How can we robustly discover dark matter?

- A modest contribution -

Clara Gatius Oliver
Nikhef junior colloquium - April 2024

Ultra-light dark matter

WIMPs

lightest super-symmetric particle

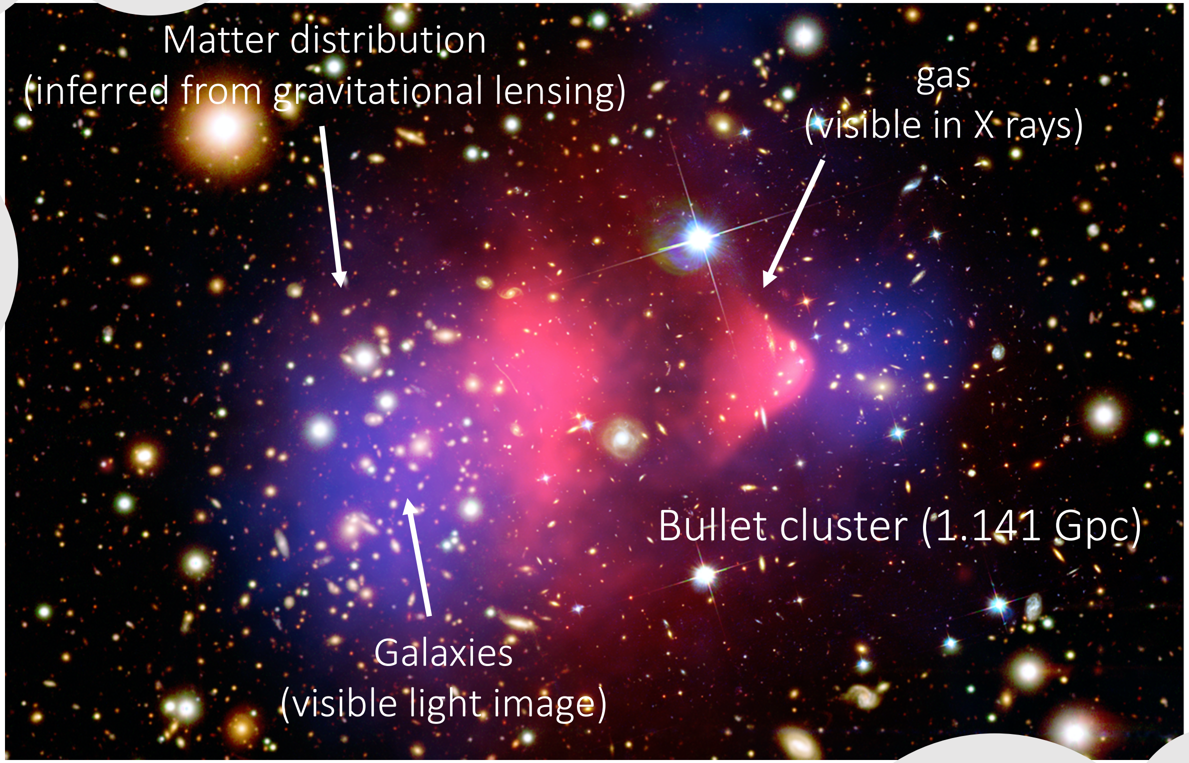
lightest Kaluza-Klein state

Dark matter as a particle

Sterile neutrinos

Axions

little constraints



Massive compact halo objects

Neutron stars

Primordial black holes

modified theories of gravity

???

!?

??!!

many models

Ultra-light dark matter

Dark matter as a particle

WIMPs

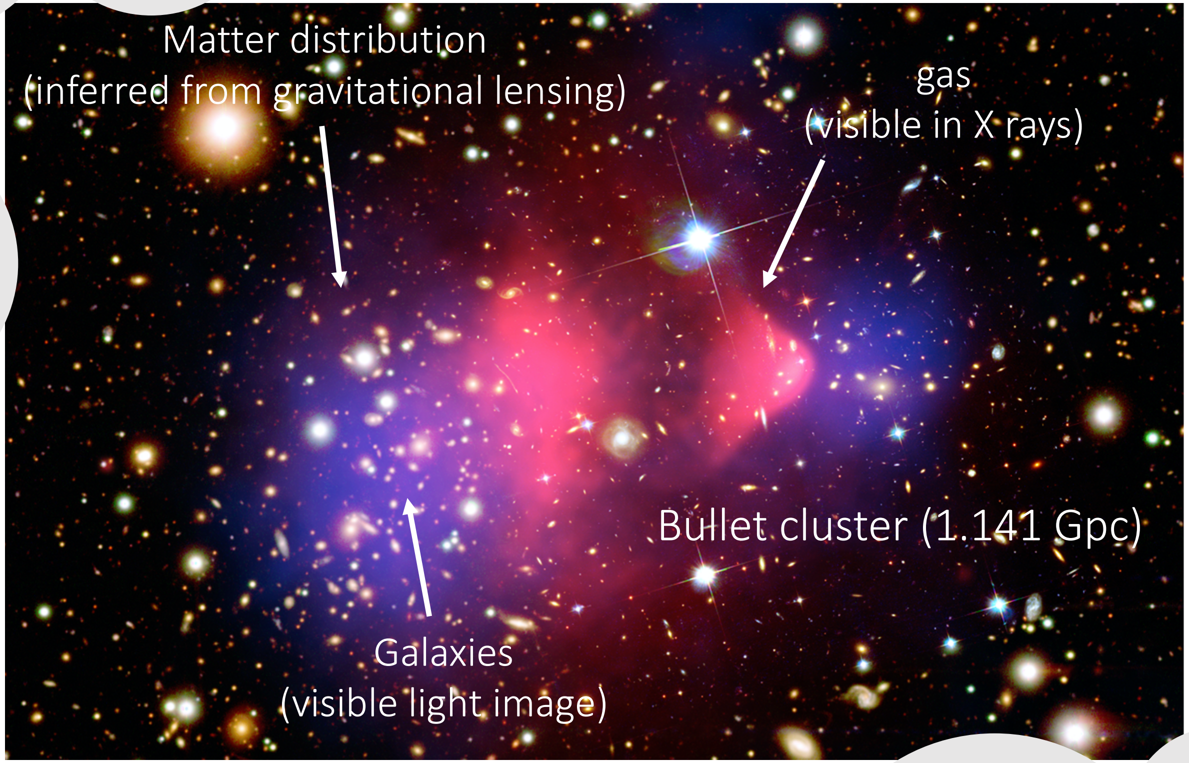
lightest super-symmetric particle

lightest Kaluza-Klein state

Sterile neutrinos

Axions

umbrella term referring to a large class of models including particles that interact with ordinary baryonic dark matter via gravity and a weak non-vanishing force



Massive compact halo objects

Neutron stars

Primordial black holes

why do we like them?

Arise naturally in many particle physics theories

Correct cosmological properties

Many and diverse set of implications for observable phenomena

!?

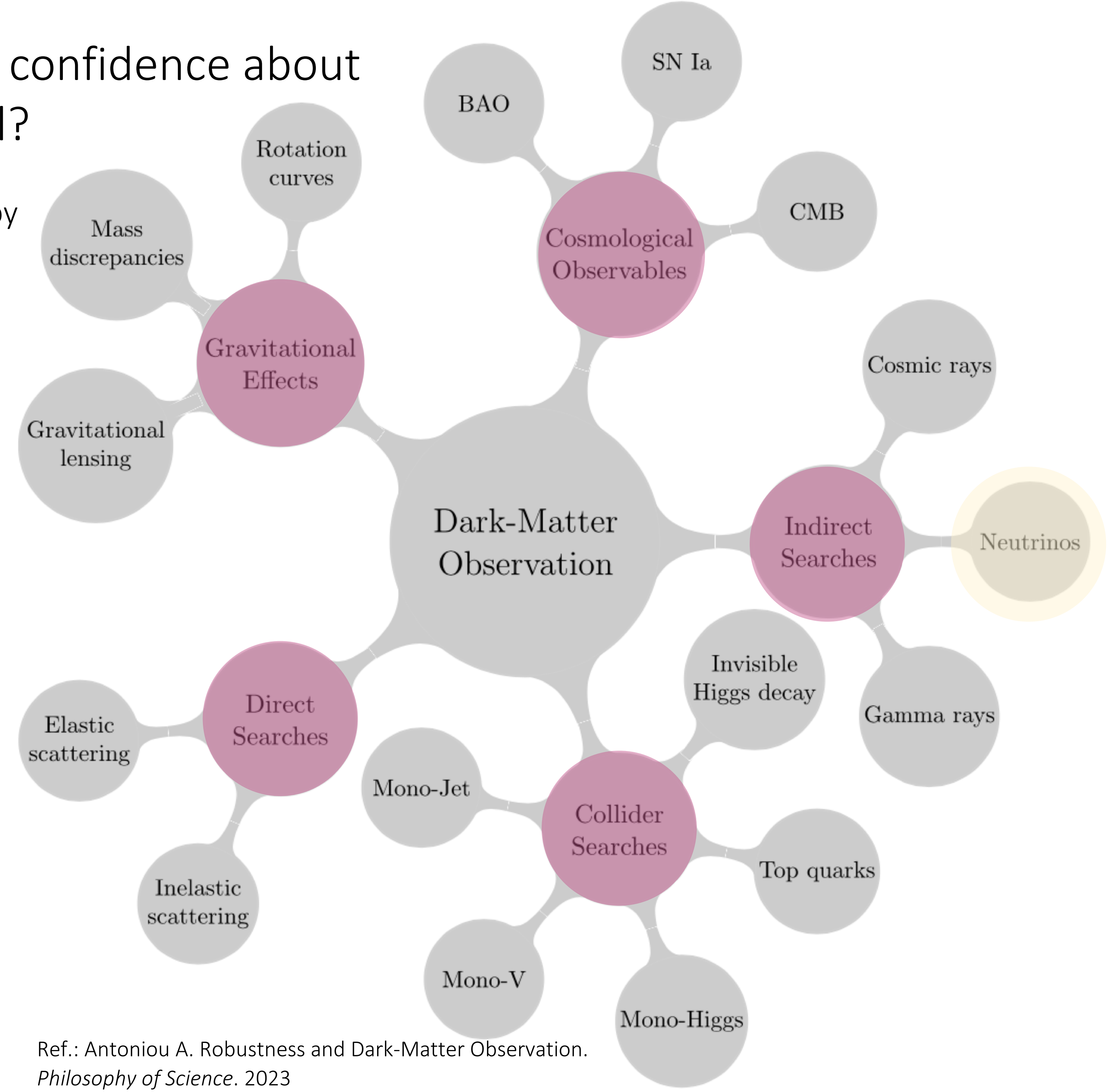
modified theories of gravity

???

??!!

How can we increase our confidence about the properties of a model?

A model is more robust if supported by more than one experimental method



Ref.: Antoniou A. Robustness and Dark-Matter Observation. *Philosophy of Science*. 2023

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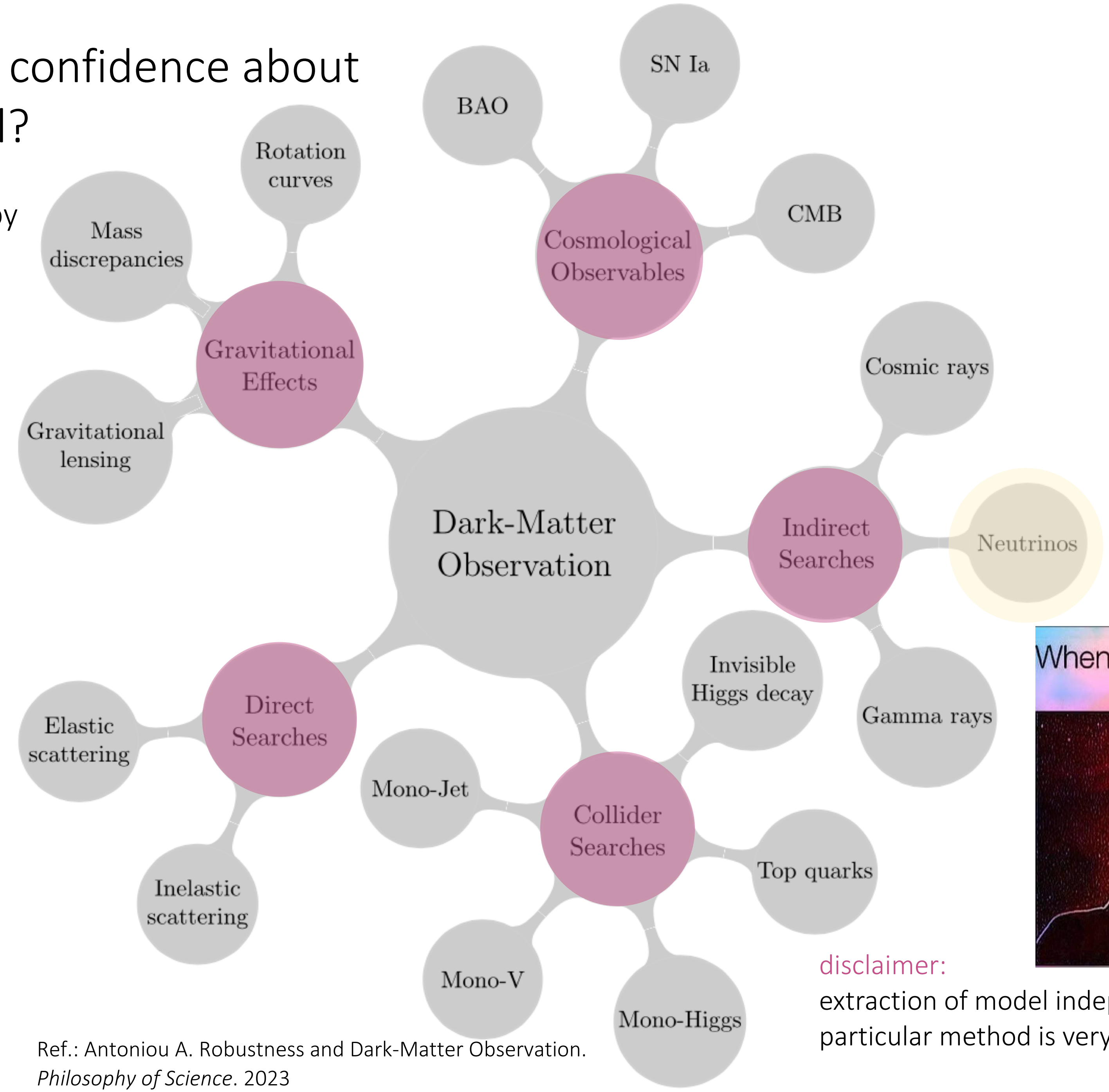

Dark matter might connect us all

disclaimer:
extraction of model independent constraints from a particular method is very challenging

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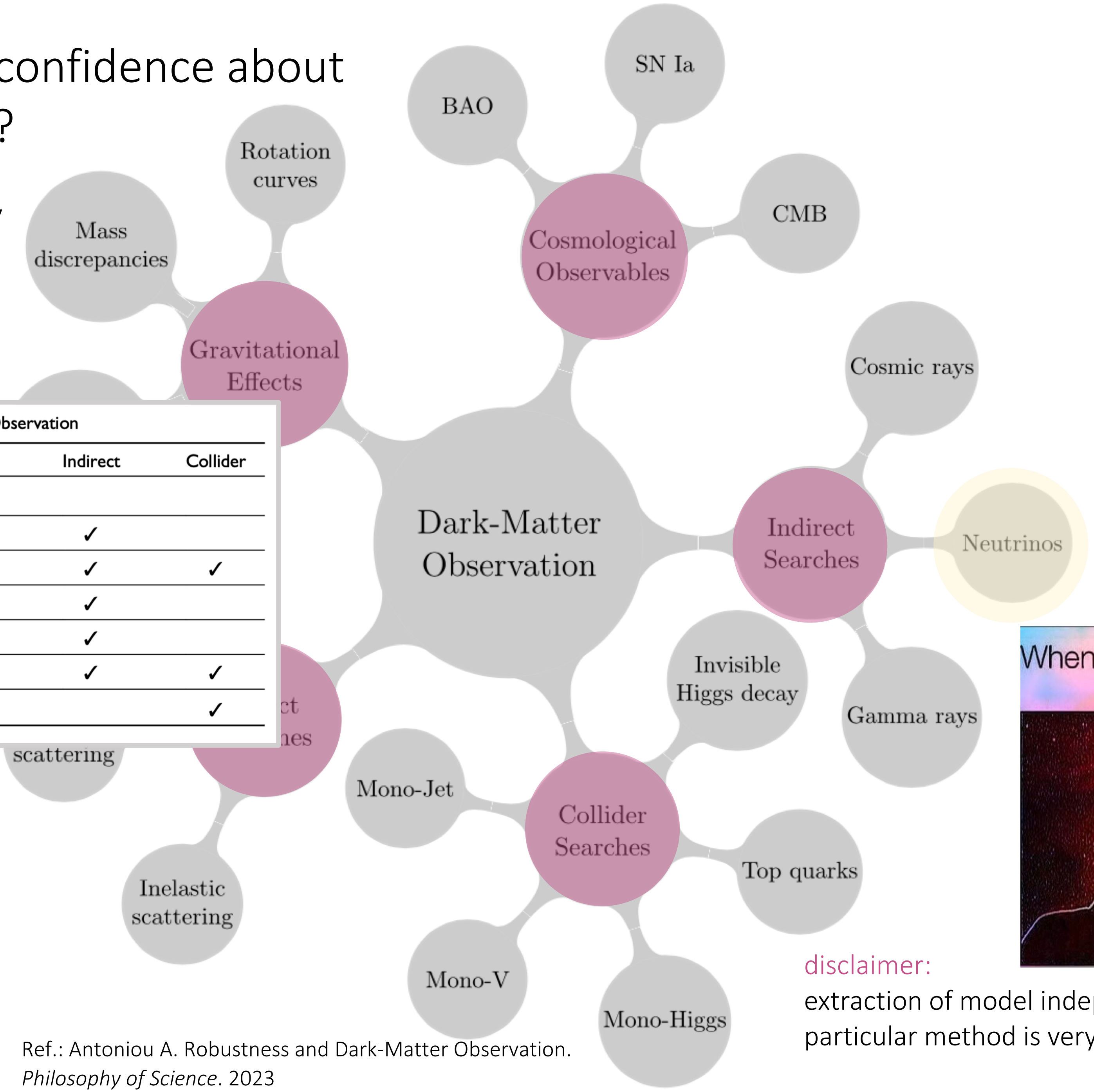
Table 1. Model Sensitivity of the Various Methods of Dark-Matter Observation

	Cosmological	Direct	Indirect	Collider
Collisionless dark matter	✓			
SIDM	✓		✓	
WIMPs	✓	✓	✓	✓
Sterile neutrinos			✓	
Axions		✓	✓	
Hidden/Complex dark matter		✓	✓	✓
Light gravitinos				✓

More on why WIMPs



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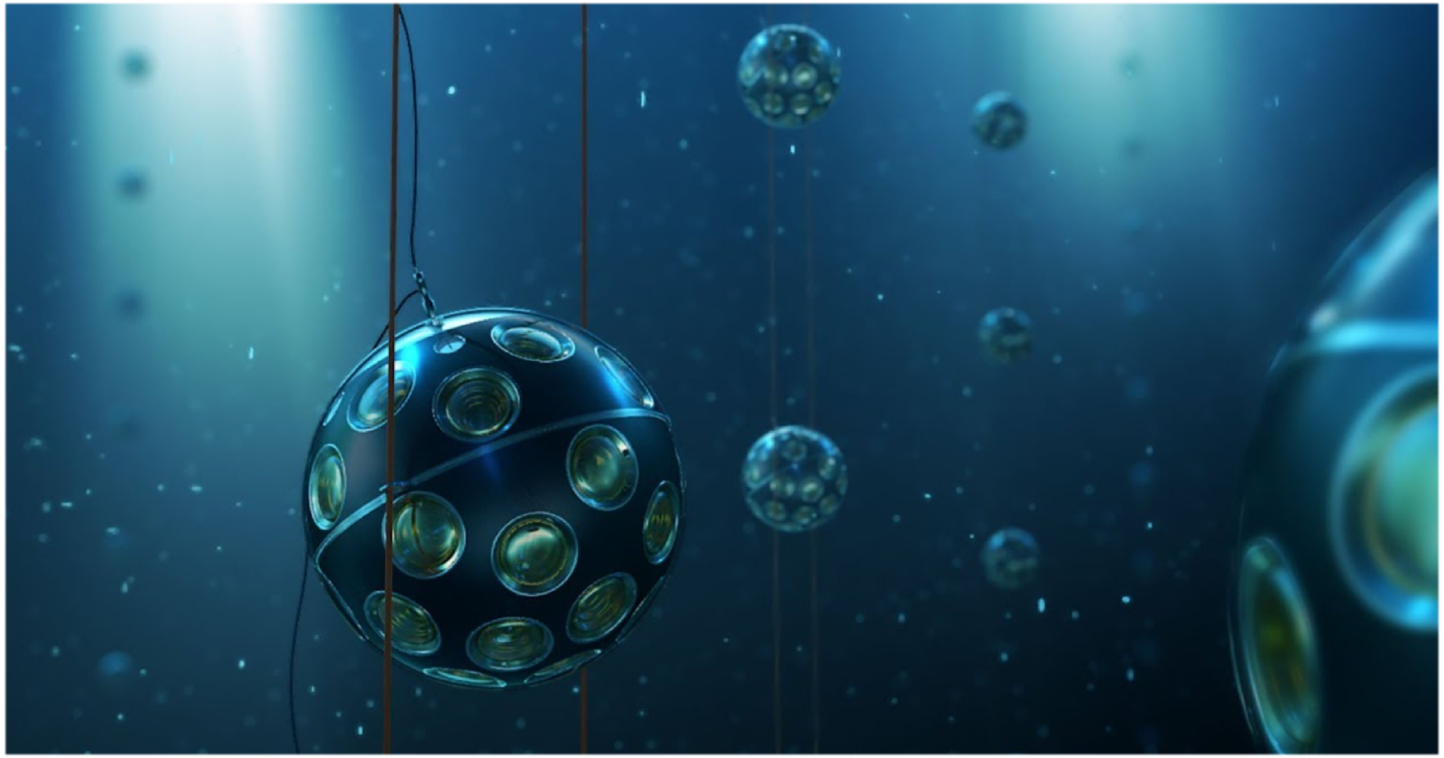
The KM3NeT telescope

Detectable neutrino energies GeV - PeV

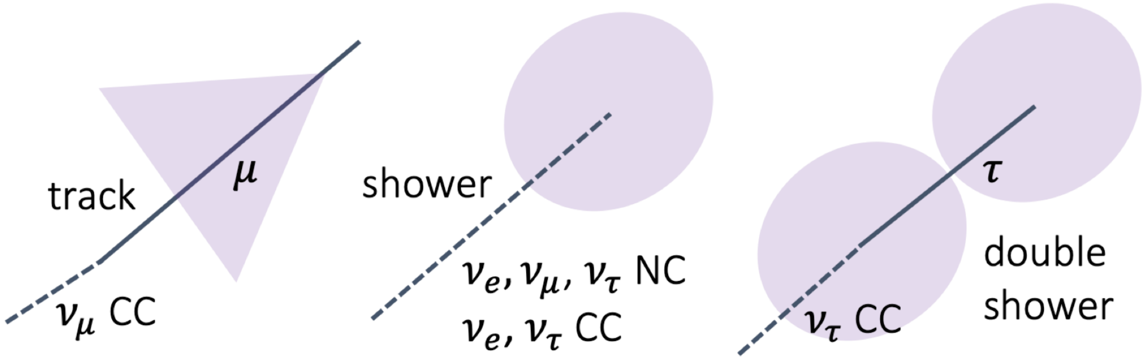
Water Cerenkov detector in the Mediterranean sea



Two sites:

ARCA (neutrino astronomy)
ORCA (neutrino oscillations)

different type of neutrino interactions
↓
different type of events



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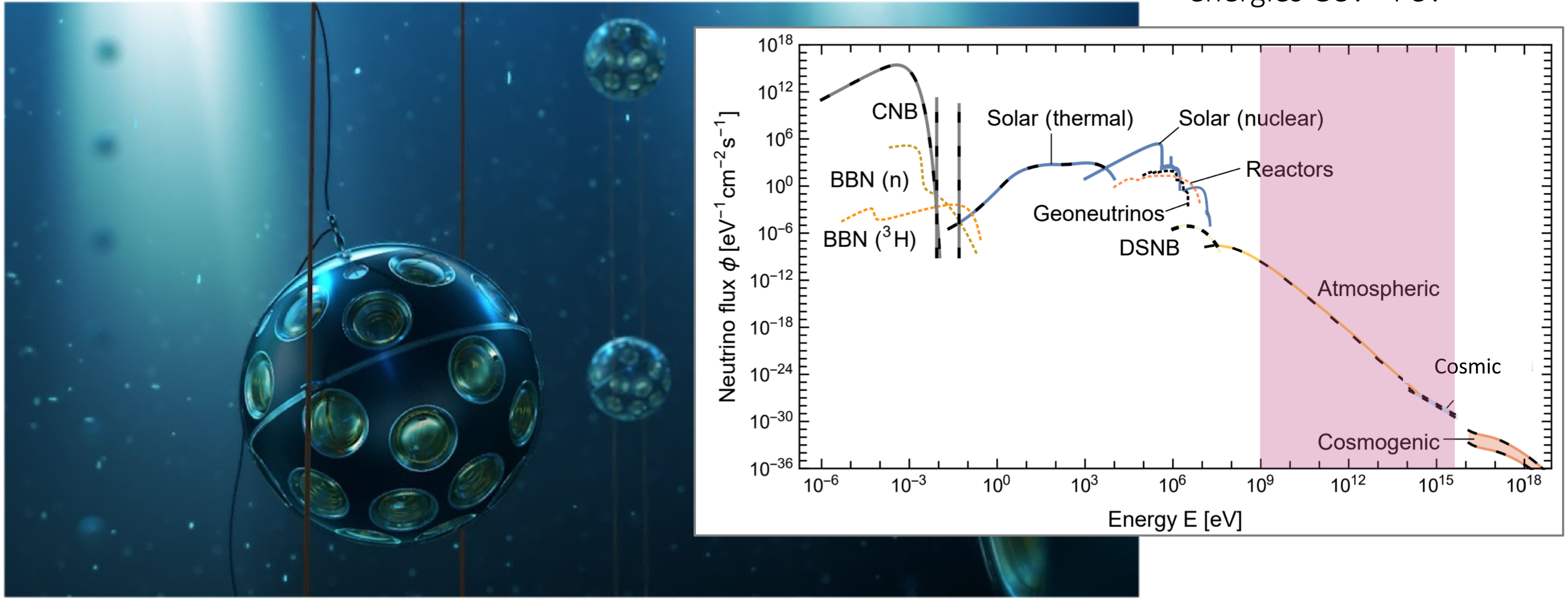

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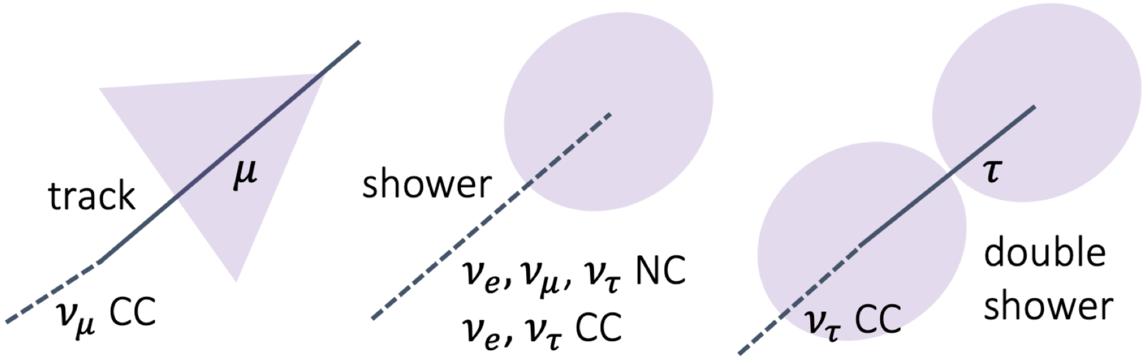
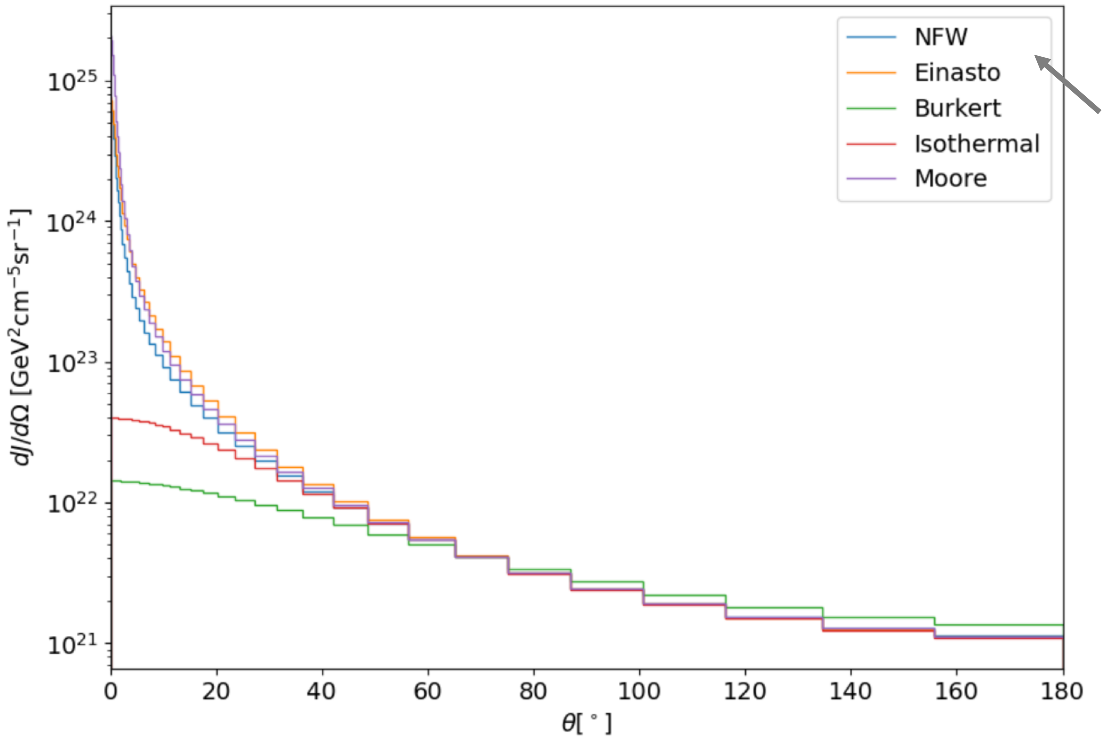


Dark matter signal

Creation of neutrinos by WIMP dark matter annihilation in the galactic centre

Spatial distribution around galactic centre:



Different profiles allowed by observations

$$\frac{d\Phi_\alpha^c}{dE\,dt} = \frac{1}{4\pi}\frac{<\sigma v>}{2m_\chi^2}\frac{dN_\alpha^c}{dE}\int_{\Delta\Omega}\int_{l.o.s.}\rho^2(\theta,l)dl\,d\Omega$$

Spectra

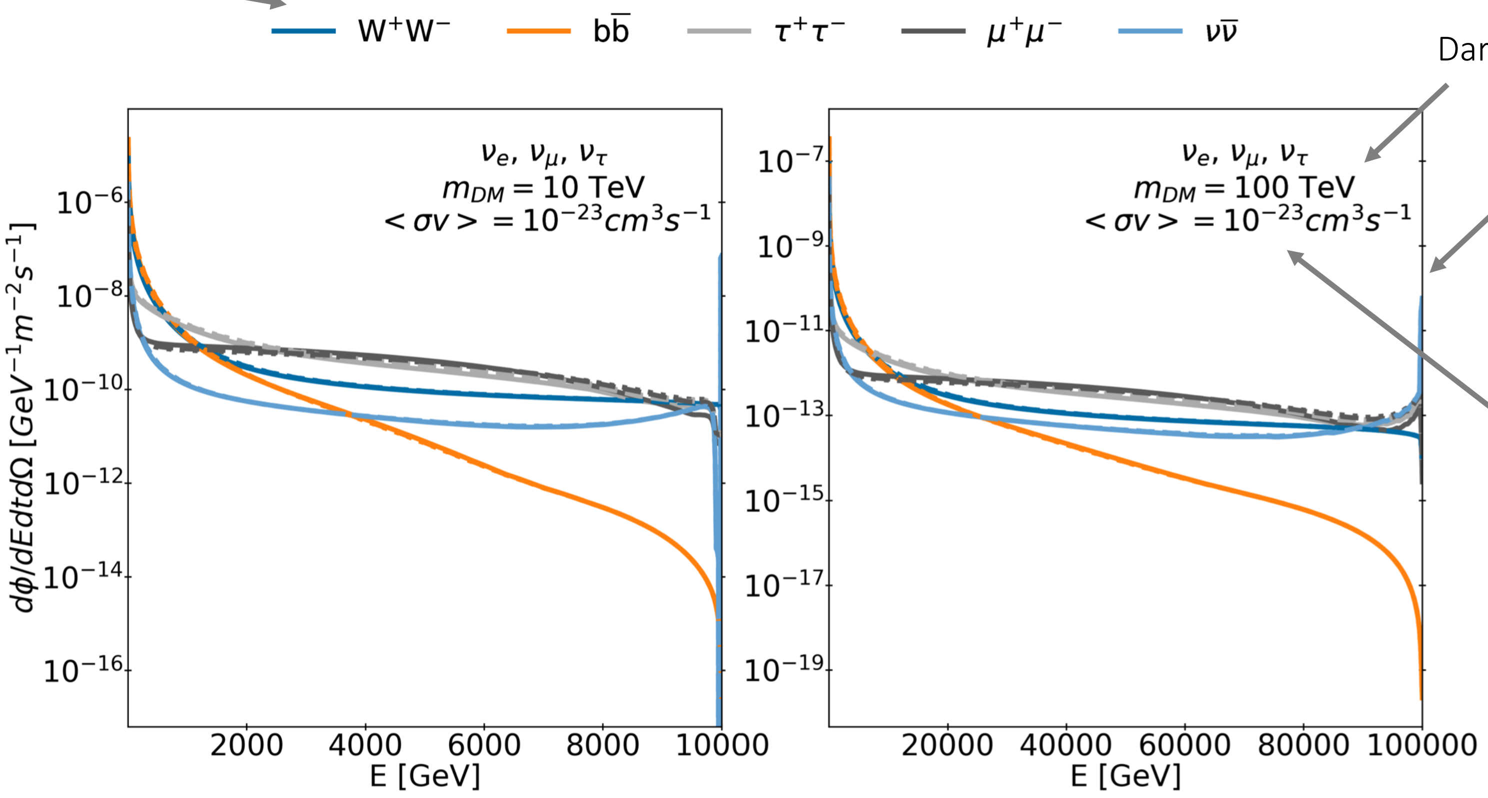
Dark matter distribution around Galactic Centre

Neutrino flux proportional to dark matter density

Dark matter signal

Creation of neutrinos by WIMP dark matter annihilation in the galactic centre

Annihilation channel



Dark matter mass

most interesting signature: the peak

Annihilation cross-section

Cut-off at dark matter mass

Flux:

$$\frac{d\Phi_\alpha^c}{dE\,dt} = \frac{1}{4\pi}\frac{<\sigma v>}{2m_\chi^2}\frac{dN_\alpha^c}{dE}\int_{\Delta\Omega}\int_{l.o.s.}\rho^2(\theta, l)\,dl\,d\Omega$$

Spectra

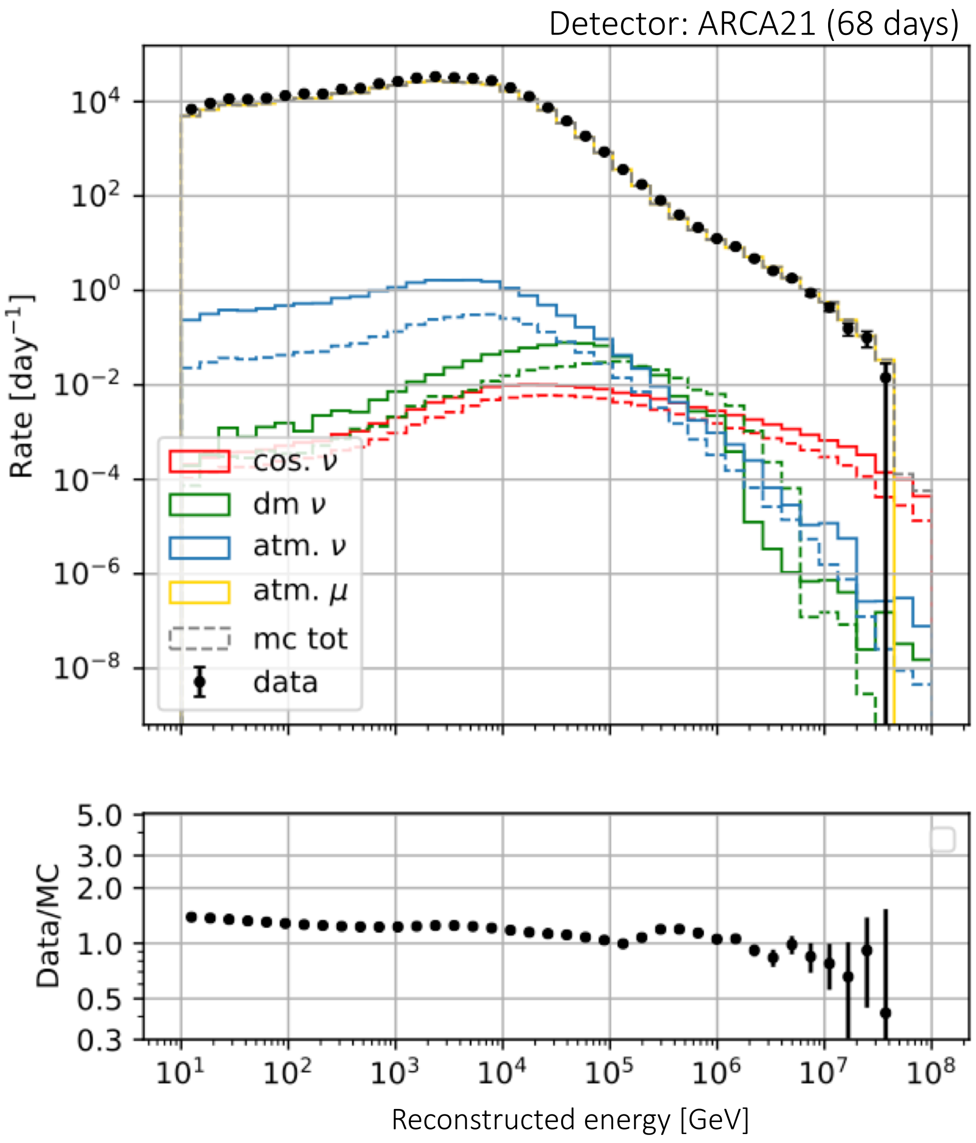
Dark matter distribution around Galactic Centre

Neutrino flux proportional to annihilation cross-section

Data selection

How can we differentiate neutrinos created by DM from other type of neutrinos?

Quite a lot of atmospheric neutrinos
(created by cosmic rays in the atmosphere)



A bunch of atmospheric muons
(created by cosmic rays in the atmosphere)

And some cosmic and dark matter neutrinos

* 100 TeV DM mass, annihilating into $\nu\bar{\nu}$, $< \sigma v > = 10^{-23}\ cm^3 s^{-1}$

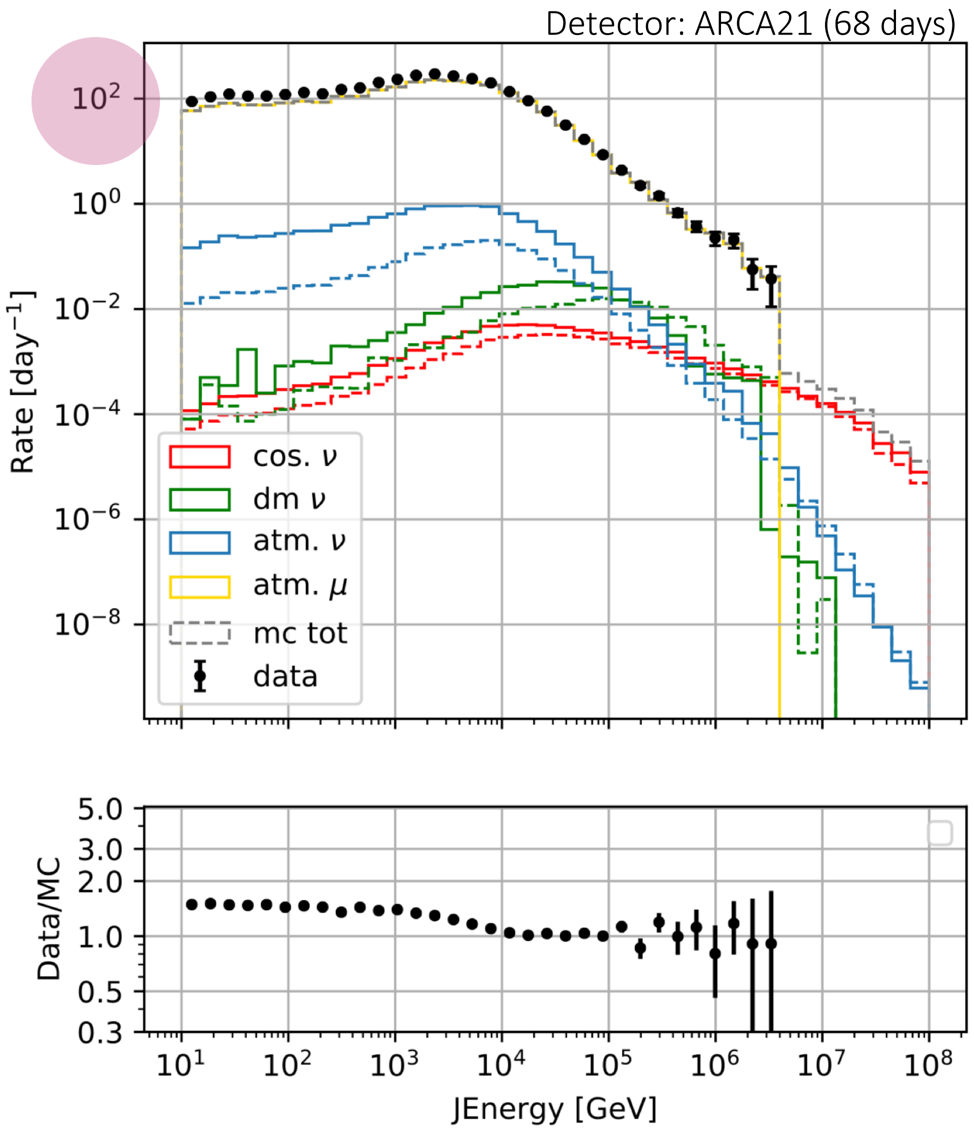
Data selection

How can we differentiate neutrinos created by DM from other type of neutrinos?

We cut all events coming from above
(we only keep events going through the Earth)

	No cuts	Cutting down-going events
data	30256697	268891
muons	24017463.38	235732.98
Atm. nu	1614.58	1009.25
Cos. nu	14.68	7.89
DM nu*	66.77	36.71

* 100 TeV DM mass, $\nu\bar{\nu}$, $<\sigma v> = 10^{-23}\ cm^3 s^{-1}$



Reduction by two orders of magnitude of the muons
(but still many of them, miss-reconstructed)

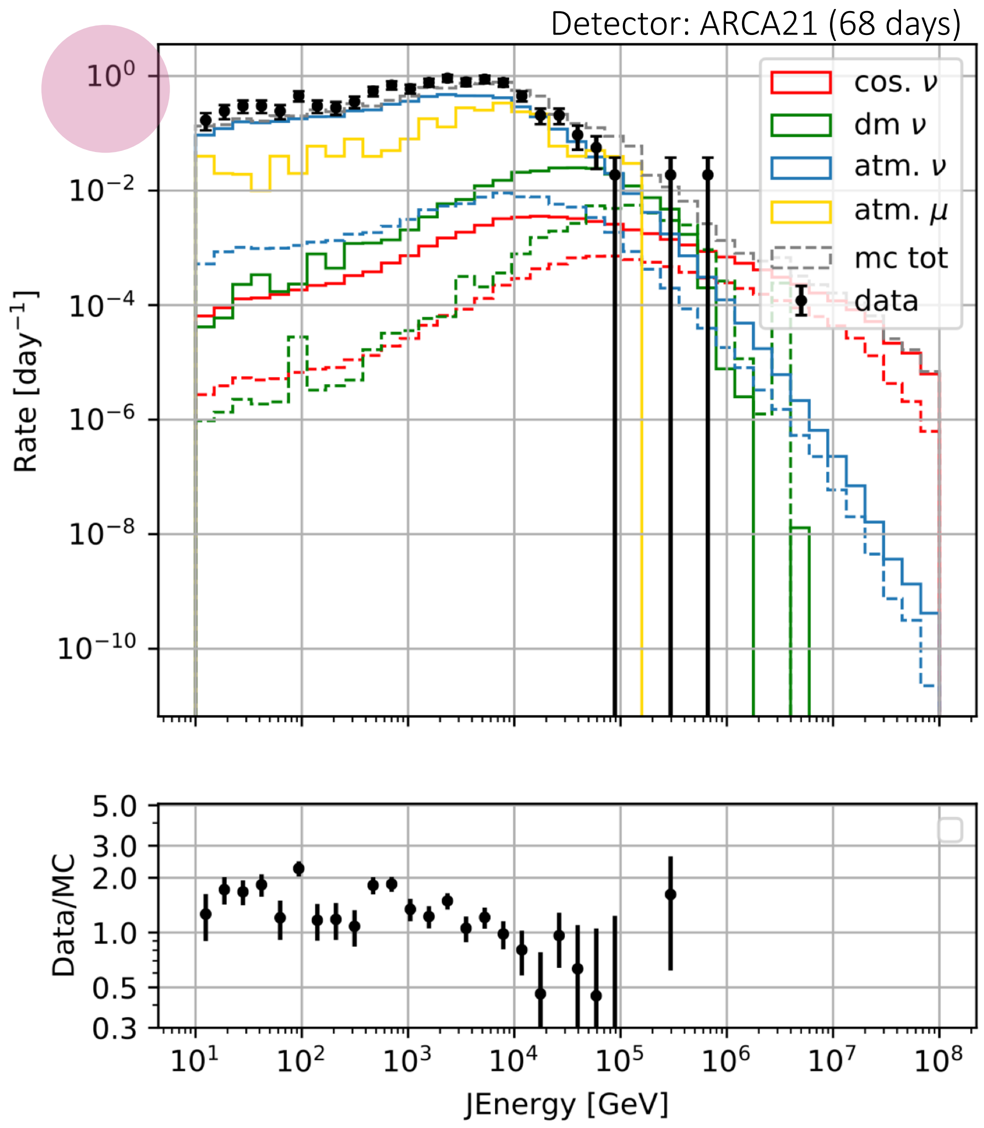
Data selection

How can we differentiate neutrinos created by DM from other type of neutrinos?

We apply quality cuts + we help us with a Boosted Decision Tree

	No cuts	Cutting down-going events	Final cuts
data	30256697	268891	**1041**
muons	24017463.38	235732.98	**420.62**
Atm. nu	1614.58	1009.25	**5111.46**
Cos. nu	14.68	7.89	**4.35**
DM nu*	66.77	36.71	**22.26**

* 100 TeV DM mass, $\nu\bar{\nu}$, $<\sigma v> = 10^{-23}\ cm^3 s^{-1}$



Reduction by two orders of magnitude more of the muons
(we also reduce the neutrinos…)

Not yet the best data-MC agreement
(we still have a small detector)

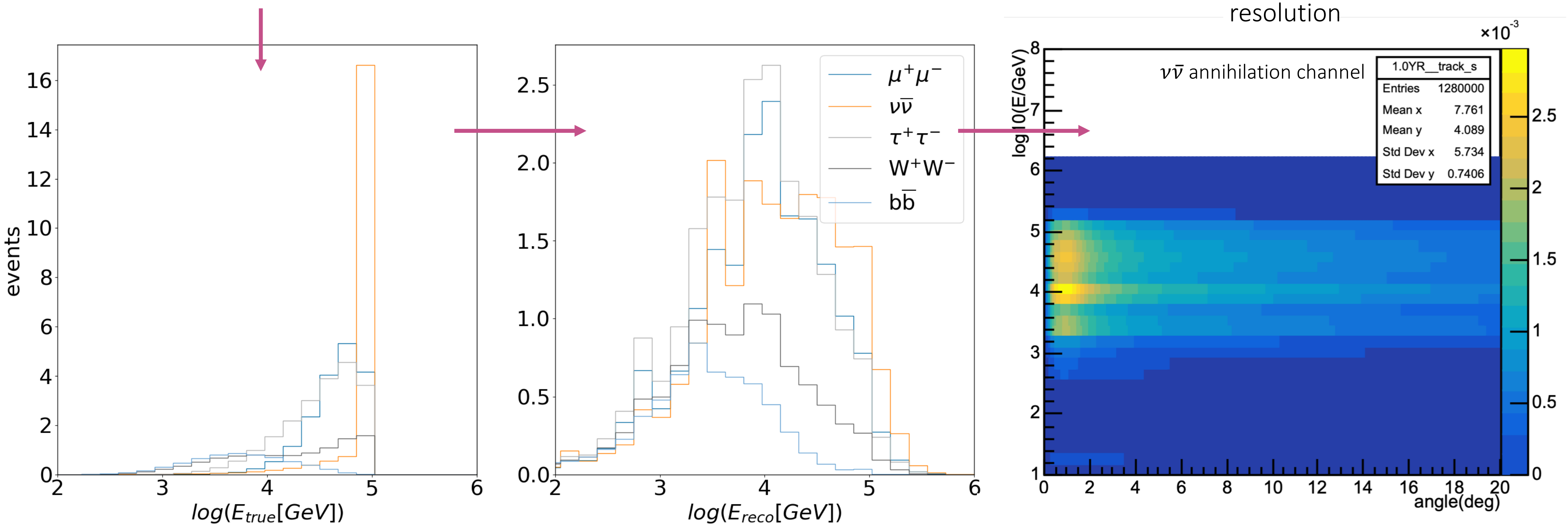
Method

Quantifies nr of neutrinos interacting in the detector volume
takes into account absorption by the Earth, neutrino interaction cross-section…
(not the real area/volume of the detector but the effective one)

Effective area x flux x observation time

Applying energy resolution

Adding the spatial dependence of the signal and adding the direction resolution



Expected signal rate

100 TeV DM mass, $< \sigma v > = 10^{-23}\ cm^3 s^{-1}$

1yr full detector

Method

Binned likelihood analysis

$$L(\mu) = \prod_i \frac{\exp\left(-(B_i + \mu S_i)\right)(B_i + \mu S_i)^{N_i}}{N_i!}$$

Likelihood
(product of Poisson probability of each bin)

Backgroung
(in bin i)

Signal
(in bin i)

Signal strength
(scaling factor)

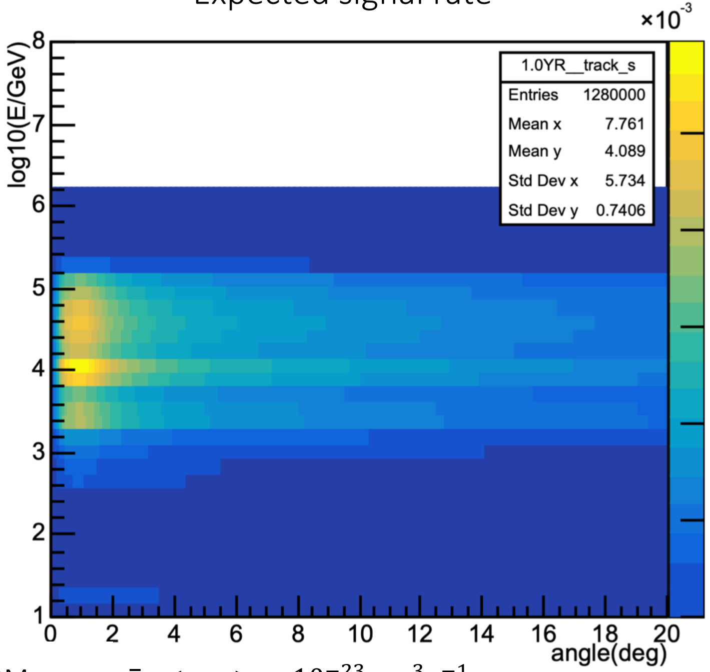
Data events
(or pseudo-experiment)

Test-statistic
(tests the signal and background hypothesis)

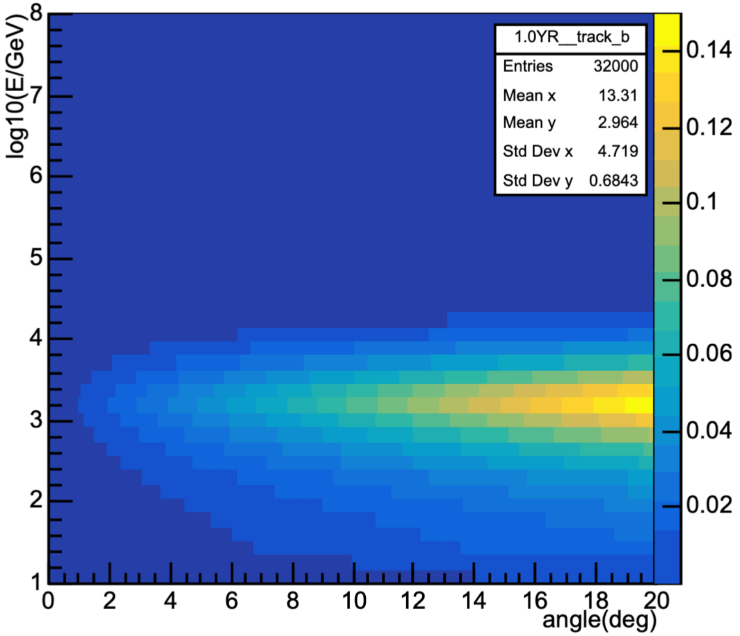
$$\lambda = \log \frac{L(\mu = \hat{\mu})}{L(\mu = 0)}$$

Signal strength maximising the likelihood of the data

Expected signal rate



Expected background rate



100 TeV DM mass, $\nu\bar{\nu}$, $<\sigma v> = 10^{-23}\ cm^3 s^{-1}$

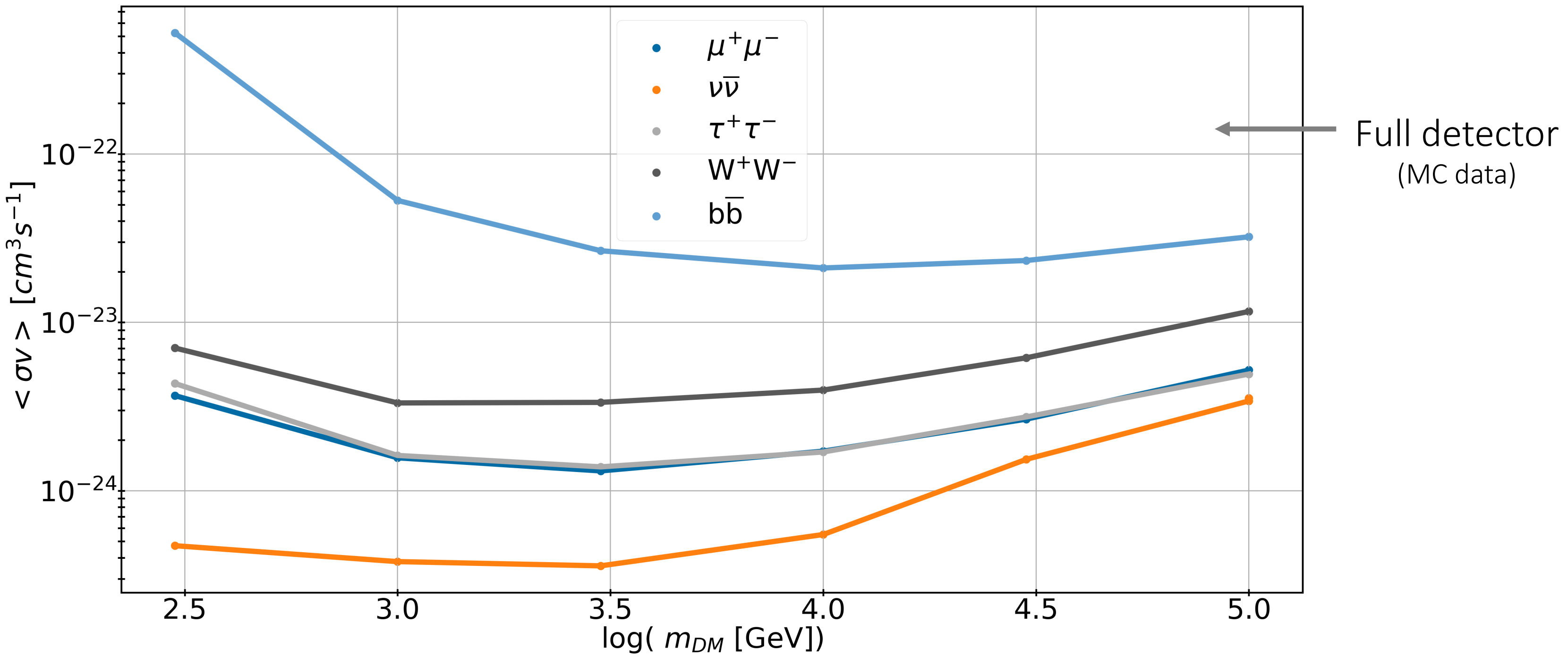
We compute the required signal strength to reject with a 90% confidence level the signal hypothesis with respect the only background one

$$\frac{d\Phi}{dE\,dt} = \frac{1}{4\pi}\frac{\hat{\mu}\langle\sigma v\rangle}{2m_\chi^2}\frac{dN_\nu}{dE}\int\int \rho^2 dl\, d\Omega$$

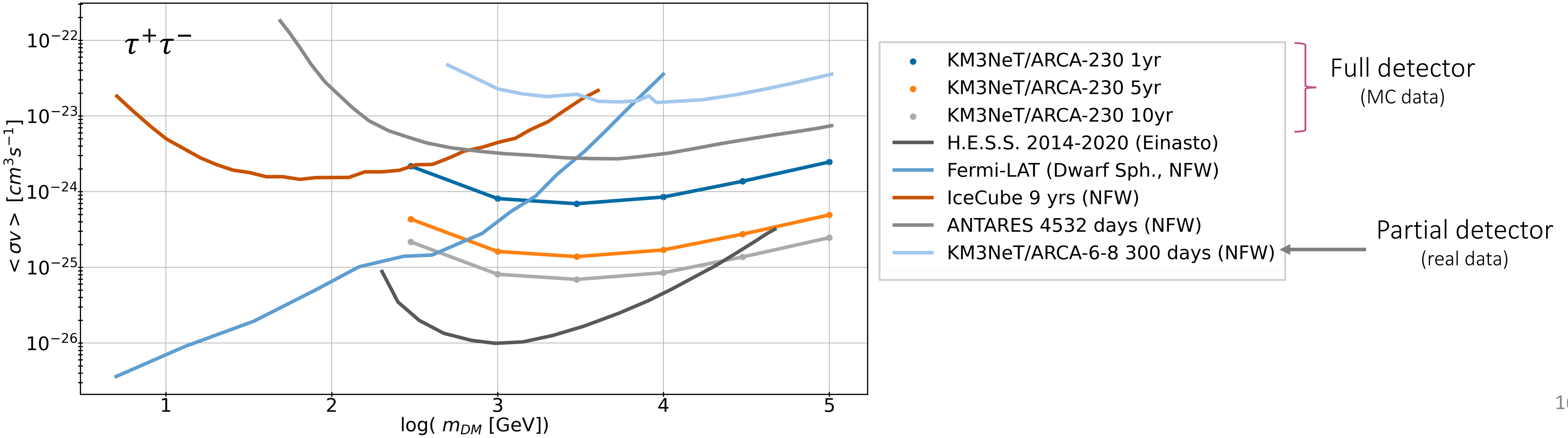
We reject annihilation cross-sections larger than $\hat{\mu}\langle\sigma v\rangle$

The modest contribution

KM3NeT/ARCA sensitivity to different annihilation channels and dark matter masses



Results in context

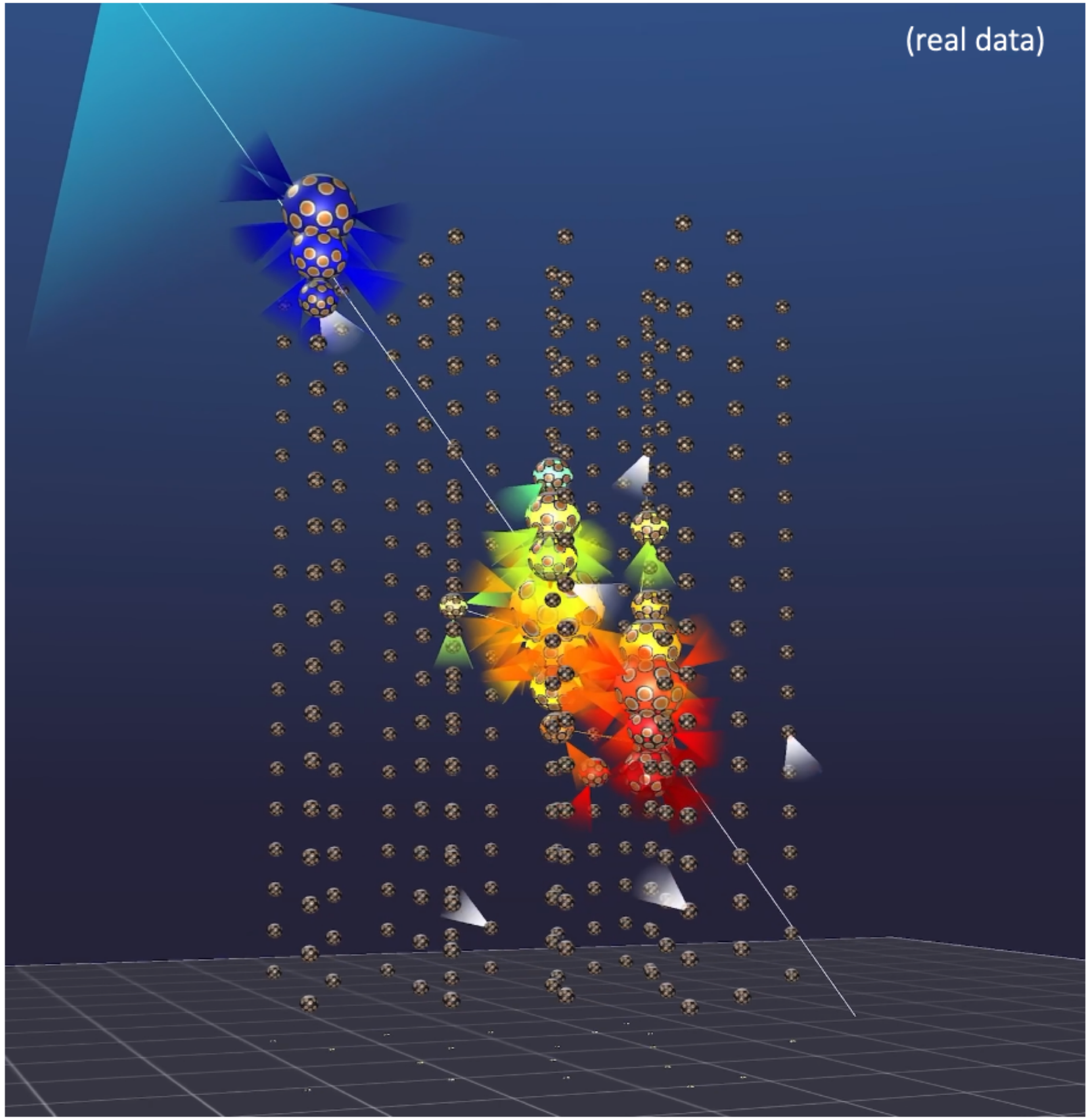


Conclusions

- Contribution to limit what can a WIMP dark matter particle be like

- In the sum of many experiments there's the discovery power!

- KM3NeT taking data and growing!!!



Additional slides: Detector response

Full detector