Fermi/eROSITA Bubbles: Past, present, and the future

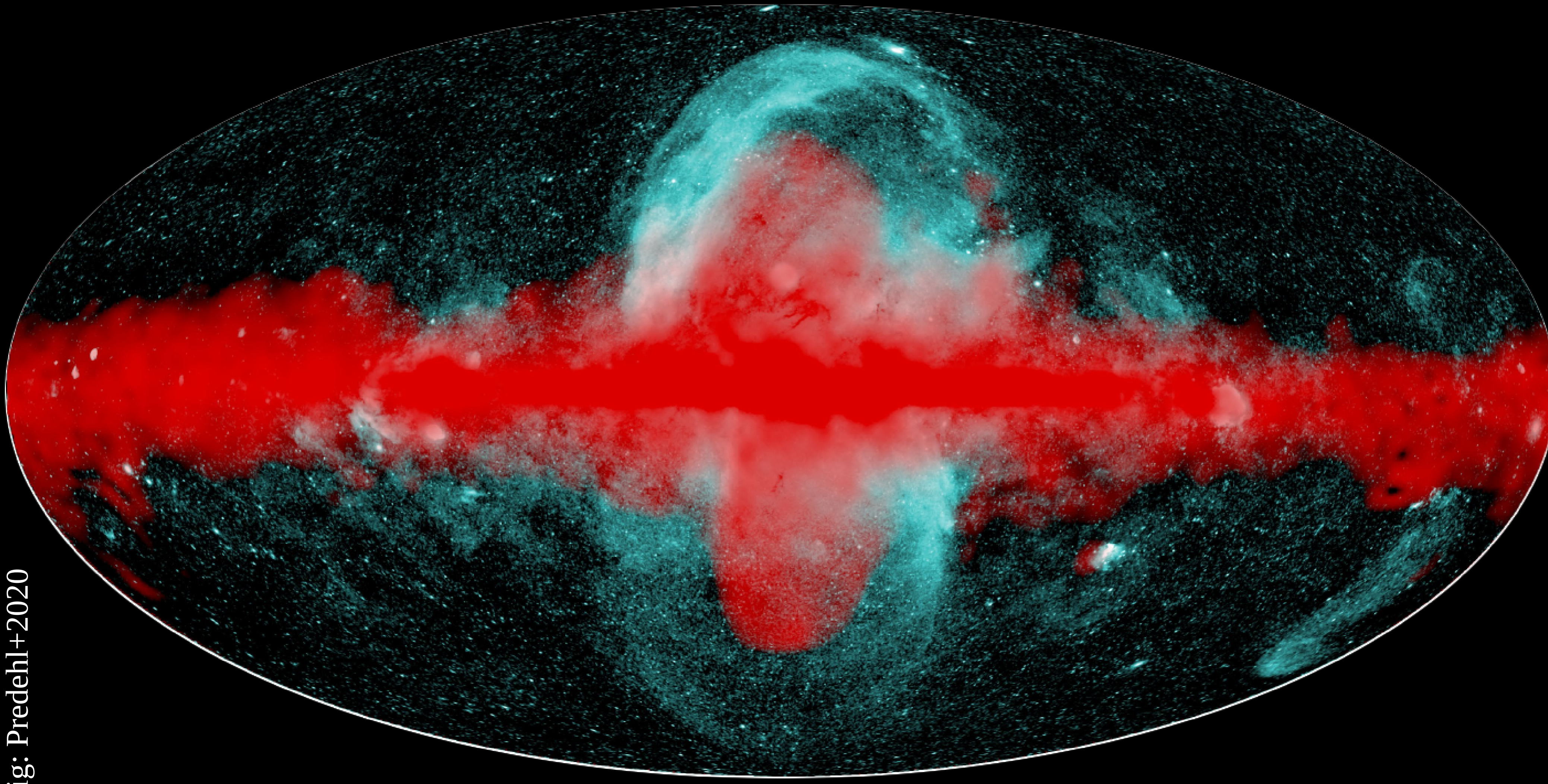


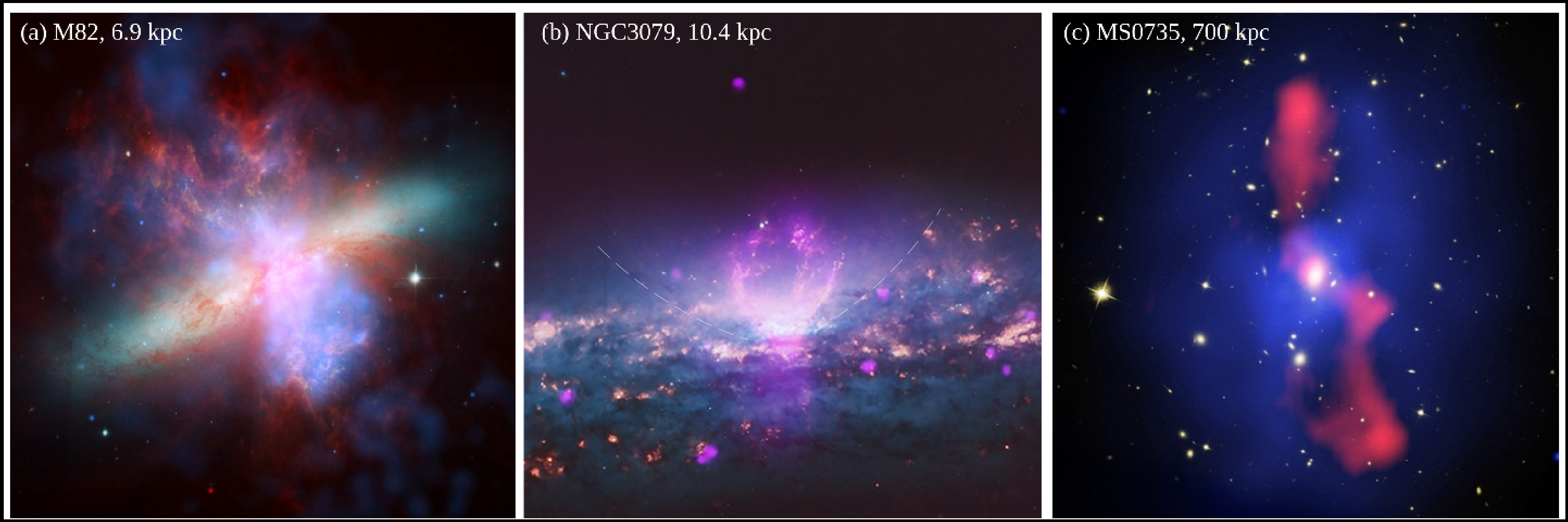
Fig: Predehl+2020

Kartick Sarkar

Indian Institute of Technology Kanpur (IIT Kanpur), India

Collaborators: Biman Nath, Prateek Sharma, Santanu Mondal, Tsvi Piran

Outflows across galaxies



$SFR \sim 10 \ M_\odot yr^{-1}$
$M_{bh} \sim ---$
$v_{rot} \sim 80 \ km \ s^{-1}$

$SFR \sim 10 \ M_\odot yr^{-1}$
$M_{bh} \sim 2\times10^6 \ M_\odot$
$v_{rot} \sim 200 \ km \ s^{-1}$

$SFR \sim ---$
$M_{bh} \sim 10^9 \ M_\odot$
$v_{rot} \sim 2000 \ km \ s^{-1}$

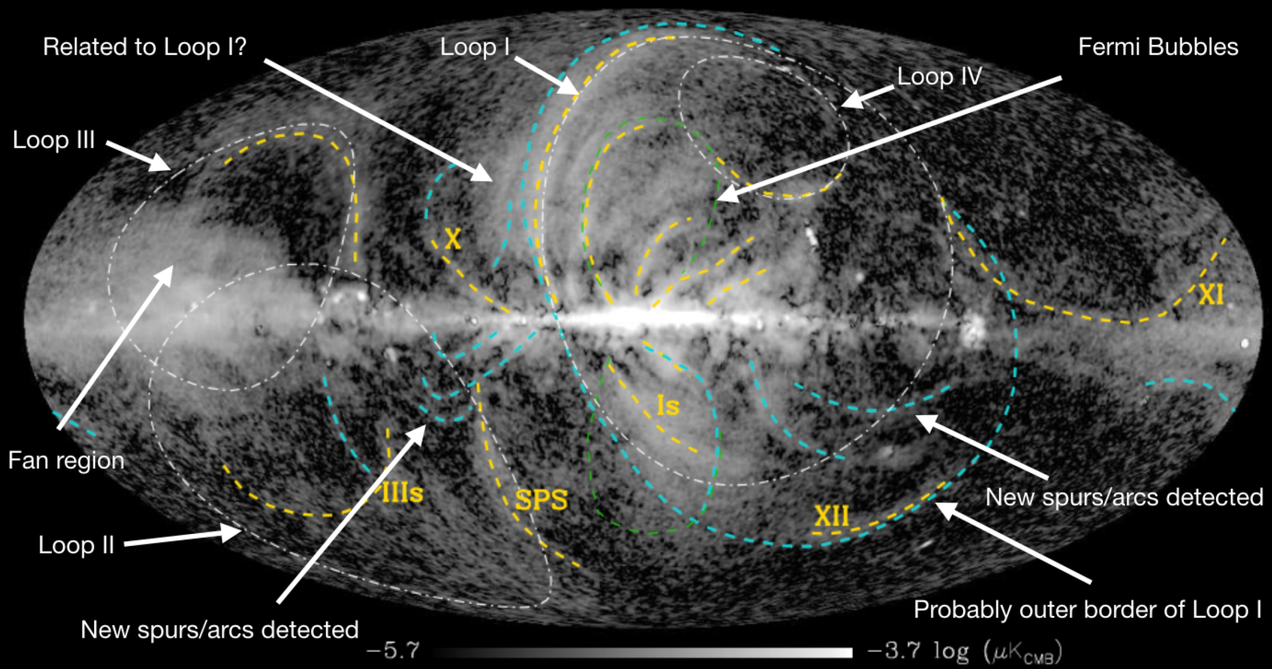
MW
$SFR \sim 0.1 \ M_\odot yr^{-1}$
$M_{bh} \sim 4\times10^6 \ M_\odot$
$v_{rot} \sim 220 \ km \ s^{-1}$

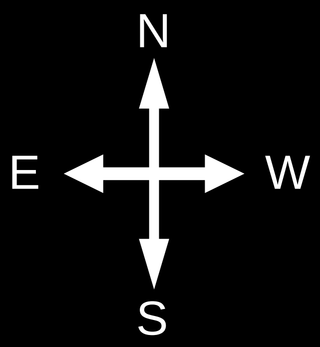
$M_{vir} \propto v_{rot}^3$

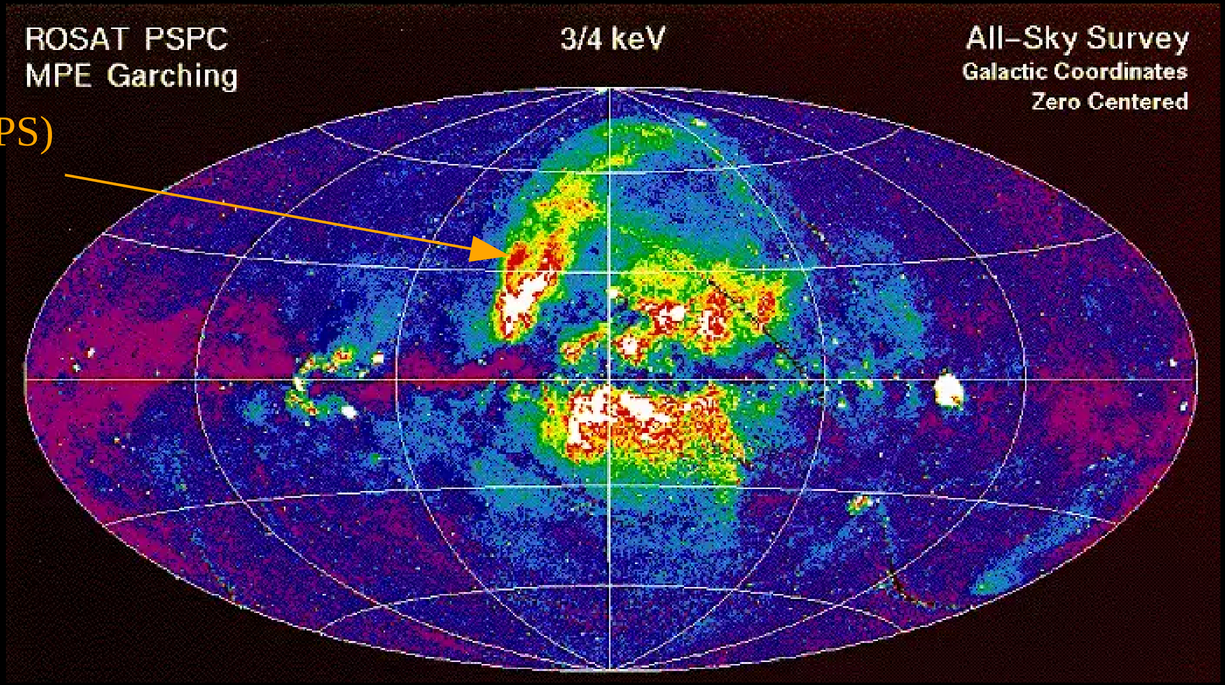
Statistically, we do expect outflows from MW !

Chandra Archive

Outflow from the Galaxy (Pre-2010)?





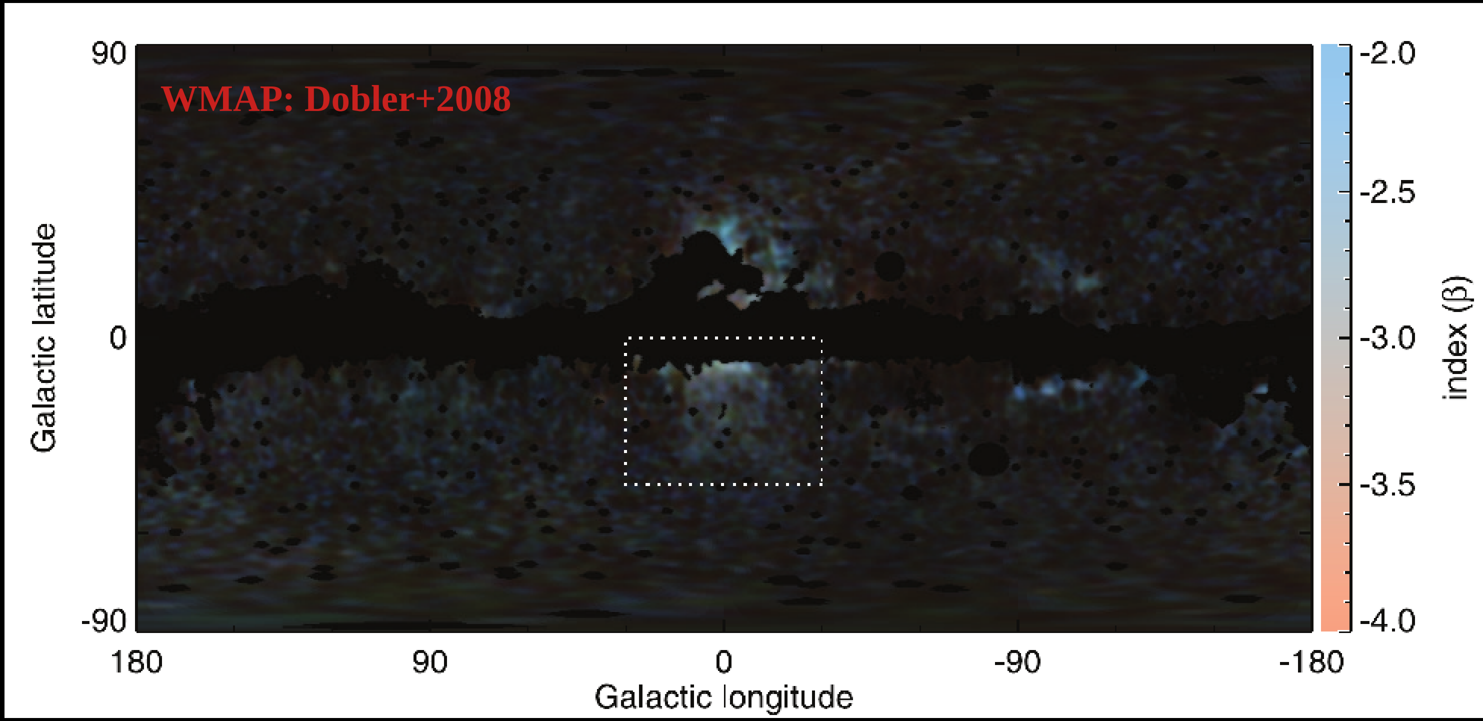


0.5 – 0.9 keV skymap from ROSAT

Is it a Galactic nuclear outflow?
Not sure.

Planck Collab+2016 (20-50 GHz); Snowden+1997

Non-thermal effects in the nuclear outflow?



$p = \frac{\chi+2}{\chi-1}$

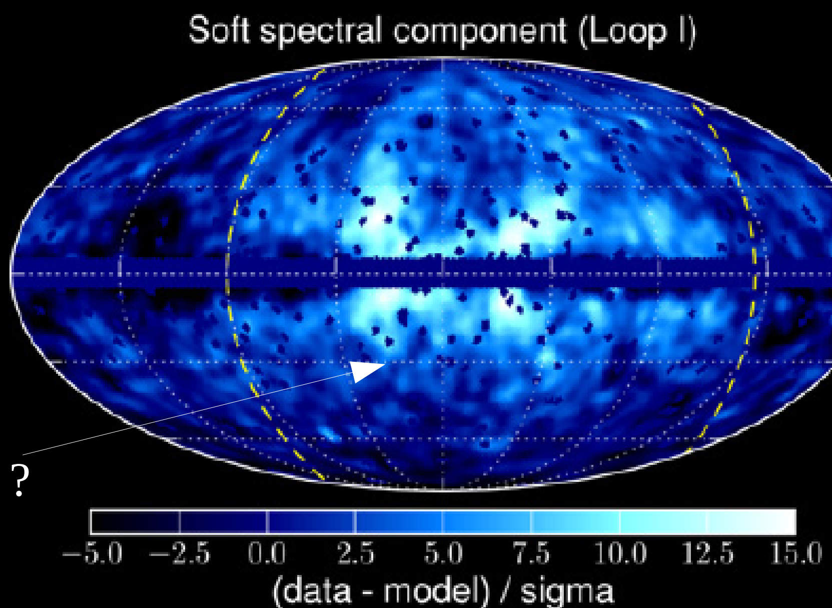
Brightness temperature: $T_b \propto \nu^{-2.56}$

CR electron spectrum: $N_e(E) \propto E^{-2.1}$ $\Rightarrow Mach \gtrsim 5$

There is a Galactic nuclear outflow !

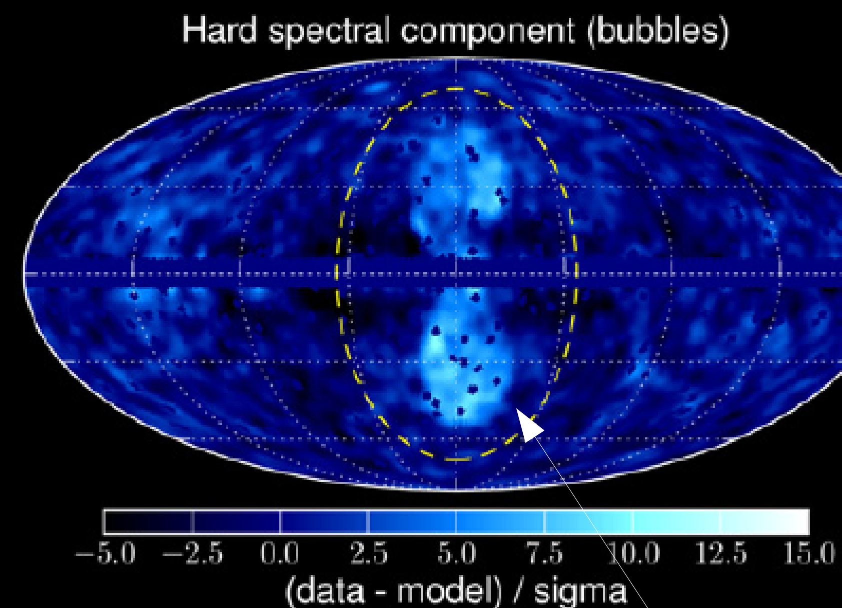
Fermi Bubbles

$$dN/dE \propto E^{-2.4}$$



SPS ?

$$dN/dE \propto E^{-1.9}$$



(0.7-10.0 GeV) significance maps

Fermi Bubbles

$$E_{\gamma} \sim 4 \times 10^{37} \ erg\, s^{-1}$$

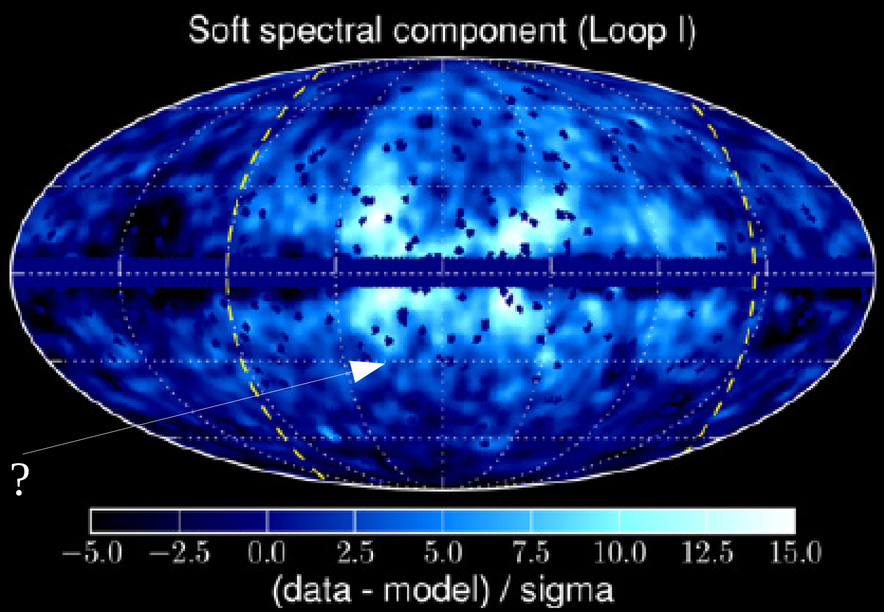
$$E_{mech} \sim 10^{54-55} \ erg\, s^{-1} \ (only\ Fermi\ bubble)$$
$$\sim 10^{56} \ erg\, s^{-1} \ (including\ NPS/Loop-I)$$

Su et. al. 2010; Ackerman etal. 2014

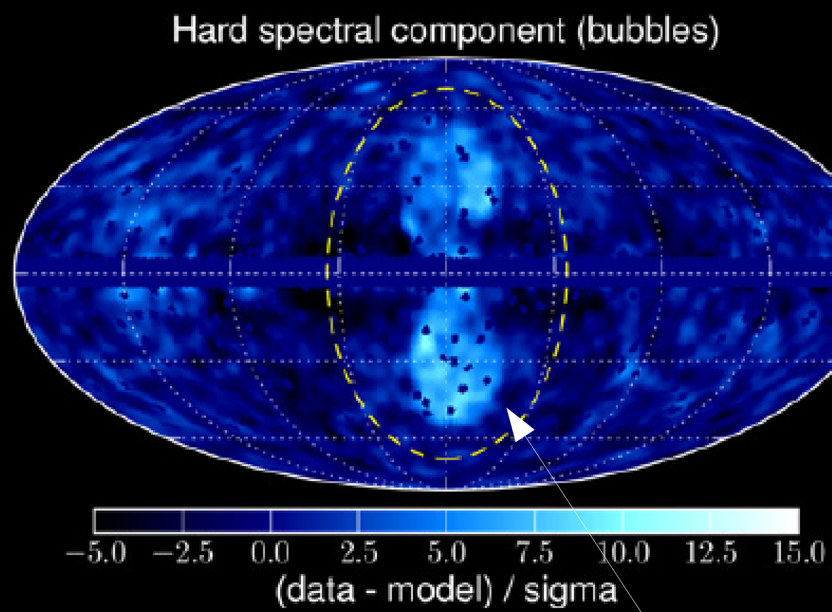
Fermi Bubbles

$dN/dE \propto E^{-2.4}$

$dN/dE \propto E^{-1.9}$



SPS ?



(0.7-10.0 GeV) significance maps

Fermi Bubbles

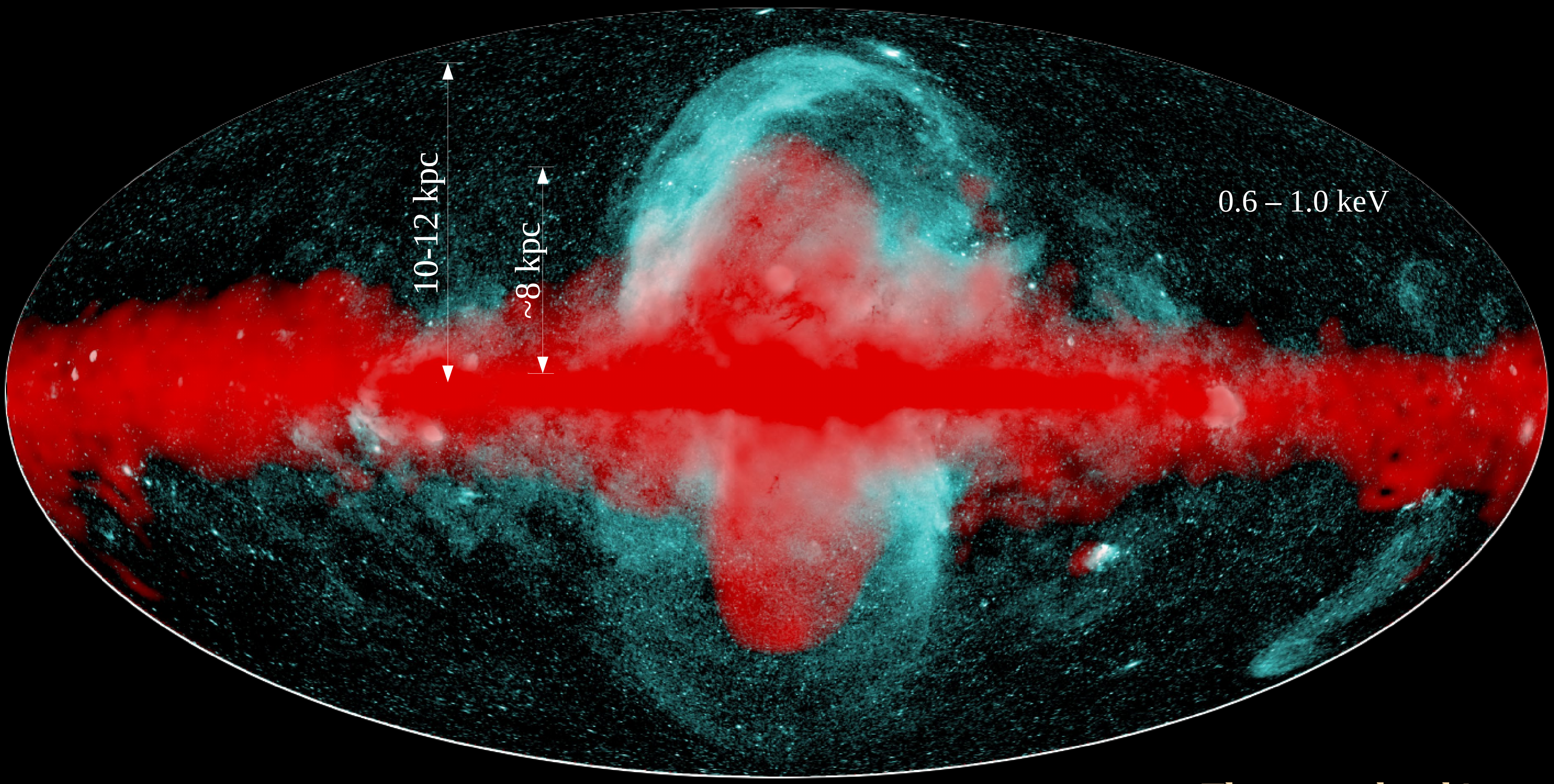
Are they related?
Confusion due to the distance of the NPS

$$E_{\gamma} \sim 4 \times 10^{37}\ erg\, s^{-1}$$

$$E_{mech} \sim 10^{54-55}\ erg\, s^{-1}\ (only\ Fermi\ bubble)$$
$$\sim 10^{56}\ erg\, s^{-1}\ (including\ NPS/Loop-I)$$

Su et. al. 2010; Ackerman etal. 2014

Fermi/eROSITA Bubbles



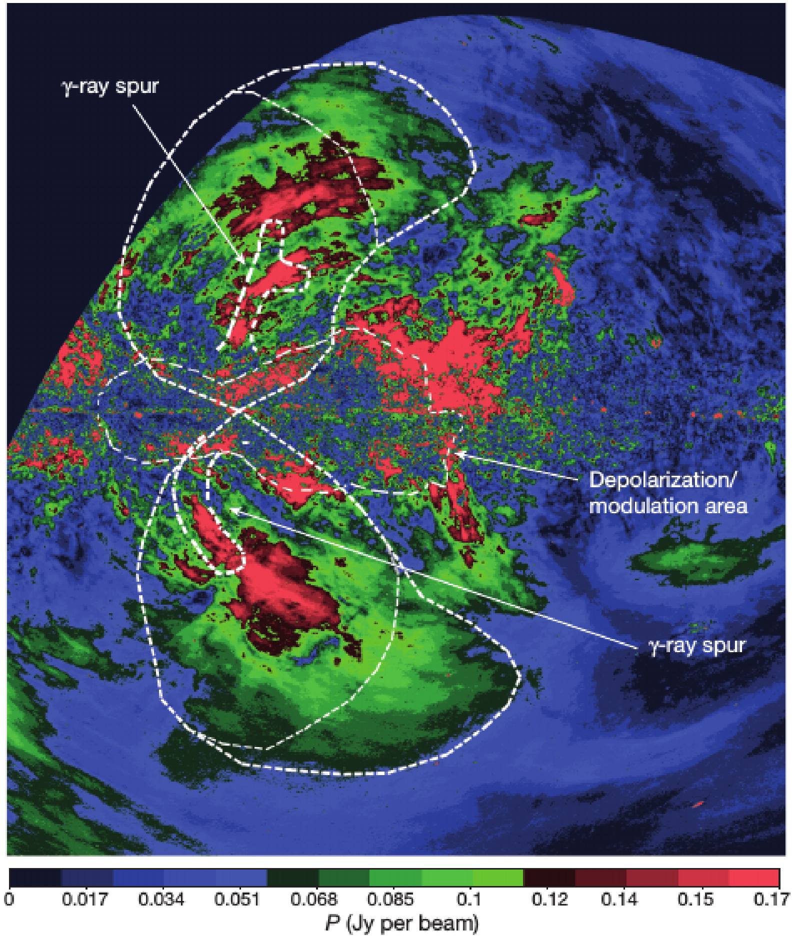
They are related !

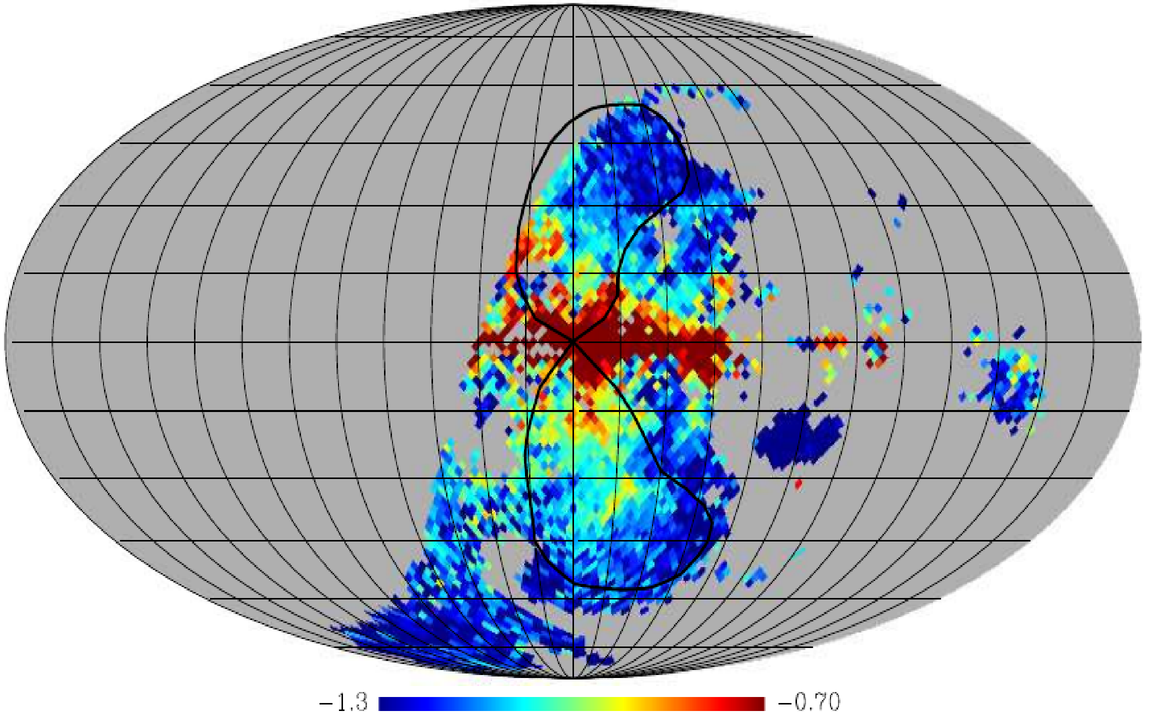
But are they from the same event?

1. Symmetric around Galactic plane
2. Symmetric around Galactic axis
3. X-ray bubbles encompass gamma-ray bubbles

Predehl+2020

Multi-wavelength features





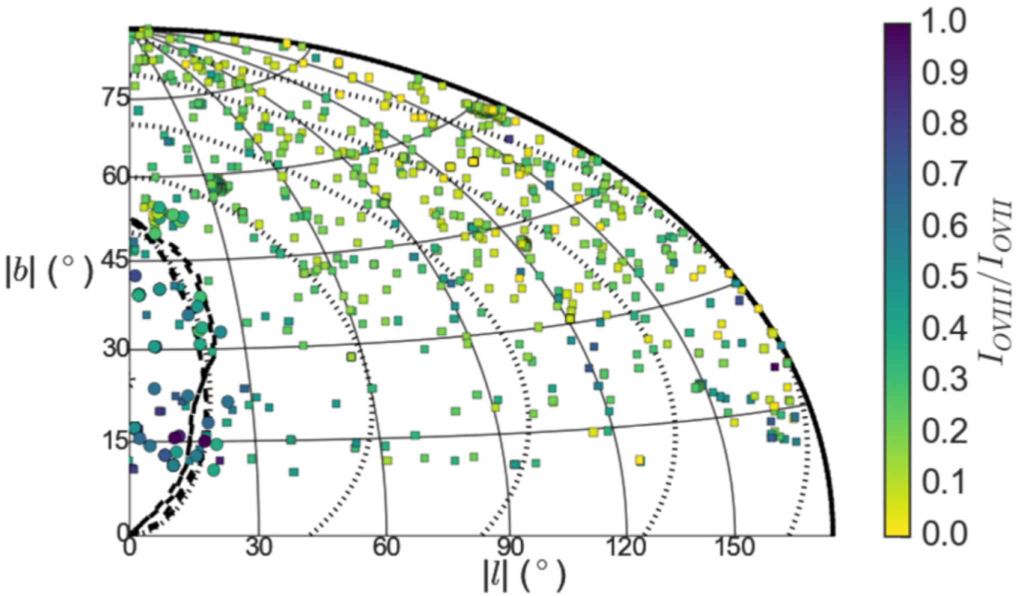
Alpha sPASS/ WMAP

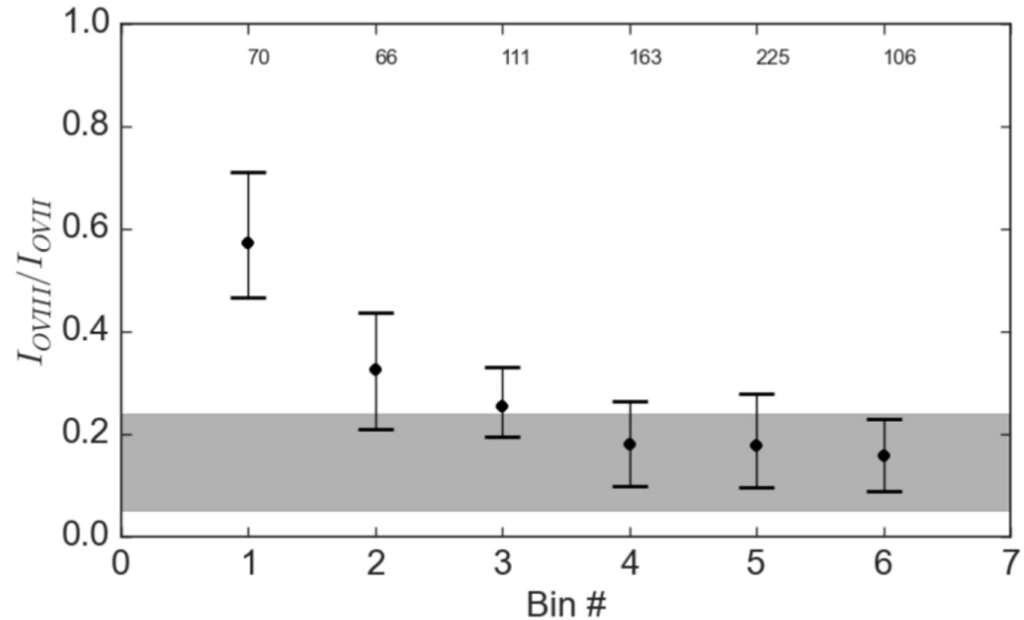
1) Polarised radio at 2.3 GHz shows extended (10°) emission, depolarisation towards the disk.

2) Softening spectra index at 2.3 GHz means $t_{age,elec} \approx 25\ Myr$

Caretti et. al. 2013

x-ray lines

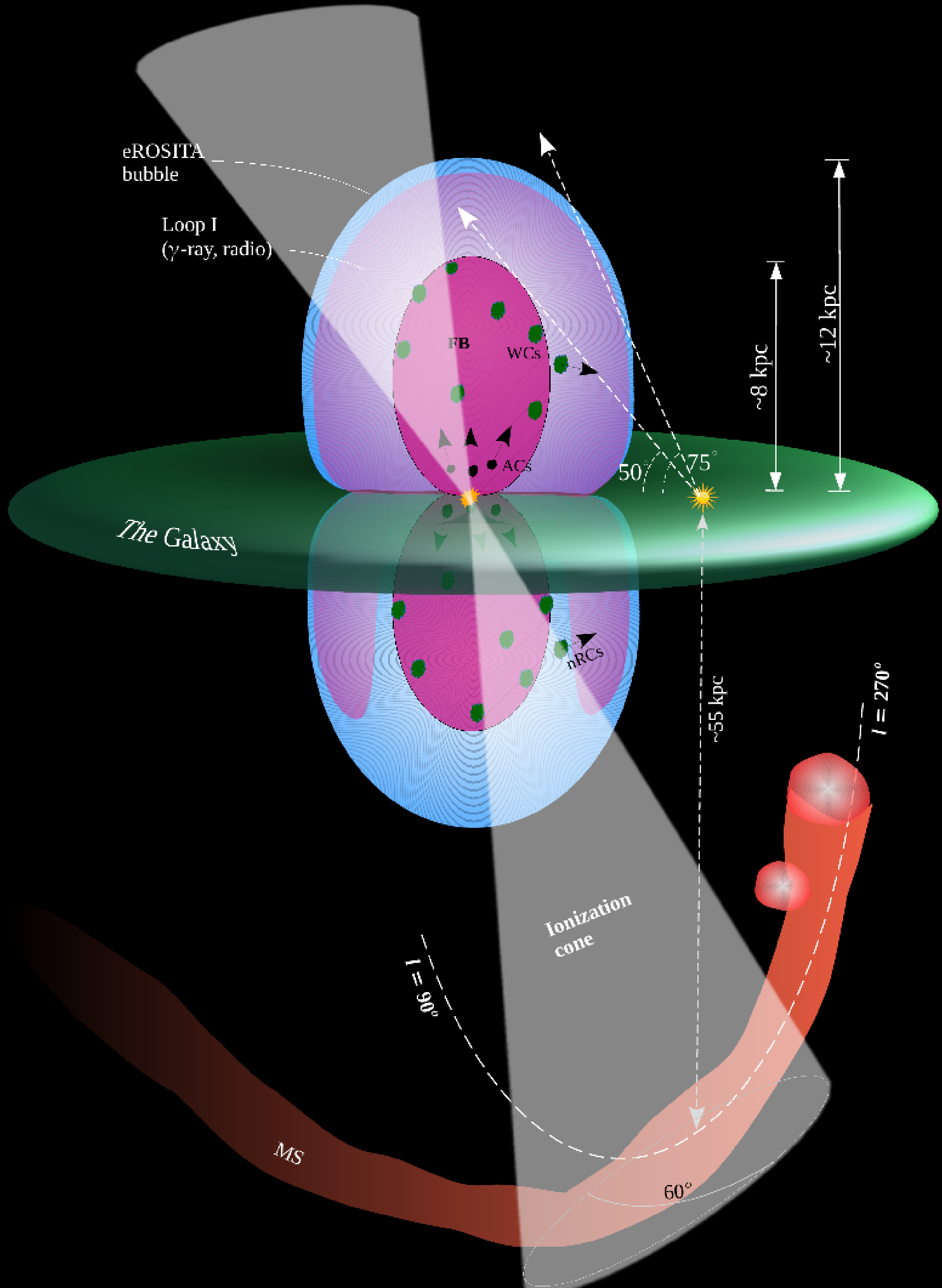




OVIII and OVII emission lines constraint the line ratio to ~ 0.5-0.8

Heated gas temperature $\approx 3\times10^{6}\ K$

Miller & Bregman, 2016


eROSITA
bubble
Loop I
(γ-ray, radio)
FB
WCs
ACs
nRCs
50°
75°
~8 kpc
~12 kpc
The Galaxy
~55 kpc
l = 270°
l = 90°
Ionization
cone
MS
60°

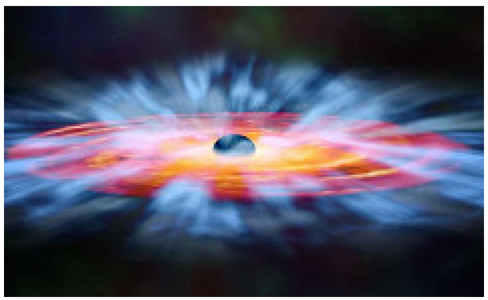
Sarkar 2024

What is the origin of this bubbles?

The Origin of the Fermi Bubbles?

Dynamical

1) Black hole activity at the Galactic center



Credit: NASA/CXC/M.Weiss

2) Supernovae activity at the Galactic center

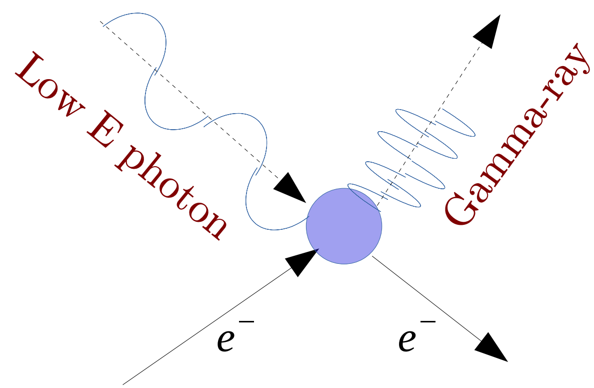
Credit: 2017 Supernovae.net

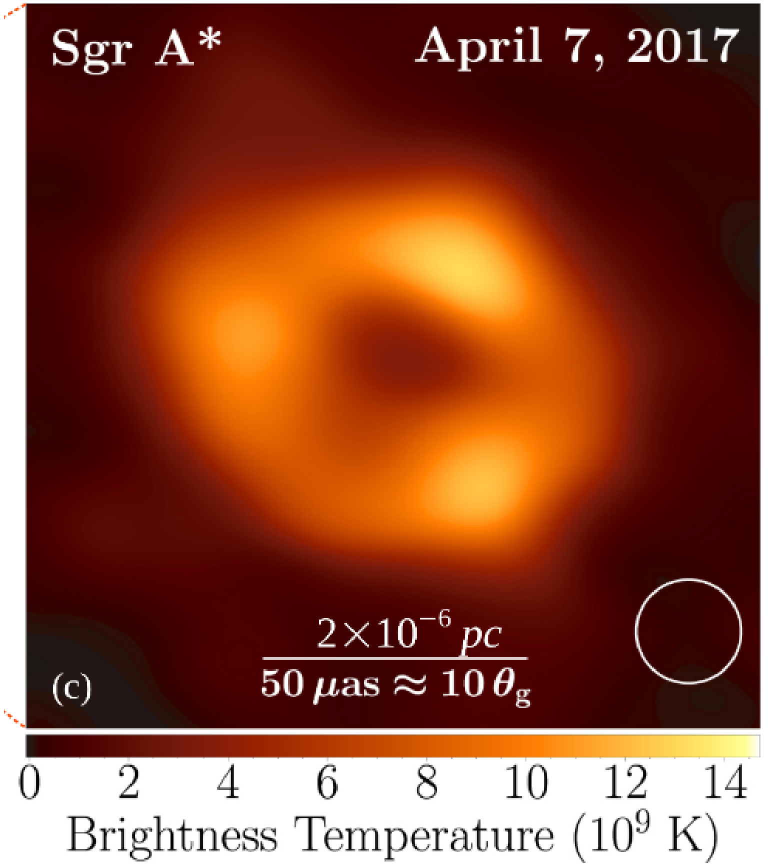
Spectral

1) Hadronic emission

$$p + p \rightarrow \pi^{\pm} + \pi^{0}$$
$$\pi^{0} \rightarrow 2\gamma$$

2) Leptonic:
Inverse Compton of CMB by high energy cosmic ray electrons.





$$M_{BH} \approx 4\times10^{6} M_{\odot} \Rightarrow L_{edd} \approx 5\times10^{44} erg\ s^{-1}$$

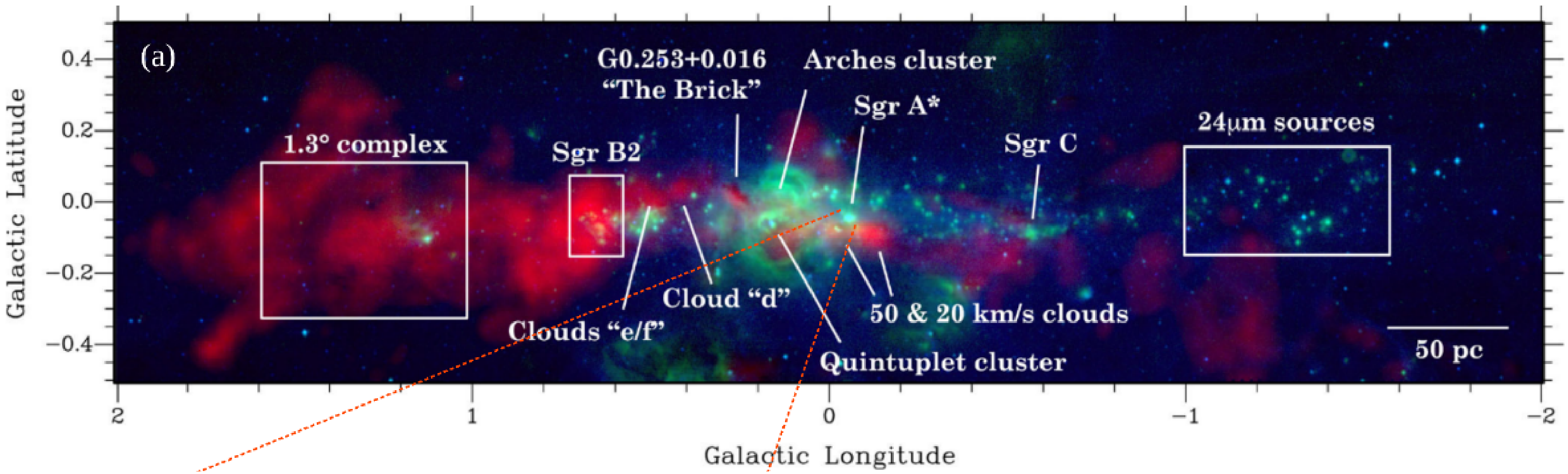
$$\dot{M}_{acc} \sim 10^{-8} M_{\odot}\ yr^{-1} \Rightarrow L_{mech} \sim 10^{38}\ erg\ s^{-1}$$

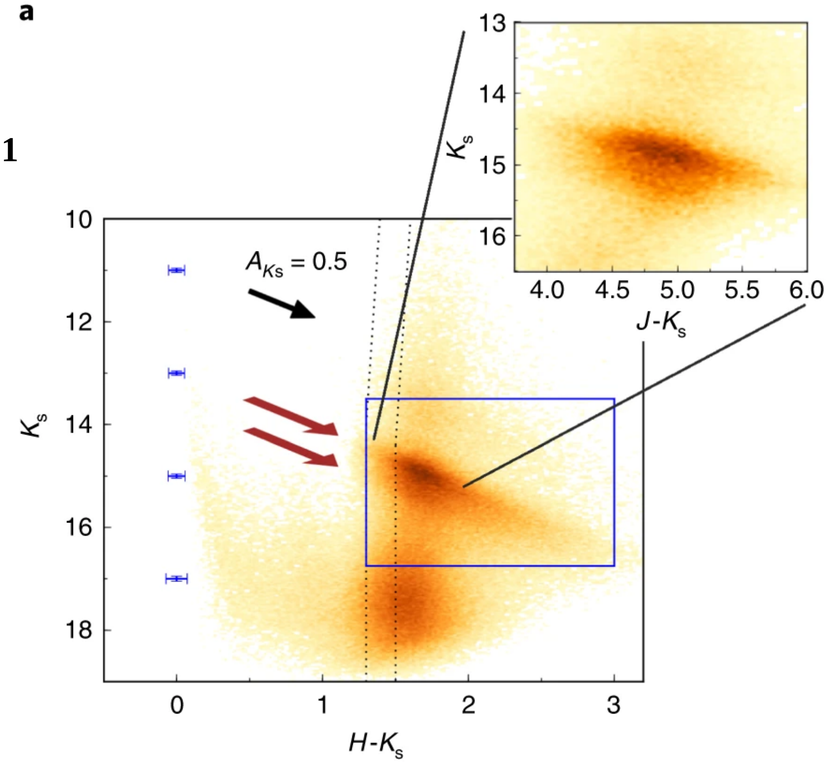
X-ray reflection from molecular clouds (fluorescent Iron) suggests $\sim 10^{3-4}$ higher luminosity ~300 yr ago

$$\Rightarrow L_{mech,\,past} \approx 10^{41-42}\ erg\ s^{-1}$$

$$at\ \ \Delta t \sim 10\ yr$$

Yuan, Quataert, Narayan 2004; Koyama+1996; EHT Collab+2022





$$SFR \approx 0.09\ M_{\odot}\, yr^{-1}$$

Over last 5 Myr

(Using young infrared sources)

or

$$0.2 - 0.8\ M_{\odot}\, yr^{-1}$$

last 30 Myr

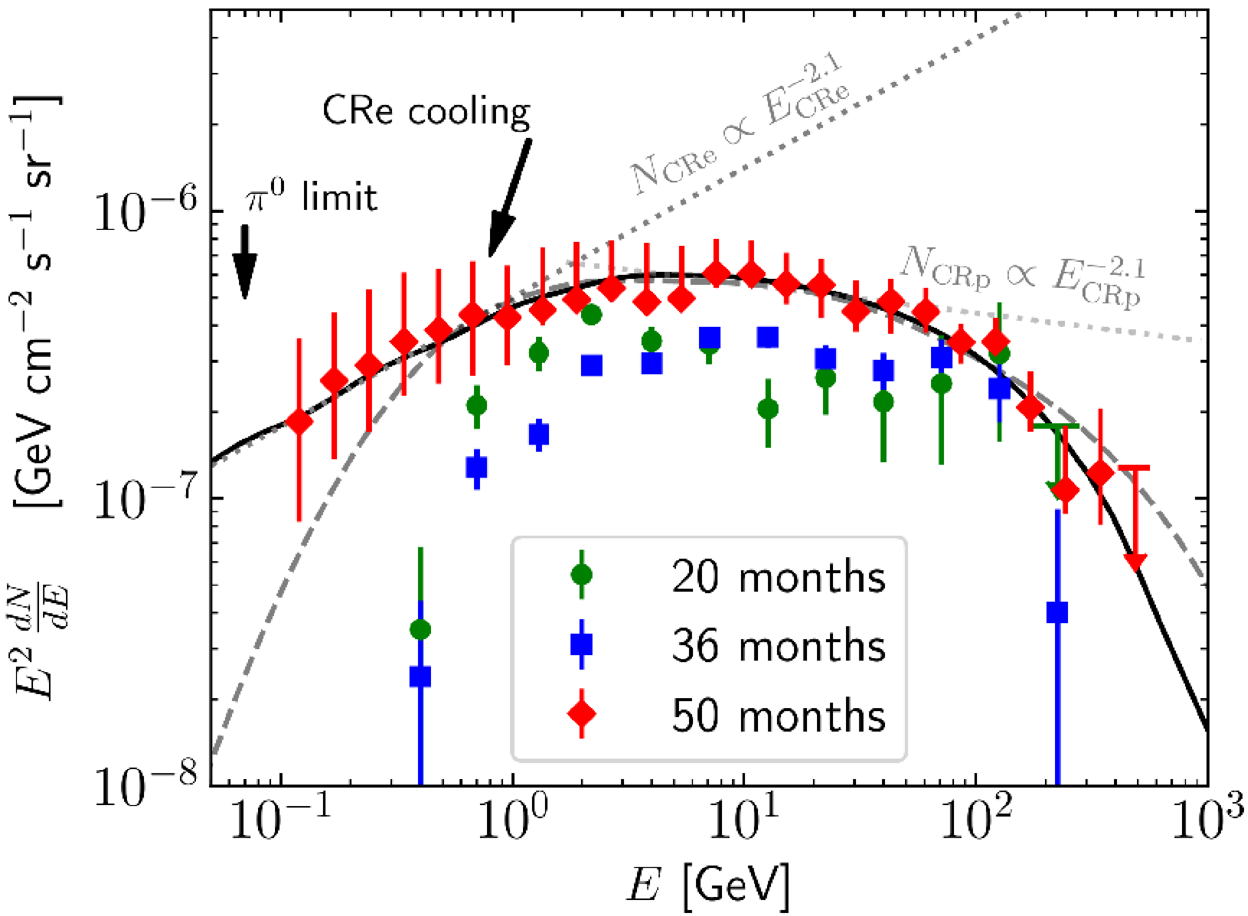
(Using color-color information)

Yusef-Zadeh+2009; Henshaw+2022; Nogueras-Lara+2020;

The Spectral origin ?

$$E^2 \frac{dN}{dE} \propto E^{0.5} \Rightarrow I_\nu \propto \nu^{-0.5}$$

$$\frac{dN_e}{dE} \propto E_e^{-2}$$



IC cooling time

$$\epsilon_{break} \approx 1\, GeV \Rightarrow t_{cool} \approx 2 \;\; Myr$$

Freshly (approx 1-2 Myr) accelerated electrons from a shock/turbulence

The dynamical origin ?

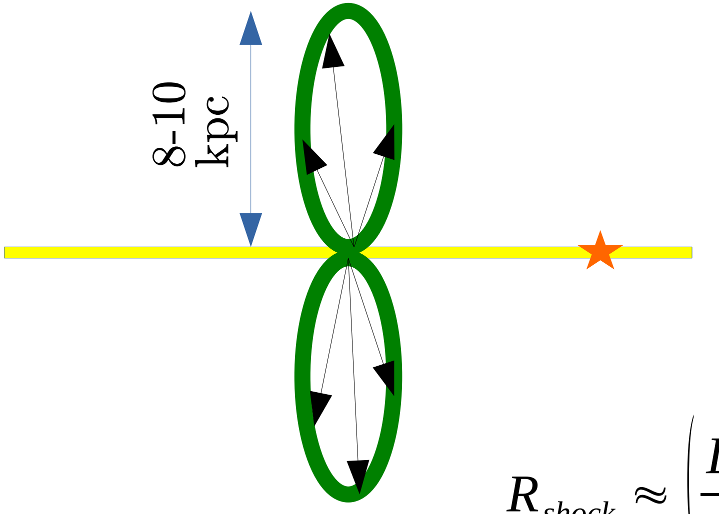
$$t_{cool} \approx 2 \ Myr$$

Case 1: Energy burst: It represents a shock

$$v \approx \frac{8\,kpc}{2\,Myr} \approx 4000\,km\ s^{-1}$$

$$L_{mech} \sim 10^{43-44} erg\ s^{-1}$$

AGN jet/blast



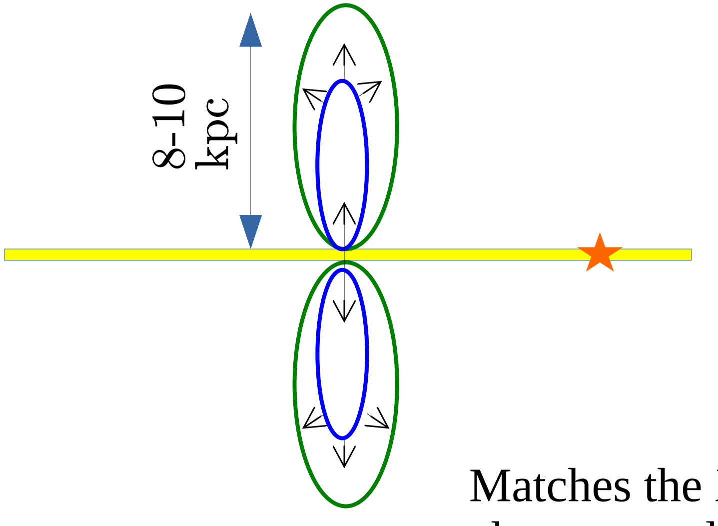
$$R_{shock} \approx \left(\frac{L_{mech} t^3}{\rho} \right)^{1/5}$$

Case 2: Slow energy release:
Shock is behind the outer layer

velocity can be anything

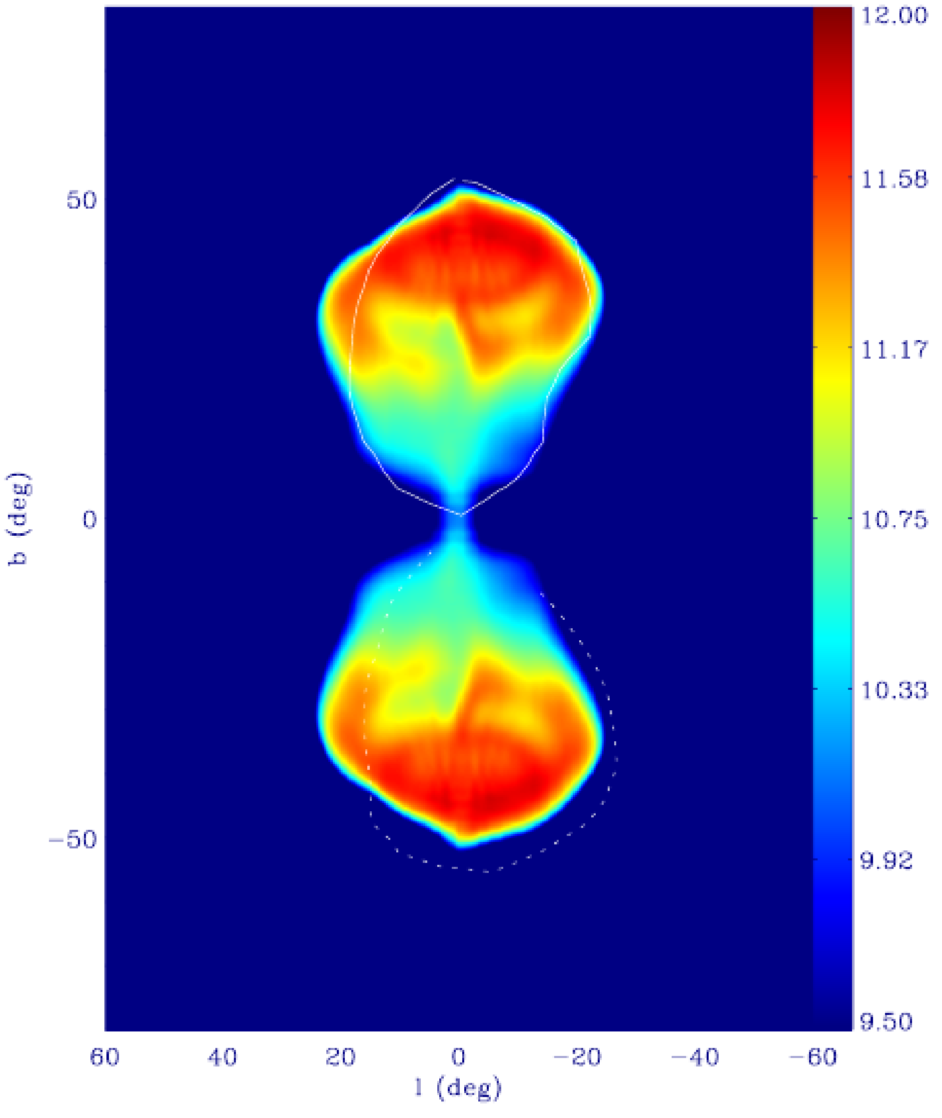
$$\boldsymbol{L_{mech} \sim 10^{41} \ erg\, s^{-1}}$$
$$\boldsymbol{t_{age} \sim 30 \ Myr}$$

AGN wind / SNe



Matches the X-ray temp and electron cooling at 1.3 GHz

Fermi/eROSITA Bubbles — AGN driven



A jet launched by central AGN

$$L_{mech} \approx 10^{43-44} \; erg\, s^{-1}$$
$$t_{age} \approx 0.3-3 \; Myr$$

Positives:

1. Small time scale allows fast CR transport

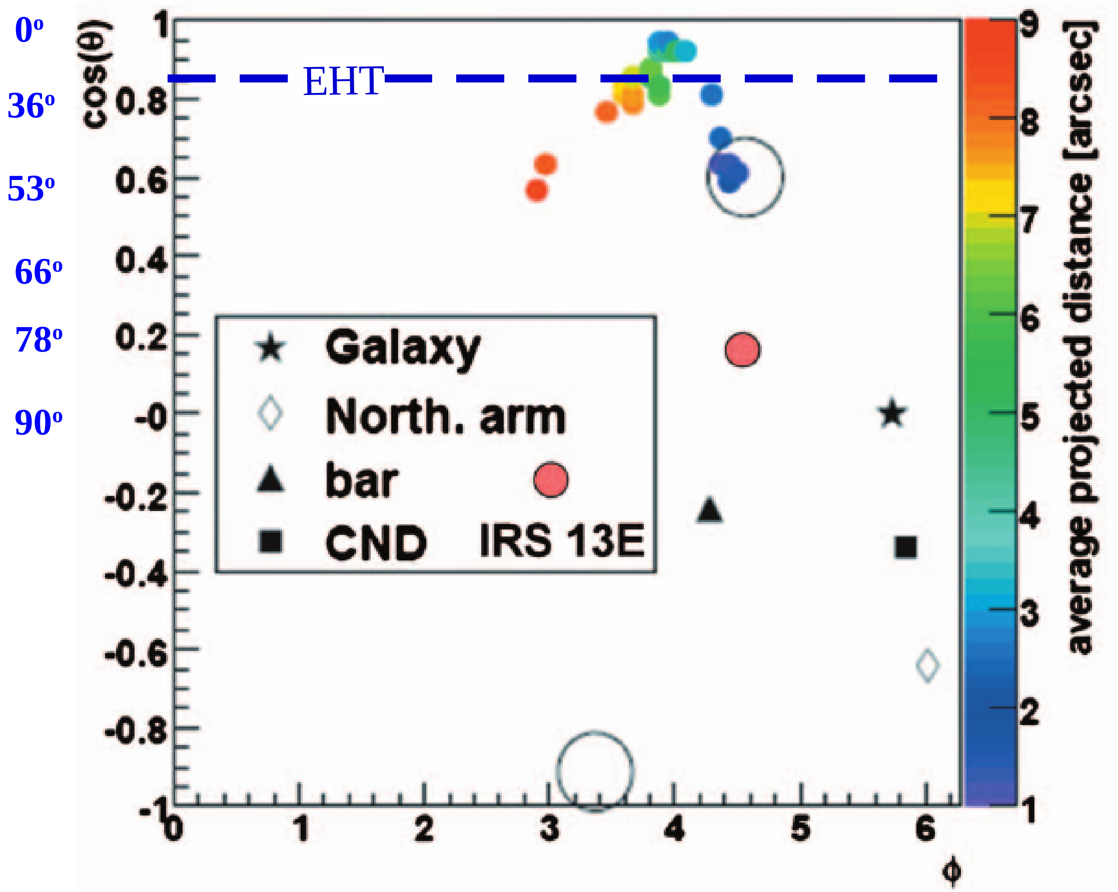
Negatives:

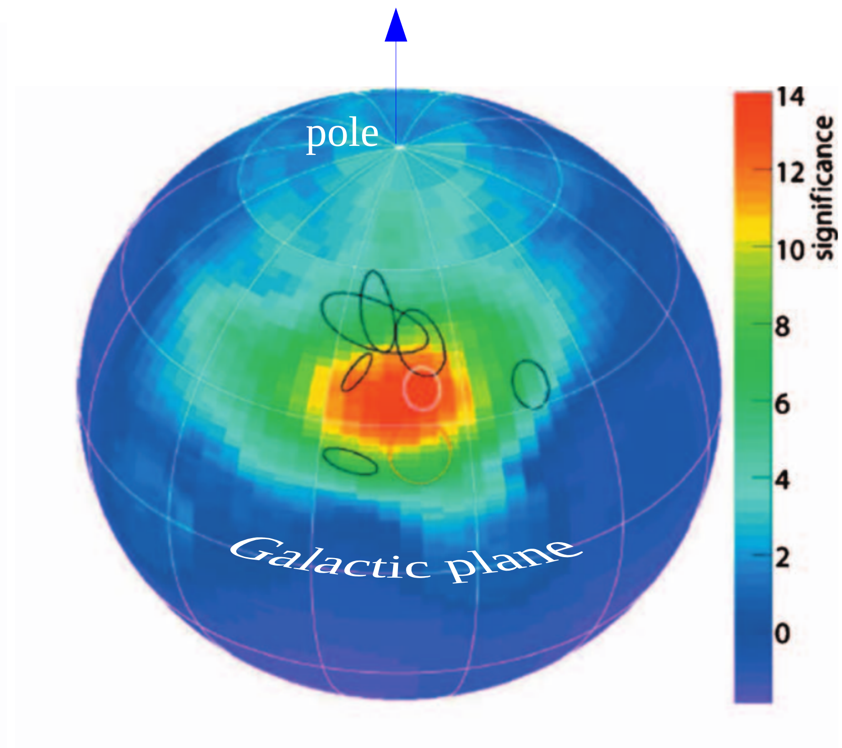
1. $L_{mech} \gg L_{SgrA}$
2. $T_{shock} \gg 3\times10^{6} \; K$ (Oviii/Ovii lines)
3. no NPS aka eROSITA bubbles
4. **The jet has to be perpendicular to the disc**

Zubovas+2011; Yang+2012; Mondal, Keshet, **Sarkar,** Gurwich 2021

Nuclear structures in our Galaxy

1” = 0.04 pc

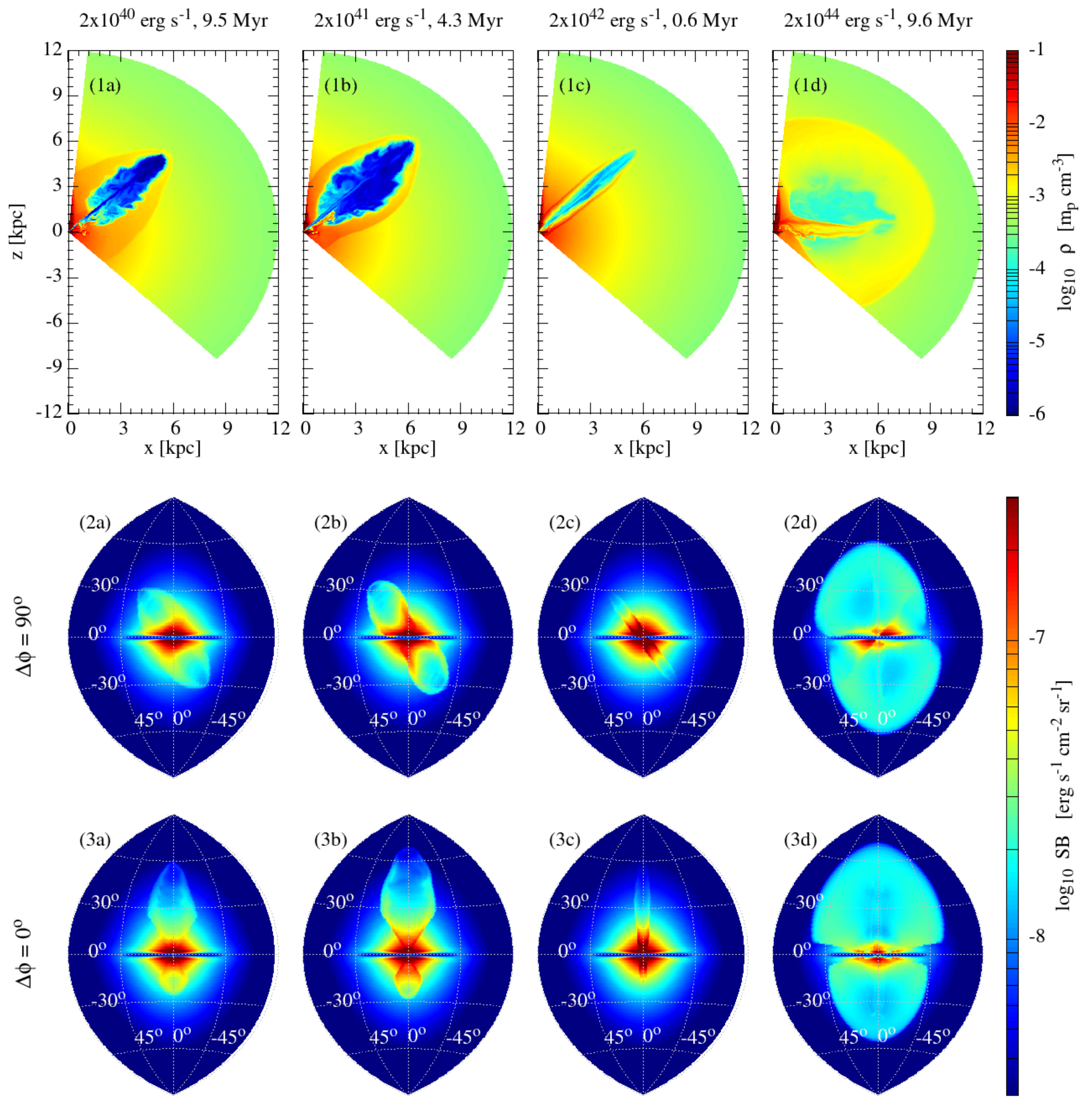




Nuclear stars are oriented at an angle ~30-50º with Galactic rotation axis

Genzel, Eisenhauer, and Gillessen, 2010

Tilted jet simulations



$$t_{jet} = \frac{E_{feb}}{L} \approx 32\ kyr\ \frac{E_{56}}{L_{44}}$$

$$t_{jet} < \frac{H_{ISM}}{v_h}$$

Tilted bubbles

Non-hemisymmetric bubbles

NOT an AGN jet!

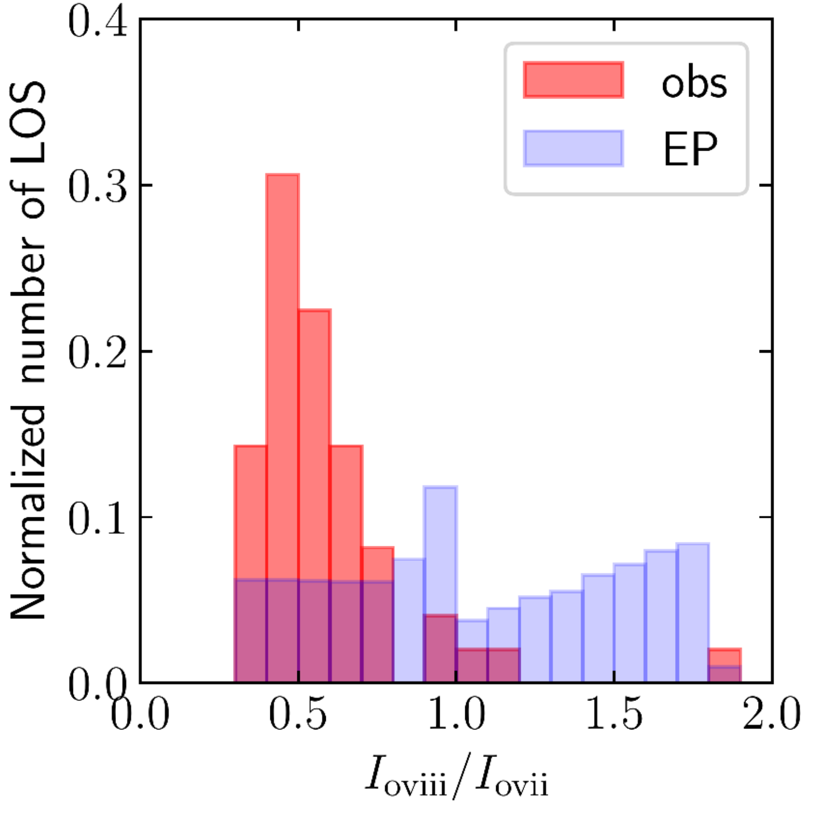
Sarkar+2023

AGN Blast?

Blast wave solution in a power law density

$$r_s = A^{5/(5-\alpha)} \left(\frac{E}{\rho_0 r_0^\alpha}\right)^{1/(5-\alpha)} t^{2/(5-\alpha)}$$

$$v_s = \frac{d}{dt} r_s = \frac{2}{5-\alpha} \frac{r_s}{t} \, .$$



NOT a blast wave!

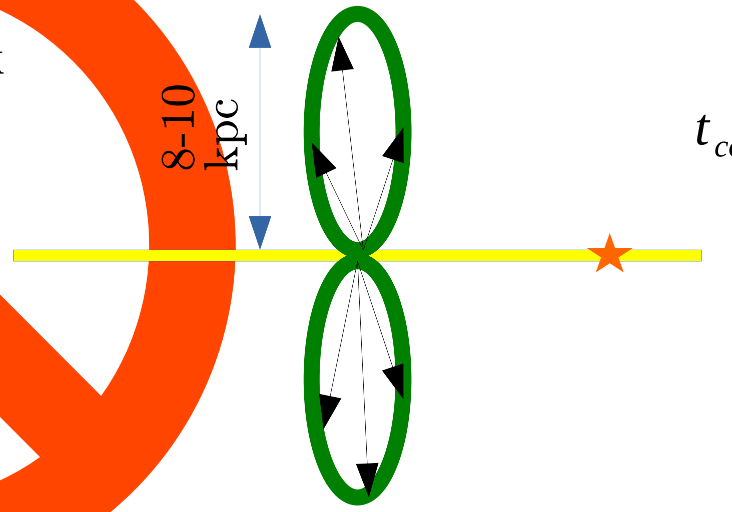
SNe / AGN wind?

Sarkar+2023

The dynamical origin ?

Case 1: Energy burst: It represents a shock

$$v \approx \frac{8\,kpc}{2\,Myr} \approx 4000\,km\ s^{-1}$$



$$t_{cool} \approx 2\ \ Myr$$

$$L_{mech} \sim 10^{43-44}\ erg\ \ s^{-1}$$

AGN jet/blast

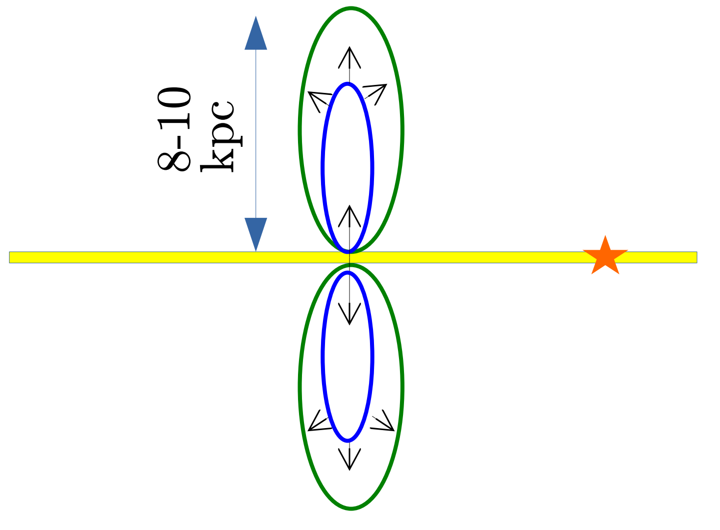
$$R_{shock} \approx \left(\frac{L_{mech}\,t^3}{\rho}\right)^{1/5}$$

Case 2: Slow energy release:

Shock is behind the outer layer

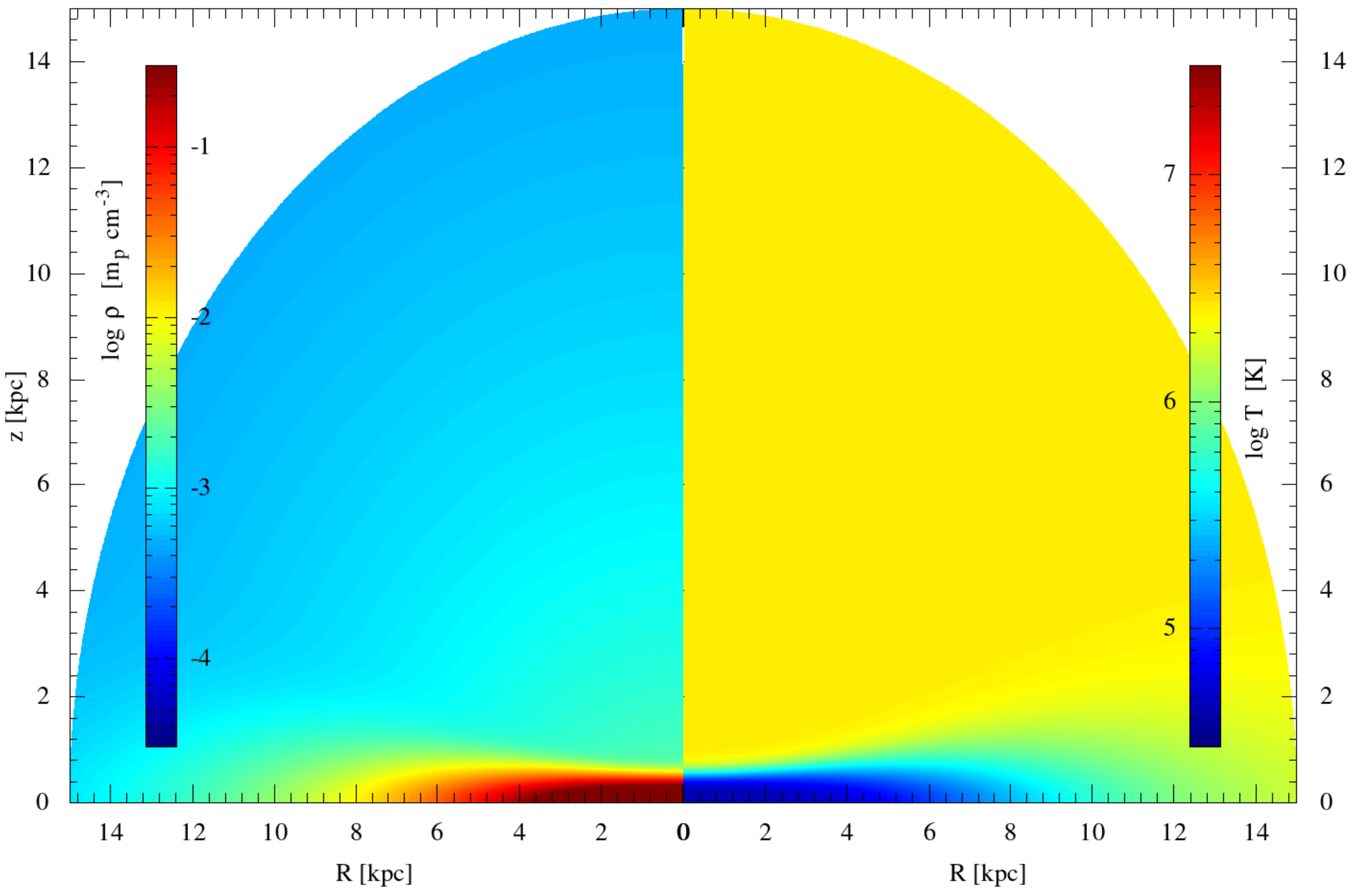
velocity can be anything

$$L_{mech} \sim 10^{41}\ \ erg\,s^{-1}$$



AGN wind / SNe

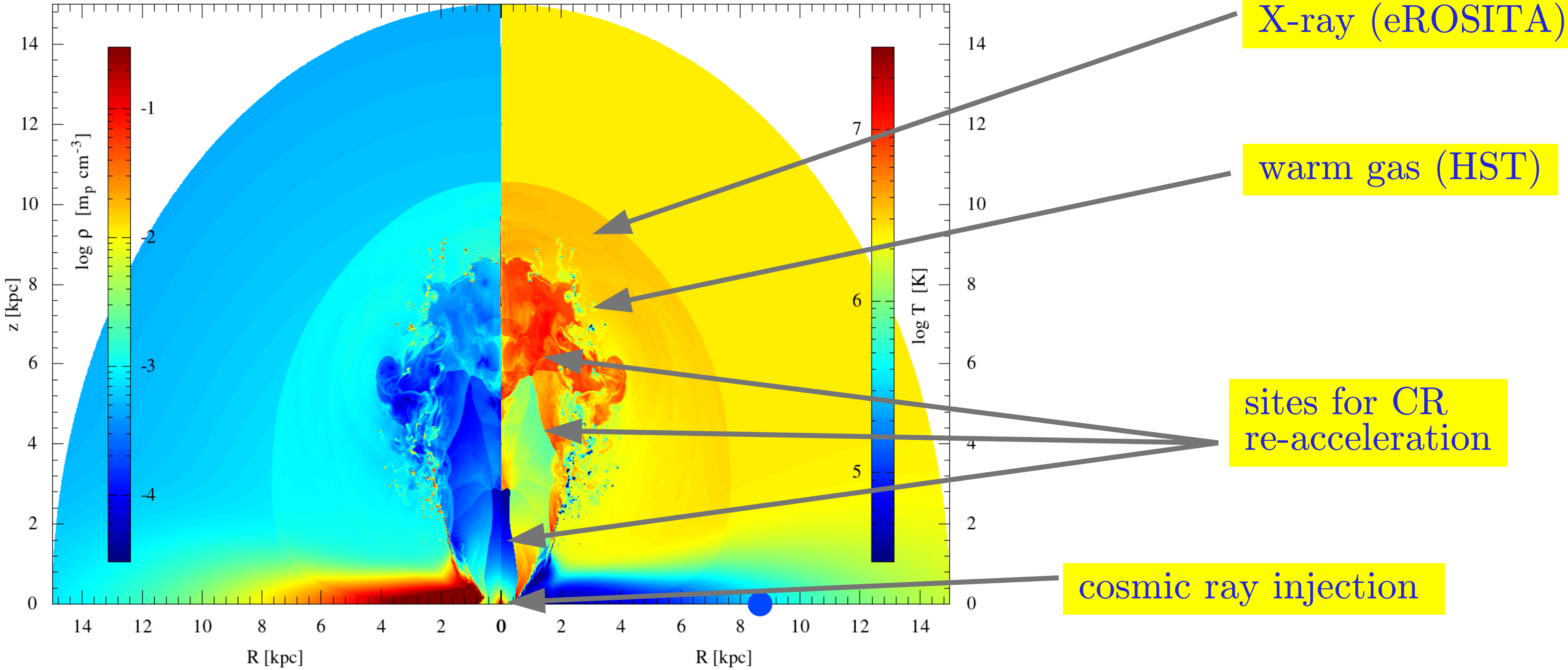
Fermi/eROSITA bubbles SNe driven



1. Gravity, radiative cooling, SNe energy injection within r< 60 pc
2. Warm rotating disk, non-rotating CGM
3. Steady state equilibruim

Sarkar et al., 2015, 2017

Fermi/eROSITA bubbles — SNe driven



For SFR $\approx 0.3-0.5\, M_\odot\, yr^{-1}$, t_{age} = 27 Myr

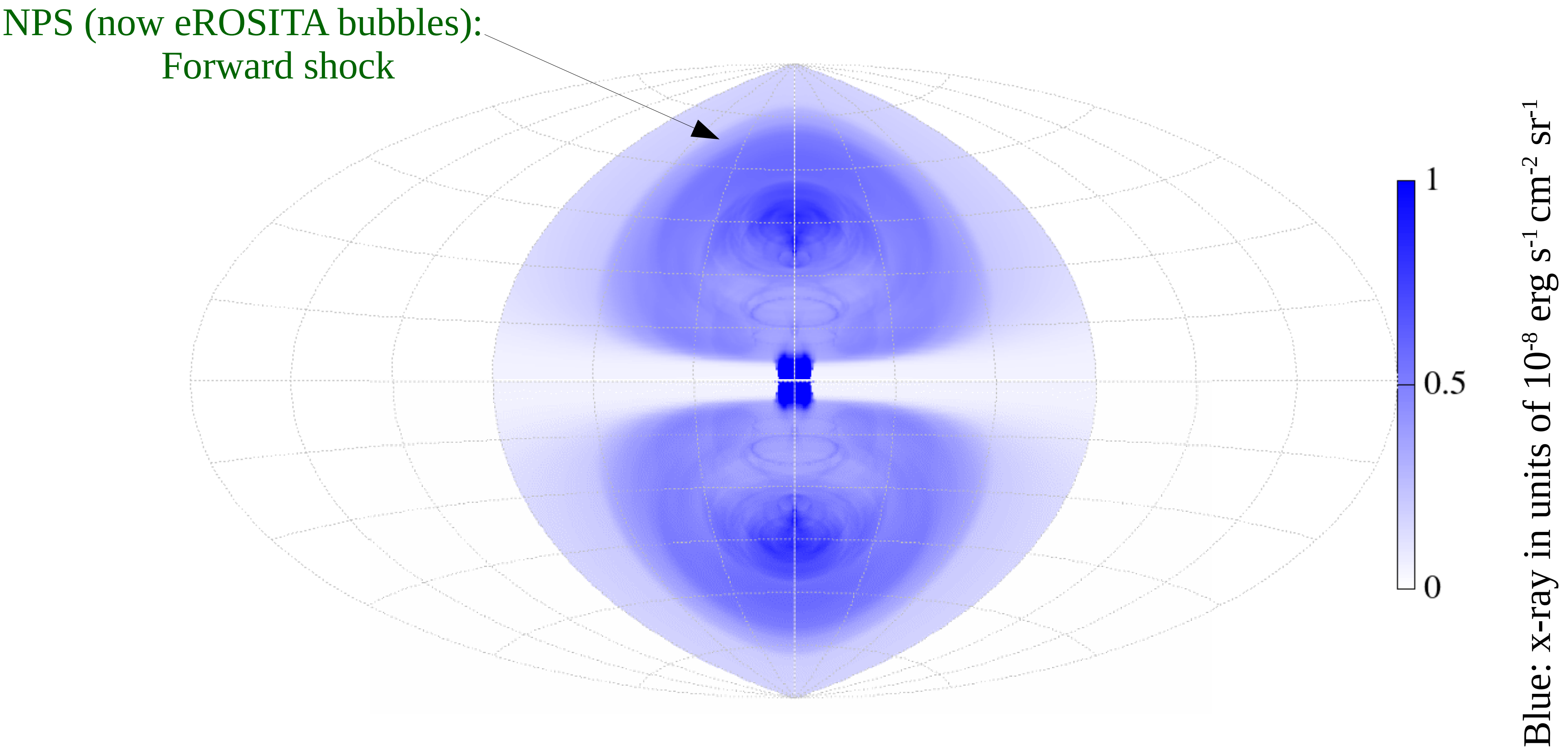
Positives:

1. gamma-ray emission
2. X-ray emission
3. UV Cloud kinematics
4. HI hole
4. OVIII / OVII line ratio
5. **Star Formation history**

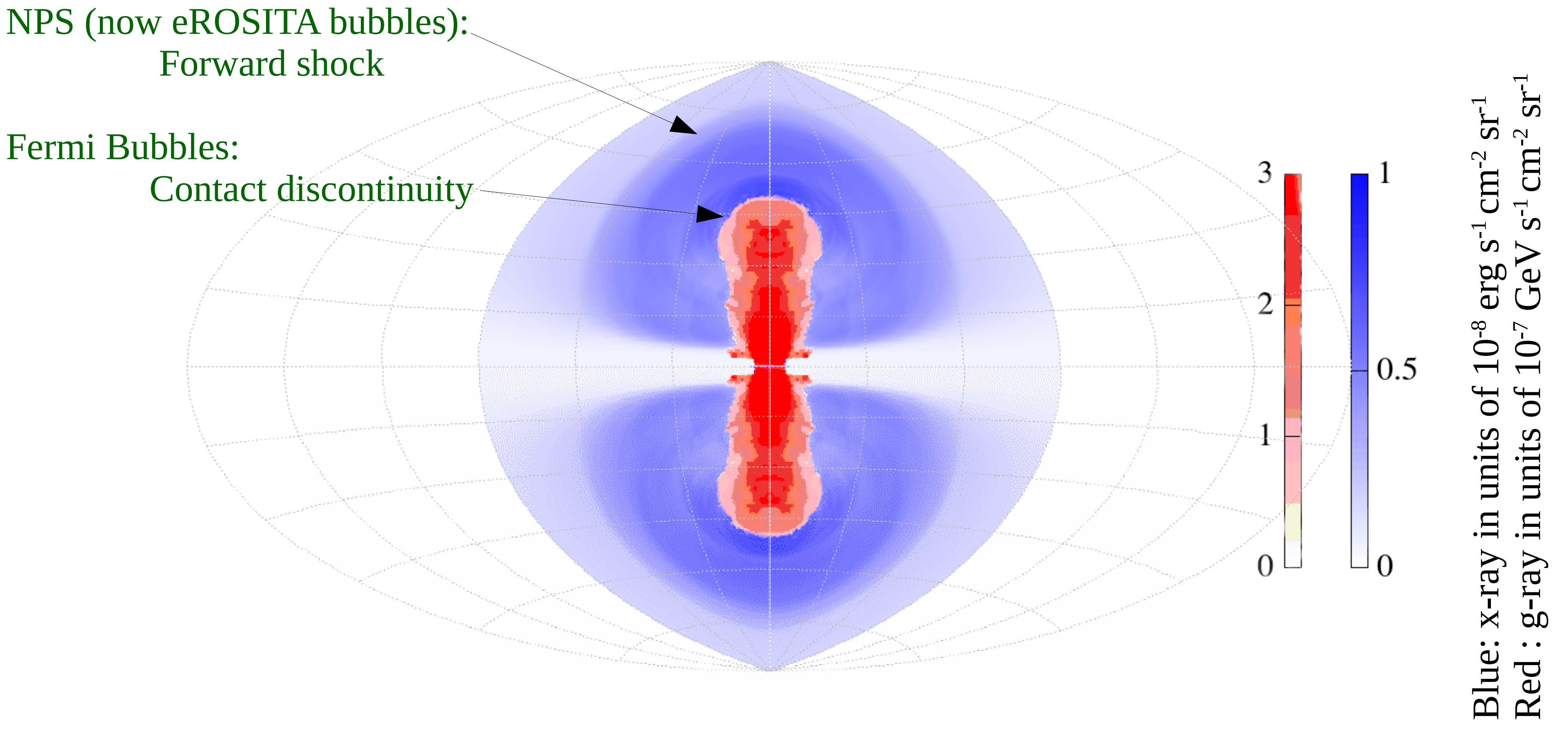
Negatives:

1. Lack MHD and proper CR physics (CR + Magnetic pressure?)

Sarkar+2015; Sarkar+2017



Sarkar et al., 2015



Producing one of them reproduces the other

↓

Fermi Bubbles and NPS originate from same event

Sarkar et al., 2015

Fermi/eROSITA Bubbles: Past, present, and the future

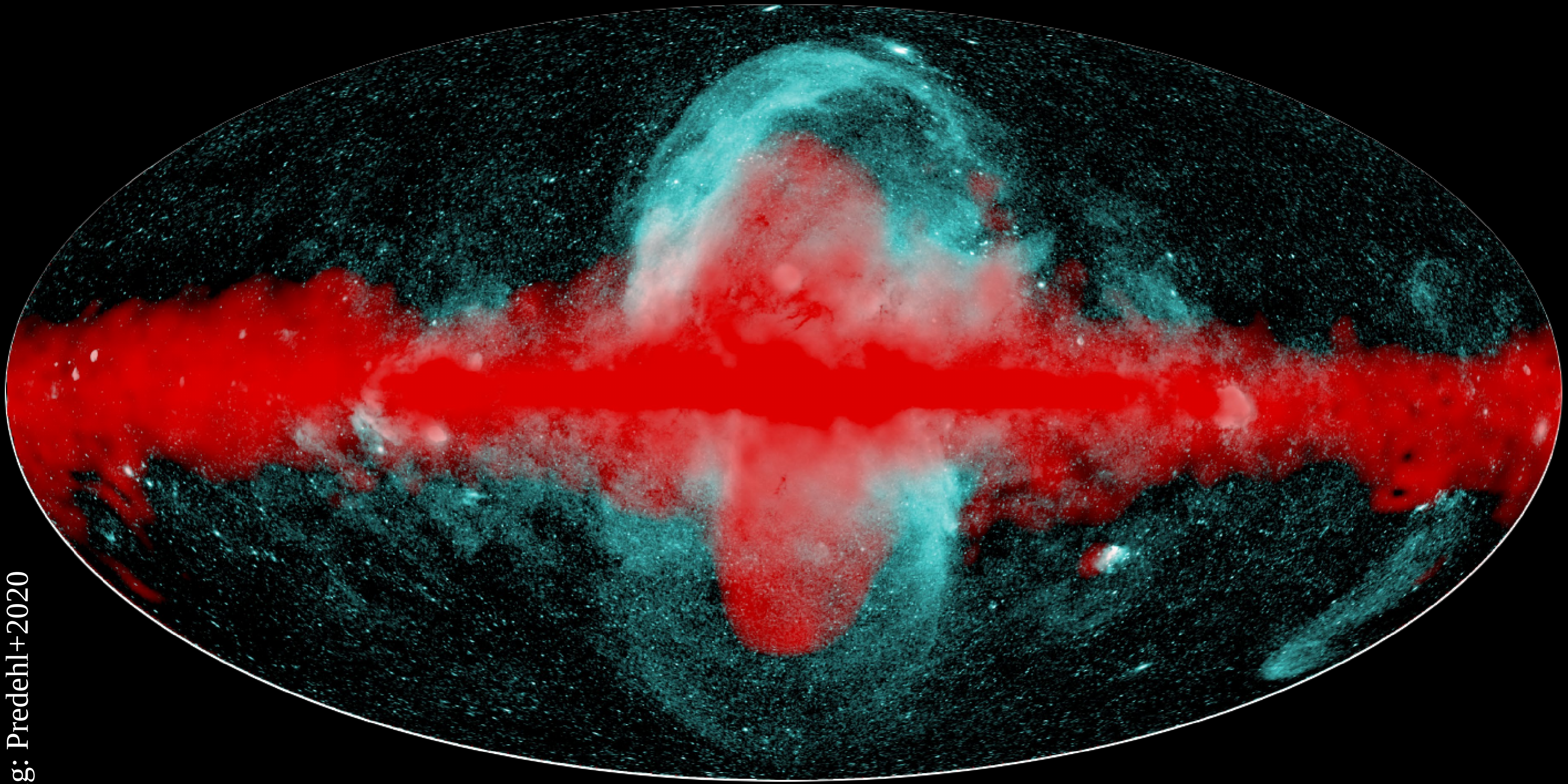


Fig: Predehl+2020

Kartick Sarkar

Indian Institute of Technology Kanpur (IIT Kanpur), India

Collaborators: Biman Nath, Prateek Sharma, Santanu Mondal, Tsvi Piran

Options

Requirements: Symmetric bubbles + consistent with x-ray observations

1. Magnetic Kink-instability: $L < L_{\rm MKI} = 4 \times 10^{41}\ {\rm erg\ s^{-1}}\ n_a\, H^2_{\rm 200pc}$ Bromberg+2016

2. Accretion disk winds: $L \approx 3\times10^{40} - 10^{41}\ erg/s$

3. TDE: random jets : Required TDE rate is ~10 times higher

4. Star-formation driven: $\boldsymbol{SFR = 0.3-0.5\ M_\odot/yr \rightarrow L \approx 3\times10^{40} - 10^{41}\ erg/s}$

1. **Fermi Bubbles and eROSITA bubbles originated from the same event**

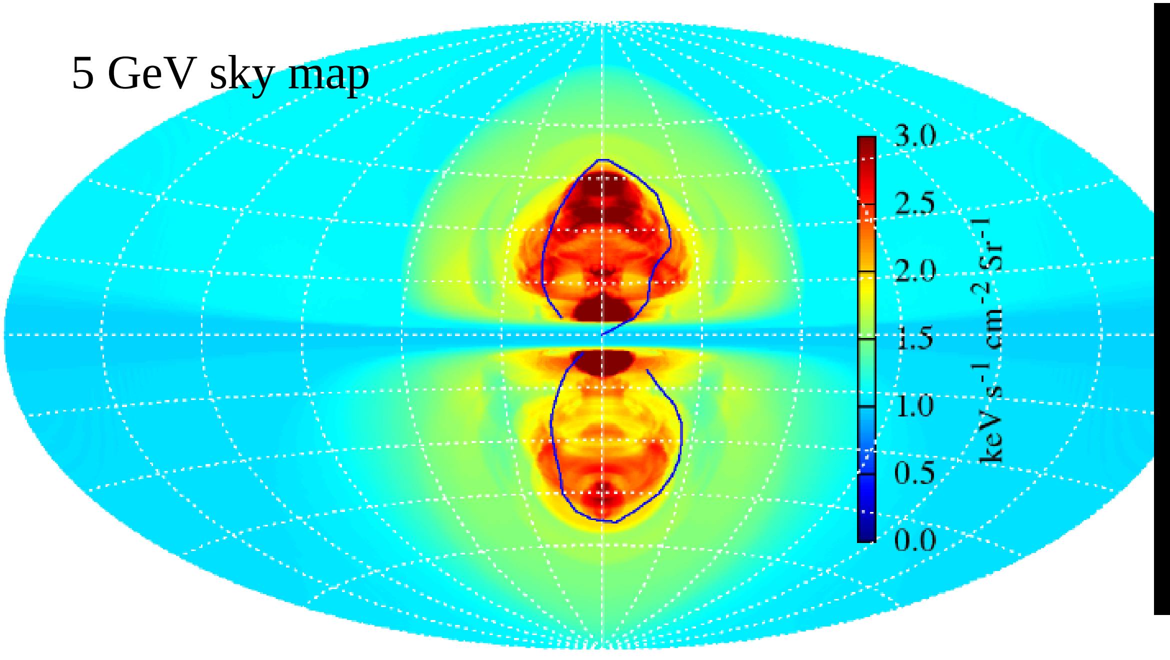
2. **Slow and steady energy release** $\boldsymbol{L \approx 3\times10^{40} - 10^{41}\ erg/s}$

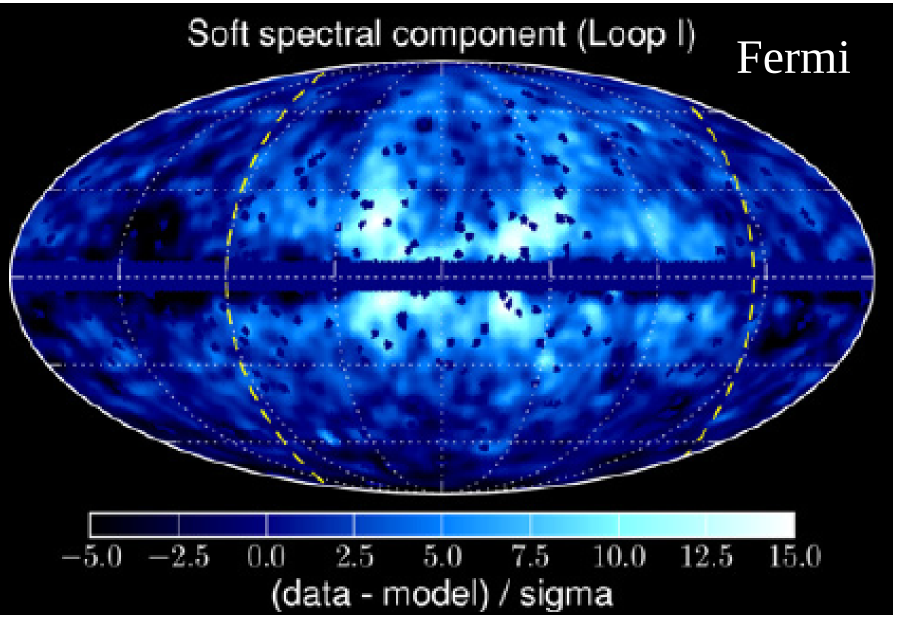
3. **Fermi Bubbles is Leptonic**

Sarkar+2023

Predictions for the future

1. Southern gamma-ray Loop-I



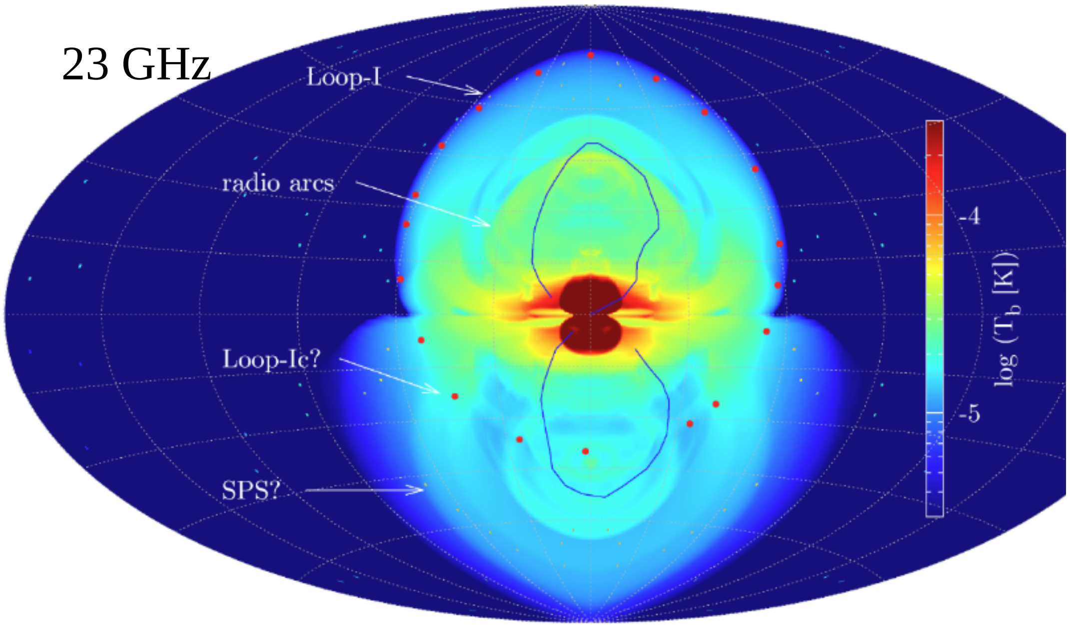


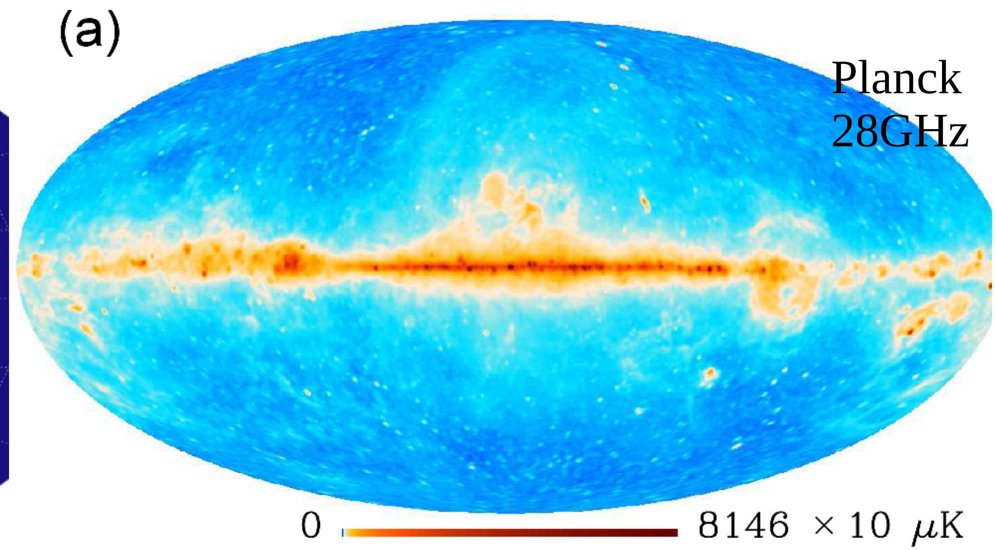
- Is there a southern gamma-ray counterpart of the Loop-I?
- Brightness?
- Spectral index?
- Required Mach number? Or age?

➔ **More integration time**
➔ **Better diffuse map analysis techniques**

Sarkar 2019; Ackermann+2014

2. Southern radio Loop-I





- Is there a southern gamma-ray counterpart of the Loop-I?
- Brightness?
- Spectral index?
- Required Mach number? Or age?

➔ **More integration time**
➔ **Better diffuse map analysis techniques**

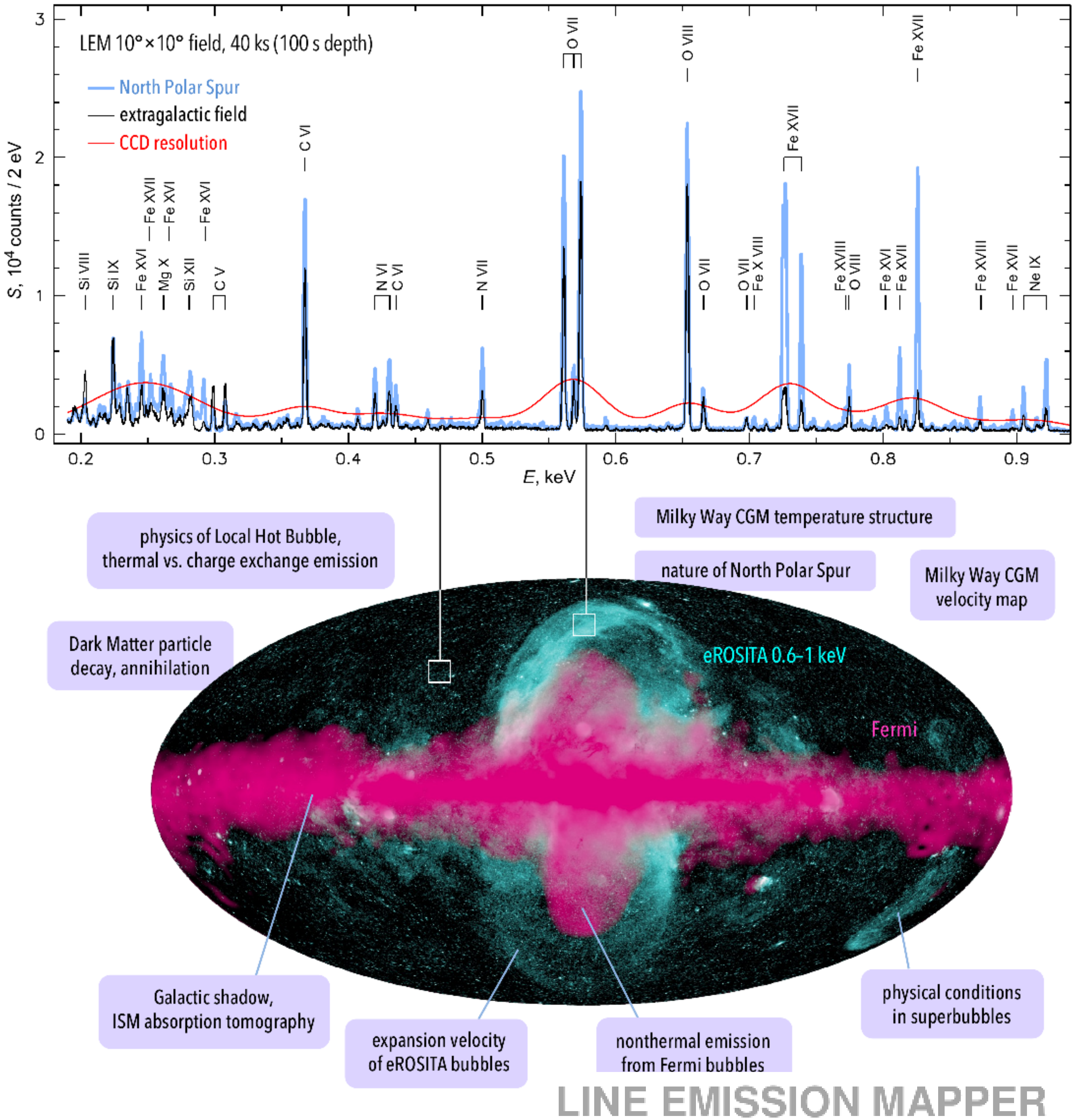
Sarkar 2019; Planck Collaboration+2016

Predictions for the future

3. Expansion velocity (X-ray)

$$v_{erosita} \sim 300 \;\; km\, s^{-1}$$

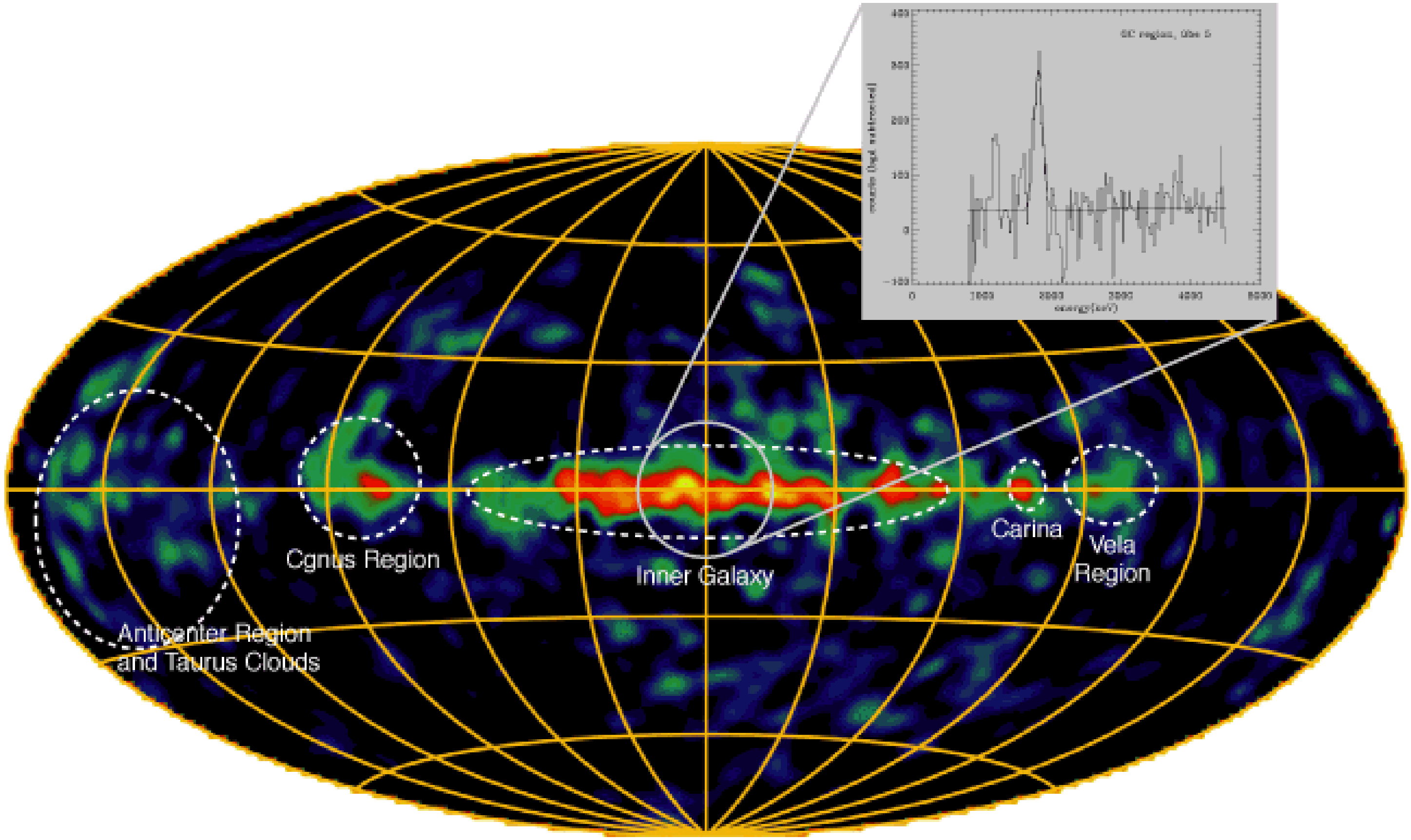
Required energy resolution **~ 1 eV**



Kraft+2022

Predictions for the future

4. SNe or AGN?



1.8 MeV Al^{26} Line map

COMPTEL 1.809 MeV map

More data and foreground subtraction technique

Other unanswered questions/possibilities

1. Temperature of the NPS/eROSITA bubbles.

- 0.3 keV (collisional eq), 0.2 keV (non-Solar abundance), 0.7 keV (non-eq ionization)
- Should be solidified once expansion velocity is constrained. XRISM/Athena/LEM?

2. Nature of the central X-shaped x-ray emission.

- Collisional eq or charge exchange?
- Need high resolution x-ray spectra. XRISM/Athena/LEM?

3. Star formation rate at the central molecular zone.

- 0.09 M_{sun}/yr (last few Myr), 0.2-0.8 M_{sun}/yr (last 30 Myr)

Thank you ...

Astron Astrophys Rev (2024)32:1
https://doi.org/10.1007/s00159-024-00152-1

REVIEW ARTICLE

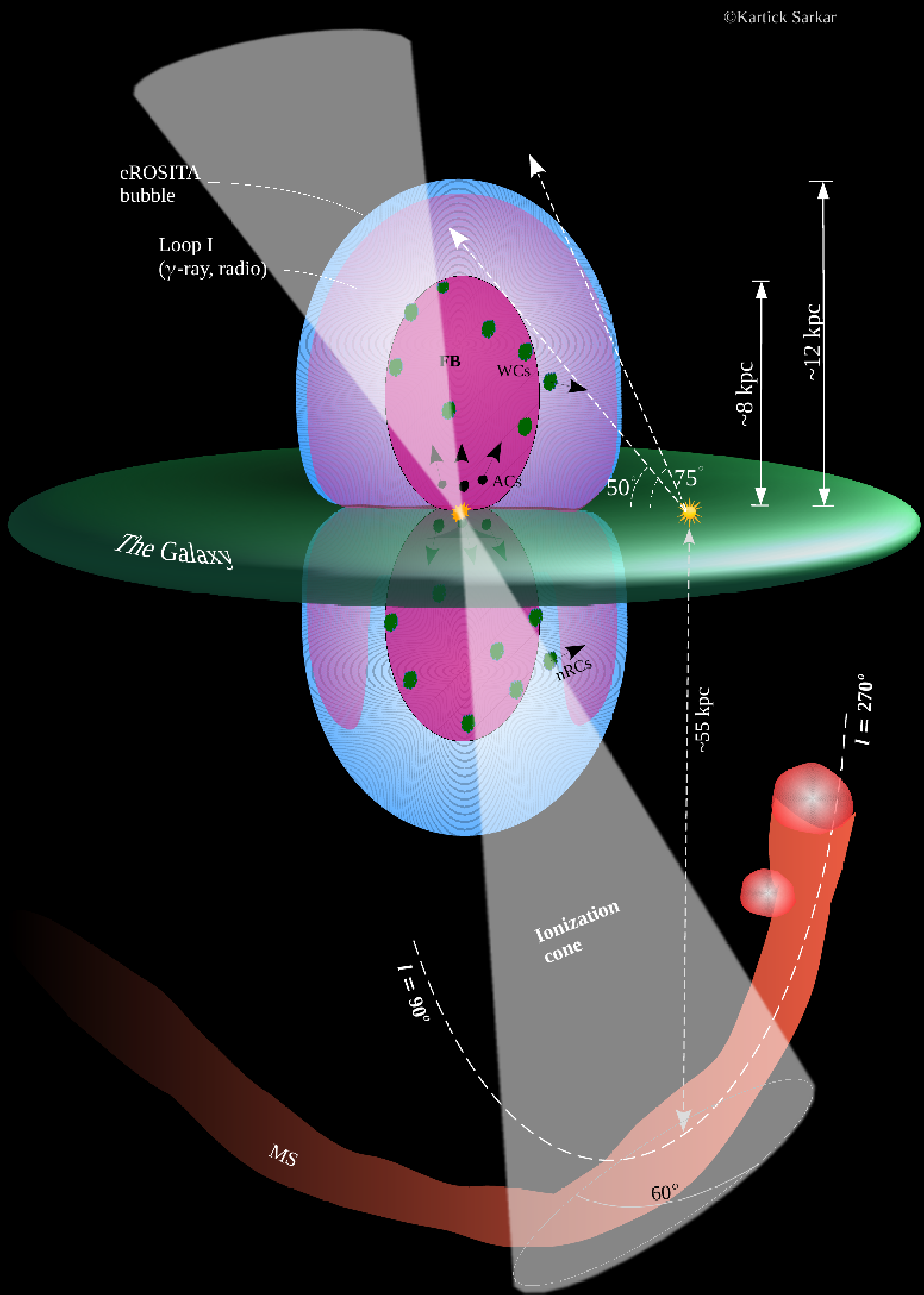
Check for updates

The Fermi/eROSITA bubbles: a look into the nuclear outflow from the Milky Way

Kartick C. Sarkar[1,2]

Received: 5 September 2023 / Accepted: 7 February 2024

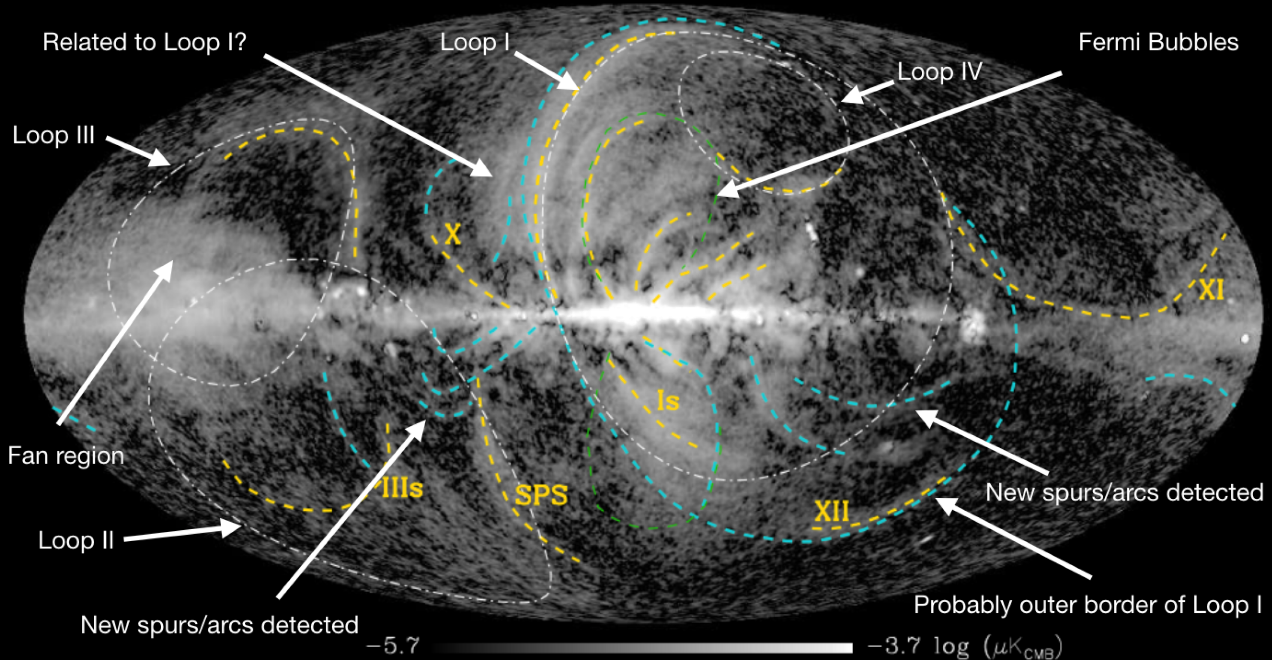
Sarkar 2024

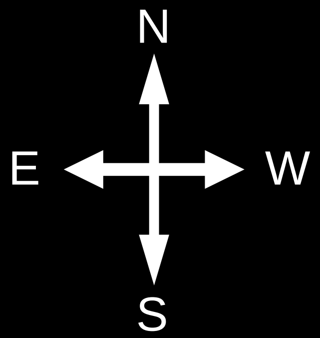

©Kartick Sarkar
eROSITA bubble
Loop I
(γ-ray, radio)
FB
WCs
ACs
nRCs
50°
75°
~8 kpc
~12 kpc
~55 kpc
The Galaxy
l = 270°
l = 90°
Ionization cone
MS
60°

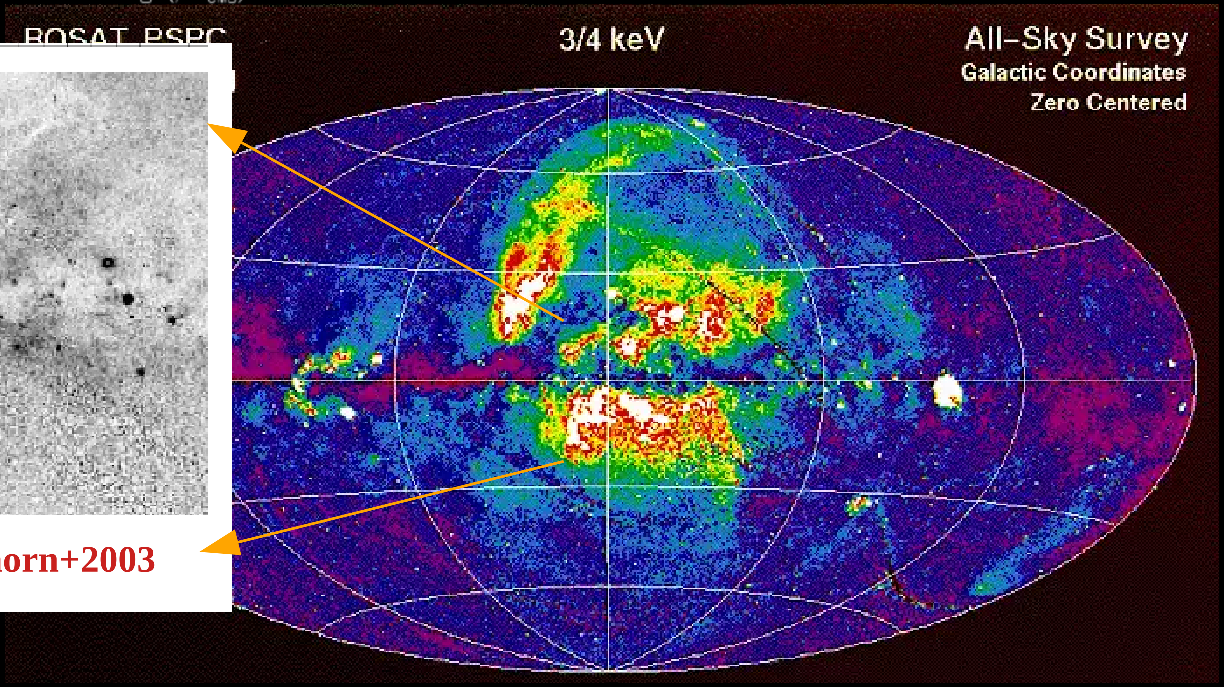
Sarkar 2024

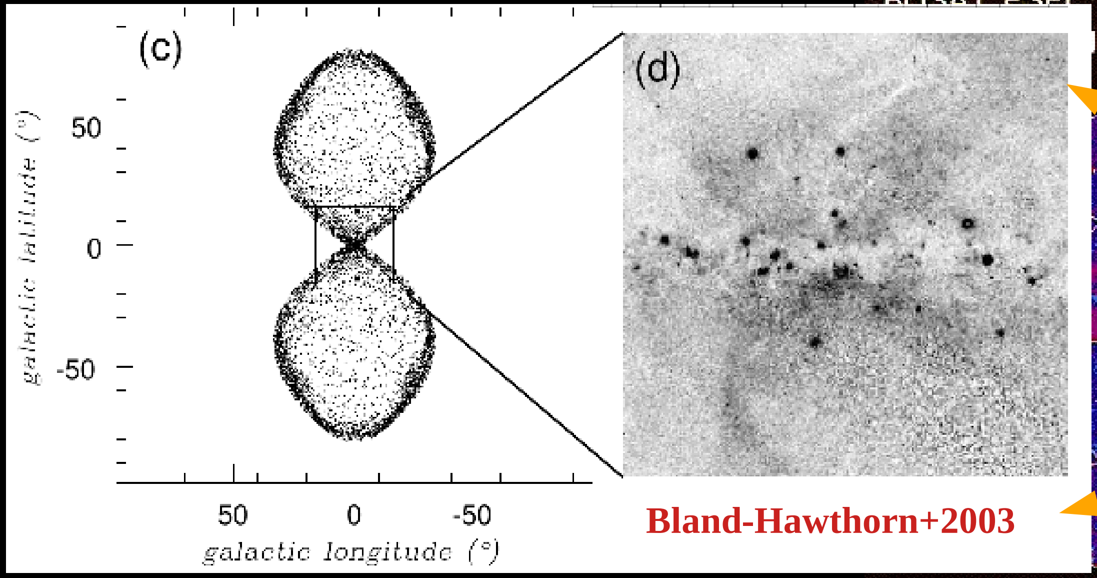
Back Up Slides ...

Outflow from the Galaxy (Pre-2010)?









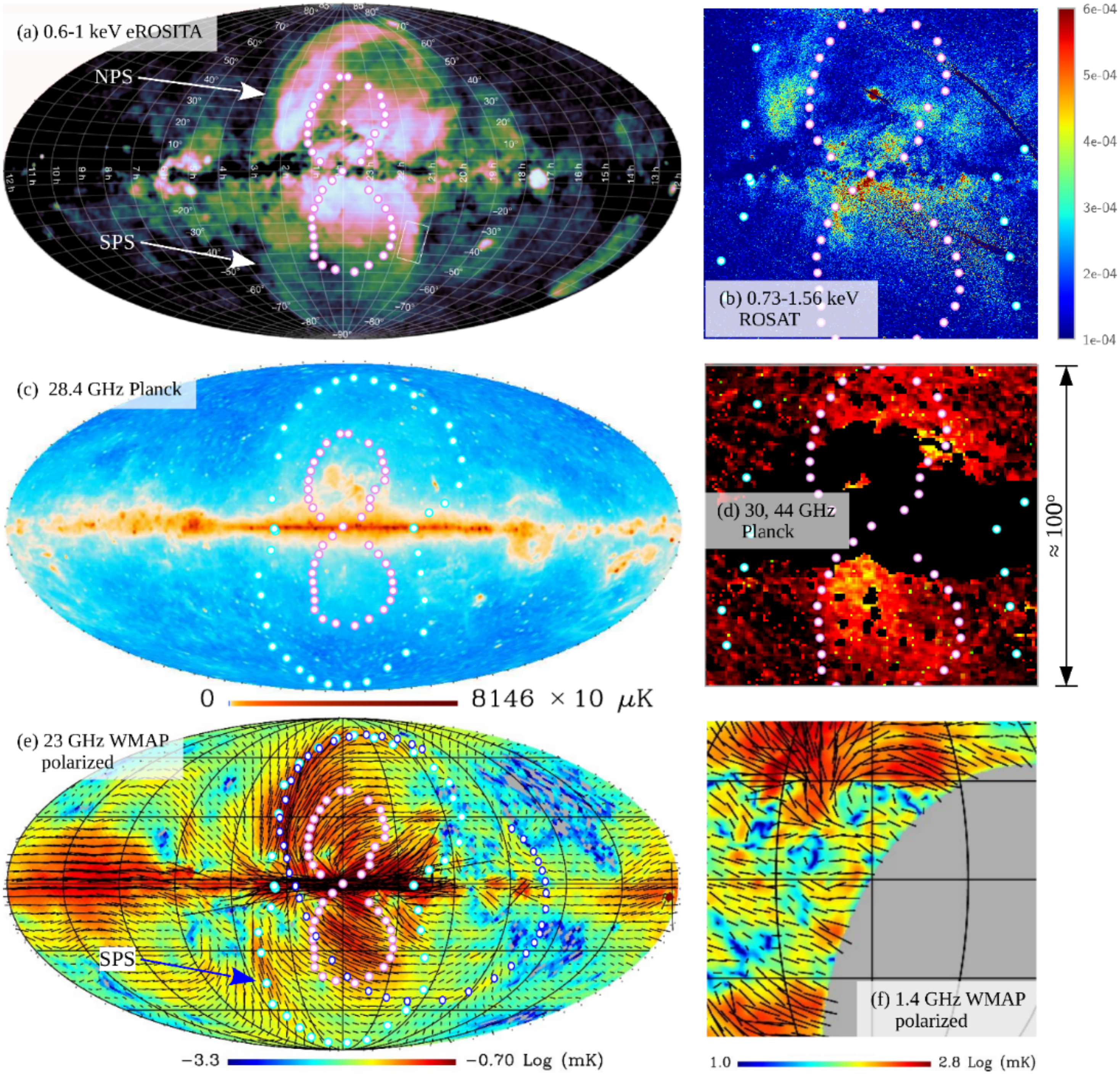
Bland-Hawthorn+2003

There is a Galactic nuclear outflow !

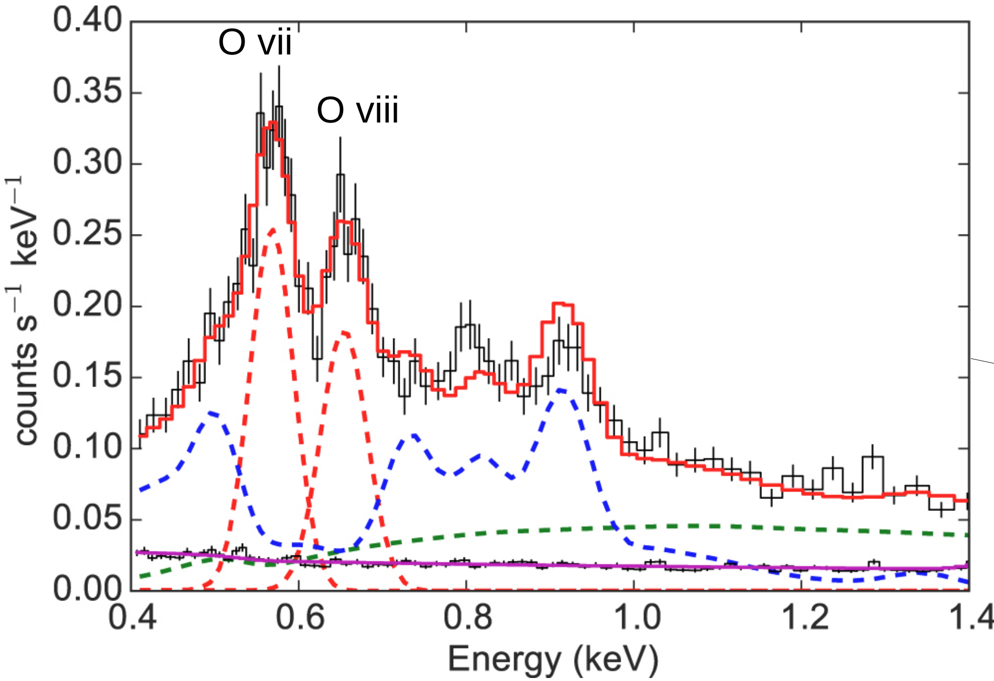
0.5 – 0.9 keV skymap from ROSAT

Planck Collab+2016 (20-50 GHz); Snowden+1997

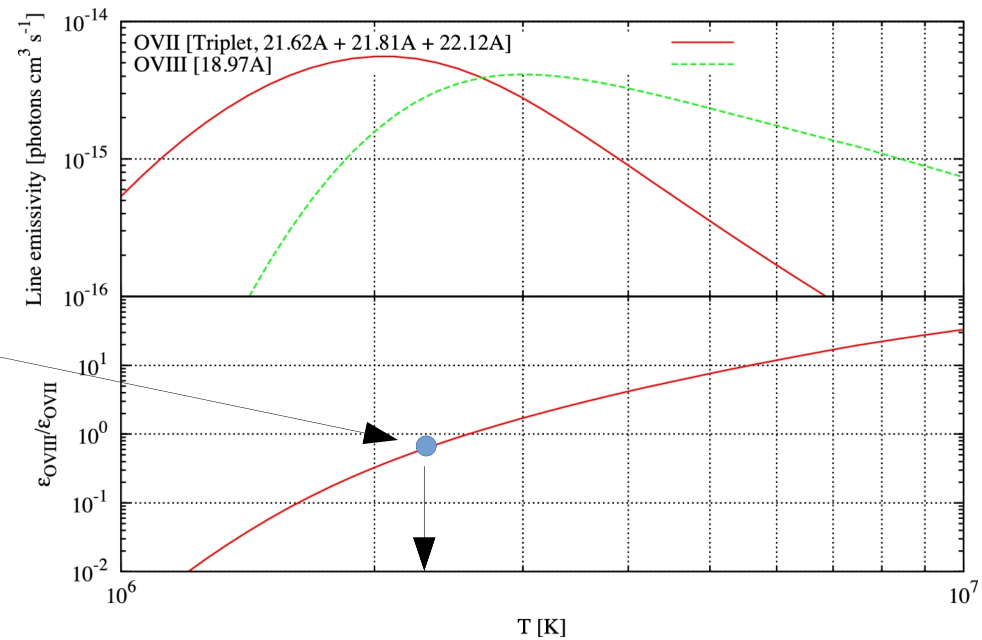
Multi-wavelength features



x-ray lines



Observed X-ray spectrum
(XMM-Newton/Suzaku)

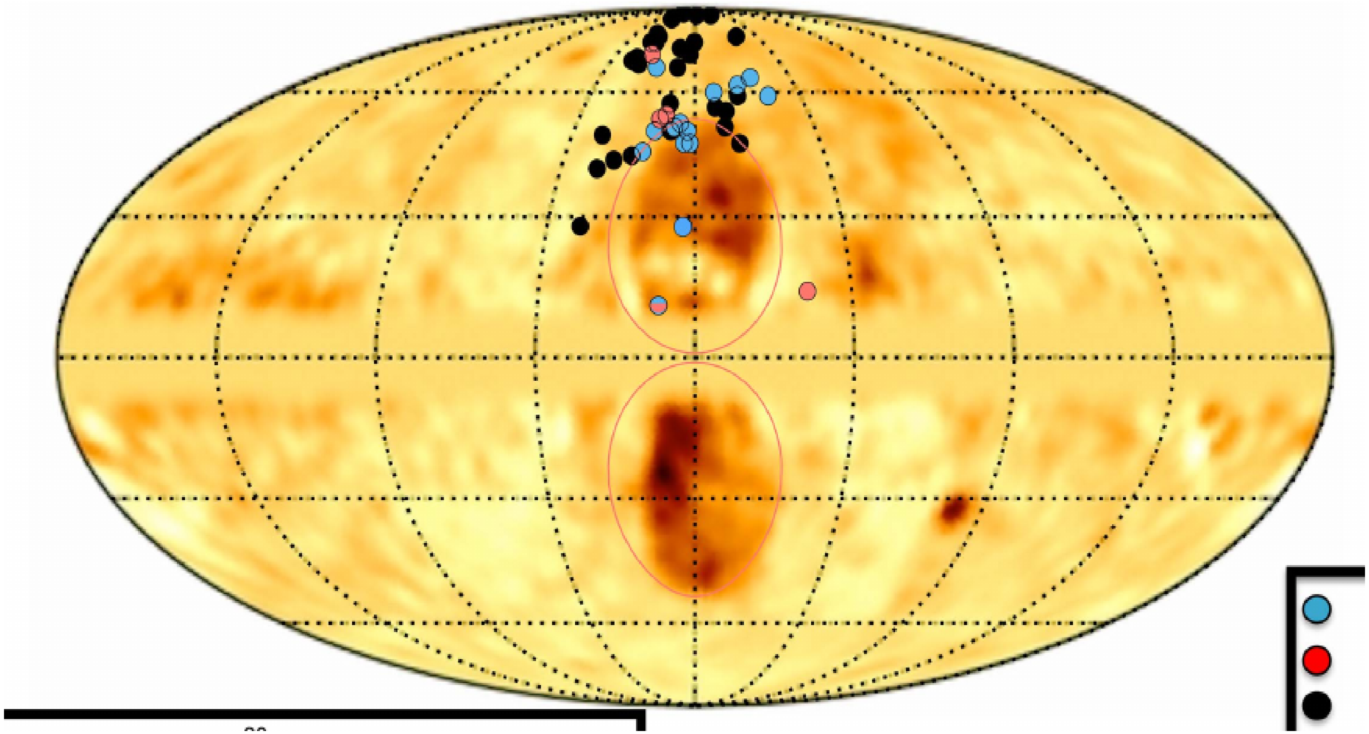


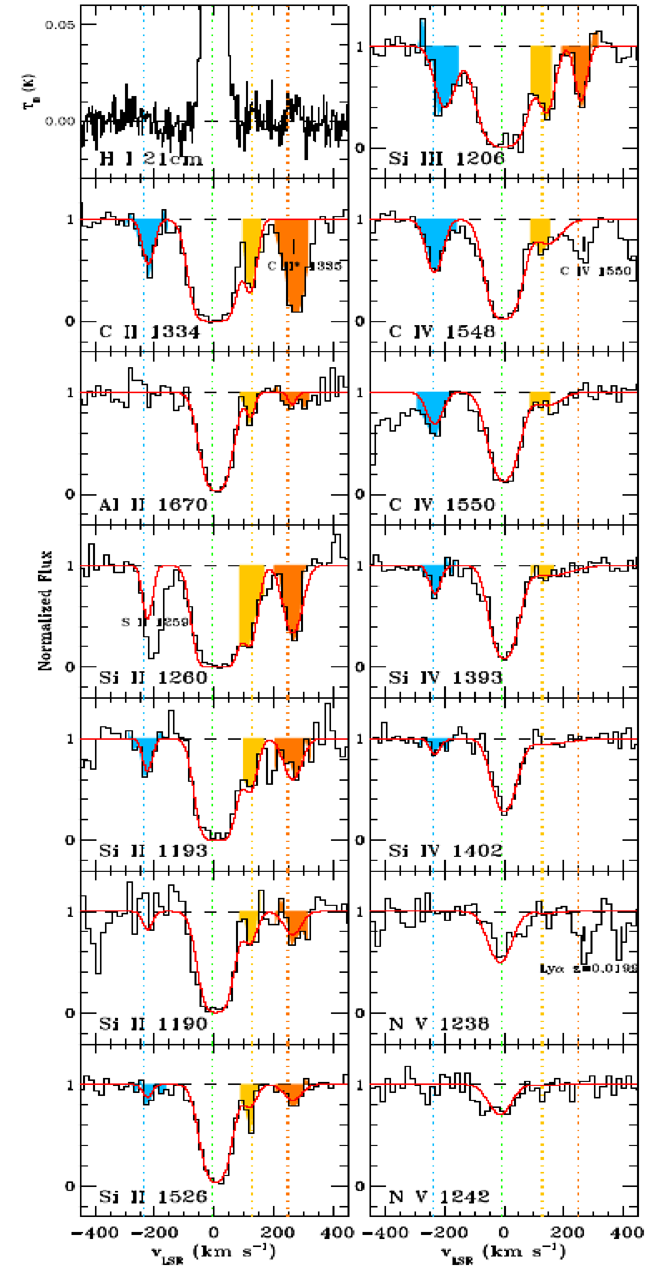
Theoretical line ratio for Oviii/Ovii

X-ray line ratio is a good way to find temperature of hot gas

Miller & Bregman, 2016

Warm clouds though Fermi Bubbles





UV absorption lines on the spectra of shows cold clouds having line of sight velocities ± 200 km s[-1]

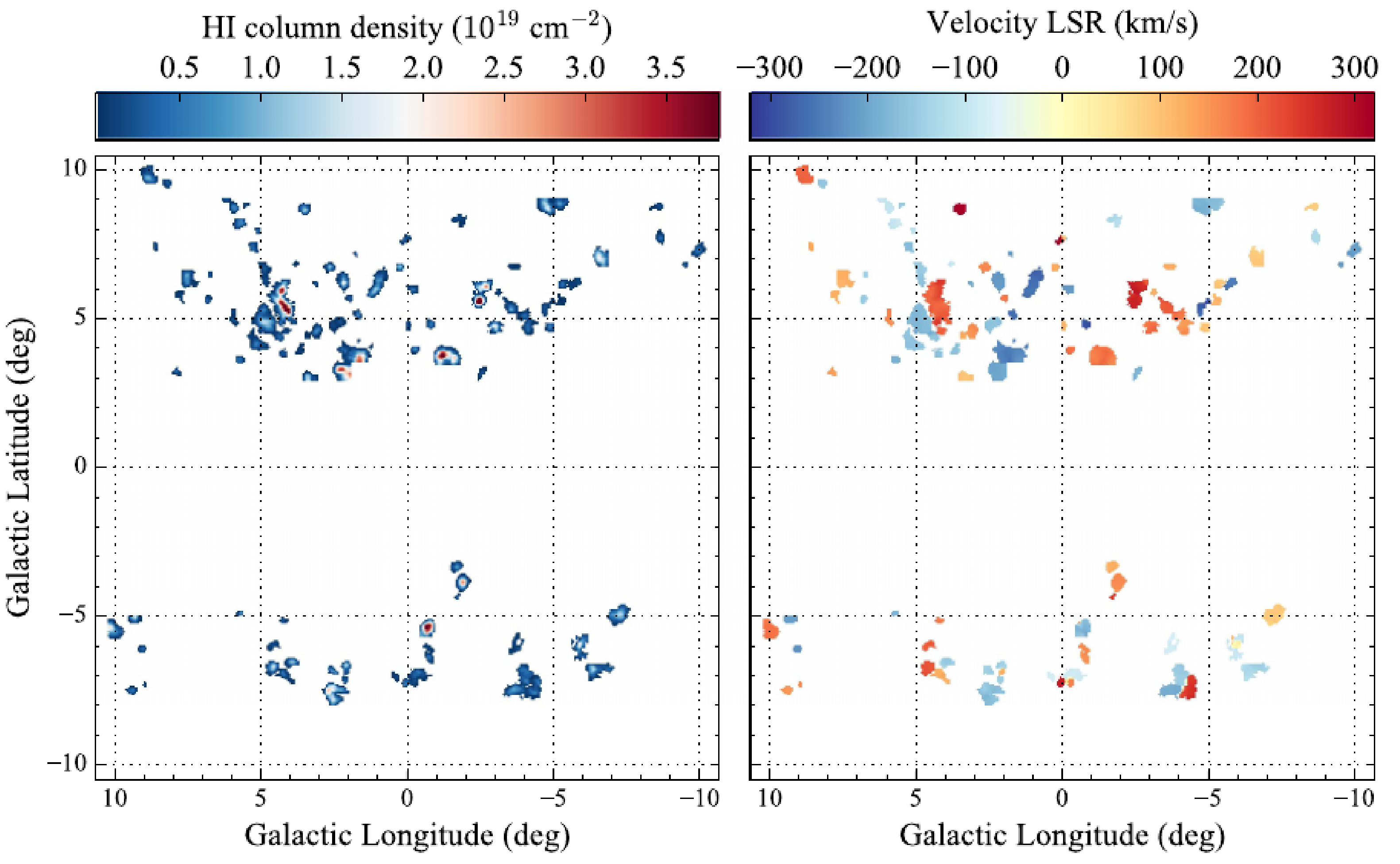
$v_{outflow} \sim 1000 \ km\,s^{-1} \rightarrow t_{age} \approx 6 \ Myr$

Only radial velocities considered!
Non radial velocities produce

$t_{age} \gtrsim 6 \ Myr$

Fox et. al., 2015; Bordoloi et al. 2017; Ashley+2020

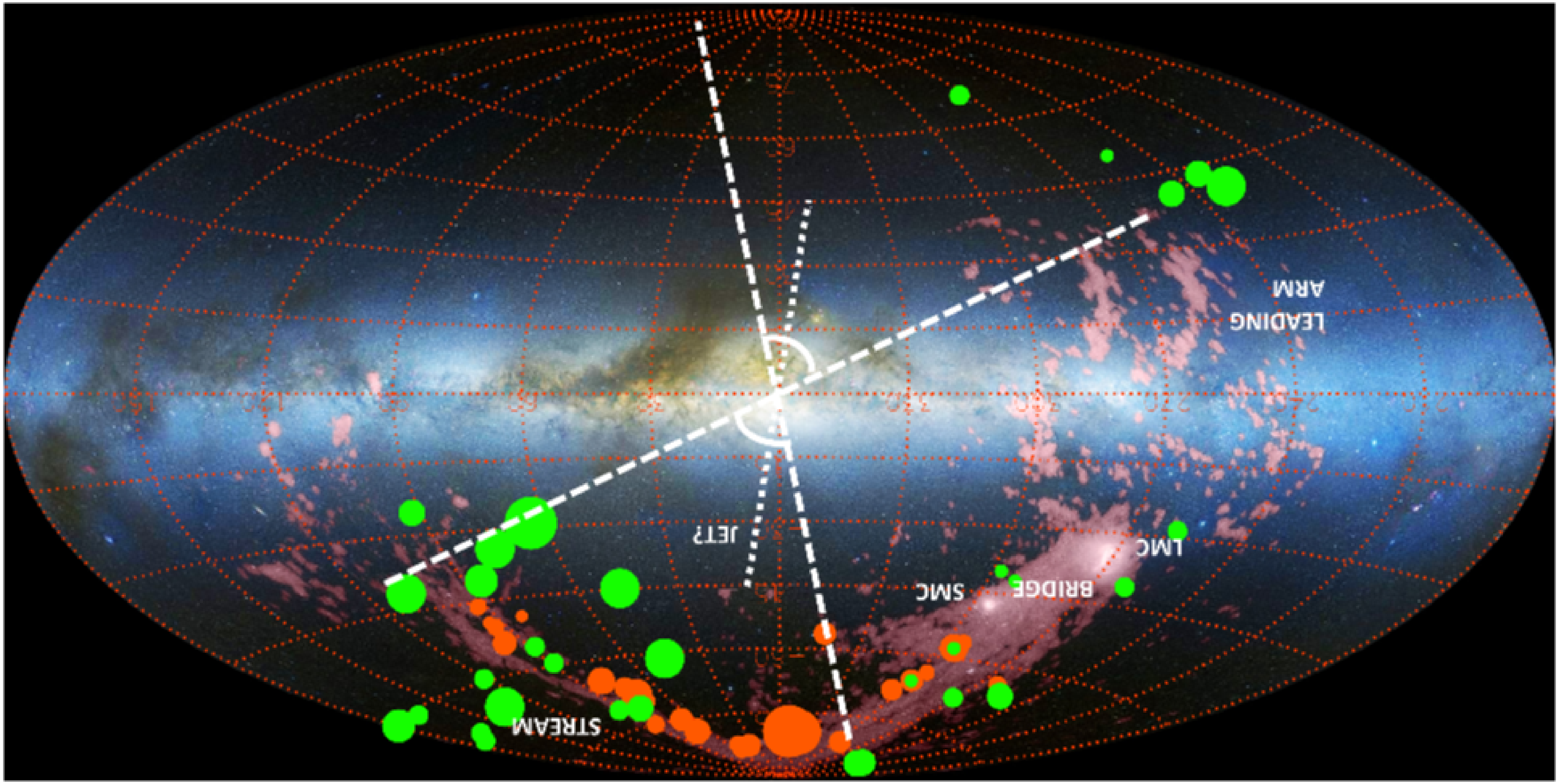
Outflow from Galactic center



$V_w \simeq 330\ \mathrm{km\,s^{-1}}$ $L_w > 3 \times 10^{40}\ \mathrm{erg\,s^{-1}}$ over the past 10 Myr,

di Teodoro+2018 (Green Bank Telescope)

Excess ionization cone from the Galactic center



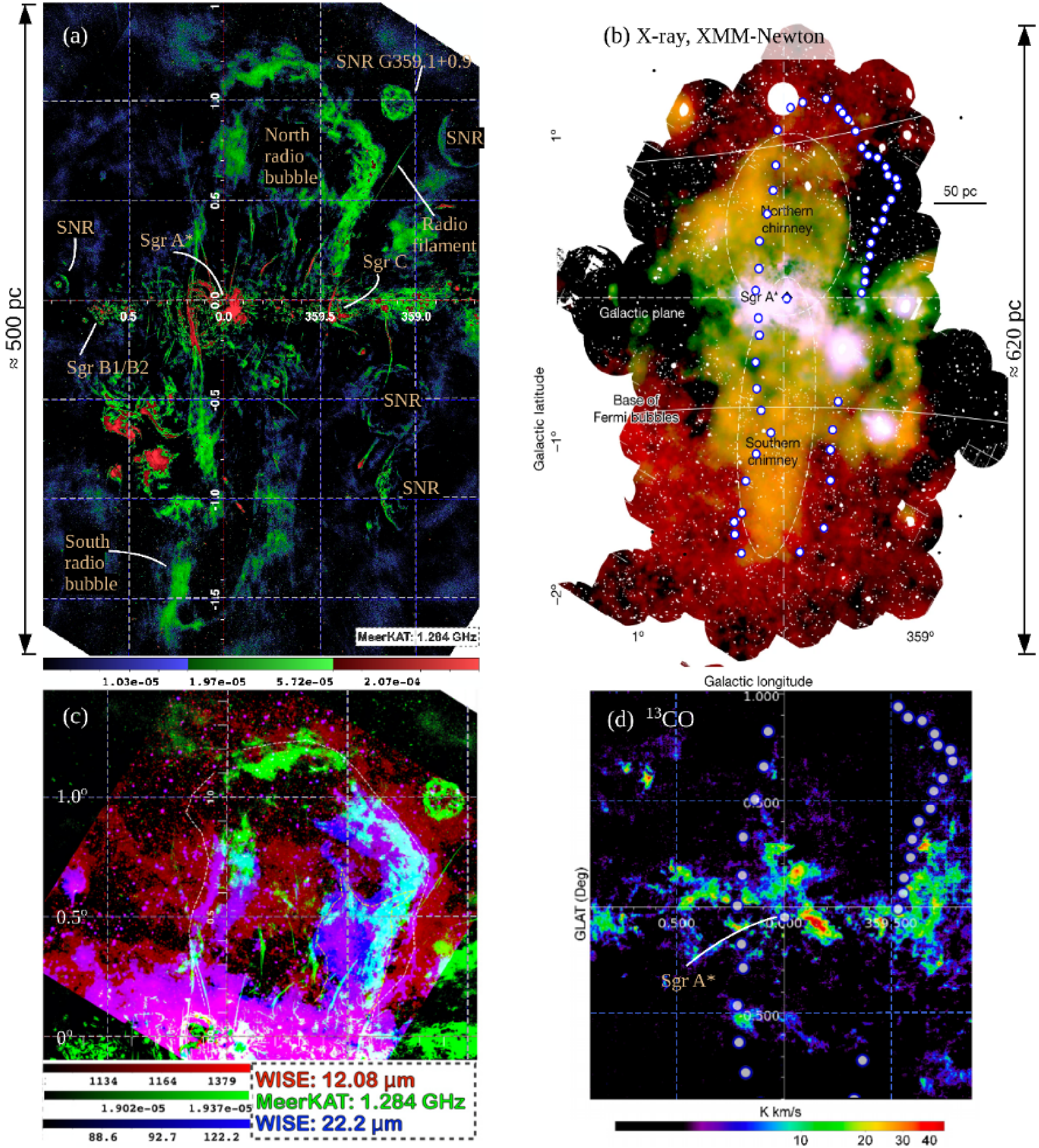
Large ionization cone: requires 0.1-1 L_{edd} at ~3 Myr ago

Nuclear star cluster (~ 0.5 pc) $M_* \approx 10^4 M_\odot$

$t_{age} \approx 6 \pm 2\, Myr$

Bland-Hawthorn+2019

Structures at the Galactic center



Required power

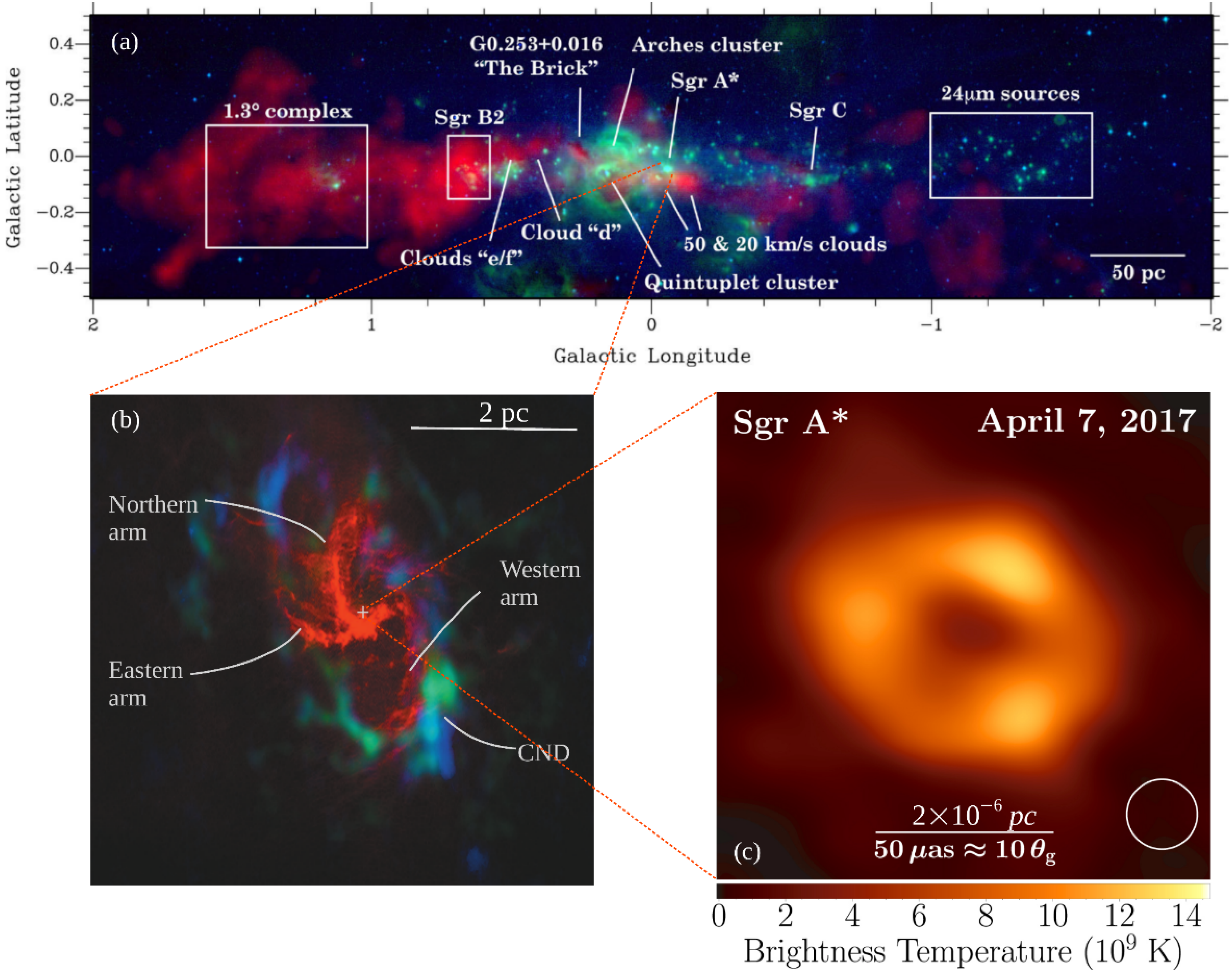
$$L_{mech} \sim 10^{37-38}\ erg\, s^{-1}$$

Radio lobe age

$$t_{age} \sim 4\ Myr$$

Could the 400 pc radio lobe be related to the excess Ionization?

Ponti+2021; Ponti+2019: Veena+2023

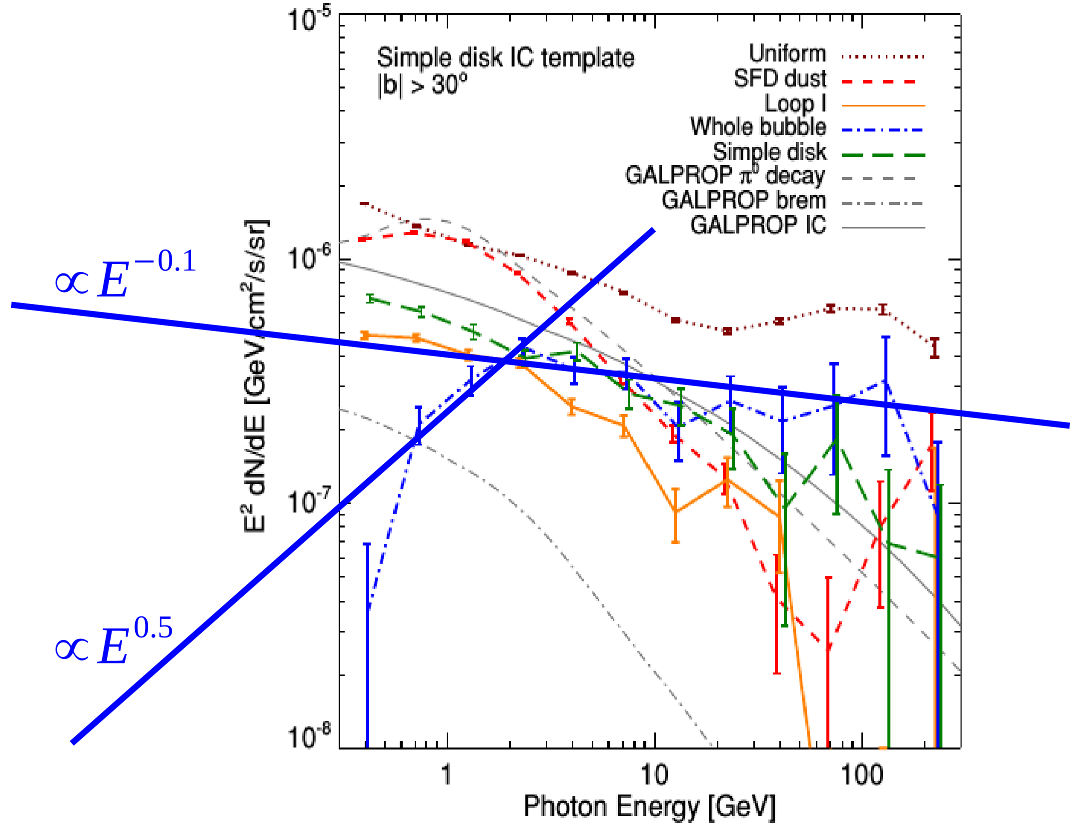


Kruijssen+2014; Genzel+2010; EHT Collab+2022

The Spectral origin ?

$$E_\gamma \sim 4\times 10^{37}\ \ erg\,s^{-1}$$

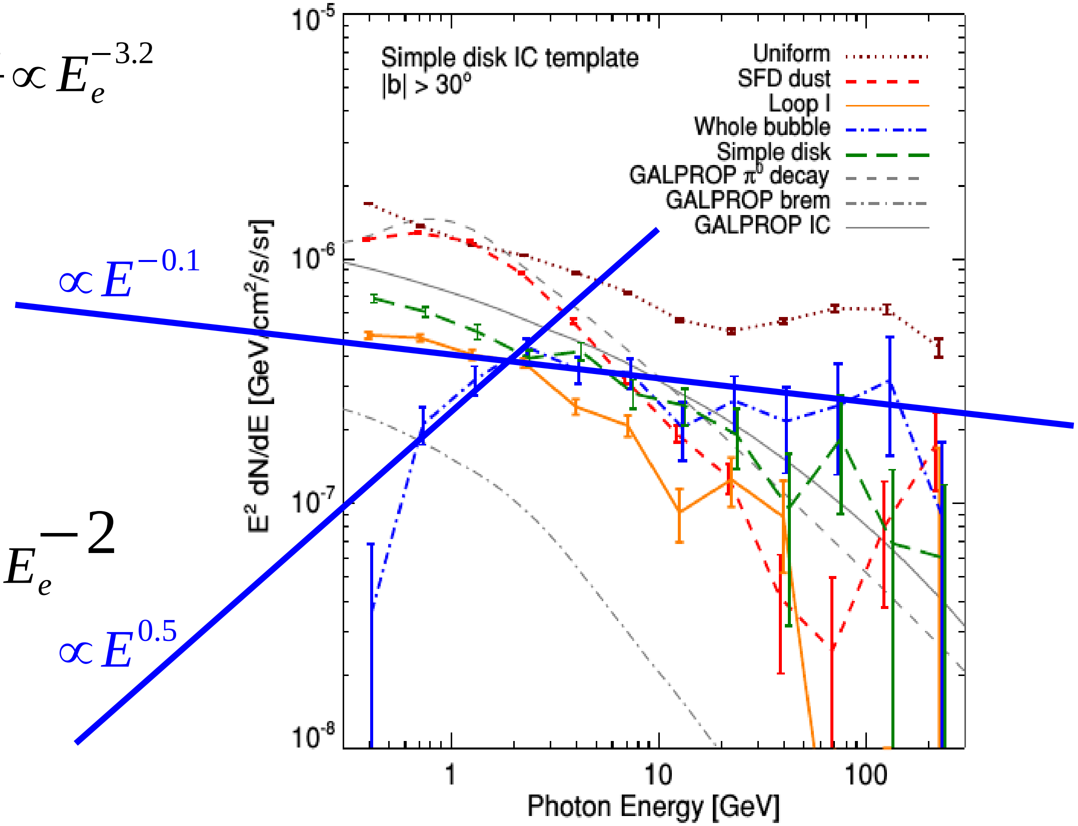
$$E_{mech} \sim 10^{54-55}\ \ erg\,s^{-1}\ \ (only\ bubble)$$
$$\sim 10^{55-56}\ \ erg\,s^{-1}\ \ (including\ NPS)$$



The Spectral origin ?

$$E^2 \frac{dN}{dE} \propto E^{-0.1} \Rightarrow I_\nu \propto \nu^{-1.1} \Rightarrow \frac{dN_e}{dE} \propto E_e^{-3.2}$$

$$E^2 \frac{dN}{dE} \propto E^{0.5} \Rightarrow I_\nu \propto \nu^{-0.5} \Rightarrow \frac{dN_e}{dE} \propto E_e^{-2}$$

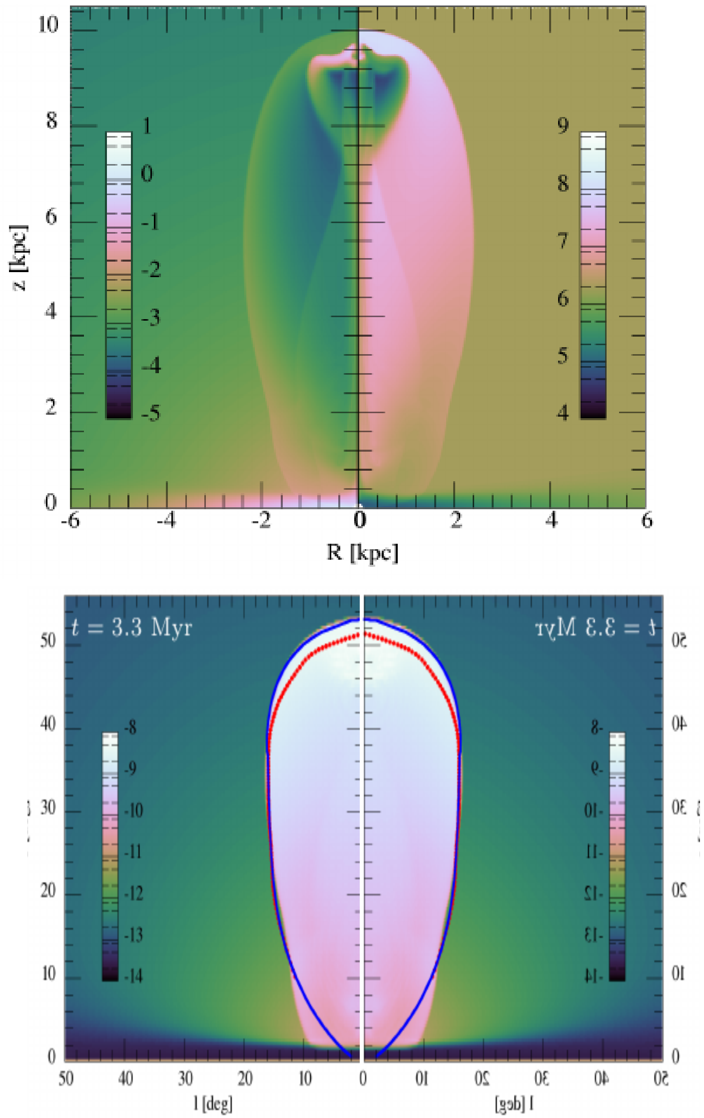


IC cooling time

$$\epsilon_{break} \approx 1\,GeV \Rightarrow t_{cool} \approx 2\ \ Myr$$

Freshly (approx 1-2 Myr) accelerated electrons from a shock/turbulence

AGN driven Fermi Bubbles



A jet launched by central AGN

$$L_{mech} \approx 2 \times 10^{44} \;\; erg\, s^{-1}$$
$$t_{age} \approx 3.3\, Myr$$

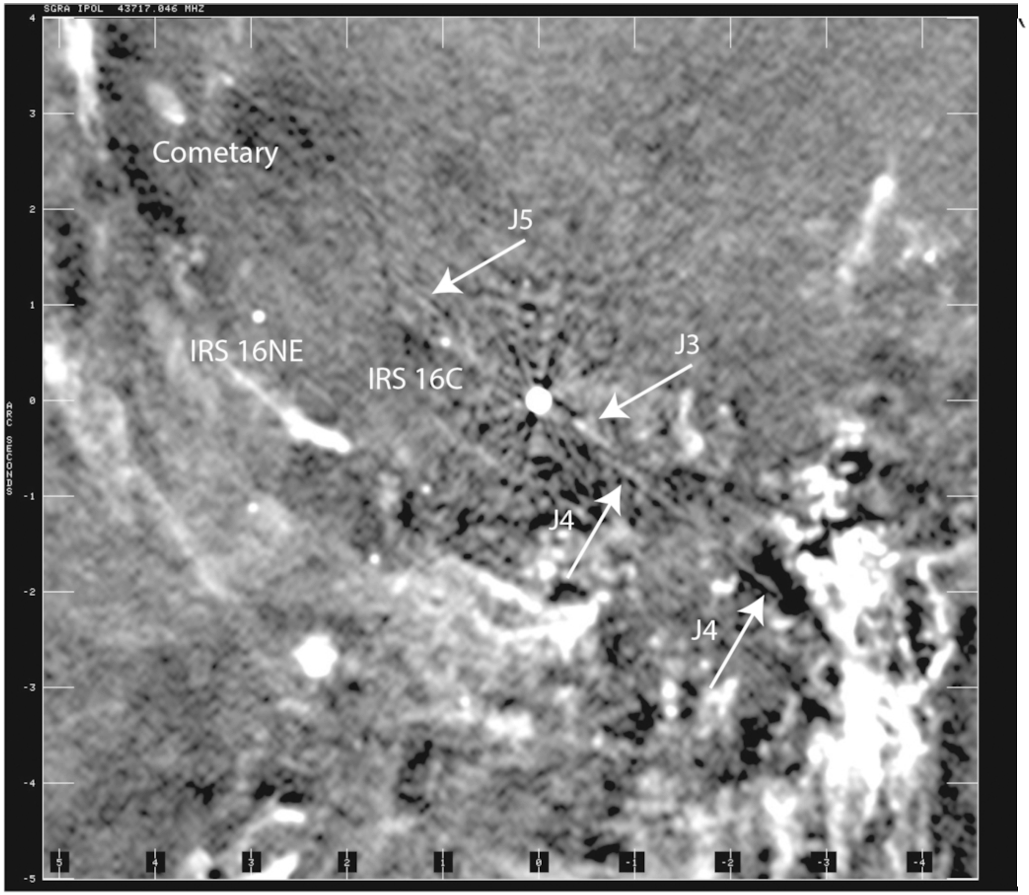
Positives:
1. Small time scale allows fast CR transport

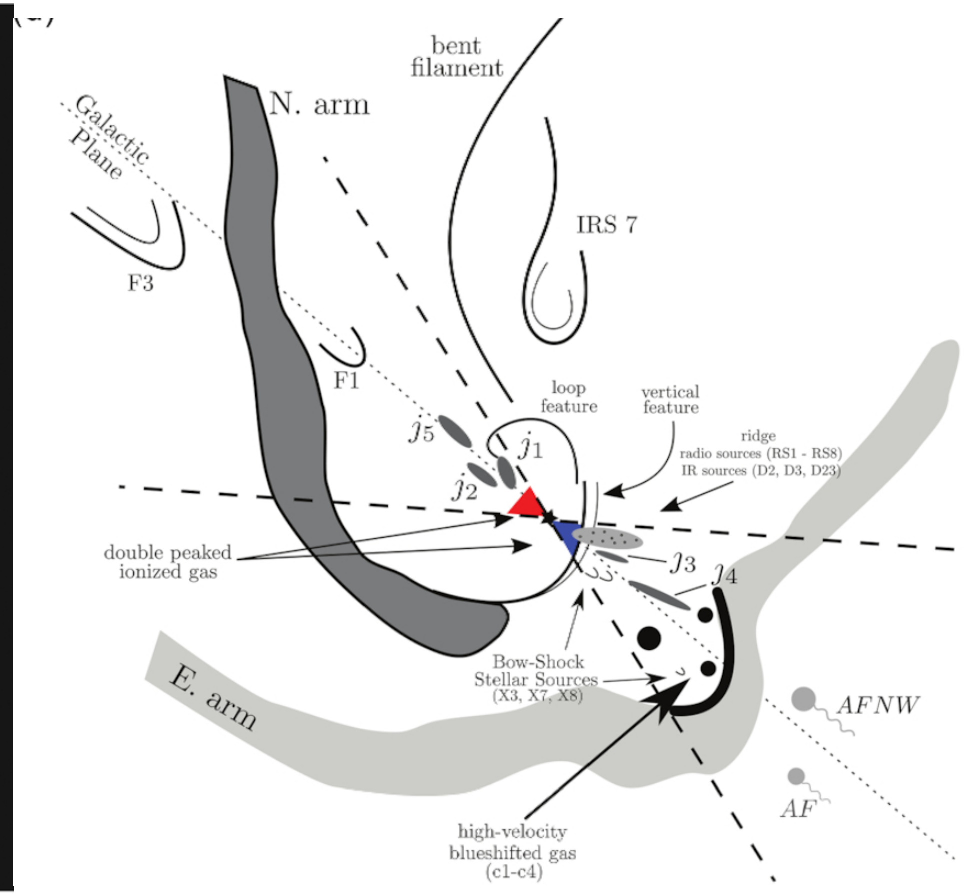
Negatives:
1. High mechanical luminosity
2. No eROSITA bubbles
3. The jet has to be perpendicular to the disc

Mondal, Keshet, **Sarkar**, Gurwich, 2021

Jets in our Galaxy?

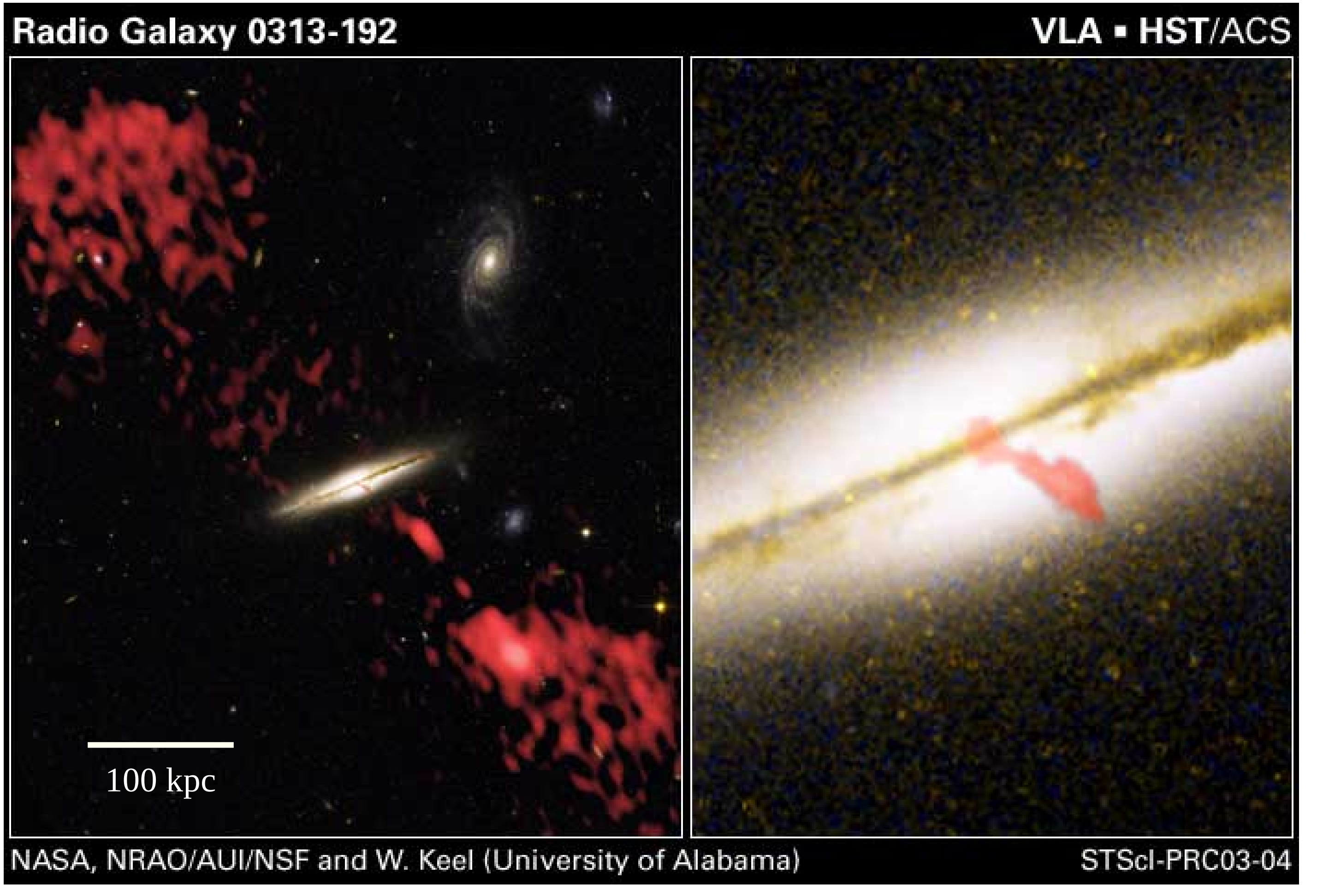
(a)





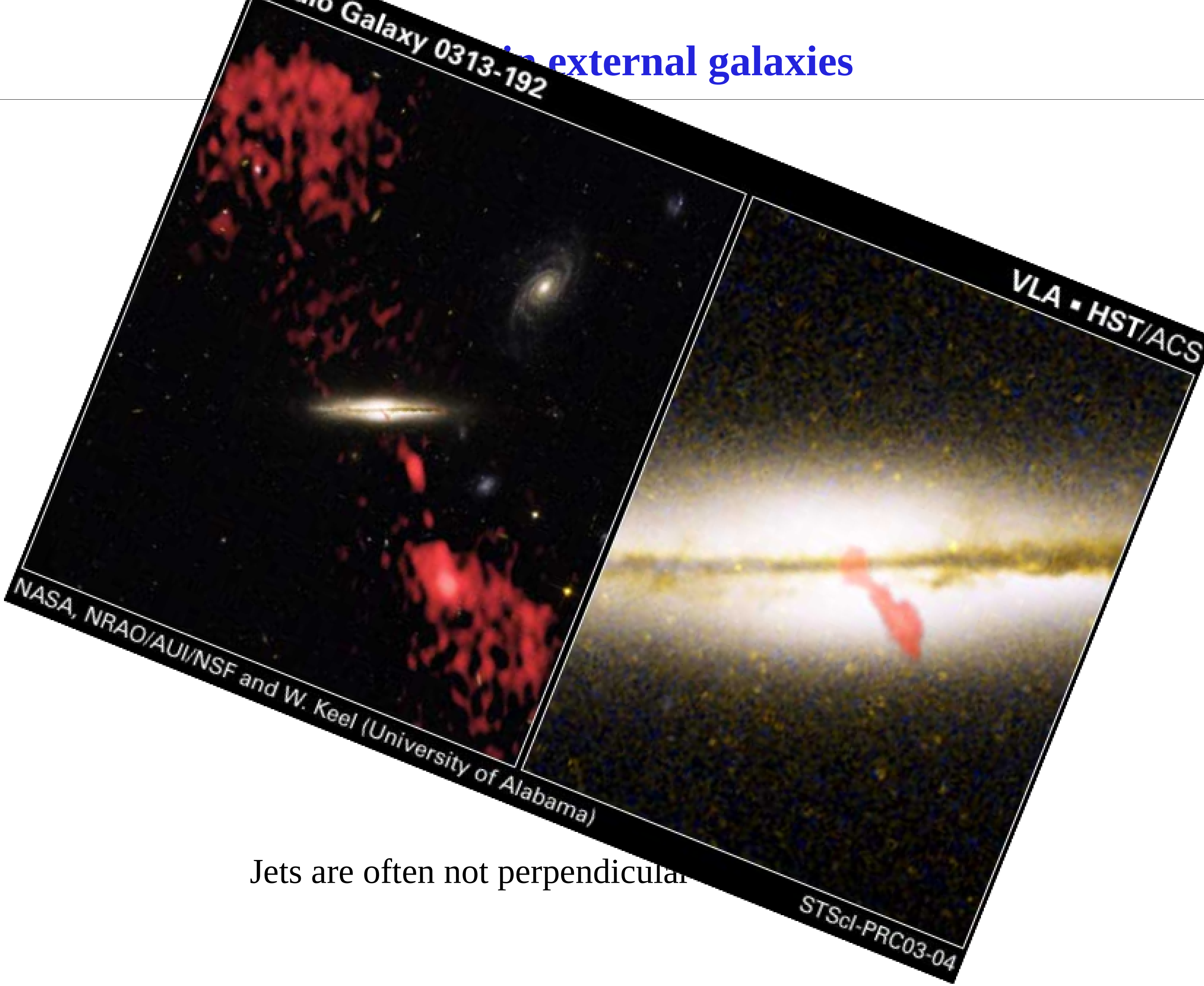
Jets are often not perpendicular to the galactic disc

Jets in external galaxies



Jets are often not perpendicular to the galactic disc

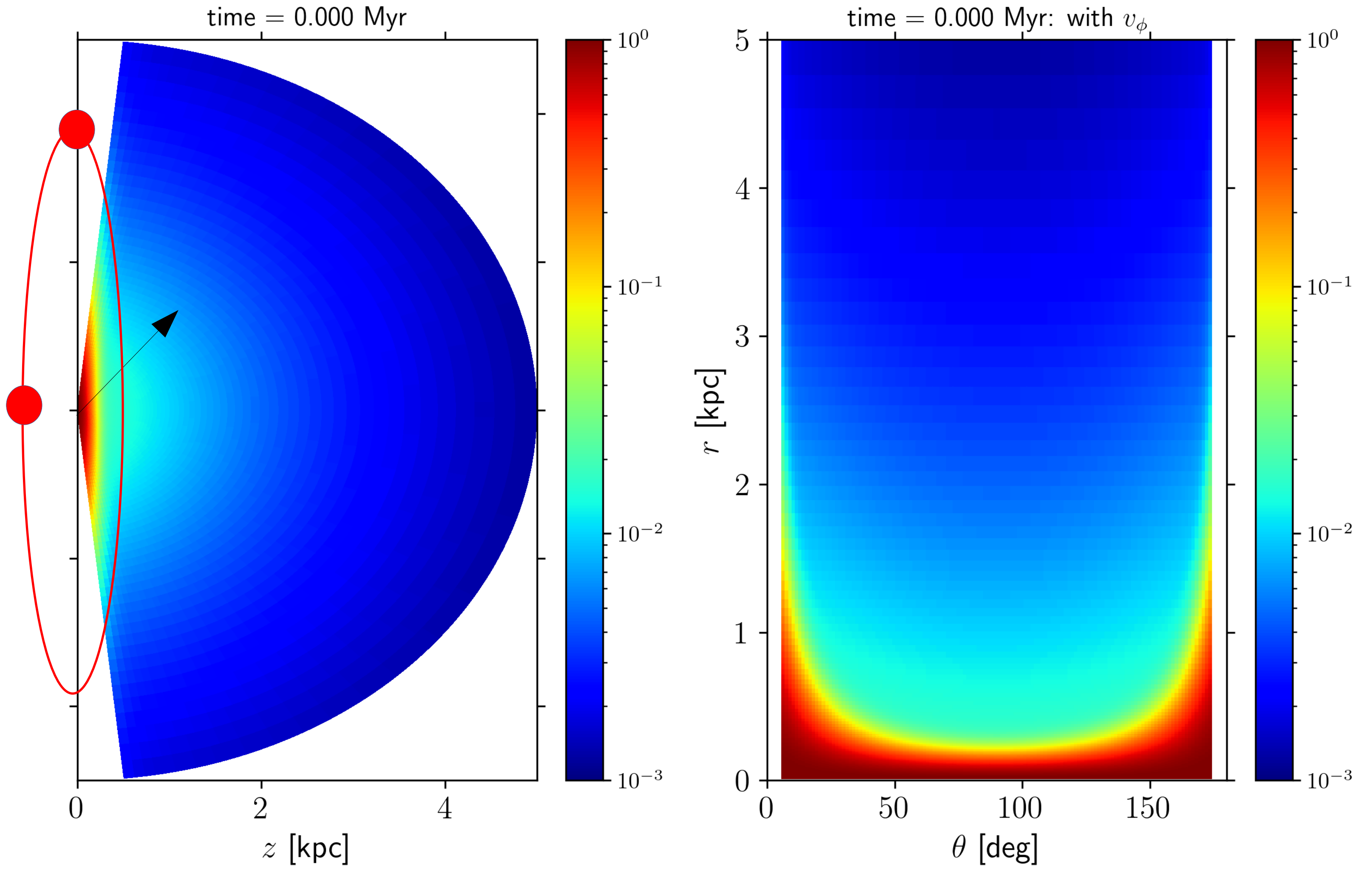
external galaxies



Jets are often not perpendicular

W. Keel (University of Alabama), M. Ledlow (Gemini Observatory), F. Owen (NRAO) and AUI/NSF

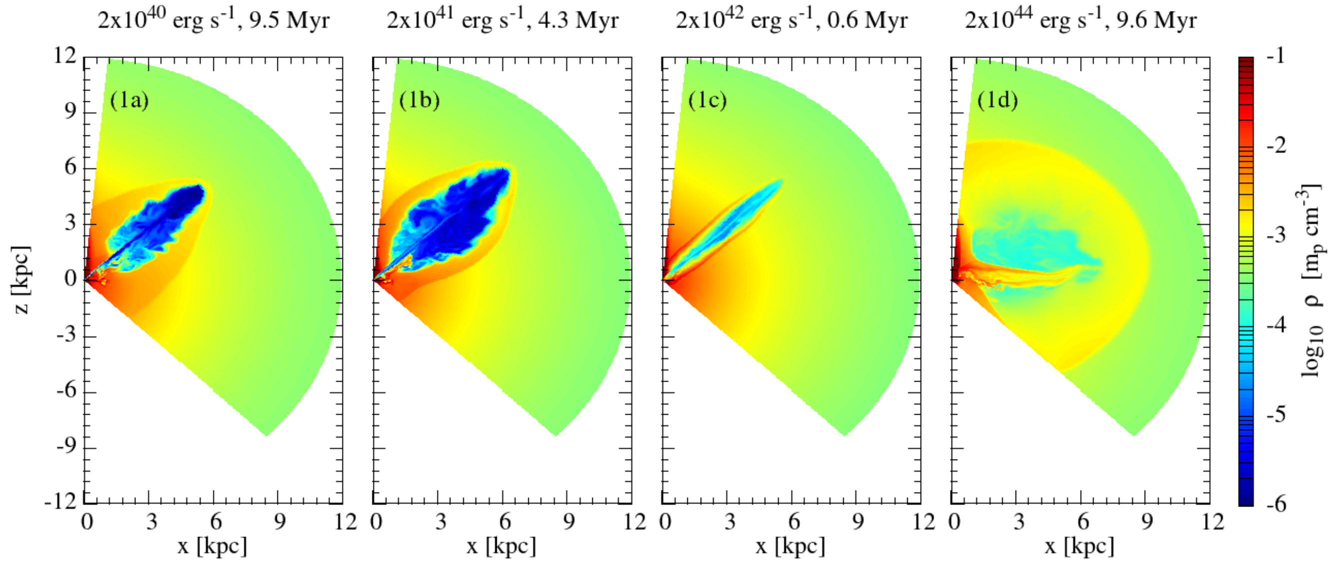
Tilted jet simulations



Play the movie

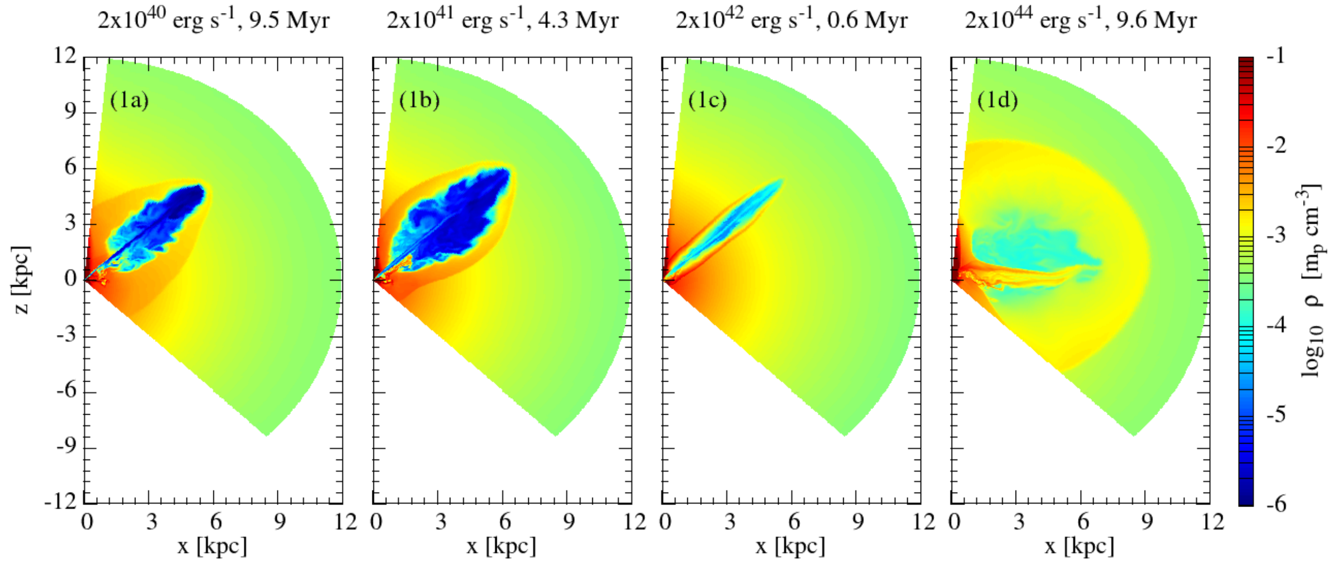
Sarkar+2023

Tilted jet simulations



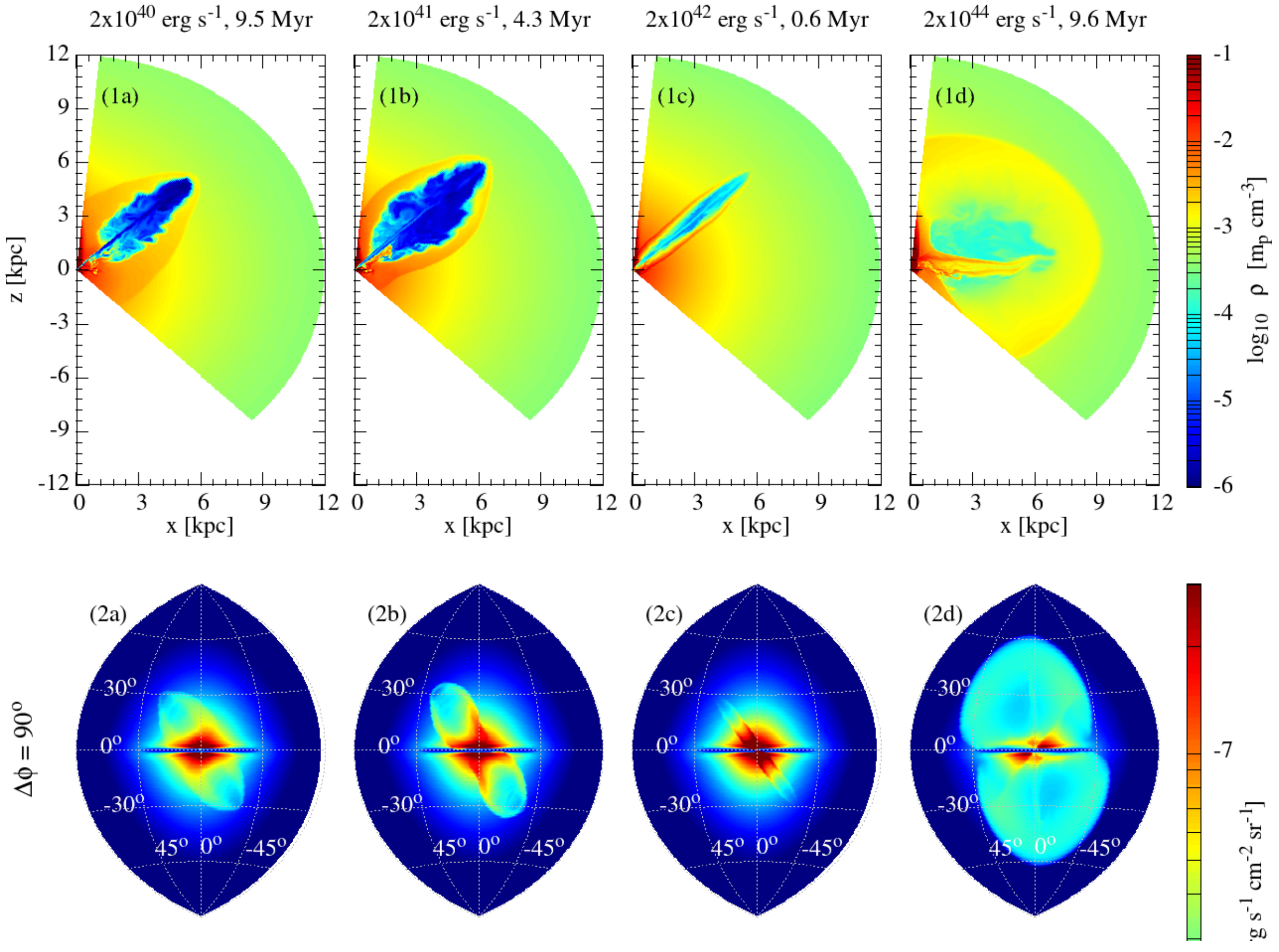
Sarkar+2023

Tilted jet simulations



Sarkar+2023

Tilted jet simulations

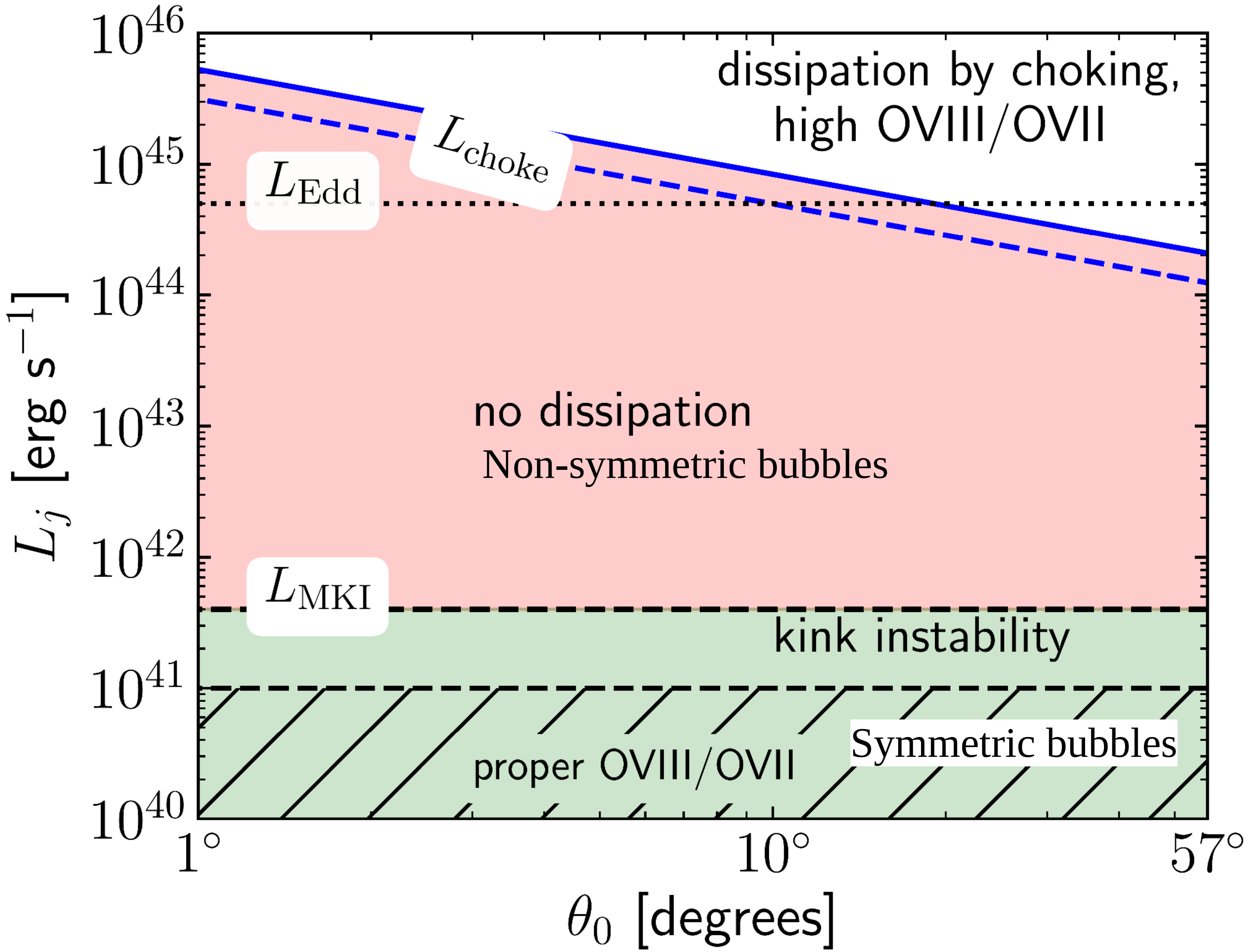


Tilted bubbles

Sarkar+2023

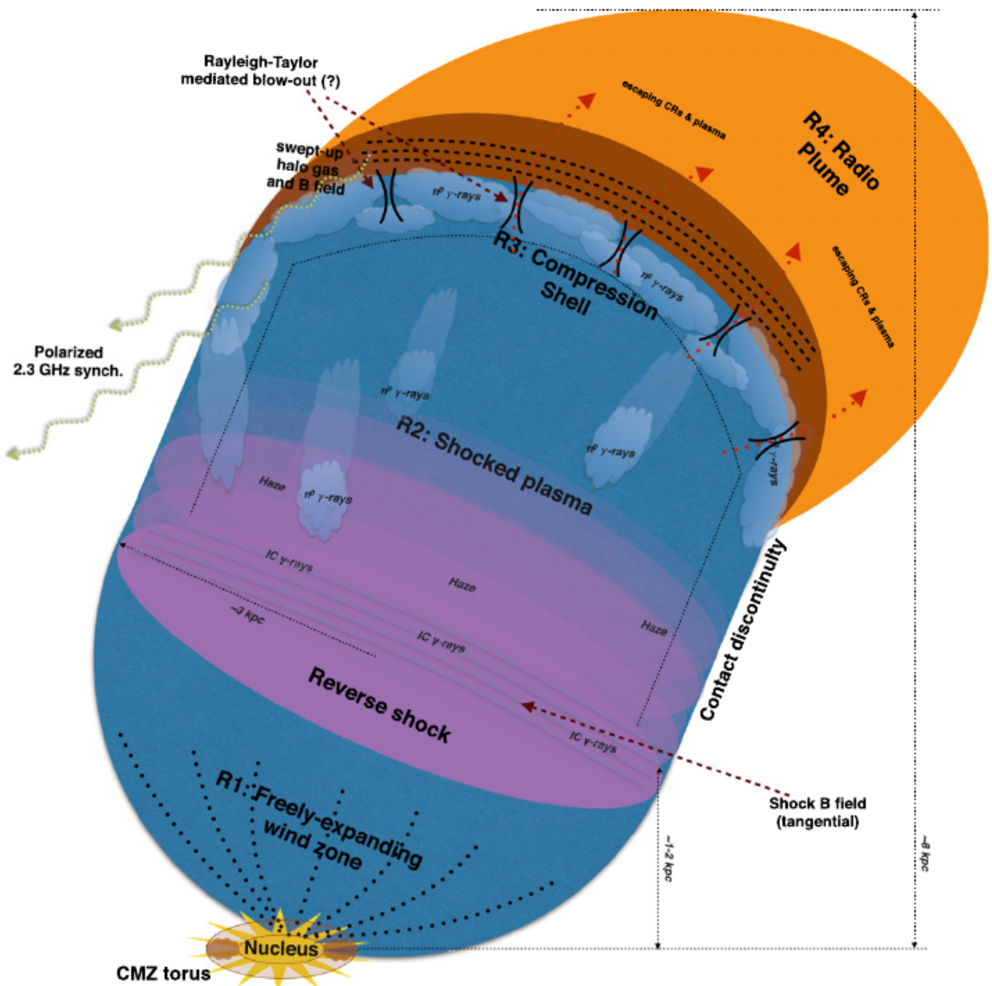
AGN sources?

Requirements: Symmetric bubbles + consistent with x-ray observations



Slow and steady energy release

Sarkar+2023



Star formation at the CMZ (200 pc)

$$L_{mech} \approx 10^{40} \ erg\, s^{-1}$$
$$\Rightarrow SFR \approx 0.1\, M_{\odot}\, yr^{-1}$$

$$t_{age} \approx 200 - 10^{3}\, Myr$$

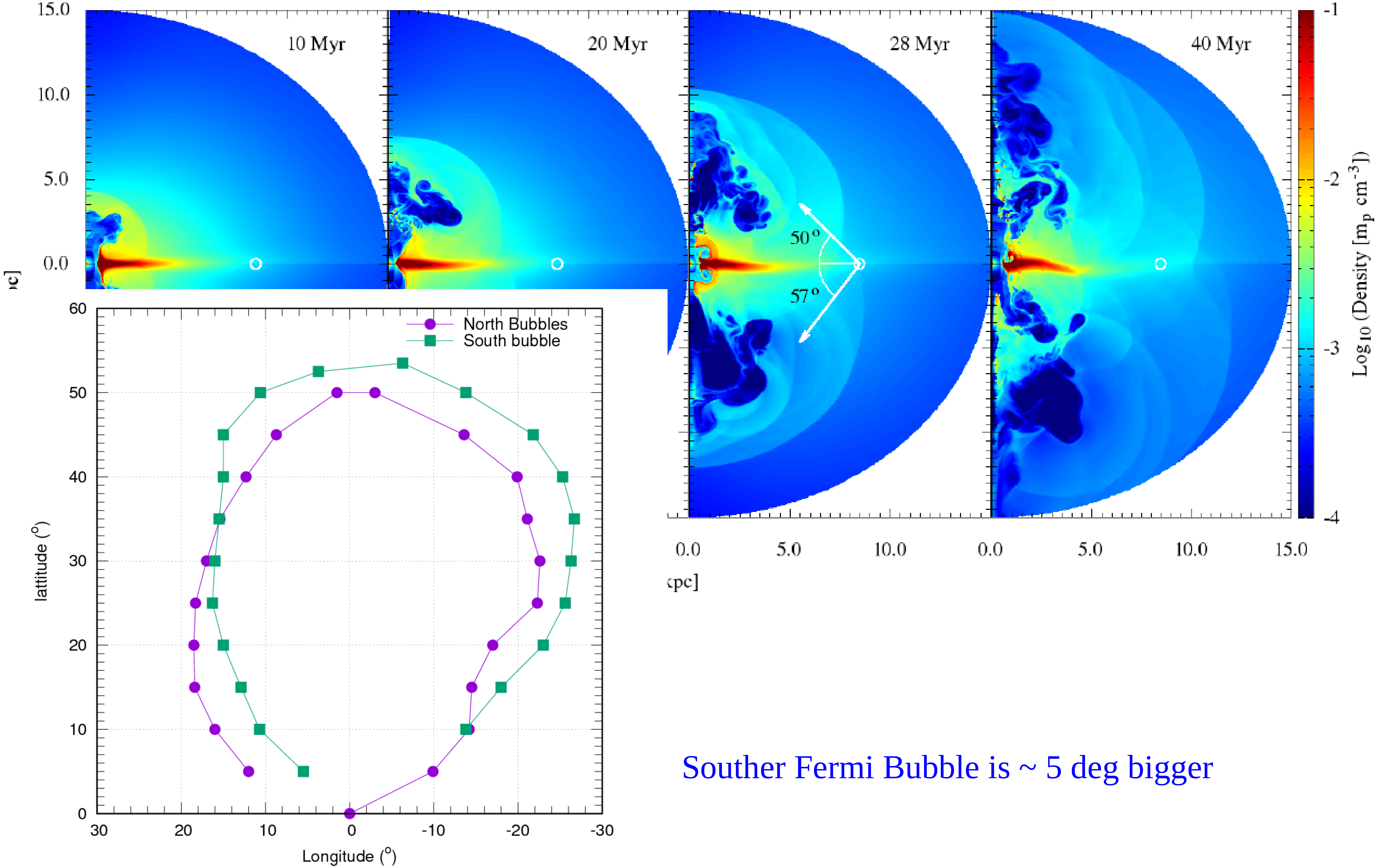
Positives:
1. SFR is close to observations
2. Radio emission
3. Gamma-ray emission

Negatives:
1. Hadronic model
2. no-eROSITA bubbles
3. Spherical symmetric assumptions

Crocker et al., 2015

Asymmetry in x-ray sky map

Assumed, 20% density asymmetry in south hemisphere

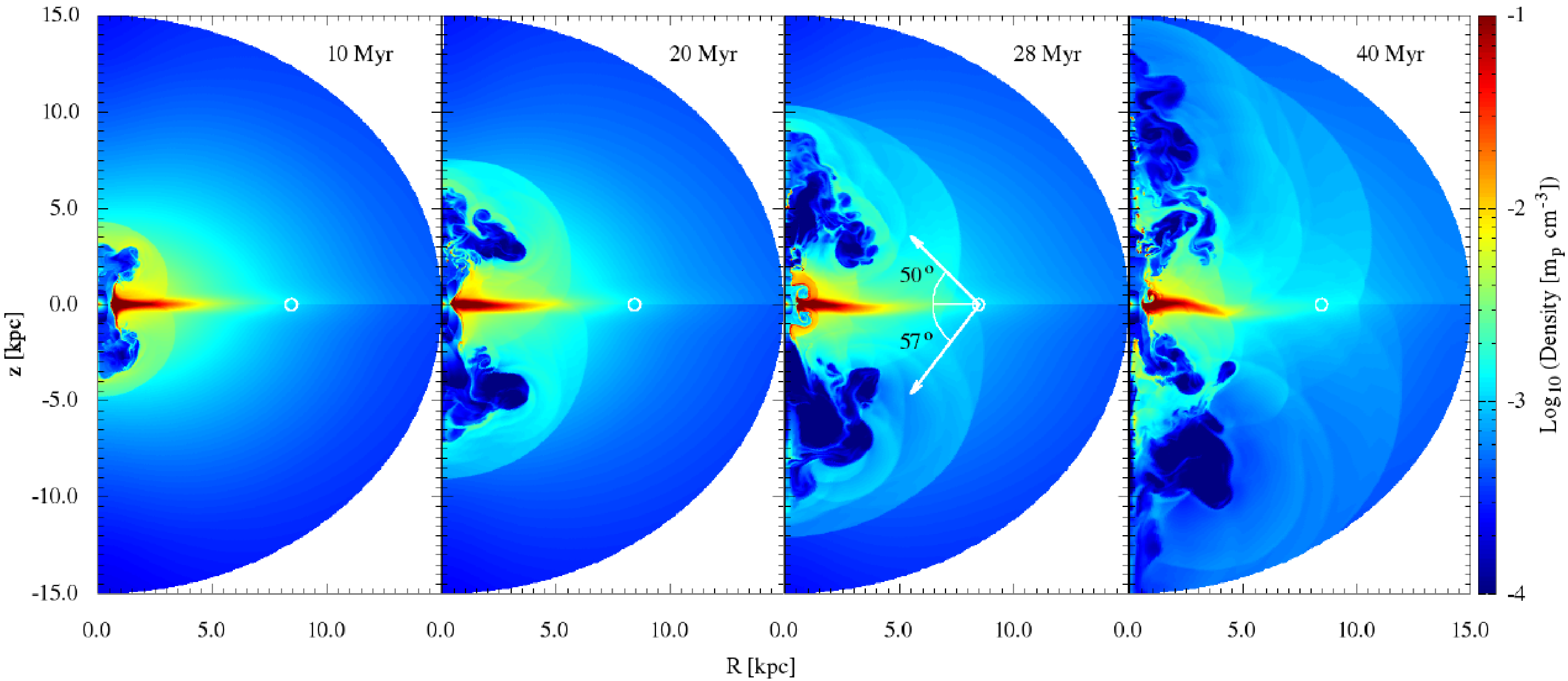


Souther Fermi Bubble is ~ 5 deg bigger

Sarkar 2019

Asymmetry in x-ray sky map

Assumed, 20% density asymmetry in south hemisphere

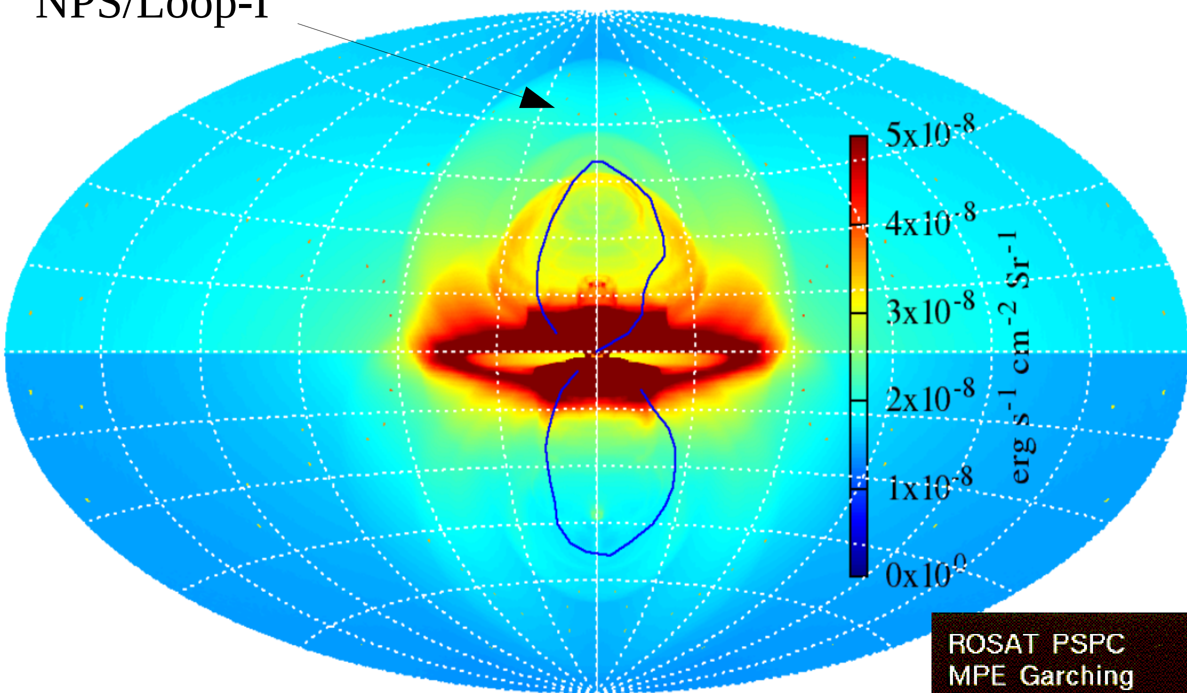


$$r_s = A^{5/(5-\alpha)} \left(\frac{E}{\rho_0 r_0^{\alpha}} \right)^{1/(5-\alpha)} t^{2/(5-\alpha)}$$

Sarkar 2019

Asymmetry in x-ray sky map

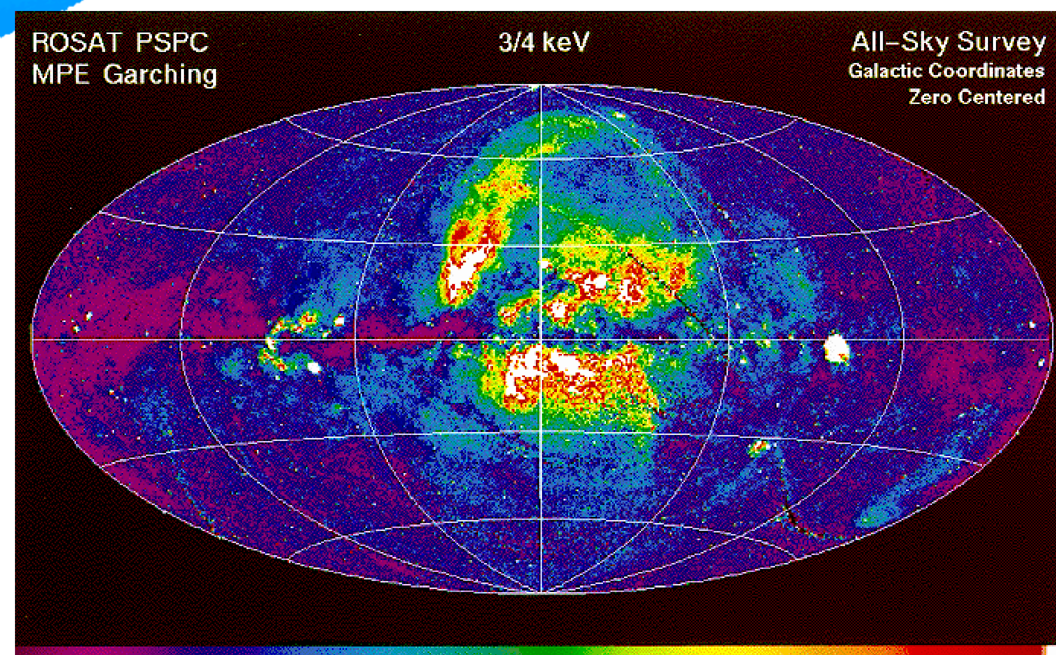
NPS/Loop-I



Assumed, 20% density asymmetry in south hemisphere

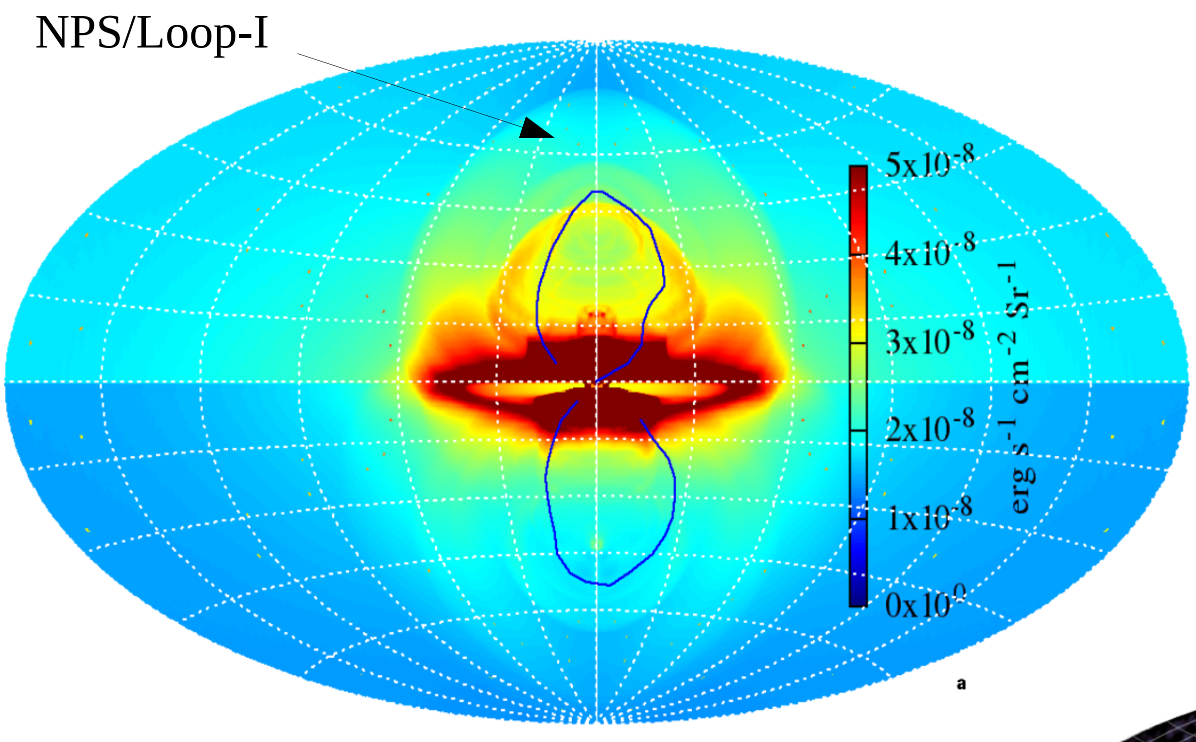
No/faint southern NPS/Loop-I

0.5-2.0 keV X-ray map generated at 28 Myr.



Sarkar 2019; Snowden 1997

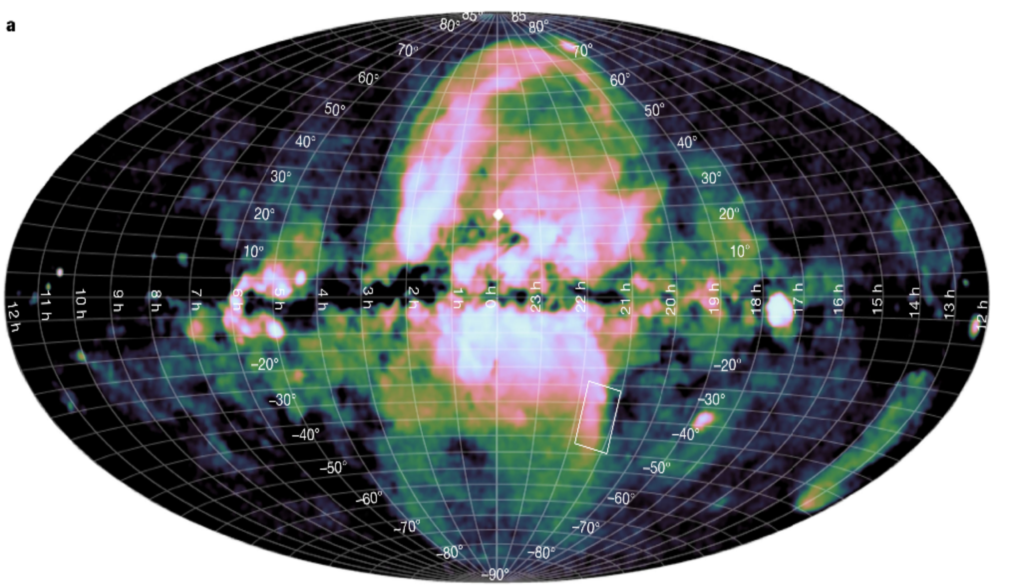
Asymmetry in x-ray sky map



0.5-2.0 keV X-ray map
generated at 28 Myr.

Assumed, 20% density asymmetry in south hemisphere

No/faint southern NPS/Loop-I



0.6-1.0 keV eROSITA map

Sarkar 2019; Predehl+2020