Gamma Rays from Fast Black-Hole Winds

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On behalf of the *Fermi*-LAT collaboration

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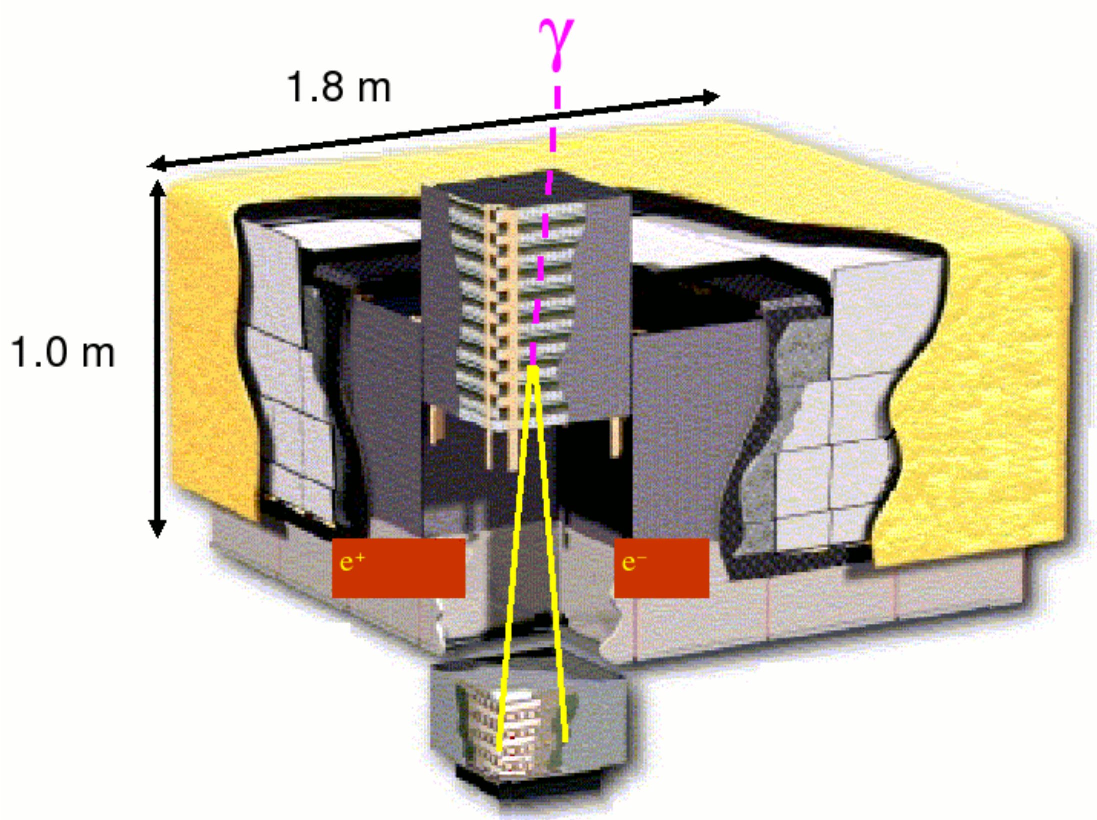
Outline

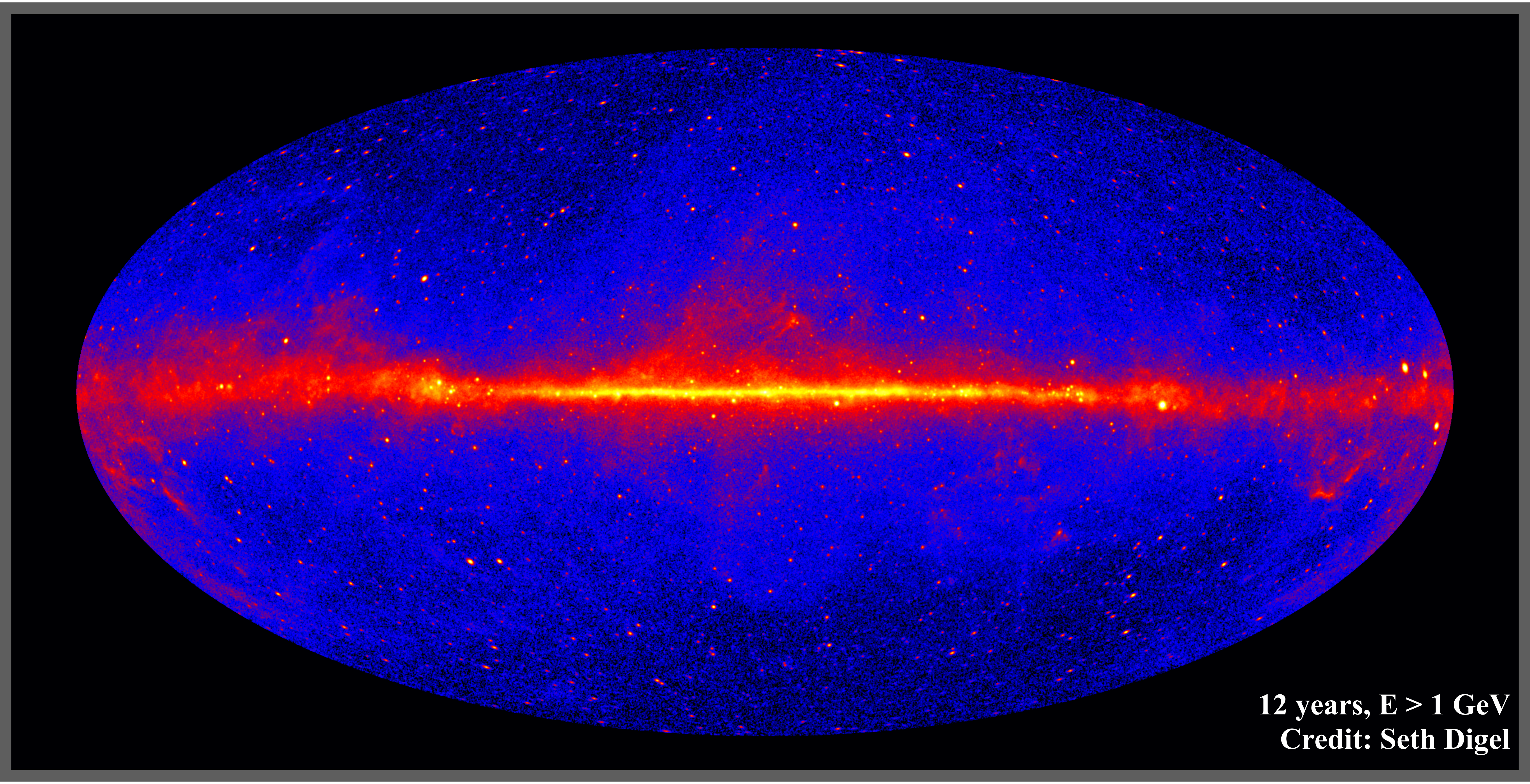
- *Fermi*-LAT
- Black-Hole winds, i.e. ultra fast outflows (UFOs)
- Stacking Analysis
- Results
- Physical Implications
- Summary

The Fermi Gamma-Ray Space Telescope

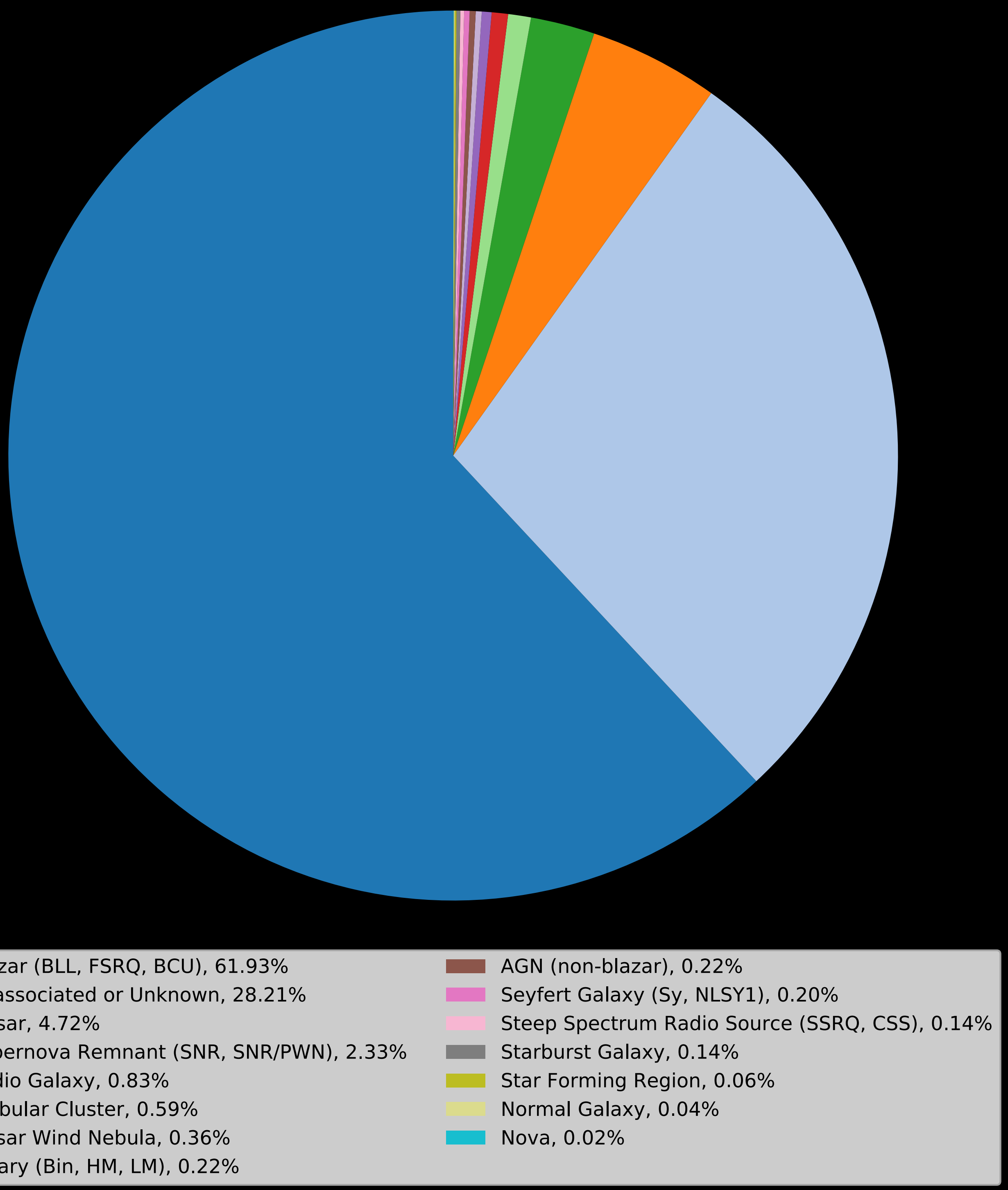


- Launched June 11, 2008
- Sensitive to gamma-rays in the energy range 20 MeV - 300 GeV
- The Large Area Telescope (*Fermi*-LAT) is the main instrument.
- Consist of an array of 16, tracker modules, 16 calorimeter modules, and a segmented anti-coincidence detector.
- Each tracker module consists of 18 XY tracker planes, and each XY plane has an array of silicon-strip tracking detectors for charged particle detection, as well as tungsten conversion plates.

The *Fermi*-LAT Sky



Gamma-Ray Sources (4FGL)



- The 4FGL contains 5065 sources.
- Chart combines associations and identifications.
- **Only ~14 known source classes!**

AGN Outflows at Different Scales

$[r]$ = pc
$[v]$ = km s^{-1}

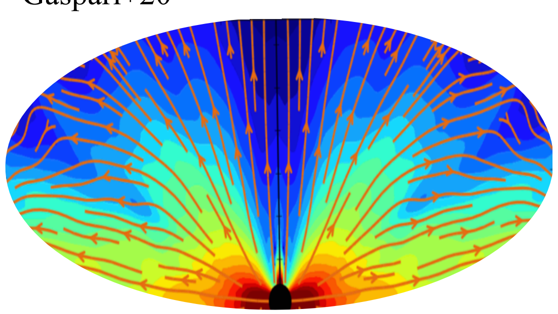
AGN Outflows

SMBH	UFOs	BALs	WAs	NALs	Molecular, Neutral, Ionized	Bubbles
	$r \sim 3\times10^{-4} - 3\times10^{-2}$	$r \sim 1\times10^{-3} - 5\times10^{2}$	$r \sim 1\times10^{-1} - 1\times10^{3}$	$r \sim 1 - 1\times10^{3}$	$r \sim 1\times10^{2} - 7\times10^{3}$	$r \sim 3\times10^{3} - 7\times10^{3}$
	$v \sim 1\times10^{4} - 1\times10^{5}$	$v \sim 1\times10^{4} - 6\times10^{4}$	$v \sim 1\times10^{2} - 1\times10^{3}$	$v \sim 1\times10^{2} - 1\times10^{3}$	$v \sim 1\times10^{2} - 1\times10^{3}$	$v \sim 3.4\times10^{2}$ km s^{-1}
	$L_{Kin} \sim (0.01 - 0.05)\ L_{Bol}$		$L_{Kin} \sim (0.001 - 0.005)\ L_{Bol}$		$L_{Kin} \sim (0.001 - 0.05)\ L_{Bol}$	$E \sim 10^{56}$ erg

→ R

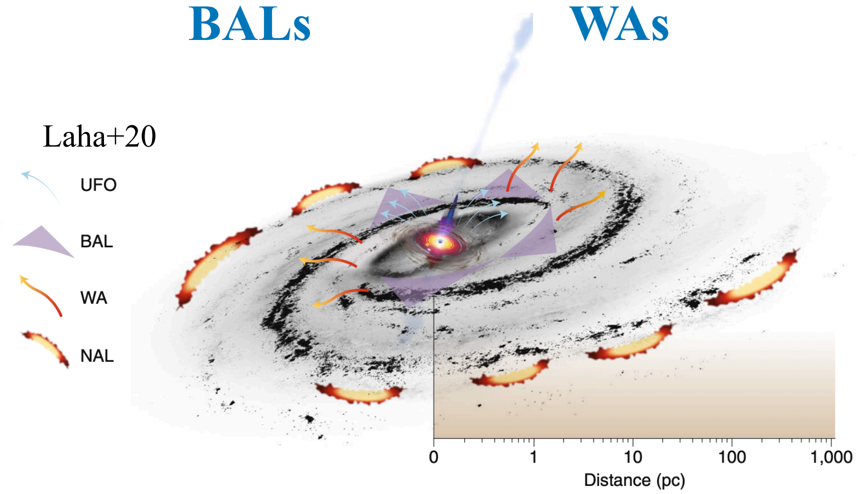
Can also be driven by starbursts

Gaspari+20

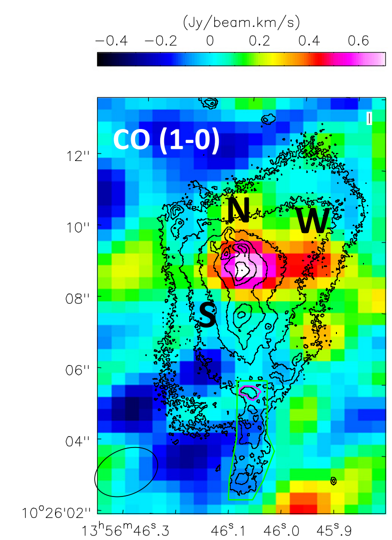


BH winds are driven by radiation pressure or MHD processes

Laha+20

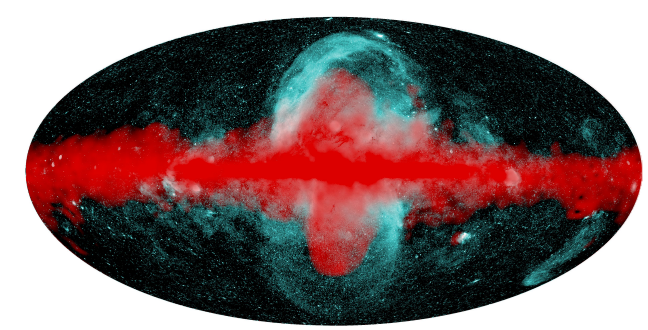


Detected in ~50-65% of AGN in the nearby Universe



Sun+14

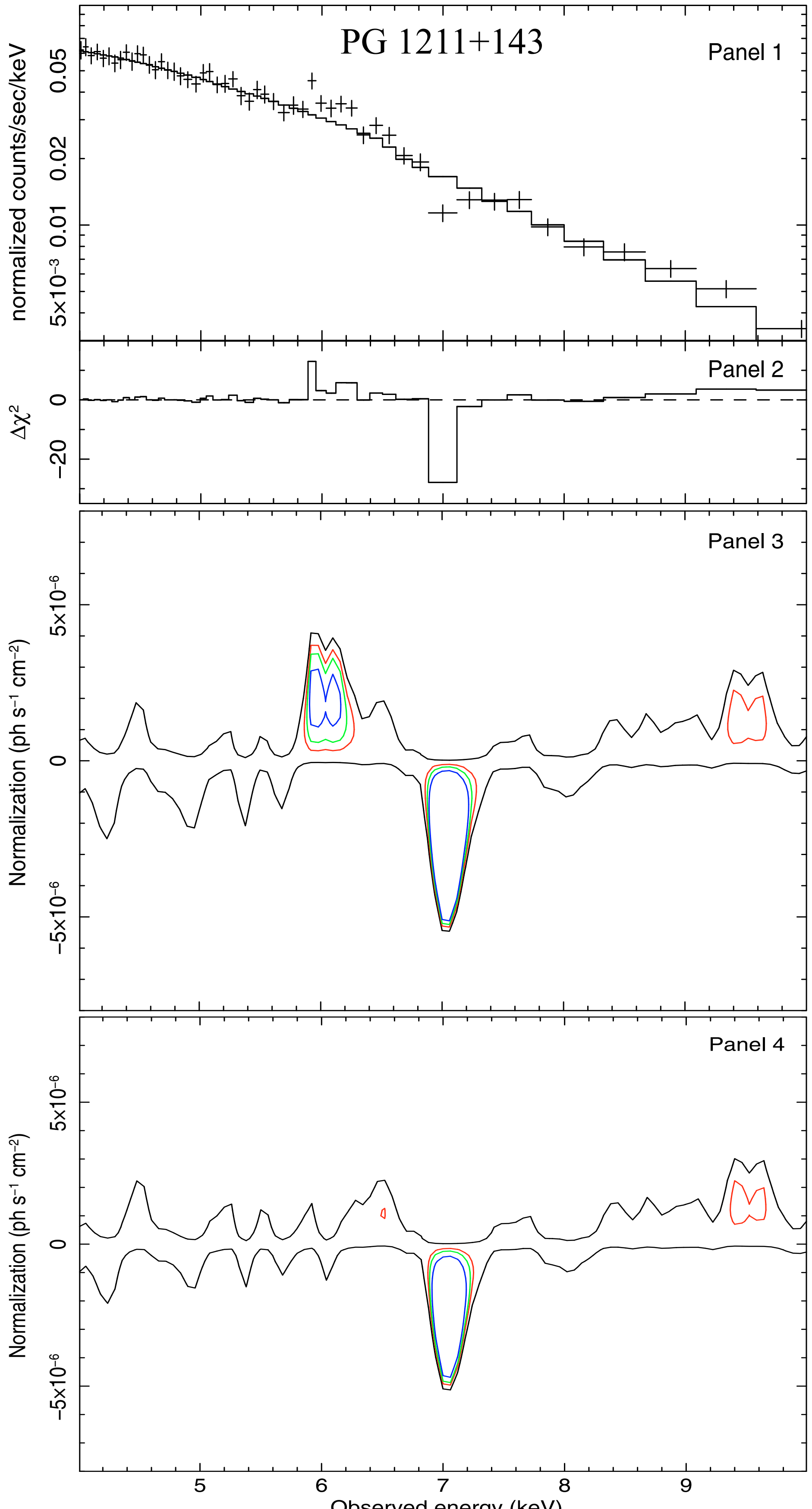
Predehl+20



Outflow types: momentum-driven, energy-driven , (radiation) pressure-driven

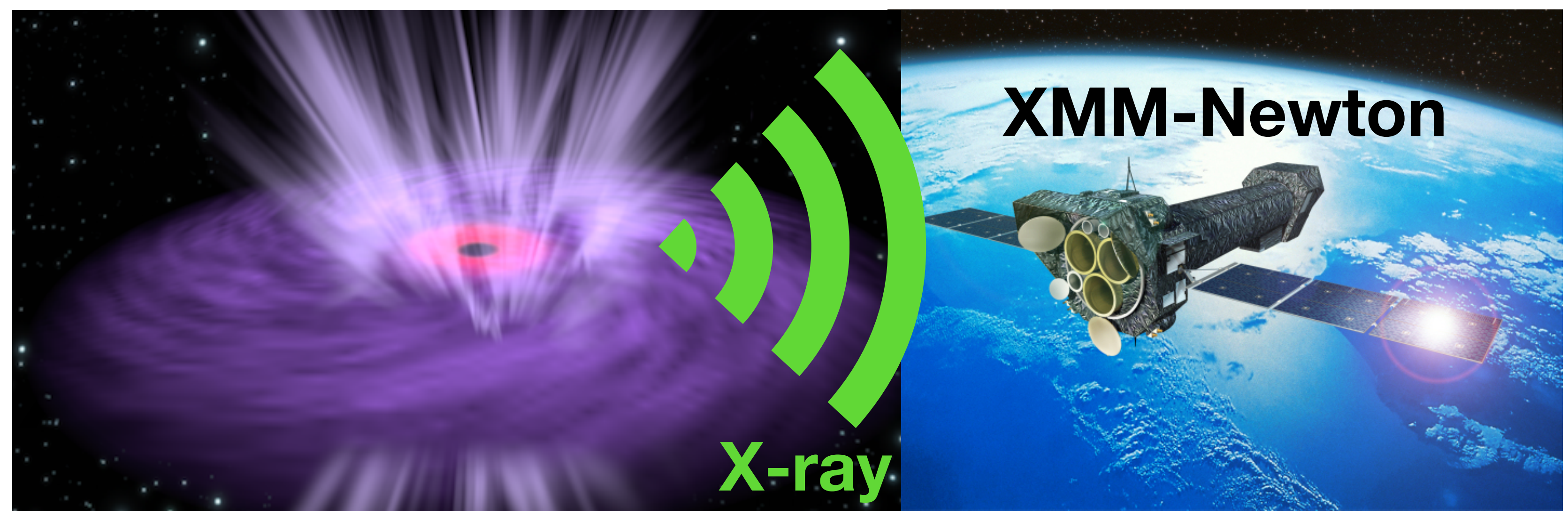
UFOs

Tombesi+10

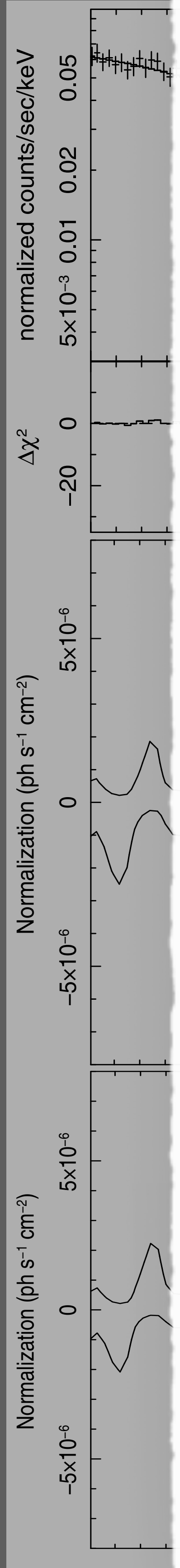


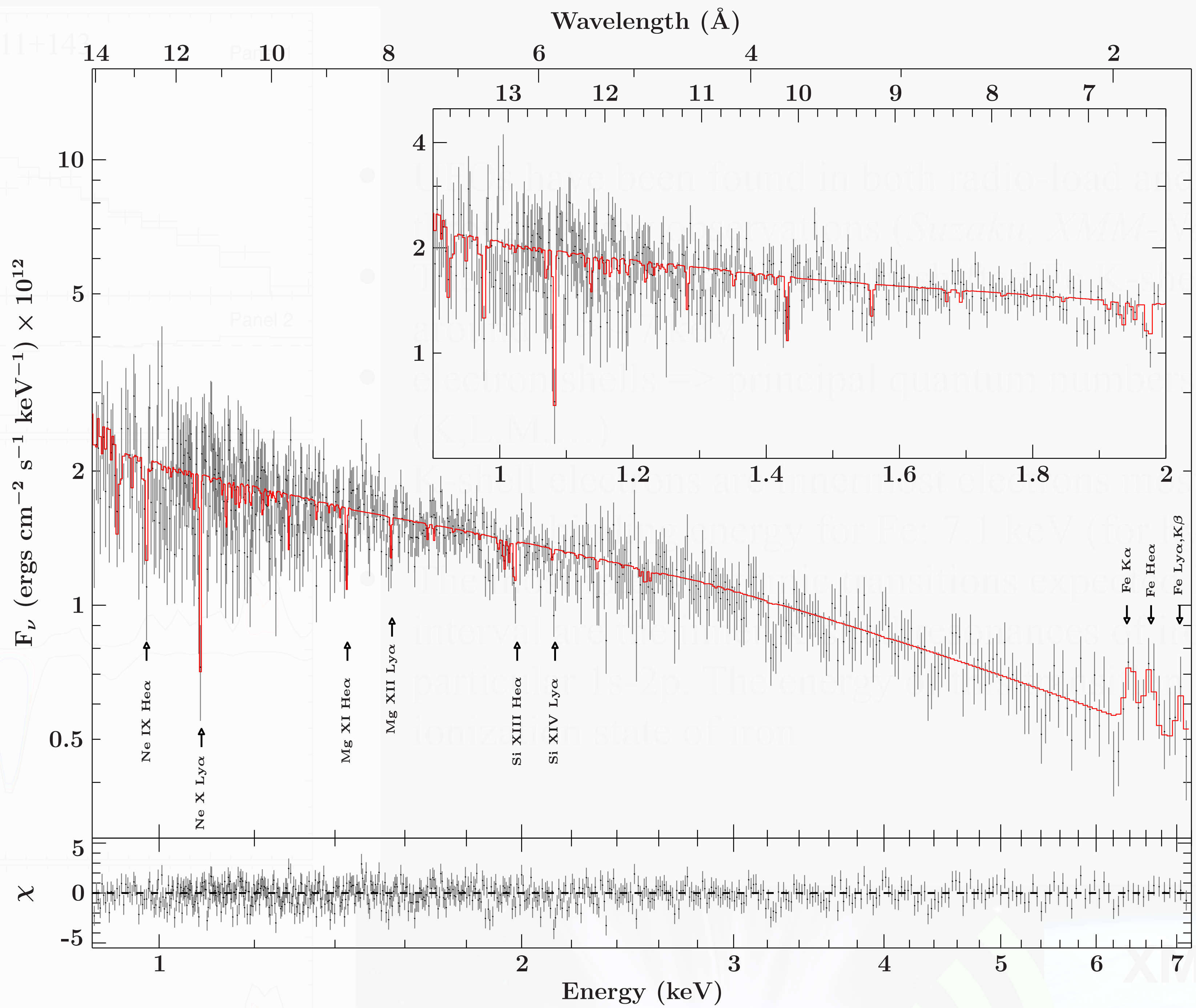
Observed frame

- UFOs have been found in both radio-load and radio-quiet AGN through X-ray observations (*Suzaku, XMM-Newton*).
- They are identified from blueshifted Fe K-shell absorption lines around E >~ 7 keV.



UFOs



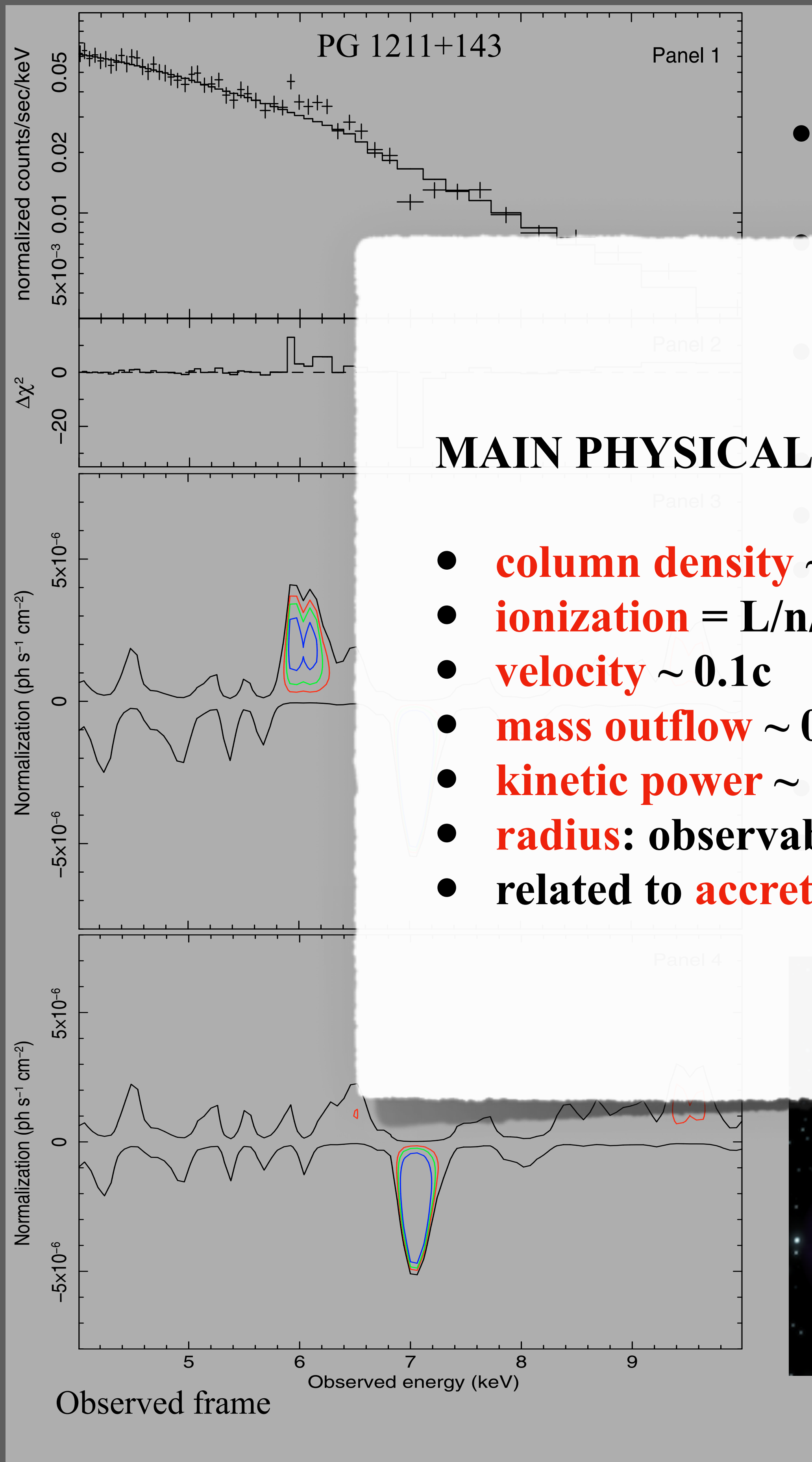


- Danehkar+18
- Quasar PG 1211+143
- *Chandra* High Energy Transmission Grating Spectrometer
- Detection of complex absorption lines from H-like and He-like ions of Ne, Mg, and Si confirming the presence of a UFO

Observed frame

UFOs

Tombesi+10



Observed frame

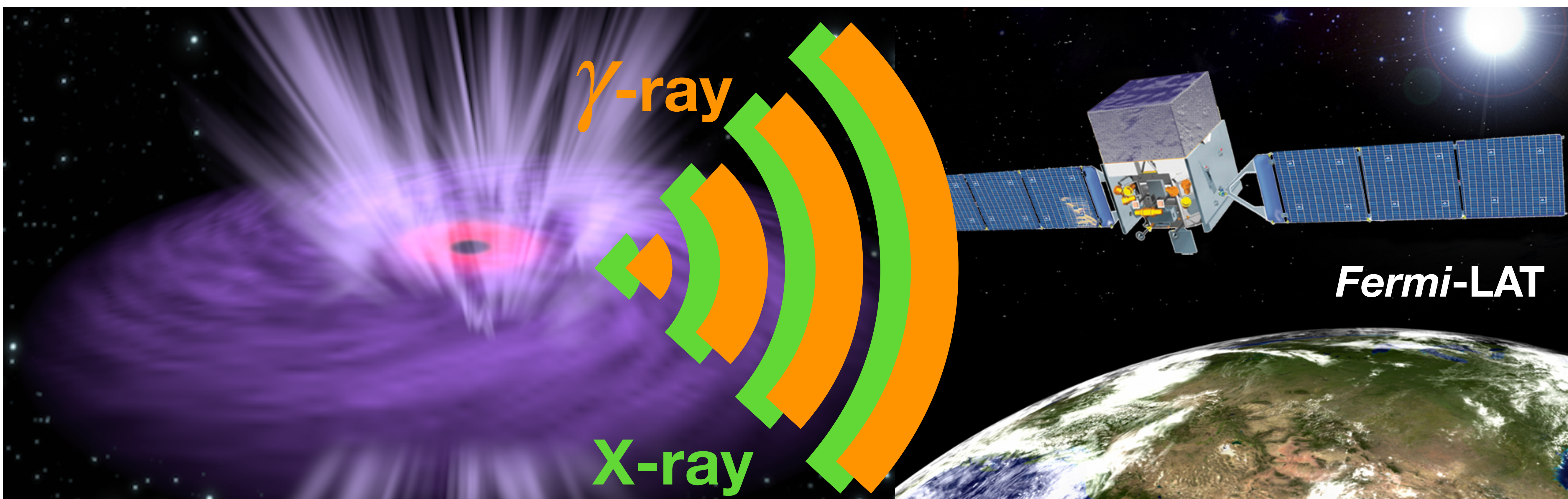
- UFOs have been found in both radio-load and radio-quiet AGN through X-ray observations (*Suzaku, XMM-Newton*).

MAIN PHYSICAL PARAMETERS:

- **column density** ~ 10^22 - 10^24 cm^-2
- **ionization** = L/n/r^2 ~ 10^4.2 erg s^-1 cm
- **velocity** ~ 0.1c
- **mass outflow** ~ 0.01-1 M_sun/yr
- **kinetic power** ~ 10^42-10^45 erg/s
- **radius**: observable at sub-parsec scales from the SMBH
- **related to accretion disk winds/outflows**

Gamma-rays from UFOs

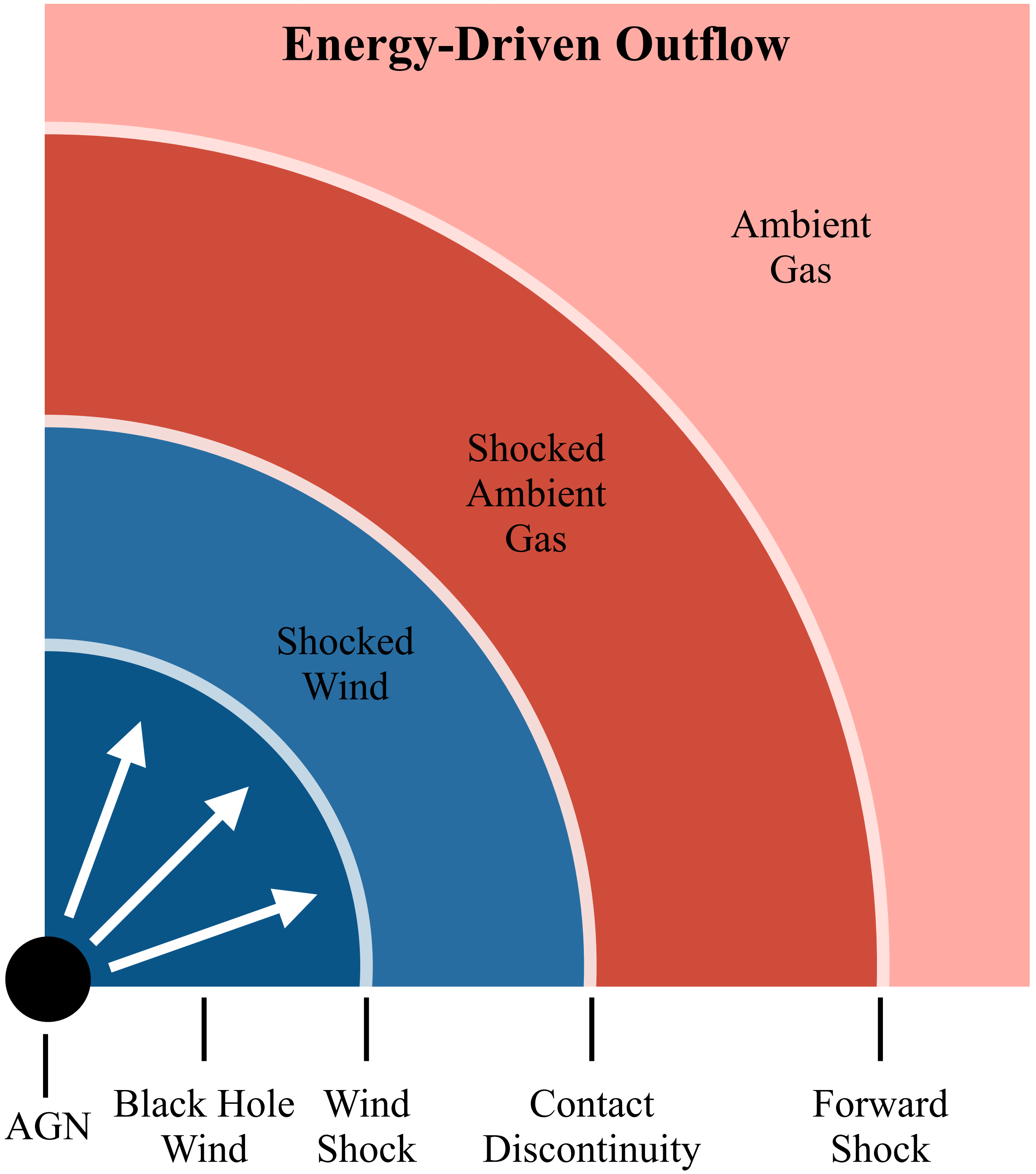
- The outflowing gas should interact with the interstellar medium, generating shock waves, which will accelerate cosmic rays via diffuse shock acceleration, similar to SNRs.
- Potential to discover new gamma-ray source class.
- UFOs likely play a significant role in different feedback processes, including the co-evolution of a galaxy and its central SMBH, as well as the cold outflows observed on galactic scales
- UFOs may contribute to the EGB and the IceCube neutrino flux.



Energy-Driven Outflows

- The BH wind is abruptly slowed in an inner (reverse) shock, i.e. **wind shock**.
- The **shocked wind gas** acts like a piston, sweeping up the host ambient gas at a **contact discontinuity** moving ahead of it.
- The swept-up gas drives an outward **forward shock** into the ISM (or **ambient gas**)
- Once the SMBH attains the critical value (given by the mass-sigma relation), the shocks move further from the AGN, and the cooling associated with the reverse shock becomes negligible. The outflow becomes **energy-driven**.
- **This produces the observed large-scale molecular outflows, that likely sweep the galaxy clear of gas, regulating both the growth of the SMBH and the galaxy itself.**

Based on King+15, Wang+16, Lamasta+17, Liu+18



UFO Sample

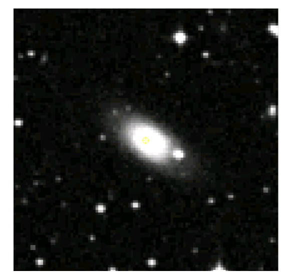
- UFOs in the local Universe are predicted to have a gamma-ray luminosity of ~1e39-1e40 erg/s, which puts them below the LAT sensitivity, and is why the haven't been detected yet
- We therefore use a stacking technique to analysis the UFOs as a population.
- Our sample consists of 11 radio-quiet UFO sources with z < 0.1 and v > 0.1c.

NGC 7582

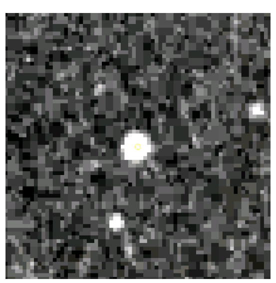
NGC 4151

Ark 120

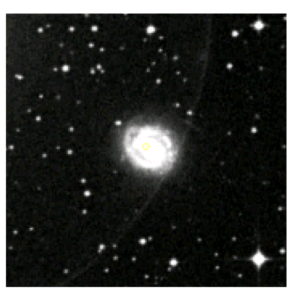
MCG 5-23-16



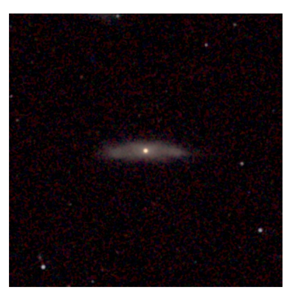
PG1211+143



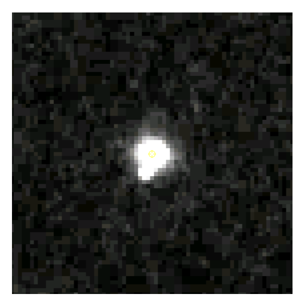
NGC 4507



NGC 5506



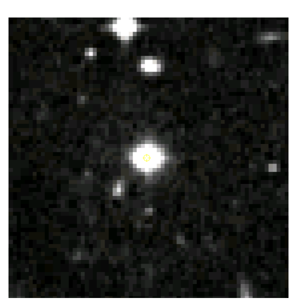
Mrk 290



Mrk 509

SW J2127.4+5654

MR 2251-178



Name	RA [∘]	DEC [∘]	Type	Redshift [z]	Velocity [v/c]	$\log M_{\rm BH}$ [$M_\odot$]	$\log \dot{E}_K^{\rm Min}$ [erg s^{-1}]	$\log \dot{E}_K^{\rm Max}$ [erg s^{-1}]	$\log L_{\rm Bol}$ [erg s^{-1}]
Ark 120[a,c]	79.05	−0.15	Sy1	0.033	0.27	8.2 ± 0.1	> 43.1	46.2 ± 1.3	45.0[f]
									44.2[h]
									44.6
MCG-5-23-16[a,c]	146.92	−30.95	Sy2	0.0084	0.12	7.6 ± 1.0	42.7 ± 1.0	44.3 ± 0.2	44.1[k]
NGC 4151[a,c]	182.64	39.41	Sy1	0.0033	0.105	7.1 ± 0.2	>41.9	43.1 ± 0.5	44.1[g]
									42.9[h]
									43.9[i]
									42.9[j]
									43.2[j*]
									43.4
PG 1211+143[a,c]	183.57	14.05	Sy1	0.081	0.13	8.2 ± 0.2	43.7 ± 0.2	46.9 ± 0.1	45.7[f]
									44.8[h]
									44.7[j]
									45.0[j*]
									45.1
NGC 4507[a,c]	188.90	−39.91	Sy2	0.012	0.18	6.4 ± 0.5	> 41.2	44.6 ± 1.1	44.3[e]
NGC 5506[b,d]	213.31	−3.21	Sy1.9	0.006	0.25	7.3 ± 0.7	43.3 ± 0.1	44.7 ± 0.5	44.3[e]
Mrk 290[a,c]	233.97	57.90	Sy1	0.030	0.14	7.7 ± 0.5	43.4 ± 0.9	45.3 ± 1.2	44.4[e]
Mrk 509[a,c]	311.04	−10.72	Sy1	0.034	0.17	8.1 ± 0.1	>43.2	45.2 ± 1.0	45.2[e]
									44.3[h]
									45.3[i]
									44.3[j]
									44.5[j*]
									44.7
SWIFT J2127.4+5654[b,d]	321.94	56.94	Sy1	0.014	0.23	∼7.2	42.8 ± 0.1	45.6 ± 0.5	44.5[d]
MR 2251-178[b,d]	343.52	−17.58	Sy1	0.064	0.14	8.7 ± 0.1	43.3 ± 0.1	46.7 ± 0.7	45.8[f]
NGC 7582[a,c]	349.60	−42.37	Sy2	0.0052	0.26	7.1 ± 1.0	43.4 ± 1.1	44.9 ± 0.4	43.3[e]

Analysis Procedure

- **Using Fermipy v0.19.0**
- **Ran on Clemson University HPC (Palmetto)**
- **Stacking code based on the codes of Marco Ajello, Vaidehi Paliya and Abhishek Desai**
- **Successfully employed for EBL, extreme blazars, star-forming galaxies.**

1. Preprocessing

- Optimize ROI for each source using a binned likelihood analysis.
- Model consists of: Galactic diffuse, isotropic, point sources, and target source modeled with a power law.

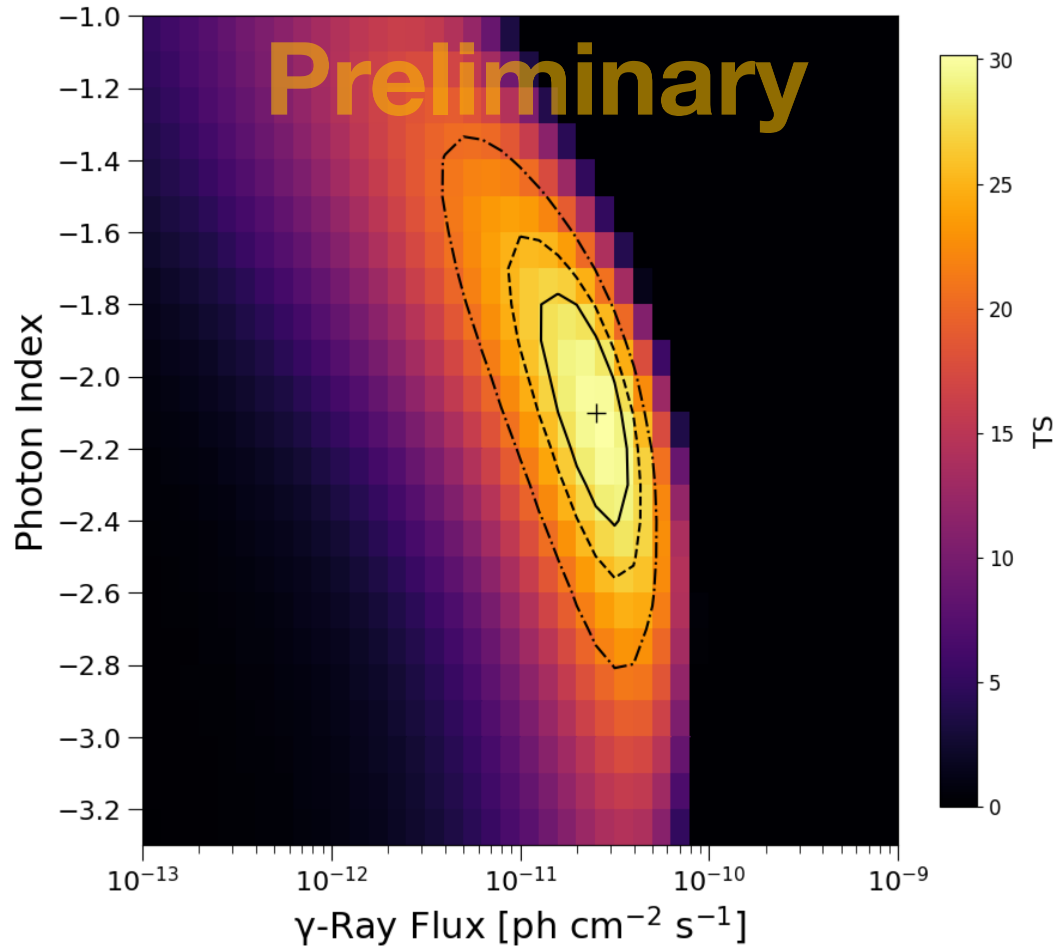
2. Stacking

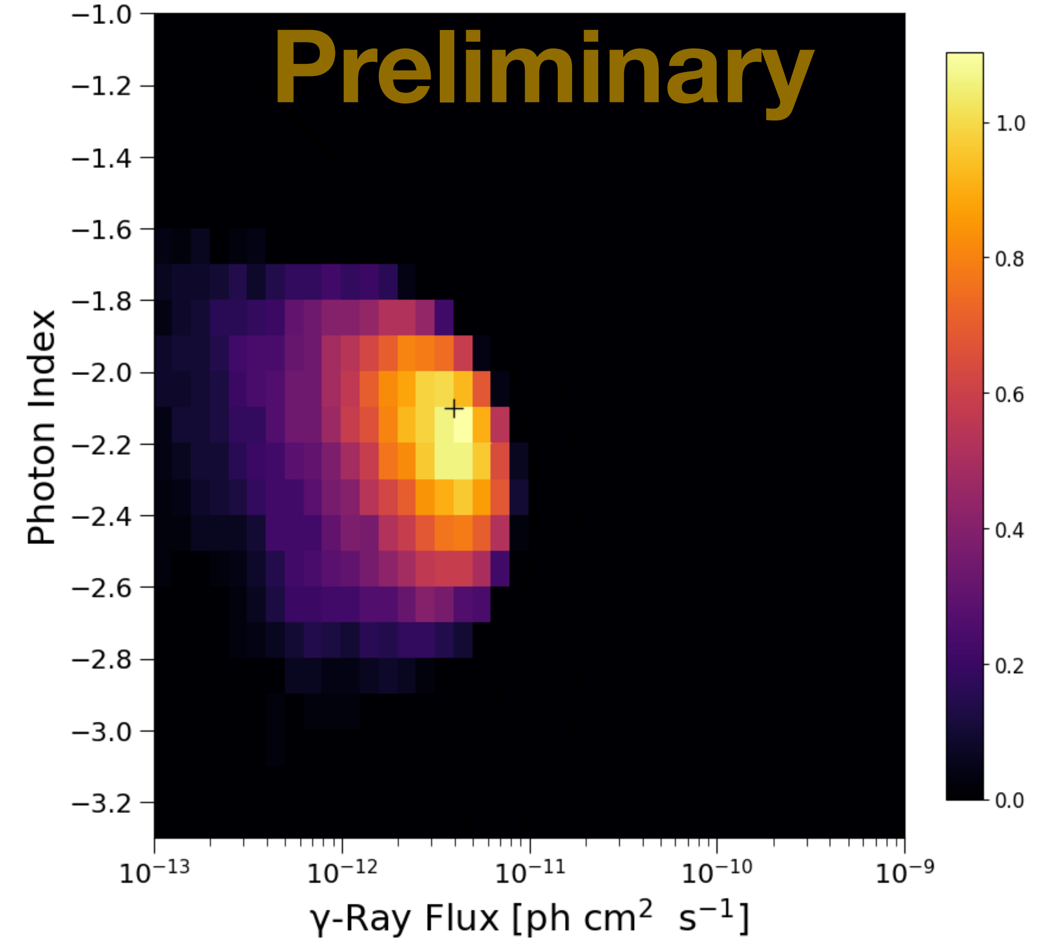
- Construct likelihood (TS) profiles for each source by iterating through index and flux
- Only free parameters in likelihood fit are Galactic diffuse and isotropic
- Sum TS profiles for all sources to obtain global significance of signal

$$\mathrm{TS} = -2(\log \mathrm{L}_0 - \log L)$$

$$\log(\mathrm{L}) = \log(L_1 L_2) = \log L_1 + \log L_2 \text{ , where } L(\theta | X) = P(X | \theta)$$

Results



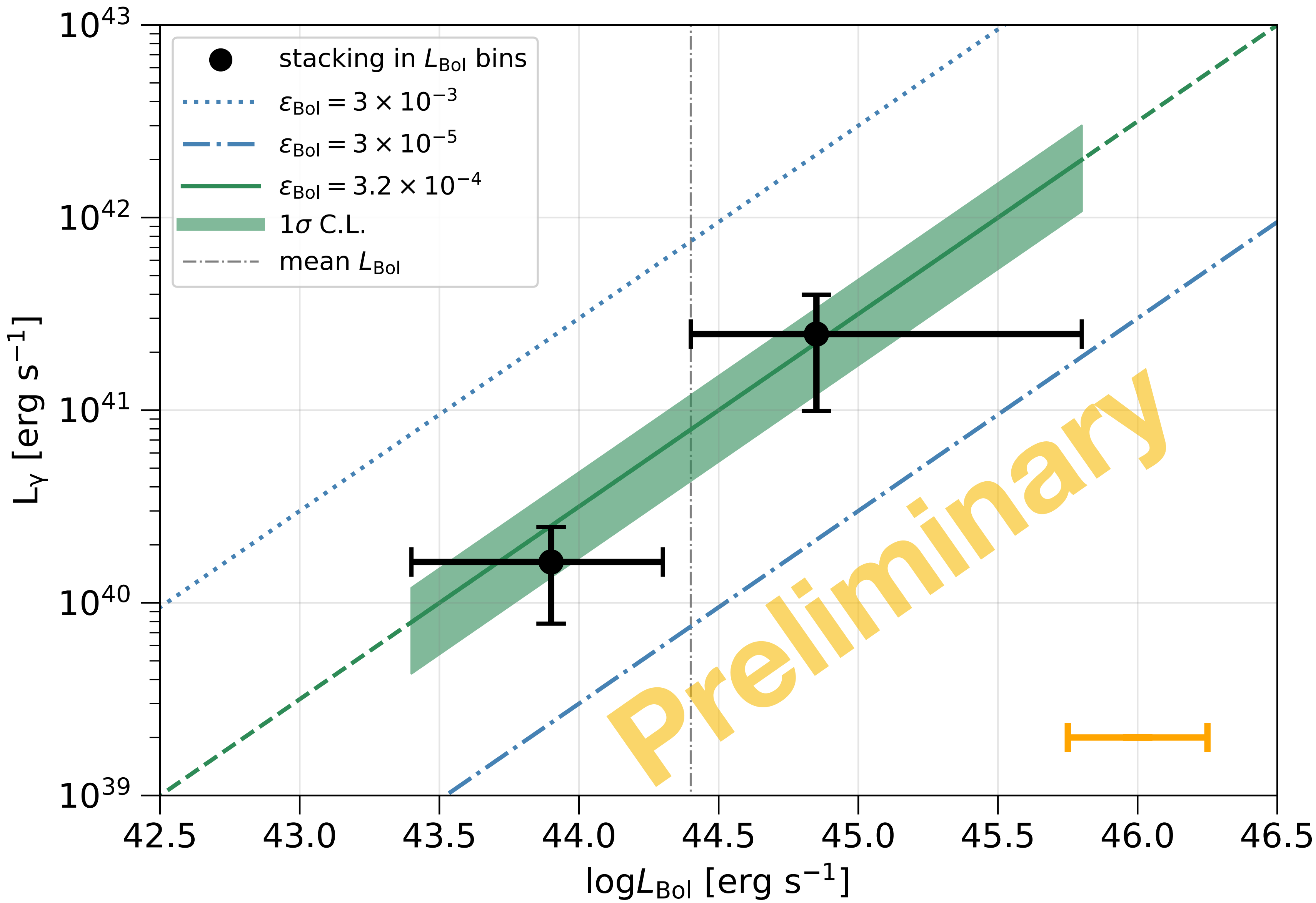


- **Benchmark sample**
- Max TS: 30.1 (5.1 sigma for 2 dof)
- Best index = 2.1 ± 0.3
- Best flux = $2.51^{+1.47}_{-0.93} \times 10^{-11}$ ph cm^{-2} s

- **Control sample**
- Max TS: 1.1

- We show that the gamma-ray emission observed in the UFOs is a factor of ~40 larger than what we would expect for star-formation activity.
- We also show that it's highly unlikely the UFO emission results from weak jets.

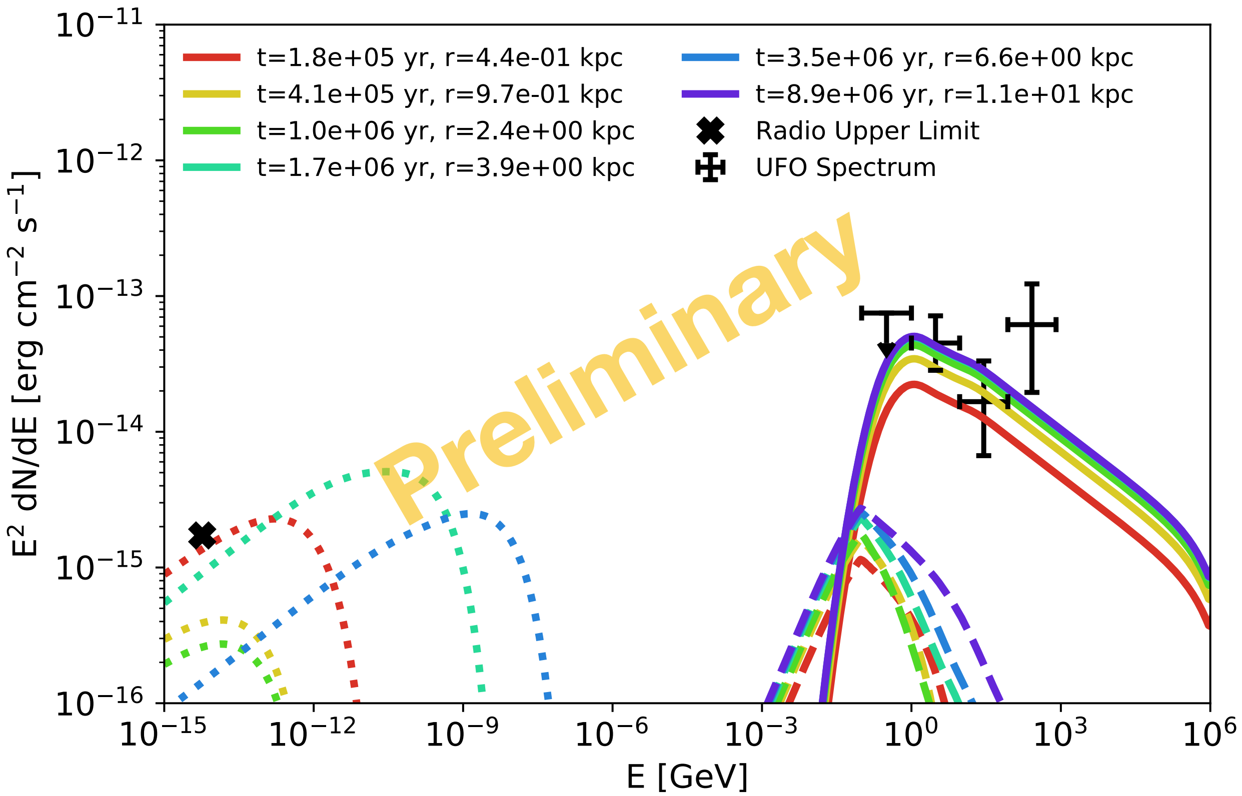
Results

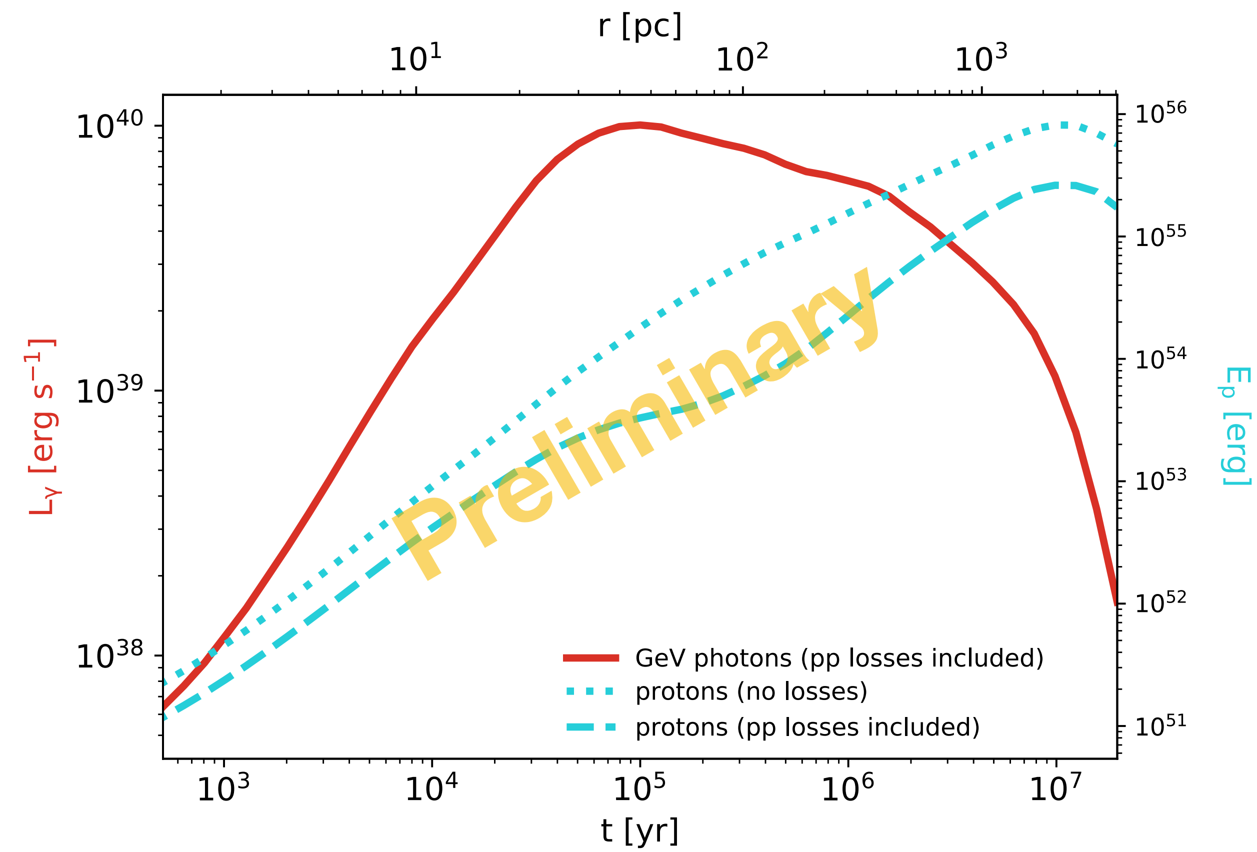


$$\epsilon = \frac{L_\gamma}{L_{\rm Bol}} = 3.2^{+1.6}_{-1.5} \times 10^{-4}$$

- Scaling of the gamma-ray luminosity as a function of bolometric luminosity

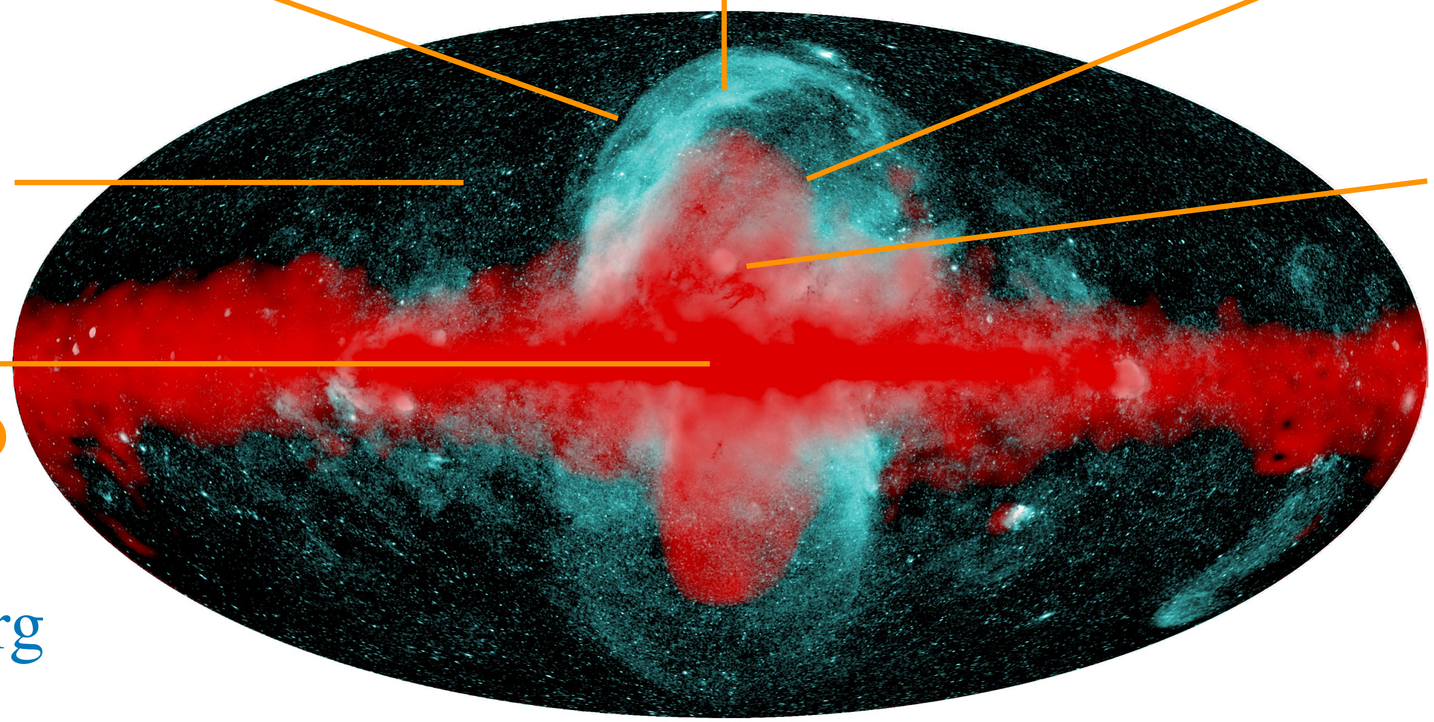
UFO Model





- We model the hadronic emission resulting from diffusive shock acceleration.
- On average, the forward shock has traveled 20-300 pc away from the SMBH.
- The max energy of protons accelerated at the shock is ~10^17 eV, making AGN winds a potential source of CRs beyond the knee of the CR spectrum (3e15 eV) and also likely contributors to the EGB and IceCube neutrino flux.

Galactic Bubbles

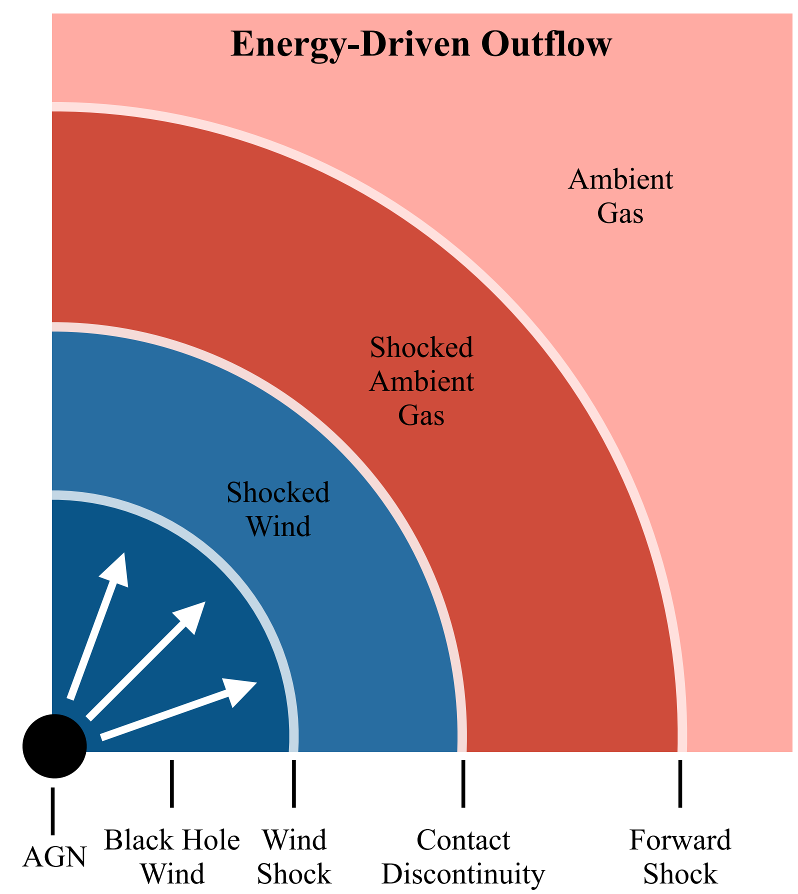


$E_{\rm th} \approx 1.3 \times 10^{56}$ erg

$t \approx 20 \times 10^{6}$ yr

$\log L_{\gamma} \approx 37.6$ erg s^{-1} $(1 - 100$ GeV$)$

- We outline the "simplest scenario", as described in Predehl+20.
- **Disclaimer:** The goal on this slide is to provide an intuitive sense of a plausible scenario for the emission. However, the exact interpretation is of course still open to debate.



Credit:
eROSITA Bubbles: Predehl+20

Galactic Bubbles

$M_{BH} \approx 4 \times 10^6\ M_\odot$

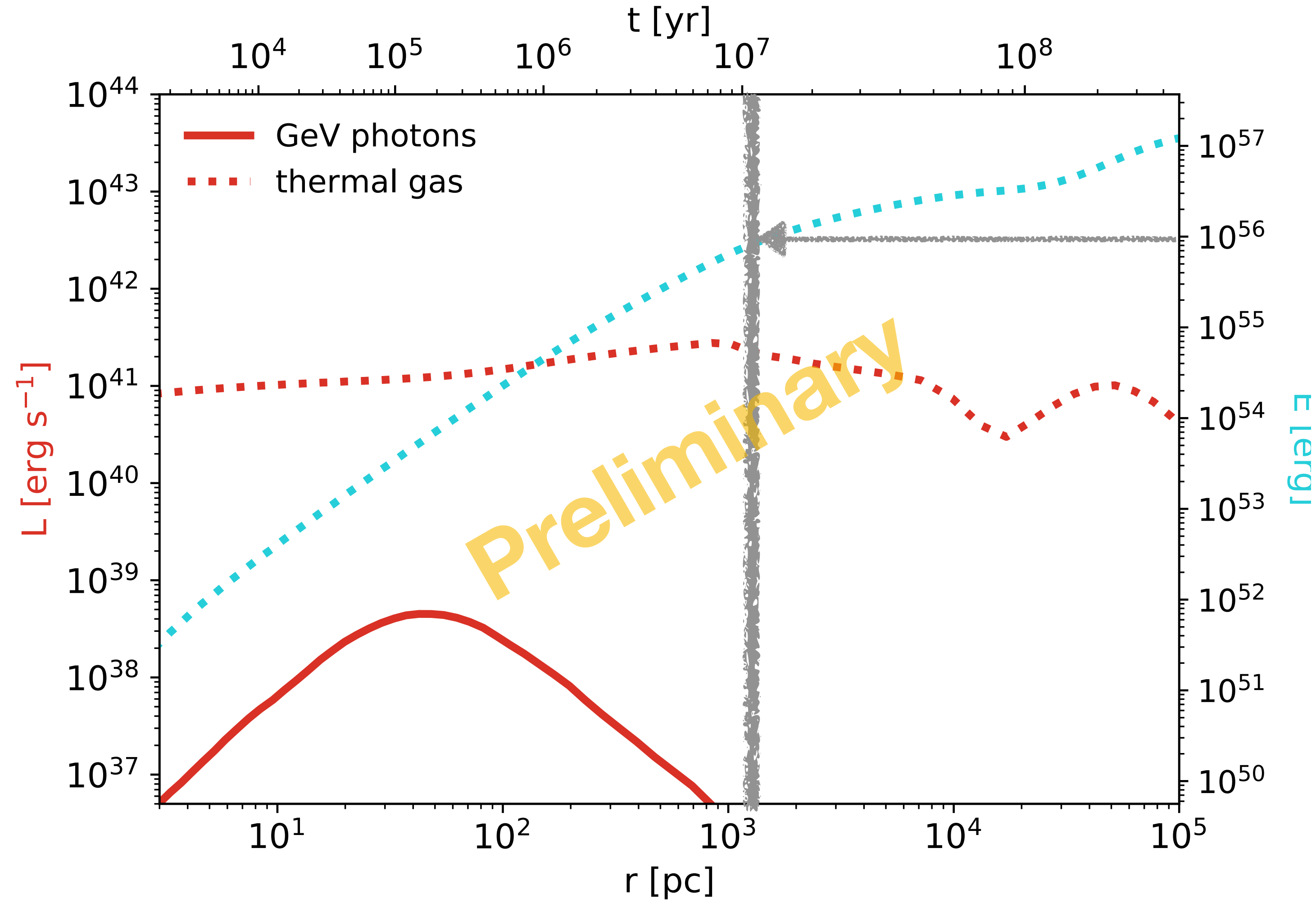
$L_{Bol} = 0.01 L_{Edd}$

$L_{Edd} = 1.26 \times 10^{38} (\frac{M_\bullet}{M_\odot})\ \mathrm{erg\ s^{-1}}$

$\Longrightarrow\ \log L_{Bol} = 42.7\ \mathrm{erg\ s^{-1}}$

$E_{Bubble} \sim 10^{56}$ erg when $t \sim 10 \times 10^6$ yrs

$\Longrightarrow\ \log L_\gamma \approx 37\ \mathrm{erg\ s^{-1}}$ (1 GeV)



- As a simple check, we do a rescaling for Sgr A* (note that the model is not optimized to the Milky Way).
- Srg A* was likely last active ~300 yrs ago (e.g. Koyama+96)
- The Eddington ratio for AGN in the local Universe ~1-10%
- The gamma-ray luminosity will decrease modestly after ~300 yrs.
- **Based on this reasonable agreement with observation, the Fermi and eROSITA bubbles may be the remnant of past UFO-like activity from the SMBH in the center of our galaxy.**

Summary

- The UFO population is detected with a TS = 30.1 (5.1 sigma for 2 dof)
- Best-fit index = 2.1 +/- 0.3
- Best-fit flux = $2.51^{+1.47}_{-0.93} \times 10^{-11}$ ph cm^{-2} s
- The gamma-ray emission scales with the bolometric luminosity
- Best-fit efficiency = $3.2^{+1.6}_{-1.5} \times 10^{-4}$
- Under the assumption that the emission results from diffuse shock acceleration, akin to SNRs, the UFO signal implies that the shock front travels ~20-300 pc from the SMBH.
- UFOs may be plausible contributors to the EGB and IceCube neutrino flux.
- The Fermi and eROSITA bubbles may be the remnant of past UFO-like activity from the SMBH in the center of our galaxy

Thank you!