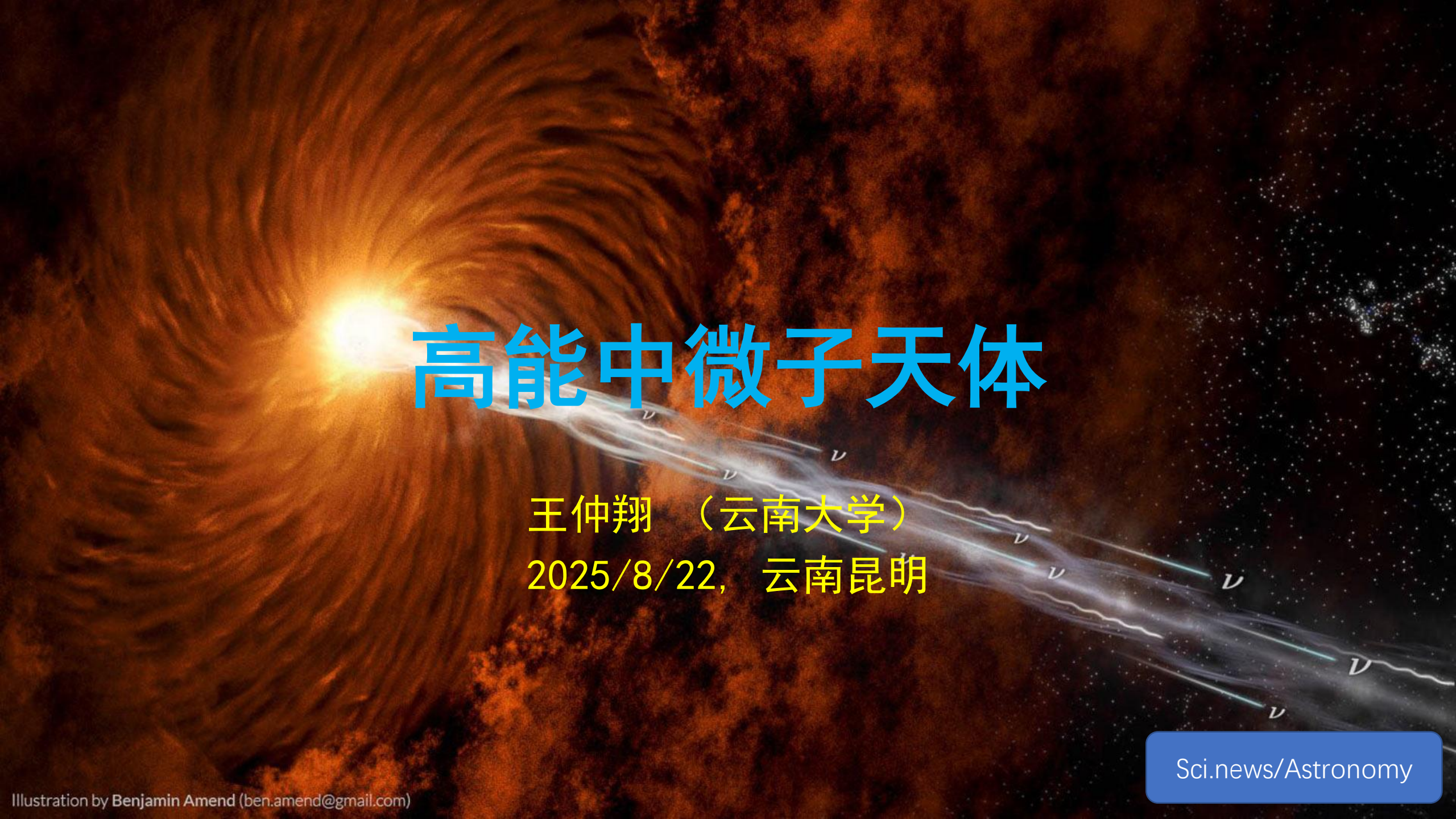
高能中微子天体

王仲翔 （云南大学）

2025/8/22， 云南昆明



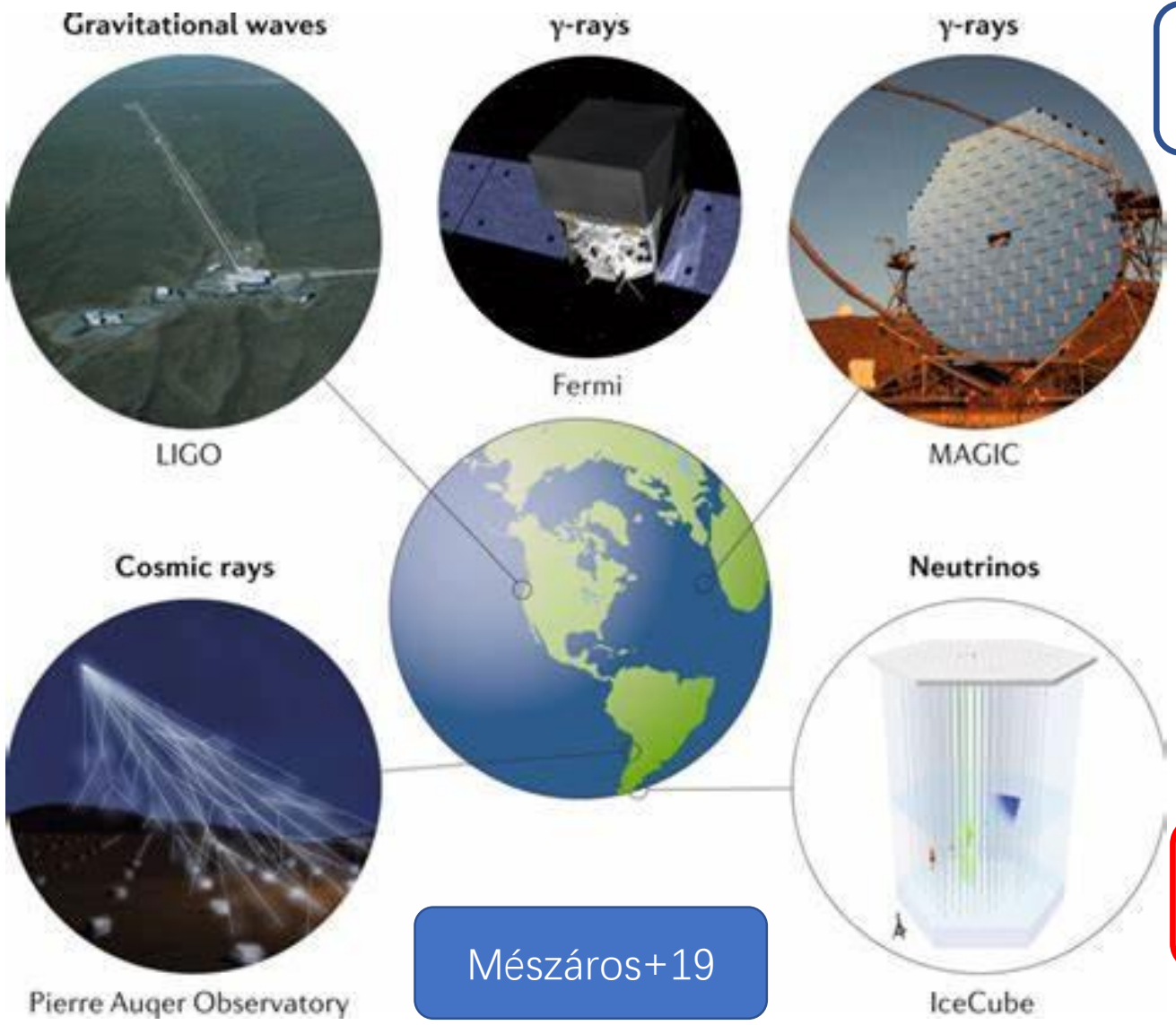
多信使时代（Multi-messenger era）

引力波

伽马射线

粒子探测

高能中微子



从传统依赖电磁波观测，转变到多信使手段：探测到以前“看不到”的物理过程

Mészáros+19

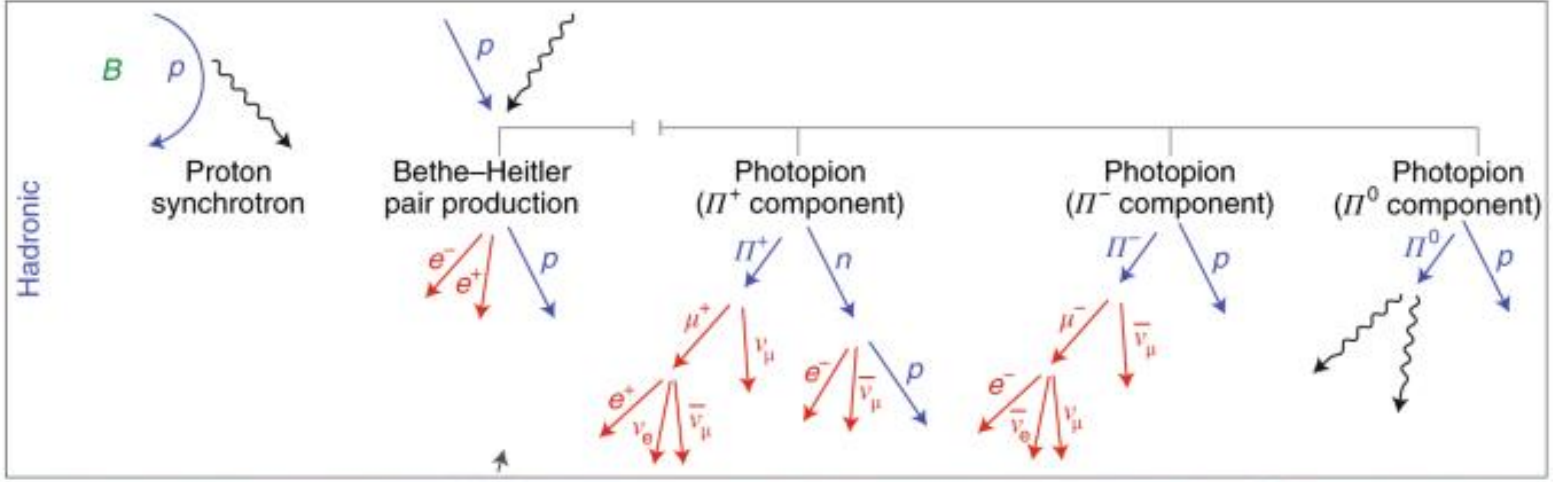
辐射的类别

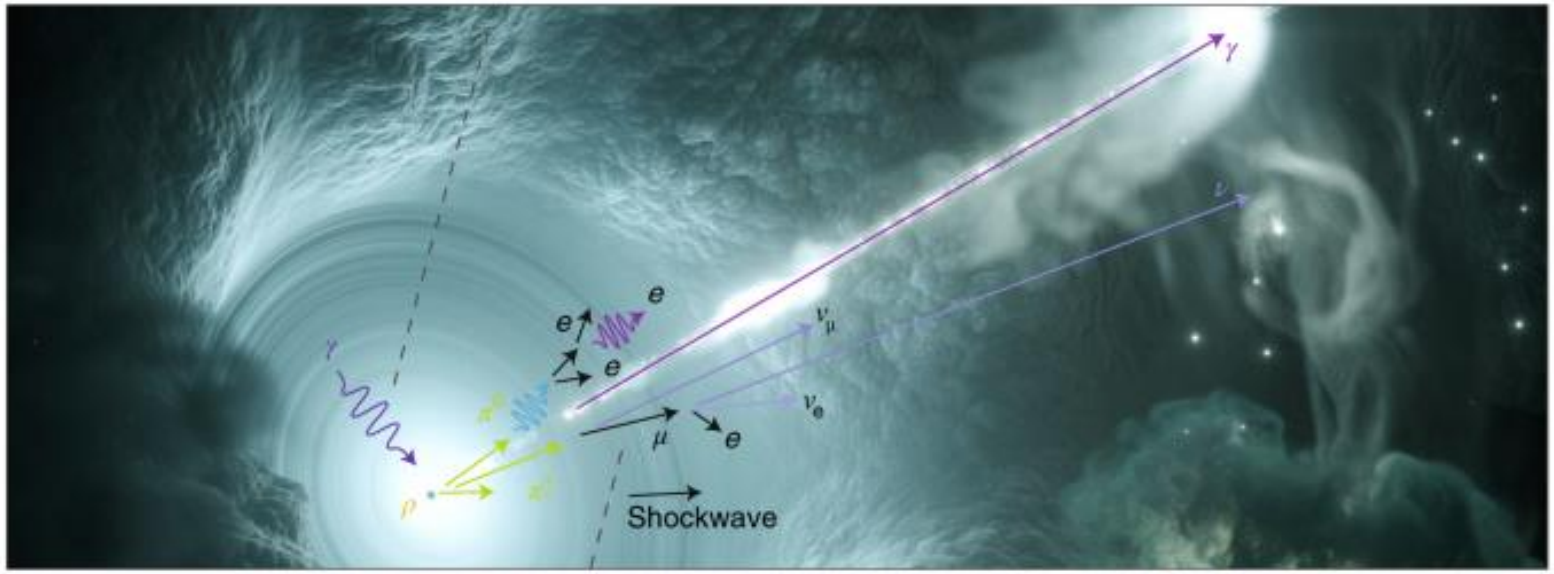
- 轻子作用（leptonic)
  - 涉及电子的辐射过程
  - 同步辐射、逆康普顿散射
- 强子作用（hadronic)
  - 涉及质子的辐射过程

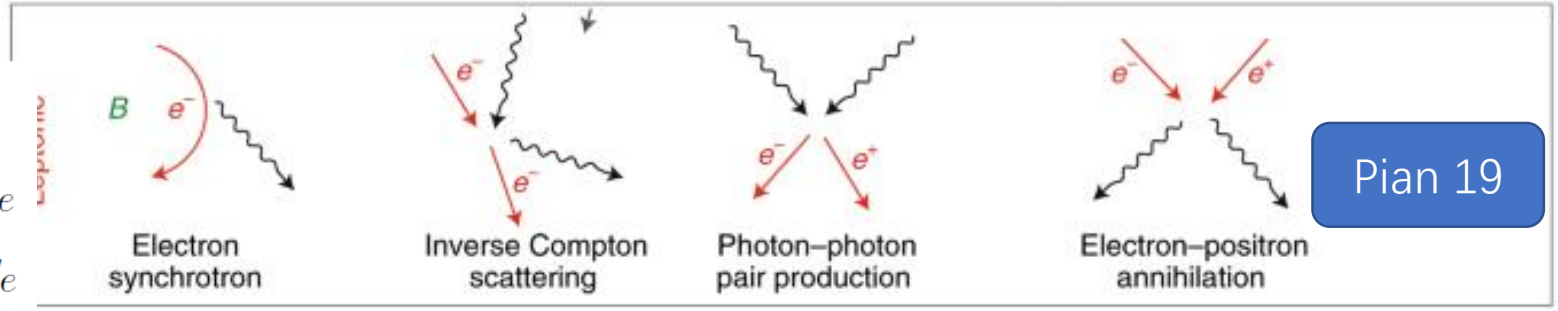
$$p + p \rightarrow p + p + \pi^0$$
$$p + p \rightarrow p + n + \pi^+$$
$$p + p \rightarrow p + p + \pi^+ + \pi^- \ldots$$
$$p + \gamma \rightarrow n + \pi^+$$
$$p + \gamma \rightarrow p + \pi^0$$

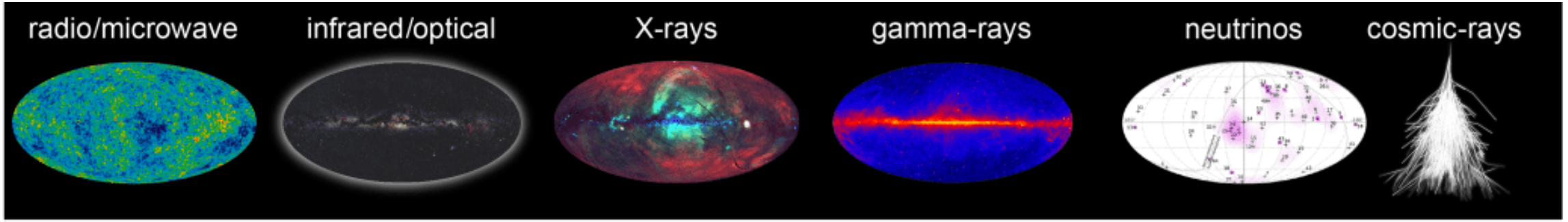
1. 存在高能质子
2. 伴随高能光子产生

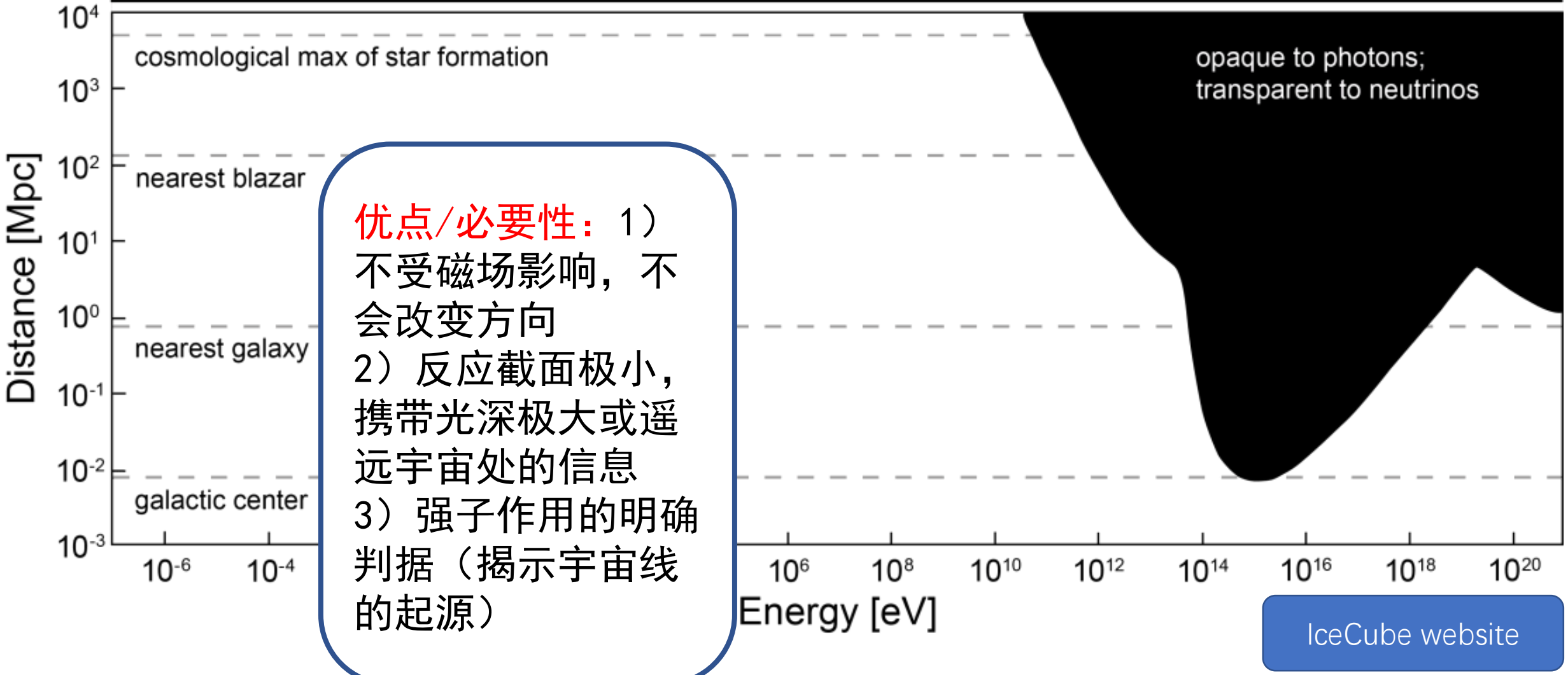
$$\pi^0 \rightarrow \gamma + \gamma$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad \text{and} \quad \mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \quad \text{and} \quad \mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$$





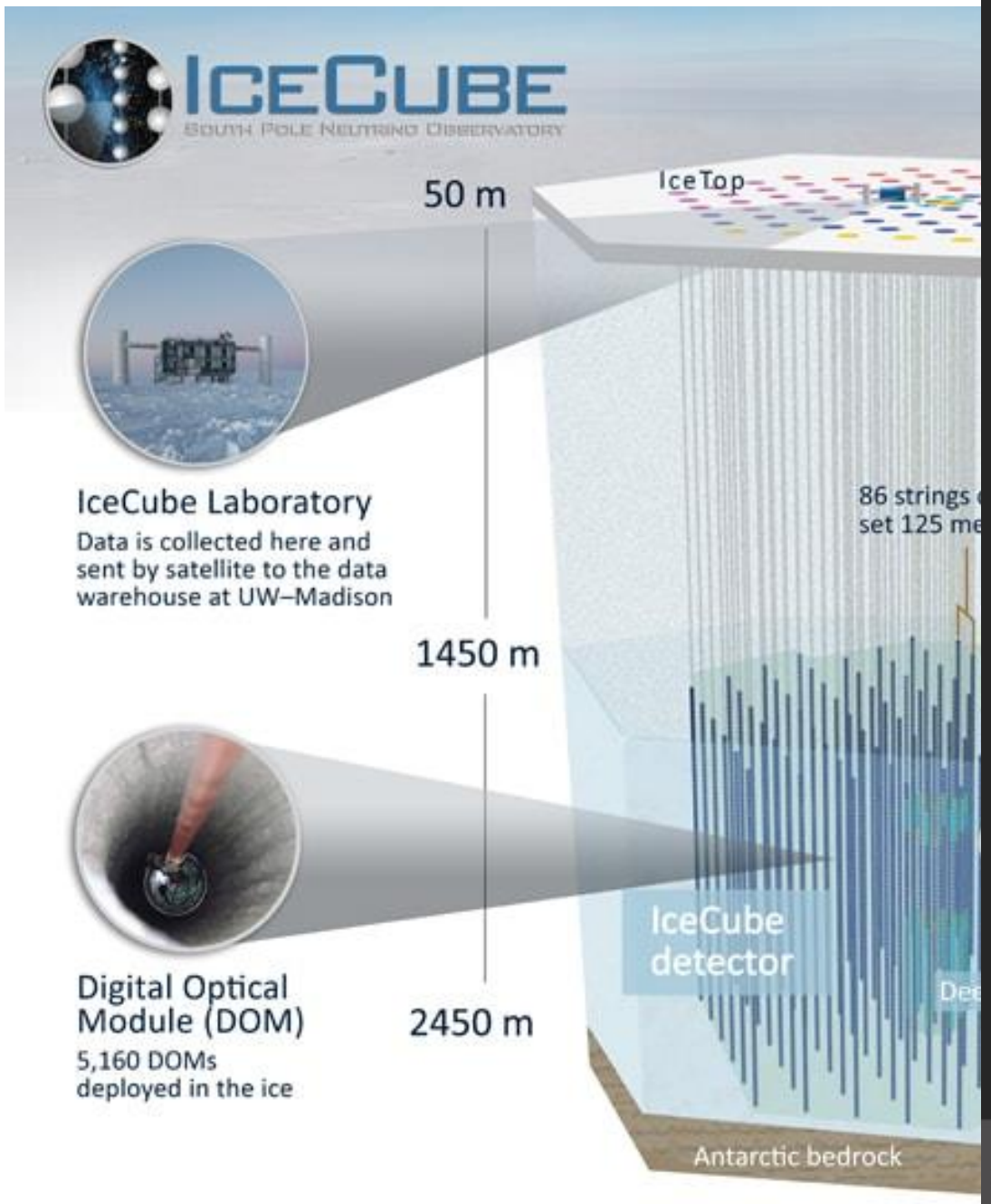






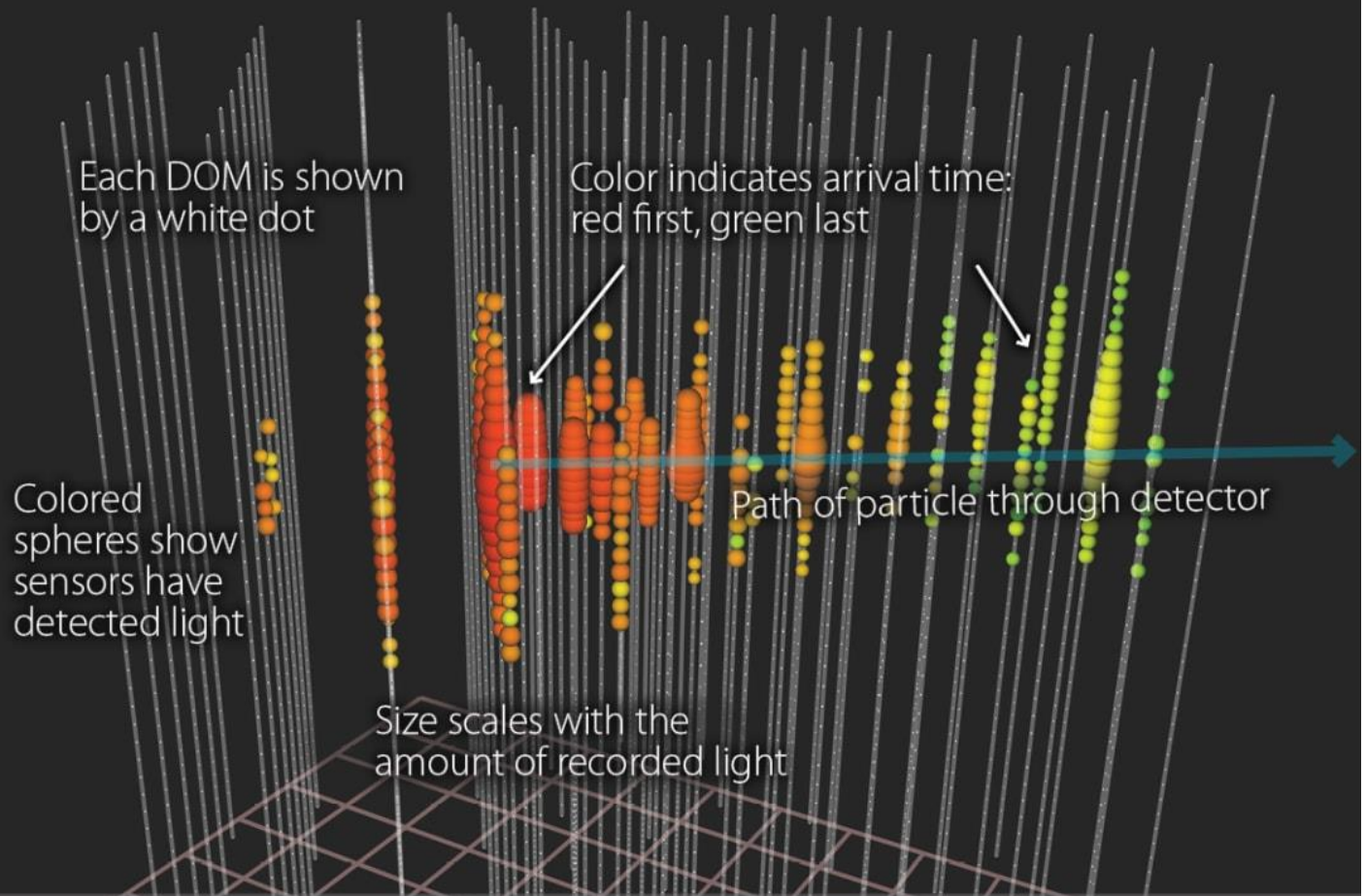
优点/必要性：1）不受磁场影响，不会改变方向
2）反应截面极小，携带光深极大或遥远宇宙处的信息
3）强子作用的明确判据（揭示宇宙线的起源）

IceCube website



How does IceCube work?

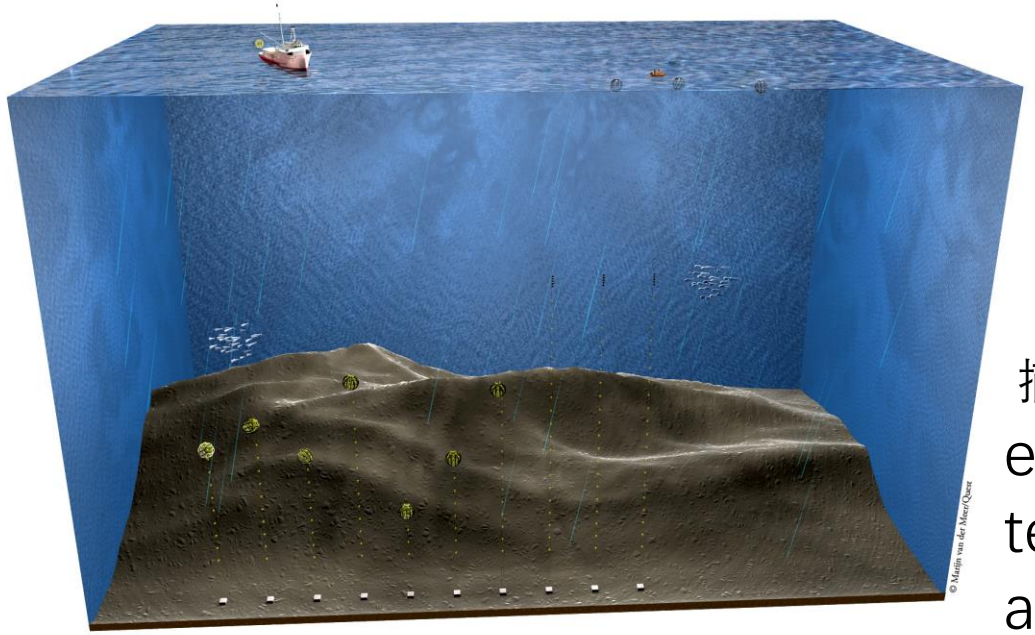
When a neutrino interacts with the Antarctic ice, it creates other particles. In this event graphic, a muon was created that traveled through the detector almost at the speed of light. The pattern and the amount of light recorded by the IceCube sensors indicate the particle's direction and energy.

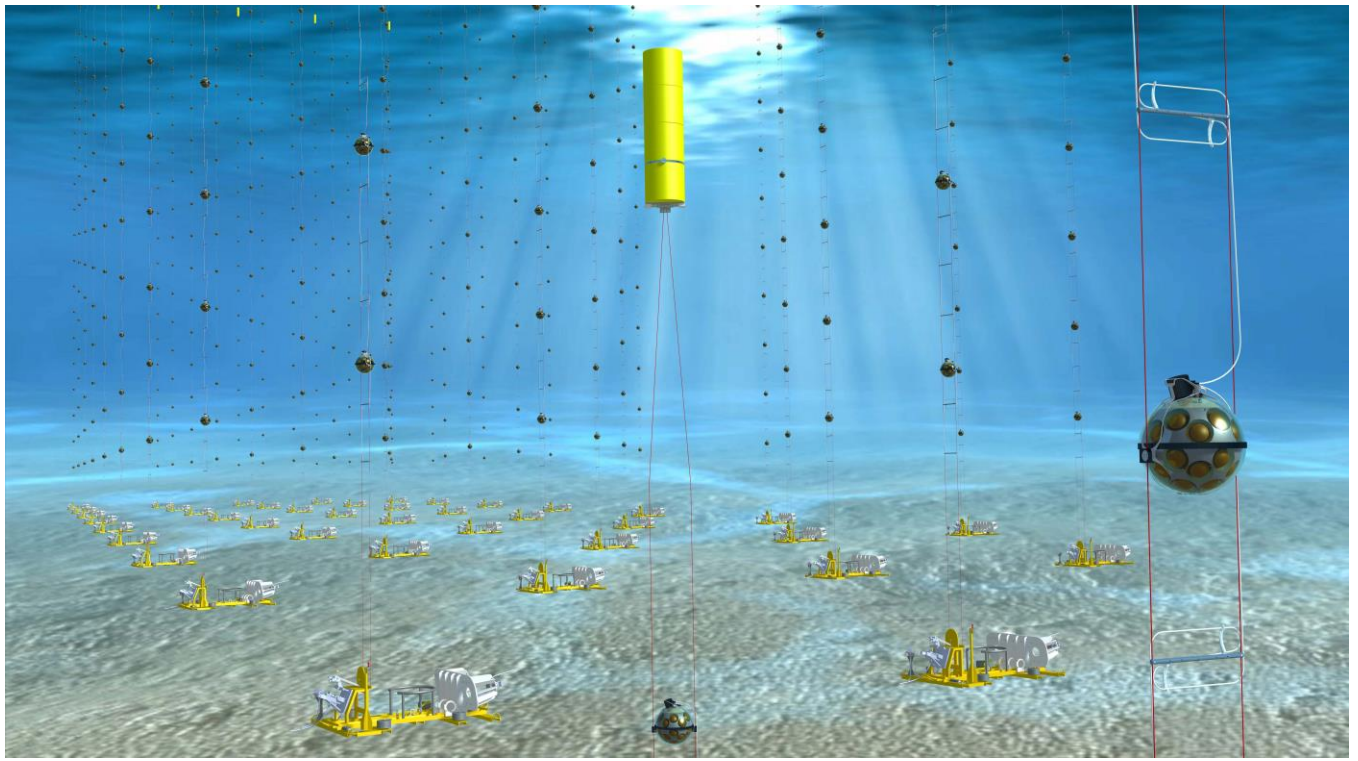


date: **November 12, 2010** duration: **3,800 nanoseconds** energy: **71.4 TeV**
declination: **-0.4°** right ascension: **110°** nickname: **Dr. Strangepork**

Observation of an ultra-high-energy cosmic neutrino with KM3NeT

- KM3-230213A
  - 中微子能量高达220 PeV
  - 引发广泛讨论





摘要：Here we report an exceptionally high-energy event observed by KM3NeT, the deep-sea neutrino telescope in the Mediterranean Sea, which we associate with a cosmic neutrino detection.

IceC

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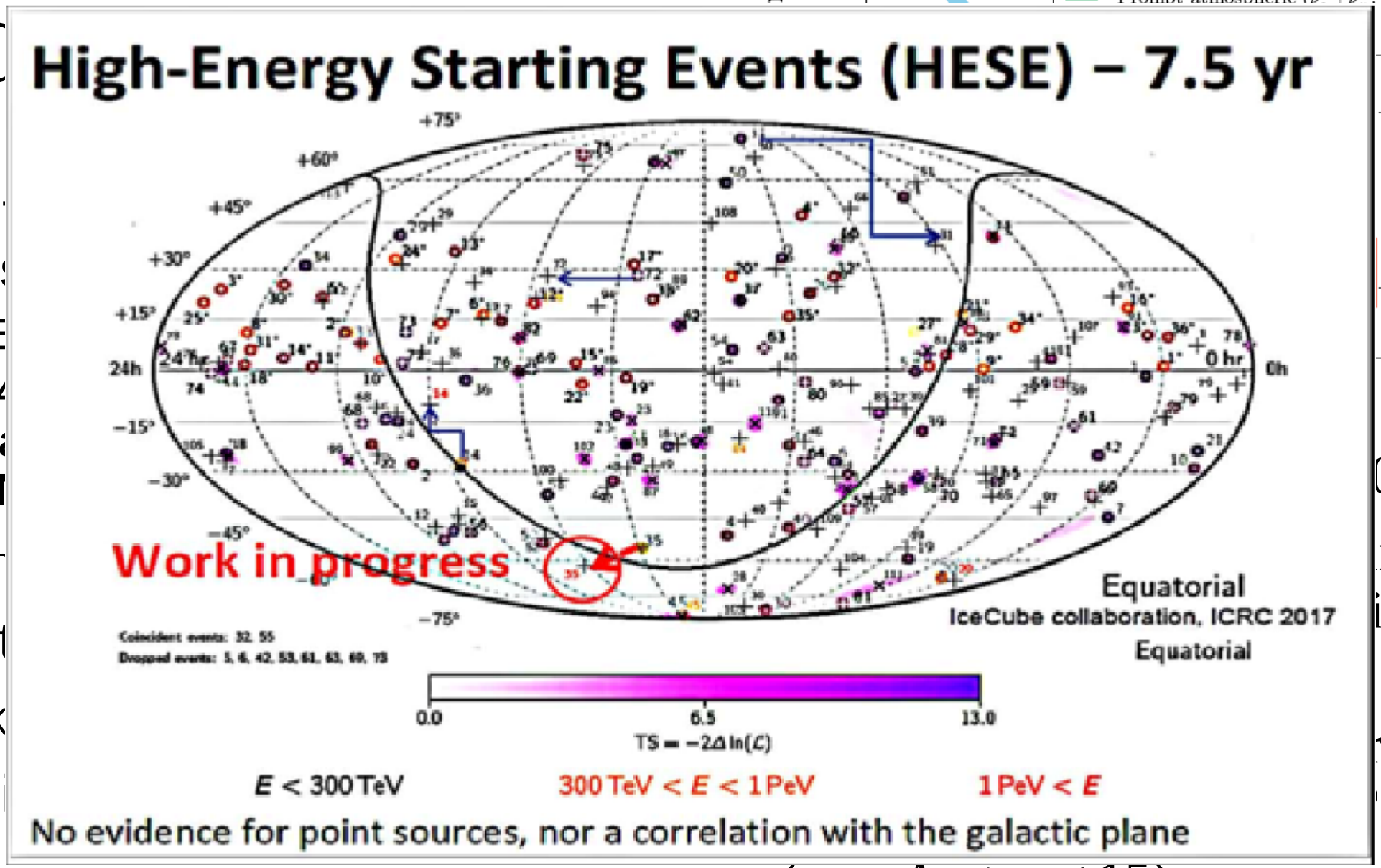
- Neut
- Dark
- Glac



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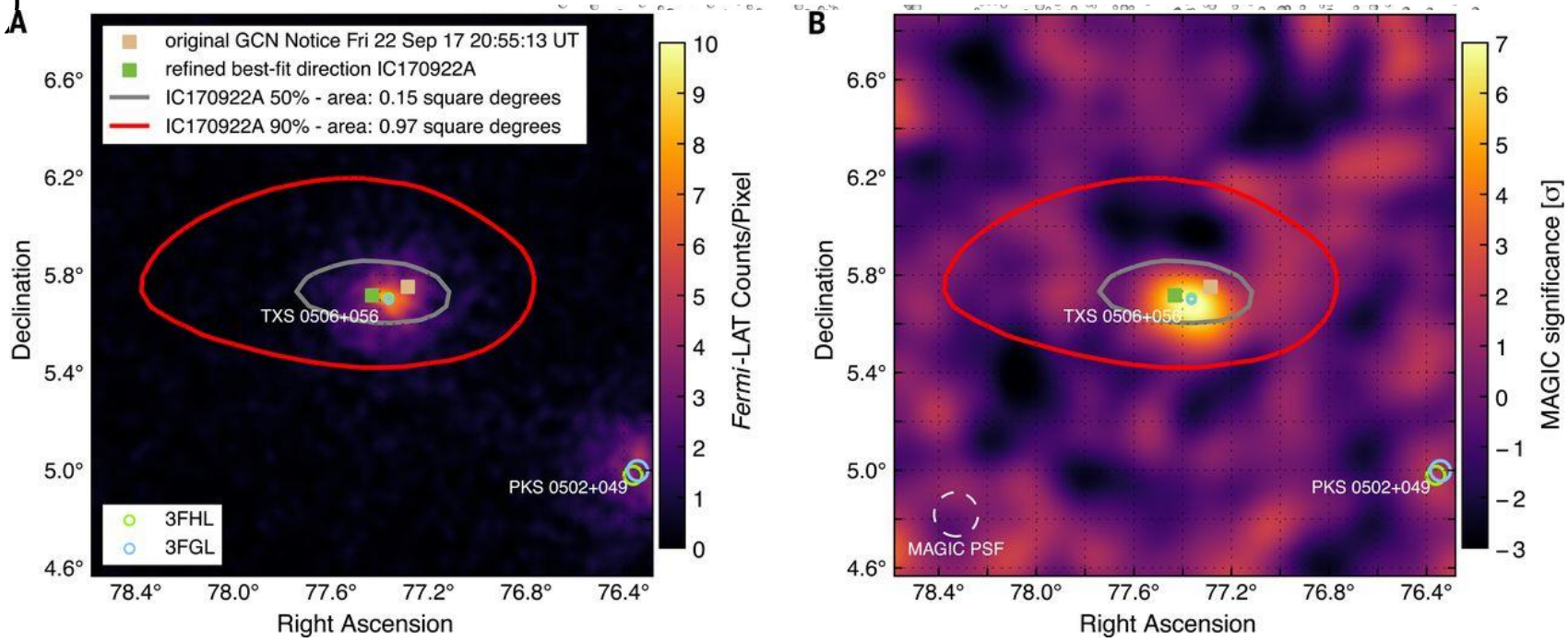
(e.g., Aartsen+15)

IceCube-170922A

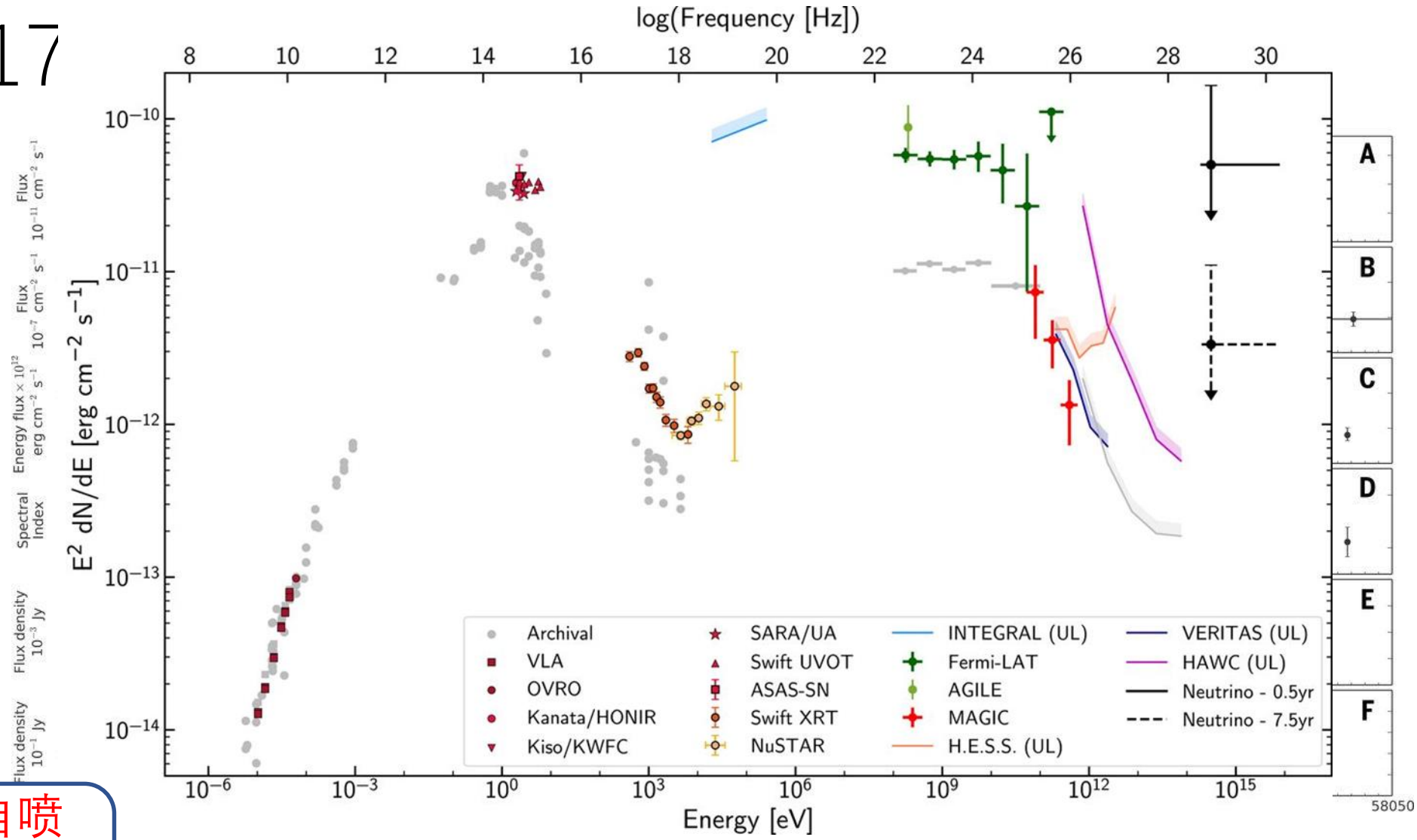
- 位置和耀变体（blazar）TXS0506+056吻合



The IceCube collaboration et al. 2018 (Science)

IceCube-17

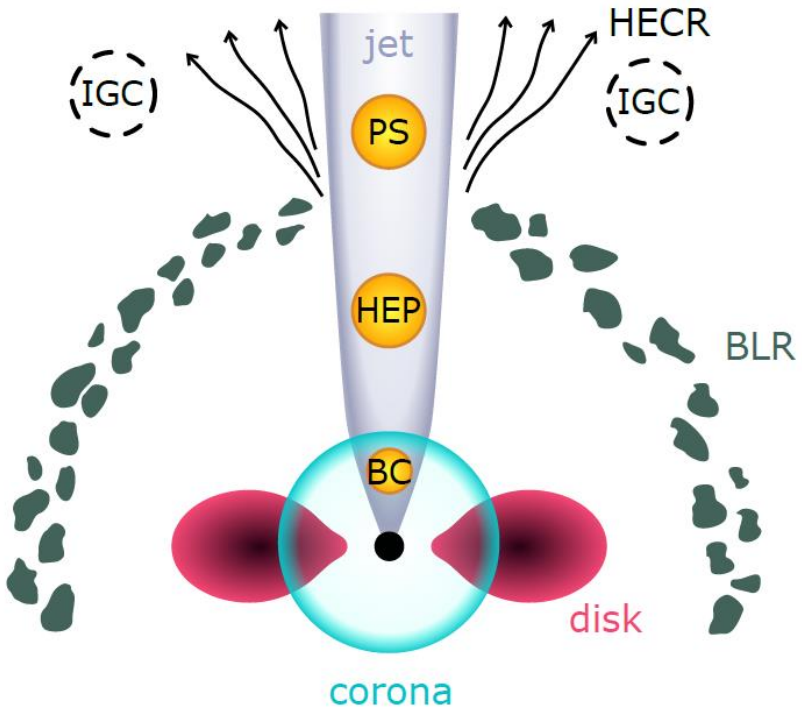
- 位置和TXS0506+056吻合
- 中微子探测时间和耀变体的耀发吻合



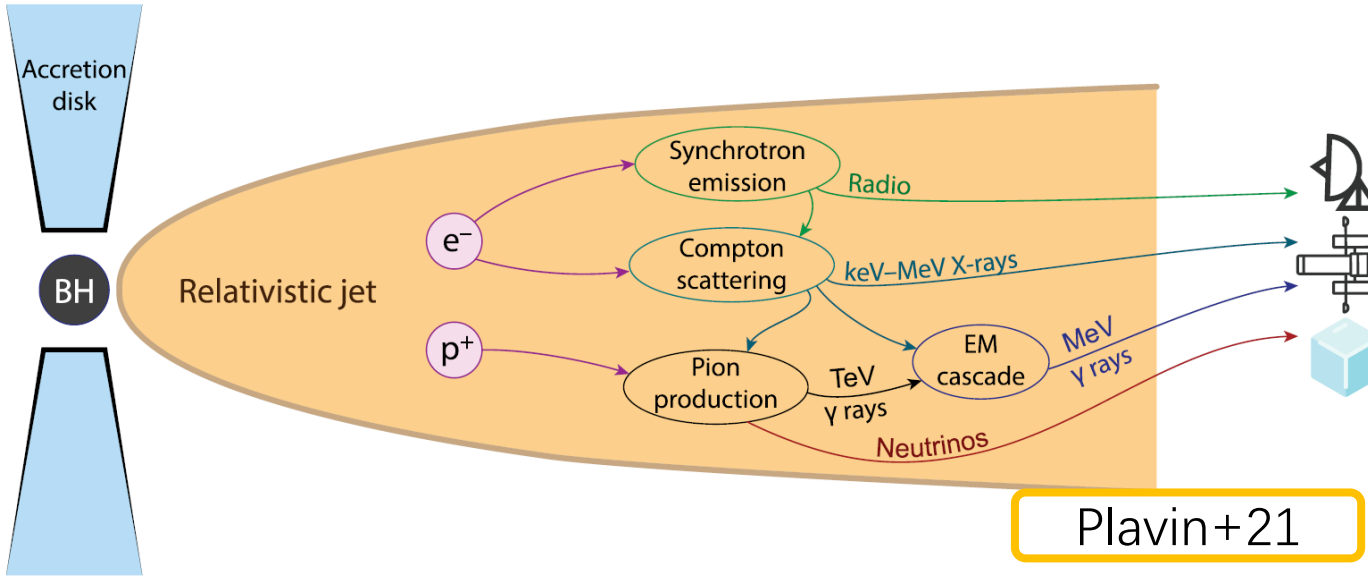
耀变体辐射：辐射来自喷流，低频峰电子同步辐射，高频峰逆康普顿（但…）

The IceCube collaboration et al. 2018 (Science)

Theoretical efforts for blazars as the emitters (many papers)

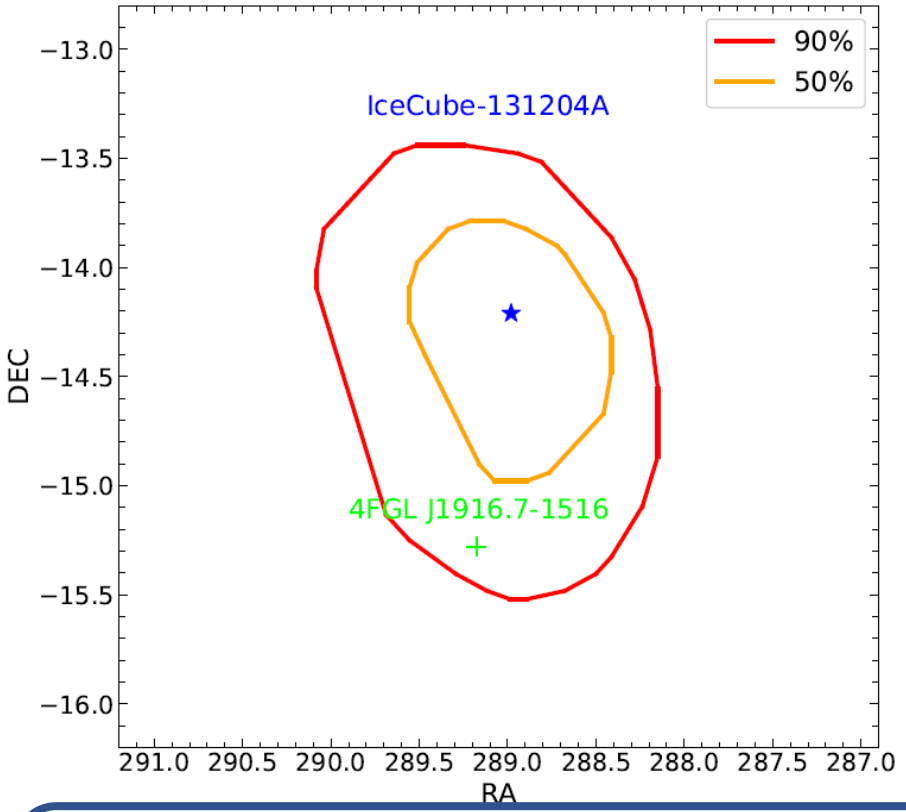


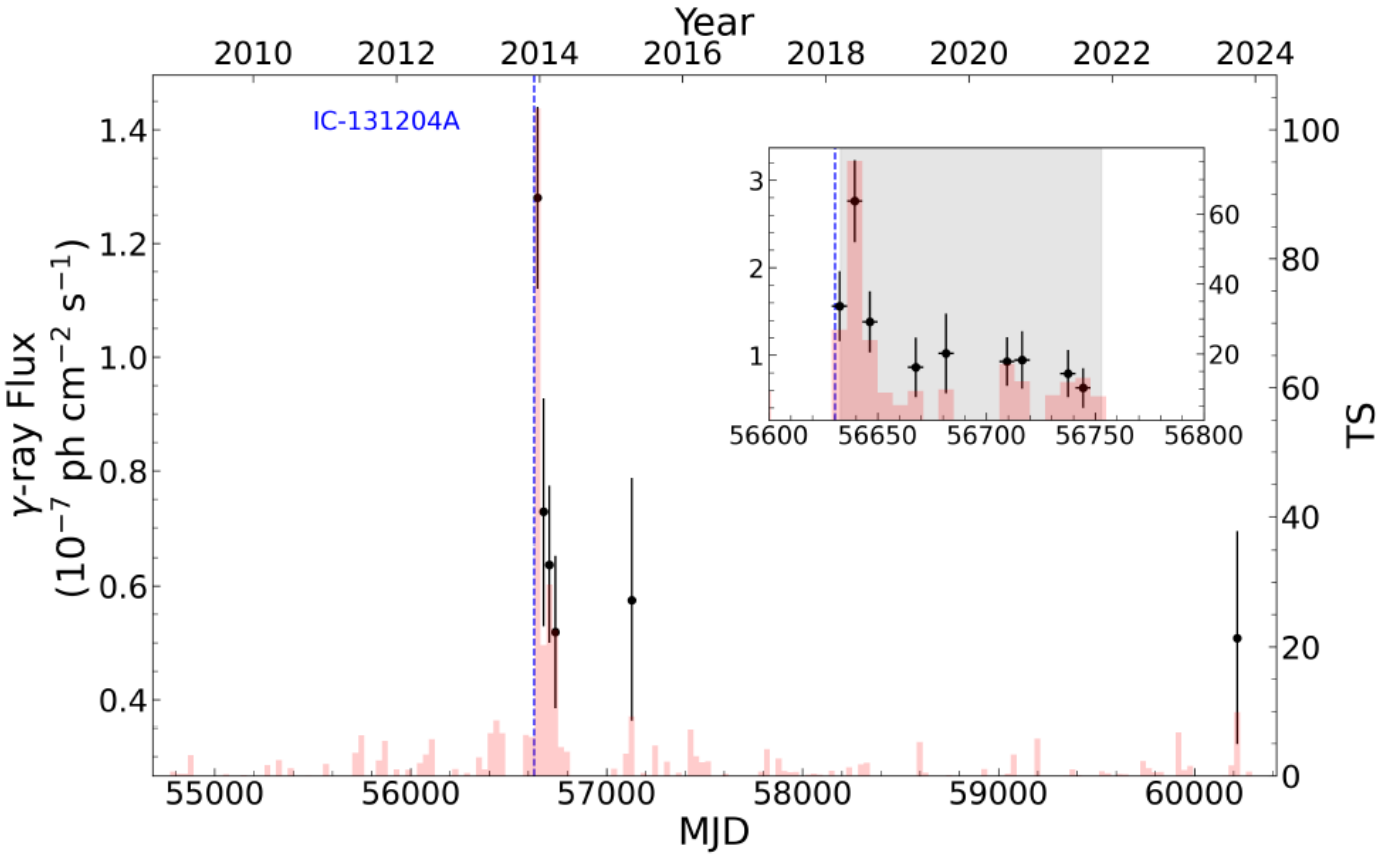
- BC: blazar core
- HEP：hidden external photon
- PS: proton synchrotron (Petropoulou+20)



- Lepto-hadronic model
  - EM emission is explained by synchrotron and inverse-Compton of electrons
  - Protons are also accelerated, interact with photons (pγ interaction); required for neutrino production
  - Secondary electron-positron pairs also contribute to EM, which come from processes such as Bethe-Heitler and photomeson
  - Other process: photon-photon pair production

Observational efforts: e.g., IceCube-131204A: PMN 1916-1519 (LSP, possible FSRQ)



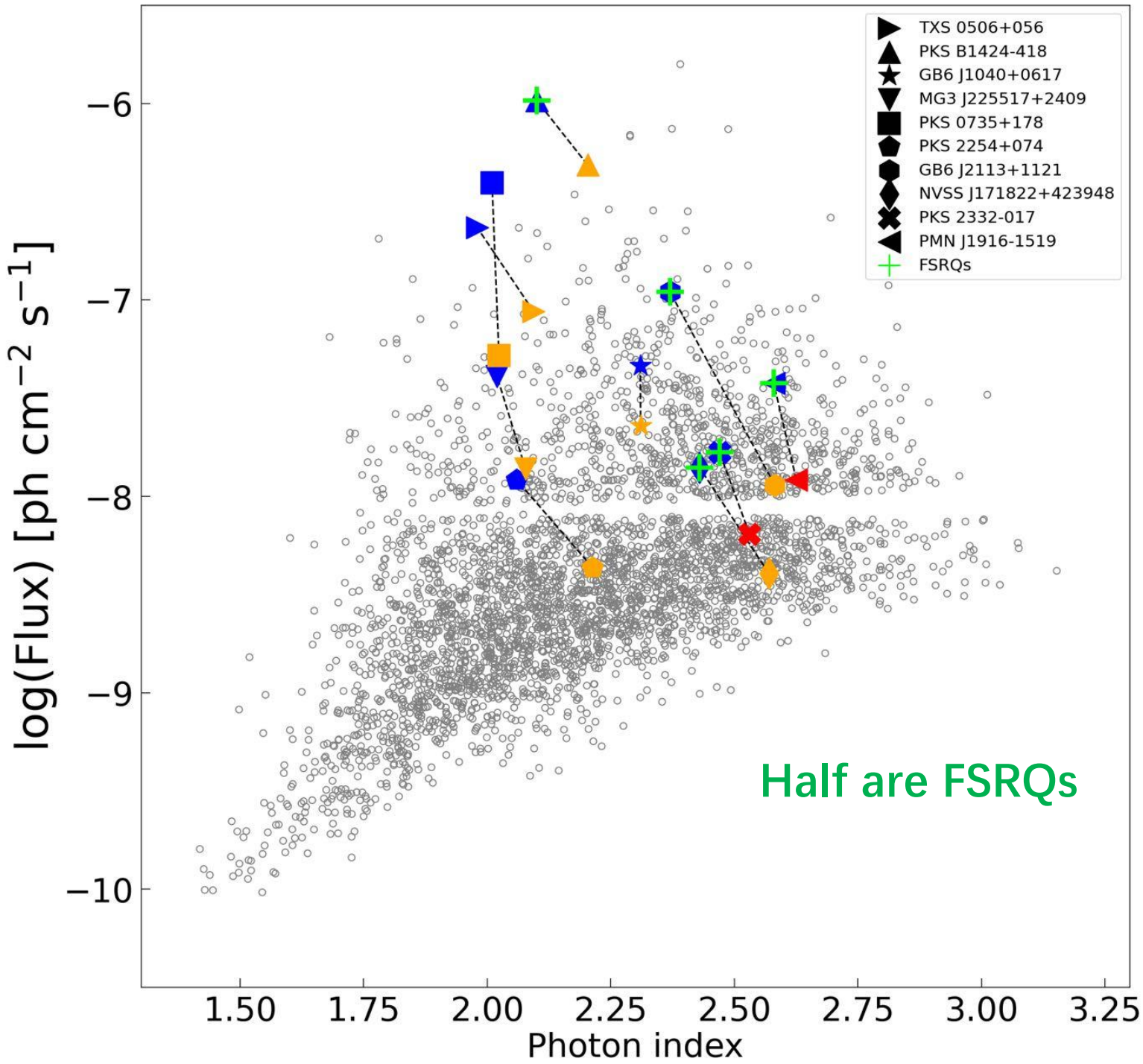


- PMN 1916-1519 was having a short, 4-month long flare (Ji, Wang, Zheng 2025 ApJ)

认证方法：有一例高能中微子事例，其位置及到达时间和一例耀变体及耀发分别吻合；多波段表现？

I. Jetted AGNs

- Current status: searching for more cases (or evidence) to connect IceCube Gold neutrinos to flaring blazars
- Thus far, 10 cases have been reported (we found 3)
- Common properties:
  1. Associated optical/MIR flares were seen
  2. Gamma-ray emission hardened during the flare
  3. Some of the flares were among the brightest



Connection between 10–100 TeV neutrinos and MeV gamma rays (Murase+20, PRL)

AGN responsible for the medium-energy ENB should contribute a large fraction ≳10–30% of the MeV EGB.

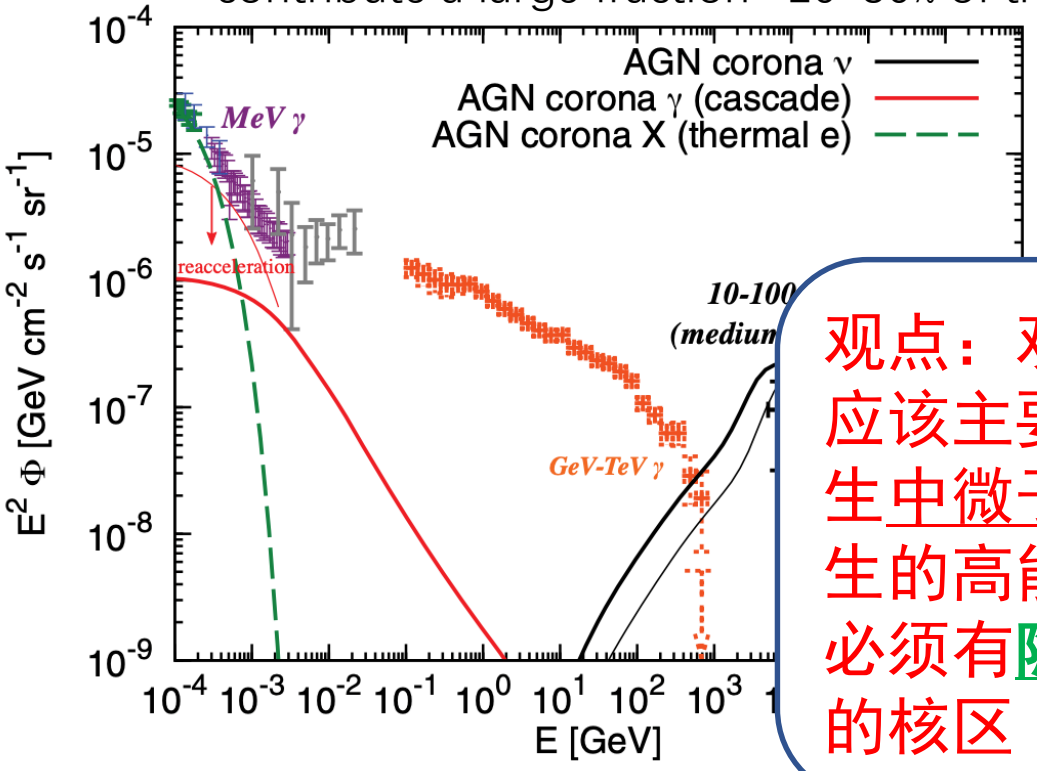


FIG. 3. EGB and ENB spectra in our AGN corona model. The data are taken from *Swift* BAT [15] (green), Nagoya balloon [100] (blue), SMM [101] (purple), COMPTEL [102] (gray), *Fermi* LAT [103] (orange), and IceCube shower events (black) [5] (consistent with the global fit [4]). Solid thick (thin) curves are for $\beta = 1$ and $q = 5/3$ ($\beta = 3$ and $q = 3/2$ with the reacceleration contribution), respectively.

观点：观测到的中微子全天辐射应该主要来自某一类天体，在产生中微子的强子作用过程中所产生的高能光子不能超过光子背景，必须有隐藏的中微子源 =》AGN 的核区

A possible unified picture of the EGB and ENB

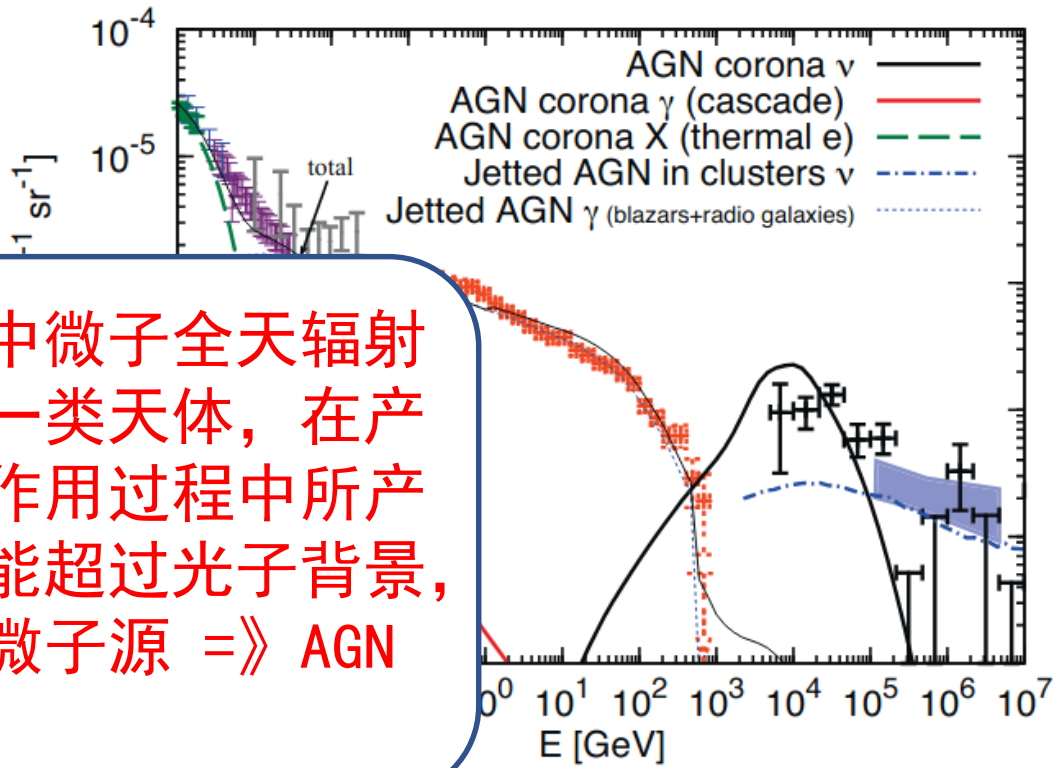
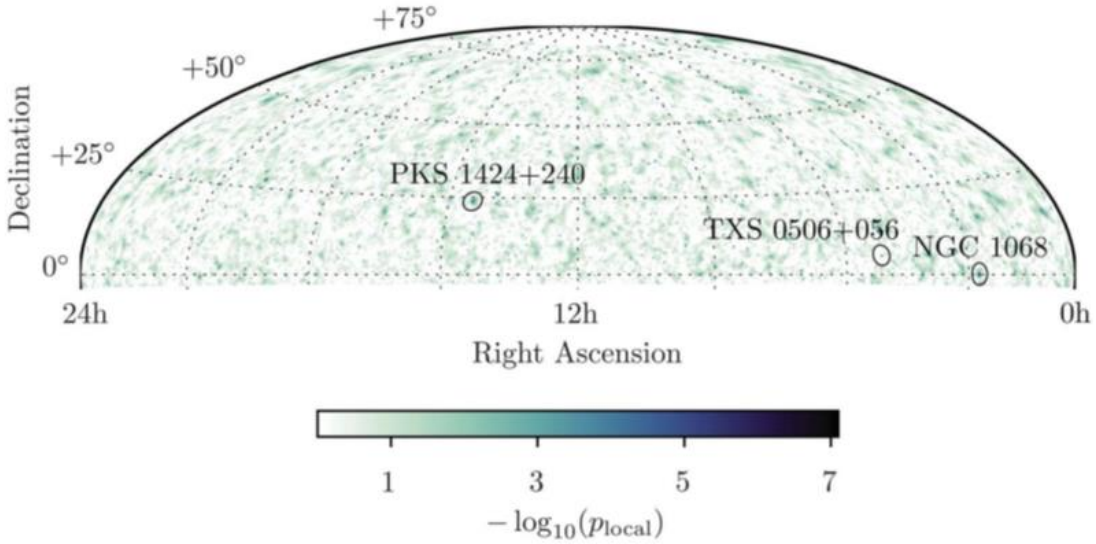
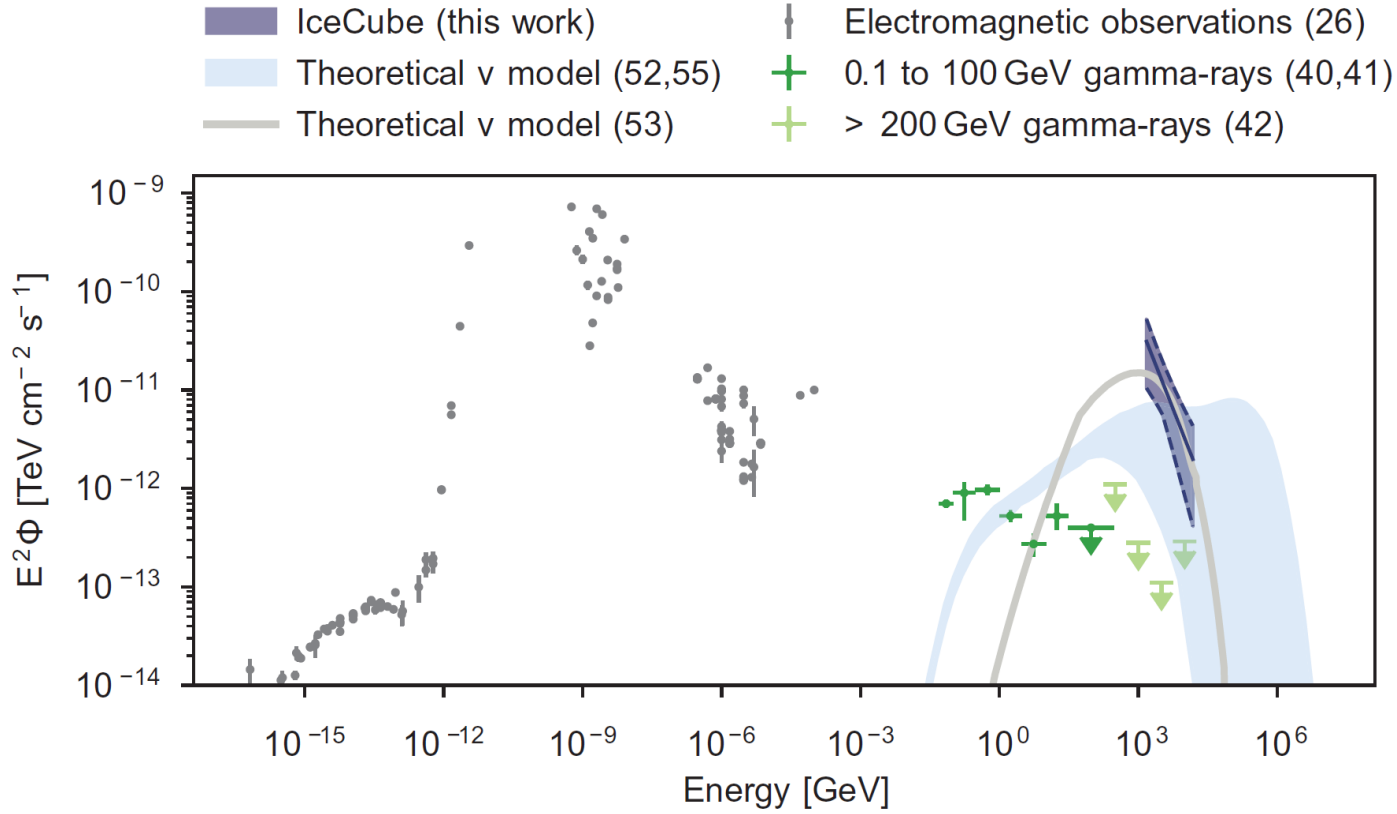


FIG. S5: A possible unified picture of the EGB and ENB, in which the MeV-TeV EGB and TeV-PeV ENB are simultaneously explained by AGN cores and jetted AGN. The data are taken from *Swift* BAT [15] (green), Nagoya balloon [98] (blue), SMM [99] (purple), COMPTEL [100] (gray), *Fermi* LAT [101] (orange), and IceCube for shower (black) [5] and upgoing muon track (blue shaded) [9] events.

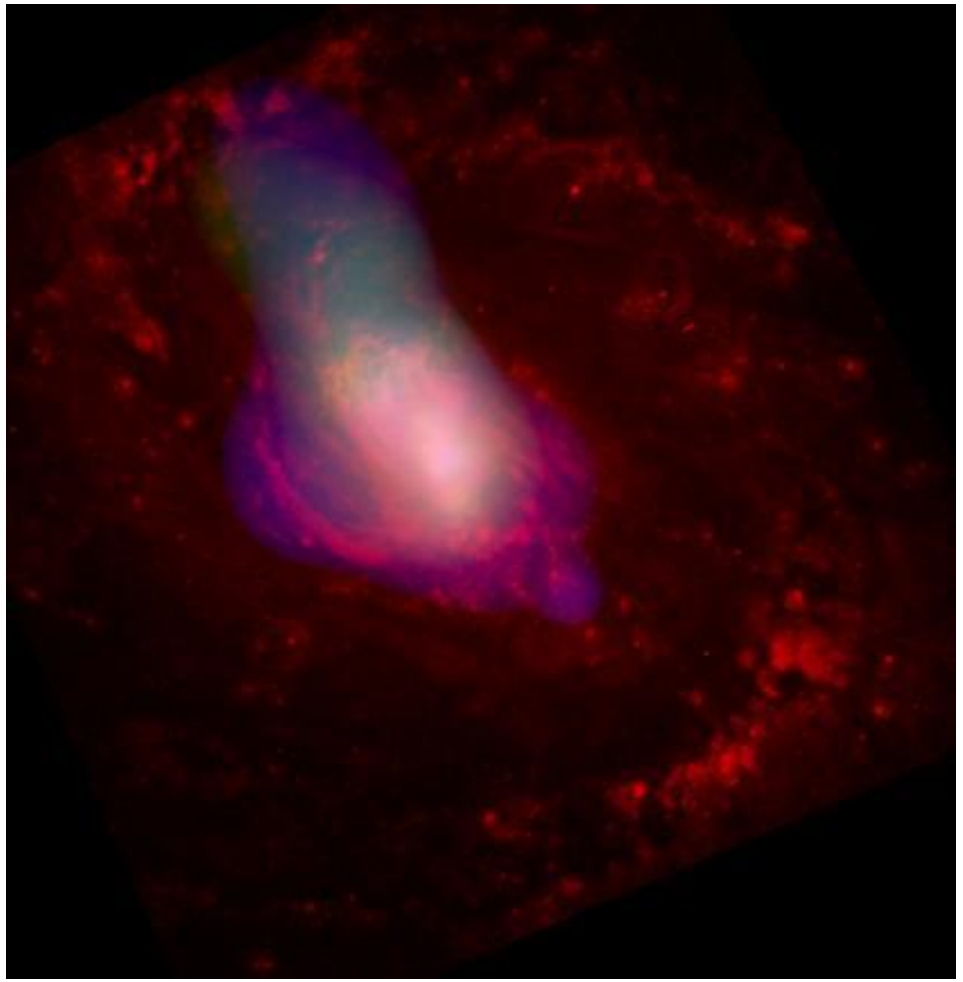
对NGC 1068的中微子探测





IceCube collaboration 2022/11/03, Science

NGC 1068 (M77):距离14 Mpc，黑洞质量10^9太阳质量，大小7角分，Type-II型AGN



AGN中微子辐射机制

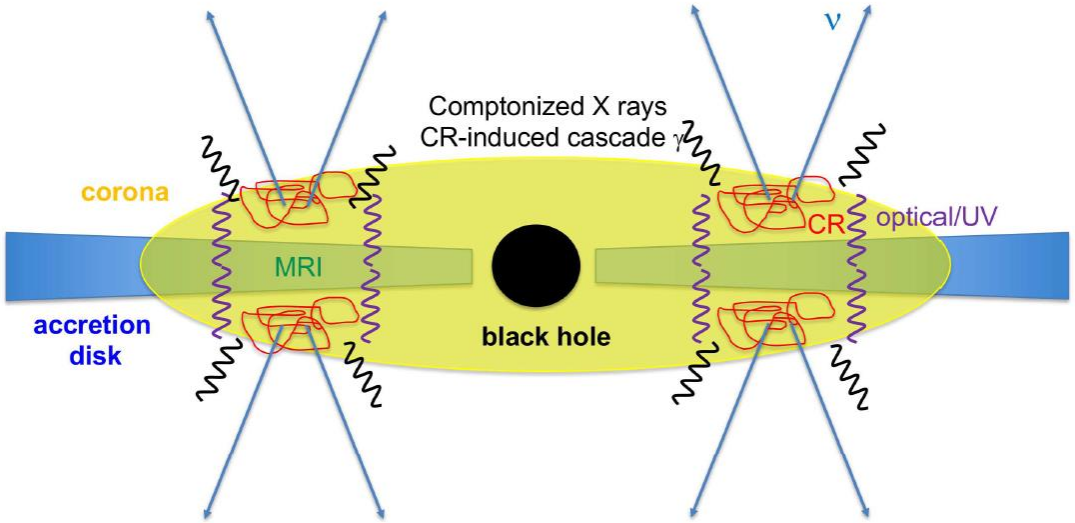
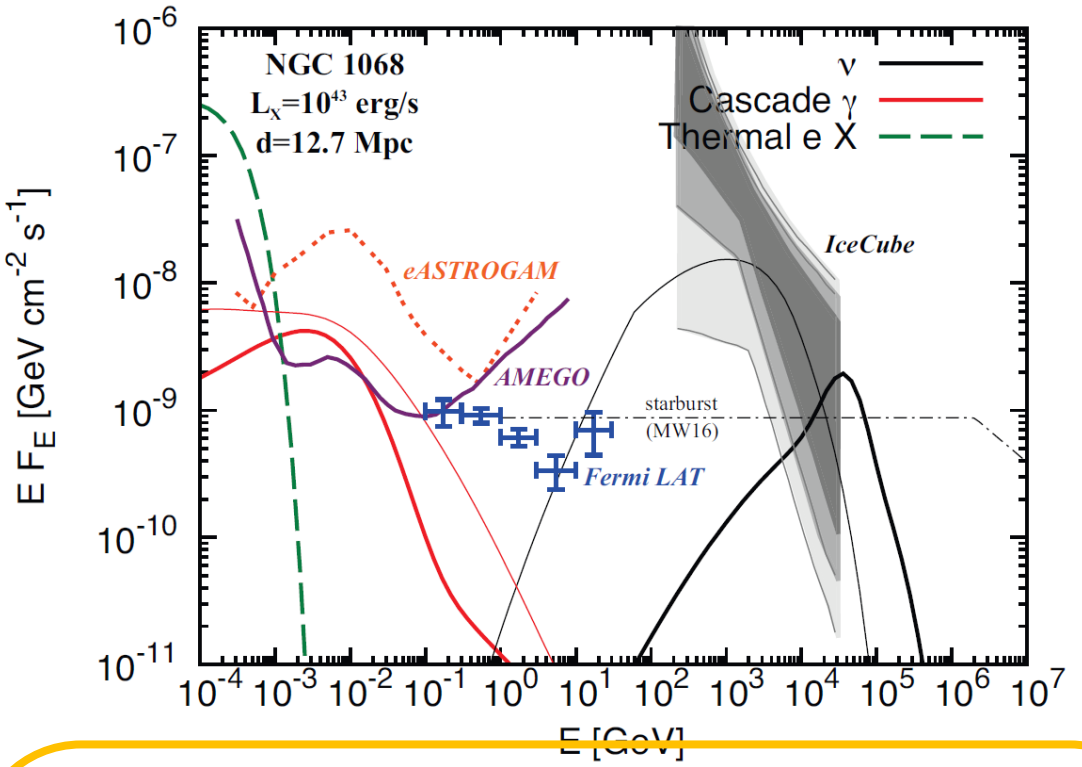


FIG. 1: Schematic picture of the AGN disk-corona scenario. Protons are accelerated by plasma turbulence generated in the coronae, and produce high-energy neutrinos and cascaded gamma rays via interactions with matter and radiation.

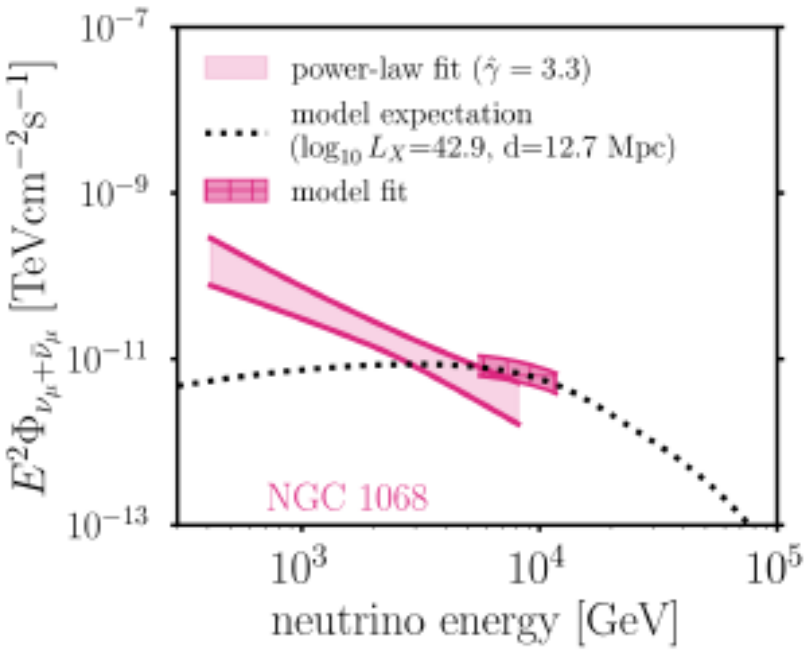
Murase et al. 2020 (PRL)

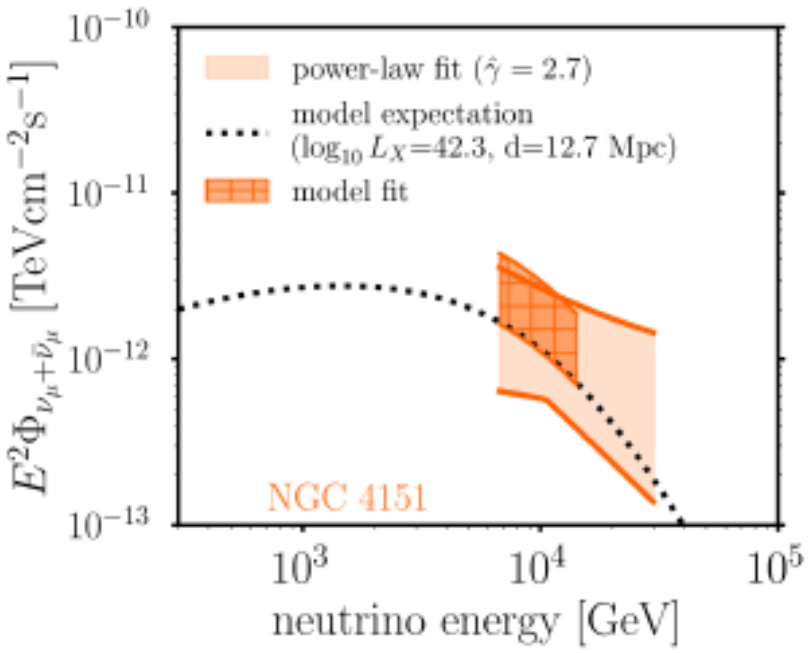


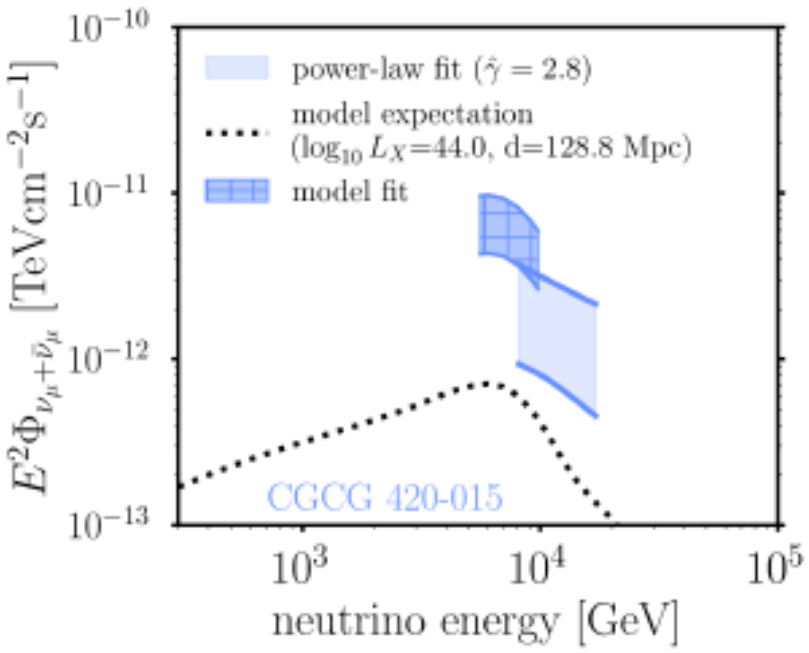
- 超大质量黑洞附近有冕，冕中可以通过磁不稳定性（或激波）加速质子
- 强子作用产生中微子，被观测到
- 强子作用或轻子作用过程产生伽马光子，但光深大，被消弱
- 伽马光子级联到硬X射线光子，终于可以跑离核区 =》强硬X射线辐射

II. AGN核区

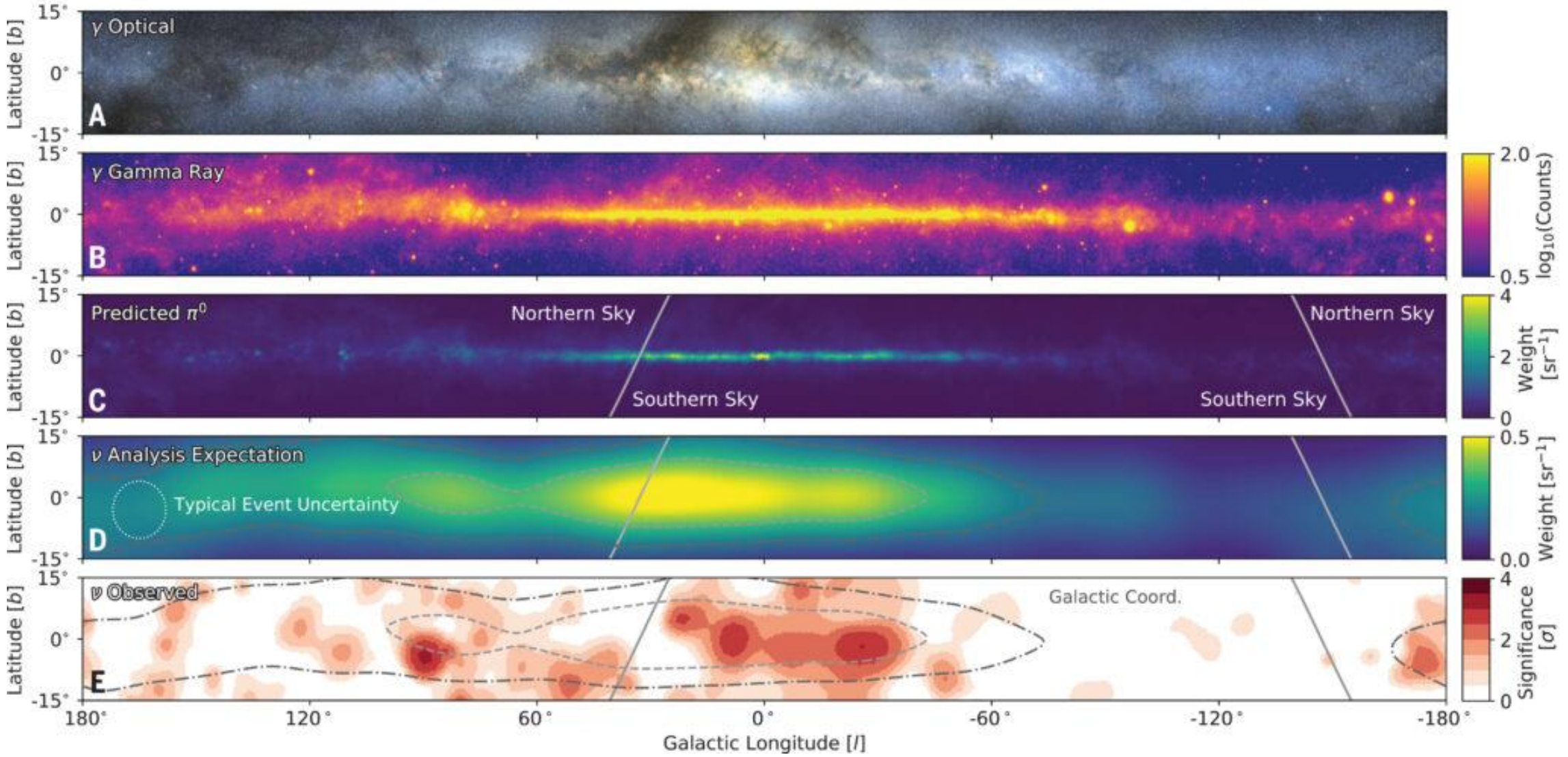
- IceCube Search for Neutrino Emission from X-ray Bright Seyfert Galaxies (NGC 4151, CGCG 420-015; Abbasi+24)





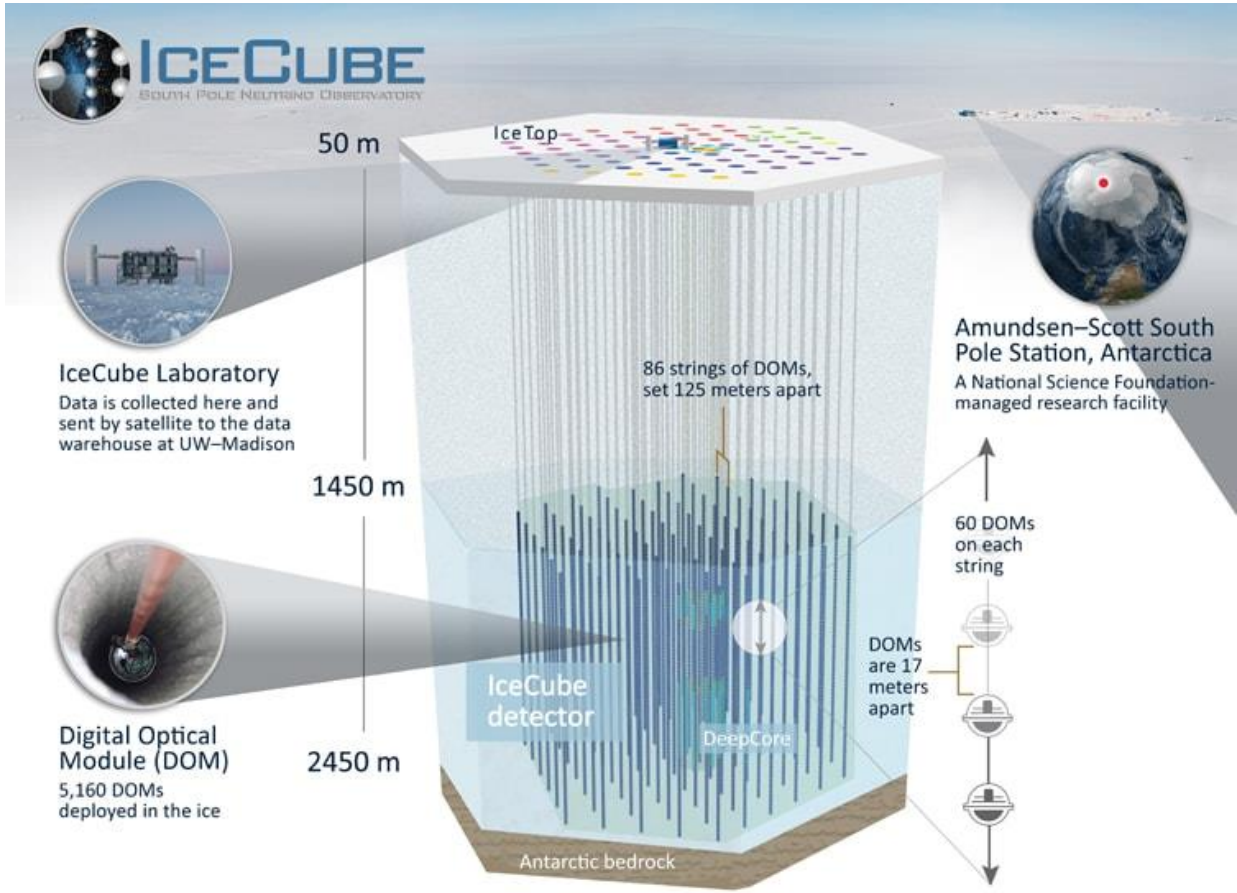


III. The Milky Way (Science, 2023)



IceCube science goals

1. **Neutrino astronomy & multi-messenger astrophysics**
   - **主要考虑喷流源**
   - **14 BL-Lac, 11 FSRQ, 6 radio galaxies, 银心，3 PWNe, 3 SNRs, 5 gamma-ray binaries**
2. Cosmic ray physics
3. Neutrino physics
4. Dark matter
5. Glaciolog (冰川学)



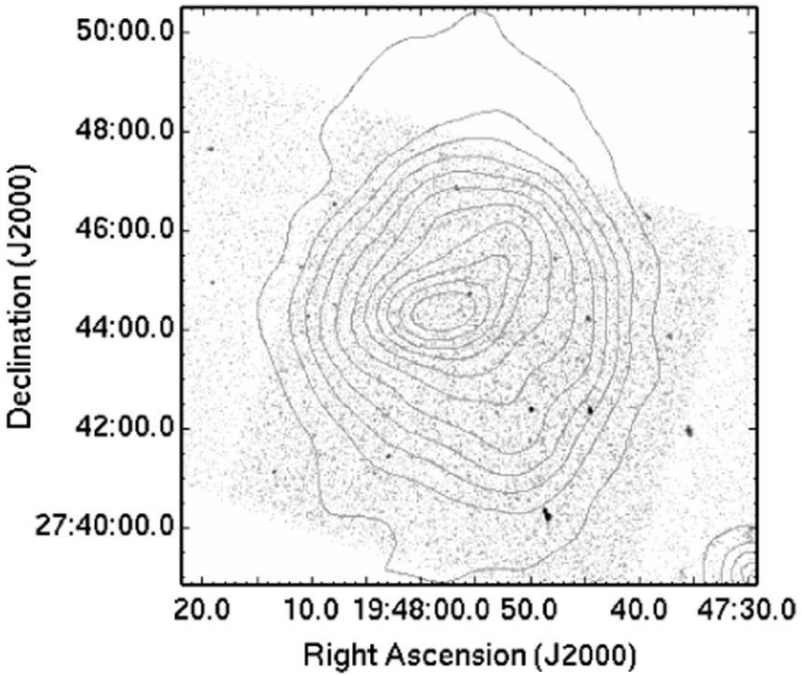
Possible Galactic Neutrino Sources

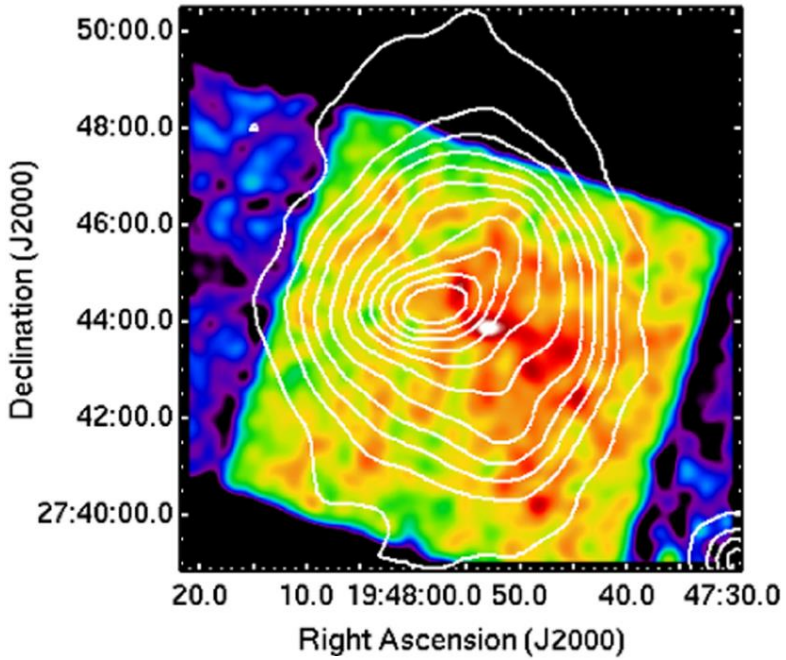
1. SNRs
   - 抛出物质中的强子作用
   - 激波加速质子（宇宙线），和分子云的强子作用
2. PSRs
   - 脉冲星磁层加速核子，核子和脉冲星辐射场、脉冲星风云光子、附近分子云物质作用
3. PWNe
   - 脉冲星风云激波加速质子，质子和光子或近邻质子的作用

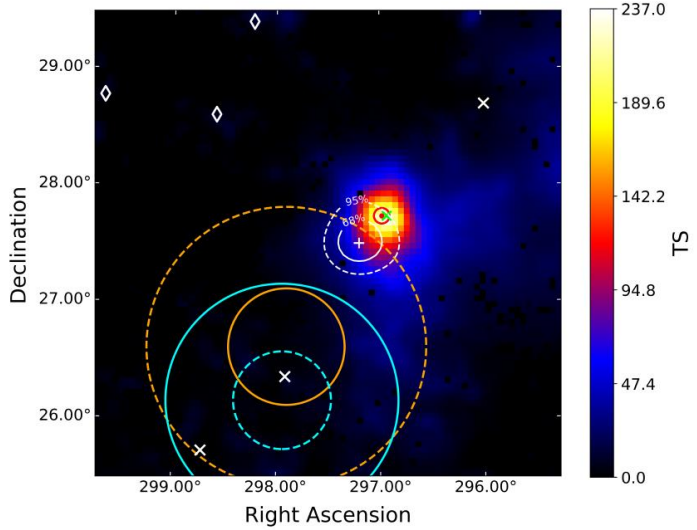
间接证据：

- 费米对SNRs的探测，表明许多SNR的伽马辐射可以由强子作用解释（最著名的W44和IC 443，2013 Science)
- 我国LHAASO对银河系PeV光子源的探测，其中包括Crab nebula（用轻子模型比较难解释）

SNR/PWN G63.7+1.1



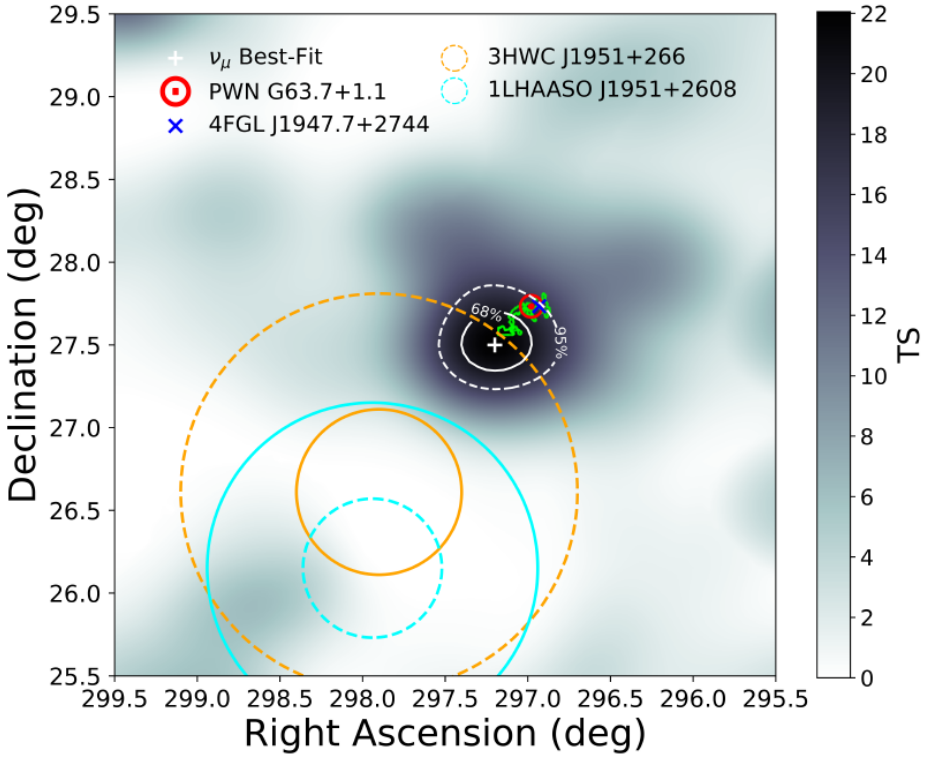


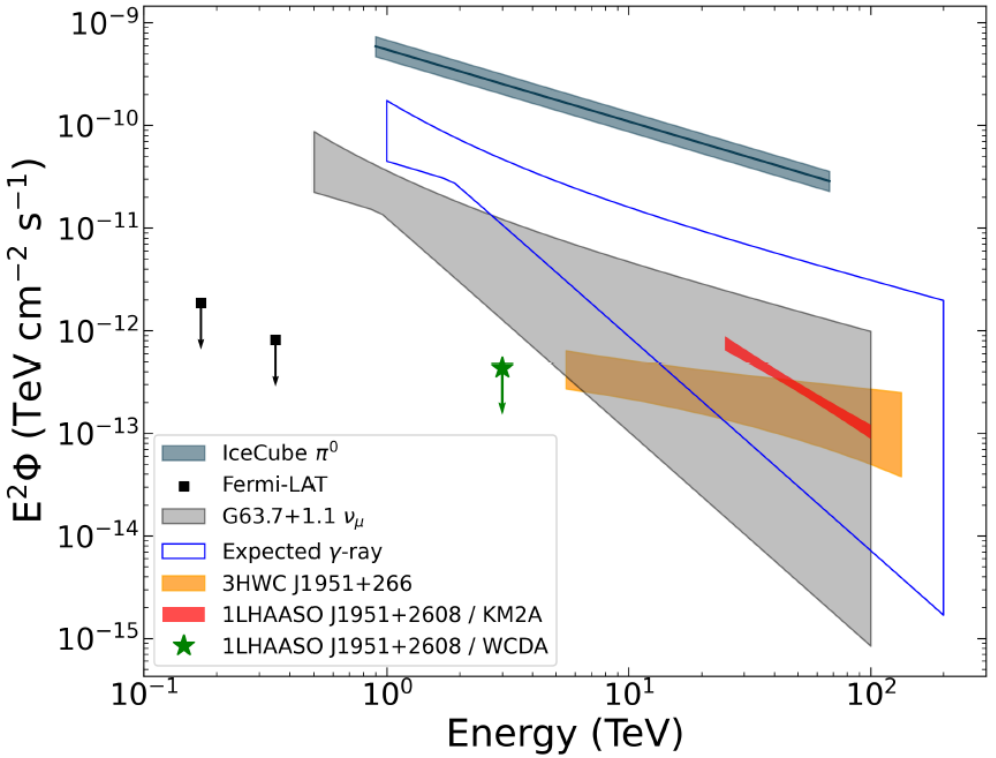


- Found in radio survey of the Galactic plane (Taylor+92)
- A filled-center SNR => containing a PWN
- Matheson+16 conducted detailed X-ray studies: X-ray PWN, >8kyr, candidate pulsar
- Fermi gamma-ray detection => we think the gamma-rays are of the pulsar （才获得了FAST观测）

Ji, Wang, et al. 2025 ApJ

IceCube detection of a hotspot at G63.7+1.1

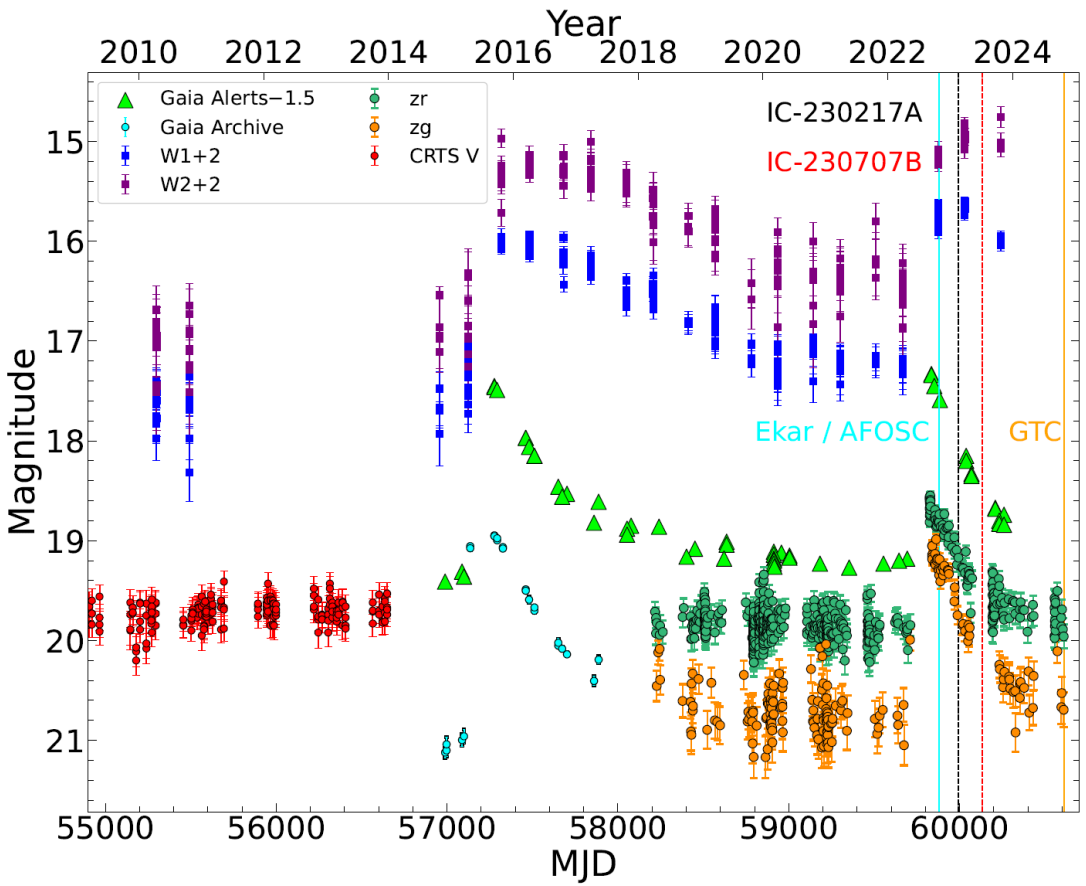




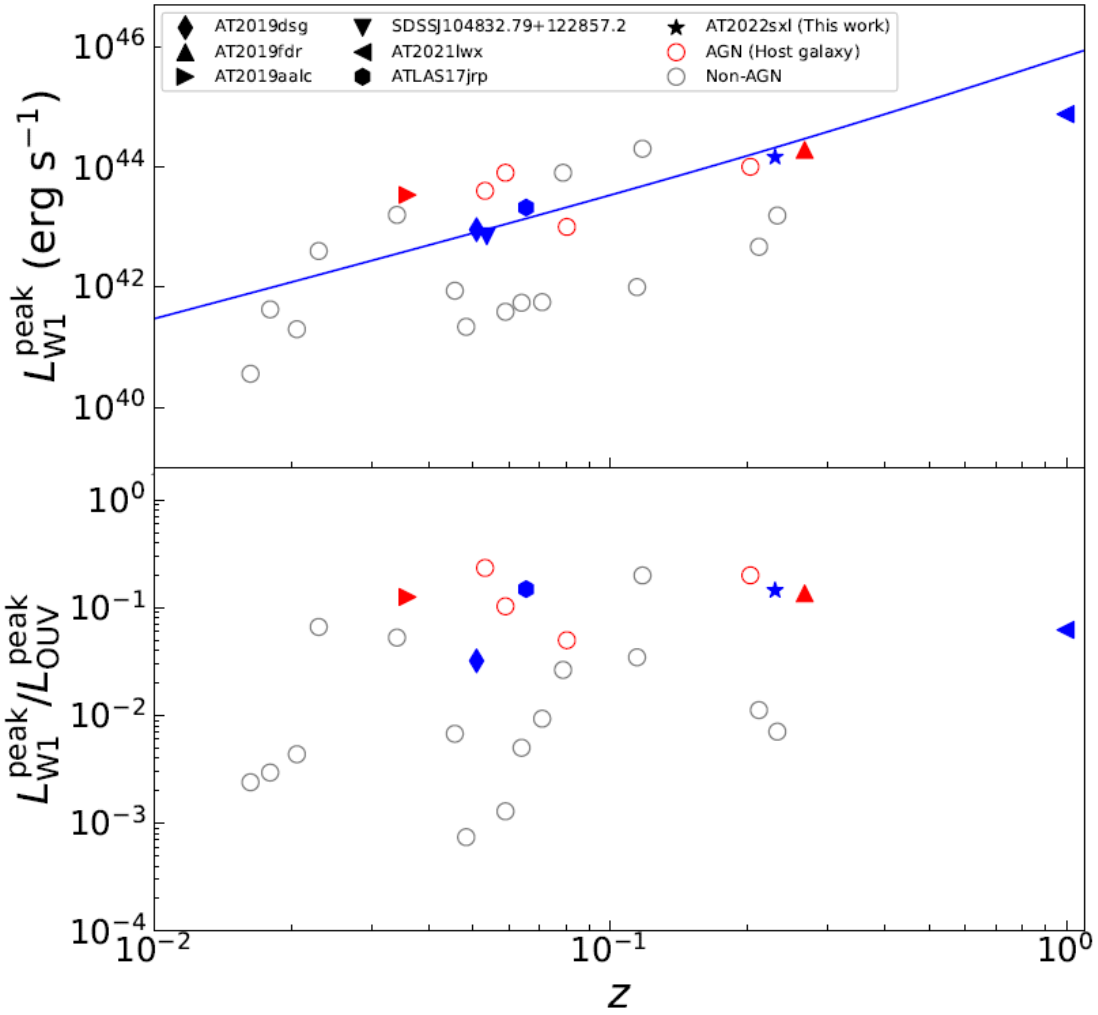
问题：
1. 为什么这么一个年老PWN?
2. 伴随中微子产生过程的光子?

- In our search for neutrinos for 14 PWNe with nearby molecular clouds, G63.7+1.1 stands out (3.2σ)
- Problems remain resolved
- A possible breakthrough: the 1st Galactic neutrino source?
- (Ji, Wang, et al. 2025 ApJ)

IV. Candidate: TDEs



Ji, Wang, et al. 2025, ApJ



- Similar to flaring blazars, several TDEs found to be in positional and temporal coincidences with neutrinos
- Better match MIR peaks than optical

Summary

- We have entered the era of high-energy neutrino astronomy
- Thus far:
  1. AGN blazars can emit neutrinos, at their flaring state (?)
  2. AGN cores can emit neutrinos, with prediction of having high X-ray emission (to be verified)
  3. The Milky Way has neutrino emission, but how about individual high-energy sources (SNRs, PWNe, PSRs, XRBs)?
  4. TDEs, to be further established
- Looking-forward: IceCube is not large enough, Let’s wait for KM3NeT!