THE GAMMA-RAY EMISSION OF GALAXY OUTFLOWS

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On behalf of the Fermi-LAT Collaboration

CREDITS

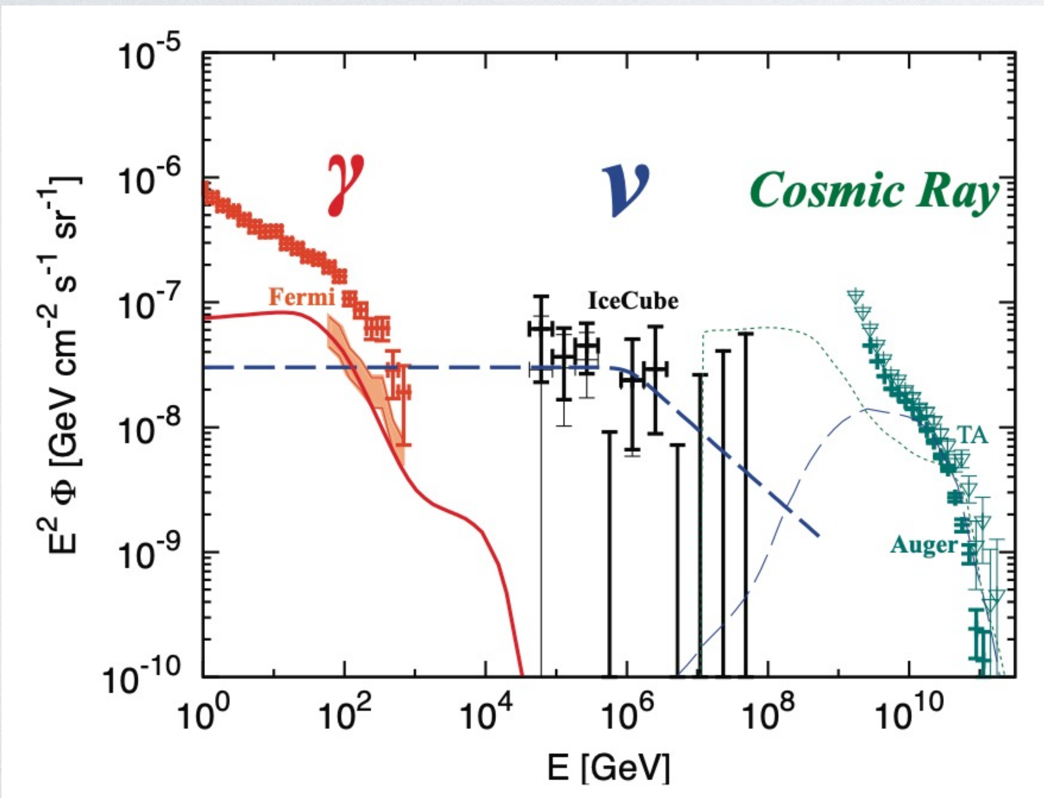
Chris Karwin
UFO paper: arXiv:2105.11469

Rebecca Diesing
Theory

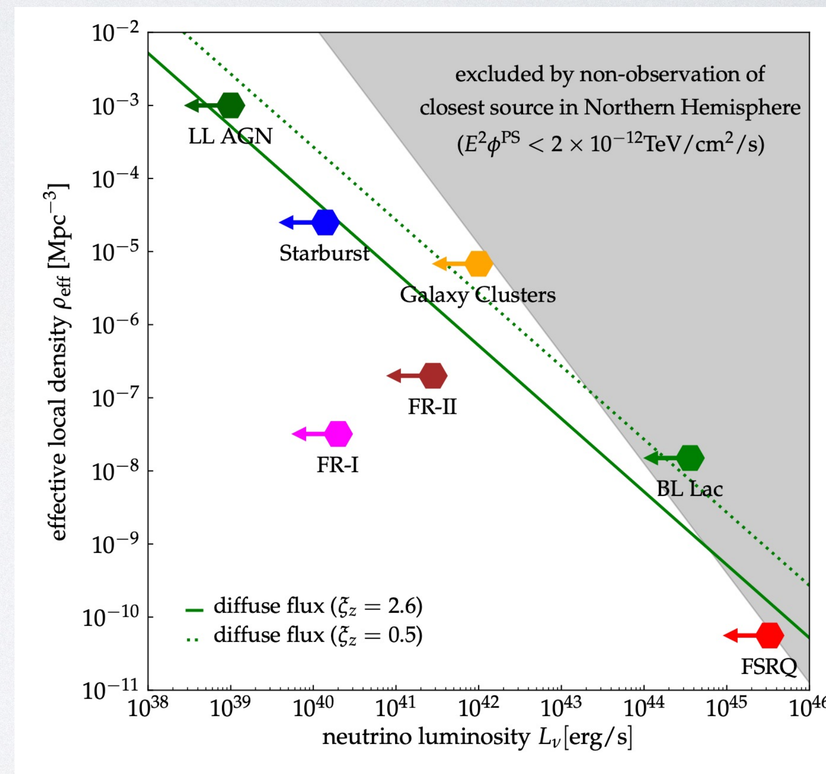
Alex McDaniel
MO paper: to be submitted

MOTIVATION

- A class of hadronic accelerators can explain the 3 backgrounds
- However, blazars and star-forming galaxies are nearly ruled out*



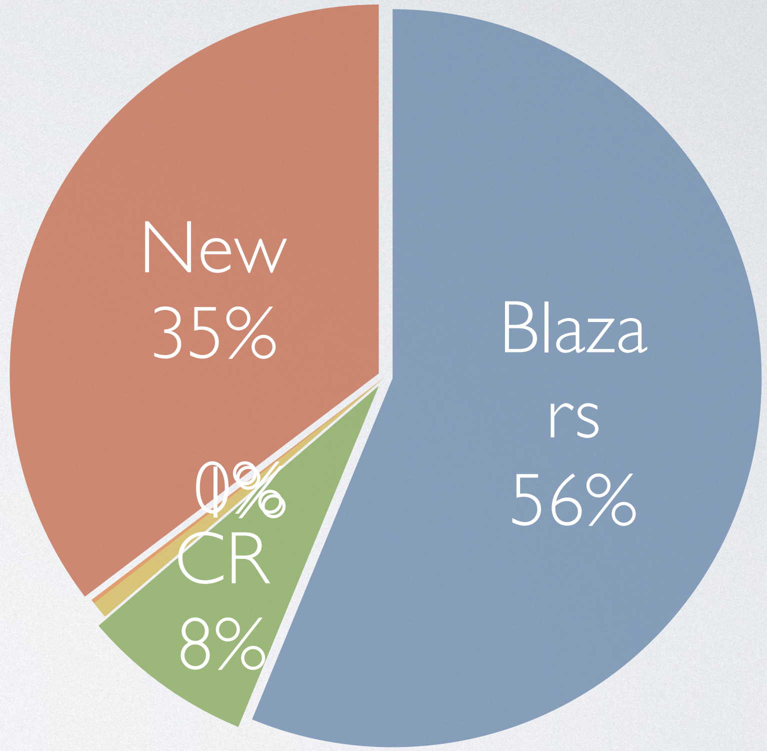
Murase 2019



Ahlers & Halzen 2018

SOURCES OF GAMMA RAYS

- 4FGL-DR3 contains 6658 gamma-ray sources !
- Jetted sources: blazars, radio galaxies and GRBs
- Cosmic-ray sources: pulsars, supernova remnants, stellar clusters, novae and star-forming galaxies



Outflows at Different Scales

$[r] = \mathrm{pc}$

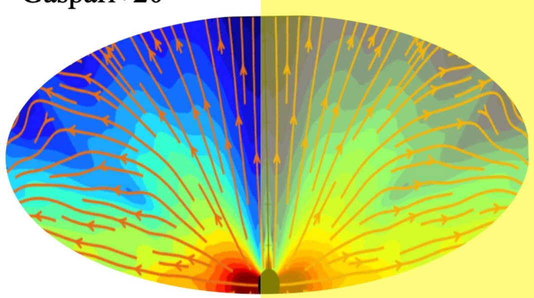
$[v] = \mathrm{km\ s^{-1}}$

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

SMBH → UFOs → BALs → WAs → NALs → Molecular, Neutral, Ionized → Bubbles → **R**

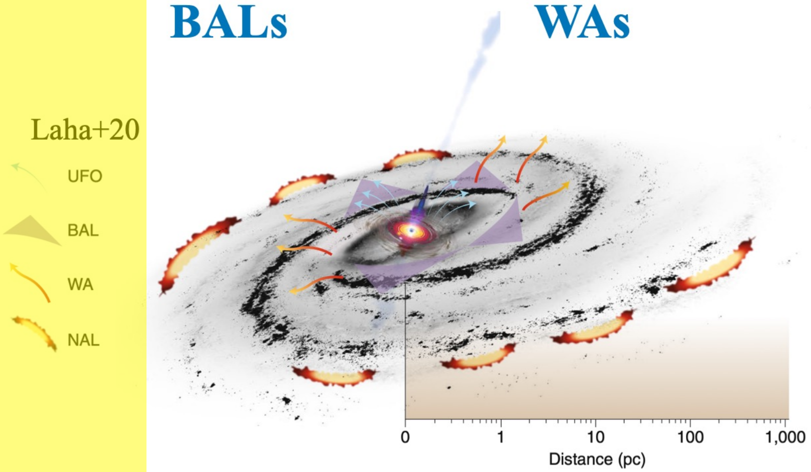
Can also be driven by starbursts

Gaspari+20

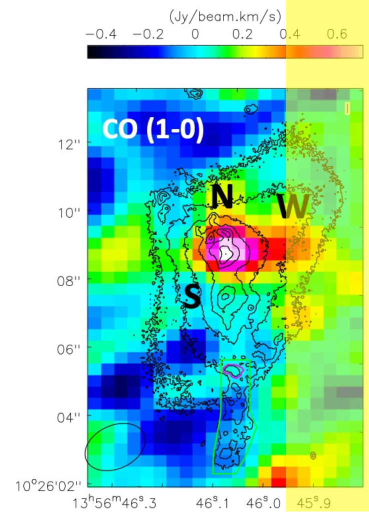


BH winds are driven by radiation pressure or MHD processes

Laha+20

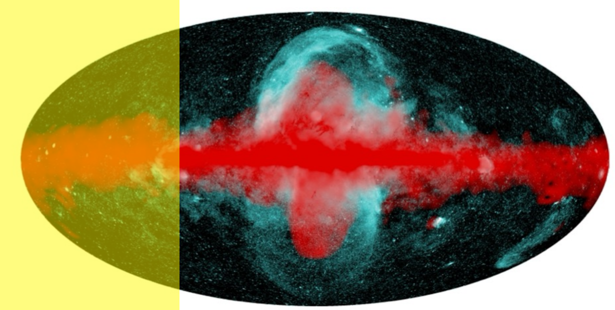


Detected in ~50-65% of AGN in the nearby Universe



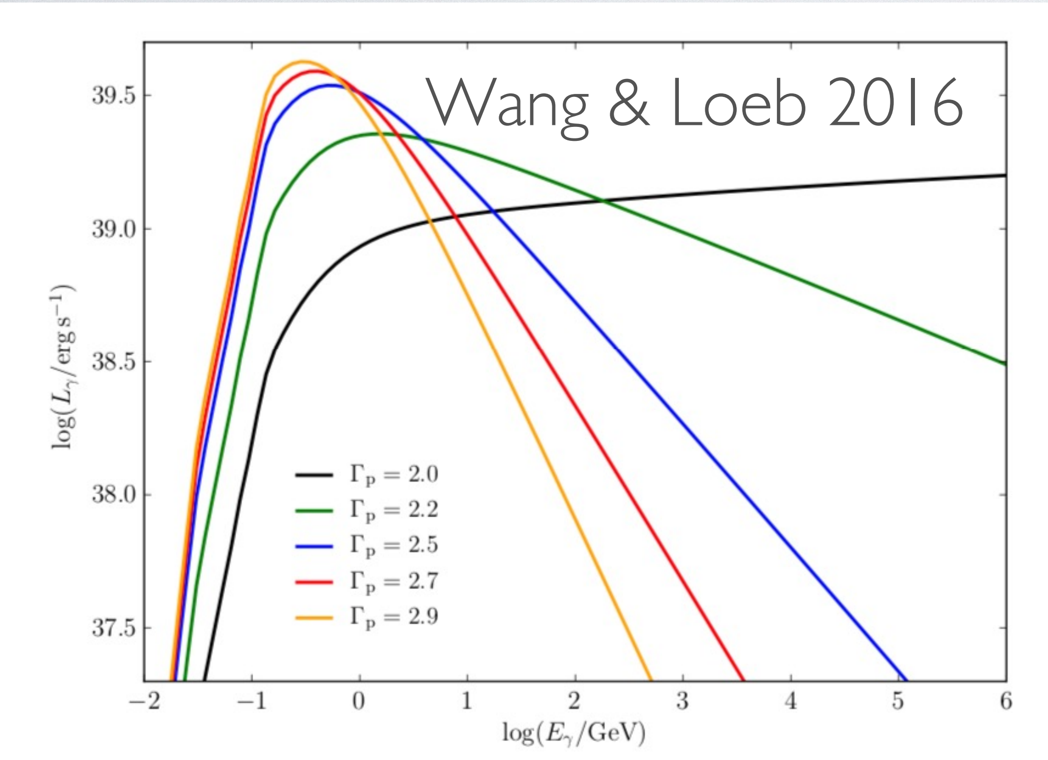
Sun+14

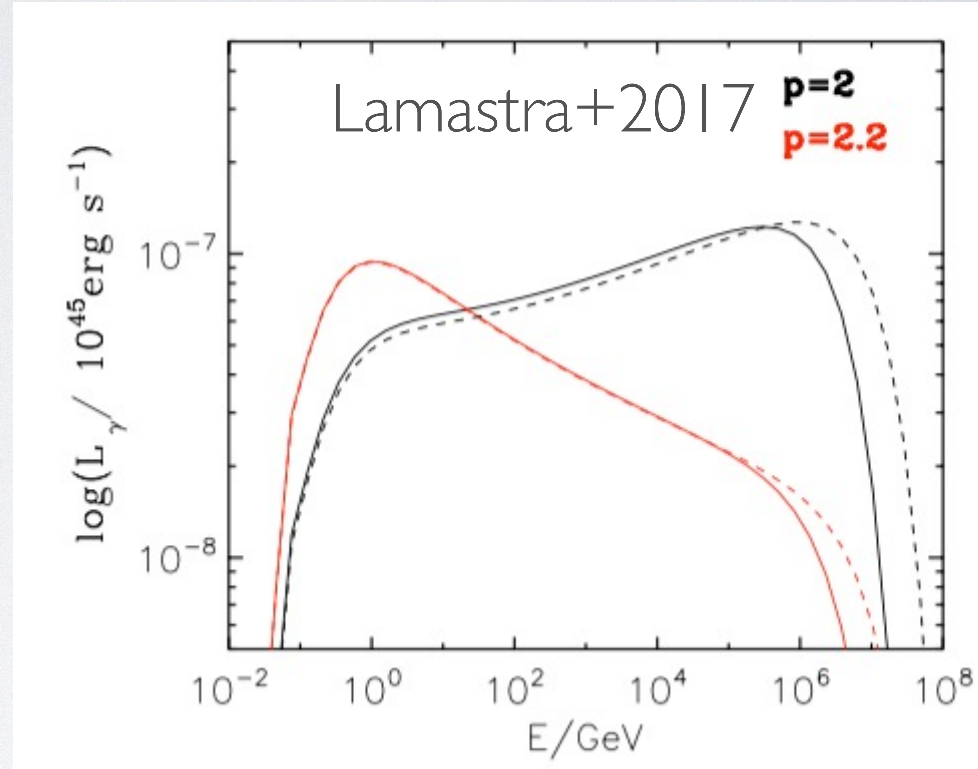
Predehl+20



Outflow types: momentum-driven, energy-driven

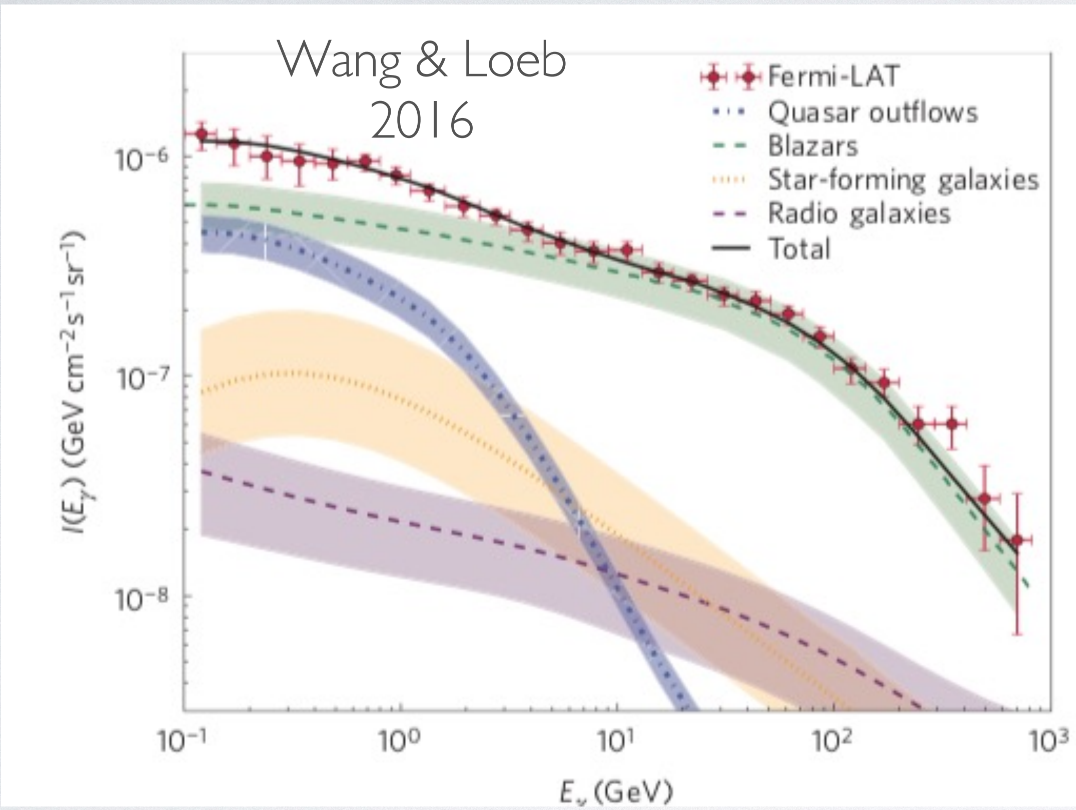
PREDICTIONS

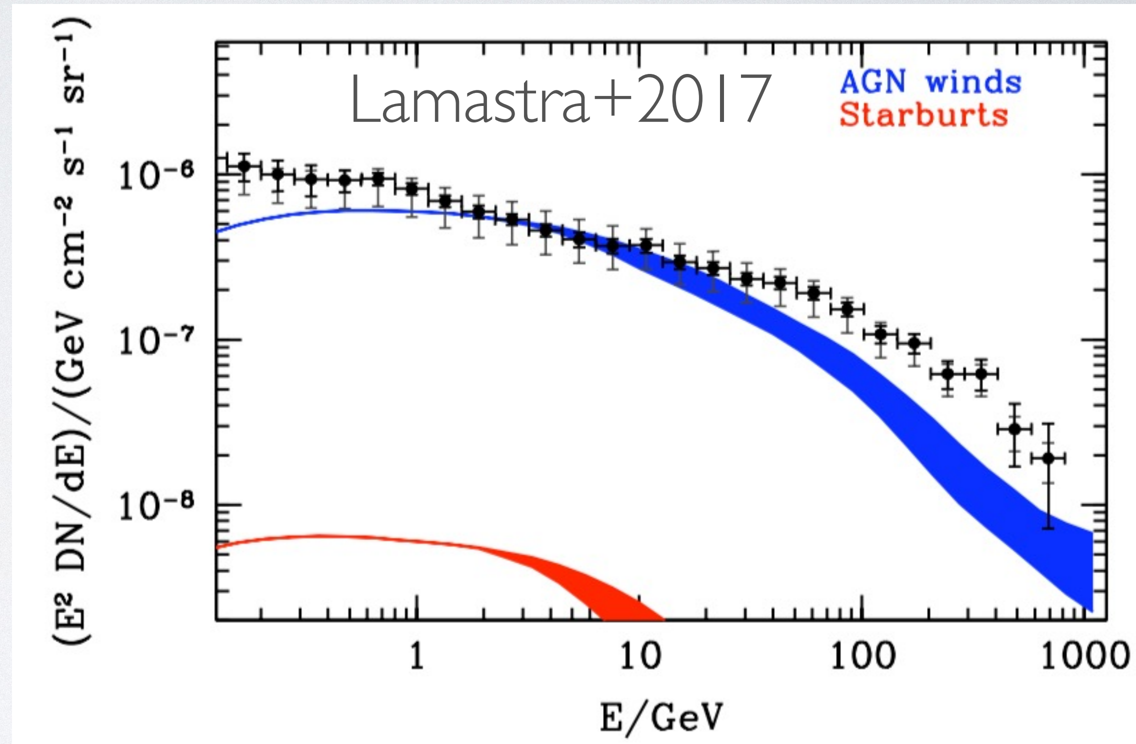




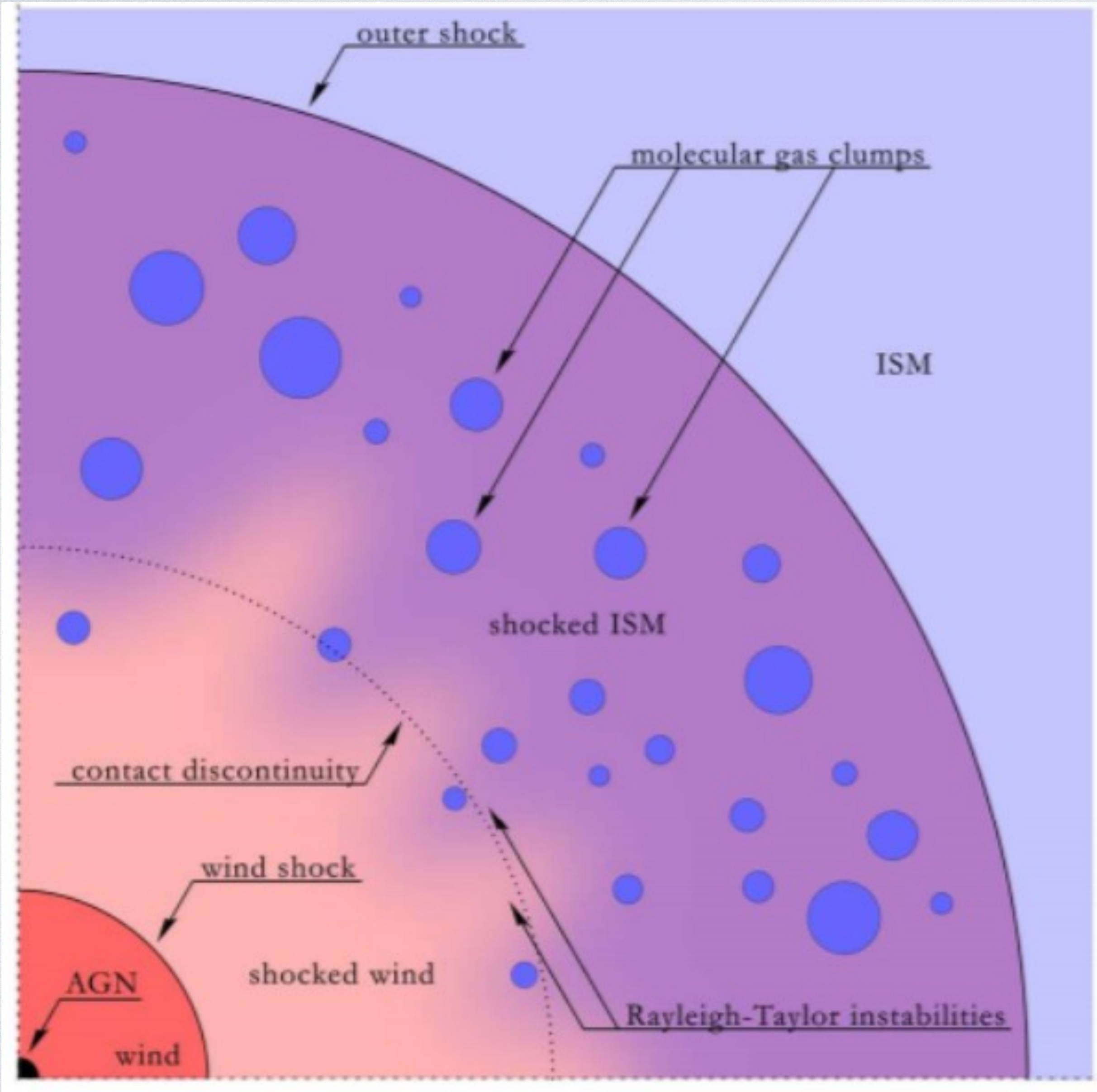
- Several prediction on the emission from AGN winds (Wang and Loeb 2016, Lamastra+2017, Liu+2018)

PREDICTIONS





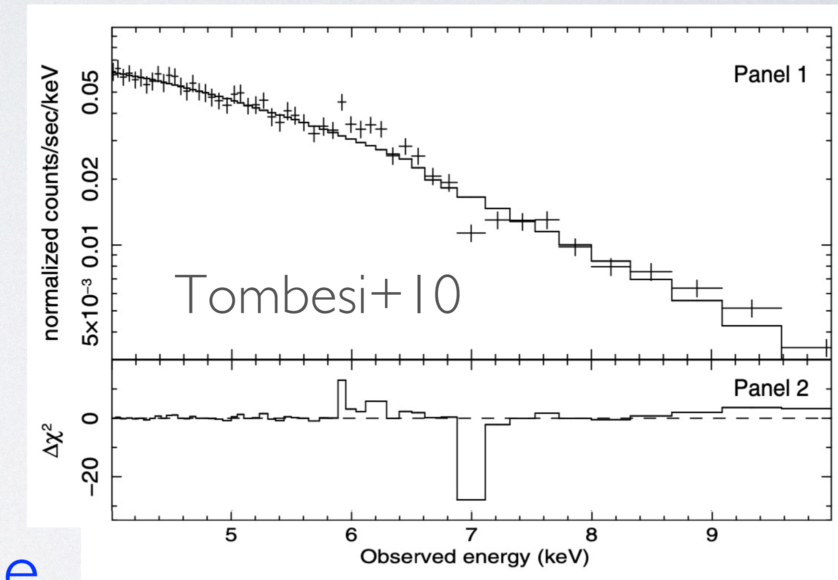
- Several prediction on the emission from AGN winds (Wang and Loeb 2016, Lamastra+2017, Liu+2018)



Schematic of an AGN driven outflow (Zubovas & King, 2014)

ULTRA-FAST OUTFLOWS

- UFOs are detected via blue-shifted Fe K-shell absorption lines in a large fraction (~30%) of nearby RL and RQ AGN (Reeves+03, Tombesi+10, Gofford+13)



  - Material is highly ionized and fast (v~0.1c)
  - Mass outflow rate: 0.01-1 $M_\odot$/yr
  - Kinetic power: $10^{42\text{-}45}$ erg/s
  - It may be a wind launched at the accretion disk scale

- AGN winds predicted to be (weak) gamma-ray and neutrino emitters (Wang and Loeb 2016, Lamastra et al 2017, Liu et al. 2018, etc.)

SAMPLE SELECTION - UFOS

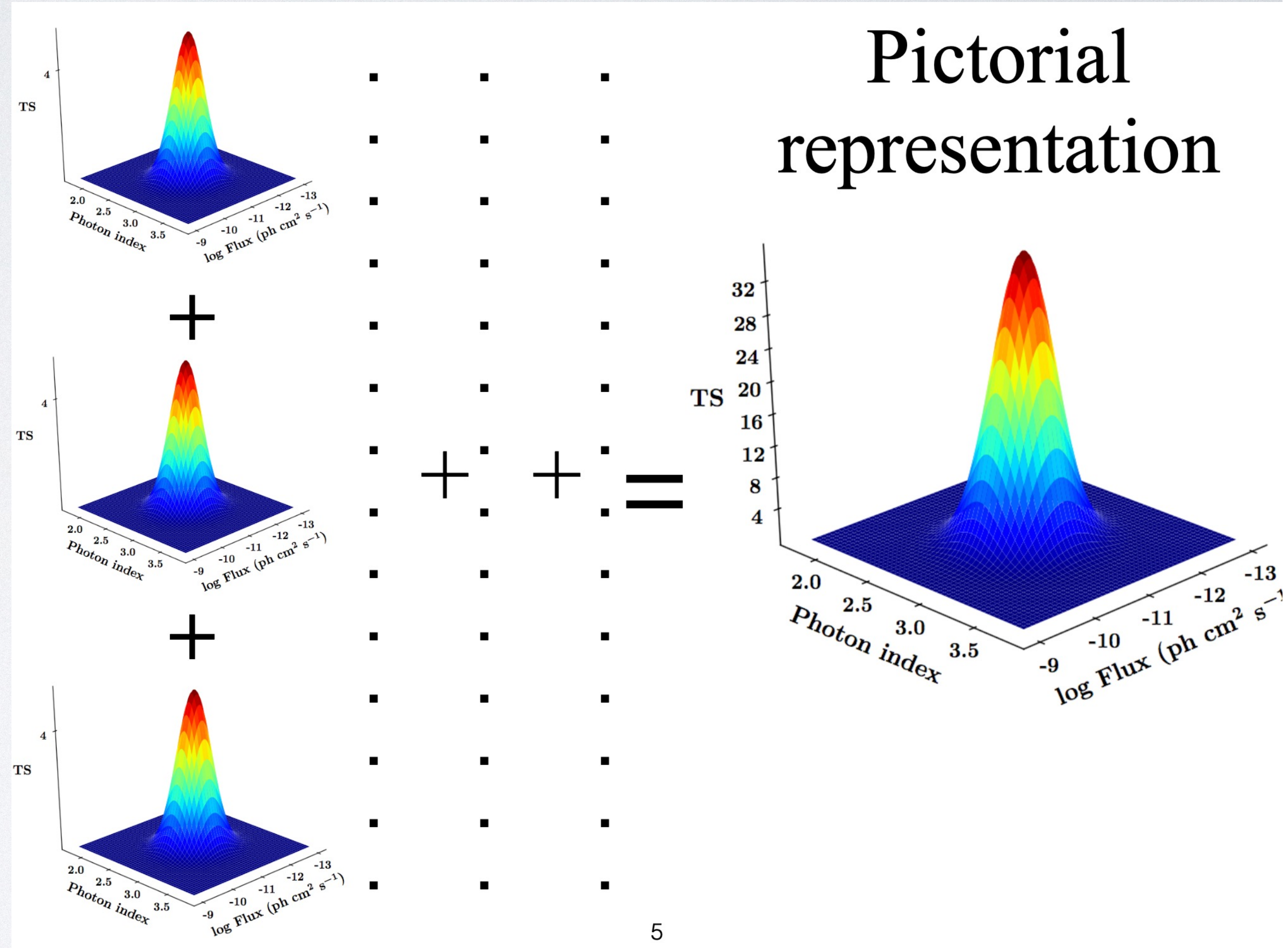
- The predicted gamma-ray luminosity of $\sim 10^{40}$ erg/s makes them virtually too faint to be detected by the LAT
- We chose the 11 RQ UFOs that have $z<0.1$ and $v>0.1c$ (Tombesi+10, Gofford+13)
- In 11 years of Fermi-LAT data, none of them are detected individually

SAMPLE SELECTION - UFOS

Name (1)	R.A. (deg) [J2000] (2)	Decl. (deg) [J2000] (3)	Type (4)	Redshift [z] (5)	Velocity [v/c] (6)	$\log M_{\rm BH}$ [$M_\odot$] (7)	$\log \dot{E}_K^{\rm Min}$ [erg s^{-1}] (8)	$\log \dot{E}_K^{\rm Max}$ [erg s^{-1}] (9)	$\log L_{\rm Bol}$ [erg s^{-1}] (10)	95% UL ($\times 10^{-11}$) [ph cm^{-2} s^{-1}] (11)
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]	7.5
									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[l]	4.3
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]	10.6
									42.9[h]	
									43.9[i]	
									42.9[j]	
									43.2[k]	
									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]	3.7
									44.8[h]	
									44.7[j]	
									45.0[k]	
									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]	3.4
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]	6.4
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]	4.5
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]	9.5
									44.3[h]	
									45.3[i]	
									44.3[j]	
									44.5[k]	
									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]	9.1
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]	7.4
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]	4.7

STACKING ANALYSIS OF FERMI-LAT DATA

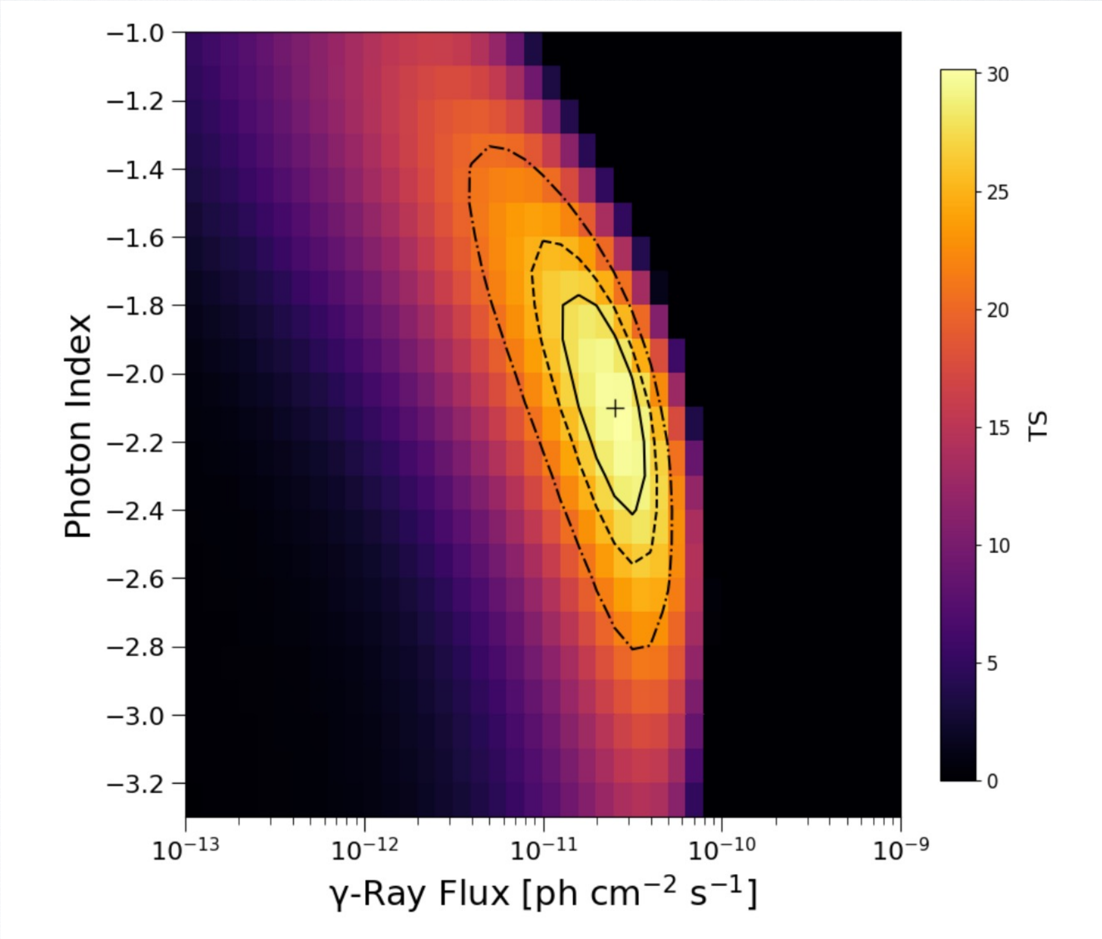
- Stacking = simultaneous fit to the gamma-ray data of the 11 sources to determine best-fit index and flux
- We evaluate the hypothesis of whether the population can be characterized by an average index and flux
- We use data in the 1-800 GeV range



Stacking used for EBL, star-forming galaxies, extreme HBLs (Abdollahi+18, Ajello+20, Paliya+19)

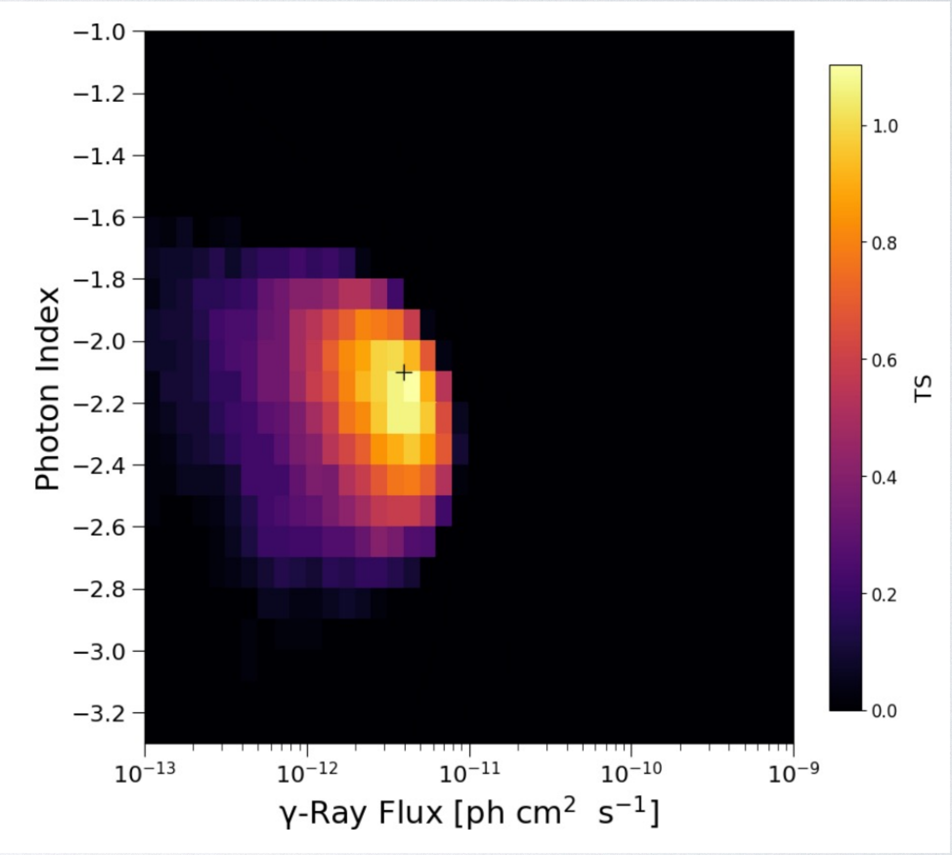
STACKING RESULTS

- Emission of UFOs detected at the ~5.2σ level
- Best-fit index = 2.1(+/-0.3)
- Best-fit flux =2.51(+1.47/-0.93)e-11 ph cm^{-2} s^{-1}



CONTROL SAMPLE & TESTS

- No emission detected in control sample (AGN with no UFOs from Tombesi+10/12 and Igo+20)
- Emission detected also in the UFO sample Igo et al. 2020
- UFO Emission is a factor x40 brighter than what expected from star-forming activity
- Objects are all radio quiet by selection



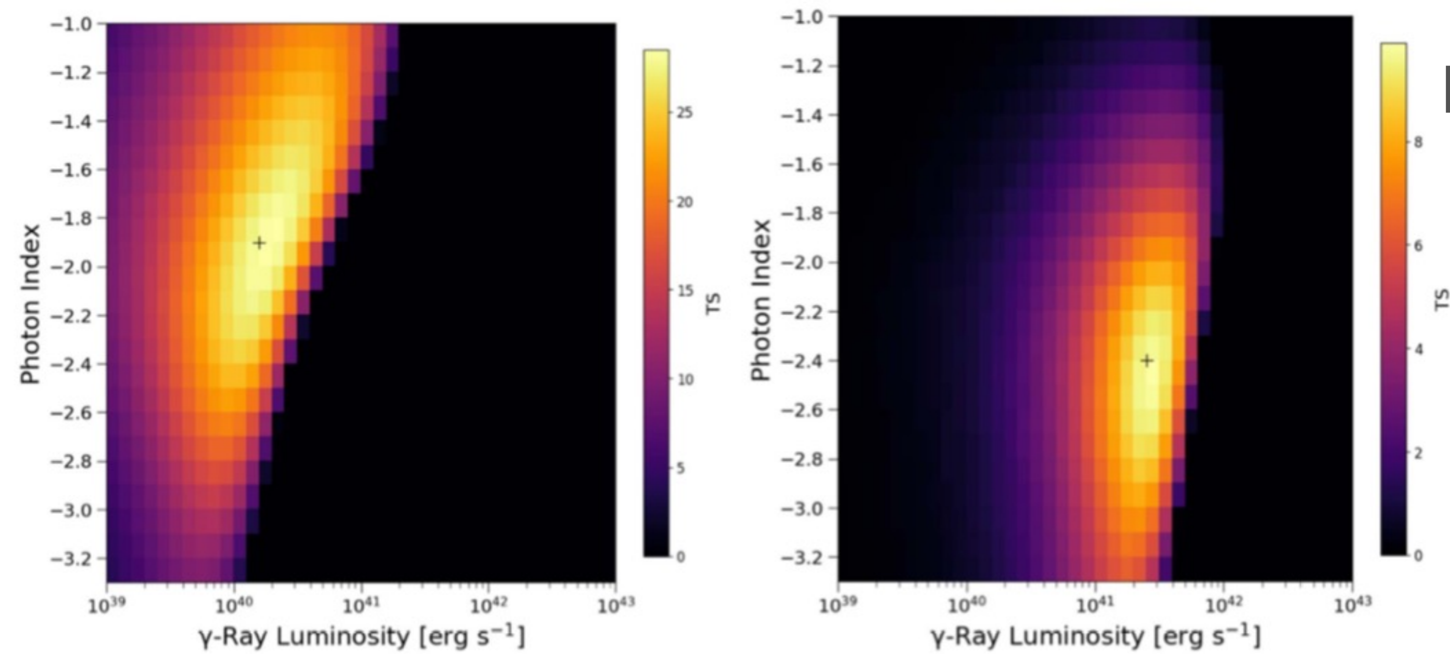
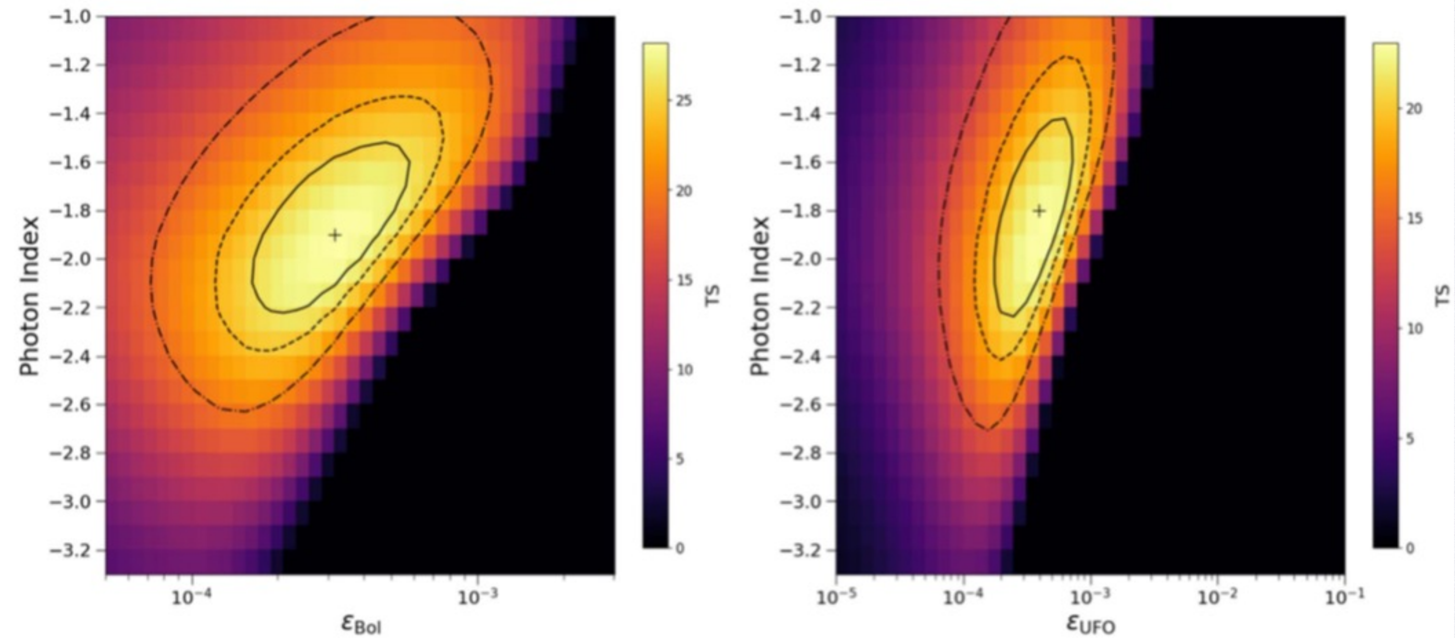


Figure 4. Stacked profiles for bins of bolometric luminosity (the mean kinetic power bins are also the same). The left and right panels show the stacking for sources with bolometric luminosity (or kinetic power) below and above the average, respectively. The color scale indicates the TS and is set to the maximum value for each bin. The black plus sign gives the best-fit parameters. The first bin consists of five sources, with a maximum TS of 28.5 (5.0σ); and the second bin consists of six sources, with a maximum TS of 9.9 (2.7σ).

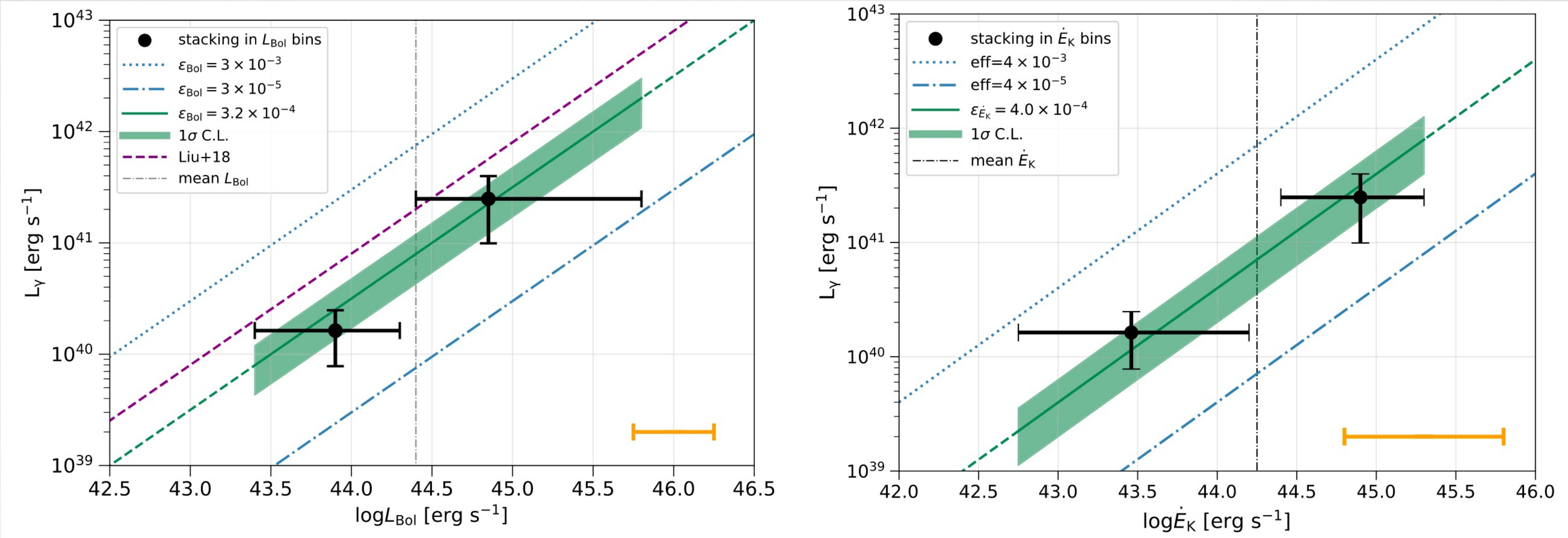


More Luminous AGN are brighter in gamma rays

Stacking in bins of bolometric luminosity

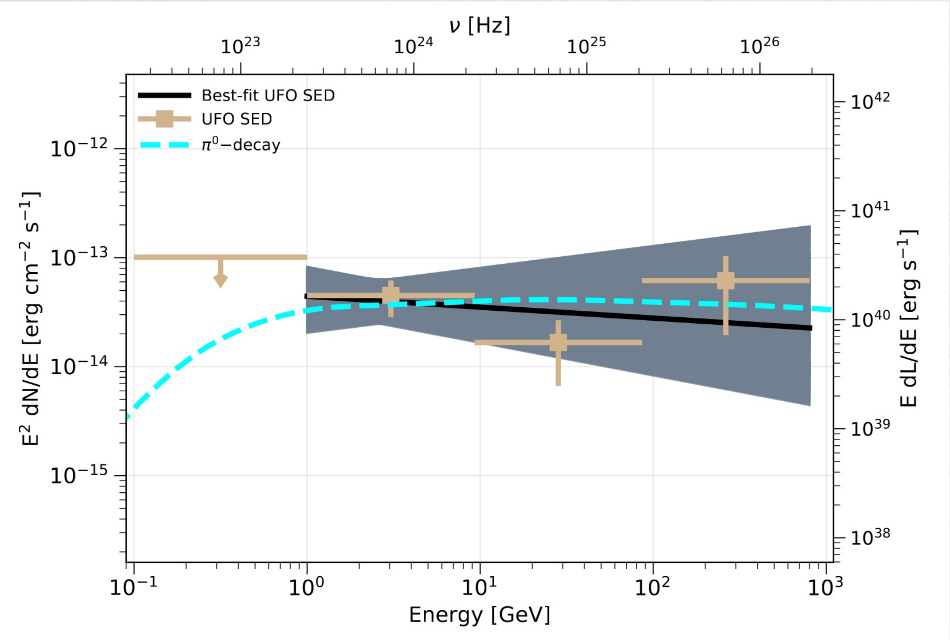
Stacking in bins of L_γ/L_{bol}

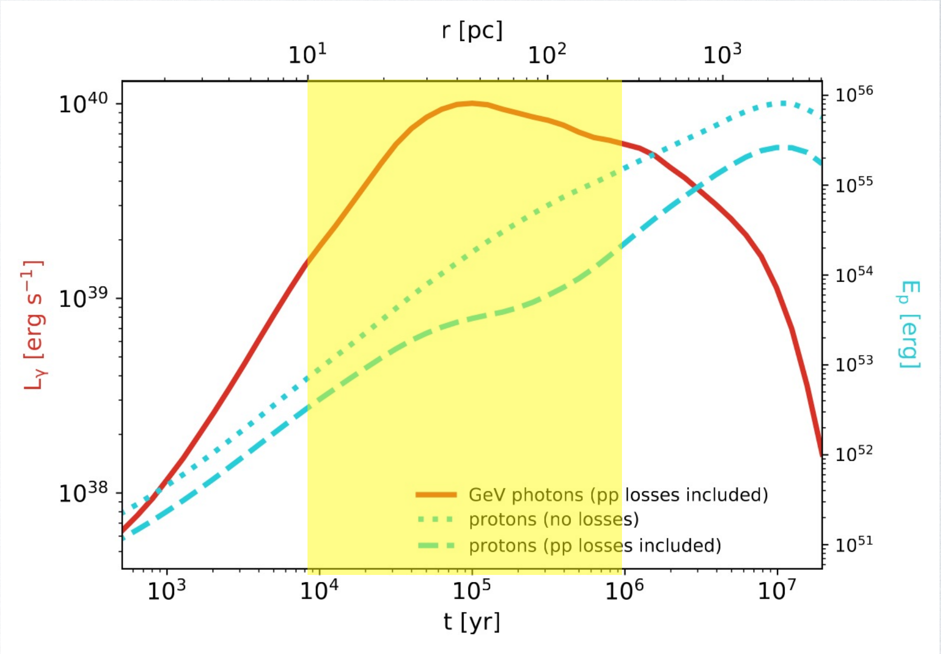
SCALING OF GAMMA-RAY LUMINOSITY



- The gamma-ray luminosity scales with the AGN Bolometric luminosity and the UFO Kinetic power
- UFOs transfer 0.04% of their mechanical power to γ rays (comparable to SN explosions)
  - i.e. UFOs can energize (if sustained for a few million years) a large fraction of the CR population

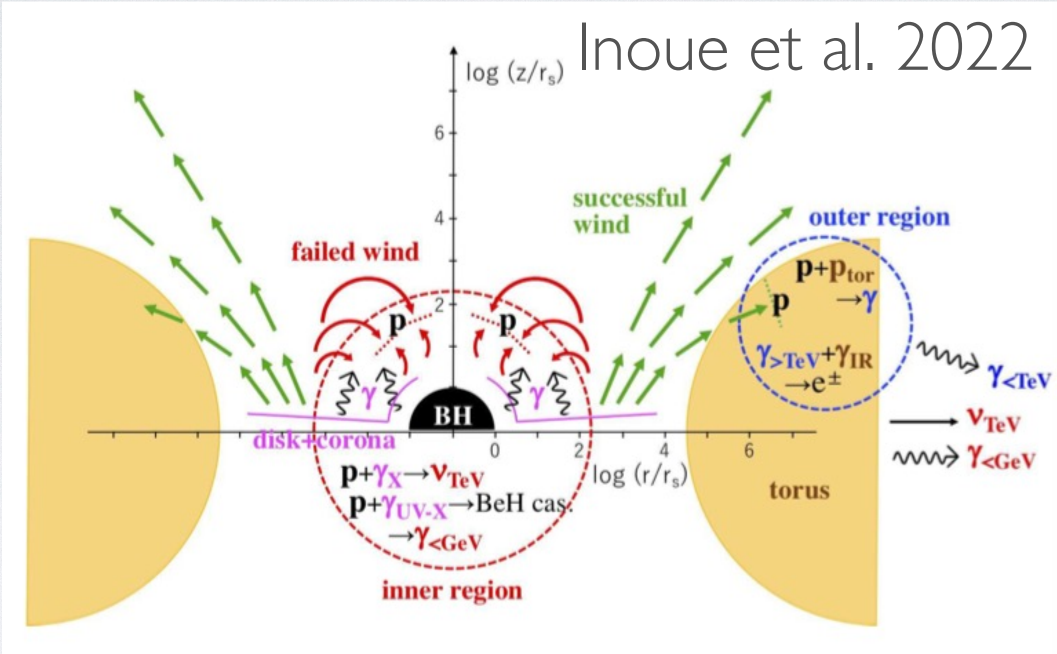
INTERPRETATION





- SED interpreted as the hadronic emission of a population of CRs accelerated at the shock front
  - Leptonic emission would be too faint and too steep to explain the SED
- It implies a shock that has traveled (10-200pc) from the SMBH
- Estimated maximum proton energy of 10^{17} eV (measured photon energy of ~300 GeV)
  - They can contribute to the IceCube neutrinos, but need CTA to detect >1 TeV photons
- The shock transfers 1e56 erg to the bubble of hot plasma in 1-3 Myr (see e.g. Fermi/eROSITA bubbles)

ALTERNATIVE INTERPRETATION



- Protons accelerated near the AGN via diffusive shock acceleration
- pγ from failed AGN wind and AGN emission
- pp when the AGN wind collides with the torus

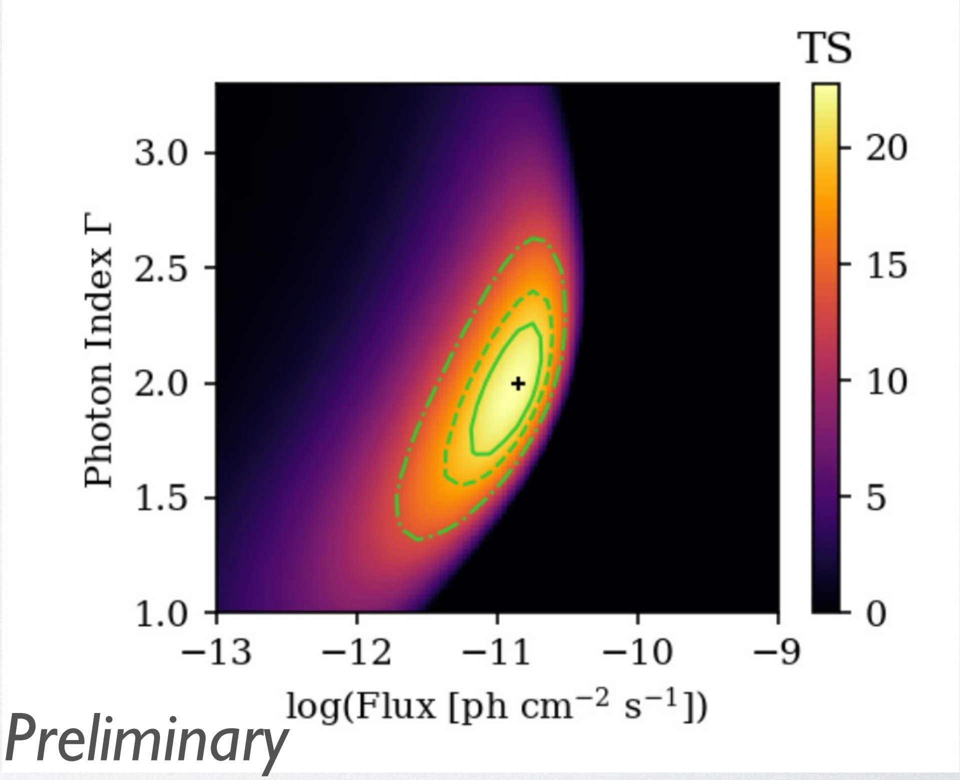
MOLECULAR OUTFLOWS

MOLECULAR OUTFLOWS

- Sample of 45 ($z<0.2$) galaxies with a molecular outflow (Fluetsch et al. 2019)
  - CO (1-0), CO(2-1) transitions
  - Mass outflow rate: 1-1500 $M_{\odot}$/yr
  - Kinetic power: 10^{40-45} erg/s
- After cleaning:
  - 7 detected ones (NGC 1068, 253, etc)
  - 29 undetected objects

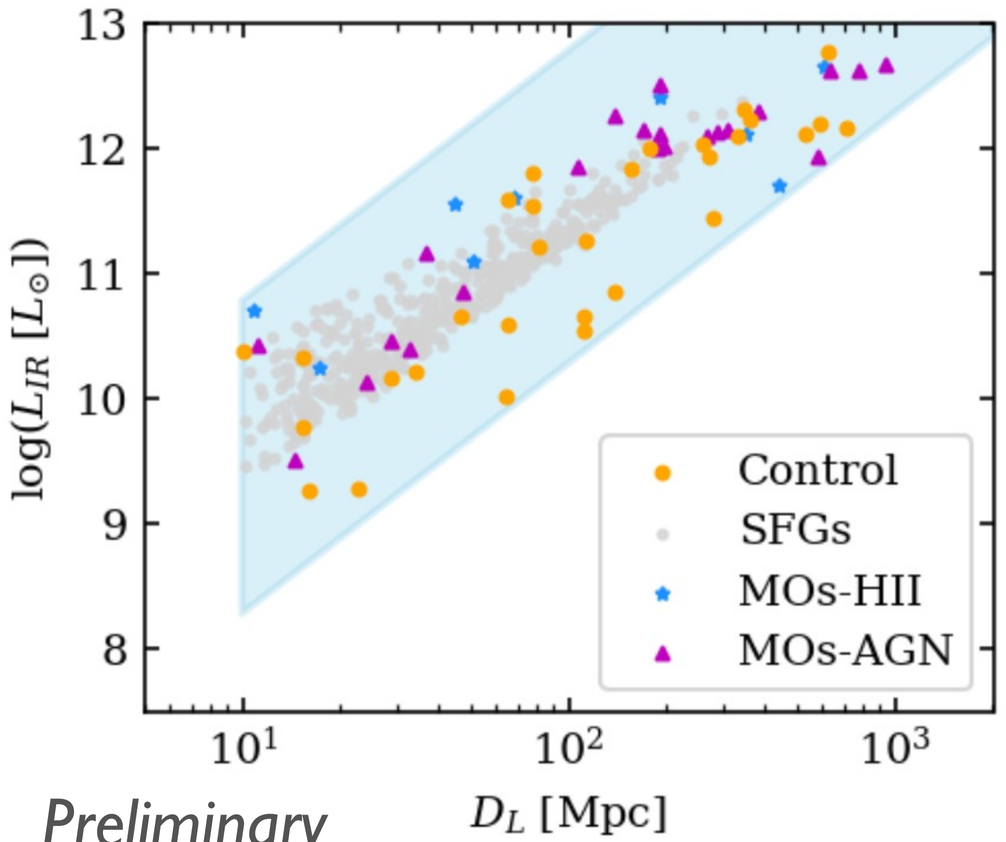
MOLECULAR OUTFLOWS

- Sample of 37 galaxies with a molecular outflow (Fluetsch et al. 2019)
    - CO (1-0), CO(2-1) transitions
- After cleaning: 29 objects at z<0.2
    - Mass outflow rate: 1-1500 $M_\odot$/yr
    - Kinetic power: $10^{40\text{-}45}$ erg/s
- Emission detected at 4.4 σ

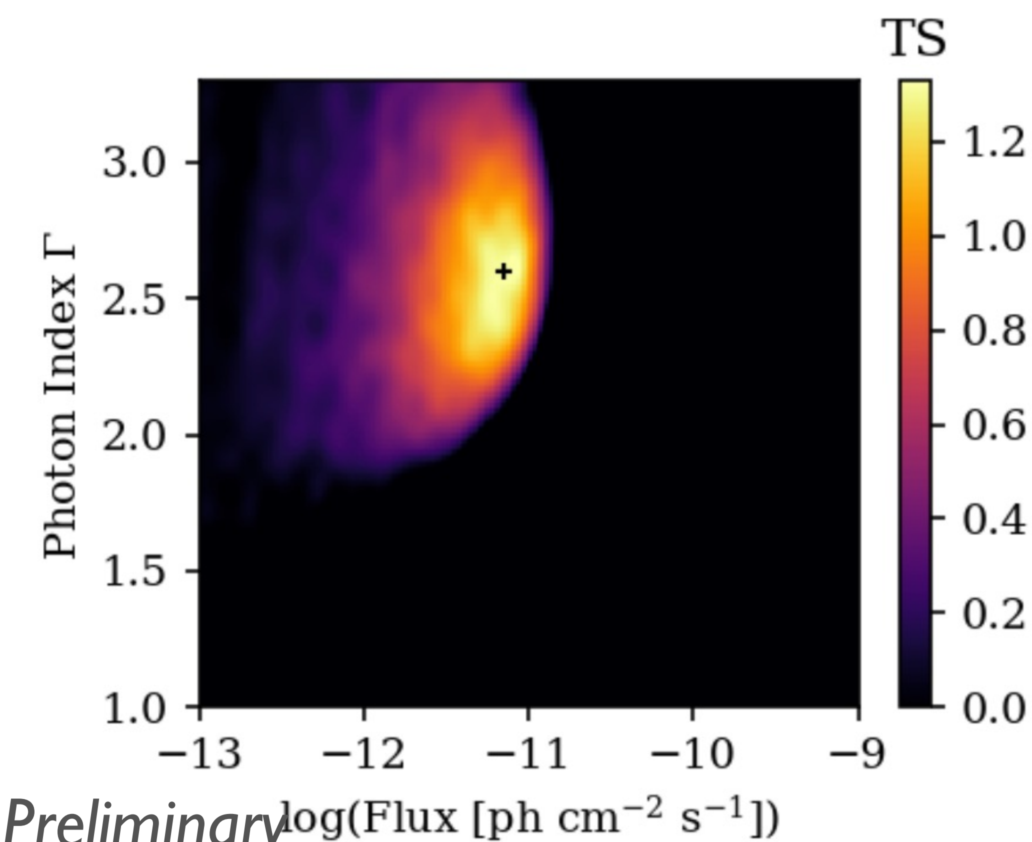


MOLECULAR OUTFLOWS & STAR FORMATION

MOS - CONTROL SAMPLE

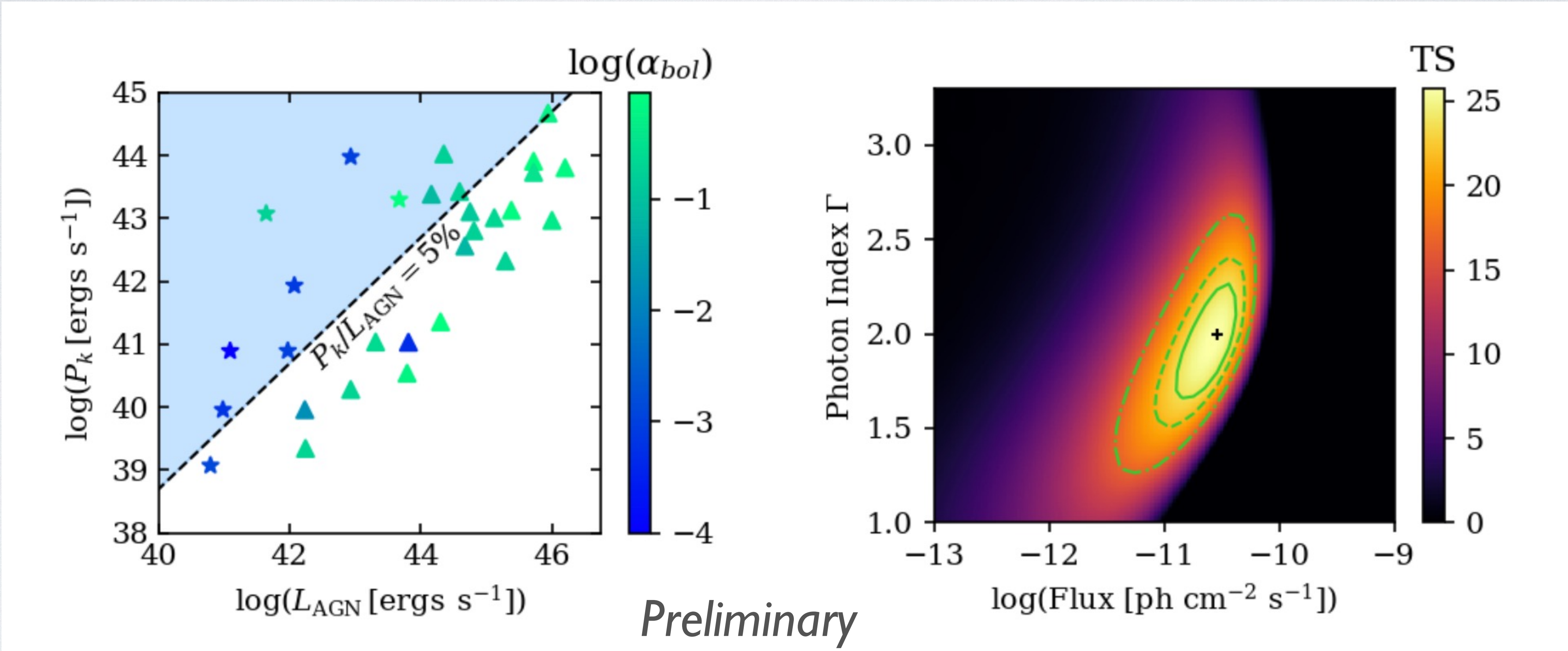


Preliminary



Preliminary

ENERGY DRIVEN REGIME



- Signal from galaxies (stars) with outflows in an energy driven regime

CORRELATIONS

- No correlation between the gamma-ray emission and the properties of the outflow or the AGN
    - i.e. no sign of direct particle acceleration by the outflow

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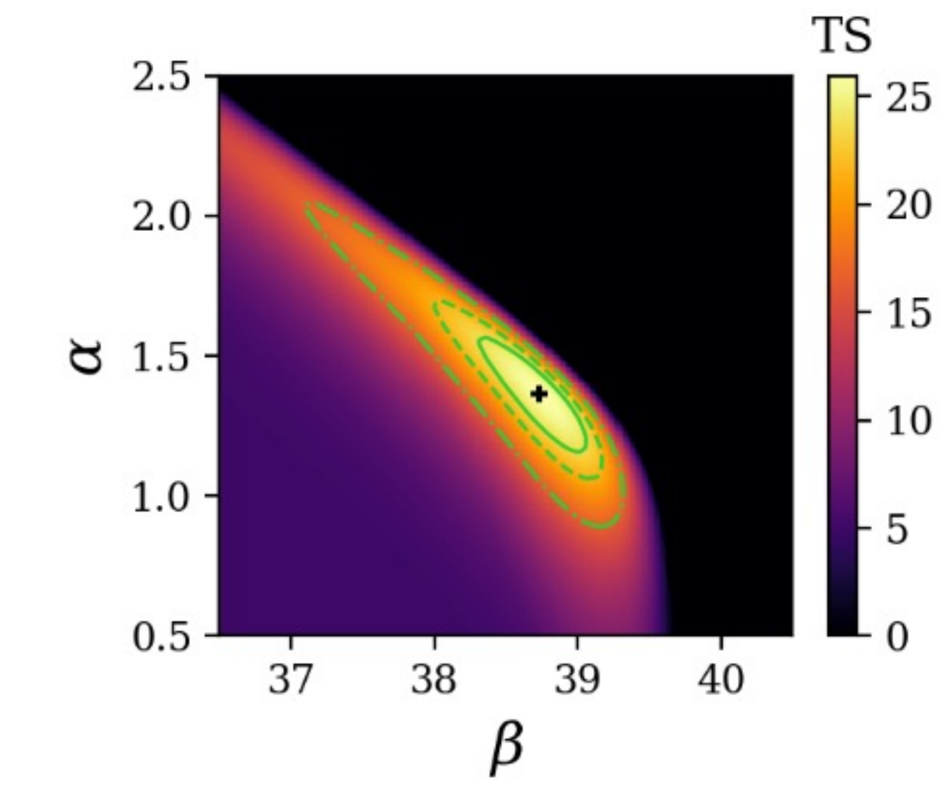
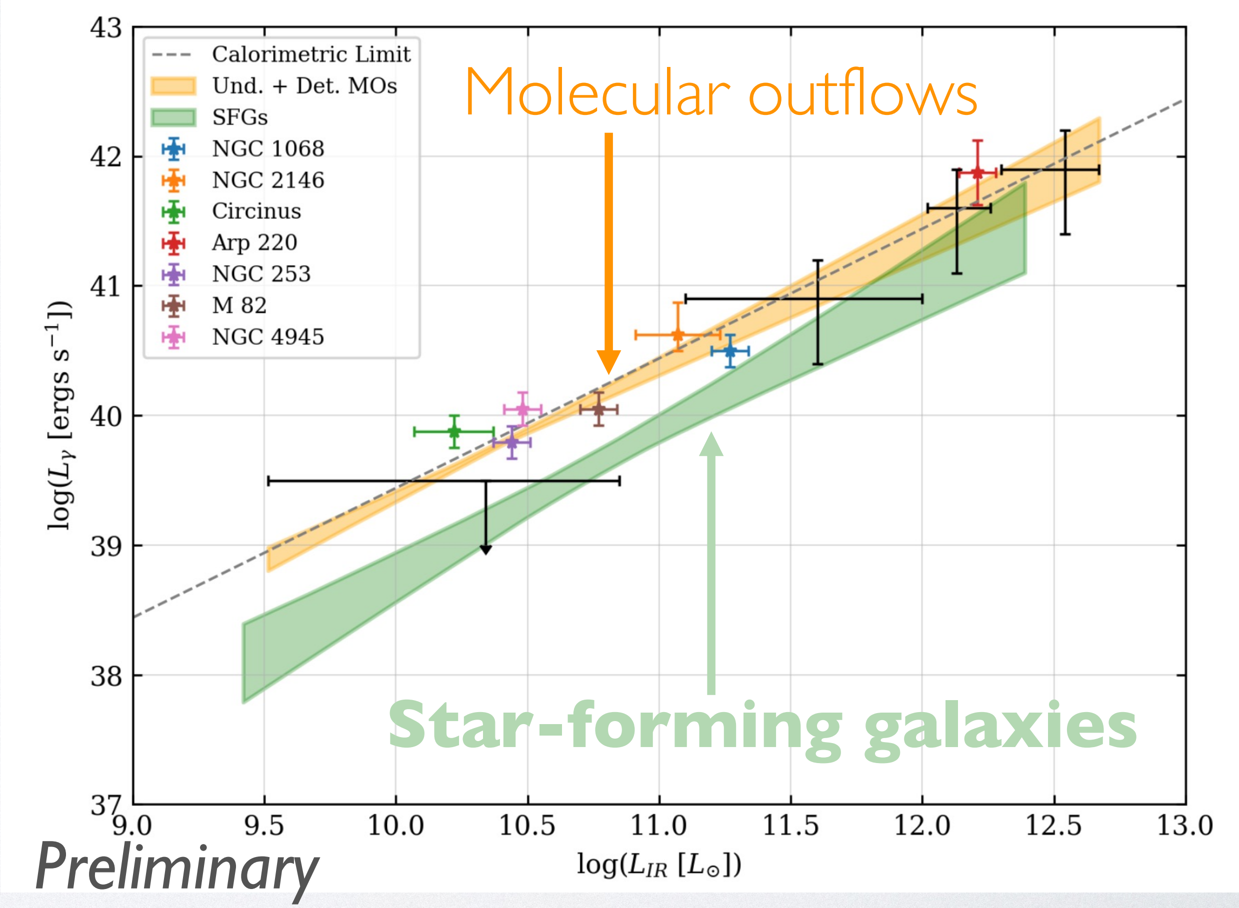
- No correlation between the gamma-ray emission and the properties of the outflow or the AGN
    - i.e. no sign of direct particle acceleration by the outflow
- The gamma-ray luminosity correlates well with the total IR luminosity (as seen in star-forming galaxies, e.g. Ajello+2020)



$$\log_{10}\left(\frac{L_\gamma}{\mathrm{erg/s}}\right) = \beta + \alpha \log_{10}\left(\frac{L_{\mathrm{IR}}}{10^{10} L_\odot}\right).$$

CORRELATIONS

- No correlation between the gamma-ray emission with the properties of the outflow or the AGN
    - i.e. no sign of direct particle acceleration by the outflow
- The gamma-ray luminosity correlates well with the total IR luminosity



Galaxies with molecular outflows are nearly perfect calorimeters

SUMMARY

- **First detection of UFOs (Ajello+2021) and Molecular Outflows (McDaniel+2023) at gamma rays !**
- UFOs are directly accelerating CRs, possibly up to 10^{17} eV (depending on the interpretation)
  - they are as efficient as star formation at energize CRs
  - they can inflate bubbles
- No evidence of acceleration by Molecular Outflows
  - Molecular Outflows are nearly perfect calorimeters


THANK YOU !

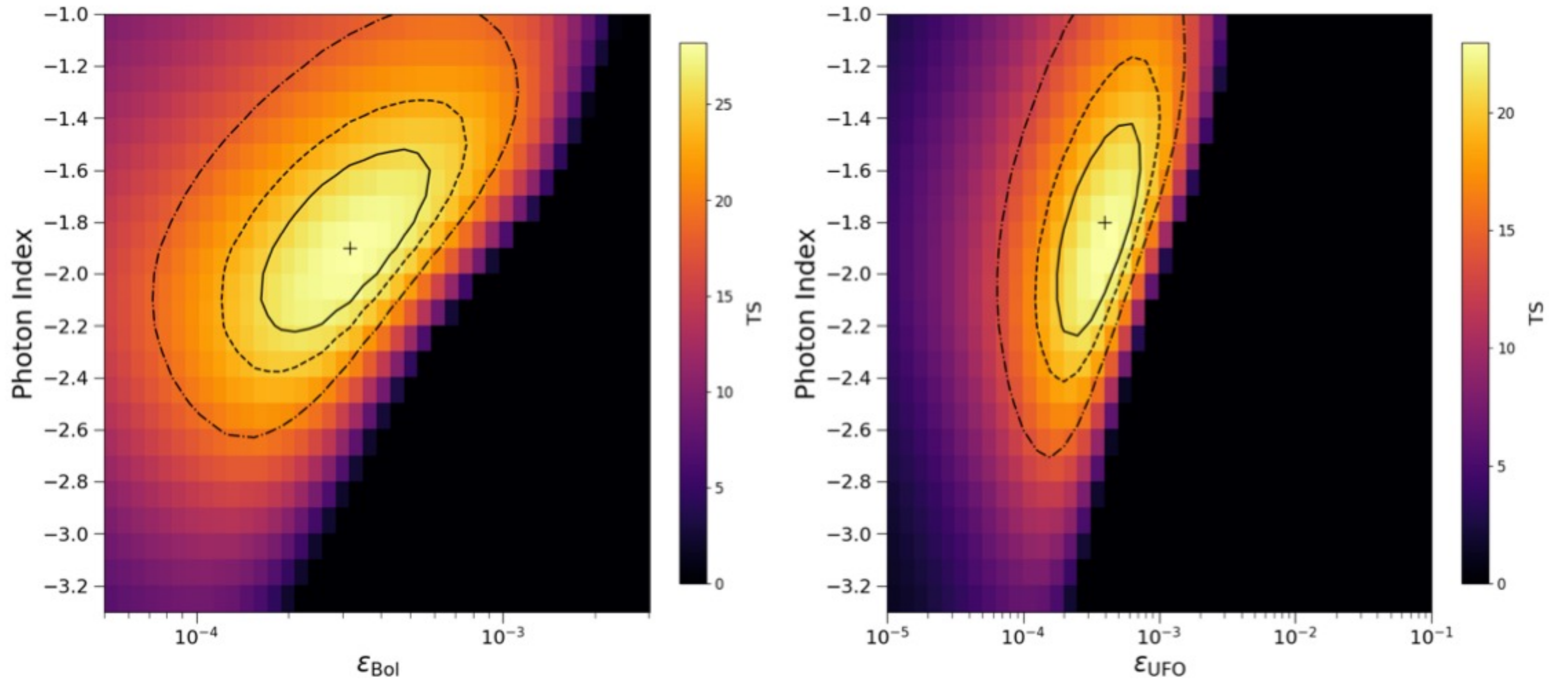
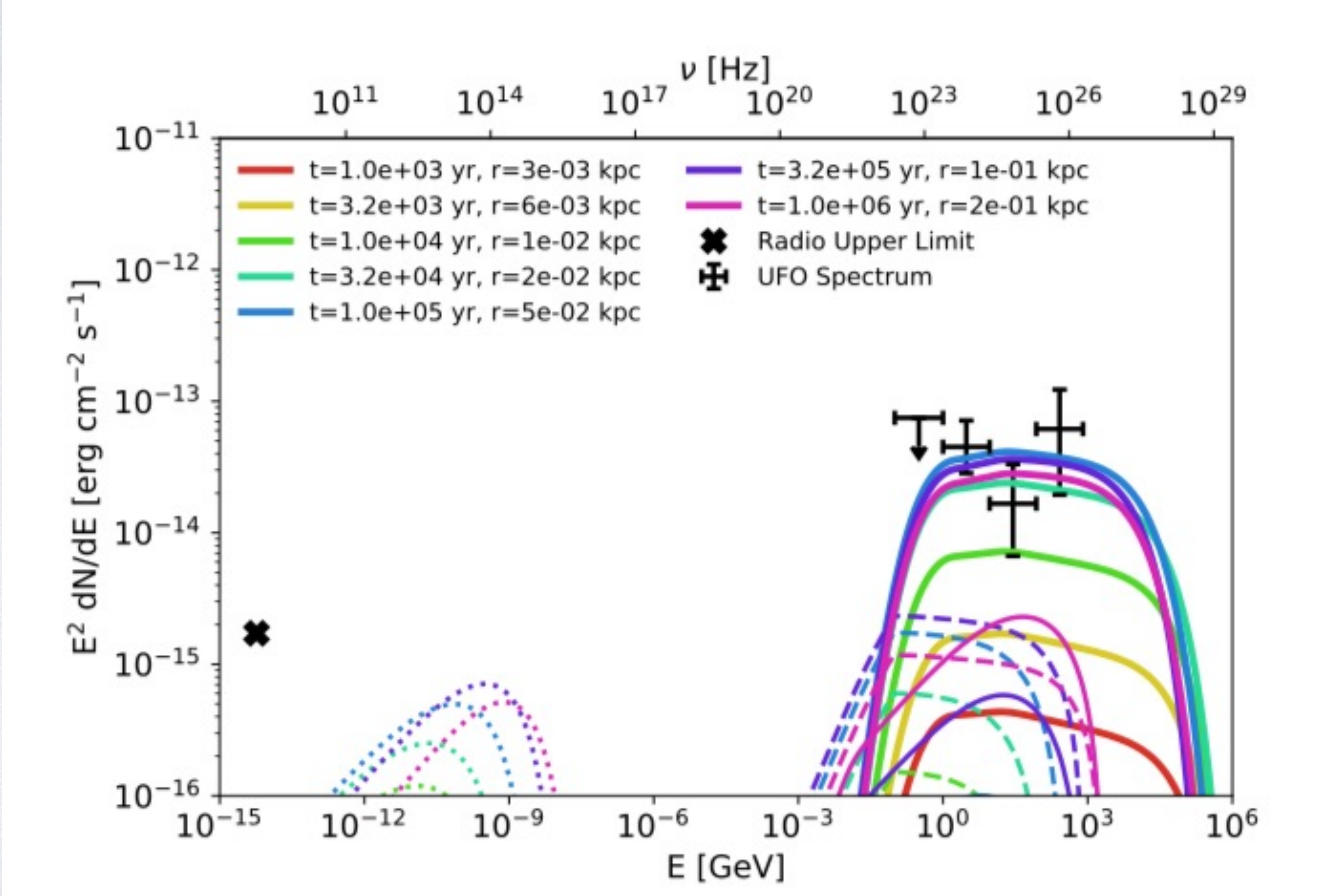


Figure 5. Stacked profiles for bolometric efficiency (left) and kinetic power efficiency (right). The color scale indicates the TS and is set to the maximum value. The black plus sign gives the best-fit parameters. Significance contours (for 2 degrees of freedom) are overlaid on the plot showing the 68%, 90%, and 99% confidence levels, corresponding to ΔTS $= 2.30$, 4.61, and 9.21, respectively.



ν [Hz]
10^11
10^14
10^17
10^20
10^23
10^26
10^29
E² dN/dE [erg cm⁻² s⁻¹]
10^-11
10^-12
10^-13
10^-14
10^-15
10^-16
t=1.0e+03 yr, r=3e-03 kpc
t=3.2e+03 yr, r=6e-03 kpc
t=1.0e+04 yr, r=1e-02 kpc
t=3.2e+04 yr, r=2e-02 kpc
t=1.0e+05 yr, r=5e-02 kpc
t=3.2e+05 yr, r=1e-01 kpc
t=1.0e+06 yr, r=2e-01 kpc
Radio Upper Limit
UFO Spectrum
10^-15
10^-12
10^-9
10^-6
10^-3
10^0
10^3
10^6
E [GeV]