ESCAPE

European Science Cluster of Astronomy & Particle physics ESFRI research Infrastructures

Conference **ESCAPE to the Future** | 25-26 October 2022

Royal Belgian Institute of Natural Sciences | Brussels, Belgium

26 October 2022, 10:55 - 11:50

The Extreme Universe Science Project

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ESCAPE to the Future
25-26 October 2022
Brussels, Belgium

Extreme Universe Project Overview

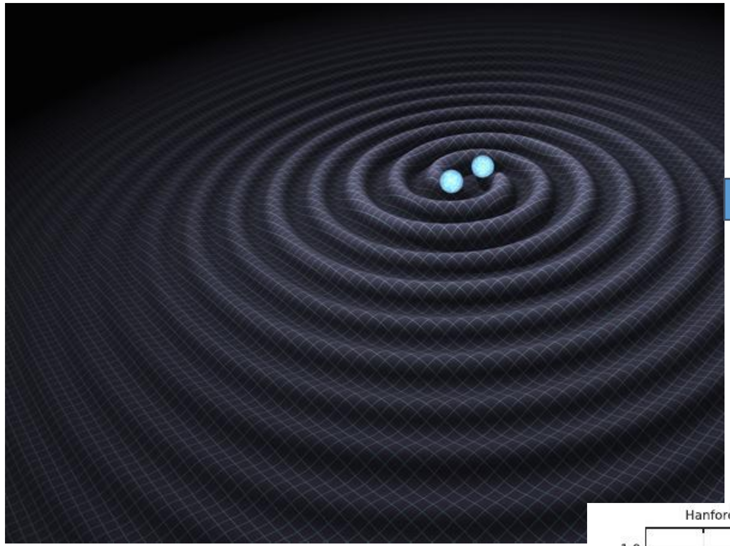
Elena Cuoco
European Gravitational Observatory and Scuola Normale Superiore

COST ACTION CA17137
A NETWORK FOR GRAVITATIONAL WAVES, GEOPHYSICS AND MACHINE LEARNING

I. Bird, A. Iess, A. Parisi, D. Vohl, H. Vedantham, J.Hessels, M. Smirnov, K. Graf, E. Pons, D. Sanchez, S. Lloyd, A. Ain, G. Cella, G. Bertone, S. Markoff

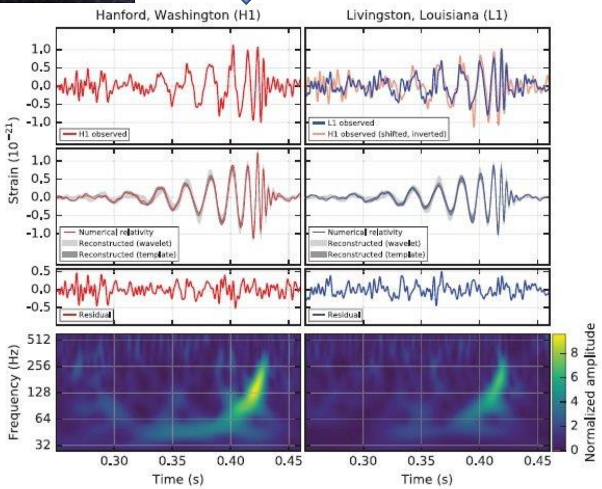
ESCAPE - The European Science Cluster of Astronomy & Particle Physics ESFRI Research Infrastructures has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement no. 824064.

The first detection of Gravitational Waves

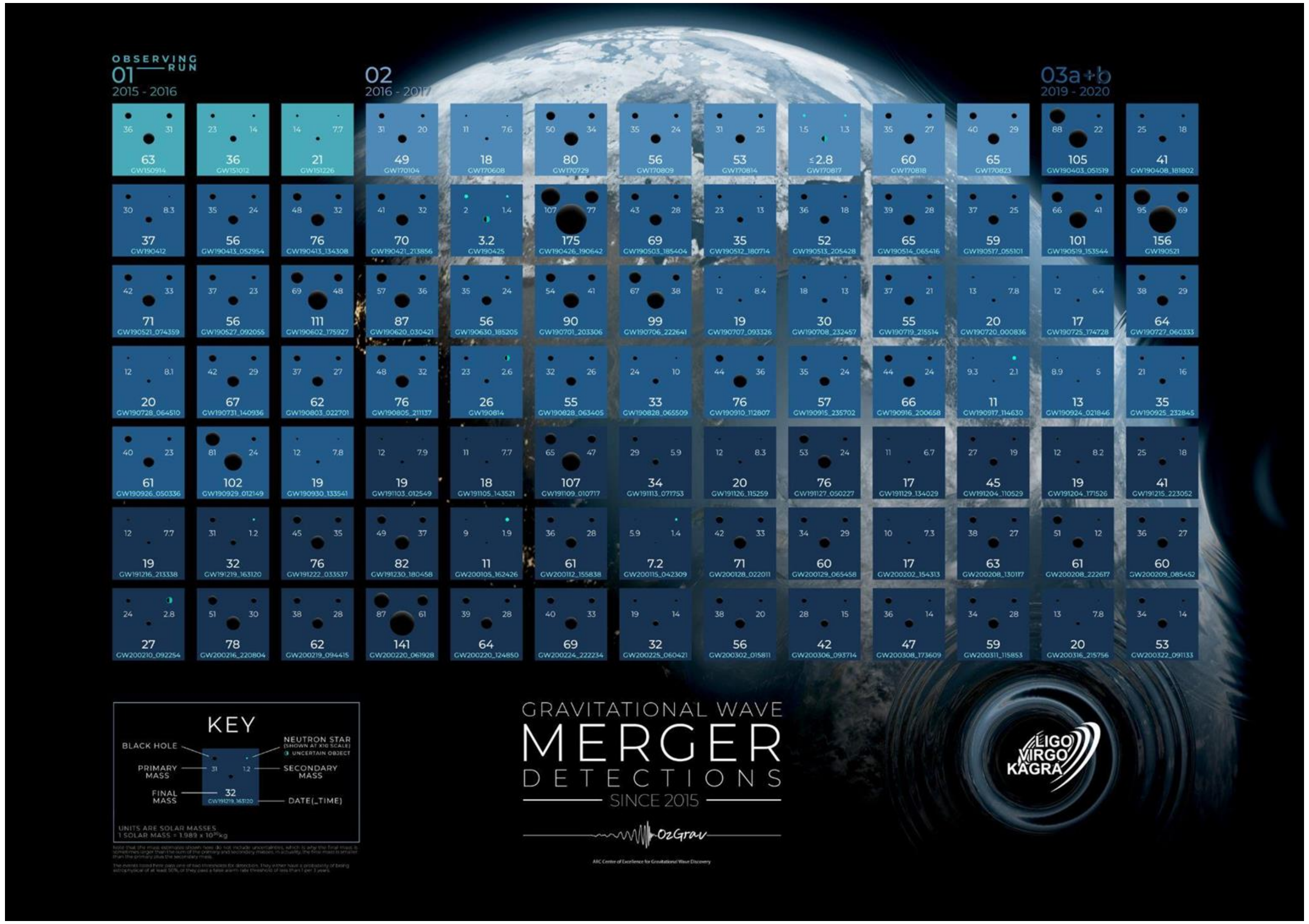


Credits: R. Hurt (Caltech-IPAC)

Black hole merger



GW150914



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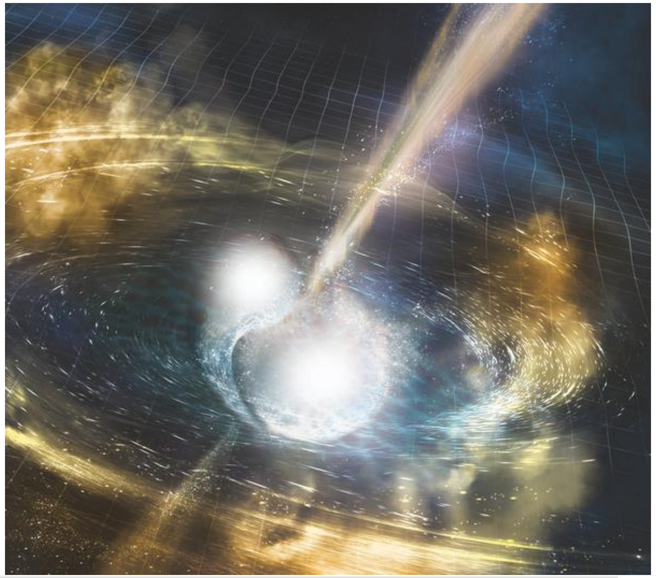
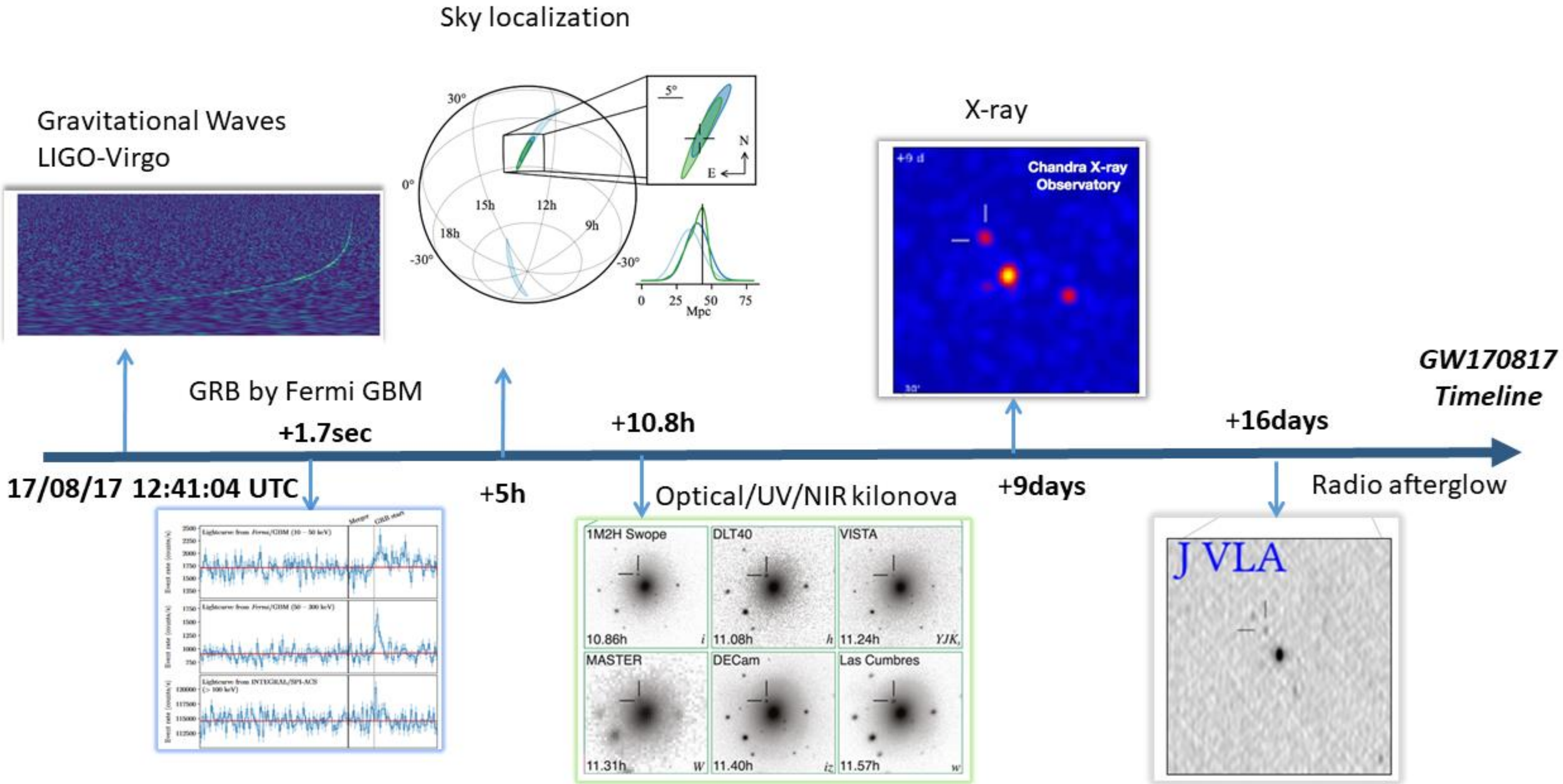
GW170817: Multi Messenger Astrophysics



Credit: NSF/LIGO/Sonoma State University/A. Simonnet

Binary Neutron Star Mergers



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Extreme Universe project overview

- **Gravitational wave discoveries and multi messenger astronomy** opened windows to new perspectives for the study of events in the Extreme Universe. New discoveries and new mysteries
- **Collaboration** among scientists of different disciplines is mandatory
- **Artificial Intelligence** tools, **innovative solutions**, easy to use data analysis platforms, **big data** tackling are common problems in astroparticle research.
- Integration with **ESCAPE EOSC services**: Common AAI, DataLake, OSSR software catalogue, **V**irtual **R**esearch **E**nvironment

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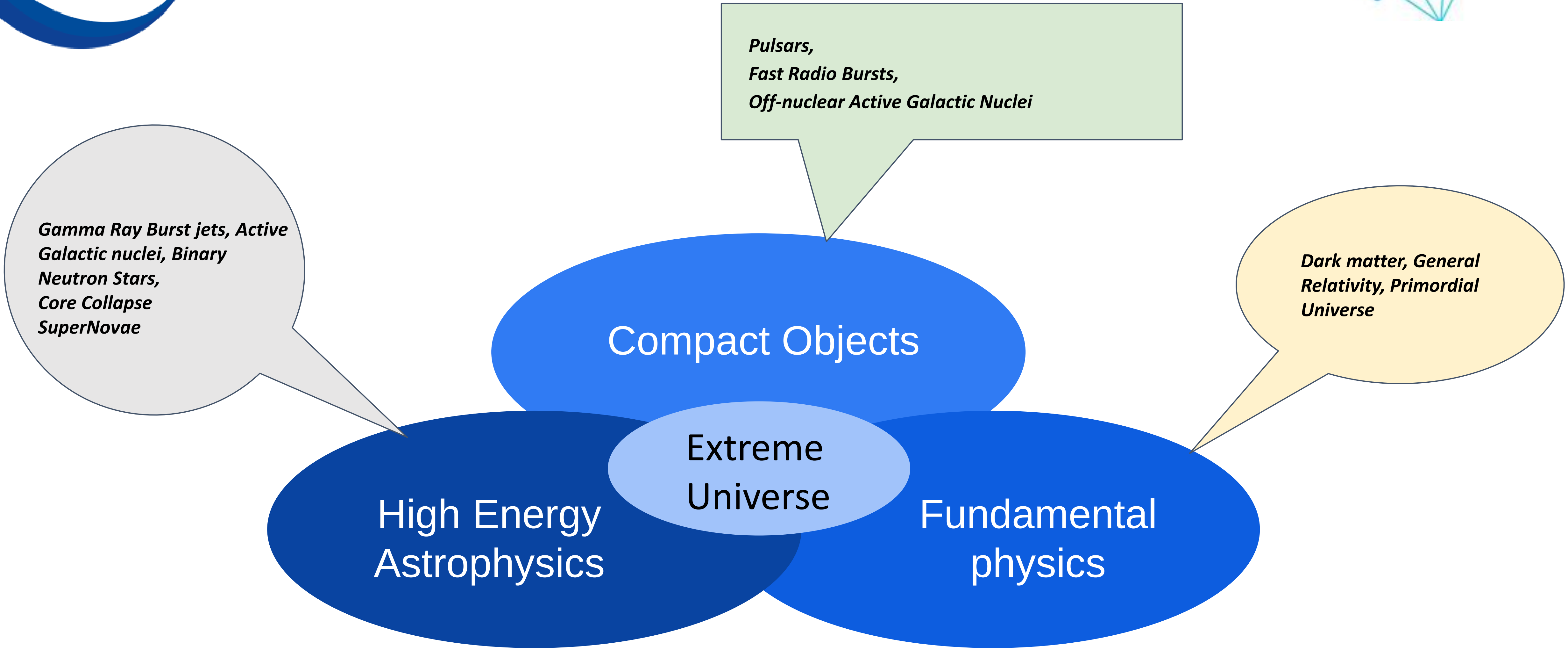
The Extreme universe physics



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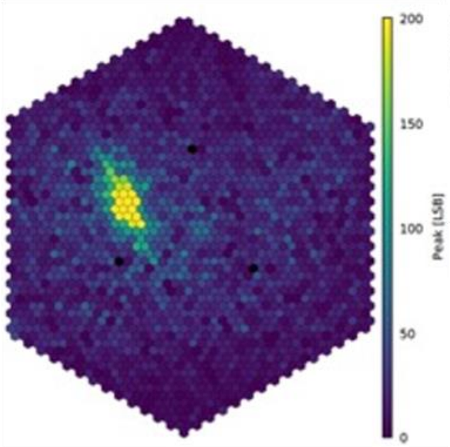
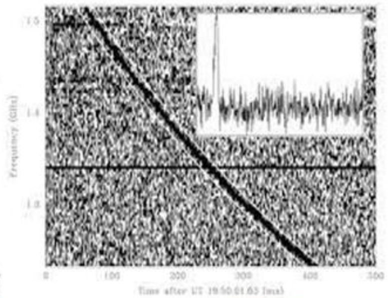
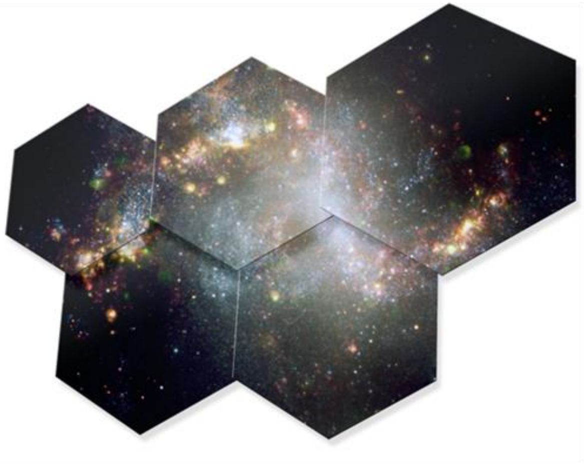
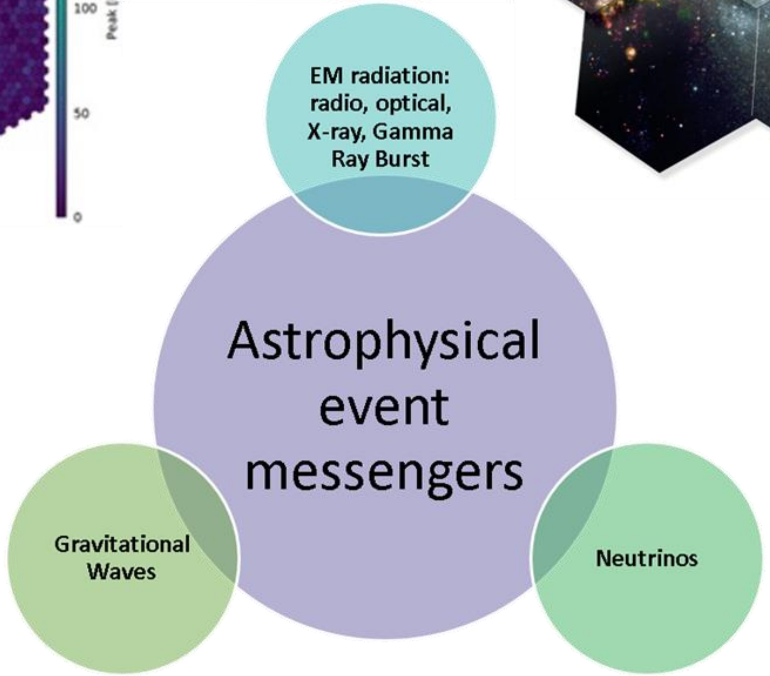
Extreme Universe Messengers

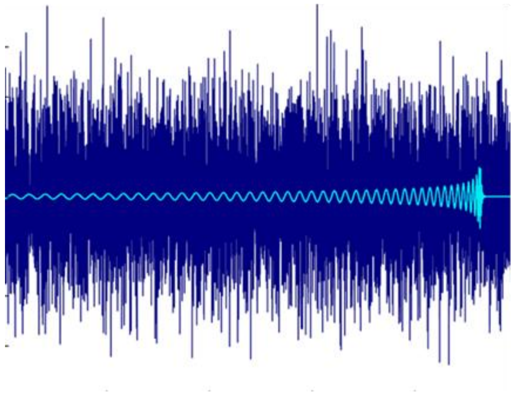
Multi-messenger observations provide key insight into the physics of the most energetic events such as SN, GRBs, AGN

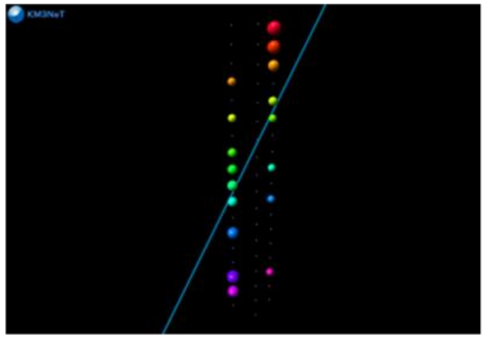












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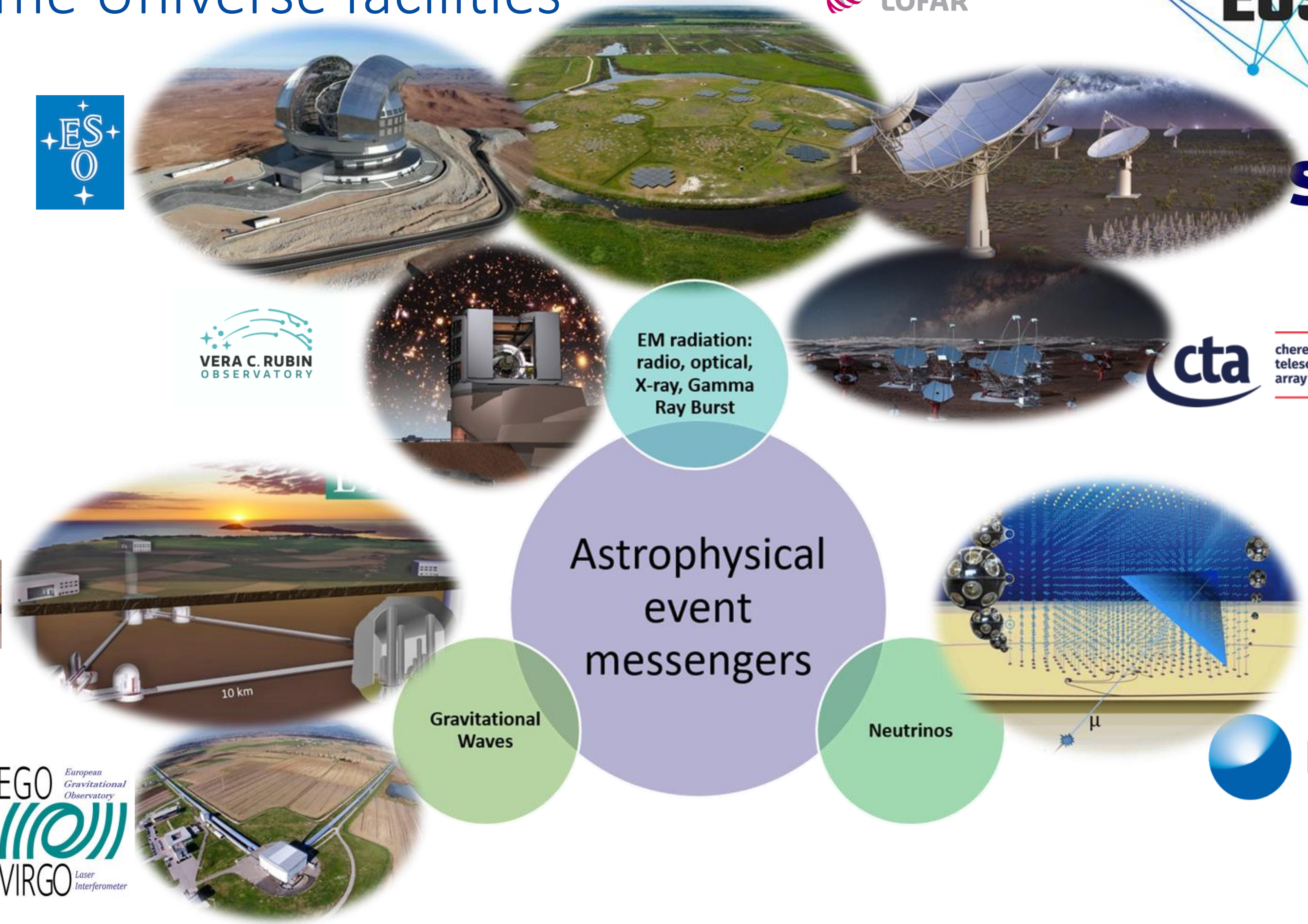
Extreme Universe facilities



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Extreme Universe Science Project goals

Leveraging EOSC to remove sociological barriers among **different communities**, exploiting synergies and complementarities across different communities

Creating a unique link between RIs' data, the **fundamental science** question of understanding the origin of the most violent phenomena in the universe and the computational-cloud tools needed to answer it.

Building through EOSC Future the **transversal environment** to provide frontier AI, analysis methods and a cloud-based analysis dashboard that allows users to exploit the e-infrastructure services.

Bringing the European research community at the leading edge of multi-messengers' modern astrophysics in an international context and driving the global synergies by promoting the EOSC concept implementation. Both ESCAPE SPs will be novel and **innovative demonstrations of the power of open science and cross-RI collaboration**, and can be seen as model demonstrators of capabilities that many other communities will benefit from through the EOSC

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TSP-EU pilot projects

Different pilot projects to deal with Extreme Universe Science

Compact objects	Compact objects	Compact objects	Fundamental Physics	Fundamental Physics	High Energy astrophysics	High Energy astrophysics
• MAP - MM/MWL Analysis Pipeline for AGN Model • Postdoc University of Amsterdam	• Broadband spectral energy distribution fitting of blazars • Postdoc LAPP	• FRB persistent radio source counterpart in dwarf galaxies. • Postdoc ASTRON	• Detecting Dark Matter with Einstein Telescope • Postdoc SNS and University of Amsterdam	• Study of angular correlation signatures induced on GW stochastic background by lensing effects • Postdoc INFN	• Wavefier: a Multi-messenger platform • Postdoc SNS	• KM3NeT Instrument Response Function for point source analysis • Postdoc FAU

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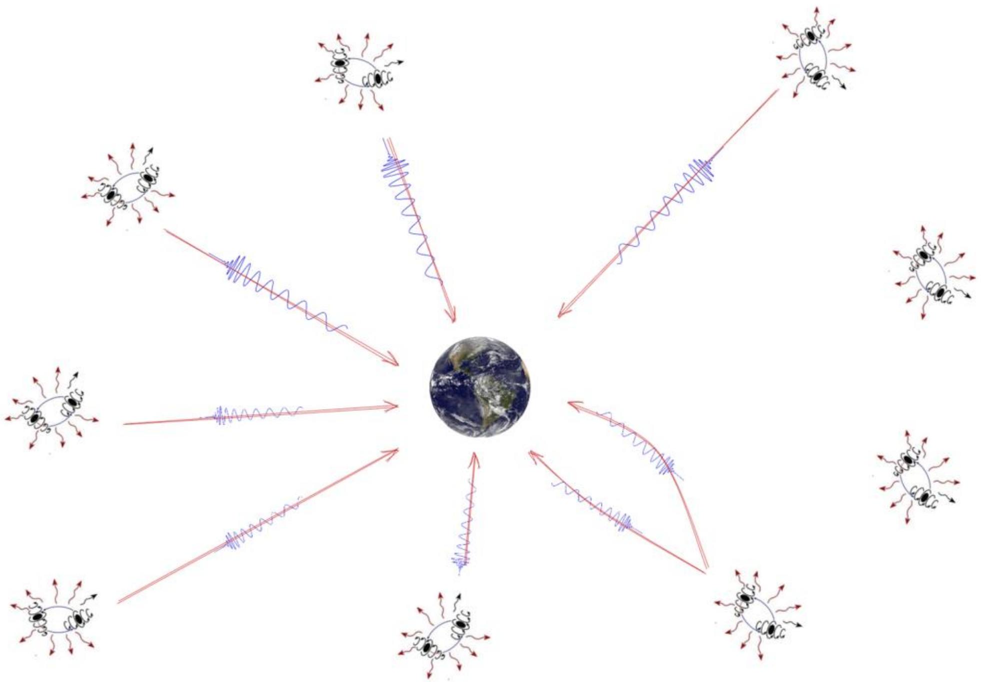
Study of angular correlation signatures induced on GW stochastic background by lensing effects

Anirban Ain, INFN-Pisa (supervised by Giancarlo Cella)

- Simulation of gravitational wave astrophysical like stochastic background signals with correlation signatures (toy model) *[months 1-3]*
- Reconstruction of GW skymaps with existing algorithm, bias effects study [months 4-10]
- Bayesian search and parameter estimation to the data (correlation signature estimation) *[months 11-18]*

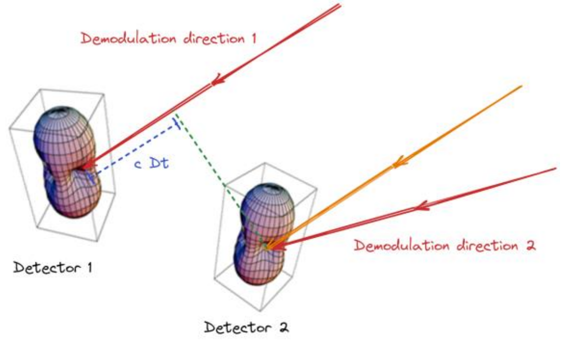


Integration with data lake/VRE

Release of simulation/estimation code
Release of typical sets of data
Notebook interface for data generation on cloud

FTE

1 postdoc
2 undergraduate students
1 senior (10%)



Approach: generalization of map reconstruction algorithm *PHYSICAL REVIEW D 105, 122001 (2022)* in presence of angular correlations. Redesign of demodulation procedure.

$$\left\langle \tilde{h}_A(f,n)\tilde{h}_B(f',n') \right\rangle = \delta_{AB} \mathcal{C}\left(n,n',f\right) \delta(f-f')P(f,n)$$

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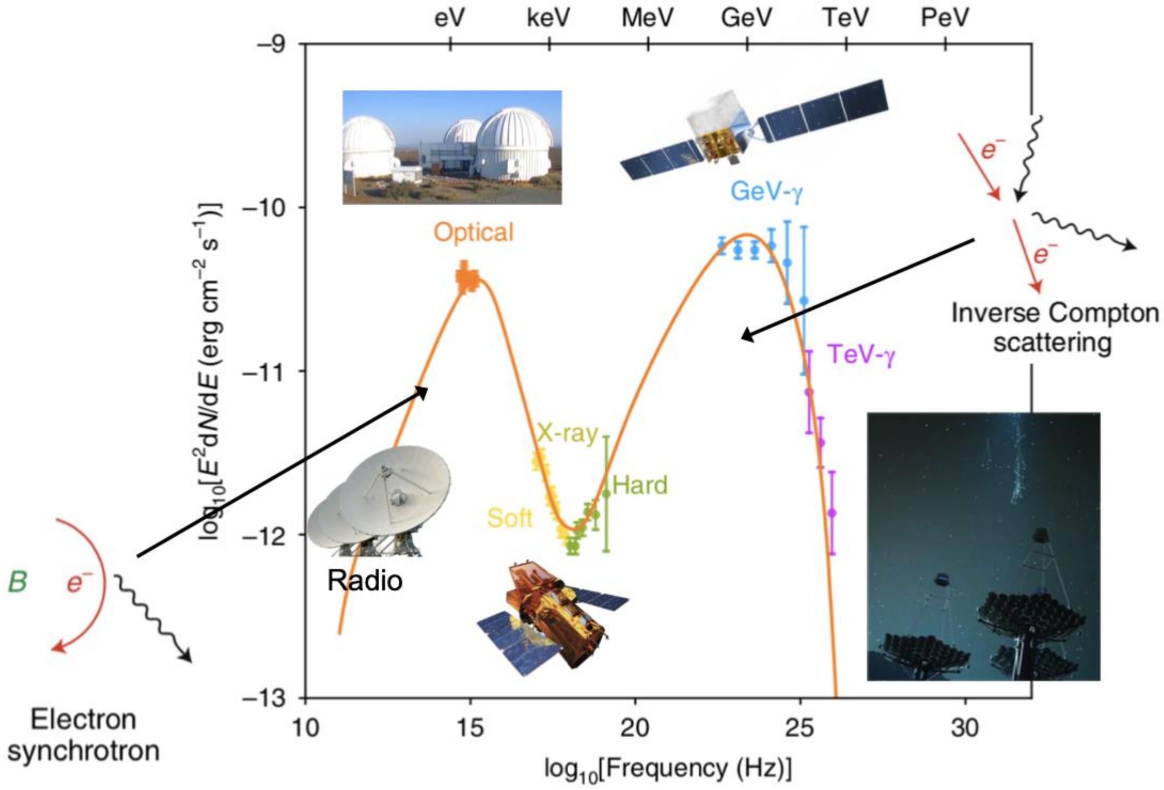
Broadband Spectral Energy Distribution fitting of Blazars

Estelle Pons, LAPP (supervised by David Sanchez)

Blazars are very bright sources, due to the relativistic beaming from the jet, and they are observed over the full range of wavelength from radio to gamma-rays. The broad band Spectral Energy distribution are easily identified by the presence of 2 humps.

- `agnpy`: modelling the radiative process of jetted AGN from radio to γ-rays (Nigro, Sitarek, Gliwny et al. 2022 A&A 660, A18)
  - Synchrotron and Inverse Compton scattering radiative processes from jet non-thermal electrons and external emitters (AGN accretion disc, torus and broad line region)
  - Open python package: https://github.com/cosimoNigro/agnpy/
  - Online tuto: https://agnpy.readthedocs.io/en/latest/tutorials/ssc_gammapy_fit.html
- VRE DLaaS environment with also `gammapy` / `sherpa` packages for the fitting



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MAP - MM/MWL Analysis Pipeline for Active Galactic Nuclei Models

Sheridan Lloyd, UvA (supervised by Sera Markoff)

- MAP to be built to open / FAIR principles.
- Pipeline analysis using *Gammapy* with joint Poissonian likelihood in instrument space with statistical and systematic uncertainties treated correctly. (see Nigro et al 2019, *joint-crab*)
- MAP will use X-Ray, CTA and KM3Net IRFs to allow for energy dependent instrument response (Unbehaun Thesis 2020) with other bands radio, optical, and IR input directly .
- MAP will wrap and integrate existing MWL AGN jet emission model code to test hadronic and leptonic scenarios. The best fit model parameters to observations can also be determined.
- Will meet with FAU, CEA, CTA and *Gammapy* team to agree the approach and science cases.

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Wavefier: A Framework For Multi-messenger Astrophysics

Alberto Iess *(Scuola Normale Superiore)*

Supervisor: E. Cuoco *(European Gravitational Observatory, Scuola Normale Superiore)*

In collaboration with: E. Cuoco, F. Morawski, B. Patricelli, E. Marzini, A. Staniscia, S. Vallero

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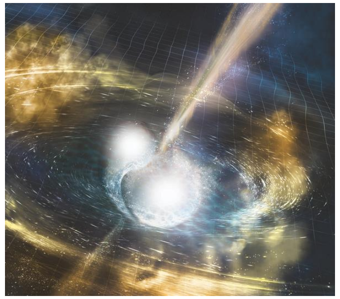
Wavefier: A Framework For Multi-Messenger Astronomy

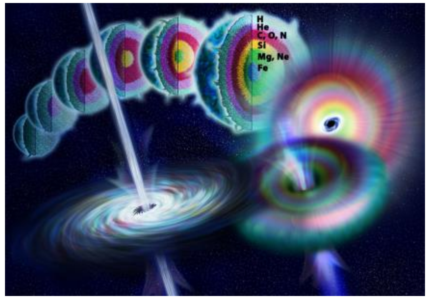
- **<u>Multi-messenger</u>** input
  (Gravitational Waves, Gamma and X-Rays, neutrinos..)
- *Real-time* analysis
- *Scalability* for big data analysis
- *Portability*
- Transient classification
- *ICT services* supporting research infrastructures
- *FAIR* data principles
- Best practices for software management

Neutron Star Merger



NSF/LIGO/Sonoma State University/A. Simonnet

Core-Collapse Supernovae



NSF/N.Rager Fuller

IN COLLABORATION WITH:

Trust-IT Services
communicating to markets

This projects acknowledges the computational resources and support provided by the following institutions: CNAF, Scuola Normale Superiore and the European Gravitational Observatory

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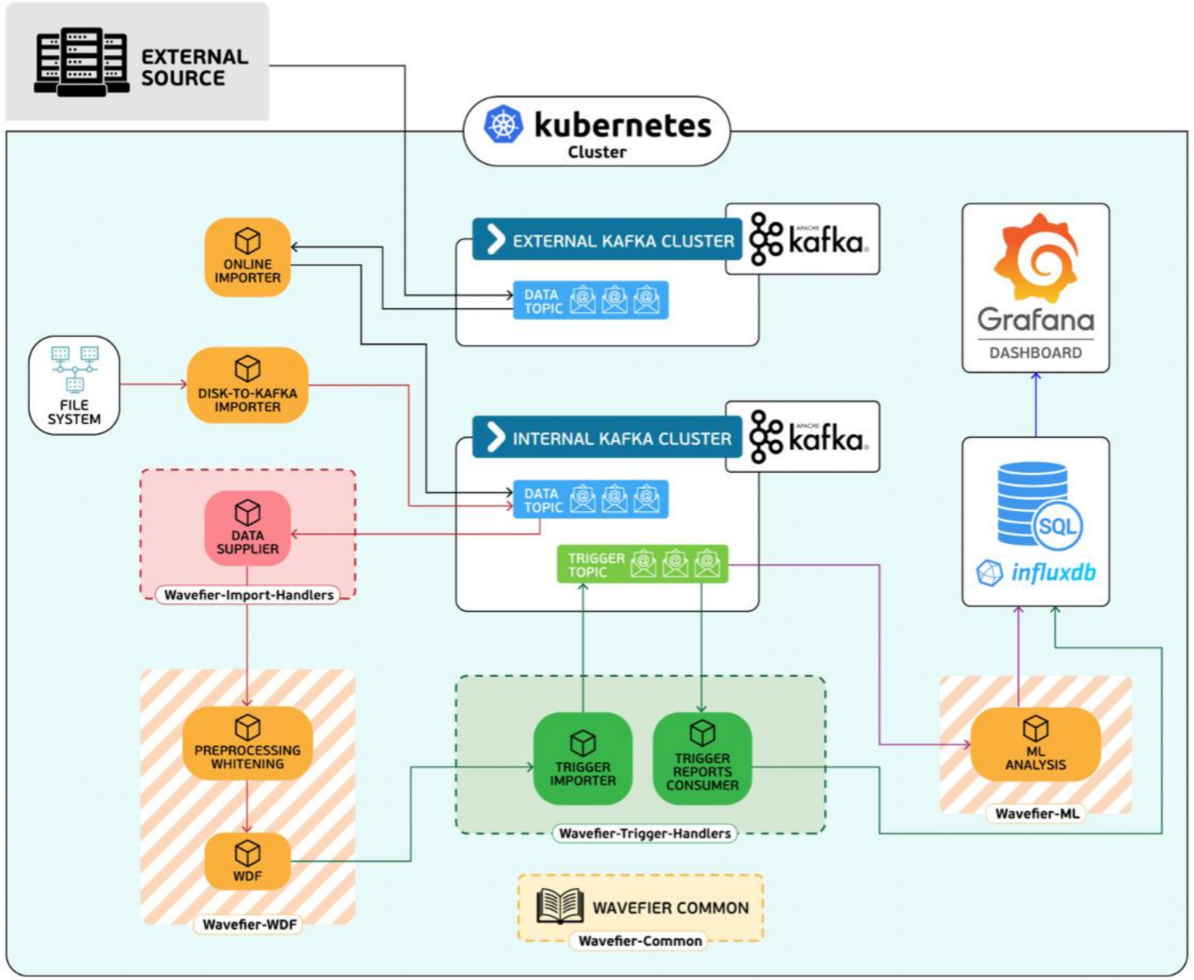
Wavefier: Structure Breakdown

WAVEFIER’s structure is composed of **python** modules:

- Dedicated gitlab project with a repository for each module.
- Continuous integration to build docker images

Docker Compose

portability!



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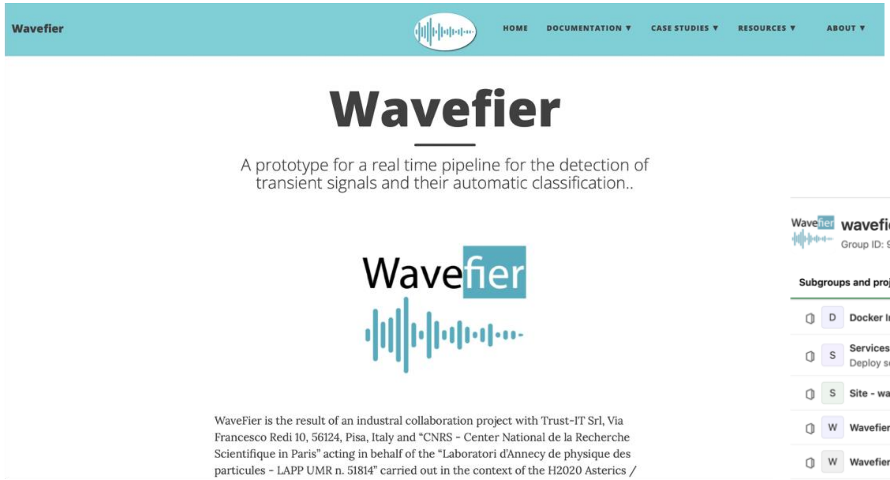
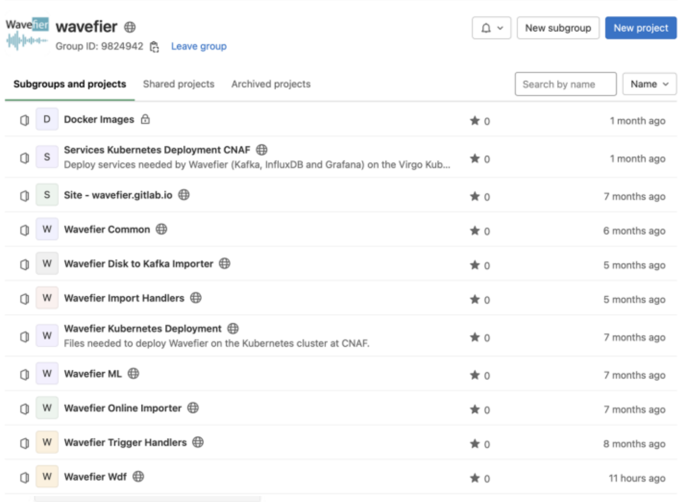
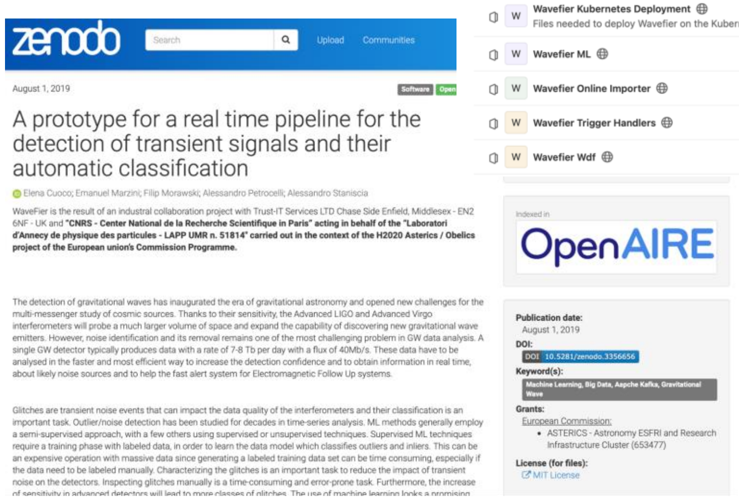
Wavefier Resources

- ***Website***
  https://wavefier.gitlab.io
- ***Gitlab repository***
  https://gitlab.com/wavefier
- ***Docker Images***
  https://gitlab.com/wavefier/docker-images
- ***Zenodo entry***
  https://zenodo.org/record/3356656#.Y035zS8RpQI







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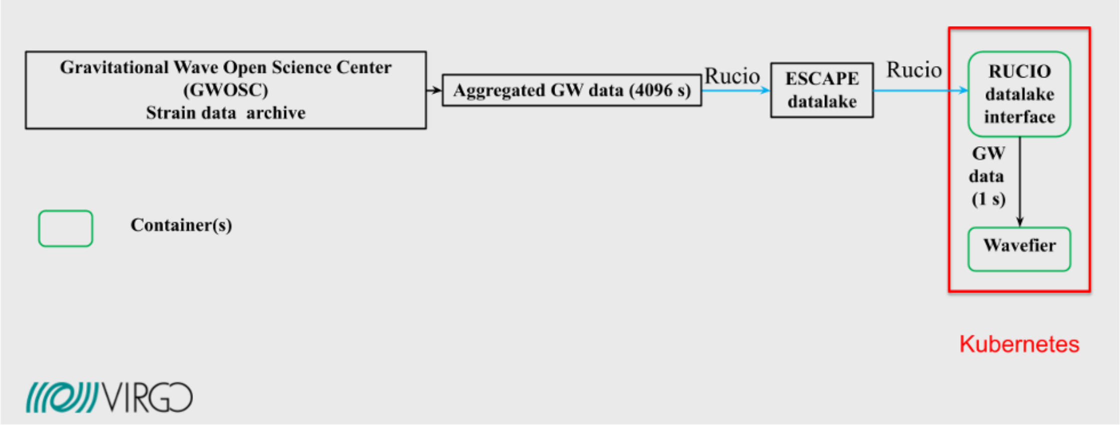
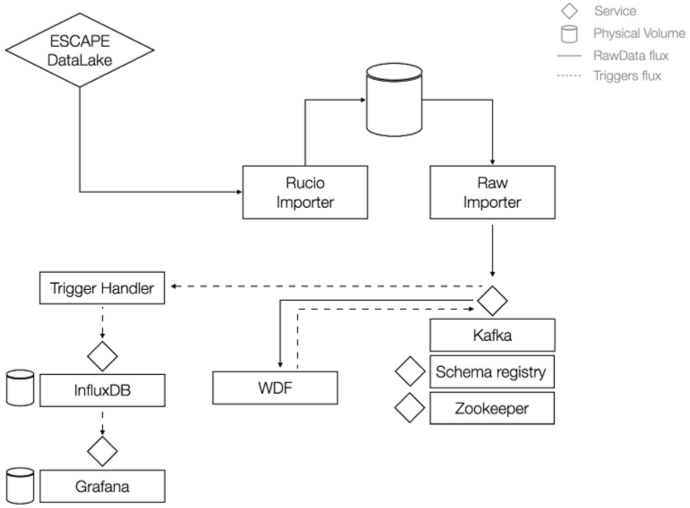
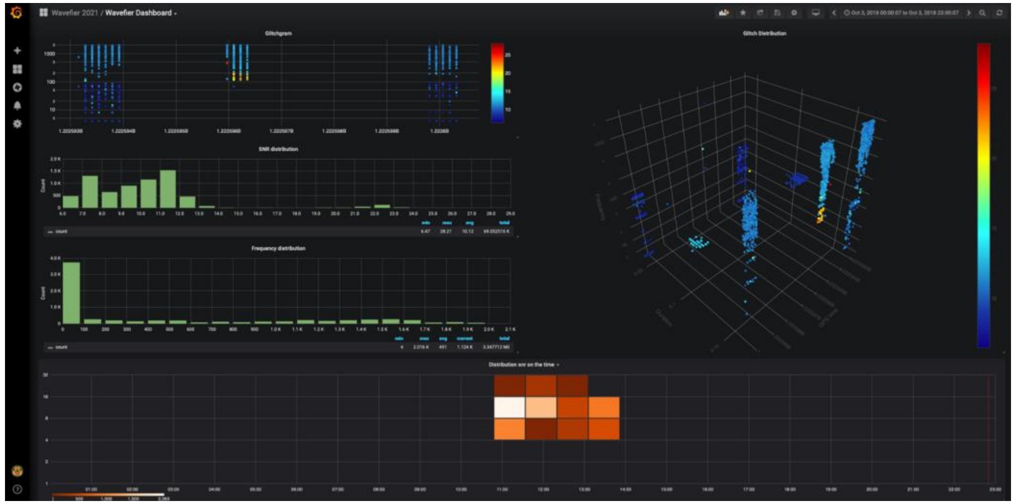
Test Case: ESCAPE Datalake

- Gravitational Wave Open Science Center data
- Successfully attached to ESCAPE datalake
- Gravitational wave specific implementation
- CNAF cloud (region Tier1) on shared Virgo **Kubernetes** cluster.
- Astrophysical signal triggers sent to Influx DB and plotted through Grafana dashboard







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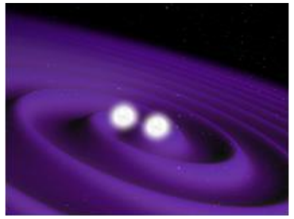
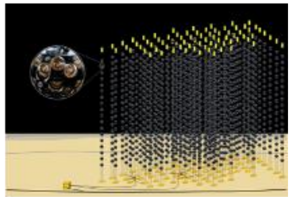
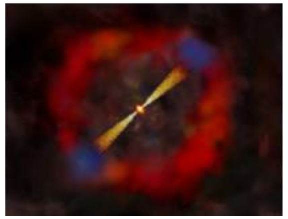
On-going Test Case: Multi-messenger Data

Different Data Formats



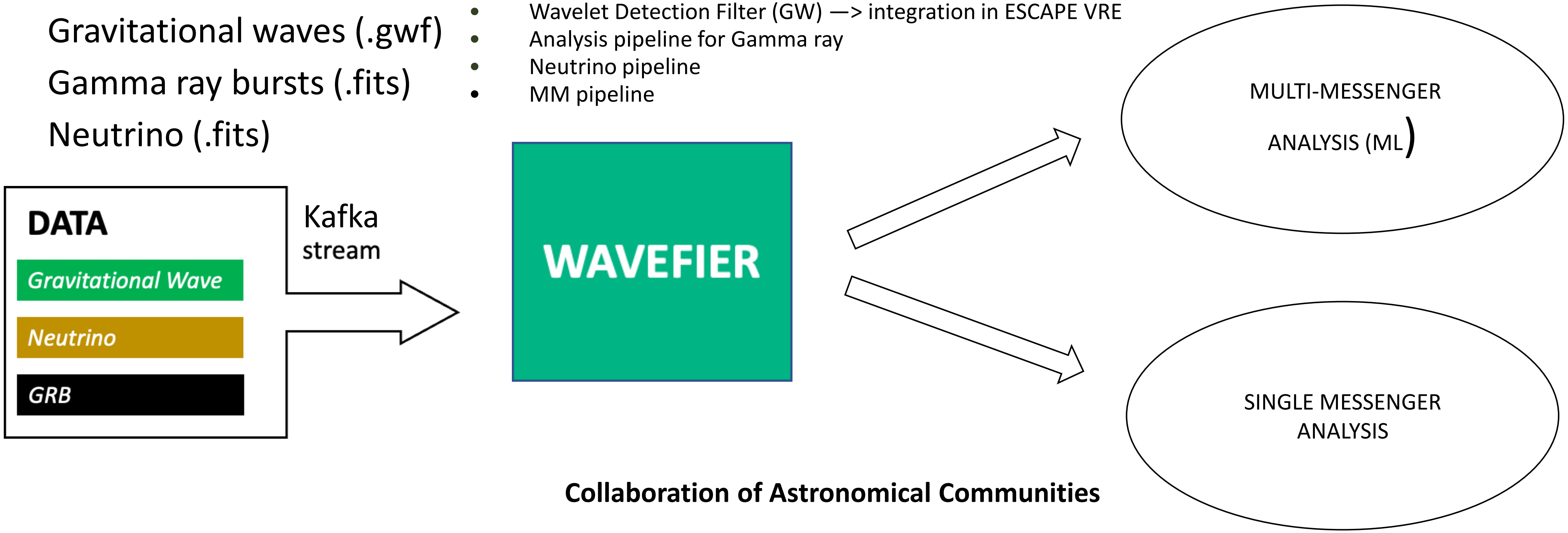




- Gravitational waves (.gwf)
- Gamma ray bursts (.fits)
- Neutrino (.fits)

Separate Analysis Pipelines

- Wavelet Detection Filter (GW) —> integration in ESCAPE VRE
- Analysis pipeline for Gamma ray
- Neutrino pipeline
- MM pipeline



Collaboration of Astronomical Communities

VIRGO cta cherenkov telescope array

KM3NeT

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Measuring the dark Matter environments of black hole binaries with Gravitational Waves

Alessandro Parisi (Scuola Normale Superiore and University of Amsterdam)

supervisors: E.Cuoco and G.Bertone

In collaboration with: G.Bertone, P.Cole, A.Coogan, B.Kavanagh, D.Gaggero, E.Cuoco, A.Iess

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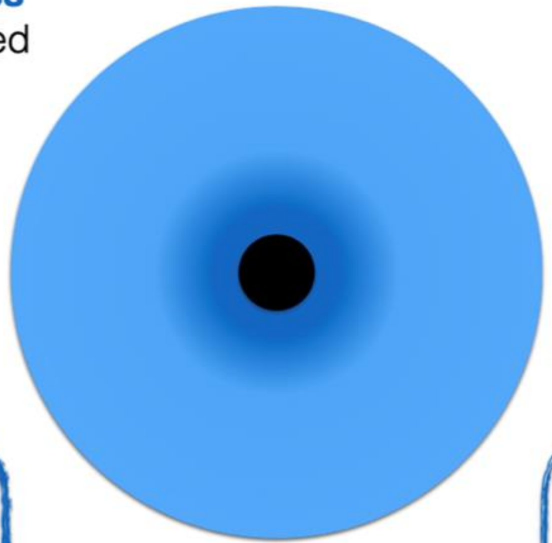
Dark Matter Spikes

Consider now a cold **DM** '**spike**' or '**dress**' around the central BH (not to be confused with ultralight boson clouds).



Study the following benchmarks:

$$m_1 = 1 M_\odot$$
$$m_2 = 10^{-2} - 10^{-4} M_\odot$$
$$\rho_{\rm DM} = \rho_6 \left(\frac{10^{-6}\,{\rm pc}}{r} \right)^{\gamma_{\rm sp}}$$

Astrophysical scenario

$$\gamma_{\rm sp} = 7/3 \approx 2.3333\ldots$$
$$\rho_6 \approx 5.45 \times 10^{15}\, M_\odot\, {\rm pc}^{-3}$$

…depending on a number of environmental factors…

[astro-ph/9906391, astro-ph/0509565, 1305.2619, …]

PBH scenario

$$\gamma_{\rm sp} = 9/4 \approx 2.25$$
$$\rho_6 \approx 5.35 \times 10^{15}\, M_\odot\, {\rm pc}^{-3}$$

[Bertschinger (1985), astro-ph/0608642, 1901.08528, …]

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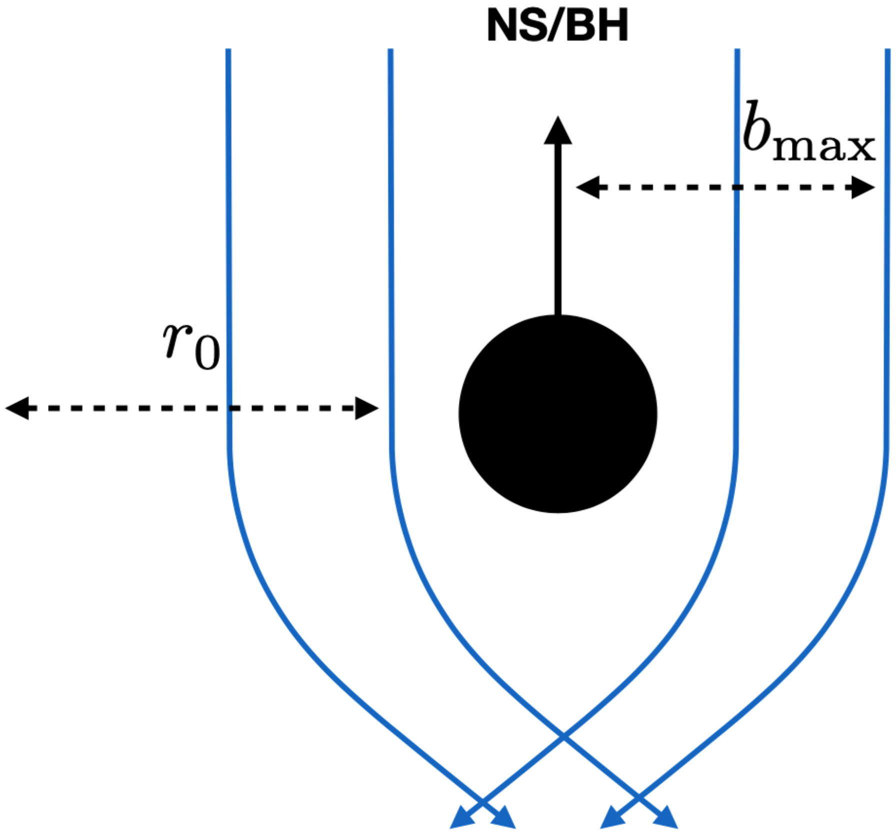
Dynamical Friction

$$\frac{dE_{\rm orb}}{dt} = -\frac{dE_{\rm GW}}{dt} - \frac{dE_{\rm DF}}{dt}.$$



$$\frac{dE_{\rm GW}}{dt} = \frac{32G^4M(m_1m_2)^2}{5(cr_2)^5}. \qquad \frac{dE_{\rm DF}}{dt} = 4\pi(Gm_2)^2\rho_{\rm DM}(r_2)\xi(v)v^{-1}\log\Lambda.$$

$$\dot{r}_2 = -\frac{64G^3Mm_1m_2}{5c^5(r_2)^3} - \frac{8\pi G^{1/2}m_2\rho_{\rm sp}\xi\log\Lambda r_{\rm sp}^{\gamma_{\rm sp}}}{\sqrt{M}m_1r_2^{\gamma_{\rm sp}-5/2}}$$

$$h_+(t) = \frac{4G_N\mu}{c^4D_L}\frac{1+\cos^2\iota}{2}(\omega r_2)^2\cos[2\Phi_{\rm orb}(t)+2\phi],$$

$$h_\times(t) = \frac{4G_N\mu}{c^4D_L}\cos\iota(\omega r_2)^2\sin[2\Phi_{\rm orb}(t)+2\phi],$$

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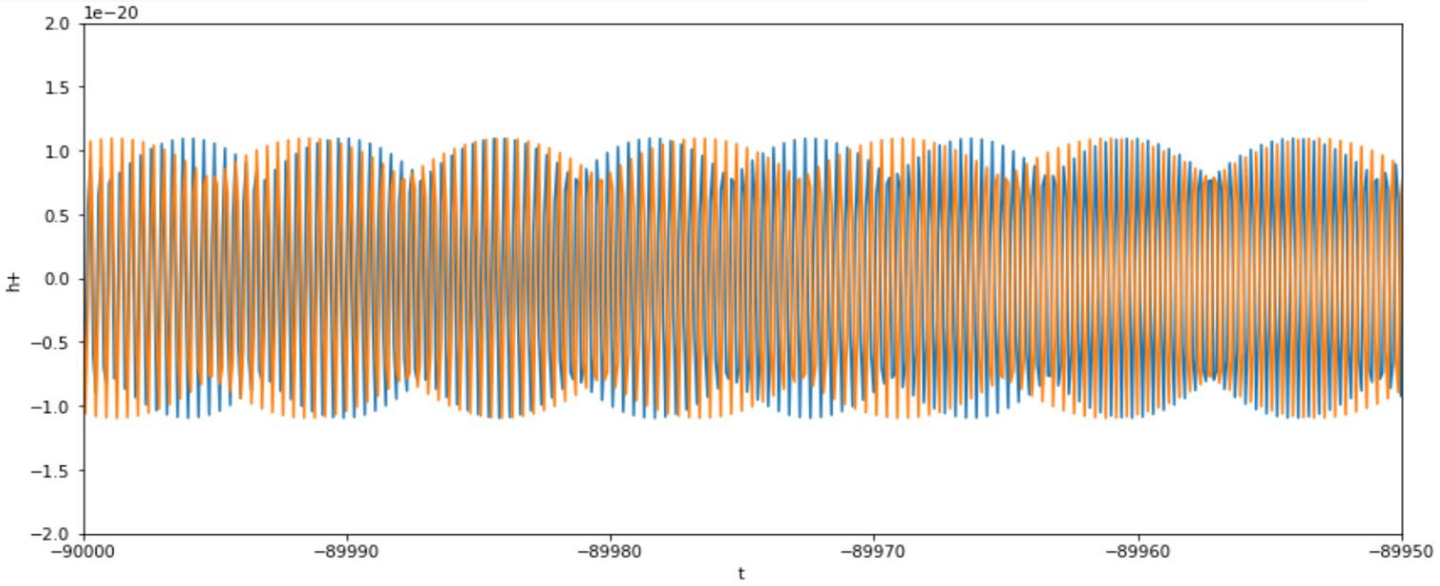
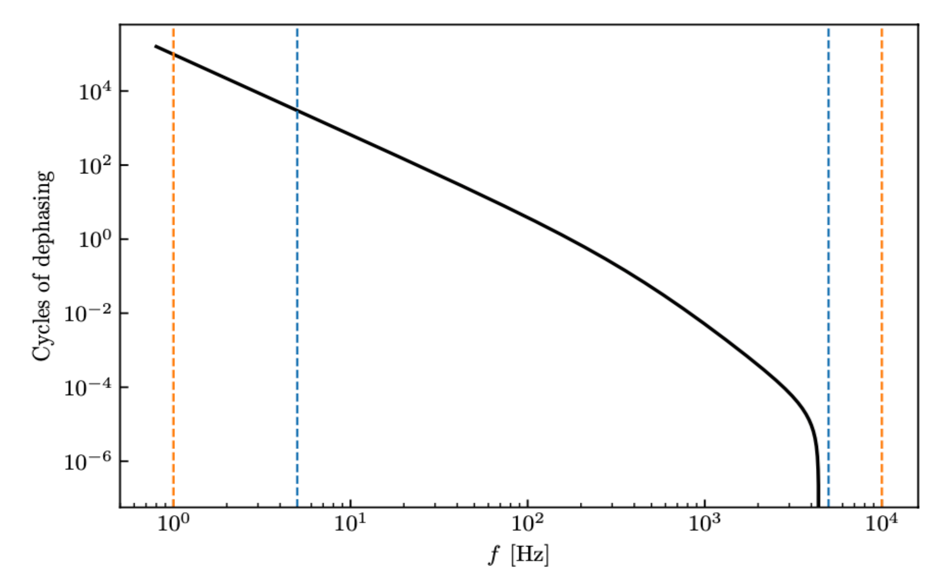
[Code available online: https://github.com/adam-coogan/pydd]

```
#EDIT WAVEFORM PARAMETERS BELOW:
#------------------------------------------------
m_1      = 1.0     # [MSun]
m_2      = 0.001   # [MSun]
t_obs    = 1*DAY   # Duration of the waveform [
t_end    = -0.0*YR   # End time of the waveforn
f_samp   = 200 # Sampling frequency [Hz]
d_l      = 100000   # Luminosity distance [pc]
iota     = 0.0   # Inclination angle [rad]
phi_c    = 0.0   # Phase at coalescence [rad]
```





$$N_{\rm cycles}(t_{\rm max}, t_{\rm min}) = \int_{t_{\rm min}}^{t_{\rm max}} f_{\rm gw}(t)dt = \int_{f_{\rm min}}^{f_{\rm max}} df_{\rm gw} \frac{f_{\rm gw}}{\dot{f}_{\rm gw}}$$

$$\Delta N_{\rm cycles} = N_{\rm cycles}^{\rm vac}(f_{\rm max}, f_{\rm min}) - N_{\rm cycles}^{\rm DM}(f_{\rm max}, f_{\rm min})$$

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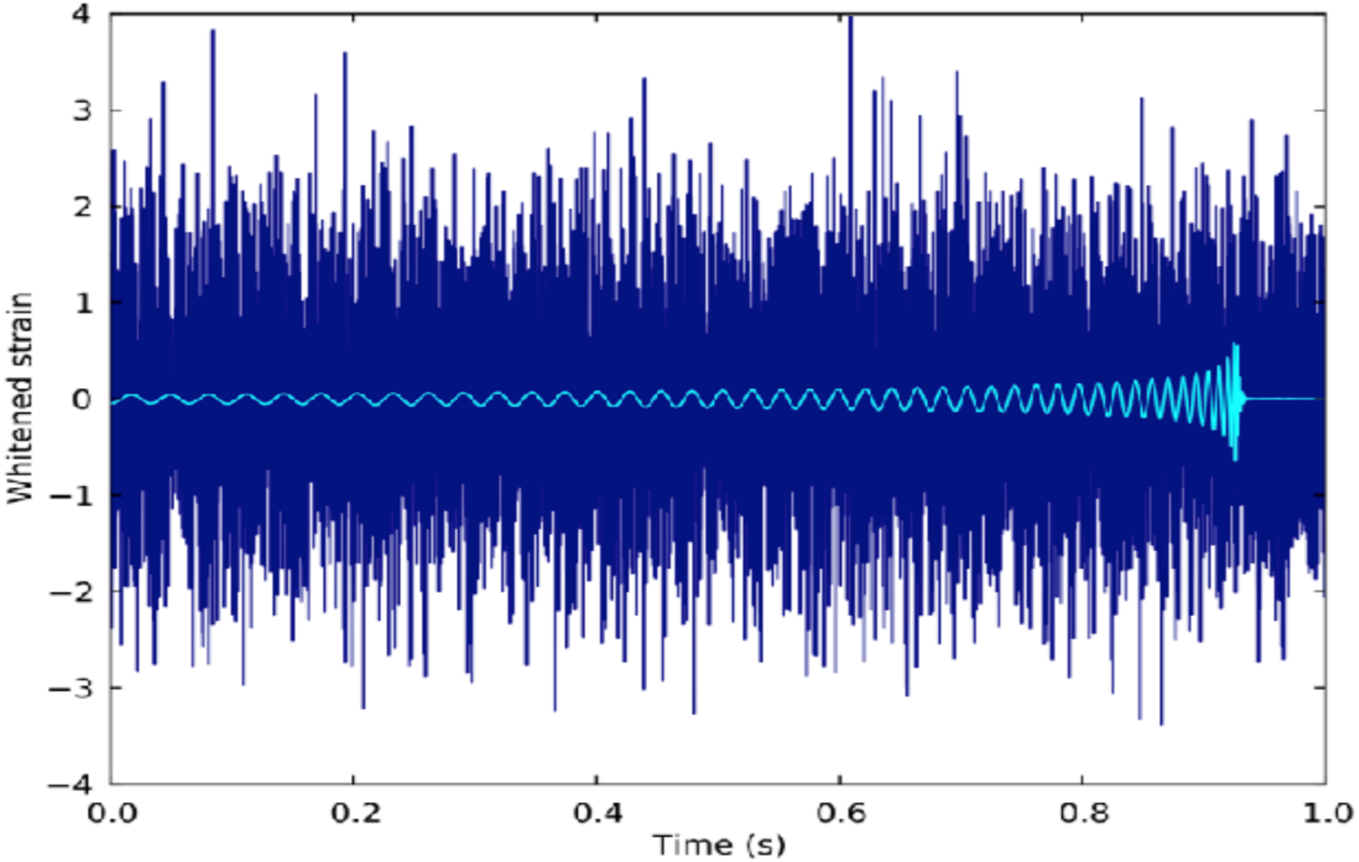
Matched Filtering



Naively, one might think that we can only make confident detections when |h(t)| > |n(t)|
However, the **majority of signals are expected to be |h(t)| ≪ |n(t)|**
Therefore, we need a method to detect signals from noise-dominated data
If we know the possible forms of h(t), we can “filter” out things that are non-signal-like

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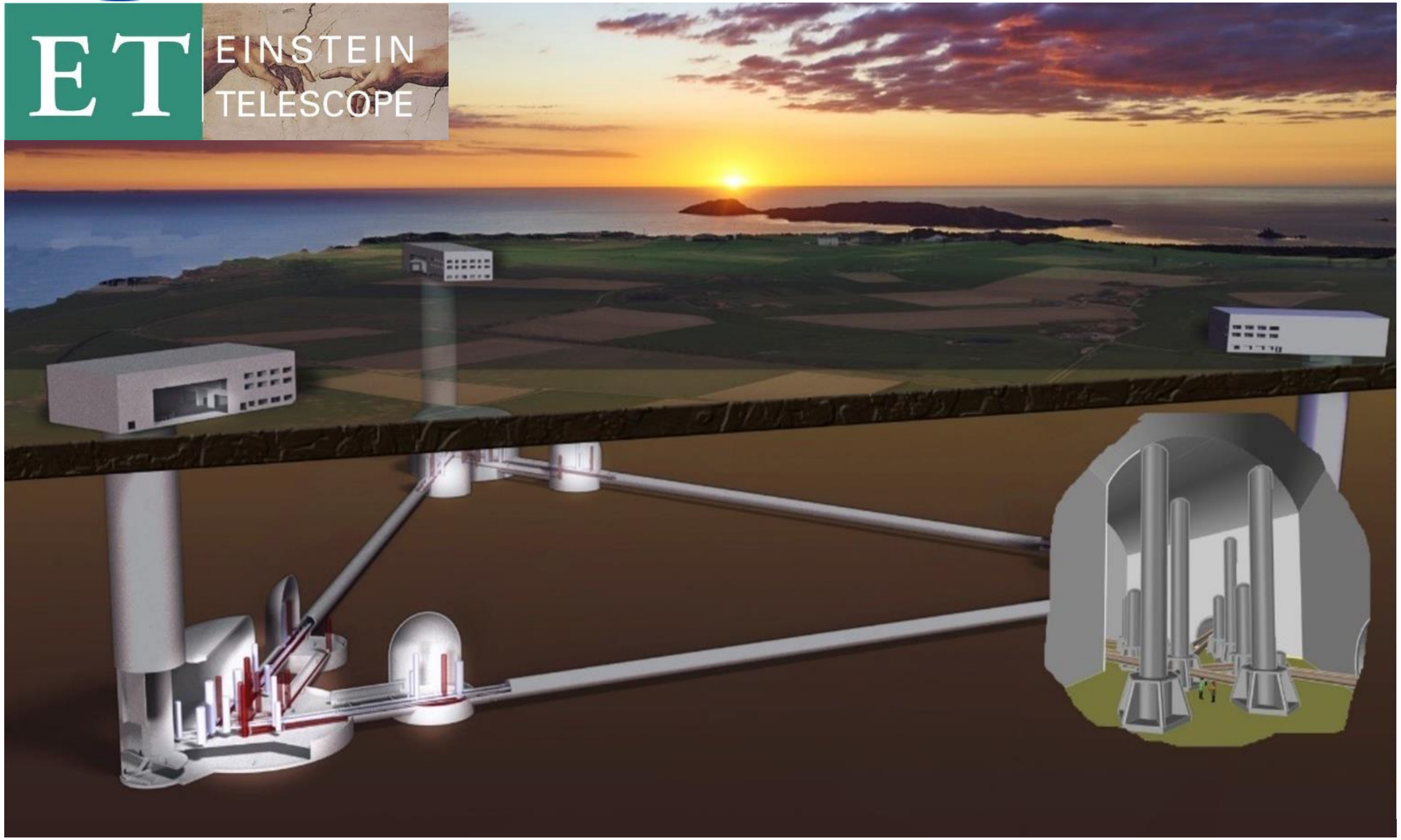
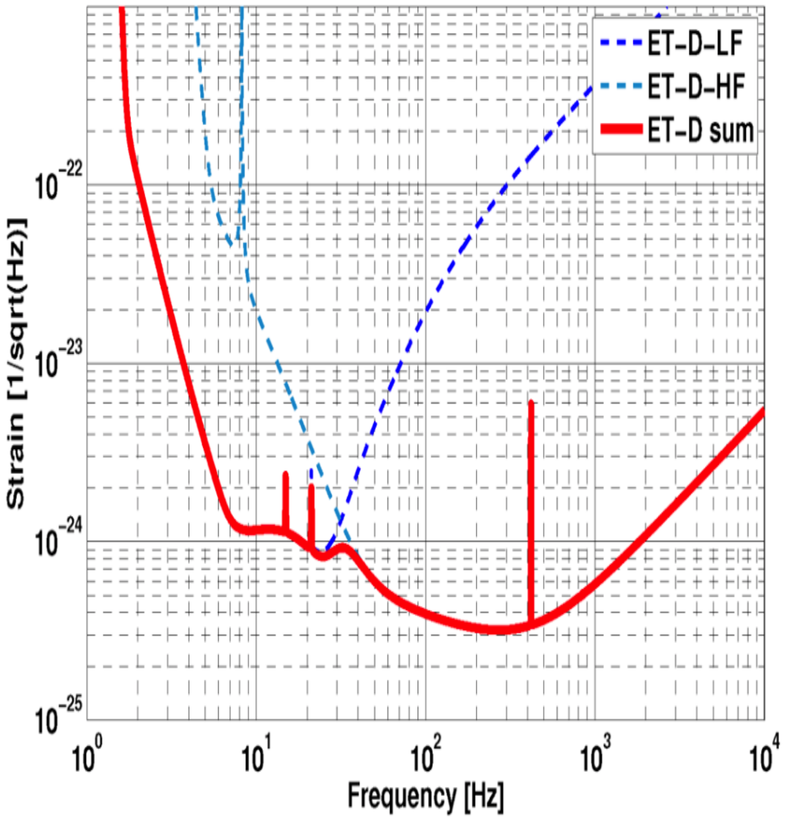
Einstein Telescope





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Waveform Dataset

Develop a catalog of waveforms for different luminosity distances and masses

Luminosity distance d = 10kpc, 20kpc, 30kpc, 40kpc, 50kpc , 60kpc, 100kpc

Mass $m_1 = 1M_\odot \quad m_2 = 10^{-2} - 10^{-4}M_\odot \quad \Delta m_2 = 0.001M_\odot$

Antenna Sensitivity 100 different directions

We have 11400 GW for the vacuum and 11400 GW with dark matter +802 GW at 100kpc

Total: 22800 waveform +802

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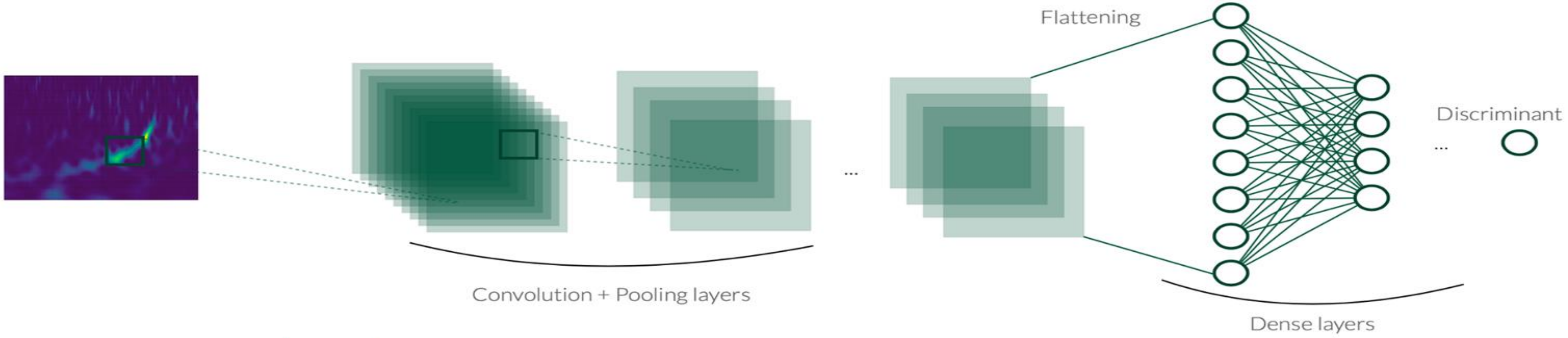
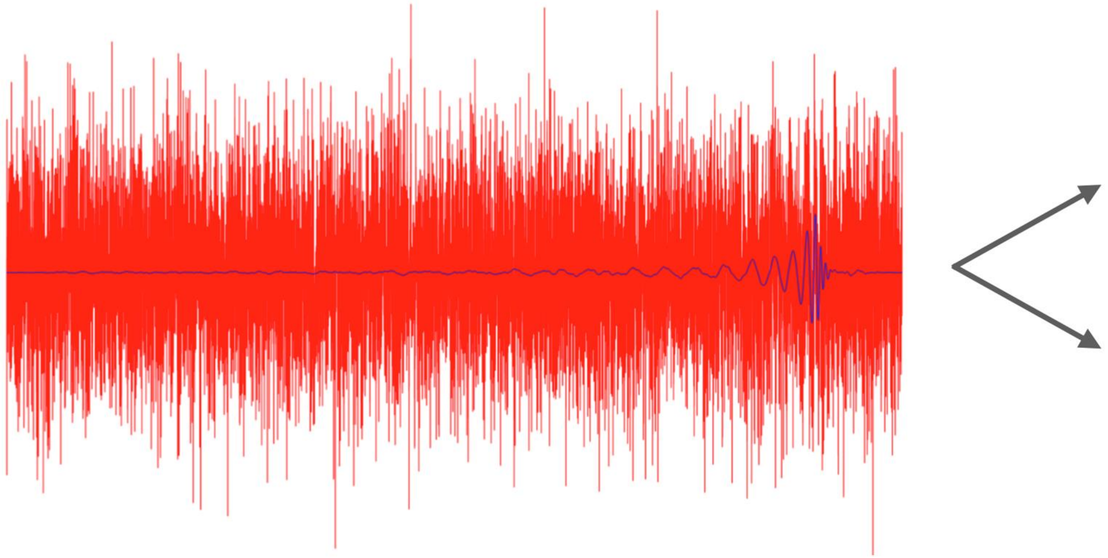
Machine Learning for classification





Vacuum

Dark Matter

This projects acknowledges the computational resources and support provided by the following institutions: Scuola Normale Superiore

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EOSC Future

KM3NeT Instrument Response Function for point-source analysis

Mikhail Smirnov
supervisor: Kay Graf

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Friedrich-Alexander-Universität Erlangen-Nürnberg

KM3NeT

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Motivation

- Adopt the most common problem of neutrino astrophysics for open science
- Provide an effective tool, which can extract IRF information from KM3NeT simulation data
- Flexibility in operation and user-defined IRF interface
- Compatibility with other astrophysical analysis, like CTA which is based on gammapy
- Easy installation procedure (preferred `pip install` package)
- Different options for output (fits, histograms, tables, GADF)

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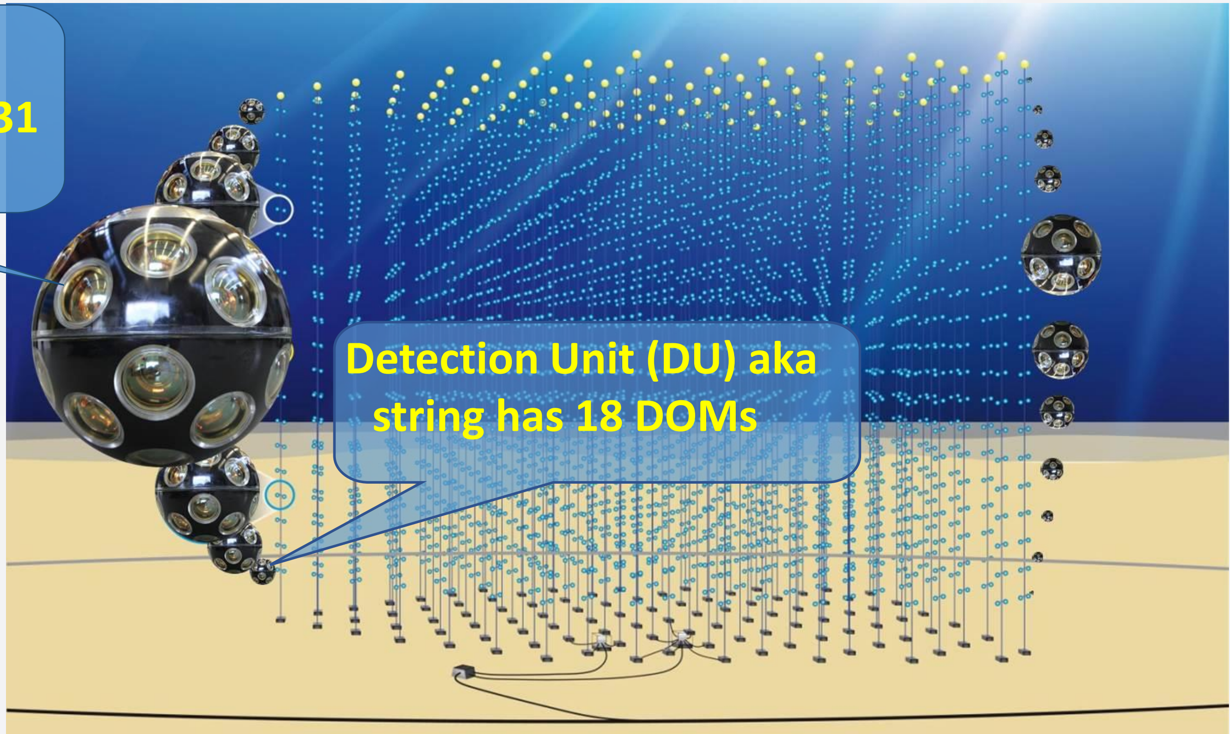
Overview of the KM3NeT detector

KM3NeT (cubic kilometer neutrino telescope) J.Phys. G43 (2016) 084001

KM3NeT/ARCA (Astroparticle Research with Cosmics in the Abyss)
discovery and observation of HE cosmic neutrino sources
(E_ν ~ GeV-PeV) high energy neutrinos
Depth – 3500 m – offshore Sicily (Italy)

KM3NeT/ORCA (Oscillation Research with Cosmics in the Abyss)
determination of the neutrino mass hierarchy
(E_ν ~ MeV - GeV) low energy neutrinos
Depth – 2500 m – offshore Toulon (France)

Parameter	ARCA	ORCA
DU distance	90 m	20 m
DOM spacing	36 m	9 m
DU height	~ 800 m	~ 200 m
Instrumented mass	2*500 Mton	7 Mton
Amount of DUs	115*2	115



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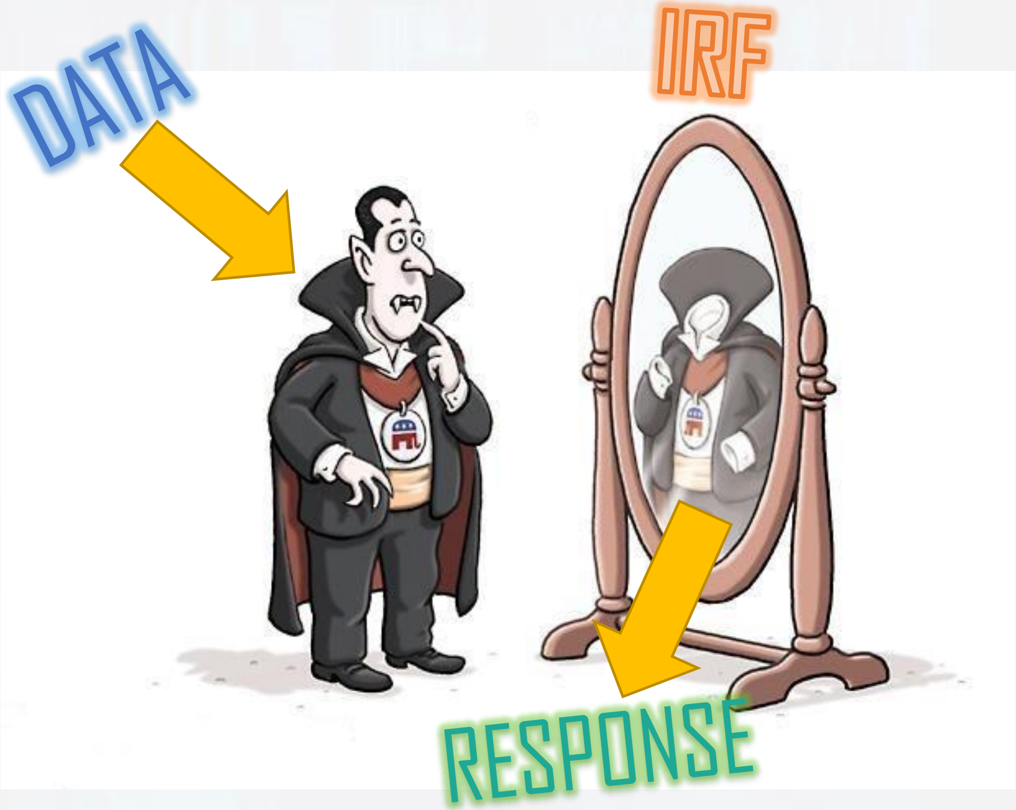
What is IRF in KM3NeT?

- IRF is a property of a neutrino telescope
- It contains information about the physical characteristics of the detector, such as angular resolution, energy resolution, effective area or volume of the detector
- It allows to quickly estimate the background
- It is based on gammapy for cross-experiment use
- In gammapy the IRF consists of 4 parts:
    - Effective area
    - Energy dispersion
    - Point spread function
    - Background



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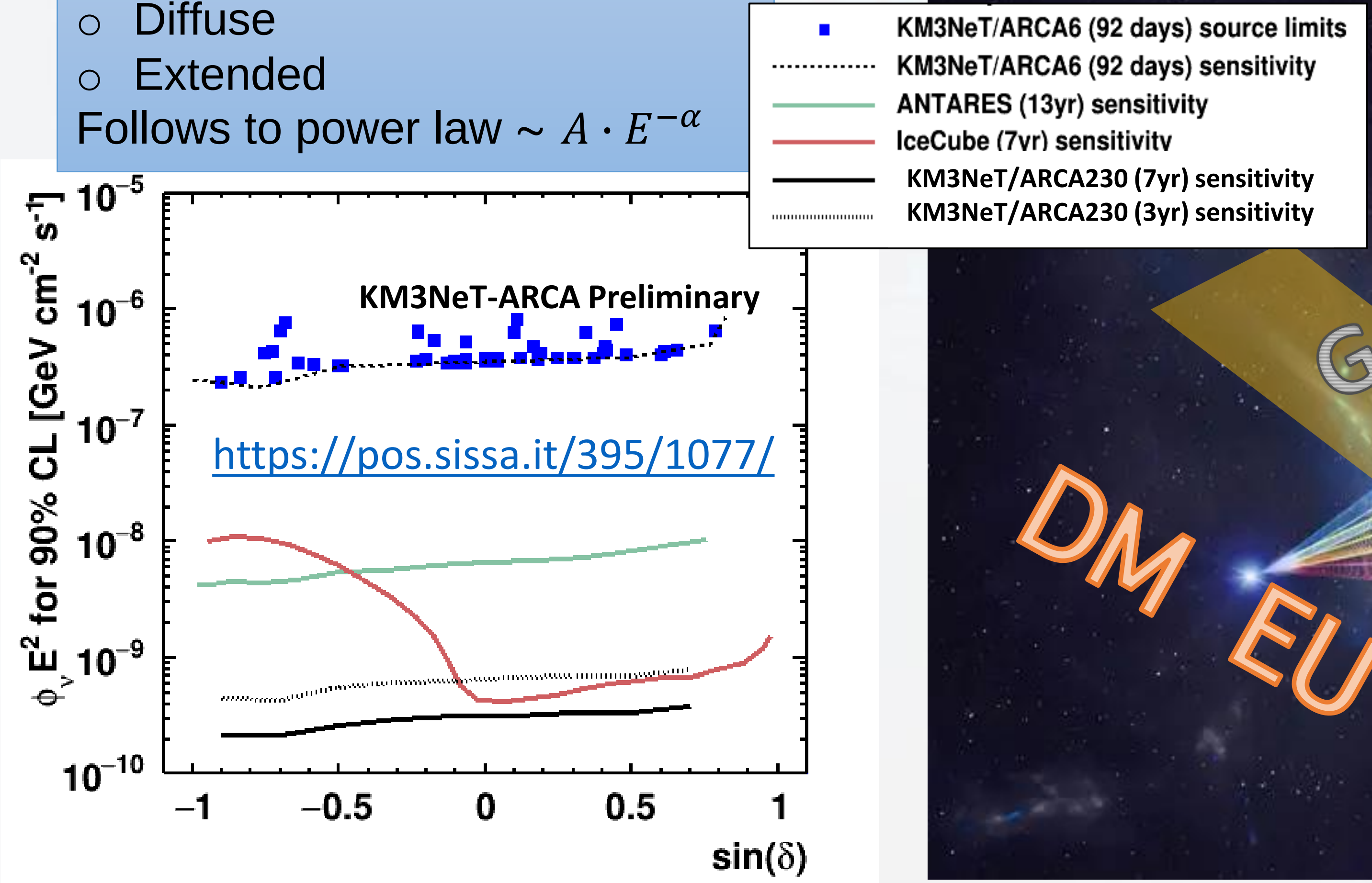
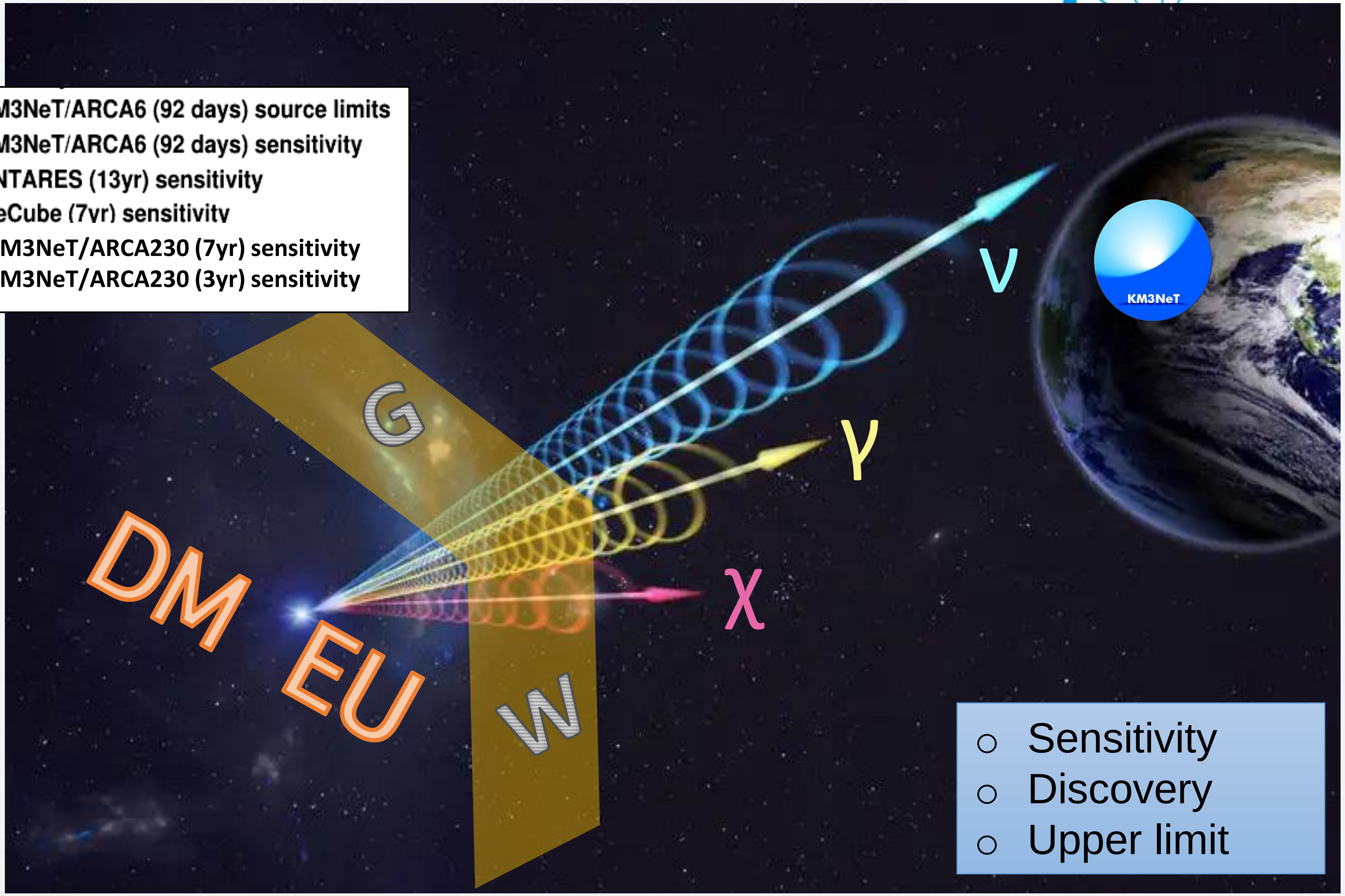
Scientific outcome – analysis of distant source

Neutrino source types:
- **Point-like**
- Diffuse
- Extended

Follows to power law $\sim A \cdot E^{-\alpha}$





- Sensitivity
- Discovery
- Upper limit

search for a neutrino excess from 46 candidate sources 92 days of data taking: May 2021 --> Sep 2021

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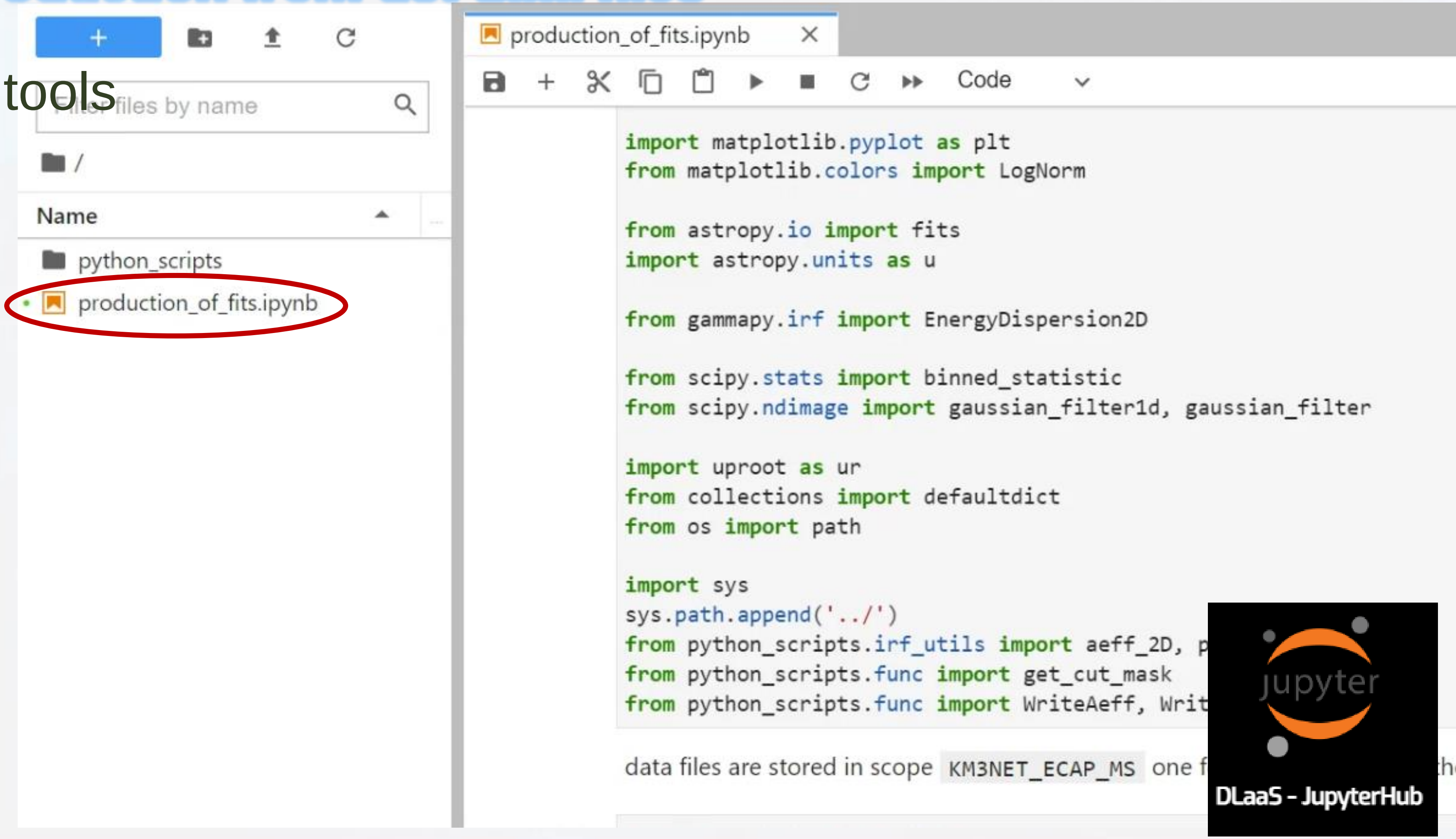
Integration with ESCAPE services

Example of IRF production from dst data files

- common gamma analysis tools
- production_of_fits.ipynb



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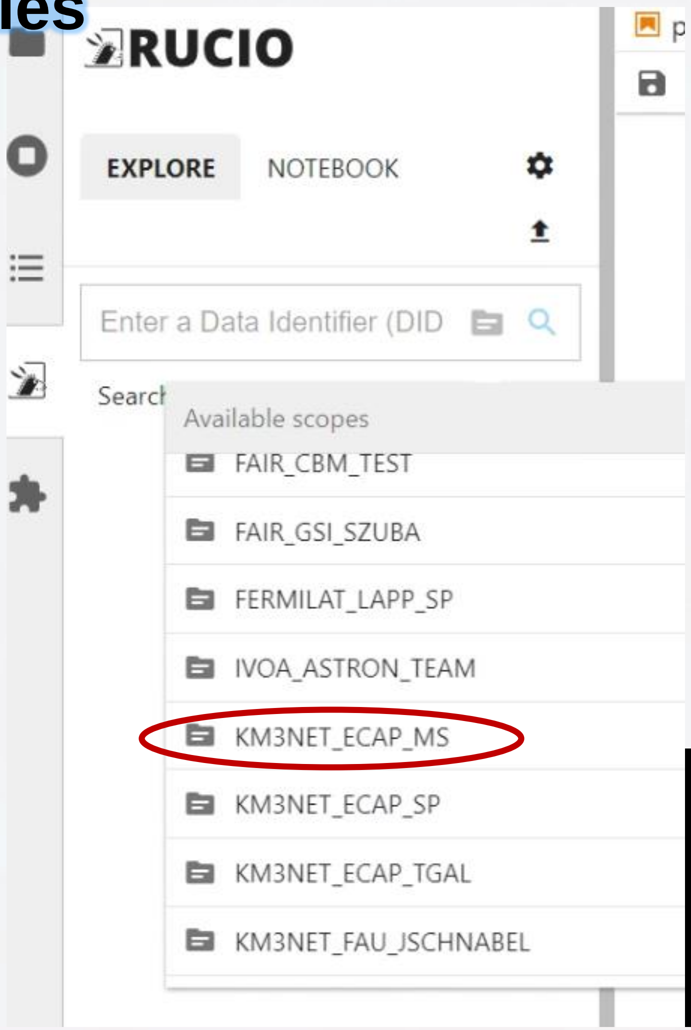
Integration with ESCAPE services

Example of IRF production from dst data files

https://gitlab.in2p3.fr/escape2020/virtual-environment/irf-from-km3net

- common gamma analysis tools
- production_of_fits.ipynb
- choose scope in RUCIO



DLaaS - JupyterHub

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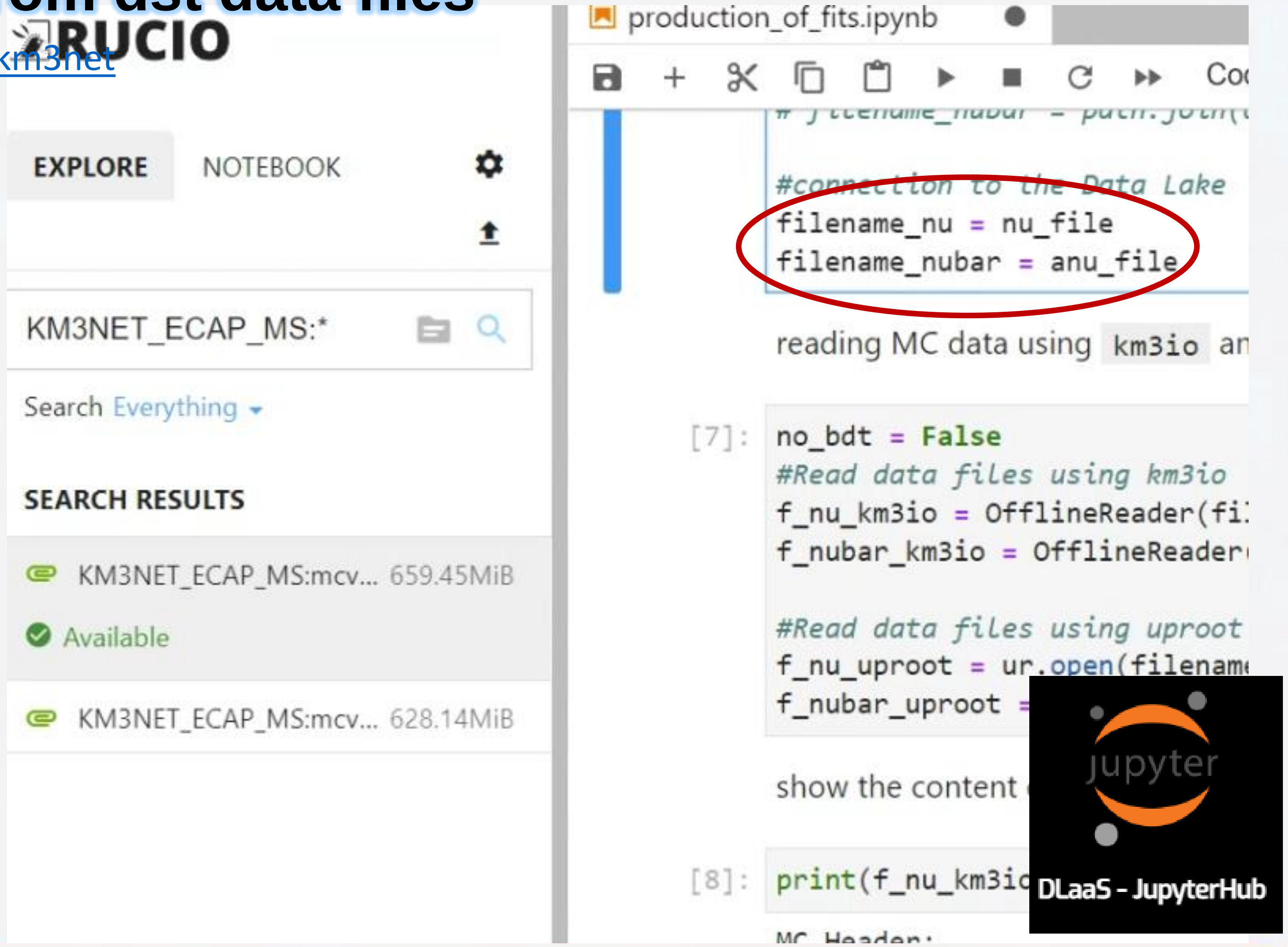
Integration with ESCAPE services

Example of IRF production from dst data files

https://gitlab.in2p3.fr/escape2020/virtual-environment/irf-from-km3net

- common gamma analysis tools
- production_of_fits.ipynb
- choose scope in RUCIO
- attach data files into notebook



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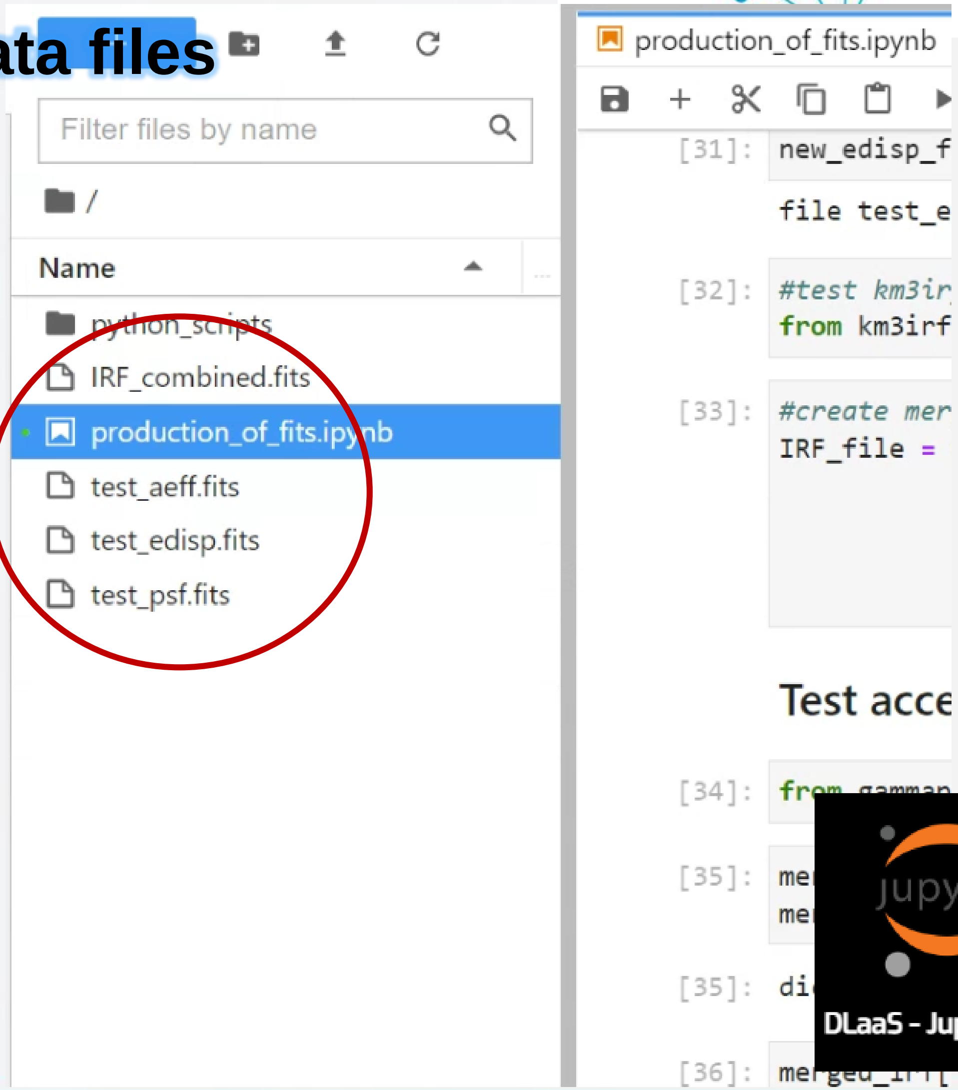
Integration with ESCAPE services

Example of IRF production from dst data files

https://gitlab.in2p3.fr/escape2020/virtual-environment/irf-from-km3net

- common gamma analysis tools
- production_of_fits.ipynb
- choose scope in RUCIO
- attach data files into notebook
- run notebook

using km3irf package



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Integration with ESCAPE services

Example of IRF production from dst data files

https://gitlab.in2p3.fr/escape2020/virtual-environment/irf-from-km3net

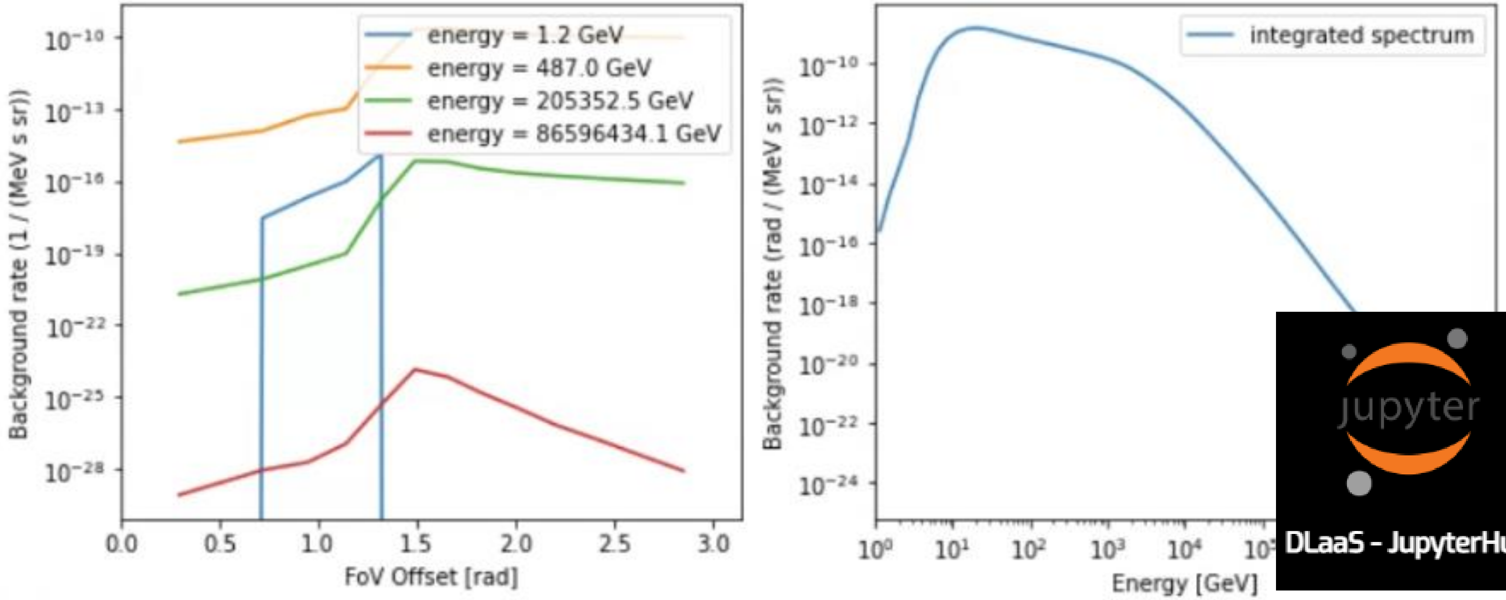
- common gamma analysis tools
- production_of_fits.ipynb
- choose scope in RUCIO
- attach data files into notebook
- run notebook
- investigate results

```
[34]: from gammapy.irf import load_irf_dict_from_file

[35]: merged_irf = load_irf_dict_from_file("./IRF_combined.fits")
      merged_irf.keys()

[35]: dict_keys(['aeff', 'psf', 'edisp', 'bkg'])

[36]: merged_irf['bkg'].peek()
```



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Integration with ESCAPE services

Example of IRF production from dst data files

https://gitlab.in2p3.fr/escape2020/virtual-environment/irf-from-km3net

- common gamma analysis tools
- production_of_fits.ipynb
- choose scope in RUCIO
- attach data files into notebook
- run notebook
- investigate results
- content of combined IRF
- reproducibility and re-use

```
[37]: for name in merged_irf.keys():
          print(merged_irf[name])

EffectiveAreaTable2D
--------------------

  axes  : ['energy_true', 'offset']
  shape : (48, 12)
  ndim  : 2
  unit  : m2
  dtype : >f8

PSF3D
-----

  axes  : ['energy_true', 'offset', 'rad'
  shape : (24, 6, 111)
  ndim  : 3
  unit  : 1 / sr
  dtype : >f8

EnergyDispersion2D
------------------

  axes  : ['energy_true', 'migra', 'offset']
  shape : (24, 56, 6)
  ndim  : 3
  unit  :
  dtype : >f8

Background2D
------------

  axes  : ['energy', 'offset']
  shape : (64, 12)
  ndim  : 2
  unit  : 1 / (MeV s sr)
  dtype : >f8
```

DLaaS - JupyterHub

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Extreme Universe VRE-DEMO: Searching for FRB persistent radio source counterpart in dwarf galaxies using LOFAR

Dany Vohl (UvA/ASTRON)
Harish Vedantham (ASTRON)
Jason Hessels (UvA/ASTRON)

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Motivation

- Current research interest in dwarf galaxies ($M_{\odot}$< $10^{9.5}$)
  - May host **intermediate-mass black holes** (IMBH)
    - Predicted, possibly detectable as compact radio source
  - Metal poor, can host superluminous supernovae
- Two repeating **fast radio burst** (FRB)
  - Localised to dwarf galaxies
  - Co-located to **persistent radio source** (PRS): energetic plerion?
- Can we find IMBH or PRS in deep radio surveys?

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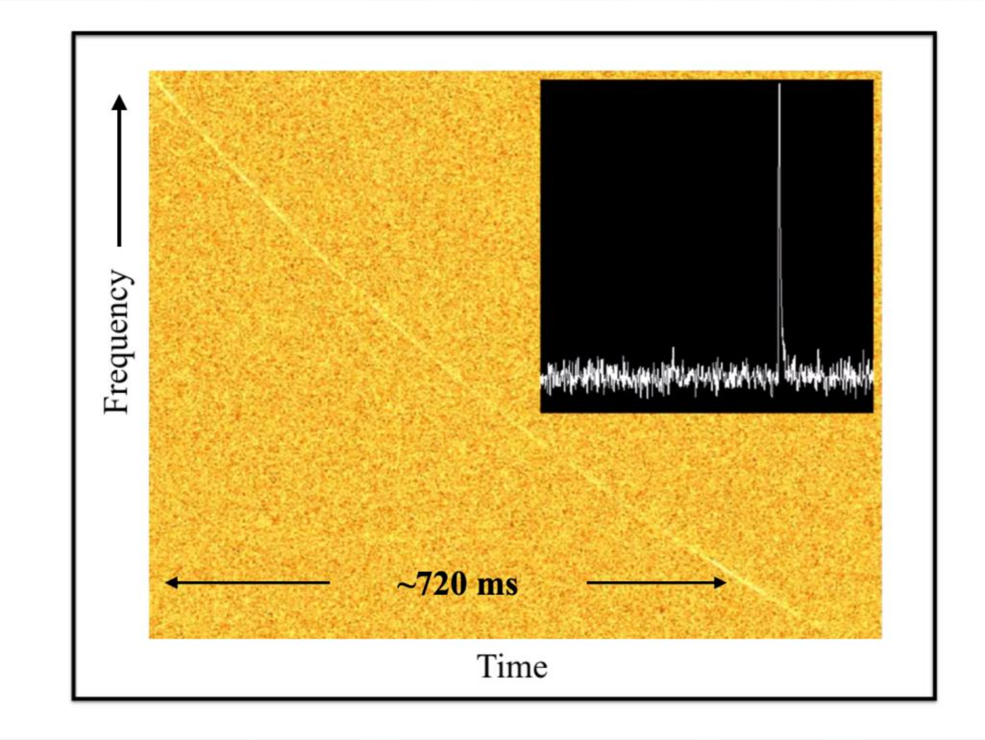
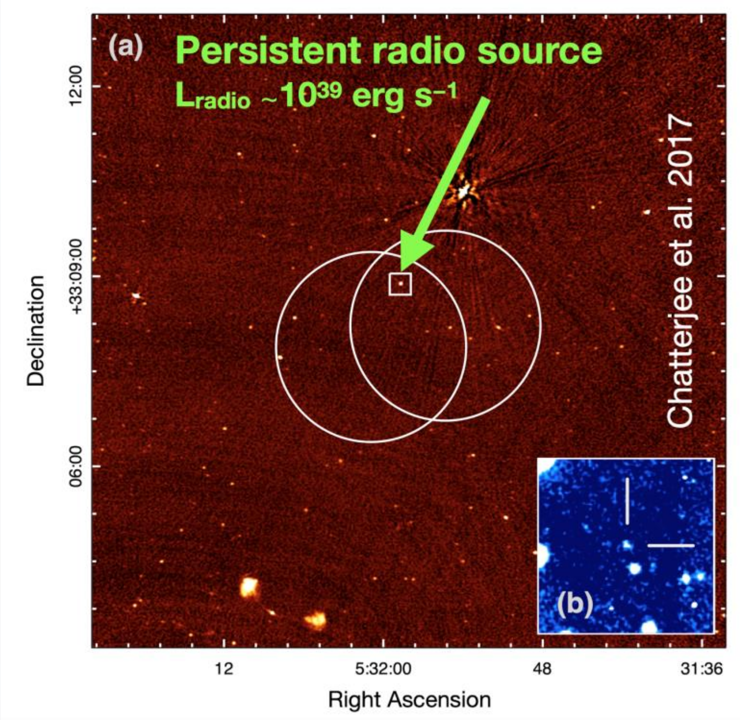
Motivation

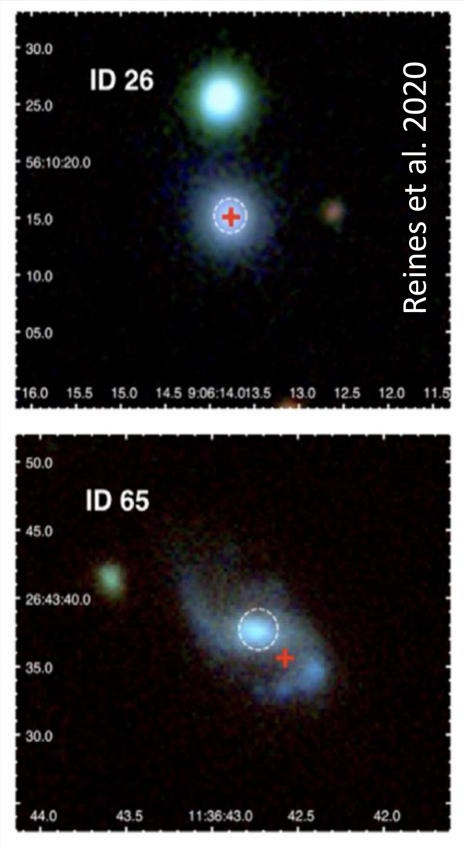
Fast Radio Bursts



PRS



IMBH



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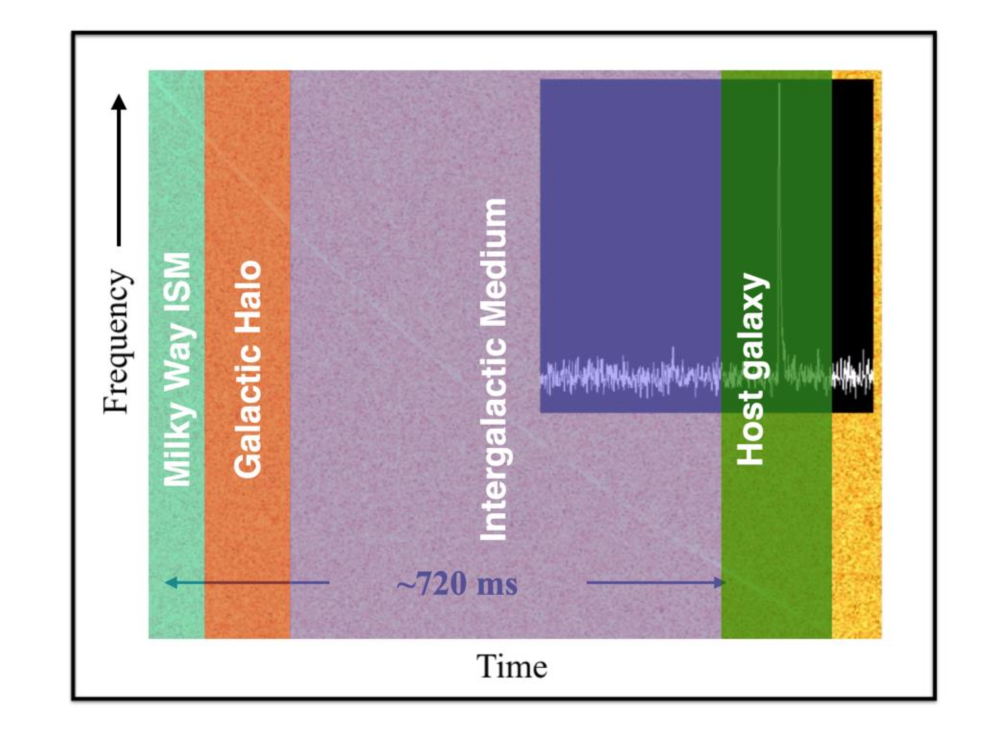
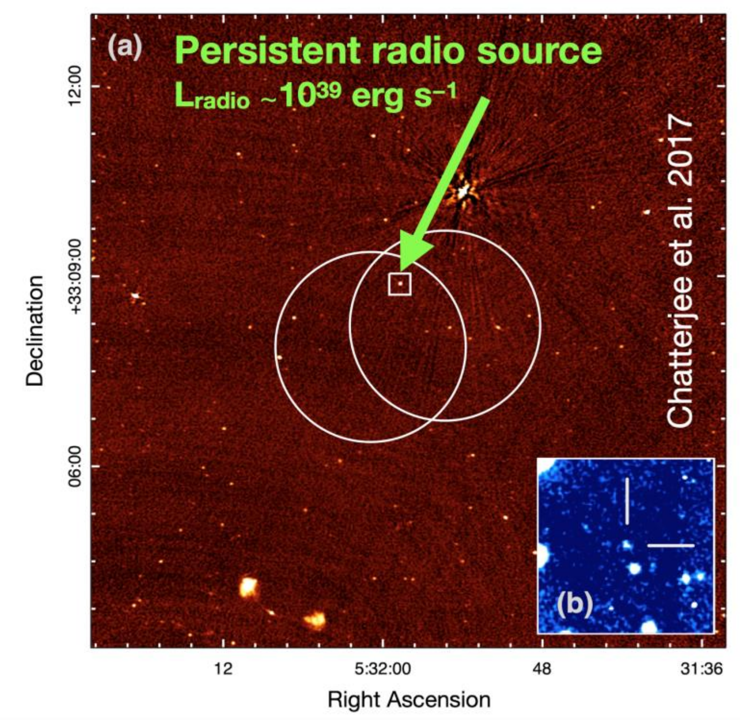
Motivation

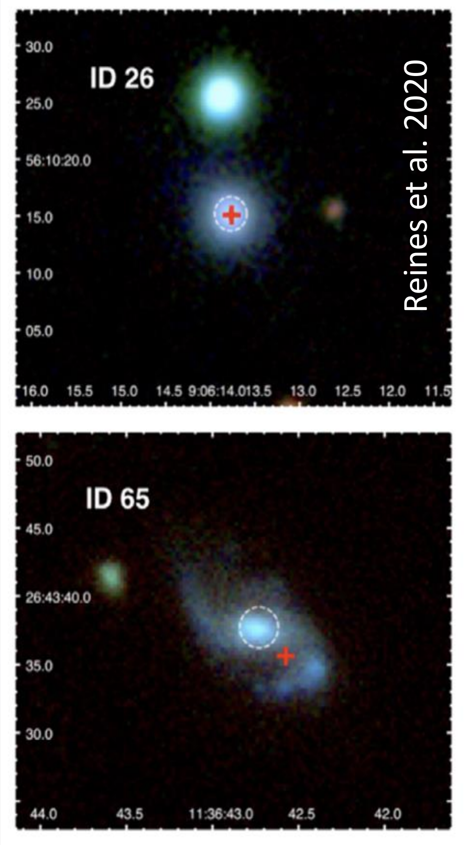
Fast Radio Bursts



PRS



IMBH



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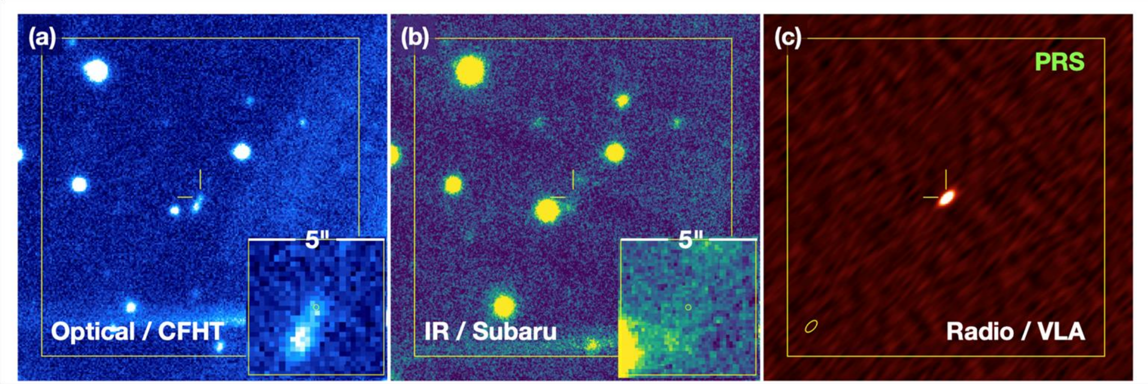
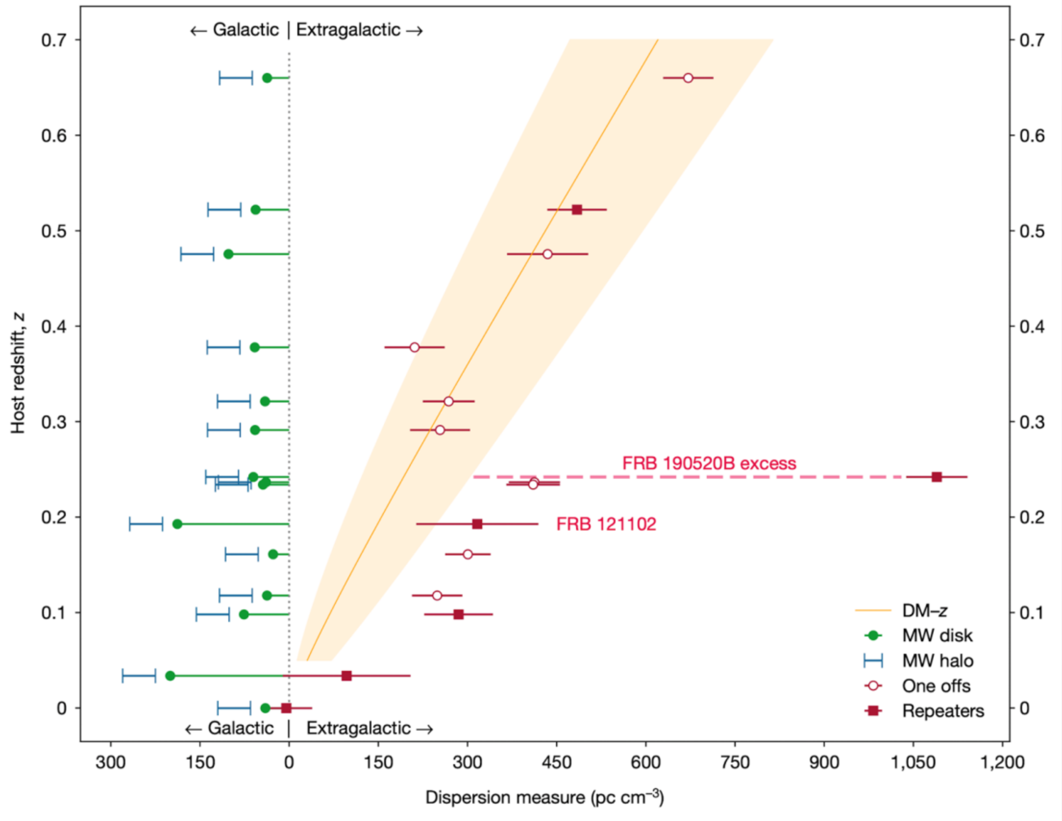
Motivation

Only the 2nd known repeating FRB co-located to PRS

- Star forming dwarf host galaxy (Niu et al. 2022)





Law et al. 2022: *"Given that FRBs occur with a high volumetric rate (comparable to that of core-collapse supernovae [...]) and that PRS are luminous,* ***it may be that PRS constitute a significant new class of extragalactic radio source."***

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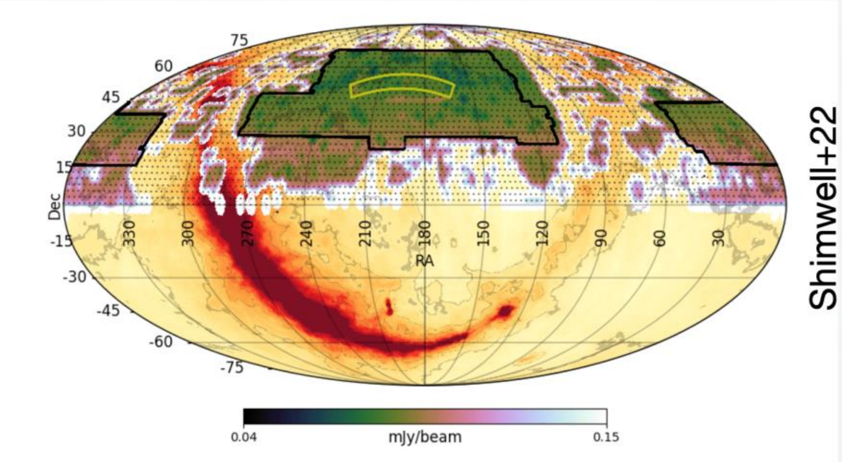
What are we looking for?

- **We aim to increase known IMBH and/or PRS sample**
- Search for **Over-luminous compact radio sources (OCRs)** in **Dwarf galaxies**
- **RADIO**: LoTSS 2nd data release (Shimwell et al. 2022; 144 MHz)
  - > 4 million radio sources over ~5500 deg^2 covered
  - 0".2 astrometric accuracy (comparable to optical surveys)
- **OPTICAL**: Census of the local Universe (CLU; Cook et al. 2019)
  - 270 000 sources over 3π of the sky; ***z* < 0.0471**
  - Spans dwarf galaxies to larger spirals
  - Provides various physical properties: e.g.
    - *Stellar mass, Star Formation Rate (SFR)*



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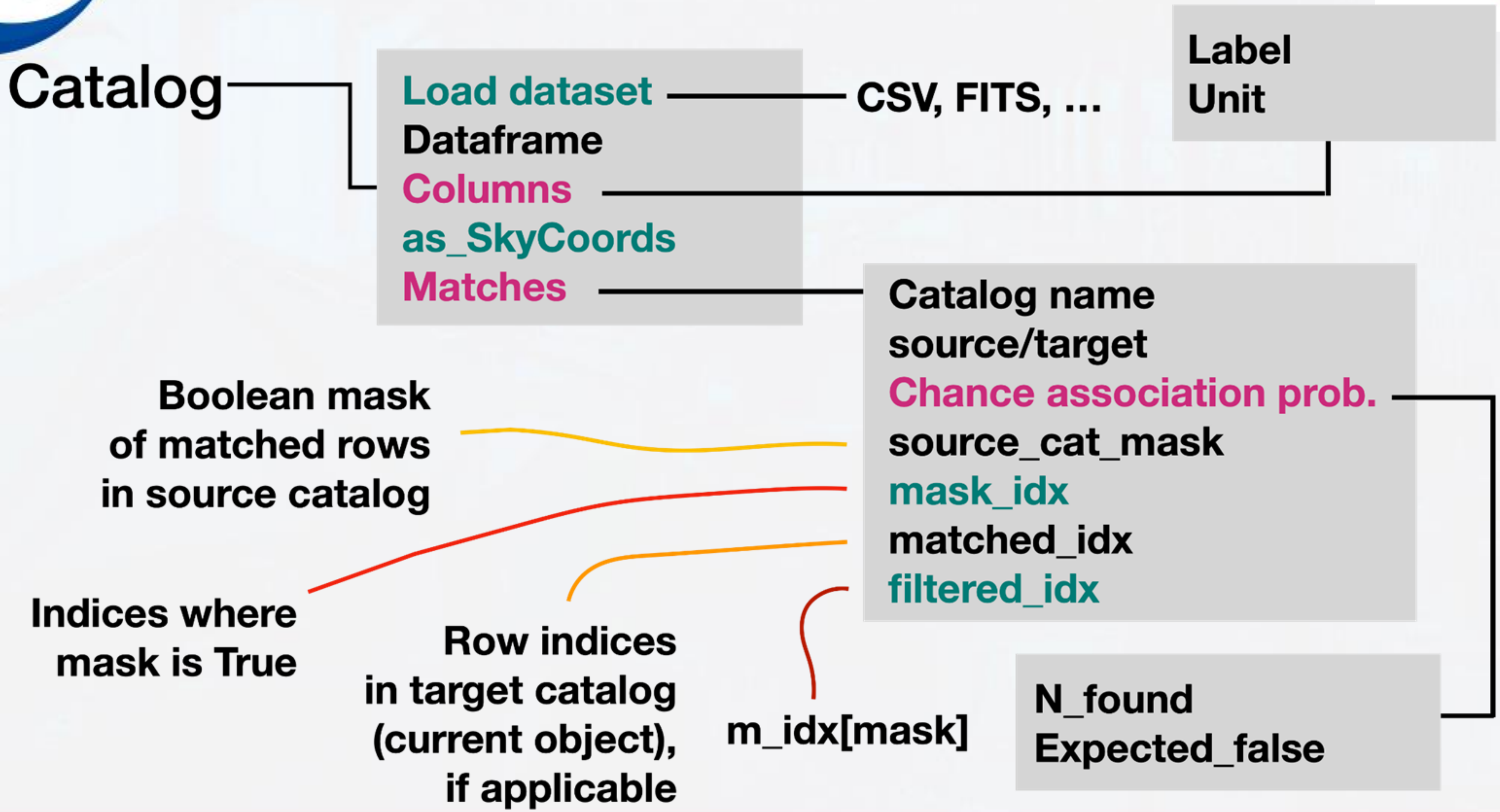
MATCHMAKER (python package)



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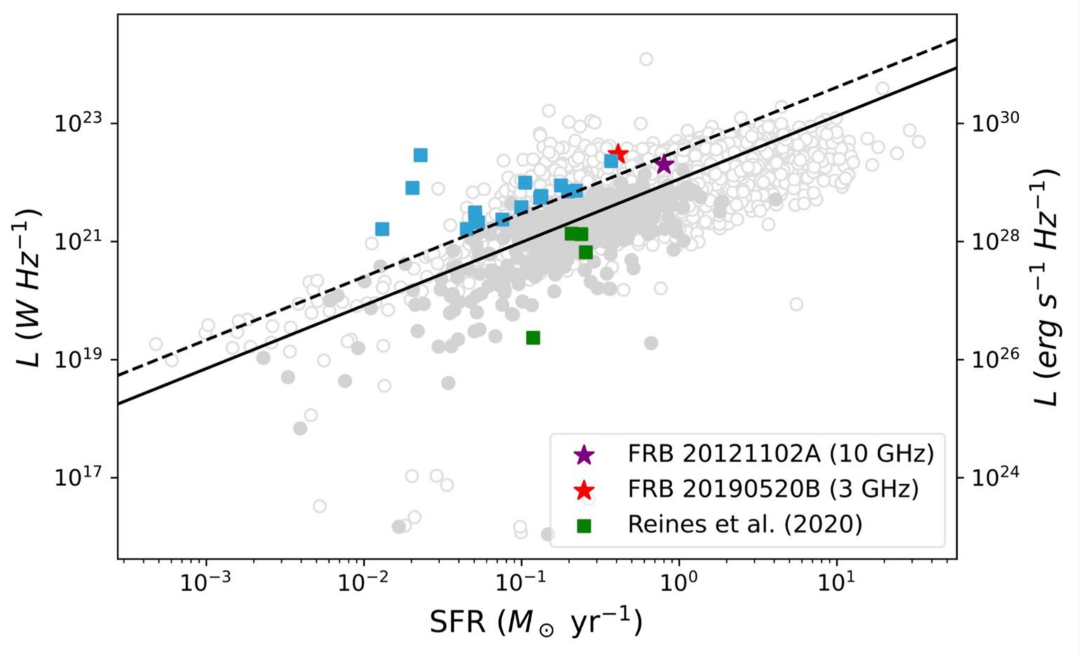
Demo: search for OCRs

1. RUCIO & Code
2. Cross-matching
3. Candidates selection
4. Query VO (SDSS, NED, ASTRON, …)
5. Composite cutout images



Special thanks to Yan Grange, Enrique Garcia, Elena Gazzarrini & Alba Vendrell Moya

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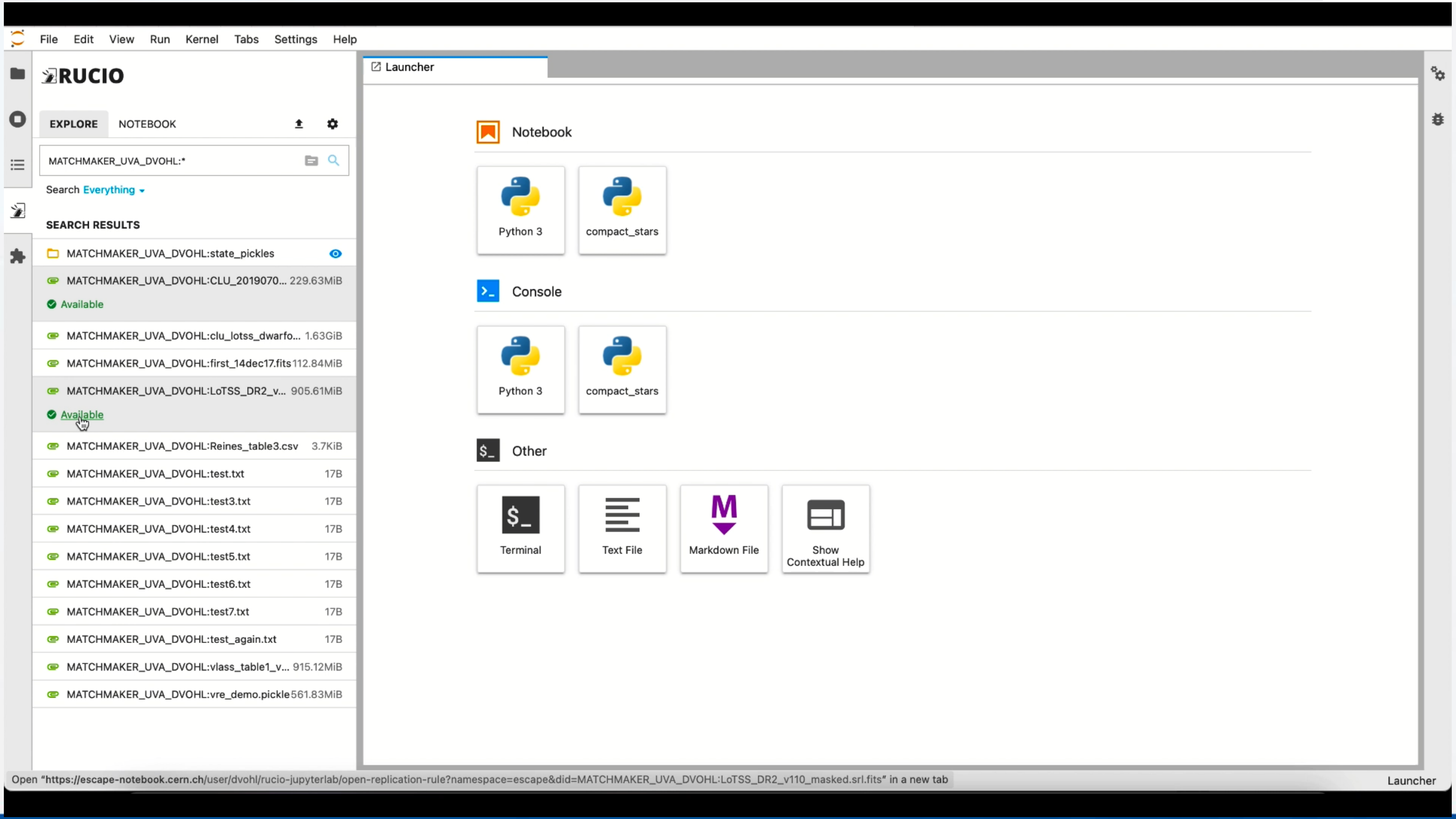
Demo: search for OCRs



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Consolidation and open challenges

Consolidation: what's next?

- Full integration in **Virtual Research Environment**
- Release of software in ESCAPE OSSR catalogue
- Tutorial and documentation in on-boarding procedures
- Strengthen and expand collaboration with aspects of interdisciplinarity
- Link to EOSC Core and EOSC EXCHANGE

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Open challenges

Low latency and Real Time analysis

Cutting-edge technologies, artificial intelligence

Training for young students

Strengthen and broaden collaboration with other science projects

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Thank you for your attention