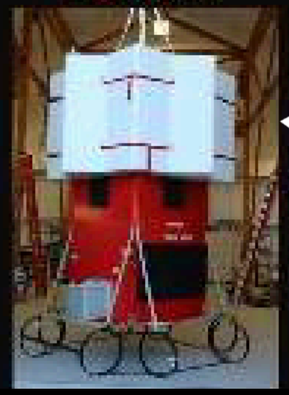
Neutrino Target-of-Opportunity Observations with EUSO-SPB2 and PBR

Tonia Venters (NASA/GSFC) for the JEM-EUSO Collaboration
TeV Particle Astrophysics 2024 | 26 August 2024

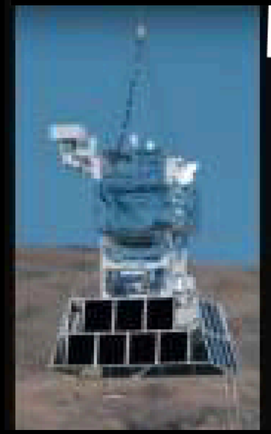
JEM-EUSO Pathway to Space

EUSO-Balloon



2014 Timmins

EUSO-SPB1



2017 Wanaka

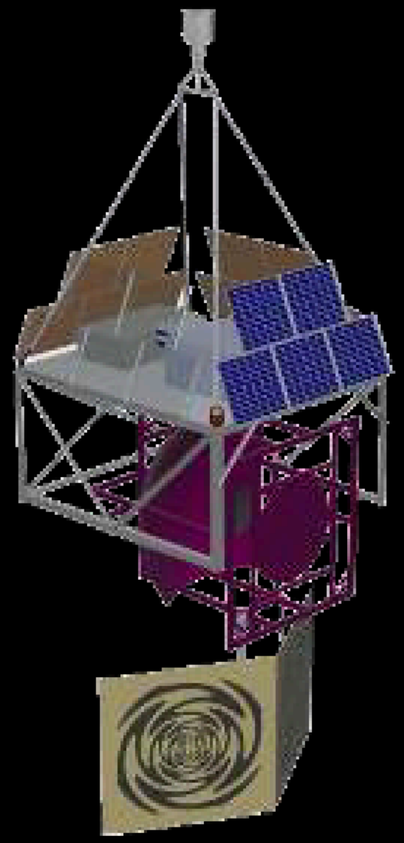
EUSO-SPB2

2023 Wanaka

MiniEUSO

2017 - present ISS

POEMMA Balloon with Radio



2027 Wanaka

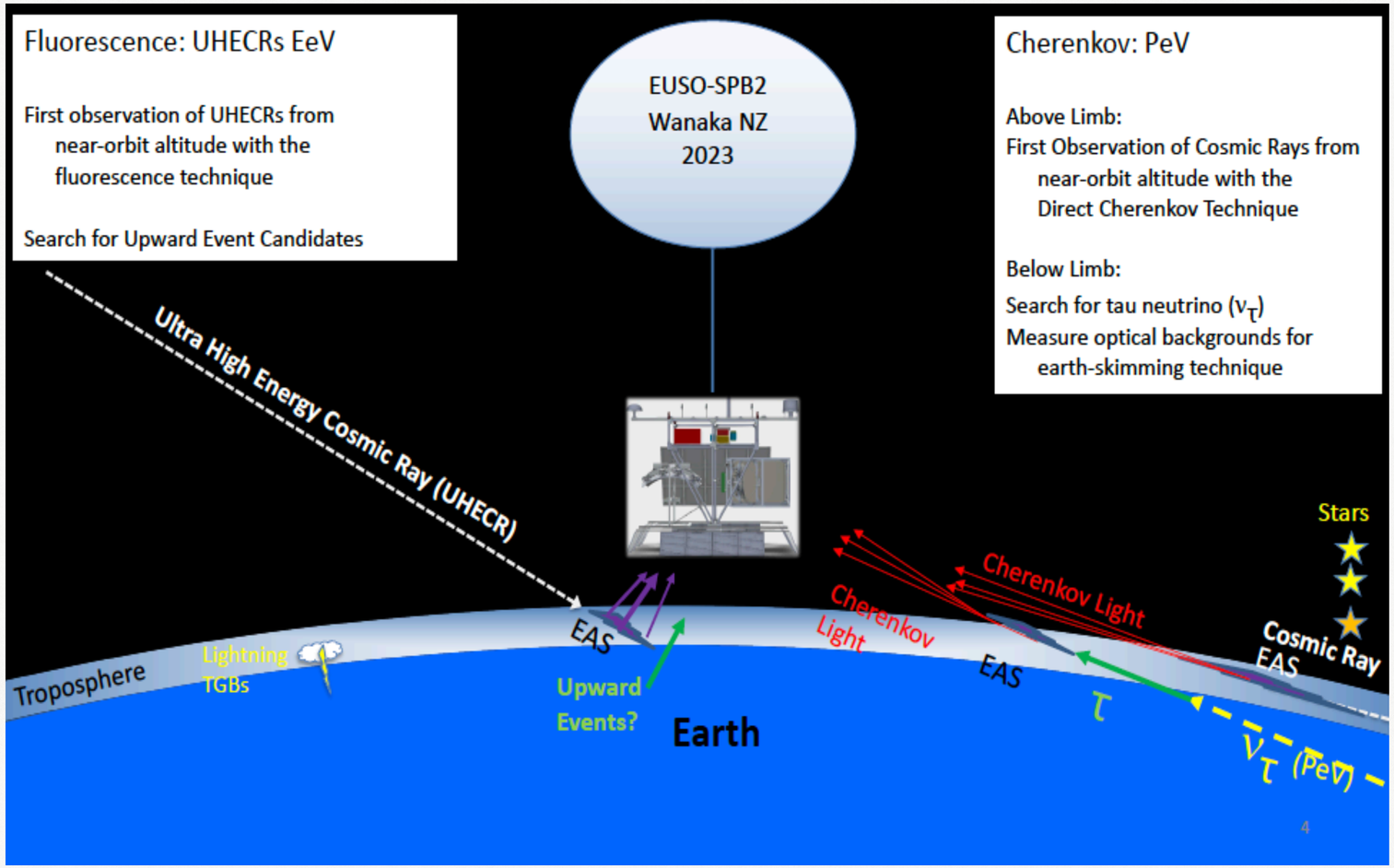
POEMMA

2030+ Earth Orbit

EUSO-SPB2

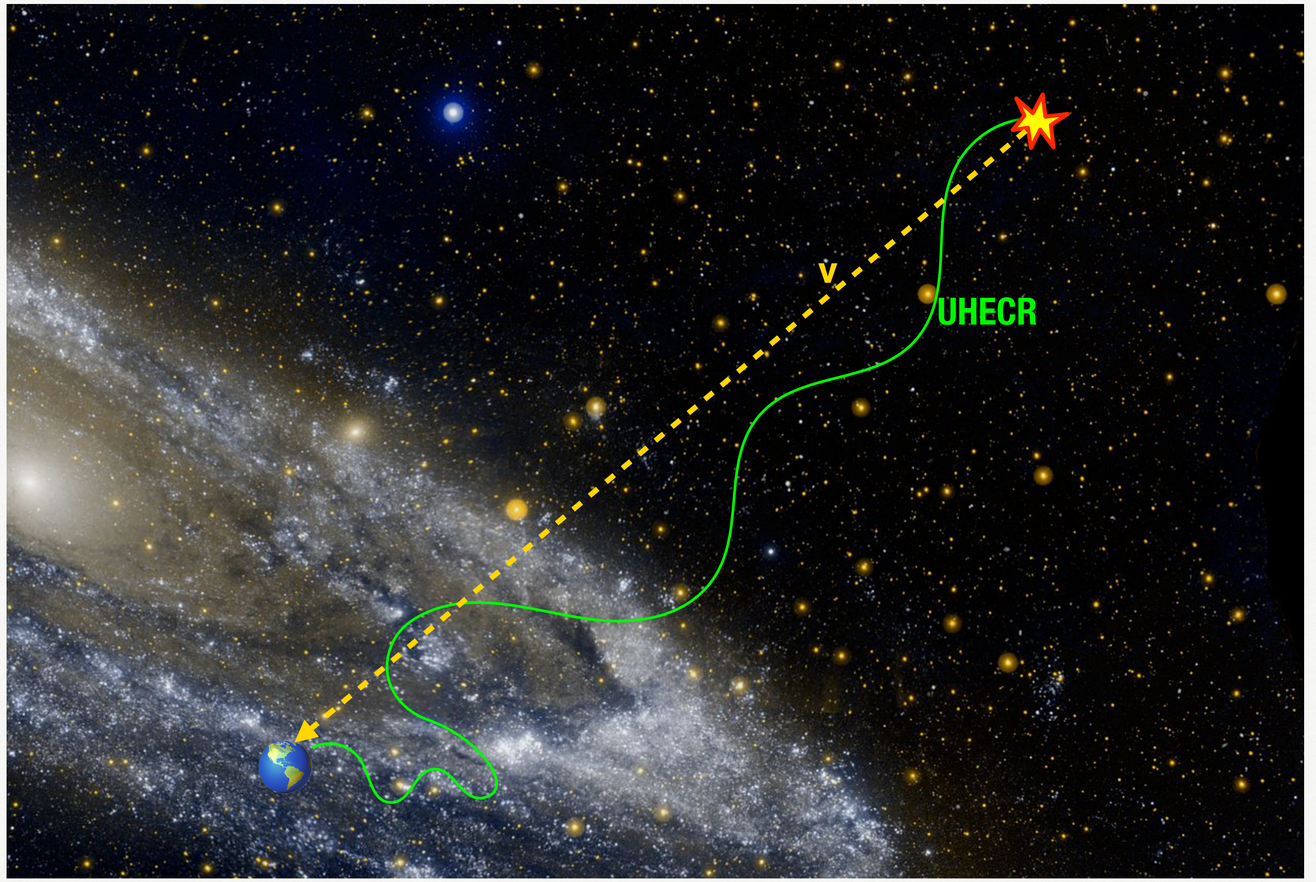
Extreme Universe Space Observatory on a Super-Pressure Balloon 2

- Launch: May 2023 from Wanaka, NZ
- Two telescopes:
  - Fluorescence telescope (FT)
  - Cherenkov telescope (CT)
- Flight time: 1 day, 12 hrs., 53 mins.
- Obs. time: 12 hrs., 55 mins.



Why Search for VHE+ Astrophysical Neutrinos?

- UHECR sources may also produce VHE and UHE vs
- EUSO-SPB2 and PBR sensitive to > PeV vs → complementarity with IceCube
- Pathfinder for future suborbital and space-based missions (e.g., POEMMA, surveyor)

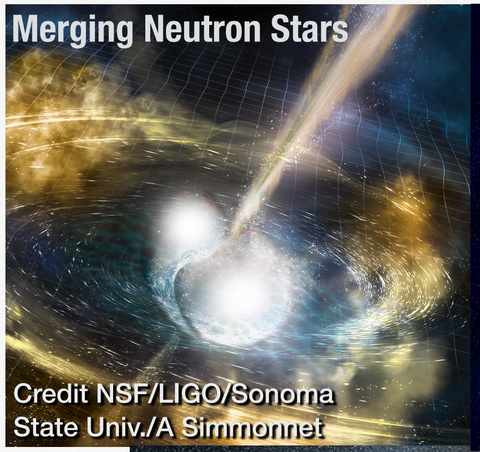


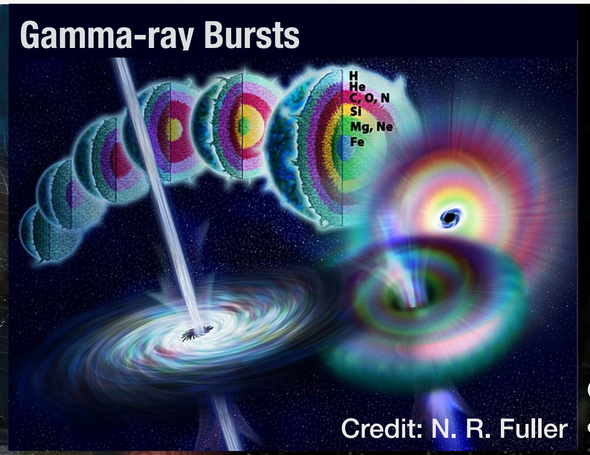
Flavor ratio at source — $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$

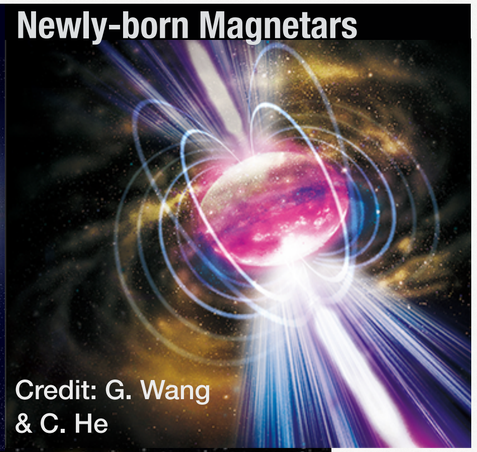
➡ ***Flavor ratio at Earth — $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$***

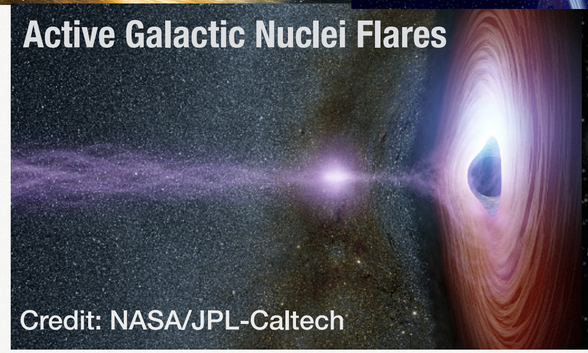
Why a Target-of-Opportunity Program?

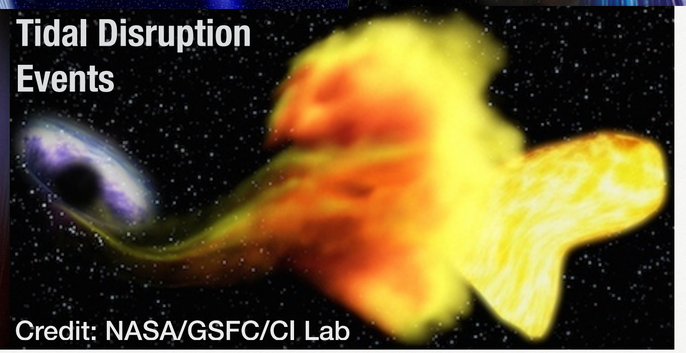
- Many candidate sources of >PeV vs exhibit transient phenomena



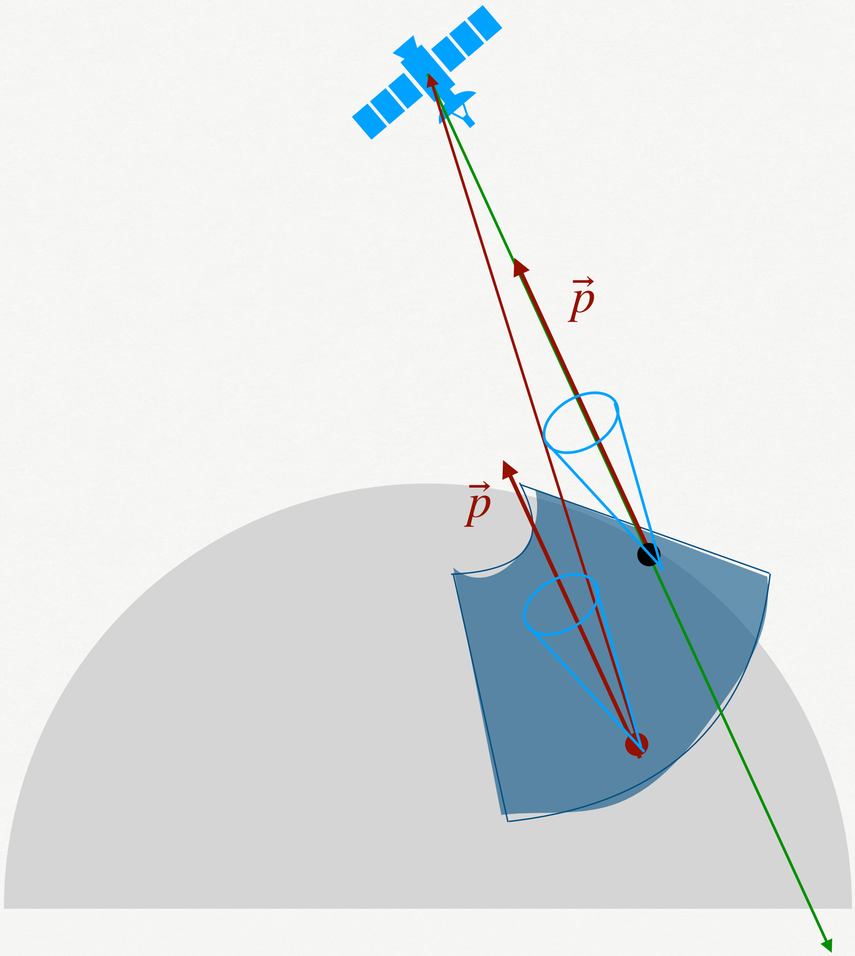


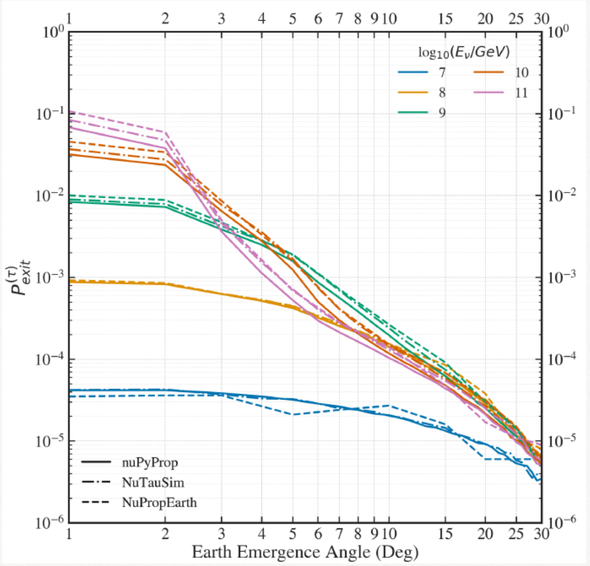


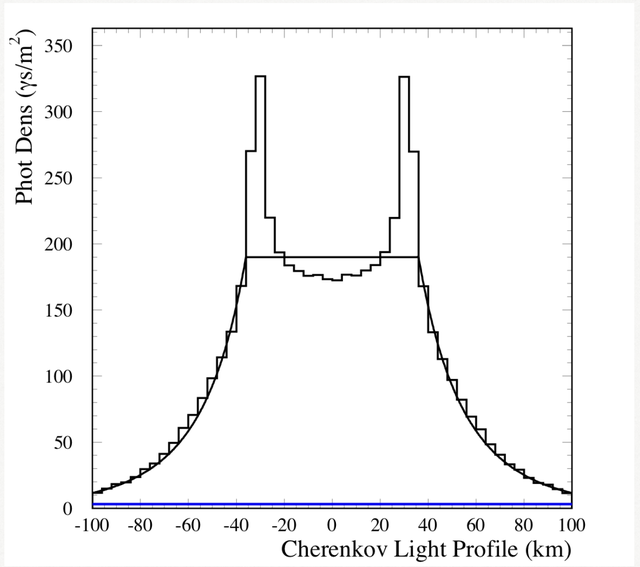




Determining ν Sensitivity to Point Sources



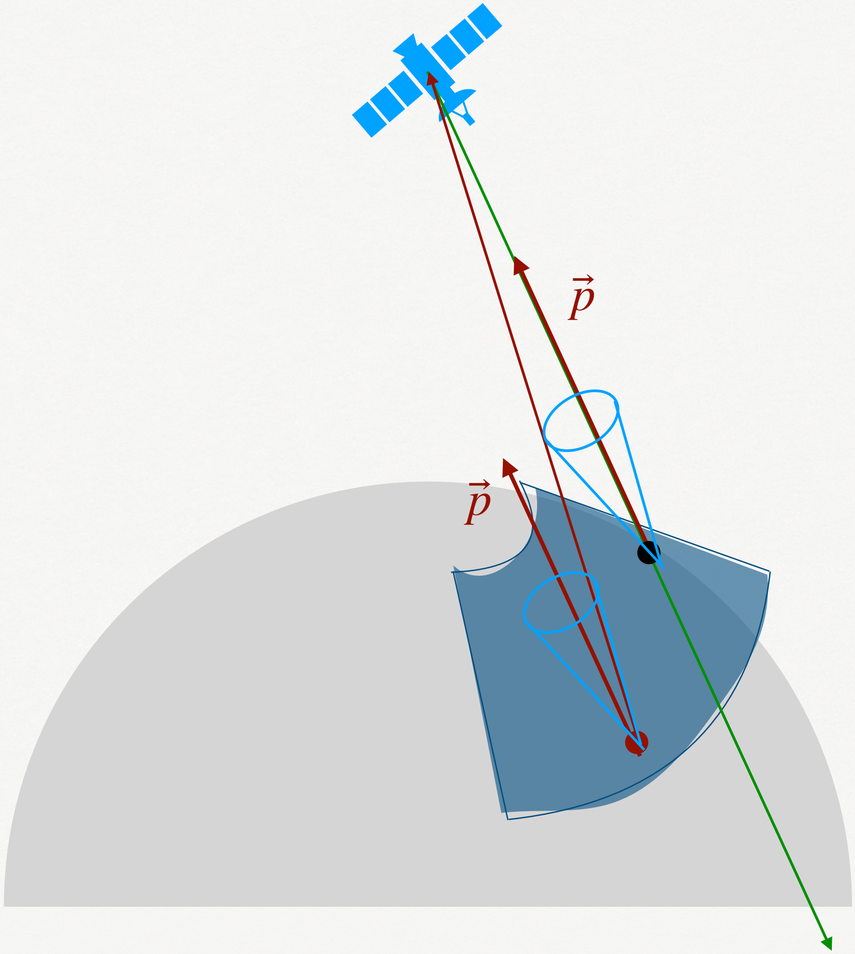


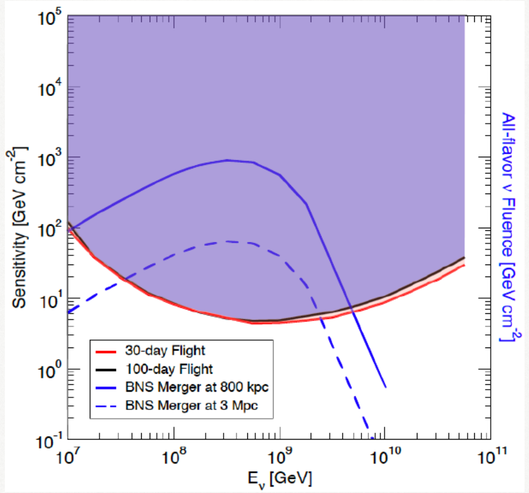


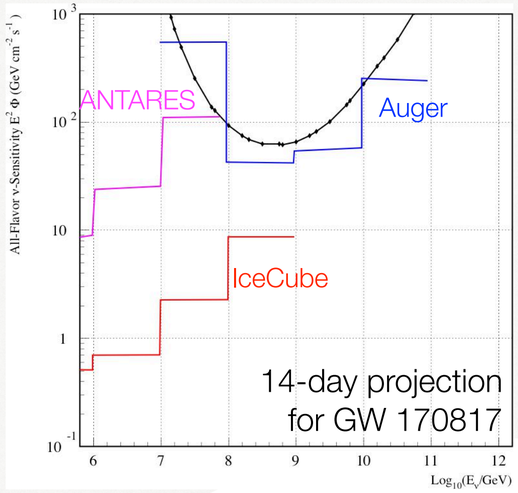
- Sample f.o.v. geometry
- Model ν_τ propagation through the Earth
- Model EAS Cherenkov signal characteristics
- Account for motion of sources in f.o.v.
- Account for Sun and Moon

Reno+ 2019, Venters+ 2020, Cummings+ 2021

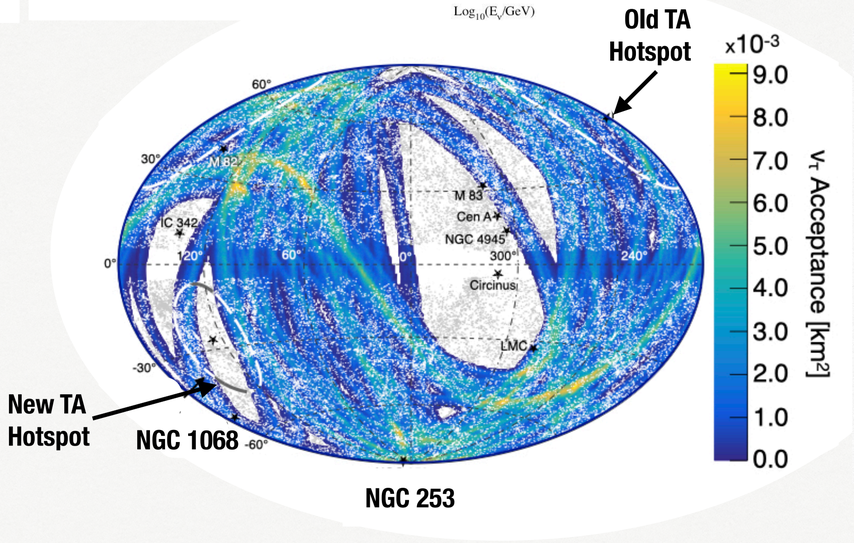
Determining ν Sensitivity to Point Sources







90% CL
all-flavor
sensitivity



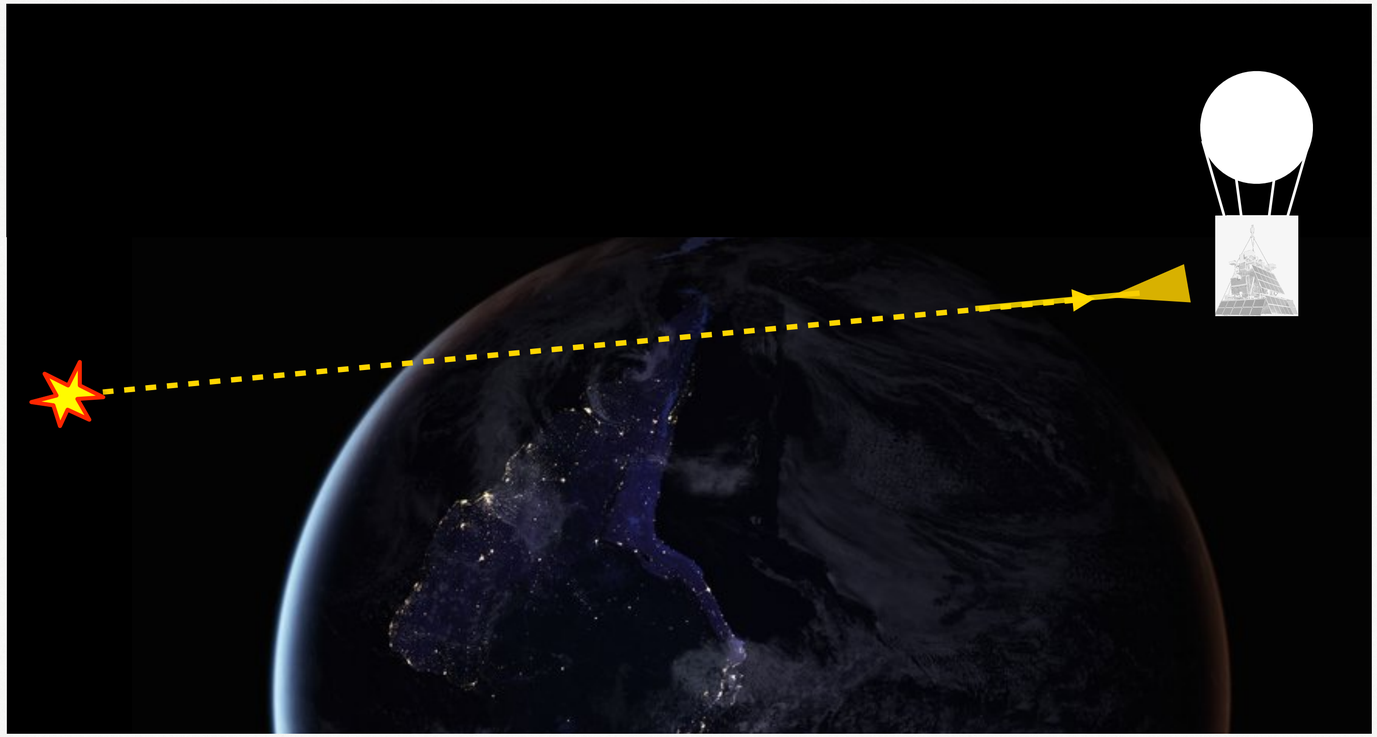
Sky Coverage

Venters+ PoS(ICRC2021), 977

Developing an Observing Strategy

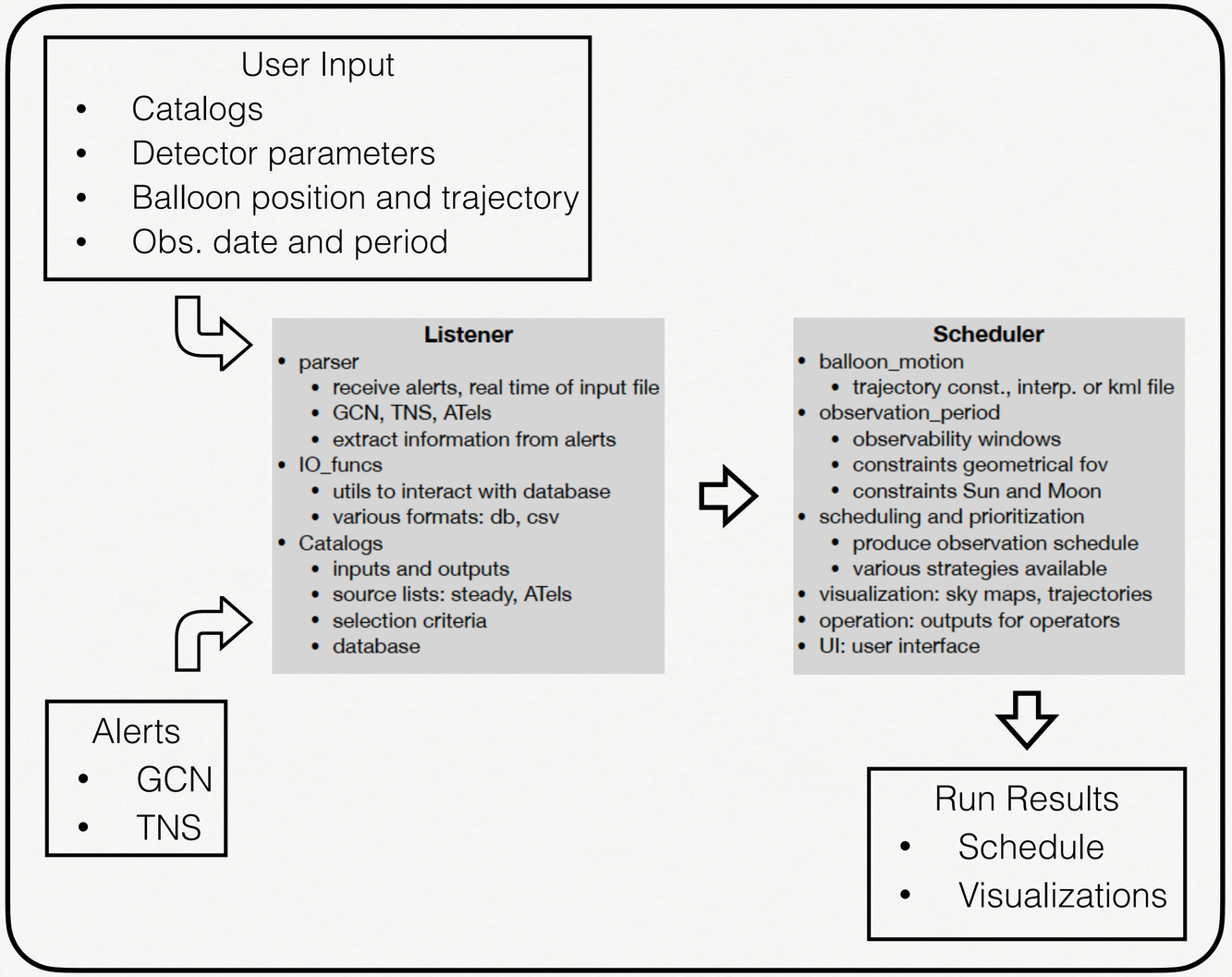
Considerations:

- Dark conditions necessary
- Observing period divided:
  - Above-the-limb pointings
  - Individual target pointings
- Telescope slew time
- Balloon location and trajectory
- Source types w/ different properties
- Realtime alerts
- Multiple sources at the same time
- Human in the loop



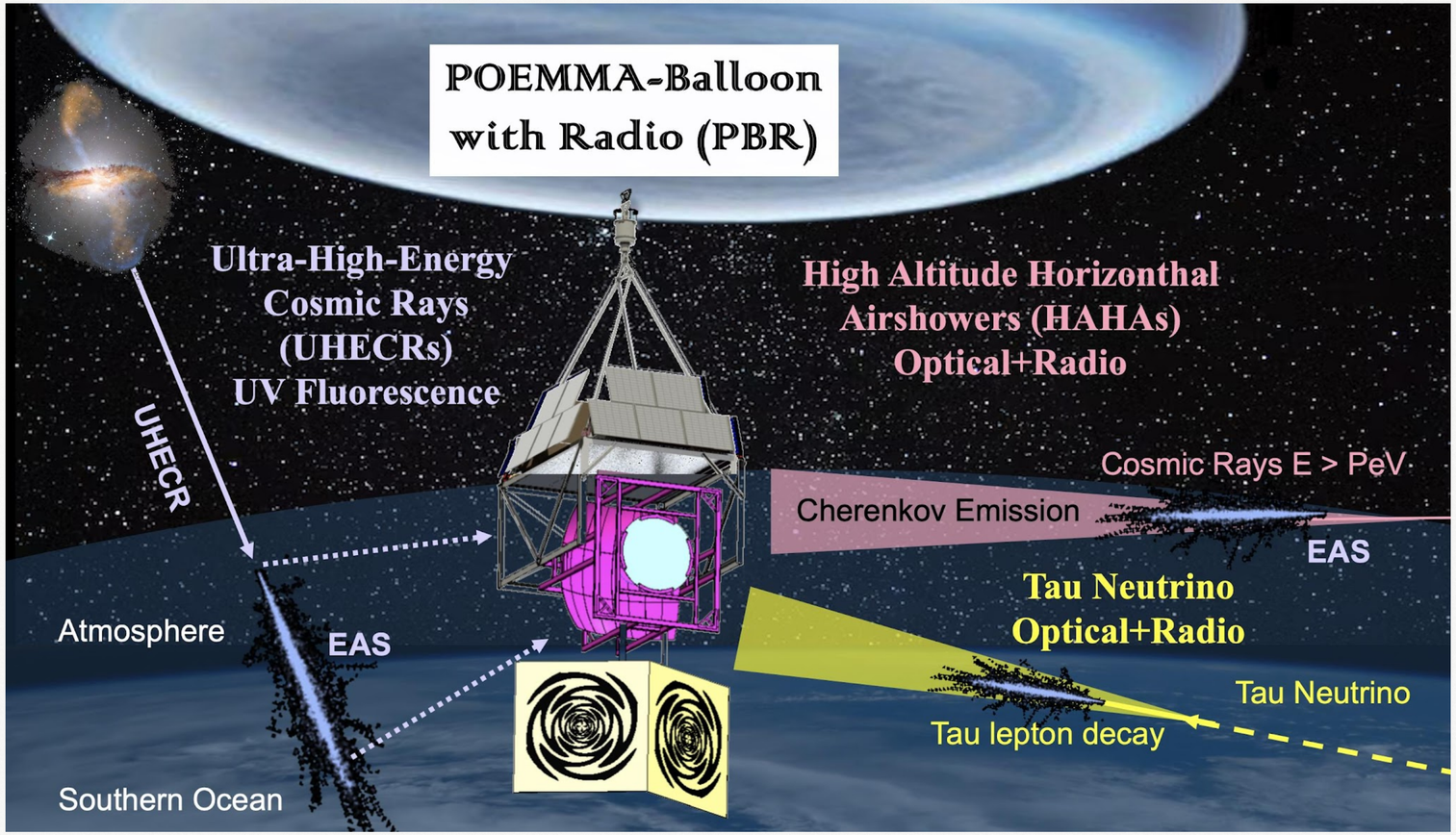
EUSO-SPB2 Observing Campaign

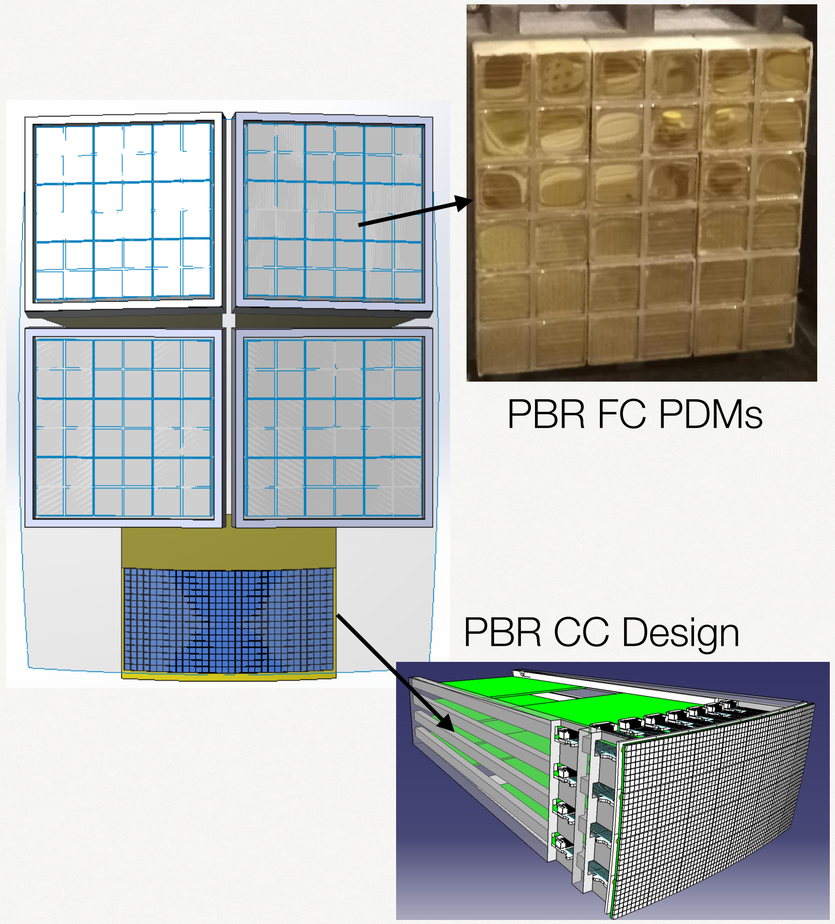
- Database of sources refreshed daily; sources obtained from:
  - Alerts (GCN, TNS, ATels)
  - Steady-source list (nearby sources and catalogs)
- Observing schedules generated based on source observability and prioritization scheme
- Prioritization motivated by:
  - Source distance
  - Observations/constraints at HEs/VHEs
  - Observability at UHEs
  - Comoving event rate densities
- Sources will be sampled from different categories (e.g., BNS mergers, TDEs, AGN flares, etc.)
- NUTS expected beta release on GitLab: end of 2024 or early 2025



Schematic of NuTargetScheduler Software

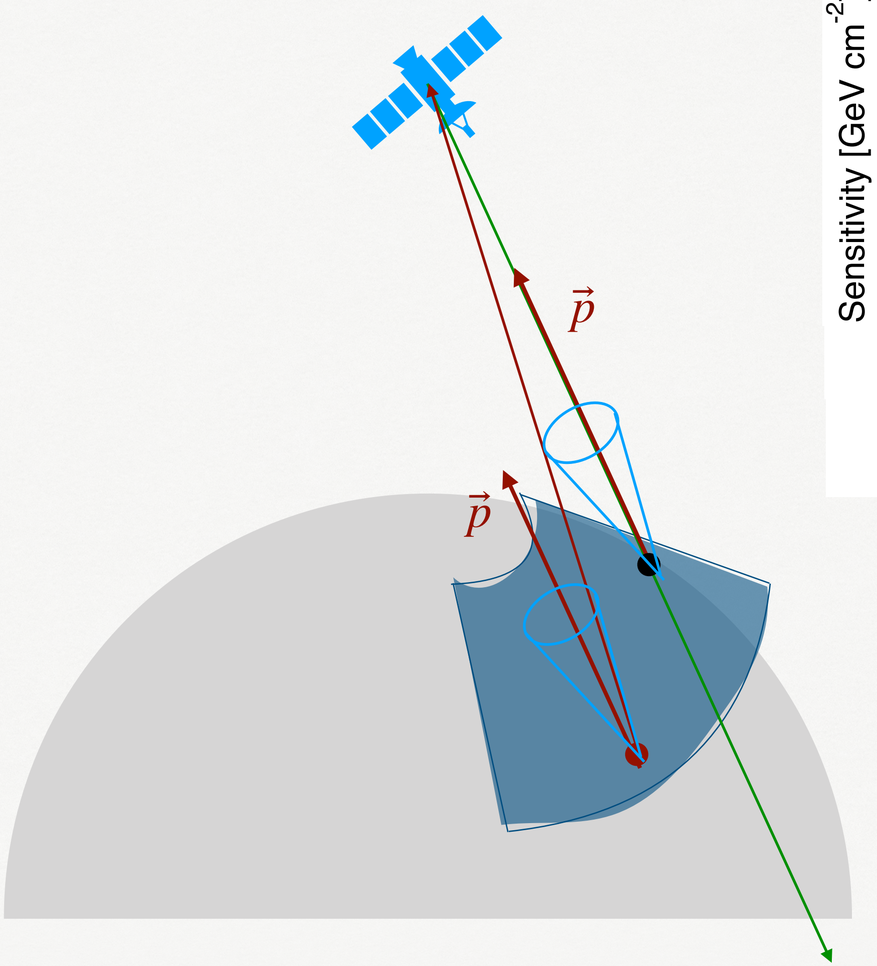
POEMMA-Balloon with Radio



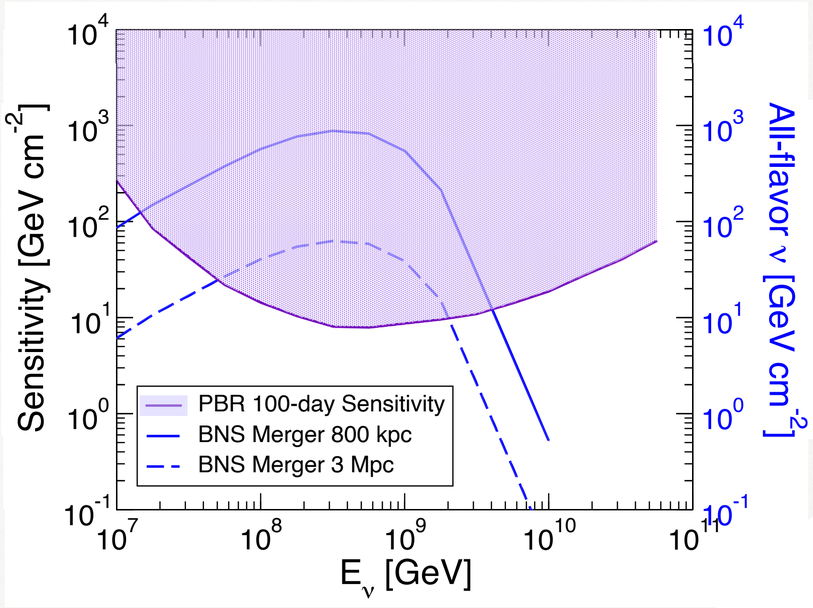


- Planned launch: Spring 2027 from Wanaka, NZ
- Fluorescence and Cherenkov detection; sensitivity to radio

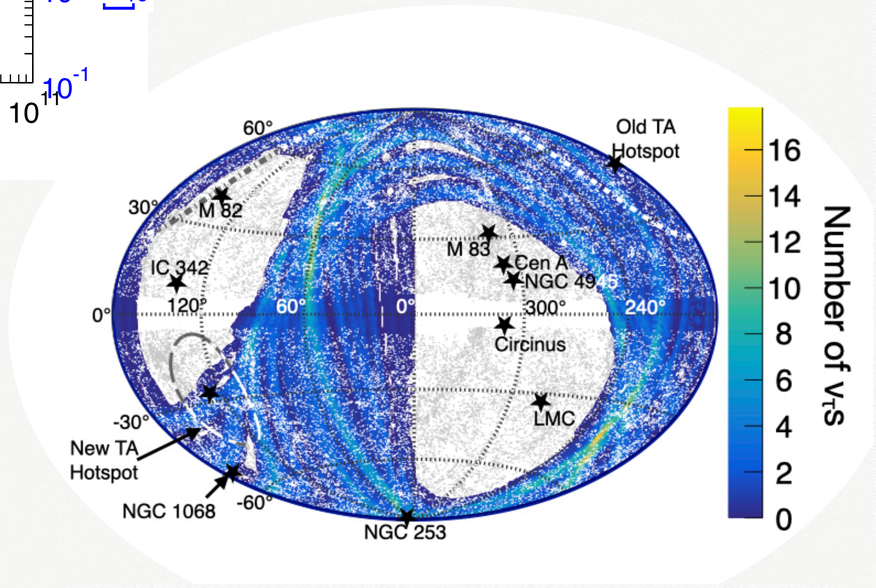
PBR ν Sensitivity to Point Sources



To distant source



Per-decade all-flavor sensitivity



Sky Coverage

Summary and Outlook

- PBR is the successor to EUSO-SPB2 and a pathfinder for future suborbital and space-based experiments devoted to UHECR and VHE ν measurements, particularly in performing ToO observations.
- In support of ToO observations, the EUSO-SPB2 science team developed an observing campaign and the NUTS software package to optimize the use of valuable observing time. Expect public beta release and journal submission later this year or early next year.
- APRA proposal for PBR accepted and funded. Design work underway, and prototyping for some parts has begun.
- Application for 2027 flight submitted.

Additional Details

- T. Venters et al. 2020, “POEMMA’s Target of Opportunity Sensitivity to Cosmic Neutrino Transient Sources”, PRD, 102, 123013
- T. Venters, “Neutrino Target-of-Opportunity Observations with Space-based and Suborbital Optical Cherenkov Detectors”, PoS(ICRC2021)977
- T. Heibges, “Overview of the EUSO-SPB2 Target of Opportunity program using the Cherenkov Telescope”, PoS(ICRC2023)1134
- J. Posligua, “Neutrino Target-of-Opportunity Sky Coverage and Scheduler for EUSO-SPB2”, PoS(ICRC2023)1038
- H. Wistrand, “The Targets of Opportunity Source Catalog for the EUSO-SPB2 Mission, PoS(ICRC2023)1184
- Upcoming publications on EUSO-SPB2 instruments and results
- NUTS journal publication in preparation

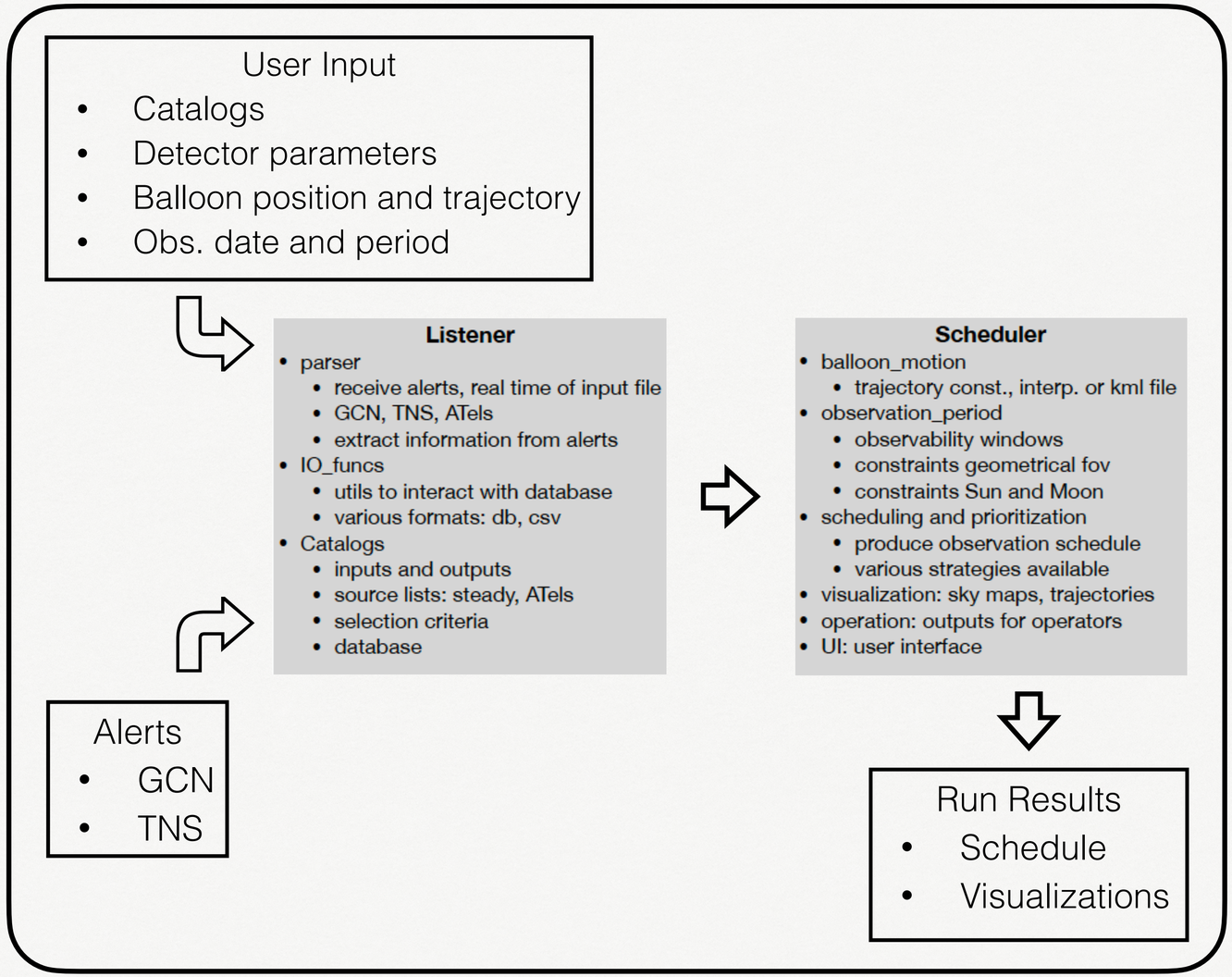
Thank you!

Backup

NuTargetScheduler (NUTS) Concept

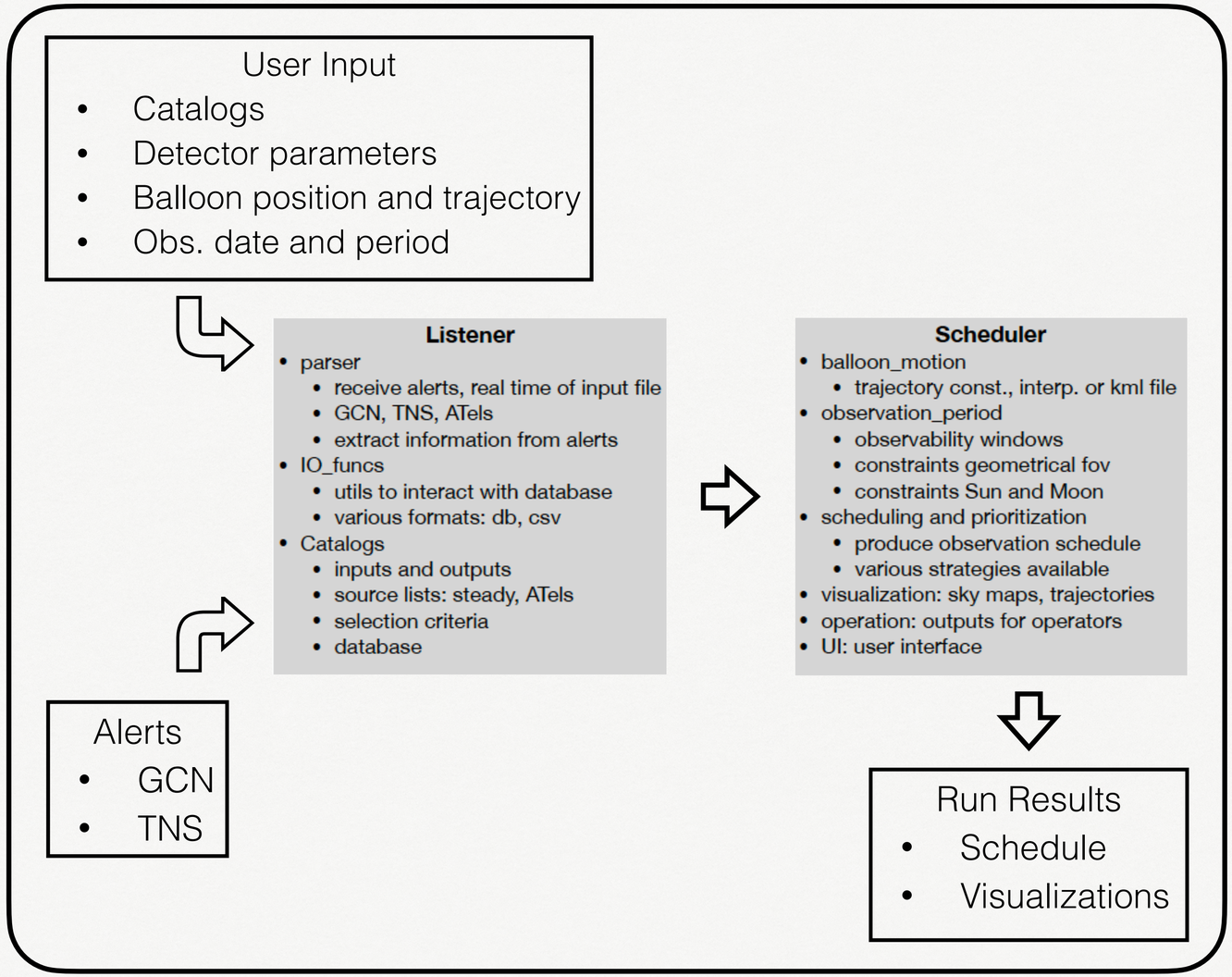
Software package to:

- Process user catalogs
- Supplement catalogs w/ alerts
- Accommodate balloon trajectory
- Account for the Sun and Moon
- Calculate observing windows
- Determine telescope pointings
- Prioritize sources
- Produce human-readable schedules



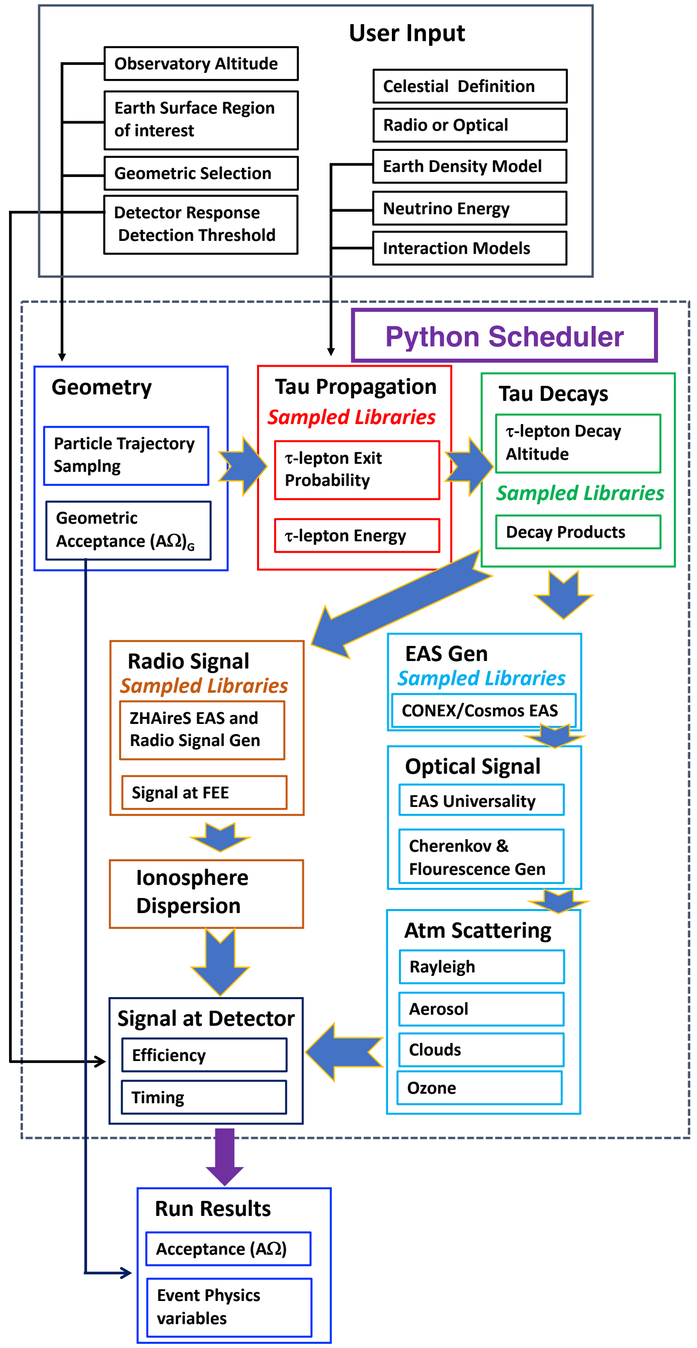
NUTS Architecture

- Language: Python
- Installation: pip
- 3rd party packages: numpy, scipy, astropy, geopandas, etc.
- Modular design
- Outputs:
  - Observing schedule (lists of sources, obs. times, pointings)
  - Visualizations
- Currently supports balloon detectors; ***let us know how we can support you!***
- Expected beta release on GitLab: end of 2024 or early 2025



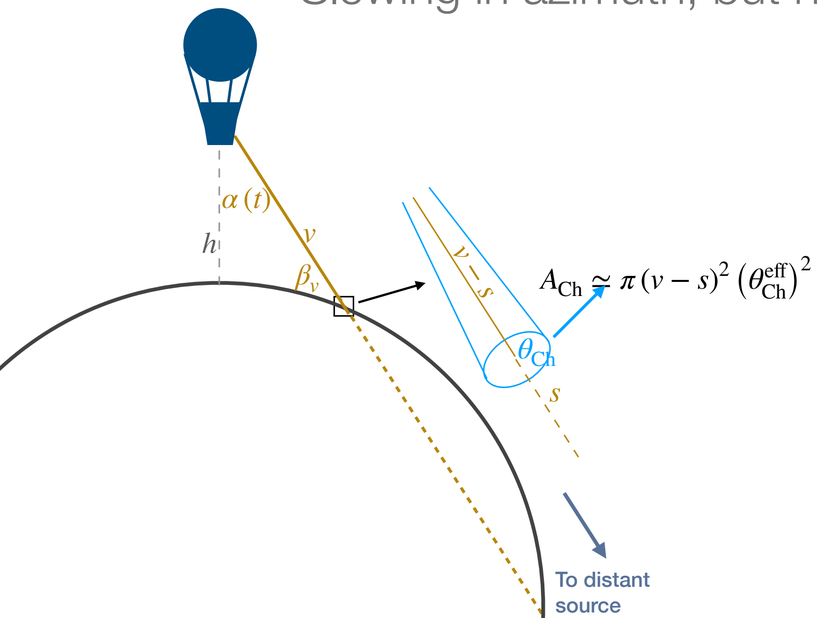
νSpaceSim

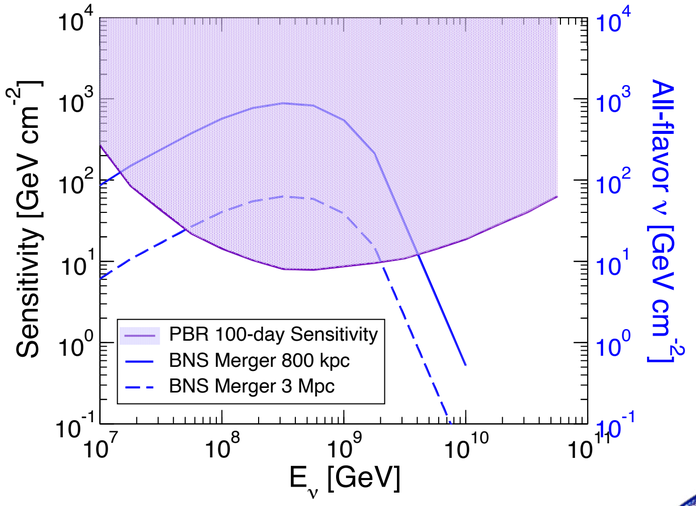
- XML user interface files
- Python wrapped modules
- Containerized distribution for Linus & MacOS
- Multi-core precessing support
- Pre-generated physics libraries (library generation code provided)
  - Neutrino propagation through the Earth (`nuPyProp`, `nuTauSim`)
  - Parameterized and simulated EAS profiles
  - Simulated Optical Cherenkov signal properties accounting for atmospheric attenuation
  - Simulated Radio signal properties (ZHAires)
  - Cloud and aerosol data from MERRA-2
- Event-by-event data output in FITS and HDF5 formats
- NASA HEASARC host site

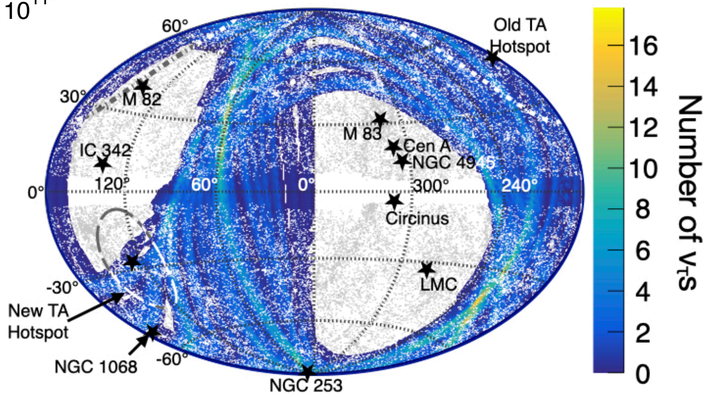


Recap of Theoretical Calculations

- Calculate ν_τ acceptance
- Leverage ν_τ propagation studies
- Account for Sun and Moon
- Assumptions:
  - Balloon trajectory from hist. wind patterns
  - Slewing in azimuth, but not in nadir

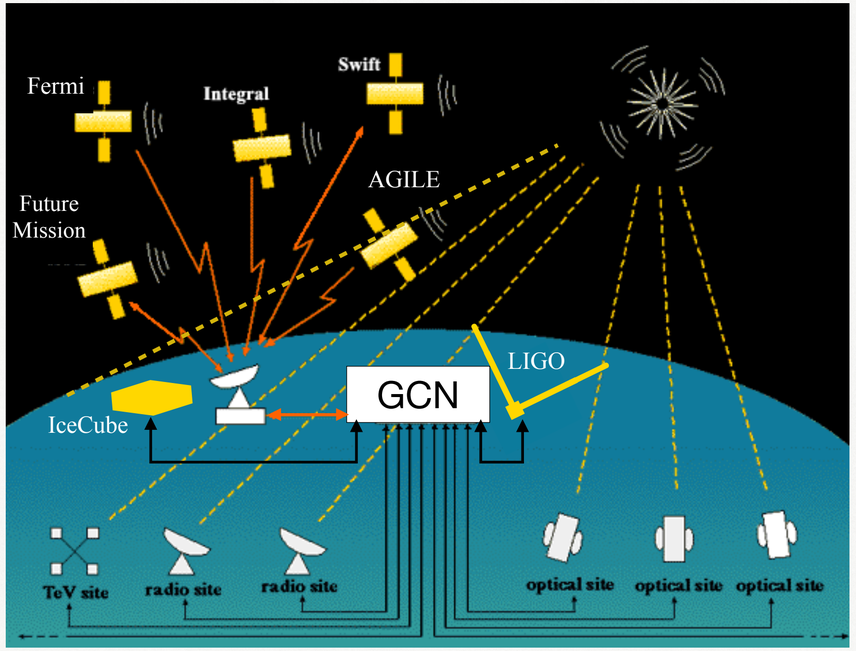


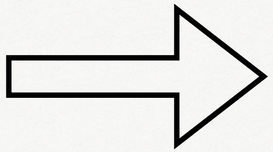




- Per decade all-flavor sensitivity
- 90% upper limit (no background -> 2.44 events)
- Muon showers excluded ($B_{shr} \simeq 83\%$)

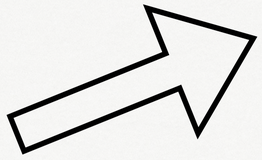
Catalog Support



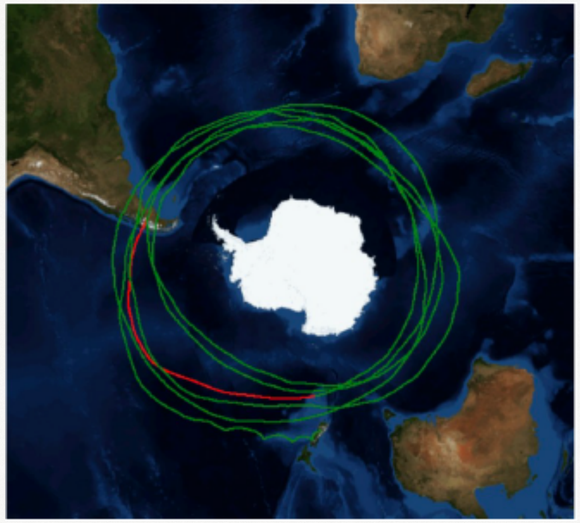


Listener

- parser
  - receive alerts, real time of input file
  - GCN, TNS, ATels
  - extract information from alerts
- IO_funcs
  - utils to interact with database
  - various formats: db, csv
- Catalogs
  - inputs and outputs
  - source lists: steady, ATels
  - selection criteria
  - database

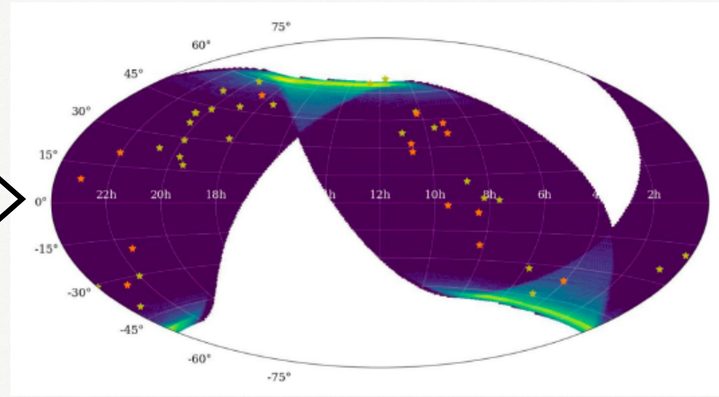


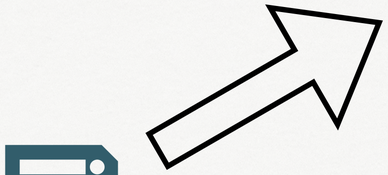
Geometry, Pointing, and Observation Time



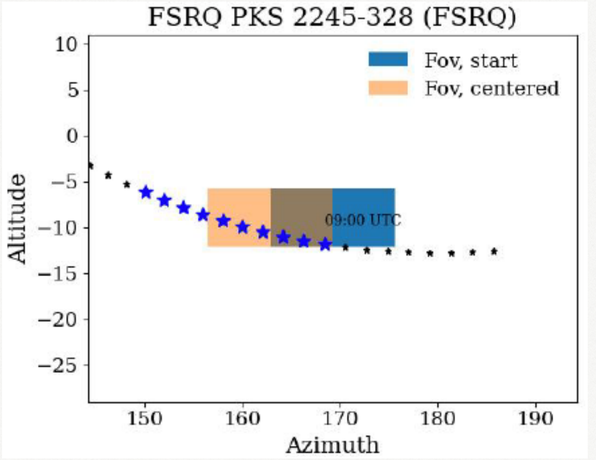
Scheduler

- balloon_motion
  - trajectory const., interp. or kml file
- observation_period
  - observability windows
  - constraints geometrical fov
  - constraints Sun and Moon
- scheduling and prioritization
  - produce observation schedule
  - various strategies available
- visualization: sky maps, trajectories
- operation: outputs for operators
- UI: user interface



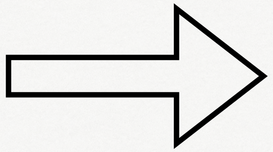


Catlog



Prioritization

Source Type	Priority
Galactic supernovae	1
Binary neutron star mergers	2
Tidal disruption events	3
Flaring blazar or active galactic nuclei	4
Gamma-ray bursts	5
Supernovae outside of the galaxy	6
Other transients	7
Steady sources	8



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Observing Schedule

Scheduler

- balloon_motion
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  - produce observation schedule
  - various strategies available
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- operation: outputs for operators
- UI: user interface

⇨

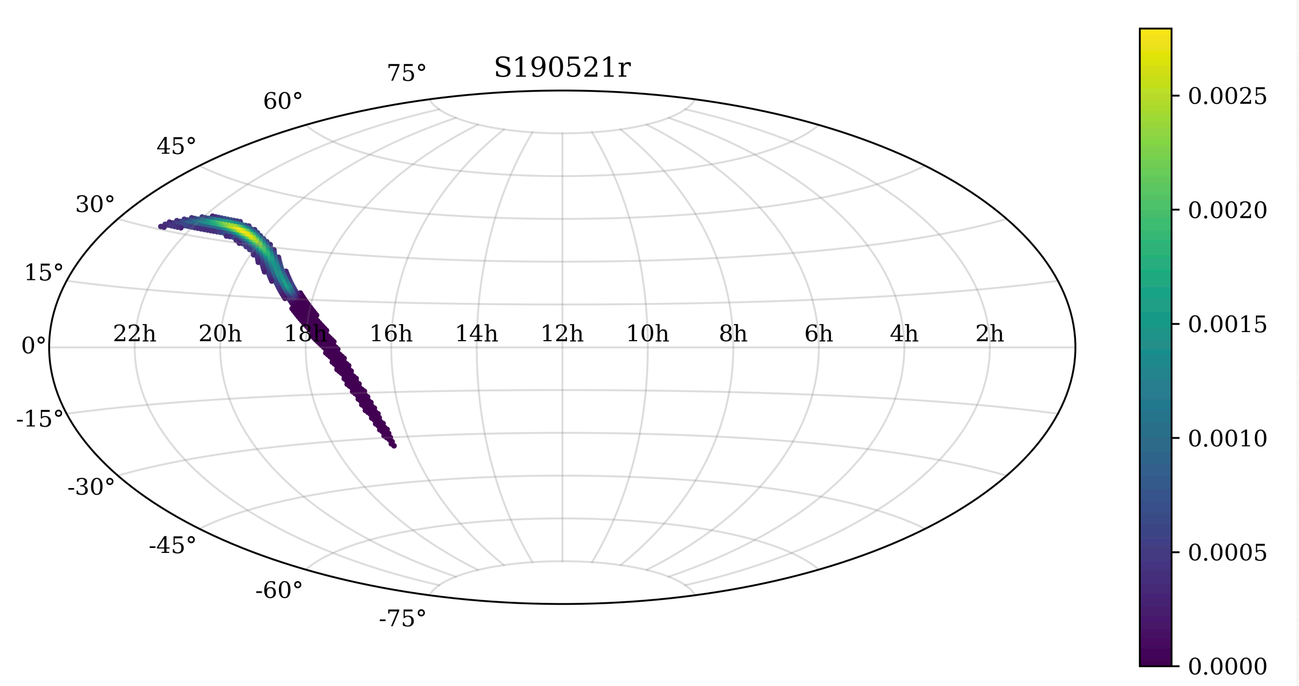
Source type, name	Pointing (az)	Move time	Start time	End time
AGN, SDSS J102906.69+555625.2	47.19°	05:00	05:10	05:30
Steady FRB, FRB 20181119A	6.23°	05:30	05:40	06:10
SN II, SN 2023ftg	81.76°	06:10	06:20	06:50
AGN, 4FGL J0910.0+4257	315.96°	07:50	08:00	08:40
GRB, GRB230503A	187.66°	09:10	09:20	10:40

Sample schedule from Wistrand et al., PoS(ICRC2023), 1185

Current and Future Development

Functionality to support:

- Poorly-localized sources
- Support for nuSpaceSim
- Additional detector types
- Anything else? Ideas welcome!



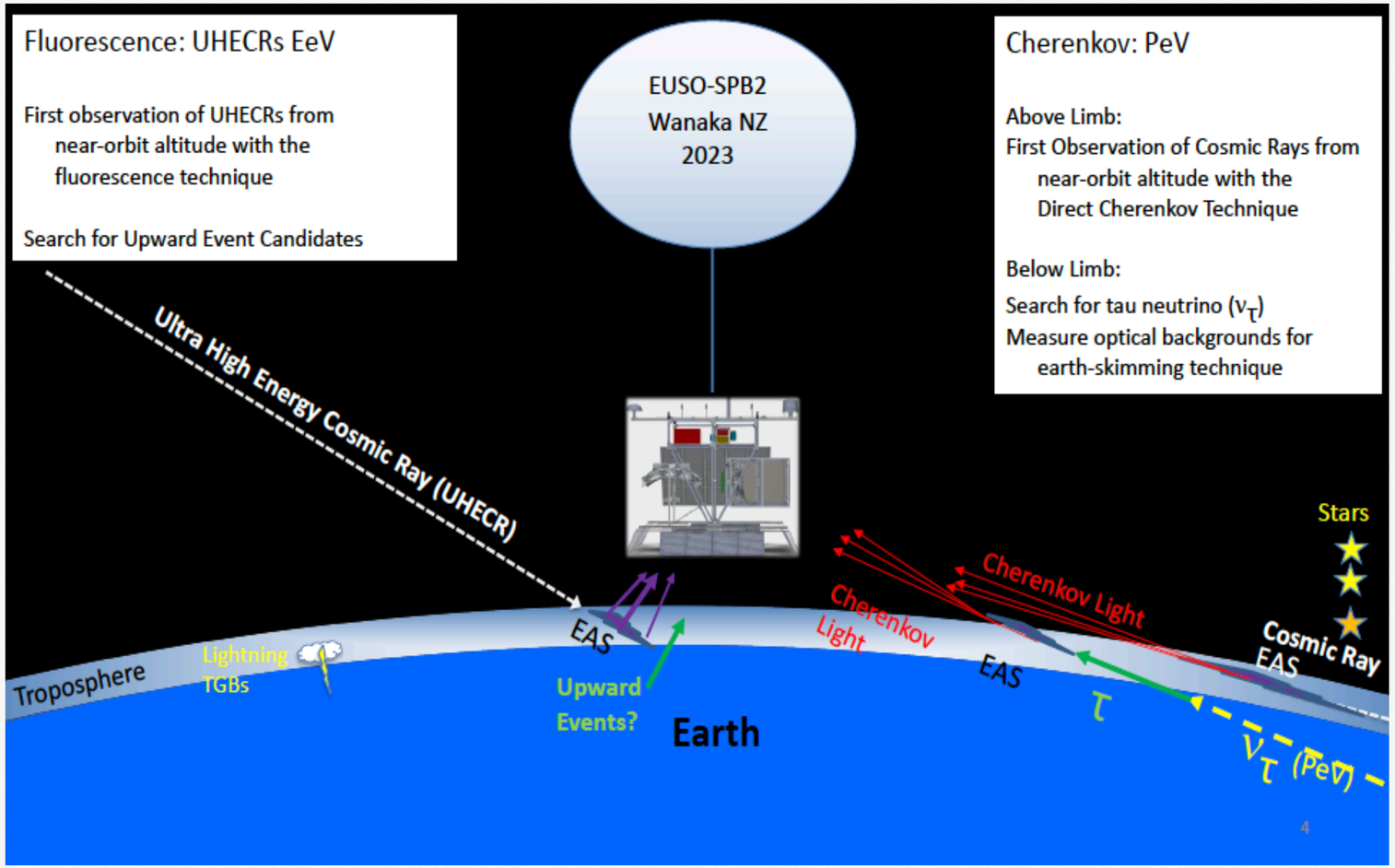
EUSO-SPB2

Extreme Universe Space Observatory on a Super-Pressure Balloon 2

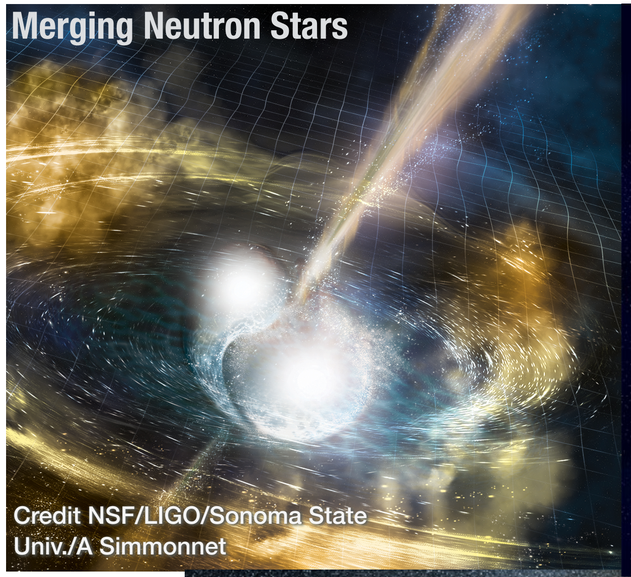
- Launch: May 2023 from Wanaka, NZ
- Two telescopes:
  - Fluorescence telescope (FT)
  - Cherenkov telescope (CT)
- Flight time: 1 day, 12 hrs., 53 mins.
- Obs. time: 12 hrs., 55 mins.

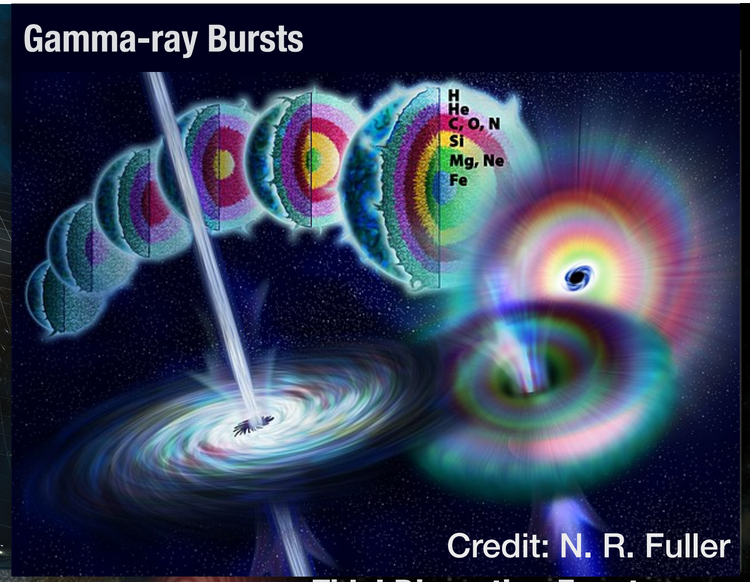
EUSO-SPB2 Talks and posters at APS
- G03: E. Gazda; L. Wiencke
- H03: T. Heibges
- T09: D. Fuehne

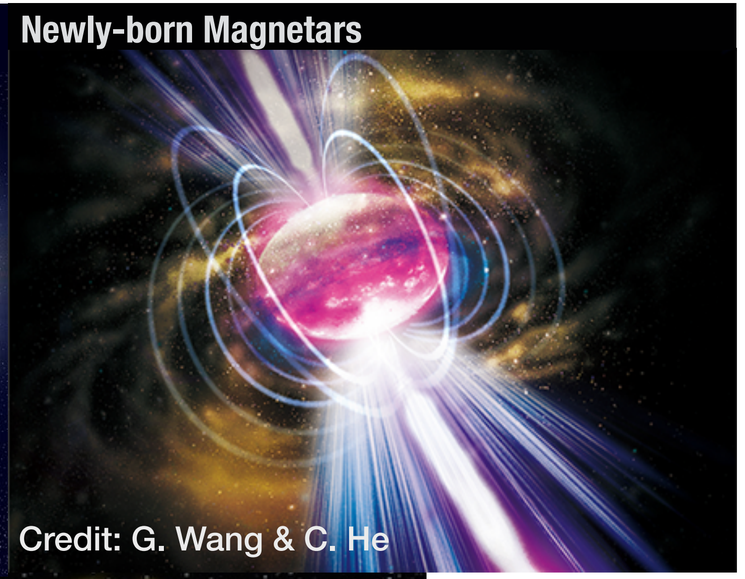
Other related APS talks and posters:
- B14: D. Garg
- D09: J. Krizmanic
- E00: L. Kupari
- J03: J. Krizmanic
- T07: M. Reno

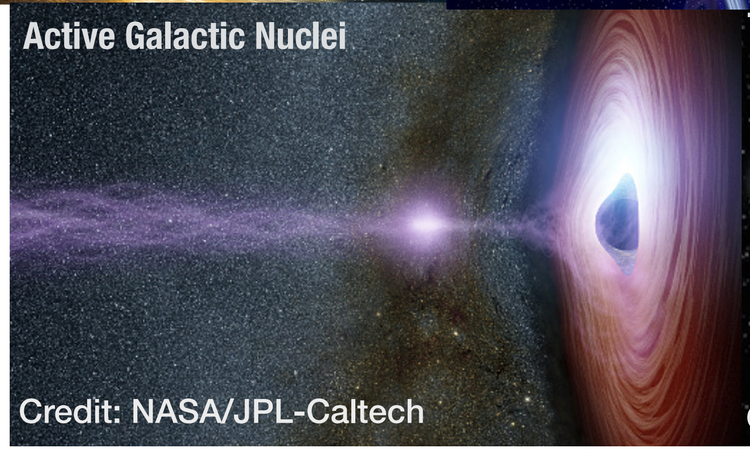


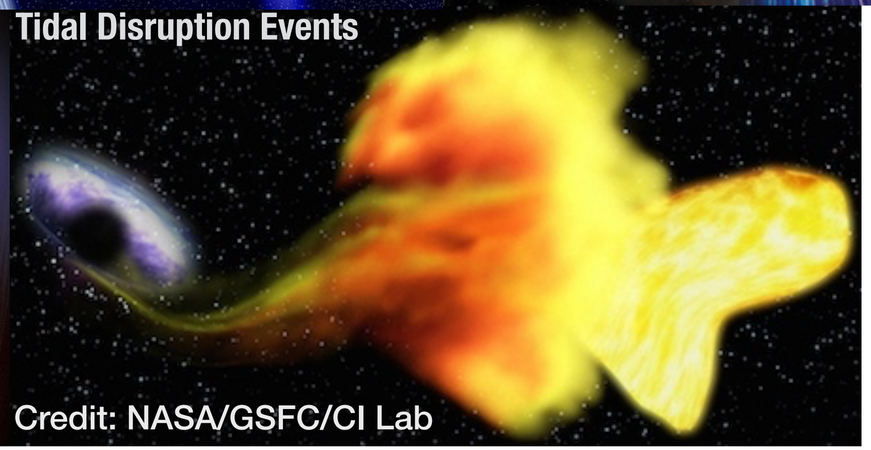
Why Search for UHE Astrophysical Neutrinos?







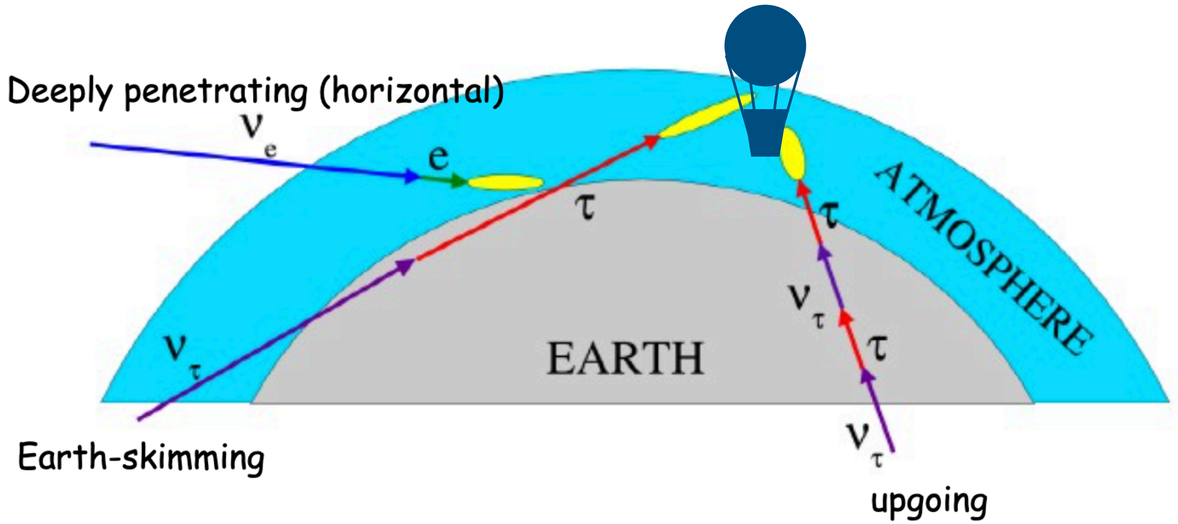




Flavor ratio at source — $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$ ➡ *Flavor ratio at Earth — $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$*

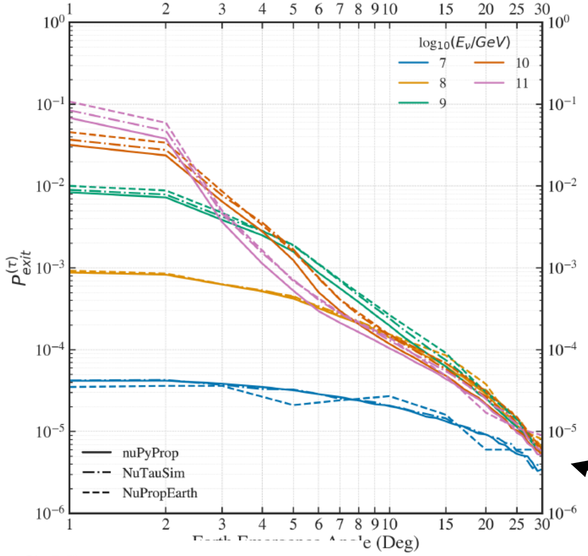
Why Search for Astrophysical Neutrinos with PBR?

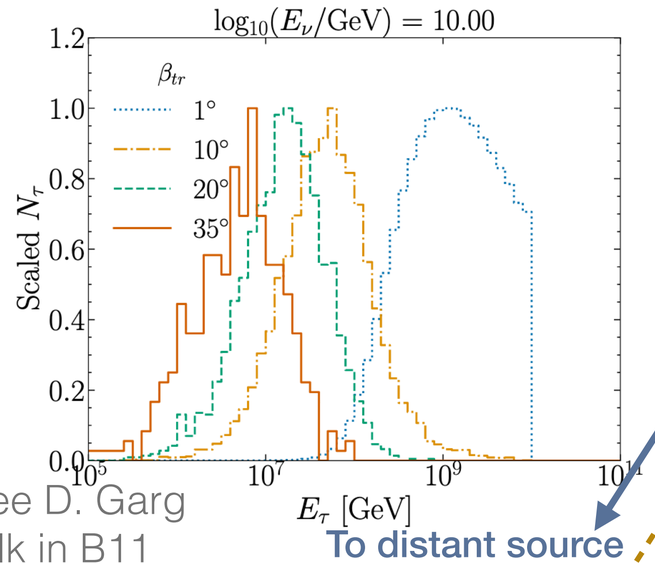
- Sensitive to PeV neutrinos → complementarity with IceCube
- Lower backgrounds at higher energies
- Pathfinder for future suborbital and space-based missions (e.g., POEMMA)



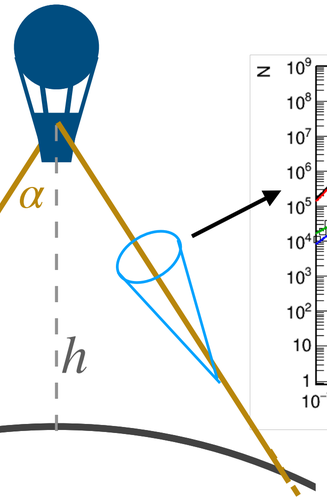
ν_τ Acceptance for Point Sources I

ν_τ Propagation Modeling



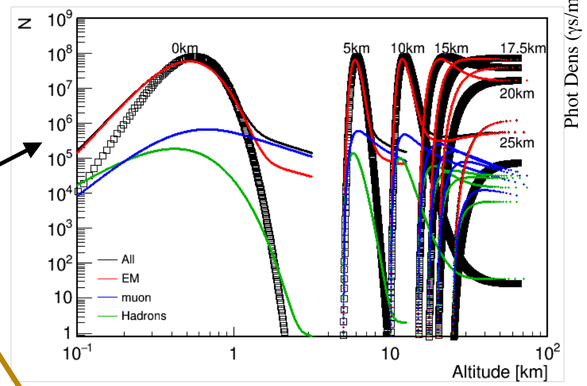


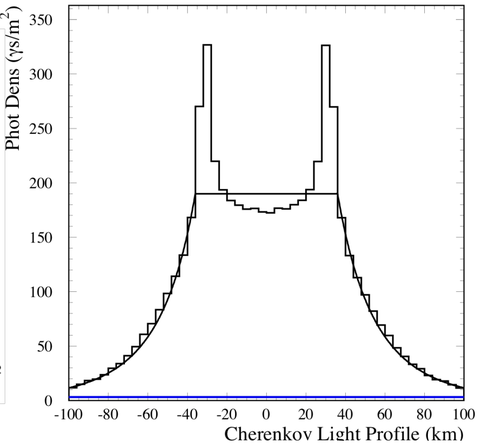
See D. Garg talk in B11

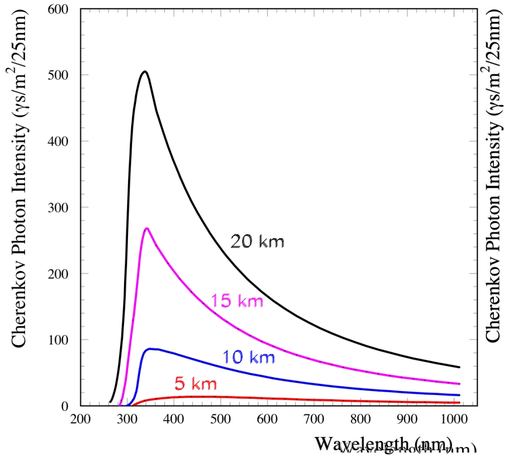


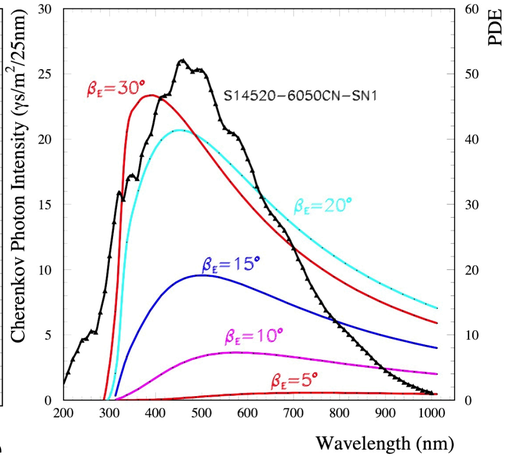
To distant source

EAS Cherenkov Signal Modeling





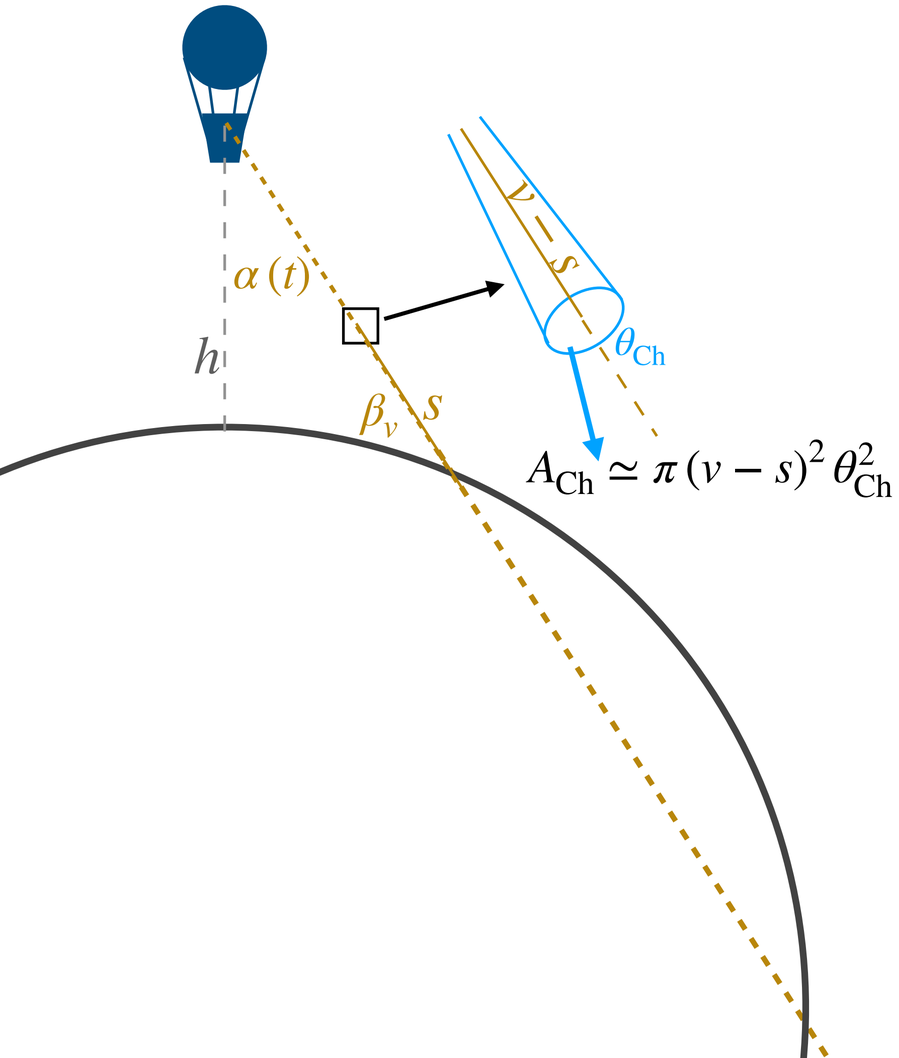


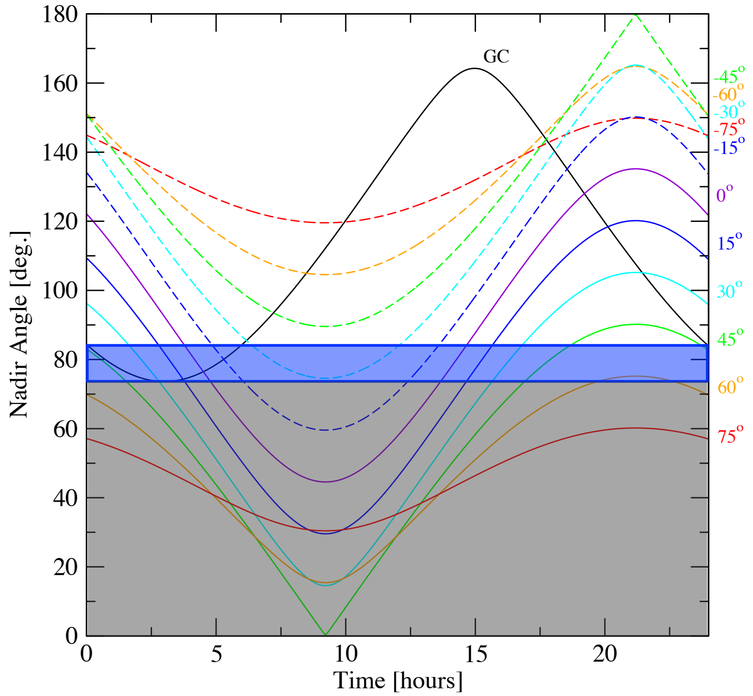


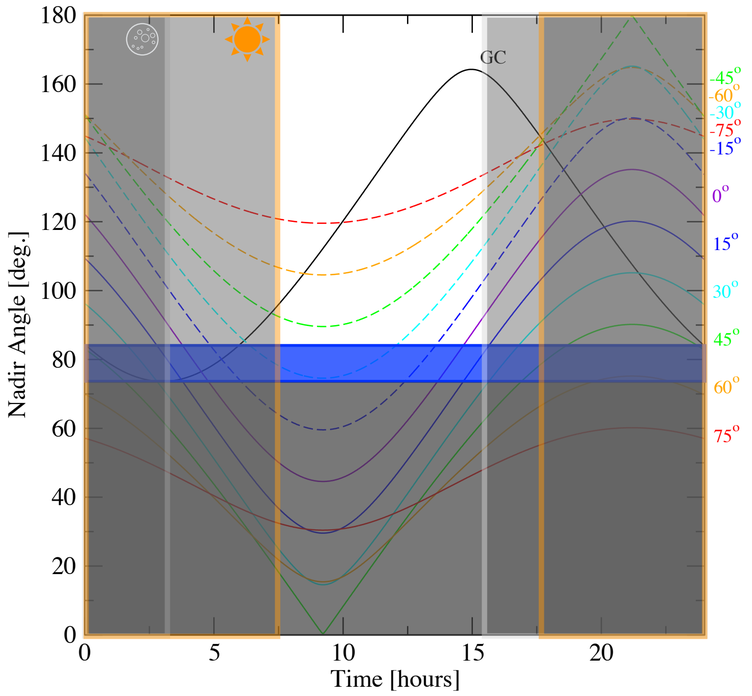
See A. Cummings talk in Q13

See also Reno+ 2019, Cummings+ 2021

ν_τ Acceptance for Point Sources II







Time-averaged effective area:

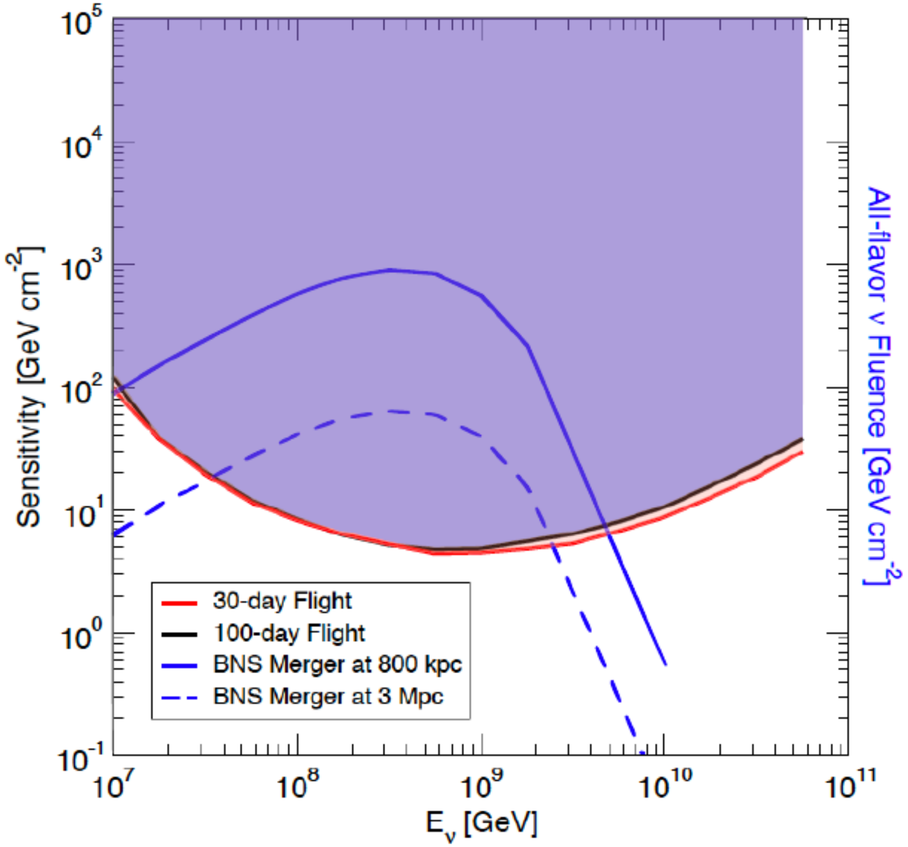
$$\left\langle A\left(E_{\nu_\tau}\right)\right\rangle_{T_{\rm obs}} = \frac{1}{T_{\rm obs}} \int_{t_0}^{t_0+T_{\rm obs}} dt \int dP_{\rm obs}\left(E_{\nu_\tau}, \beta_\nu, s\right) A_{\rm Ch}(s)$$

Per-decade All-flavor Sensitivity (x E_ν^2):

$$\frac{N_\nu^{90\%}}{\ln(10)} \times \frac{N_{\rm fl} E_\nu}{f_t \left\langle A(E_\nu)\right\rangle_{T_{\rm obs}}} = \frac{2.44}{\ln(10)} \times \frac{3E_\nu}{f_t \left\langle A(E_\nu)\right\rangle_{T_{\rm obs}}}$$

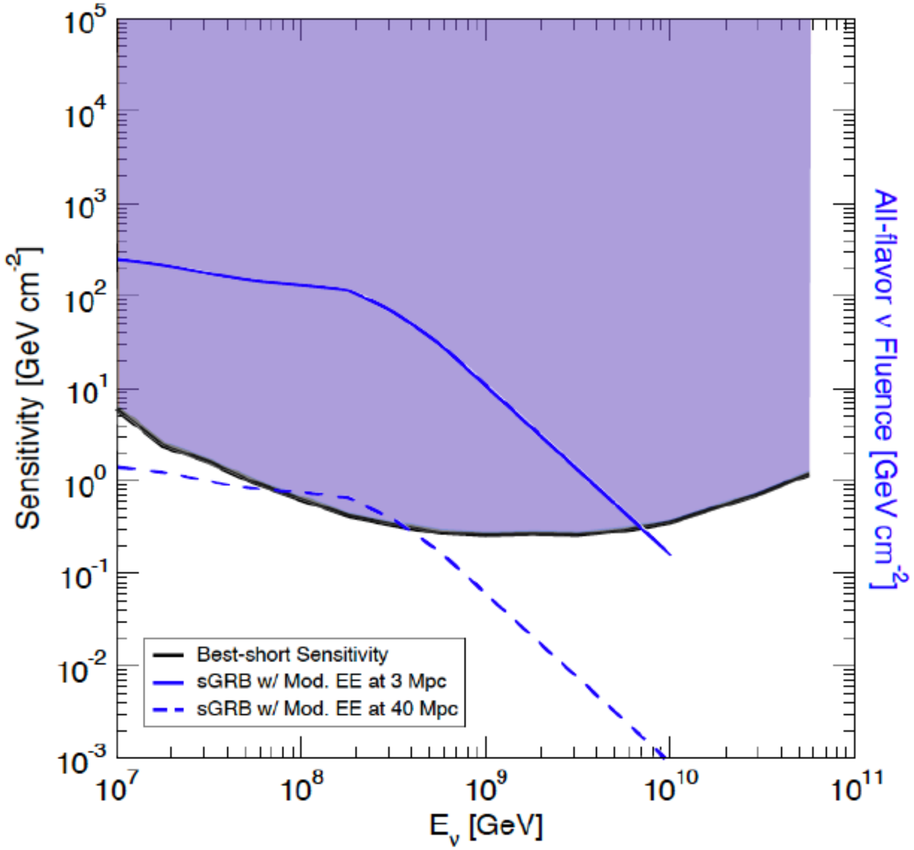
Point-source Sensitivity

Long Duration



- Steady or long-duration events lasting ~days or weeks
- Sensitivity averaged over one or more days
- Accounts for Sun+Moon constraints

Best Short

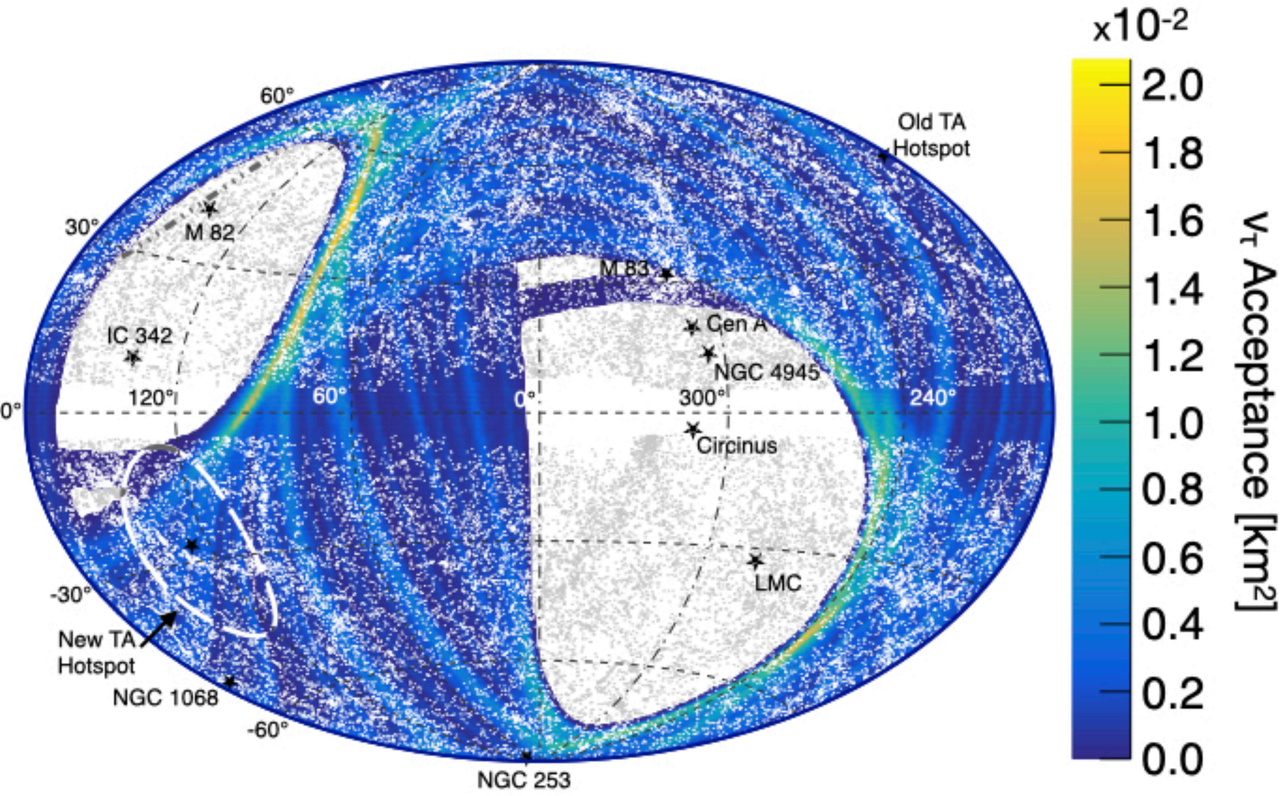


- Short duration events (≲ 1000 s)
- Best sensitivity — averaged over 1000 s after source dips below Earth's limb
- No Sun+Moon constraints

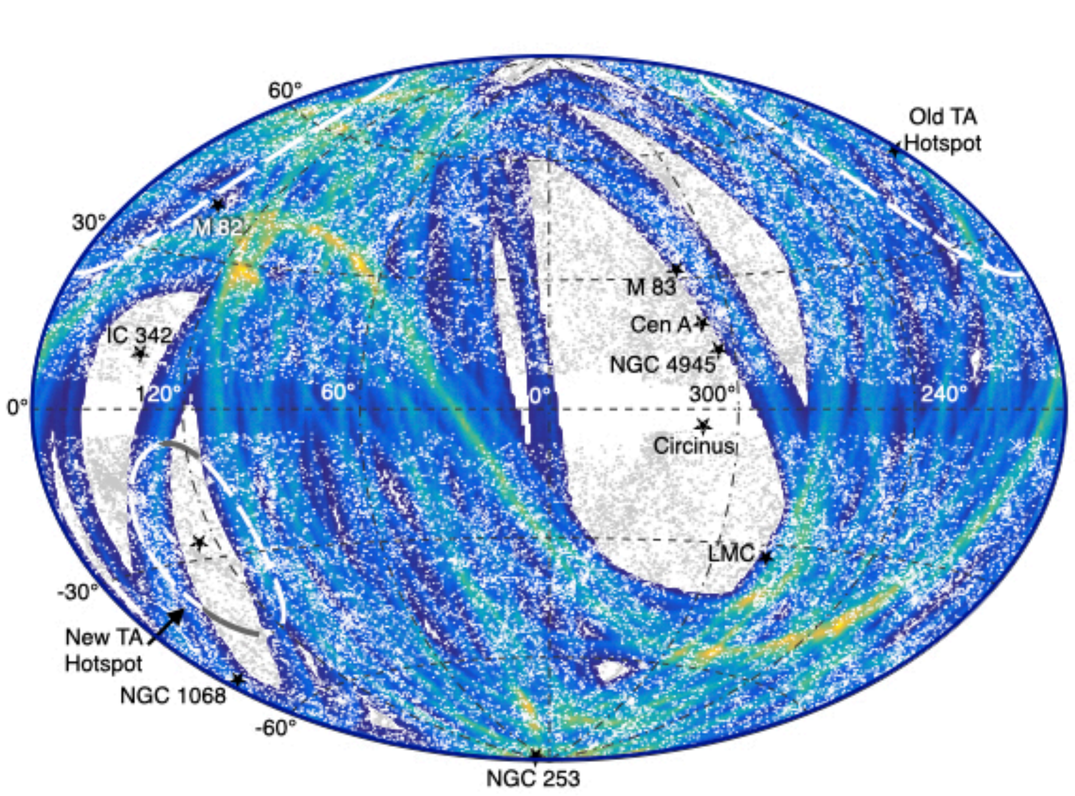
Models: Fang & Metzger 2017, Kimura+ 2017

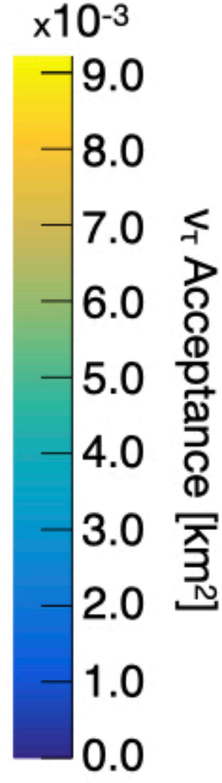
See TMV+ 2020, TMV+, ICRC2021

Sky Coverage Map



Stationary — 100 days





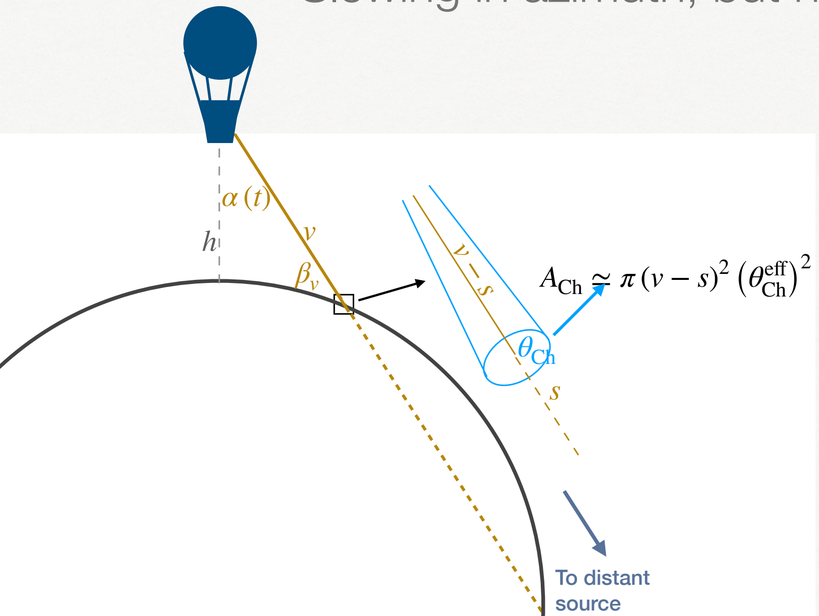
2016 COSI Trajectory

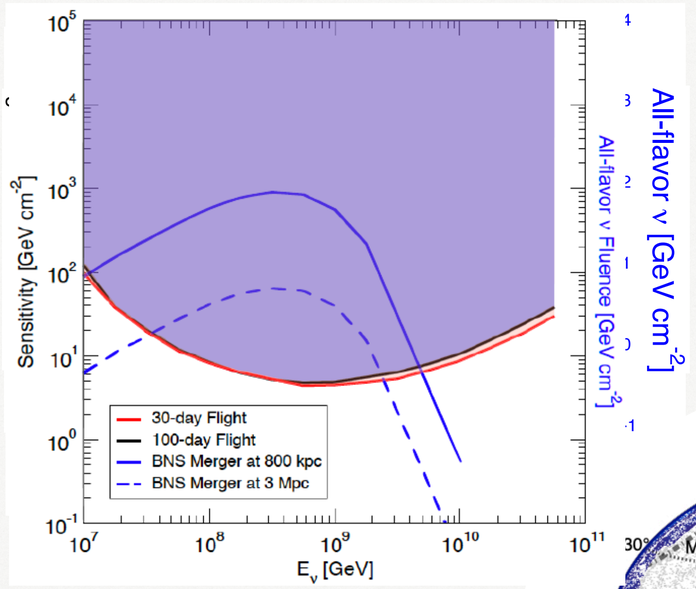
$E = 10^{8.5}$ GeV

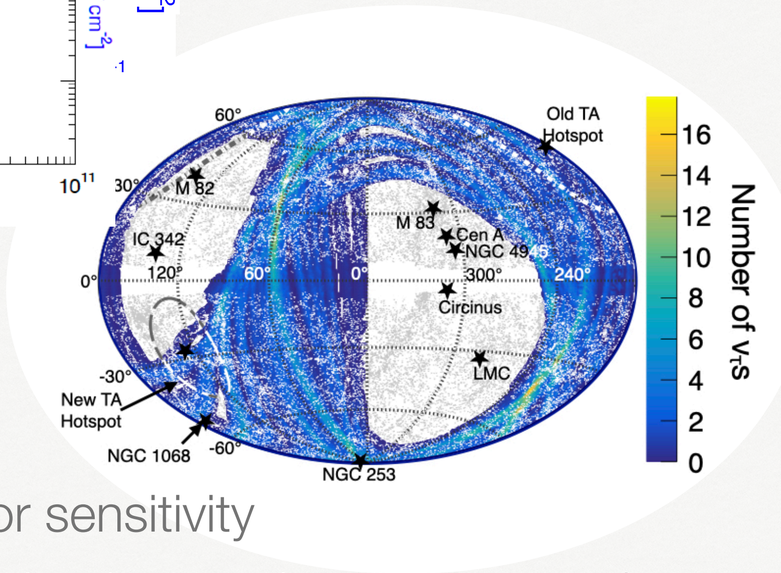
See TMV+ 2020, TMV+, ICRC2021

Recap of Theoretical Calculations

- Calculate ν_τ acceptance
- Leverage ν_τ propagation studies
- Account for Sun and Moon
- Assumptions:
  - Balloon trajectory from hist. wind patterns
  - Slewing in azimuth, but not in nadir



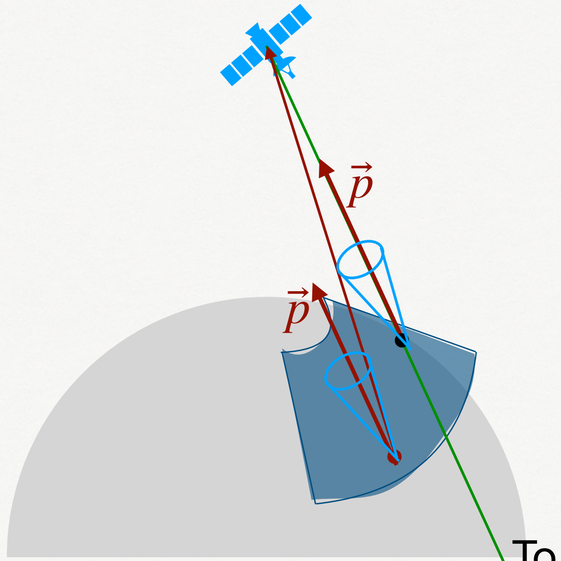


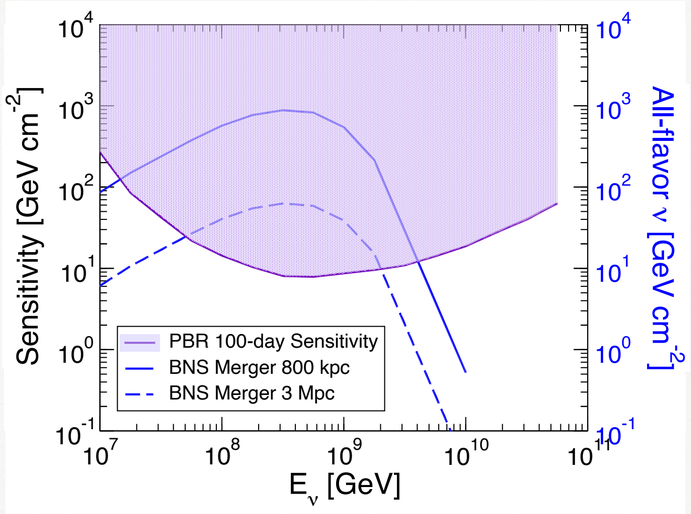


- Per decade all-flavor sensitivity
- 90% upper limit (no background -> 2.44 events)
- Muon showers excluded ($B_{shr} \simeq 83\%$)

Point-Source Sensitivity Projections for EUSO-SPB2

- Calculate ν_τ acceptance
- Leverage ν_τ propagation studies
- Account for Sun and Moon
- Assumptions:
  - Balloon trajectory from hist. wind patterns
  - Slewing in azimuth, but not in nadir





- Per decade all-flavor sensitivity
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