ASTRO-PARTICLE PHYSICS: THE ROAD AHEAD

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Invisibles Workshop, Bologna

July 5, 2024

Some Big Questions

-What is the nature of dark matter?

-What drives the acceleration of cosmic expansion?
(what is the nature of dark energy?)

-How was the matter-antimatter asymmetry generated?

-What is the physics of inflation?

-What is the origin of the cosmic ray spectrum?

-What is the origin of neutrino mass?

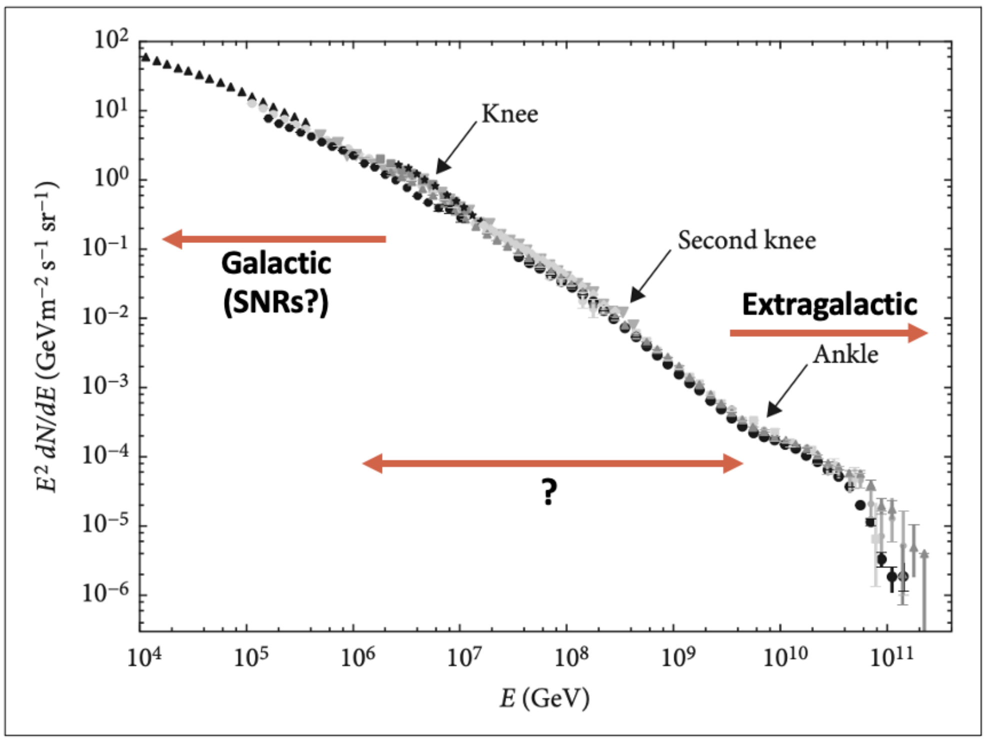
-What is the nature of quantum gravity?

The Many Mysteries of Cosmic Rays

- Since they were discovered more than a century ago, cosmic rays have perplexed astronomers
- Today, we still lack answers to the most central of these questions:

-Where do the cosmic rays come from?

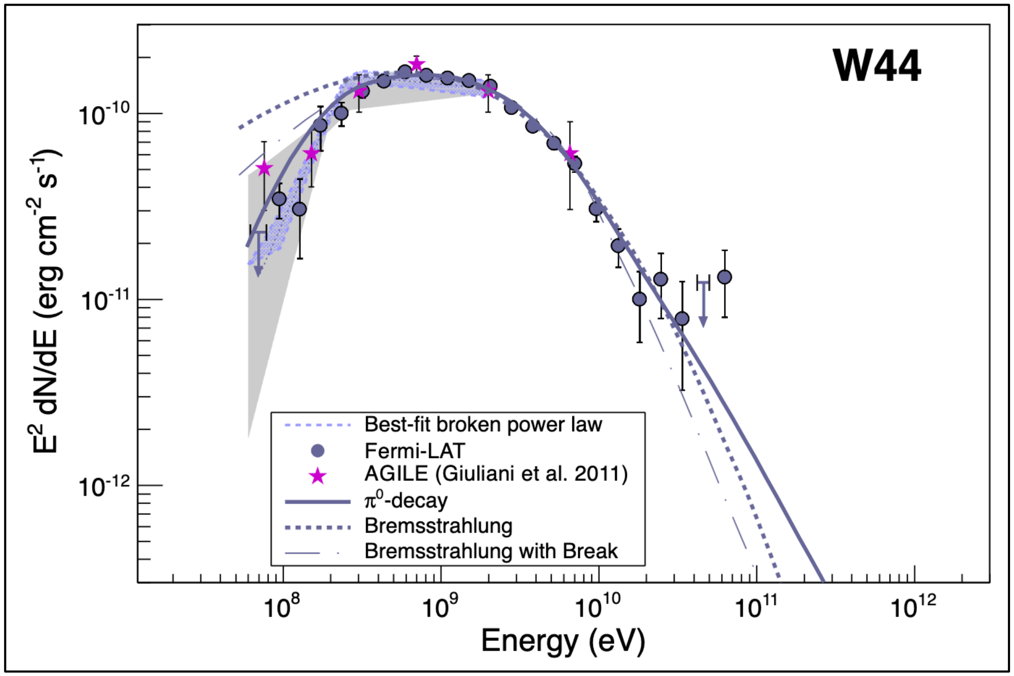
-How are these particles accelerated?

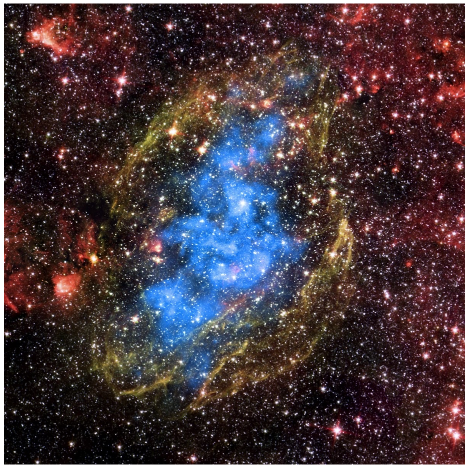


Victor Hess, preparing to measure cosmic rays from a balloon in 1911

The Origin of the Galactic Cosmic Rays

- Below ~PeV-scale energies, the cosmic ray spectrum is thought to originate from Galactic sources, likely including supernova remnants
- Gamma ray observations of several SNRs (W44, IC 443, SNR G106.3+2.7) have identified characteristic spectral features associated with pion decay
- While its hard to completely rule out leptonic processes (ICS, bremsstrahlung), non-hadronic interpretations of this data seem highly fine-tuned



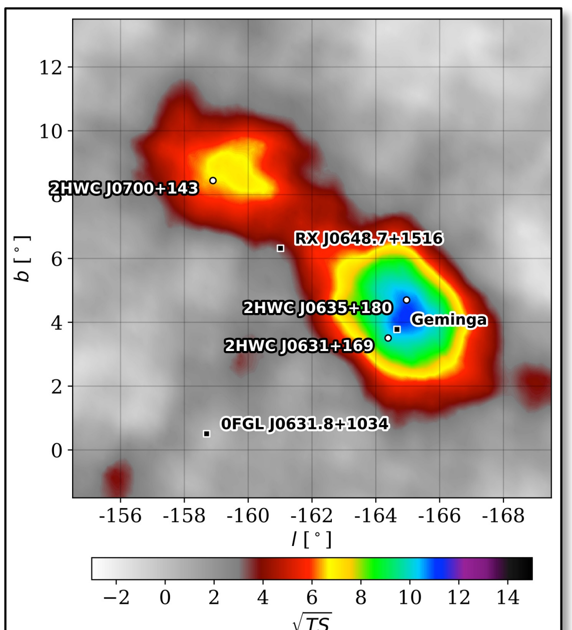


Supernova Remnant, W44

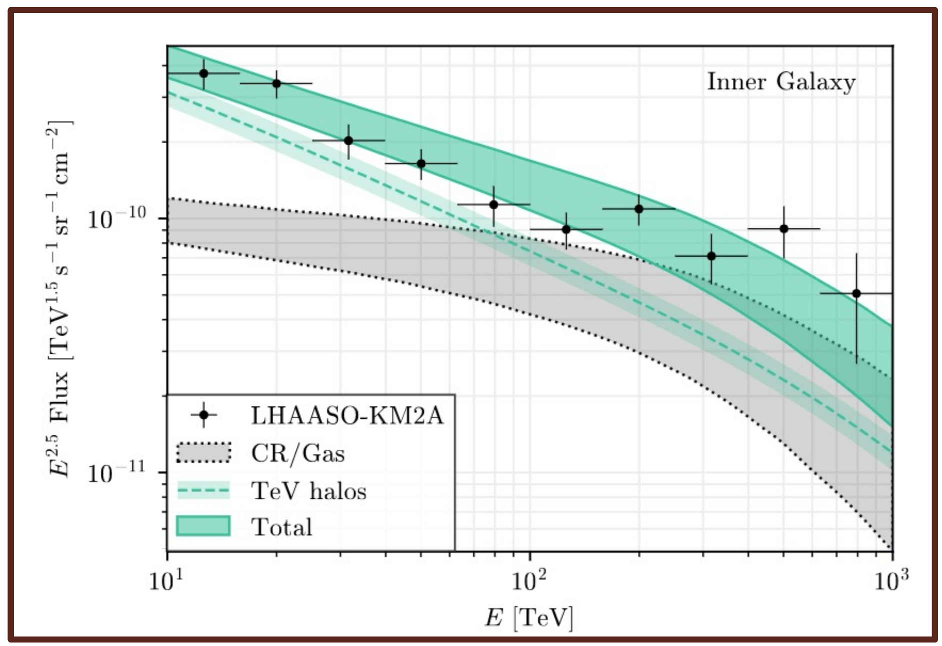
Fermi Collaboration, *Science*, arXiv:1302.3307; Fang, PRL, arXiv:2208.05457

The Origin of the Galactic Cosmic Rays

- Despite these indications of pion production, it remains an open question whether SNRs produce merely some, or perhaps nearly all, of the Galactic cosmic rays
- One might think that a map of the gamma ray sky could settle this issue, but it is often difficult to distinguish gamma rays that are produced through pion decay from those that are produced through leptonic processes
- Further complicating this situation are measurements by HAWC and LHASSO, which suggest that much of the diffuse gamma-ray emission observed at very-high-energies (~1-100 TeV) comes from pulsar halos rather than from SNRs



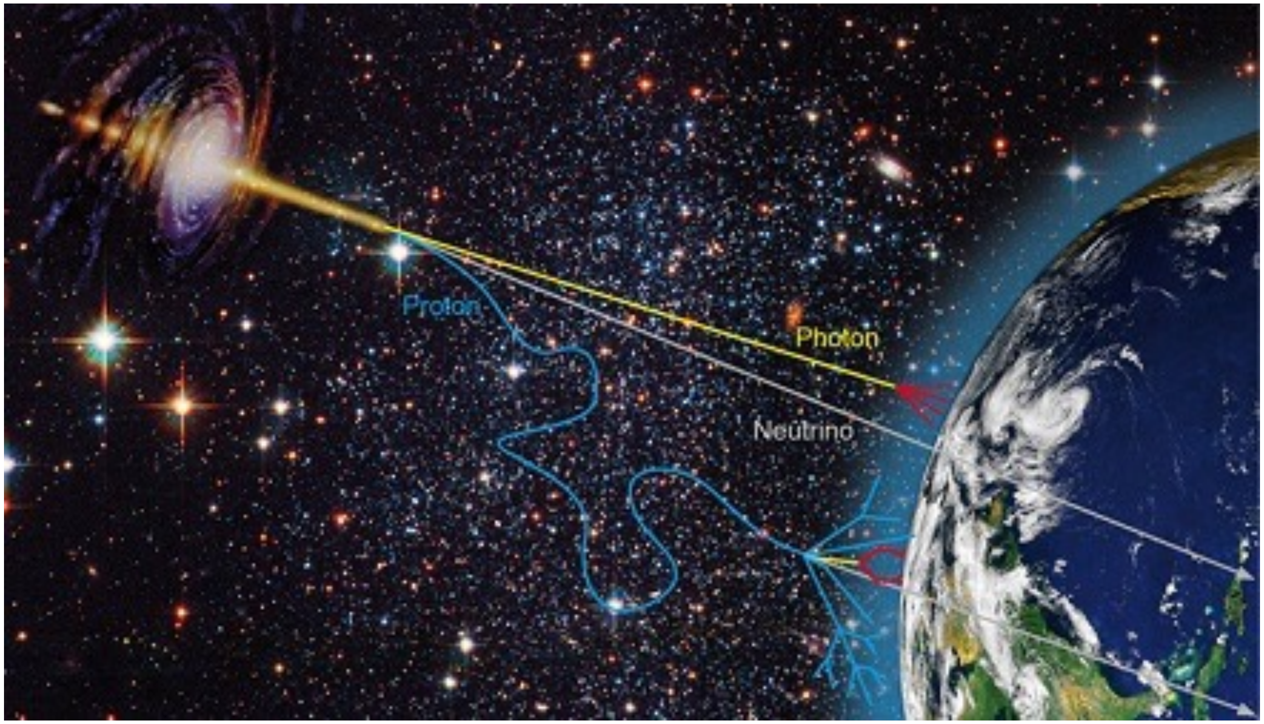
HAWC Collaboration, arXiv:1702.02992



Dekker, Holst, DH, et al., arXiv:2306.00051

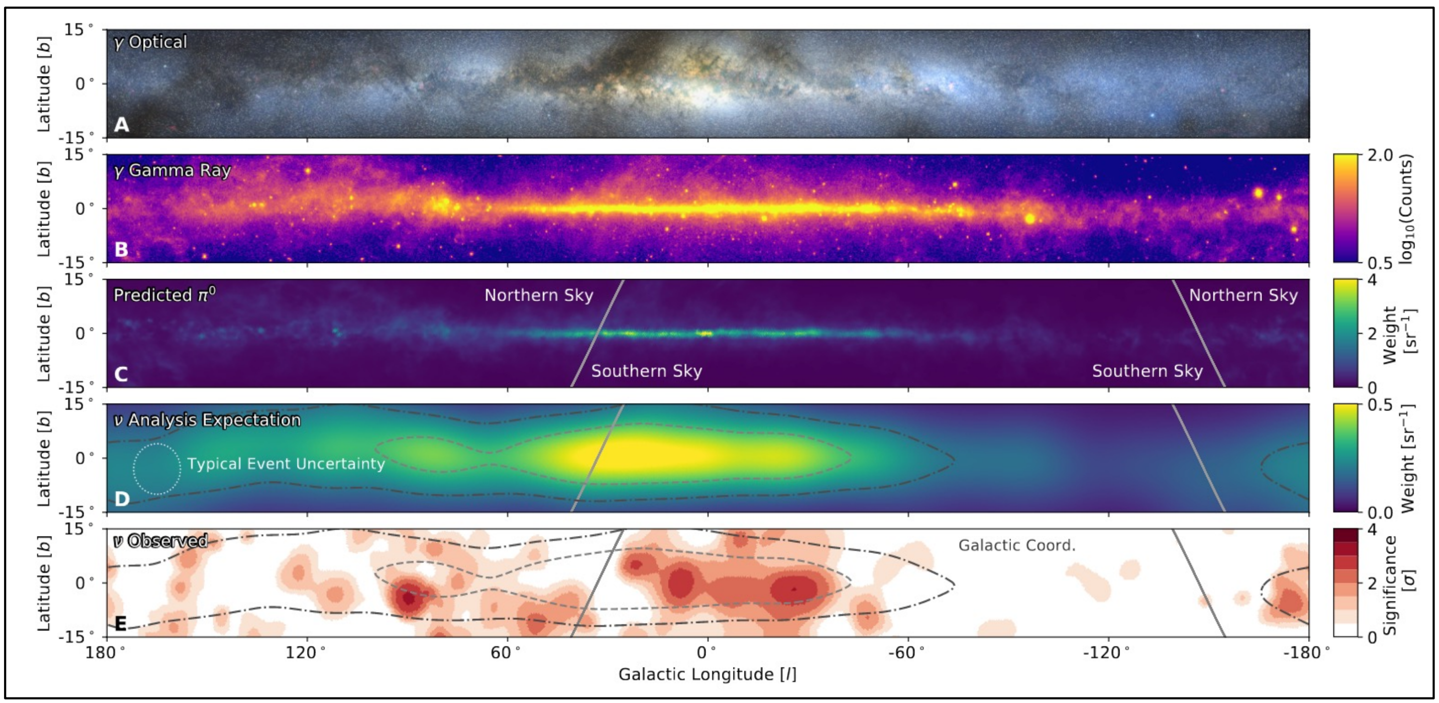
The Neutrino/Gamma Ray/Cosmic Ray Connection

- Cosmic rays scatter with gas and radiation to produce pions, which decay to produce photons and neutrinos → it is therefore *inevitable* that the sources of the cosmic rays will also be sources of gamma rays and high-energy neutrinos
- Unlike cosmic rays, gamma rays and neutrinos are not deflected by magnetic fields and thus point in the directions of their sources
- Unlike gamma rays, high-energy neutrinos are only produced through hadronic interactions, and are not significantly attenuated



Neutrinos as a Tracer of Galactic Cosmic Rays

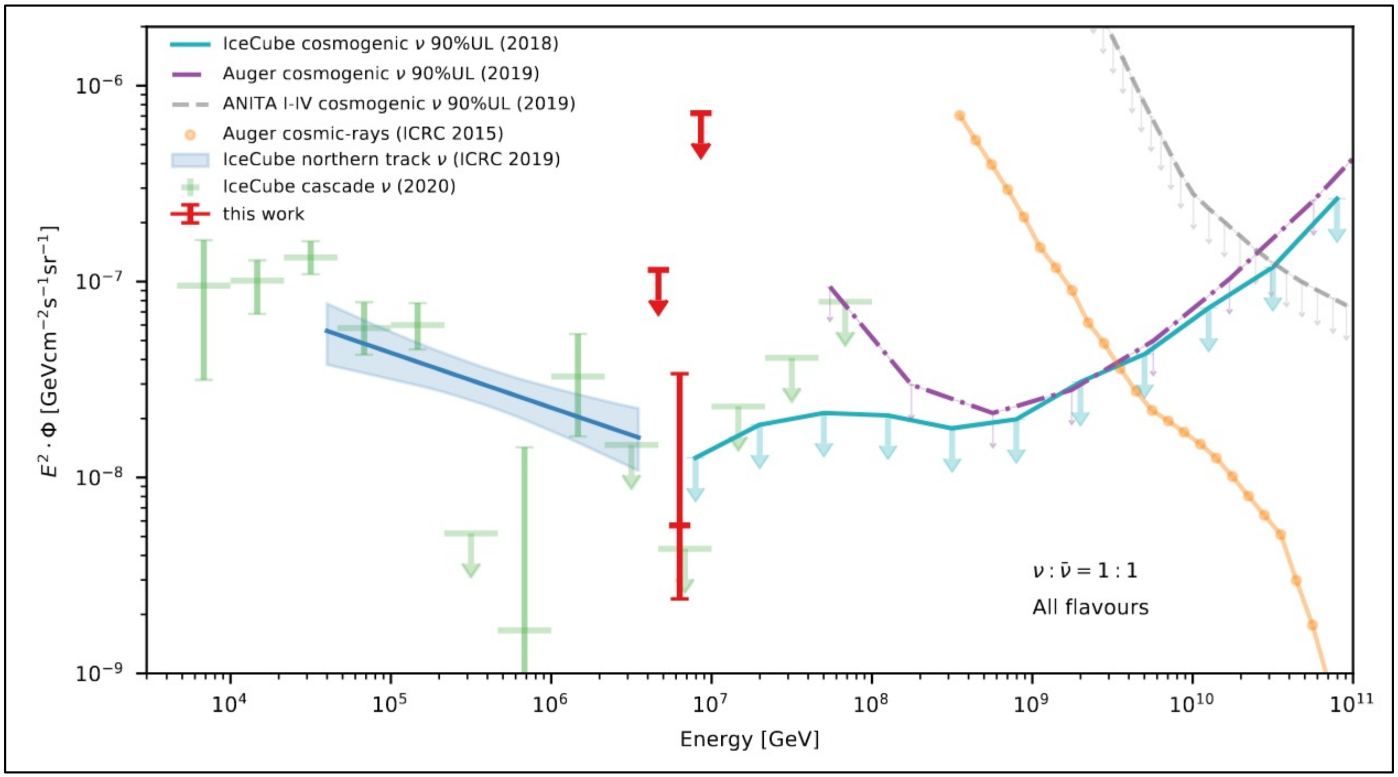
- It has long been appreciated that high-energy neutrinos from SNRs would be a smoking gun that these objects accelerate cosmic rays
- Last year, IceCube announced that they had detected neutrino emission from the Galactic Plane (at 4.5**σ** significance); they also reported suggestive correlations with a catalog of SNR and/or PWN (at 3.2**σ**)
- Although many questions remain to be answered, these results represent a major step toward establishing the detailed origin of the Galactic cosmic ray spectrum



IceCube, *Science*, 2307.04427

IceCube's High-Energy Neutrinos

- IceCube has measured a diffuse and approximately isotropic spectrum of astrophysical neutrinos, with a roughly power-law spectrum, $dN/dE \sim E^{-2.3}$, extending between ~10 TeV and several PeV (at least)
- The origin(s) of these particles remains unknown, but they are almost certainly connected to the sources of the high-energy cosmic rays



IceCube, arXiv:2110.15051

From the Cosmic Ray Spectrum to the High-Energy Neutrino Spectrum

- Back in the late 1990s, Waxman and Bahcall presented an argument that allowed them to use the observed cosmic-ray spectrum to estimate the flux of high-energy neutrinos that should be produced by the same sources
- For optically-thin sources (those with little absorption), this estimate is given as follows:

$$E_\nu^2 \frac{dN_\nu}{dE_\nu} = \int E_{\rm CR}^2 \frac{d\dot{N}_{\rm CR}}{dE_{\rm CR}}(z)\, \epsilon\, f_{\pi^\pm} f_\nu \frac{c}{4\pi} \frac{dt}{dz} \frac{dz}{(1+z)}$$

The fraction of energy in CRs that goes into π's

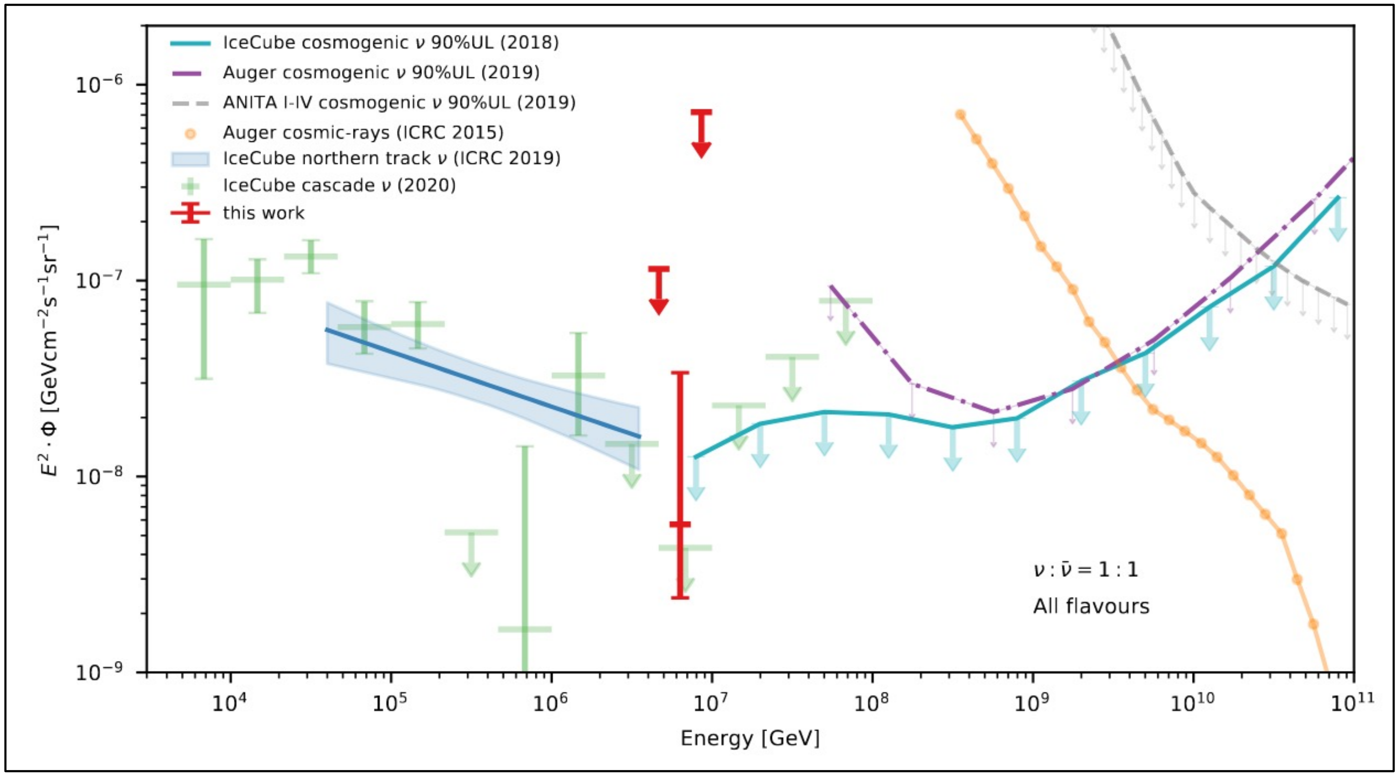
$f_{\pi^\pm} \sim \frac{1}{2}, \frac{2}{3}$

$f_\nu \sim \frac{3}{4}$

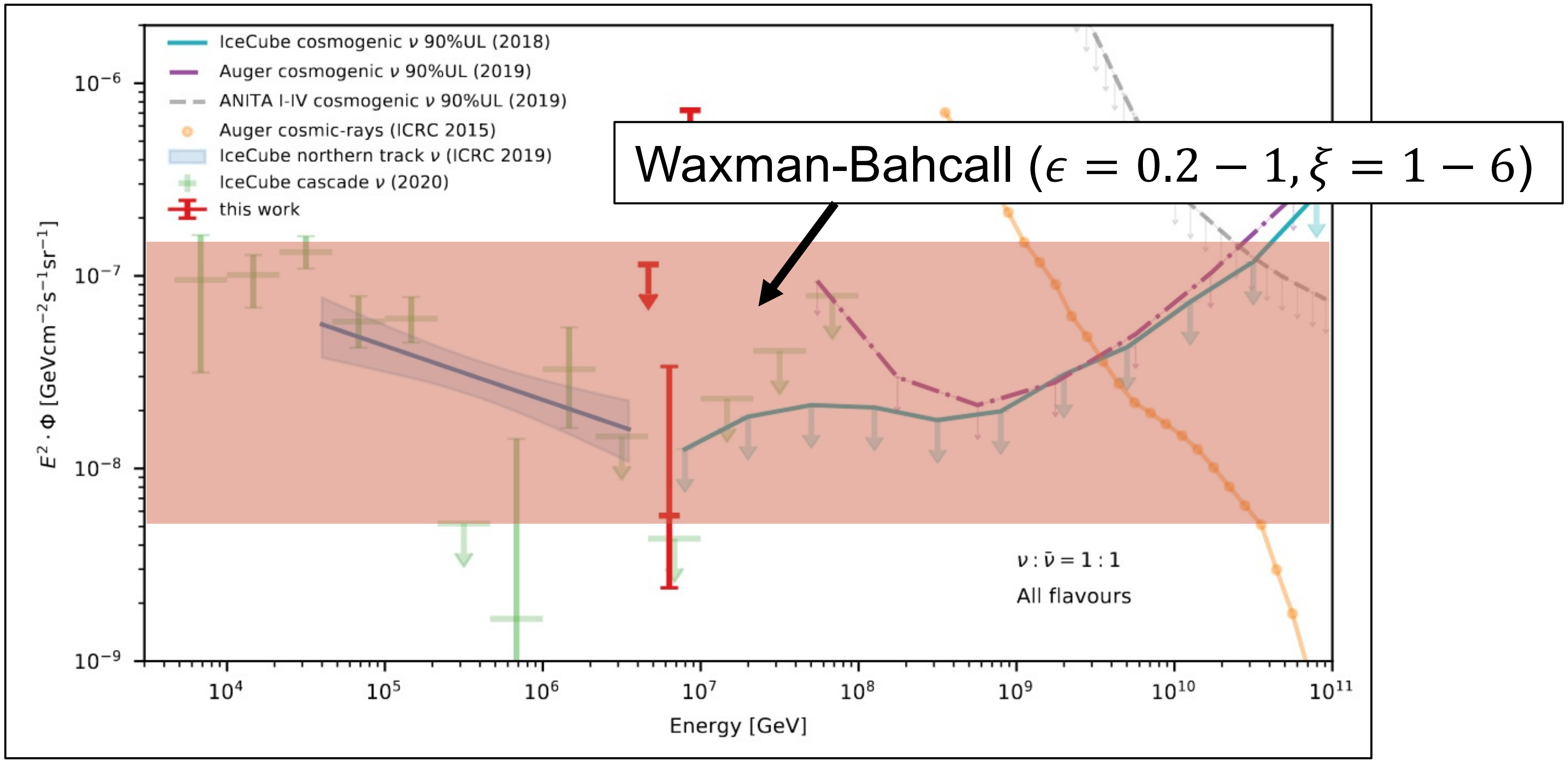
$\xi \sim 1-6$ (for realistic z distributions)

$$E_\nu^2 \frac{dN_\nu}{dE_\nu} \approx 2.5 \times 10^{-8}\, {\rm GeV/cm^2/s/sr} \times \left(\frac{\epsilon}{1}\right)\left(\frac{f_{\pi^\pm}}{0.5}\right)\left(\frac{\xi}{1}\right)$$

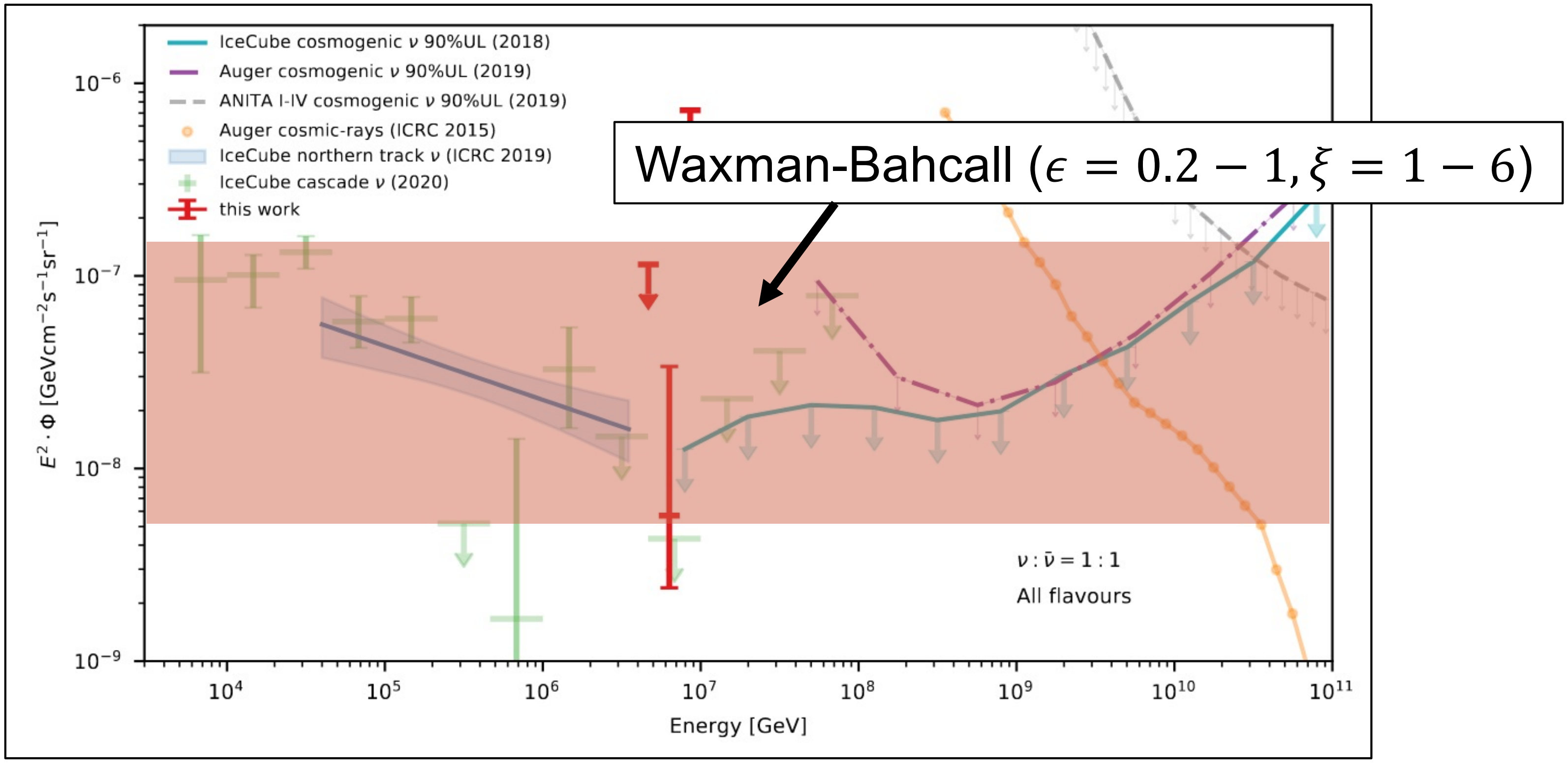
IceCube's High-Energy Neutrinos



IceCube's High-Energy Neutrinos



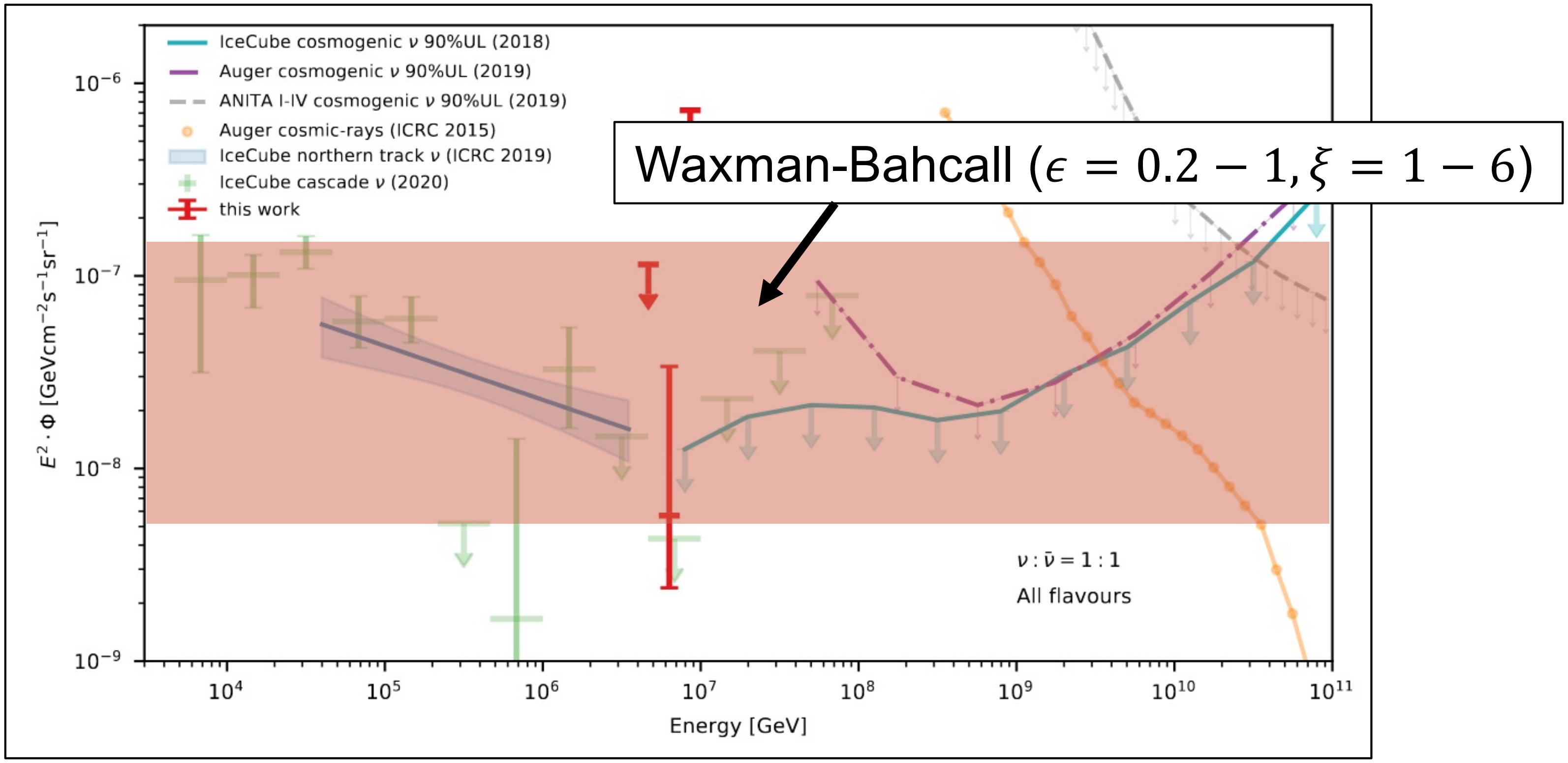
IceCube's High-Energy Neutrinos



This leaves us with two possibilities:

1) IceCube's neutrinos come from the main sources of the high-energy cosmic rays, and those sources have an average optical depth of $\epsilon \sim 0.2 - 1$

IceCube's High-Energy Neutrinos



This leaves us with two possibilities:

1) IceCube's neutrinos come from the main sources of the high-energy cosmic rays, and those sources have an average optical depth of $\epsilon \sim 0.2 - 1$

2) IceCube's neutrinos come from optically thick sources ("hidden sources"), which absorb most of the cosmic rays and gamma rays that they produce before they can escape

The Sources of IceCube's High-Energy Neutrinos

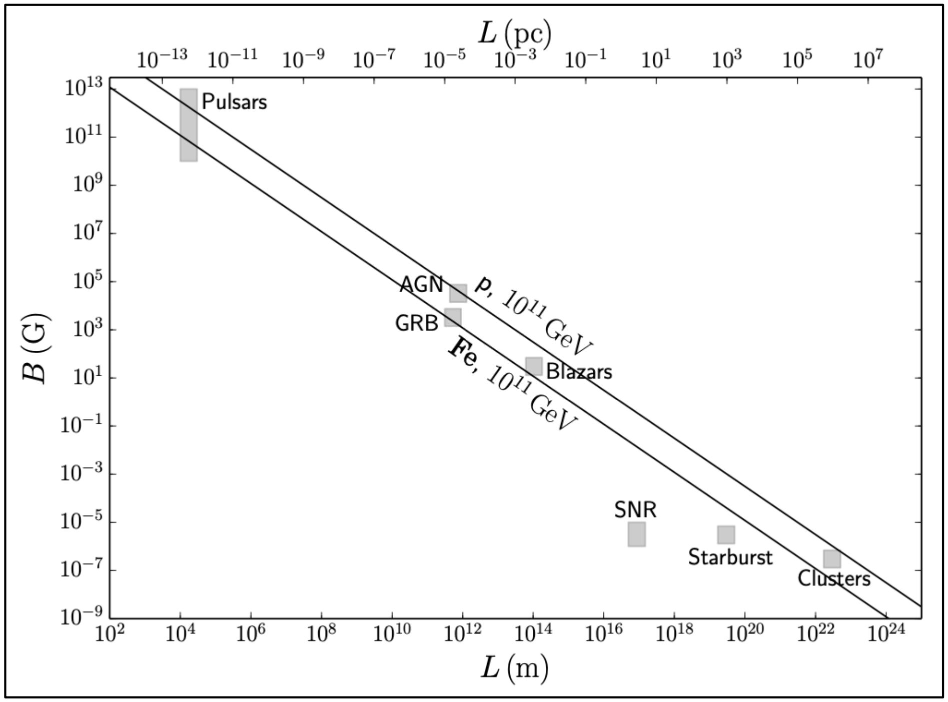
- The production of ~1-10 PeV neutrinos requires ~10^2 PeV protons
- There are not many astrophysical environments that are expected to be capable of accelerating particles to such high energies (ie. that meet the "Hillas criteria")
- In light of this, there is a relatively short list of candidates for the sources of the highest-energy neutrinos detected by IceCube
- These possibilities include:

  -Gamma-Ray Bursts

  -Blazars

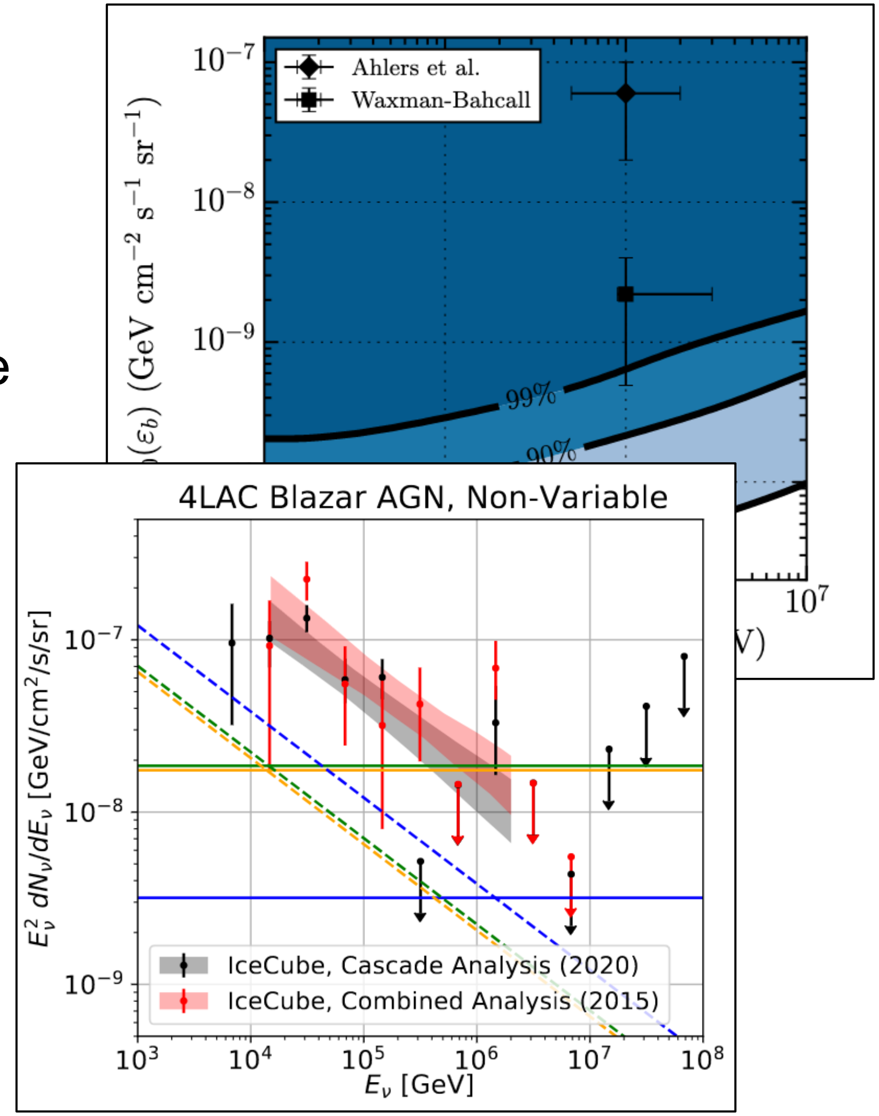
  -Other Active Galactic Nuclei

  -Star-Forming/Starburst Galaxies



Neutrinos From Gamma-Ray Bursts and Blazars

- Individual GRB are bright and brief, making it possible to search for neutrino events with very low backgrounds, yet no such events have been observed
- Blazars are relatively rare ($\sim 10^4$ in the observable universe), most of which have been detected in the gamma ray and/or radio bands; no correlations have been observed between the directions of known blazars and the arrival directions of neutrinos

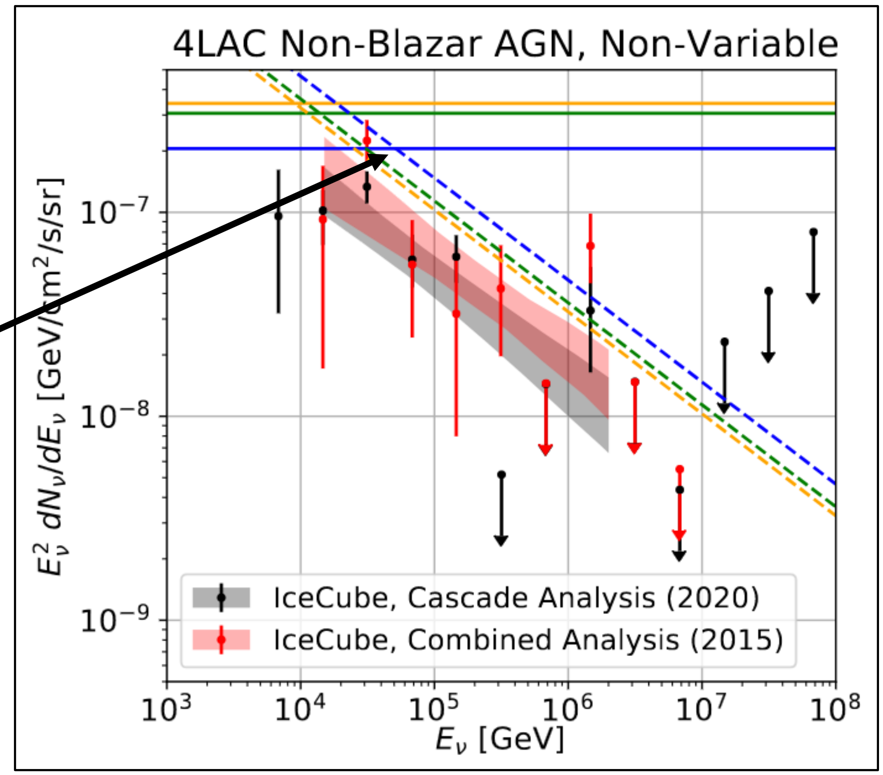


Conclusion: *GRB are blazars cannot produce most of IceCube's neutrino flux; whatever sources are responsible for these neutrinos must be less individually bright and more numerous*

IceCube, 2205.11410, 1702.06868, 1601.06484, 1412.6510, 1204.4219
Smith, et al., 2007.12706, IceCube, 2304.12675, Kun et al., 2203.14780, Zhou et al., 2103.12813

Neutrinos from *Non-Blazar* AGN

- For every blazar, there are $\sim 10^4$ AGN, making it much more difficult to search for correlations between these objects and the arrival directions of individual neutrinos
- It remains plausible that AGN could generate the entire astrophysical neutrino flux observed by IceCube
- IceCube is currently approaching the level of sensitivity that would be required to test this hypothesis

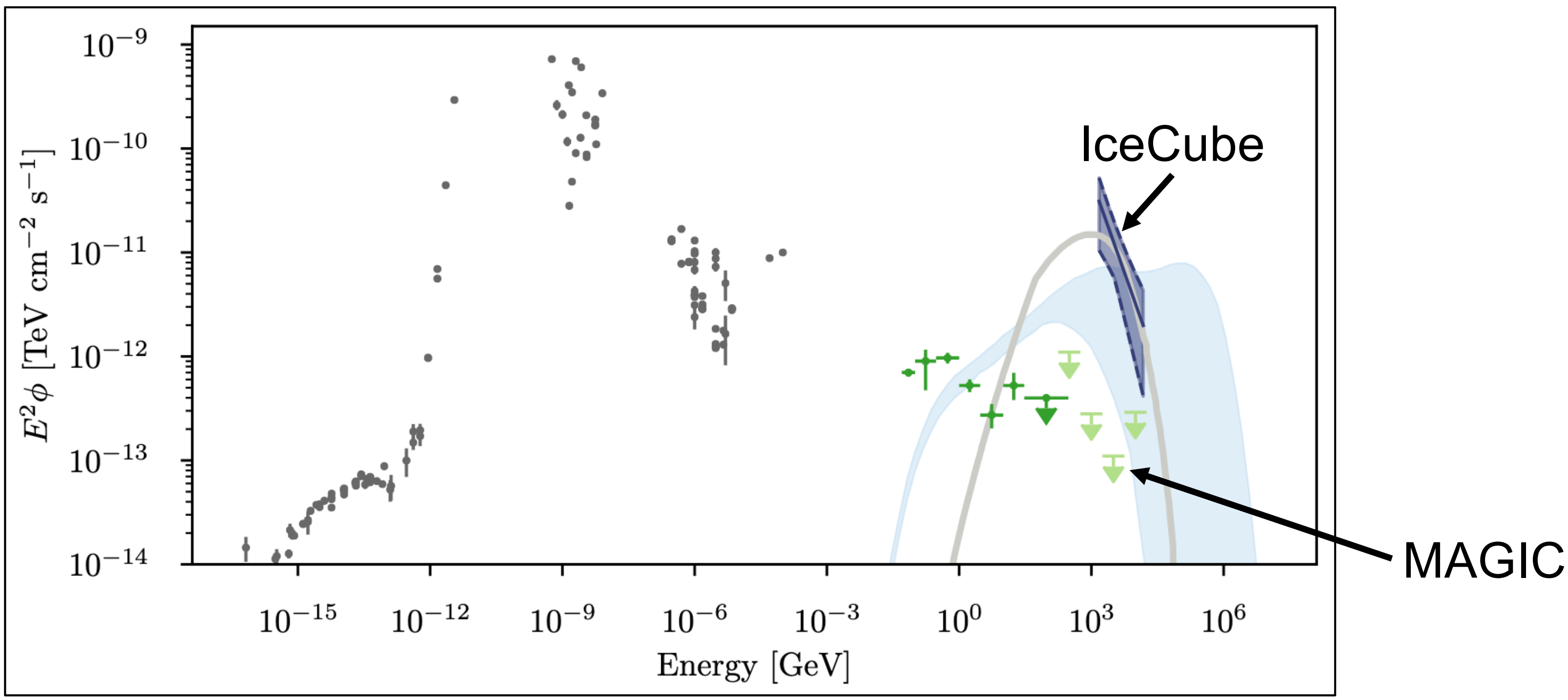


Smith, DH, Vieregg (2020)

IceCube, arXiv: 2304.12675, 1611.03874
Kun et al, 2203.14780
Zhou et al., 2103.12813

Neutrinos From NGC 1068

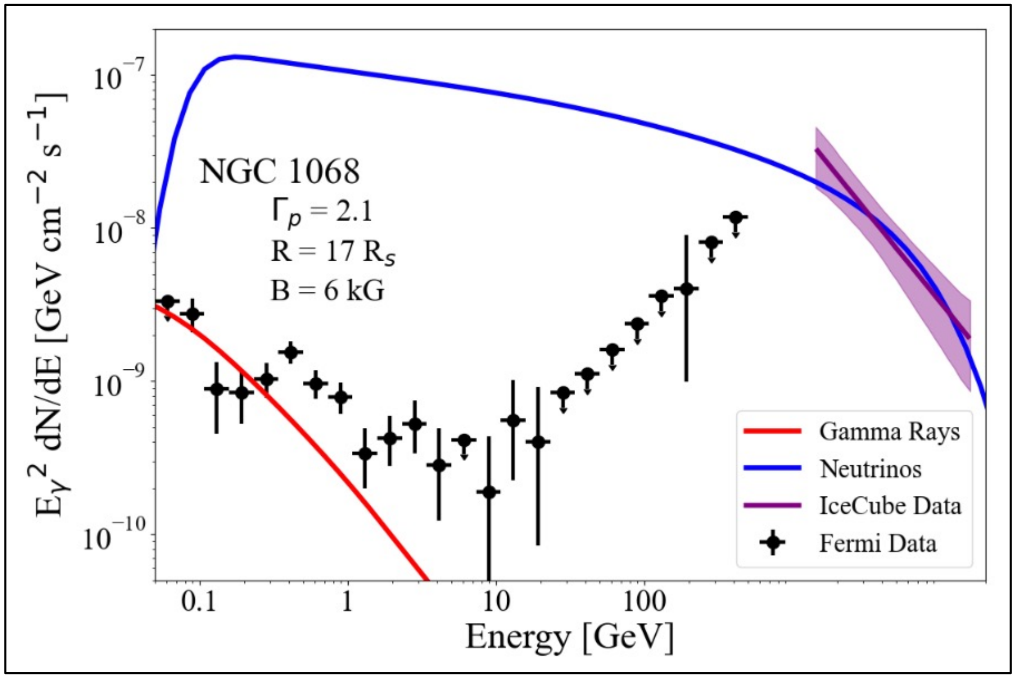
- In 2022, the IceCube Collaboration reported the detection of TeV-scale neutrinos from the direction of the nearby AGN, NGC 1068 (4.2σ, post-trials)
- As you can see from this figure, the neutrino emission reported by IceCube is more than an order of magnitude higher than the upper limit on its gamma-ray emission → *Where are the gamma-rays from pion decay?!?*



IceCube, Science, 2211.09972

Neutrinos From NGC 1068

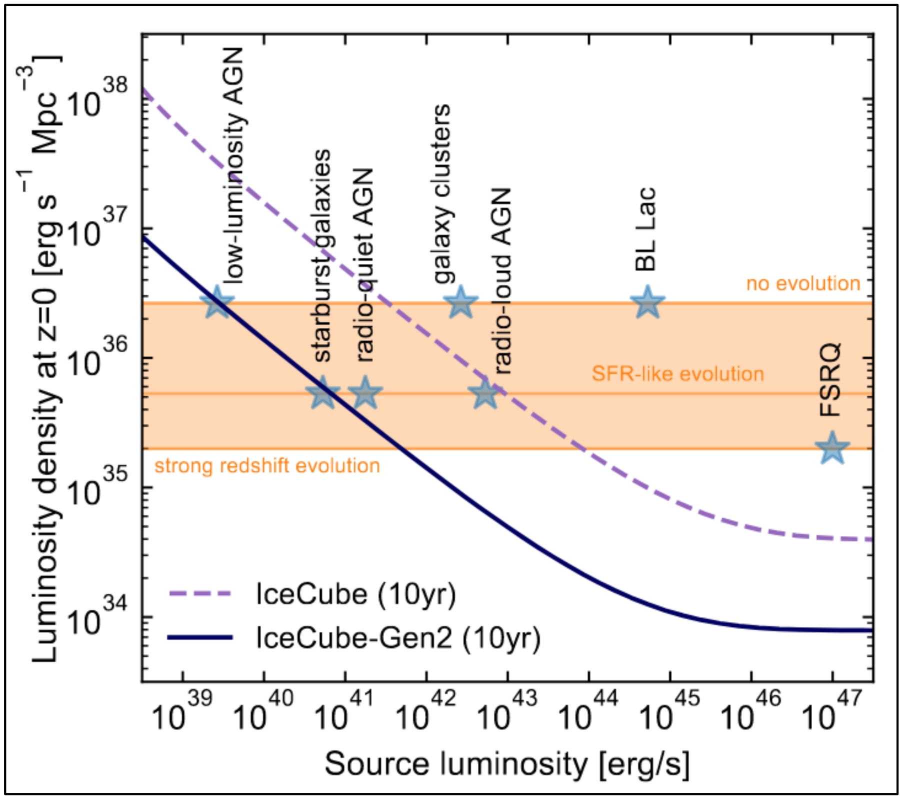
- In order for the TeV-scale gamma-rays to be sufficiently absorbed, the protons that are responsible for these neutrinos must be accelerated within the dense and optically thick corona that surrounds NGC 1068's supermassive black hole; this is a "hidden source"
- This requires rather large magnetic fields (B > 6 kG), but otherwise quite plausible physical conditions
- To normalize the observed neutrino flux requires there to be similar luminosities in high-energy protons and X-rays (L_p~L_X)
- This source will be a very exciting target for future MeV-scale gamma-ray telescopes (such as AMEGO-X, e-ASTROGAM)



Blanco, DH, Linden, Pinetti, arXiv:2307.03259

Looking Forward: IceCube-Gen2

- To finally solve the puzzle of the origin of the cosmic rays, we are going to need more data (ie. bigger detectors!)
- Existing data tells us that IceCube's neutrinos cannot come from a small number of very bright sources, ruling out GRB and blazars, and favoring non-blazar AGN, starburst galaxies
- With IceCube-Gen2, we will be able to look for correlations with non-blazar AGN, starforming galaxies, etc., testing even the most difficult of these scenarios



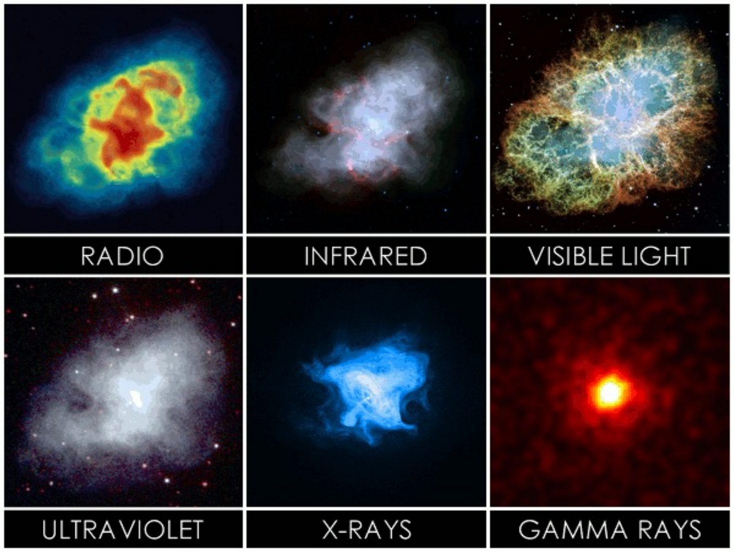
Snowmass White Paper, 2203.08096

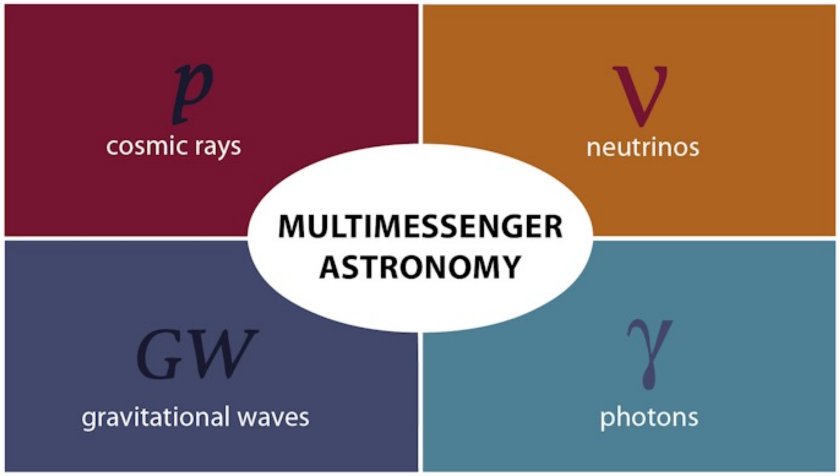
IceCube made the first detections of high-energy astrophysical neutrinos

IceCube-Gen2 will tell us where those neutrinos come from, and will finally reveal the origin of the cosmic ray spectrum

The Era of Multi-Messenger Astronomy

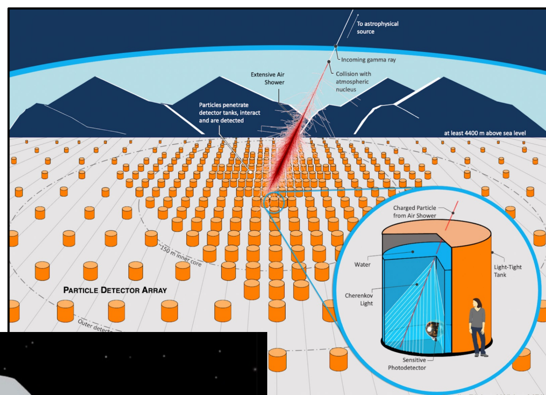
- Up until the middle of the 20th century, essentially all of astronomy was conducted using visible light; although obviously useful, these photons carry only a tiny fraction of the total information that reaches us
- As time went on, astronomers developed ways of detecting and studying light at IR/UV/radio/X-ray/gamma-ray wavelengths
- Modern astronomy makes use not only of light, but other cosmic messengers, cosmic rays, neutrinos, and gravitational waves, each of which provides us with different kinds of complementary information
- The future of astronomy is multi-messenger and multi-wavelength

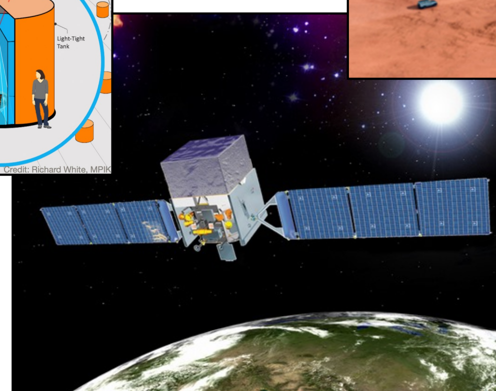




The Many Exciting Paths Forward for Gamma-Ray Astronomy

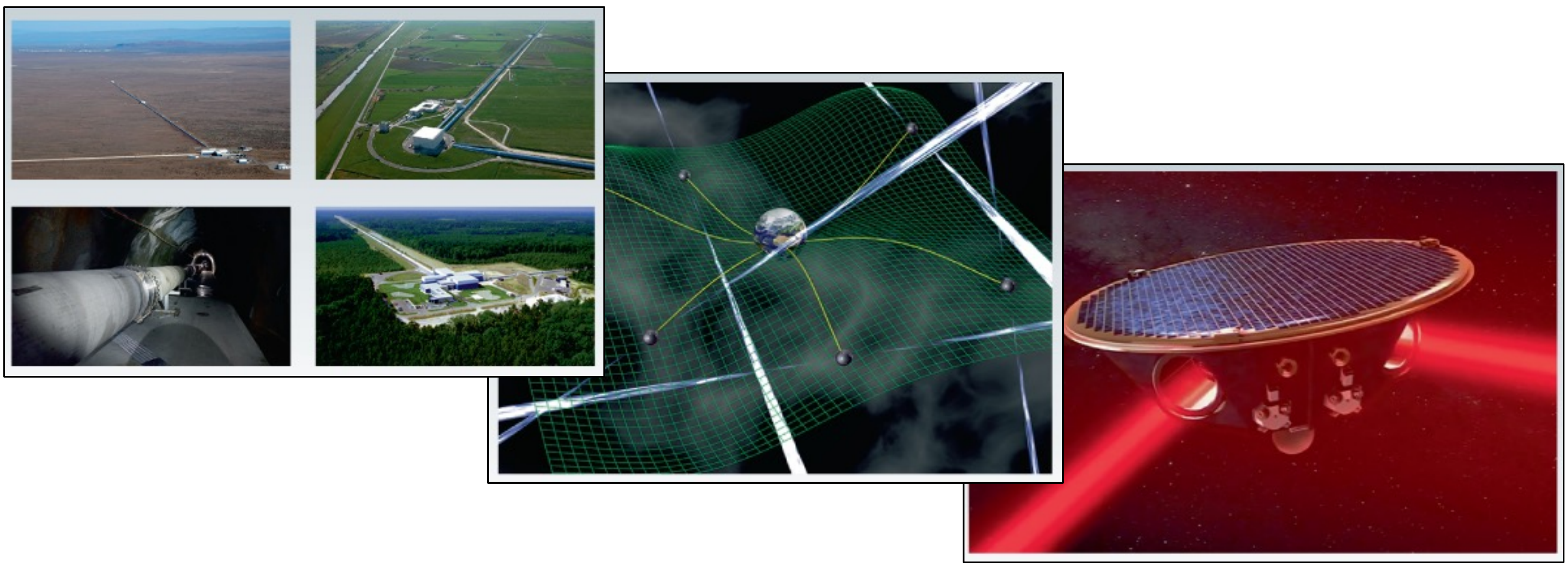
- Air Cherenkov: The Cherenkov Telescope Array (CTA)
- Water Cherenkov: The Southern Wide-Field Gamma-Ray Observatory (SWGO)
- Space-Based MeV: AMEGO-X/eASTROGAM
- Space-Based GeV: The Advanced Particle-Astrophysics Telescope (APT)





The Future of Gravitational Wave Astronomy

- In recent years, gravitational waves have become an increasingly important part of high-energy and multi-messenger astrophysics
- In the years and decades ahead, ground-based gravitational wave interferometers (LIGO/Virgo/KAGRA → Einstein Telescope, Cosmic Explorer), pulsar timing arrays (NANOGrav/IPTA), and space-based interferometers (→ LISA/DECIGO) are all expected to advance substantially – This is going to be a very exciting time for high-energy and multi-messenger astrophysics



High-Energy Neutrinos as a Probe of Fundamental Physics

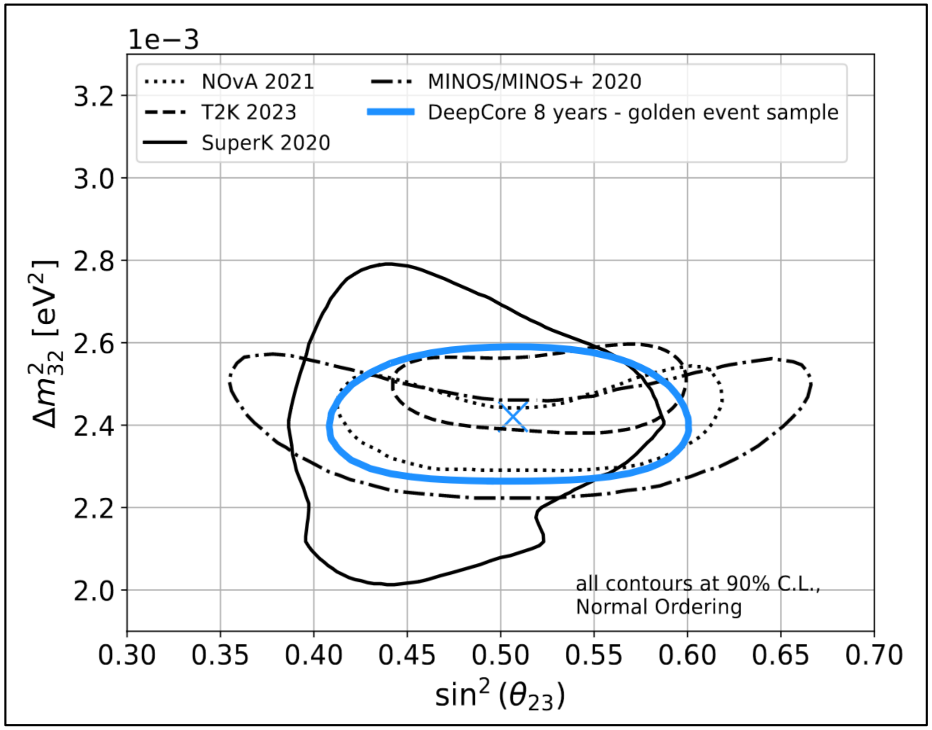
To astrophysicists, the importance of neutrino astronomy is obvious – neutrinos are the key to unraveling the puzzle of the origin of the cosmic rays, and they provide us with our clearest view of our universe's most violent and energetic environments

But when I give talks about neutrino astronomy at particle physics conferences, I sometimes find some people asking, "But this is all astrophysics! Why should I care?"

Measuring Neutrino Oscillation Parameters

- At ~5-100 GeV energies, earth-crossing ν_μ oscillate nearly maximally into ν_τ
- This enables IceCube/DeepCore to precisely measure both $\sin\theta_{23}$ and Δm^2_{32}
- In contrast to oscillation measurements that use MeV-scale neutrinos, IceCube's are largely insensitive to the value of δ_{CP} and are not subject to many of the other uncertainties that negatively impact accelerator-based measurements (ie. nuclear scattering cross sections)
- The IceCube Upgrade (planned for 2025/26) will significantly enhance this program's ability to detect and measure GeV-TeV scale neutrinos – this will be critical for measuring oscillation parameters (including the neutrino mass hierarchy)

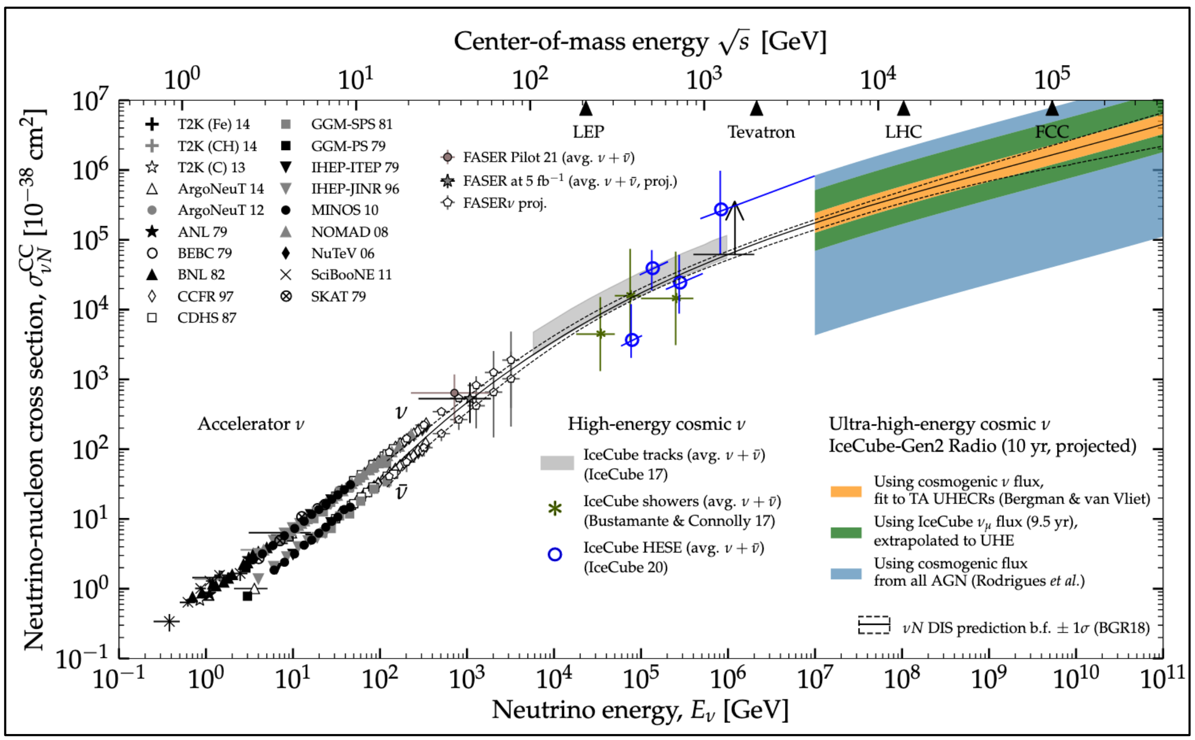
$$P_{\nu_\alpha \to \nu_\beta} = \sin^2(2\theta)\,\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$



IceCube, arXiv:2304.12236

High-Energy Neutrinos as a Probe of Fundamental Physics

- Neutrino telescopes allow us to measure the interactions of neutrinos at much ***higher energies*** and over much ***longer baselines*** than in any existing laboratory experiment
- Such measurements can serve as a probe of many scenarios featuring physics beyond the Standard Model



Ackermann, et al. (Snowmass White Paper), arXiv:2203.08096

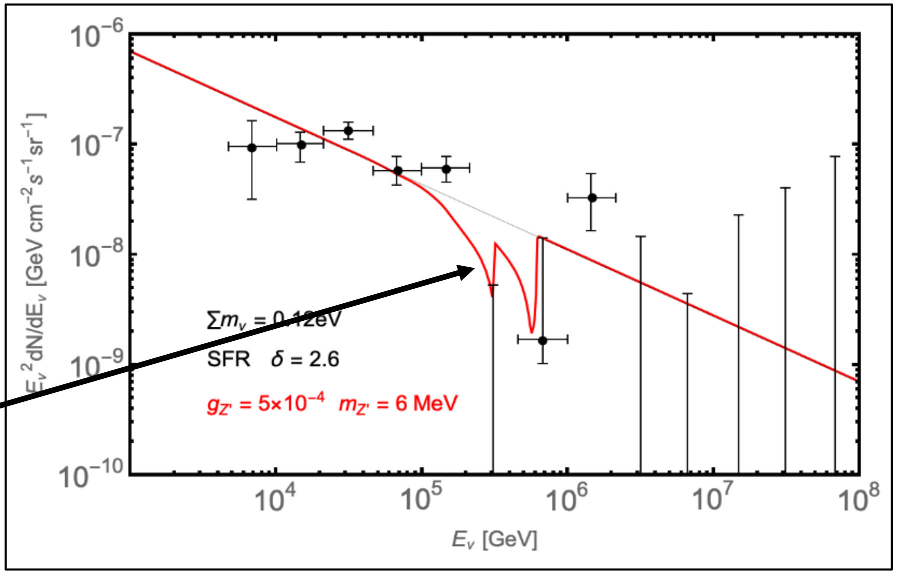
Probes of New Interactions?

- As an example, consider a light Z' that couples to muons (and muon neutrinos), with a gauge coupling that can explain the FNAL/BNL measurements of g_μ-2
- Over cosmological distances, such a Z' would cause high-energy neutrinos to scatter with the cosmic neutrino background, leading to resonant absorption features at:

$$E_\nu \approx \frac{m_{Z'}^2}{2m_{\nu,i}\,(1+z_{\rm abs})}$$

$$\approx 1\,{\rm PeV} \times \left(\frac{m_{Z'}}{10\,{\rm MeV}}\right)^2 \left(\frac{0.05\,{\rm eV}}{m_{\nu,i}}\right) \left(\frac{1}{1+z_{\rm abs}}\right)$$

- This could even provide an explanation for the dip-like feature that is hinted at around ~200-1000 TeV



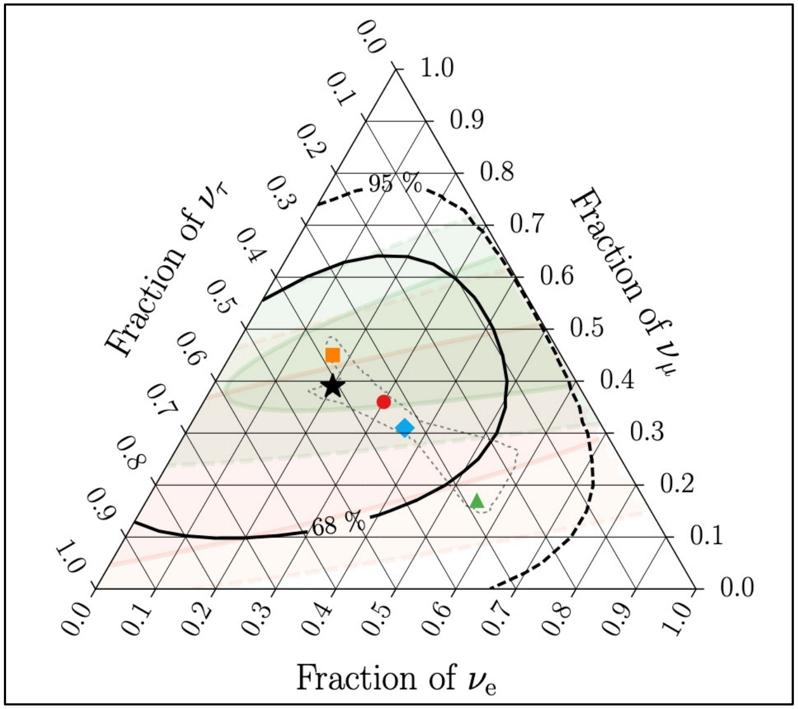
DH, Iguaz, Serpico, arXiv:2302.03571
DiFranzo, DH, arXiv:1507.03015
DH, arXiv:0701194

Neutrino Decay?

- It is possible that one or more neutrino species could be (slightly) unstable
- Such decays would be imperceptible in laboratory experiments, but would impact the flavor ratios of the astrophysical neutrinos that reach Earth
- Measurements by IceCube-Gen2 could plausibly enable us to improve constraints on the neutrino lifetime by several orders of magnitude, to roughly $\tau_\nu > 10^4\ s$

TABLE I: Flavor ratios for various decay scenarios.

Unstable	Daughters	Branchings	$\phi_{\nu_e} : \phi_{\nu_\mu} : \phi_{\nu_\tau}$
ν_2, ν_3	anything	irrelevant	6 : 1 : 1
ν_3	sterile	irrelevant	2 : 1 : 1
ν_3	full energy degraded ($\alpha = 2$)	$B_{3\to 2} = 1$	1.4 : 1 : 1 1.6 : 1 : 1
ν_3	full energy degraded ($\alpha = 2$)	$B_{3\to 1} = 1$	2.8 : 1 : 1 2.4 : 1 : 1
ν_3	anything	$B_{3\to 1} = 0.5$ $B_{3\to 2} = 0.5$	2 : 1 : 1



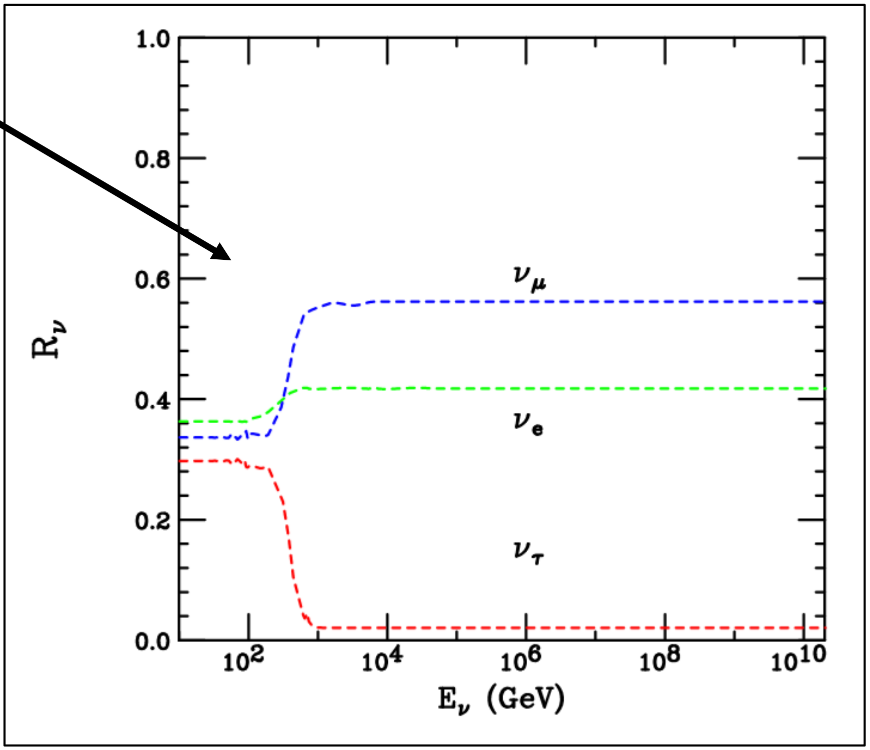
IceCube, arXiv:2011.03561

Beacom, Bell, DH, Pakvasa, Weiler, arXiv:0211305

Probing Quantum Gravity

- Over cosmological baselines, the effects of quantum gravity (such as Lorentz or CPT violation) could potentially lead to observable changes in the flavor ratios of the neutrinos that reach Earth
- Back in 2005, my collaborators and I pointed out that a telescope like IceCube could potentially probe this kind of physics
- Here is an example of the neutrino flavor ratios that are predicted for the case of a dimension-5 QG operator:

$$H = \frac{m^2}{2E} + \frac{\eta}{2}\left(\frac{E}{M_{Pl}}\right)^2$$

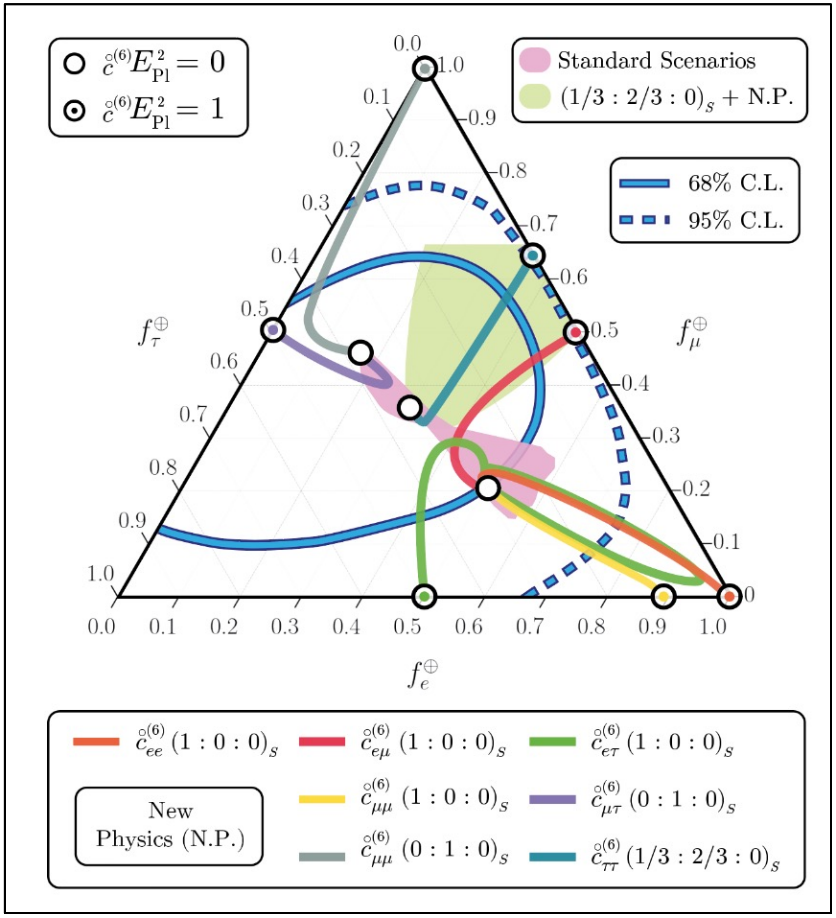


- At the time (2005), this seemed like an almost inconceivably difficult measurement

DH, Morgan, Winstanley, arXiv:0506091, 0410094

Probing Quantum Gravity

- Amazingly, IceCube published their first constraints on this class of models in 2021
- These measurements can be sensitive to well motivated quantum gravity scenarios, even for effective operators that are suppressed by the Planck scale
- For example, these measurements rule out dimension-6 operators with coefficients as small as $\sim 10^{-4}\, M_{Pl}^2$



DH, Morgan, Winstanley, arXiv:0506091
IceCube, arXiv:2111.04654, 2308.00105

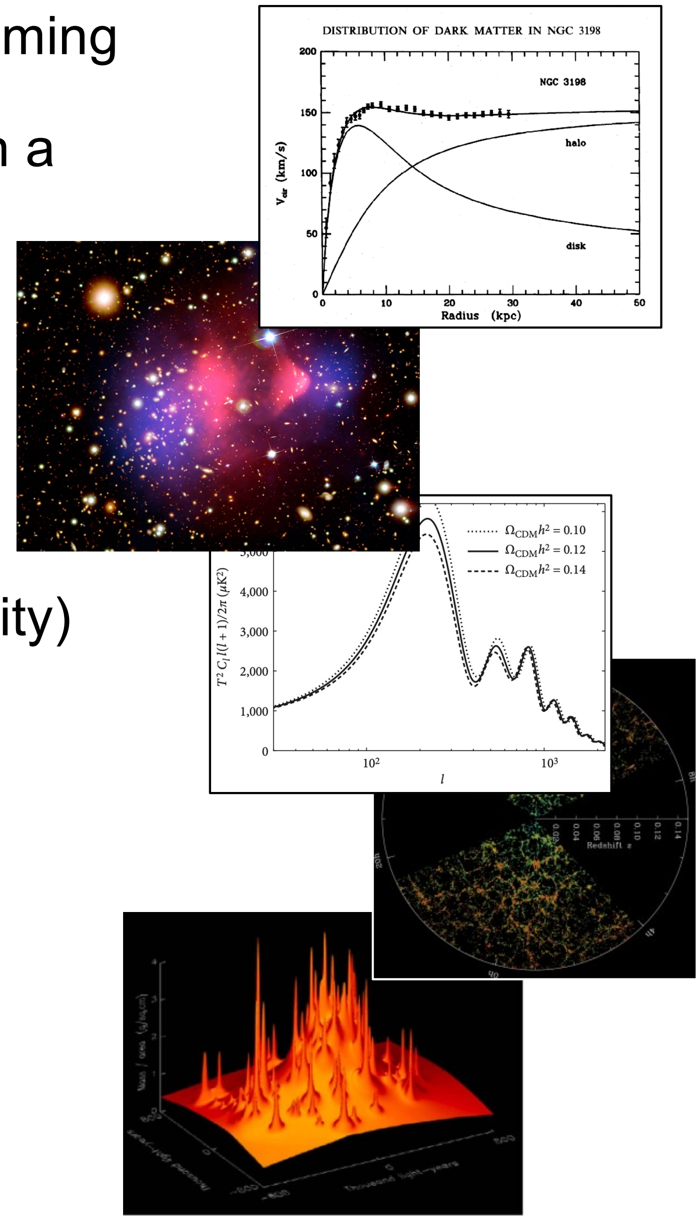
The Puzzle of Dark Matter

- The evidence in support of dark matter is overwhelming
- The varieties of this evidence are diverse and span a wide range of length scales
- These observations may not tell us what exactly the dark matter is, but they do tell us that dark matter must be:

  -Stable (or at least very long-lived, $\tau_X > 10^2\, t_{age}$)

  -Cold (non-relativistic since matter-radiation equality)

  -Very feebly interacting with the Standard Model



The Case for WIMPs

- From among the many candidates for dark matter that have been proposed, I would argue that thermal relics with roughly weak-scale masses and couplings stand out as particularly well-motivated

If we make the following two quite reasonable assumptions:

1) The dark matter was in equilibrium at some point in the early universe
2) The early universe was radiation dominated

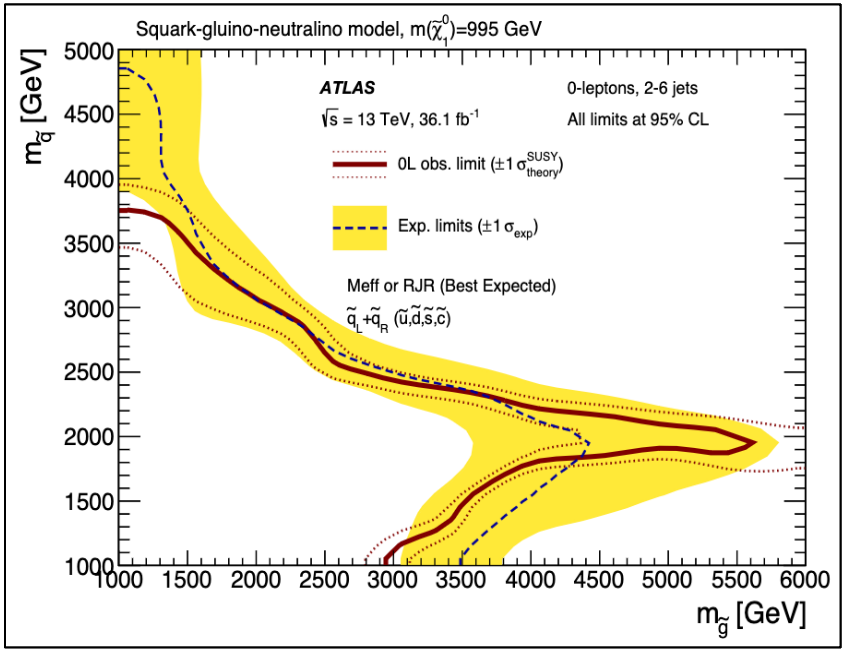
Then we can conclude that the dark matter must be:

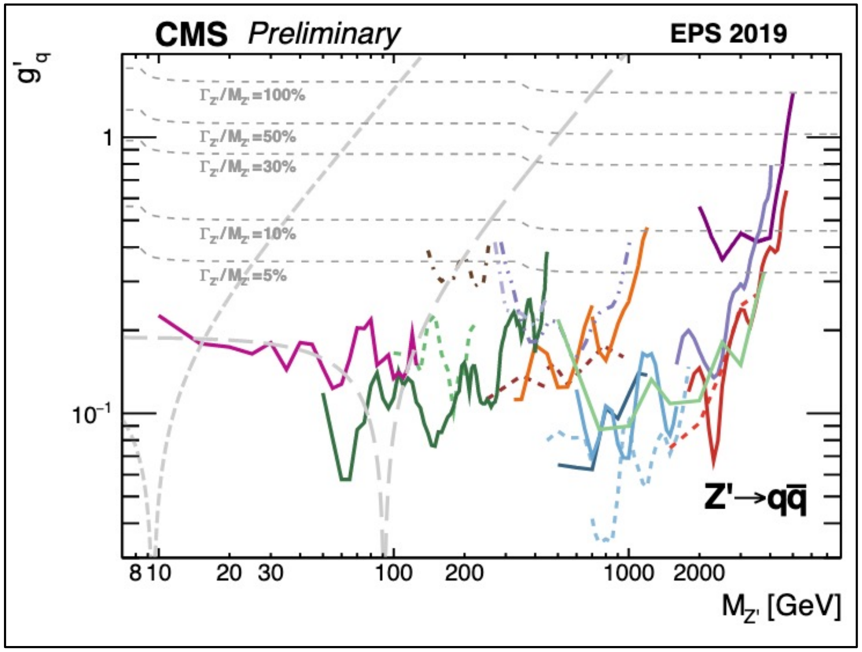
1) Heavier than ~1 MeV (to avoid ruining BBN)
2) Lighter than ~100 TeV (to avoid overproduction)

- To freeze-out with the measured dark matter abundance, such a particle must annihilate through an interaction comparable in strength to the weak force – this is sometimes referred to as the *"WIMP Miracle"*

The Impact of the LHC on WIMPs

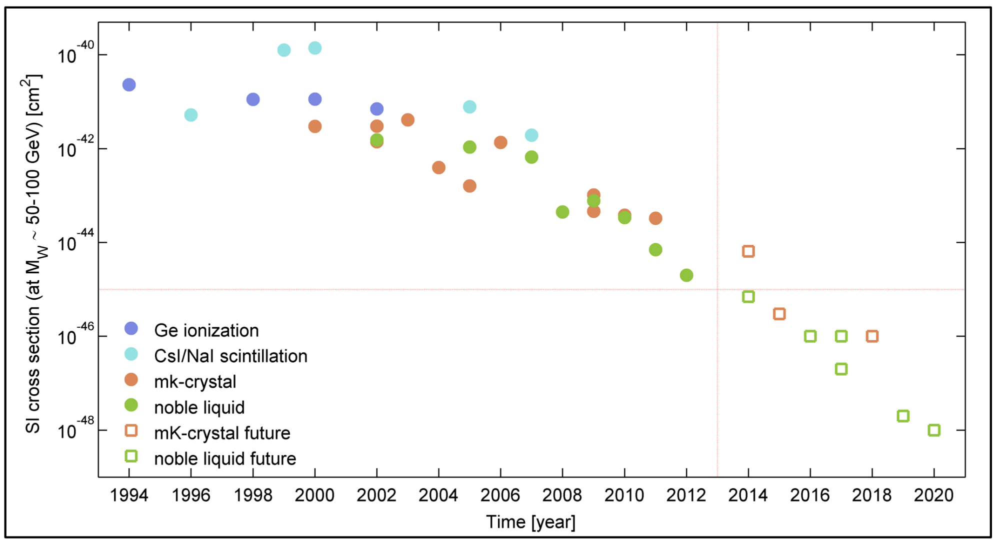
- The LHC has performed beautifully, and yet no compelling signs of dark matter (or other BSM physics) have been discovered
- This machine has led to very strong constraints on certain classes of new physics, such as particles that can be produced with large cross sections (squarks, gluinos, etc.), and particles which lead to particularly distinctive signatures (such as dijet or dilepton resonances from a Z')
- In contrast, the constraints on WIMPs from the LHC remain quite weak

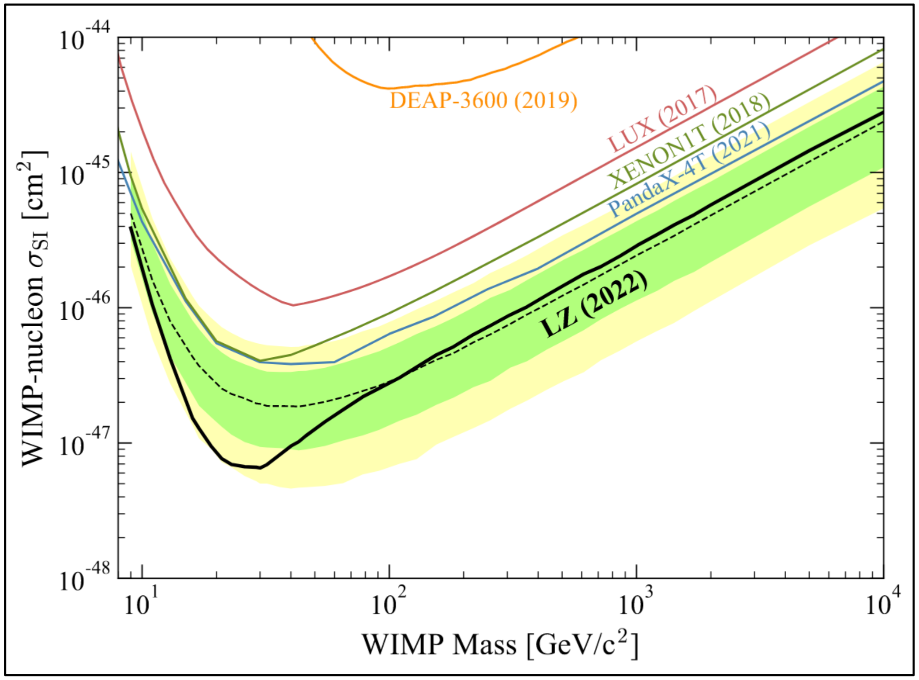




The Impact of Direct Searches on WIMPs

- The null results of underground experiments searching for evidence of dark matter scattering with nuclei have very meaningfully impacted our understanding of dark matter; much more so than the LHC, in my opinion
- Over the past two decades, direct detection experiments have performed better than we had any right to expect, improving in sensitivity at a rate faster than Moore’s Law – and yet no WIMPs have appeared
- It is fair to say that most – although certainly not all – simple WIMP models predict scattering rates with nuclei that exceed current bounds





So, is the WIMP Paradigm Dead?

So, is the WIMP Paradigm Dead?

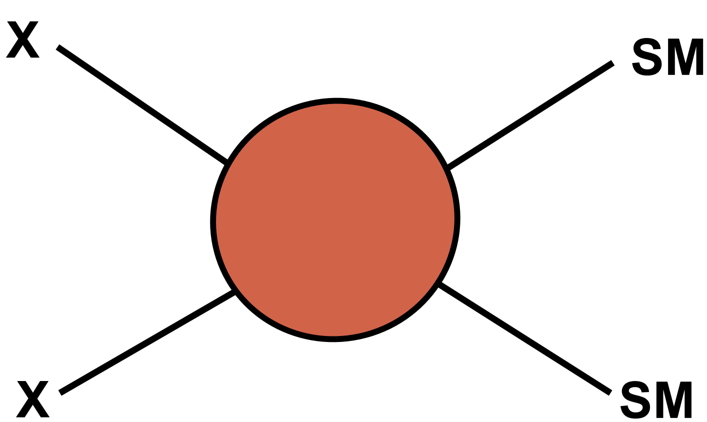
No, not at all.

Despite the very stringent constraints that have been placed on the nature of dark matter, there remain many viable options for WIMP model building

An (Incomplete) List of Ways to Reconcile WIMP Dark Matter With All Current Constraints:

Common Theme: Mechanisms that deplete the dark matter abundance in the early universe without leading to large elastic scattering rates with nuclei

Unsuppressed



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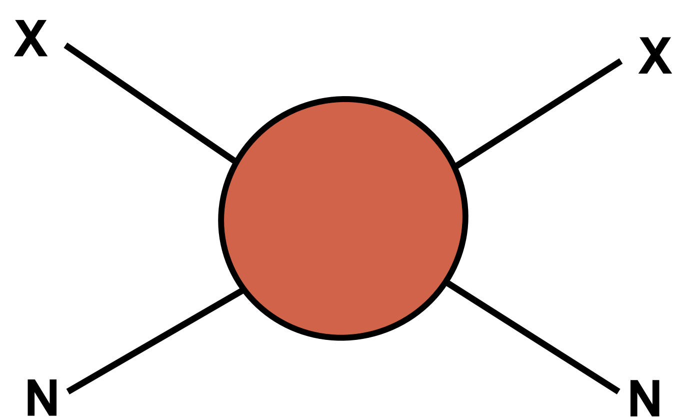


An (Incomplete) List of Ways to Reconcile WIMP Dark Matter With All Current Constraints:

1) Co-annihilations between the dark matter and another state

2) Annihilations to W, Z and/or Higgs bosons; scattering with nuclei only through highly suppressed loop diagrams

3) Interaction which suppress elastic scattering with nuclei by powers of velocity or momentum

4) Dark matter that is lighter than a few GeV (relaxing direct constraints)

5) Departures from radiation domination in the early universe (early matter domination; late-time reheating, etc.) which result in the depletion of the dark matter's relic abundance

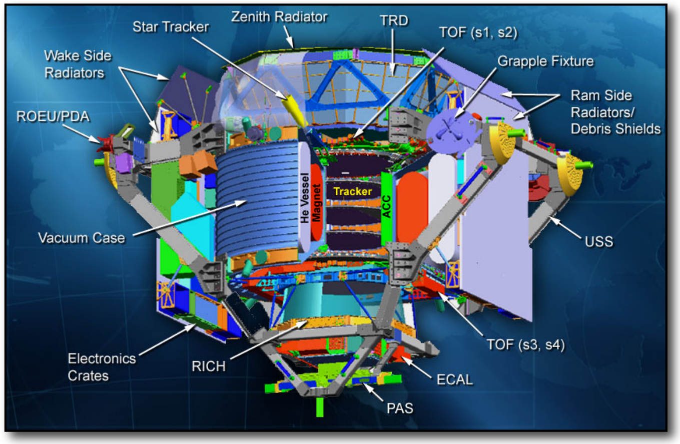
6) The dark matter annihilates to unstable non-Standard Model states (*ie*. hidden sector models)

The Motivation for Indirect Searches

- Recall that to account for the observed dark matter abundance, a thermal relic must have an annihilation cross section (at freeze-out) of $\sigma v \sim 2\times10^{-26}$ cm^3/s
- Although many model-dependent factors can cause the dark matter to possess a somewhat lower or higher annihilation cross section today, most models predict current annihilation rates that are within an order of magnitude or so of this estimate
- Indirect detection experiments that are sensitive to dark matter annihilating at approximately this rate will be able to test a significant fraction of WIMP models

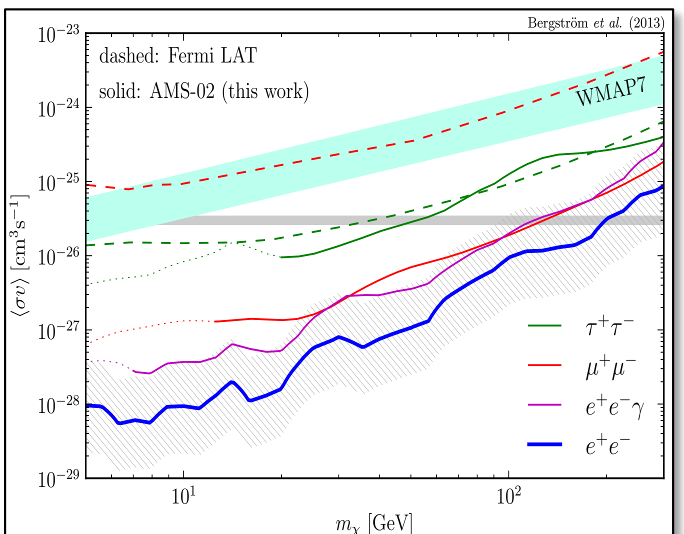
Fermi

AMS-02

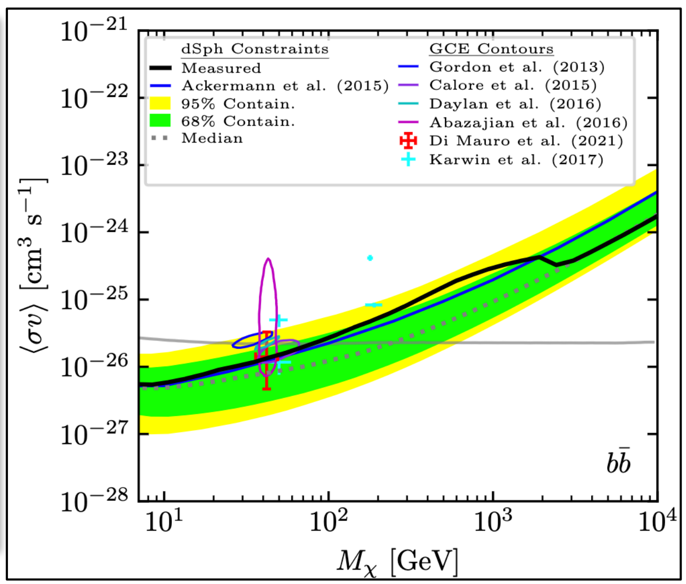


Constraints from Indirect Detection

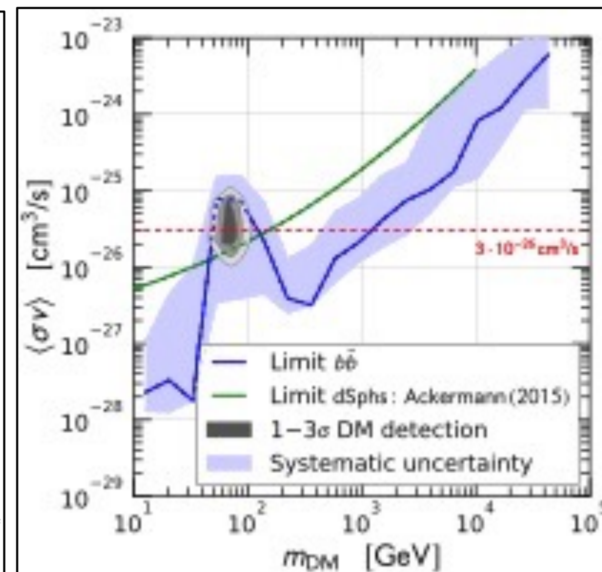
- A variety of gamma-ray searches (GC, dwarfs, IGRB, etc.) as well as cosmic-ray antiproton and positron measurements are currently sensitive to dark matter with annihilation cross sections in the range predicted for a simple thermal relic, for masses up to $\mathcal{O}(100)$ GeV
- This program is not a fishing expedition, but is testing a wide range of our most well-motivated dark matter models



Bergstrom, *et al.*, arXiv:1306.3983



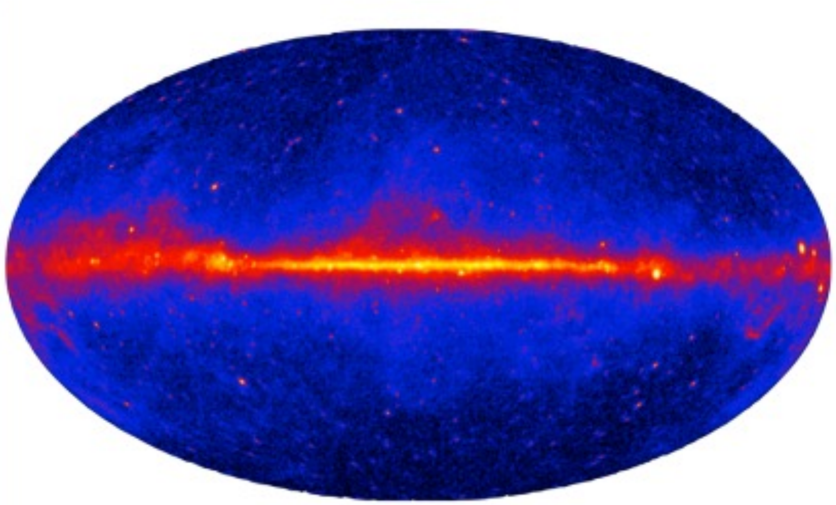
Fermi Collaboration, arXiv: 2311.04982



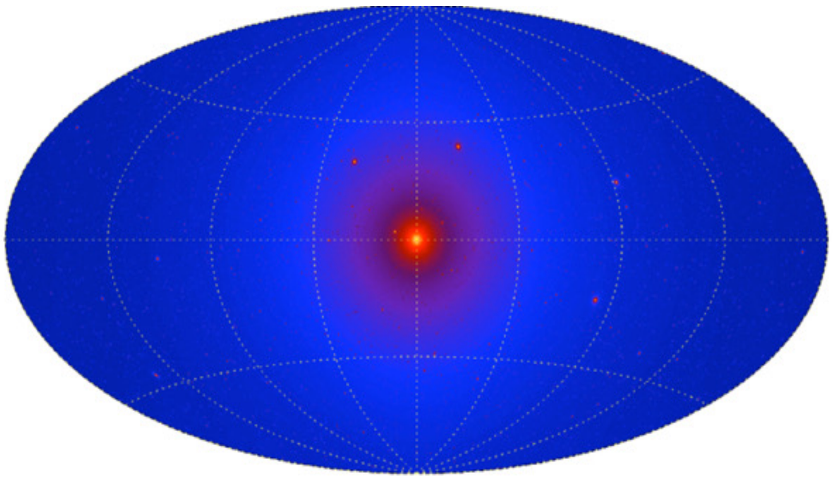
Cuoco, *et al.*, arXiv:1610.03071
Cui, *et al.*, arXiv:1610.03840

Gamma Ray Searches for Dark Matter

- The brightest gamma-ray signal from annihilating dark matter is expected to come from the direction of the Galactic Center
- The astrophysical backgrounds are also bright in this region of this sky, and can be difficult to model
- Despite these backgrounds, the signal that would be predicted from a ~1-200 GeV thermal relic was widely expected to be within reach of the Fermi telescope



Gamma-Rays Measured by Fermi



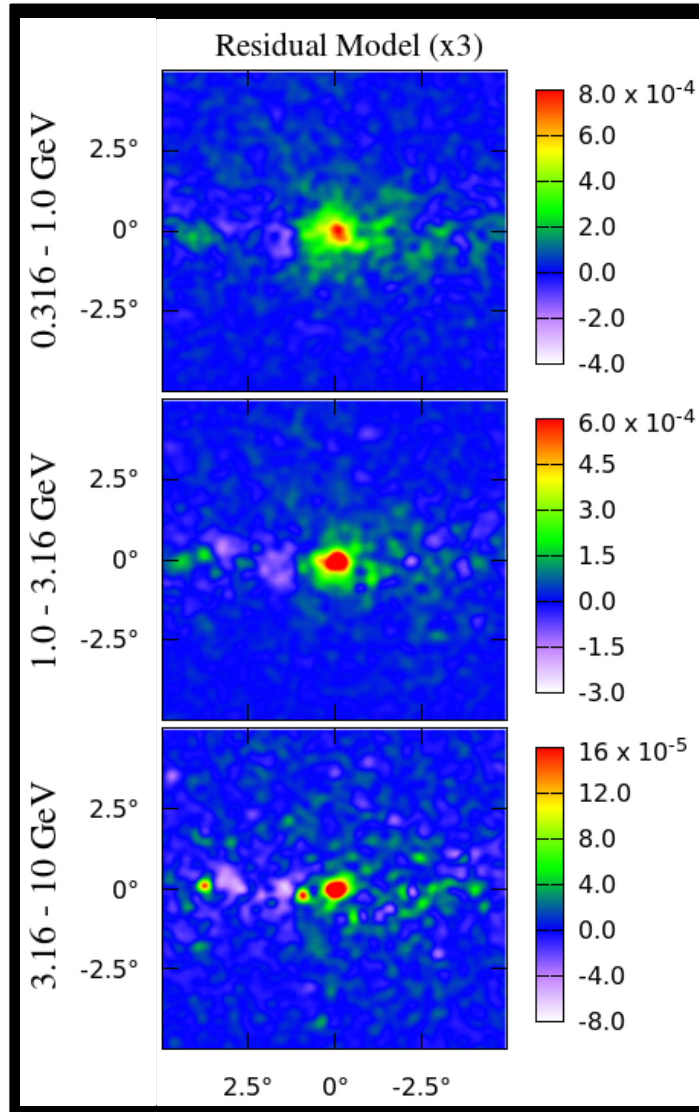
Signal Predicted From Dark Matter

The Galactic Center Gamma-Ray Excess

- There is an excess of GeV-scale emission from the direction of the Inner Galaxy in the Fermi data, relative to *all models* of known astrophysical backgrounds
- This signal is bright and highly statistically significant – its existence is not in dispute
- It is very difficult to explain this signal with known astrophysical sources or mechanisms
- The observed characteristics of this signal are consistent with those expected from annihilating dark matter

Among other references, see:
DH, Goodenough (2009, 2010)
DH, Linden (2011)
Abazajian, Kaplinghat (2012)
Gordon, Macias (2013)
Daylan, DH, et al. (2014)
Calore, Cholis, Weniger (2014)
Murgia, et al. (2015)
Ackermann et al. (2017)

Fermi



The Galactic Center Gamma-Ray Excess

Morphology

-The gamma-ray excess exhibits approximate spherical symmetry about the Galactic Center, with a flux that falls as $\sim r^{-2.4}$ out to at least ~20° (if interpreted as annihilating dark matter, this implies $\rho_{DM} \sim r^{-1.2}$)

Spectrum

-The spectrum of the excess is uniform across the Inner Galaxy and is well fit by a ~30-70 GeV particle annihilating to quarks or gluons

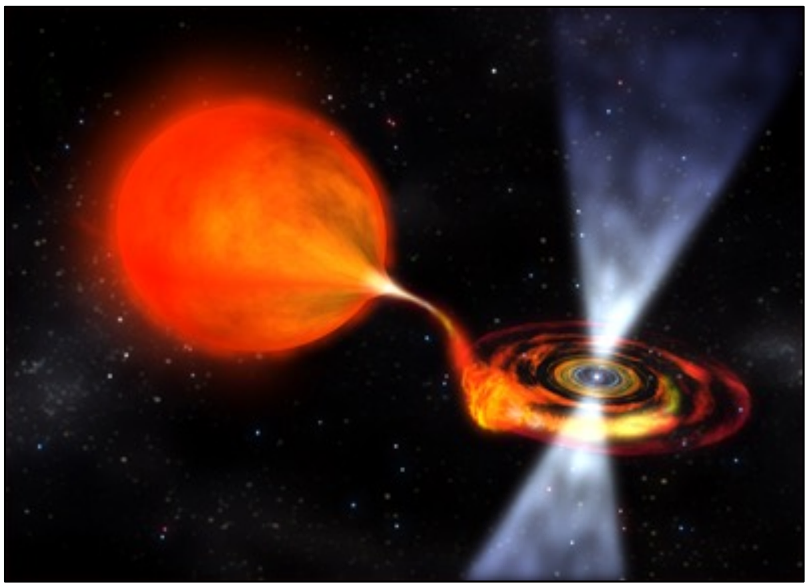
Intensity

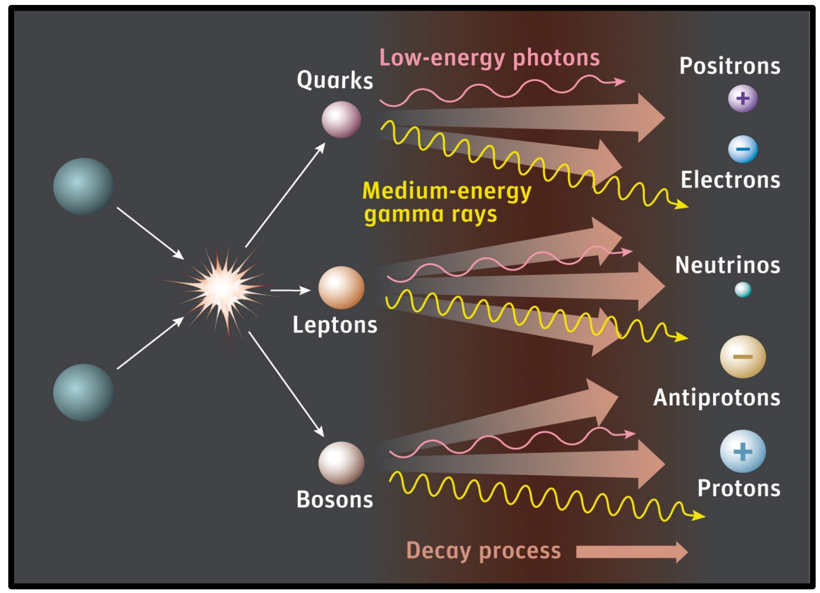
-To produce the observed intensity of the excess, the dark matter particles must annihilate with a cross section of $\sigma v \sim (1\text{-}2) \times 10^{-26}$ cm^3/s, remarkably similar to that expected of a thermal relic

Daylan et al. (2014)
Calore, Cholis, Weniger (2014)
Calore, Cholis, McCabe, Weinger (2014)

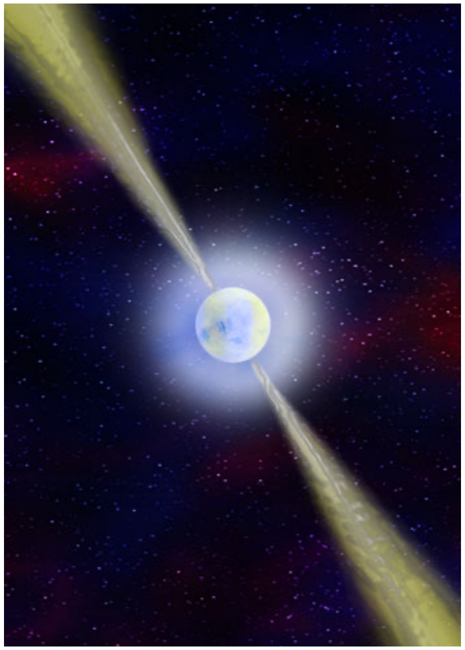
What Produces the Galactic Center Excess?

- A large population of centrally located millisecond pulsars?
- Annihilating dark matter?





Millisecond Pulsars and The Galactic Center Gamma-Ray Excess



Arguments in Favor of Pulsars:

- The gamma-ray spectrum of observed pulsars
- Claims of small-scale power in the gamma-ray emission from the Inner Galaxy
- Claims that the excess traces the Galactic Bulge/Bar

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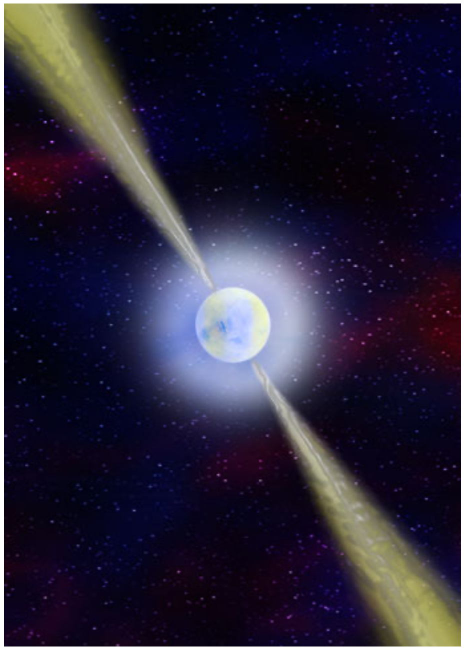

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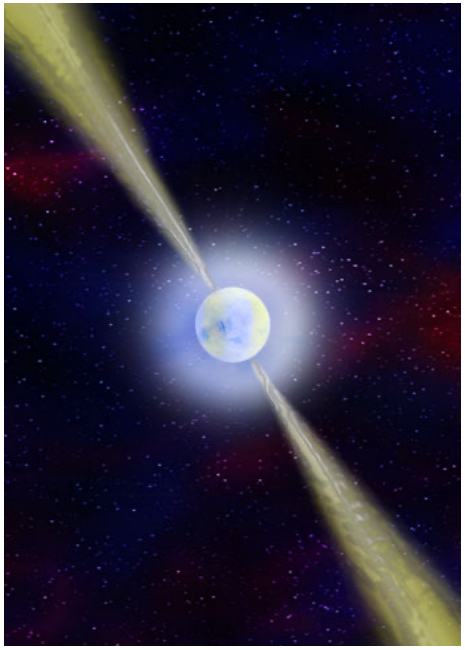
- ~~Claims that the excess traces the Galactic Bulge/Bar~~

For some important recent developments, see:
Leane and Slatyer, arXiv:1904.08430
Zhong, McDermott, Cholis, Fox, arXiv:1911.12369
Zhong, Cholis, arXiv:2401.02481
McDermott *et al.*, arXiv:2209.00006; 2112.09706
Di Mauro, arXiv:2101.04694

Millisecond Pulsars and The Galactic Center Gamma-Ray Excess



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- The gamma-ray spectrum of observed pulsars
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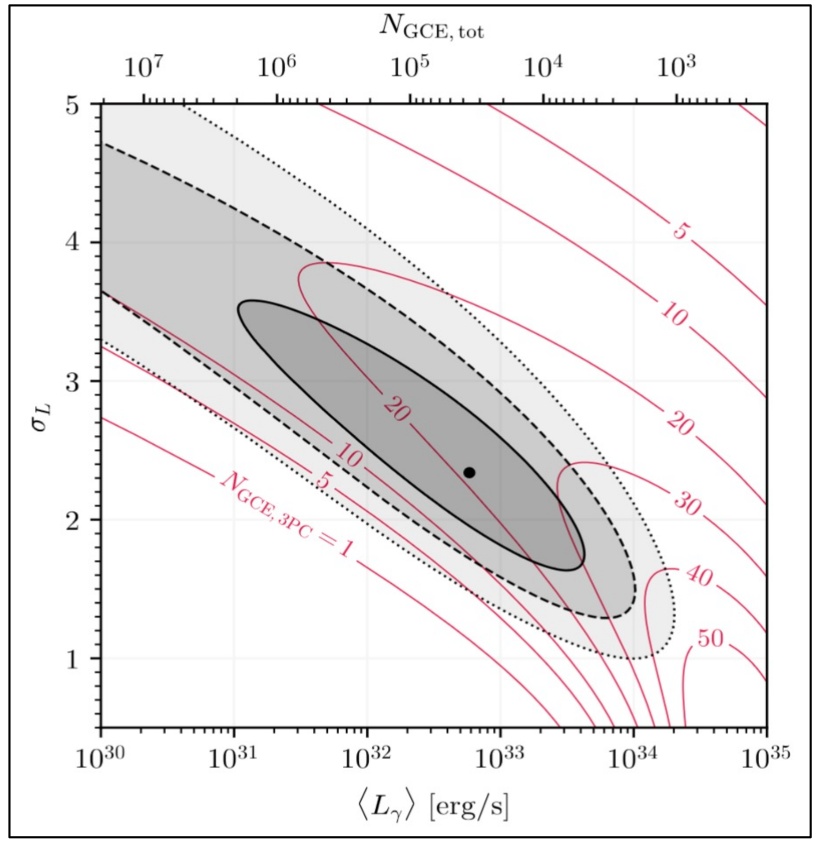
- ~~Claims that the excess traces the Galactic Bulge/Bar~~

Arguments Against Pulsars:

- The lack of pulsars detected in the Inner Galaxy
- The lack of low-mass X-ray binaries in the Inner Galaxy

Why Don't We See More Pulsars in the Inner Galaxy?

- To date, Fermi has detected only three gamma-ray pulsars that could potentially reside within a few kpc of the Galactic Center (PSR J1747-4036, J1649-3012, J1833-3840)
- In contrast, if the gamma-ray excess is produced by pulsars with this same luminosity function as those observed elsewhere, then Fermi should have already detected ~20 Inner Galaxy pulsars



- One of the following must be true:

  -Pulsars produce less than 39% of the gamma-ray excess

  -The MSPs in the Inner Galaxy are at least ~5 times less luminous than the pulsars present in the Galactic Disk

  (the later option would require >200,000 MSPs in the Inner Galaxy)

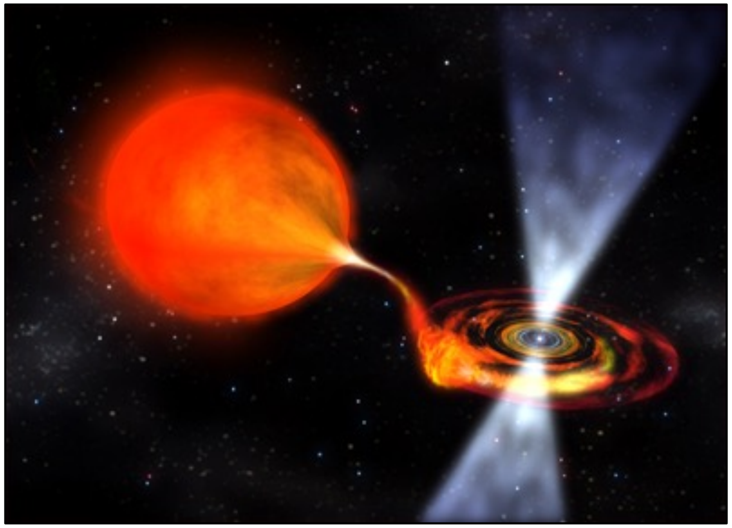
Holst, DH, arXiv:2403.00978 (see also Dinsmore, Slatyer, 2112.09699, List, Rodd, Lewis, 2107.09070, Mishra-Sharma, Cranmer, 2110.06931)

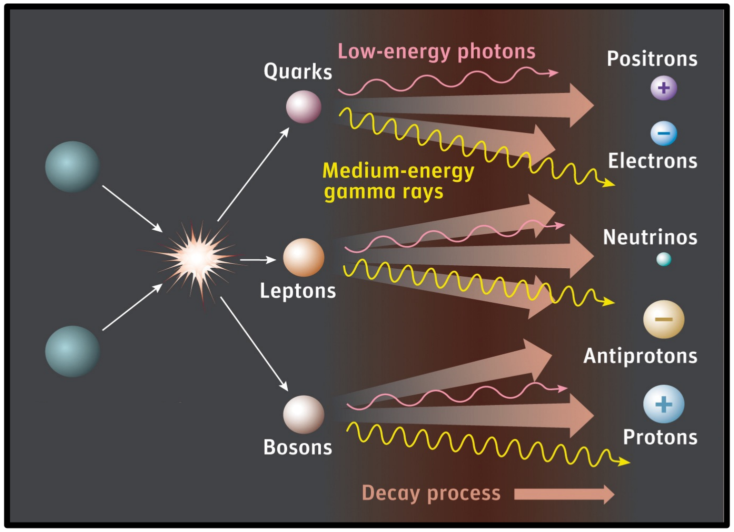
What Produces the Galactic Center Excess?

Bottom Line:

The measured spectrum, morphology, and intensity of the Galactic Center Gamma-Ray Excess each agree well with the predictions of annihilating dark matter in the form of a ~50 GeV thermal relic

The excess could be generated by pulsars, but this would require a very large and exotic population of low-luminosity millisecond pulsars

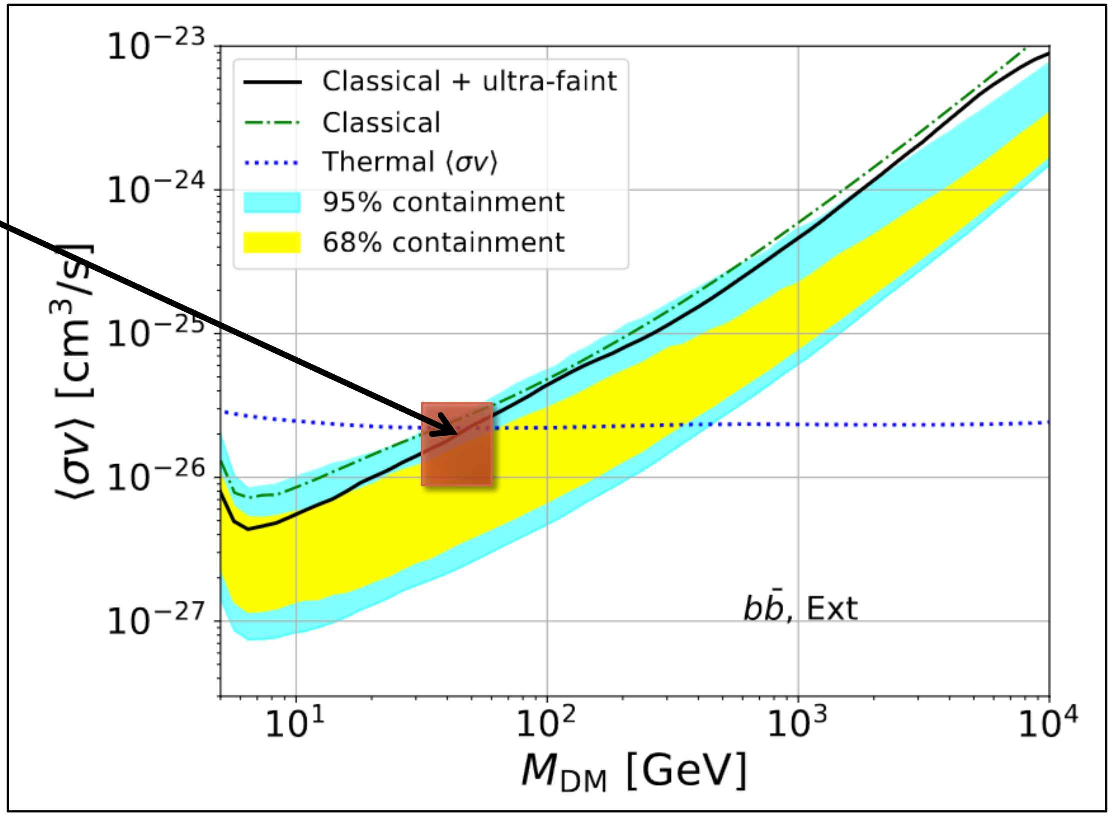




Gamma-Ray Observations of Dwarf Galaxies

- Current Fermi dwarf constraints are based on observations of a few dozen dwarf galaxies, including many that were discovered by DES and other recent surveys
- Although these constraints are currently compatible with dark matter interpretations of the Galactic Center excess, even modest improvements in sensitivity would shed significant light on this interpretation

Region favored by the GCE



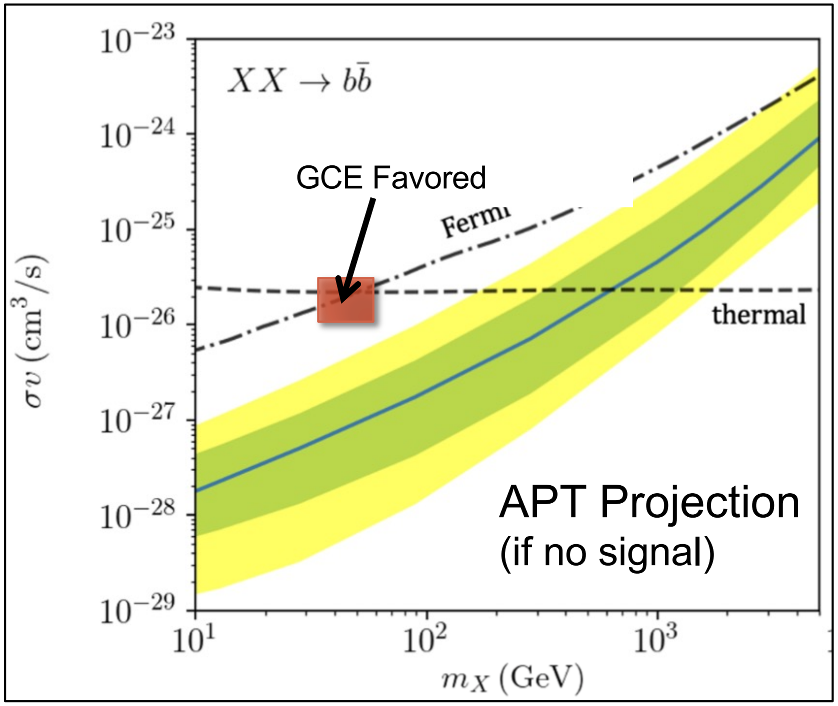
Di Mauro, Stref, Calore, arXiv:2212.06805 (see also, Fermi Collaboration, arXiv:2311.04982)

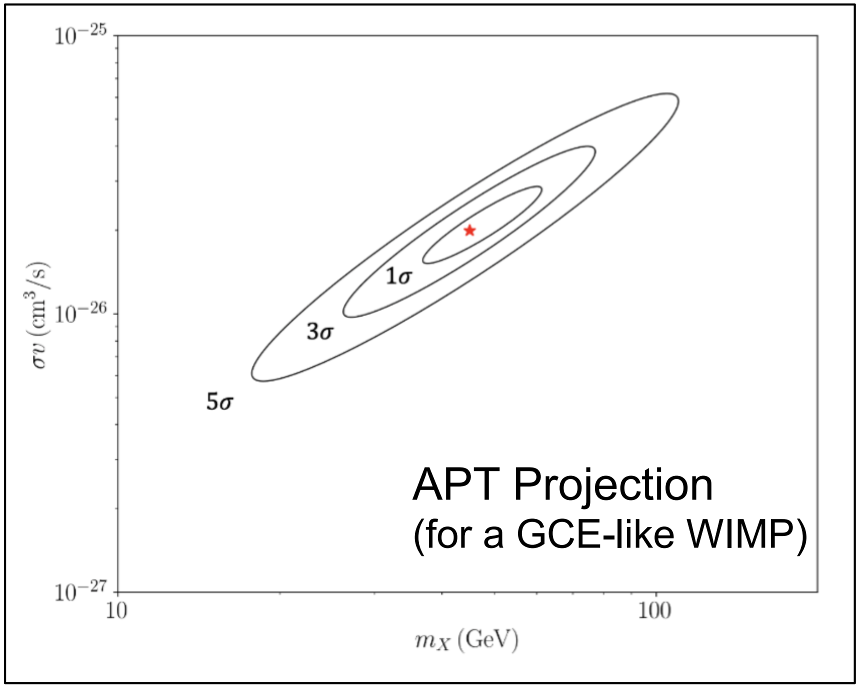
Dwarf Galaxies in the Rubin Era

- The Rubin Observatory (first light in 2024-25!) is expected to discover ~150-250 new Milky Way dwarf galaxies (compared to ~50 at present)
- Once these new dwarfs are discovered, we can use already existing Fermi data to look for gamma-ray signals from annihilating dark matter
- With Rubin, Fermi's sensitivity to dark matter annihilation in dwarf galaxies could plausibly increase by a factor of ~2-3, finally enabling us to test much (perhaps all?) of parameter space favored by the Galactic Center excess

Telescopes Beyond Fermi

- Dark matter searches using gamma rays from dwarf galaxies are limited by statistics; their sensitivity could be dramatically improved by larger telescopes
- As an example, consider the projected sensitivity of the proposed Advanced Particle-astrophysics Telescope (APT)





F. Xu and DH, arXiv:2308.15538

New Directions in Dark Matter

- Although I remain enthusiastic about WIMPs, the lack of signals in direct detection experiments has motivated many of us to consider other ways in which the dark matter could have been created in the early universe; especially ways that could produce a population of extremely feebly interacting particles

- Some well-known examples include:

  -Misalignment production (axions, etc.)

  -Production through out-of-equilibrium decays (moduli/topological defects)

  -Production via freeze-in or leak-in (*ie*. semi-thermal mechanisms)

- Another way to produce extremely feebly interacting dark matter particles would be through the Hawking evaporation of primordial black holes in the early universe

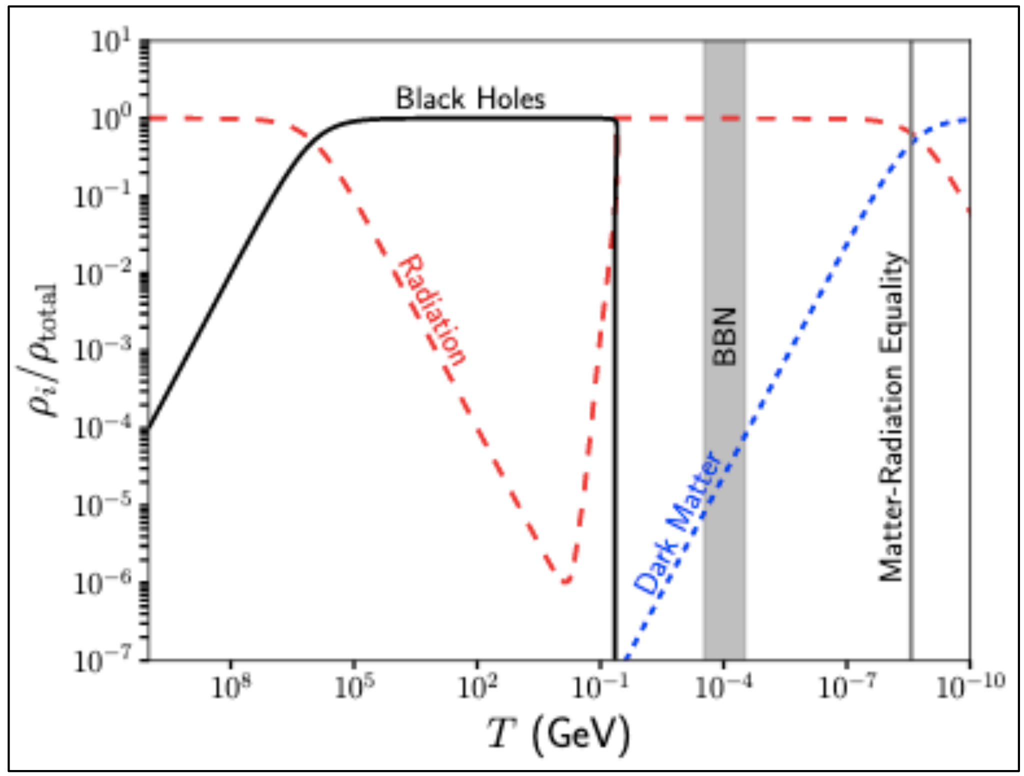
The Democratic Nature of Gravity

- Hawking evaporation is a consequence of gravity, which (unlike other forces) treats all forms of matter and energy in the same way
- Hawking evaporation produces *all* kinds of particles (so long as they are lighter than its temperature), regardless of their electric charge, QCD color, or any other quantum numbers
- This includes any number of particle species that we have *not discovered yet!* – axions, hidden photons, right-handed neutrinos, gravitons, supersymmetric particles, *etc*.
- Black holes are the ideal factories of exotic particles

A Plausible Picture

- After inflation ended, the universe was still rapidly expanding; at the earliest times (T_{RH}~10^{12}-10^{15} GeV) the cosmic horizon contained a total energy of M_{hor}~10^2-10^8 grams
- Black holes in this mass range evaporate quickly, disappearing before BBN
- As the universe expands, the fractional energy density in black holes grows with the scale factor, $\boldsymbol{\rho}_{BH}$ /$\boldsymbol{\rho}_{rad}$ $\boldsymbol{\alpha}$ a, potentially leading to an era that is dominated by black holes
- The evaporating black holes will not only reheat the SM bath, but could also produce very feebly interacting particles…

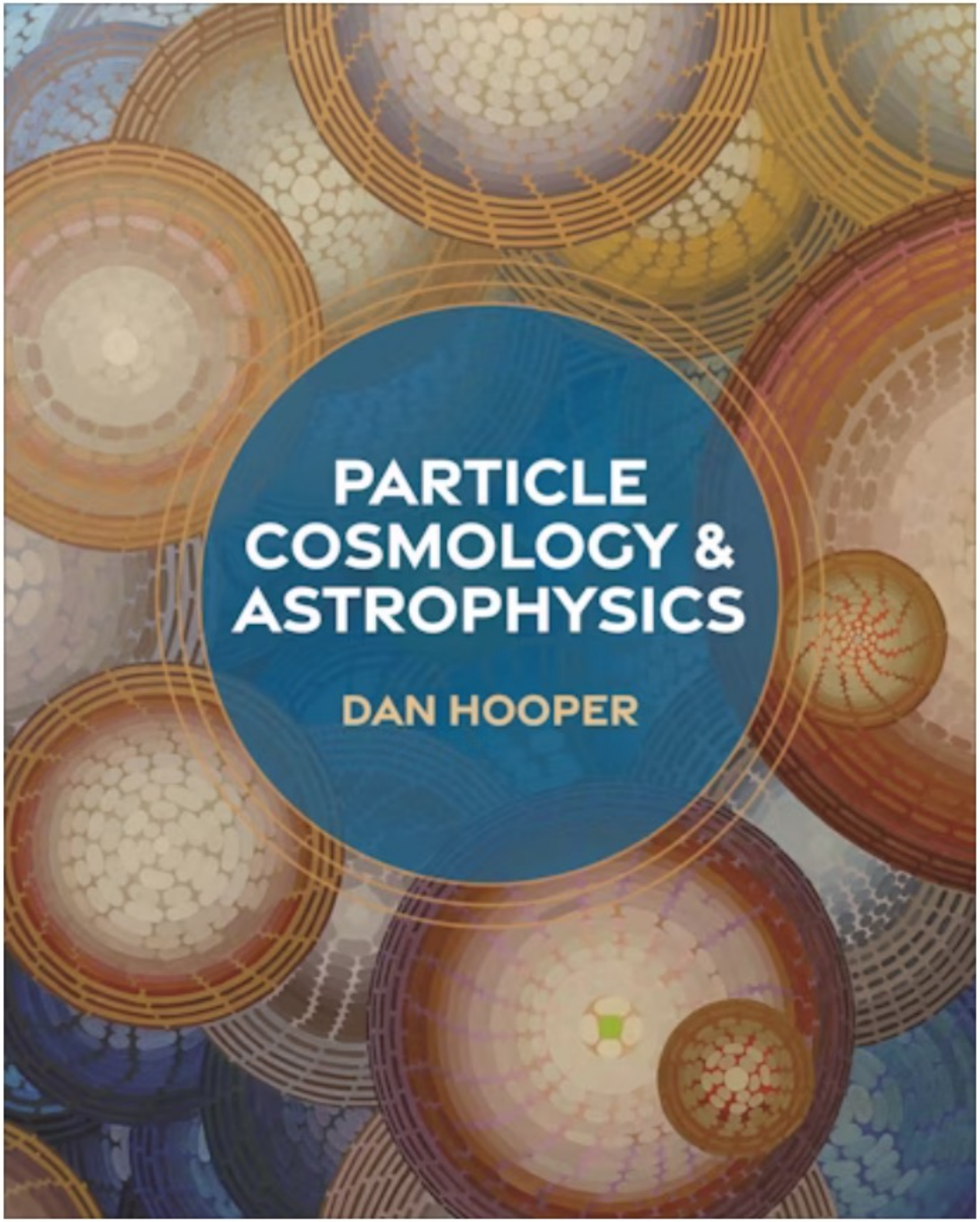
  -Dark matter
  -Dark radiation
  -Baryogenesis



Krnjaic, DH, McDermott, arXiv:1905.01301

Summary

- We are finally closing in on the sources of the cosmic ray spectrum – this is fundamentally a question of multi-messenger astrophysics, with important roles being played by high-energy neutrino telescopes, gamma-ray telescopes, and cosmic-ray detectors
- Existing neutrino telescopes do not yet have the sensitivity that we will likely need to identify the sources of the cosmic ray spectrum, but IceCube-Gen2 will be able to conclusively identify the sources of the observed diffuse neutrino flux, and with it the sources of the cosmic rays
- WIMPs remain well-motivated as a class of dark matter candidates, despite the incredible sensitivities achieved by direct detection experiments
- Indirect searches are testing dark matter in the form of thermal relics for masses up to $\sim\mathcal{O}(100)$ GeV; this program is testing the WIMP paradigm!
- The Galactic Center's GeV excess remains compelling as a possible signal of dark matter, and is not easily explained by pulsars or other known astrophysics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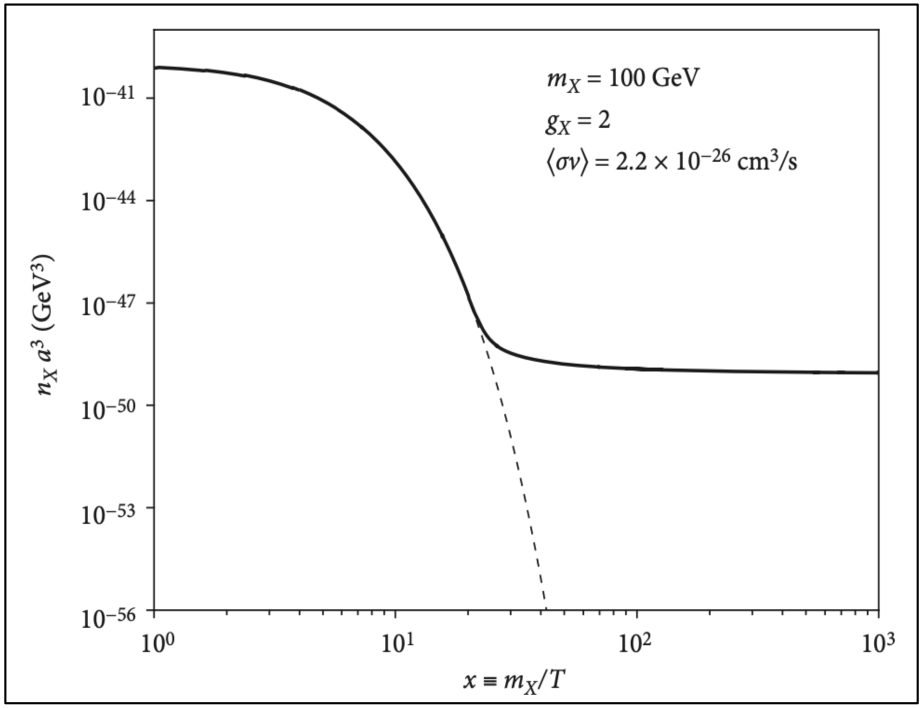
DAN HOOPER

The Abundance of a Thermal Relic

- Consider a stable particle species that was in equilibrium with the thermal bath in the early universe; the abundance of these particles will evolve according to the following Boltzmann equation:

$$\frac{dn_X}{dt} = -3Hn_X - \langle \sigma v \rangle \left[n_X^2 - (n_X^{\mathrm{Eq}})^2 \right]$$



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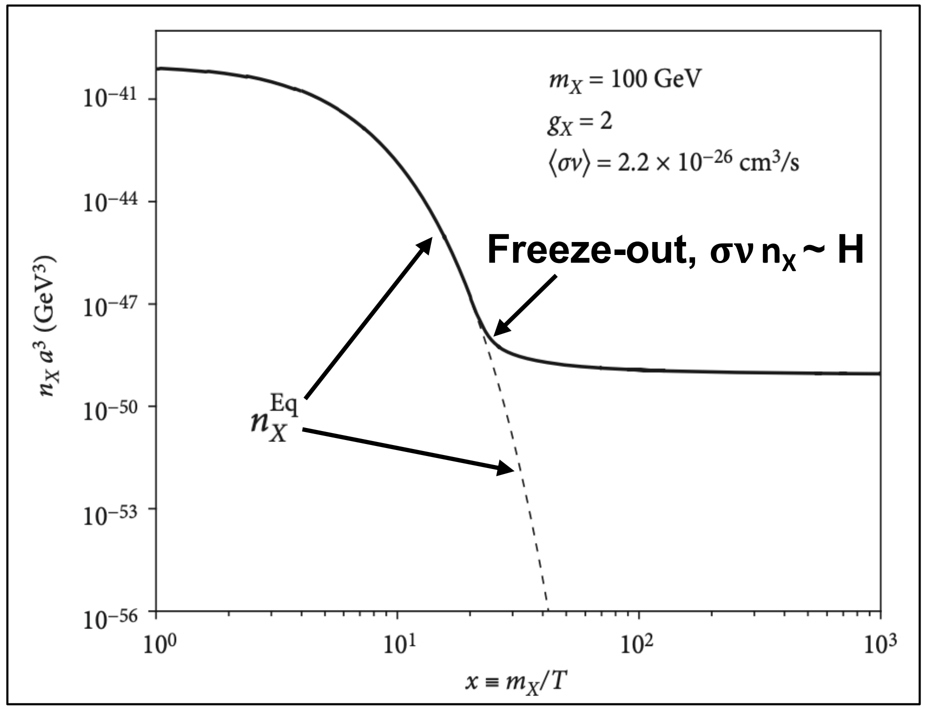
- The number density of these particles will be held near their equilibrium value until their production/annihilation rate falls below the rate of Hubble expansion – *thermal freeze out*
- After a particle species has frozen-out, it is no longer created or destroyed in significant numbers
- The resulting abundance of such a relic is set by the temperature at which it freezes out of equilibrium; this is directly related to its annihilation cross section:

$$\Omega_X \sim 0.27 \times \left(\frac{2.2 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}}{\langle\sigma v\rangle}\right)$$



Why Don't We See More Low-Mass X-Ray Binaries?

- Millisecond pulsars are formed when they are spun up by a binary companion; the precursors to MSPs are low-mass X-ray binaries (LMXBs)
- By measuring the ratio of the gamma-ray emission (from MSPs) to the number of bright LMXBs in globular clusters, and comparing this to the number of bright LMXBs in the Inner Galaxy, we can estimate the number of MSPs in the Inner Galaxy:

Measure

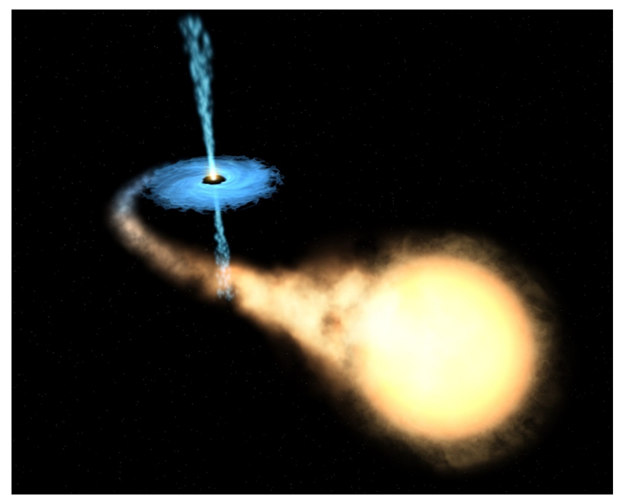
Infer

$$\left.\frac{F_\gamma}{N_{\mathrm{LMXB}}}\right|_{\text{Globular Clusters}} = \left.\frac{F_\gamma}{N_{\mathrm{LMXB}}}\right|_{\text{Inner Galaxy}}$$

Measure

Measure

- This procedure finds that only 4-11% of the gamma-ray excess is attributable to MSPs
- If the entire excess was from MSPs, INTEGRAL should have detected ~10^3 LMXBs in the Inner Galaxy; they actually detected 42



Haggard, Heinke, DH, Linden, arXiv:1701.02726
(see also Cholis, DH, Linden, arXiv:1407.5625)