

# HIGH ENERGY AND ULTRA-HIGH ENERGY NEUTRINOS

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Stephanie Wissel, Penn State  
Markus Ackermann, Mauricio Bustamante, Lu Lu,  
Nepomuk Otte, Mary Hall Reno

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# WHITE PAPER OUTLINE

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- Physics Opportunities with energetic cosmic neutrinos
  - Starting point Lols: Snowmass Lols on HE/UHE Fundamental Physics and UHE neutrinos
- High-energy (TeV-PeV) and Ultra-High Energy (>100 PeV)

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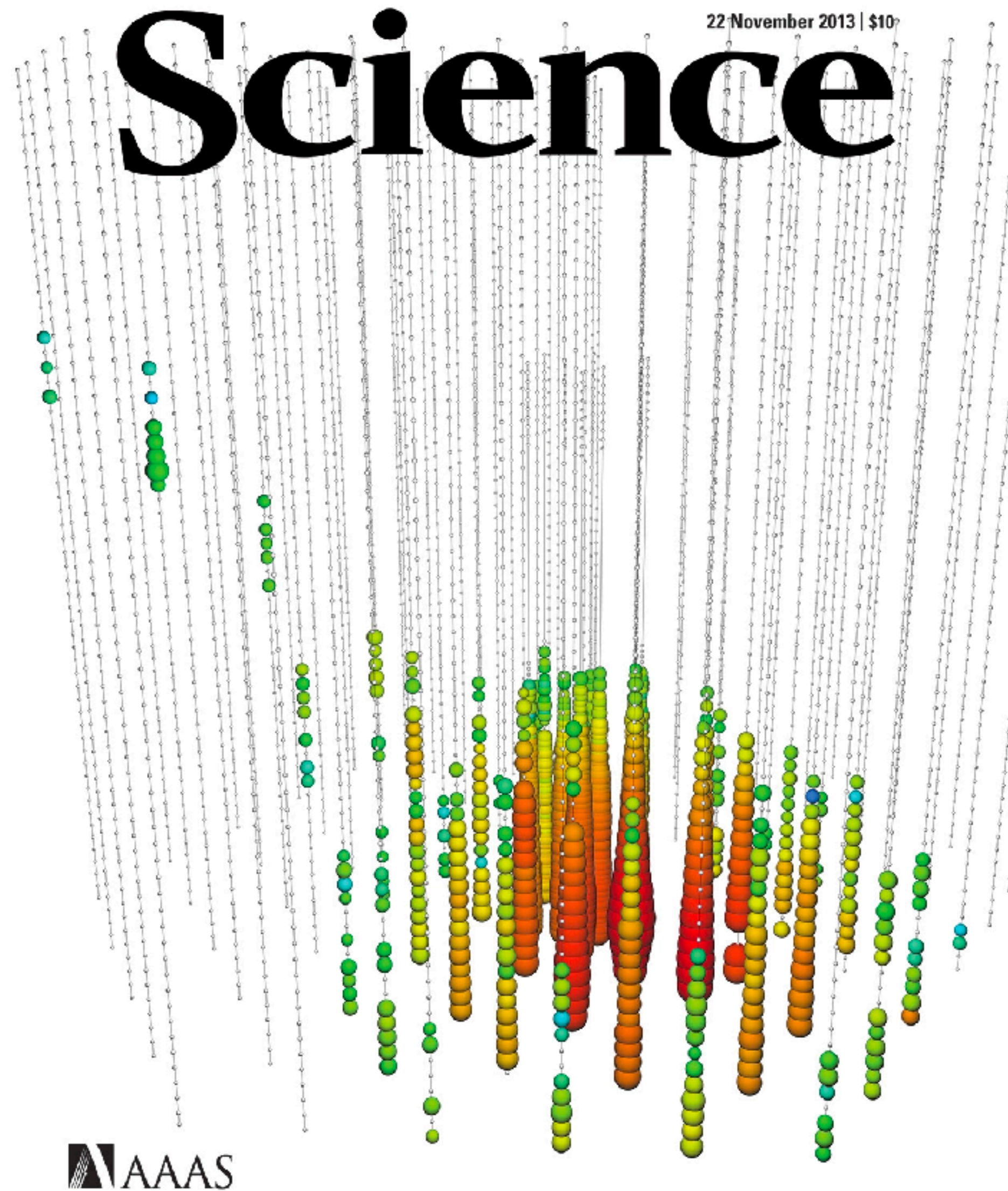
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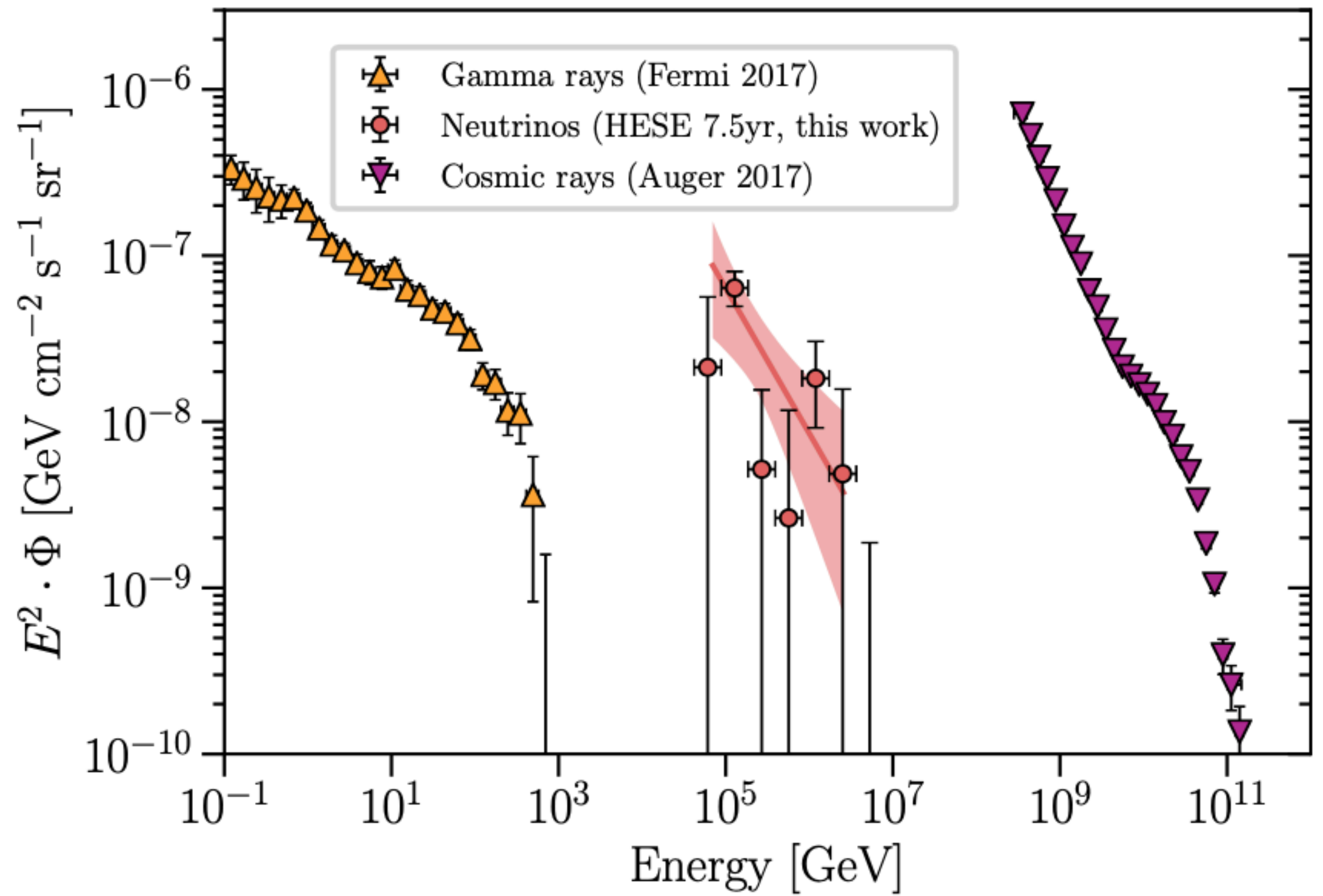
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# THIS DECADE: DISCOVERY OF HIGH-ENERGY NEUTRINOS



*IceCube Science 2013*

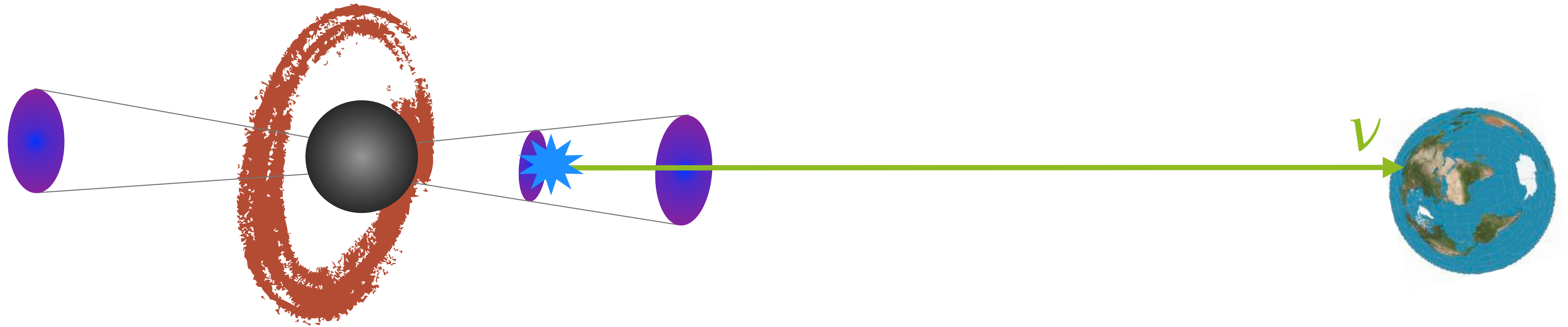


*PRD 2021 [arXiv:2011.03545](https://arxiv.org/abs/2011.03545)*

# NEUTRINO SOURCES

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## Cosmic Ray Accelerator



## ★ Astrophysical $\nu$ 's:

Cosmic ray interactions at the sources

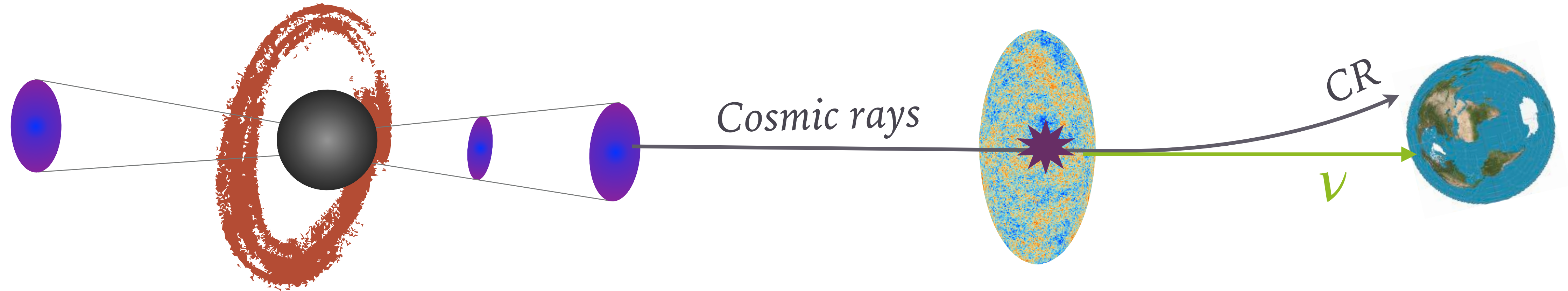
## ★ Cosmogenic $\nu$ 's:

Origin of the most energetic cosmic rays



# NEUTRINO SOURCES

## Cosmic Ray Accelerator



## ★ Astrophysical $\nu$ 's:

Cosmic ray interactions at the sources

## ★ Cosmogenic $\nu$ 's:

Origin of the most energetic cosmic rays

### GZK Effect

Cosmic Ray

$$p + \gamma \rightarrow \Delta^+ \rightarrow \pi^+ + n$$

CMB photon

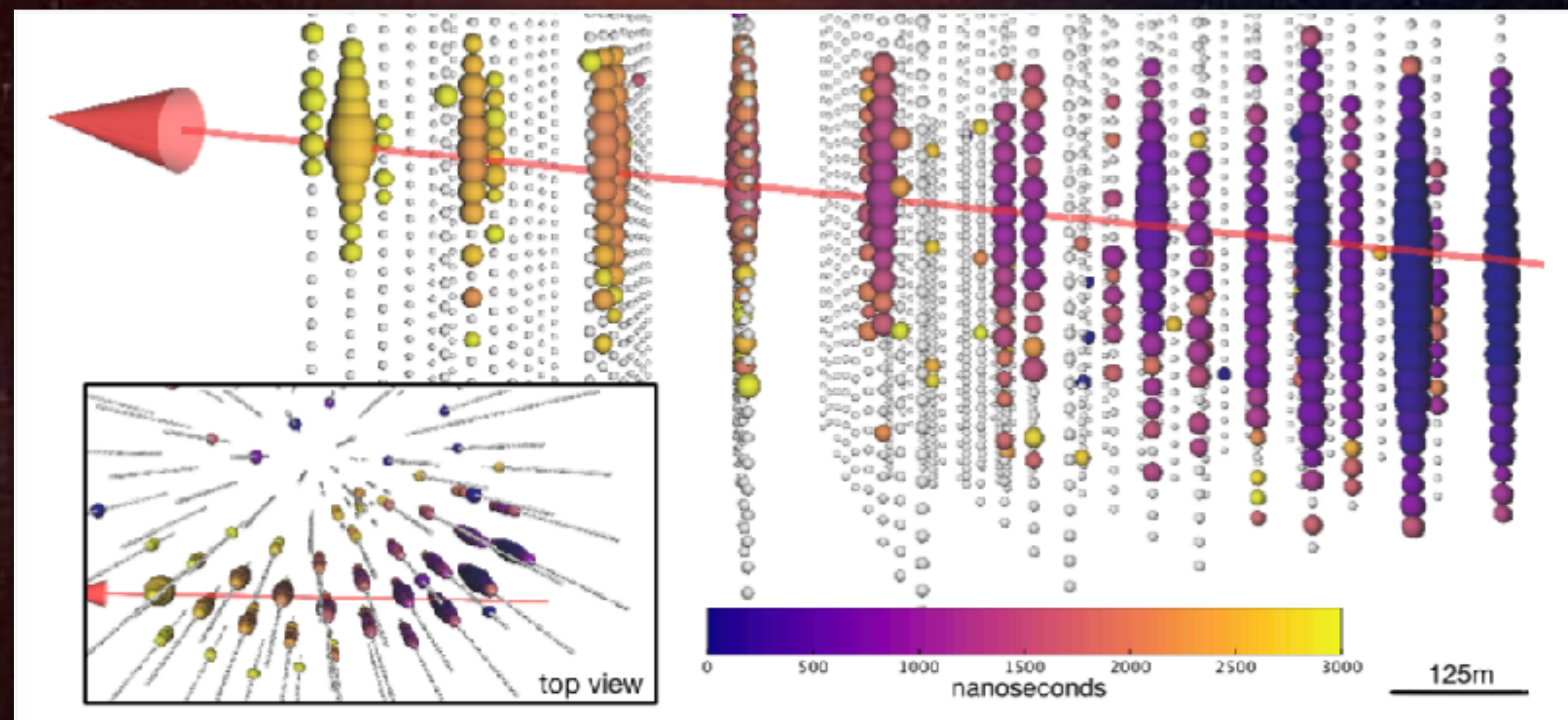
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$



# First Candidate Neutrino Point Source

TXS 0506+056 Flare coincident with IC170922A  
Archival neutrino flare at  $3.5\sigma$



Science 361 (2018) no.6398, 147-151

Science 361 2018

NASA/IceCube



# Science Targets in Astrophysics

*Origin of cosmic rays*

*Revealing the sources of cosmic neutrinos*

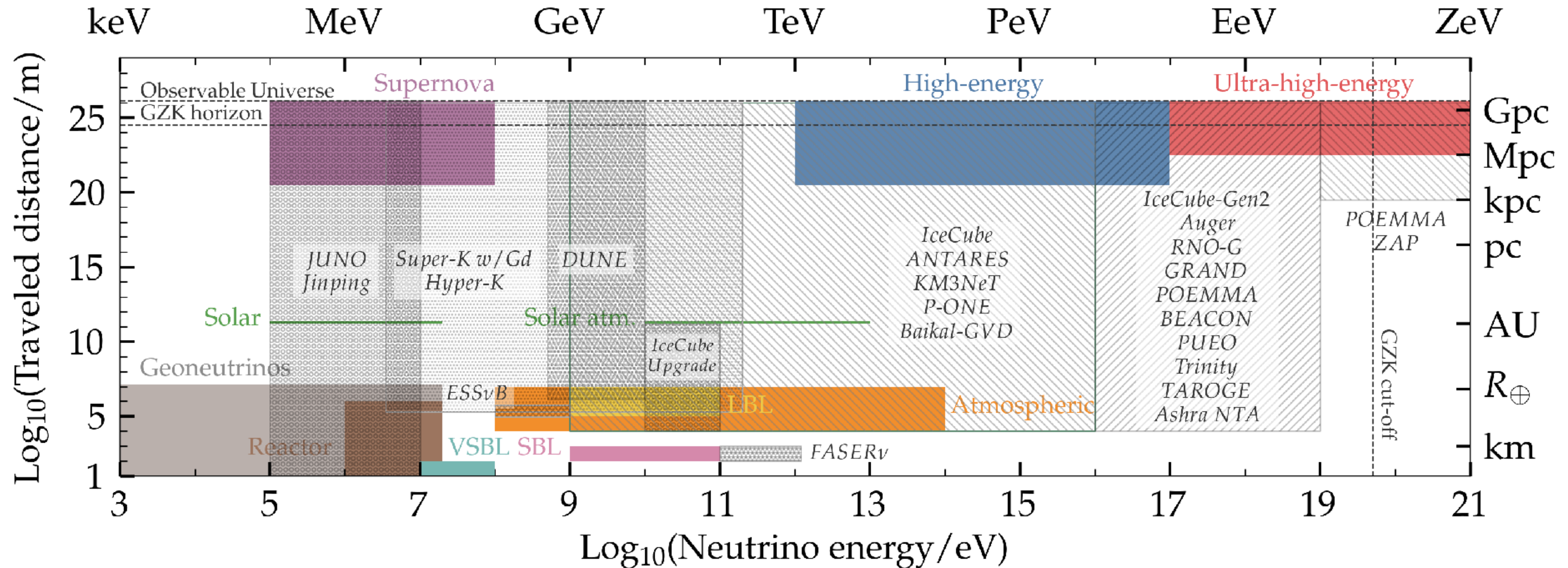
*Neutrino point sources*

*New era of multi-messenger astrophysics*



# FUNDAMENTAL PHYSICS AT THE HIGHEST ENERGIES

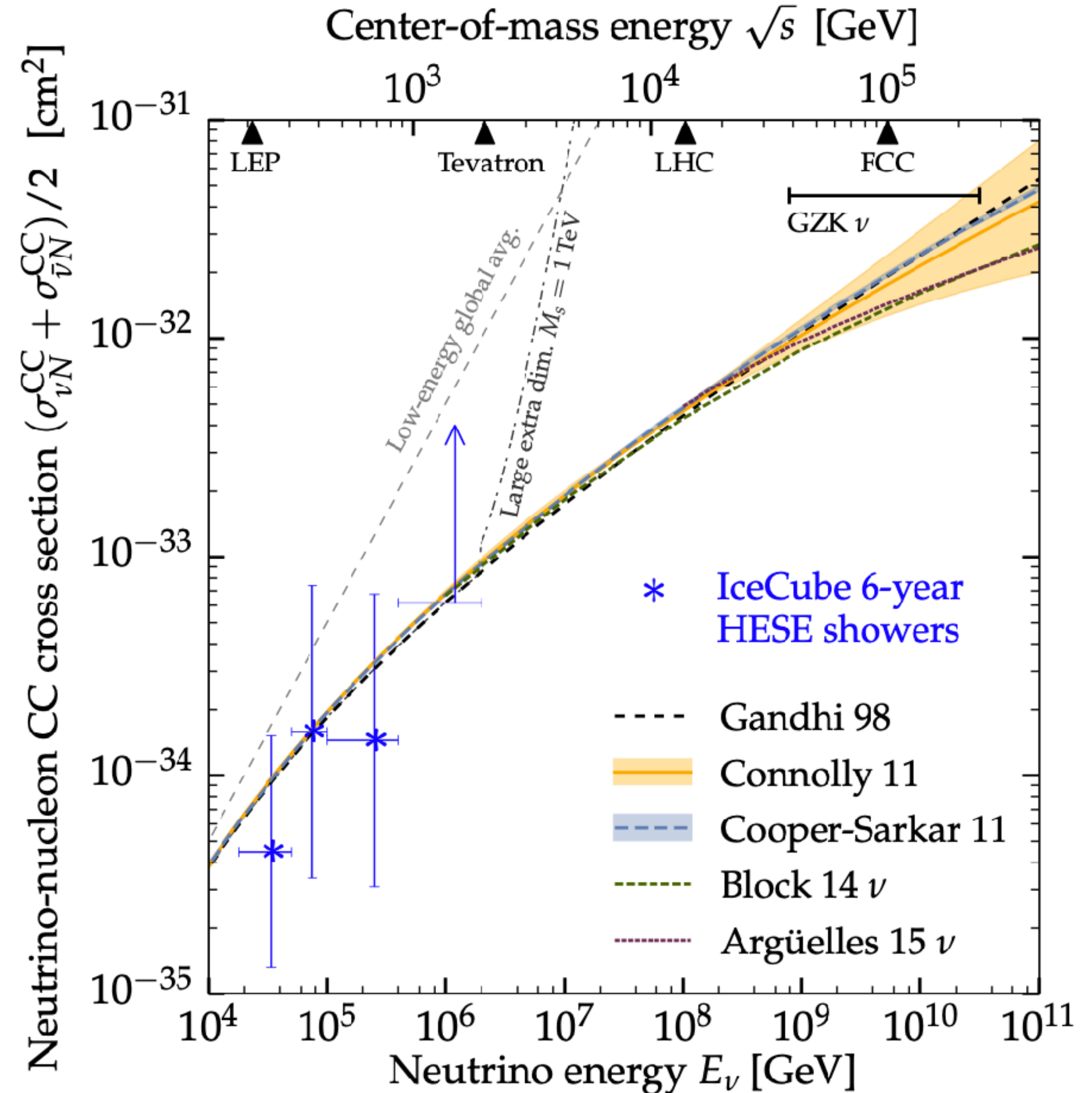
- Fundamental physics probe at the highest energy scales (TeV to ZeV)
- Longest baselines ( $\sim$ Gpc) allow even small effects to accumulate





# CROSS SECTIONS IN A NEW ENERGY REGIME

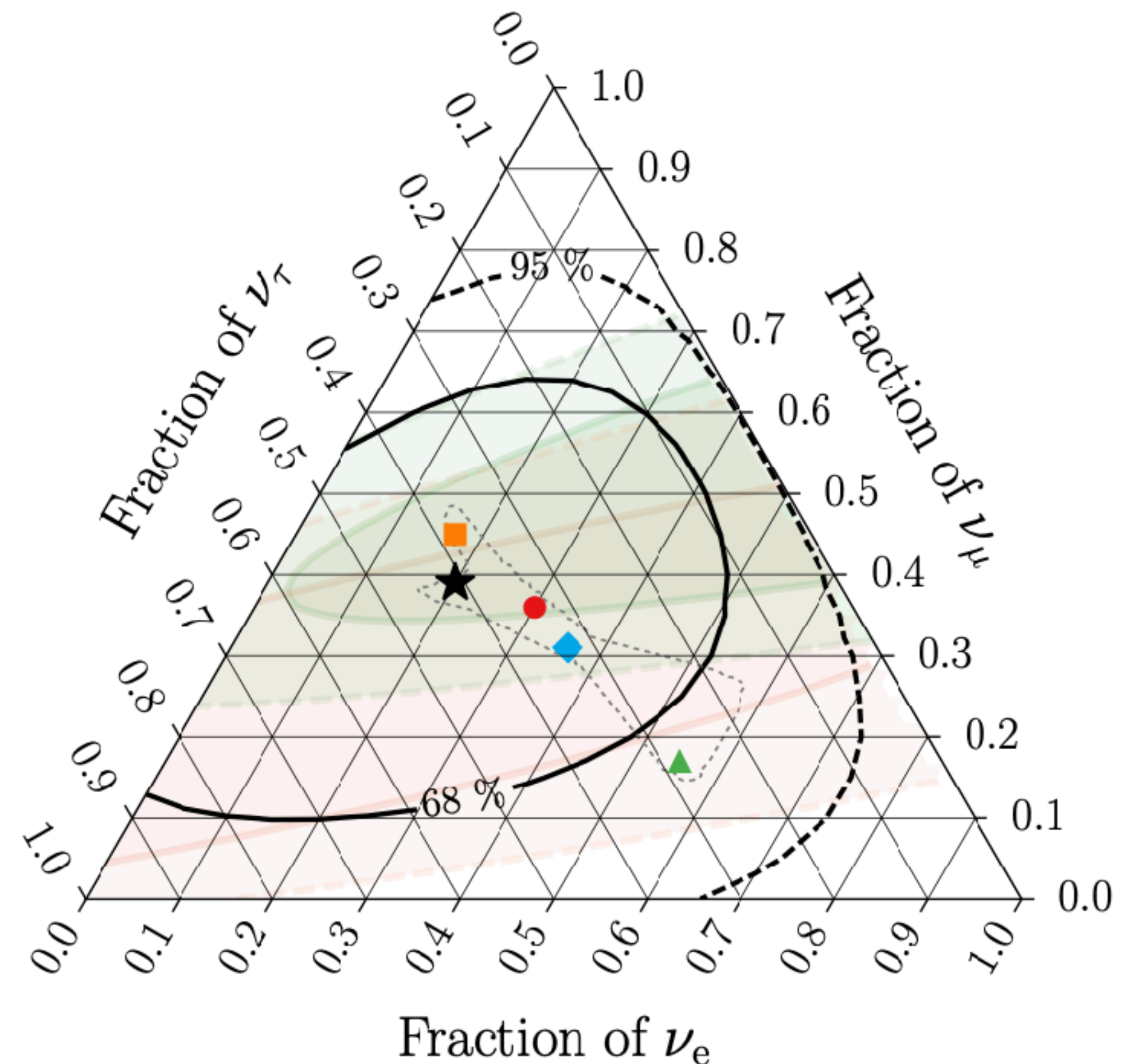
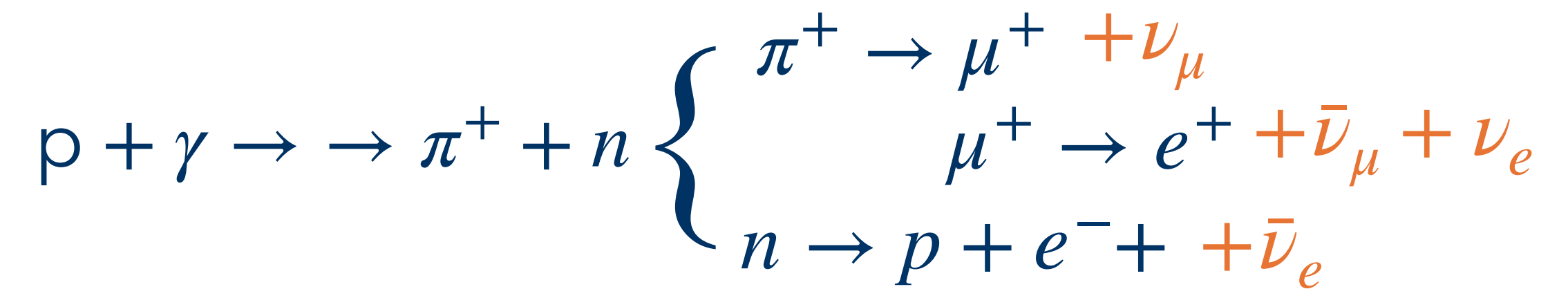
- Probe neutrino interactions previously unmeasured
- Will improve with better statistics
- Push to ultra-high energies to probe new energy regime
- EeV neutrinos  $\rightarrow \sqrt{s} \sim 30$  TeV



# NEUTRINO FLAVOR

- At the sources, we expect only  $\nu_e$  and/or  $\nu_\mu$
- Even Flavor ratios  $1 \nu_e : 1 \nu_\mu : 1 \nu_\tau^*$   
expected due to flavor oscillations  
over Gpc length scales

*\*Deviations from standard flavor ratios expected from  
Beyond-Standard-Model scenarios*





# Fundamental Physics Tests with TeV-PeV and EeV neutrinos

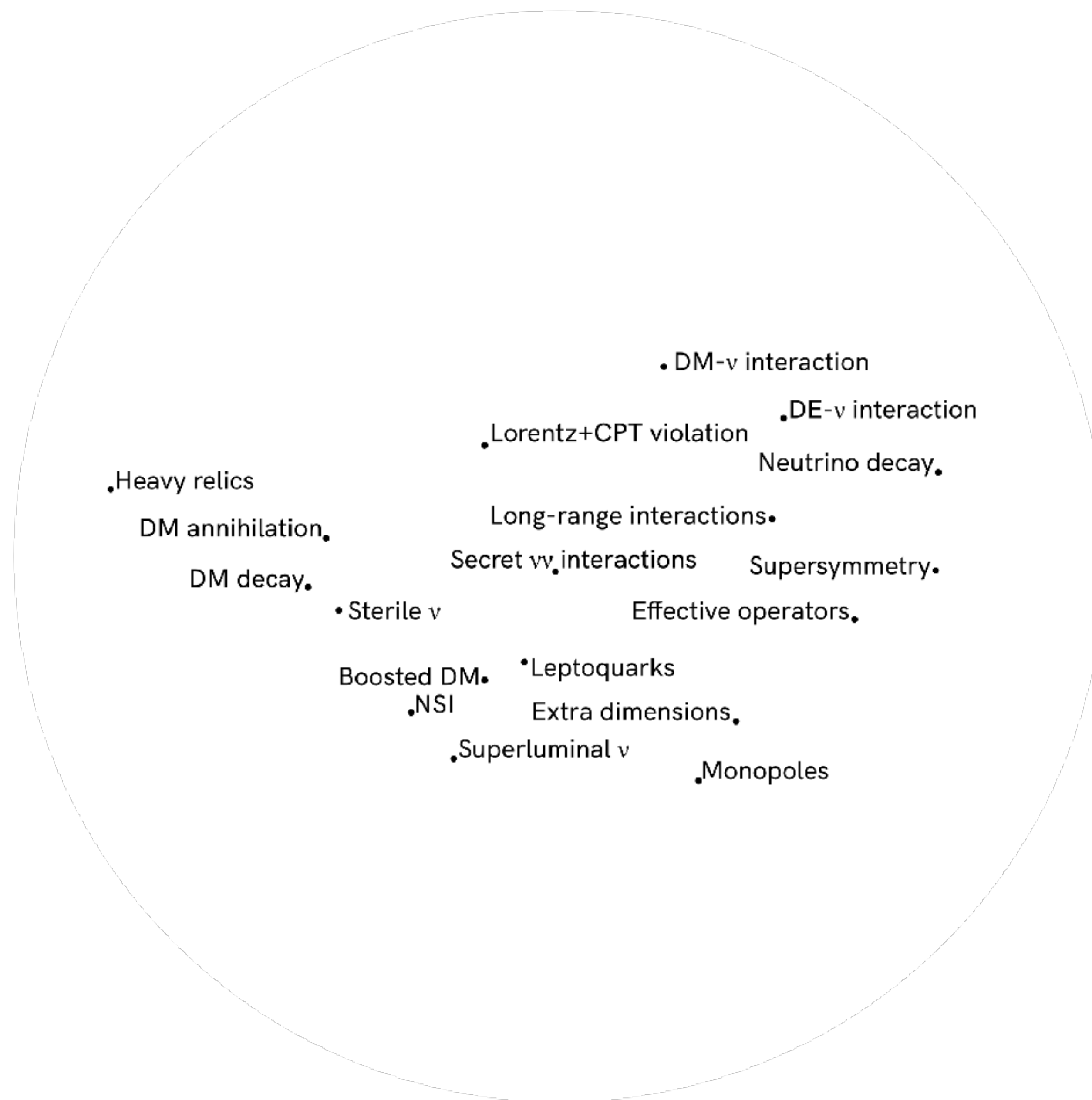
*How do cross sections behave at higher energies?*

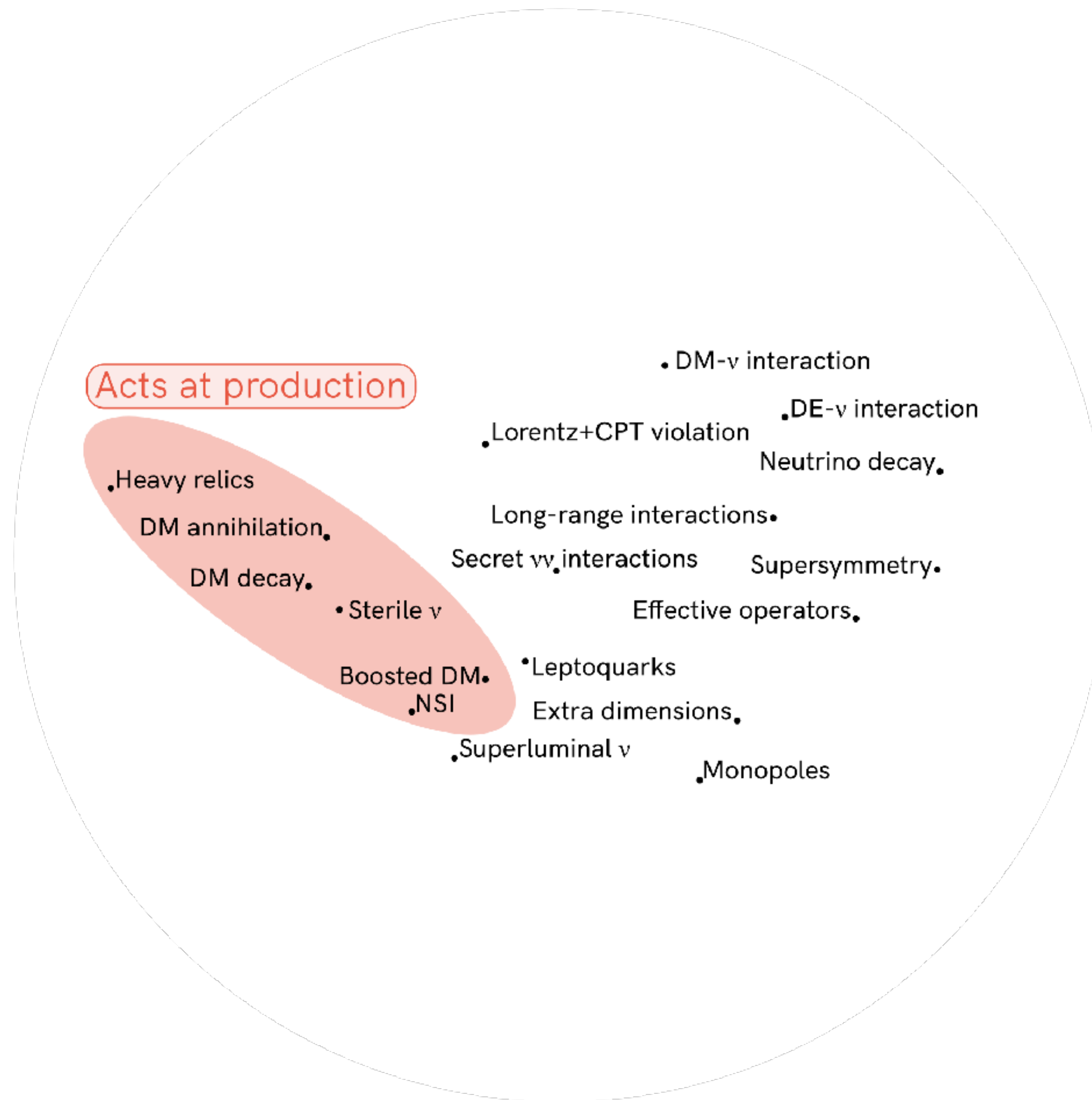
*How do flavors mix at high energies?*

*What are the fundamental symmetries of Nature?*

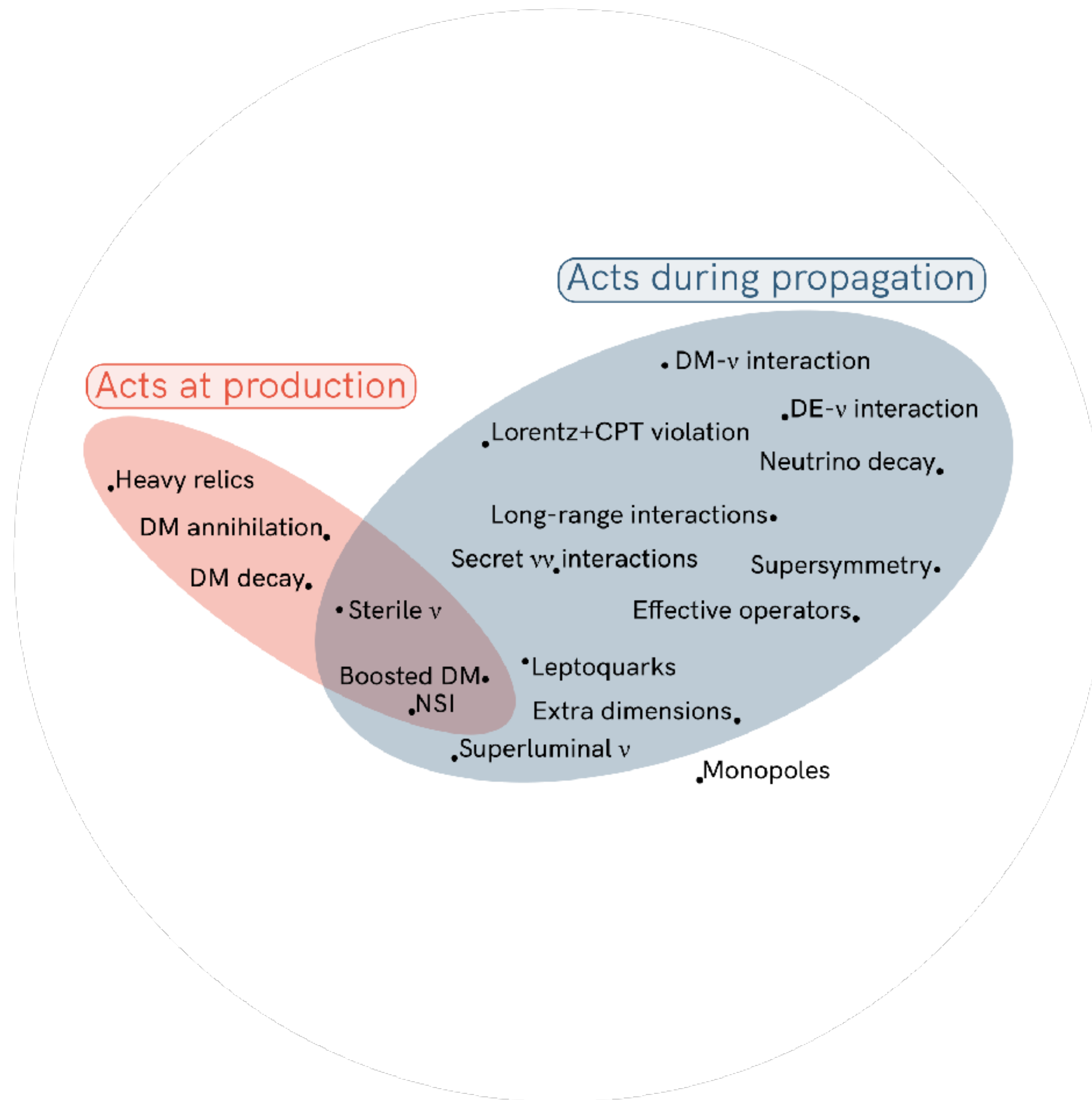
*Evidence of dark matter?*

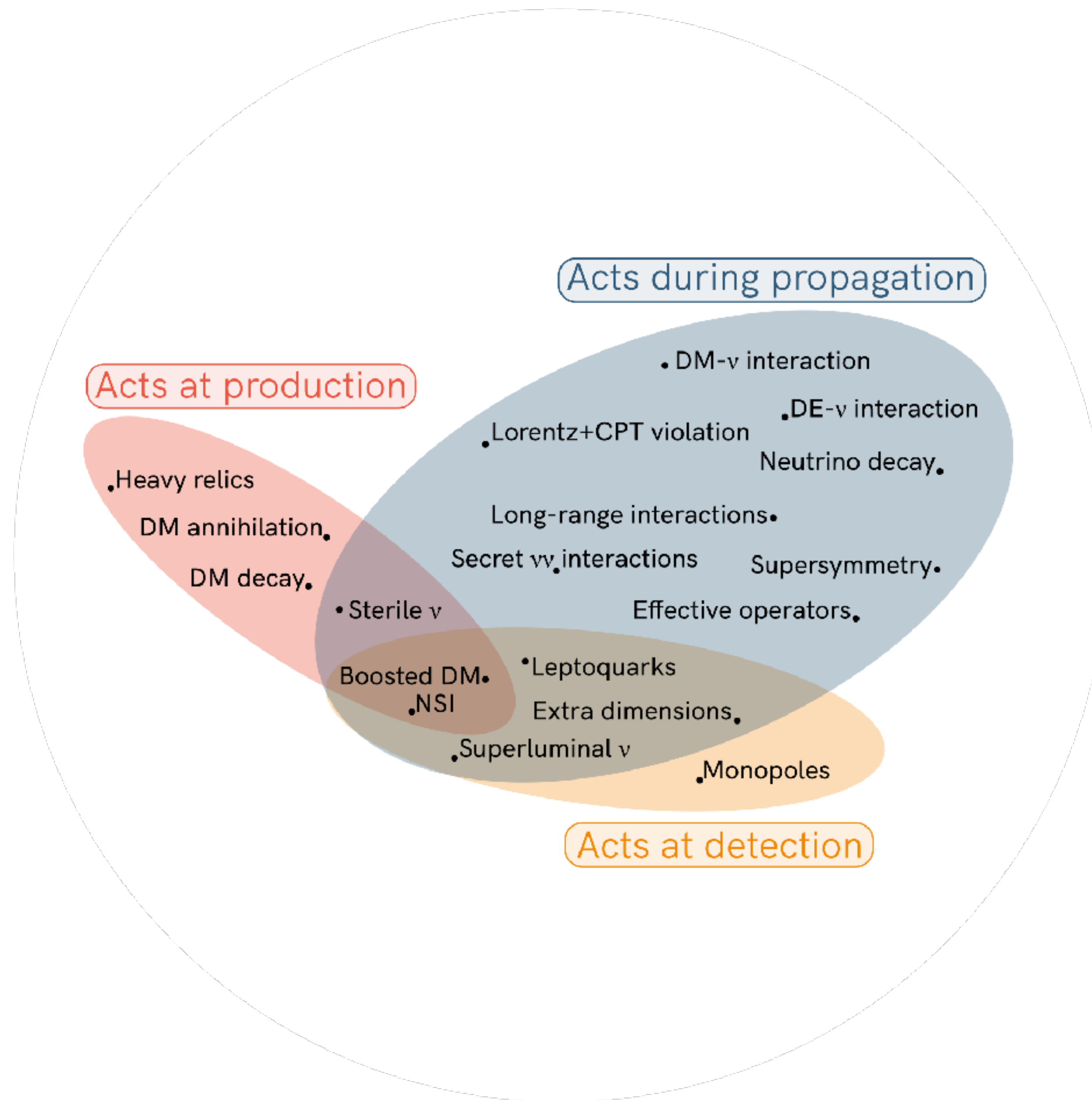
*Hidden interactions with cosmic backgrounds?*

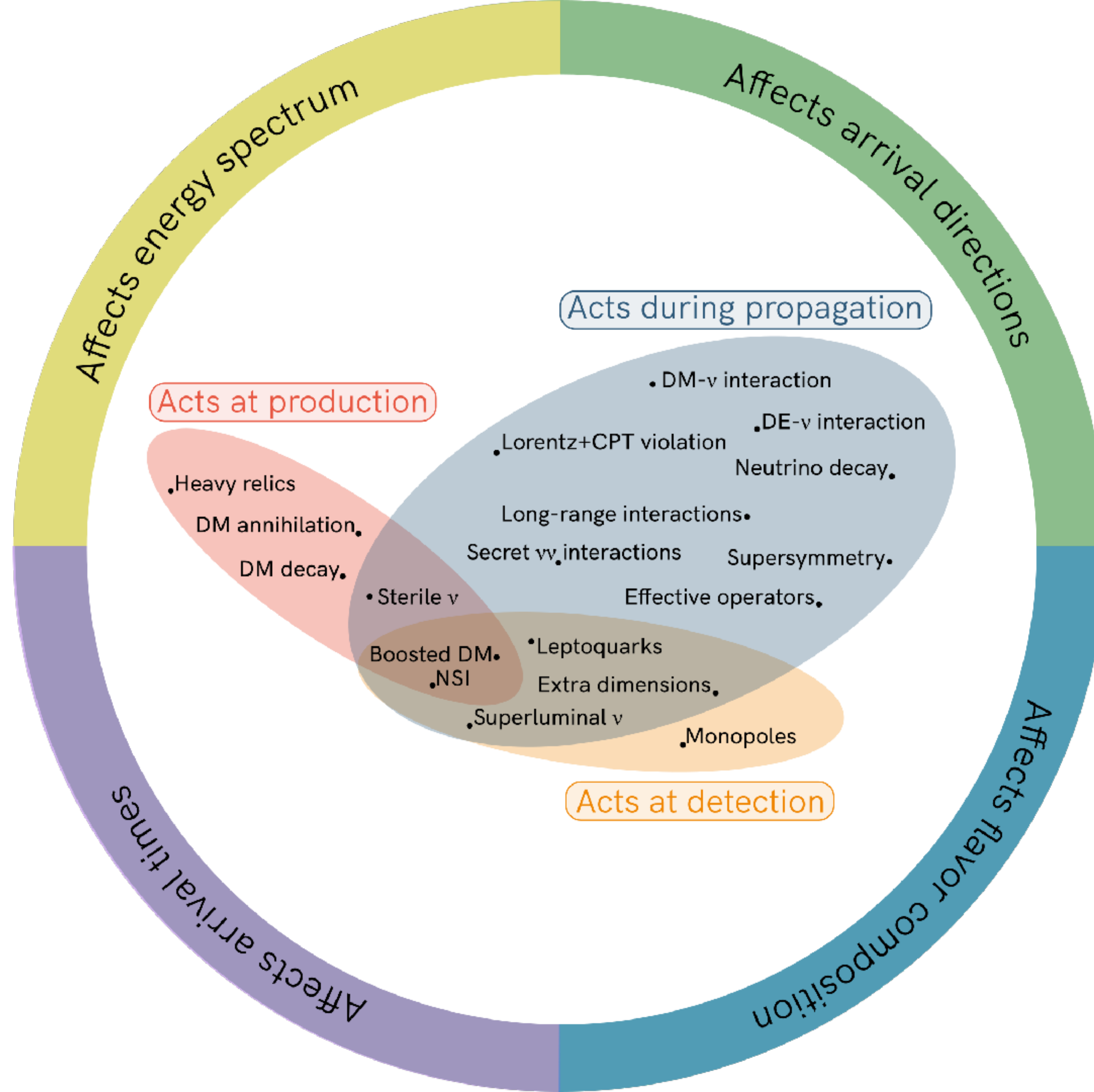




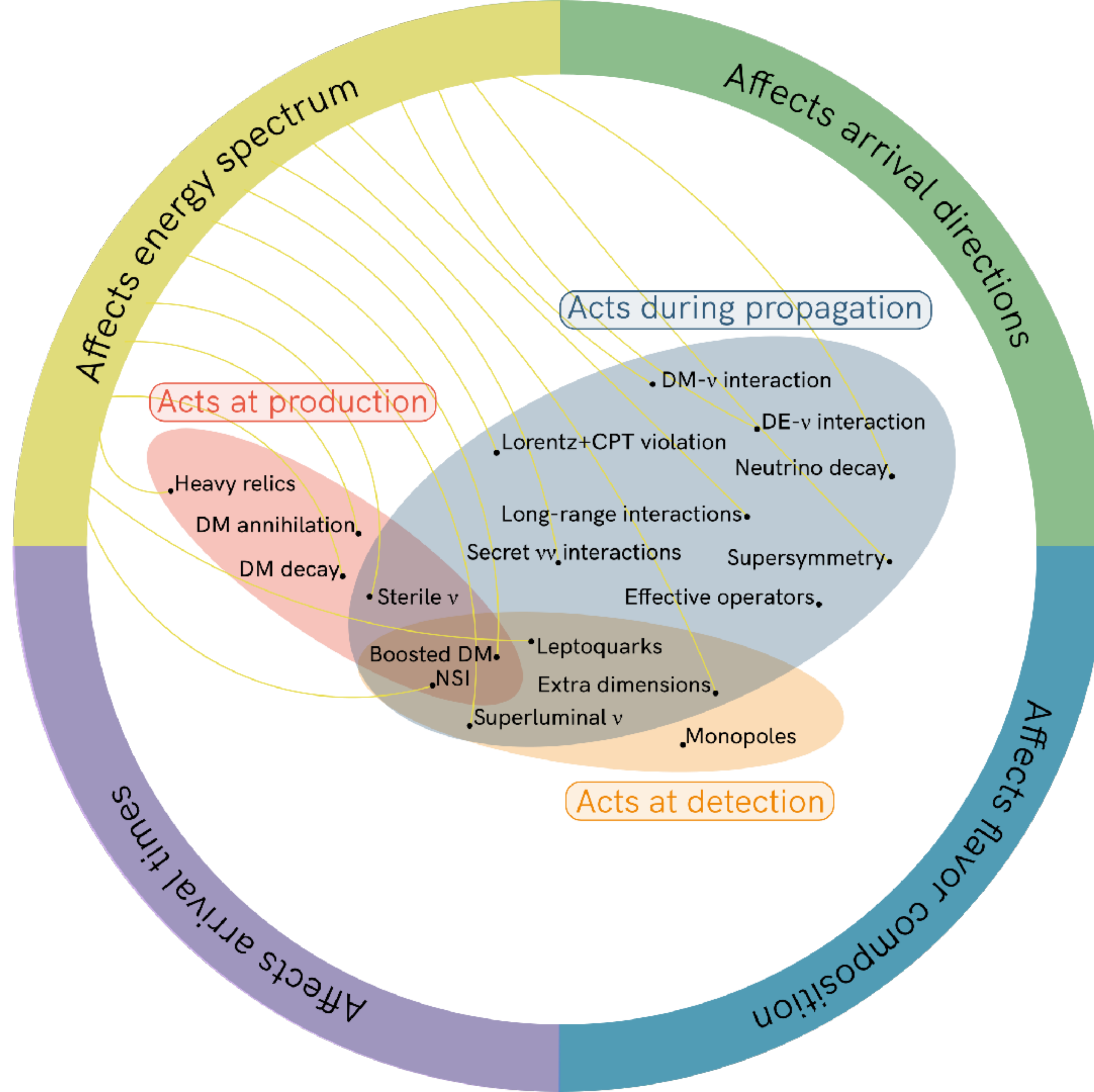


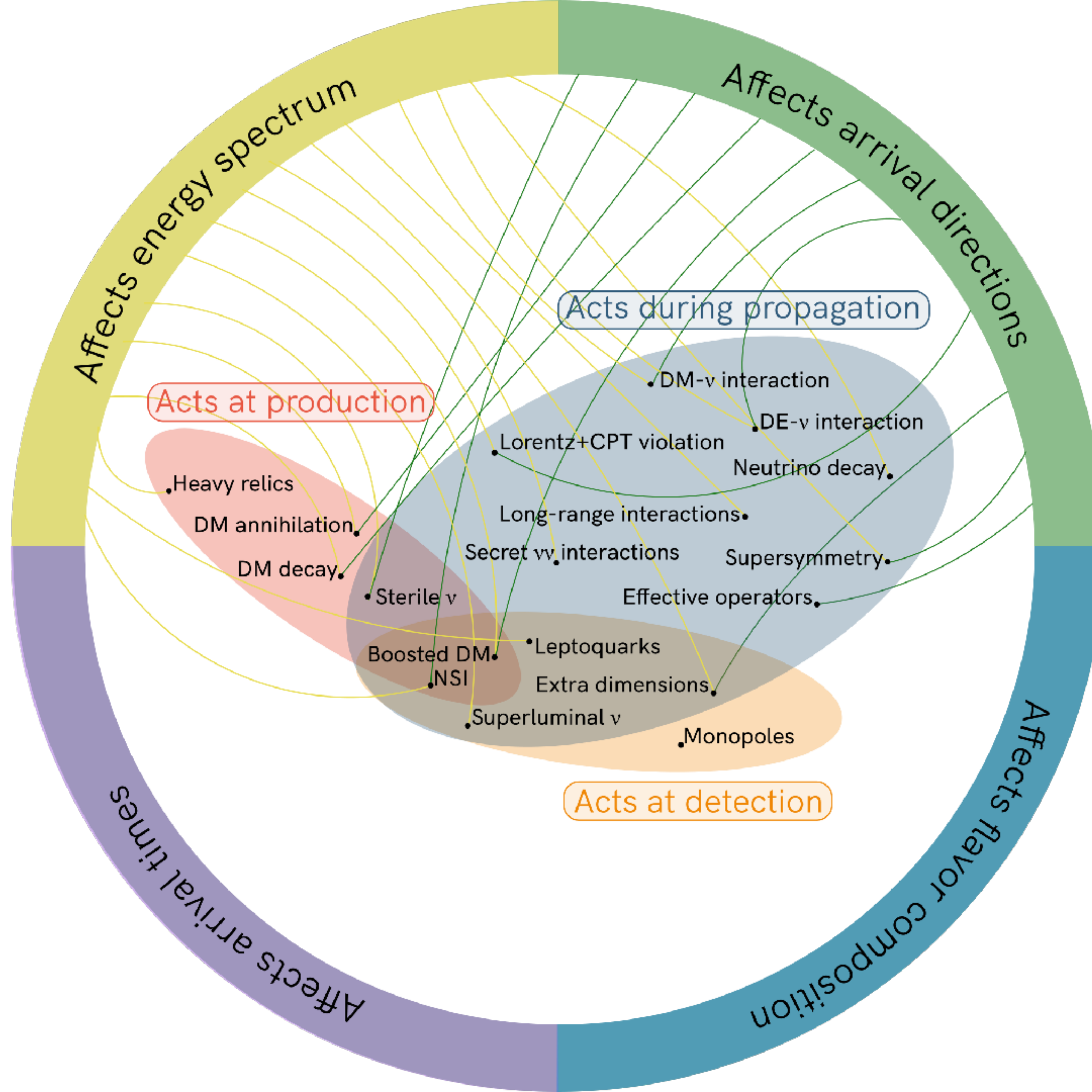




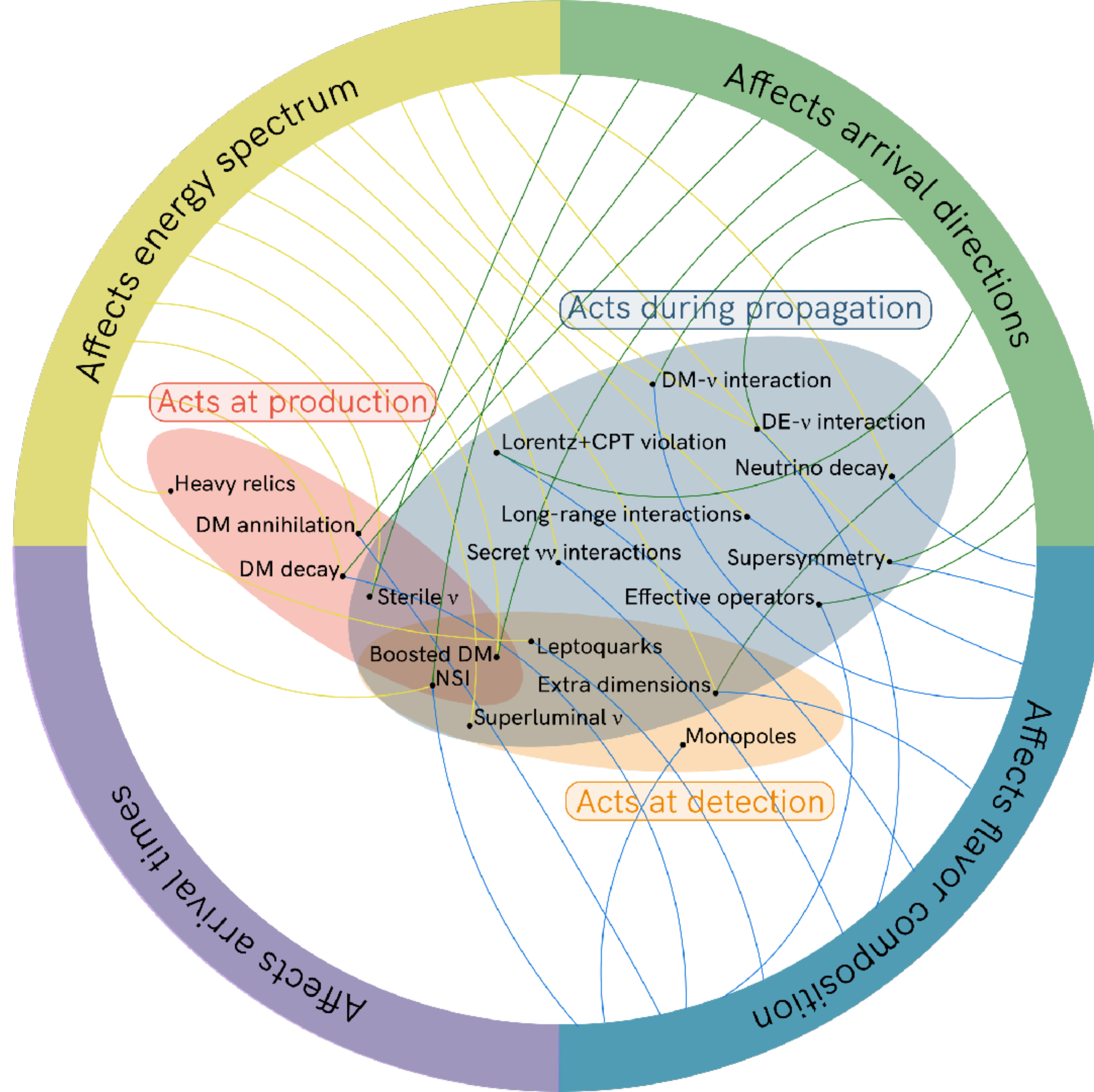




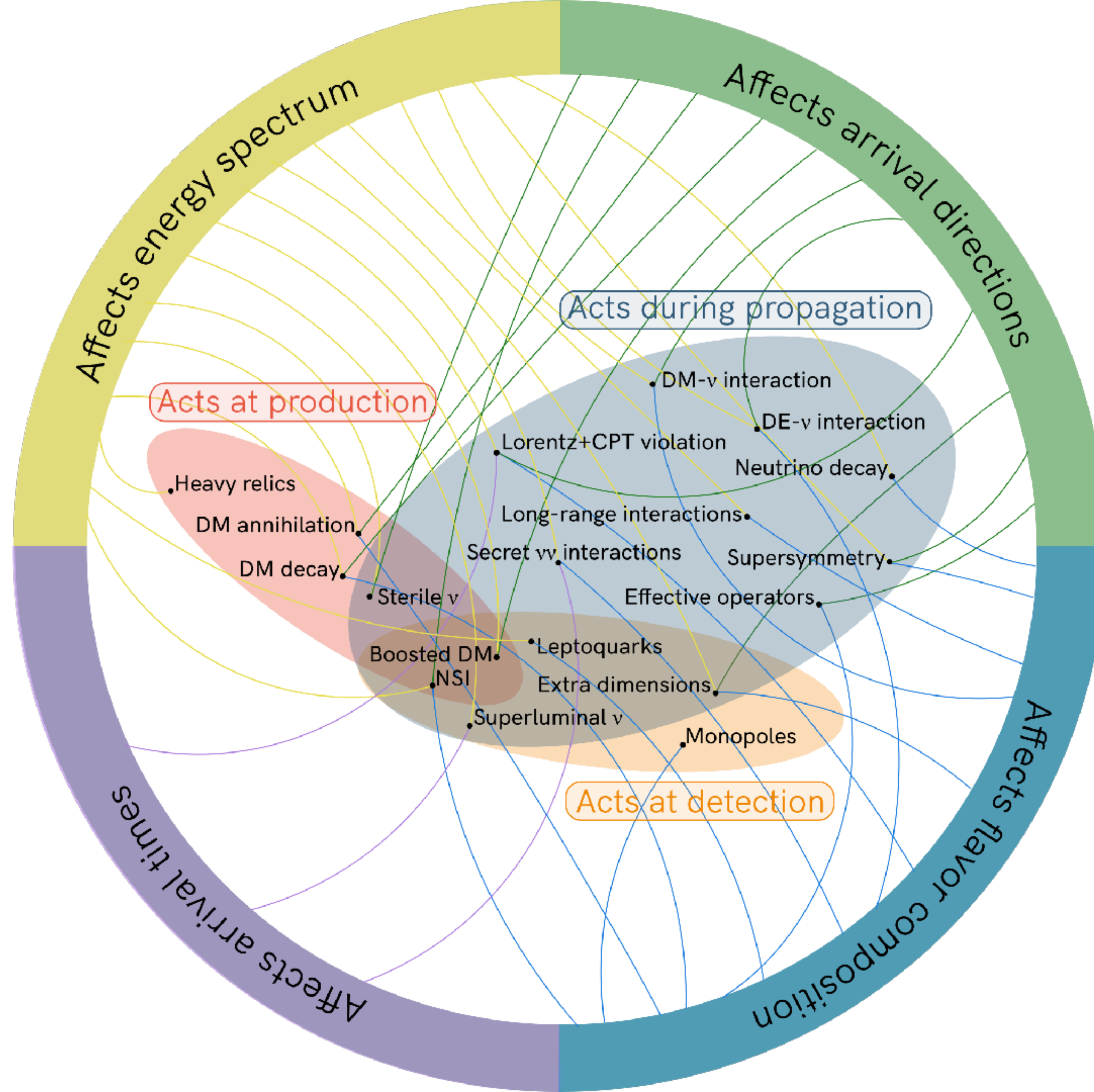






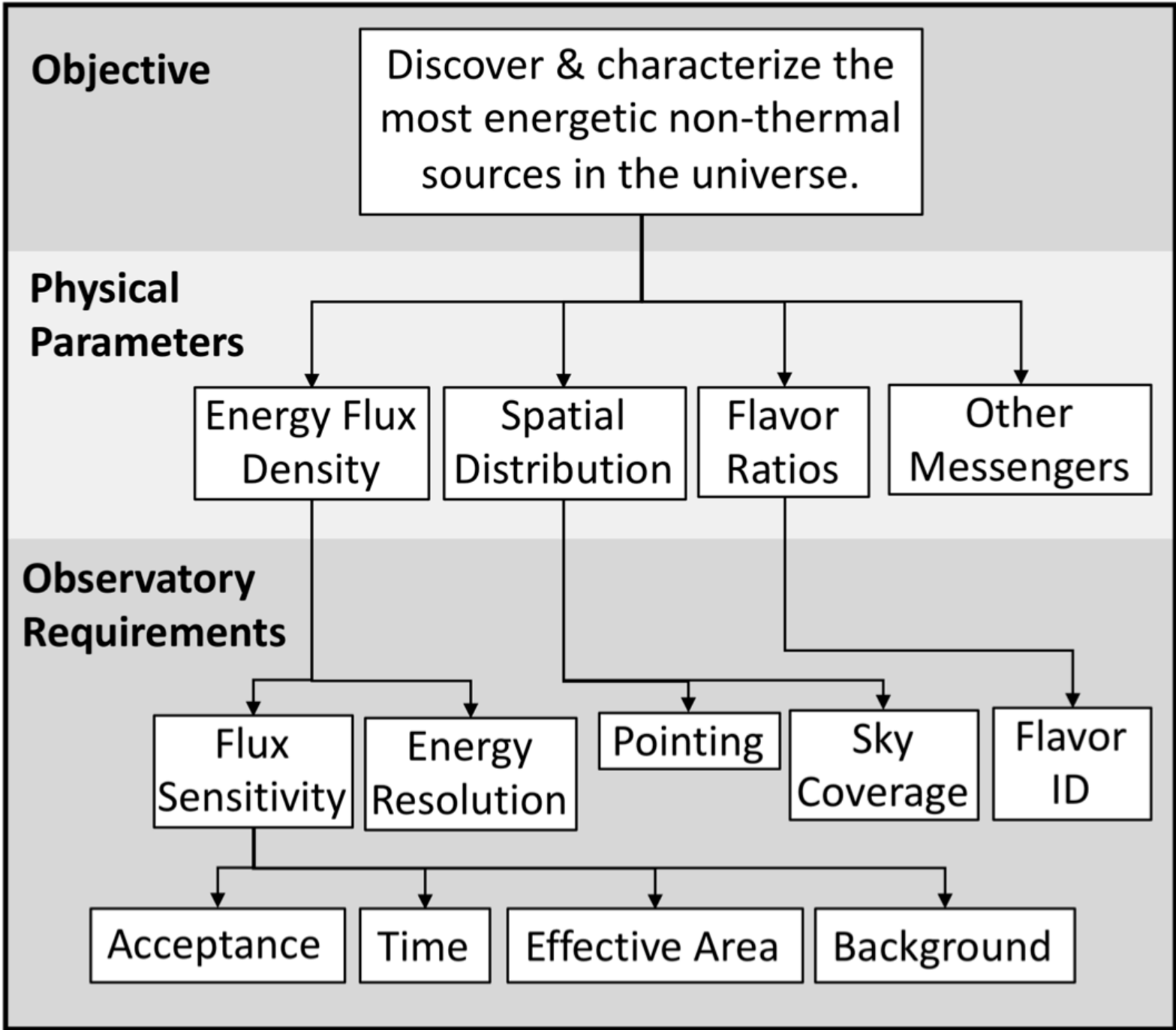
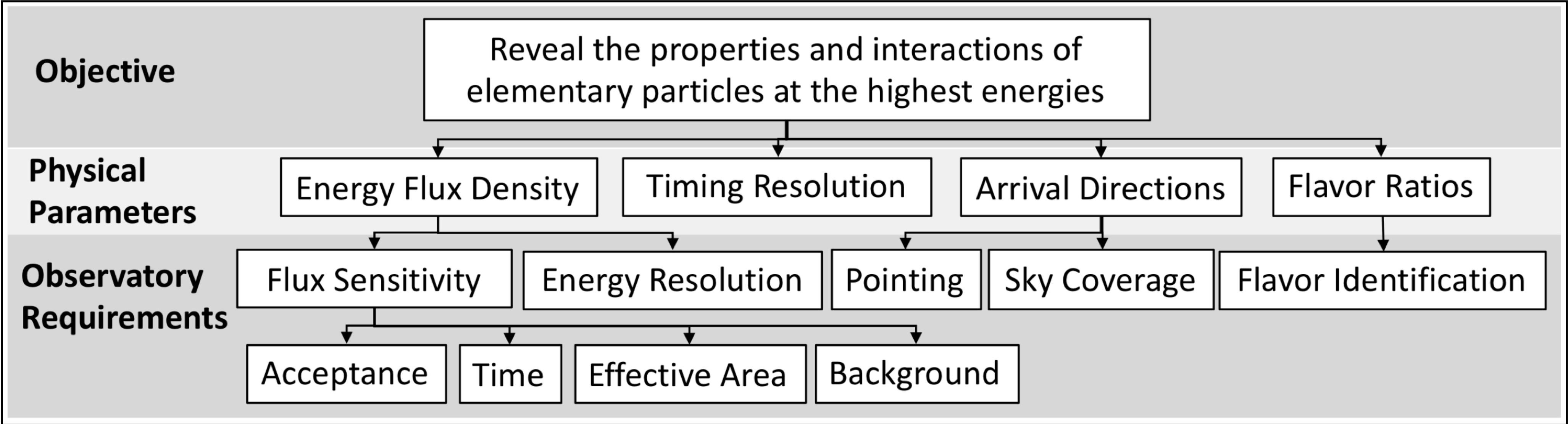






# DETECTOR GOALS FOR THE NEXT DECADE

➤ Update for Snowmass

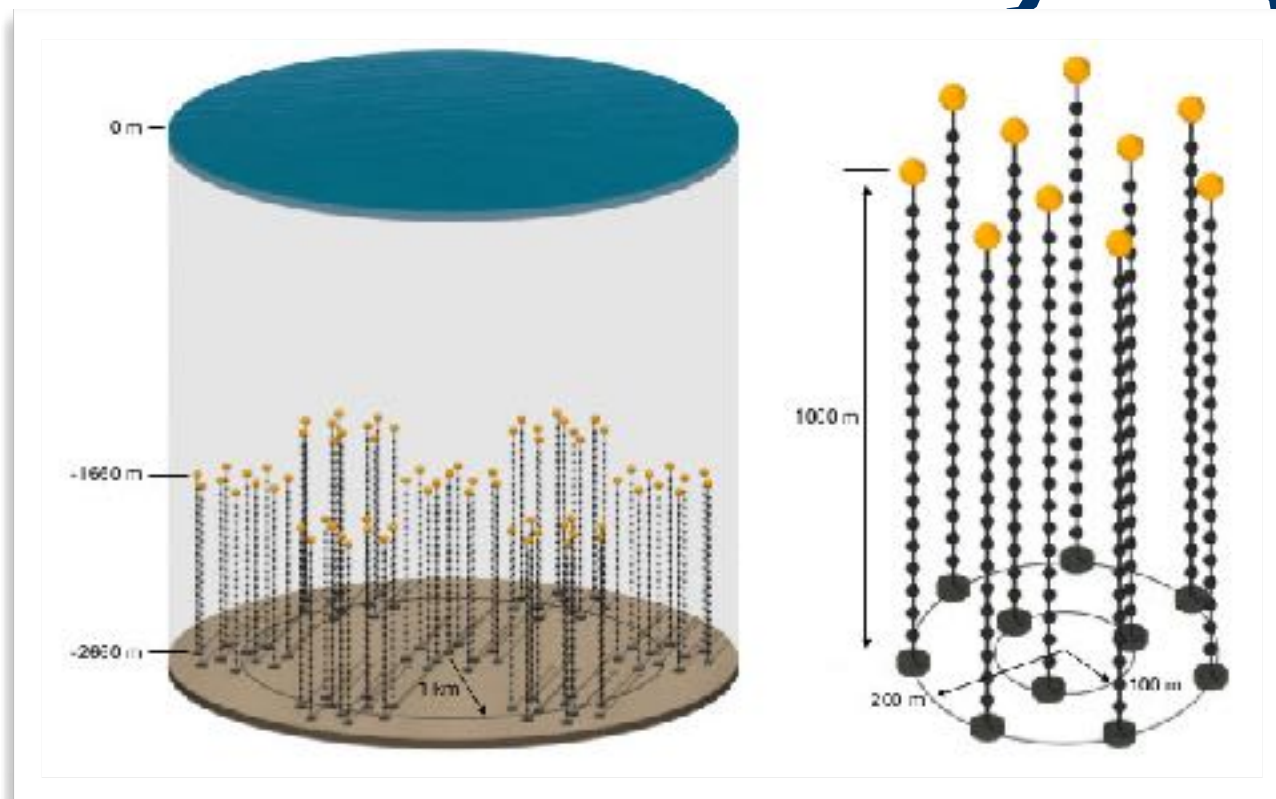


Astro2020  
[arXiv:1903.04334](https://arxiv.org/abs/1903.04334)  
[arXiv:1903.04333](https://arxiv.org/abs/1903.04333)

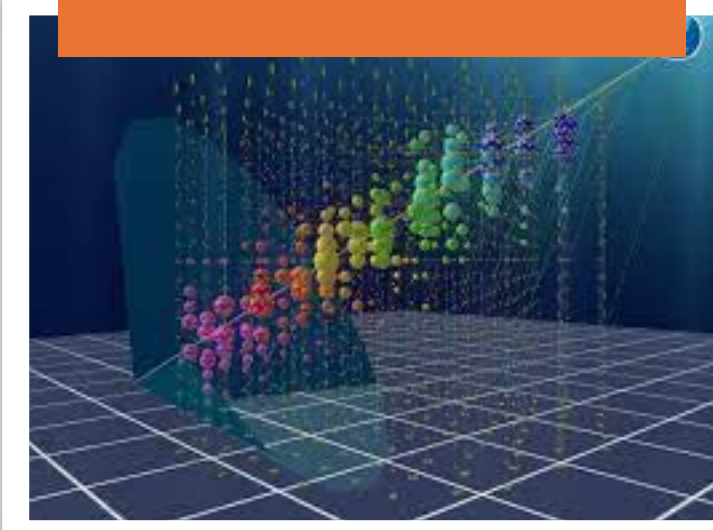


# EXPERIMENTAL LANDSCAPE: LARGE WATER CHERENKOV TELESCOPES

P-ONE



KM3Net



Baikal-GVD



IceCube





# EXPERIMENTAL LANDSCAPE: IN-ICE RADIO EXPERIMENTS

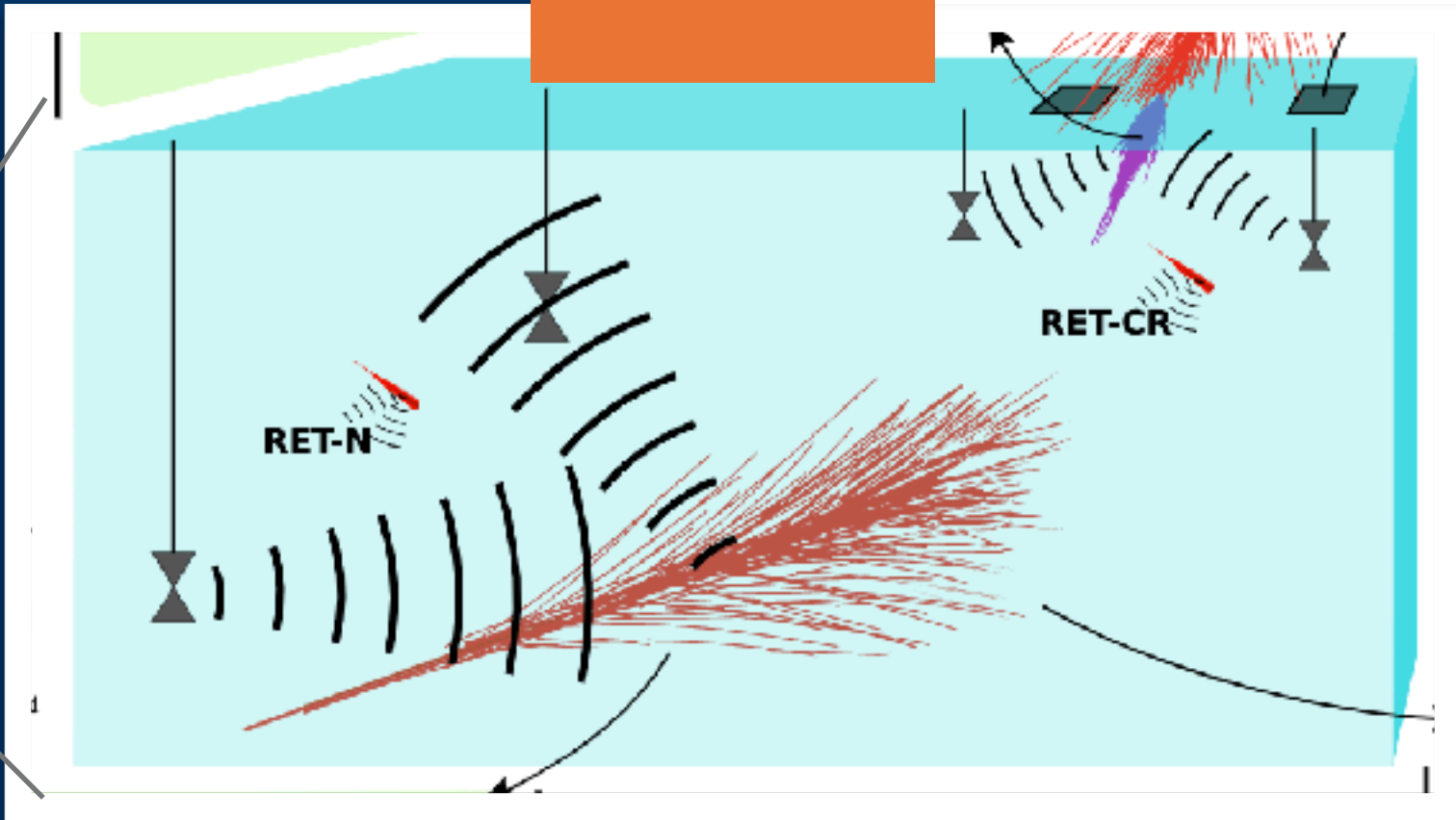
ARA at the South Pole



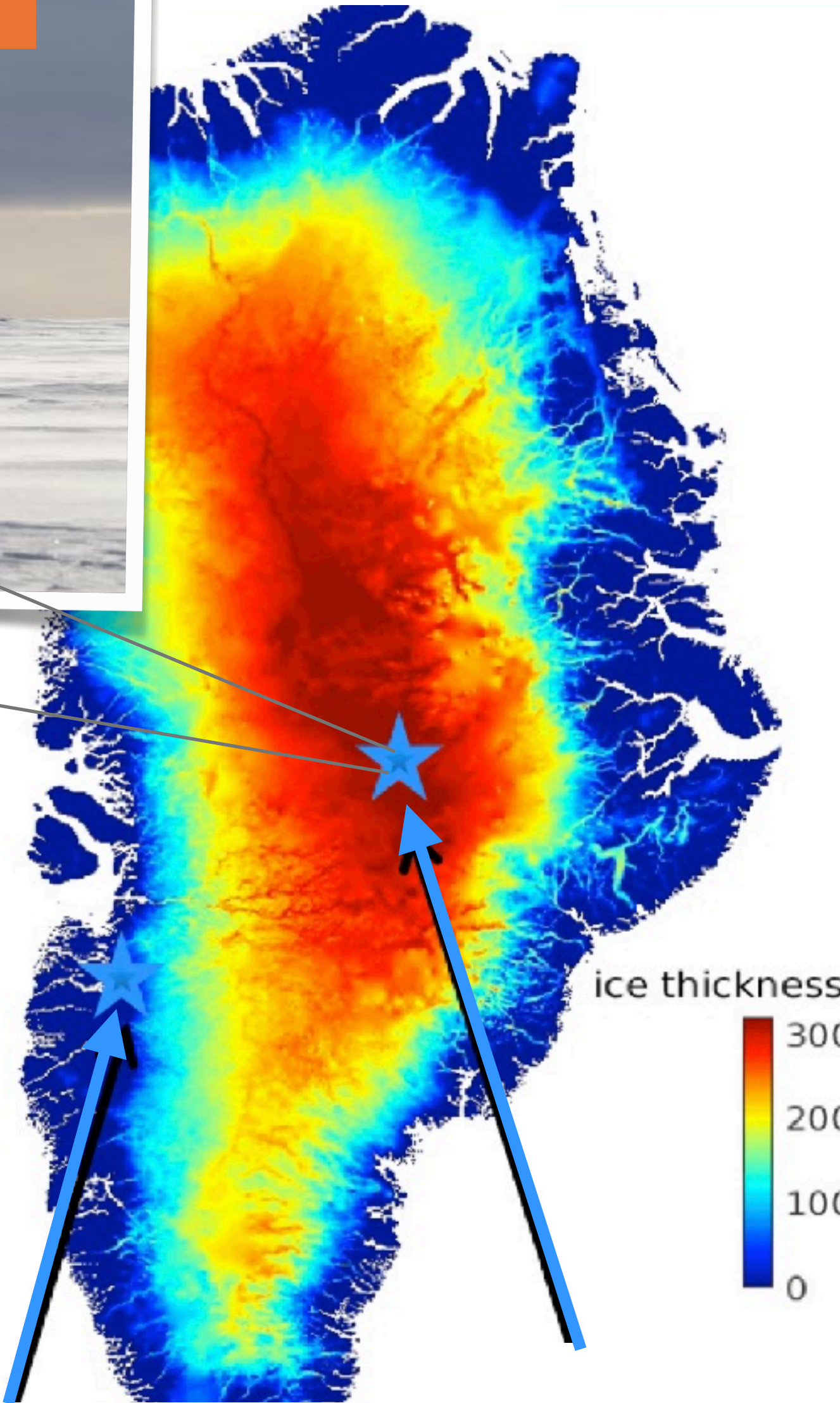
RNO-G at the South Pole



RET



ARIANNA at the Ross Ice Shelf (and the South Pole)



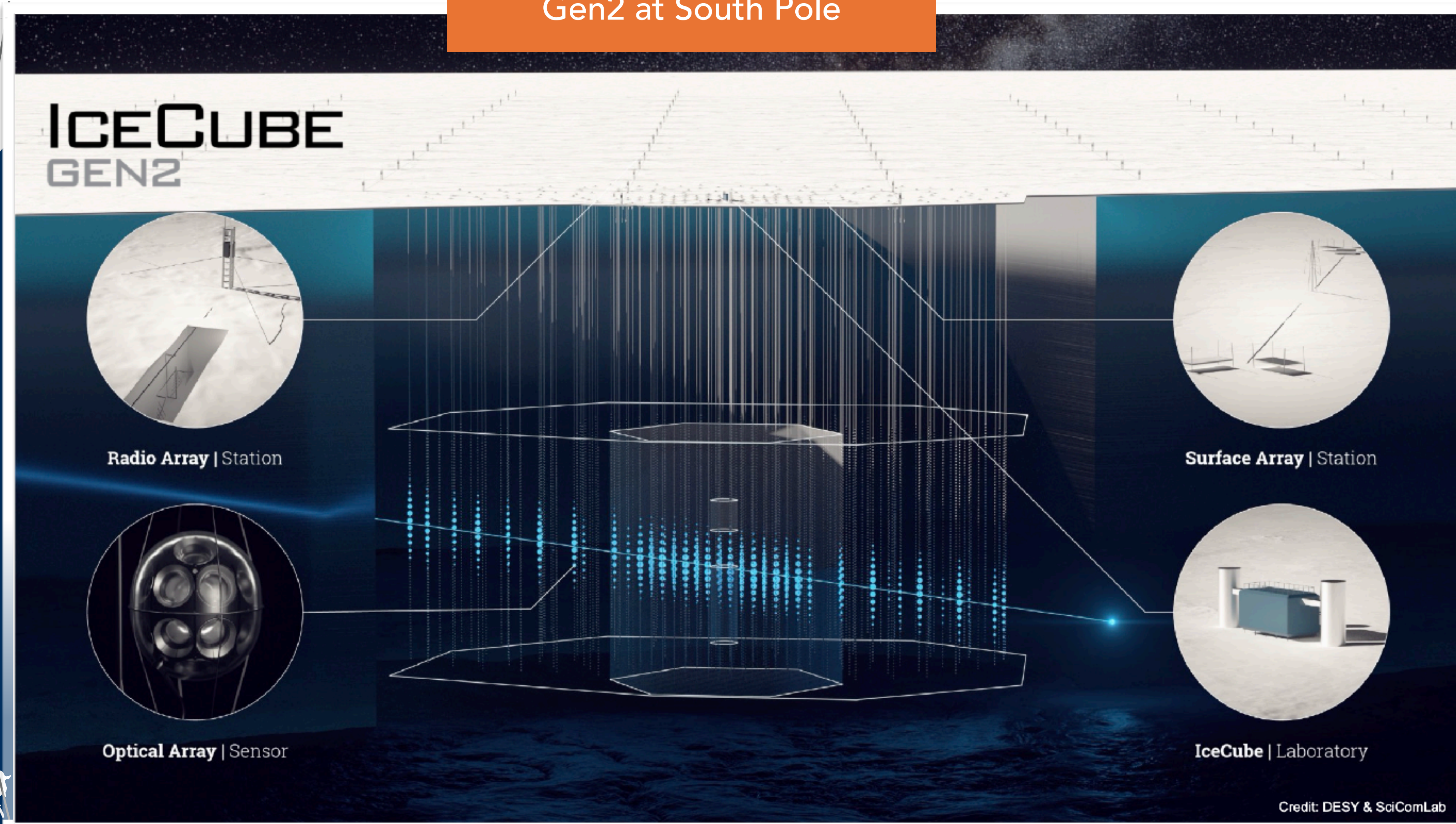
Kangerlussuaq

Summit Station



# EXPERIMENTAL LANDSCAPE: IN-ICE EXPERIMENTS

Gen2 at South Pole



Credit: DESY & SciComLab

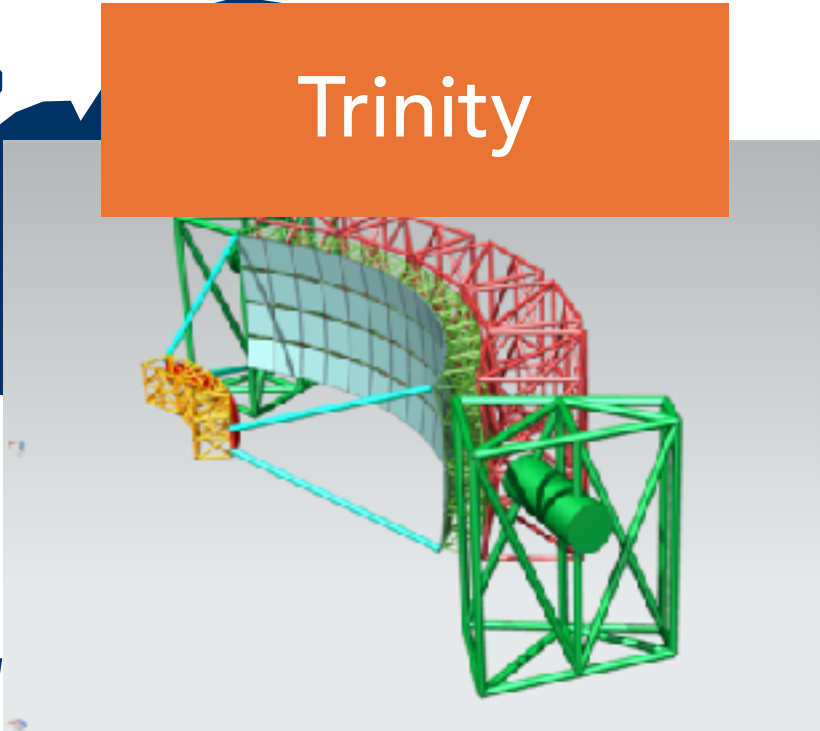


# EXPERIMENTAL LANDSCAPE: EARTH-SKIMMING TAU NEUTRINOS



BEACON

BEACON  
JCAP 2020



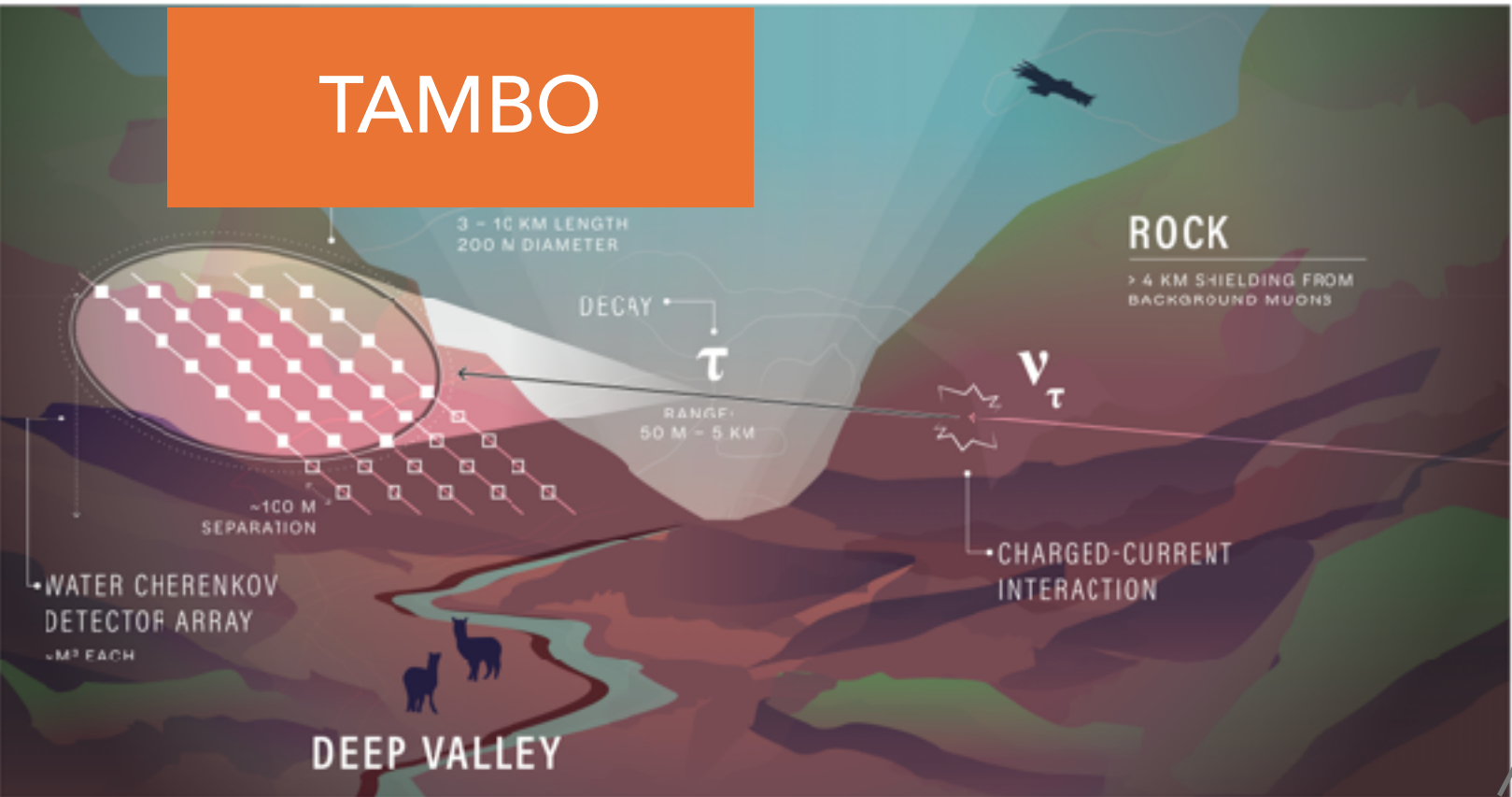
Trinity

Trinity  
Phys. Rev. D  
2019



GRAND

GRAND  
Sci. China-Phys. Mech.  
Astron. 63, 219501  
(2020)



TAMBO

TAMBO  
arXiv:2002.06475



Auger Prime



TAROGE-M

TAROGE  
Int. J. Mod. Phys  
D. 2016 &



# EXPERIMENTAL LANDSCAPE: SPACE MISSIONS





# RELATIONSHIP WITH TAU NEUTRINO WHITEPAPER

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## ➤ **Tau Neutrinos in the Next Decade: from GeV to EeV**

- Focus on tau neutrinos across a wide range of energies
  - At HE/UHE energies, many science topics and experimental techniques overlap
  - [NuTau2021 Workshop](#) in September
- 
- The HE/UHE whitepaper is broader than the tau paper in the following ways:
    - Astrophysics *and* particle physics topics
    - All flavor
  - ....but more focused on  $>\text{TeV}$  energy regime

# HOW DO I GET INVOLVED?

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- Join our slack channel: **#wp-cf07-he-uhe-nu** on [snowmass2021.slack.com](https://snowmass2021.slack.com)
  - Find instructions to join here:  
[https://snowmass21.org/#join\\_slack\\_workspace\\_and\\_snowmass\\_email\\_list](https://snowmass21.org/#join_slack_workspace_and_snowmass_email_list)
- View-only Overleaf: <https://www.overleaf.com/read/pwcjvtxjyrvy>
- Contact the editor(s): Markus Ackermann, Mauricio Bustamante, Lu Lu, Nepomuk Otte, Mary Hall Reno, Stephanie Wissel
  - Indicate what you'd like to contribute. We will send you the editable Overleaf link
- Schedule: First draft due by Jan. 7