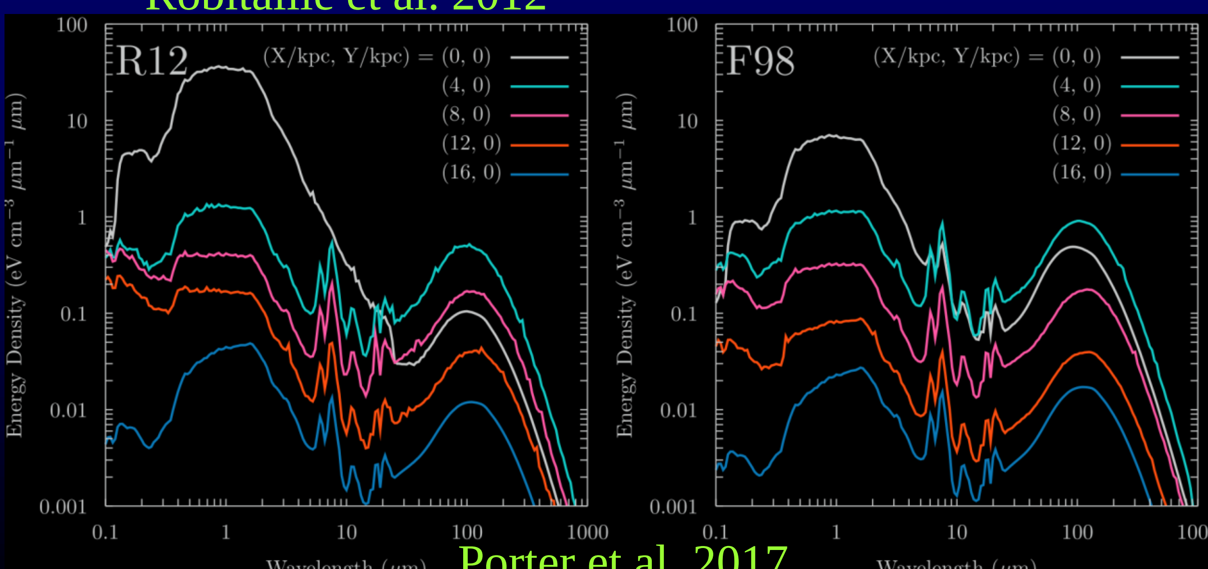
$\frac{U_{SL}}{U_R} \approx 0.92$

$\frac{U_{SL}}{U_R} \approx 0.94$

$\frac{U_{SL}}{U_R} \approx 0.95$

$\frac{U_{SL}}{U_R} \approx 0.96$

Robitaille et al. 2012



Porter et al. 2017

Gurwich & Keshet 2015, in prep.

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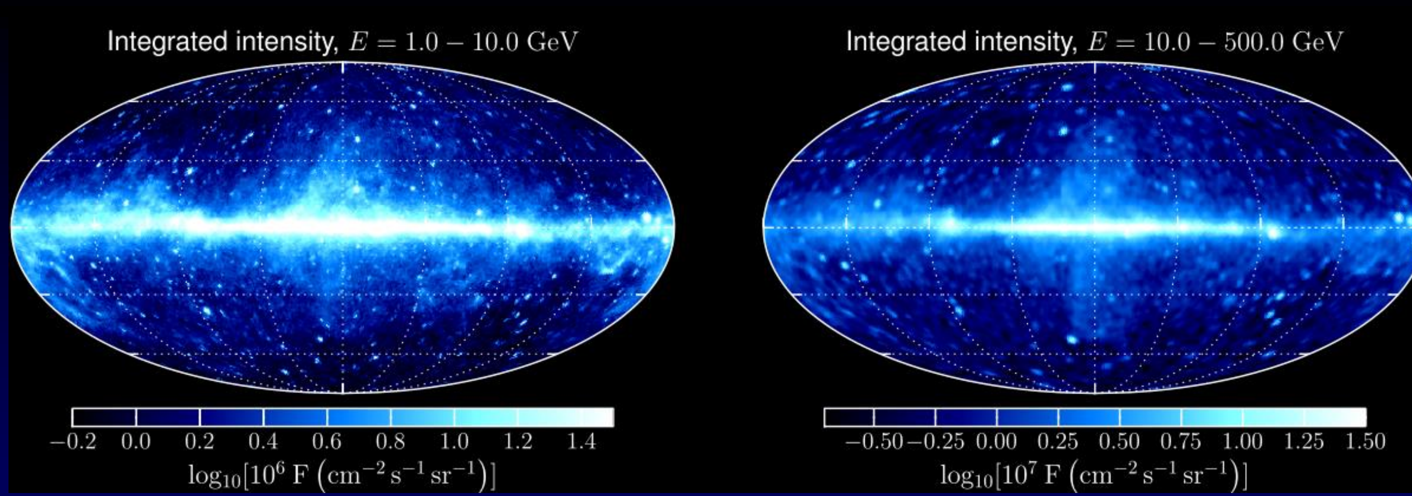
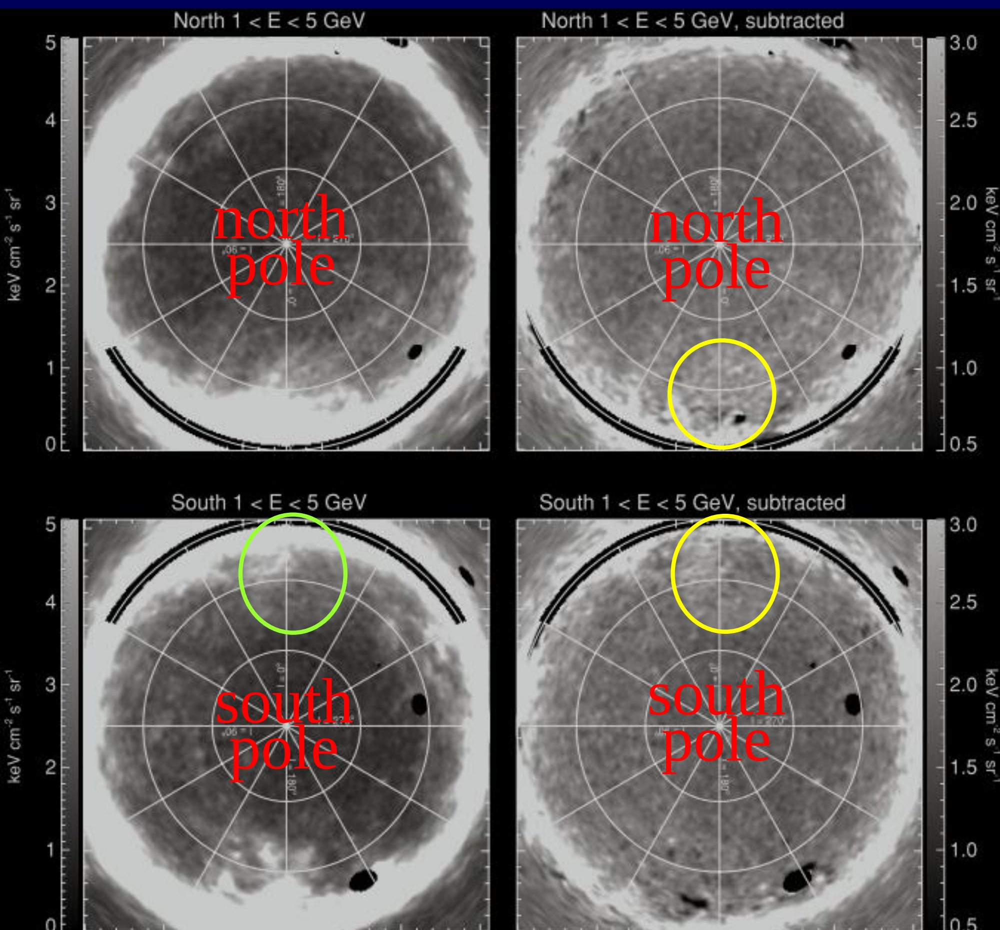
Edges:

higher energies:



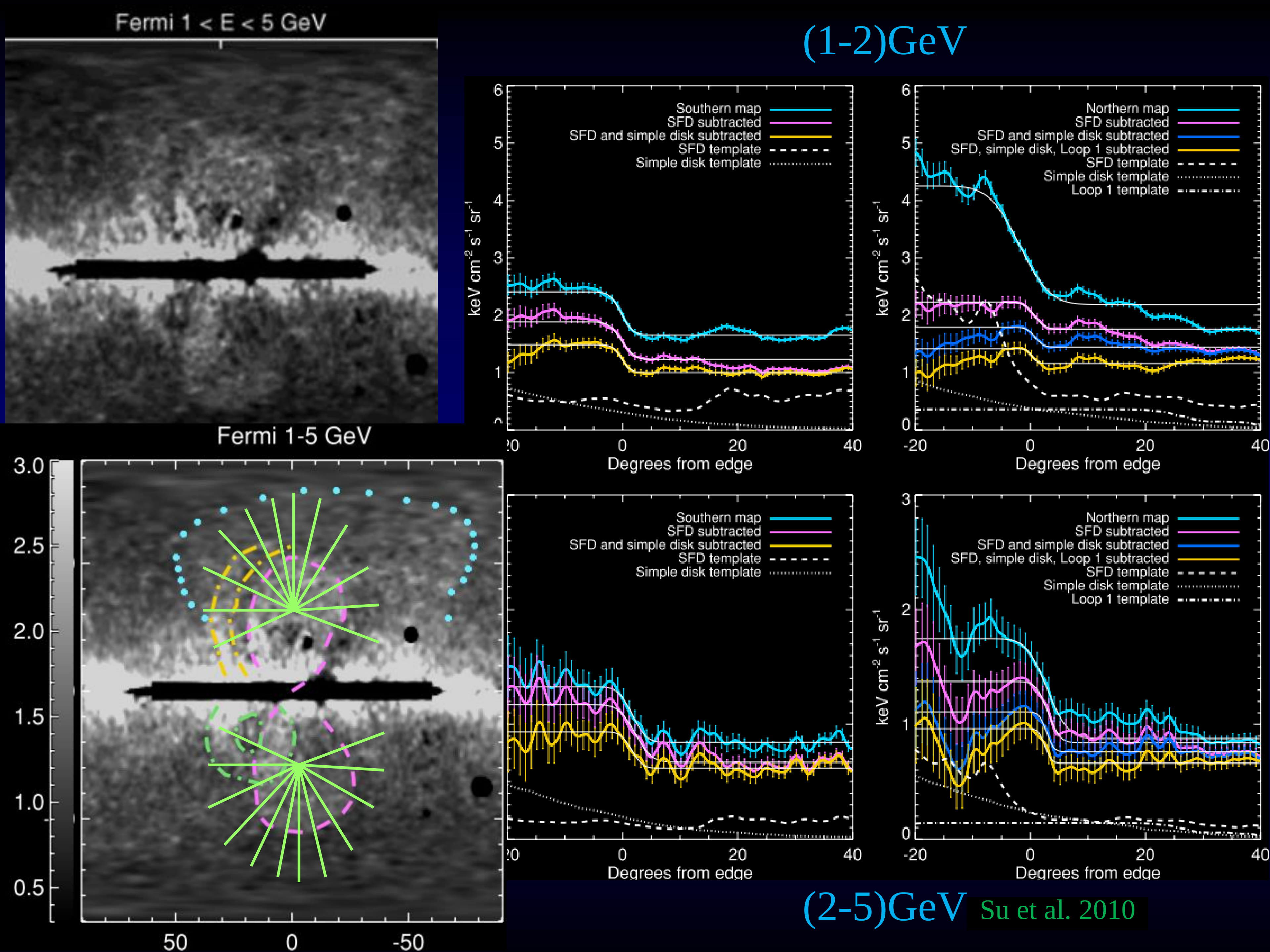
Fermi collaboration 2014



in particular in the South
(less interfering structure)

Su et al. 2010

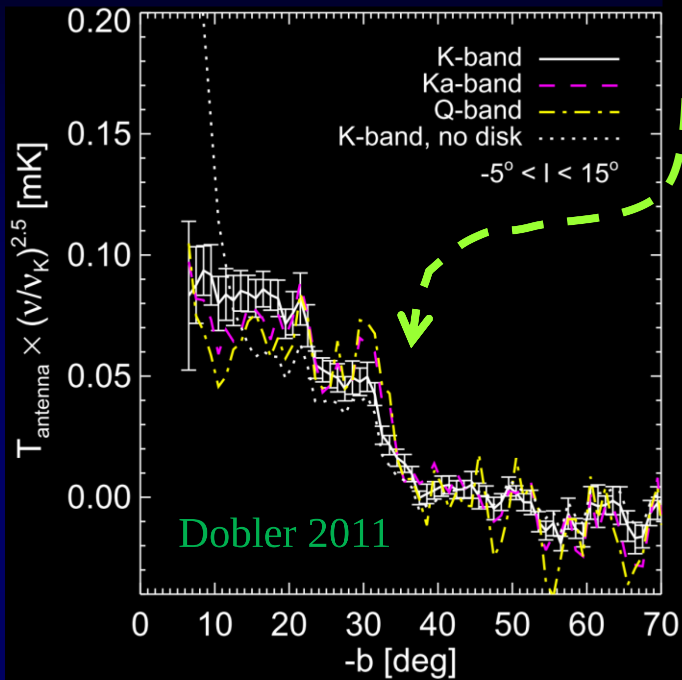
(1-2)GeV



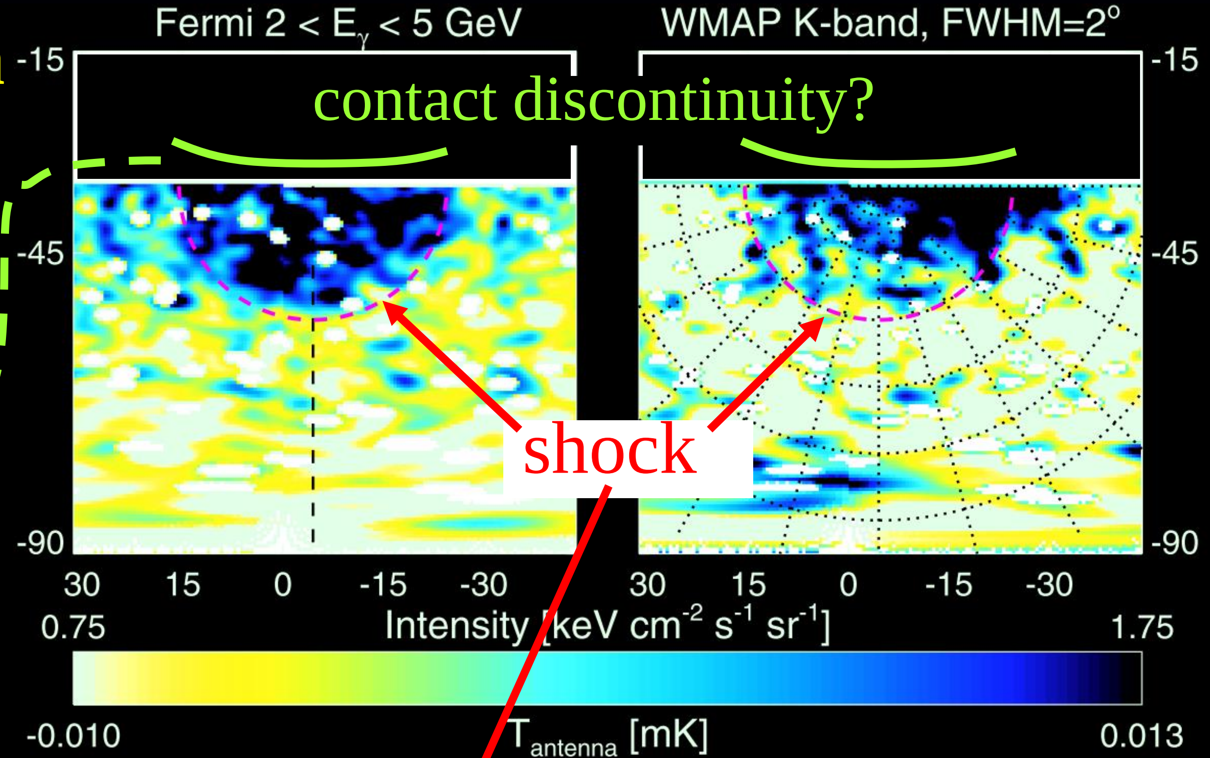
(2-5)GeV

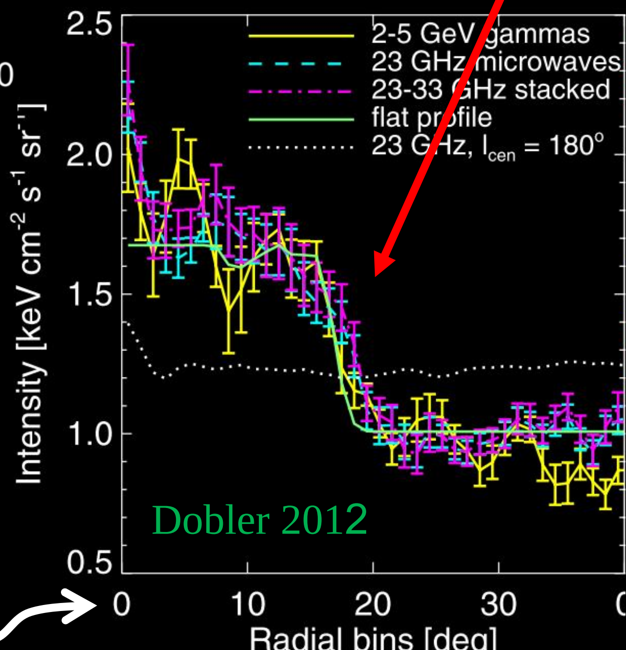
Su et al. 2010

Overlapping edges in γ-rays & microwave



Similar @Hao Liu's talk





35+

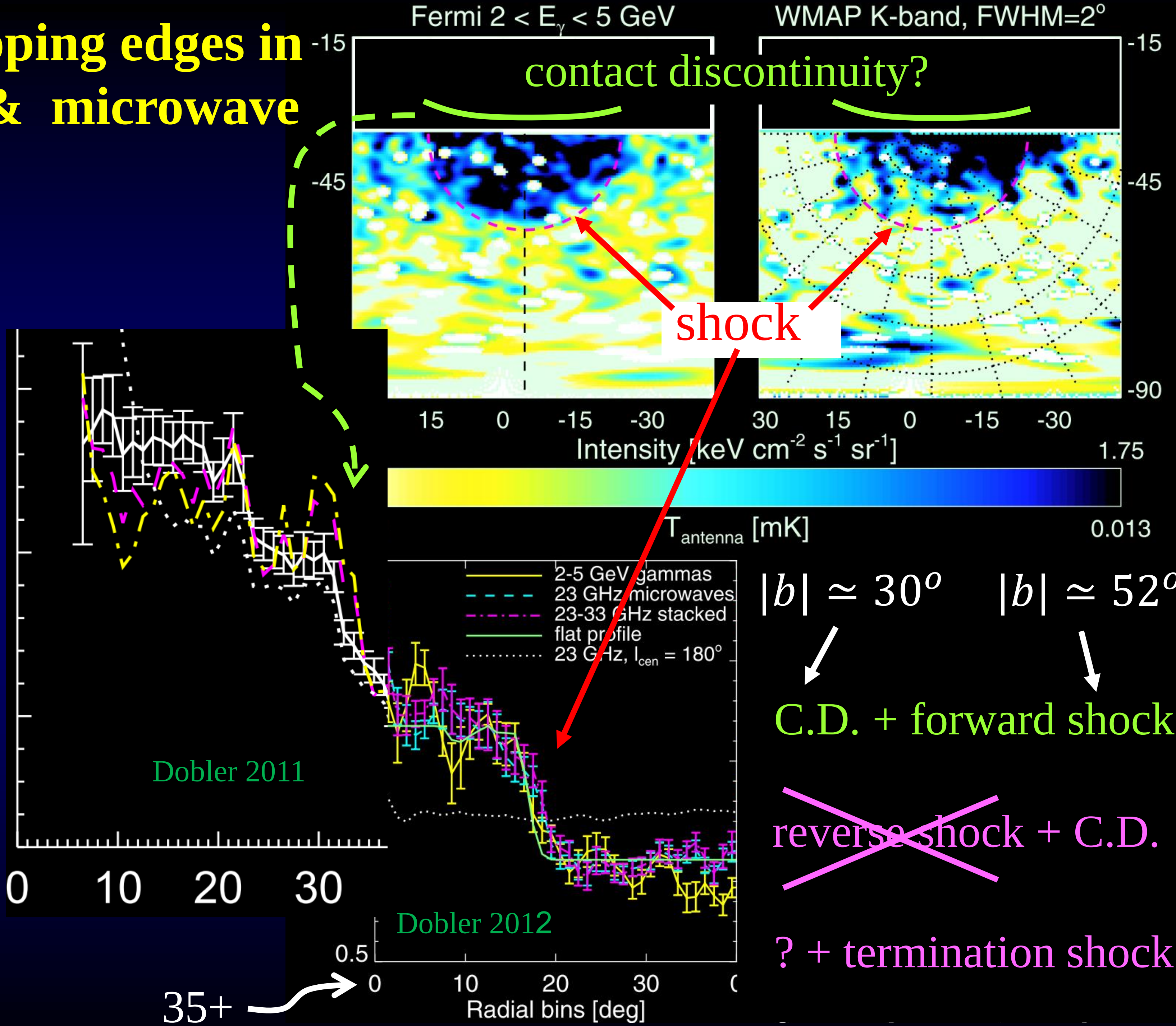
$|b| \simeq 30^o$ $|b| \simeq 52^o$

C.D. + forward shock

reverse shock + C.D.

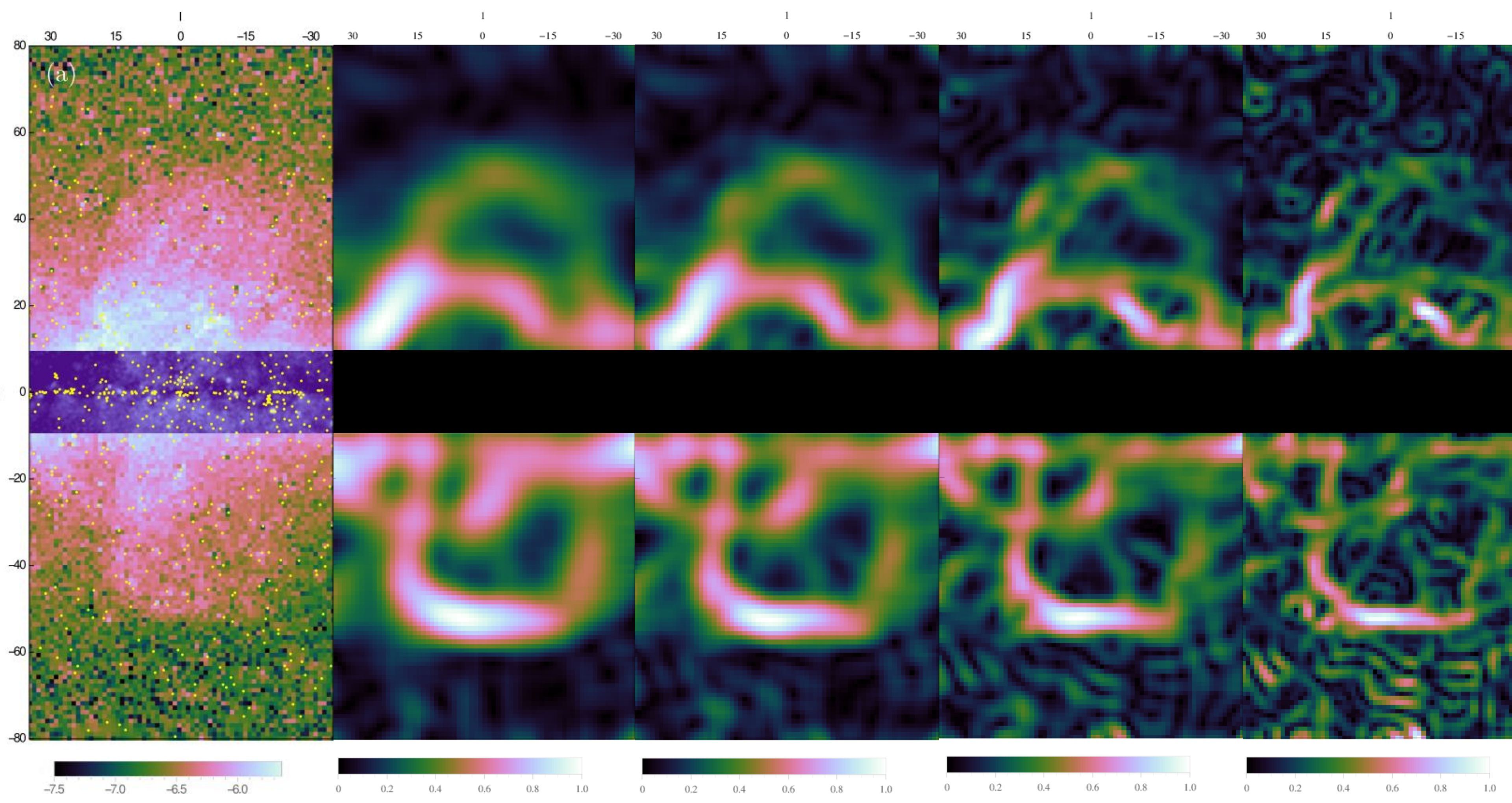
? + termination shock

Overlapping edges in γ-rays & microwave



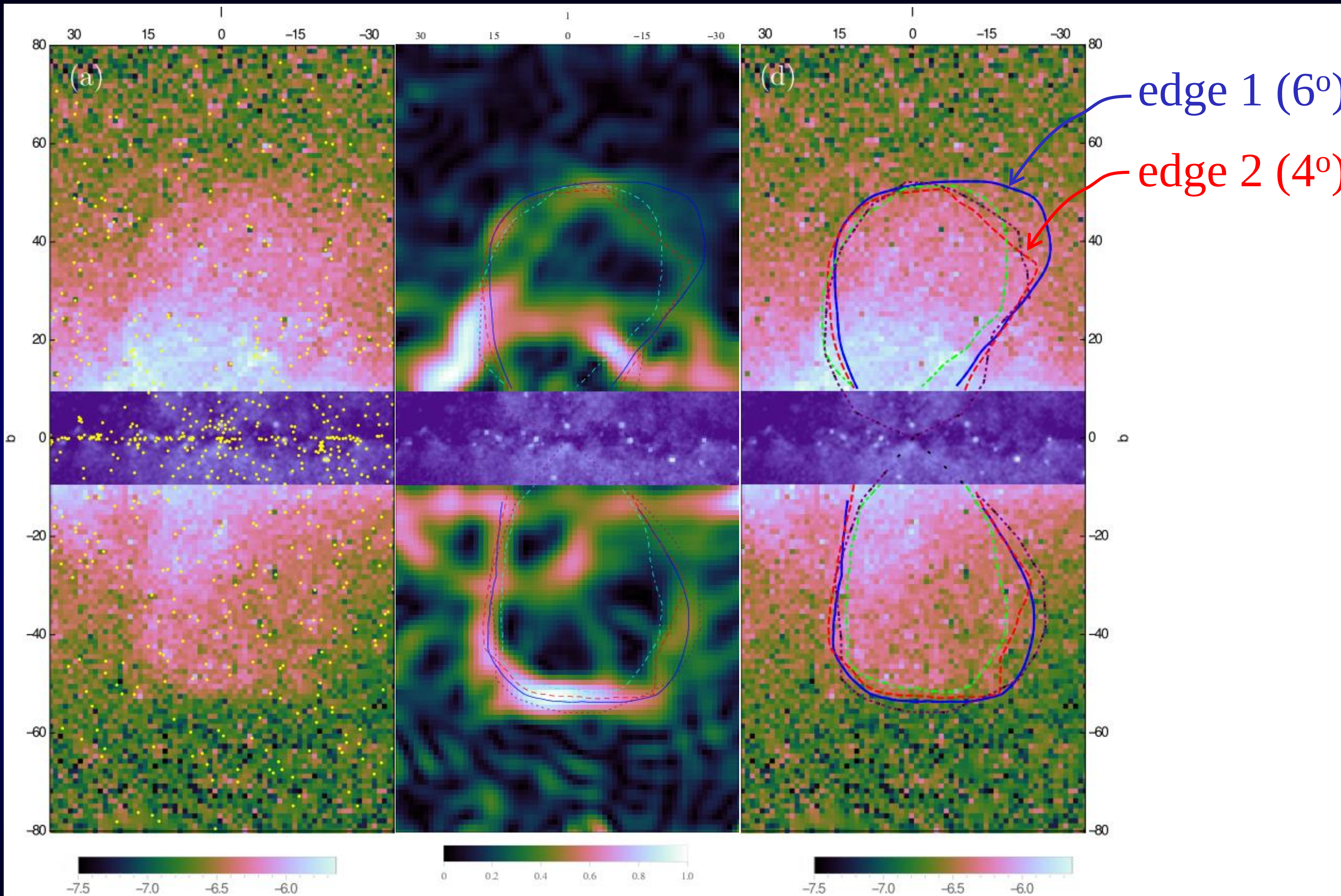
Gradient filter

(Gaussian filter of scale ψ + standardized Bessel derivative kernel)



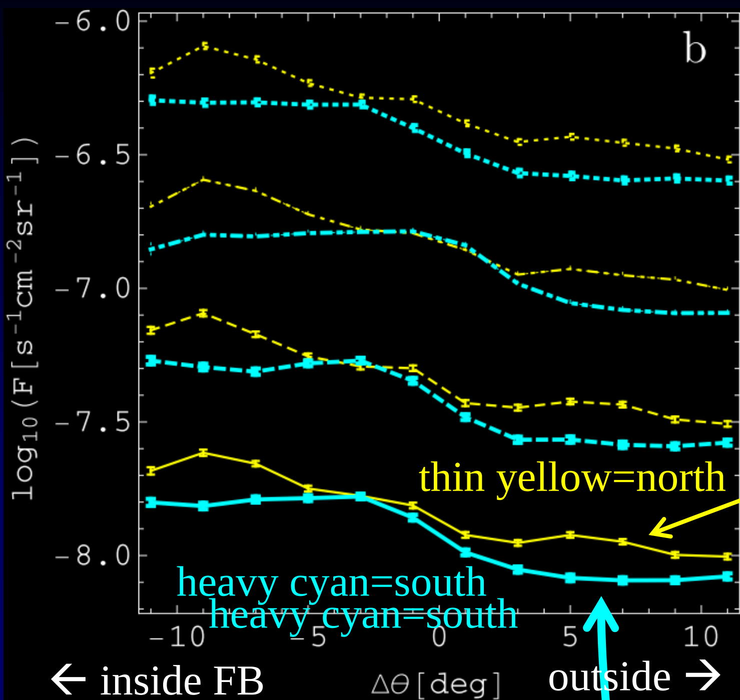
LAT Pass-8 $\psi = 8^o$ $\psi = 6^o$ $\psi = 4^o$ $\psi = 2^o$

Keshet & Gurwich 2016



Keshet & Gurwich 2016

~5° edges @3-100GeV



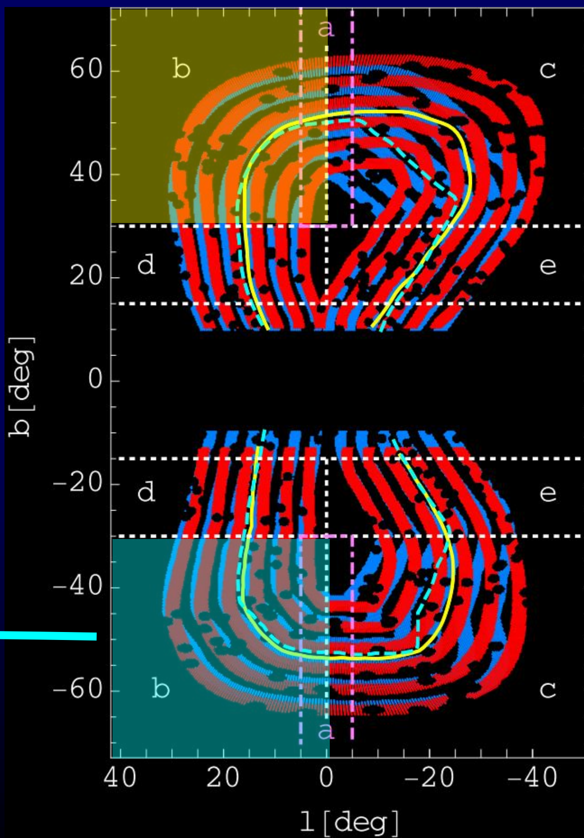
edges (2,3,4 shifted upward for visibility):

4

3

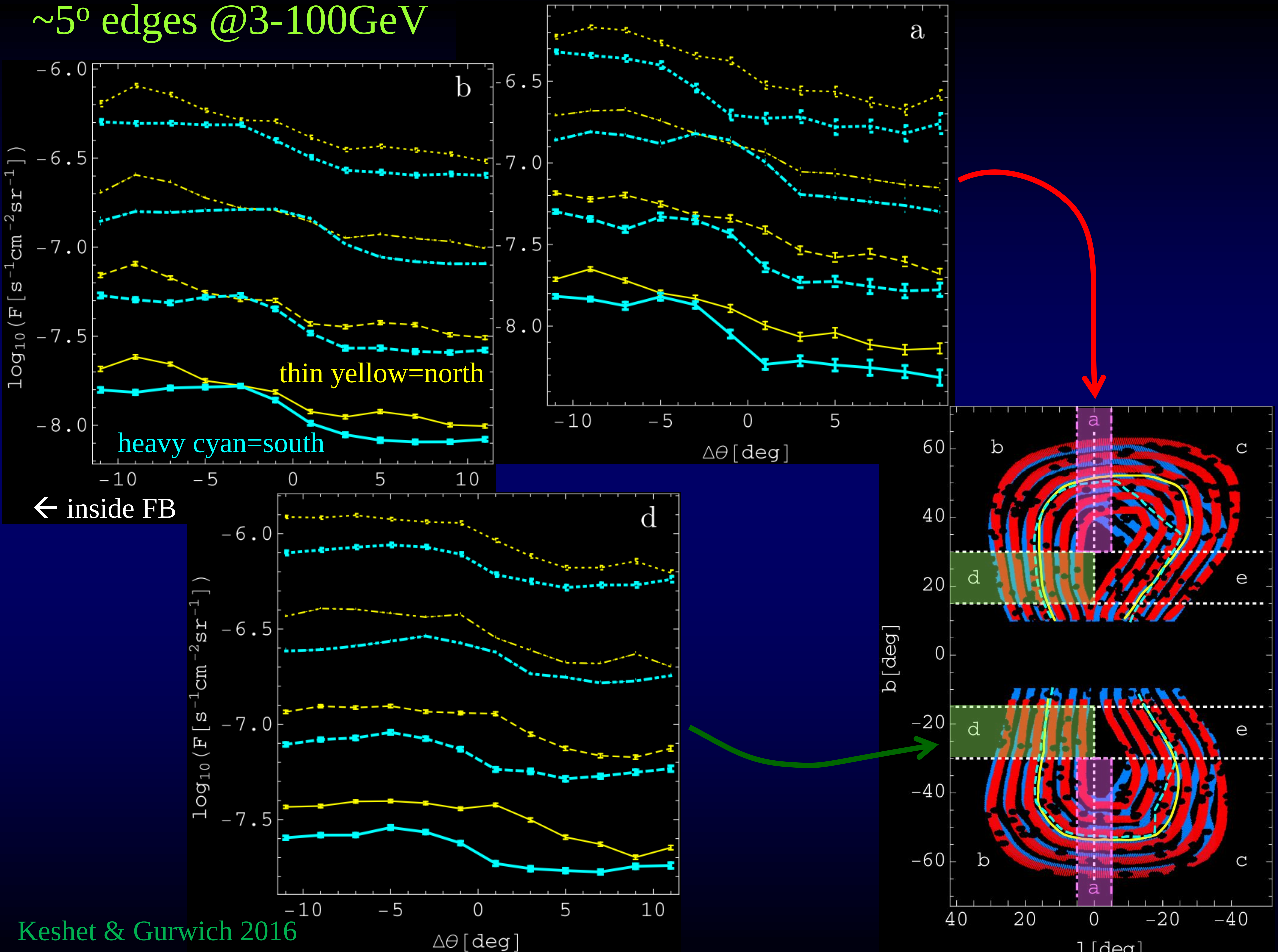
2

1

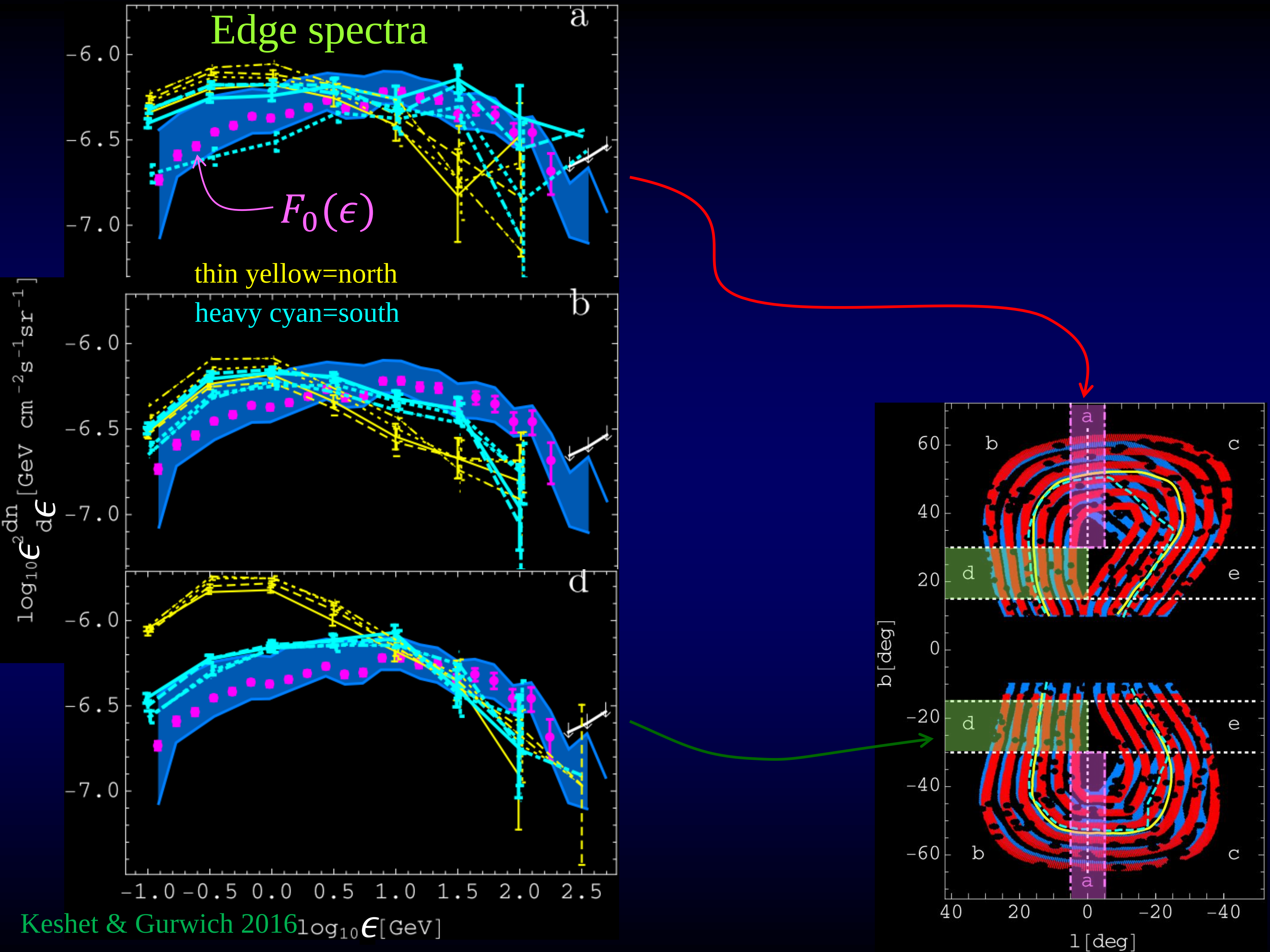


Keshet & Gurwich 2016

~5º edges @3-100GeV

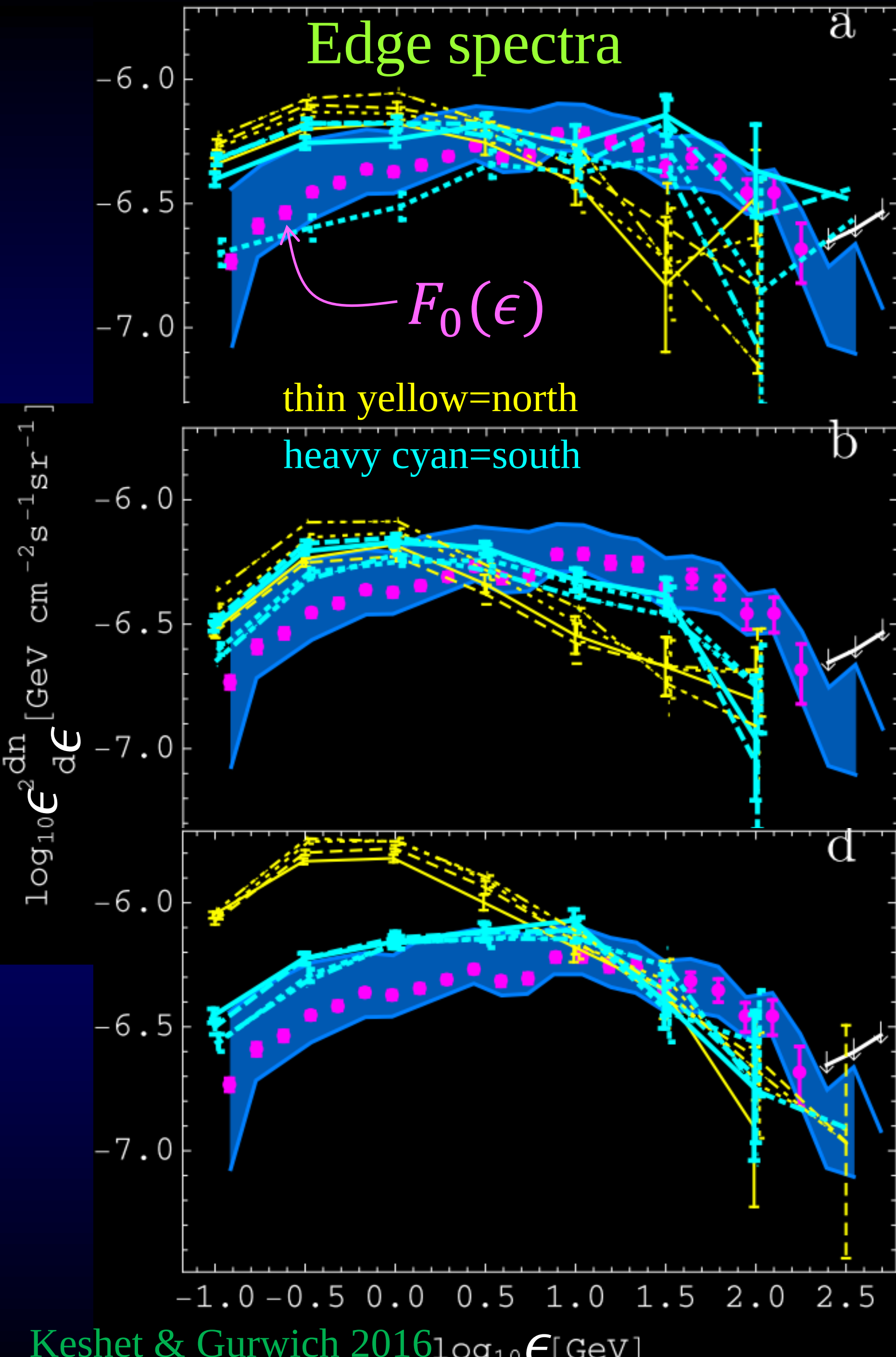


Keshet & Gurwich 2016

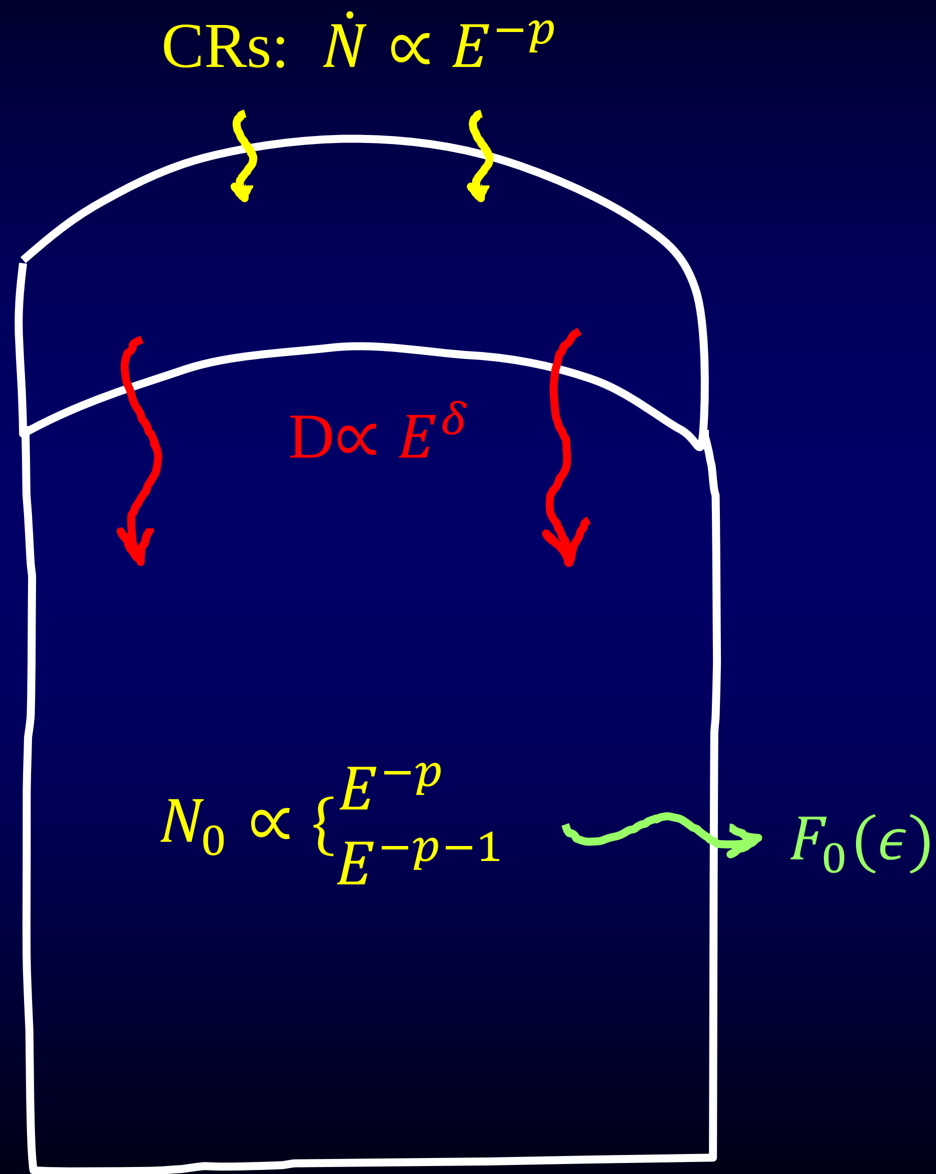


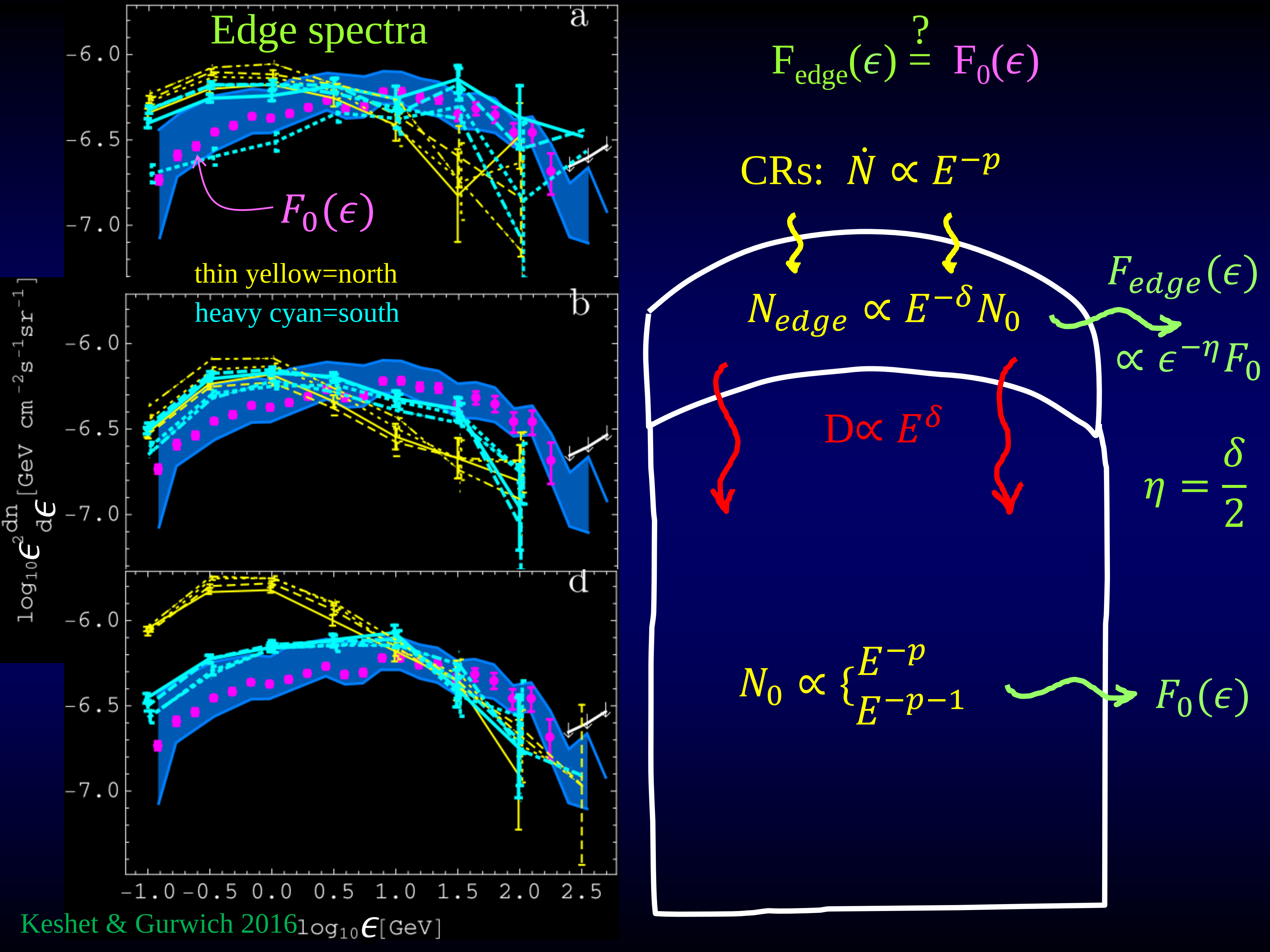
Edge spectra
a
b
d
$F_0(\epsilon)$
thin yellow=north
heavy cyan=south
$\log_{10}\epsilon^2\frac{dn}{d\epsilon}$ [GeV cm^{-2}s^{-1}sr^{-1}]
$\log_{10}\epsilon$ [GeV]
b [deg]
l [deg]
Keshet & Gurwich 2016

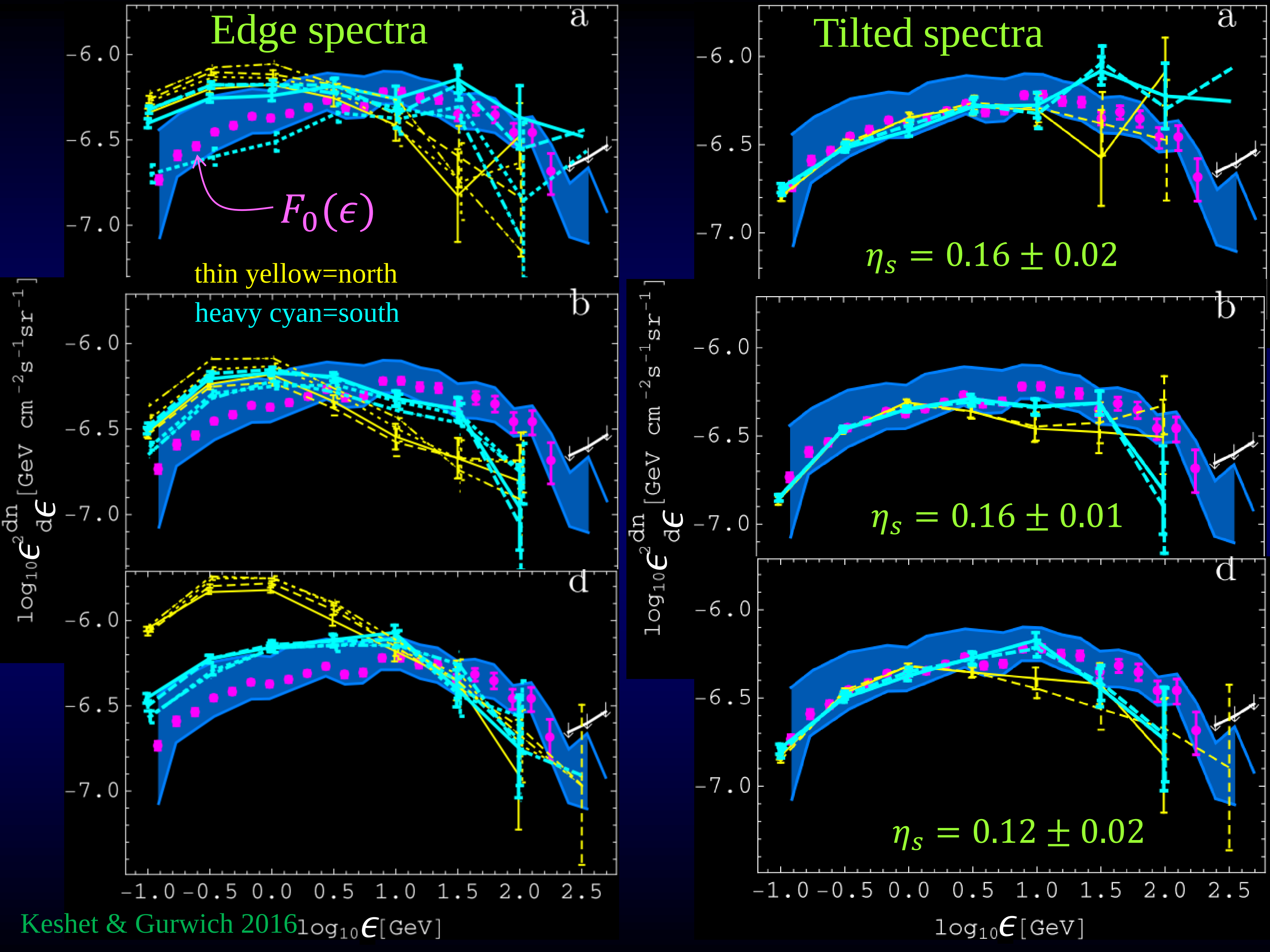
$$F_{edge}(\epsilon) \stackrel{?}{=} F_0(\epsilon)$$



Keshet & Gurwich 2016




Edge spectra
a
b
d
−6.0
−6.5
−7.0
−1.0 −0.5 0.0 0.5 1.0 1.5 2.0 2.5
$\log_{10}\epsilon^2\frac{dn}{d\epsilon}$ [GeV cm^{-2}s^{-1}sr^{-1}]
$\log_{10}\epsilon$[GeV]
$F_0(\epsilon)$
thin yellow=north
heavy cyan=south
Keshet & Gurwich 2016
$F_{edge}(\epsilon) \overset{?}{=} F_0(\epsilon)$
CRs: $\dot{N} \propto E^{-p}$
$N_{edge} \propto E^{-\delta} N_0$
$F_{edge}(\epsilon)$
$\propto \epsilon^{-\eta} F_0$
D$\propto E^{\delta}$
$\eta = \frac{\delta}{2}$
$N_0 \propto \{ {E^{-p} \atop E^{-p-1}}$
$F_0(\epsilon)$


Edge spectra
Tilted spectra
$F_0(\epsilon)$
thin yellow=north
heavy cyan=south
$\eta_s = 0.16 \pm 0.02$
$\eta_s = 0.16 \pm 0.01$
$\eta_s = 0.12 \pm 0.02$
$\log_{10}\epsilon^2 \frac{dn}{d\epsilon}$ [GeV cm^{-2}s^{-1}sr^{-1}]
$\log_{10}\epsilon$[GeV]
a
b
d
Keshet & Gurwich 2016

1. Diffusion strong and measured in situ

Averaging along the FB edge:

$$\delta = 2\eta = 0.48 \pm 0.02 \; (95\% \text{ CL})$$

(Kraichnan diffusion?)

Same tilt both above and below the cooling break:

$$D \simeq 3 \times 10^{29} (E/10 \text{ GeV})^{0.48 \pm 0.02} \text{ cm}^2 \text{ s}^{-1}$$

2. Shock must be strong

Along the FB edge $\Delta\eta = \pm 0.05$ ➡ $\Delta p = \pm 0.10$

Assuming
$$\begin{cases} p = 2\dfrac{M^2+1}{M^2-1} \\ \dfrac{\Delta M}{M} > 0.25 \end{cases}$$
➡ $M > 5$

Keshet & Gurwich 2016

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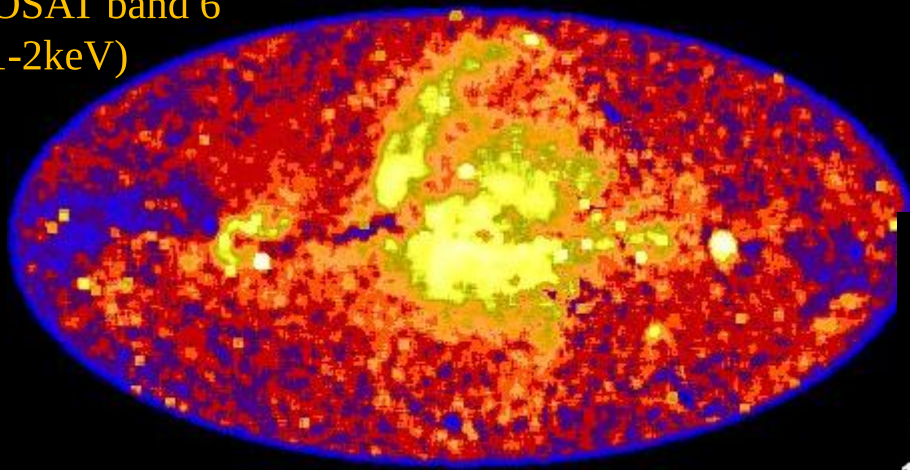
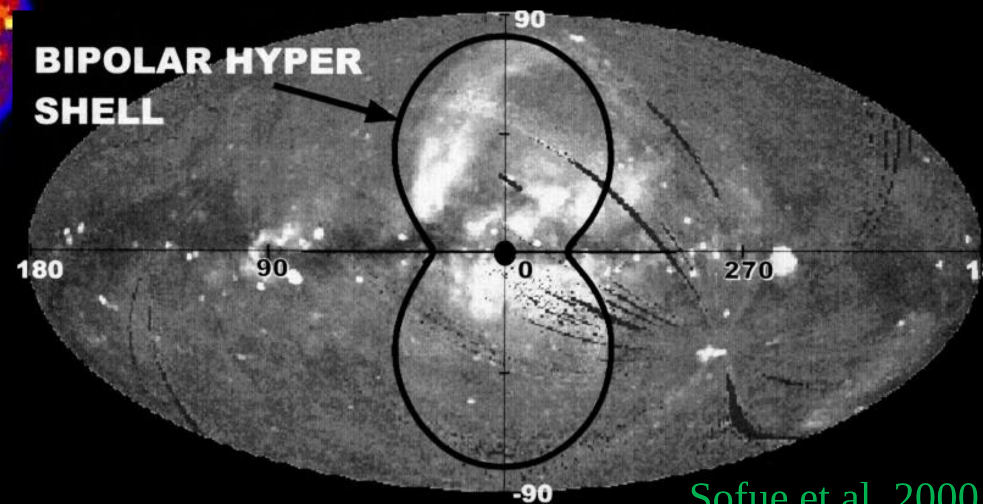
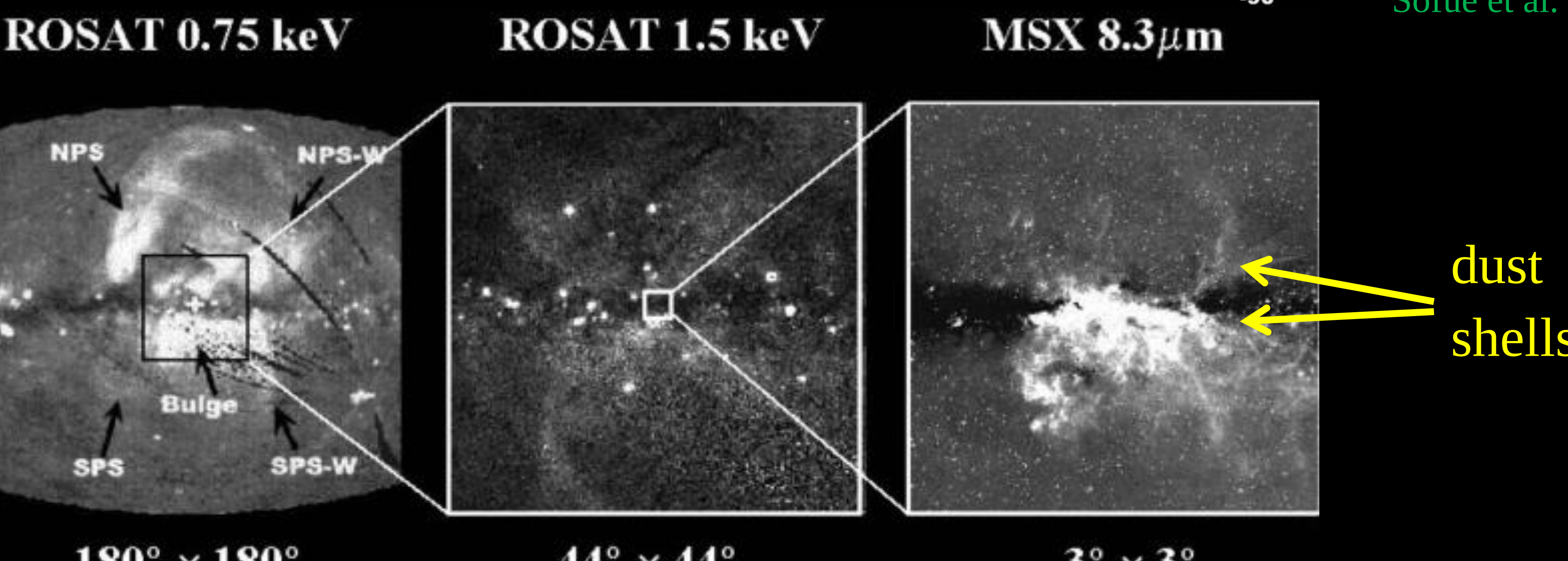


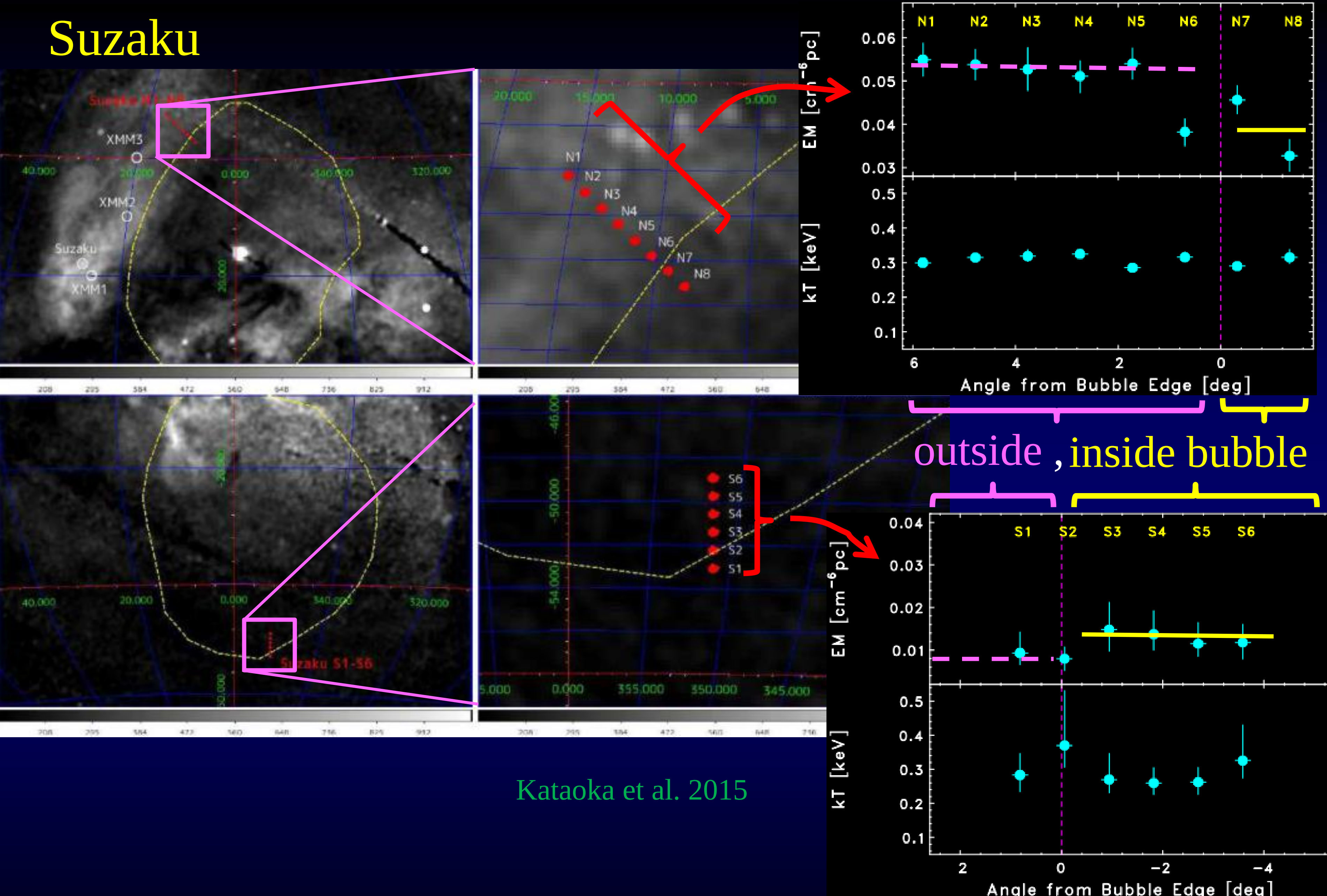


Sofue et al. 2000



Bland-Hawthorn & Cohen 2003

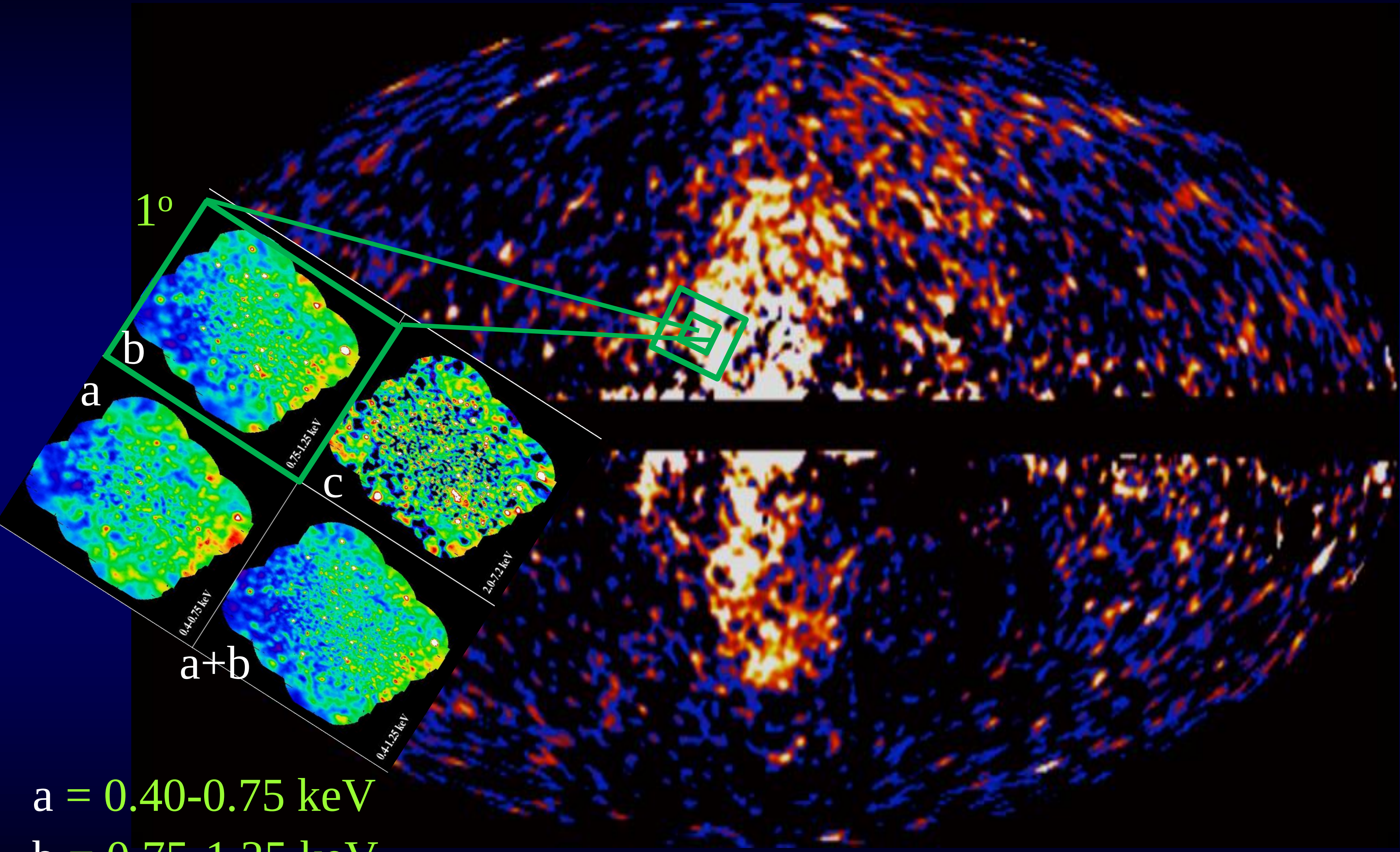
Suzaku



Kataoka et al. 2015

The emission measure (EM) of the 0.3 keV plasma decreases by $\simeq$ 50% toward the inner regions of the north-east bubble, with no accompanying temperature change. However, such a jump in the EM is not clearly seen in the south bubble data.

XMM



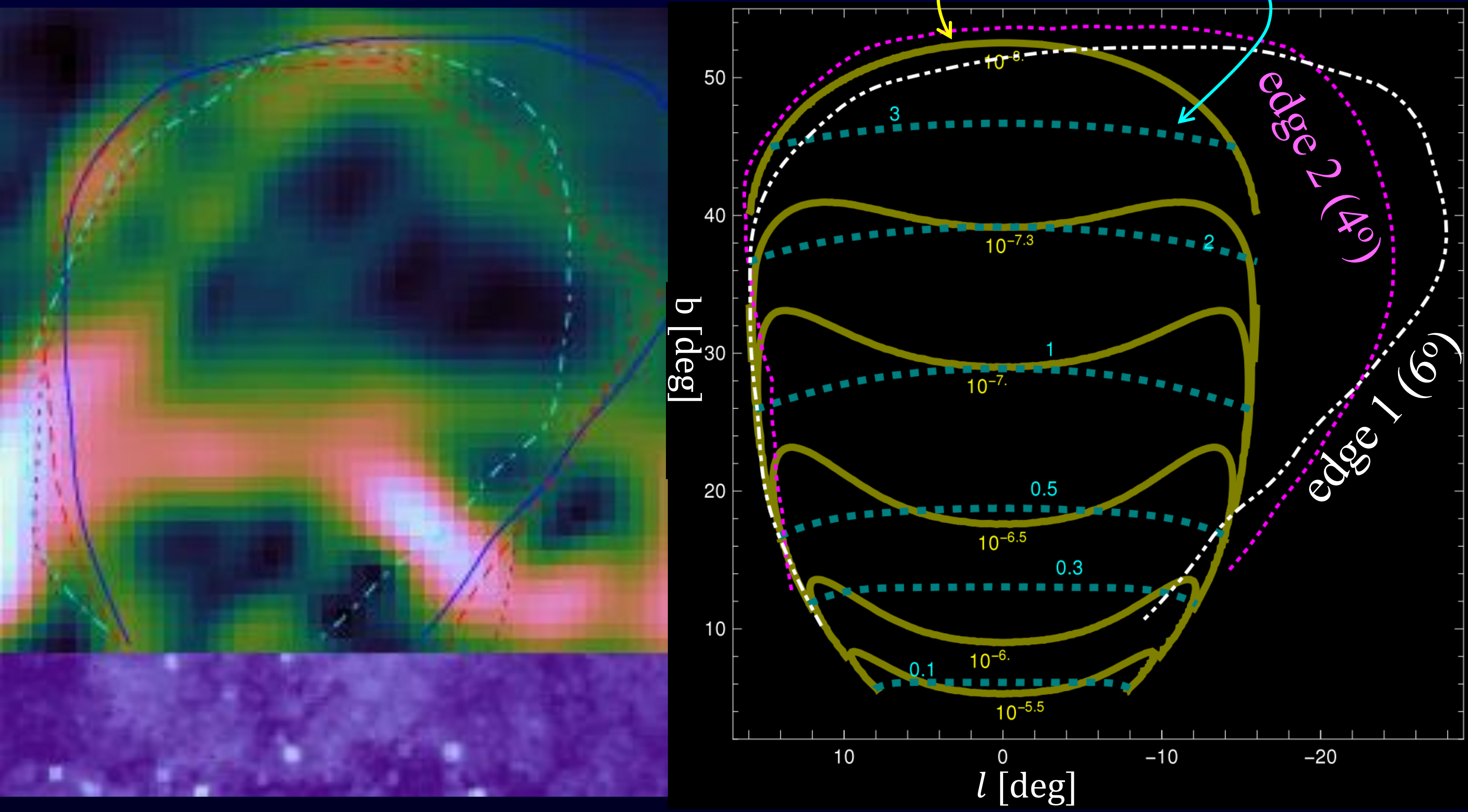
a = 0.40-0.75 keV

b = 0.75-1.25 keV

c = 2.0-7.2 keV (l,b)=(14:30,8:30)

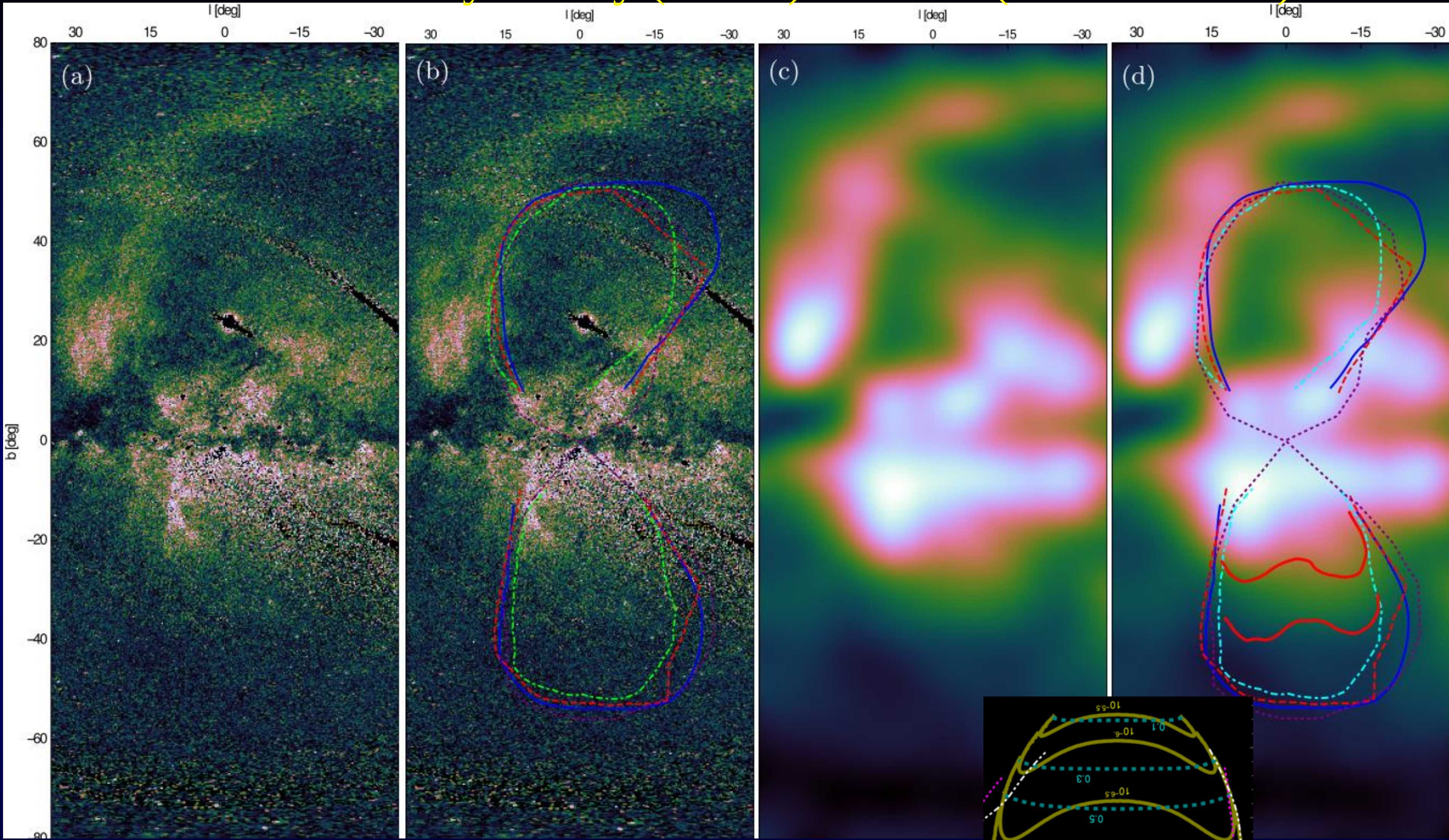
$$\text{Halo: } n_e \simeq 10^{-3}\left(\frac{r}{10kpc}\right)^{-2} cm^{-3}\,; \quad T_e \simeq 0.15\text{keV}.$$

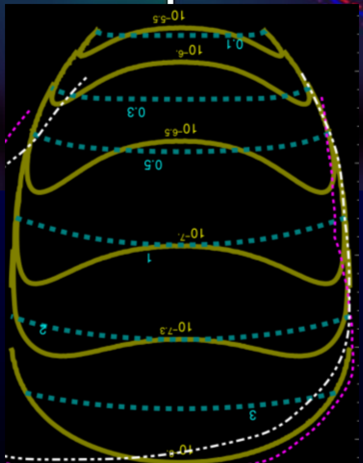
Assume: strong shock + Primakoff $v \propto r$



Keshet & Gurwich 2017b

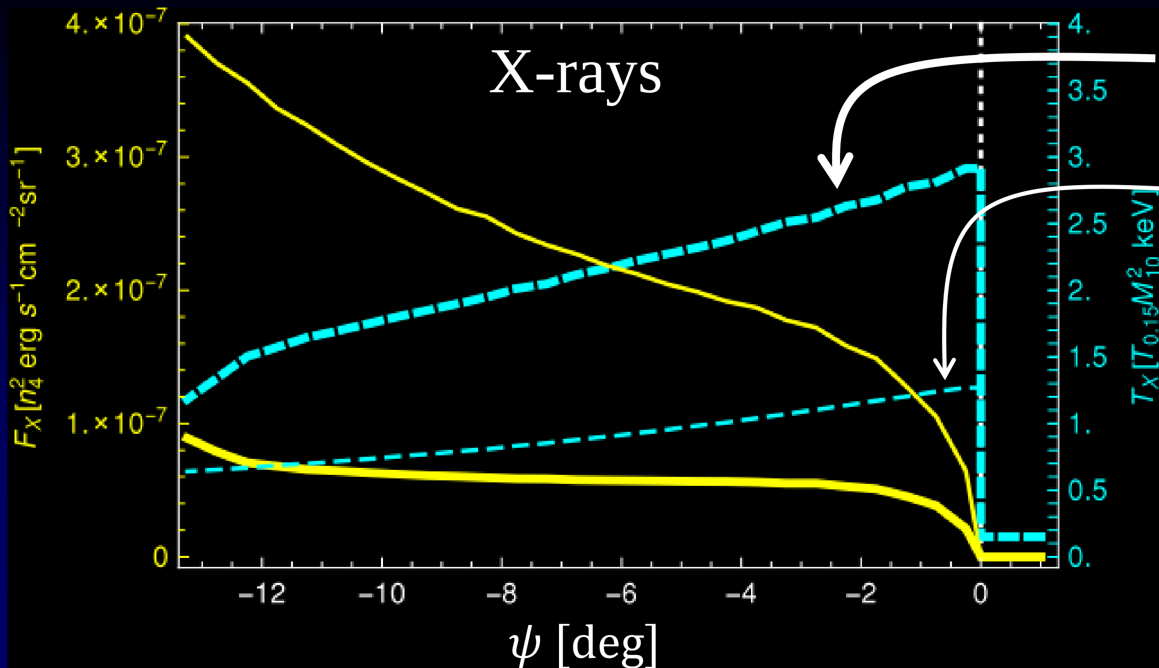
ROSAT All Sky Survey (RASS) band R6 (0.73-1.56keV)

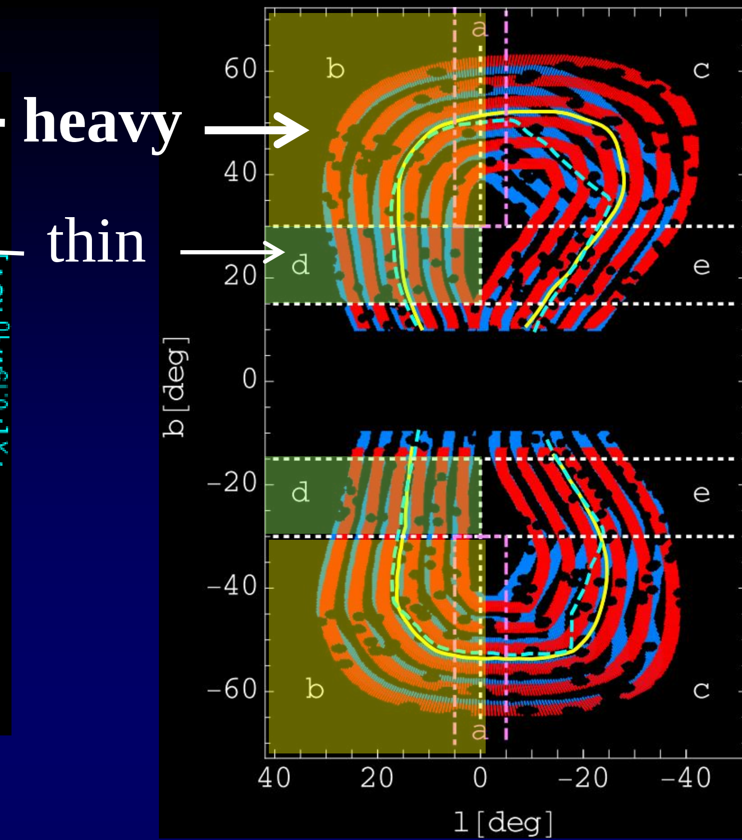


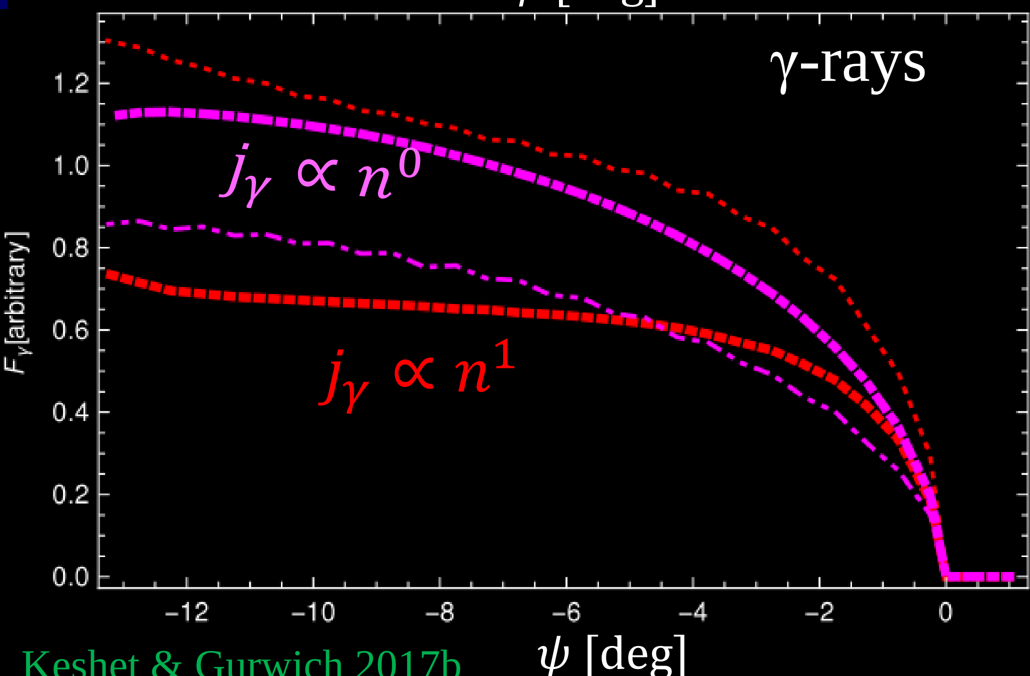


Keshet & Gurwich 2017b

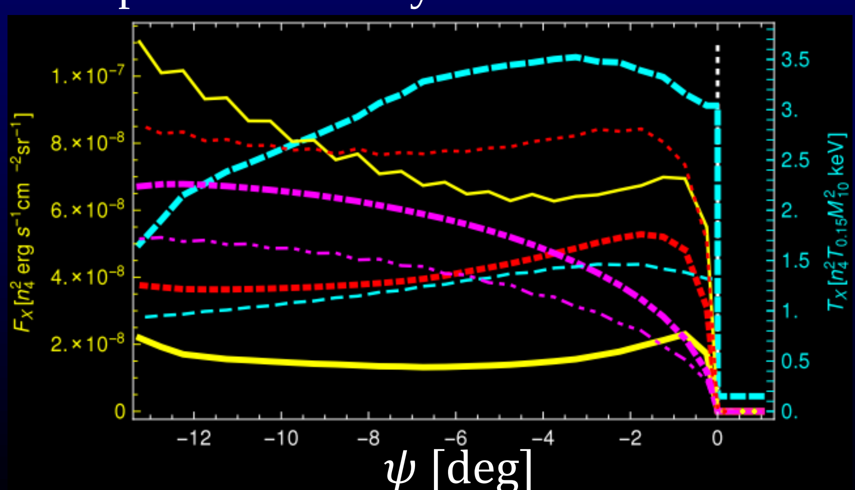
Projected signatures





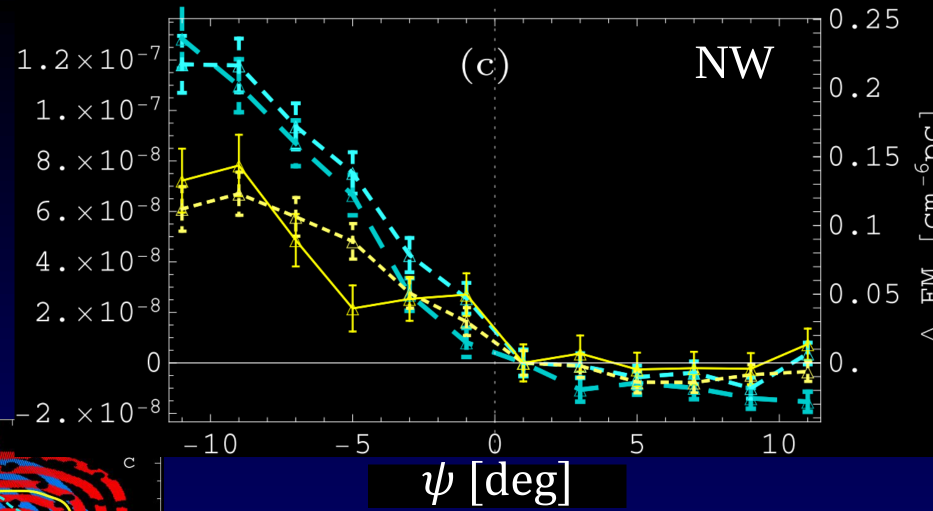


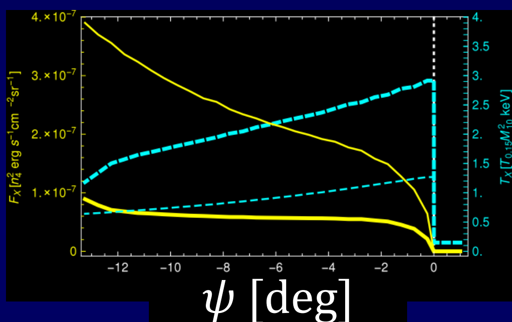
Compare: Sedov-Taylor-von Neumann

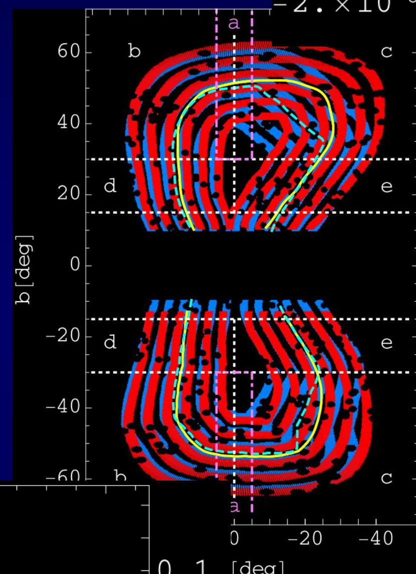


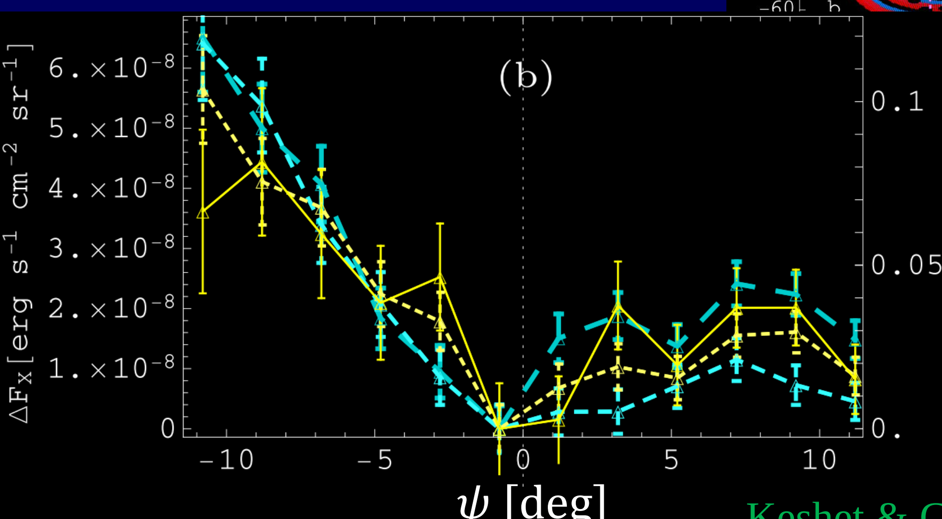
Keshet & Gurwich 2017b

ROSAT profiles





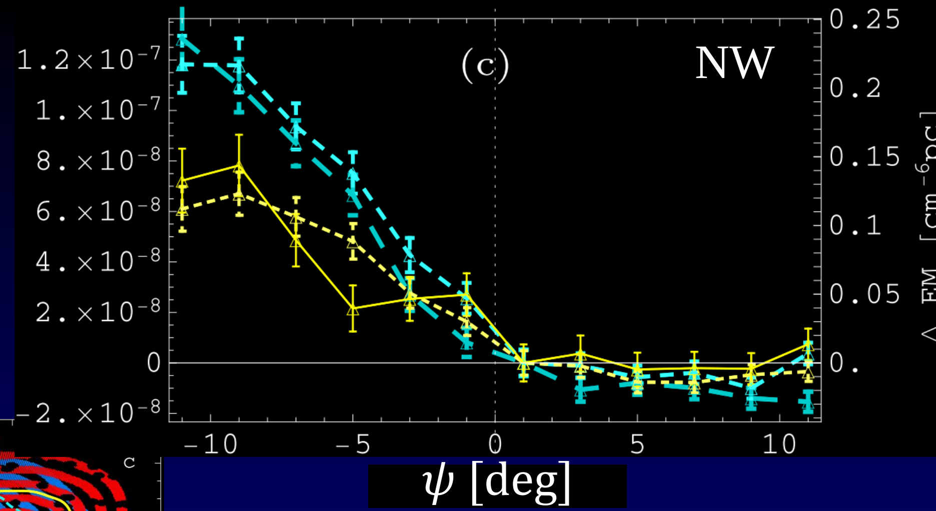


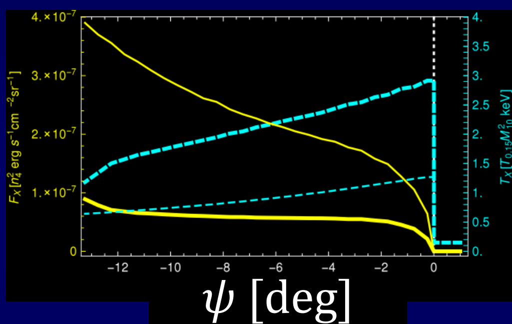


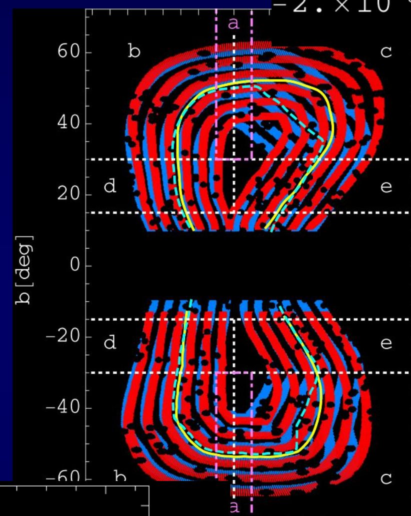
ROSAT bands { R4, R5, R6, R7

Keshet & Gurwich 2017b

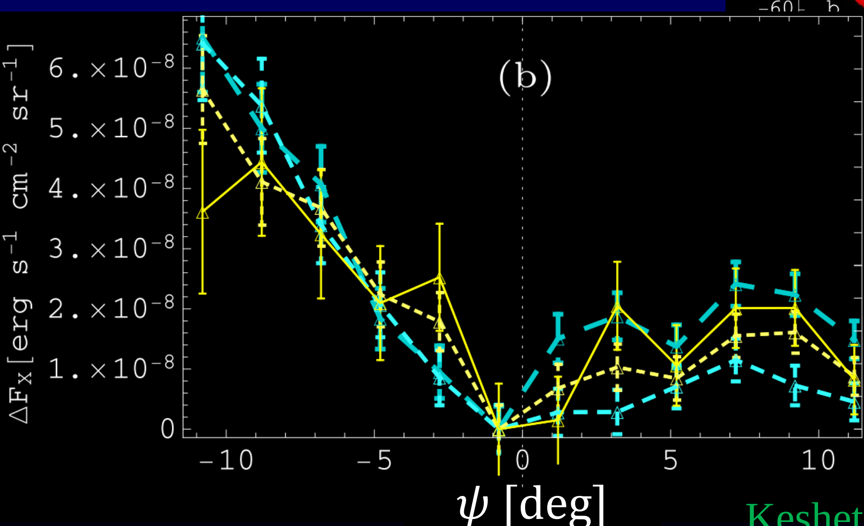
ROSAT profiles

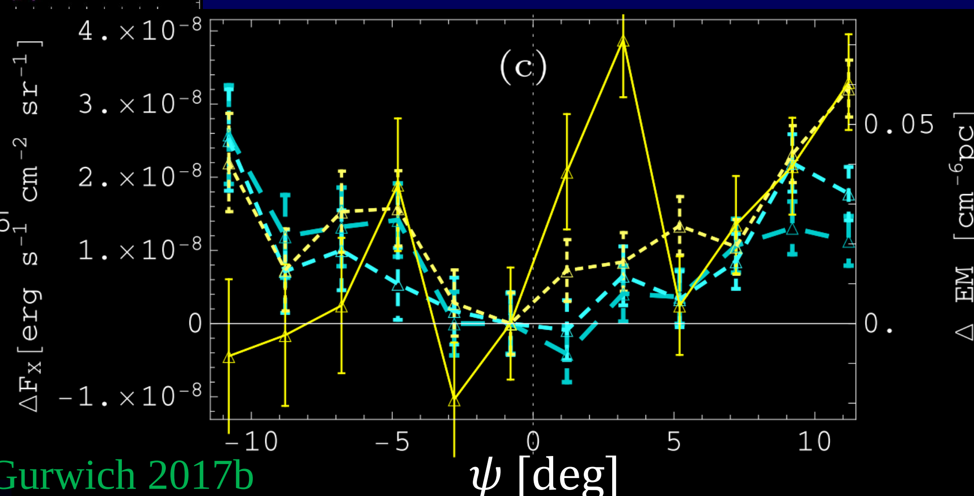




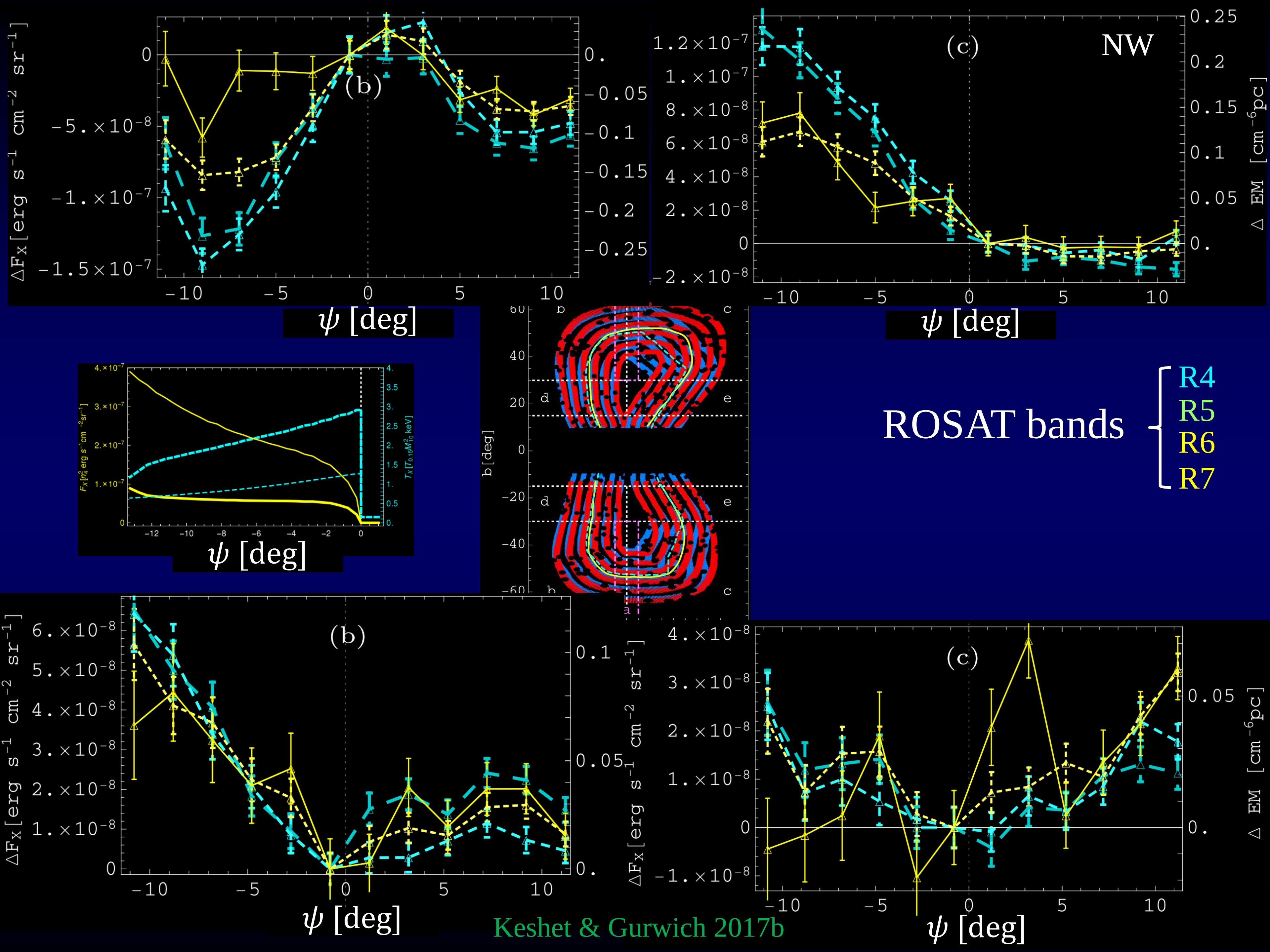


ROSAT bands
- R4
- R5
- R6
- R7





Keshet & Gurwich 2017b



(b)
ΔFx [erg s-1 cm-2 sr-1]
ψ [deg]
(c)
NW
Δ EM [cm-6pc]
ψ [deg]
ψ [deg]
b [deg]
b
c
d
e
ROSAT bands
R4
R5
R6
R7
(b)
ΔFx [erg s-1 cm-2 sr-1]
ψ [deg]
(c)
ΔFx [erg s-1 cm-2 sr-1]
Δ EM [cm-6pc]
ψ [deg]
Keshet & Gurwich 2017b

ROSAT implications

$n_e(10\text{ kpc}) \simeq 4 \times 10^{-4}\text{cm}^{-3}$

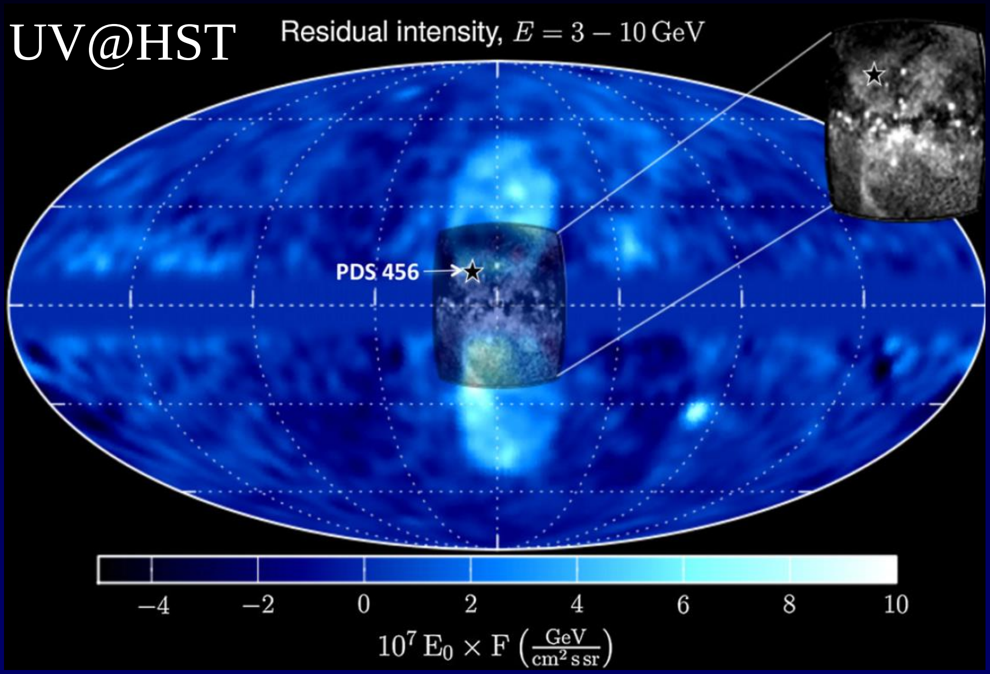
$M(10\text{ kpc}) \simeq 5T_{u,0.15keV}^{-1/2} \times (T_i/T_e)^{1/2}$

$\text{E} \simeq 10^{56}\text{erg} \times T_i/T_e$

$\text{t} \simeq 6.6\text{ Myr} \times (T_i/T_e)^{-1/2}$

Keshet & Gurwich 2017b

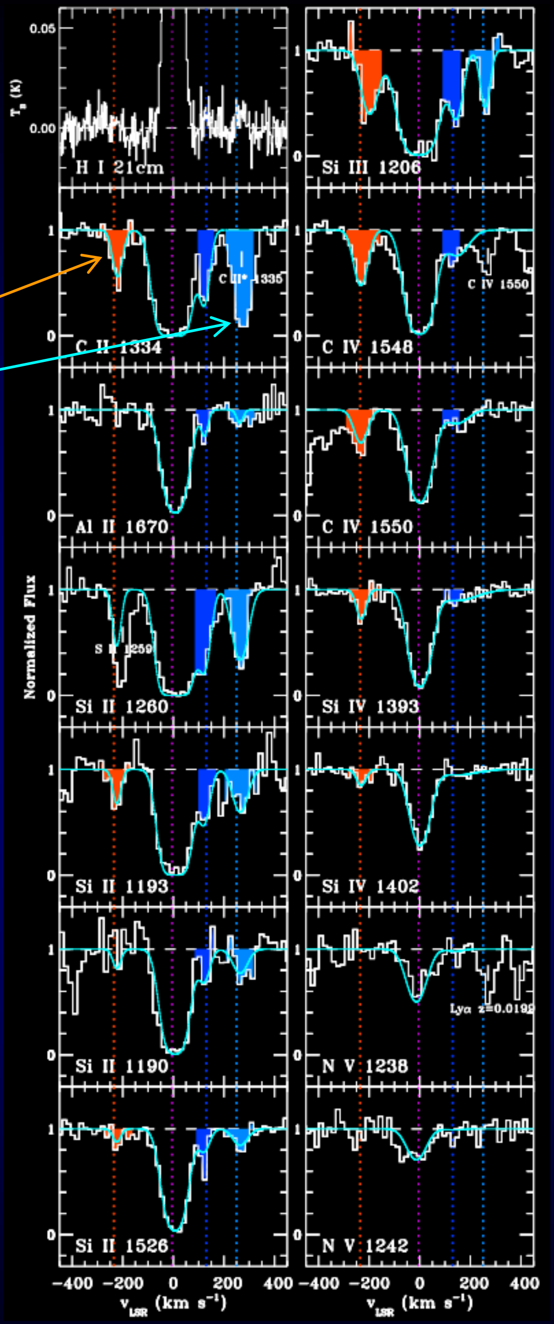
ROSAT implications



Fox et al. 2015

-235 km s^{-1}

+250 km s^{-1}



outflow velocity $\gtrsim 900$ km s^{-1} → t~2.5-4.0 Myr

Di Teodoro+2017 - HI flow w/ similar velocities

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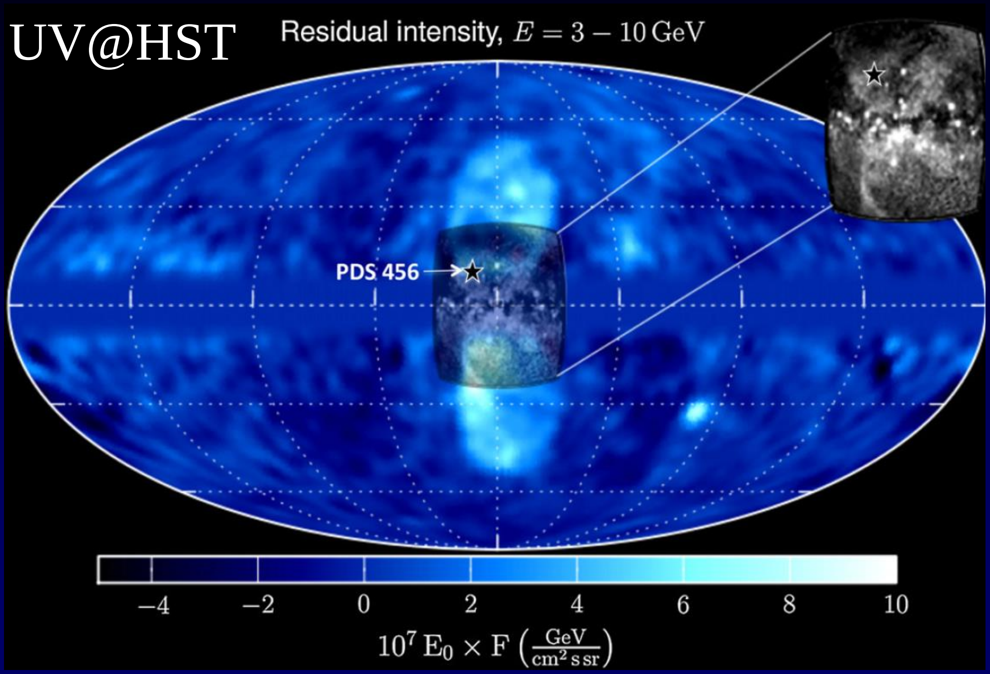
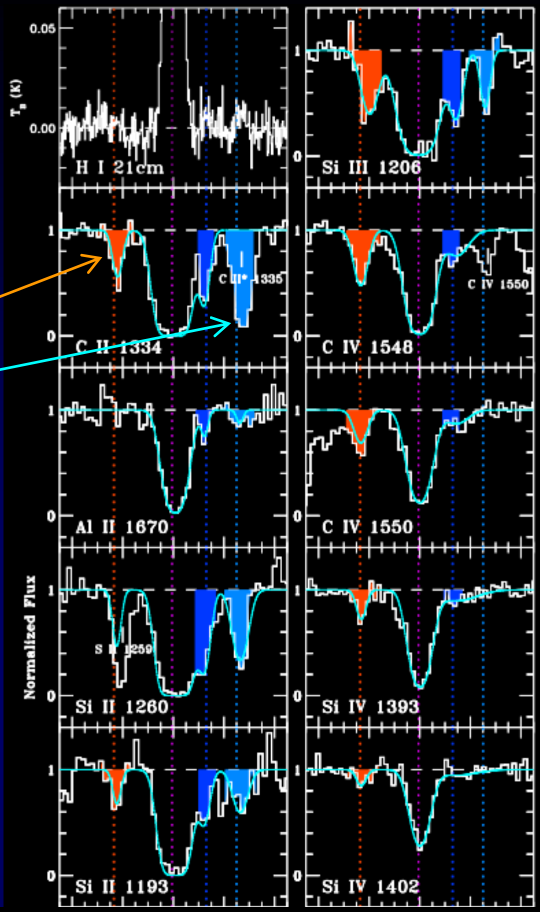
Keshet & Gurwich 2017b

ROSAT implications



Fox et al. 2015



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$T_i/T_e \simeq 10$

$M \simeq 10$

$\mathrm{E} \simeq 10^{57}\mathrm{erg}$

$\mathrm{t} \simeq 3\ \mathrm{Myr}$

Keshet & Gurwich 2017b

Summary and Discussion

- There is a natural single-zone model with no ad-hoc spectral features:
  - (2-4)Myr bubbles with $B \sim (2-3)\mu G$
  - FBs gauge the ISRF: starlight 2-3 times stronger than thought
  - FB event clears the dust extinction?
- Edge spectra: no template needed
  - Strong, Kraichnan(?) diffusion measured
  - Strong, Mach$\gtrsim$5 forward shock
- X-ray high-latitude signal identified
  - Supersonic shell: FB edges are Mach$\sim$10 forward shocks
  - Upstream density should decline roughly as $n \propto r^{-2}$
- The FBs are proving to be an excellent laboratory for CR physics.

Fin

Thanks:

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Ido Reiss

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May 2018, Bangalore, India:

Galactic outflows: from superbubbles to Fermi Bubbles