Phenomenology and Astrophysical Probes of Lorentz Invariance Violation and Doubly Special Relativity

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4. 2. 2026.

BridgeQG Workshop - Bridging High-Energy Astrophysical Modelling and Lorentz Invariance Violation Studies, LAPP

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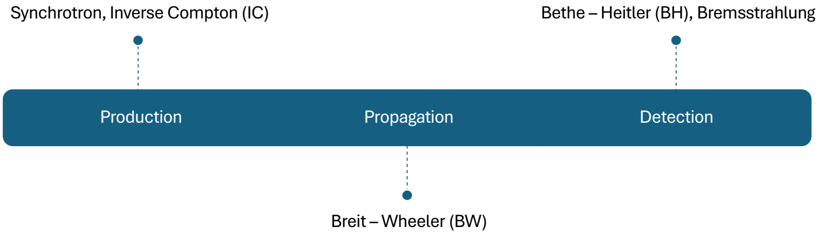
CAPA

Stages of life of a gamma ray

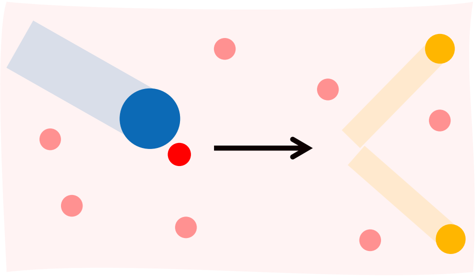


- Synchrothron: $e^- + B \rightarrow e^- + \gamma$
- IC: $e^- + \gamma \rightarrow e^- + \gamma_{\mathrm{HE}}$
- BW: $\gamma_{\mathrm{HE}} + \gamma_{\mathrm{BKG}} \rightarrow e^- + e^+$
- BH: $\gamma + N \rightarrow e^- + e^+$
- Bremsstrahlung: $e^{\pm} + N \rightarrow e^{\pm} + \gamma$

Attenuation of gamma-ray flux

The Universe is permeated by diffuse **low-energy photon backgrounds** (CMB, EBL, radio, ...). **Gamma rays** propagating through this medium interact with it producing **electron–positron pairs**; the Breit–Wheeler process [Breit & Wheeler, 1934]:

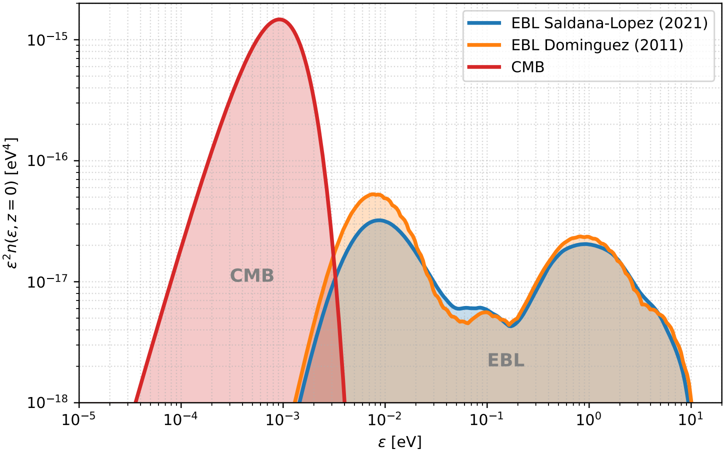
$$\gamma + \gamma_{\rm BKG} \rightarrow e^{+} + e^{-}$$



The gamma-ray energy determines the dominant target photon field for absorption [De Angelis, 2013]:

- 10 GeV $\leq E \leq$ 100 TeV $\rightarrow$ **EBL**
- 100 TeV $\leq E \leq$ 10 EeV $\rightarrow$ **CMB**

Low energy background distribution



How is the **survival probability** of gamma rays traveling through this medium affected in models with broken or deformed symmetries?

Special Relativity and Beyond

Lorentz Invariance Violation (LIV)

- Systematic effective field theory framework introduced in Colladay & Kostelecký (1998): *Standard Model Extension (SME)*
- Explicit **breaking** of Lorentz invariance $\Rightarrow$ emergence of a preferred frame
- LIV effects parameterized by SME coefficients, suppressed by a high energy scale $\sim E_{\mathrm{Pl}} \approx 1.2 \cdot 10^{19}$ GeV

Modified dispersion relation (MDR)

General modifications to the dispersion relation of a high-energy photon:

$$E^2 - \vec{k}^2 = E^2 \sum_{n=1}^{\infty} S_n \left(\frac{E}{E_{\mathrm{QG},n}} \right)^n , \quad S_n = \pm 1 .$$

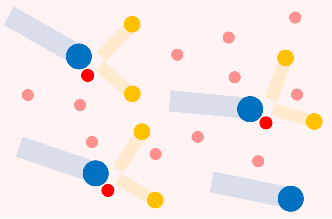
Quadratic subluminal scenario

The modified dispersion relation of the **gamma ray** is given by

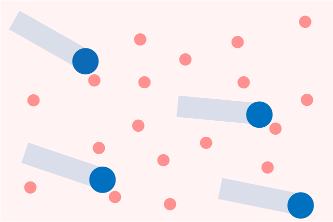
$$E^2 - \vec{k}^2 = -\frac{E^4}{\Lambda_{\mathrm{LIV}}^2}$$

If there were a finite Λ_{LIV}, could we in principle infer the existence of it from the fluxes of VHE/UHE sources? $\Rightarrow$ YES!

Modifications in the kinematics lead to observable consequences:



SR

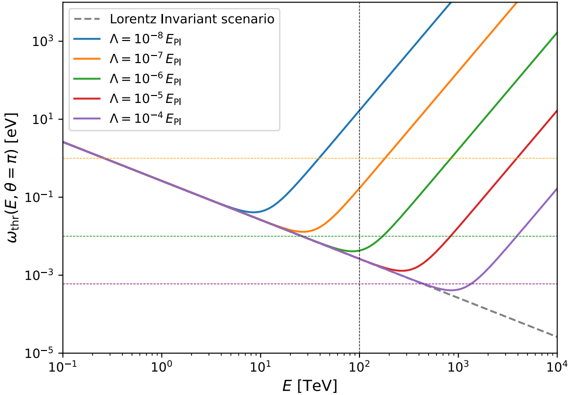


LIV

An extended phenomenological study of this model can be found in [Carmona et al., 2024].

Quadratic subluminal LIV – threshold kinematics

$$\omega_{\rm thr}(E,\theta;\Lambda_{\rm LIV}) = \underbrace{\frac{2m_e^2}{E(1-\cos\theta)}}_{\rm SR} + \underbrace{\frac{E^3}{2\Lambda_{\rm LIV}^2(1-\cos\theta)}}_{\rm LIV}$$



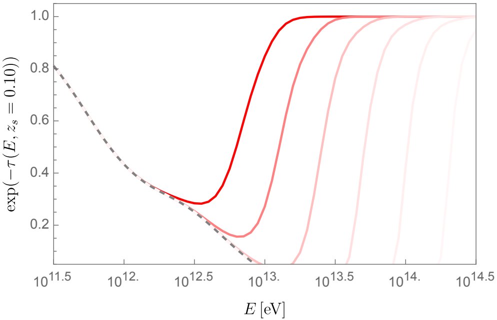
Previous studies with extragalactic sources:
$\Rightarrow \Lambda_{\rm LIV} \gtrsim 10^{-7} E_{\rm Pl}$, see, e.g. [Ofengeim & Piran, 2025] and [H.E.S.S., 2019].

Back-of-the-envelope argument:

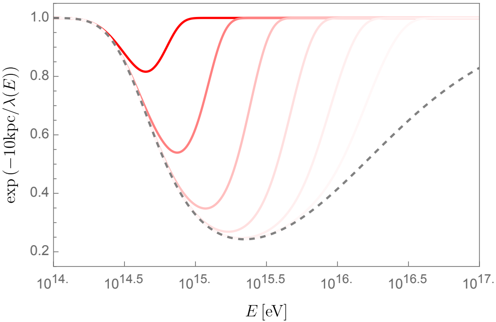
$$\frac{d\omega_{\rm thr}}{dE} = 0 \;\Rightarrow\; E_{\rm obs} \simeq 8.5{\times}100\,{\rm TeV}\left(\frac{\Lambda_{\rm LIV}}{10^{-4}E_{\rm Pl}}\right)^{1/2}$$

Quadratic subluminal LIV - observational consequences

Survival probability calculated using the novel result for the cross section. The grey dashed line represents the SR (BW) case.



$\Lambda_{\rm LIV}/E_{\rm Pl} \in [10^{-8.5}, 10^{-6}]$ (with steps of 0.5)



$\Lambda_{\rm LIV}/E_{\rm Pl} \in [10^{-4.5}, 10^{-2}]$ (with steps of 0.5)

Source: [Carmona et al., 2024]

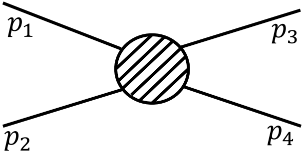
Doubly Special Relativity (DSR)

- DSR is a **deformation** of relativistic symmetries with two invariant scales:

$$c \quad \text{and} \quad \Lambda_{\mathrm{DSR}}$$

- **No** local spacetime EFT *lagrangian description*
- Conceptual issues:
  - *Spectator problem*
  - *Soccer-ball problem*

Trademark: **modified composition of momenta**



$$p_1 \oplus p_2 = p_3 \oplus p_4$$

New perspective on DSR

Introduced in [Carmona et al., 2023] as *departure from locality of interactions*.

Characteristics of the model

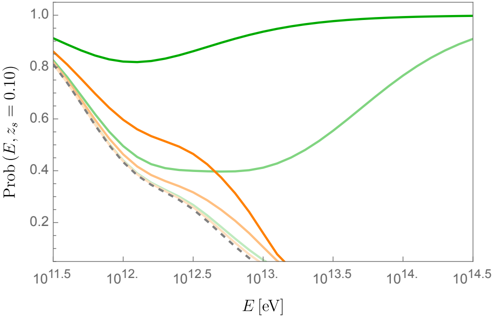
- Single-particle states are undeformed:
  - Standard SR dispersion relation
  - No energy-dependent propagation speed
  - No time-of-flight constraints
- Physical effects arise in *multi-particle interactions*
- Deviations from locality are controlled by a length scale

$$l \sim \Lambda_{\mathrm{DSR}}^{-1}$$

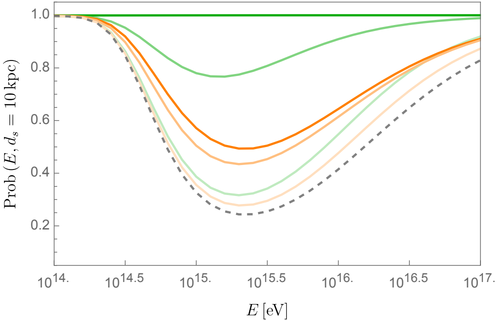
An extended phenomenological study of a scenario based on this model can be found in [Carmona et al., 2025].

New perspective on DSR - observational consequences

Survival probability for the minimum interaction (green) and equal probable channels (orange) scenarios.The grey dashed line represents the SR (BW) case.



$\Lambda_{\mathrm{DSR}}/\mathrm{eV} = 10^{12}, 10^{13}$ and 10^{14} (from darker to lighter).



$\Lambda_{\mathrm{DSR}}/\mathrm{eV} = 10^{14}, 10^{15}$ and 10^{16} (from darker to lighter).

There are multiple channels through which interactions can occur. **How do we weigh the different channels?**

Source: [Carmona et al., 2025]

	SR	**LIV**	**DSR** (one channel)
Threshold condition	$\frac{2E\omega(1-\cos\theta)}{4m_e^2} \geq 1$	$\frac{2E\omega(1-\cos\theta)}{4m_e^2} - \frac{E^4}{4m_e^2\Lambda_{\text{LIV}}^2} \geq 1$	$\frac{2E\omega(1-\cos\theta)}{4m_e^2(1+E/\Lambda_{\text{DSR}})} \gtrsim 1$
Appearance of effect		For $E \ll \Lambda_{\text{LIV}}$	For $E \sim \Lambda_{\text{DSR}}$
Second threshold	✗	✓	✗

Astrophysical Tests

The strategy is to look for deviations from the expected absorption patterns of high-energy gamma rays!

Example

Carpet-3 observation of a $\sim 300\,\text{TeV}$ photon from the BOAT (GRB 221009A, $z = 0.151$) event position [Dzhappuev et al., 2025]

- Standard expectations predict strong absorption at that redshift, above ~ 10–$20\,\text{TeV}$
- Type of flux anomalies that threshold modifications could produce
- See [Ofengeim & Piran, 2025], [Satunin & Troitsky, 2025] and [Song & Ma, 2025] as examples of LIV studies of this event

Sources of Interest

Characteristics

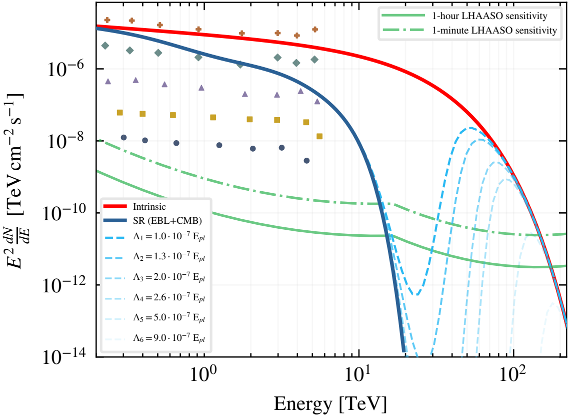
- **Hard and bright gamma-ray sources** are required to probe LIV and DSR effects in the VHE/UHE regime
- **Extragalactic sources:**
  - Hard spectra extending into the VHE regime
- **Galactic sources:**
  - Extension into the UHE regime
  - E.g. PeVatrons observed by LHAASO (2021)

Case studies:

- GRB 221009A (BOAT)
- PKS 2155–304 as a benchmark extragalactic source for SWGO
- Test of LHAASO Galactic PeVatrons

Is There New Physics Beyond 30 TeV in the BOAT?

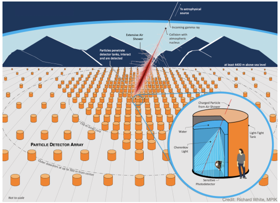
Study of GRB 221009A LHAASO data.



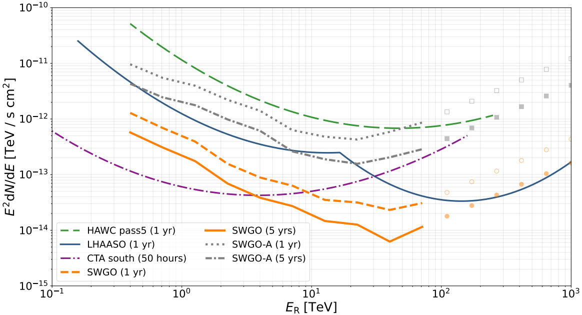
For more information, you can find our recent analysis on ArXiv: 2511.15542.

Southern Wide-field Gamma-ray Observatory (SWGO)

Southern Wide-field Gamma-ray Observatory (SWGO)

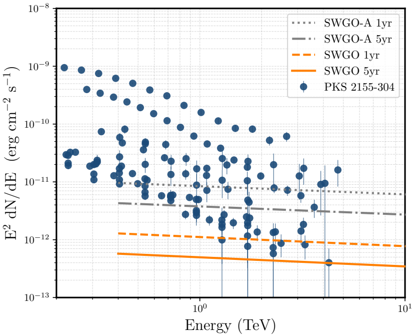


- Water Cherenkov Detector units
- Location: Atacama Astronomical Park, Chile (altitude: 4770 m)
- Energy range: 10^2 GeV – 10 PeV
- **SWGO-A:**
    - 385 WCD units
    - 65% fill factor
- For a detailed overview: [White Paper]

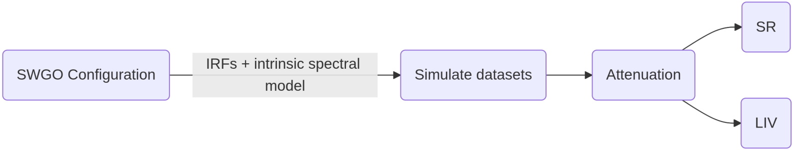


PKS 2155-304 and SWGO workflow

- Observed in both baseline and flaring states by [H.E.S.S.; 2010, 2011, 2013]
- Redshift: $z = 0.116$
- One of the brightest sources in the southern sky

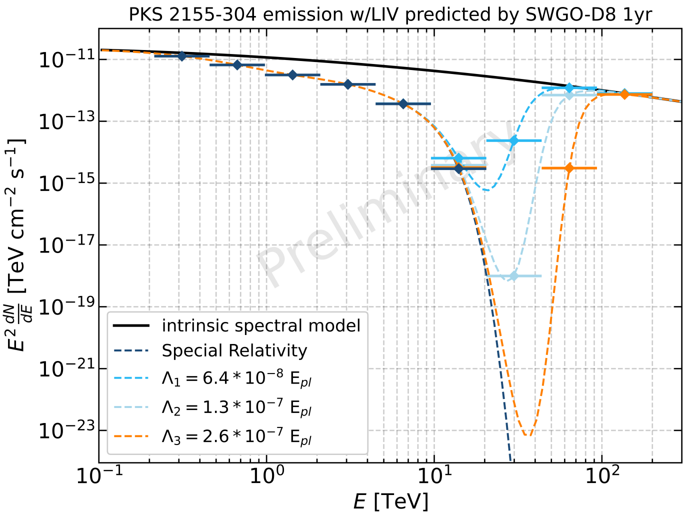


Workflow:



Performed using **Gammapy**.

SWGO observations of PKS 2155-304



Presented last year at the BridgeQG Conference. You can find my talk [here].

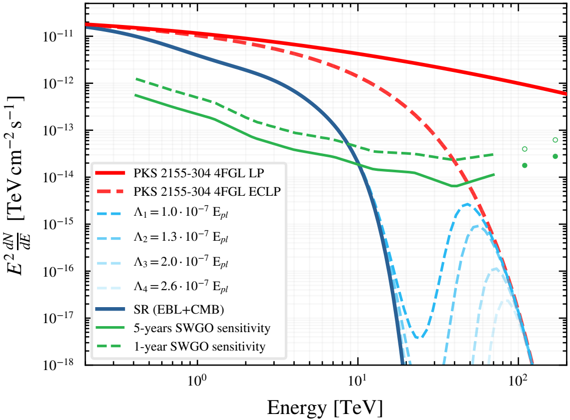
Summary and open questions

Summary

- Current sensitivity forecasts rely on simulated or extrapolated spectra
- Problem of source availability
- Galactic PeVatrons still need to be studied

Open questions

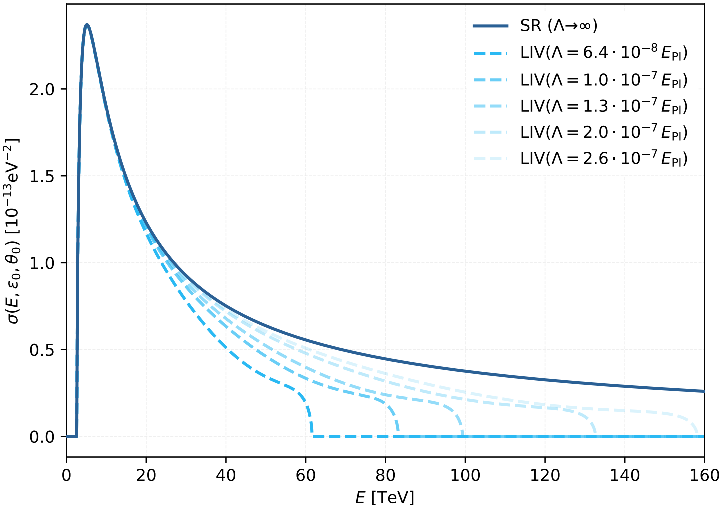
- Are there other promising southern-sky galactic or extragalactic candidates we should consider?
    - How to model/extrapolate fluxes of viable candidates to $E \gtrsim 100$ TeV, to make sense?
- Can stacking be used to enhance sensitivity to LIV effects when individual sources lie below the nominal detection threshold of SWGO?

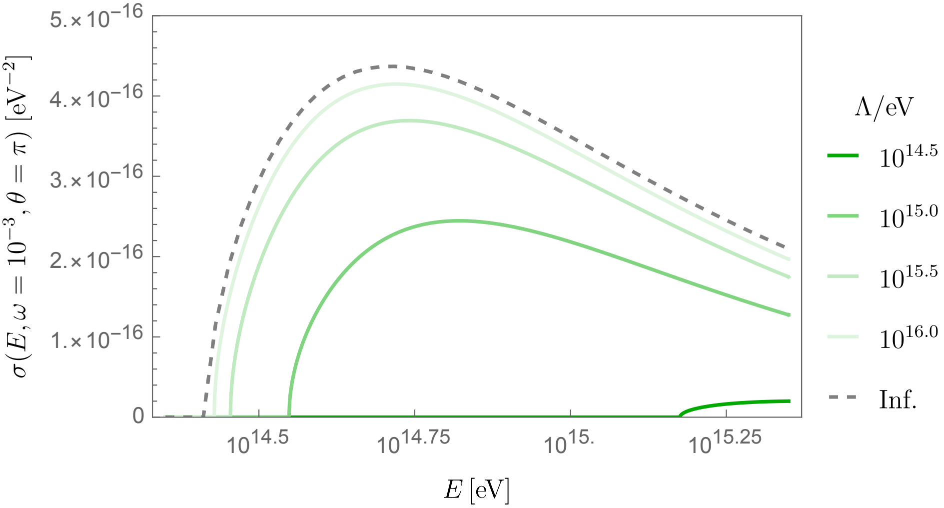


$E_{\rm obs}$	10 TeV	100 TeV	1 PeV	10 PeV	100 PeV
$\Lambda_{\rm LIV}$	$10^{-8} E_{\rm Pl}$	$10^{-6} E_{\rm Pl}$	$10^{-4} E_{\rm Pl}$	$10^{-2} E_{\rm Pl}$	$E_{\rm Pl}$

Back-up slides

Quadratic subluminal LIV - cross section





5.×10^−16
4.×10^−16
3.×10^−16
2.×10^−16
1.×10^−16
0
σ(E, ω = 10^−3, θ = π) [eV^−2]
10^14.5
10^14.75
10^15.
10^15.25
E [eV]
Λ/eV
10^14.5
10^15.0
10^15.5
10^16.0
Inf.

General LIV effects

Types of effects

- **Single particle**: propagation effects
- **Multi particle**: interaction and threshold effects

These include:

- Vacuum birefringence
- Photon splitting: $\gamma \to 3\gamma$
- Time delays
- Photon decay: $\gamma \to e^- e^+$
- Modified BH interaction

For a theoretical summary and experimental bounds on the LIV scale from these observational effects, see the QGMM Review.

Opacity and mean free path

Observed flux:

$$\frac{dN_{\rm obs}}{dE} = \frac{dN_{\rm int}}{dE_z} \times e^{-\tau(E,z_s)}\,, \quad E_z = E(1+z_s)$$

Opacity:

$$\tau(E,z_s) = \int_0^{z_s} dz\,\frac{dl}{dz}\int_{-1}^{1} d\cos\theta\left(\frac{1-\cos\theta}{2}\right)\int_{\varepsilon_{\rm thr}(E,\theta,z)}^{\infty} d\varepsilon\; n(\varepsilon,z)\,\sigma(E(1+z),\varepsilon,\theta)$$

In the local Universe:

$$\tau(E) \approx \frac{d_s}{\lambda(E)}$$

[Carmona et al.; 2023] Modified composition of momenta:

$$(a \oplus b)_0 = a_0 \Pi(b) + \frac{1}{\Pi(a)} \left(b_0 + \frac{\vec{a} \cdot \vec{b}}{\Lambda_{\mathrm{DSR}}} \right)$$

$$(a \oplus b)_i = a_i \Pi(b) + b_i \,,$$

where

$$\Pi(a) = \frac{a_0}{\Lambda_{\mathrm{DSR}}} + \sqrt{1 + \frac{a_0^2 - |\vec{a}|^2}{\Lambda_{\mathrm{DSR}}}}$$

Consider two inertial frames S and S' in relative motion with velocity $\mathbf{v}$.

In Galilean relativity, velocities add linearly:

$$\mathbf{v} + \mathbf{u}$$

In Special Relativity, this is replaced by the velocity composition law:

$$\mathbf{v} \oplus \mathbf{u} = \frac{1}{1 + \frac{\mathbf{u} \cdot \mathbf{v}}{c^2}} \left(\mathbf{v} + \mathbf{u} + \frac{1}{c^2} \frac{\gamma_{\mathbf{v}}}{1 + \gamma_{\mathbf{v}}} \mathbf{v} \times (\mathbf{v} \times \mathbf{u}) \right) ,$$

where $\gamma_{\mathbf{v}} = (1 - v^2/c^2)^{-1/2}$.

SWGO – D8 configuration

- 3 - zone configuration with FFs: 70%, 4%, 1.7%
- Up to 600 m in radius
- Total area ≈ 1 km^2