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Revisiting γγ absorption for UHE photons

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Outline

- Ultra-high-energy photons
- Photon background
- Cross sections
- Results
- Conclusions

Ultra-high-energy photons

UHE photons

- Ultra-high-energy (UHE, $E > 10^{18}$ eV) photons → by-product of the photo-meson reactions $p\gamma_{\mathrm{CMB}} \rightarrow \Delta^{+} \rightarrow p\pi^{0} \rightarrow p\gamma\gamma$ (GZK radius)
- Resulting UHE photons interaction with background photons γ_{b}
- UHE photons absorbed via processes $\gamma_{\mathrm{UHE}}\gamma_{\mathrm{b}} \rightarrow$ any
- Considered processes:
  - $\gamma\gamma \rightarrow e^{+}e^{-}$
  - $\gamma\gamma \rightarrow e^{+}e^{-}e^{+}e^{-}$

Gelmini et al., 2007, 2008
Aab et al., 2017
Heiter et al., 2018

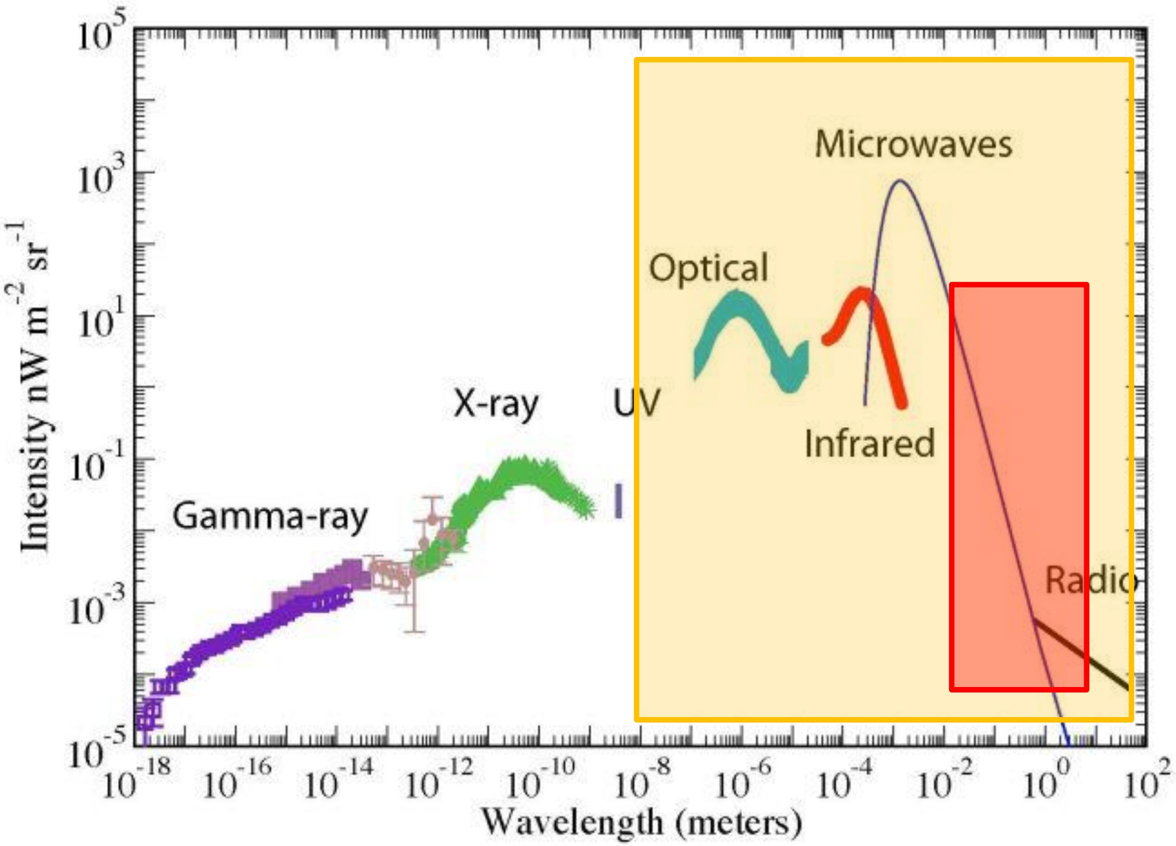
UHE photon propagation

Are other processes beyond the already considered ones $\gamma\gamma \rightarrow e^+e^-$ and $\gamma\gamma \rightarrow e^+e^-e^+e^-$ relevant for UHE photons?

YES: $\gamma\gamma \rightarrow \mu^+\mu^-$ and $\gamma\gamma \rightarrow$ hadrons give sizable effects for energies $E > 10^{19}$ eV

Photon background

Photon background



- Hard produced photons with energy E > 100 GeV interact mainly (near the threshold) with soft background photons with energy ε < 10 eV ($\gamma\gamma \rightarrow e^+e^-$)
- High background photon density from optical to radio wavelengths (**yellow area**)
- Sizable modification in the optical depth τ in low-microwave – radio range (**red area**)

Photon background (2)

EBL (Extragalactic Background Light)

- UV-optical-infrared background
- Direct product of the *stellar radiation* and *light absorbed and reradiated* by the *dust* during the whole cosmic evolution
- Photon number density from model of Gilmore et al., 2012

CMB (Cosmic Microwave Background)

- Photons (now redshifted) existing in the Universe at the time of photon decoupling for the formation of neutral atoms
- Black body photon number density at temperature T = 2.7 K

Radio Background

- Diffuse thermal and nonthermal, galactic and extragalactic radiation
- Photon number density from model of Gervasi et al., 2008

Cross Sections

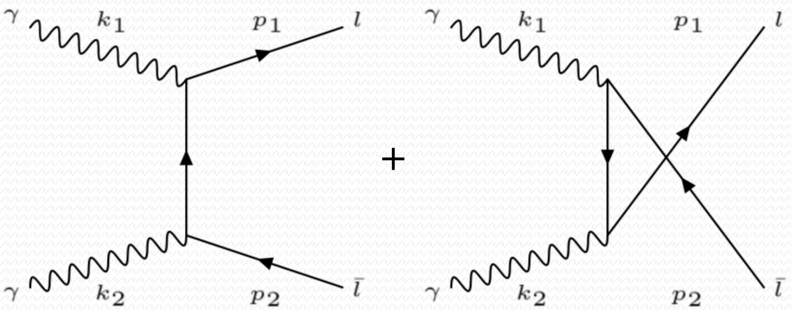
Leptonic sector

SINGLE PAIR PRODUCTION

- $\gamma\gamma \rightarrow l^+l^-$ ($l = e, \mu, \tau$)

$$\sigma_{\gamma\gamma\to l\bar{l}}(\omega,p) = \frac{\pi\alpha^2}{\omega^2}\left\{\left(1+\frac{m^2}{\omega^2}-\frac{1}{2}\frac{m^4}{\omega^4}\right)\times \times \ln\left[\frac{(\omega+p)^2}{m^2}\right] - \frac{p}{\omega}\left(1+\frac{m^2}{\omega^2}\right)\right\}$$

- $\gamma\gamma \rightarrow e^+e^-$ already considered
- $\gamma\gamma \rightarrow \mu^+\mu^-$ gives sizable effects
- $\gamma\gamma \rightarrow \tau^+\tau^-$ negligible



CM: $k_1 \equiv (\omega, \boldsymbol{\omega})$; $k_2 \equiv (\omega, -\boldsymbol{\omega})$; $p_1 \equiv (\omega, \mathbf{p})$; $p_2 \equiv (\omega, -\mathbf{p})$
$\omega \rightarrow$ photon energy; $\mathbf{p} \rightarrow$ lepton 3-momentum
$s_{CM} = 4\omega^2$

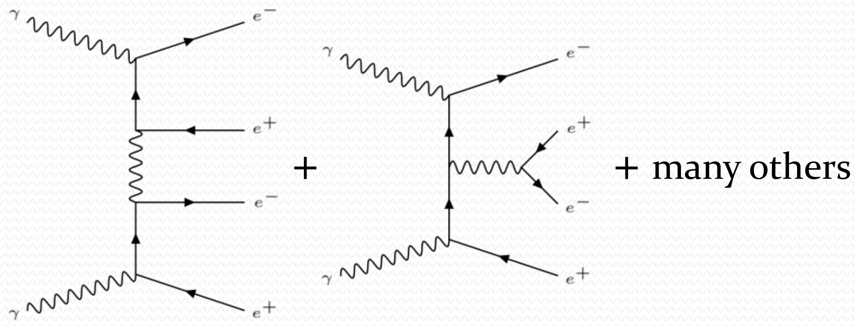
See also: Breit & Wheeler, 1934

DOUBLE PAIR PRODUCTION

- $\gamma\gamma \rightarrow e^+e^-e^+e^-$ already considered

$$\sigma_{\rm DPP}(s) = \frac{\alpha^4}{\pi m_e^2}\left(\frac{175}{36}\zeta(3)-\frac{19}{18}\right)\left(1-\frac{16m_e^2}{s}\right)^6$$

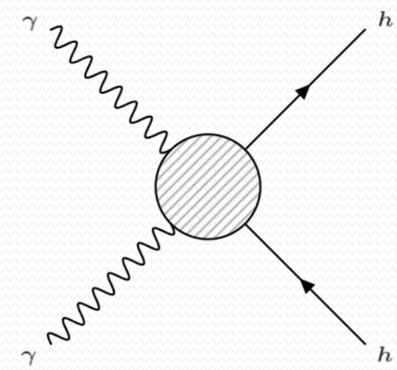
- Other four lepton production negligible

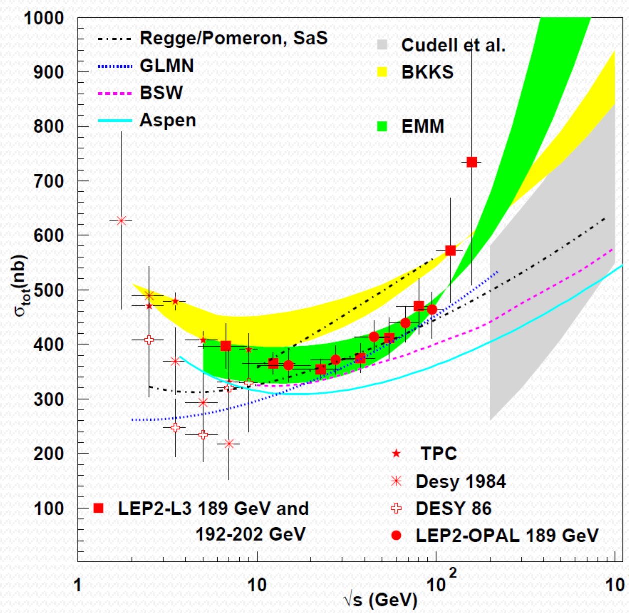


Brown, Hunt, Mikaelian & Muzinich, 1973
da Silva & Kapusta, 2012

Hadronic sector

- $\gamma\gamma \rightarrow$ hadrons
- QCD non perturbative effects complicate a calculation from *first principles*
- Phenomenological approach
- Lowest massive hadrons → $\pi^{\pm}$, π^{0} mesons
- Threshold → $E_{th} = 2\, m_{\pi}$
- Near threshold $\sigma_{\gamma\gamma \rightarrow \text{hadrons}}$ similar (bigger) as respect to $\sigma_{\gamma\gamma \rightarrow \pi^{+}\pi^{-}}$ (sQED)
- At high energies → data from colliders
- Smooth low-high energy junction with uncertainty





Godbole, Roeck, Grau & Pancheri, 2003

Resonances

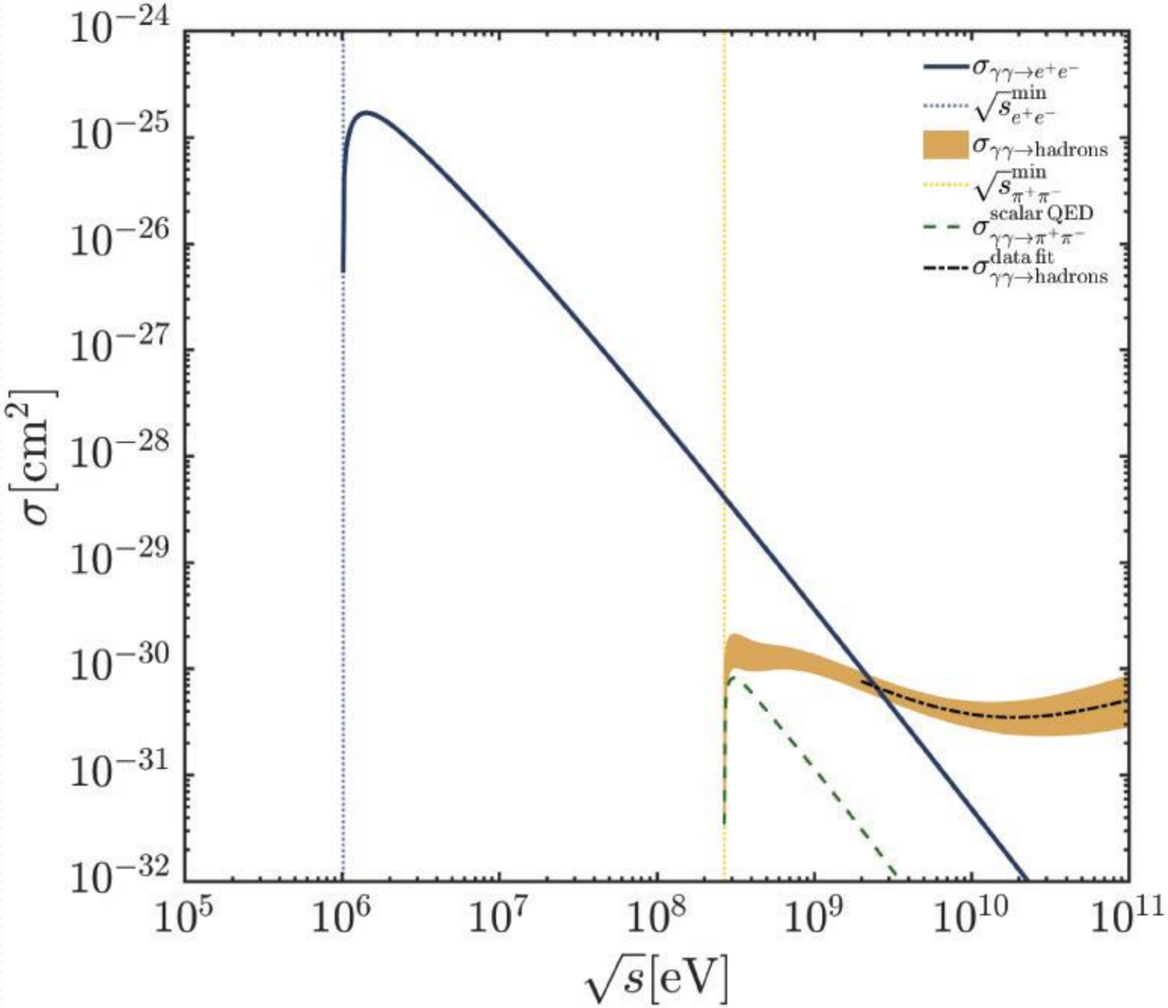
- Prototype: single π^o production $\gamma\gamma \rightarrow \pi^o$
- Inverse process of π^o decay

$$\sigma_{\gamma\gamma\to\pi^0}(s) = \frac{8\pi^2}{m_{\pi^0}}\Gamma_{\pi^0\to\gamma\gamma}\delta\left(s - m_{\pi^0}^2\right)$$

- $\Gamma_{\pi^o \rightarrow \gamma\gamma}$ → experimental π^o decay rate
- We consider:
  - Single neutral meson production (π^o, η, η', η_c)
  - *para*-positronium *p*-Ps production
- Decay rates and masses from experimental data

DATA from: Tanabashi et al., (Particle Data Group), 2018

Cross sections



Galanti, Tavecchio, Piccinini & Roncadelli, in preparation

- Hadronic data fitting function (high energies):
- $\sigma_{\gamma\gamma \to \mathrm{hadrons}}(s) =$
  $= A \cdot s^{\varepsilon} + B \cdot s^{-\eta}$

with

  - $A = 51 \cdot 10^{-33}$ cm²
  - $B = 1132 \cdot 10^{-33}$ cm²
  - $\varepsilon = 0.240$
  - $\eta = 0.358$

Godbole, Roeck, Grau & Pancheri 2003

- At low energies:
- $\sigma_{\gamma\gamma \to \mathrm{hadrons}} =$
  $= \kappa\, \sigma_{\gamma\gamma \to \pi^+\pi^-}$

with $\kappa = 1.25 - 2.5$

Results

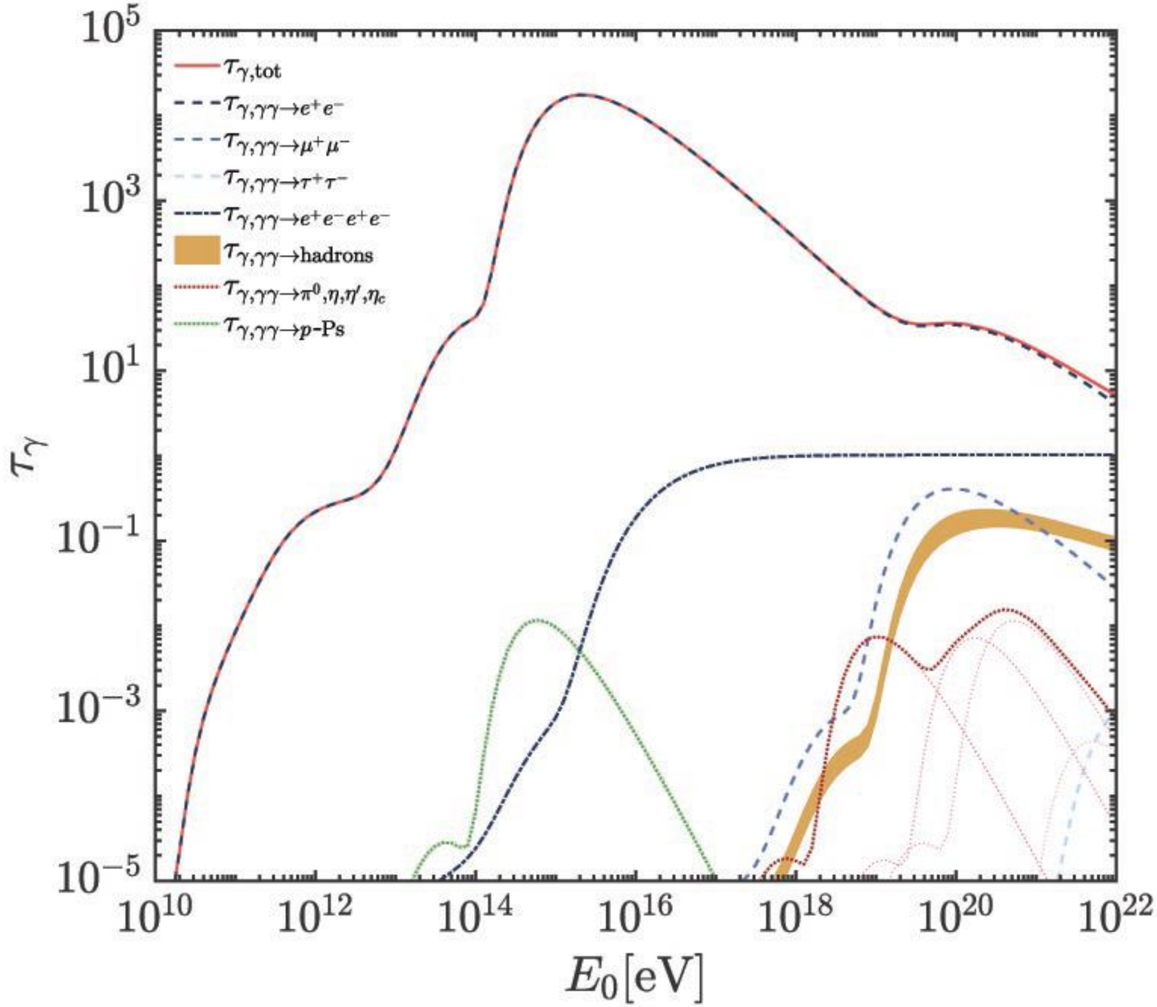
Calculation of the optical depth

- CM frame: $s_{CM} = 4\omega^2$ → generic frame: $s_{gen} = E\,\varepsilon\,(1 - \cos\varphi)$
  - E → incoming hard photon energy (E_0 → observed energy)
  - ε → background photon energy
  - φ → angle between the two photon 3-momenta
- Optical depth τ_γ at a redshift z_s of a photon of energy $E = (1 + z_s)E_0$

$$\tau_\gamma(E_0, z_s) = \int_0^{z_s} \mathrm{d}z\, \frac{\mathrm{d}l(z)}{\mathrm{d}z} \int_{-1}^{1} \mathrm{d}(\cos\varphi)\, \frac{1-\cos\varphi}{2} \int_{\epsilon_{\mathrm{thr}}(E(z),\varphi)}^{\infty} \mathrm{d}\epsilon(z)\, n_\gamma(\epsilon(z), z)\, \sigma_{\gamma\gamma}\big(E(z), \epsilon(z), \varphi\big)$$

  - $\mathrm{d}l(z)$ → line element
  - n_γ → background photon number density
  - $\sigma_{\gamma\gamma}$ → cross section of one of the considered processes $\gamma\gamma$ → any
  - $\varepsilon_{thr} = m_{thr}^2/2E(1 - \cos\varphi)$, m_{thr} → total mass of the produced particles
- Photon survival provability: $P_\gamma = e^{-\tau_\gamma}$

Optical depth z_s = 0.03 (≈130 Mpc)



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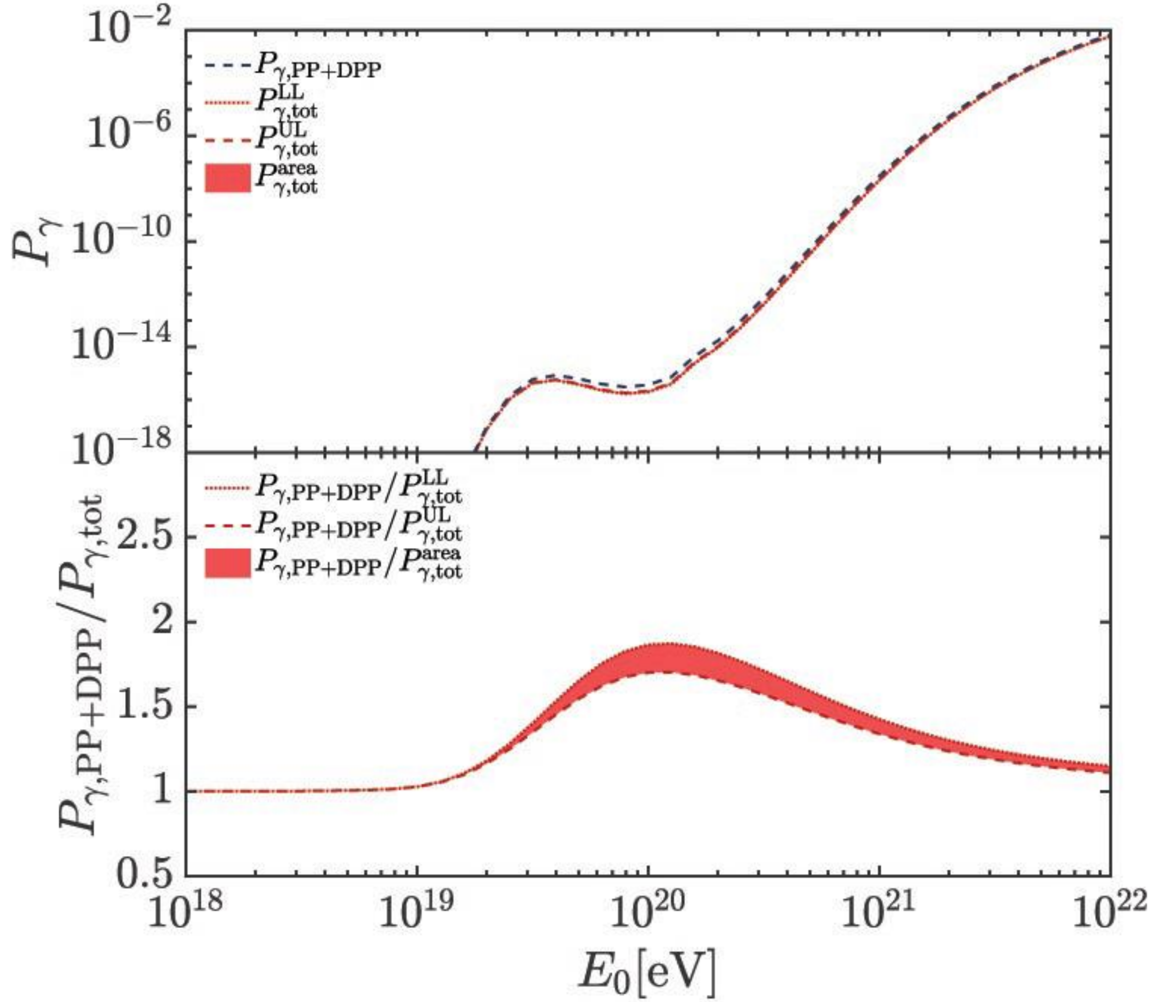
Photon survival probability



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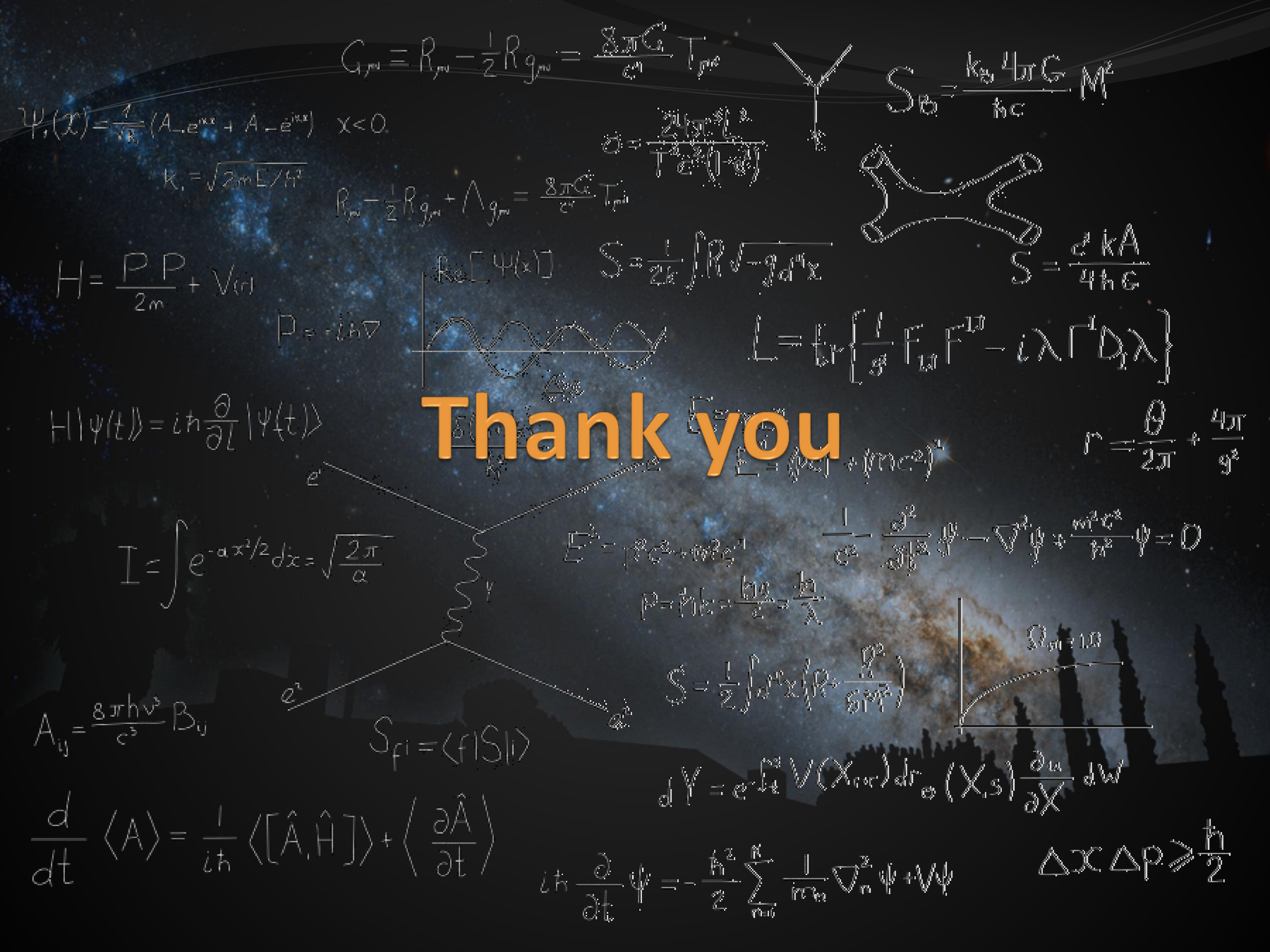
Conclusions

Conclusions

- Already considered processes: $\gamma\gamma \rightarrow e^+e^-$ and $\gamma\gamma \rightarrow e^+e^-e^+e^-$
- $\gamma\gamma \rightarrow \mu^+\mu^-$ and $\gamma\gamma \rightarrow$ hadrons are not negligible in the UHE band and especially around 10^{20} eV
- Other processes are subdominat
- Some uncertainty in the hadronic sector
- Total optical depth $\tau_{\gamma,tot}$ changes by about 2%
- The photon survival probability $P_{\gamma,tot}$ modified by a factor of 2 at redshift $z_s = 0.03$ ($\approx$ 130 Mpc)
- Upper limits of UHE photon flux should be accordingly modified

Thank you



$G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$
$H = \frac{P \cdot P}{2m} + V(r)$
$H|\psi(t)\rangle = i\hbar \frac{\partial}{\partial t} |\psi(t)\rangle$
$I = \int e^{-\alpha x^2/2} dx = \sqrt{\frac{2\pi}{\alpha}}$
$E = mc^2$
$E^2 = (pc)^2 + (mc^2)^2$
$S = \frac{c^3 kA}{4\hbar G}$
$A_{ij} = \frac{8\pi h \nu^3}{c^3} B_{ij}$
$S_{fi} = \langle f|S|i \rangle$
$\frac{d}{dt} \langle A \rangle = \frac{1}{i\hbar} \langle [\hat{A}, \hat{H}] \rangle + \left\langle \frac{\partial \hat{A}}{\partial t} \right\rangle$
$\Delta x \Delta p \geq \frac{\hbar}{2}$