Astroparticle theory efforts at the Université catholique de Louvain

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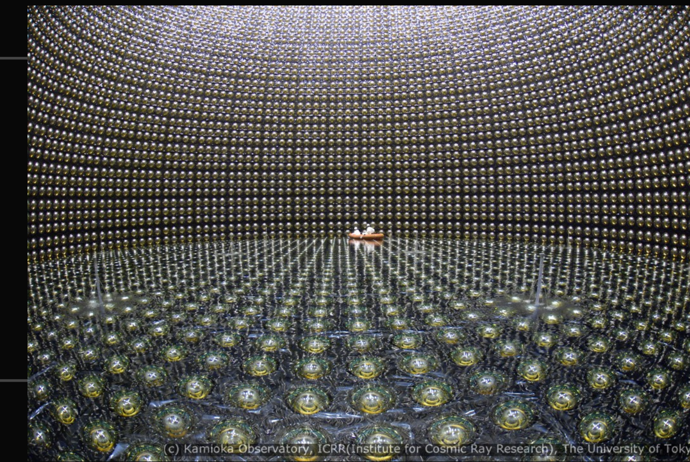
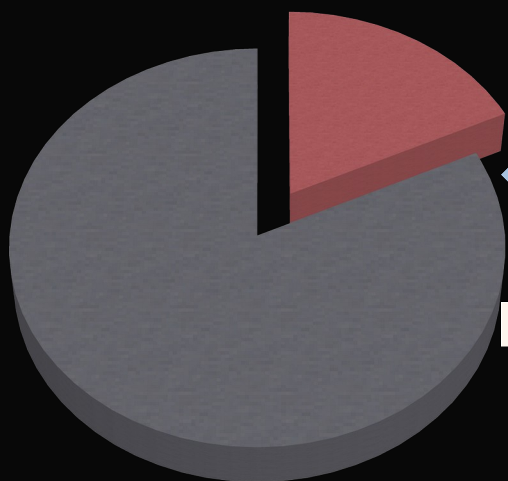
Université catholique de Louvain

October 29th 2021

❖ What is the origin of neutrino mass?



Possible key to embed Standard Model in a more fundamental theory of Nature

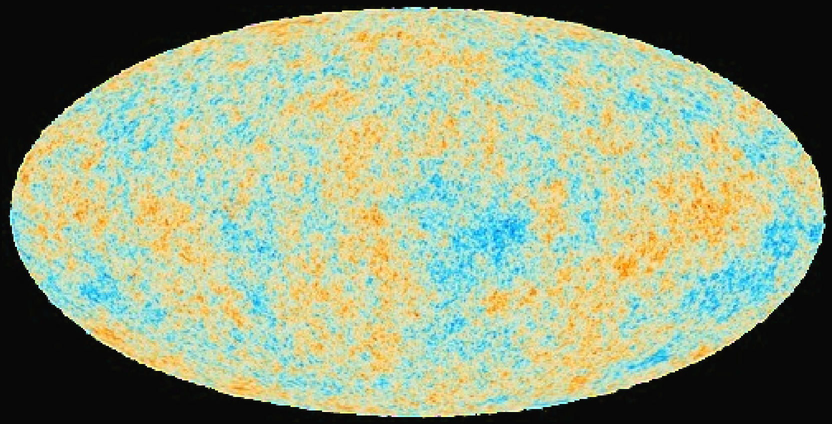


❖ What is the Dark Matter made of?

It makes up most of the mass in the universe.

❖ Why was there more matter than antimatter in the early universe?

…so that some matter survived the mutual annihilation to form galaxies, stars etc.



❖ What set the initial conditions for the "hot big bang"?

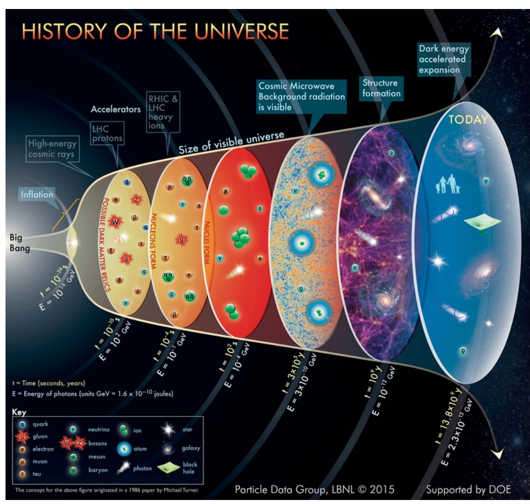
Cosmic inflation? How did the transition to the radiation dominated epoch happen?

Cosmology

Particle Physics

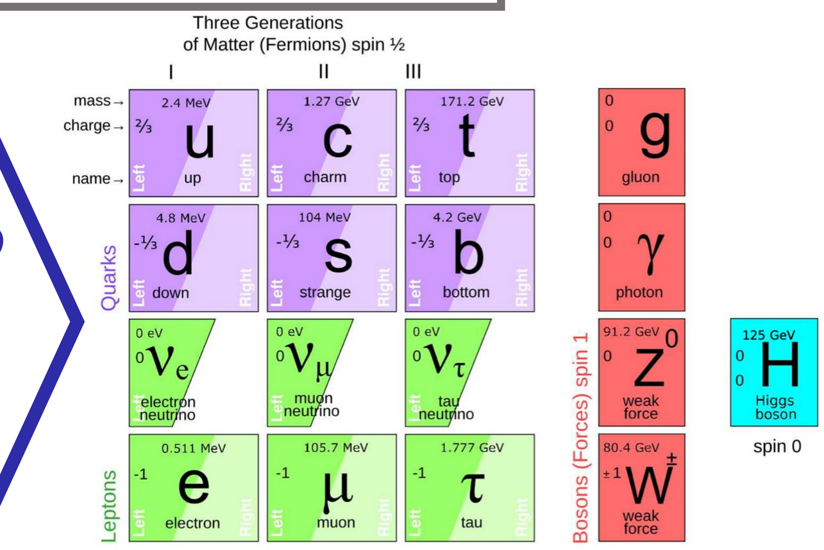
Extreme conditions in the early universe can probe particle physics theories in regimes inaccessible to laboratory experiments

Theories beyond the "Standard Model" can provide explanations for puzzles in cosmology



CP3 Particle Cosmology Group

Marco Drewes, Garv Chauhan, Juraj Klaric, Jamie McDonald, Isabel Oldengott, Mubarak Abdallah, Yannis Georis, Valentin Weber



Testable baryogenesis scenarios.
Making predictions for collider and intensity frontier experiments.

New paths to Hidden Sectors.
Turning every stone, full exploration of accelerator facilities' discovery potential.

Dark Matter Quantum Kinetic Theory.
Production in the early universe, predictions for experiments.

Neutrino masses as a key to New Physics.
Combine different "frontiers" to unveil the origin of neutrino mass

Nonequilibrium dynamics of scalar fields.
Inflation, reheating and the CMB

Neutrinos in extreme environments.
Early universe, compact stars…

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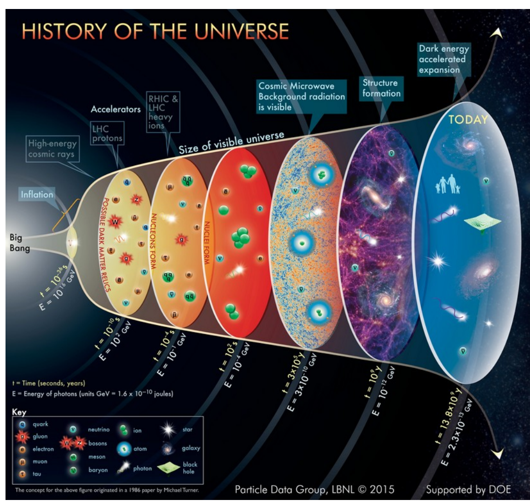

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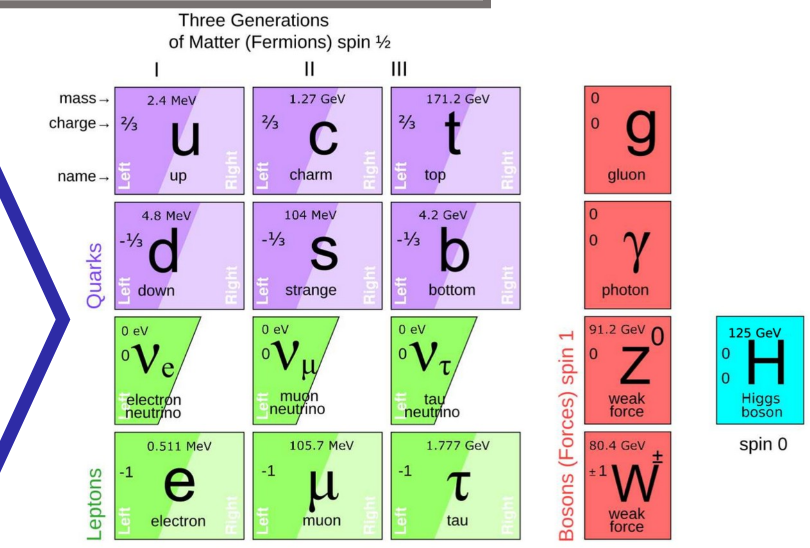

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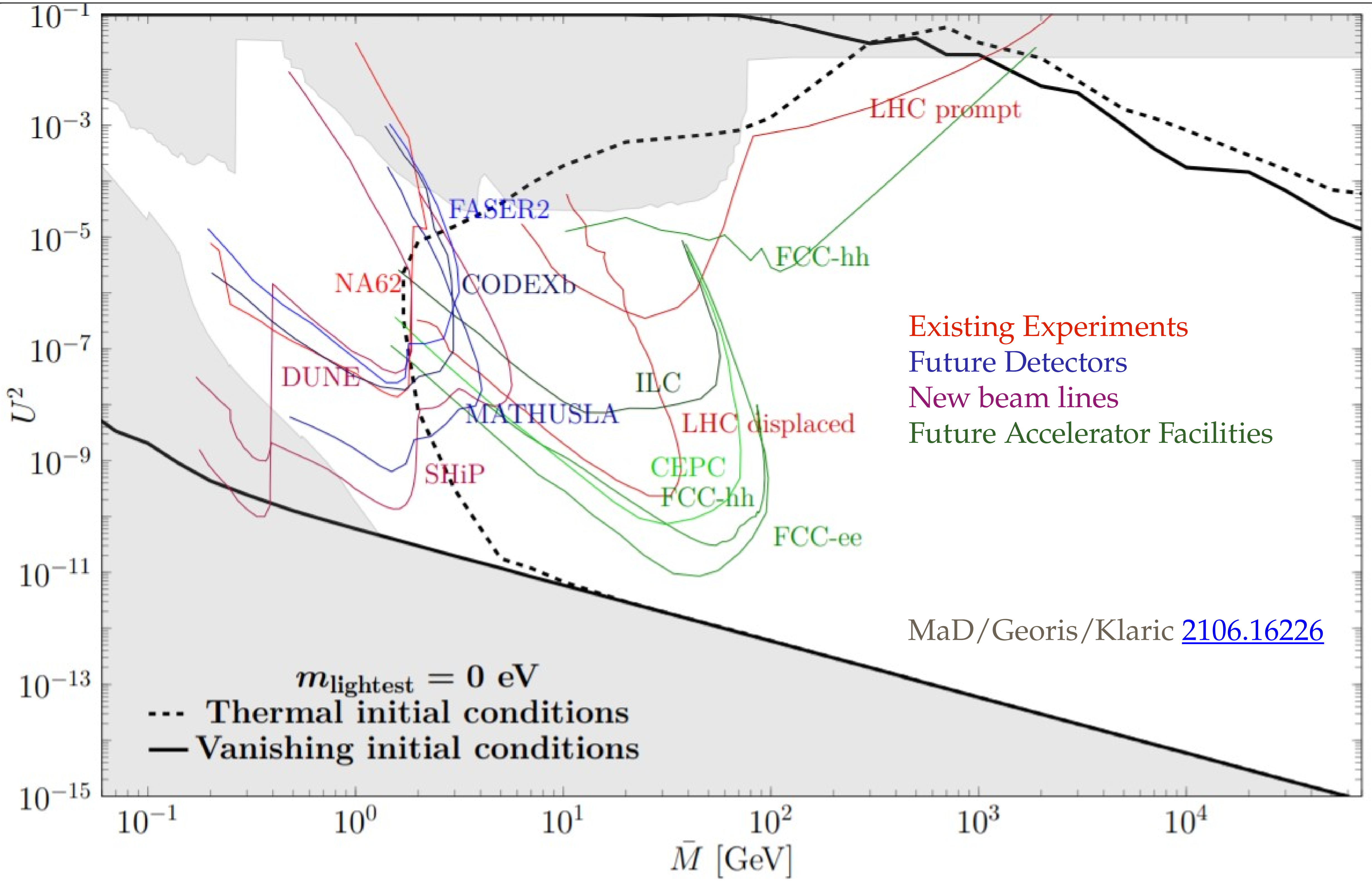
Leptogenesis Parameter Space



MaD/Georis/Klaric [2106.16226]

Cosmology   Particle Physics

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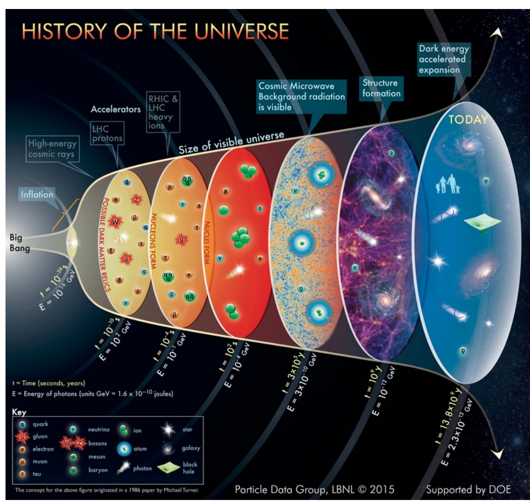

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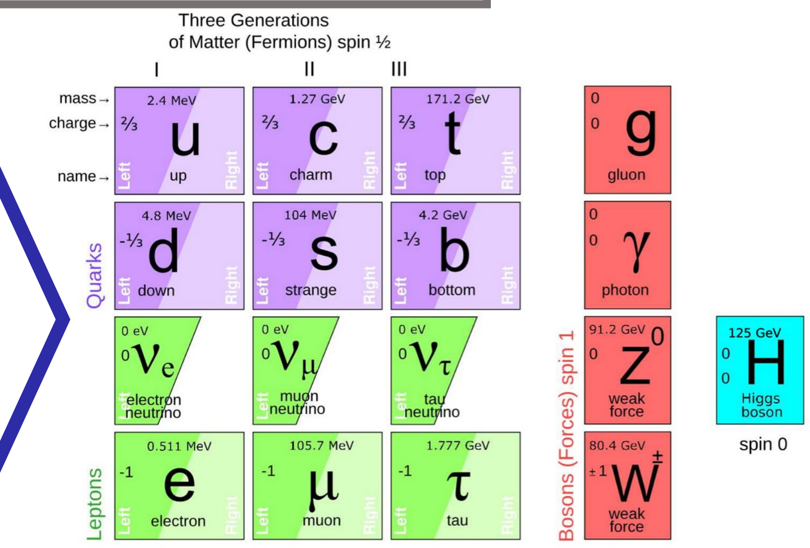

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New Benchmark for N_{eff} in the SM

$$\frac{\rho_\nu}{\rho_\gamma}\Big|_{T/m_e\to 0} \equiv \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}^{\rm SM}$$

- N_{eff} is important cosmological parameter
- N_{eff} in the SM would be 3 only if
  1) electrons were massless during decoupling
  2) the primordial plasma were an ideal gas in perfect equilibrium
  3) the decoupling was instantaneous.
- Deviations from SM prediction are important probe of BSM physics
- $O(e^3)$ correction to equation of state is equally important as neutrino oscillations! Bennet/Buldgen/De Salas/MaD/Gariazzo/Pastor/Wong 2012.02726

New state of the art value $N_{\rm eff}^{\rm SM} = 3.0440 \pm 0.0002$

Standard-model corrections to $N_{\rm eff}^{\rm SM}$	Leading-digit contribution
m_e/T_d correction	$+0.04$
$\mathcal{O}(e^2)$ FTQED correction to the QED EoS	$+0.01$
Non-instantaneous decoupling+spectral distortion	-0.005
$\mathcal{O}(e^3)$ FTQED correction to the QED EoS	-0.001
Flavour oscillations	$+0.0005$
Type (a) FTQED corrections to the weak rates	$\lesssim 10^{-4}$

Cosmology **Particle Physics**

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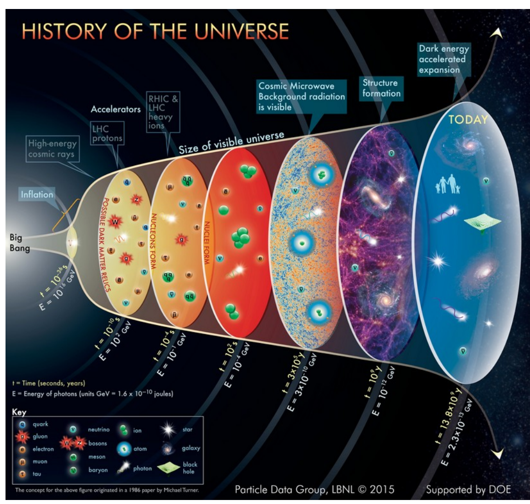

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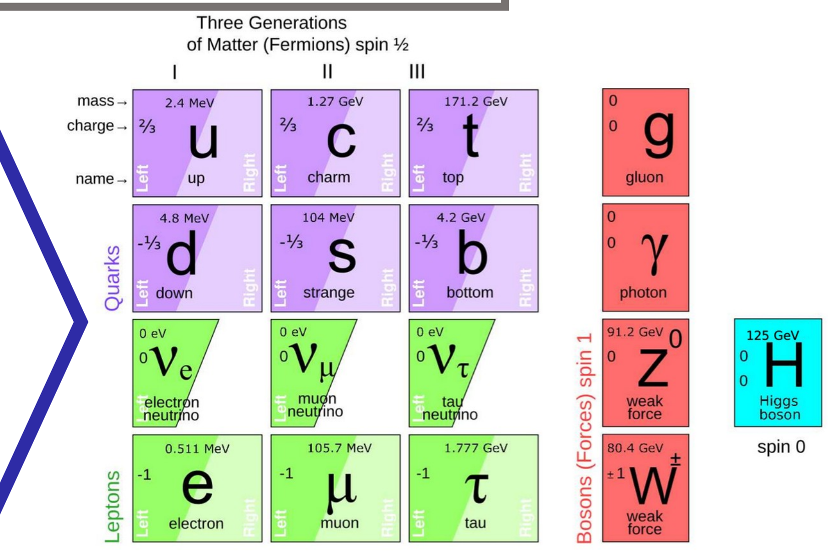

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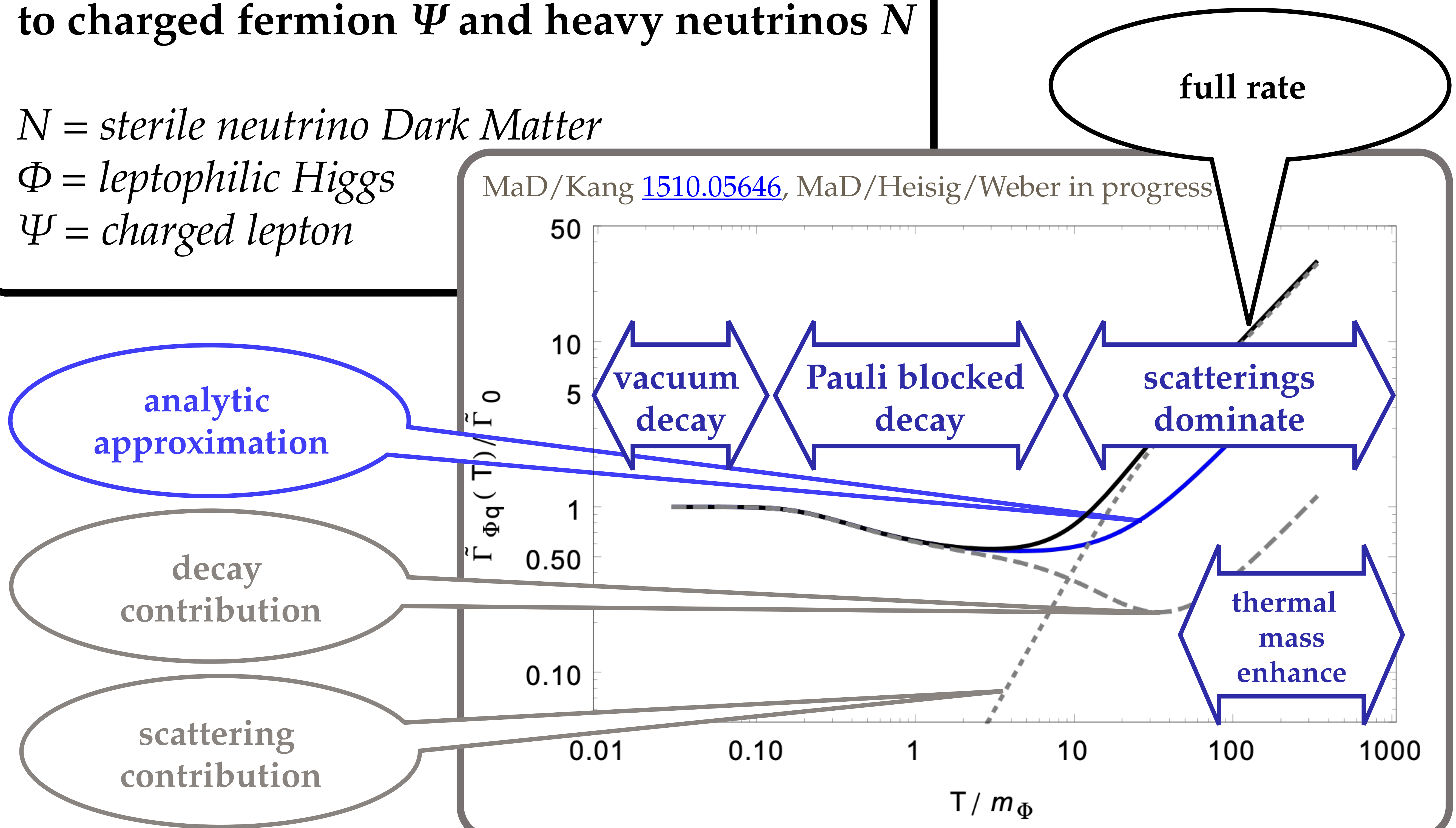
Thermal Corrections to DM Production

new scalar Φ with Yukawa coupling $y\Phi\Psi N$ to charged fermion Ψ and heavy neutrinos N

N = sterile neutrino Dark Matter
Φ = leptophilic Higgs
Ψ = charged lepton



MadDM

arXiv:1308.4955 arXiv:1804.00044
arXiv:1505.04190 arXiv:2012.09016

Numerical tool to compute particle dark matter observables in generic new physics models.

MadDM

MadGraph

UFO model

MadDM

Relic density

Indirect detection

Direct detection

MadDM team
Chiara Arina, Jan Heisig, Kyoungchul Kong, Fabio Maltoni, Luca Mantani,
Daniele Massaro, Olivier Mattelaer, Gopolang Mohlabeng

Studying dark matter with MadDM: Lines and loops

C. Arina, J. Heisig, F. Maltoni, D. Massaro, O. Mattelaer, arXiv:2107.04598

Loop-induced processes

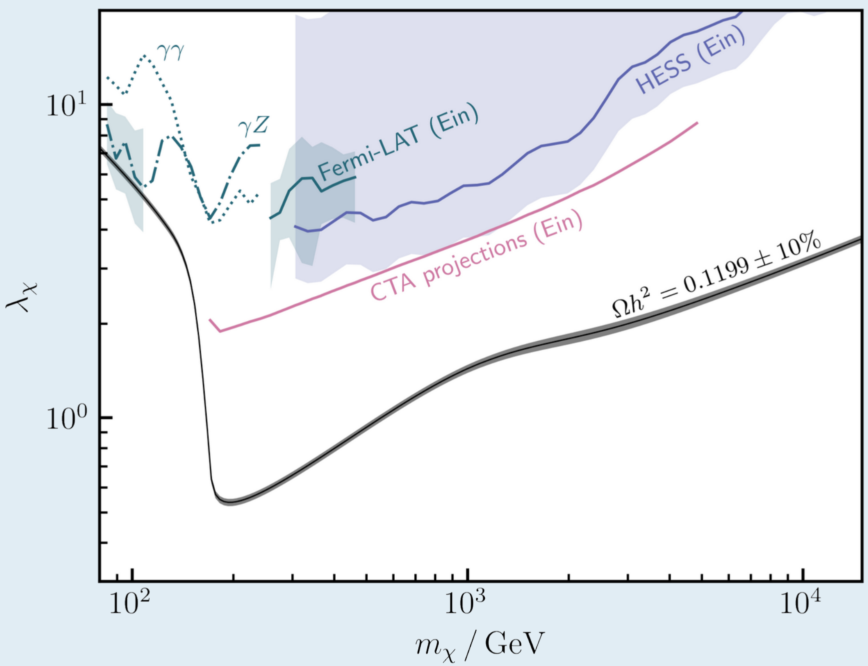
Automatic generation of annihilations into $\gamma X, X = \gamma, Z, h, Z_2-$even

MadDM v3.2

Dedicated analysis pipeline of γ-line spectrum + Fermi-LAT, HESS upper limits.

Top-philic model

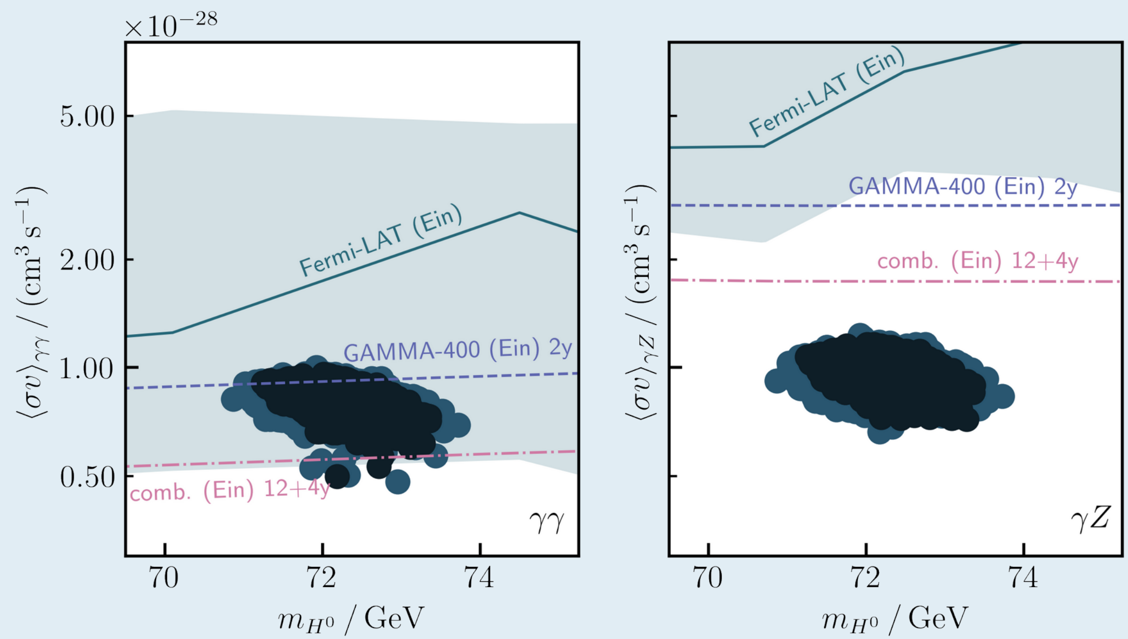
$$\mathcal{L}_{t\text{-philic}} = \mathcal{D}_\mu \tilde{t} (\mathcal{D}_\mu \tilde{t})^\dagger - m_{\tilde{t}}^2 \tilde{t}^\dagger \tilde{t} + \overline{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \lambda_\chi \tilde{t}\, \bar{t}\, P_{\mathrm{L}} \chi + \mathrm{h.c.}$$



Inert Doublet Model

$$\Phi = \begin{pmatrix} H^\pm \\ \frac{1}{\sqrt{2}}(H^0 + iA^0) \end{pmatrix}$$

$$V = \mu_1^2 |H|^2 + \mu_2^2 |\Phi|^2 + \lambda_1 |H|^4 + \lambda_2 |\Phi|^4 + \lambda_3 |H|^2 |\Phi|^2 + \lambda_4 |H^\dagger \Phi|^2 + \frac{\lambda_5}{2}\left[(H^\dagger \Phi)^2 + \mathrm{h.c.}\right]$$



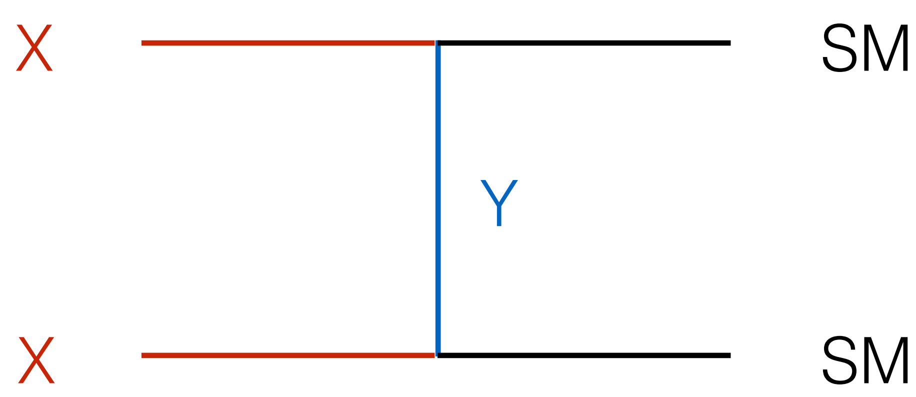
Simplified t-channel dark matter models

C. Arina, L. Mantani, B. Fuks, L. Panizzi, J. Salko, H. Meis

[Eur.Phys.J.C 80 (2020); Phys.Lett.B 813 (2021)]

Very generic Uber-UFO model with 6 dark matter and 24 mediators of different spin coupling to all SM quarks

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kin} + \mathcal{L}_F(\chi) + \mathcal{L}_F(\tilde{\chi}) + \mathcal{L}_S(S) + \mathcal{L}_S(\tilde{S}) + \mathcal{L}_V(V) + \mathcal{L}_V(\tilde{V})$$



$$\mathcal{L}_F(X) = \left[\lambda_{\mathbf{Q}}\bar{X}Q\varphi_Q^\dagger + \lambda_{\mathbf{u}}\bar{X}u\varphi_u^\dagger + \lambda_{\mathbf{d}}\bar{X}d\varphi_d^\dagger + \text{h.c.}\right]$$

$$\mathcal{L}_S(X) = \left[\hat{\lambda}_{\mathbf{Q}}\bar{\psi}_Q Q X + \hat{\lambda}_{\mathbf{u}}\bar{\psi}_u u X + \hat{\lambda}_{\mathbf{d}}\bar{\psi}_d d X + \text{h.c.}\right]$$

$$\mathcal{L}_V(X) = \left[\hat{\lambda}_{\mathbf{Q}}\bar{\psi}_Q \not{X} Q + \hat{\lambda}_{\mathbf{u}}\bar{\psi}_u \not{X} u + \hat{\lambda}_{\mathbf{d}}\bar{\psi}_d \not{X} d + \text{h.c.}\right]$$

New couplings

Fermionic real dark matter represents SUSY like models (i.e. X = bino-like neutrino + Y = squark-like mediator)

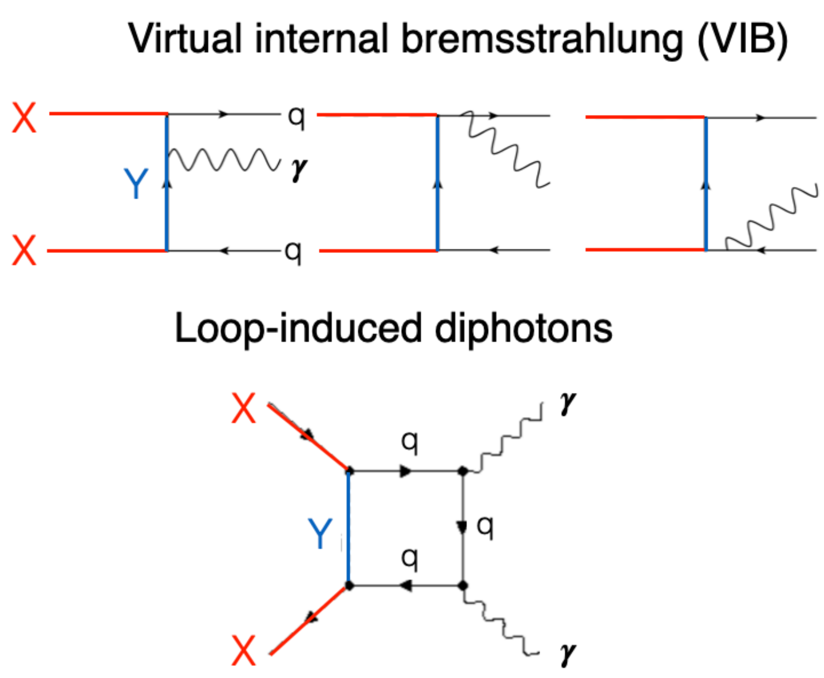
Uber-UFO:

- Used by dark matter working group for t-channel analyses
- Allows for global analyses with MadDM and MG5

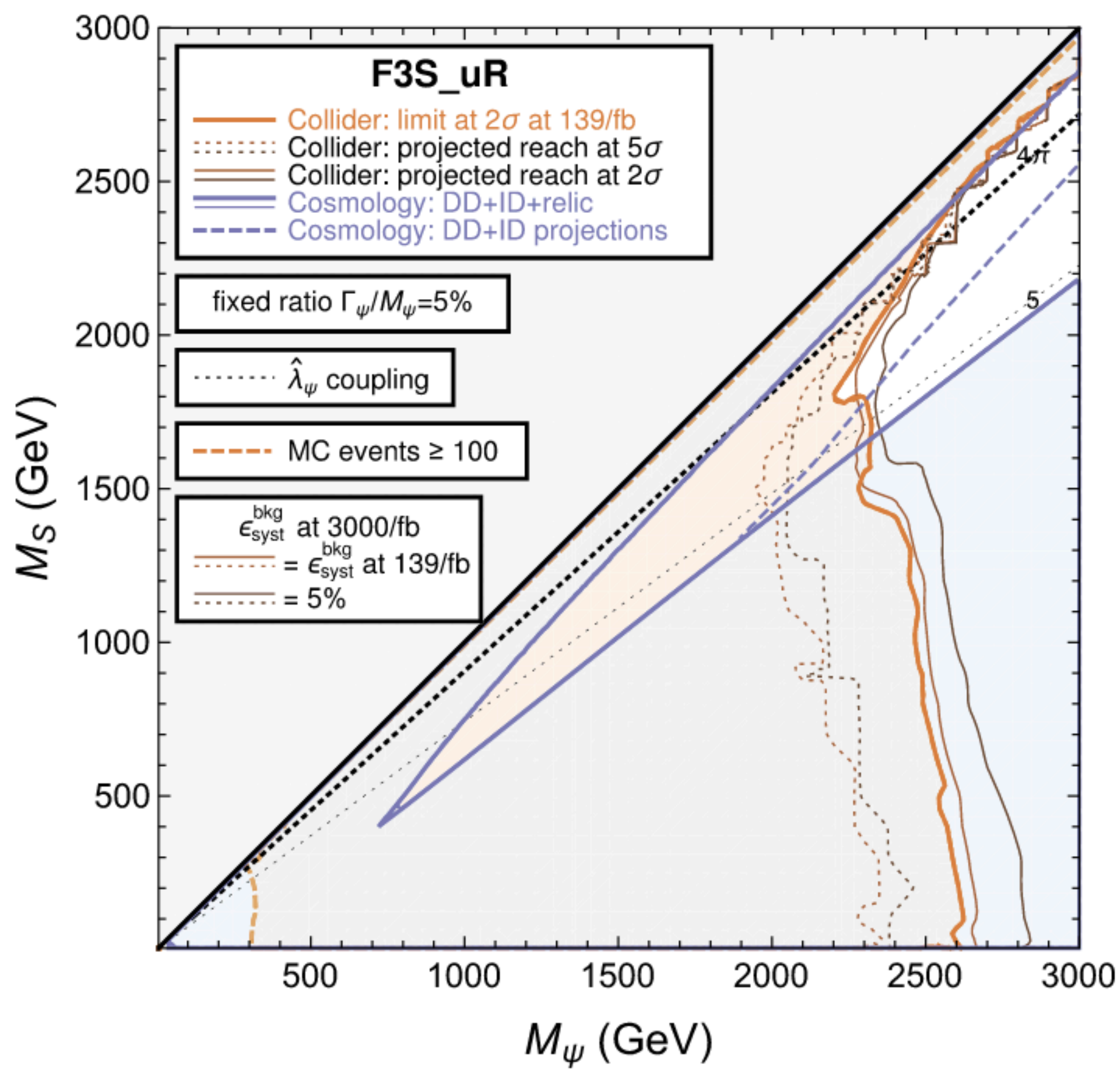
Model files and documentation are available here:
http://feynrules.irmp.ucl.ac.be/wiki/DMsimpt

Real dark matter models coupling to up-right quark

- Sampled relic density, direct detection, NLO indirect detection if relevant (it uplifts the p-wave suppression and produce a sharp feature in the gamma-ray energy spectrum)
- Computed LHC bounds and projections at NLO in QCD for mediator pair production



Agreement of MadDM v3.2 with literature for NLOcomputation [Giacchino et al. (JCAP 2013), Garny et al. (JCAP 2013), Giacchino et al. (JCAP 2014)]



- Most of the parameter space is already disfavored by the combination of current searches
- Next decade: all standard freeze-out dark matter region will be probed
- Freeze-in region and other quark couplings can still have a larger viable parameter space

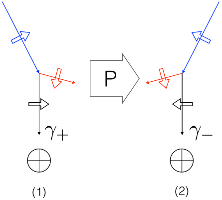
Circular polarised photons from BSM interactions

Céline Boehm, Céline Degrande, Olivier Mattelaer, and Aaron C. Vincent, JCAP 05 (2017) 043
Marina Cermeño, Céline Degrande and Luca Mantani, arXiV: 2103.1458

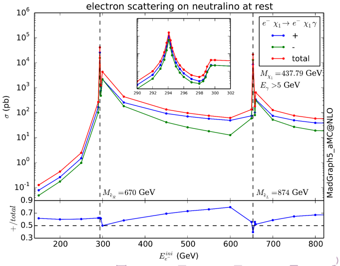
- A net circular polarisation signal is generated when there is an excess of one photon polarisation state over the other
- Parity must be violated in at least one of the dominant photon emission processes

$$\mathcal{A}_- \neq \mathcal{A}_+, \quad \mathcal{A}_\pm = \sum_{spins} |\epsilon_\pm^\mu \mathcal{M}_\mu|^2$$

$$\epsilon_\pm^\mu(k) = \frac{1}{2}(\mp\epsilon_1^\mu(k) - i\epsilon_2^\mu(k))$$



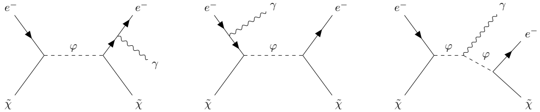
- There must be an asymmetry in the number density of one of the particles in the initial state or CP must be violated
- A P violating interaction like $e^-\tilde{\chi} \to e^-\tilde{\chi}\gamma$ in a region with an abundance of electrons over positrons → circularly polarised photons
- No net polarisation from $\tilde{\chi}\tilde{\chi} \to e^-e^+\gamma$, initial state is a CP-eigenstate



Circular polarised photon flux from DM-e^- interactions

Marina Cermeño, Céline Degrande and Luca Mantani, arXiV: 2103.1458

$$\mathcal{L}_{DM} = i\bar{\psi}_{\tilde{\chi}}(\not{D} - m_{\tilde{\chi}})\psi_{\tilde{\chi}} + D_\mu\varphi^\dagger D^\mu\varphi - m_\varphi\varphi^\dagger\varphi + (a_R\,\bar{e}_R\,\psi_{\tilde{\chi}}\,\varphi + h.c.)\,.$$



The flux of circularly polarised photons from $e^-\tilde{\chi} \to e^-\tilde{\chi}\,\gamma_\pm$ at a distance d from the source

$$\frac{d\Phi_{e\chi,pol}}{dE_\gamma} = \frac{1}{m_{\tilde{\chi}}}\frac{1}{\Delta\Omega_{\text{obs}}}\int_{\Delta\Omega_{\text{obs}}} d\Omega \int_{\text{l.o.s}} ds\,\rho(r(s,\theta))\,f(r(s,\theta)) \int dE_e \frac{d\phi}{dE_e}\left|\frac{d\sigma_+}{dE_\gamma}(E_e,E_\gamma) - \frac{d\sigma_-}{dE_\gamma}(E_e,E_\gamma)\right|$$

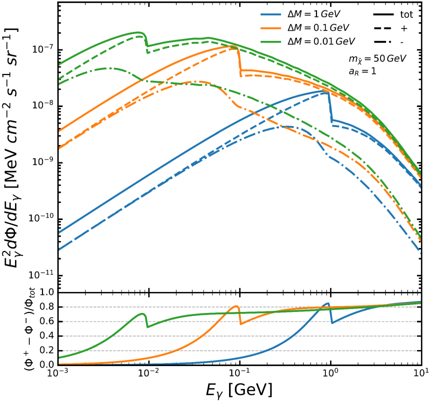
- $f(r)$ e^- spatial distribution, $\rho(r(s,\theta))$ DM density profile
- $\frac{d\phi}{dE_e}$ the electron energy spectrum in units of $\text{GeV}^{-1}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$
- $\frac{d\sigma_\pm}{dE_\gamma}(E_e,E_\gamma)$ the differential cross section for $e^-\tilde{\chi} \to e^-\tilde{\chi}\,\gamma_\pm$, with E_e the incoming electron energy, $m_{\tilde{\chi}}$ the DM mass and E_γ the photon energy

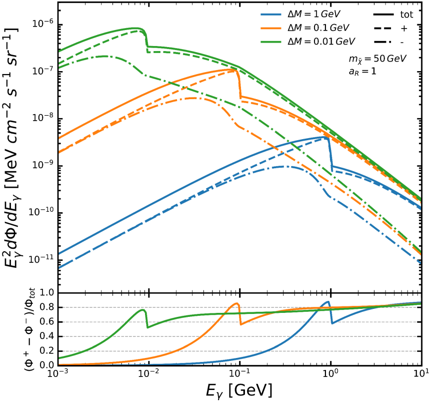
Circular polarised photon flux from the GC

Marina Cermeño, Céline Degrande and Luca Mantani, arXiV: 2103.1458

LIS $E_e^{-1.2}$ for $E_e < 0.05$ GeV
E_e^{-2} for $0.05 \text{ GeV} \lesssim E_e \lesssim 4$ GeV

Injected $E_e^{-2.13}$ for $E_e \leq 0.109$ GeV
$E_e^{-2.57}$ for $E_e > 0.109$ GeV



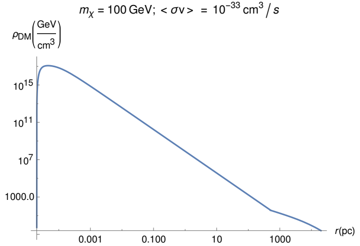


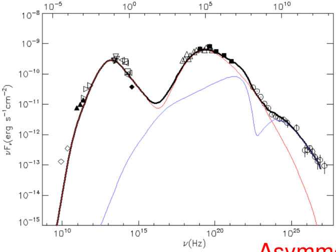
$$\frac{\Phi^+ - \Phi^-}{\Phi_{\rm tot}} \equiv \frac{\frac{d\Phi_{e\tilde{\chi},pol}}{dE_\gamma}}{\frac{d\Phi_{e\tilde{\chi}}}{dE_\gamma}}\,, \qquad \frac{d\Phi_{e\tilde{\chi},pol}}{dE_\gamma} = \frac{d\Phi_{e\tilde{\chi},+}}{dE_\gamma} - \frac{d\Phi_{e\tilde{\chi},-}}{dE_\gamma}$$

- Asymmetries up to $90\,\%$
- Detectable fluxes for $m_\chi \sim 5$ GeV, but $m_\chi \sim m_\varphi > M_Z/2 = 45$ GeV

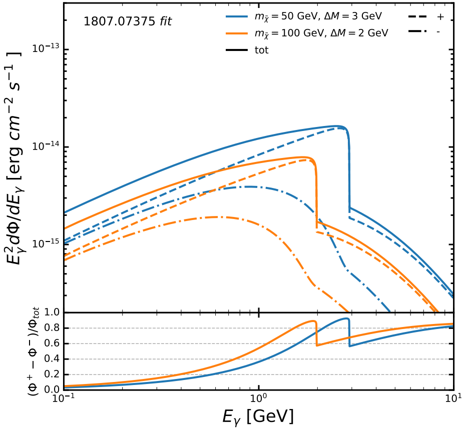
Circular polarised photon flux from Cen A

Marina Cermeño, Céline Degrande and Luca Mantani, in preparation





Relic candidates not excluded by DD, ID and colliders



Asymmetries close to $100\,\%$

Sensitivity of Fermi-LAT to measure this flux around $5\ 10^{13}$ erg cm^{-2} s^{-1}

Thanks for your attention