GW Studies @ iLAPP-CFUMUP

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Astrophysics and Particle Physics

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COMPETE 2020 PROGRAMA OPERACIONAL COMPETITIVIDADE E INTERNACIONALIZAÇÃO

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POCH

Main Topics in this Talk

- What is iLAPP-CFUMUP?
- What are we currently doing on GW?

...a flavour of future plans?

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CF-UM-UP

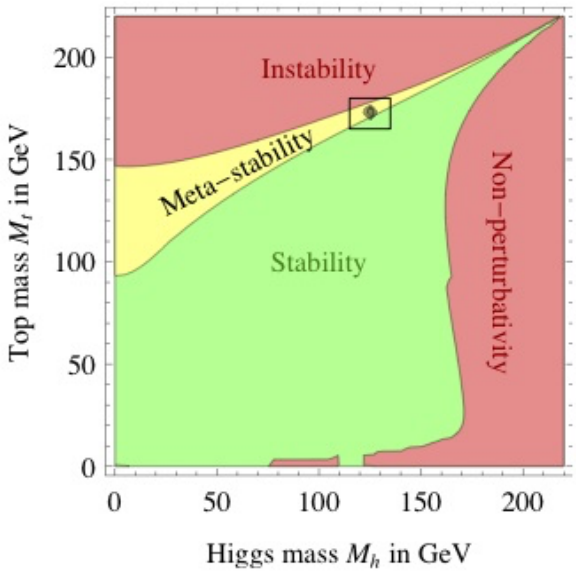
What is iLAPP?

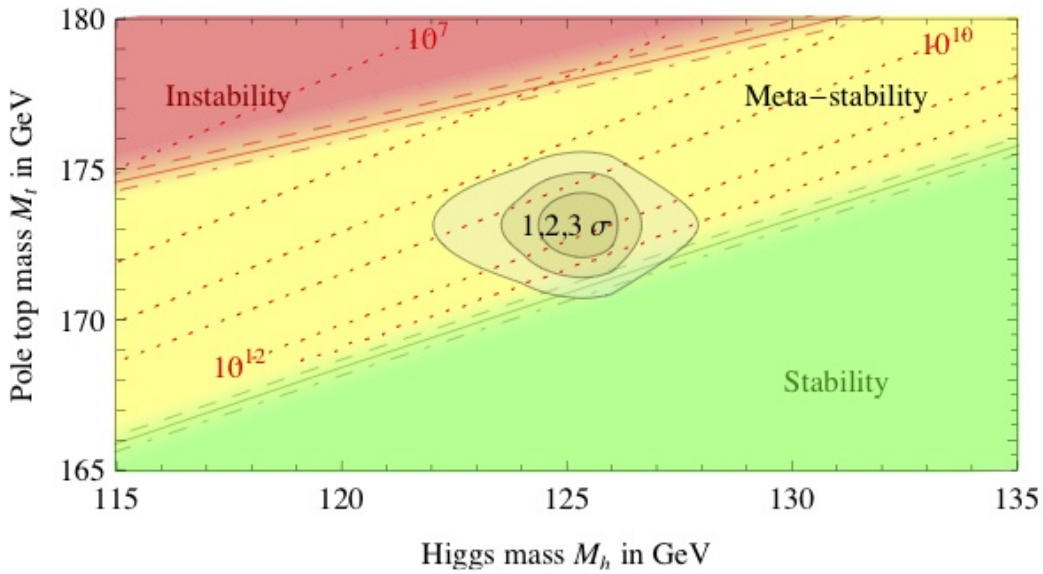
- It stands for:
  Interdisciplinary Laboratory for Astrophysics and Particle Physics @ **CF-UM-UP, University of Minho**
- ...a bit of history
  - Formarly approved May 2019 @ University of Minho
  - Scientific Program Focus on:
    - ☞ **Particle Physics (past experience): elementary particles and fields (top quark and Higgs Physics) @ CERN**
    - ☞ **Astrophysics: mainly in GW (Black Holes, Neutron Stars mergers, etc.)**
- Strong on-going collaboration with **Toni Font** group, Department of Astronomy and Astrophysics (DAA), University of Valencia (with **Alejandro Torres-Forne,** first contacts through Nico Sanchis-Gual) as well as
  University of Aveiro (**Felipe Freitas**, **António Morais** and **Carlos Herdeiro**)
- About myself: First came to UM in 2010, birth of LIP-Minho CELEBRATING 10 YEARS in 2020 (30 members in 2020) ☞iLAPP @ UM

Particle Physics: Global Fits of LHC data EFT Wilson Coefficients and anomalous Couplings

Why the top quark and Higgs boson?

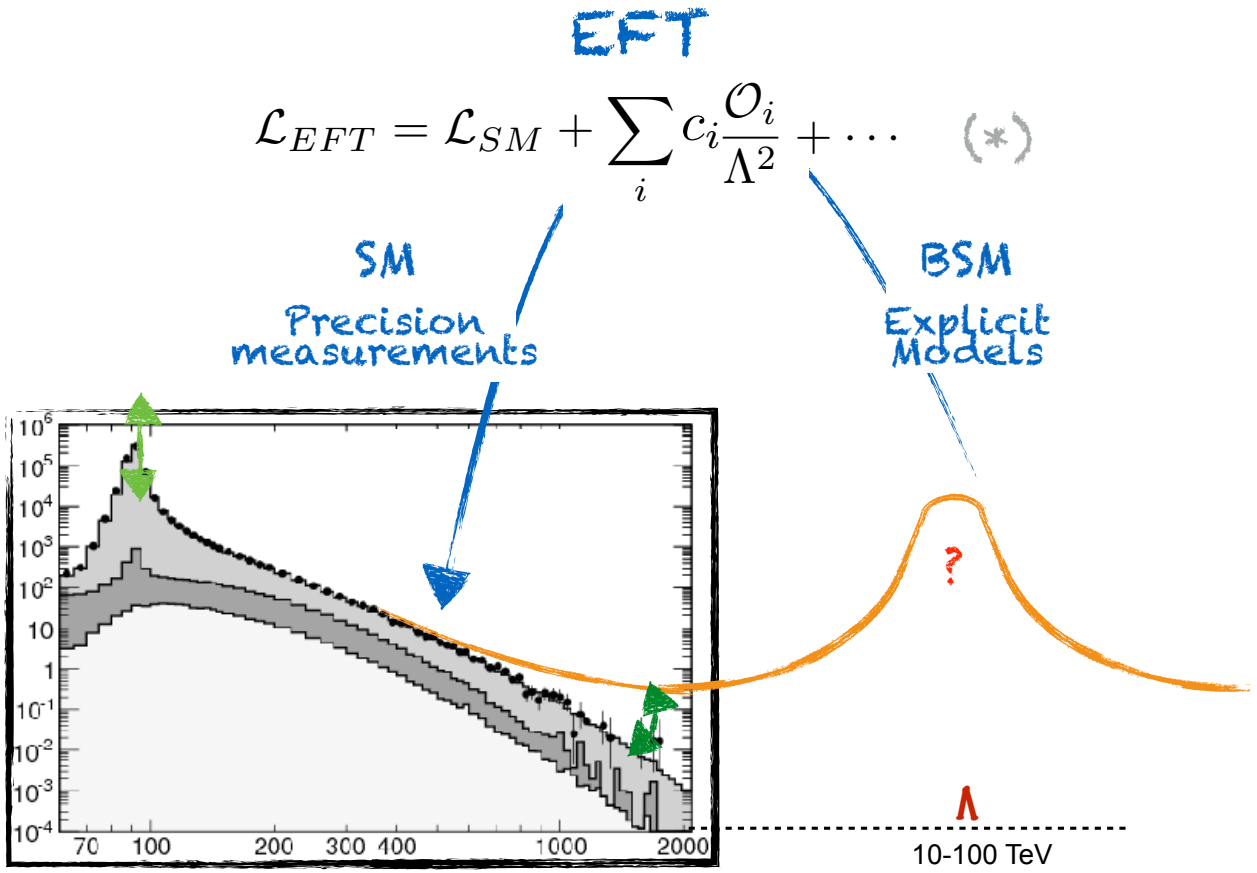
☞ apparently they are connected to the stability of the Universe





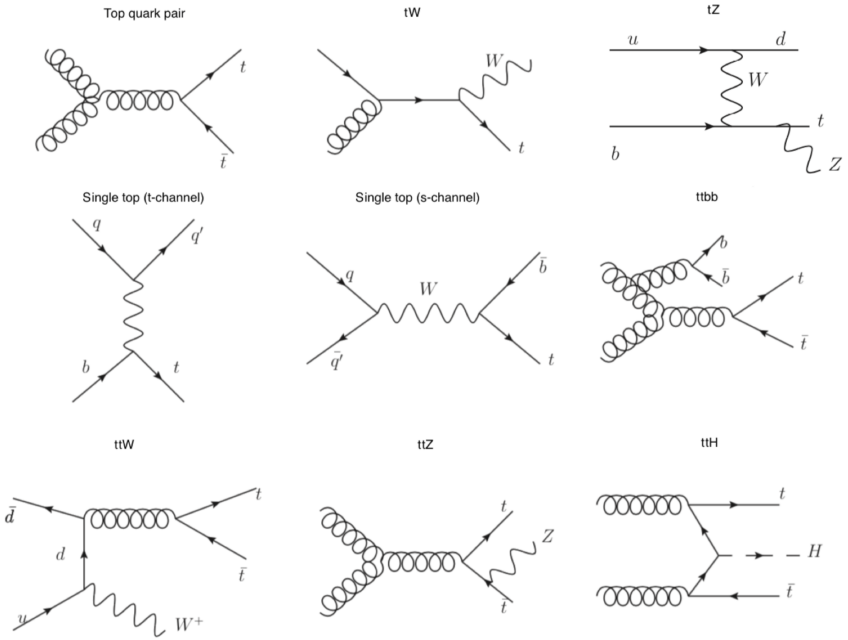
[Improvements from Theory]

☞ Effective Field Theory approach (EFT):



[Improvements from Theory]

☞ Towards a Global SMEFT Fit:

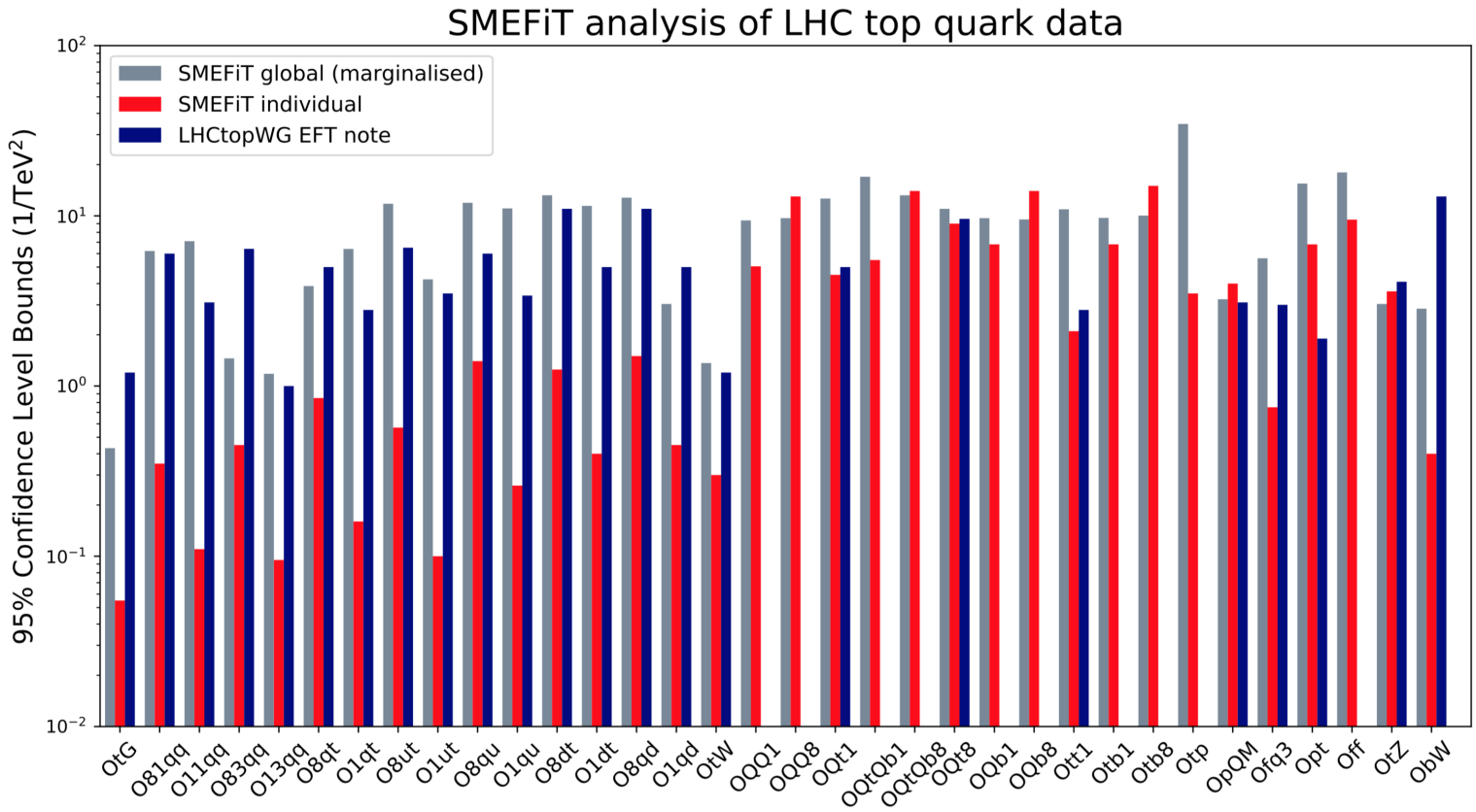


- Maltoni et al., arXiv:1901.05965
- 34 d.o.f., $\geq$ 100 observables

Notation	Sensitivity at $\mathcal{O}(\Lambda^{-2})$ ($\mathcal{O}(\Lambda^{-4})$)								
	$t\bar{t}$	single-top	tW	tZ	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}H$	$t\bar{t}t\bar{t}$	$t\bar{t}b\bar{b}$
OQQ1								✓	✓
OQQ8								✓	✓
OQt1								✓	✓
OQt8								✓	✓
OQb1									✓
OQb8									✓
Ott1								✓	
Otb1									✓
Otb8									✓
OQtQb1									(✓)
OQtQb8									(✓)
O81qq	✓				✓	✓	✓	✓	✓
O11qq	[✓]				[✓]	[✓]	[✓]	✓	✓
O83qq	✓	[✓]		[✓]	✓	✓	✓	✓	✓
O13qq	[✓]	✓		✓	[✓]	[✓]	[✓]	✓	✓
O8qt	✓				✓	✓	✓	✓	✓
O1qt	[✓]				[✓]	[✓]	[✓]	✓	✓
O8ut	✓					✓	✓	✓	✓
O1ut	[✓]					[✓]	[✓]	✓	✓
O8qu	✓					✓	✓	✓	✓
O1qu	[✓]					[✓]	[✓]	✓	✓
O8dt	✓					✓	✓	✓	✓
O1dt	[✓]					[✓]	[✓]	✓	✓
O8qd	✓					✓	✓	✓	✓
O1qd	[✓]					[✓]	[✓]	✓	✓
OtG	✓		✓		✓	✓	✓	✓	✓
OtW		✓	✓	✓					
ObW		(✓)	(✓)	(✓)					
OtZ				✓		✓			
Off		(✓)	(✓)	(✓)					
Ofq3		✓	✓	✓					
OpQM				✓		✓			
Opt				✓		✓			
Otp							✓		

[Improvements from Theory]

☞ Towards a Global SMEFT Fit: Results



- Maltoni et al., arXiv:1901.05965 [LHCTopWG EFT note, arXiv:1802.07237]

Anomalous couplings/EFT parameters in global fits

General Wtb vertex

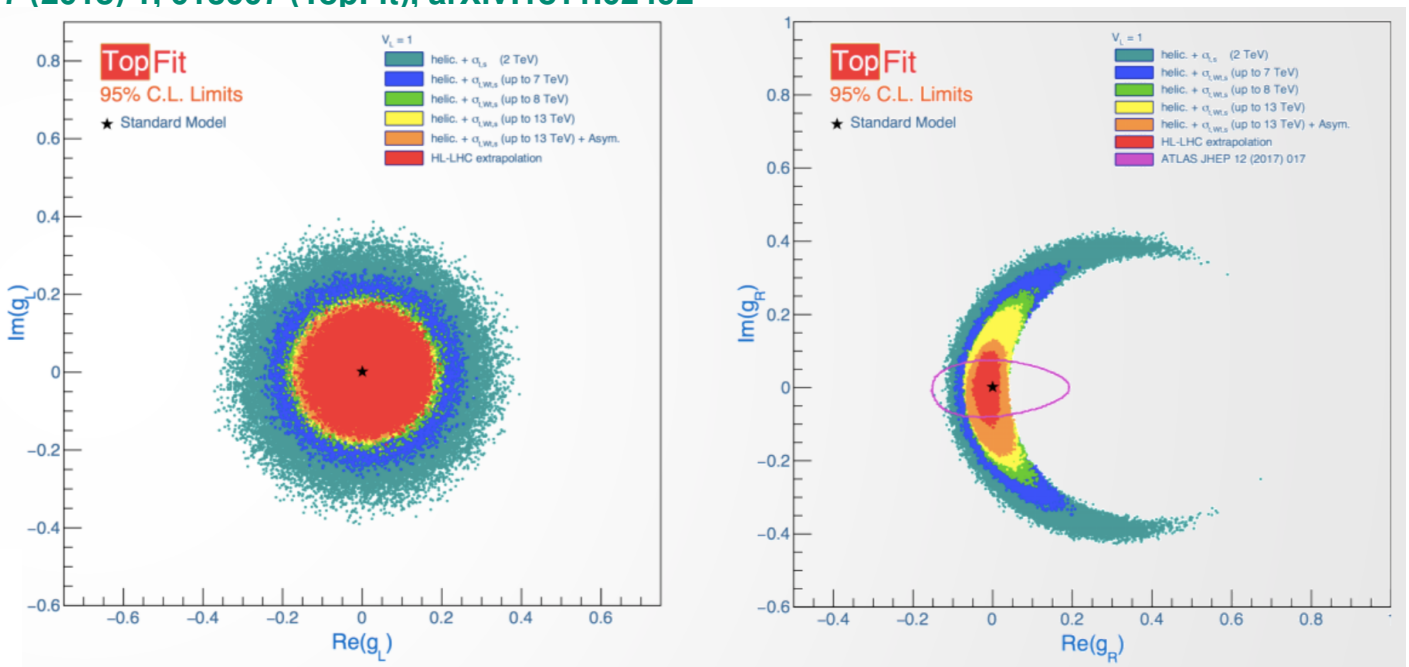
Eur.Phys.J. C50 (2007) 519-533

$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(V_{\rm L}P_{\rm L} + V_{\rm R}P_{\rm R}\right)t\,W^{-}_{\mu} - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(g_{\rm L}P_{\rm L} + g_{\rm R}P_{\rm R}\right)t\,W^{-}_{\mu}$$

vector ($V_{\rm R}$) and tensor like couplings ($g_{\rm L}$, $g_{\rm R}$) zero @ tree level in SM

☞ EFT parameters: anomalous couplings described by effective operators $\mathcal{O}_{uW}$,$\mathcal{O}_{dW}$, $\mathcal{O}^{(3)}_{\phi q}$ and $\mathcal{O}_{\phi ud}$ i.e., constraints on anomalous couplings equivalent to constraints on EFT parameters (a more integrating framework) [arXiv:1802.07237]

PRD 97 (2018) 1, 013007 (TopFit), arXiv:1811.02492



Fits Using:

σ, W_{hel}, A_{FB} @ 7,8,13 TeV

Main Topics in this Talk

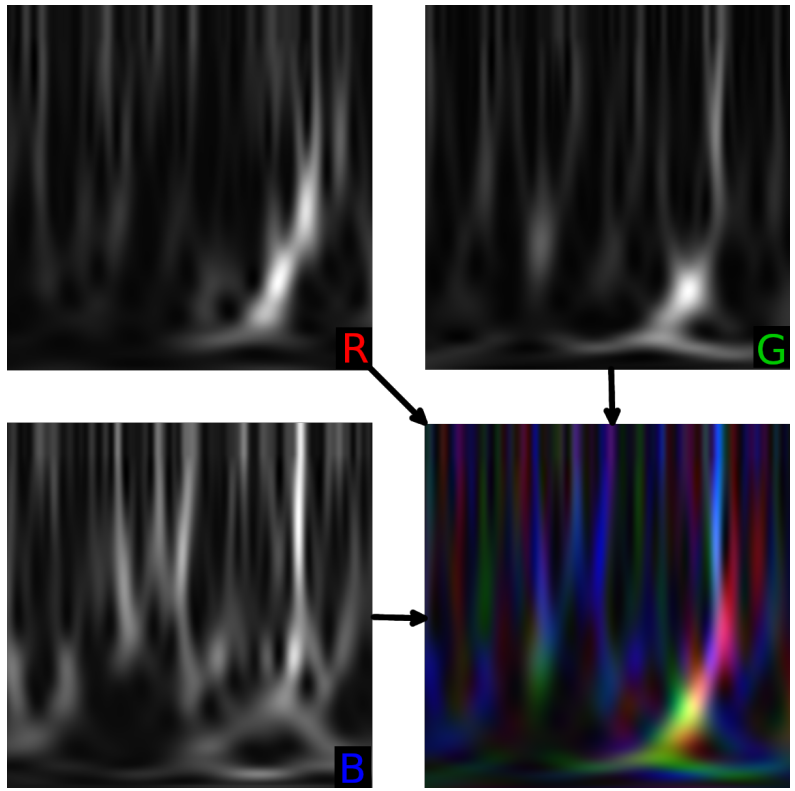
- What is iLAPP-CFUMUP?
- What are we currently doing on GW?

...a flavour of future plans?

What are we currently doing on GW?

- ☞ All about trying to understand GW
  - use Machine Learning/Deep Learning tools to understand their:
    - ▷ nature
    - ▷ sources and distances
    - ▷ masses of mergers
    - ▷ spins, etc.
- ☞ The research plan has been
  - Use generated BH mergers spectrograms from GW waveforms injected in real noise conditions (see if what we inject is actually what we extract)
  - Understand 1 detector versus 3 detector (LIGO⊕Virgo) responses
  - Compare ML/DL results with published data
- ☞ ...several question needed an answer, Q1, Q2, Q3...

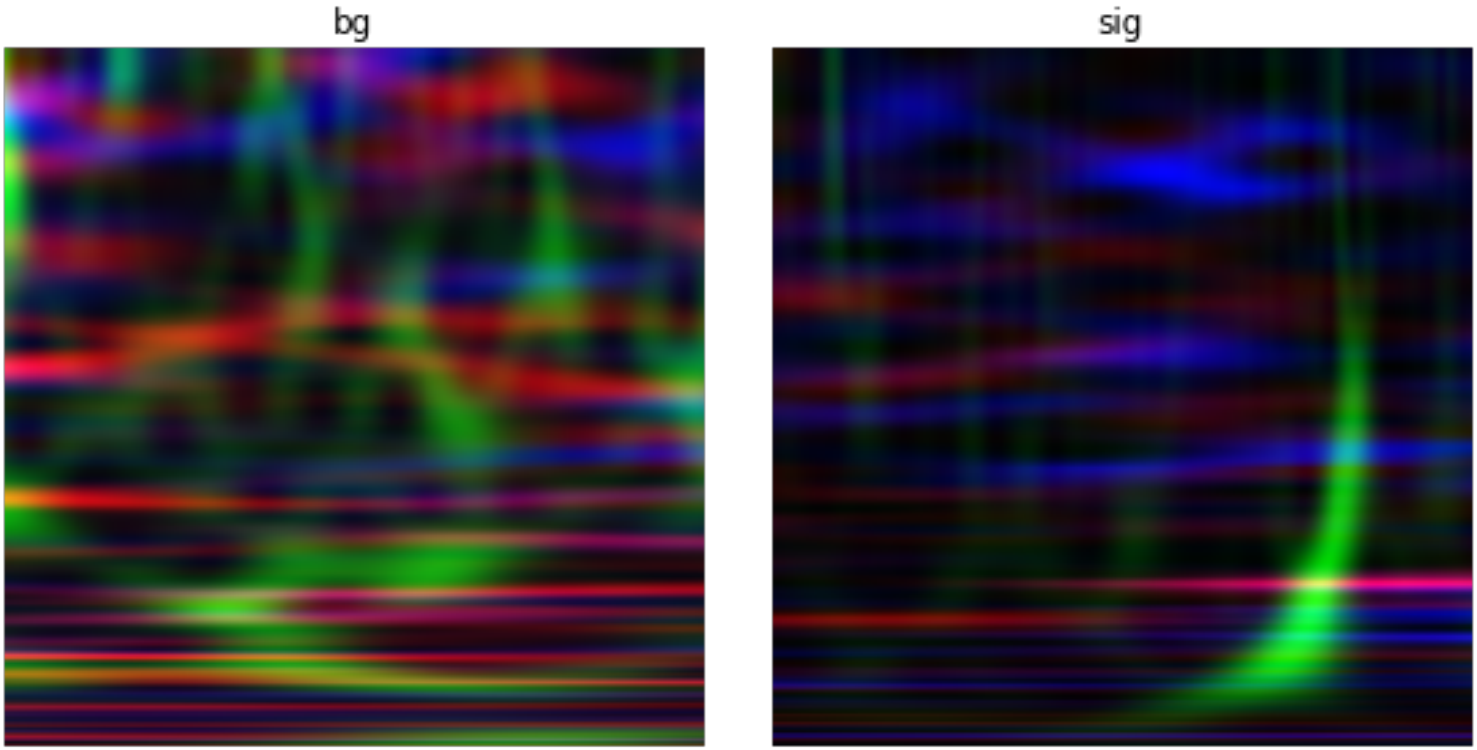
Q1: What is the best strategy? ...Osvaldo's idea



☞ **The idea: I) create 2 sets of spectrograms** (no spin to start with) i.e., **noise from each single detector** in GPS random window, **signal generated with pyCBC** (using SEOBNRv4_ROM approximant) injected in noise

II) combine single detector spectrogram data into a single RGB image, to be used combined by the deep learning network architectures. The **Hanford (top-left)**, **Livingston (top-right)** and **Virgo (bottom-left)** spectrogram data, are used as the Red, Green and Blue images, respectively, to build the **full RGB image (bottom-right)**.

Q1: What is the best strategy? ...Osvaldo's idea



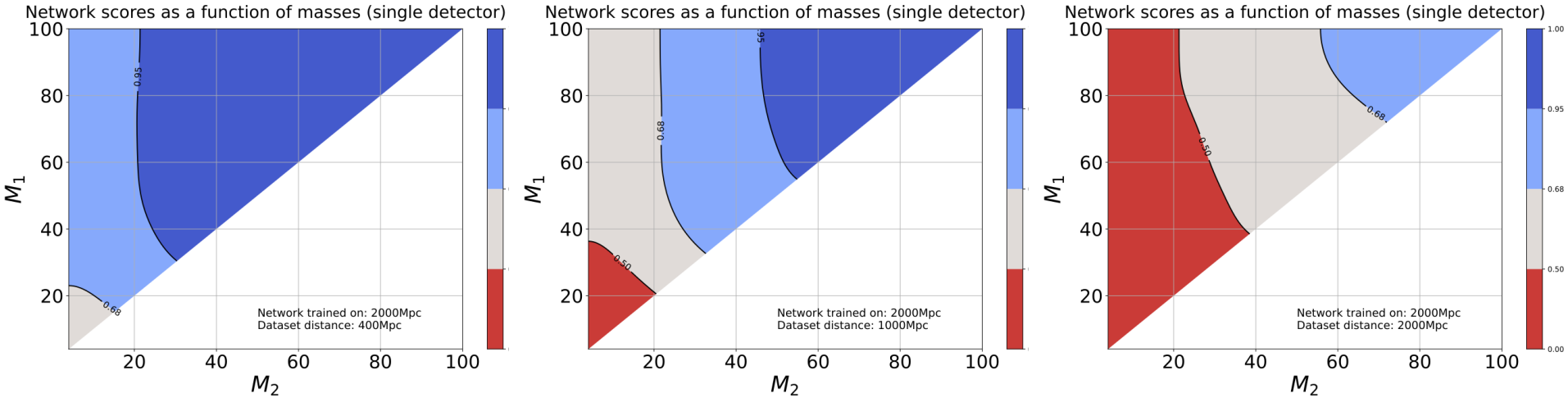
RGB image from **background labeled spectrogram (left)** as compared with a spectrogram where a **GW waveform was injected into real conditions noise(right).**

...a lot of additional tools prepared by **Felipe Freitas**, the ML/DL expert of the team

Q1: What is the best strategy (1 detector)?

Deep Learning Net. Scores for BBH for random (M1,M2) masses
Simulated Signal Scores @ Different Distances

400Mpc 1Gpc 2Gpc



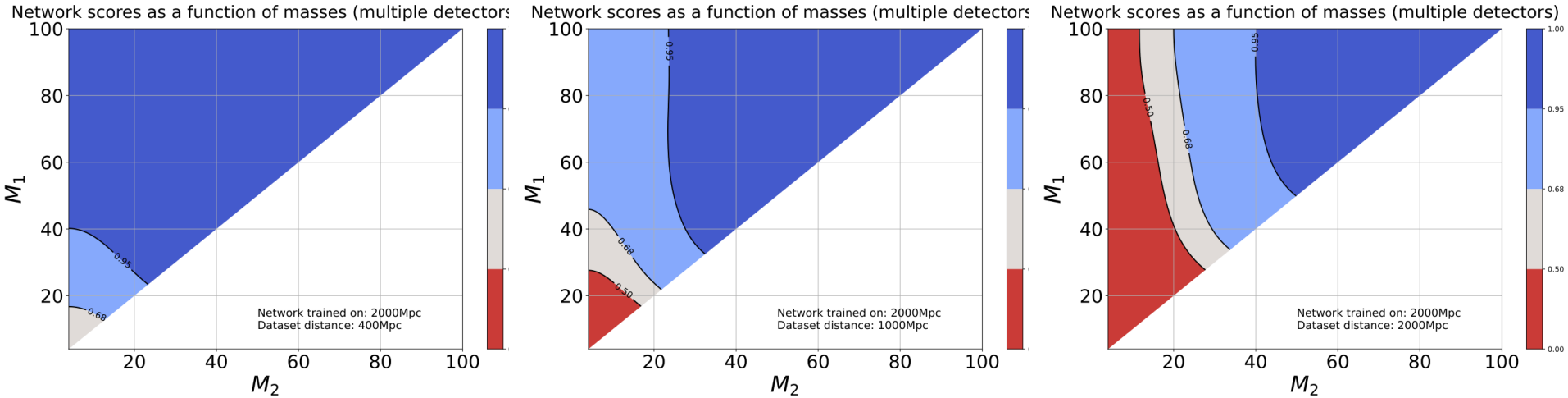
Simulated signal scores using **1 detector**, for different luminosity distances, evaluated with deep learning networks trained with GW waveforms from binary black-holes mergers (BH-BH) at a luminosity distance of 2000 Mpc. Results, as a function of the BH masses of the binary system, M1 and M2, are shown for GW signals from **sources at 400 Mpc (left)**, **1000 Mpc(center)** and **2000 Mpc(right)**, are shown.

☞ Deep Neural Network (DNN), 34 layer ResNet used for Classification

Q1: What is the best strategy (3 detector)?

Deep Learning Net. Scores for BBH for random (M1,M2) masses
Simulated Signal Scores @ Different Distances

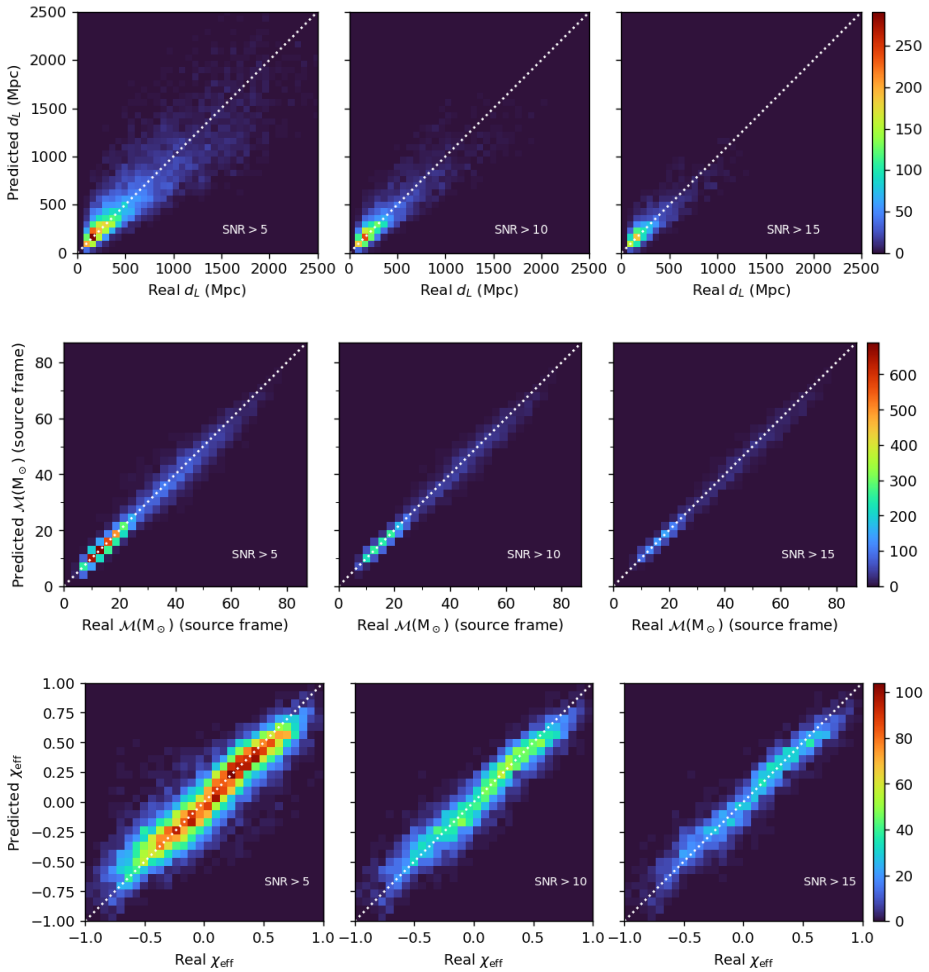
400Mpc 1Gpc 2Gpc



Simulated signal scores using **3 detectors**, for different luminosity distances, evaluated with deep learning networks trained with GW waveforms from binary black-holes mergers (BH-BH) at a luminosity distance of 2000 Mpc. Results, as a function of the BH masses of the binary system, M1 and M2, are shown for GW signals from **sources at 400 Mpc (left)**, **1000 Mpc(center)** and **2000 Mpc(right)**, are shown.

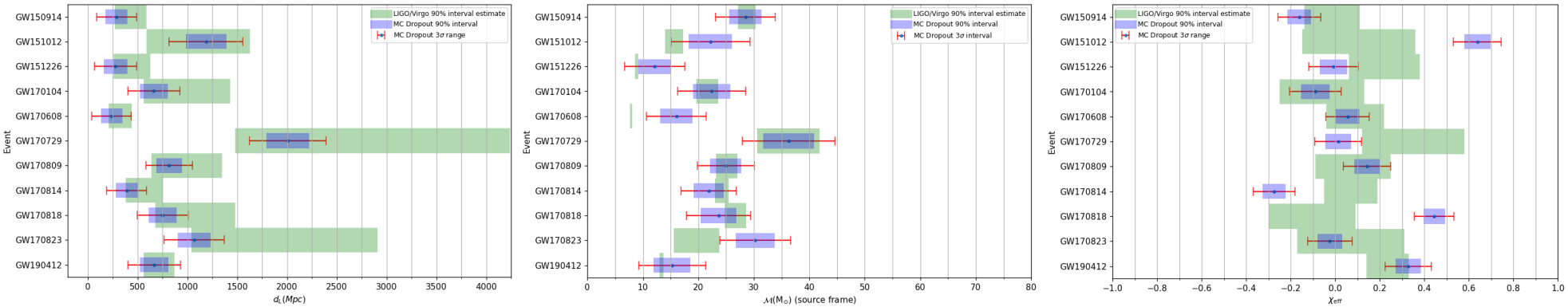
☞ Deep Neural Network (DNN), 34 layer ResNet used for Classification

Q2: Is it possible to extract what we inject?



Calibration from Deep Regression (xResNet18) with drop out results:
d_L**(top)**, **chirp mass (mid.)**, and **effective inspiral spin (bot.)**

Q3: How does DL results compare to literature?



Compare DL results with published results:
d_L**(left)**, **chirp mass (middle)**, and **effective inspiral spin (right)**

GWTC-1 catalog(O1+O2): Physical Review X **9**,031040 (2019)
GW190412 (O3): Physical Review D **102**,043015 (2020)

Conclusions

iLAPP-CFUMUP GW activities:

CF-UM-UP

1) Interface laboratory @ UM, Astrophysics $\oplus$ Particle Physics is a reality nowadays, which nicely complements on-going research in Minho
2) GW activities are becoming quite important, where new ML/DL techniques are being exercised ☞results seem OK! prospects are good for the future....
3) There is an on-going close collaboration established with research groups and experts

Special thanks to: Toni Font, Alejandro Torres-Forné, Felipe Freitas, António Morais, Carlos Herdeiro, Osvaldo Freitas, João Dinis, Solange Nunes for all the work done!

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