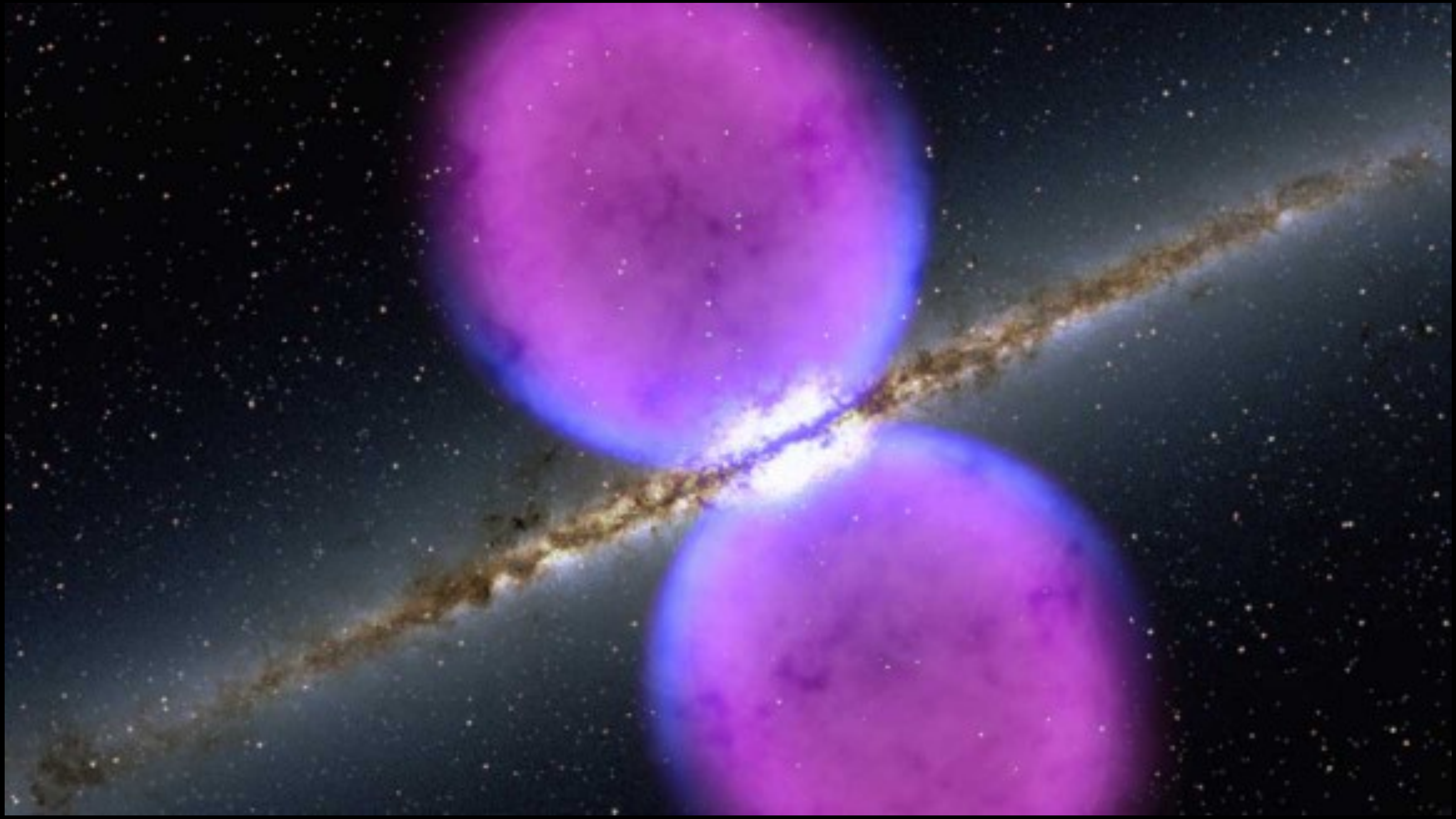
Forging connections: Mapping the nuclear outflow of the Milky Way seen as the Fermi bubbles



Rongmon Bordoloi
Hubble Fellow
Massachusetts Institute of Technology

Galaxies are not closed boxes…

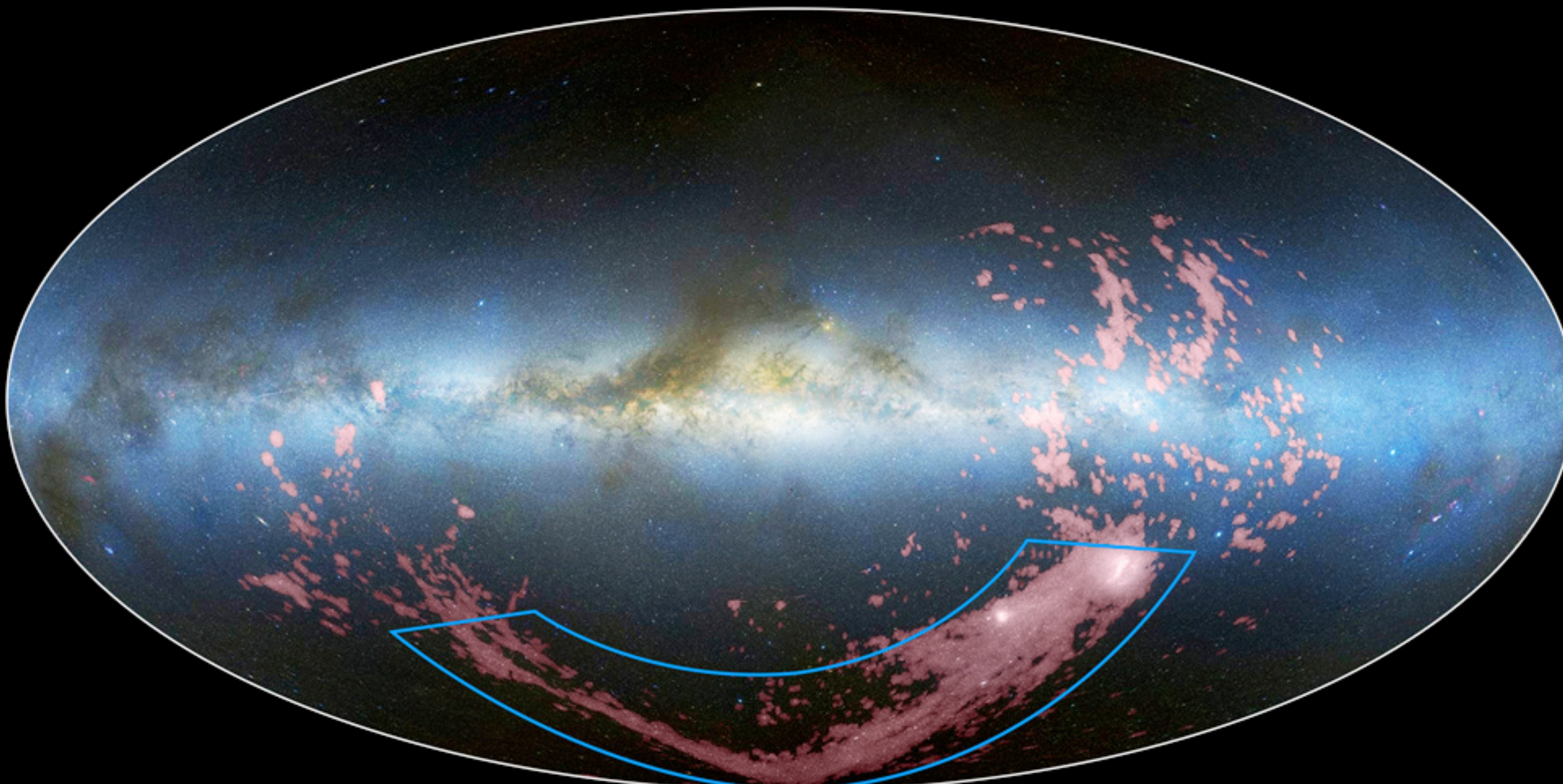
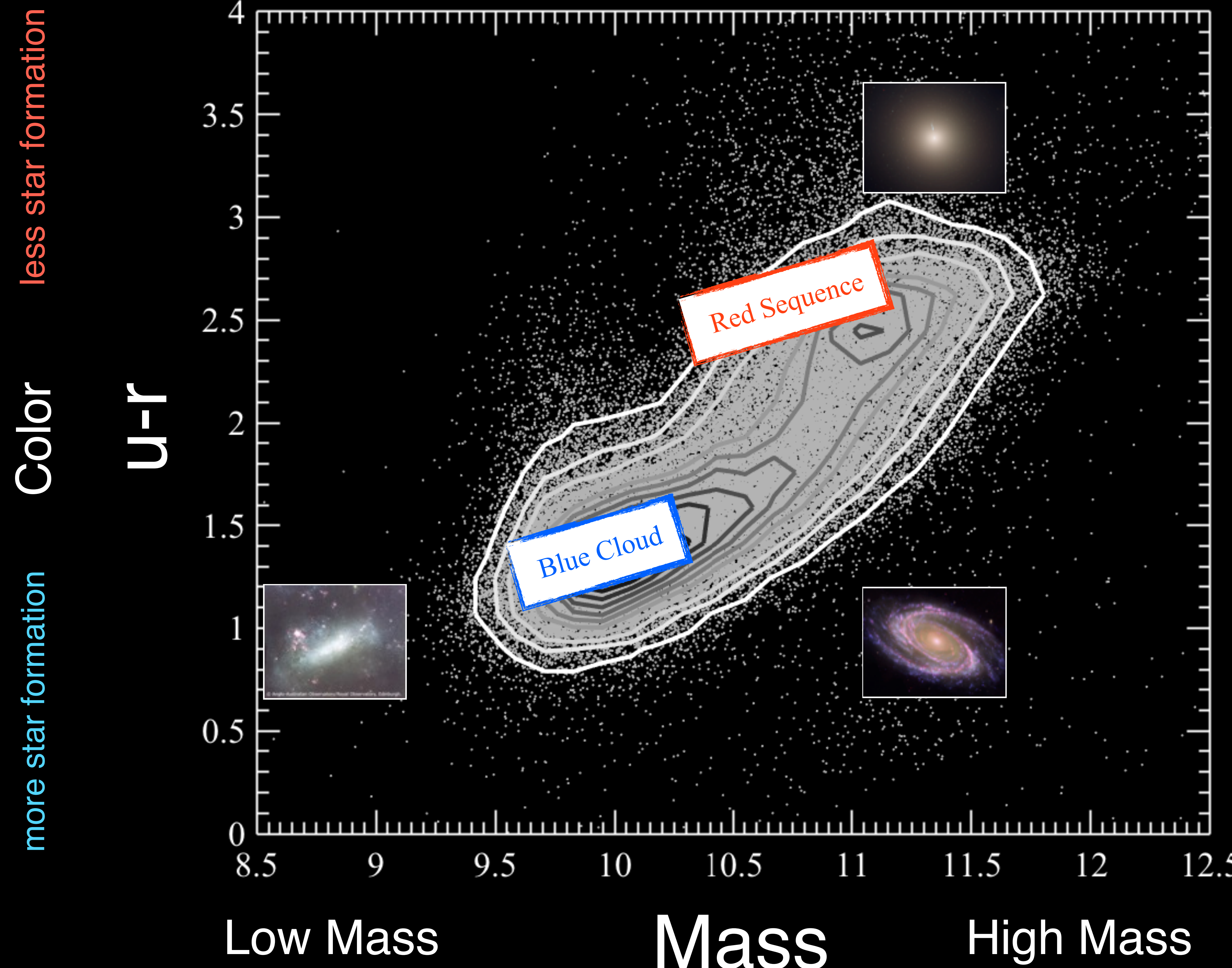


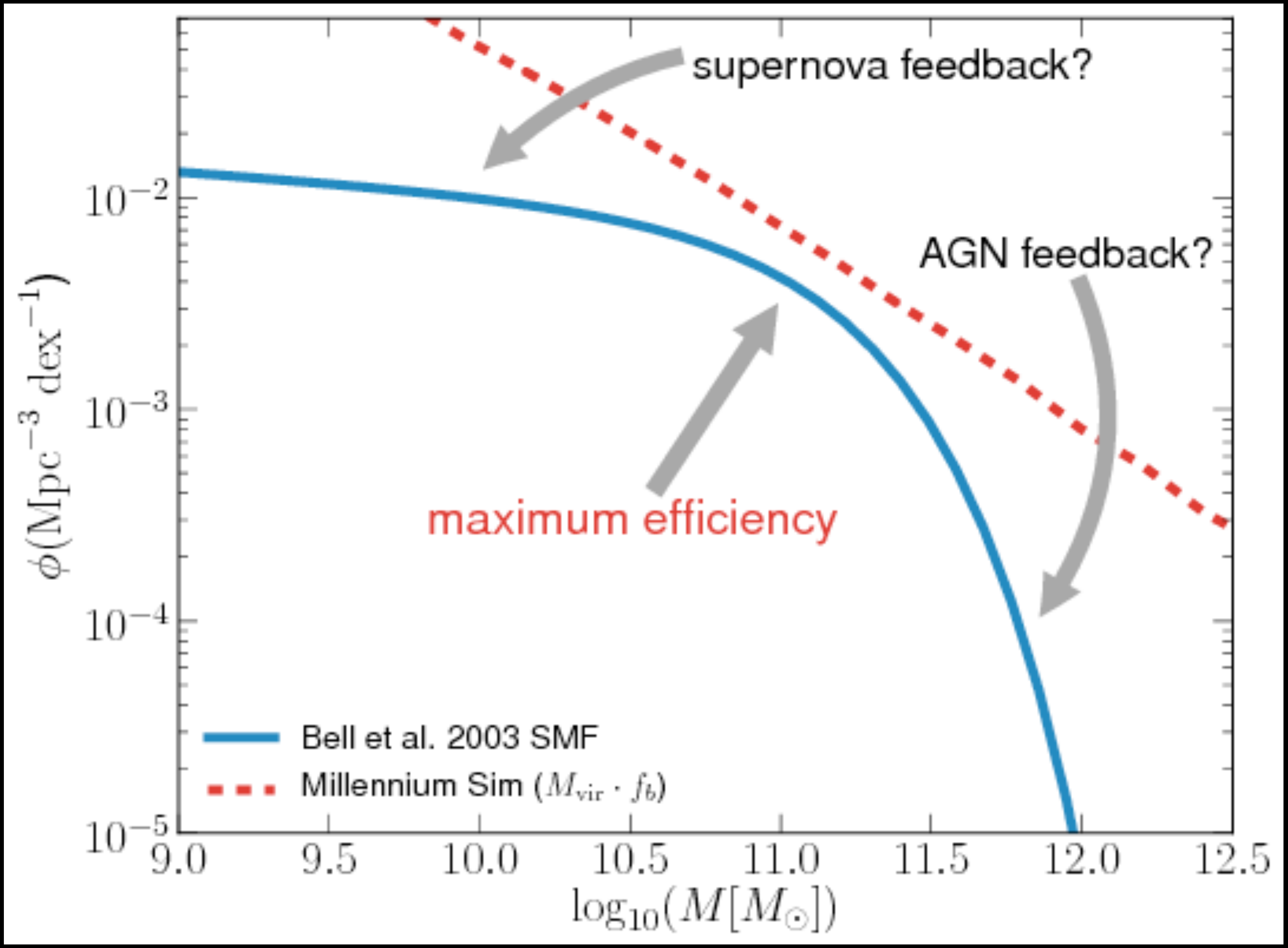
Image Credit: NASA, ESA, D. Nidever et al., NRAO/AUI/NSF, A. Mellinger, LAB Survey.

The Modern View: Color / Mass Bimodality



See e.g.
Blanton+2003
Faber+07
Drory+09
Tomczak+14
+many more

The bare bone galaxy evolution model…



Outflows…

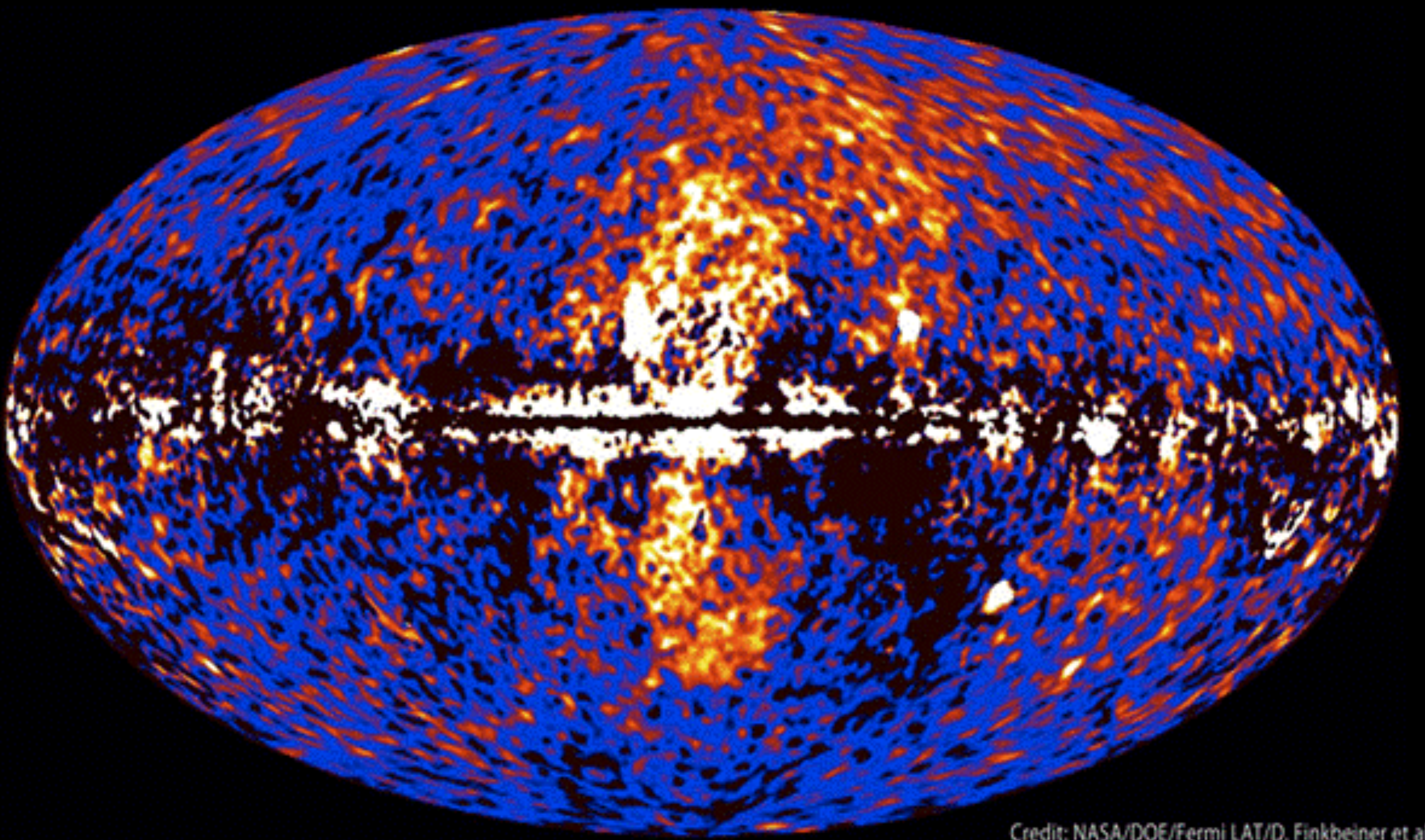
- Widely studied over cosmic time.
- Statistical sampling of one sightline for each of a sample of galaxies.

NASA, ESA, and The Hubble Heritage Team (STScI/AURA)

Our vantage point inside the disk of the Milky Way gives us a unique opportunity to break this deadlock and study the outflowing gas from the Milky Way itself, using multiple sightlines.

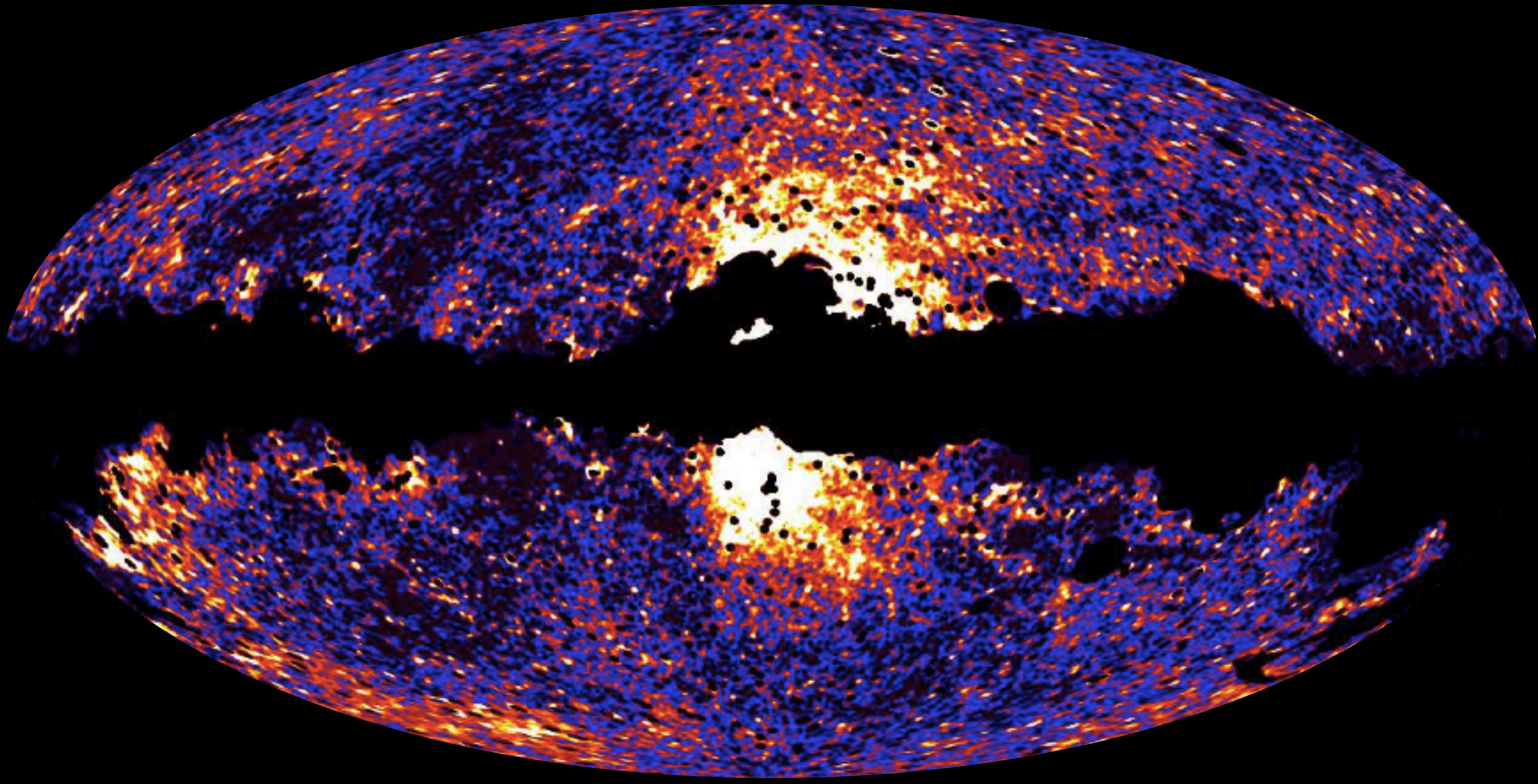
See e.g.
Heckman+2002
Villeux+05
Martin+05
Weiner+09
Rubin+10
Rubin+14
Bordoloi+14
+many many more

Fermi Bubbles (in γ-rays)



Su+2010

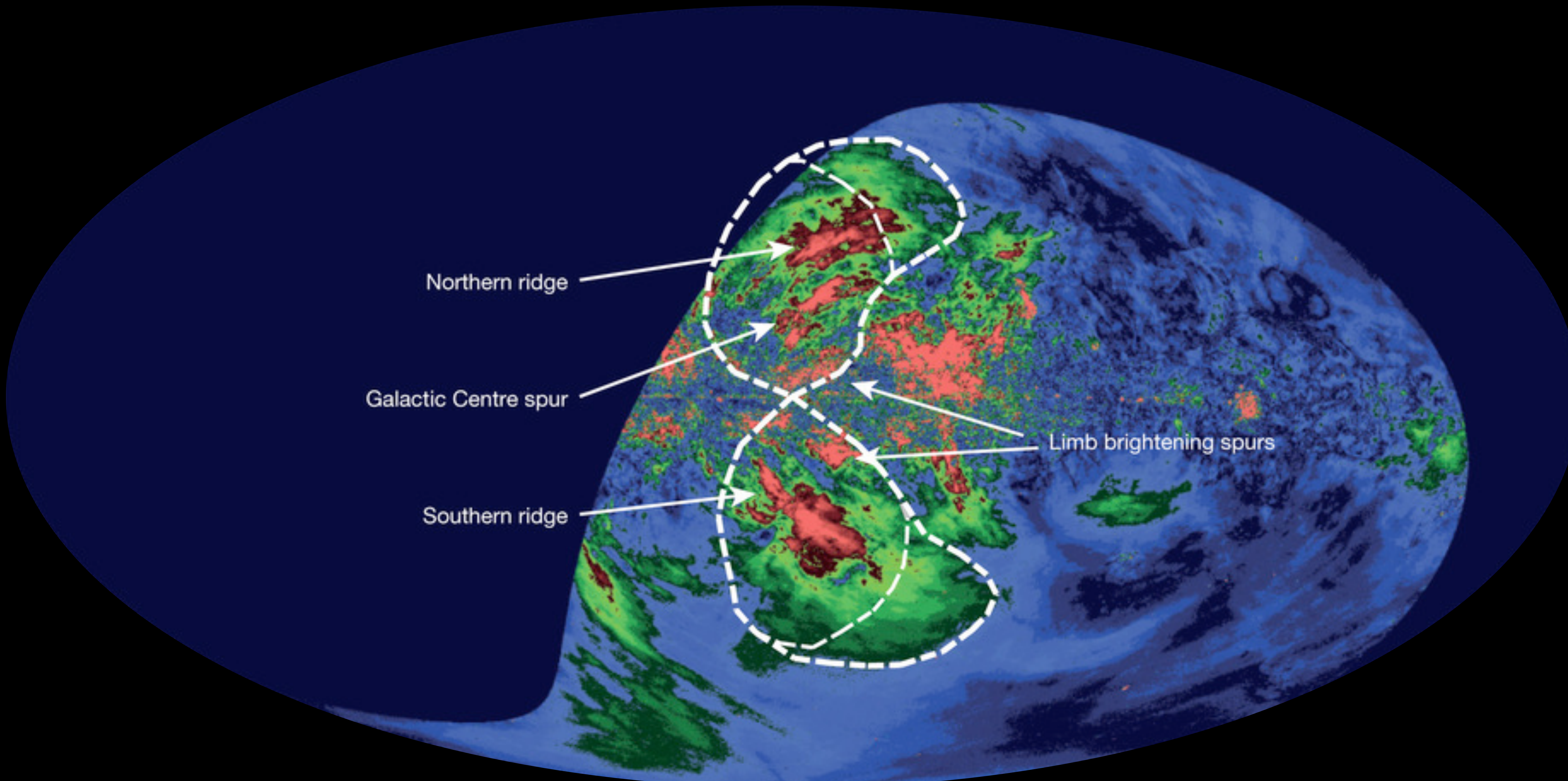
WMAP K-band



WMAP haze (microwave)
(23-94 GHz)

Finkbeiner (2004)

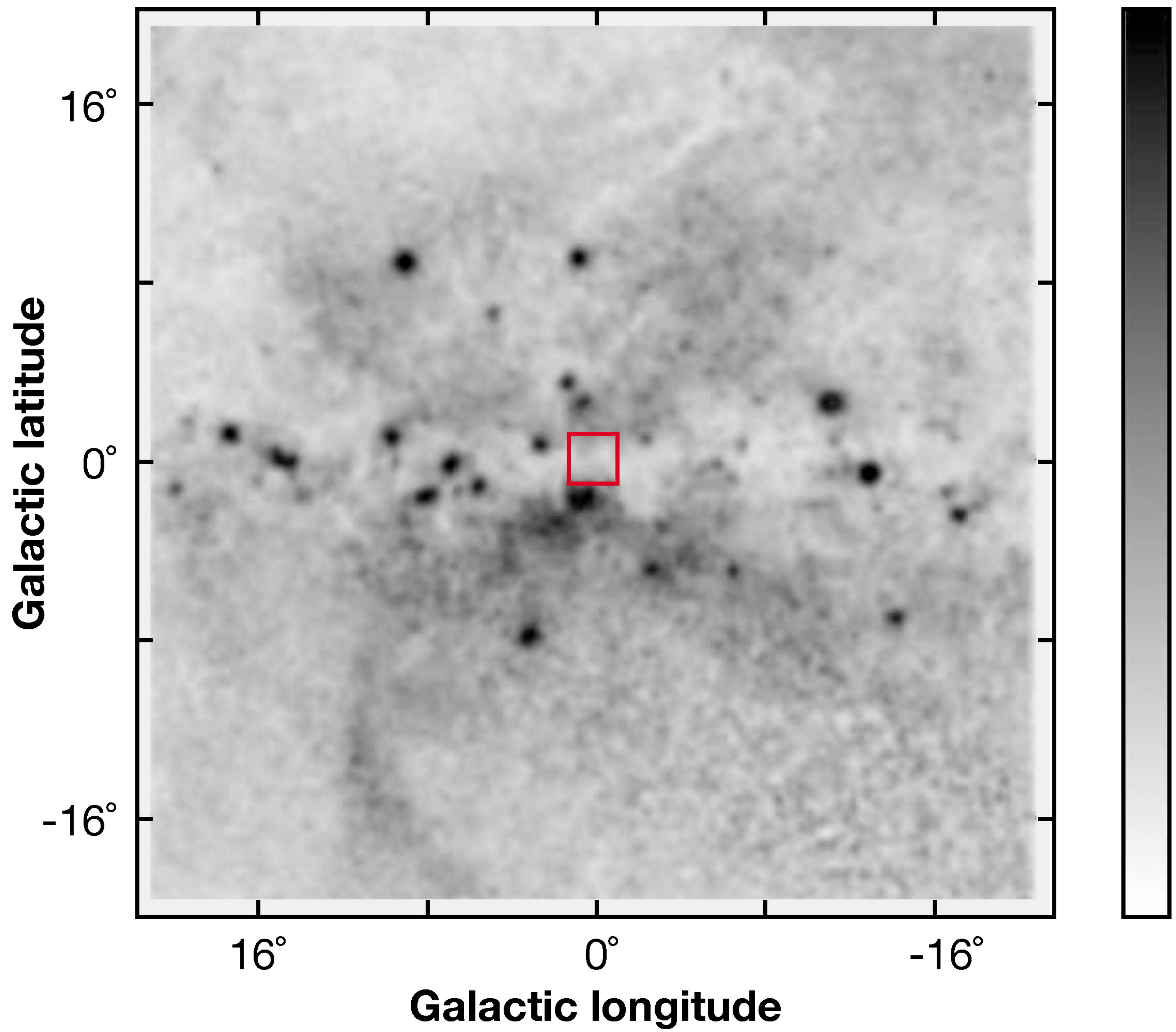
SPASS survey in 2.3 GHz



Polarized Radio Emission 2.3 GHz (Synchrotron; follows FB)

Carretti+2013

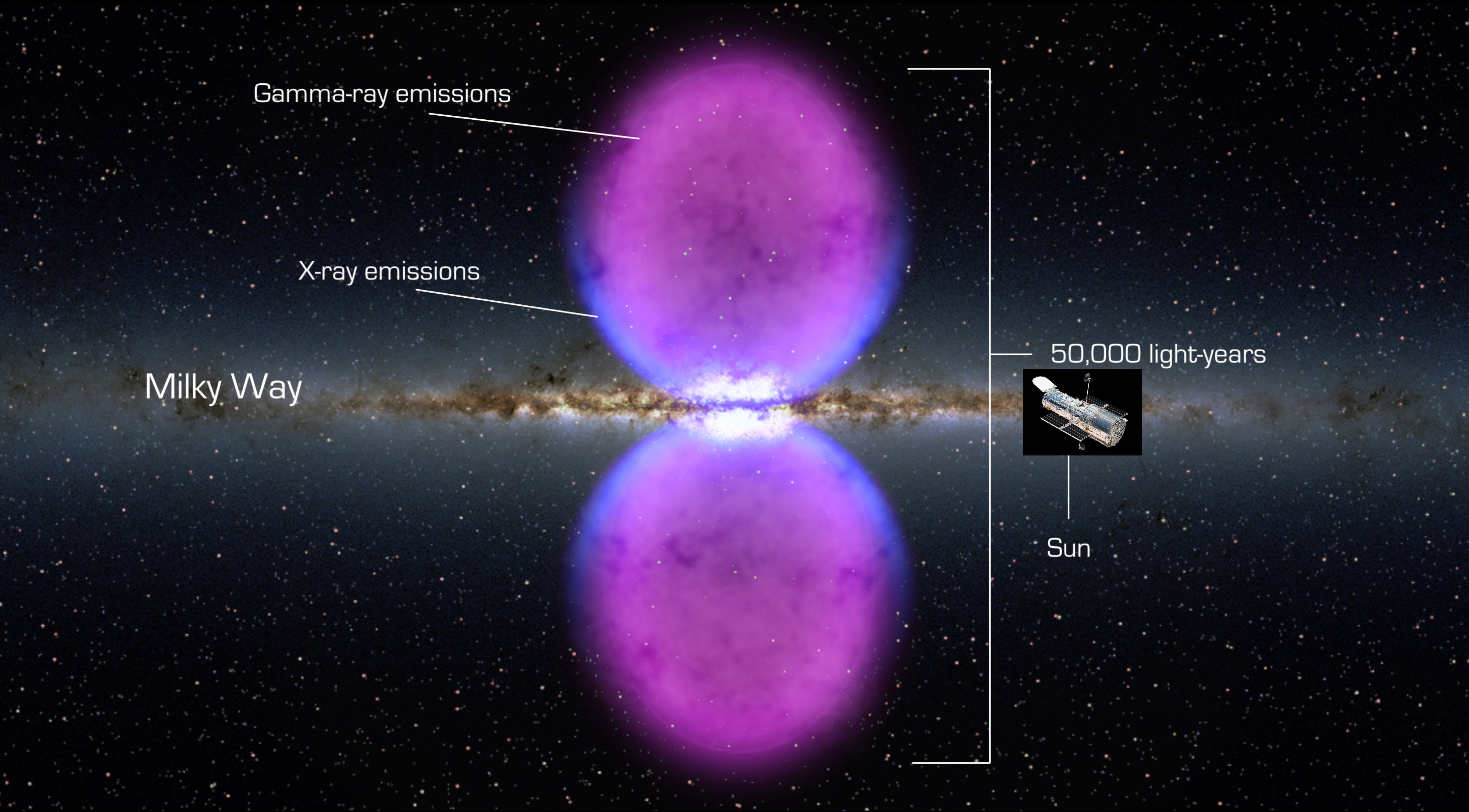
The Milky Way's Biconical Nuclear Outflow



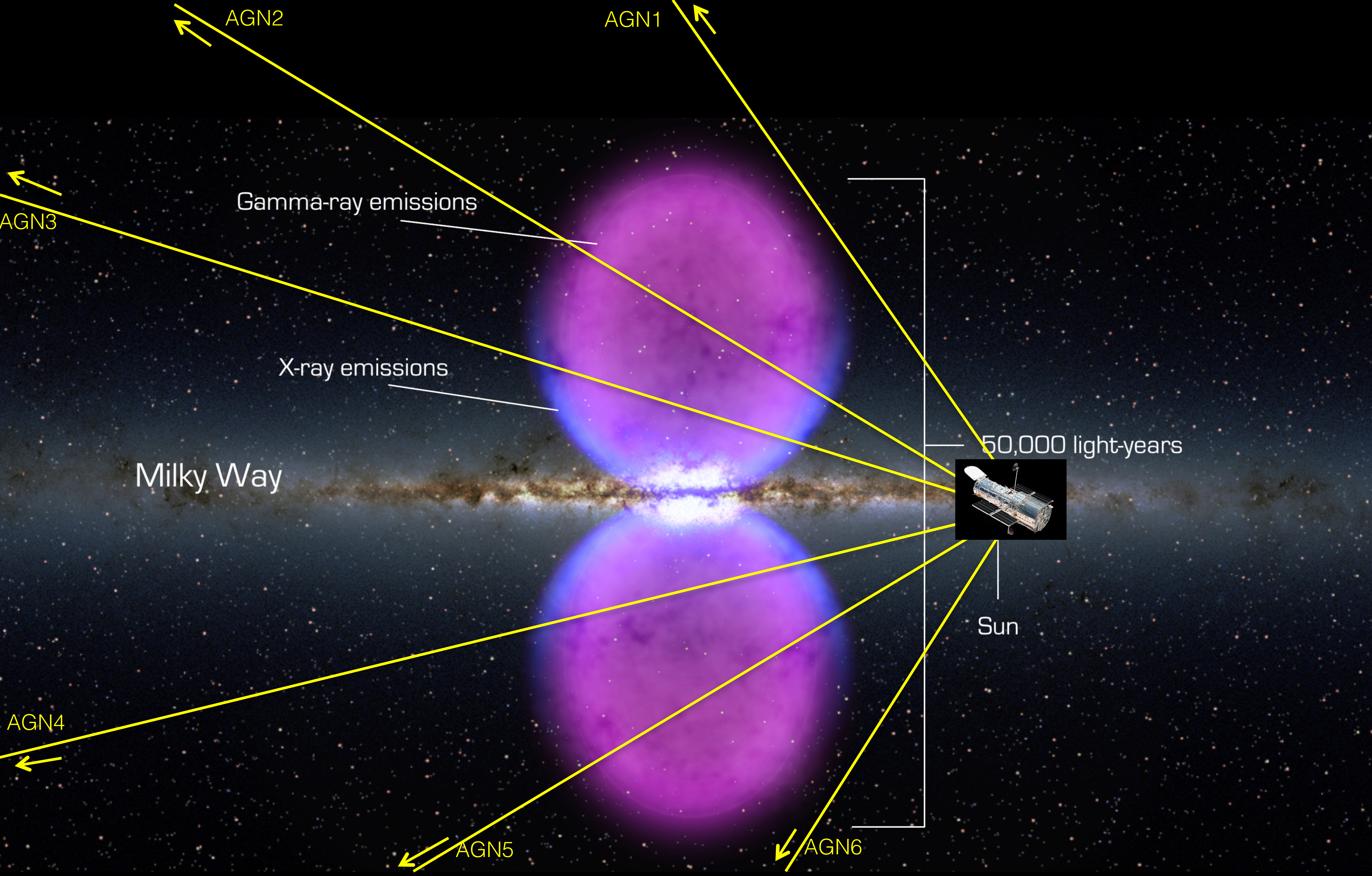
X-rays (40°x40° field around Galactic Center)

ROSAT 1.5 keV map, Bland-Hawthorn & Cohen (2003)

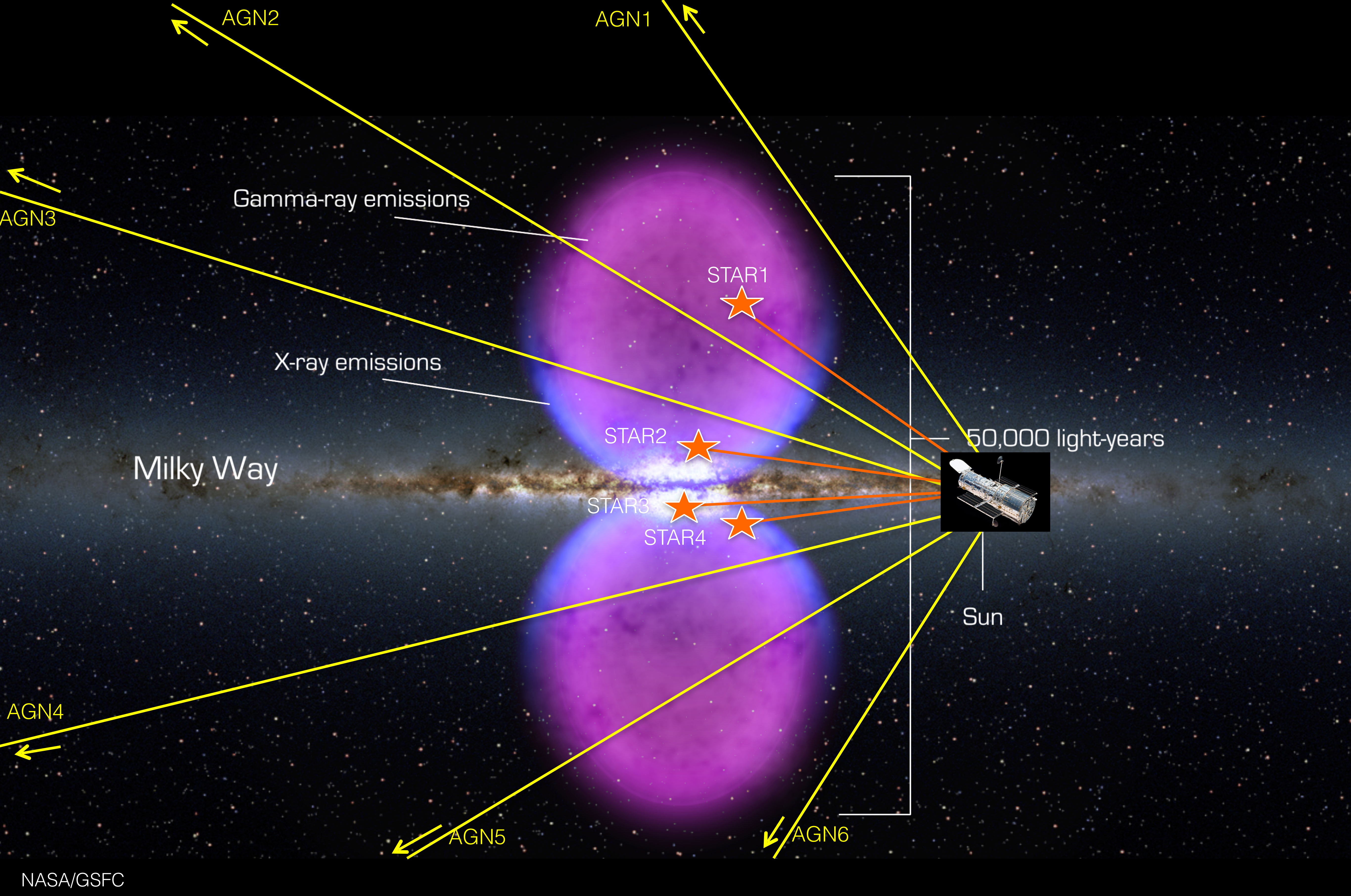
A Hubble Experiment

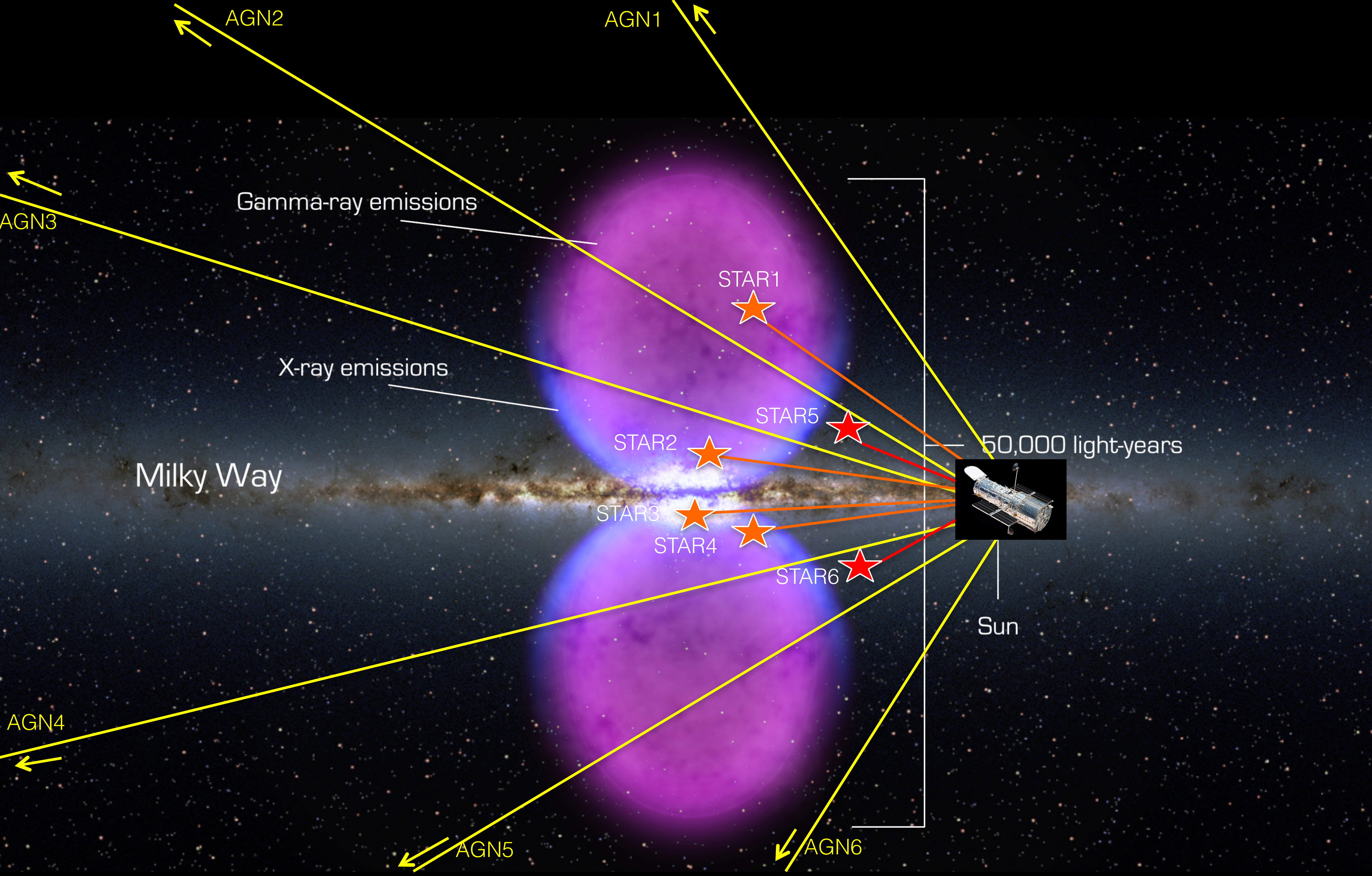


NASA/GSFC


AGN2
AGN1
Gamma-ray emissions
AGN3
X-ray emissions
50,000 light-years
Milky Way
Sun
AGN4
AGN5
AGN6

NASA/GSFC

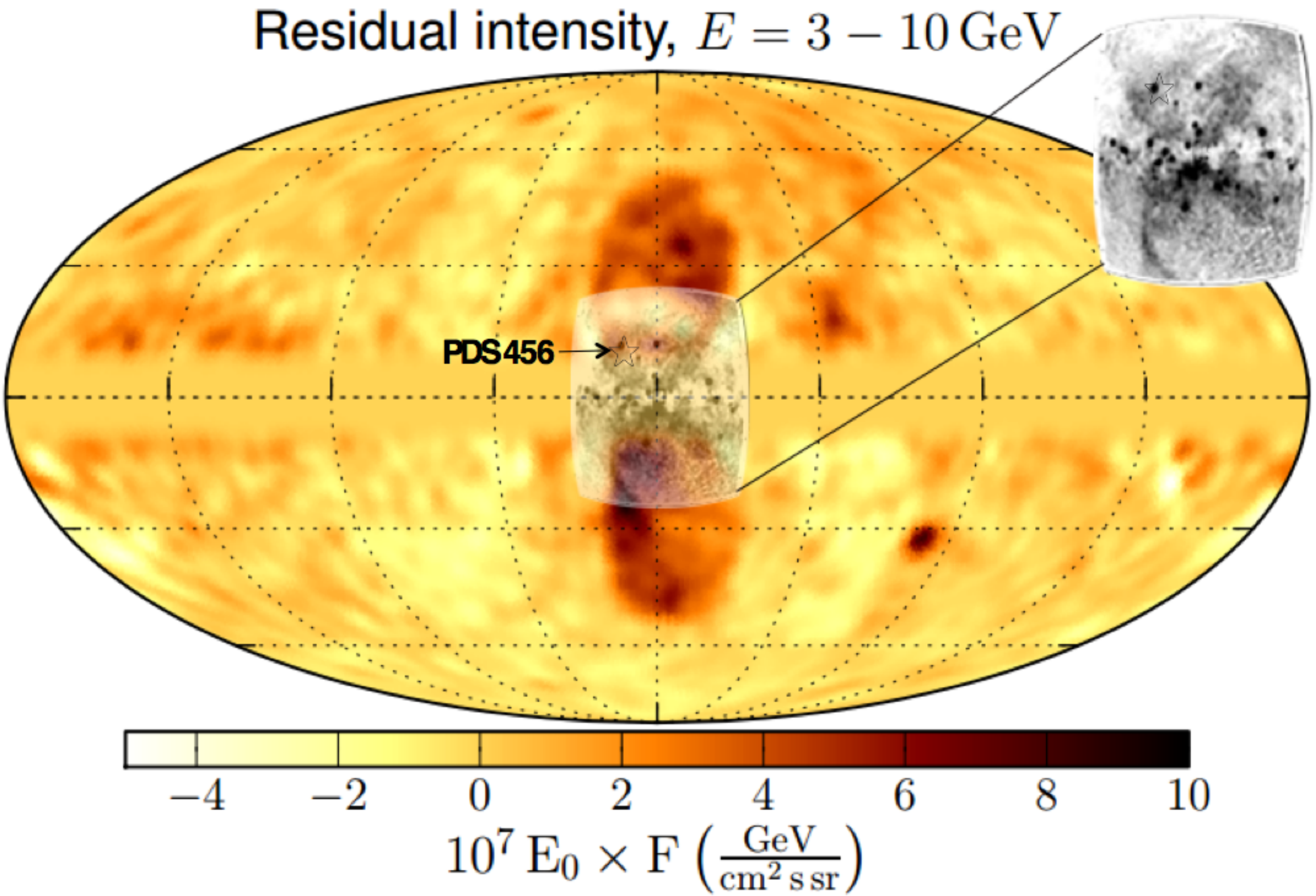

AGN2
AGN1
AGN3
Gamma-ray emissions
STAR1
X-ray emissions
STAR2
50,000 light-years
Milky Way
STAR3
STAR4
Sun
AGN4
AGN5
AGN6
NASA/GSFC


AGN2
AGN1
AGN3
Gamma-ray emissions
STAR1
X-ray emissions
STAR5
STAR2
50,000 light-years
Milky Way
STAR3
STAR4
STAR6
Sun
AGN4
AGN5
AGN6

NASA/GSFC

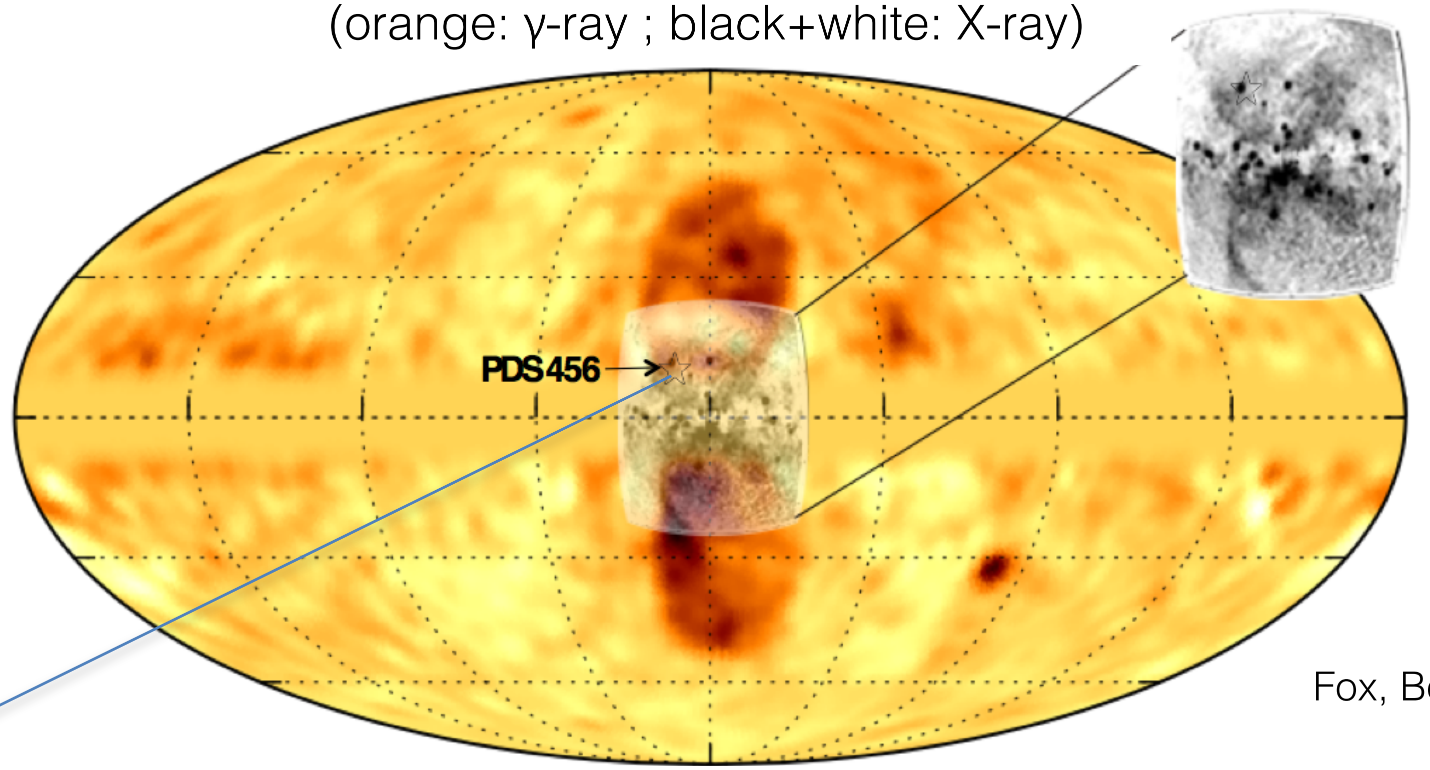
Results toward QSO PDS 456 (l, b=10.4°, 11.2°)

Fox, Bordoloi, Savage et al. 2015, ApJL, 799, 1.



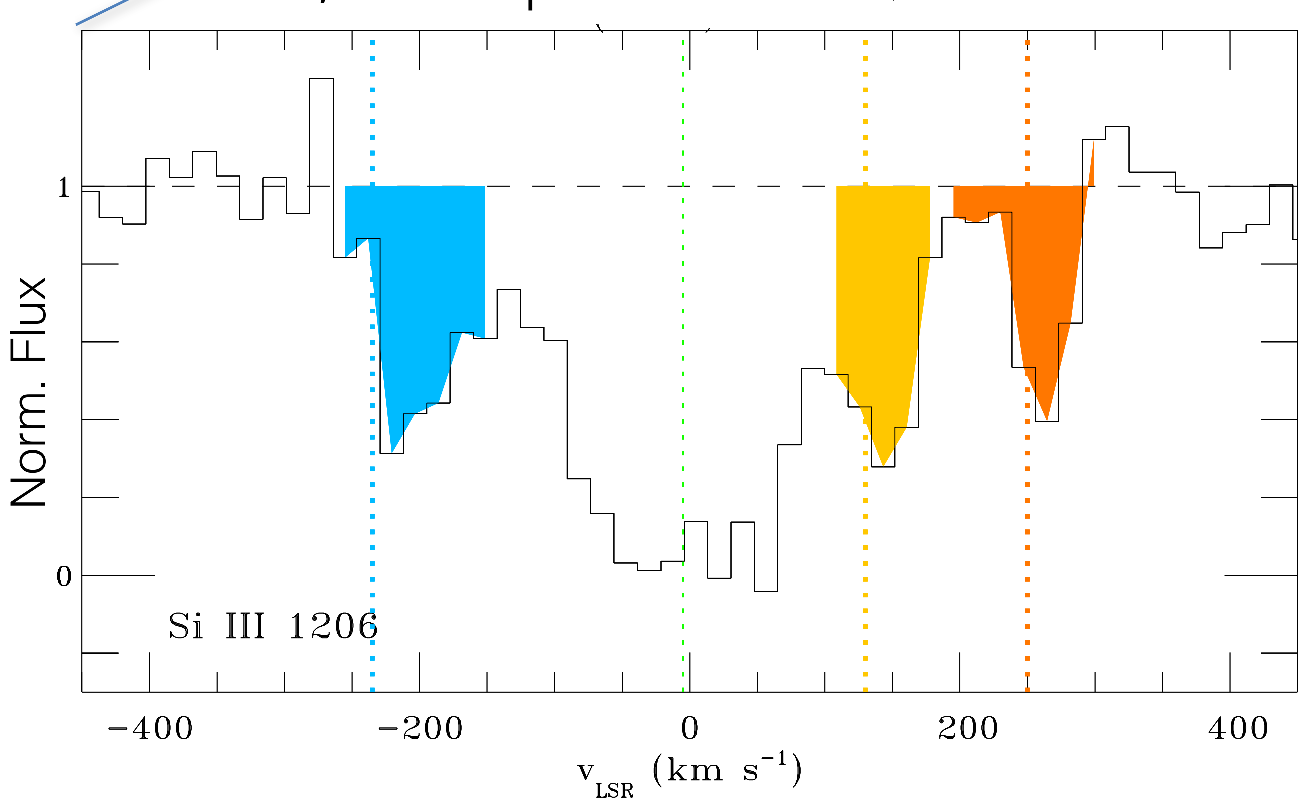
UV studies of the Milky Way's Nuclear Outflow

The Fermi Bubbles
(orange: γ-ray ; black+white: X-ray)

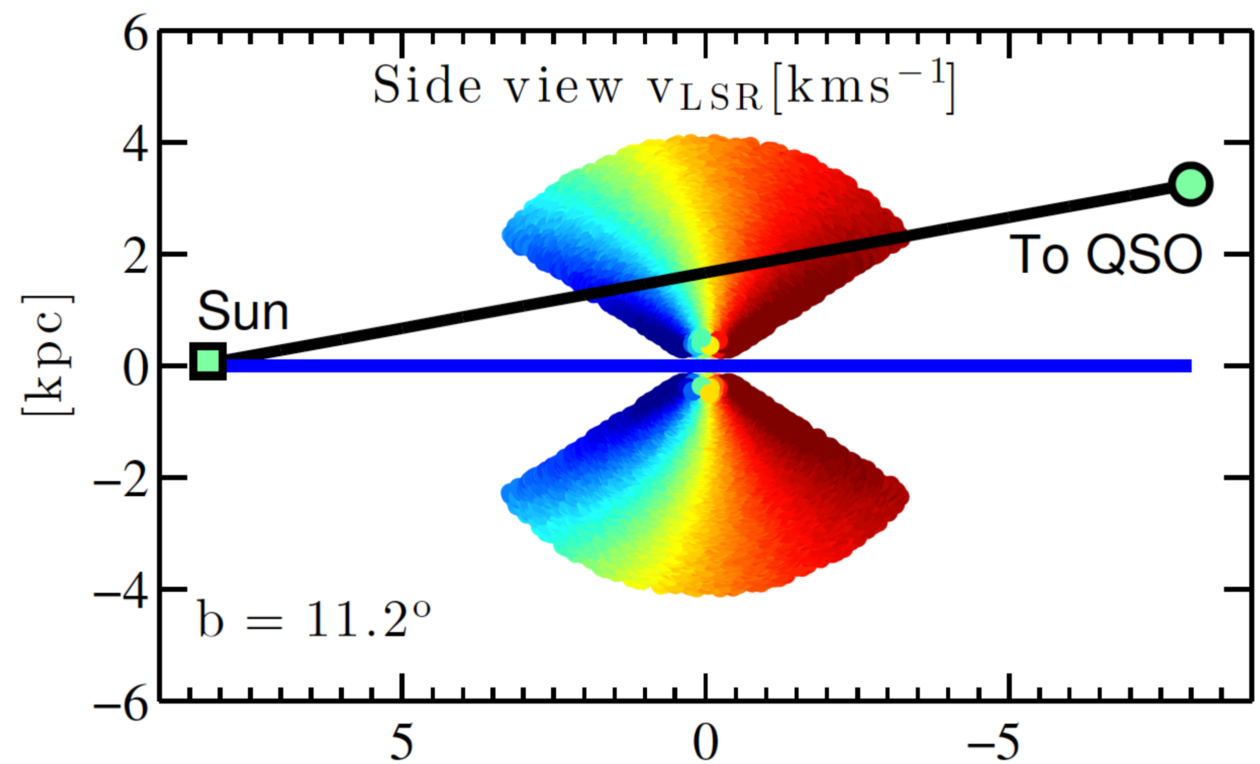


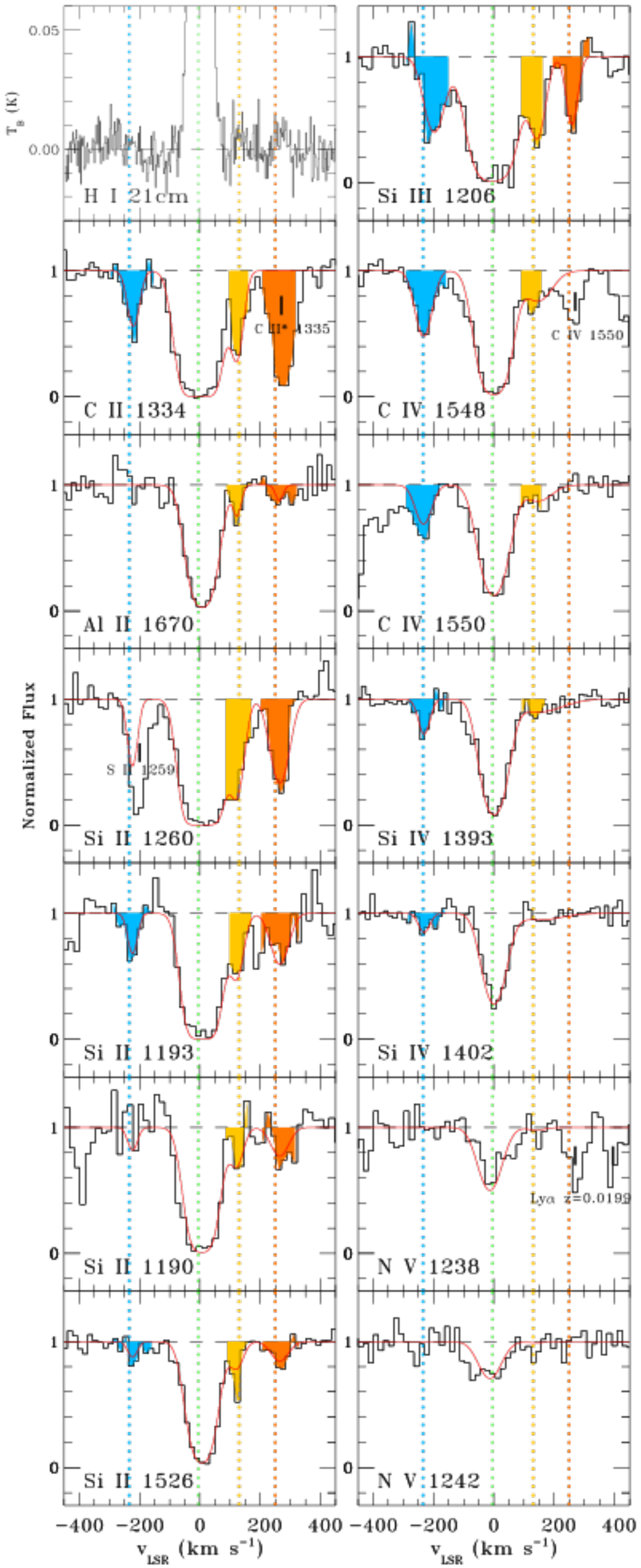
Fox, Bordoloi, Savage et al. 2015.

HST/COS spectrum of QSO PDS 456



Biconical Outflow Model

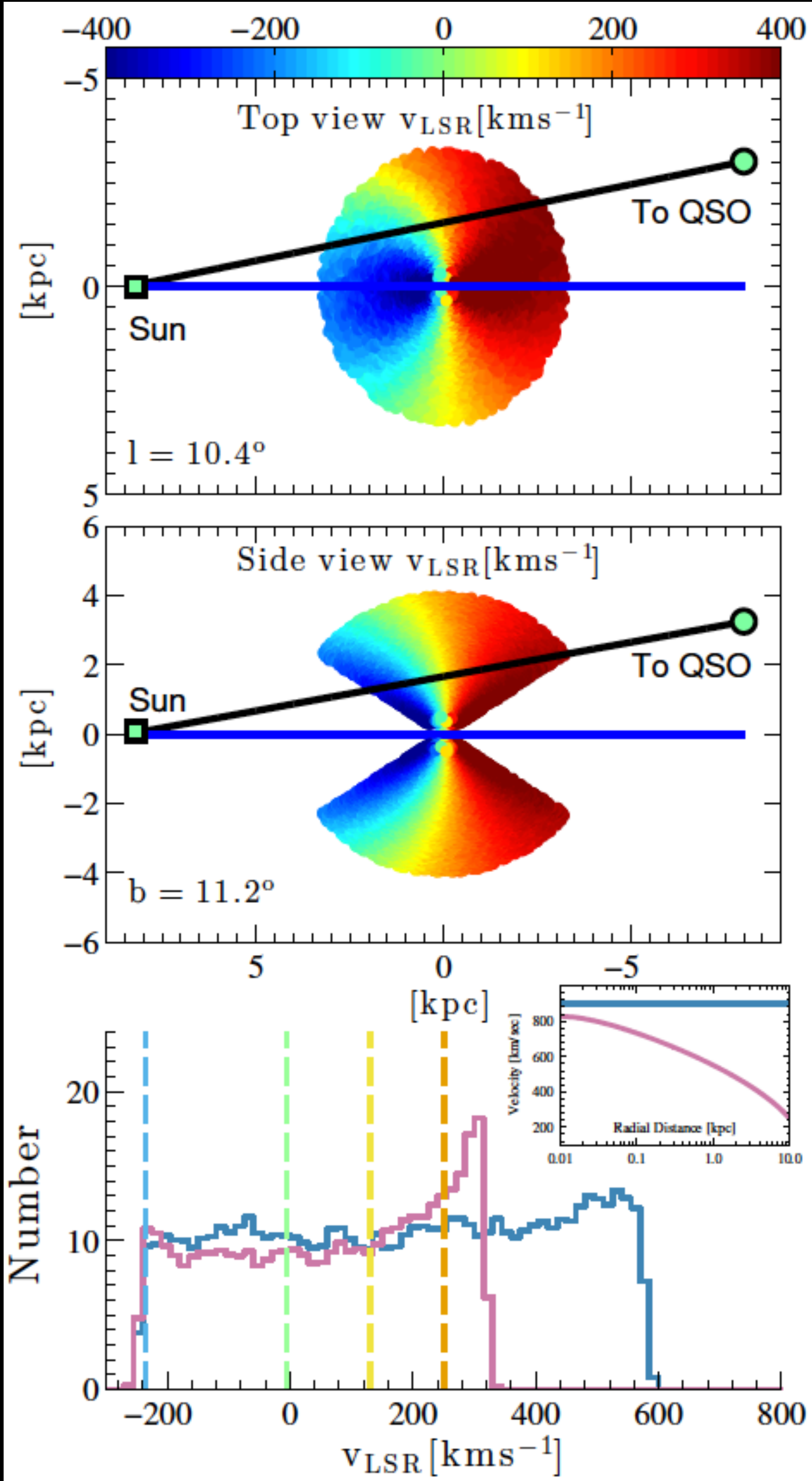




Hubble/COS spectra

- Three high-velocity components detected (shaded) at −235, +130, +250 km/s .
- Seen in low-ions (C II, Si II, Al II, Si III) and high-ions (C IV, Si IV).
- Not seen in Green Bank Telescope 21 cm emission spectra down to N(H I)=3×10^{17} cm^{-2} (so gas is highly ionized).
- Highly unlikely that these components trace foreground high-velocity clouds (HVCs) given low latitude of sightline.
- Our interpretation: seeing near (blueshifted) and far (redshifted) side of expanding biconical Galactic wind.

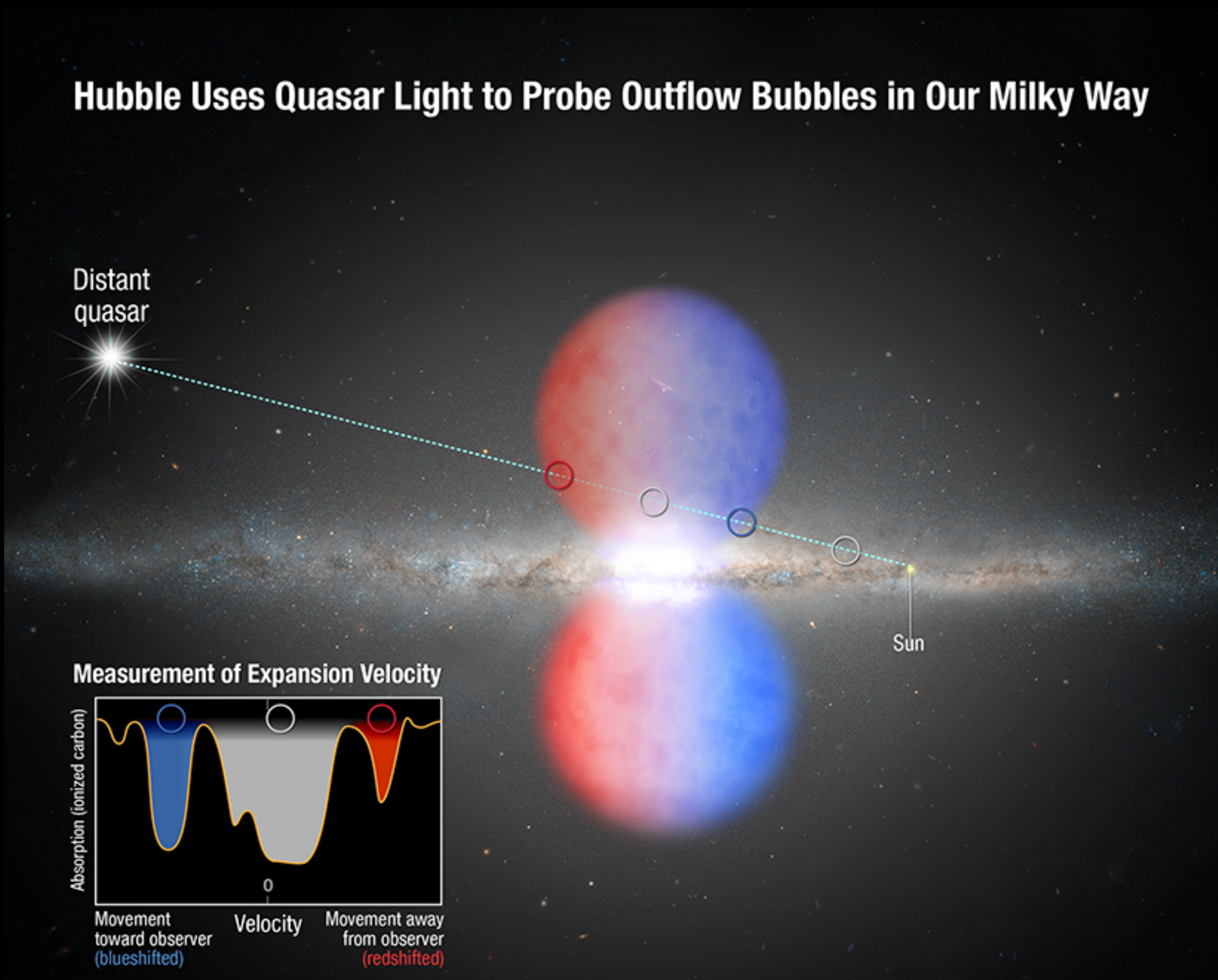
Fox, Bordoloi, Savage et al. 2015



Kinematic Biconical Outflow Models

- Set full opening angle =110° to match X-rays.
- find outflow velocity ~ 1000 km/s needed to match HV components.
- top two panels show velocity structure.
- lower panel shows velocity distribution after 100 realizations of the models.
- momentum-driven (ballistic) wind favored over constant-velocity wind.

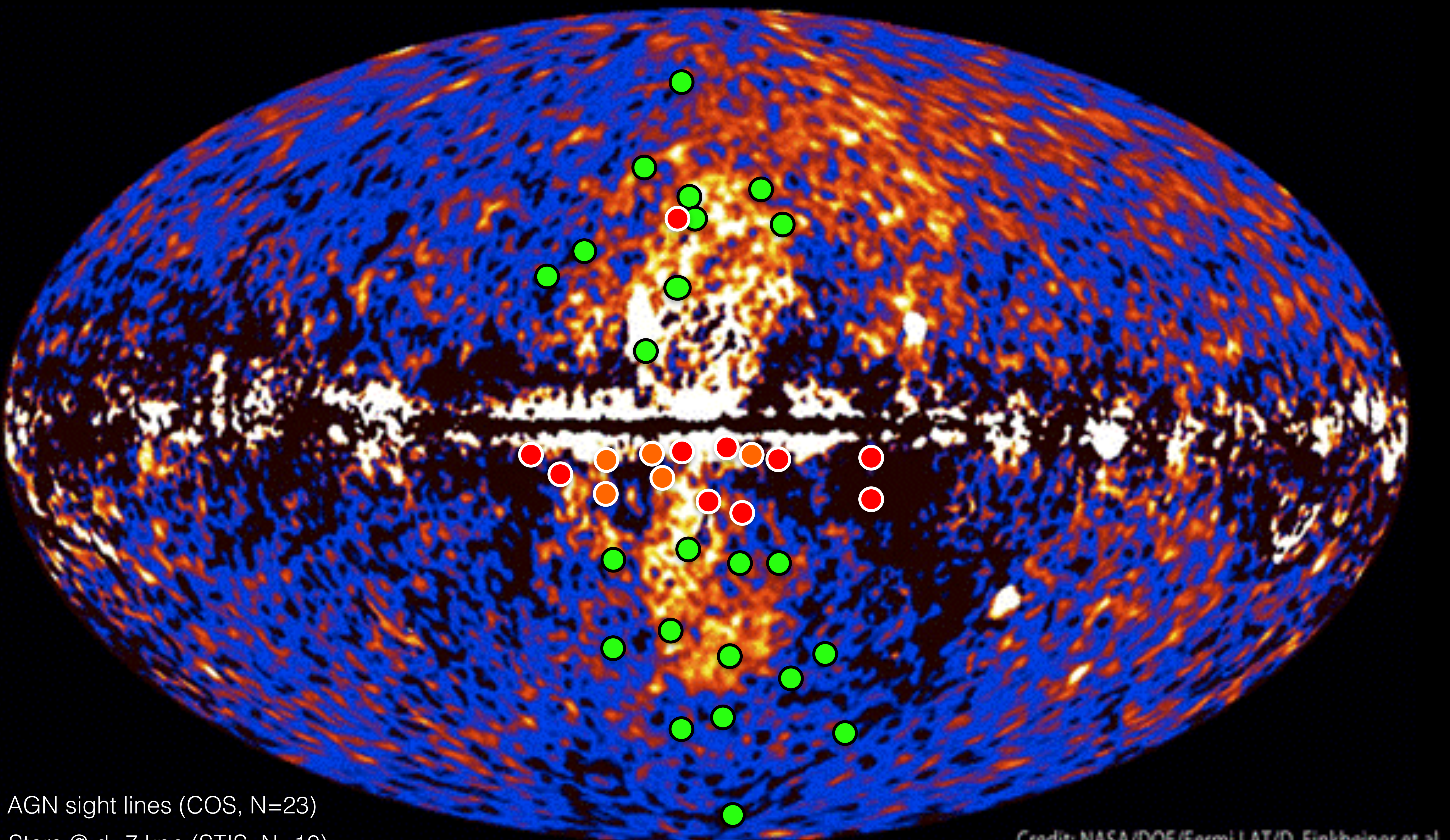
Fox, Bordoloi, Savage et al. 2015



NASA Press Release

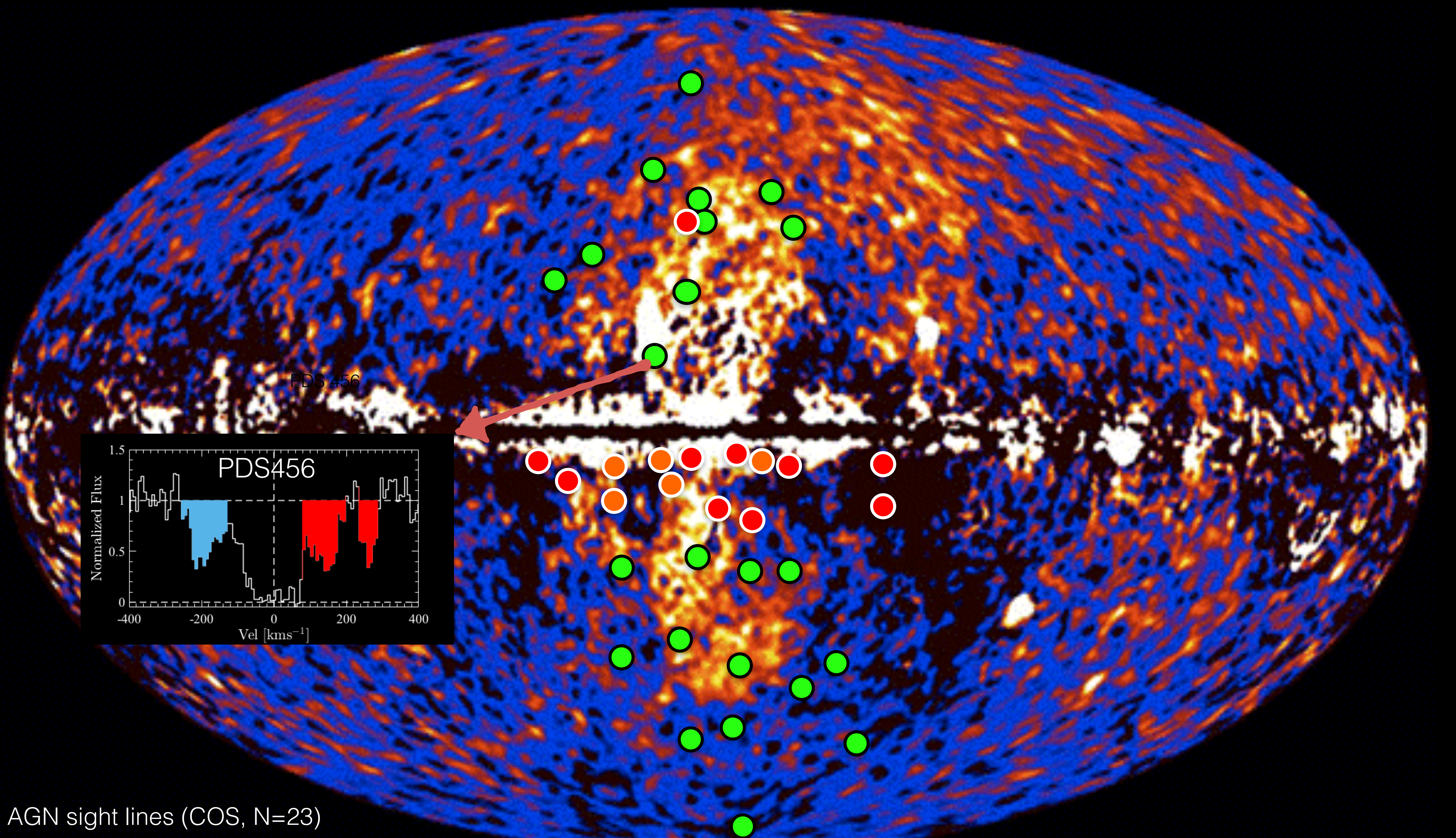
Illustration Credit: NASA, ESA, and A. Feild (STScI)

Kinematically Mapping the FBs



AGN sight lines (COS, N=23)
Stars @ d>7 kpc (STIS, N=10)
Stars @ d<7 kpc (STIS, N=5)

Kinematically Mapping the FBs



- AGN sight lines (COS, N=23)
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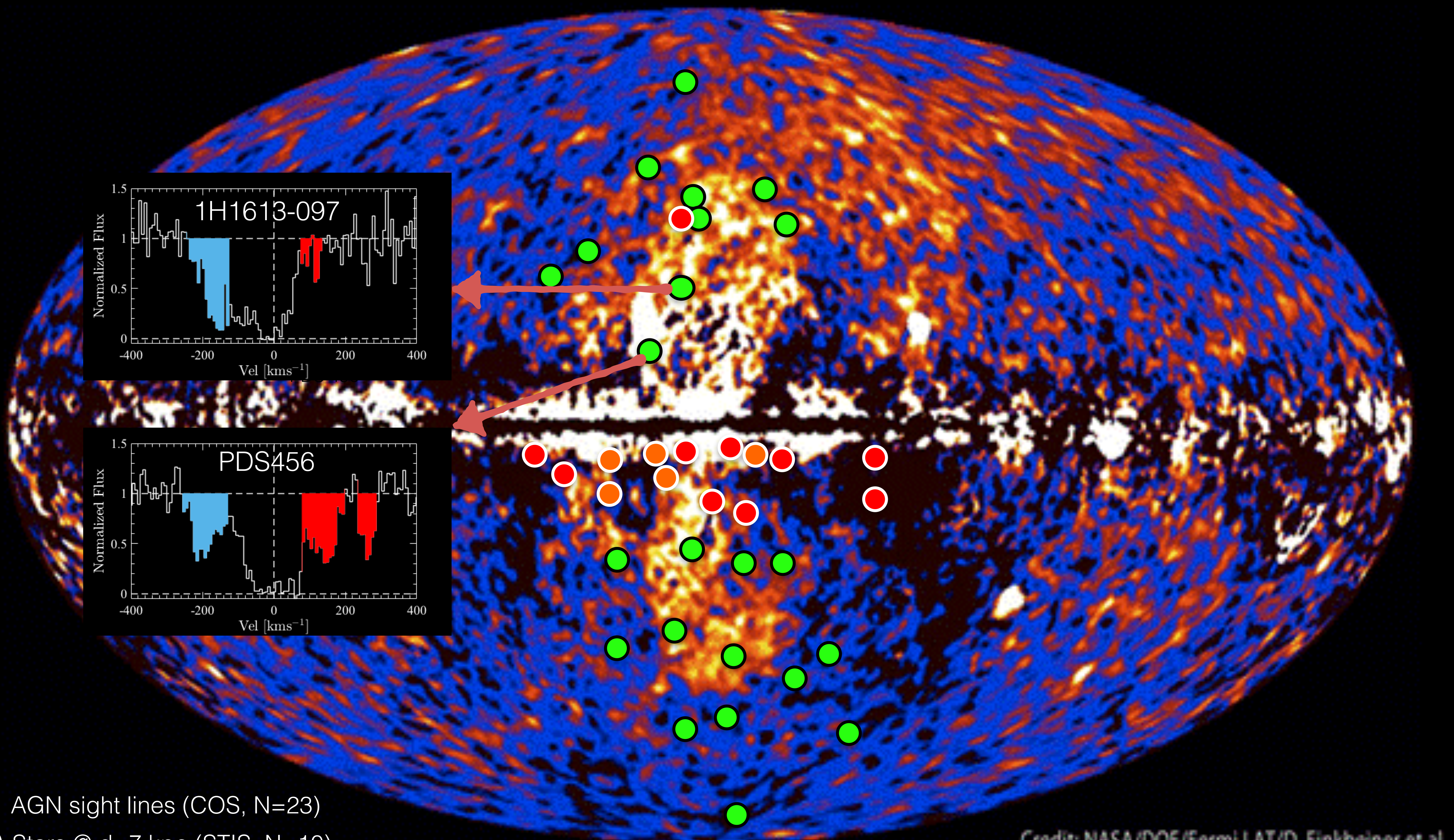
Kinematically Mapping the FBs



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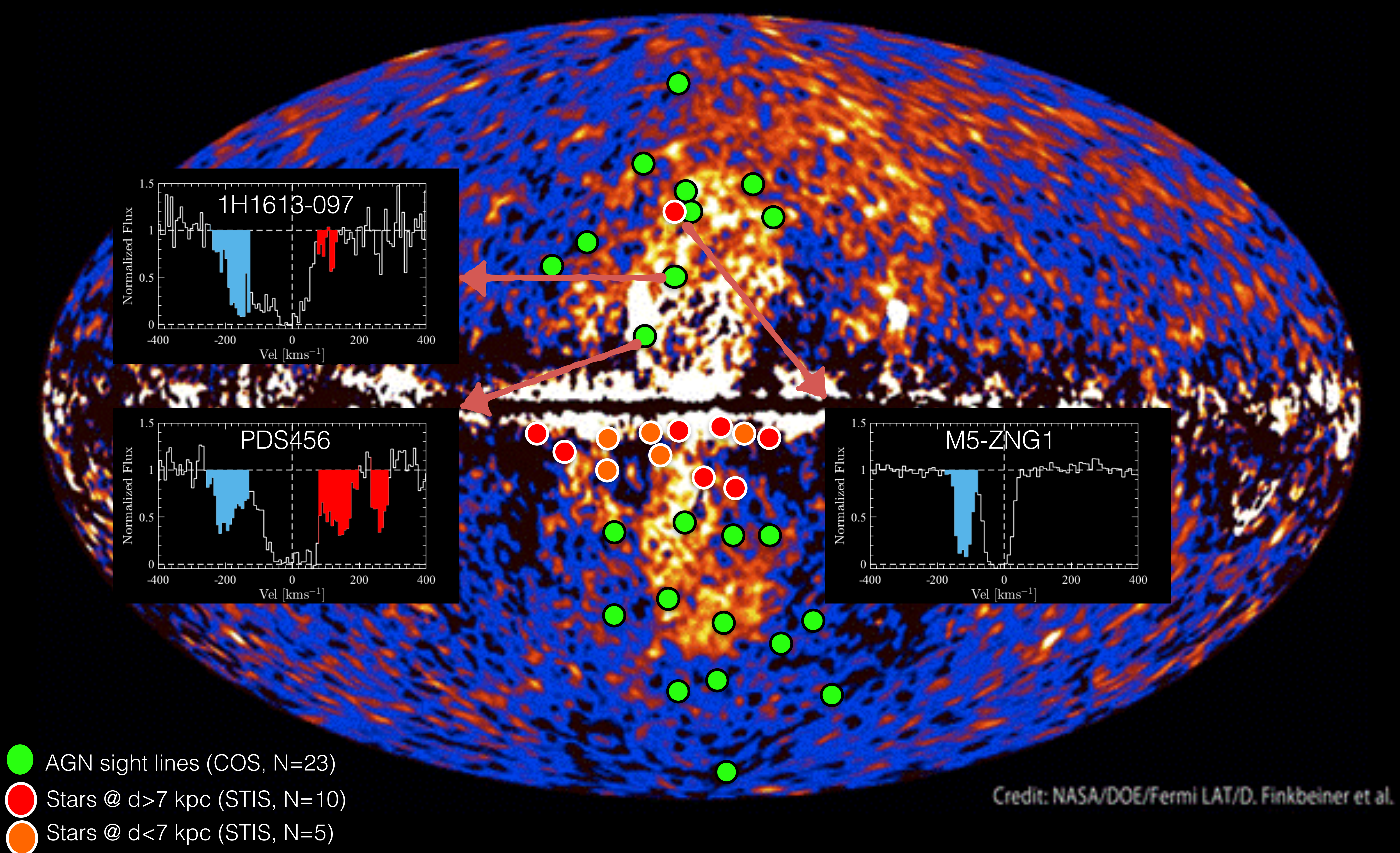
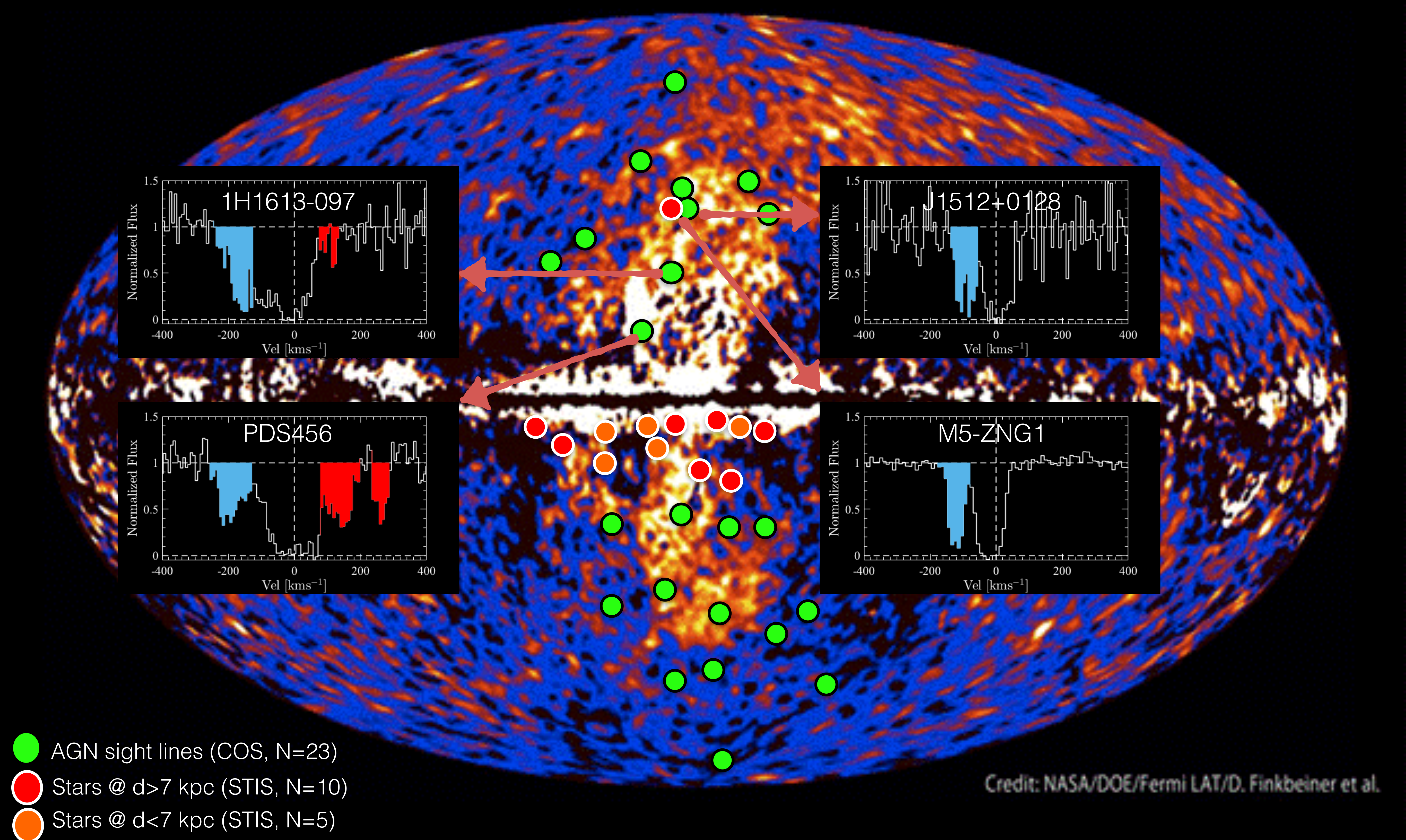
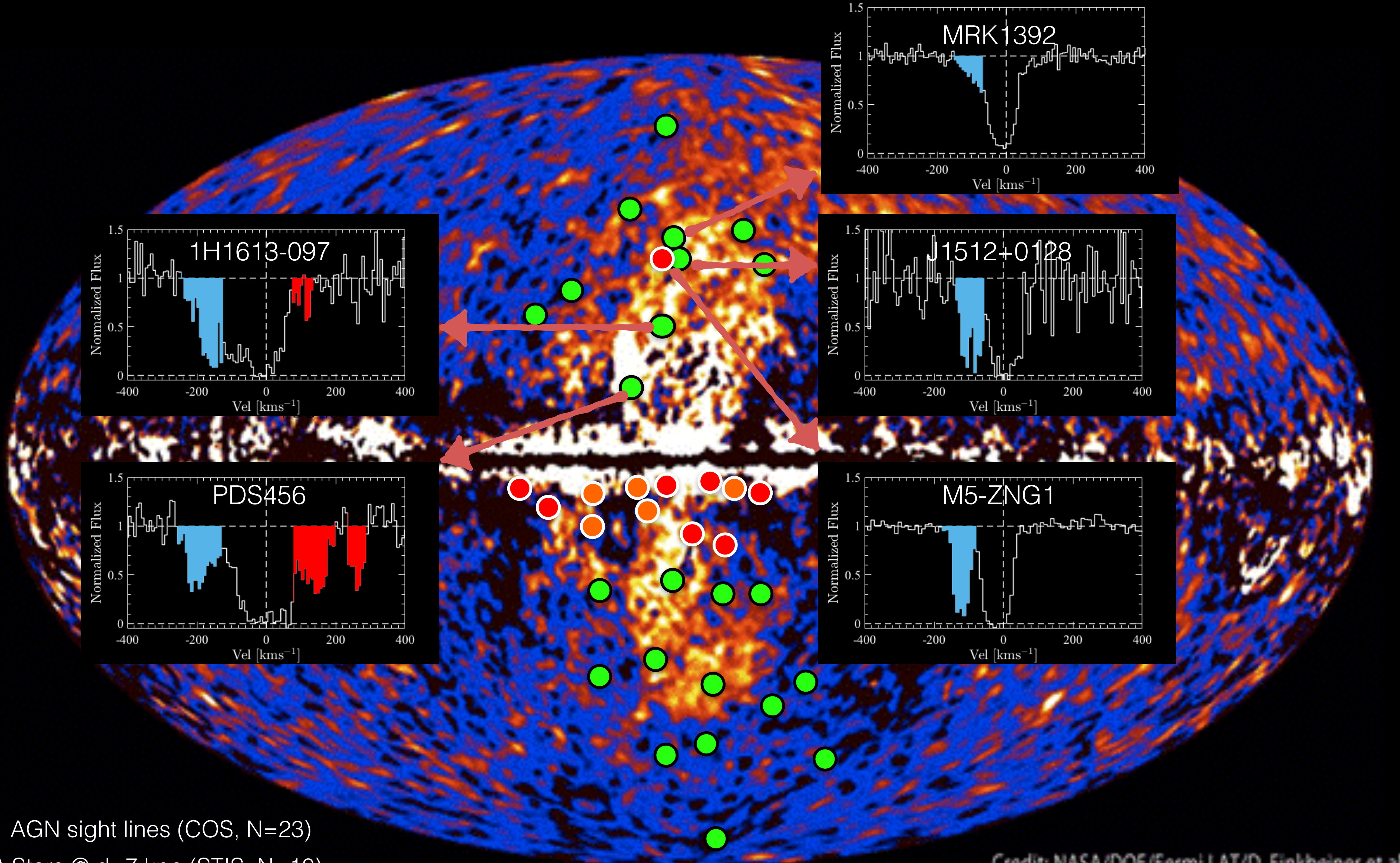
Kinematically Mapping the FBs



Kinematically Mapping the FBs

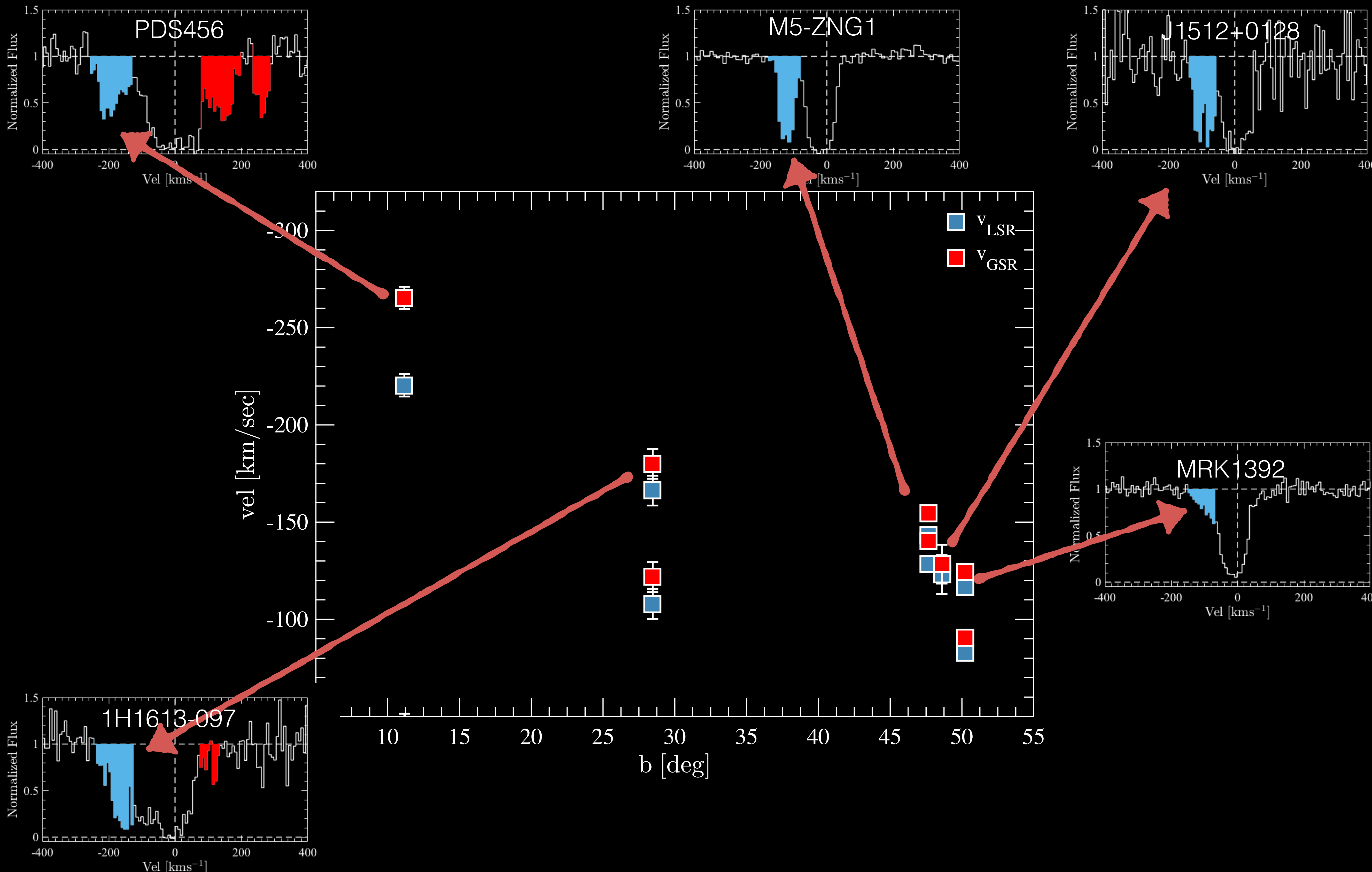


Kinematically Mapping the FBs



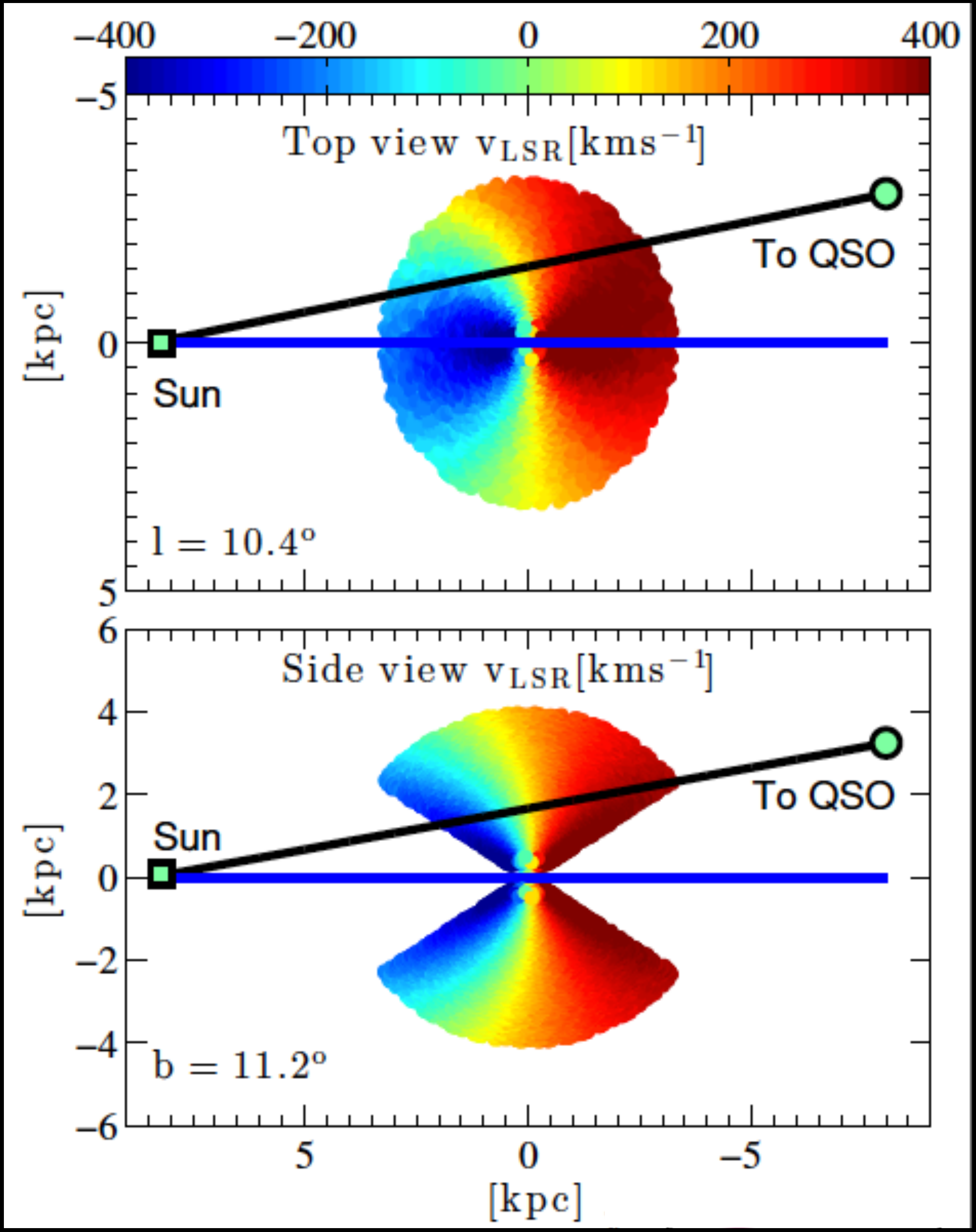
- AGN sight lines (COS, N=23)
- Stars @ d>7 kpc (STIS, N=10)
- Stars @ d<7 kpc (STIS, N=5)

Observed Projected Velocity Profile



Bordoloi+17

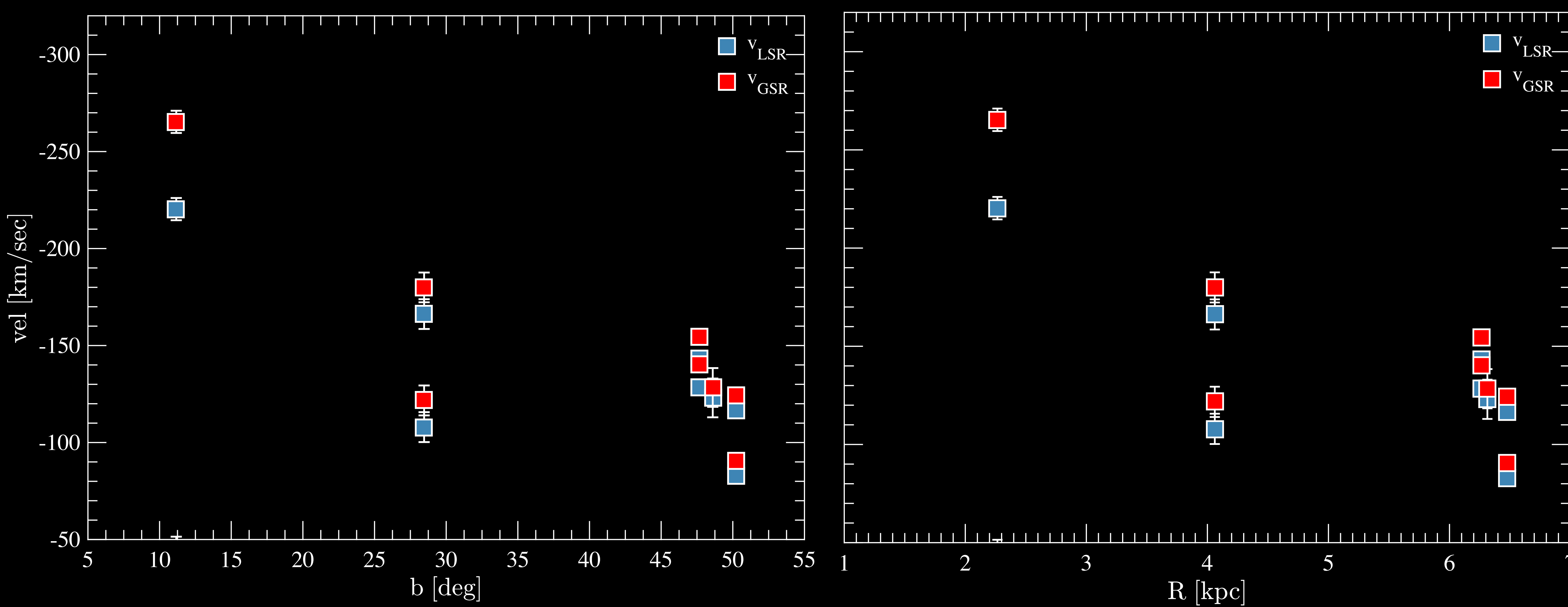
Kinematic Biconical Outflow Models



Fox, Bordoloi, Savage et al. 2015

Bordoloi, Fox, Lockman et al. 2017

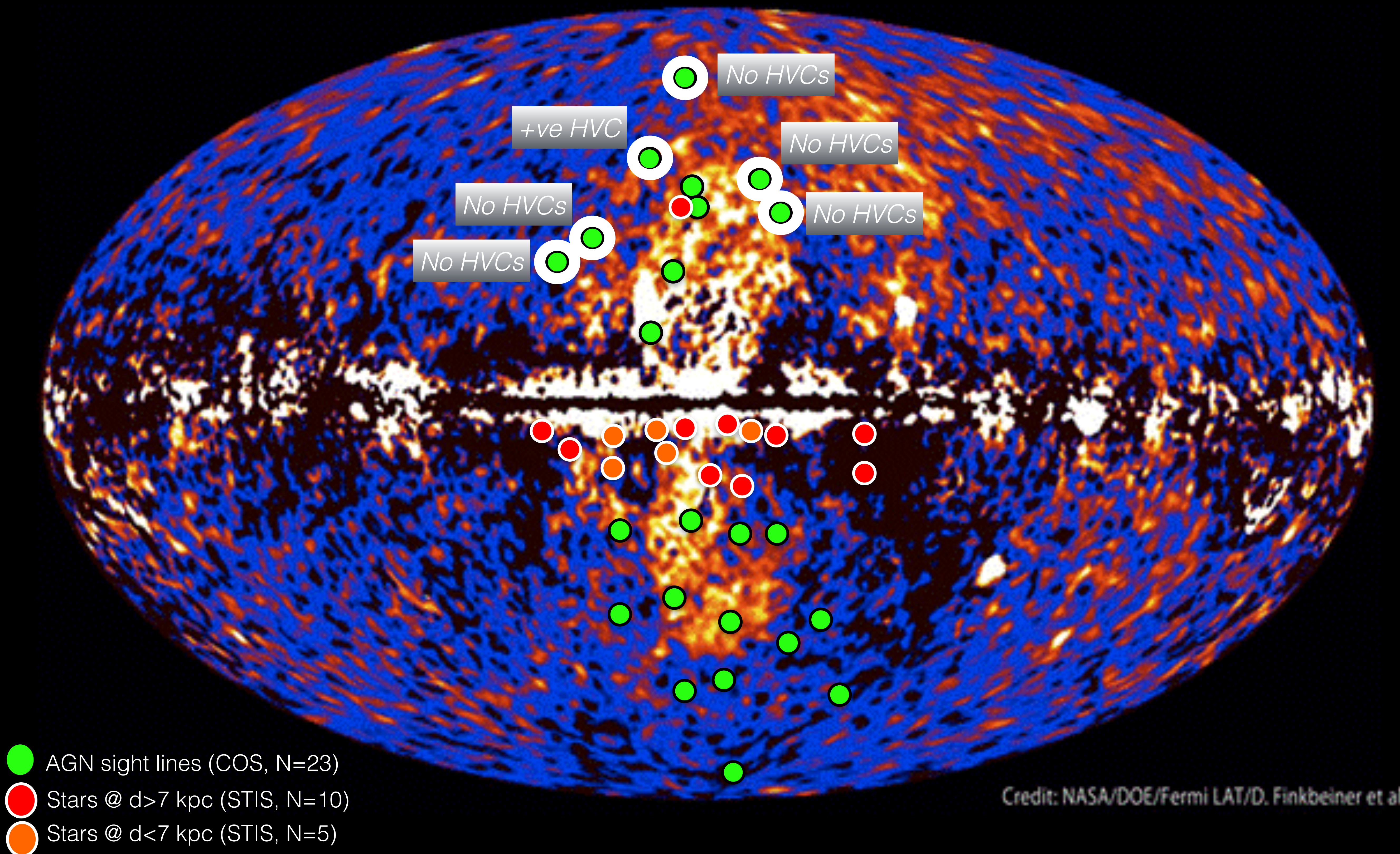
Projected Outflow velocity Radial Profile



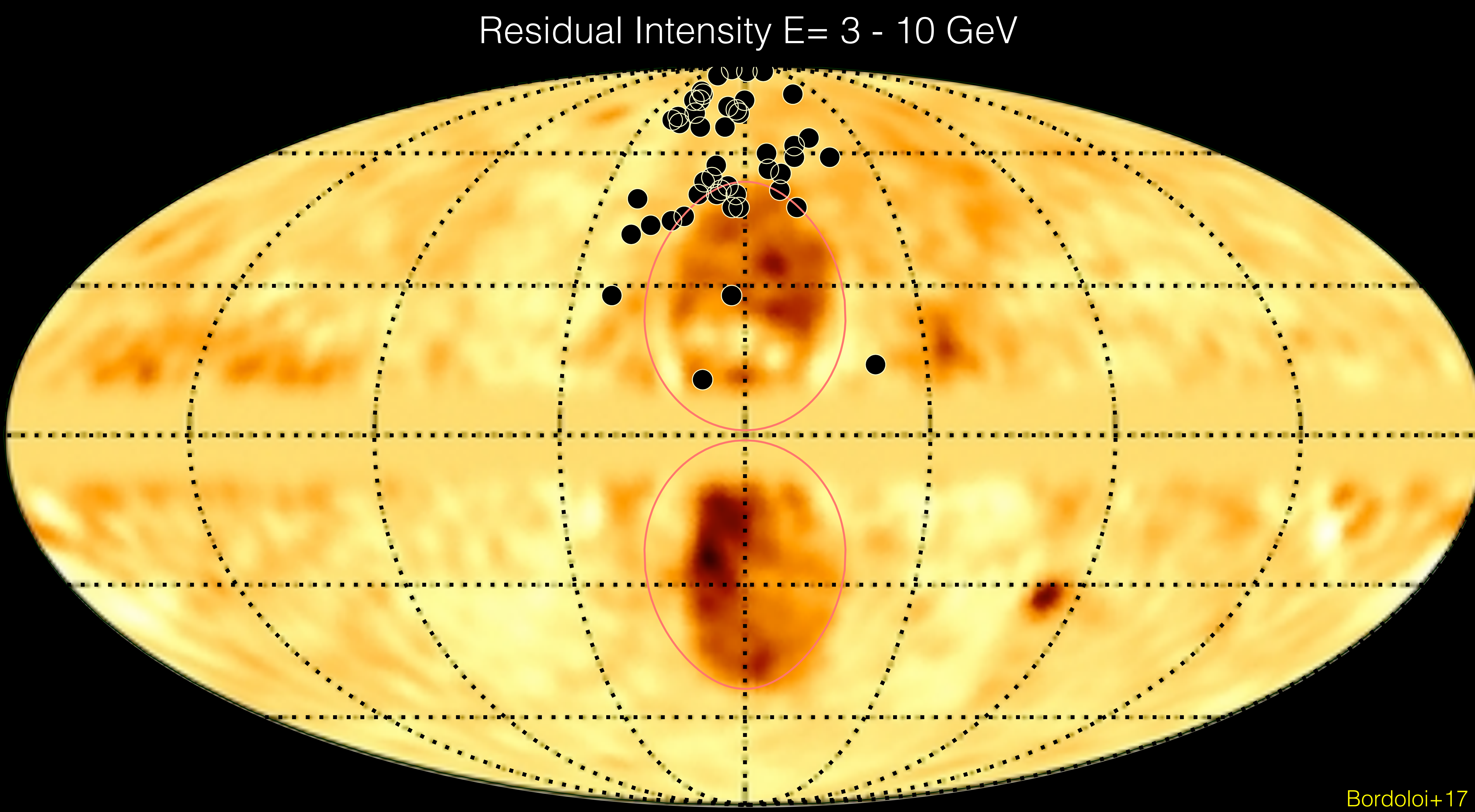
- Outflow velocity is ~1000-1200 km/s.
- Implies wind age ~ 6-9 Myr (travel time from Galactic Center), matching Fermi Bubble age estimates.

Bordoloi+17

Incidence of HVCs around the northern Fermi Bubble



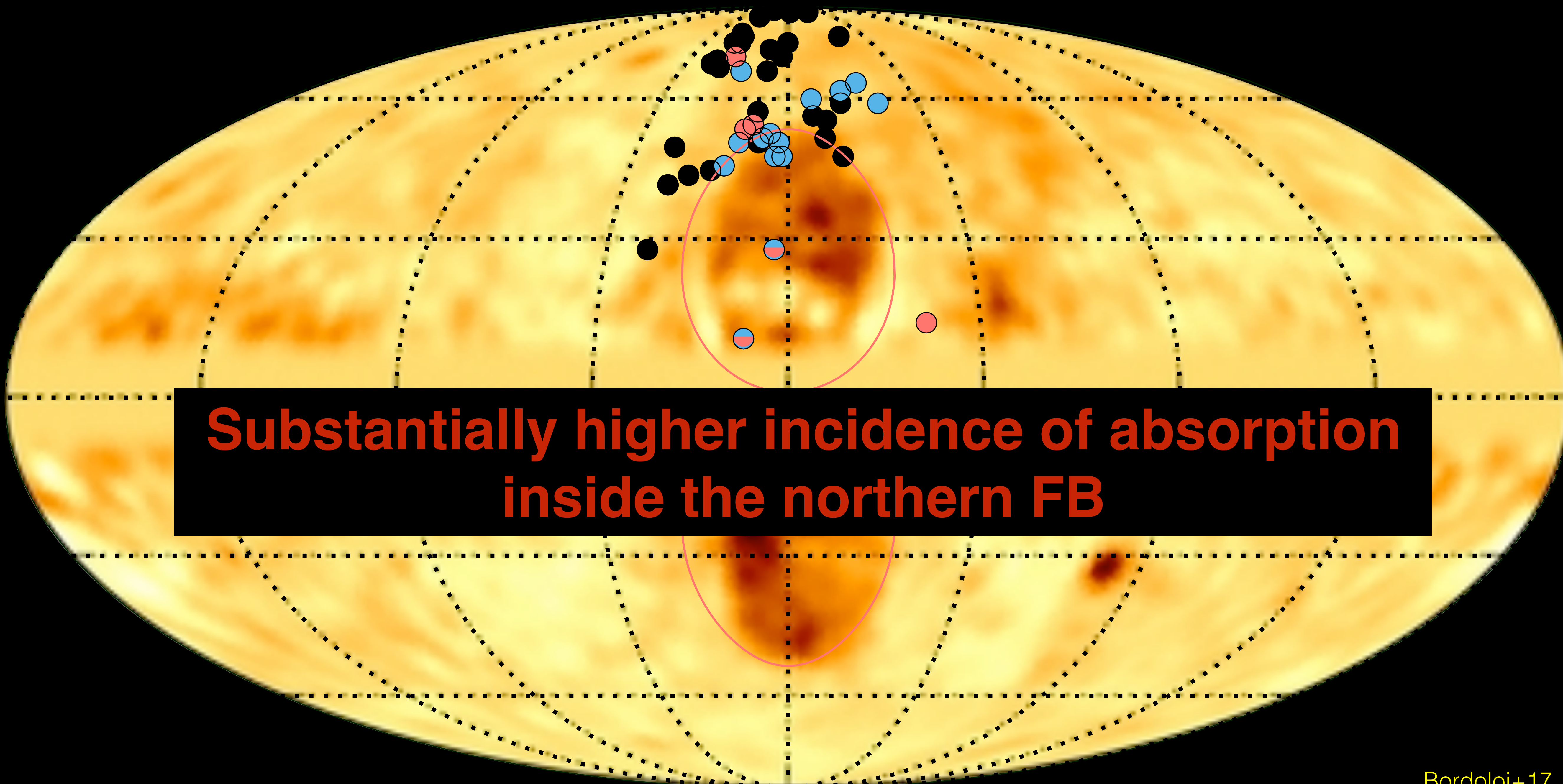
Incidence of HVCs in the northern Fermi Bubble



Total : 47 Lines of sight.
5 Inside FB.
34 Outside FB.
8 Interface LOS.

Incidence of HVCs in the northern Fermi Bubble

Residual Intensity E= 3 - 10 GeV



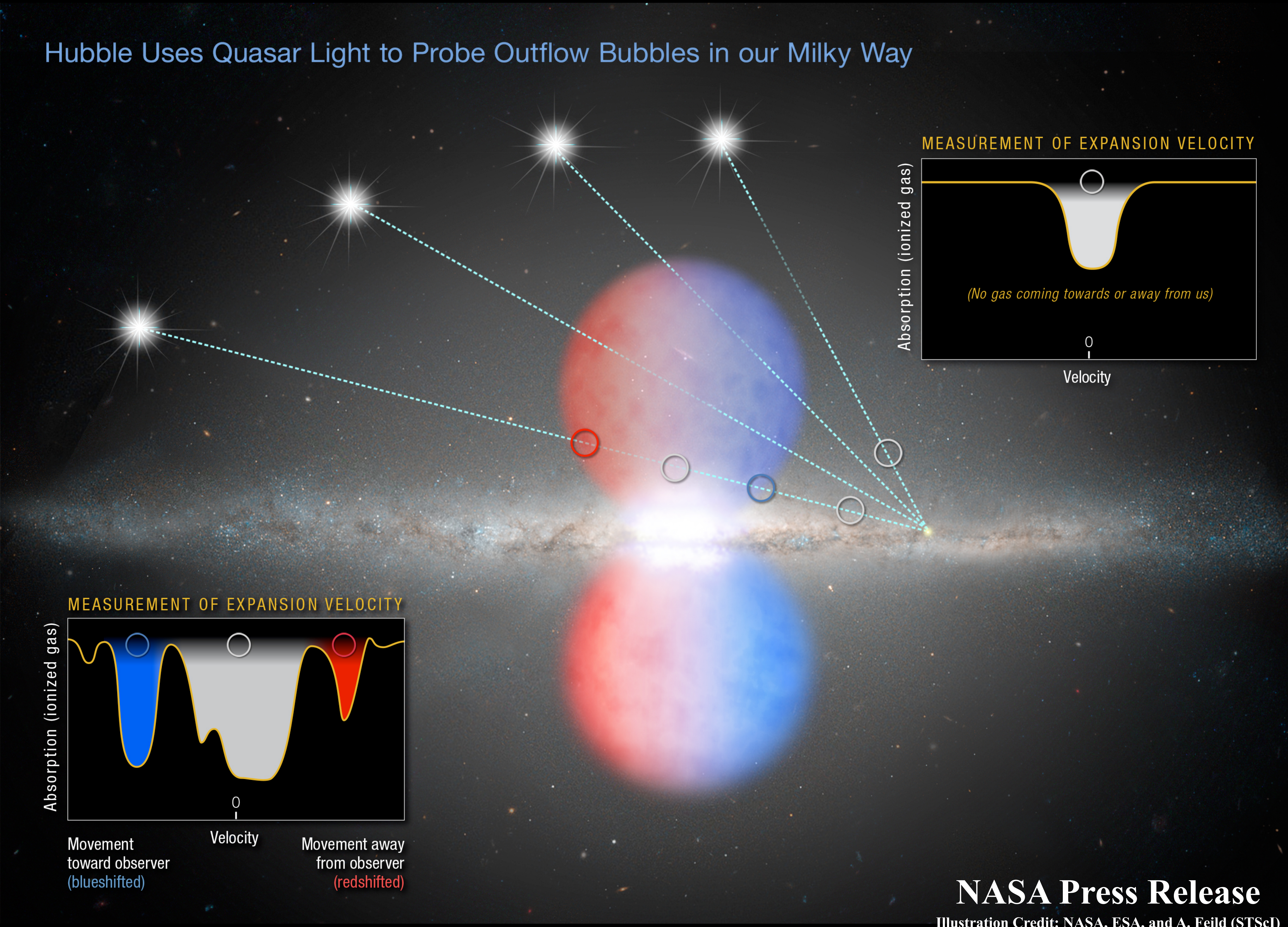
Bordoloi+17

Blueshifted HVC:

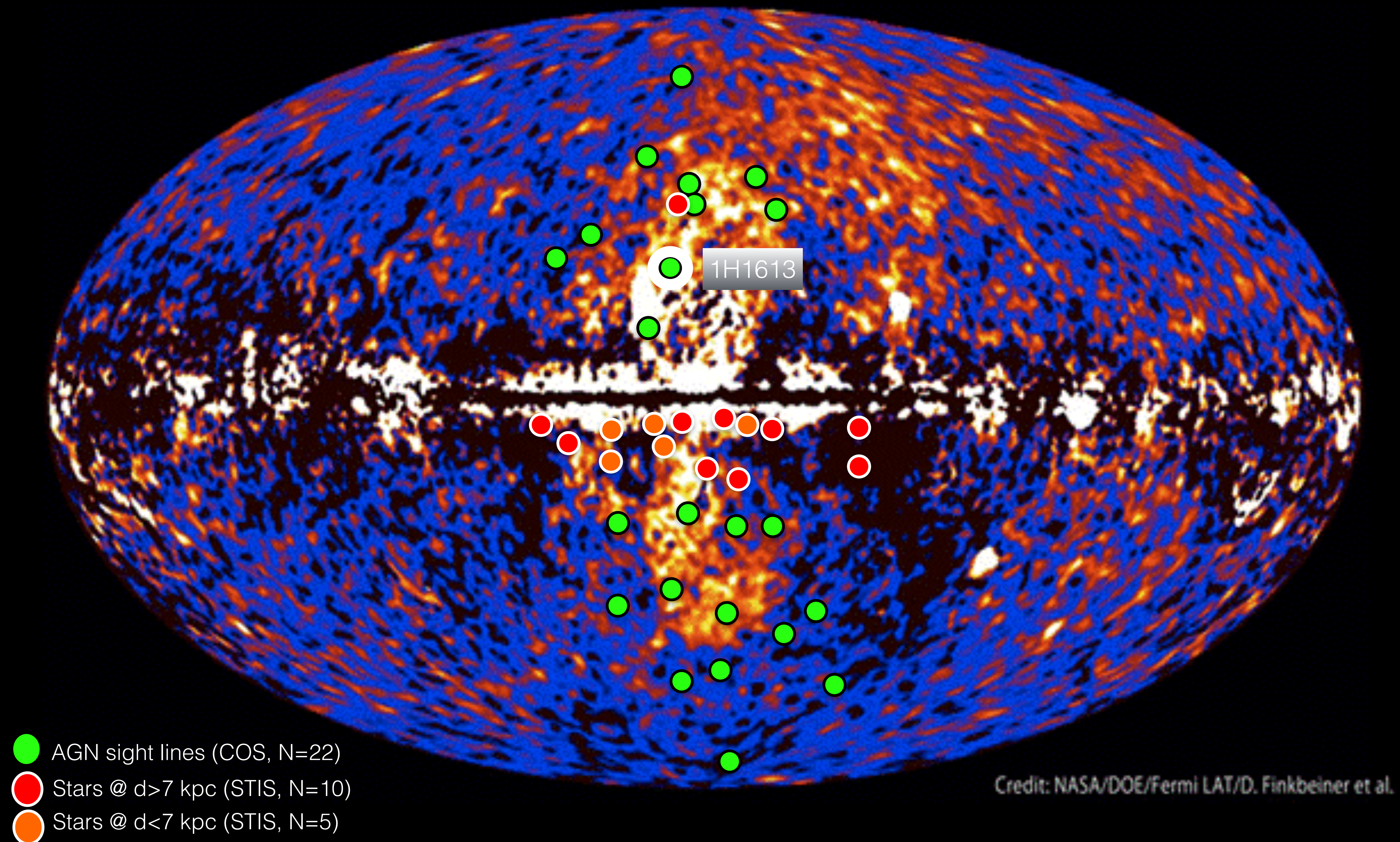
5/5 Inside FB.
5/34 Outside FB.
4/8 Interface LOS.

Redshifted HVC:

2/5 Inside FB.
4/34 Outside FB.
0/8 Interface LOS.


Hubble Uses Quasar Light to Probe Outflow Bubbles in our Milky Way
MEASUREMENT OF EXPANSION VELOCITY
Absorption (ionized gas)
(No gas coming towards or away from us)
0
Velocity
MEASUREMENT OF EXPANSION VELOCITY
Absorption (ionized gas)
0
Movement toward observer (blueshifted)
Velocity
Movement away from observer (redshifted)
NASA Press Release
Illustration Credit: NASA, ESA, and A. Feild (STScI)

Going back to sight line 1H1613-097

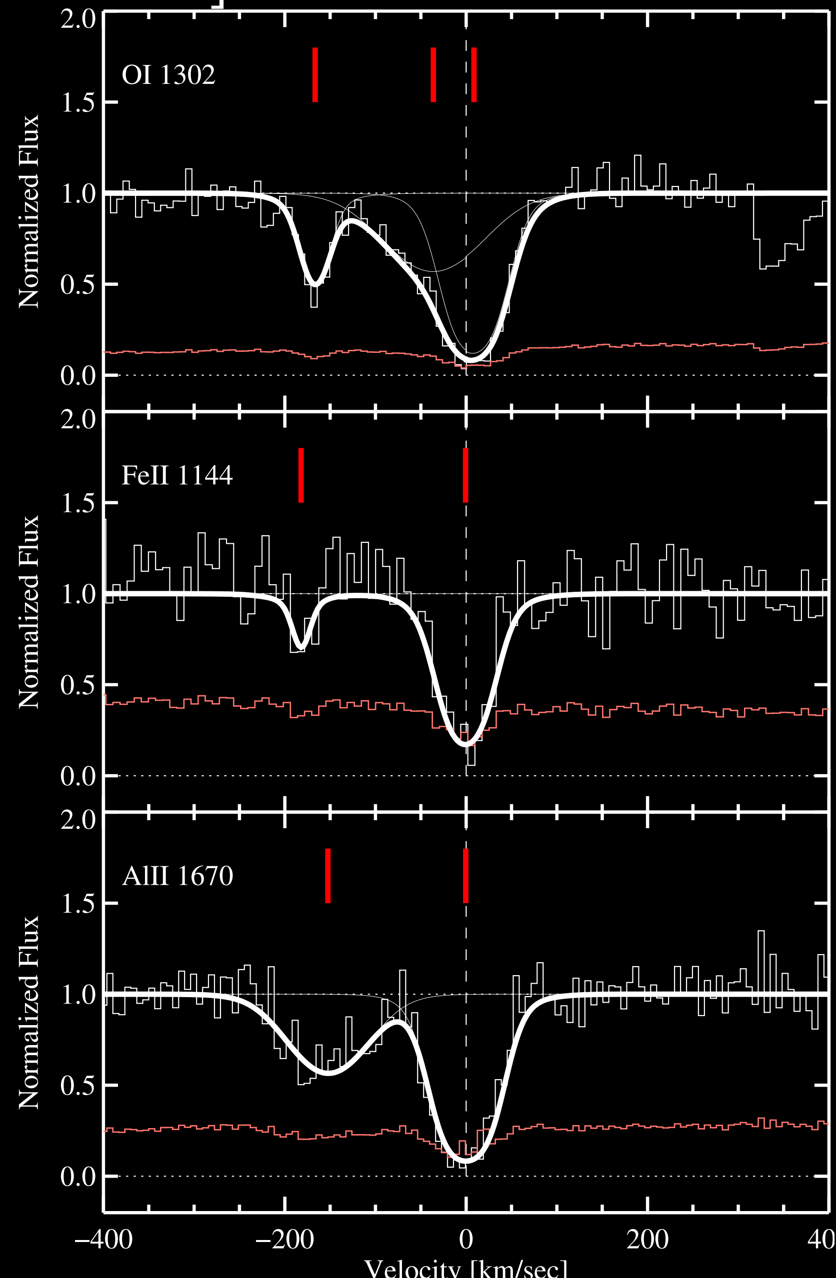


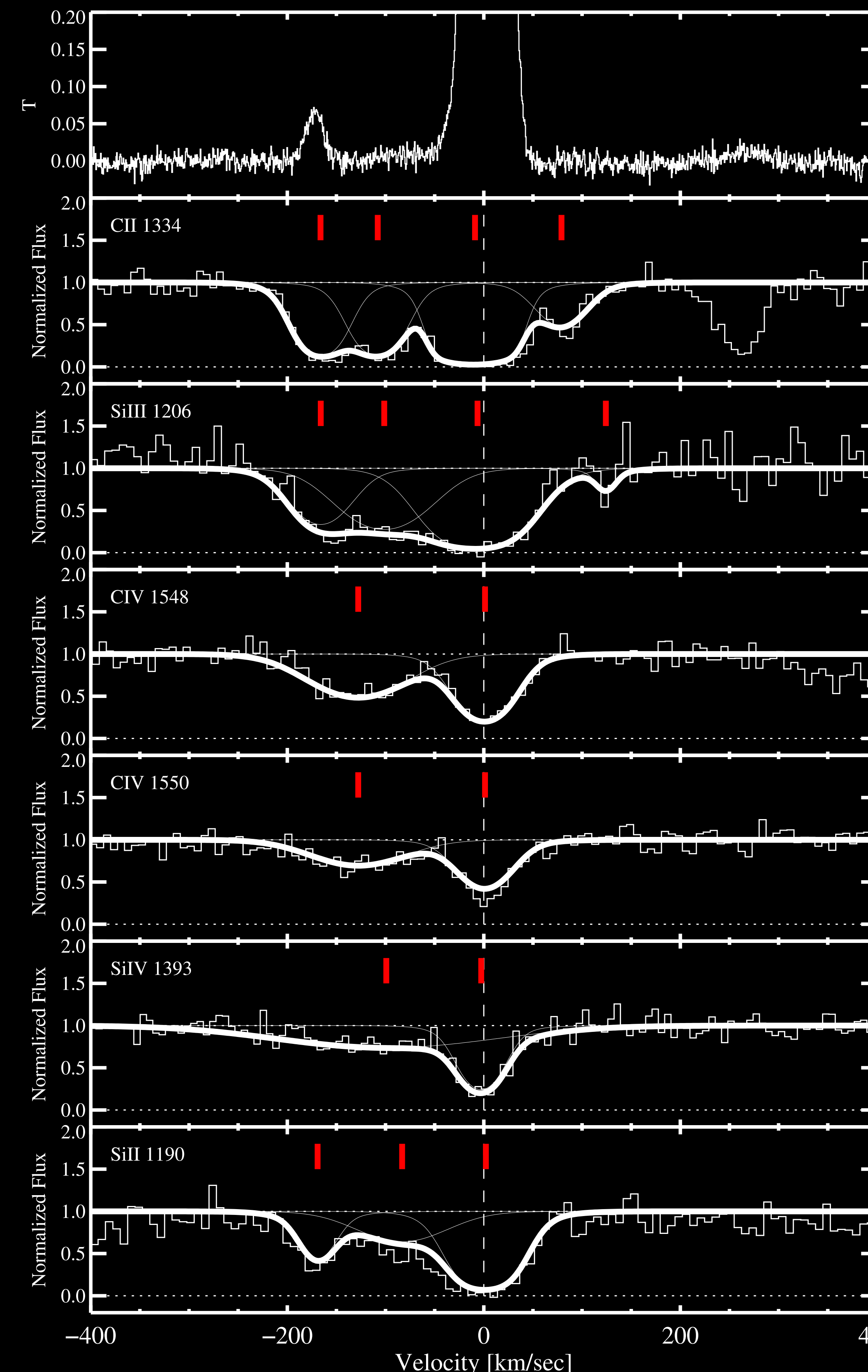
Metallicity towards 1H1613-097

21 cm HI detection:

– log N_{HI} ~ 18.23 cm^{-2}
– log N_{OI} ~ 14.28 cm^{-2}
– [O/H] $\gtrsim$ -0.54 $\gtrsim$ 30% solar.

[Small ionization correction]





Bordoloi+17

Musings on Mass outflow Rates:

For a mass conserving outflow:

$$\dot{\mathrm{M}}_{\mathrm{out}}(\mathrm{b}) = 0.41\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}\ \frac{\mu}{1.5}\ \frac{\alpha}{30^\circ}\ \frac{N_H(b)}{10^{19}\ cm^{-2}}\ \frac{b}{25kpc}\ \frac{v_r}{200kms^{-1}},$$

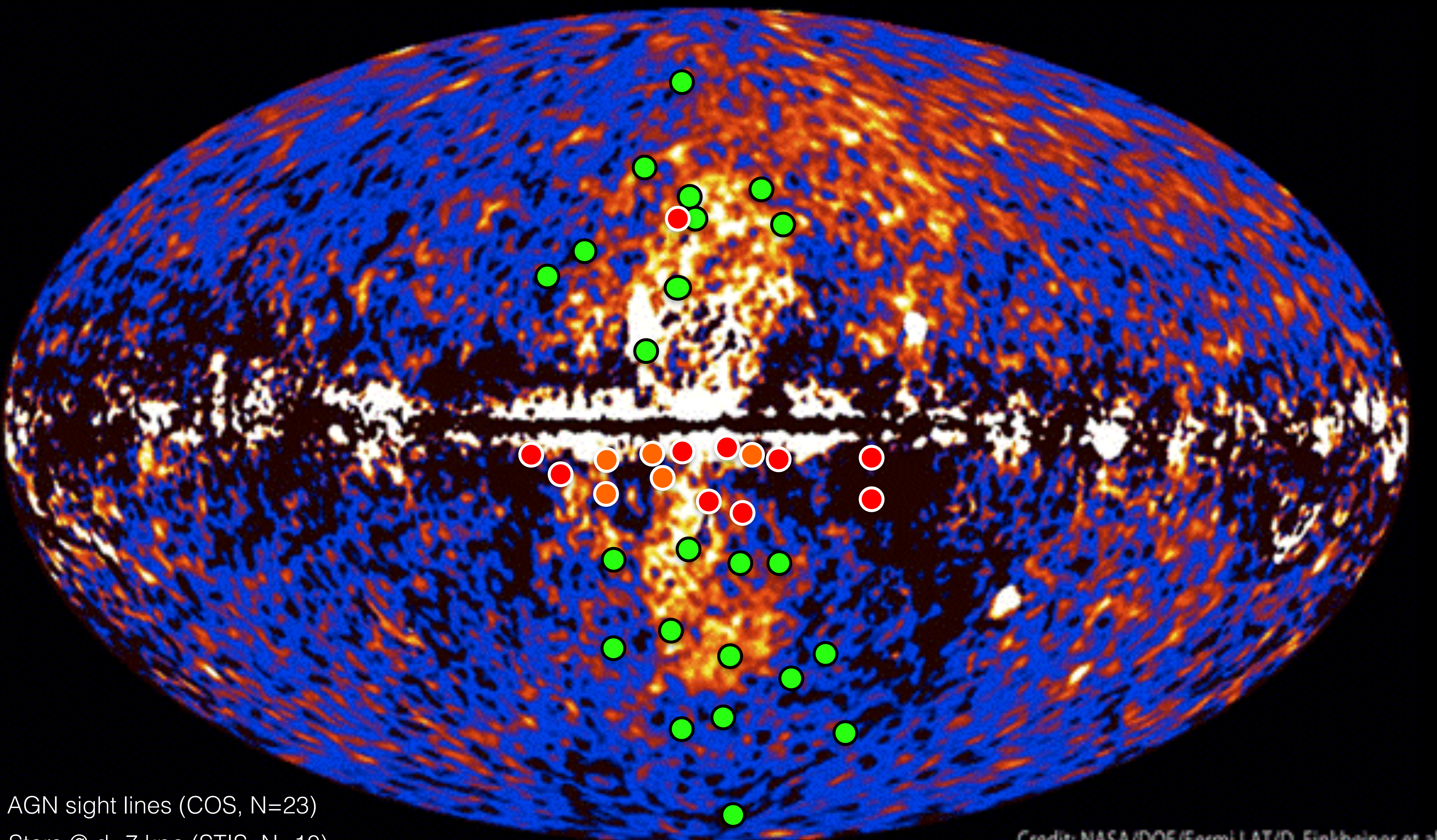
FB Mass loss rate ≳ 0.2-0.5 M⊙/Yr

Assuming a constant mass loss for the kinematic age of the bubble, we estimate the total mass of cool gas entrained in the FBs ≳ 2×10^6 M⊙.

Health Warning: Back of the envelope calculations!!!!

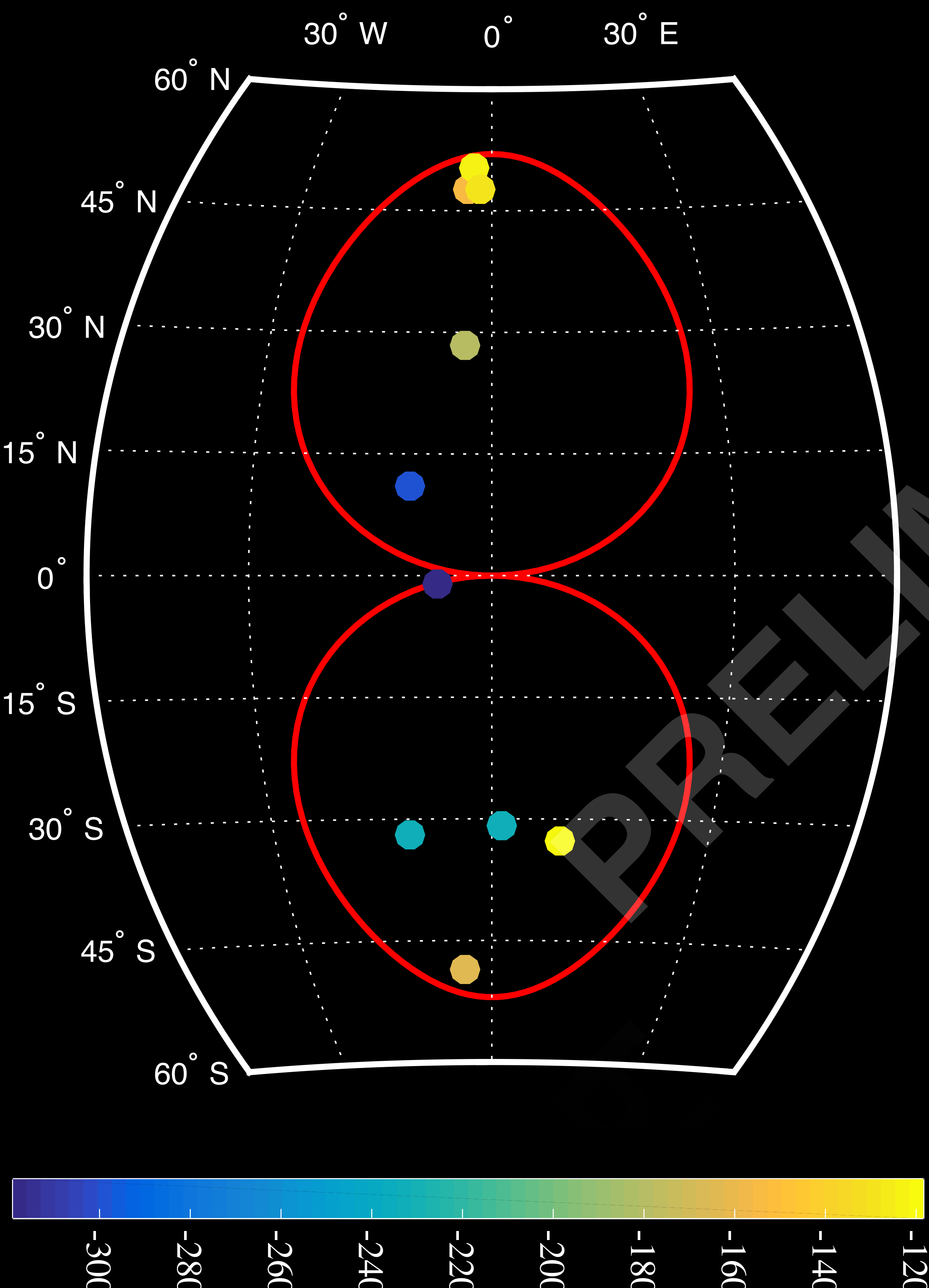
Bordoloi+17

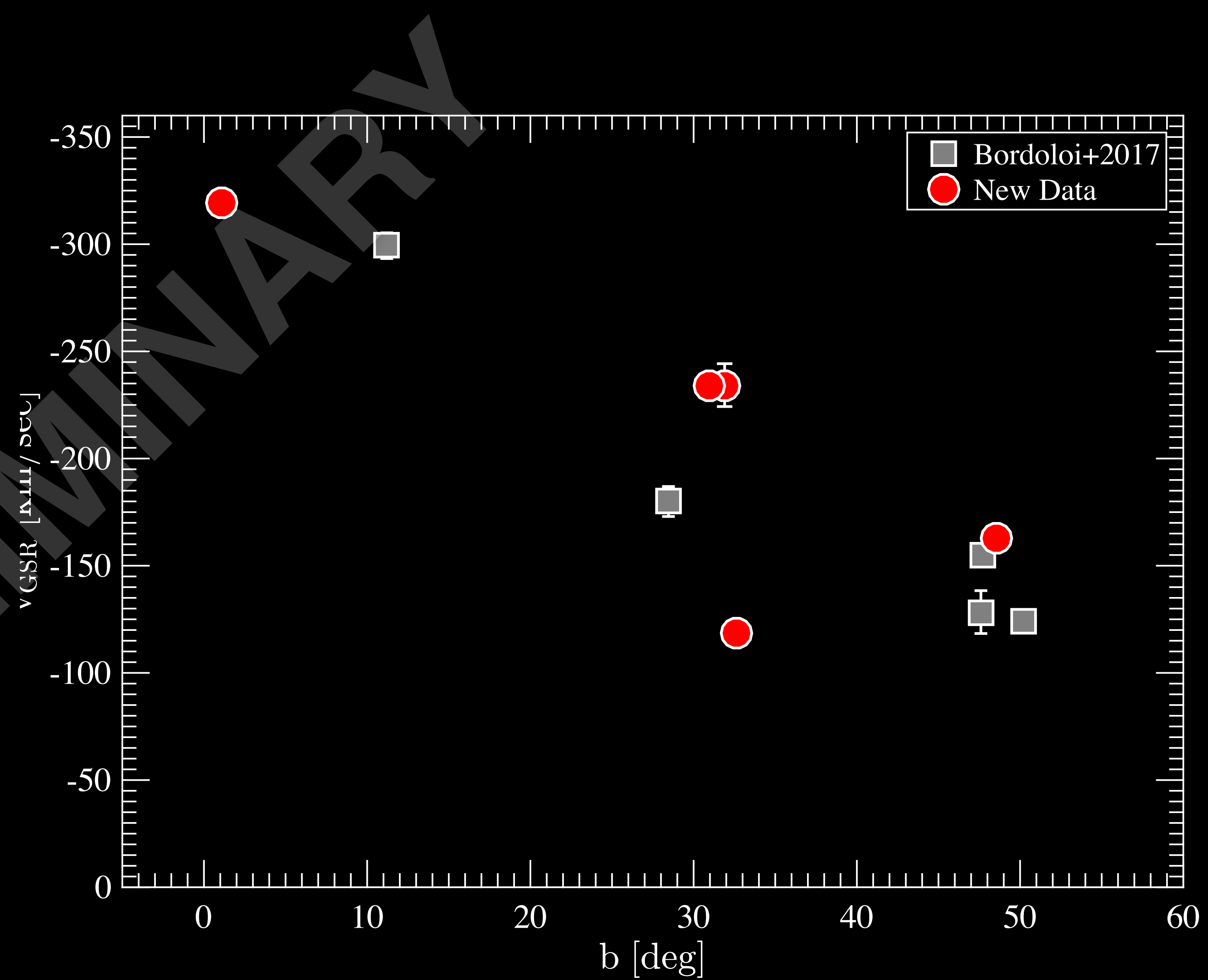
Experiment Design



- AGN sight lines (COS, N=23)
- Stars @ d>7 kpc (STIS, N=10)
- Stars @ d<7 kpc (STIS, N=5)

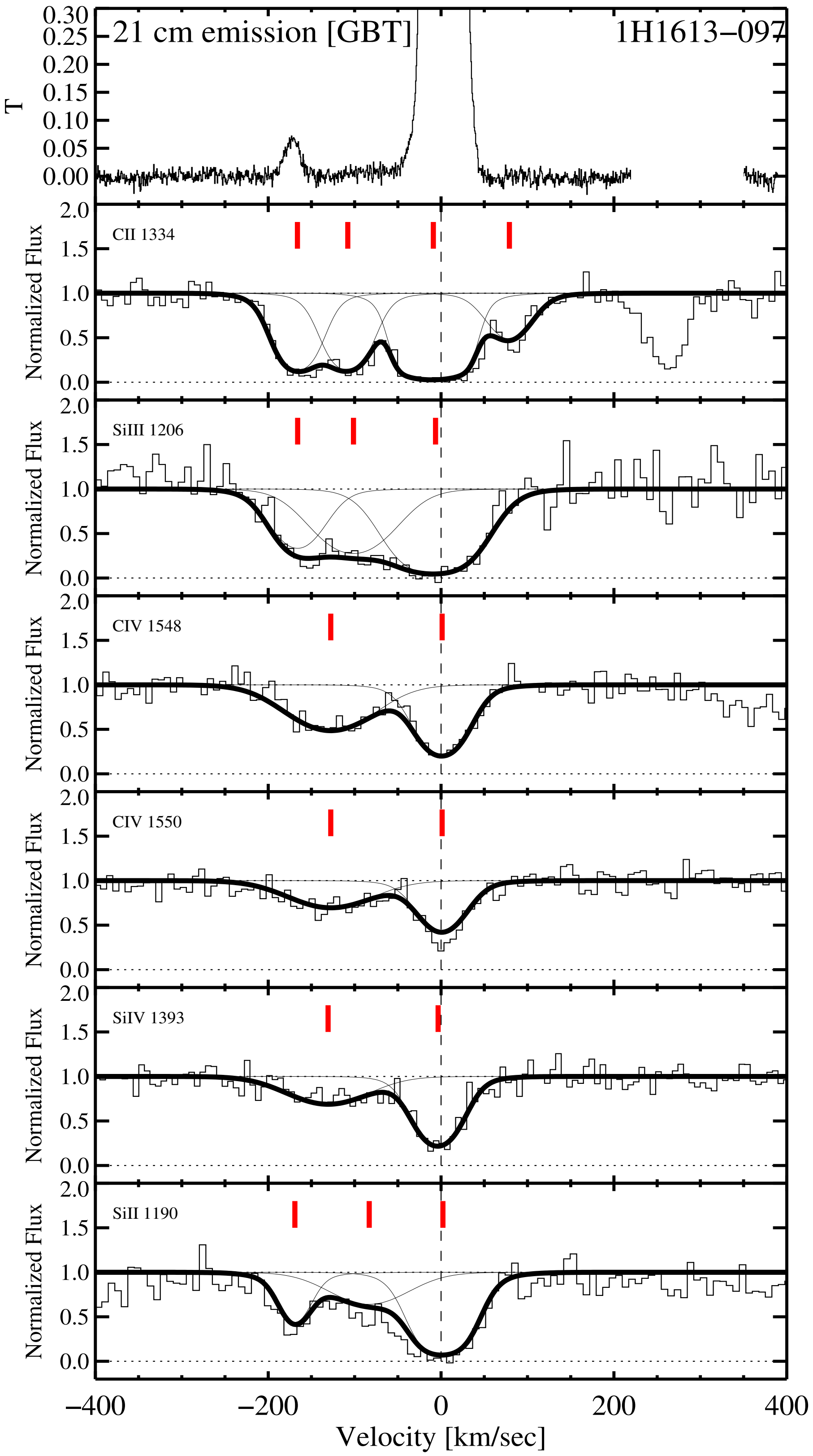
Radial Velocity profile along both the FBs

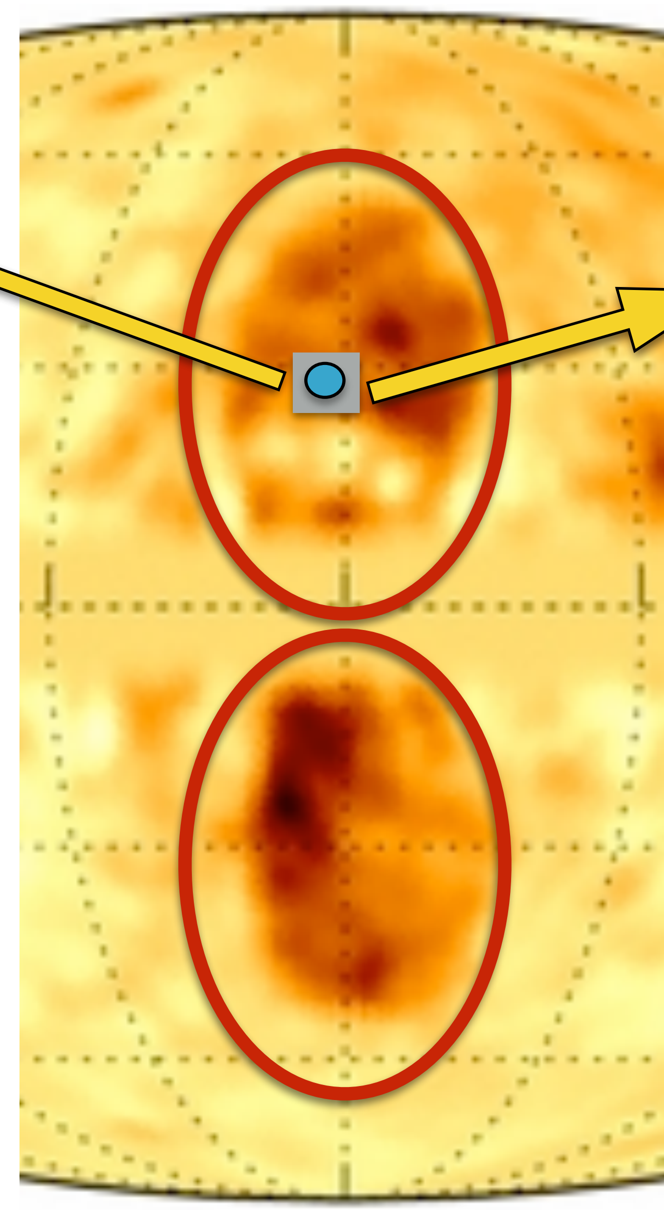


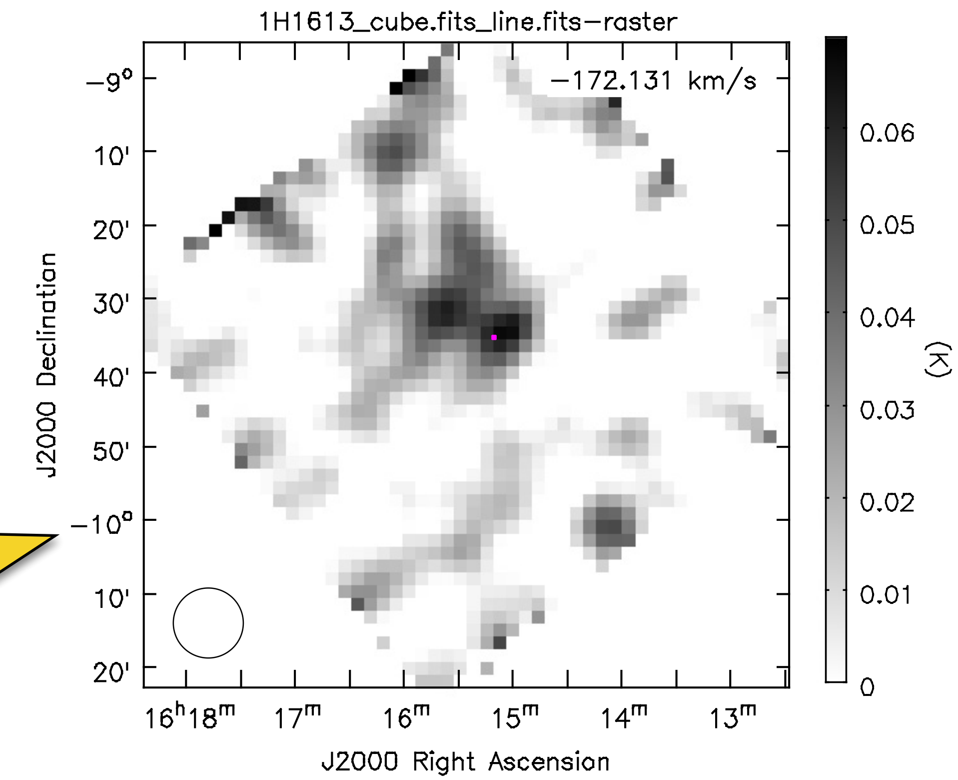


Coming Soon….

Only HVC close to the FBs







GBT DD observations (PI: Bordoloi)

Coming Soon:
Additional 78 hours of GBT observations.
(PI: Bordoloi)

Summary

- Milky Way's nuclear wind detected via Doppler signature.
- Outflow velocity is ~1000-1200 km/s.
- Seeing cool gas venting into the Fermi Bubbles.
- Implies kinematic wind age of ~6-9 Myr (travel time from Galactic Center).
- Higher incidence of HVC absorption inside the northern FB.
- First map of wind velocities with distance from the Galactic Center.
- Suggests a mass loss rate $\gtrsim 0.2$-$0.5\ M_\odot$/Yr and a total mass of cool gas entrained in the FBs $\gtrsim 2 \times 10^6\ M_\odot$.

Thank You!