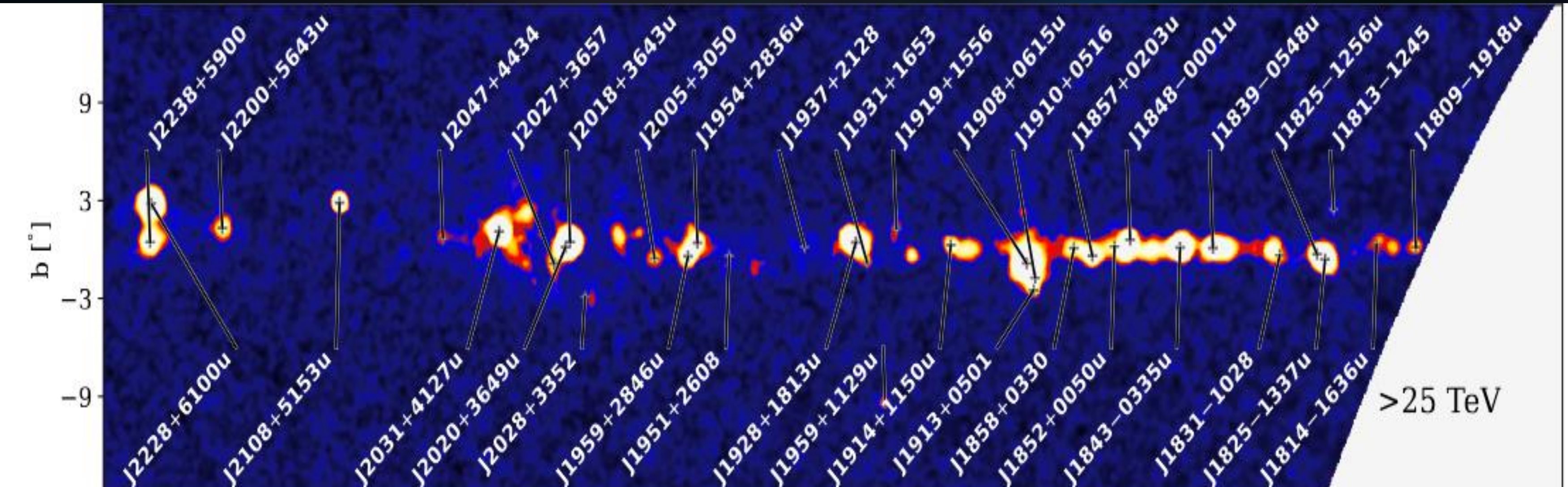
Traces of the Galactic Center PeVatron

Shuo Zhang
Department of Physics and Astronomy
Michigan State University

Identification of Individual PeVatron – a New Possibility

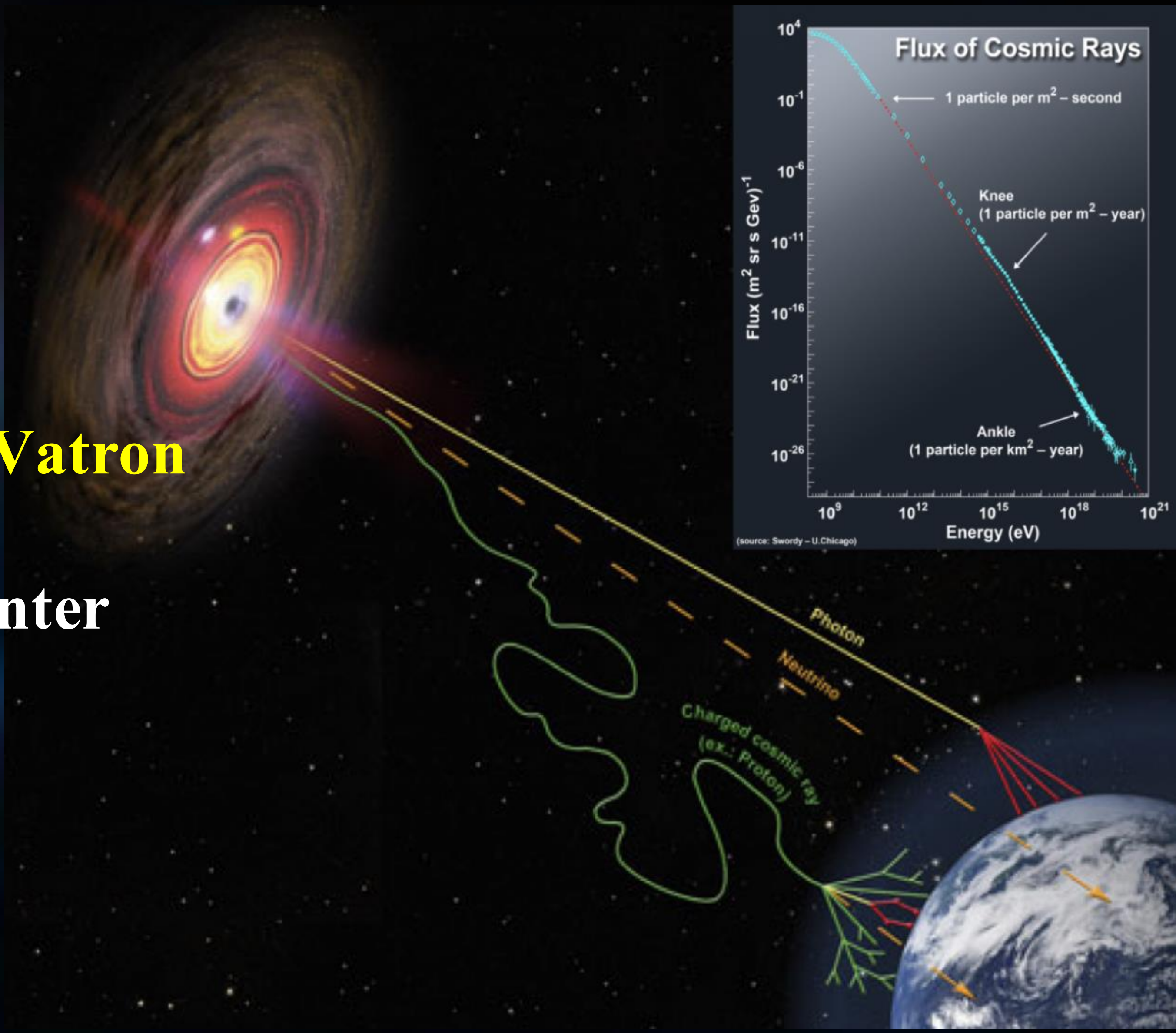
- IceCube detected neutrino at 4.5σ from the Galactic Plane (IceCube collab., Science, 2023)
- LHAASO released the 1st catalogue of UHE sources (Cao+, Nature, 2021; ApJs, 2023, etc.)
- These recent discoveries made identification of individual PeVatrons a new possibility, and

calls for identification of Galactic hadronic PeVatrons as required by the IceCube results.

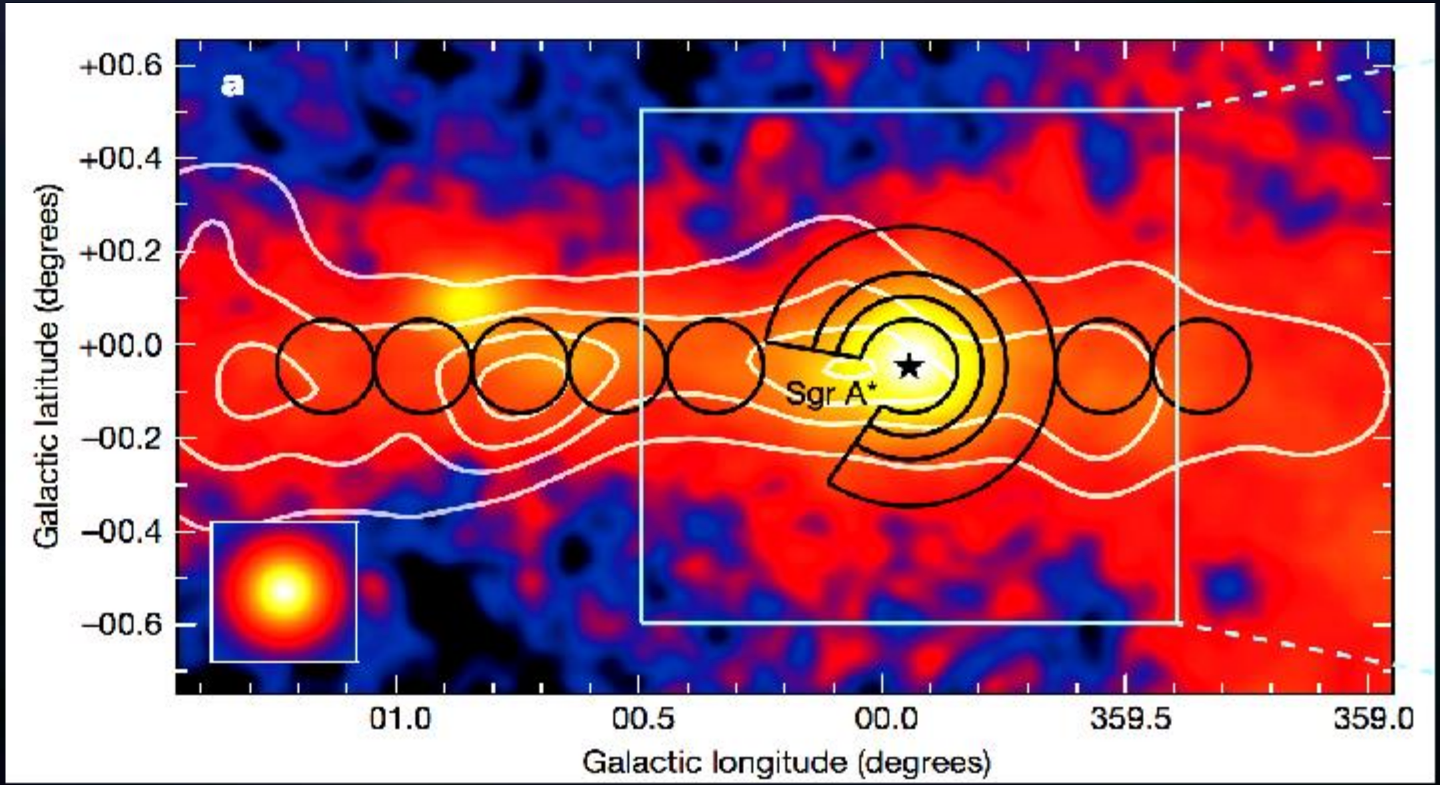


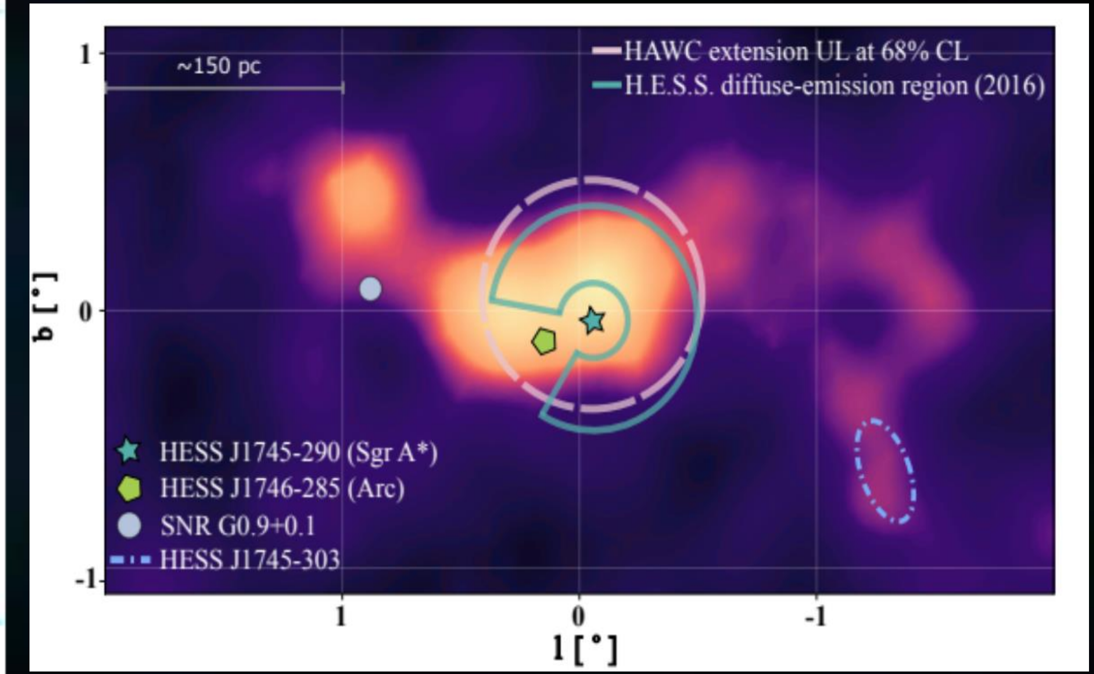
Outline

- The Galactic Center Hadronic PeVatron
- PeVatrons outside of Galactic Center



Galactic Center PeVatron





- H.E.S.S. discovered a Galactic Center PeVatron coinciding with Sgr A* (H.E.S.S., Nature, 2016)
- HAWC detection up to 114 TeV without cut-off confirmed it (Huang et al., ApJL 2024)
- ➔ Is Sgr A* the Galactic Center PeVatron? If so, what observational effects can we detect?

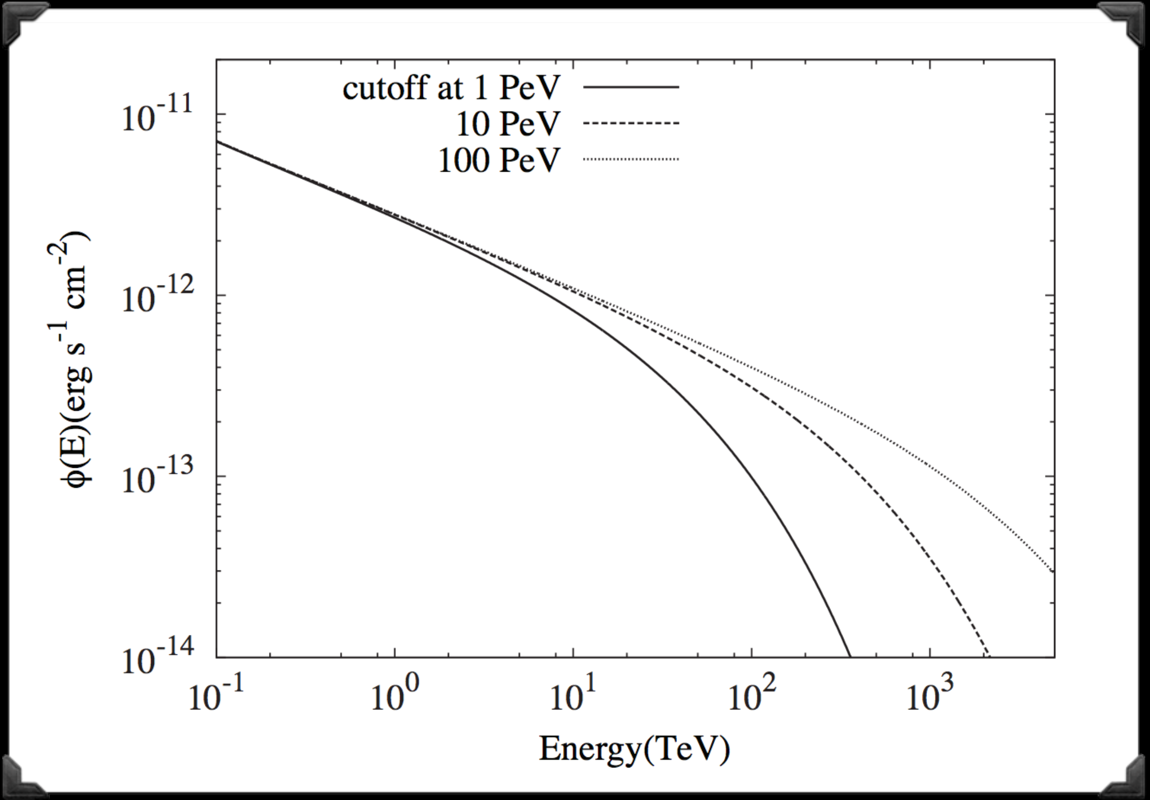
Multi-wavelength and Multi-messenger signatures of Galactic Center PeVatron

- Secondary particles from *p*-*p* interaction of PeV proton and nuclei in ambient gas:

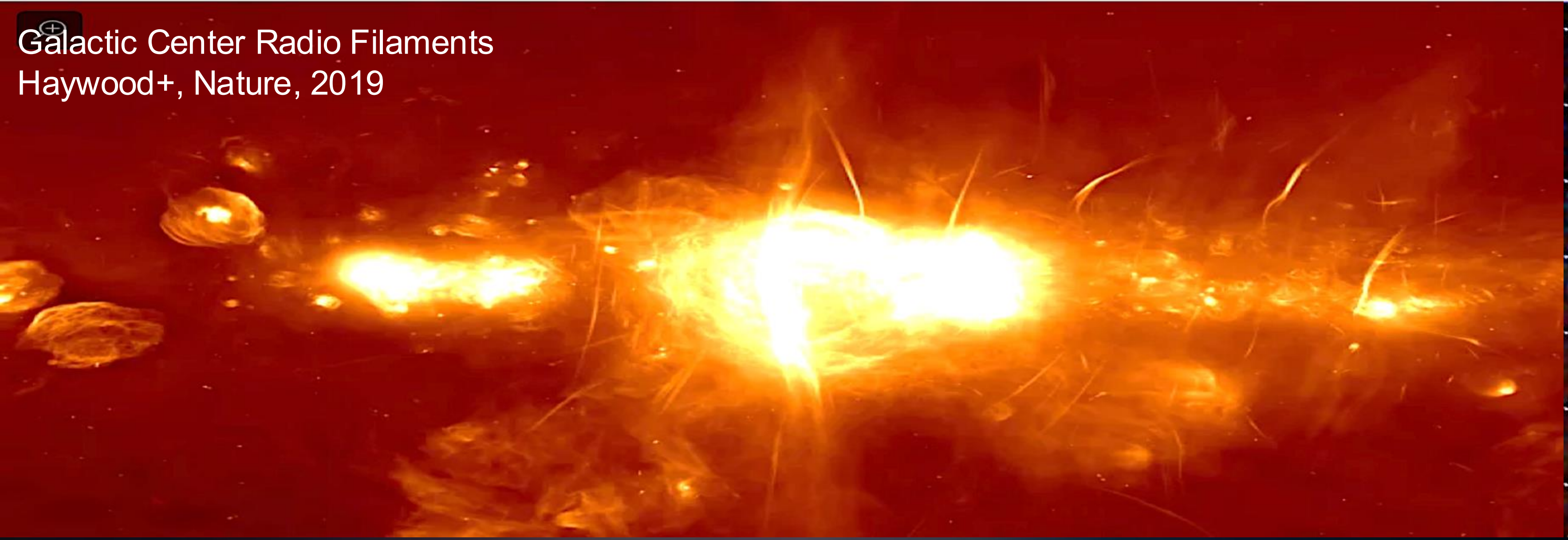
- **<u>Multi-TeV neutrinos</u>**: theoretically detectable by current neutrino detectors

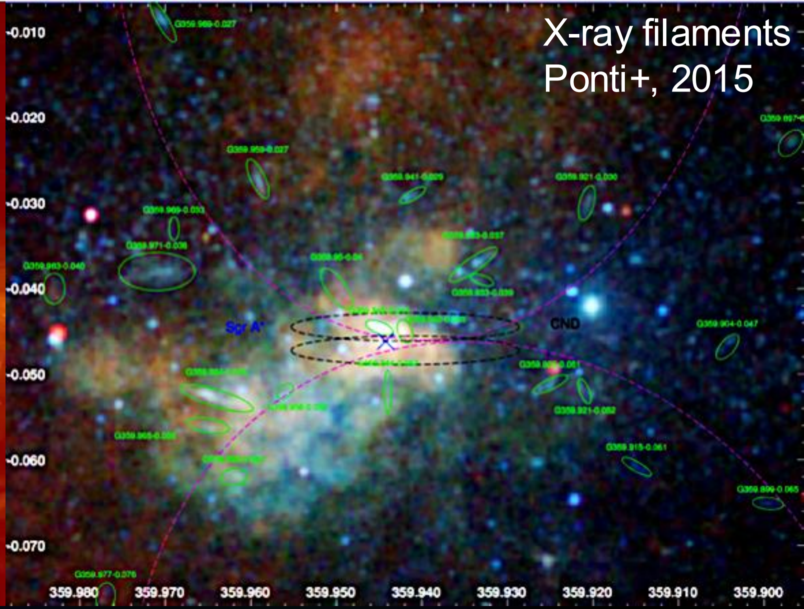
- **<u>Neutral pions</u>** decay into gamma-ray photons as observed by gamma-ray telescopes

- **<u>~100 TeV electrons</u>**: producing synchrotron emission detectable by X-ray telescopes



SED of neutrinos from the same parent PeV protons that produced the observed TeV emission (HESS 2016)





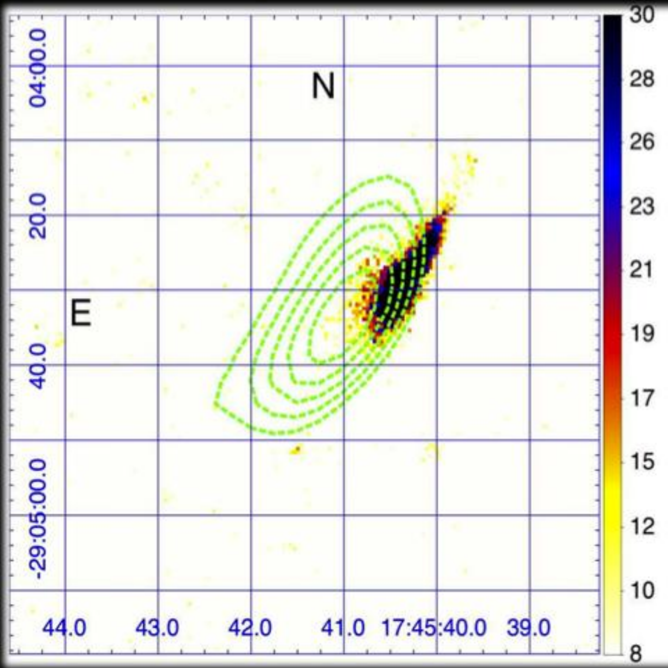
	Radio Filament	X-ray Filament
Number	~150	~20
Length	tens of pcs	a few pcs
Polarization	Detected	not yet
Feeding source	GeV electrons	**~100 TeV electrons!**
Origin of CRs	Particle acceleration	Particle acceleration/ secondary products of hadronic process

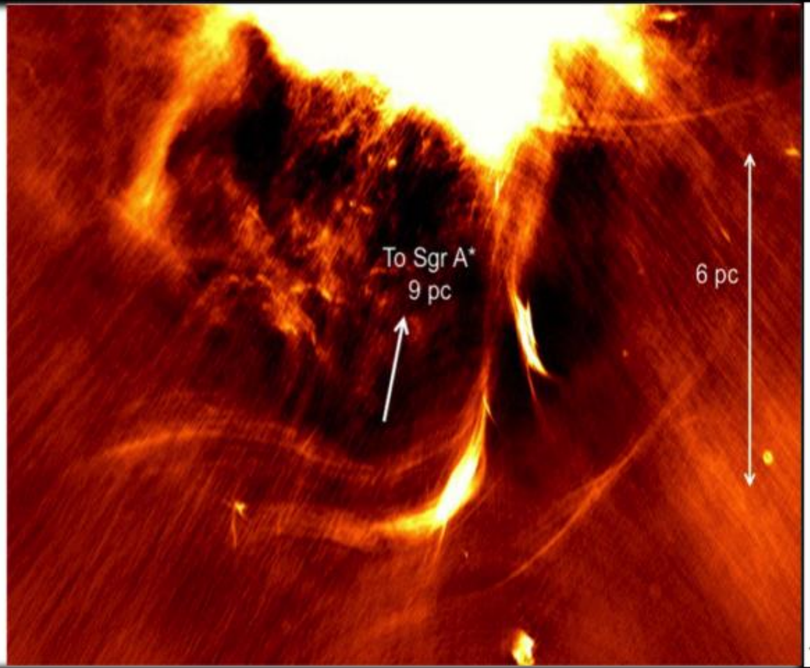
B ~ 100-400 μG (Yusef-Zadeh 2022)

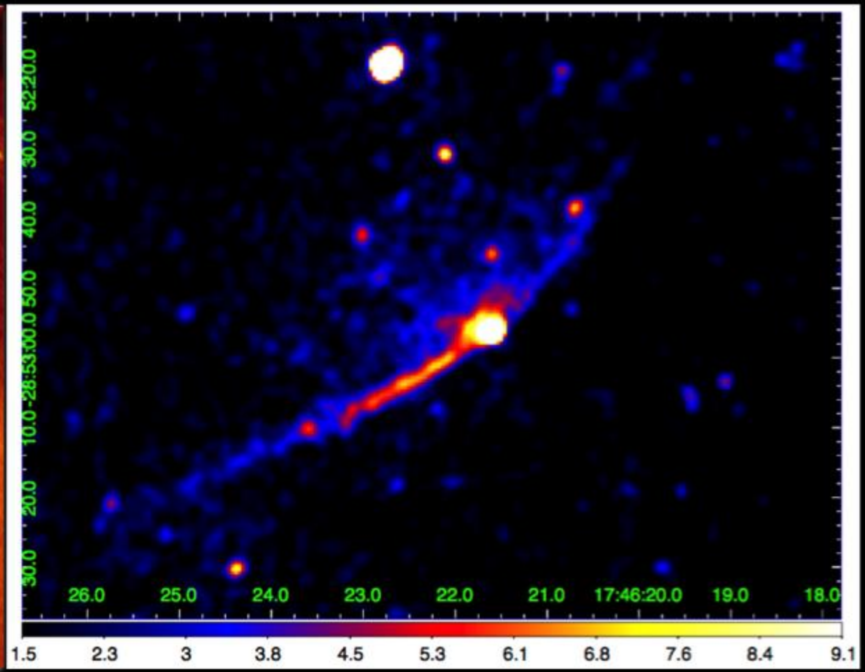
B field lines along filaments

Stable magnetic flux tubes for decades!

X-ray Filaments in the Galactic center





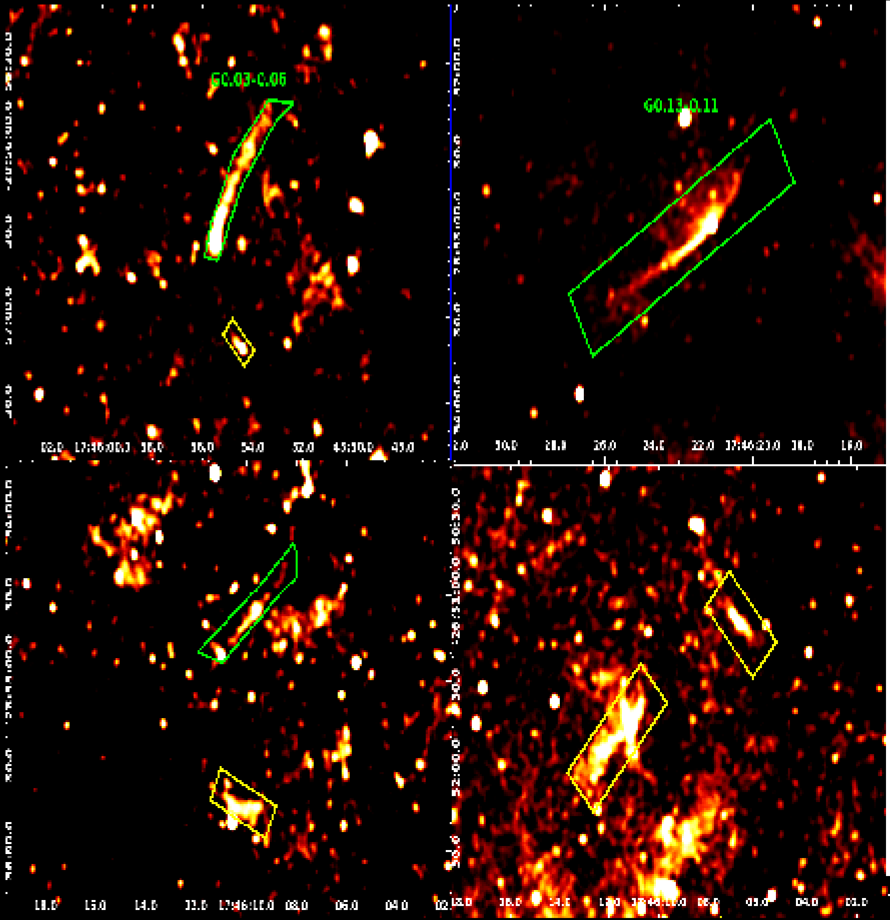


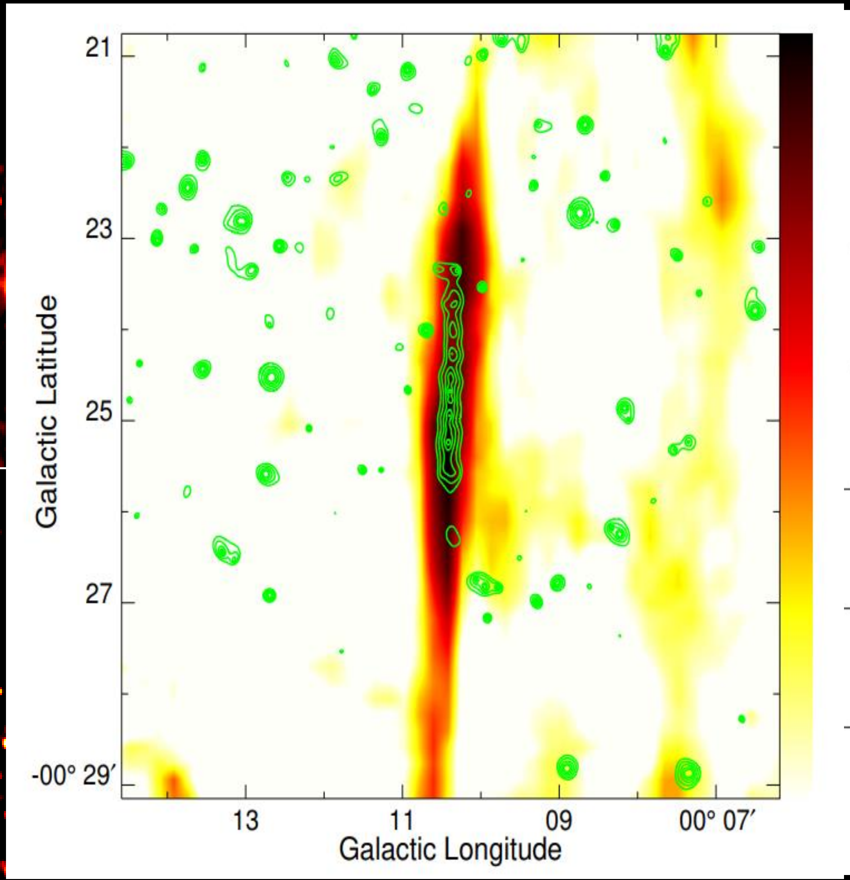
Sgr A-E (10 pc from Sgr A*): magnetic structure trapping 100-200 TeV electrons
Zhang+ (2014), Morris+ (2014)

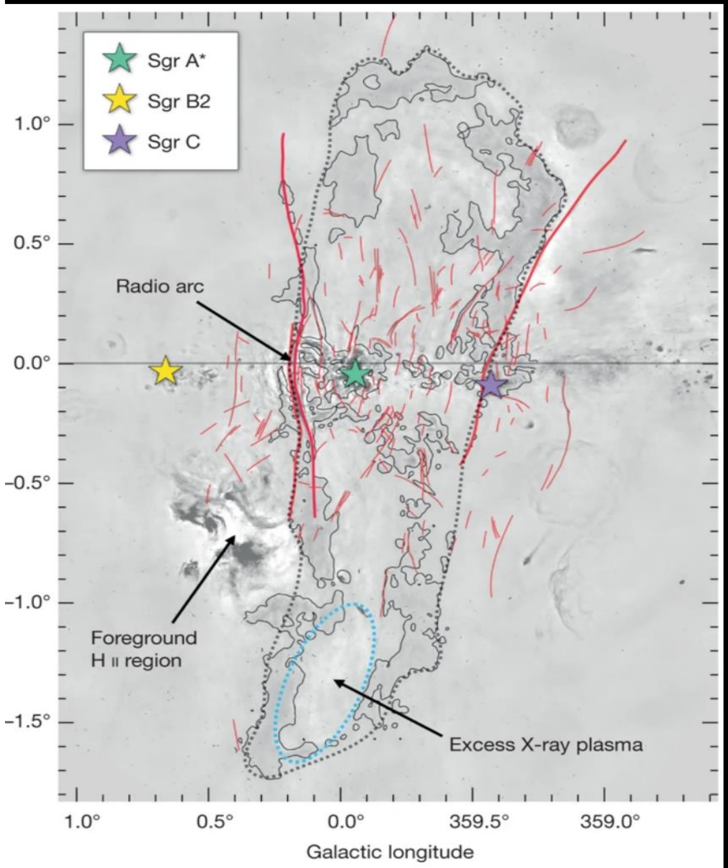
G0.13-0.11 (30 pc from Sgr A*): PWN driven magnetic structure
Zhang+ (2020)

Synchrotron emission up to ~50 keV with B=100-300 μG requires 100-200 TeV CR electrons.
Origin?? — Particle accelerator (BH, SNR, PWN), or secondary particles of hadronic processes?

On-going observational efforts: A systematic study of X-ray/radio magnetic filaments >> test whether Sgr A* can be a Pevatron



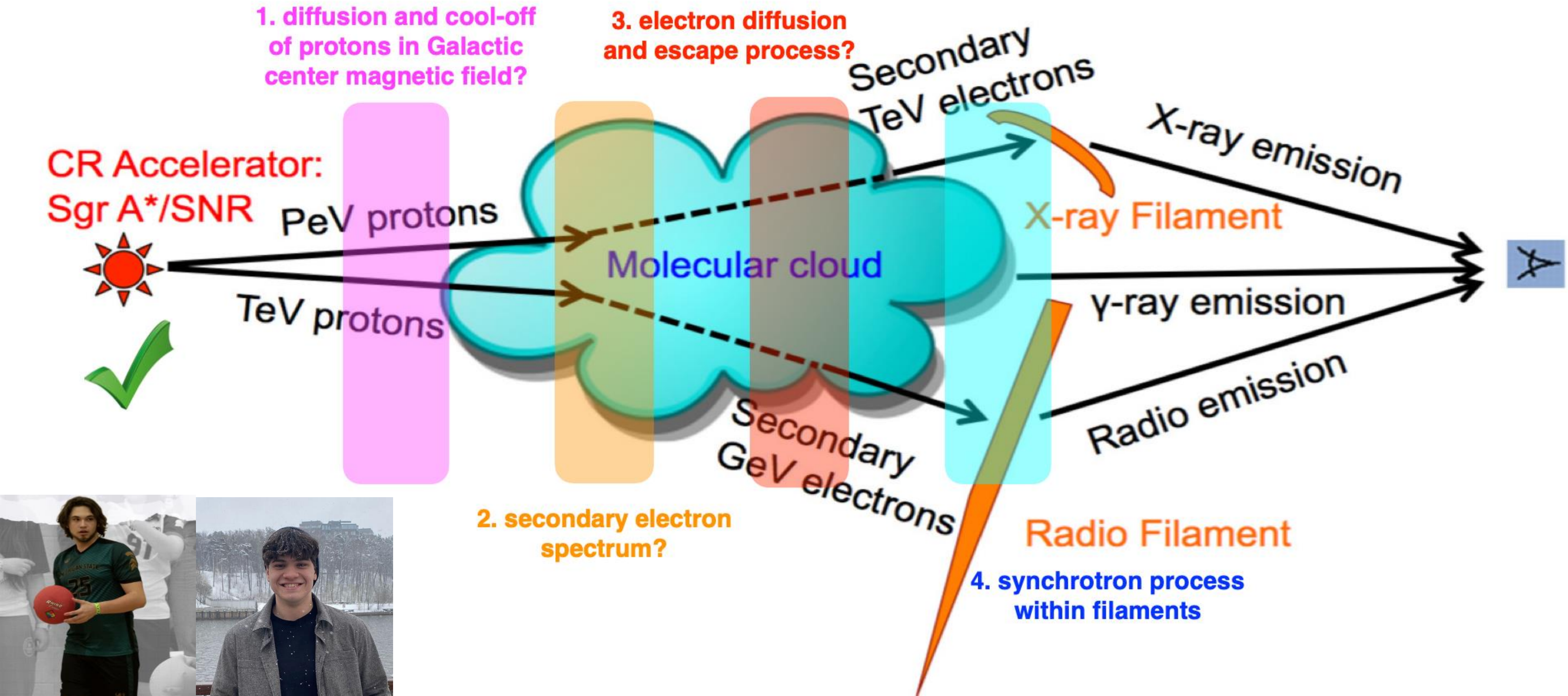




Zhang+, ApJ 2014, 2020; Wang+, ApJ 2021; Deen, Zhang in prep.

Heywood+, Nature, 2019
Yusef-Zadeh+, 2022, 2023

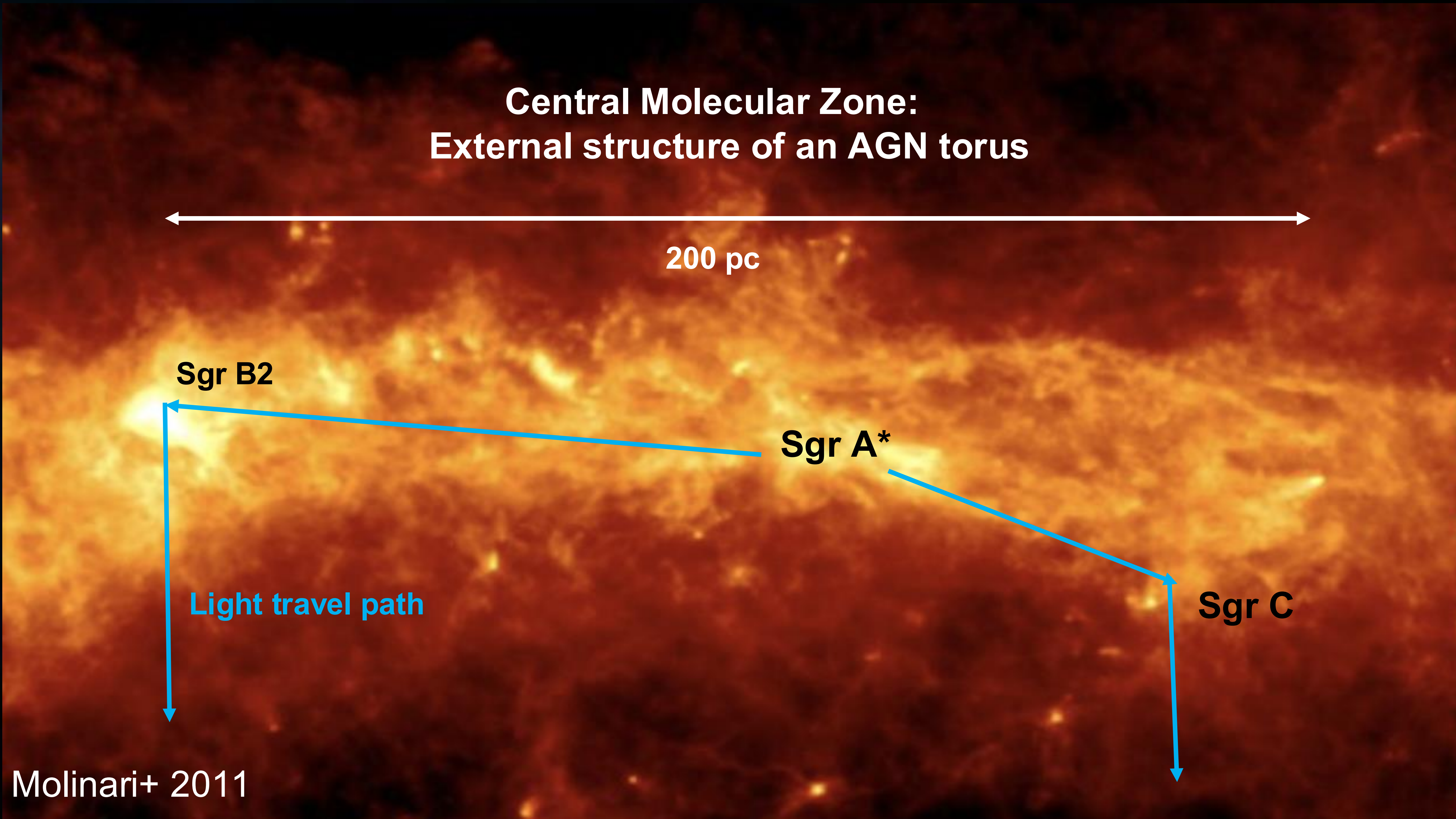
Addressing Missing Links via simulation in Near Future

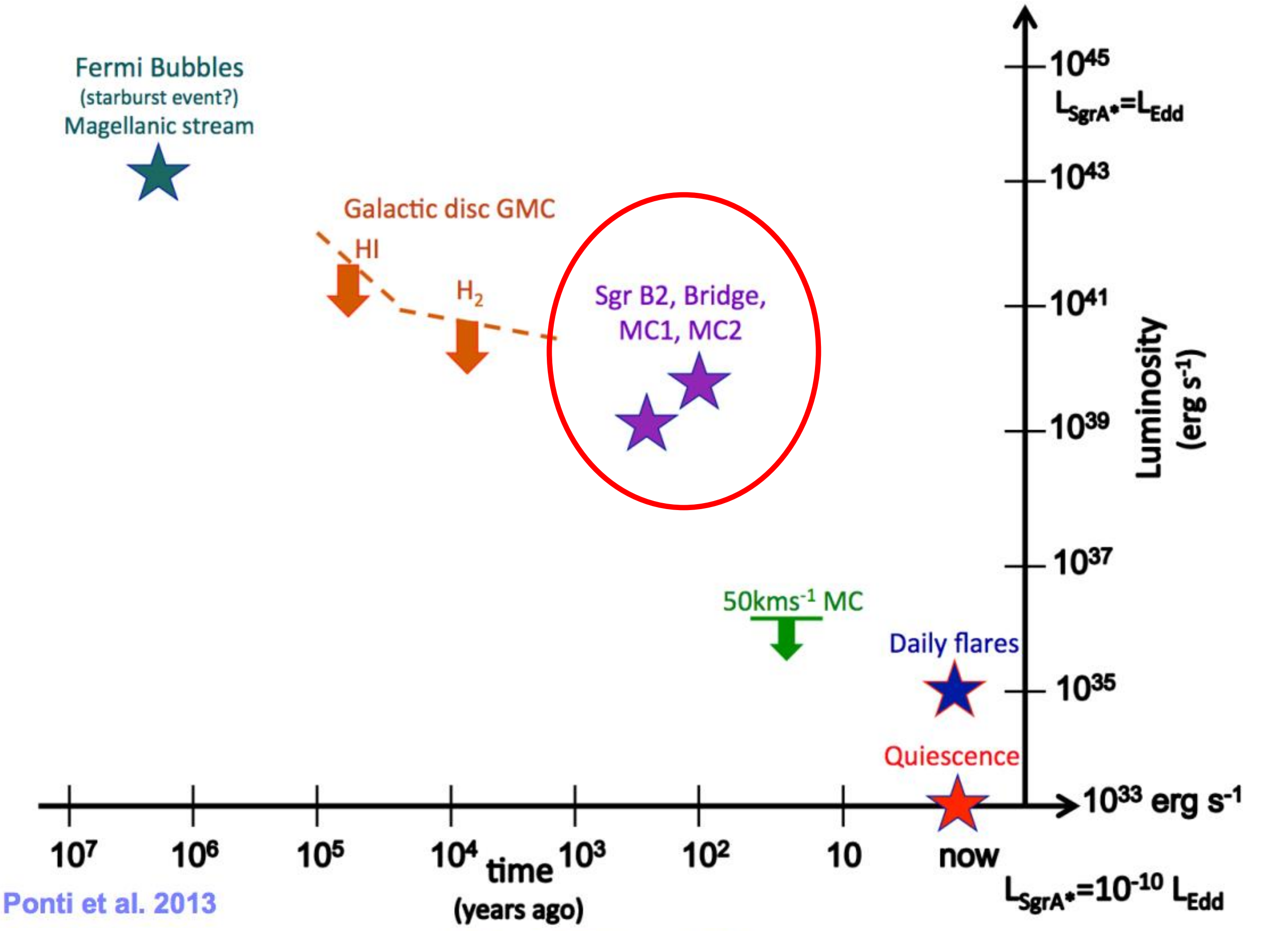


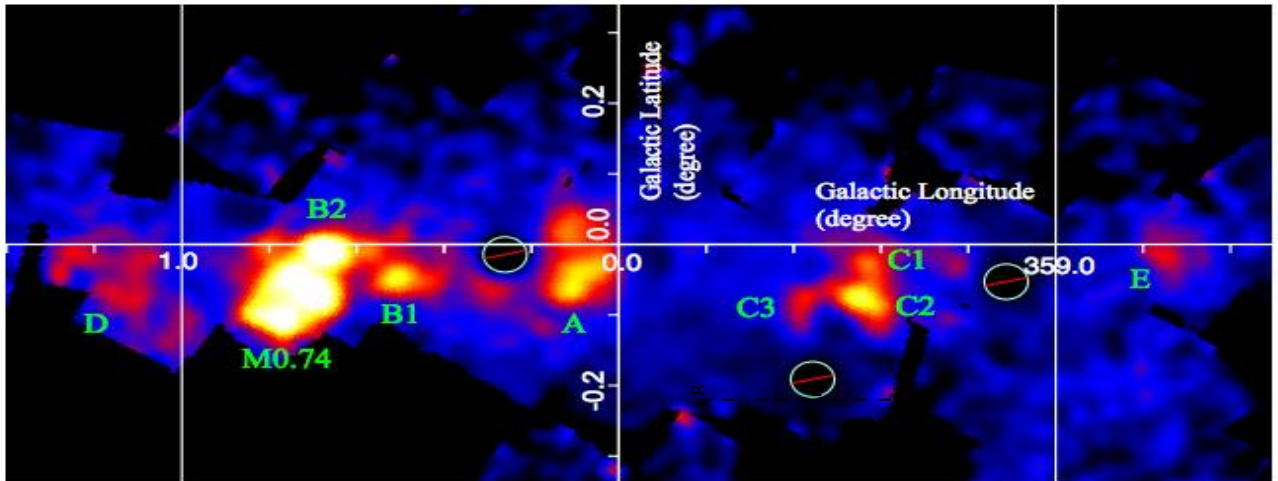
Can the Supermassive Black Hole Sgr A* Serve as the Galactic Center PeVatron?

- Mass: $M = 4 \times 10^6 \, M_\odot$
- Distance: D = 8 kpc
- Closest supermassive black hole: at the dynamical center of the Galaxy
- Currently the least active super massive black hole known, with a bolometric luminosity 7-8 orders lower than its Eddington Luminosity
- **There are current flaring events and prominent past outbursts from Sgr A***

Credit: Wide-field X-ray: NASA/CXC/SAO, Close-up X-ray: NASA/UMass/D.Wang et al., IR: NASA/STScI


Central Molecular Zone:
External structure of an AGN torus
200 pc
Sgr B2
Sgr A*
Sgr C
Light travel path
Molinari+ 2011





Reconstructing Sgr A* outburst history in past a few hundred years using highly variable X-ray Emission from Molecular Clouds

From fluorescence
(Sunyaev & Churazov 1998):

$$L \propto I_{Fe}\, d^2\, \tau_T^{-1}$$

From Compton Scattering
(Zhang+ 2015):

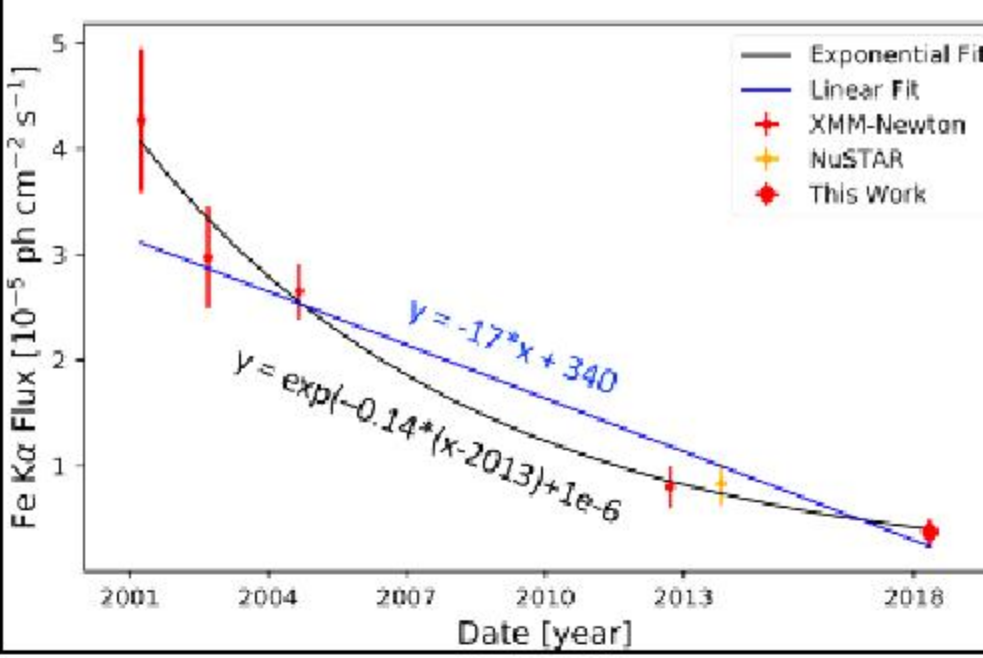
$$L \propto I_{Con}\, d^2\, \tau_T^{-1} f(\theta)$$

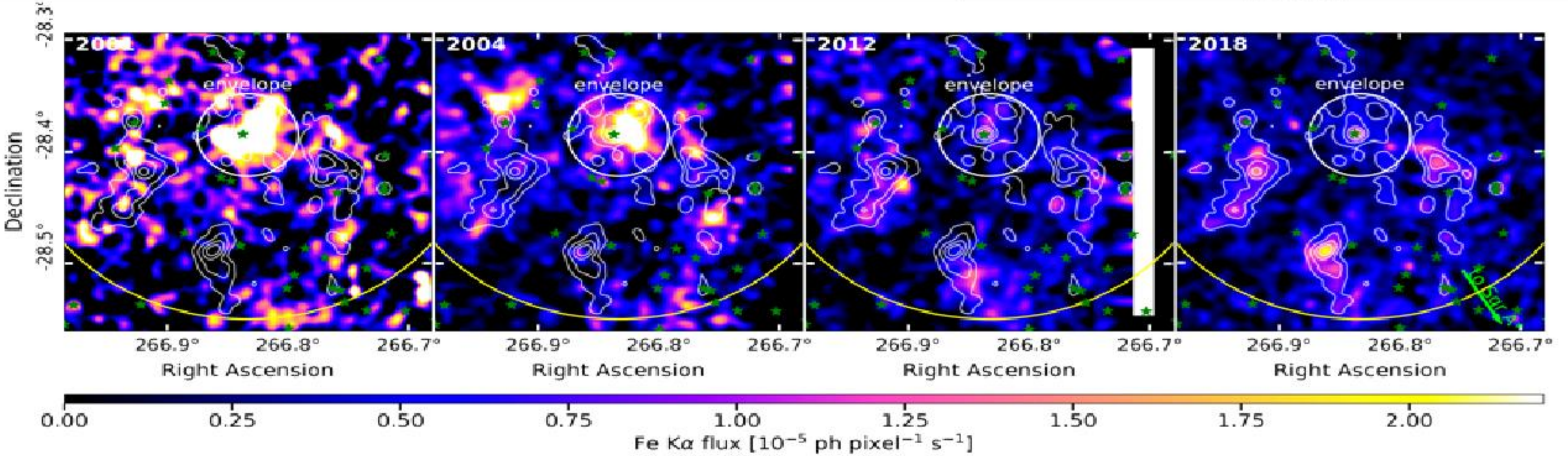
- Observations suggest decreasing Sgr A* X-ray activities in the past few hundred years: decreasing from Lx~10^{39} erg/s to Lx~$10^{33\text{-}35}$ erg/s.

Sgr B2 Molecular Cloud: 20-years of X-ray Fading

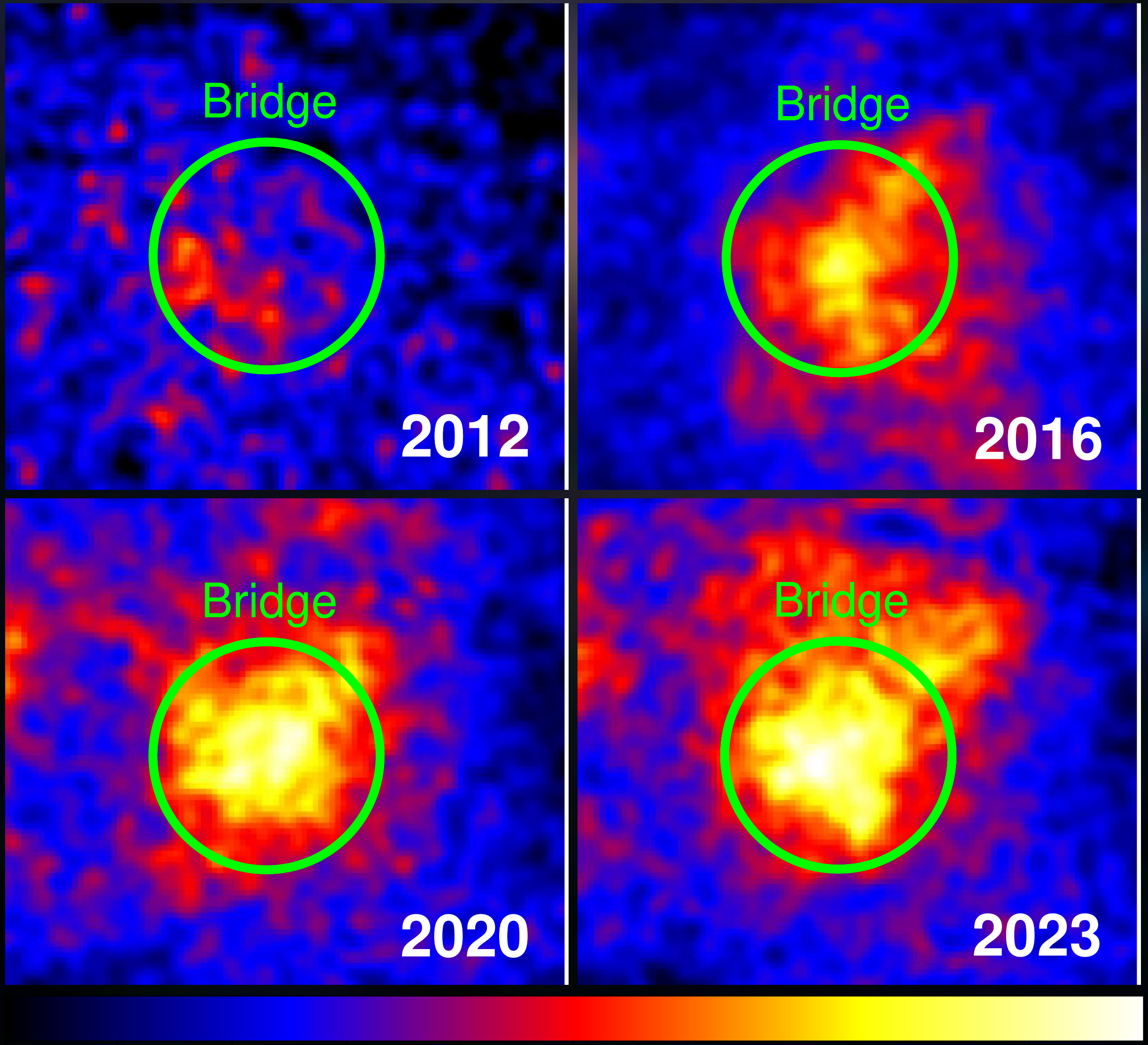
- IoLocated at ~100 pc from Sgr A* in projected distance
- X-ray luminosity has been decaying in the past two decades
- Peak luminosity of the Sgr A* outburst that illuminated Sgr B2 ~110 yrs ago: $L_X \sim 5\times10^{38}(d/100\mathrm{pc})^2$ erg s^{-1}

Rogers, Zhang et al. (2022)

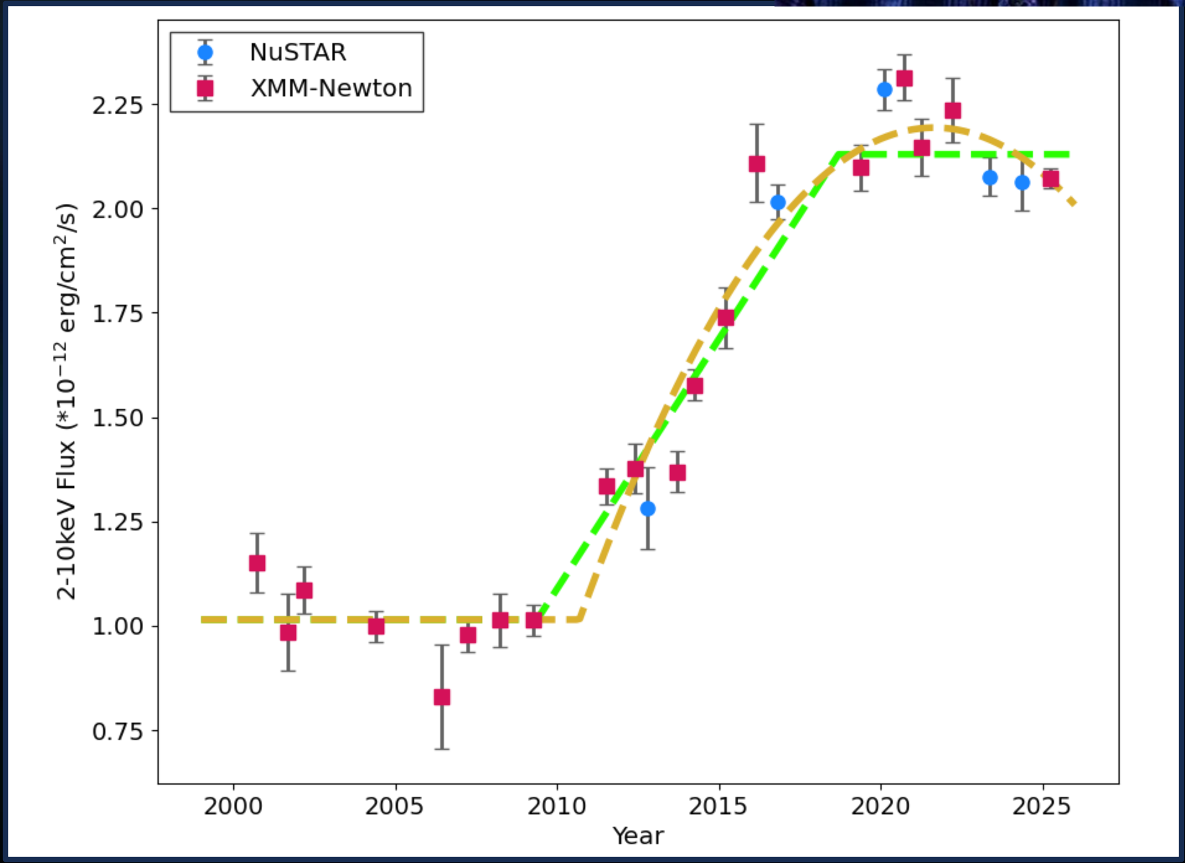




Bridge molecular cloud: 25 years of X-ray Brightening

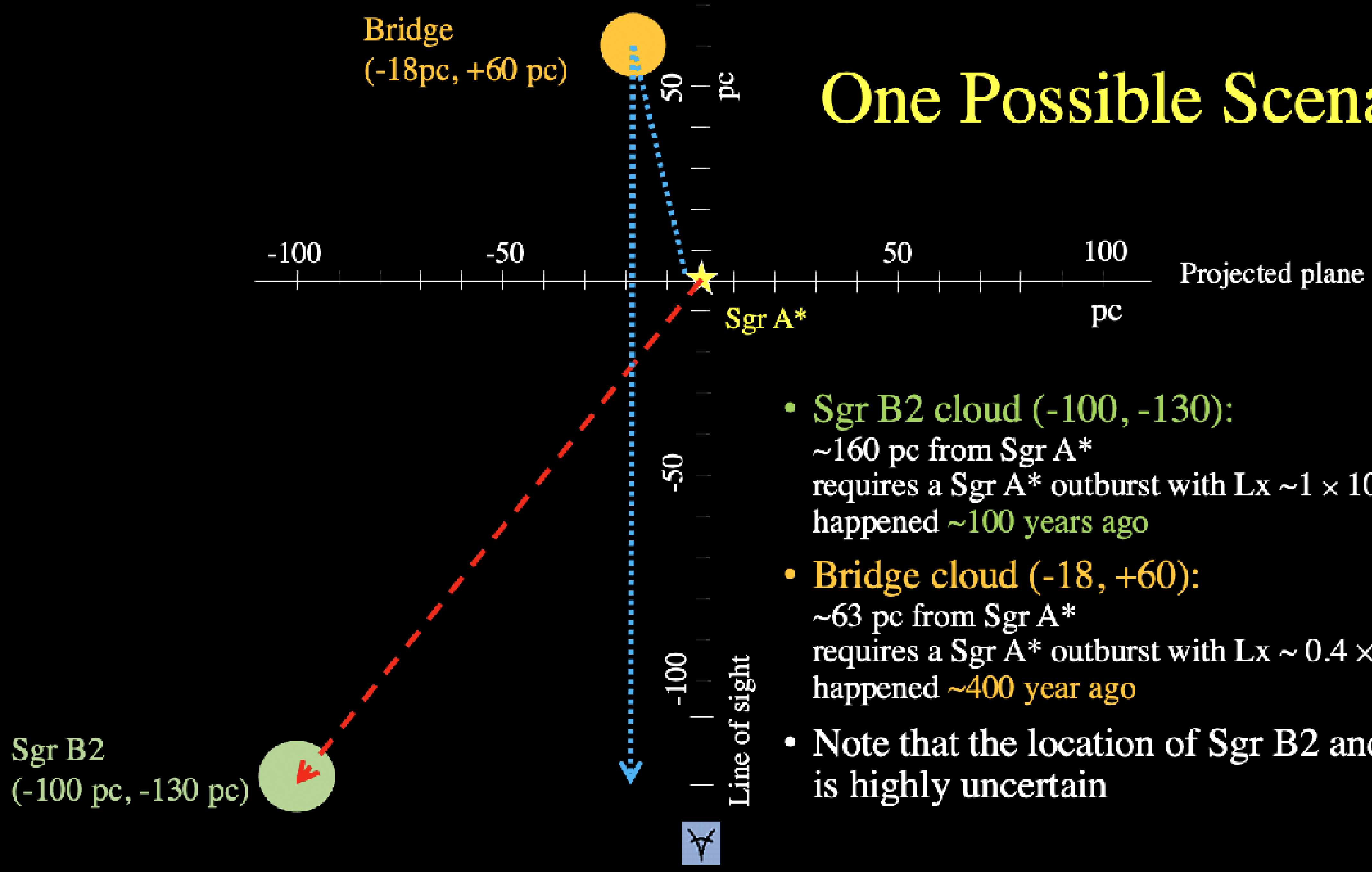


Bridge Molecular cloud
Long-term Light Curve



Zhang, DiKerby & Uteg, in prep.

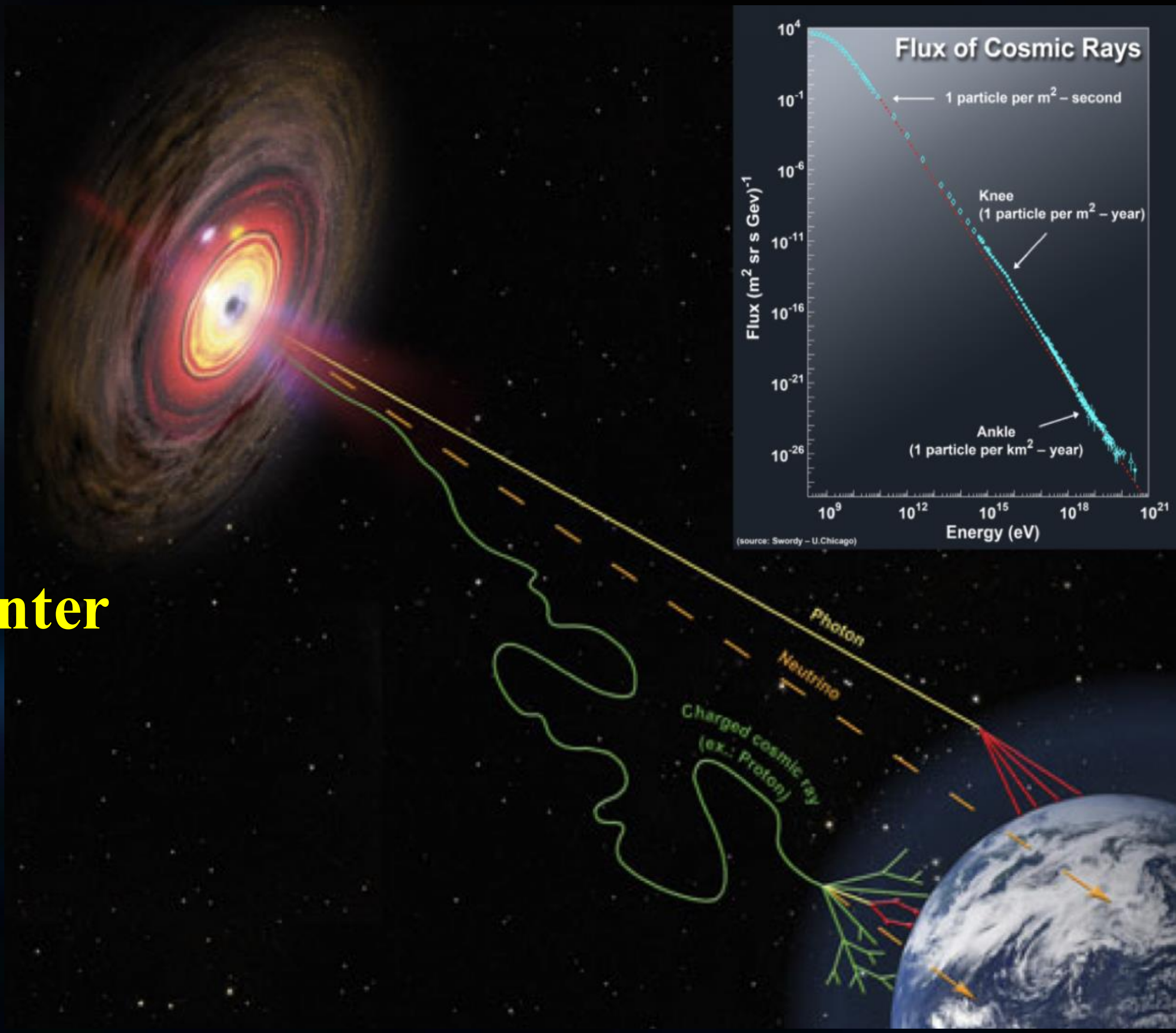
One Possible Scenario



- Sgr B2 cloud (-100, -130):
  ~160 pc from Sgr A*
  requires a Sgr A* outburst with Lx ~1×10^{39} erg/s
  happened ~100 years ago
- Bridge cloud (-18, +60):
  ~63 pc from Sgr A*
  requires a Sgr A* outburst with Lx ~ 0.4×10^{39} erg/s
  happened ~400 year ago
- Note that the location of Sgr B2 and Bridge is highly uncertain

Outline

- The Galactic Center PeVatron
- PeVatrons outside of Galactic Center



Search for Counterparts of New PeVatrons

- LHAASO revealed group of four UHE sources which have no apparent particle accelerators such as PWNe, SNRs or star clusters in the vicinity.

Why no low-energy counterparts: poorly explored or Transient PeVatron?

Table 1: A list of the four DaPA targets detected by LHAASO

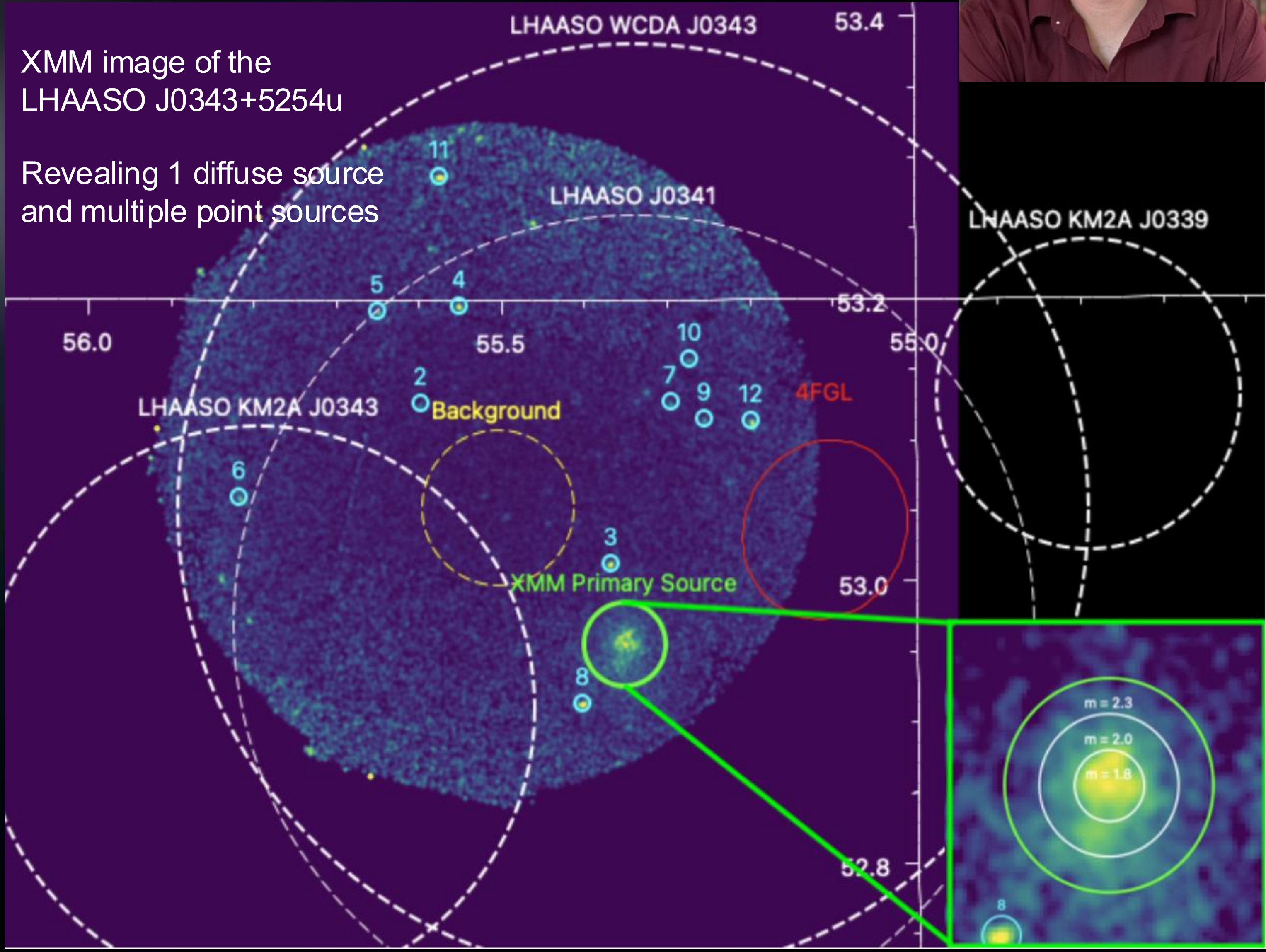
LHAAASO source	HAWC counterpart	TeV source size	VERITAS observation	Previous X-ray observations	Requested *XMM* exposure	*XMM* visibility
J2108+5157	Yes	$< 0.26^\circ$ (point-like)	Yes	*XMM* (10 ks)	80 ks	May–Jul 23 & Nov–Apr 24
J0341+5258	N/A	0.29° (extended)	Yes	*Chandra* (10 ks)	80 ks	Aug–Sep 23 & Feb–Mar 24
J1956+2845	Yes	$< 0.3^{\circ a}$	TBD	N/A	2×60 ks	May, Oct–Nov 23 & Apr 24
J0621+3755	$\sim 0.3^\circ$ away?	0.40° (extended)	Yes	*Chandra* (2 ks)	80 ks	Sep–Oct 23 & Mar–Apr 24

[a] The source extent is unknown and it was assumed to be a point source for the LHAASO detection [1].

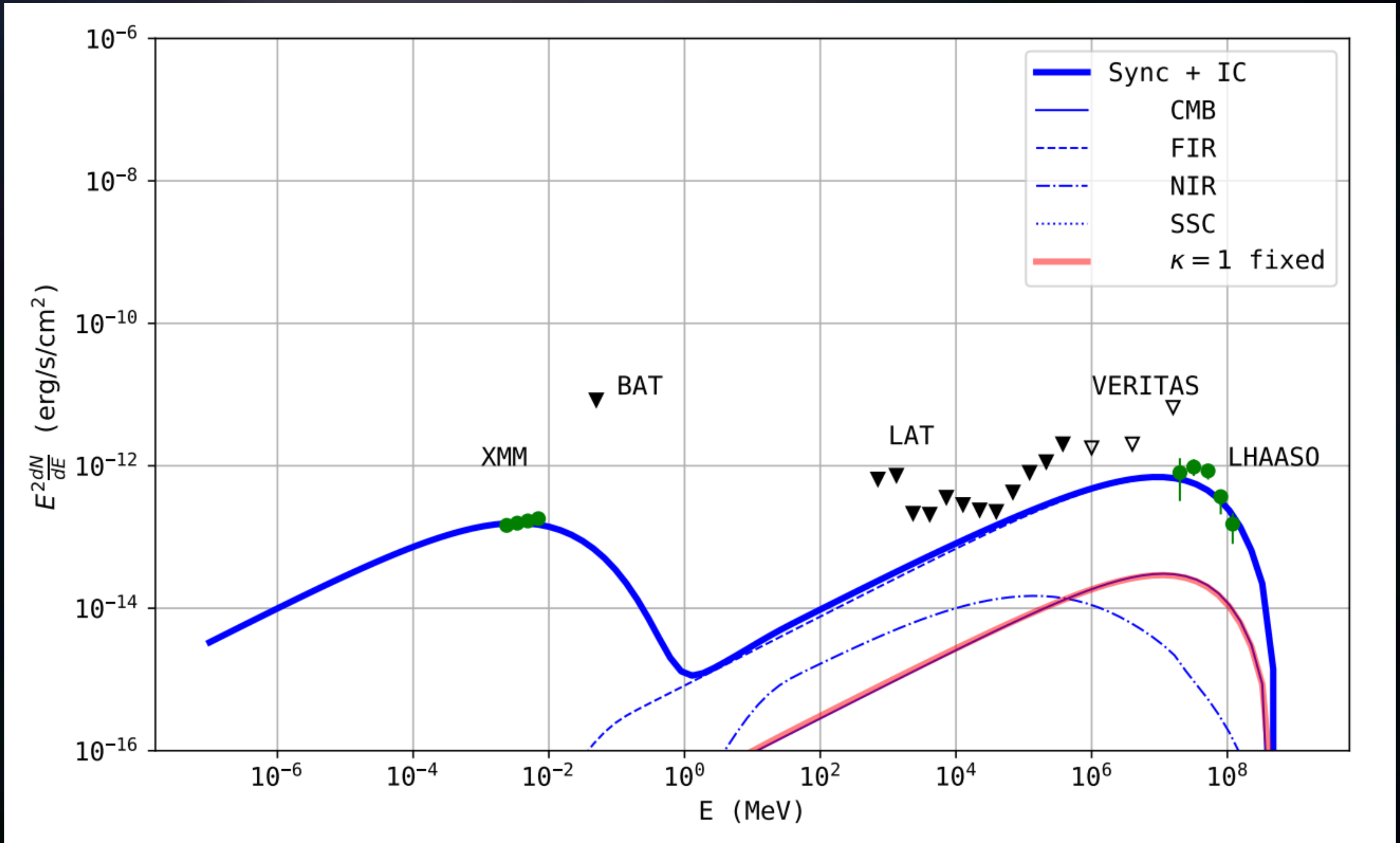
Discovery of a PWN candidate associated with PeVatron LHAASO J0343+5254u using 2024 XMM-Newton observation

- Detected by LHAASO up to 200 TeV as extended source (0.29 °);
- No low-energy counterparts confirmed before (dark PeVatron);
- Our XMM-Newton observation on 2024 Feb 15-16 led to discovery of a PWN candidate as a potential X-ray counterpart

DiKerby, Zhang+, APJ, 2025b



Multi-wavelength Emission Modeling for LHAASO J0343+5254u with New X-ray Measurement



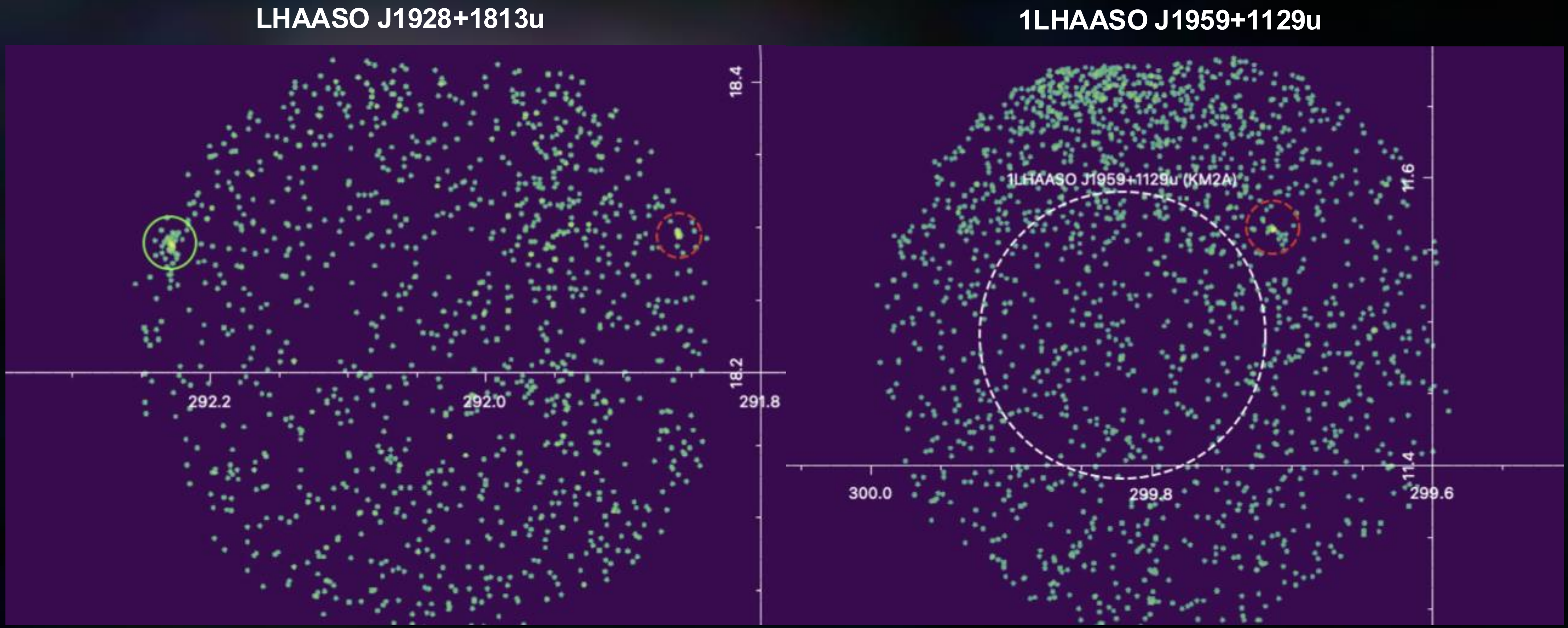
A synchrotron and IC dominated leptonic model can fit to the broadband X-ray to ~100 TeV data very well. B ~ 5 μG.

The newly discovered X-ray source, with spatial and spectral features much like other PWN such as the Eel, likely bears the same nature.

→ This VHE source is likely a PWN, although a hadronic/hybrid model cannot be fully ruled out at this moment.

DiKerby, Zhang +, ApJ, 2025b

Swift ToO Follow-up of 5 LHAASO Sources



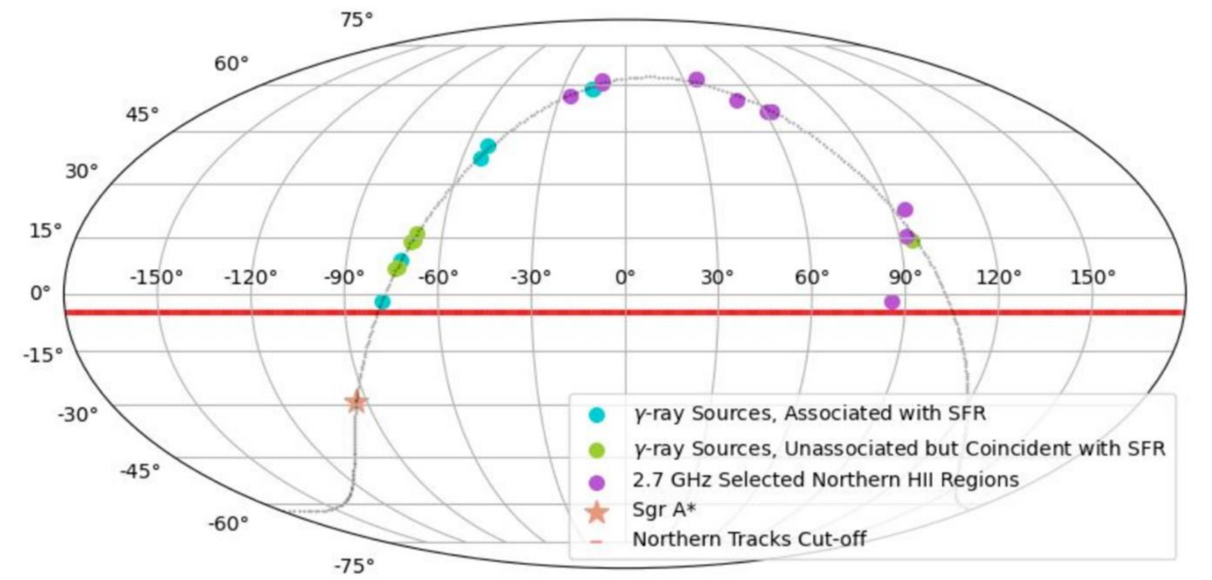
Quick Look at Swift ToO Observations of 5 LHAASO sources obtained in Sep-Oct 2024: some result in positive X-ray detection.

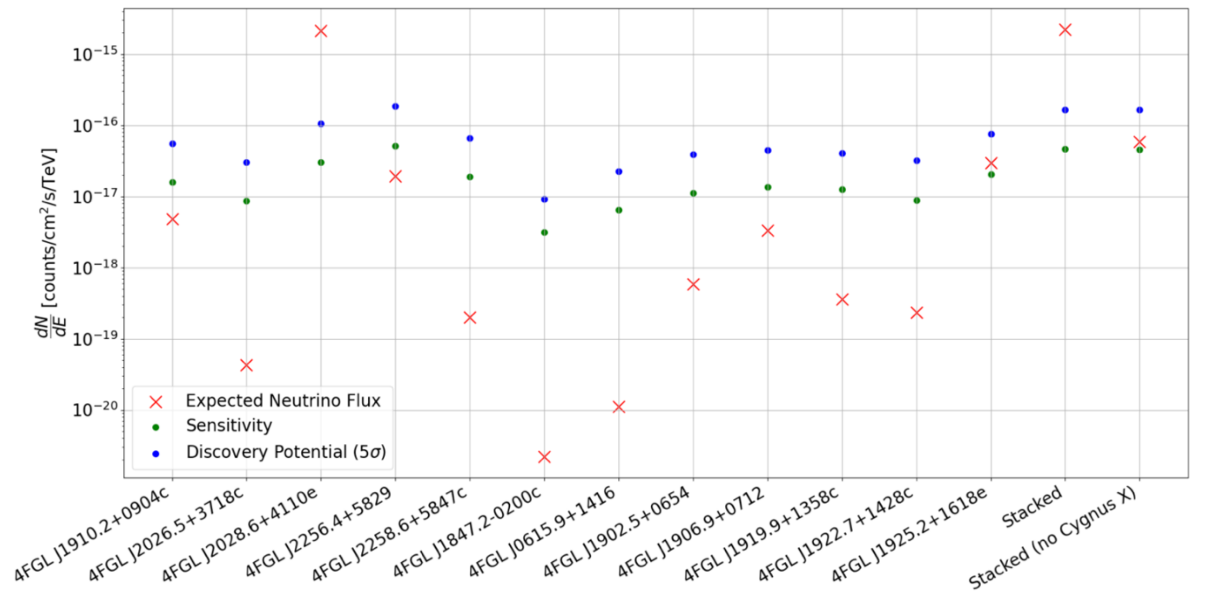
Amiri Walker, Ella Werre, Shaan Kerim, Dikerby (2025) Research Notes of AAS, 9, 89

Stellar cluster and Star Forming Regions as Hadronic PeVatrons?

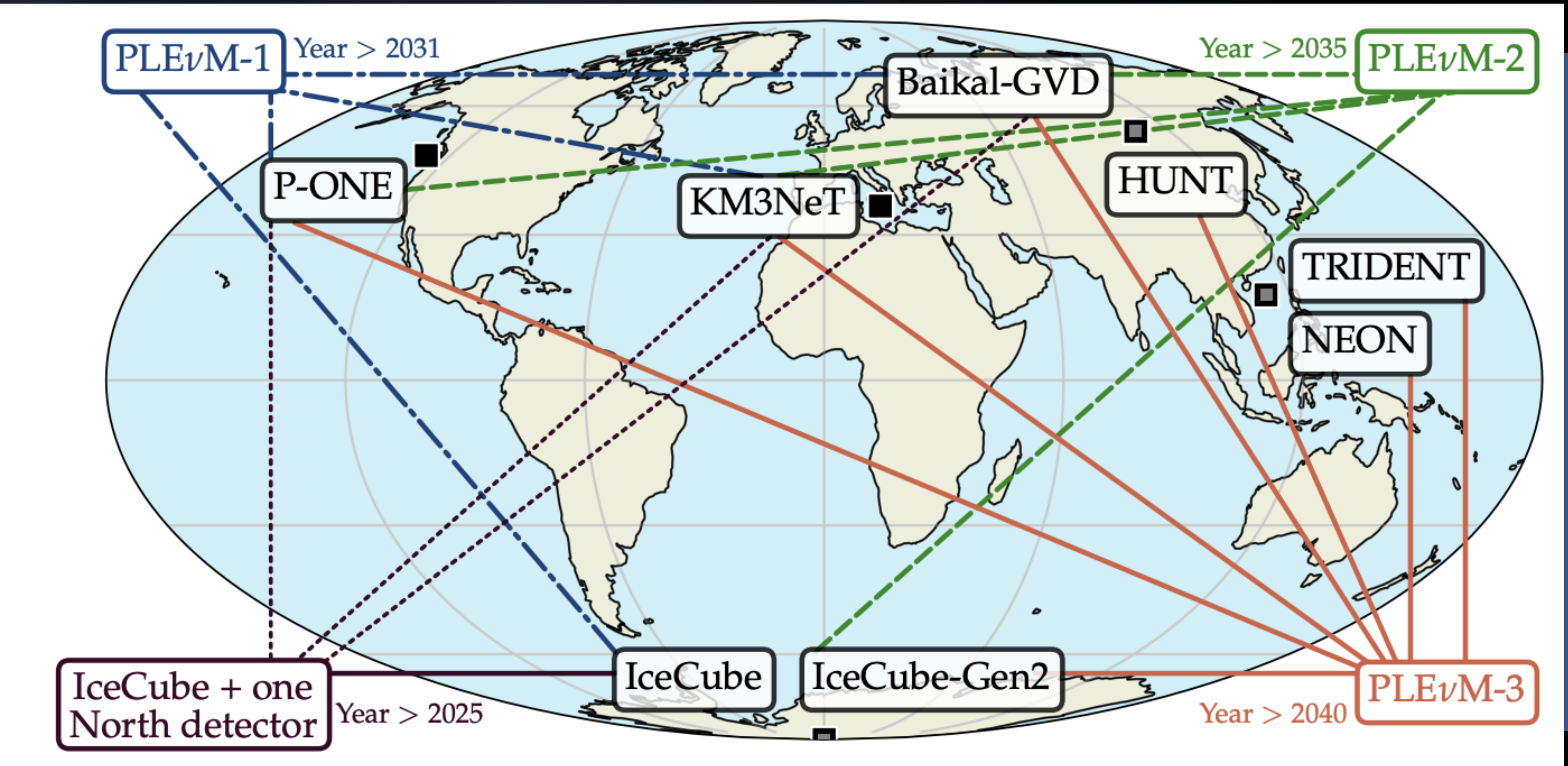
- Stacked source analysis using IceCube data
- Gamma-rays produced by colliding stellar winds, shock acceleration up to ~PeV energy range
- Selected a star forming region sample in the Northern sky optimized for IceCube analysis

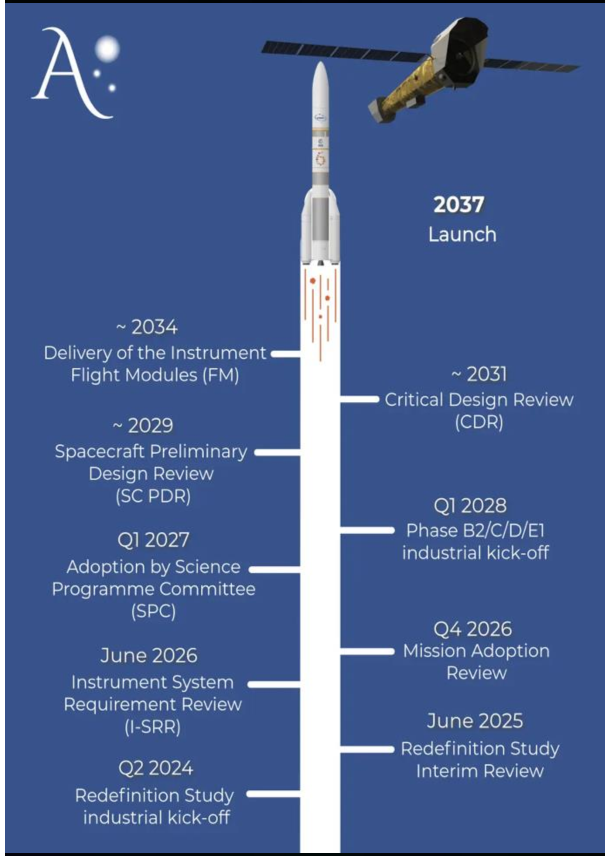
New session on stellar clusters?





Define PeVatron Programs in the Era of Global Monitoring for High-energy Neutrino Astronomy and NewAthena!



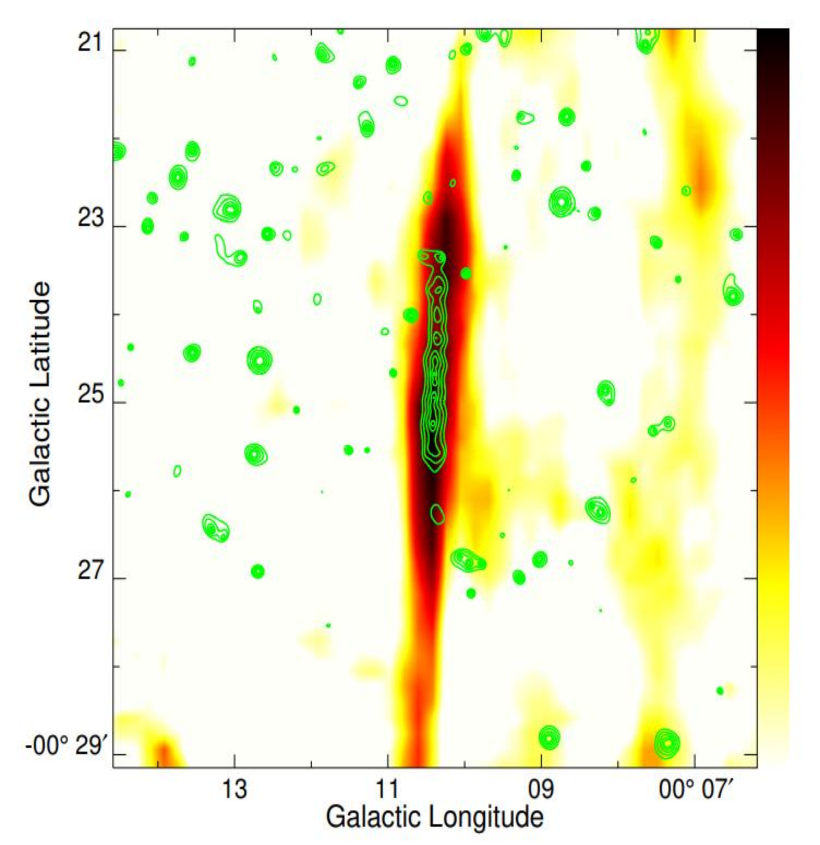


Locations of the neutrino telescopes that make up PLEνM. PLEνM-1 consists of IceCube, KM3NeT, P-ONE, and Baikal-GVD. PLEνM-2 with IceCube replaced by a detector 7.5 times larger IceCube-Gen2. PLEνM-3 adds the three planned detectors (Schumacher et al. 2025)

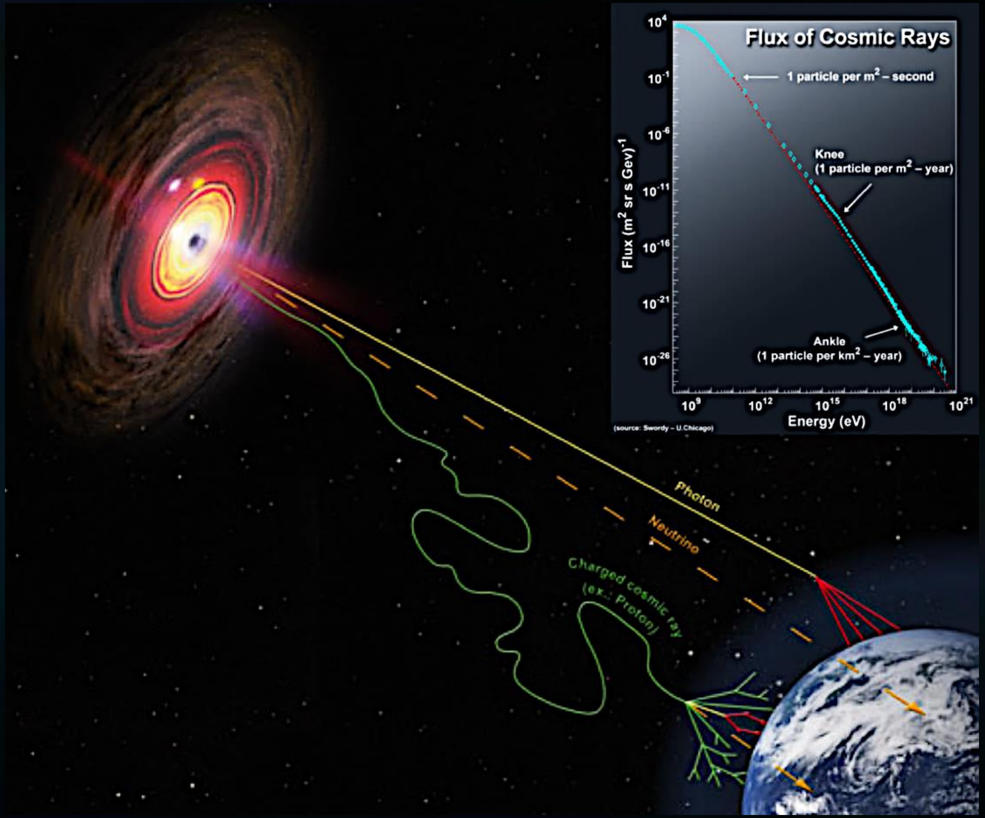
NewAthena WG5: transient and multi-wavelength group. White papers under preparation.

Summary

Filaments possibly connected to Galactic Center PeVatron



More PeVatron Hunting

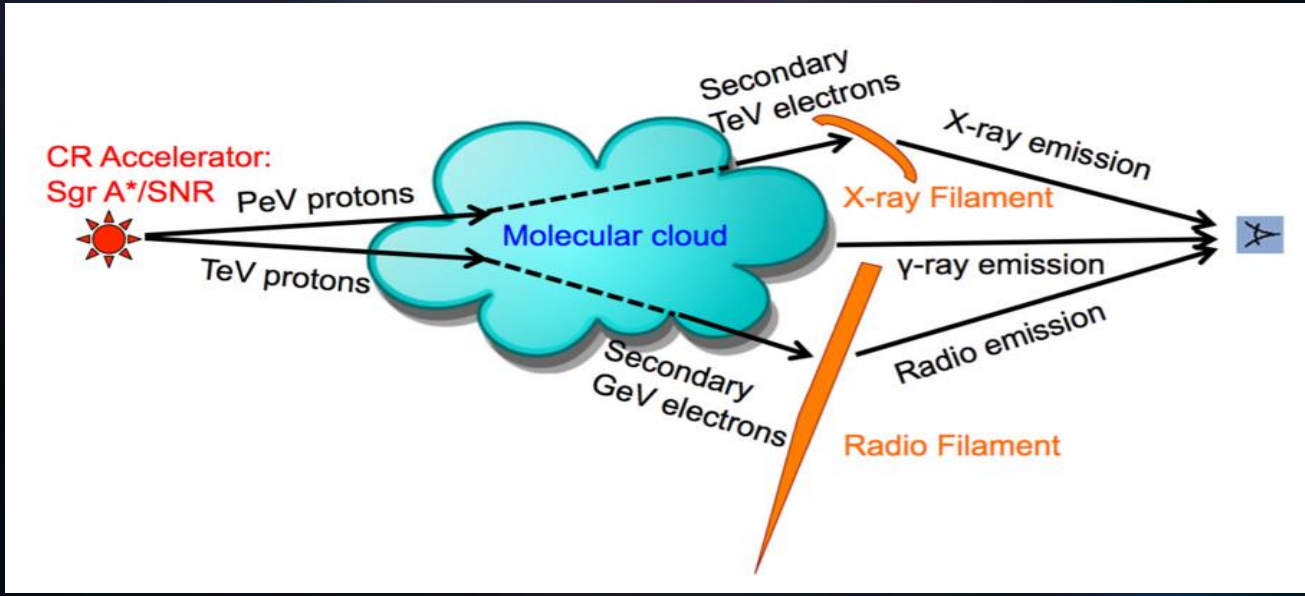


Shuo Zhang, Michigan State University, zhan2214@msu.edu

Back up Slides

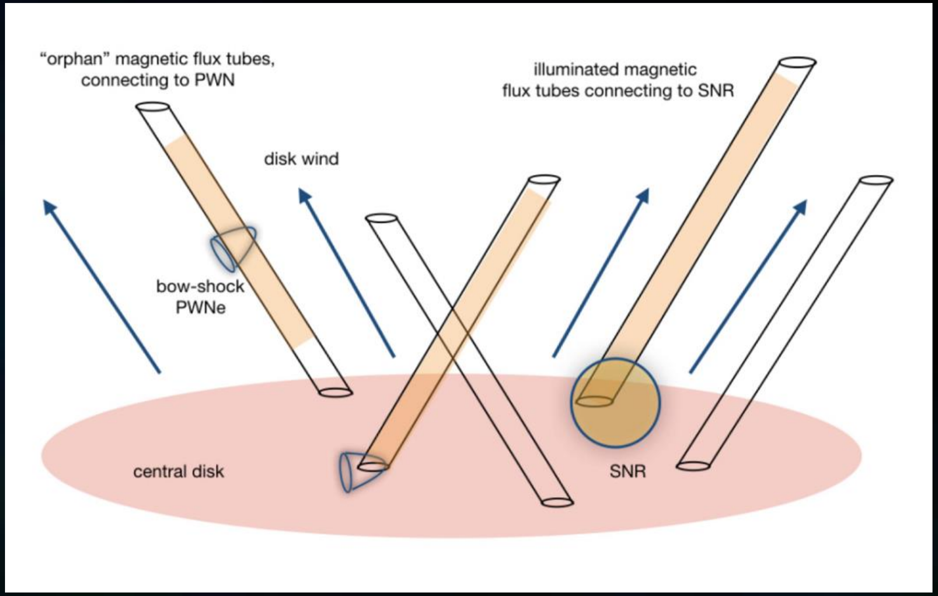
Filament Origin: global vs. local model

Electron origin: secondary particles from PeVatron driven p-p collision



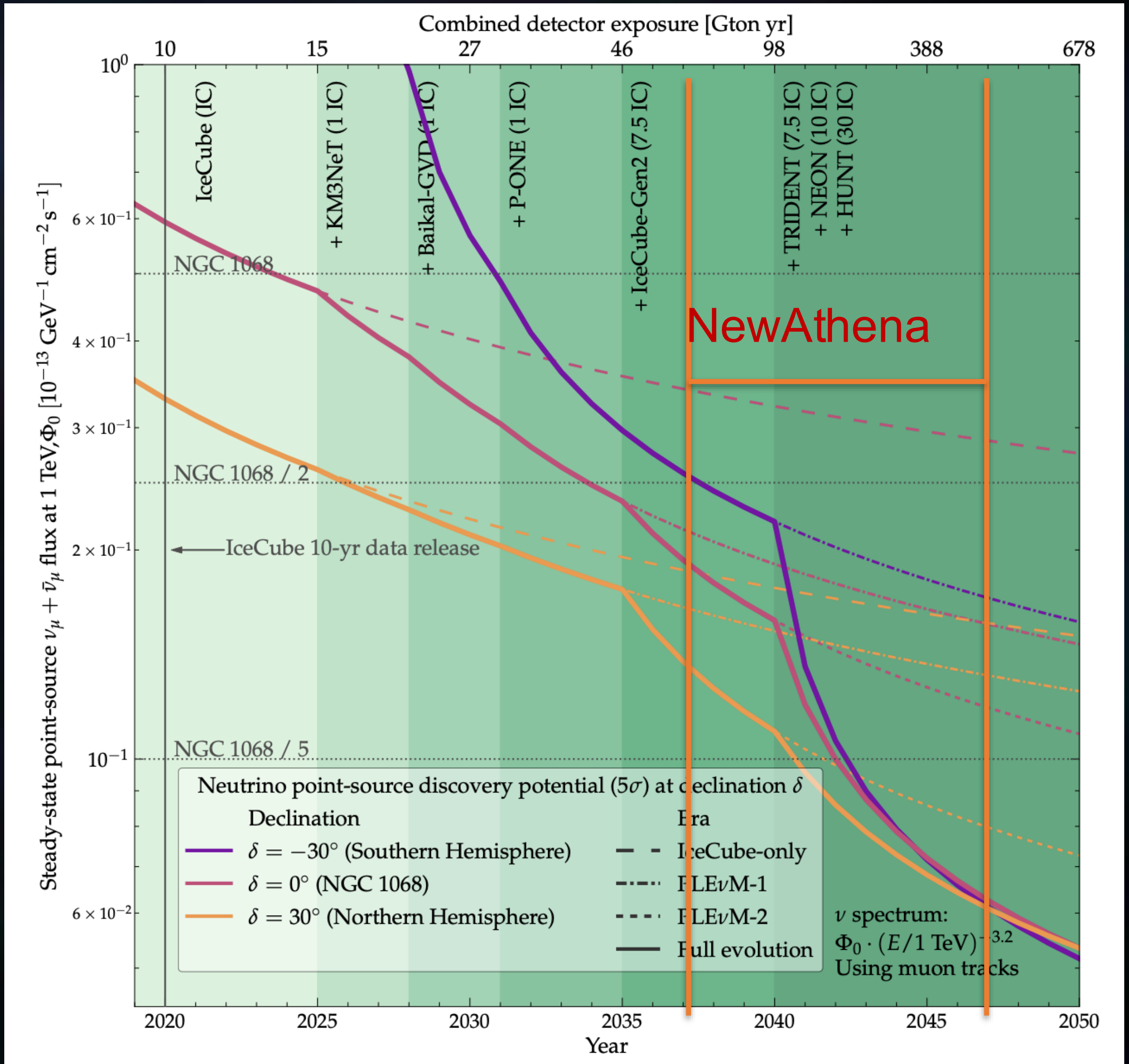
Zhang+, 2014, 2020; Deen, Zhang+, in prep.

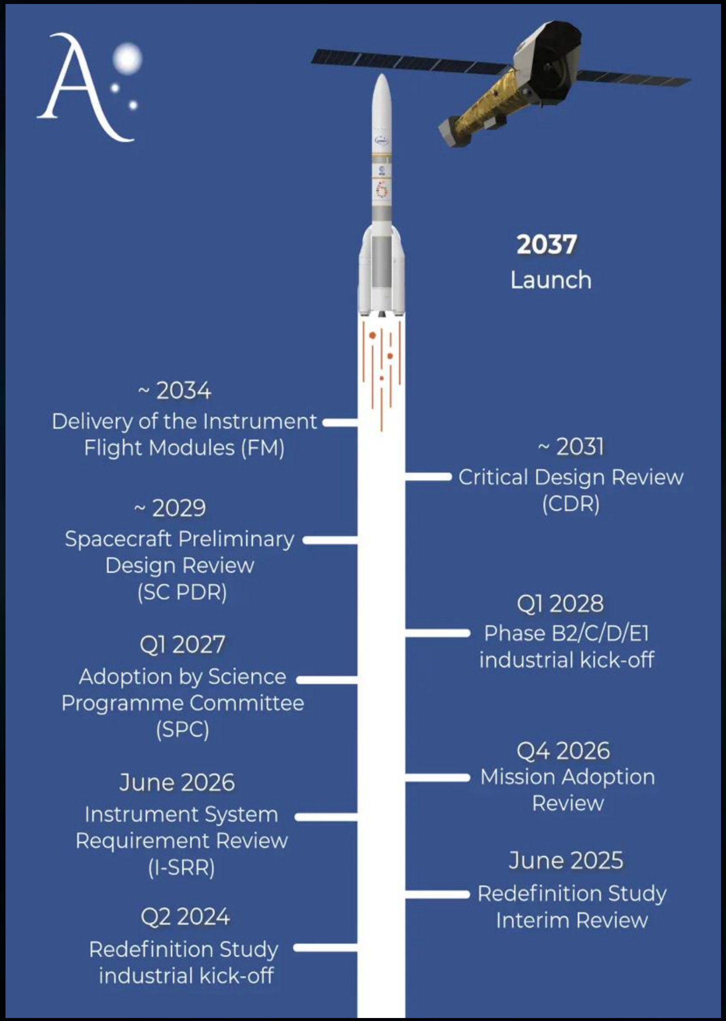
Electron origin: local direct acceleration by PWN, SNR



Barkov+, 2019a, b

Projected Discovery Potential of Point Sources of High-energy Neutrinos in the NewAthena Era





By mid 2040s, cumulative exposure of a global network of neutrino telescopes could enable the discovery of neutrino sources 5 times dimmer than NGC 1068 anywhere in the sky with angular resolution better than 0.1°