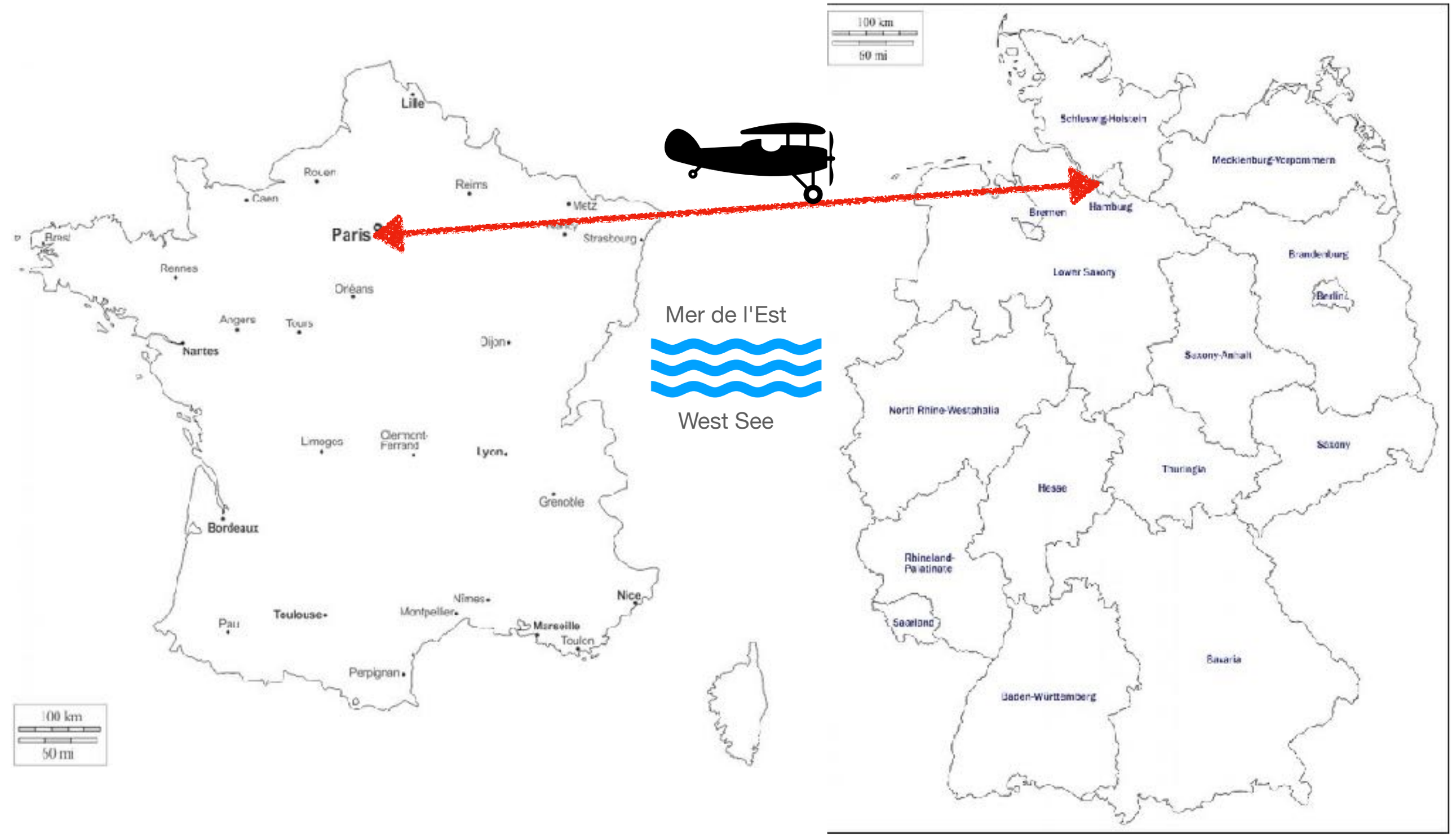
# Report on ongoing theory DMlab projects

Adam Falkowski 16/11/2023

# Planned and ongoing collaborations and interactions

- Adam Falkowski (IJClab) <->  Guilherme Guedes (DESY)
- Edoardo Alviani (IJClab) <-> Jasper Roosmale Nepveu (DESY)
- Panagiotis Marinellis (IJClab) <-> Massimiliano Riva (DESY)
- Jordan Koechler (LPTHE)  <-> Kai Holberg-Schmidt (DESY)
- Simon Clery (IJClab)  <-> Mathias Pierre (DESY)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Mecklenburg-Vorpommern
Bremen
Hamburg
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Lower Saxony
Berlin
Saxony-Anhalt
North Rhine-Westphalia
Saxony
Thuringia
Hesse
Rhineland-Palatinate
Saarland
Bavaria
Baden-Württemberg
Lille
Rouen
Caen
Reims
Metz
Nancy
Strasbourg
Paris
Brest
Rennes
Orléans
Angers
Tours
Nantes
Dijon
Limoges
Clermont-Ferrand
Lyon
Grenoble
Bordeaux
Pau
Toulouse
Nîmes
Montpellier
Nice
Marseille
Toulon
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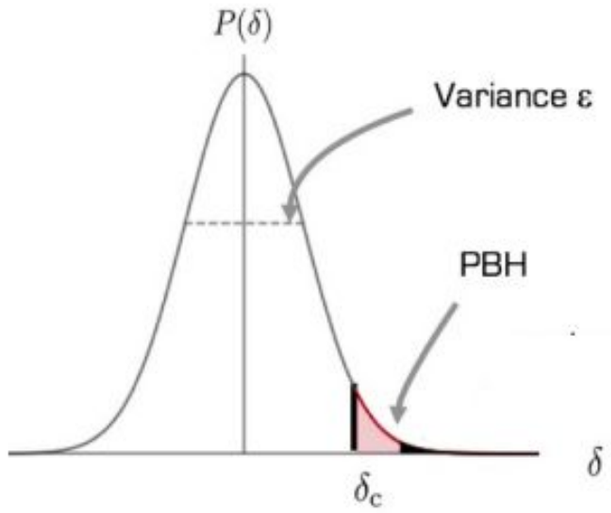
# Project: Gravitational waves from primordial black holes

## DMLab project

**Mathias Pierre and Simon Cléry**



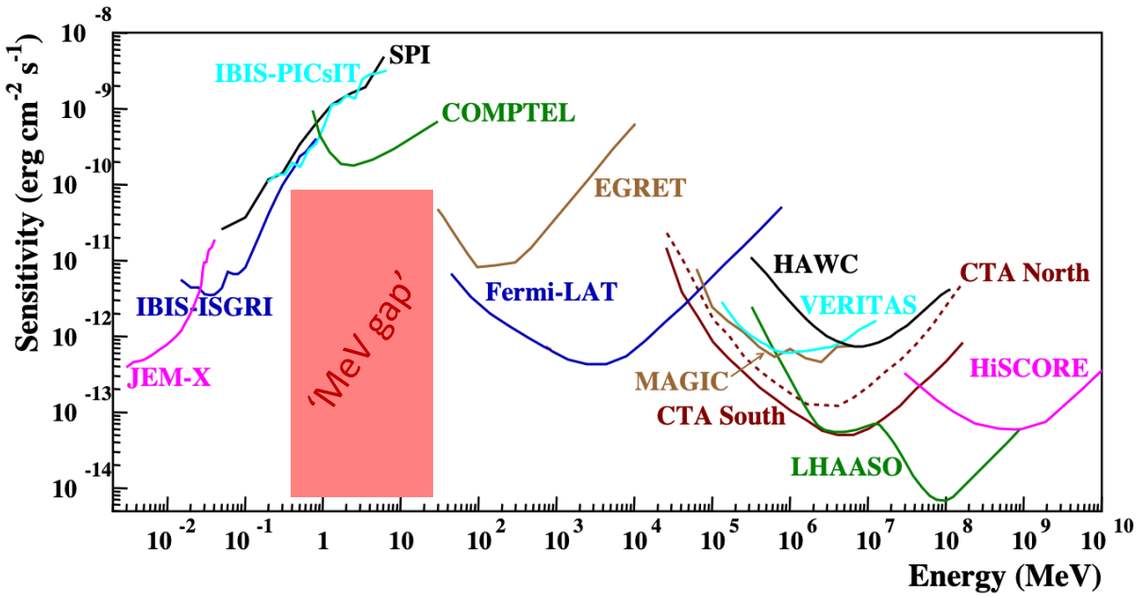

- Large perturbations of curvature can be generated in some models of inflation, studied to generate Primordial Black Holes (PBH)
- Scalar (curvature) perturbations can source second order Gravitational Waves (GWs) spectrum

$$h''_{ij} + 2\mathcal{H}h'_{ij} - \partial_k\partial^k h_{ij} = \mathcal{P}^{ab}{}_{ij}\{T_{ab}\} \approx \mathcal{P}^{ab}{}_{ij}\{\partial_a\delta\varphi\partial_b\delta\varphi\} \quad \Rightarrow \quad \mathcal{P}_h \propto \mathcal{P}^2_{\delta\varphi} \text{ with } \mathcal{P}_{\delta\varphi} \sim \mathcal{P}_{\mathcal{R}}$$ (curvature spectrum)

- Look at the production of GWs induced by large perturbations of curvatures generated during inflation, related to the formation of PBH
- Study the effect of Non-Gaussianities and the consequences of non-linear dynamics for the GWs spectrum and its anisotropy

# Project: X ray constraints on sub-GeV dark matter

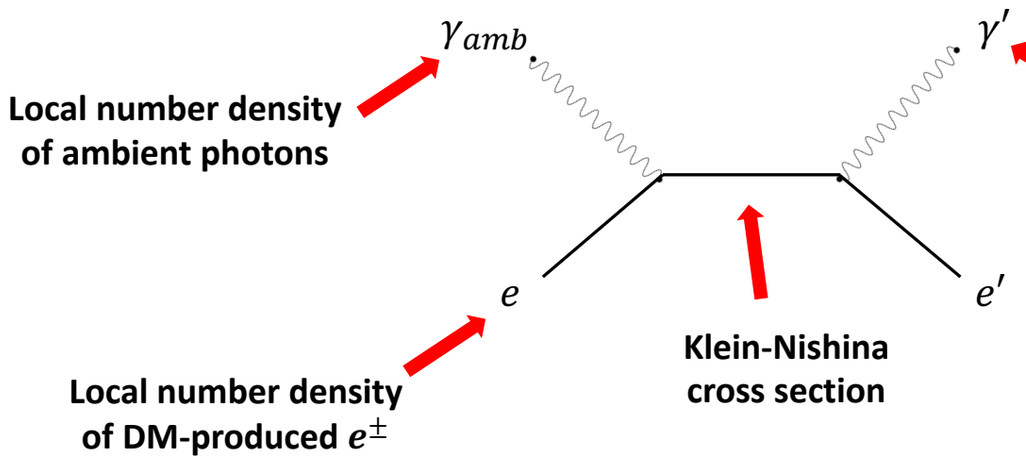
Based on [arXiv:2303.08854] by M. Cirelli, N. Fornengo, J. Koechler, E. Pinetti, B. M. Roach



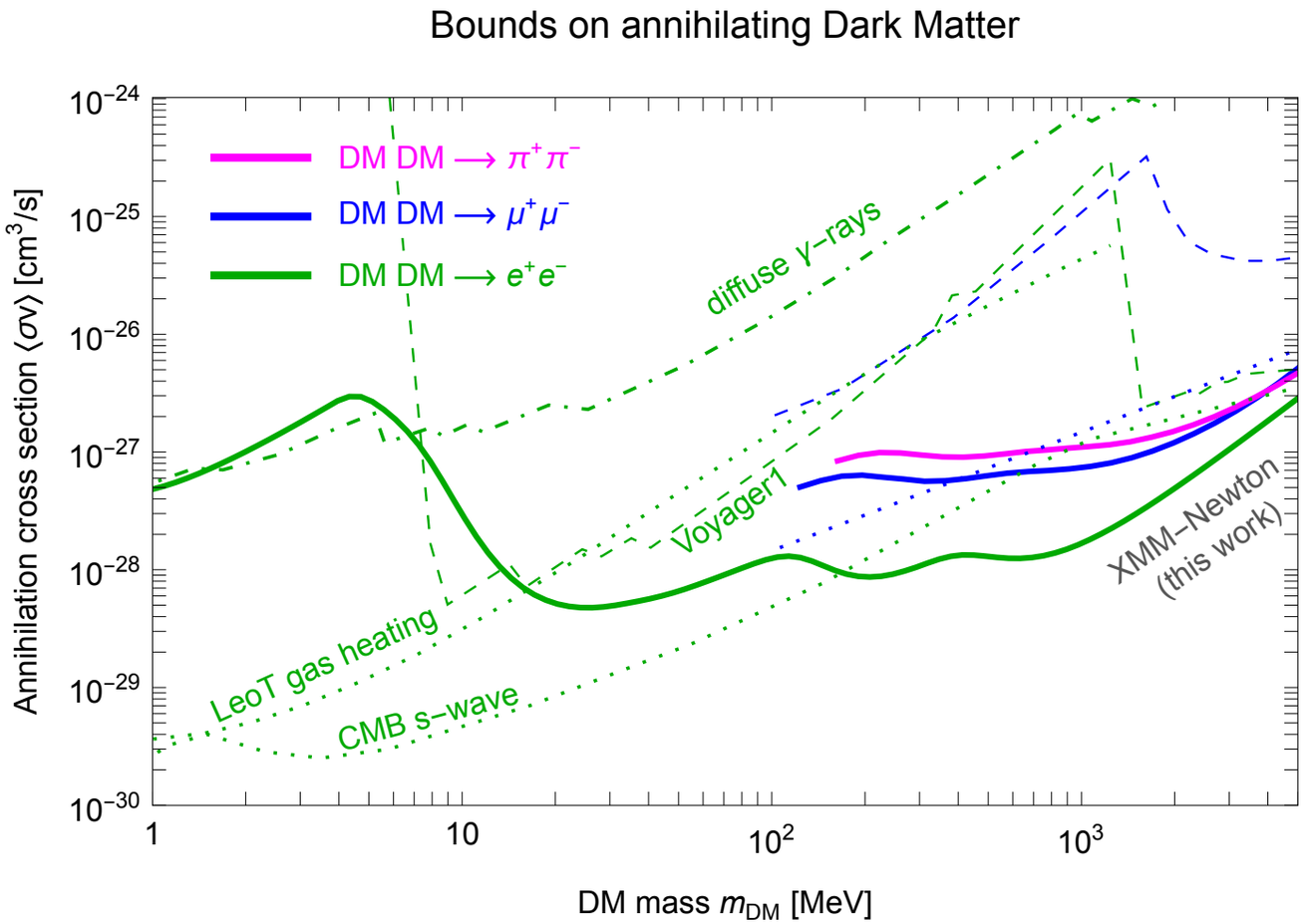

Adapted from De Angelis et al., eASTROGAM coll., 1611.02232

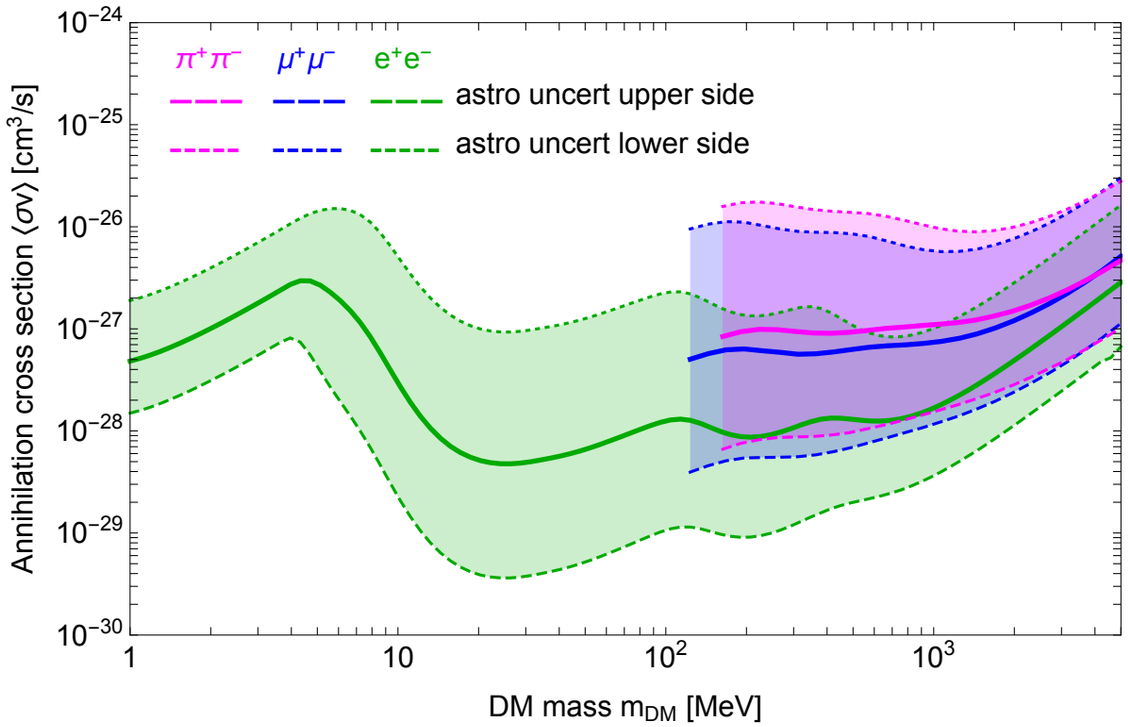
- Prompt emissions:
  - **Final state radiation** (FSR): DM (DM) $\rightarrow \mu^+\mu^-\gamma$
  - **Radiative decay** (Rad): DM (DM) $\rightarrow \mu^+\mu^- \rightarrow \mu^+ e^-\bar{\nu}_e\nu_\mu\gamma$
- Secondary emissions:
  - **Inverse-Compton scattering** (ICS): up-scattering of ambient photons thanks to DM-produced $e^\pm$

DM (DM) $\rightarrow \cdots \rightarrow e$ — $e'$, $\gamma_{amb}$ — $\gamma$



# Project: X ray constraints on sub-GeV dark matter

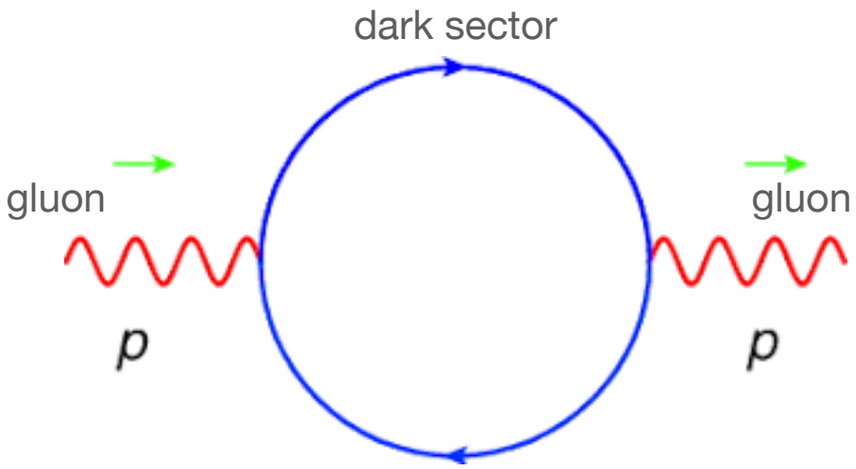


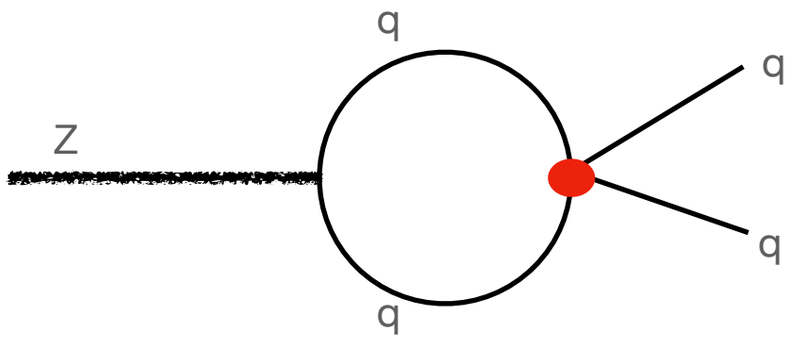

Uncertainties are still large: using more up-to-date ingredients may improve the situation,
Background modelling should further improve the constraints
Extension to p-wave annihilation and constraints on specific BSM models envisaged,

# Project: Precision constraints on strongly interacting dark particles

Adam Falkowski <-> Guilherme Guedes




$$2g_{\rm s}^{-2}M_W^{-2}Z \;=\; \Pi''_{GG}(0) \qquad\qquad \mathcal{O}_{GG} \;=\; (D_\rho G^A_{\mu\nu})^2/2g_{\rm s}^2$$

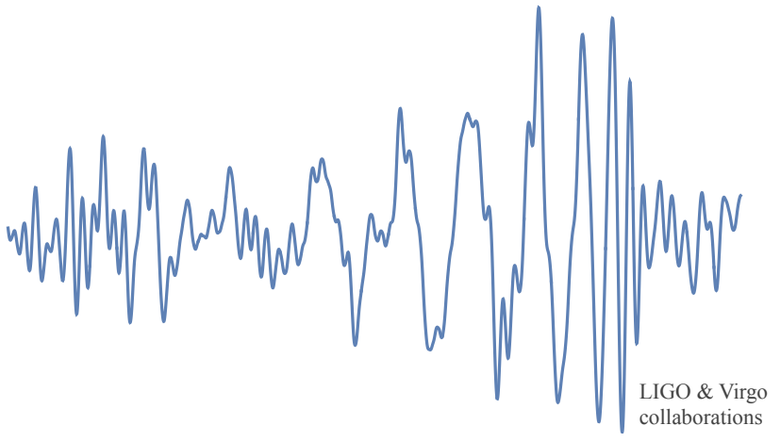



| Observable | Experimental value | SM prediction | Definition |
|---|---|---|---|
| $\Gamma_Z$ [GeV] | $2.4955 \pm 0.0023$ [4, 28] | 2.4941 | $\sum_f \Gamma(Z \to f\bar{f})$ |
| $\sigma_{\rm had}$ [nb] | $41.4802 \pm 0.0325$ [4, 28] | 41.4842 | $\frac{12\pi}{m_Z^2}\frac{\Gamma(Z\to e^+e^-)\Gamma(Z\to q\bar{q})}{\Gamma_Z^2}$ |
| $R_e$ | $20.804 \pm 0.050$ [4] | 20.734 | $\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to e^+e^-)}$ |
| $R_\mu$ | $20.785 \pm 0.033$ [4] | 20.734 | $\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to \mu^+\mu^-)}$ |
| $R_\tau$ | $20.764 \pm 0.045$ [4] | 20.781 | $\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to \tau^+\tau^-)}$ |
| $A_{\rm FB}^{0,e}$ | $0.0145 \pm 0.0025$ [4] | 0.0162 | $\frac{3}{4}A_e^2$ |
| $A_{\rm FB}^{0,\mu}$ | $0.0169 \pm 0.0013$ [4] | 0.0162 | $\frac{3}{4}A_eA_\mu$ |
| $A_{\rm FB}^{0,\tau}$ | $0.0188 \pm 0.0017$ [4] | 0.0162 | $\frac{3}{4}A_eA_\tau$ |
| $R_b$ | $0.21629 \pm 0.00066$ [4] | 0.21581 | $\frac{\Gamma(Z\to b\bar{b})}{\sum_q \Gamma(Z\to q\bar{q})}$ |
| $R_c$ | $0.1721 \pm 0.0030$ [4] | 0.17222 | $\frac{\Gamma(Z\to c\bar{c})}{\sum_q \Gamma(Z\to q\bar{q})}$ |
| $A_b^{\rm FB}$ | $0.0996 \pm 0.0016$ [4, 29] | 0.1032 | $\frac{3}{4}A_eA_b$ |
| $A_c^{\rm FB}$ | $0.0707 \pm 0.0035$ [4] | 0.0736 | $\frac{3}{4}A_eA_c$ |
| $A_e$ | $0.1516 \pm 0.0021$ [4] | 0.1470 | $\frac{\Gamma(Z\to e_L^+e_L^-)-\Gamma(Z\to e_R^+e_R^-)}{\Gamma(Z\to e^+e^-)}$ |
| $A_\mu$ | $0.142 \pm 0.015$ [4] | 0.1470 | $\frac{\Gamma(Z\to \mu_L^+\mu_L^-)-\Gamma(Z\to \mu_R^+\mu_R^-)}{\Gamma(Z\to \mu^+\mu^-)}$ |
| $A_\tau$ | $0.136 \pm 0.015$ [4] | 0.1470 | $\frac{\Gamma(Z\to \tau_L^+\tau_L^-)-\Gamma(Z\to \tau_R^+\tau_R^-)}{\Gamma(Z\to \tau^+\tau^-)}$ |
| $A_e$ | $0.1498 \pm 0.0049$ [4] | 0.1470 | $\frac{\Gamma(Z\to e_L^+e_L^-)-\Gamma(Z\to e_R^+e_R^-)}{\Gamma(Z\to e^+e^-)}$ |
| $A_\tau$ | $0.1439 \pm 0.0043$ [4] | 0.1470 | $\frac{\Gamma(Z\to \tau_L^+\tau_L^-)-\Gamma(Z\to \tau_R^+\tau_R^-)}{\Gamma(Z\to \tau^+\tau^-)}$ |
| $A_b$ | $0.923 \pm 0.020$ [4] | 0.935 | $\frac{\Gamma(Z\to b_Lb_L)-\Gamma(Z\to b_Rb_R)}{\Gamma(Z\to b\bar{b})}$ |
| $A_c$ | $0.670 \pm 0.027$ [4] | 0.668 | $\frac{\Gamma(Z\to c_L\bar{c}_L)-\Gamma(Z\to c_R\bar{c}_R)}{\Gamma(Z\to c\bar{c})}$ |
| $A_s$ | $0.895 \pm 0.091$ [30] | 0.936 | $\frac{\Gamma(Z\to s_L\bar{s}_L)-\Gamma(Z\to s_R\bar{s}_R)}{\Gamma(Z\to s\bar{s})}$ |
| $R_{uc}$ | $0.166 \pm 0.009$ [9] | 0.1722 | $\frac{\Gamma(Z\to u\bar{u})+\Gamma(Z\to c\bar{c})}{2\sum_q \Gamma(Z\to q\bar{q})}$ |

- It is conceivable that dark sectors particles with only strong interactions and no electroweak interactions exist
- They would contribute to the so-called Z parameter (analogue of electroweak S,T parameters) corresponding to a specific dimension-6 operator in SMEFT
- This operators is equivalent to a linear combination of 4-quark operators in the Warsaw basis
- Goal: map out precise constraints on the Z parameter from electroweak precision measurements at LEP

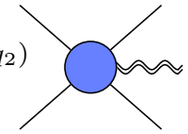
# Project: Gravitational waves in modified gravity

Panagiotis Marinellis <-> Massimiliano Riva




Frequency space

$$\text{waveform}(\omega) = \frac{1}{\text{distance}} \int \mathrm{d}^4 q_1 \mathrm{d}^4 q_2 \, \delta(p_1 \cdot q_1) \delta(p_2 \cdot q_2) \delta^4(k - q_1 - q_2) \, e^{ib \cdot (q_1 - q_2)}$$



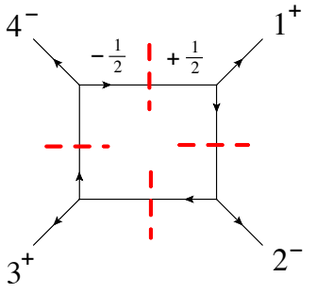
*Cristofoli, Gonzo, Kosower & DOC*

- It's the golden age of gravitational wave astronomy
- On-shell amplitude techniques have pushed forward precision calculations of waveforms emitted in black hole/neutron star collisions, in GR and EFT extension thereof
- Less explored are the application in scalar-tensor theories where gravity is coupled to a cosmologically light scalar
- Using on-shell amplitude techniques simplifies calculation of both gravitational waves and scalar waves for Schwarzshild and Kerr black holes

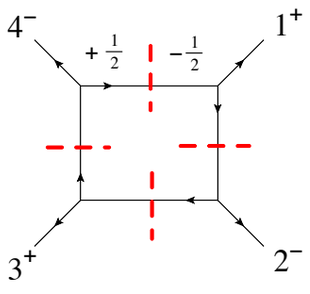
# Project: Anomalies on shell

Edoardo Alviani <-> Jasper Roosmale Nepveu

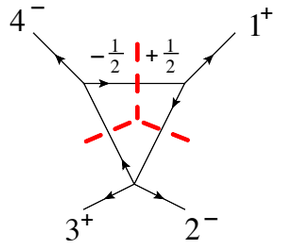
$$-\frac{t^4 s^2}{u^4}$$

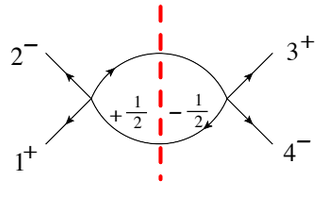



$$-\frac{s^4 t^2}{u^4}$$



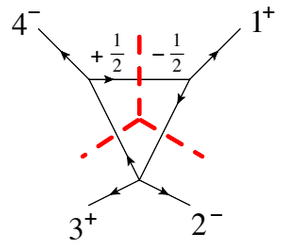

$$\frac{t^4 s}{u^4}$$

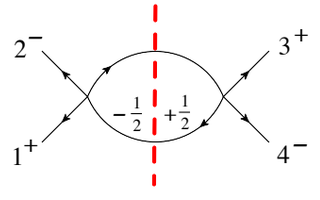



$$\frac{t(su - 6st - 2ut)}{6u^3}$$

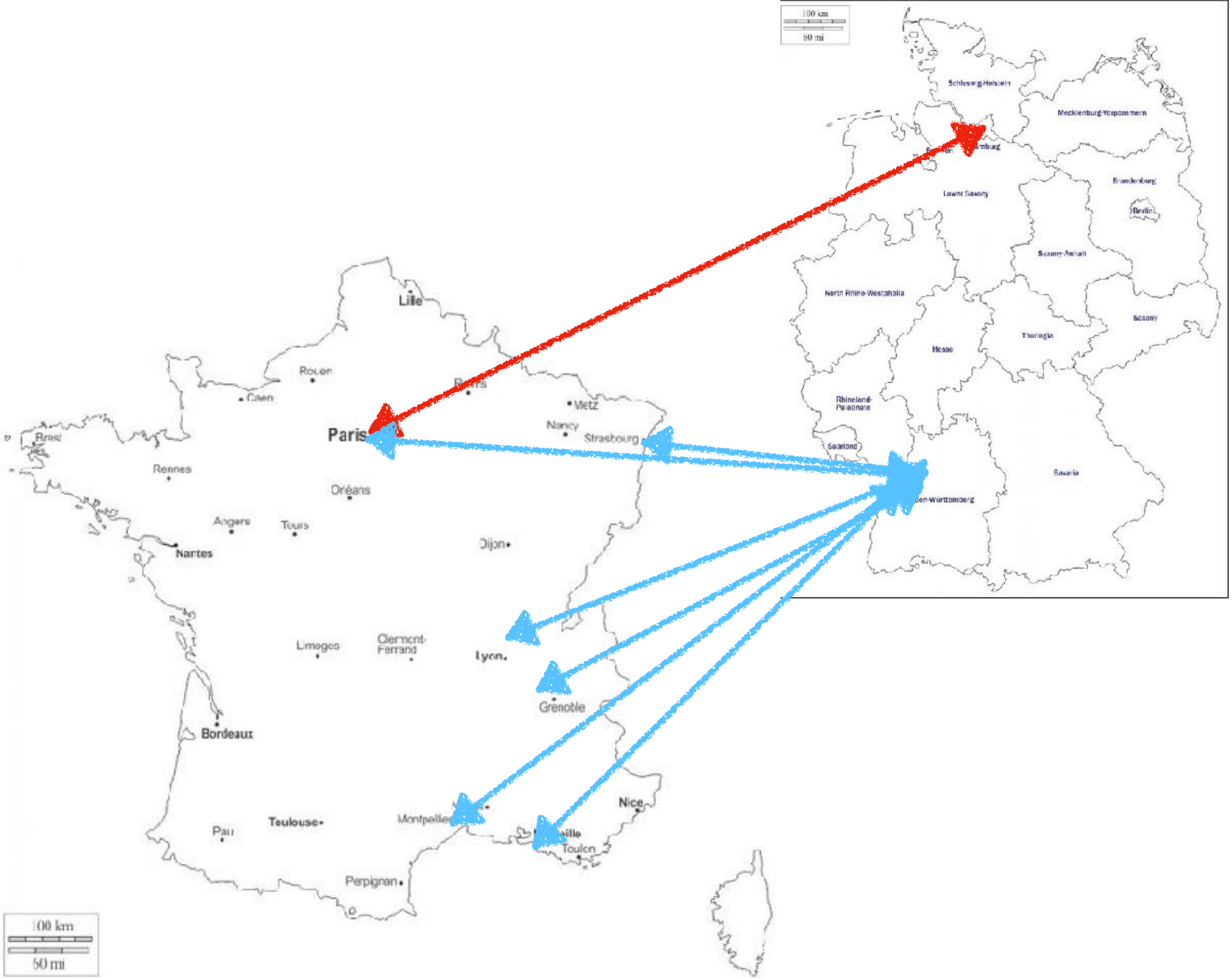
$$\frac{t^2 s^3}{u^4}$$




$$\frac{t(4s^2 + 2t^2 - 7su)}{6u^3}$$

- Anomalies play an important role in quantum theory
- Usually formulated as an inconsistency between loop regulators and current conservation
- In on-shell formulation of QFT there is no gauge symmetry to start with. What are anomalies on shell?
- Partial answers in Huang Mc Gady arXiv:1307.4065 : clash between unitarity, cut terms, and rational terms in 1-loop amplitudes
- Lots of loose ends: what about U(1) anomalies, non-renormalisation beyond 1 loop, trace anomalies etc.
- On-shell formulation often brings new physical perspective and powerful new calculation tools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Hesse
Rhineland-Palatinate
Saarland
Bavaria
Lille
Rouen
Caen
Paris
Metz
Nancy
Strasbourg
Brest
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