Astroparticle Physics Session Introduction

Marcus Niechciol

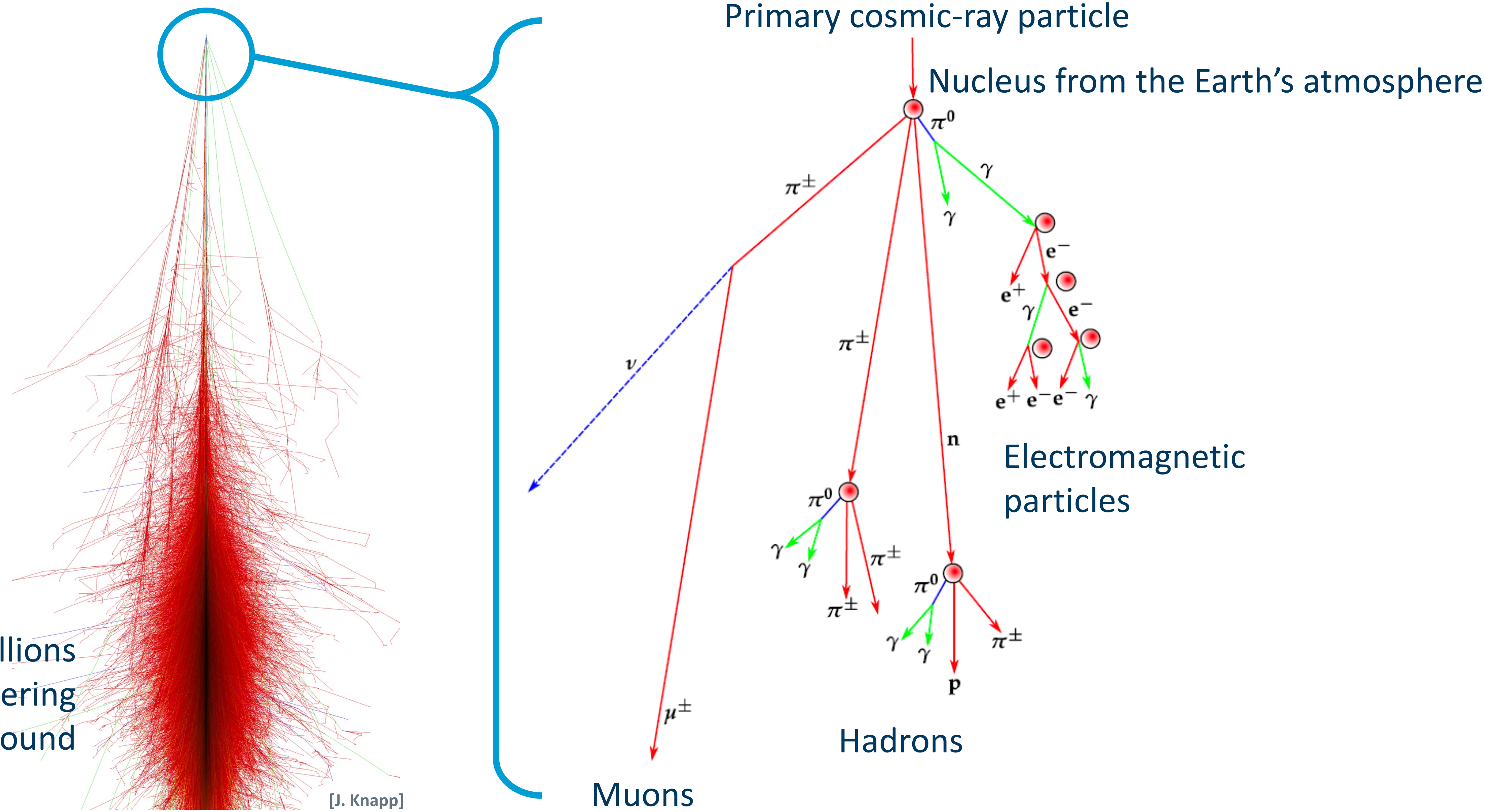
Center for Particle Physics Siegen, University of Siegen

CPPS Retreat

15 February 2024

Photo by S. Saffi (Univ. of Adelaide)

Extensive Air Showers



Primary cosmic-ray particle

Nucleus from the Earth’s atmosphere

Electromagnetic particles

Hadrons

Muons

Cascade of billions of particles, covering a large area on ground

[J. Knapp]

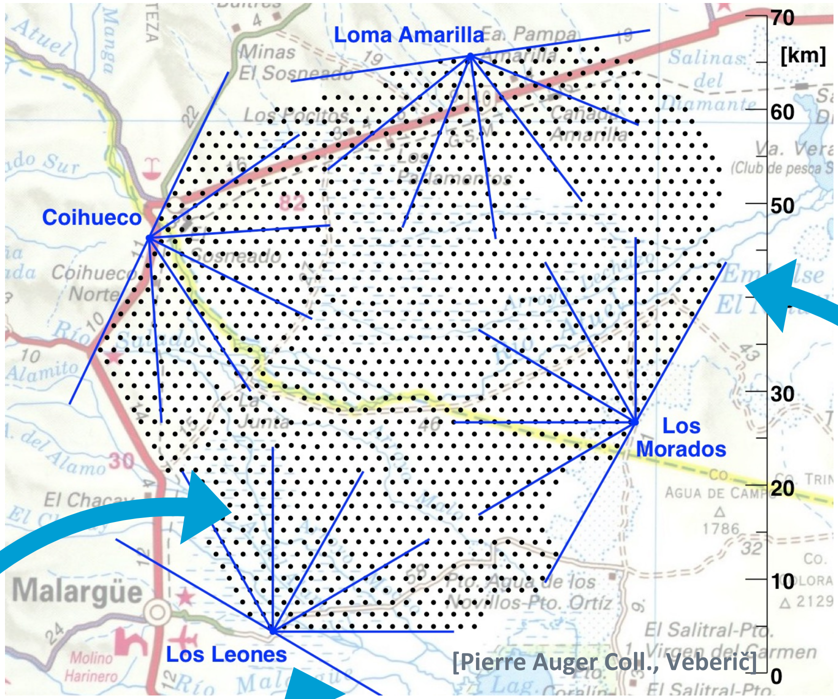
Pierre Auger Observatory

- **Surface Detector (SD)**
  - ~1660 water Cherenkov detector stations, covering about 3000 km^2
- **Fluorescence Detector (FD)**
  - Four FD stations with 27 telescopes
- Data taking started in **2004**
- Detector upgrade (**AugerPrime**) ongoing

PIERRE AUGER OBSERVATORY

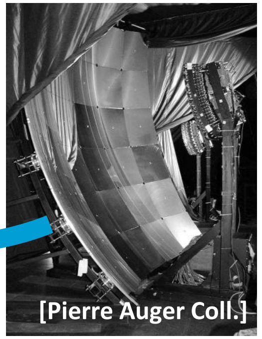

[Pierre Auger Coll.]

[Pierre Auger Coll., NIM A 798 (2015) 172]



[Pierre Auger Coll., Veberić]

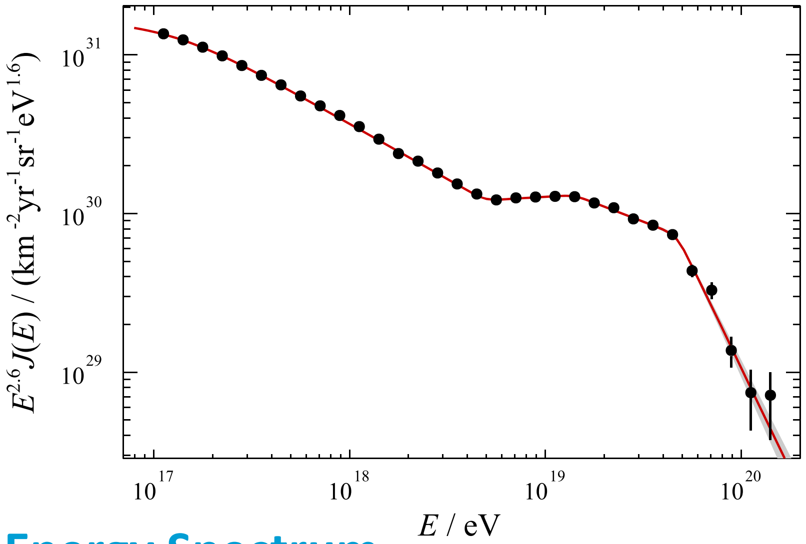

[Pierre Auger Coll.]


[Pierre Auger Coll.]

[CIA]

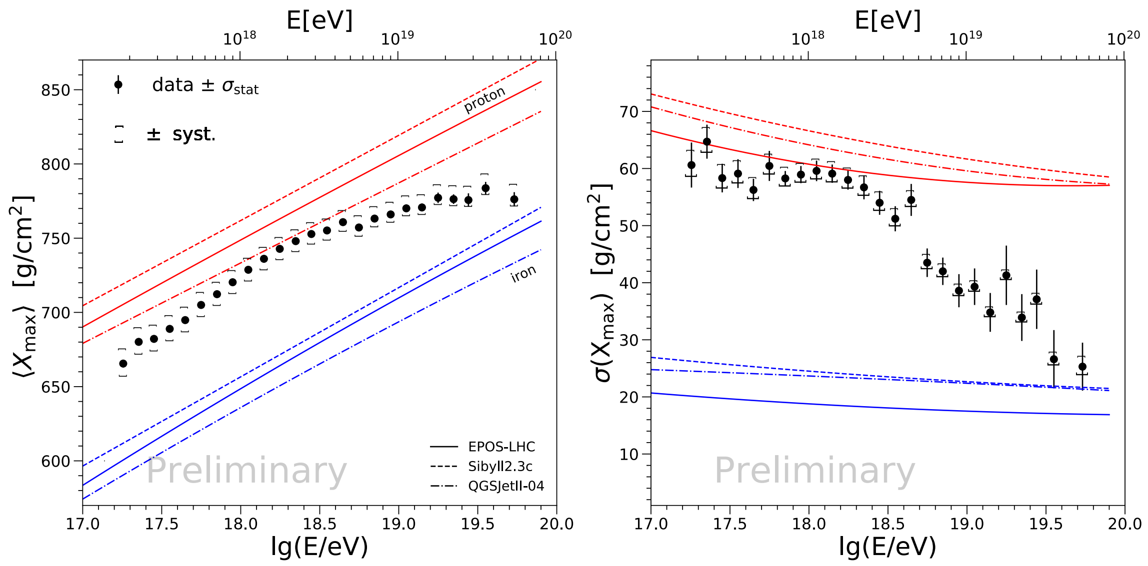
Pierre Auger Observatory – Key Results

[Pierre Auger Coll., Eur. Phys. J. C 81 (2021) 966]

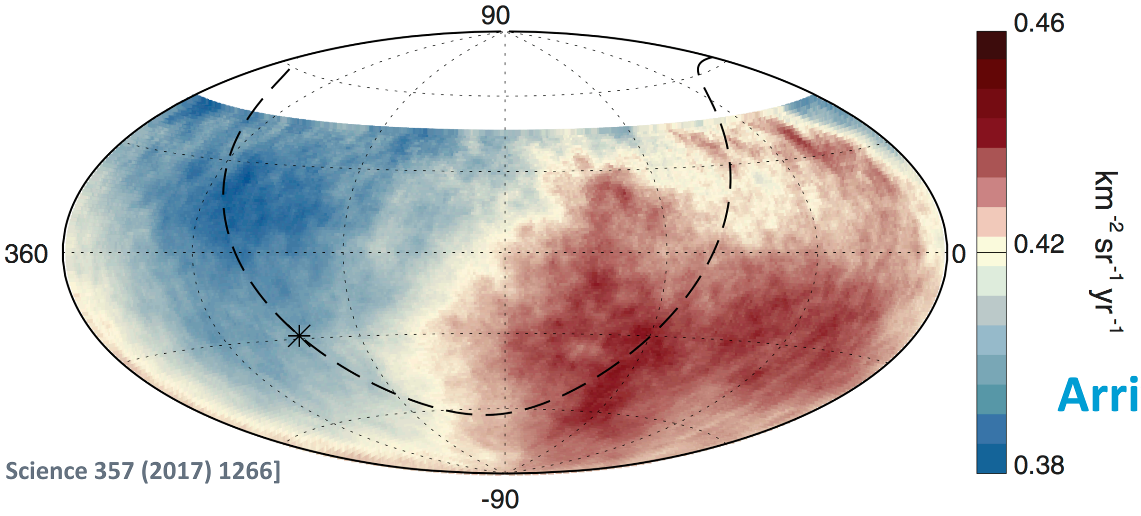


Energy Spectrum

[A. Yushkov (Pierre Auger Coll.), PoS (ICRC2019) 482]



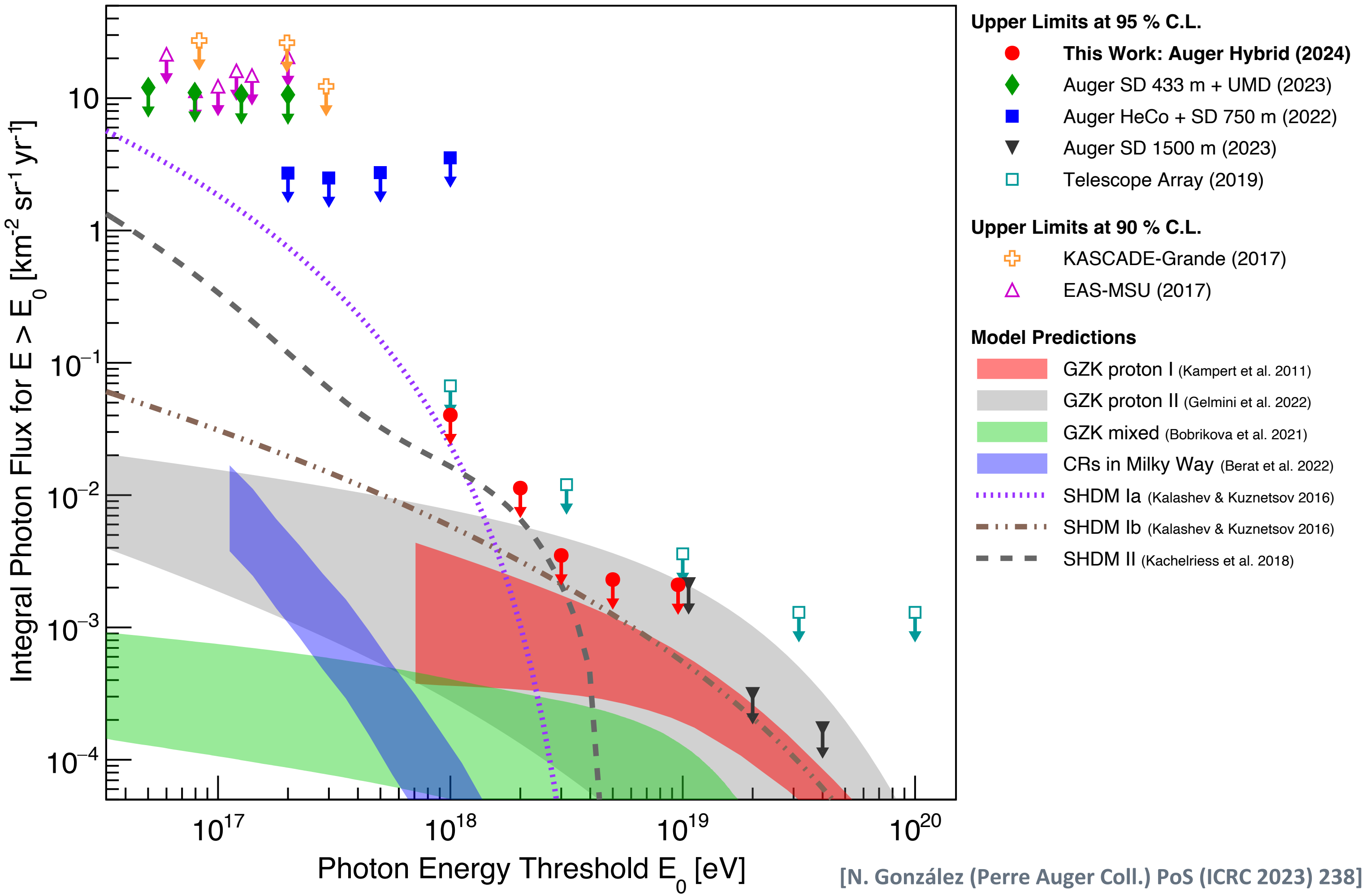
Composition



Arrival Directions

[Pierre Auger Coll., Science 357 (2017) 1266]

Upper Limits on the Diffuse Flux of UHE Photons



[N. González (Perre Auger Coll.) PoS (ICRC 2023) 238]
[Pierre Auger Coll., ApJ 933 (2022) 125]
[Pierre Auger Coll.), in prep.]
[Pierre Auger Coll., JCAP 05 (2023) 021]
[Pierre Auger Coll., Universe 8 (2022) 579]

- **No primary UHE photon** could be unambiguously identified so far
- **Most stringent limits** on the diffuse flux of photons over a wide energy range come from Auger
- Predictions of some **cosmogenic models** (e.g., involving GZK interactions) are within reach
- Limits also useful to constrain BSM models involving **SHDM particles**

[Pierre Auger Coll., PRL 130 (2023) 061001]
[Pierre Auger Coll., PRD 107 (2023) 042002]

- Also done: follow-up search for photons for GW events from LIGO/Virgo/KAGRA [Pierre Auger Coll., ApJ 952 (2023) 91]

Violations of Lorentz Invariance and Extensive Air Showers

Funded by
Deutsche Forschungsgemeinschaft
German Research Foundation

In collaboration with:
J.S. Díaz, F. Duenkel, F.R. Klinkhamer, M. Risse

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CPPS Retreat
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Photo by S. Saffi (Univ. of Adelaide)

LV in the Photon Sector in the Standard Model Extension

[Colladay, Kostelecký; Phys. Rev. D 58 (1998) 116002]

- Look at the **Lagrangian density:**

$$\mathcal{L}(x) = \begin{aligned} &\boxed{\begin{aligned} &-\frac{1}{4}F^{\mu\nu}(x)F_{\mu\nu}(x) \\ &+\bar{\psi}(x)\left(\gamma^{\mu}\left[i\partial_{\mu} - eA_{\mu}(x)\right] - m\right)\psi(x) \end{aligned}} \\ &\boxed{-\frac{1}{4}(k_F)_{\mu\nu\rho\sigma}F^{\mu\nu}(x)F^{\rho\sigma}(x)} \end{aligned}$$

  - First two terms correspond to **conventional quantum electrodynamics (QED)**
  - **Last term** introduces a dimension-four operator that gives rise to LV while preserving CPT and gauge invariance [Chadha, Nielsen; Nucl. Phys. B 217 (1983) 125] [Kostelecký, Mewes; Phys. Rev. D 66 (2002) 056005]
  - **Notes on notation:** natural units $\hbar = c = 1$ and the Minkowski metric $\eta_{\mu\nu} = [\mathrm{diag}(+1,-1,-1,-1)]_{\mu\nu}$ are used; the Maxwell field strength tensor is defined as usual through $F_{\mu\nu} \equiv \partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu}$

Isotropic, Nonbirefringent LV

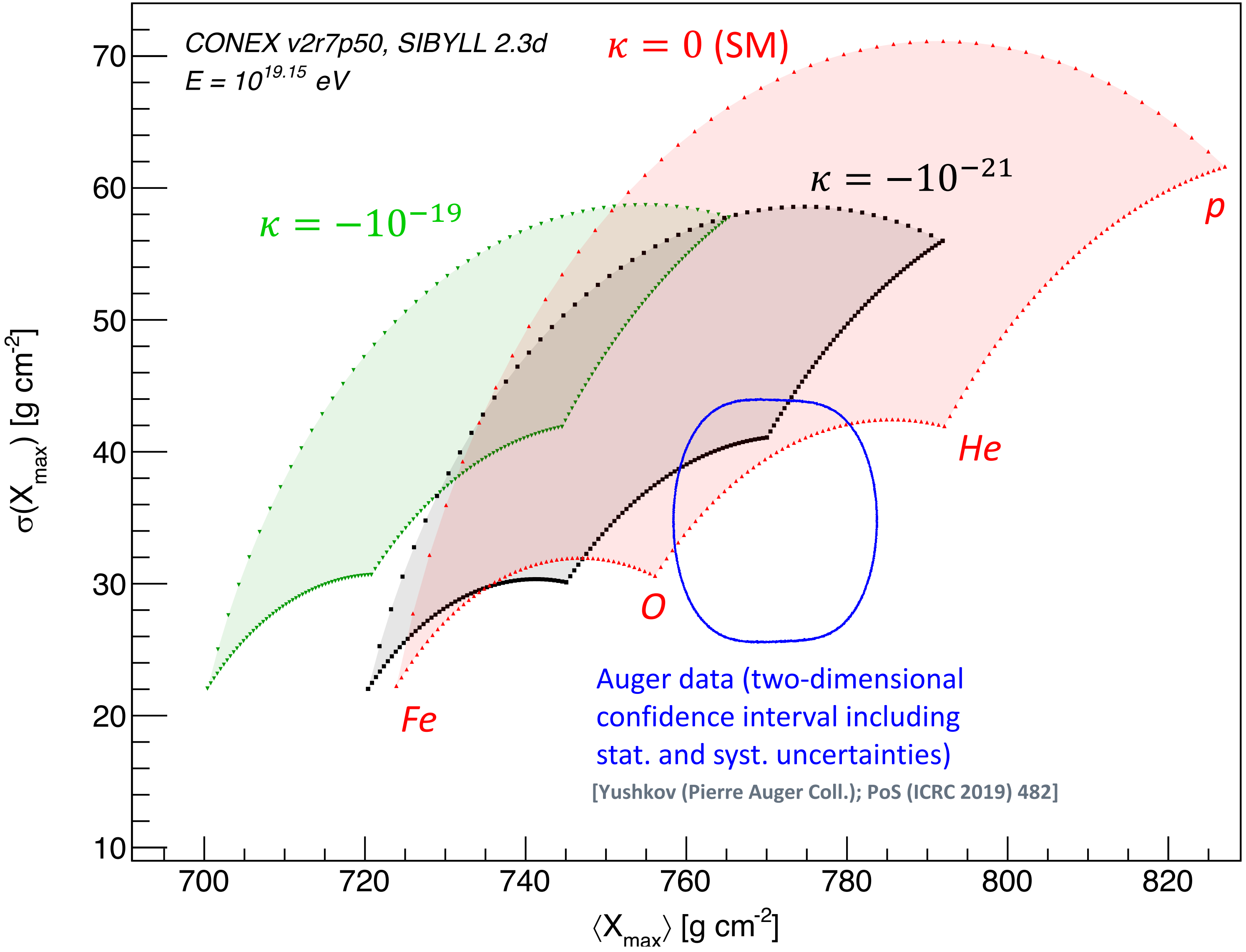
- **Restriction on κ** from microcausality and unitarity: $\kappa \in (-1, 1]$ [Klinkhamer, Schreck; Nucl. Phys. B 848 (2011) 90]
- Photon propagation is determined by the field equations obtained from the previous equations: look specifically at the **phase velocity of the photon**

$$v_\gamma = \frac{\omega}{|\vec{k}|} = c\sqrt{\frac{1-\kappa}{1+\kappa}}$$

  - **Note:** c refers here to the maximum attainable velocity of a massive Dirac fermion (but still $c = 1$ in natural units)
- For **non-zero values** of κ, certain processes **forbidden** in the conventional, Lorentz-invariant theory ($\kappa = 0$) become **allowed** [Jacobson, Liberati, Mattingly; Ann. Phys. 321 (2006) 150] [Kaufhold, Klinkhamer; Nucl. Phys. B 734 (2006) 1]
  - $\kappa > 0$: **vacuum Cherenkov radiation** (VCh), $f^\pm \to f^\pm + \tilde{\gamma}$
  - $\kappa < 0$: **photon decay** (PhD), $\tilde{\gamma} \to e^- + e^+$

Including $\sigma(X_{\max})$

[Duenkel, MN, Risse; Phys. Rev. D 104 (2021) 015010]



Auger data (two-dimensional confidence interval including stat. and syst. uncertainties)

[Yushkov (Pierre Auger Coll.); PoS (ICRC 2019) 482]

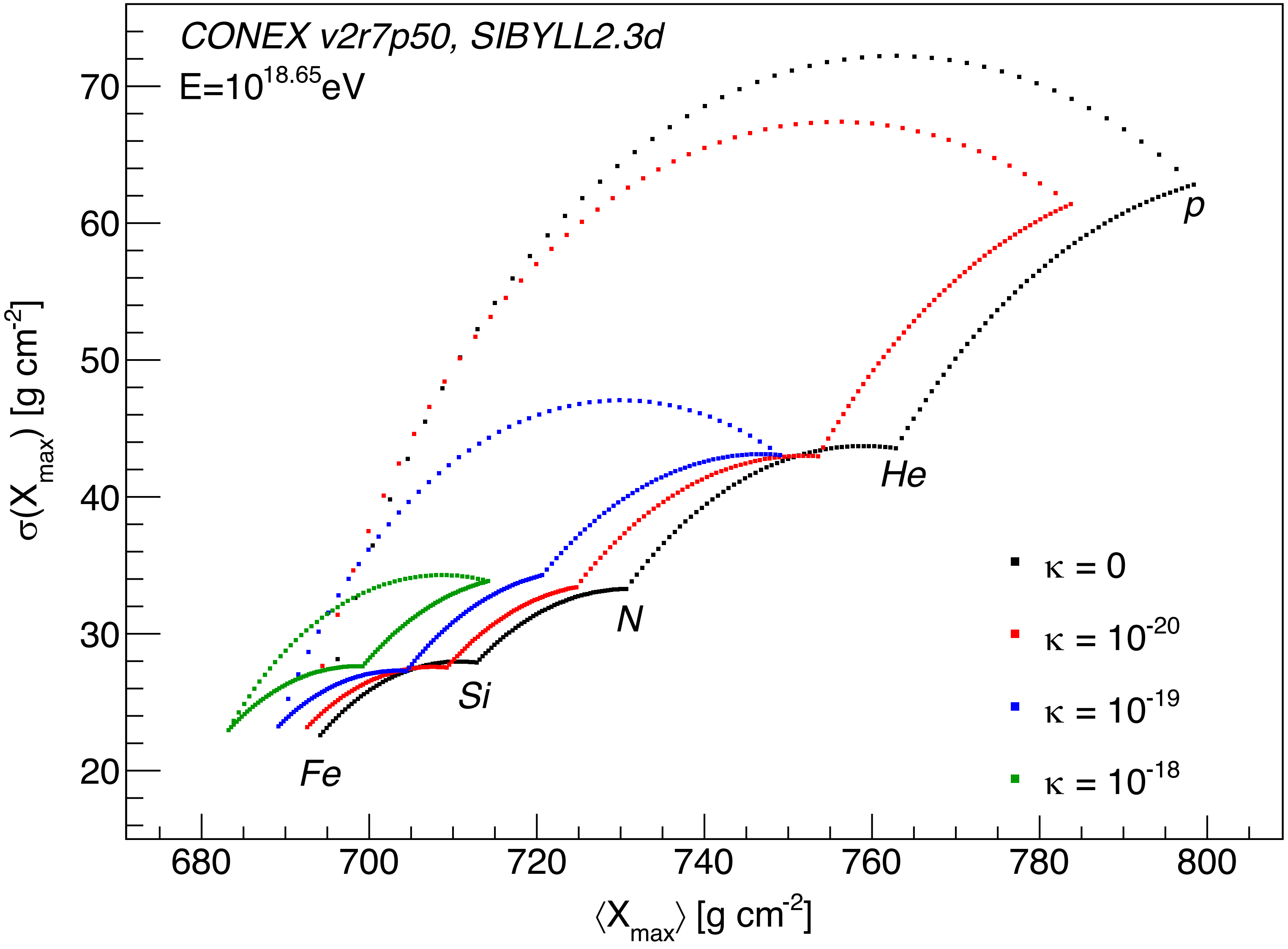
Simulate **mixtures** of protons and heavier nuclei (He, O, Fe)

The **"umbrellas"** bracket the range of allowed values in the $\langle X_{\max}\rangle/\sigma(X_{\max})$ space for a given κ (and energy)

If there is **no overlap** with data in any energy bin, then this κ can be **excluded**

Back to the Umbrella Plots

[Duenkel, MN, Risse; Phys. Rev. D 107 (2023) 083004]



Consequence:

Umbrellas get smaller as more primaries drop out

Result after comparison with Auger data:

$\boldsymbol{\kappa < 3 \times 10^{-20}}$ (98 % C.L.)

Universität Siegen

Naturwissenschaftlich-Technische Fakultät

Searching for photons beyond PeV energies from galactic sources

●Chiara Papior, Marcus Niechciol, Markus Risse

Experimentelle Astroteilchenphysik

Center for Particle Physics Siegen

Universität Siegen

CPPS Retreat 15.02.2024

Funded by

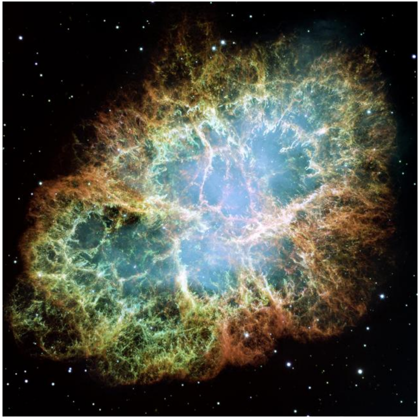
DFG Deutsche Forschungsgemeinschaft

German Research Foundation

PeVatrons as Sources

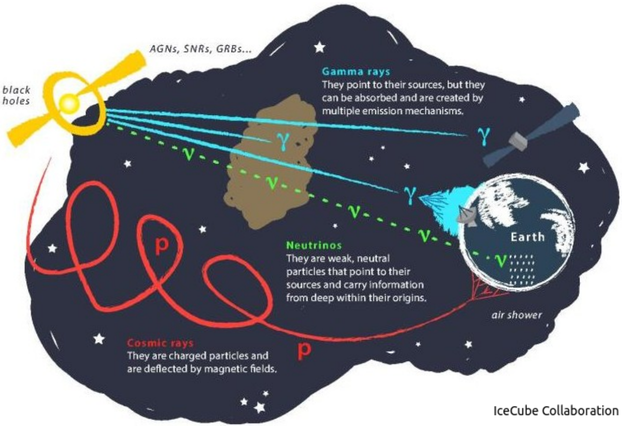
Crab Pulsar: one of the first identified PeVatrons

- PeVatrons: galactic sites of lepton/hadron acceleration up to PeV energies
- Potentially responsible for cosmic rays up to the knee ($\approx 3 - 4\,\mathrm{PeV}$)
- potential PeVatron objects: pulsars and pulsar wind nebulae, supernova remnants, etc.



Hubble image of Crab Nebula, NASA/ESA/JPL/Arizona State Univ.

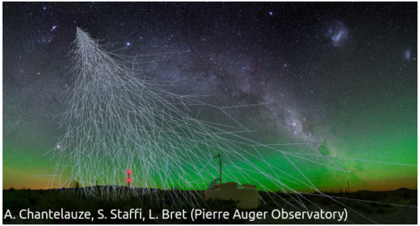
Probing PeVatrons



IceCube Collaboration

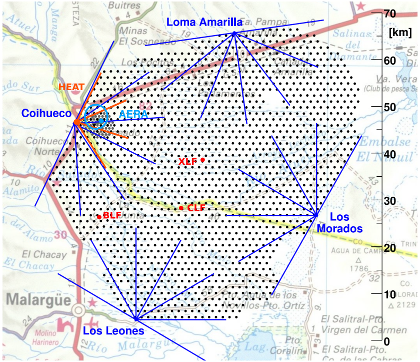
- Charged particles are affected by magnetic fields during their propagation → challenging to trace them back to source
- During their acceleration and propagation, they interact and produce secondary photons → second messenger from PeVatrons

Can we measure PeVatron photons at even higher energies with giant air-shower arrays?


A. Chantelauze, S. Staffi, L. Bret (Pierre Auger Observatory)

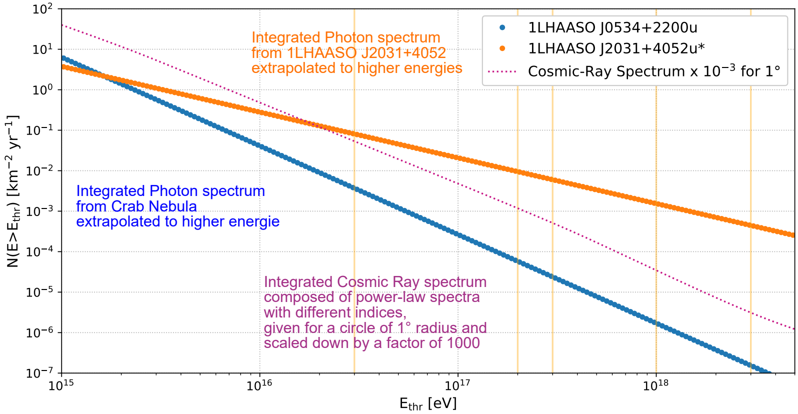
- measurement of secondary particles in air-showers
- challenges: differentiating between hadron- and photon-induced air-showers

The Pierre Auger Observatory as an example of giant-air shower arrays: present minimum energy: $3 \times 10^{16}\,\mathrm{eV}$

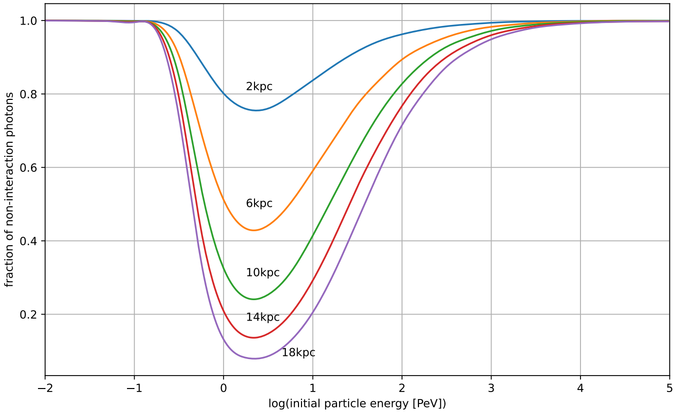


Pierre Auger Coll. Universe 4, 128 (2018)

Comparing photon spectra and cosmic ray background



Work in Progress: Propagational effects

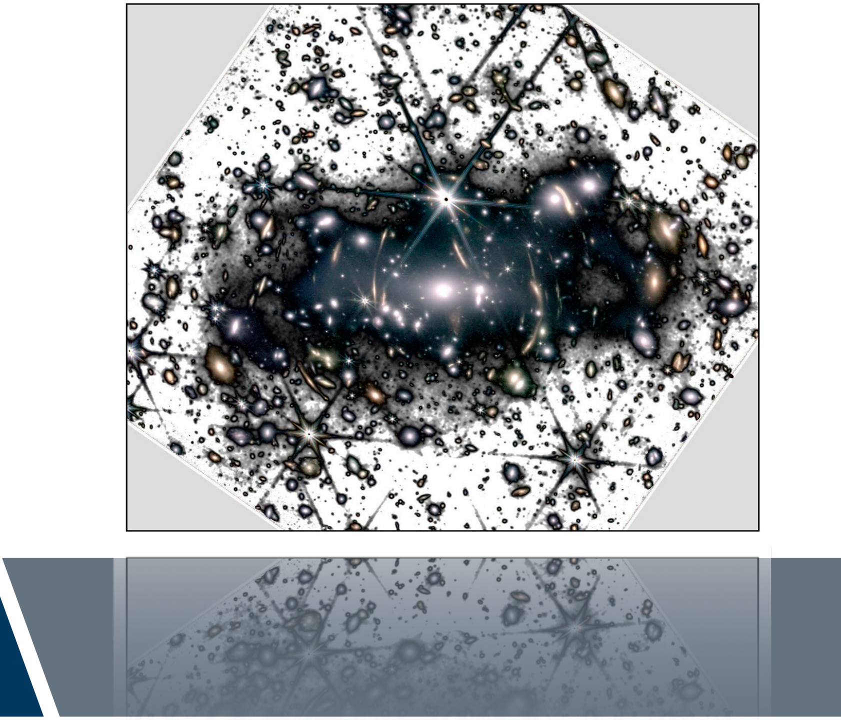


- How do propagational effects influence the measured spectra?
- What kind of effect can we expect for extrapolated spectra?

Universität Siegen

TP1 Theoretical Particle Physics

CPPS Center for Particle Physics Siegen



Super-Heavy Dark Matter

Tom Tong

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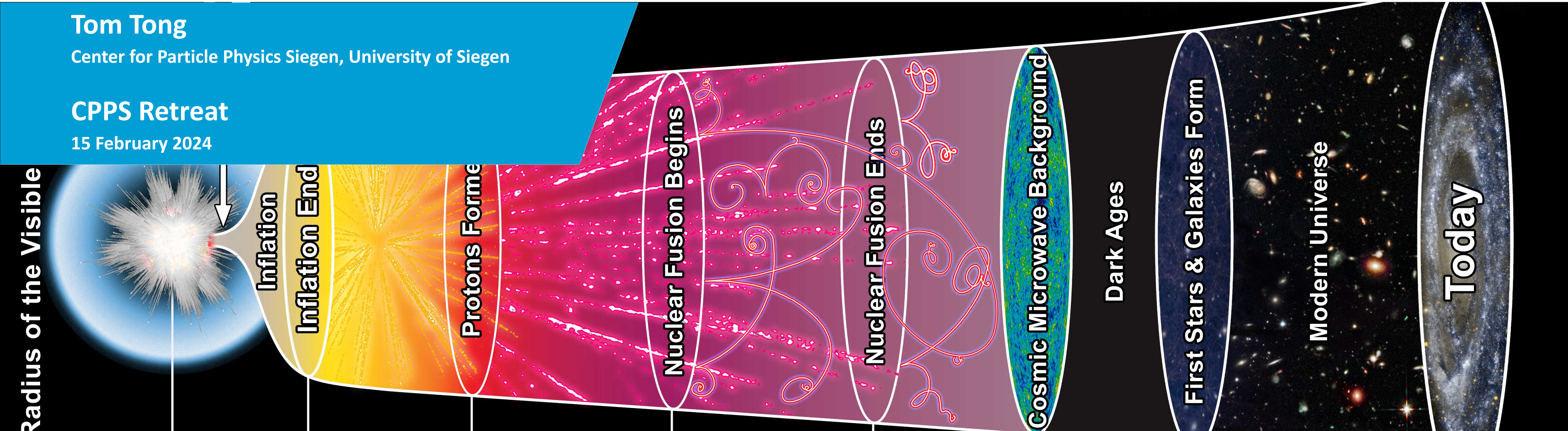
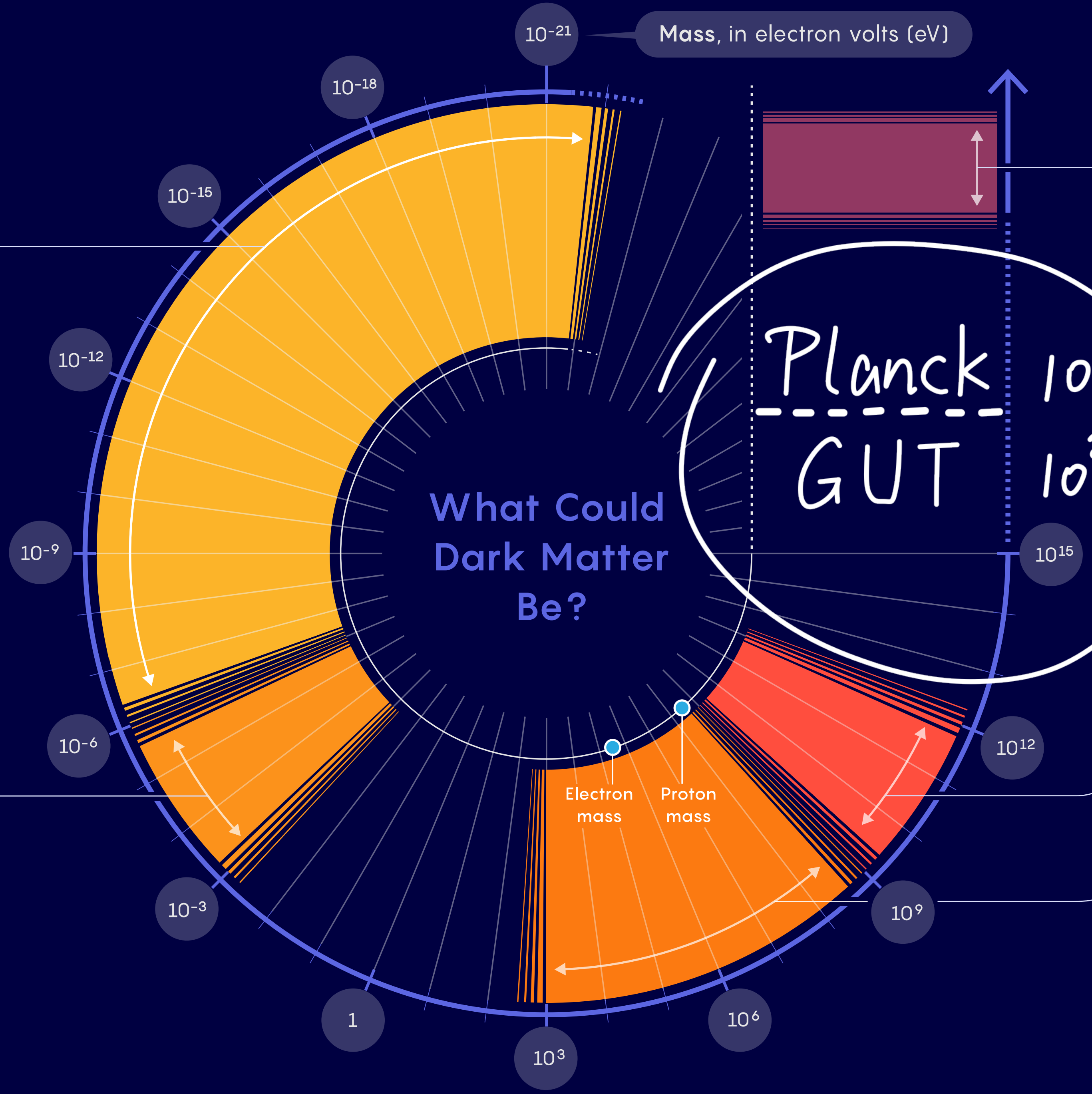


What Could Dark Matter Be?



Planck 10^{28}

GUT 10^{25}

?

ULTRALIGHT DARK MATTER

Mass range
~10^{-22} eV to ~10^{-6} eV

Experiments
CASPEr, MAGIS-100

AXIONS

Mass range
~10^{-6} eV to ~10^{-3} eV

Experiments
ADMX, MADMAX,
QUAX, CAPP-8TB

PRIMORDIAL BLACK HOLES

Mass range
~1 to ~30
solar masses

Experiments
LIGO/Virgo

WIMPs

Mass range
~1 GeV to ~1 TeV

Experiments
XENONnT,
PandaX-4T,
LZ, CRESST, DAMA,
COSINE-100

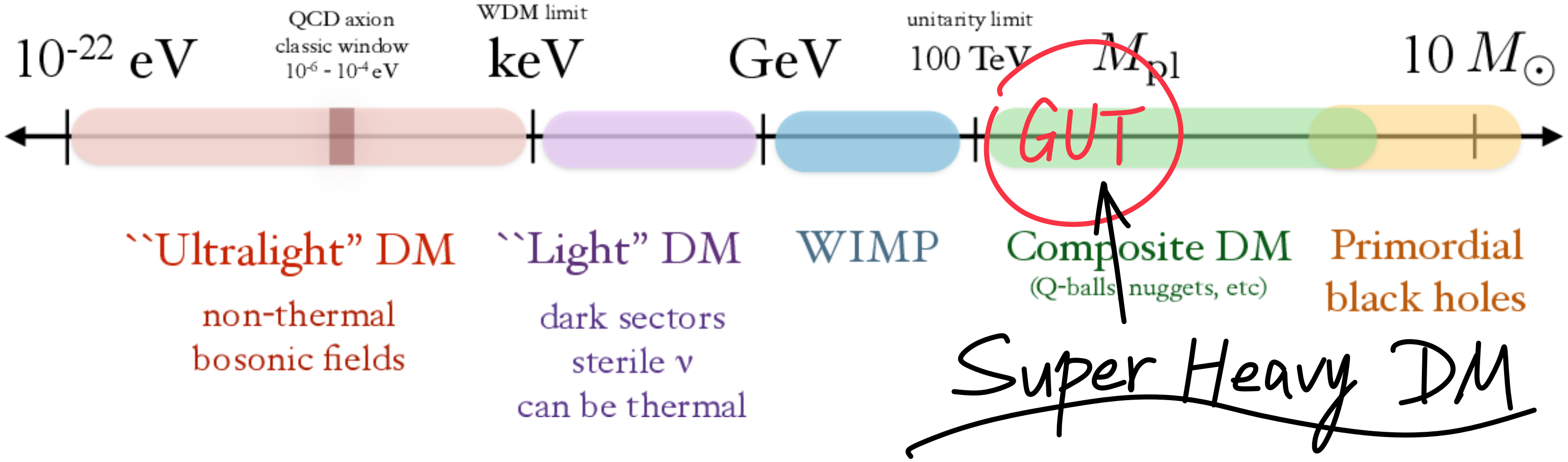
SUB-GeV DARK MATTER

Mass range
~1 keV to ~1 GeV

Experiments
SENSEI, TESSERACT

Mass scale of dark matter

(not to scale)



``Ultralight" DM

non-thermal bosonic fields

``Light" DM

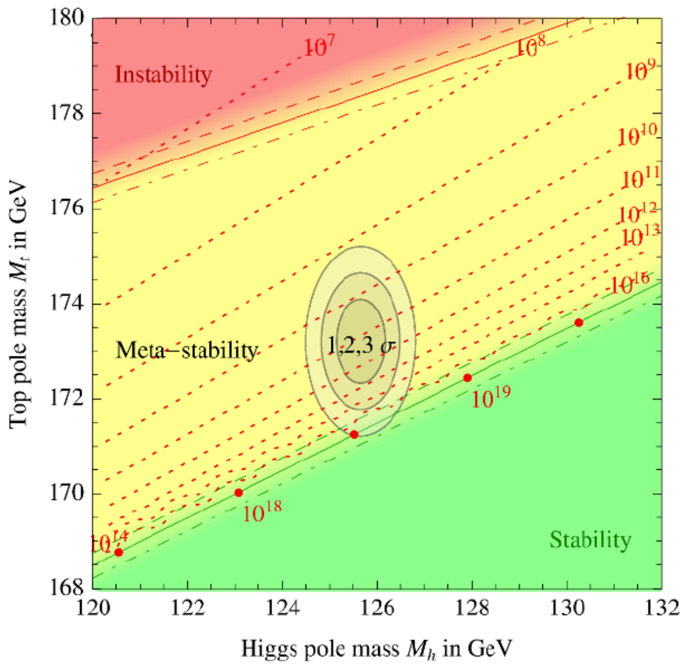
dark sectors
sterile ν
can be thermal

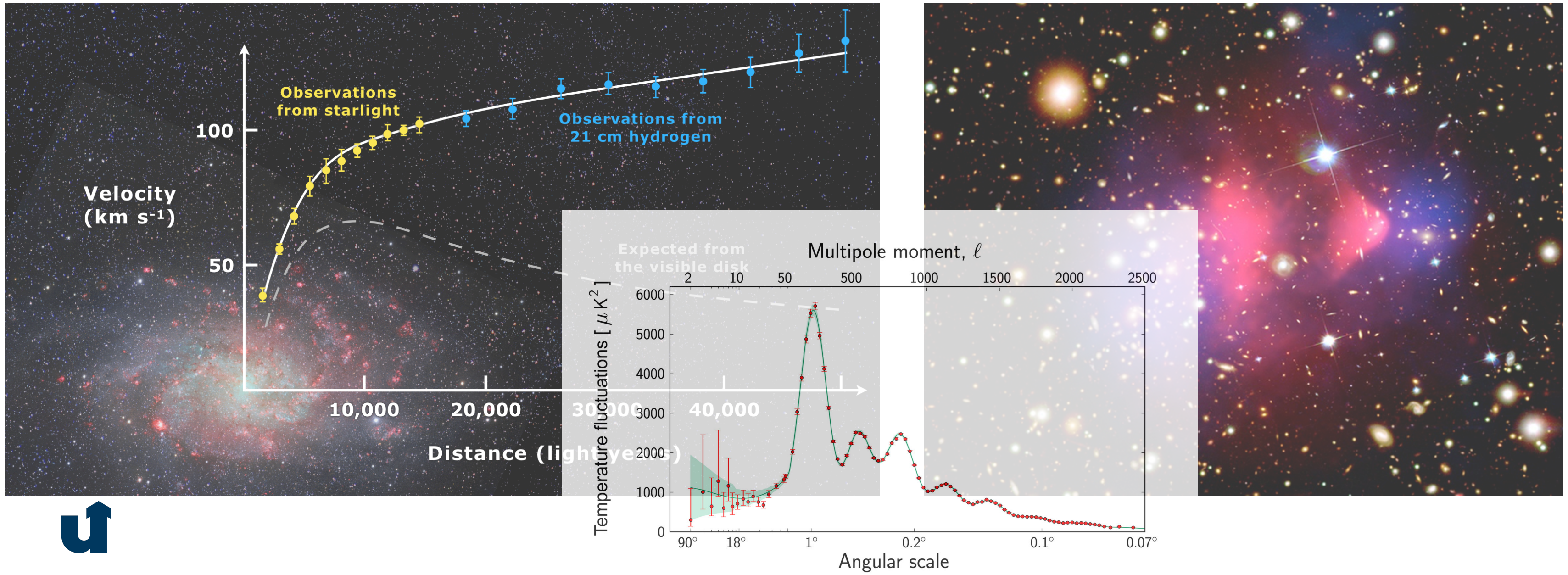
WIMP

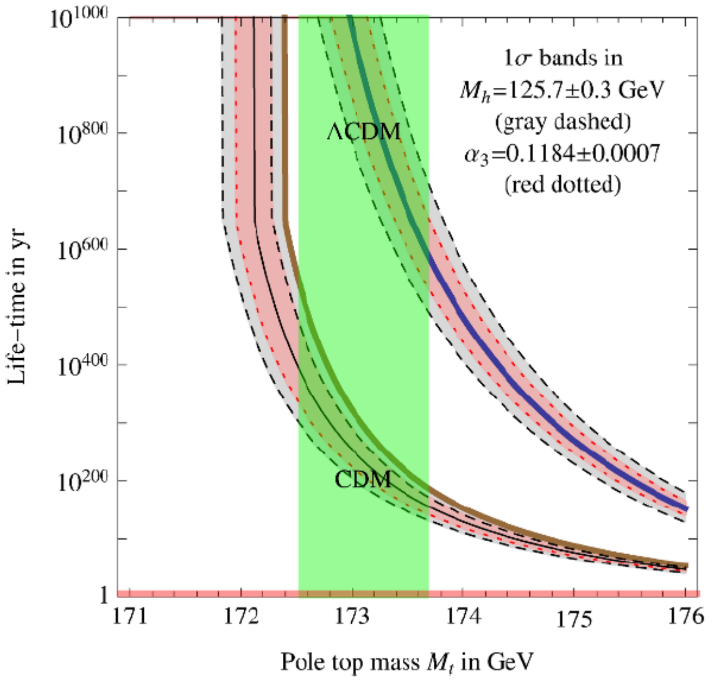
Composite DM
(Q-balls, nuggets, etc)

Primordial black holes

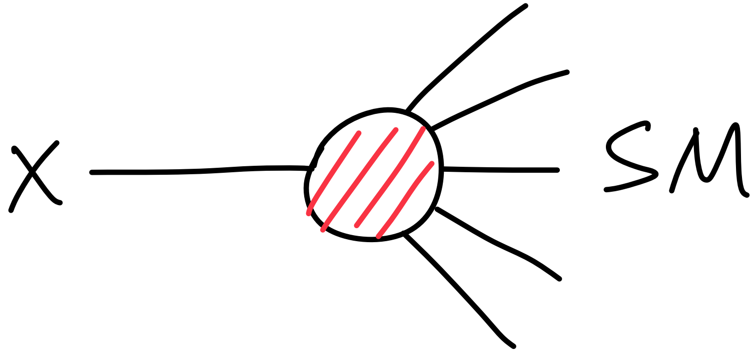
Super Heavy DM







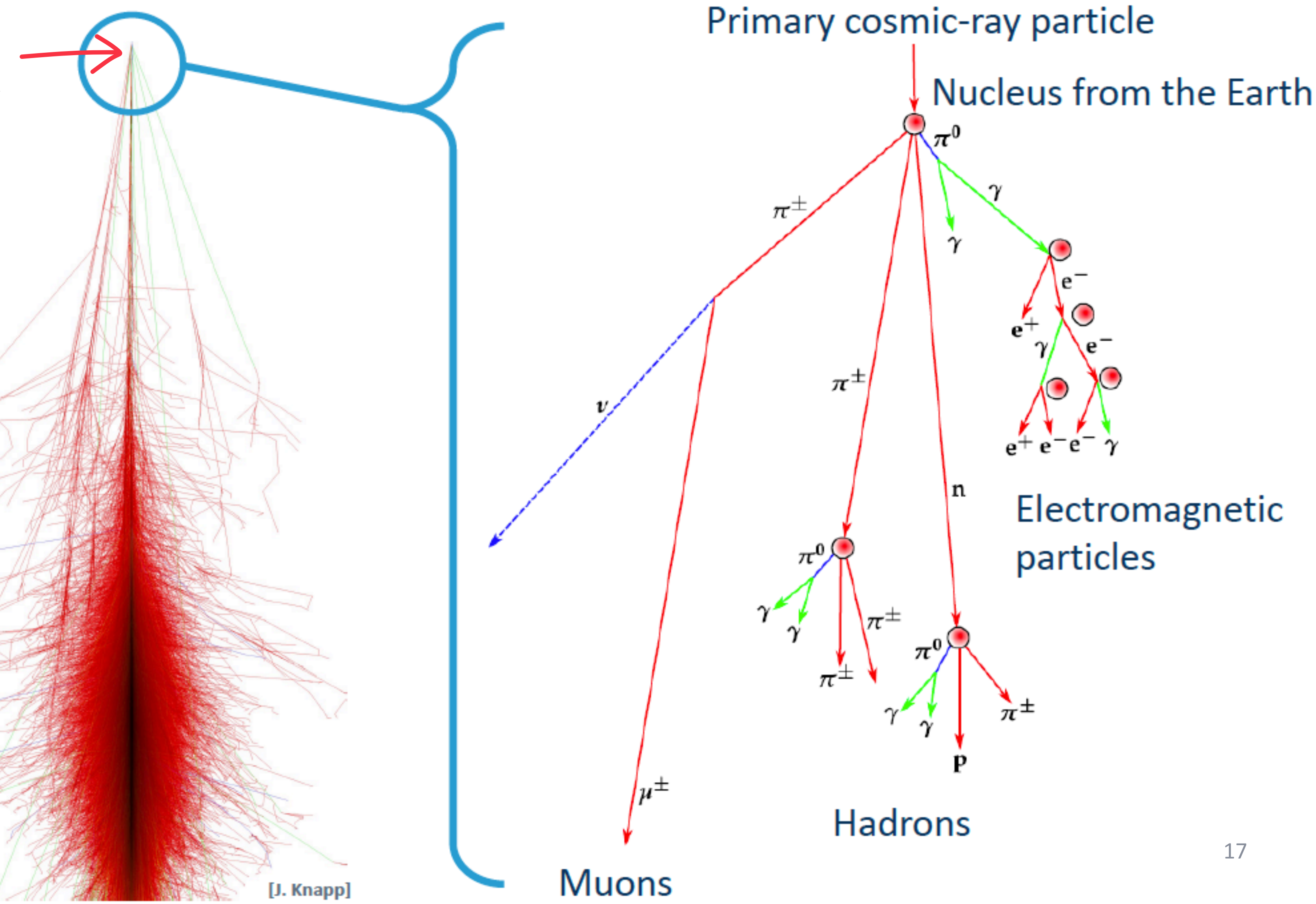
SHDM Decay Scenario: Pertubative, with a small coupling to the SM



$$\mathcal{L} = \frac{g}{\Lambda^n} X [SM]$$

$$\tau_X \sim \frac{1}{g^2}\left(\frac{\Lambda}{M_X}\right)^{2n}$$

$$\Lambda \sim GUT \sim 10^{16} GeV$$


[J. Knapp]

Primary cosmic-ray particle

Nucleus from the Earth

Electromagnetic particles

Hadrons

Muons

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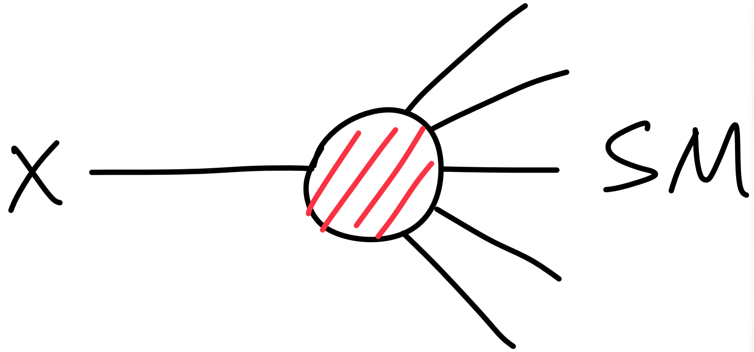

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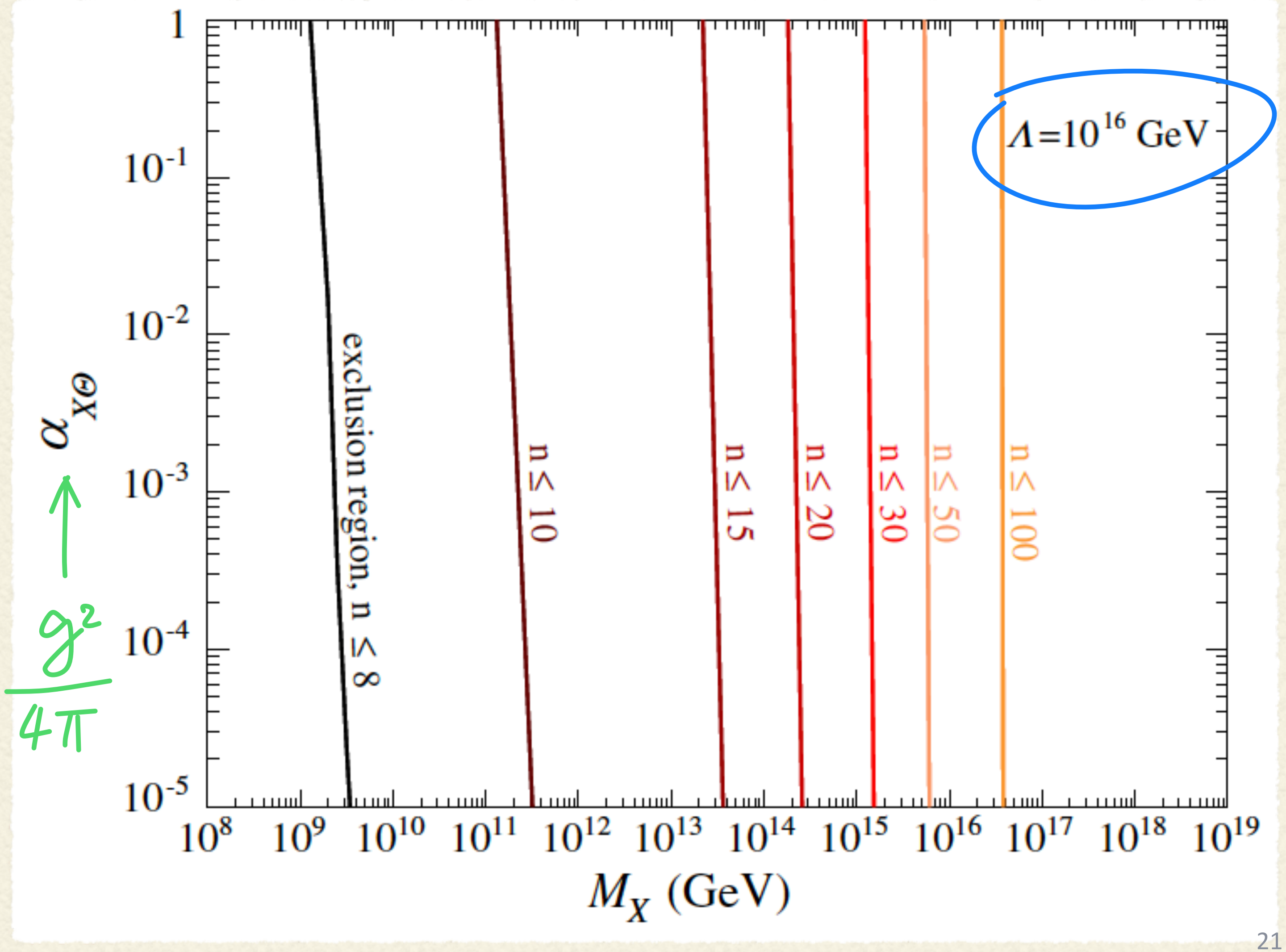
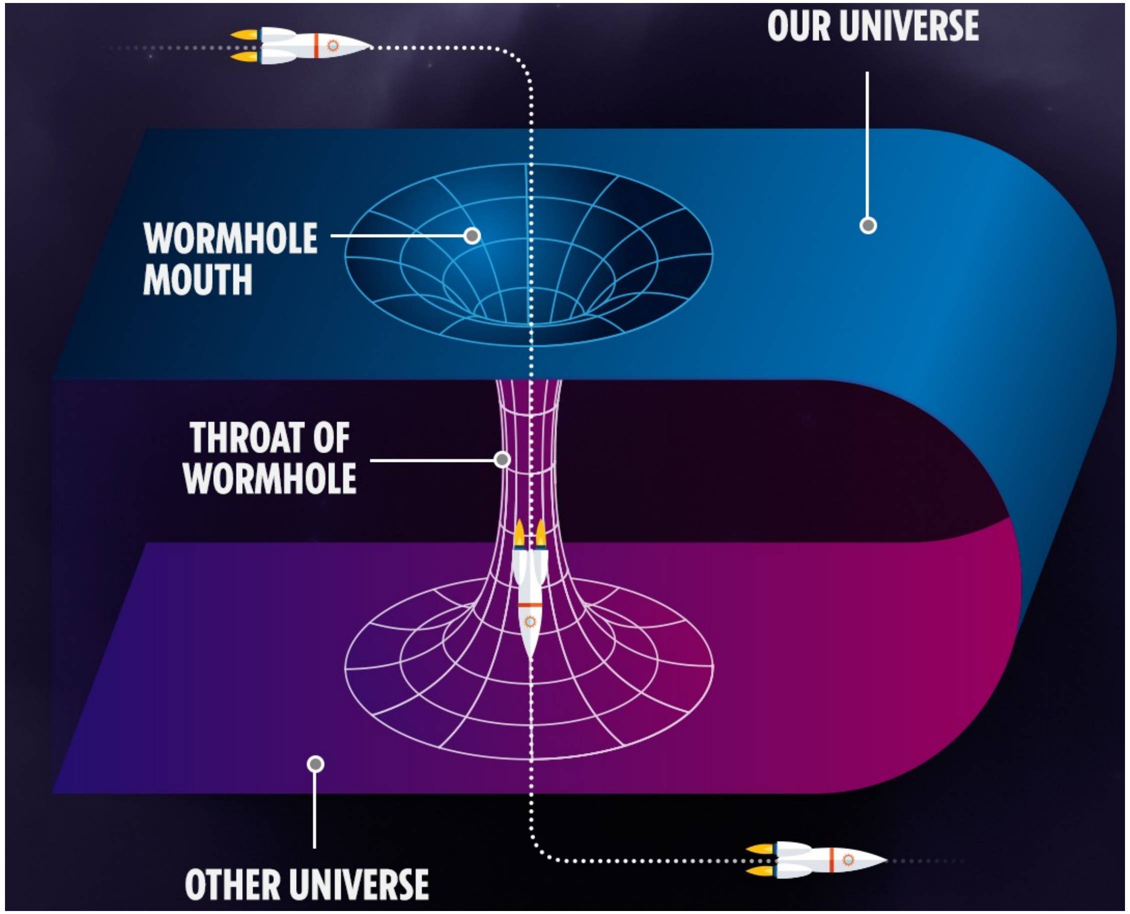
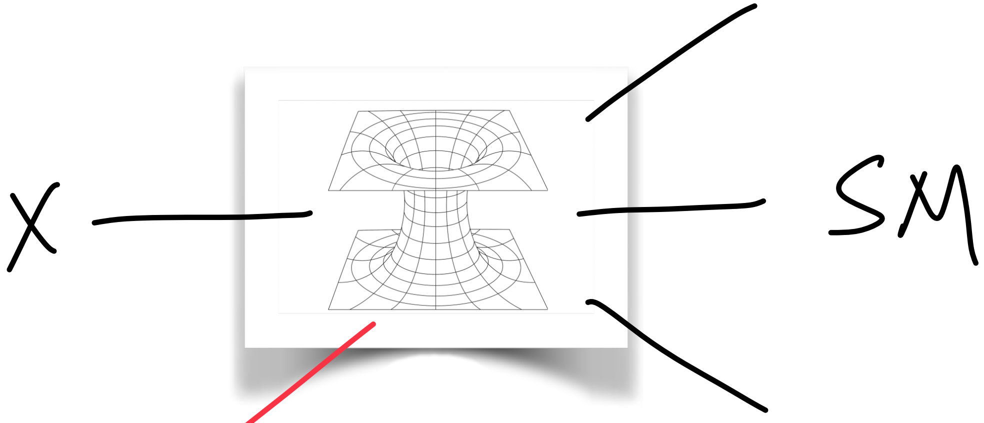


Gravity eats ALL



- Assume the DM is stable
- Protected by a global symmetry
- The new quantum number is respected by all particle interactions
- Even such a DM particle can decay
- Through gravitational instanton
- Quantum gravity effects!

SHDM Decay Scenario: Non-pertubative



$$e^{-S}, \quad S \sim \left(\frac{R}{L_P}\right)^2 > 80 \approx \frac{8\pi^2}{g_s^2}$$

$$\tau_X \sim \frac{e^{2S}}{M_X} \sim \frac{e^{\frac{4\pi}{\alpha}}}{M_X} > 10^{22} y$$