



Finanziato
dall'Unione europea
NextGenerationEU



Ministero
dell'Università
e della Ricerca



Italiadomani
PIANO NAZIONALE
DI RIPRESA E RESILIENZA



KM3NeT

Il caso scientifico

Tommaso Chiarusi
INFN - Sezione di Bologna

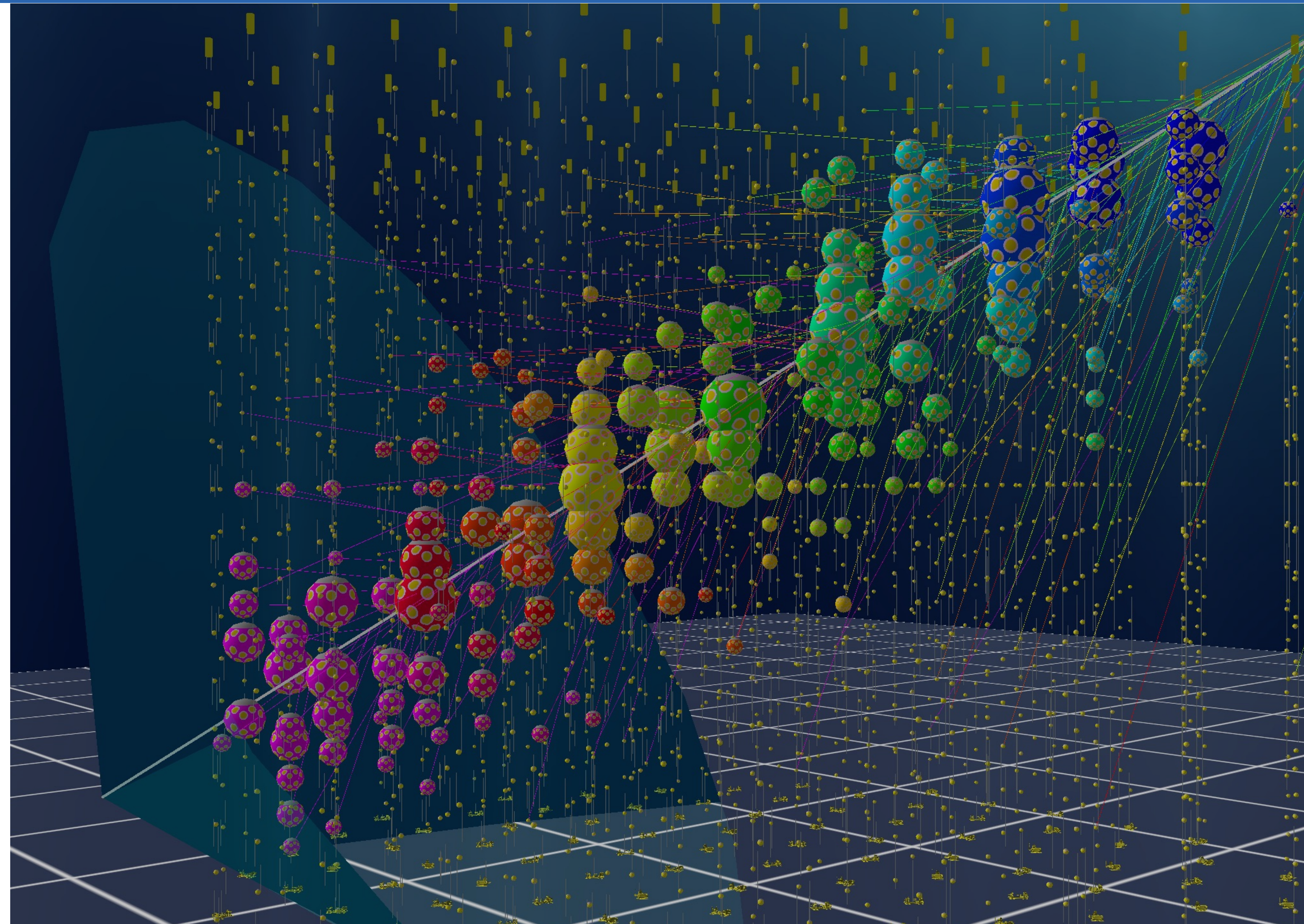
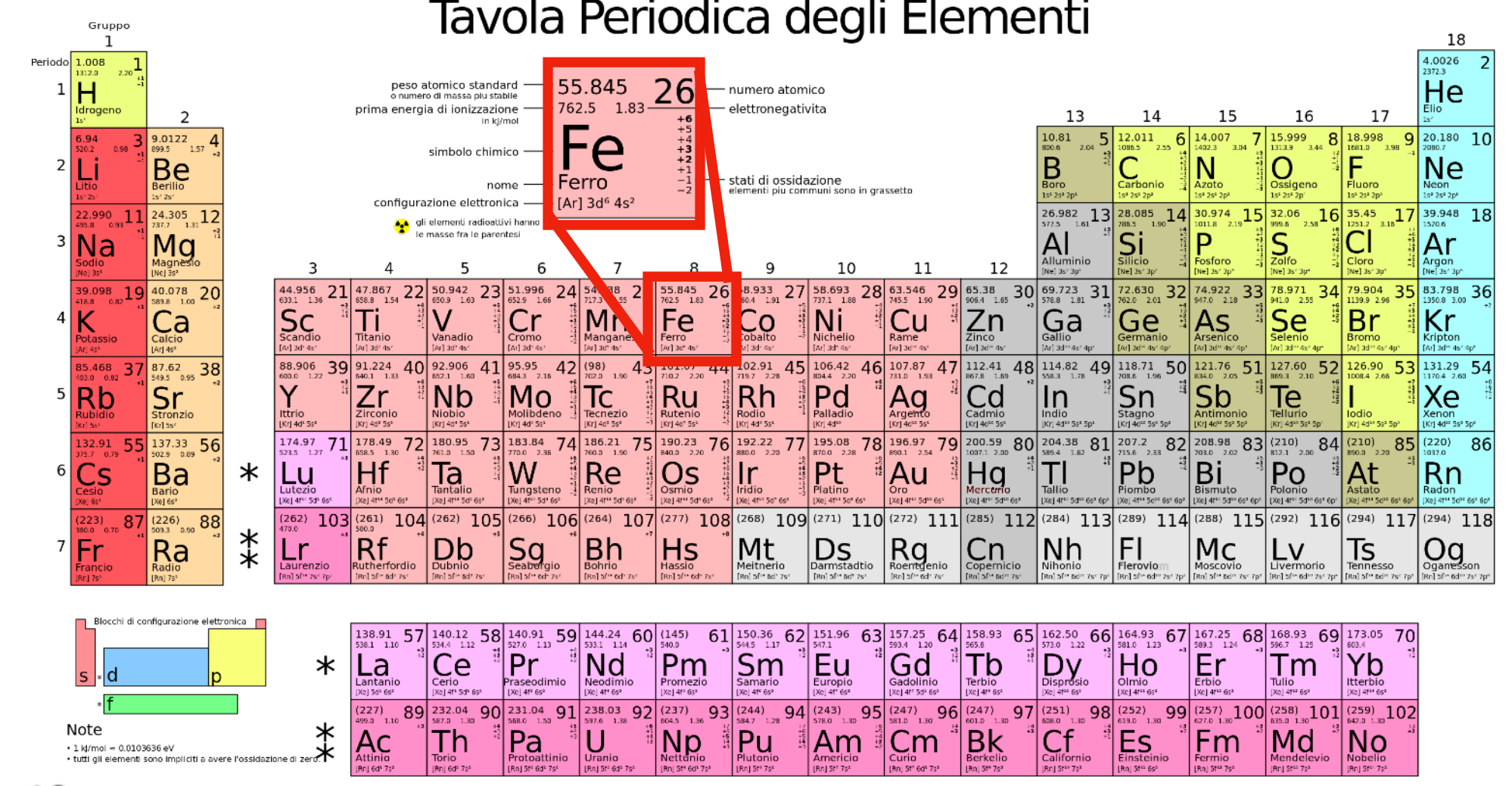


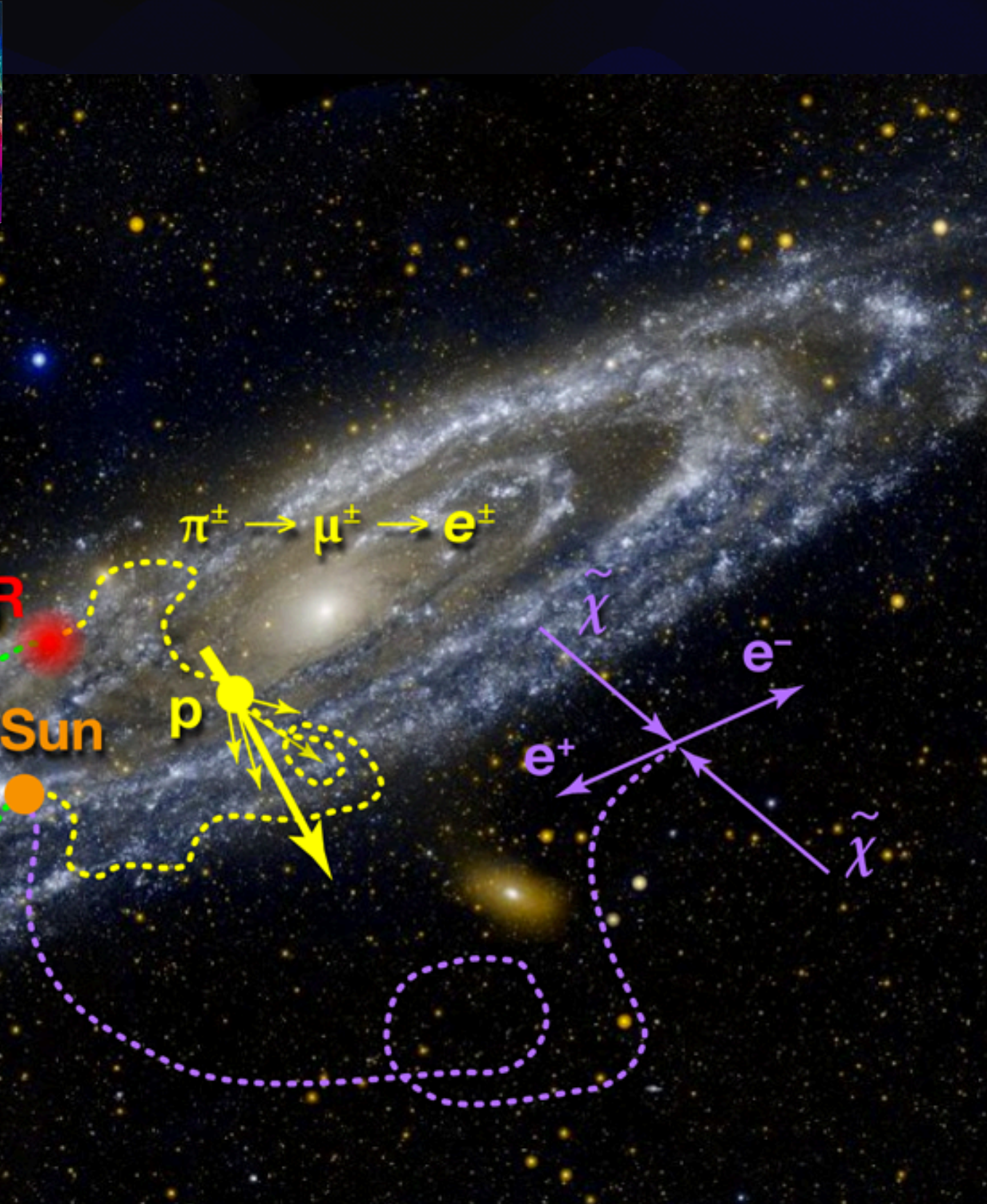
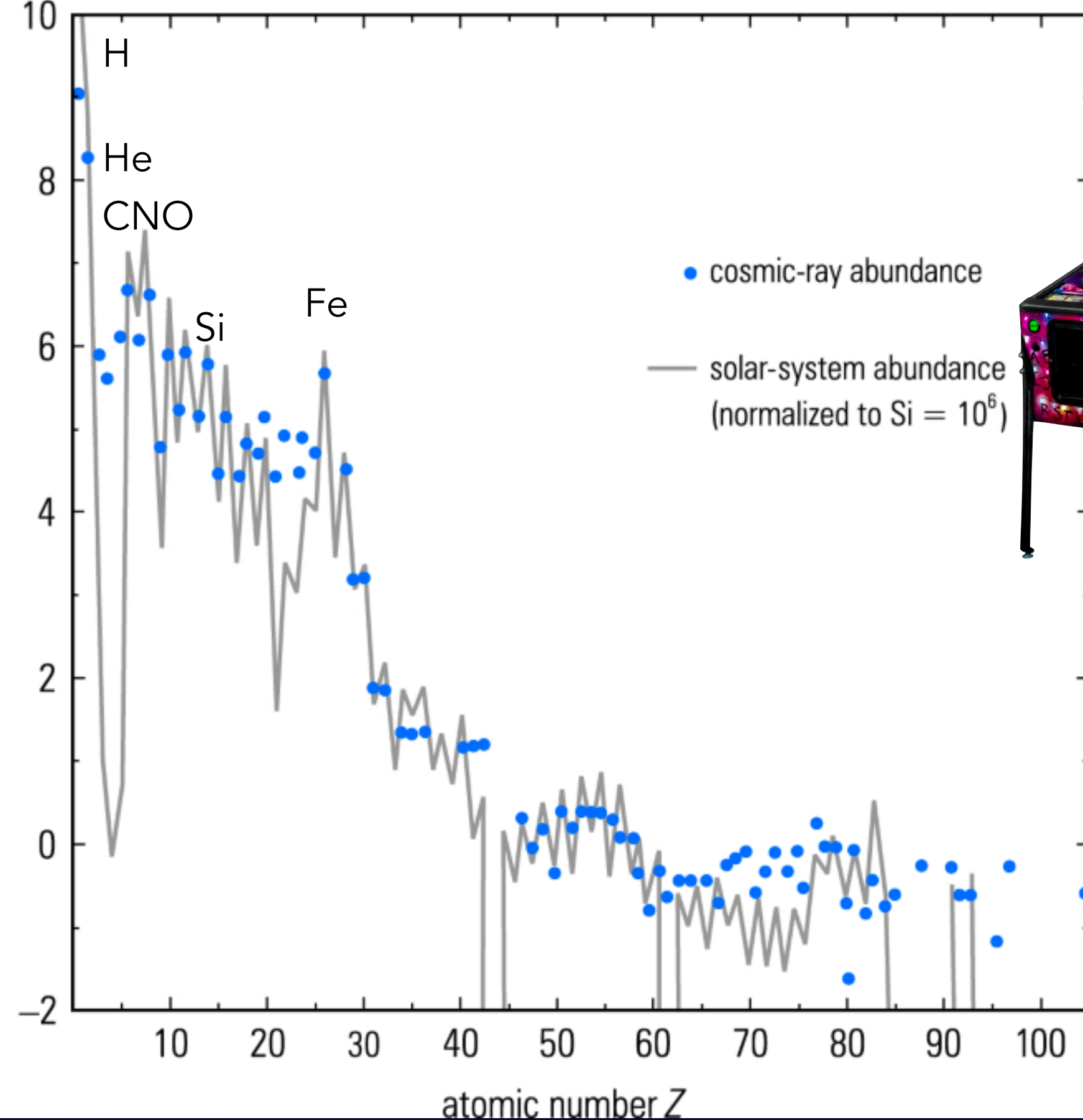
Tavola Periodica degli Elementi



Problemi principali legati ai raggi cosmici

- Dove sono prodotti ?
- Dove sono accelerati ?
- Cosa incontrano nel loro cammino fino alla Terra ?
- Quanto tempo impiegano ad arrivare ?
- Quanti sfuggono via (e da dove) ?
- Quanti sopravvivono ?
- L'abbondanza relativa dei nuclei è universale ?

Supernovae



Buchi neri



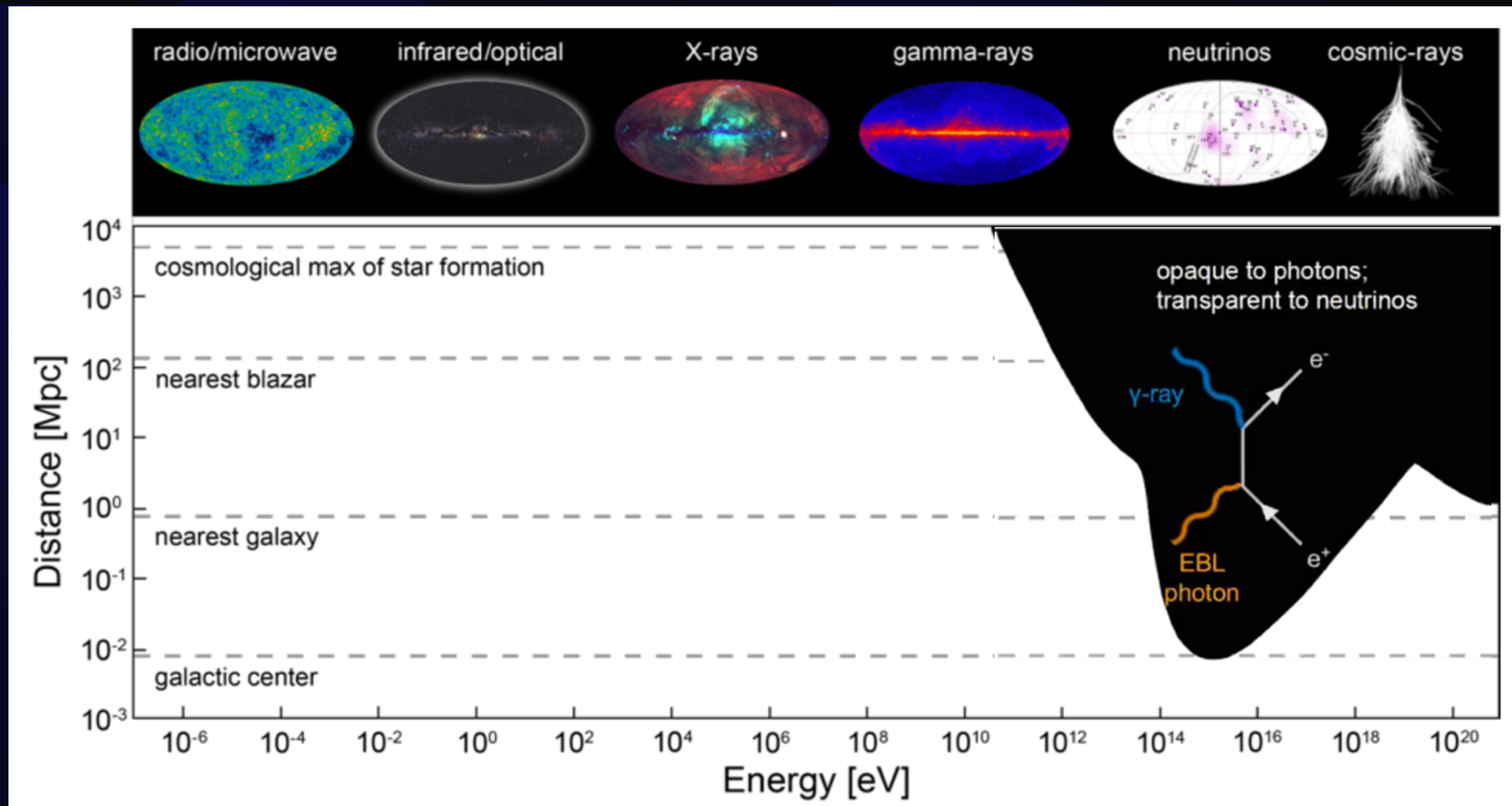
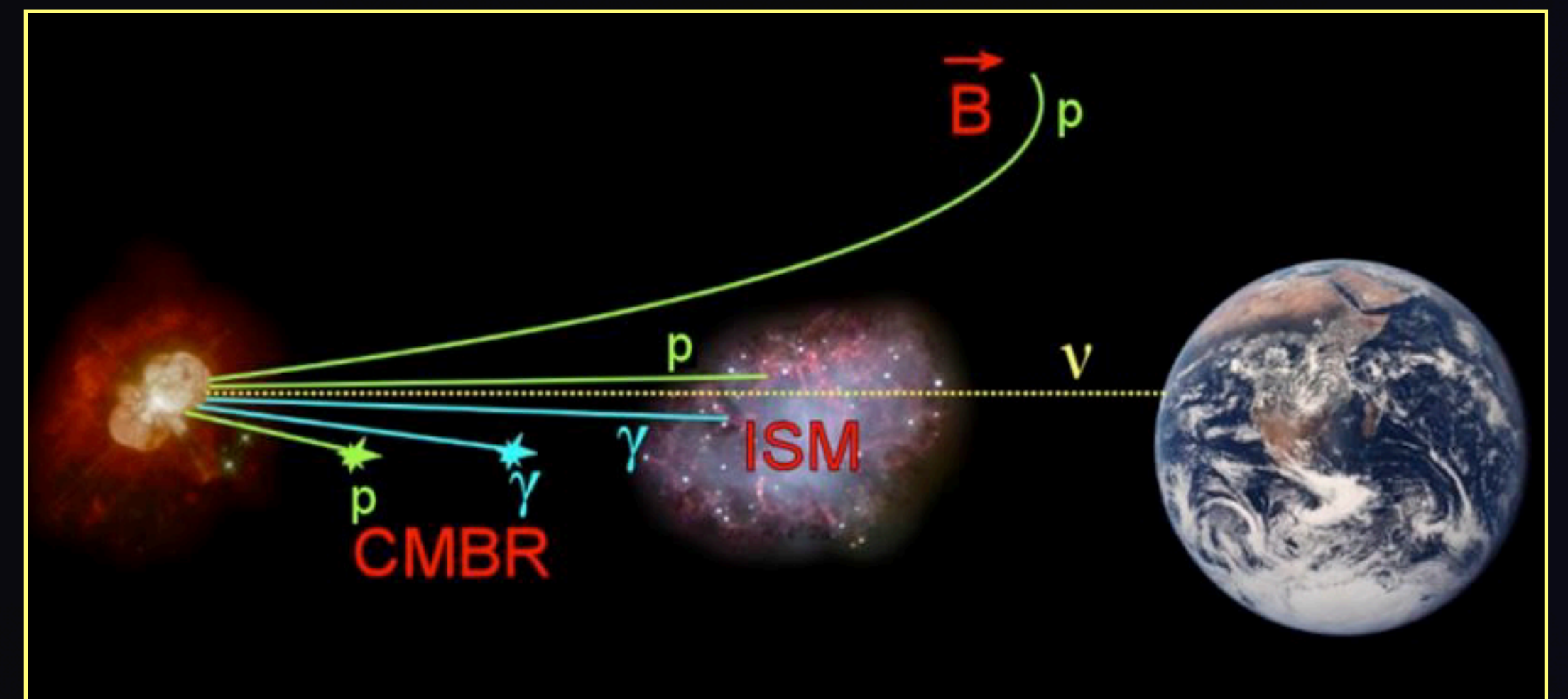
Lampi di raggi gamma



I Raggi Cosmici di media alta energia sono deflessi dai campi magnetici (inter-)galattici o distrutti lungo il cammino

I Raggi γ sono assorbiti lungo il cammino

I neutrini persistono imperterriti



Il neutrino interagisce solo debolmente con **sezioni d'urto** estremamente basse:

$$\sigma_{\nu N} \sim 8 \times 10^{-36} \frac{E_{\nu}^{0.36}}{1 \text{ GeV}} \text{ cm}^2$$

per $E_{\nu} > 1000 \text{ GeV}$

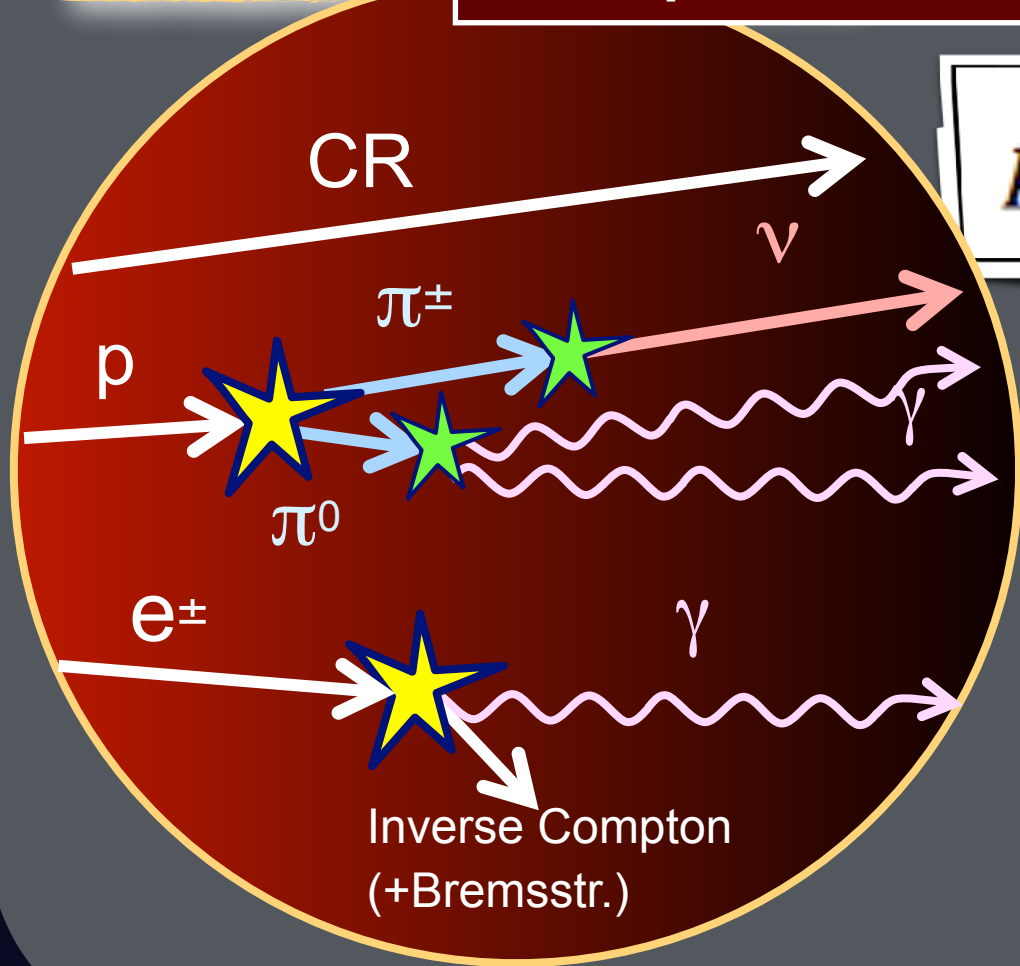
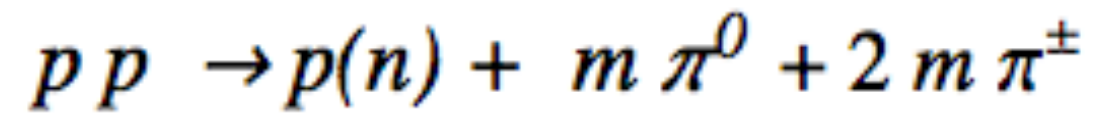
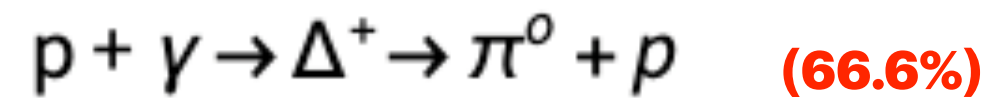
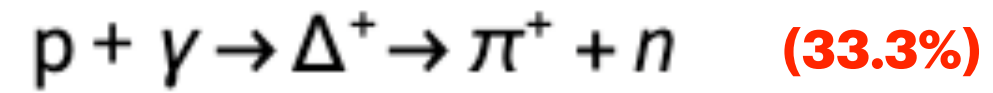
Nota: un **elettone della stessa energia** ha una sezione d'urto con la materia **~ 10 ordini di grandezza maggiore**

I neutrini usati per investigare le parti più remote del Cosmo ... dove avvengono i fenomeni più violenti dell'Universo

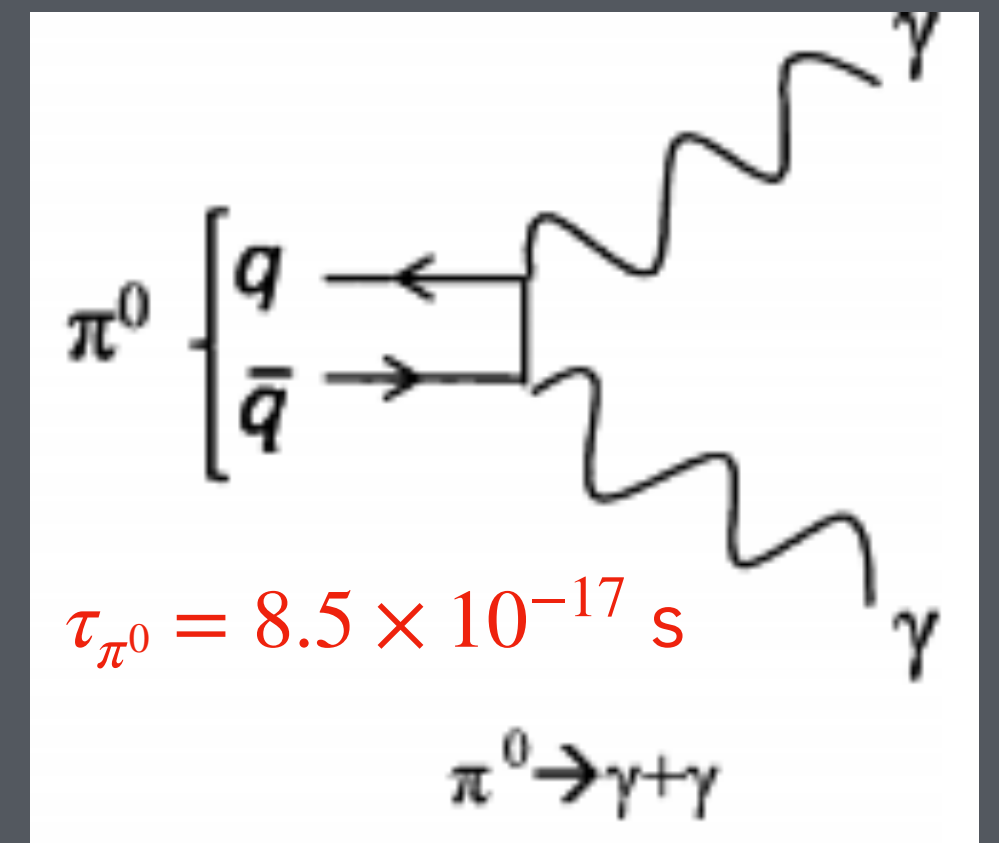
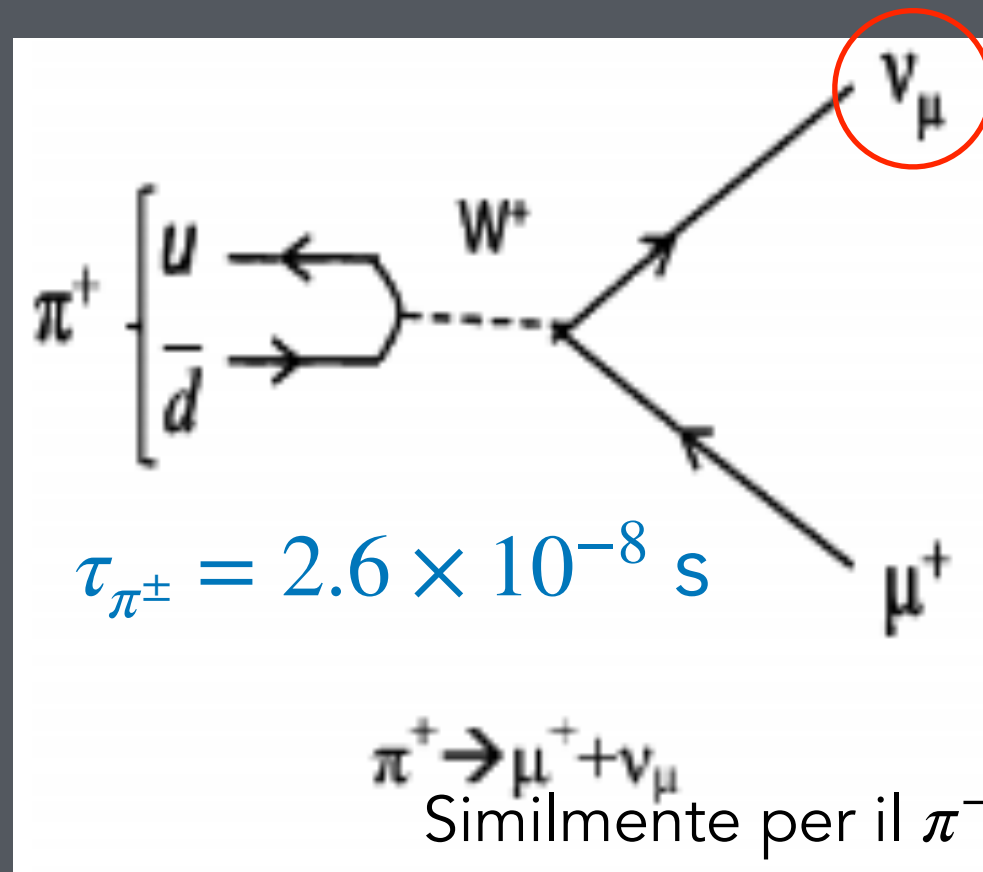
Alle sorgenti



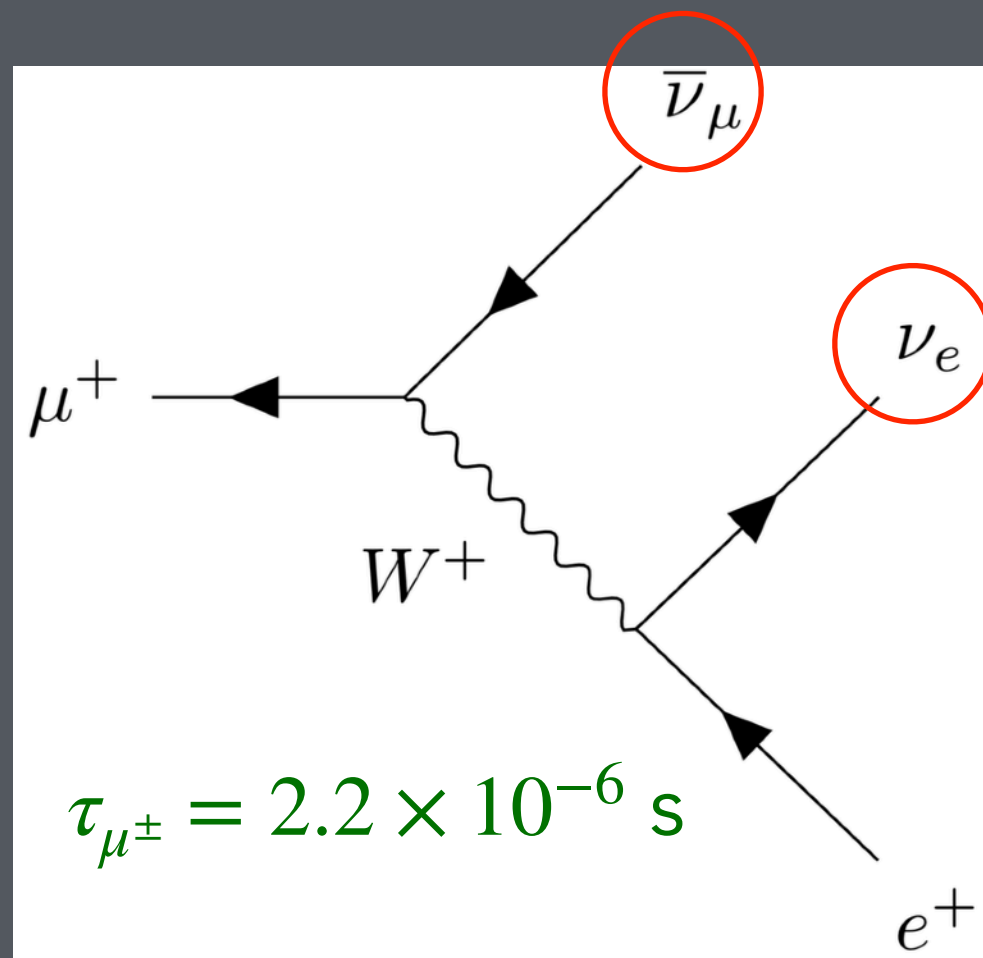
Campo di radiazione o materia



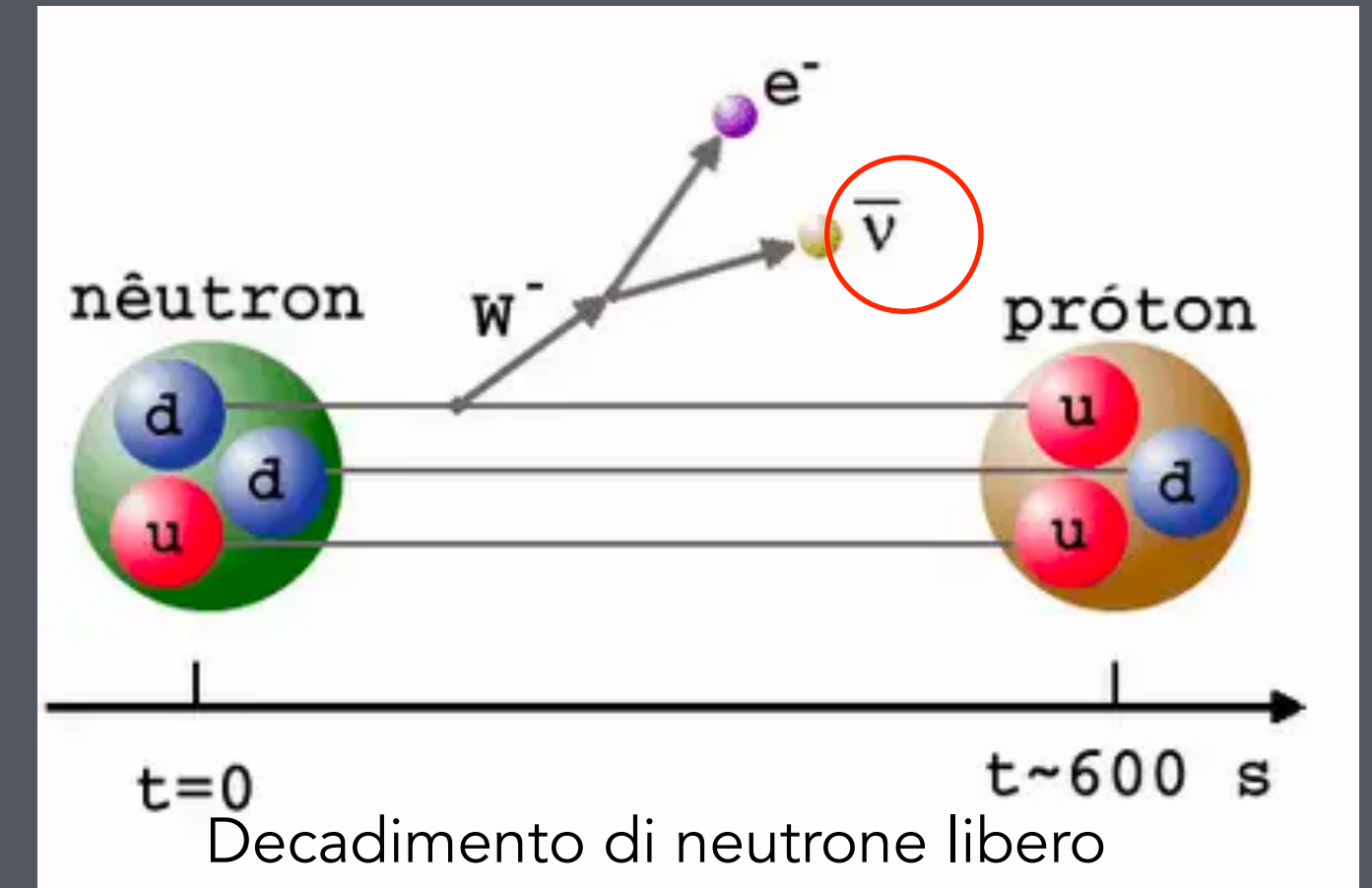
“Poco” dopo...



“L’approccio **Multi-messaggero** è importante per correlare i flussi misurati tra Raggi- γ e neutrini

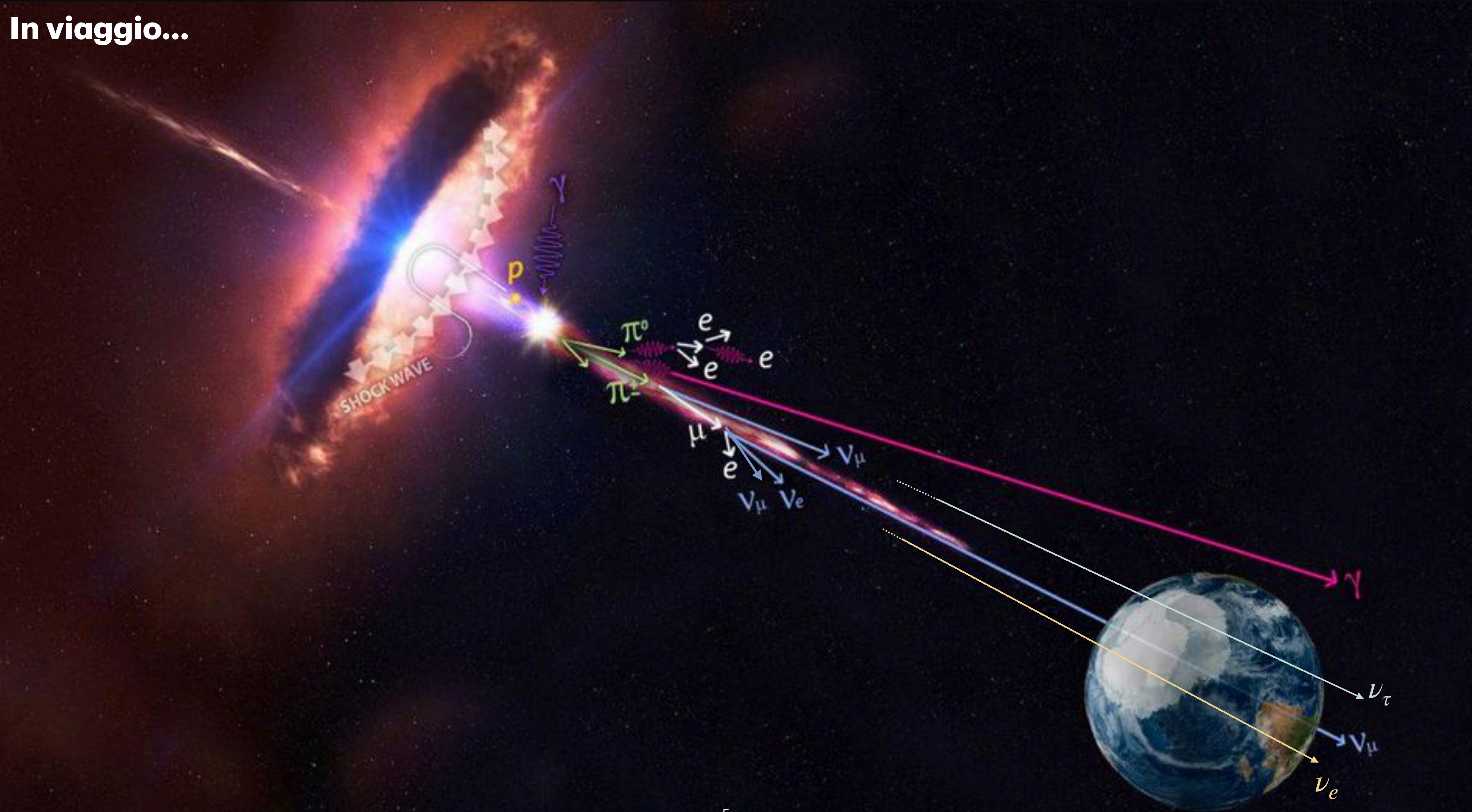


Il decadimento del muone

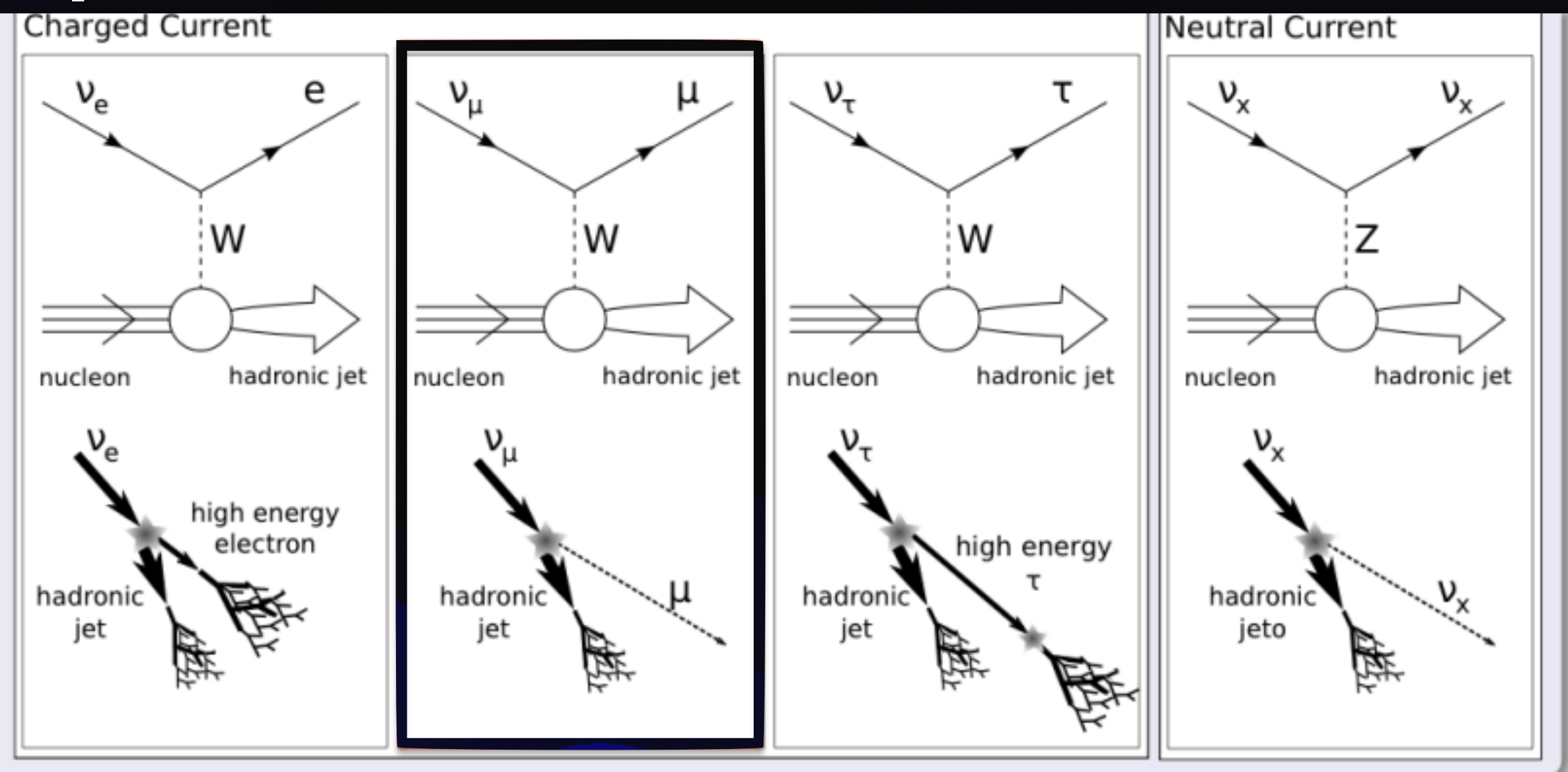


Se i neutroni sono liberi di decadere...

In viaggio...



E poi sulla terra...



Miglior canale per la stima di energia

Canale "d'oro" per l'Astronomia

"Double bang" @ $E > 1 \text{ PeV}$ (tau range $> 50 \text{ m}$)
Eventi molto rari

Informazione parziale sull'energia



Moisey Markov
1908-1994

Bruno Pontecorvo
1913-1993

M. Markov:

"Proponiamo di installare rivelatori in profondità in un lago o in mare e di determinare la direzione delle particelle cariche con l'aiuto della radiazione Cherenkov."

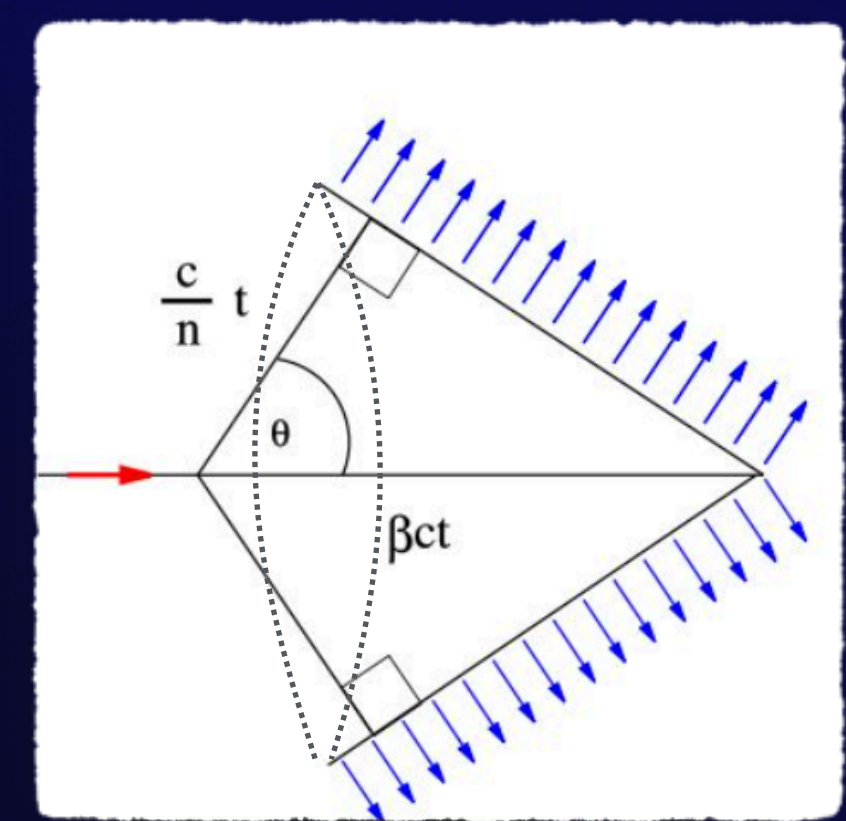
1960, Rochester Conference



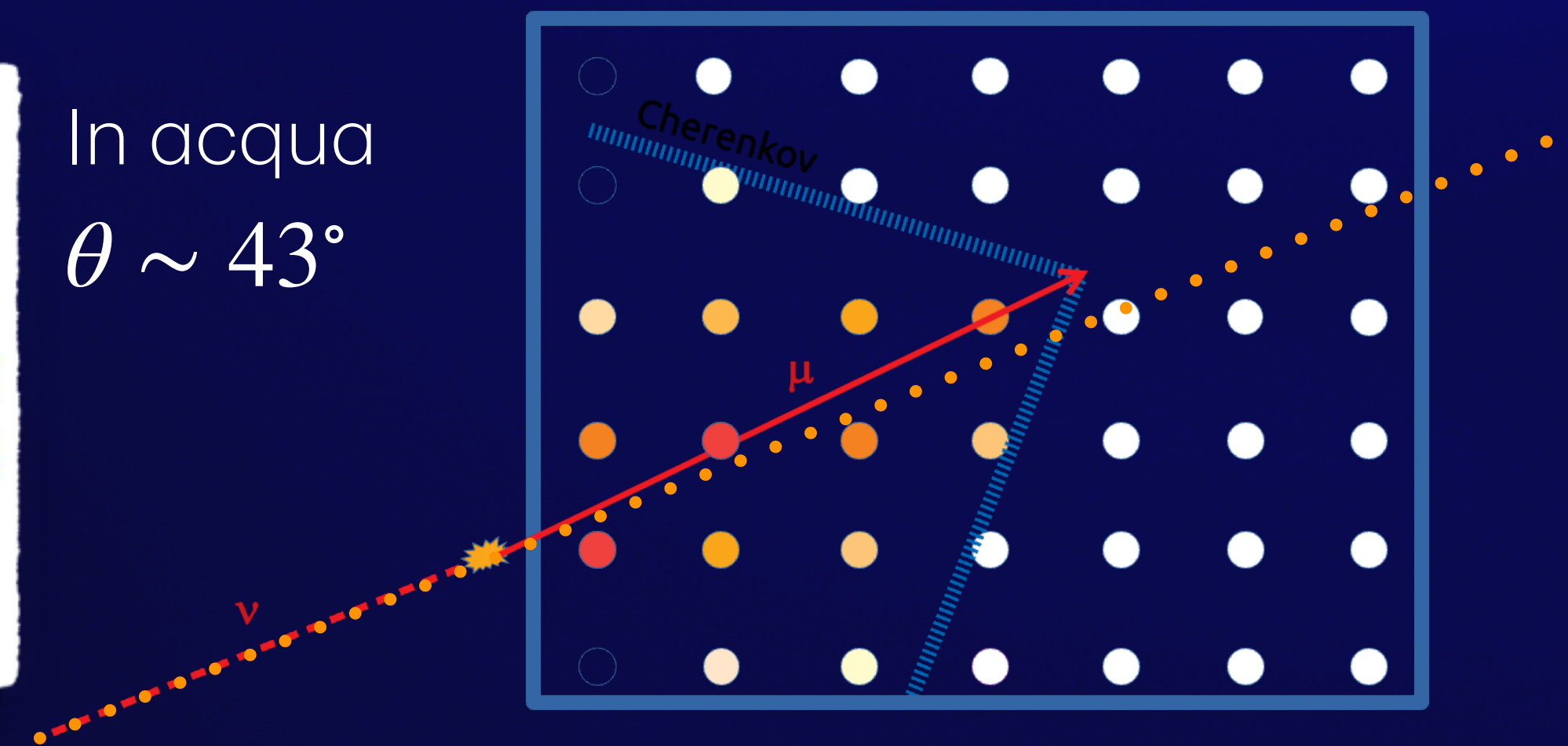
Cherenkov



Pavel A. Cherenkov,
1904-1990

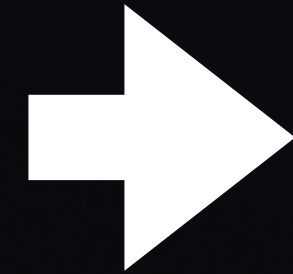


In acqua
 $\theta \sim 43^\circ$

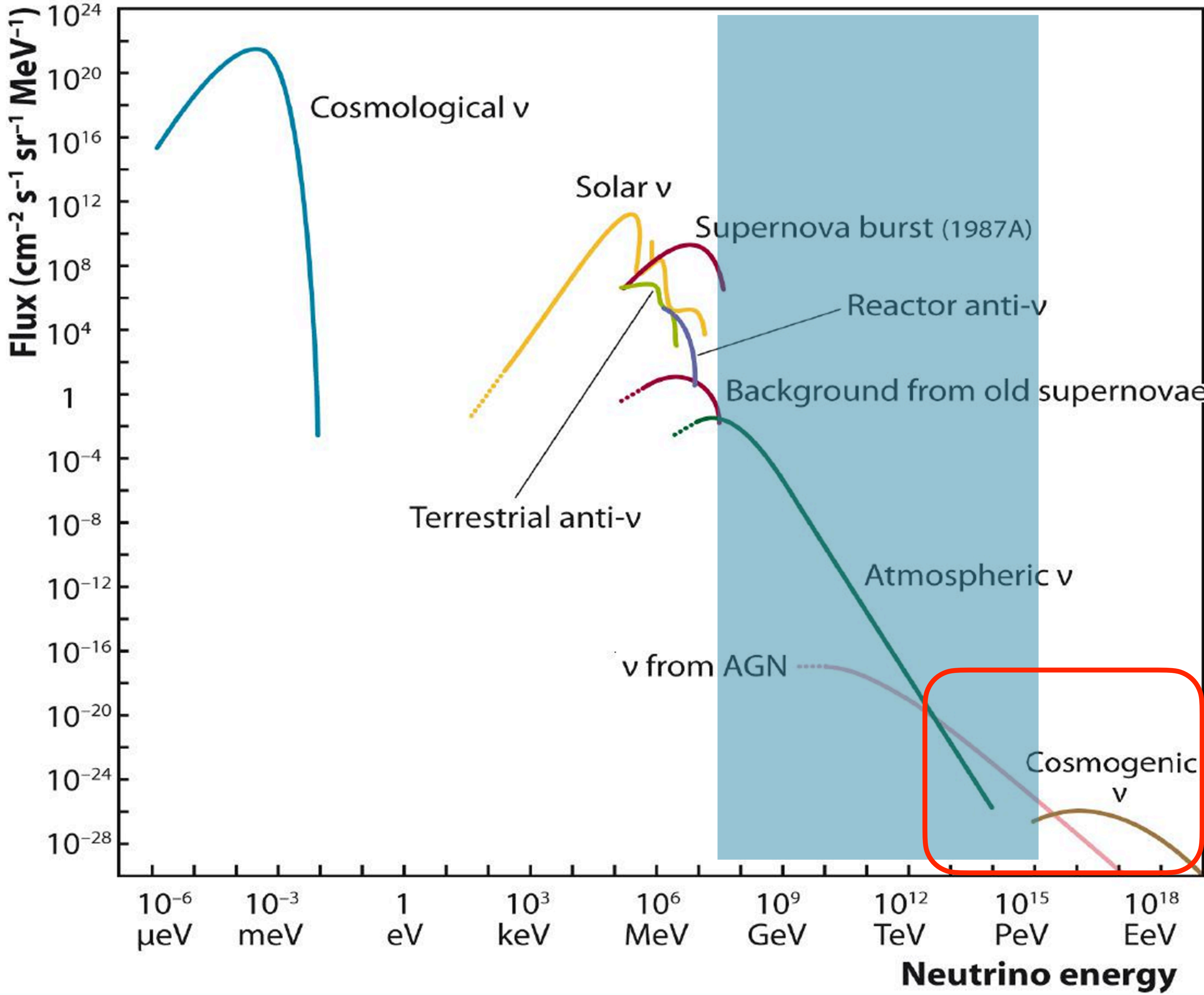


“Vincoli” di un telescopio per neutrini astrofisici

Il fondo di particelle: **sciame atmosferici**



Occorre schermare il più possibile \Rightarrow **profondità abissali**
... ma i *neutrini atmosferici* sono un fondo ineliminabile con
qualsiasi schermatura



Small ν_{astro} fluxes

$$\Phi(E_\nu) = \Phi_0 \left(\frac{E_\nu}{100\text{TeV}} \right)^{-\gamma}$$

$$\Phi_0 = 1.8 \cdot 10^{-18} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1}$$

$$\gamma = 2.5$$

PoS(ICRC2023)1064

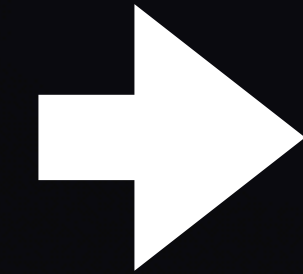
Small ν -matter cross-sections

$$\sigma_{\nu N} \sim 8 \times 10^{-36} \frac{E_\nu^{0.36}}{1 \text{ GeV}} \text{ cm}^2$$

Intervento di Francesco Filippini

“Vincoli” di un telescopio per neutrini astrofisici

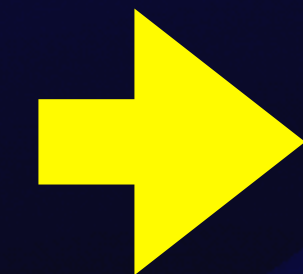
Il fondo di particelle: **sciami atmosferici**



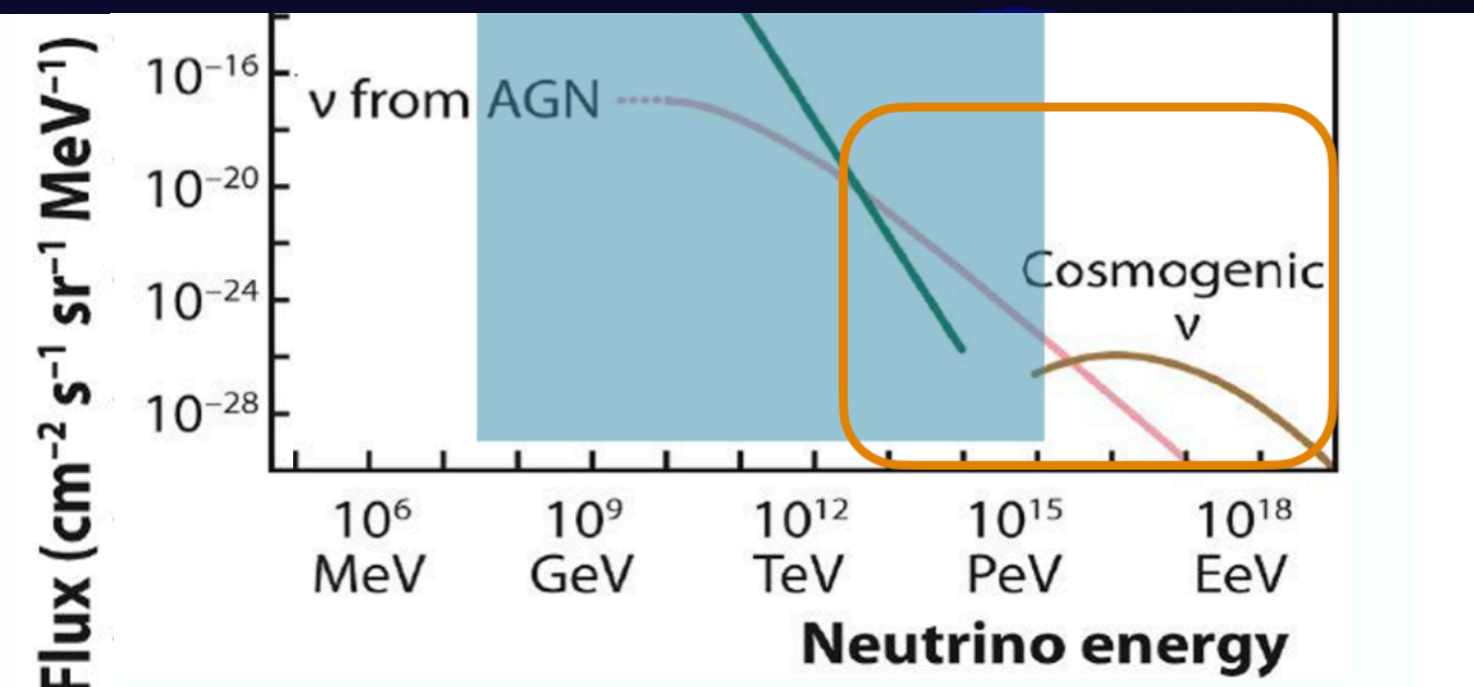
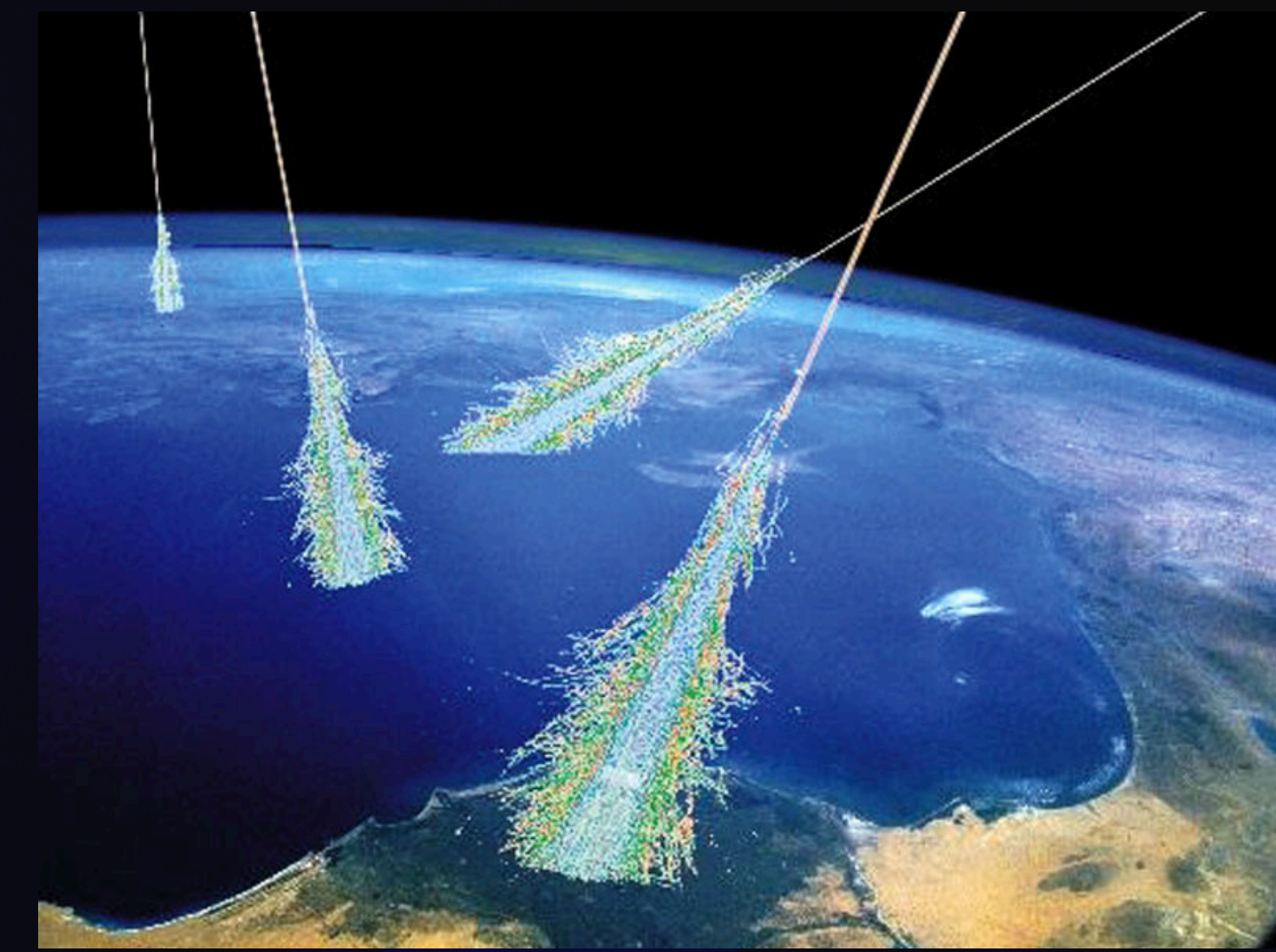
Occorre schermare il più possibile \Rightarrow **profondità abissali**
... ma i *neutrini atmosferici* sono un fondo ineliminabile con qualsiasi schermatura

Selezione in base all'energia.... $\nu_{astro} > 100 \text{ TeV}$

“pesci” rari dunque... quindi “reti enormi”



Volume $\sim \text{km}^3$ -scale per O(1) evento astrofisico / anno
Tempo di vita su scala decennale



“Vincoli” di un telescopio per neutrini astrofisici

Il fondo di particelle: **sciami atmosferici**

➔ Occorre schermare il più possibile ⇒ **profondità abissali**
... ma i *neutrini atmosferici* sono un fondo ineliminabile con qualsiasi schermatura

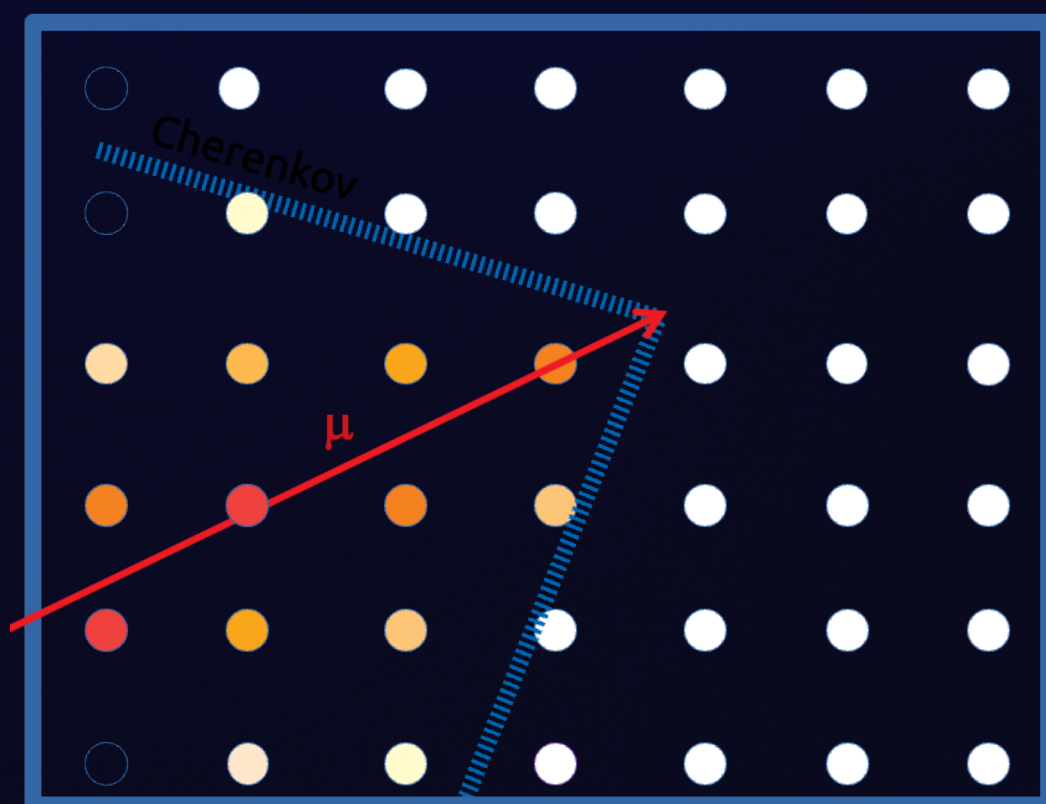
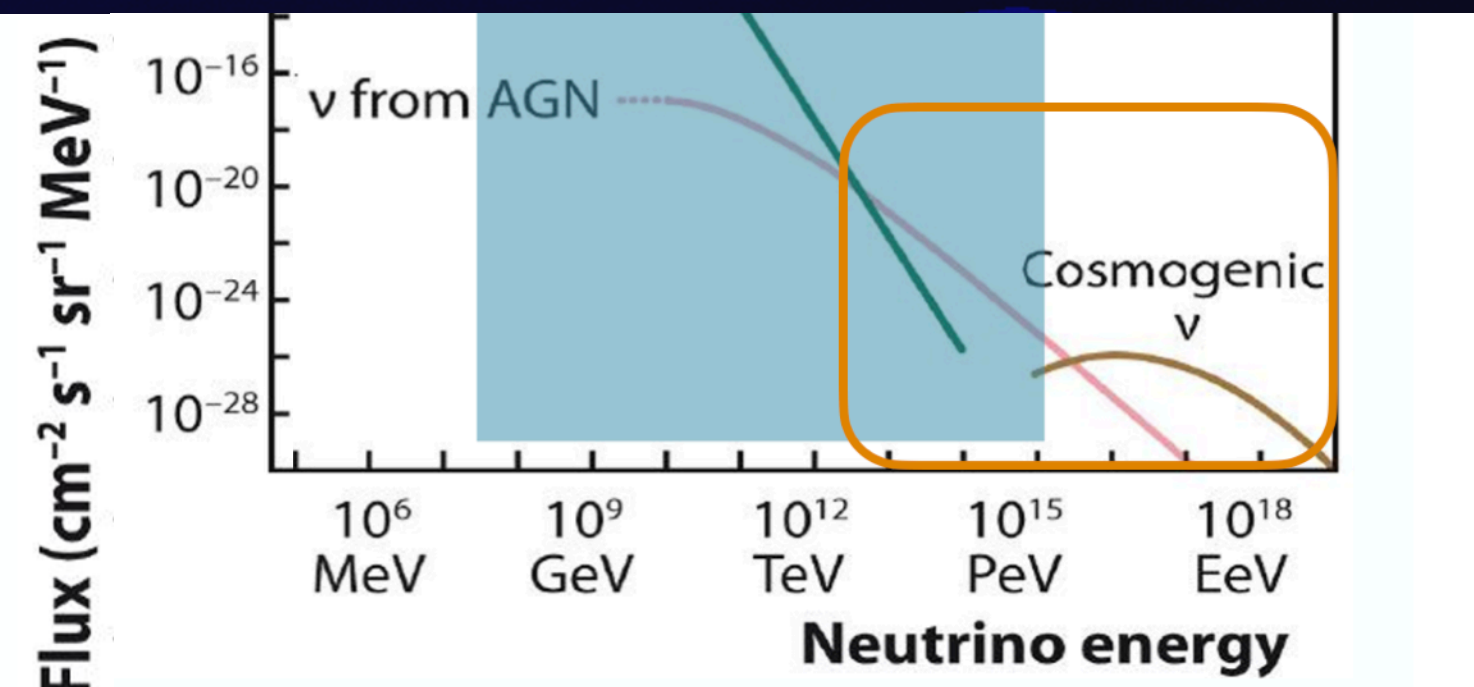
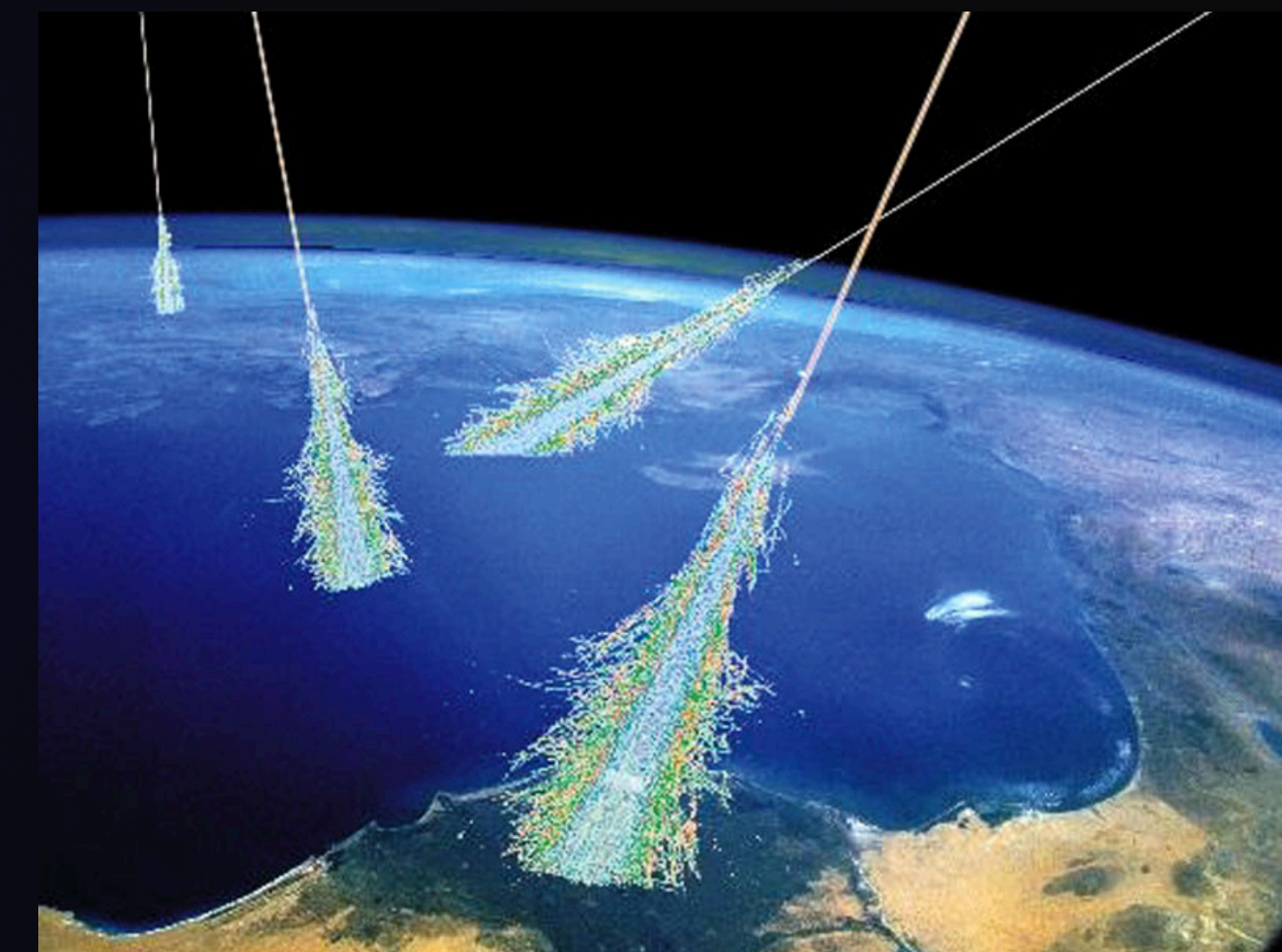
Selezione in base all'energia.... $\nu_{astro} > 100 \text{ TeV}$

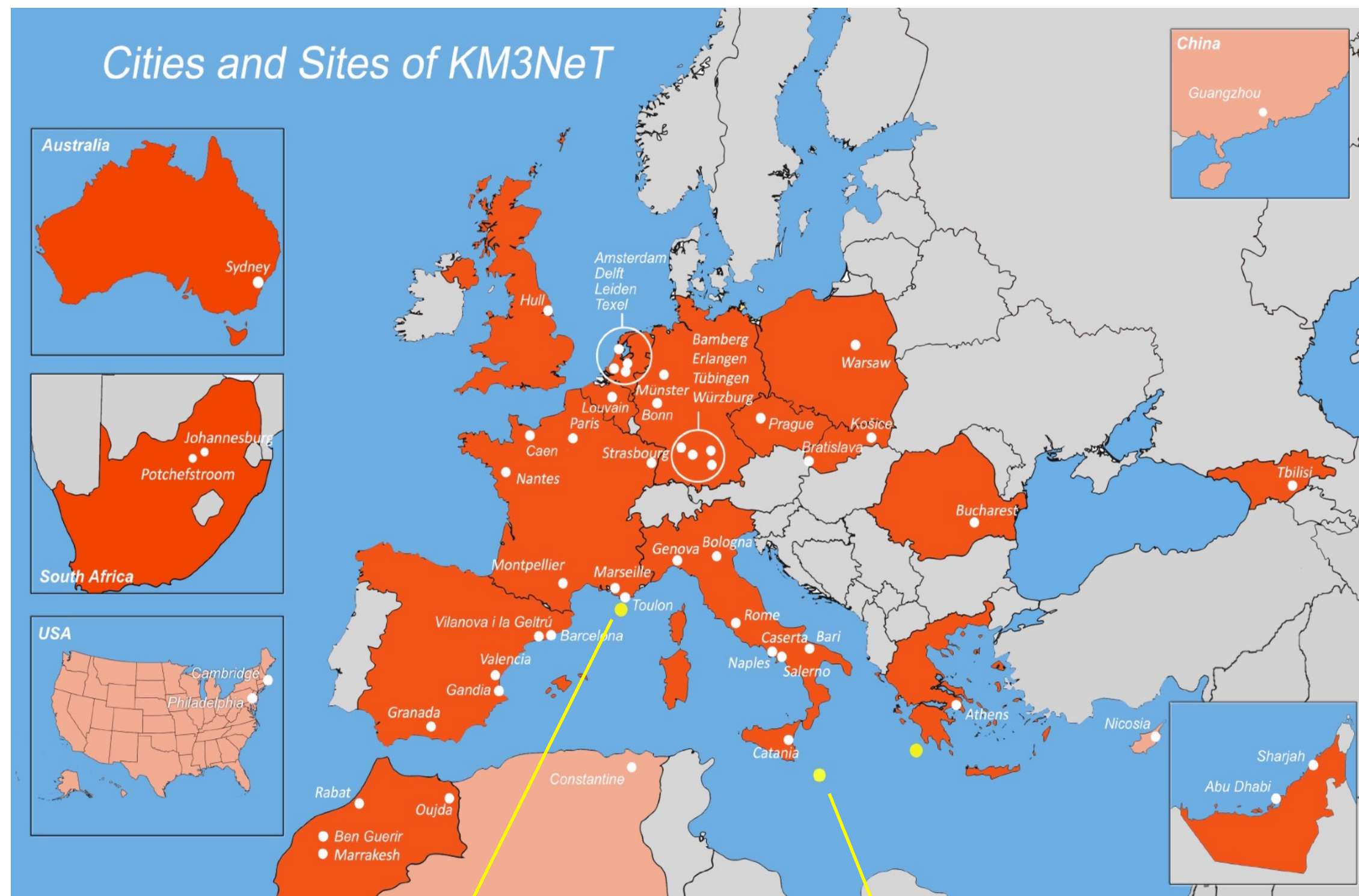
“pesci” rari dunque... quindi “reti enormi”

➔ Volume ~ km³-scale per O(1) evento astrofisico / anno
Tempo di vita su scala decennale

Risoluzione angolare $< O(0.25) \text{ deg}$

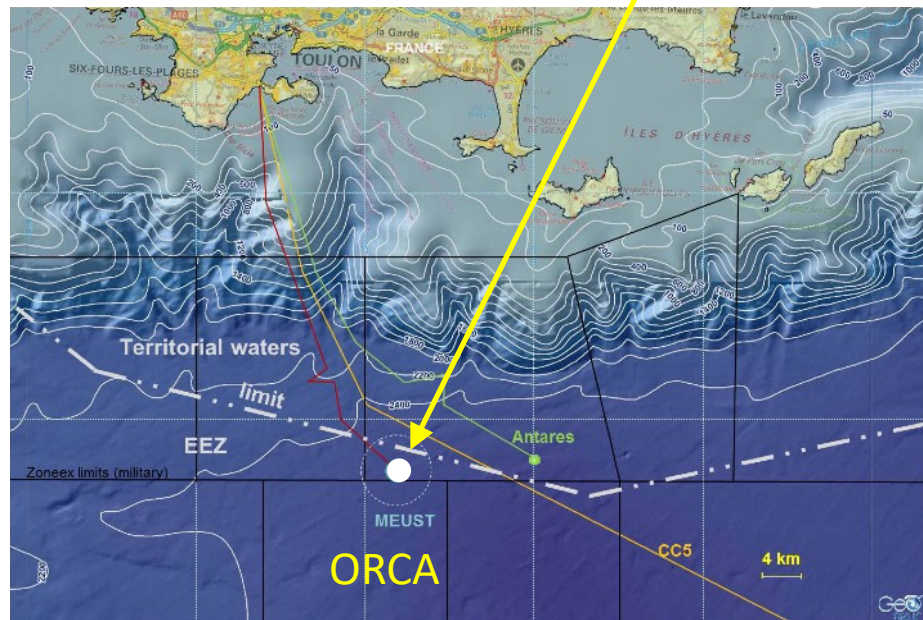
➔ O(5000) rivelatori ottici / km³ ➔ Timing $< O(1) \text{ ns}$
Posizionam. $< O(10) \text{ ns}$



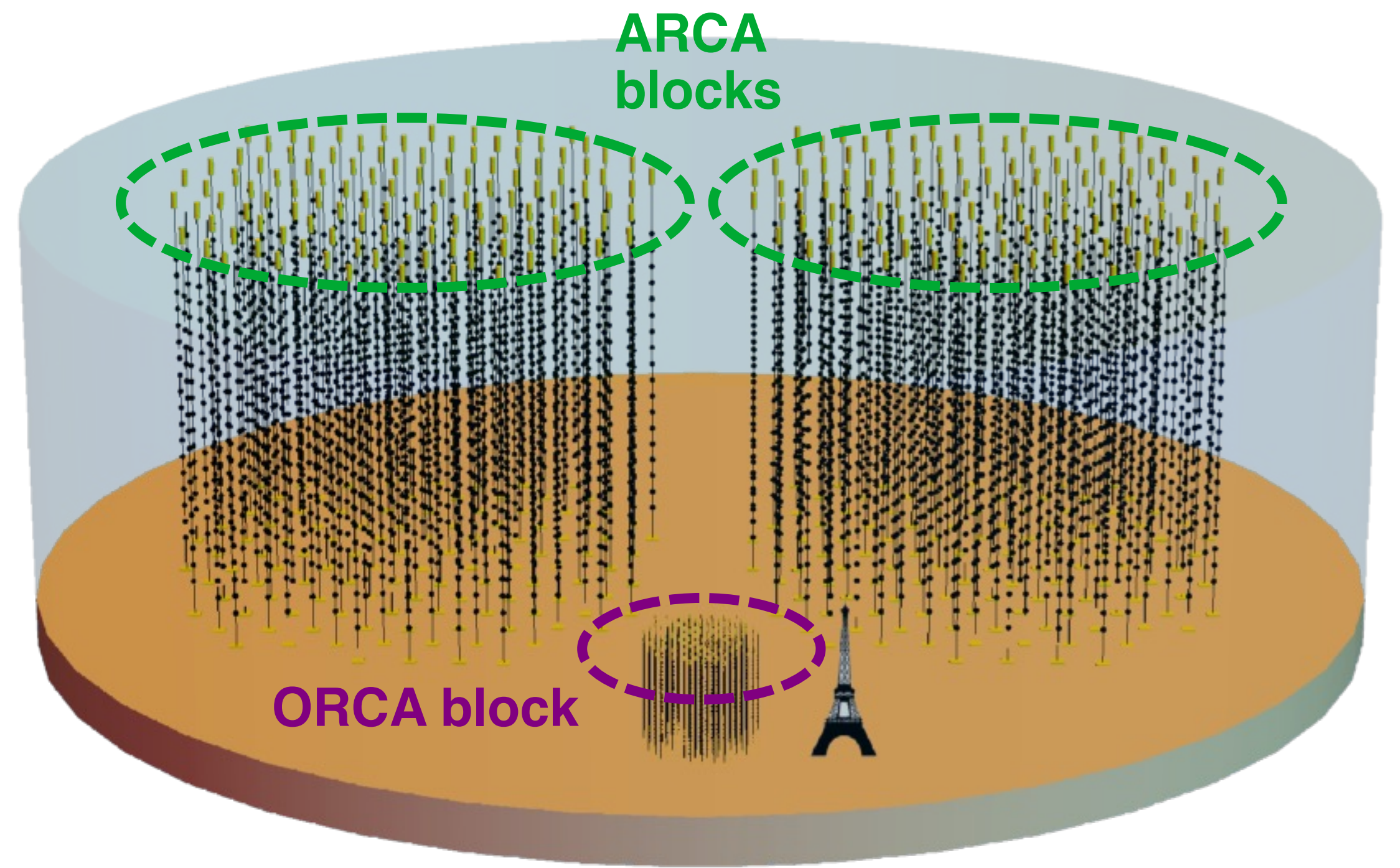


62 institutes ; 22 countries; 5 continents

Oscillation Research with Cosmics in the Abyss



Astroparticle Research with Cosmics in the Abyss



	ARCA	ORCA
Location	Italy (Sicily)	France (Toulon)
Anchor depth	3450 m	2450 m
Distance from shore	100 km	40 km
DUs	115x2 blocks	115
DU horizontal spacing	90 m	20 m
DOM vertical spacing	36 m	9 m
DOMs/DU	18	18
PMTs/DOM	31	31
Instrumented water mass	1 Gton	7 Mton
DUs deployed so far	28→33	23

Detection Unit 115 DUs per Building Block

DU Paper: [Eur. Phys. J. C 76 \(2016\) 76:54](#)

Digital Optical Module (DOM)

31x 3" **PMTs** (Physics)

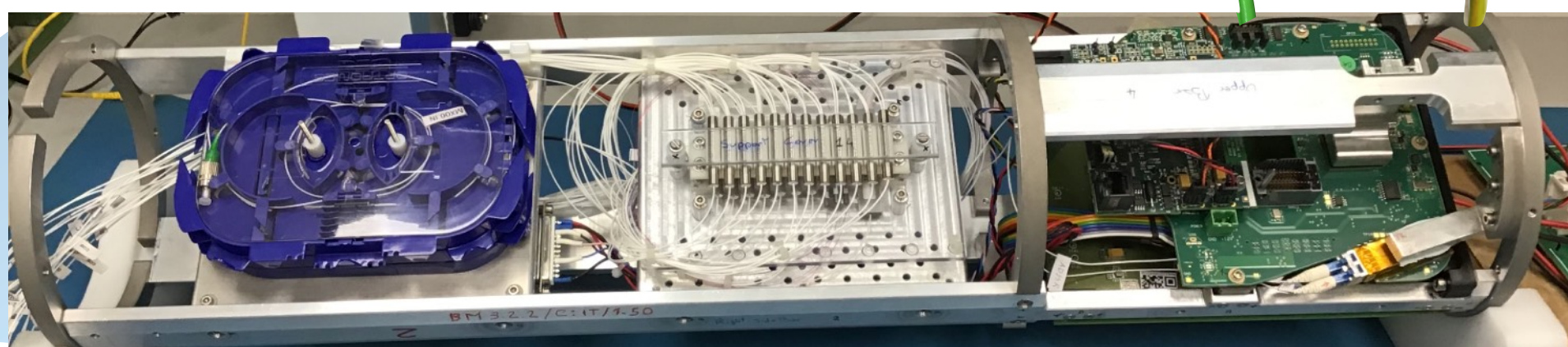
piezo acoustic sensor (positioning)
system **sensors** (monitoring)

[2022 JINST 17 P0703](#)



18 DOMs/DU

DU-Base Module (DU-BM)
- Instruments - no PMT



Hydrophone

Acoustic beacon



Intervento di Annarita Margiotta

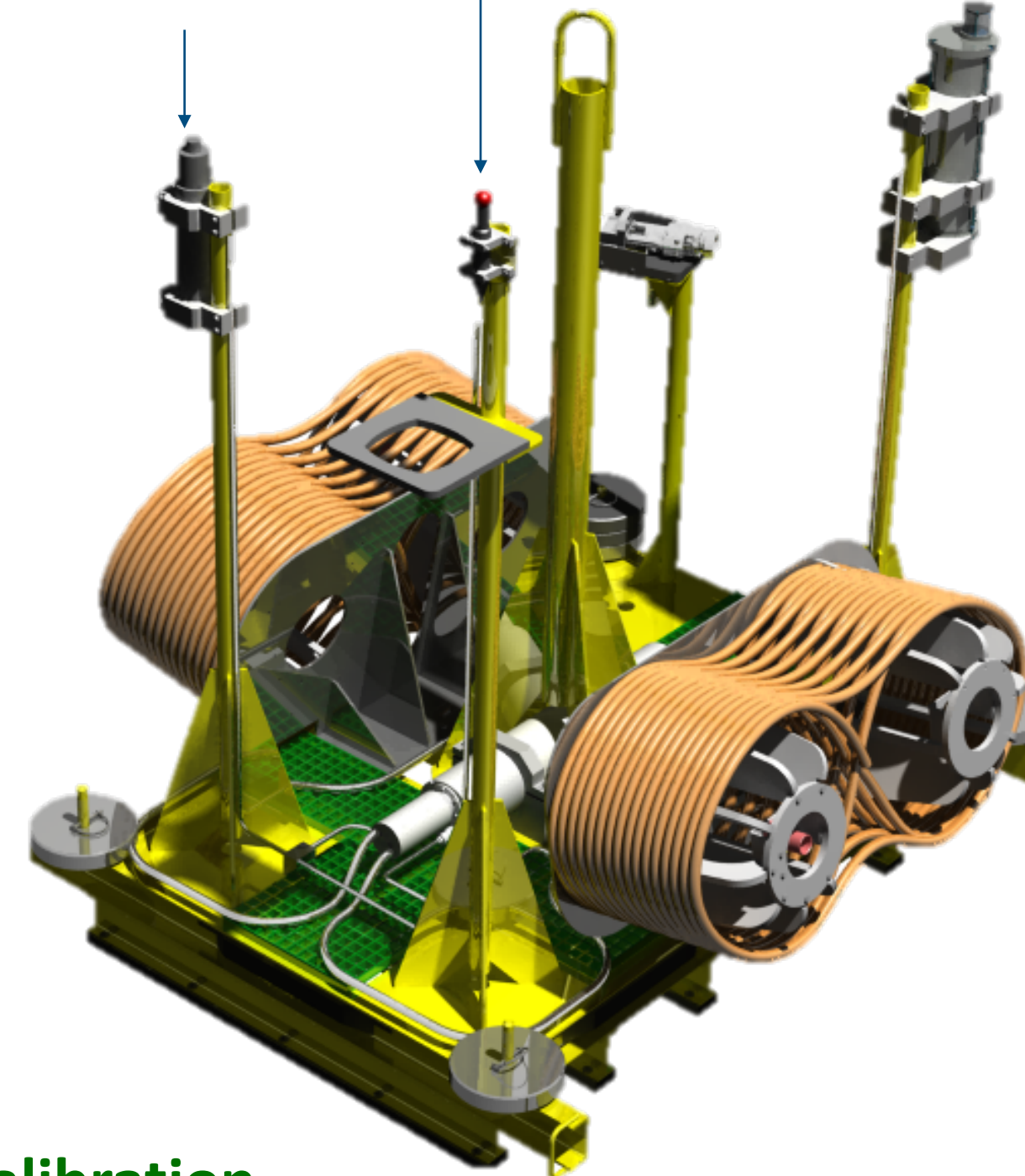
Calibration Unit

0(1) CUs per Building Block

Laser beacon

Hydrophone

Acoustic beacon



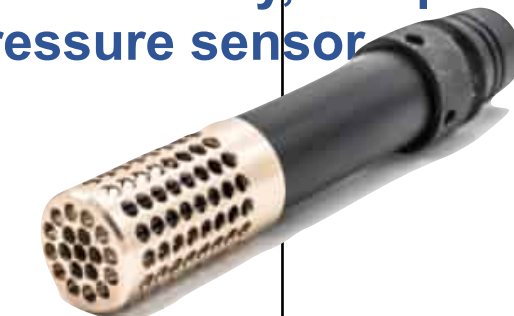
Calibration

Base Module (CU-BM)

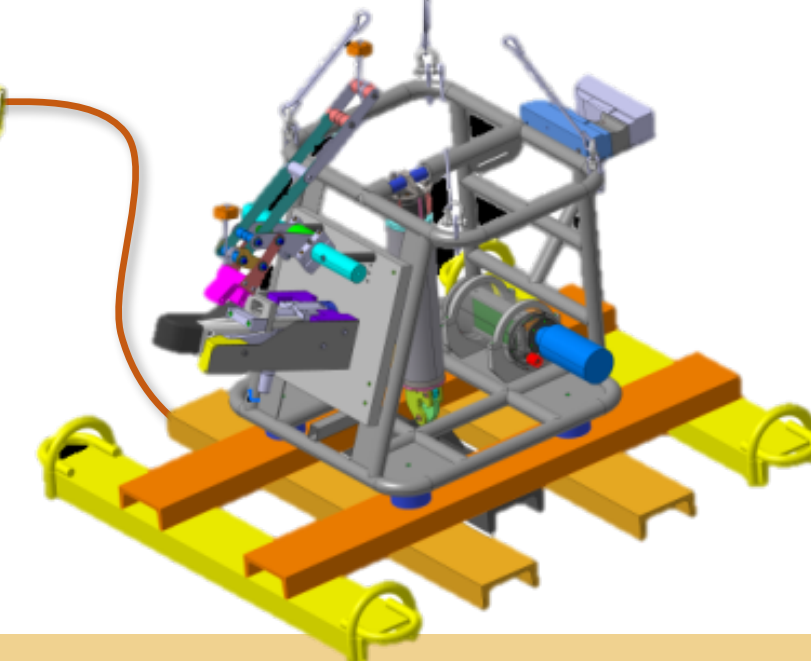
ADCP: Curent Profiler



CTD: Conductivity, Temperature
and Pressure sensor



SV: Sound Velocity

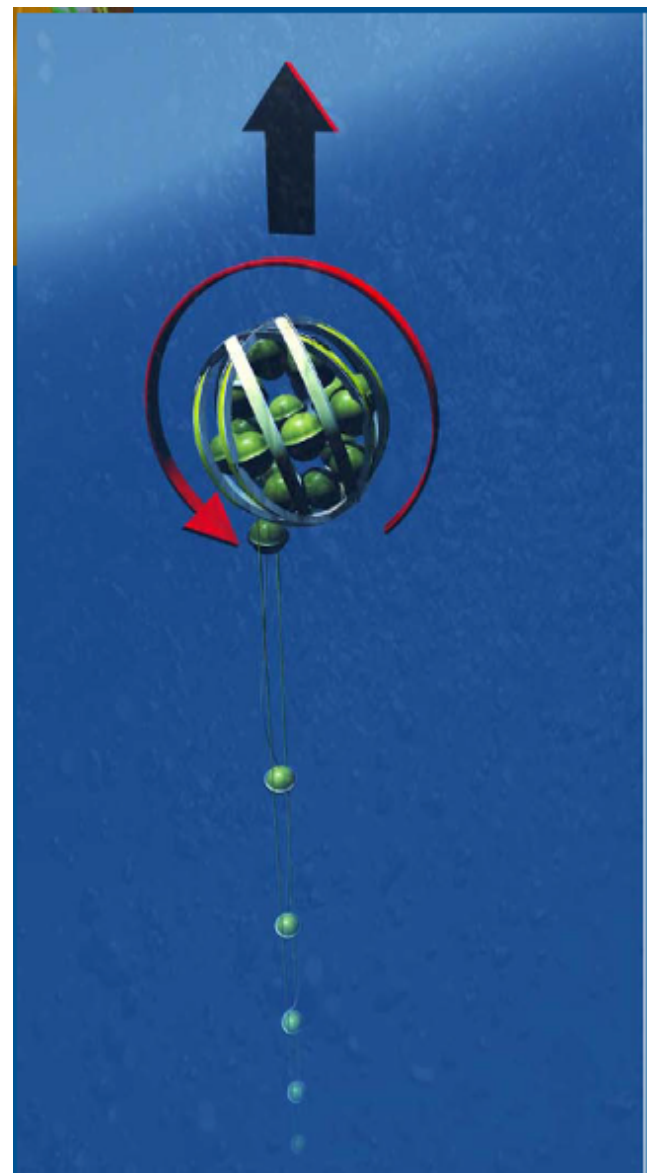


Instrumentation Line

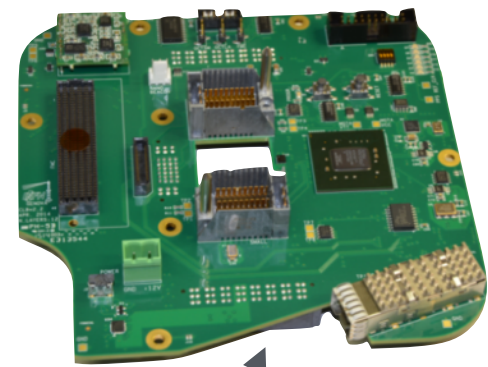
Intervento di Francesco Benfenati

Acoustic beacon





Siti di integrazione DOM: 8 BM: 4 DU: 3



The Central Logic Board (Xilinx Kintex7 FPGA based)

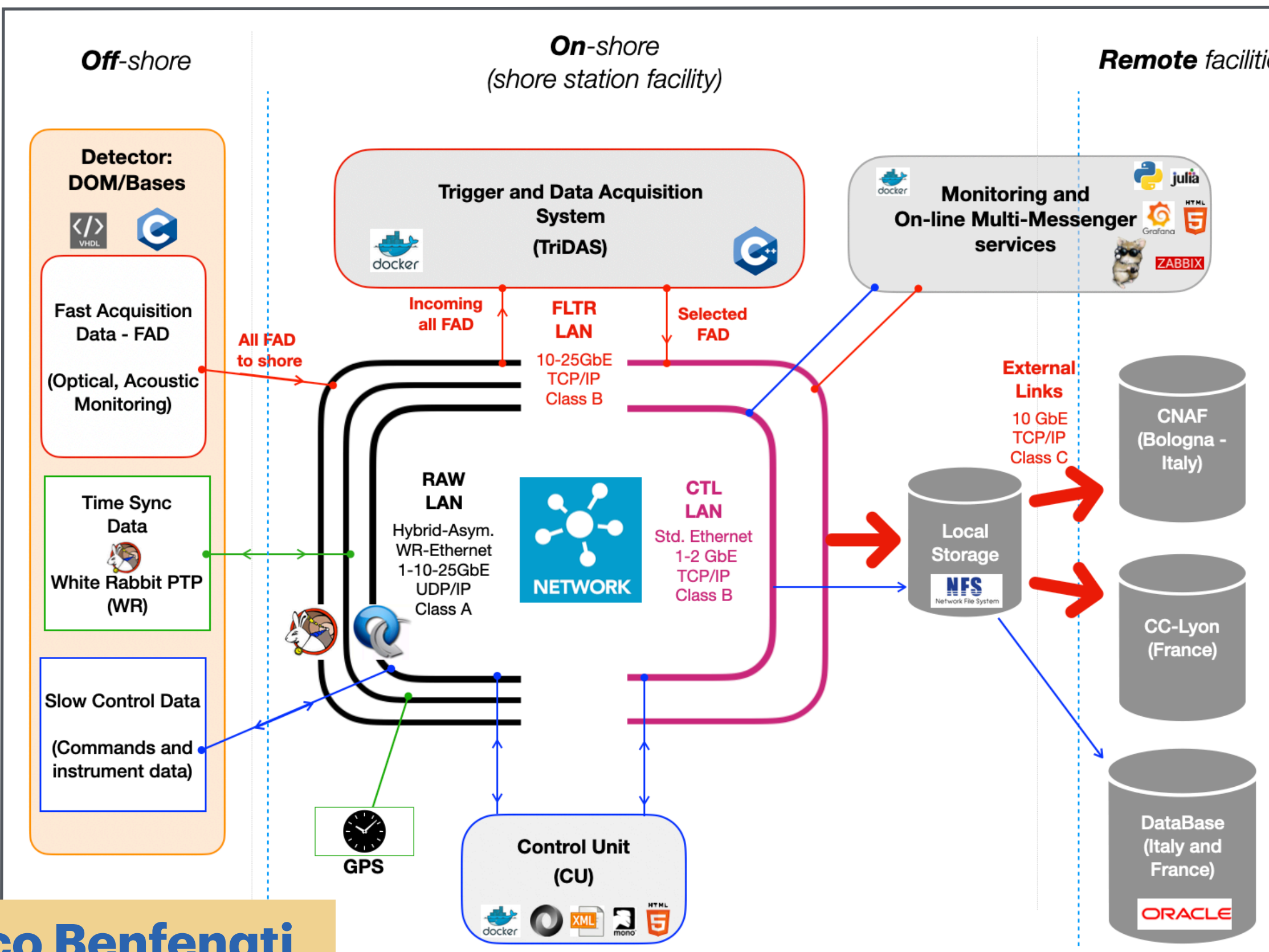
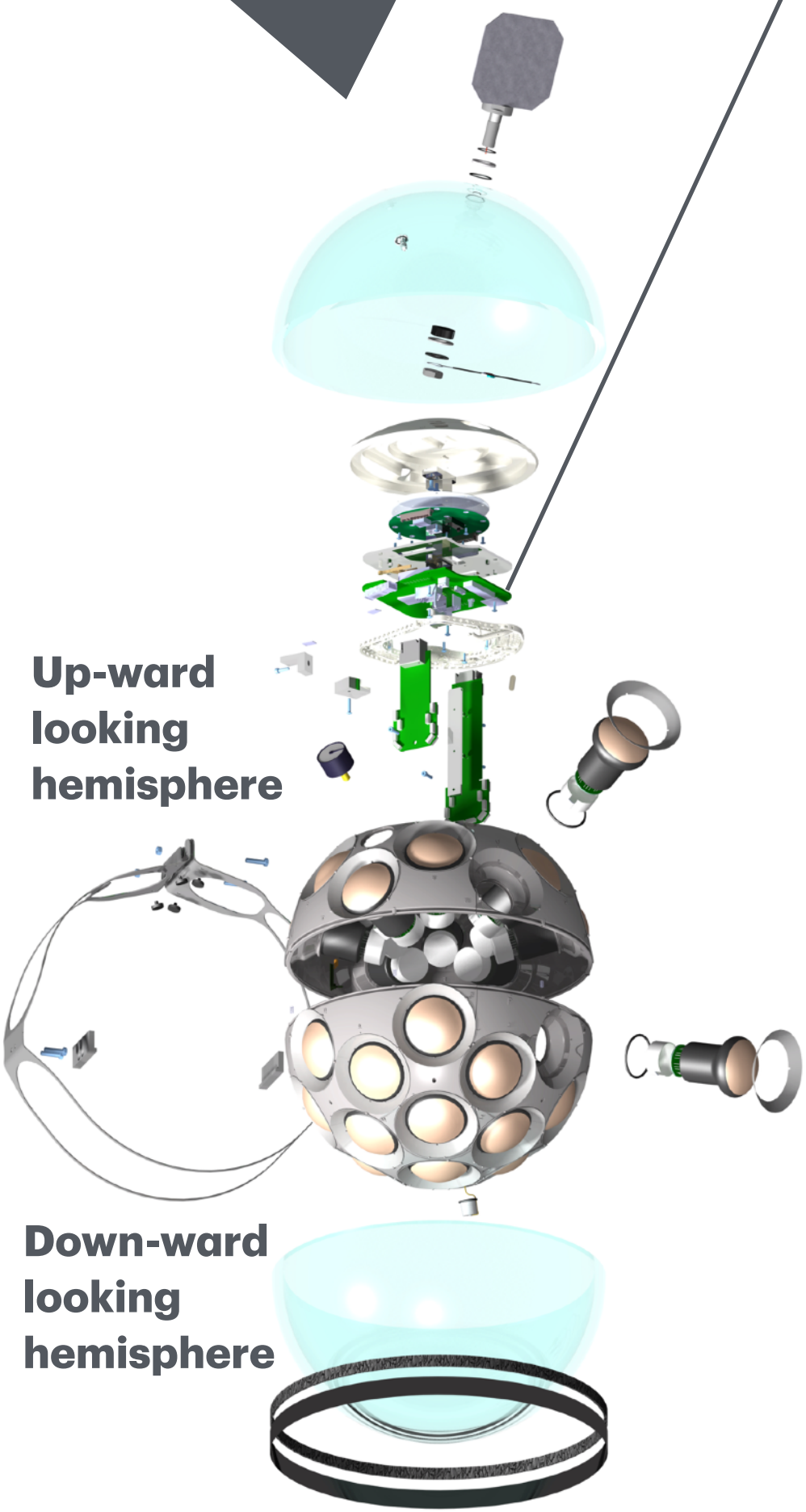
Node of a submersed 1GbE ethernet network connected to shore via optical fibers.
Timing (<1 ns accuracy, 100 ps precision) is distributed to all DOMs via the White Rabbit Technology



Relevant optical background due to ⁴⁰K and bioluminescence ↔ 3" PMT single rate (@ 0.5 p.e.)
~6 kHz ARCA / <8 kHz ORCA

Trigger-less streaming readout DAQ model (aka "all data to shore").

All complexity of data-filtering performed onshore in the computing resources in the shore station



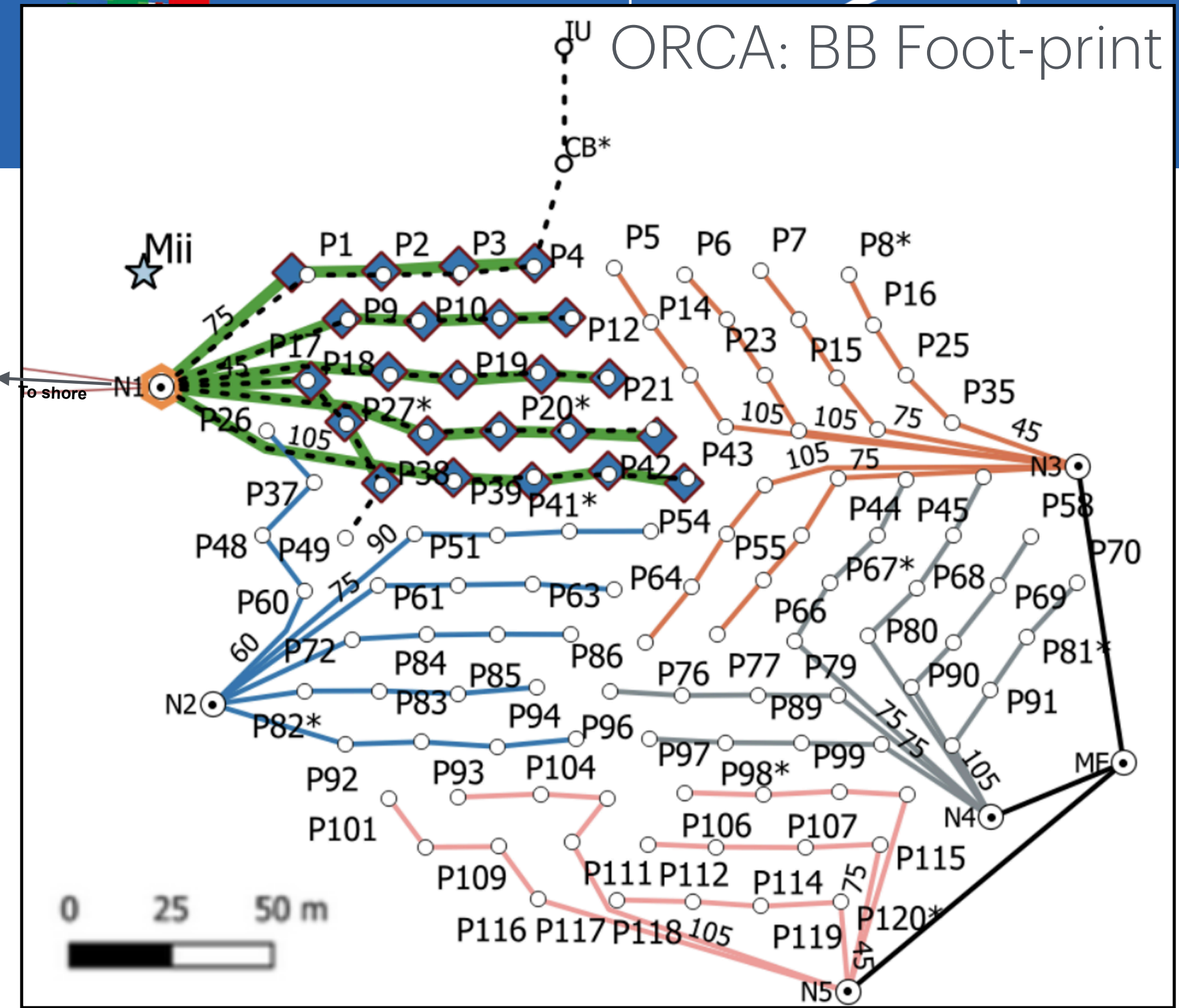
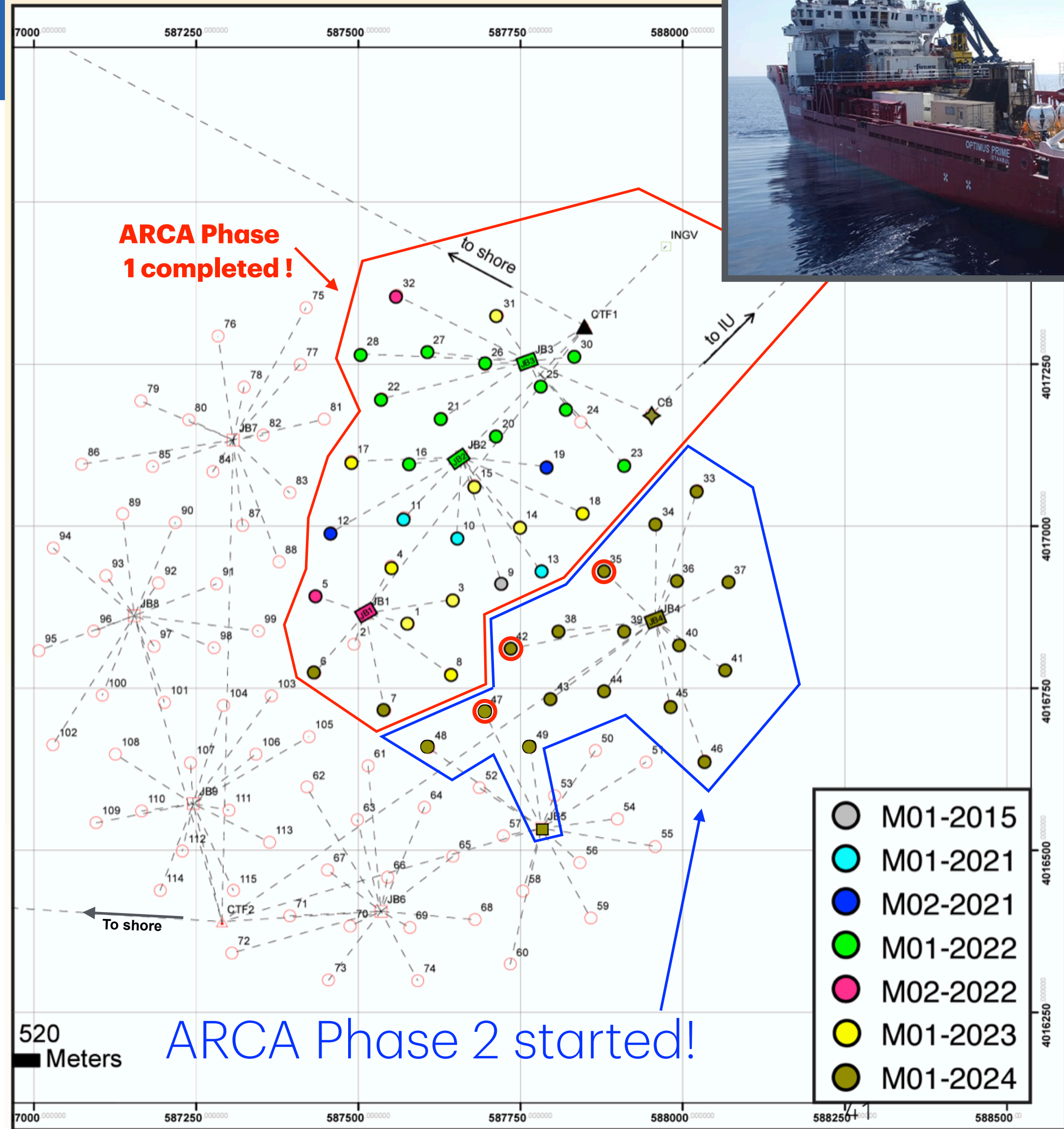
Large throughput from the detector O(100) Gbps
Large band - high performance network infrastructure on shore

Scalable on-shore computing facility (Tier-0) to allow for data taking during detector stages of installation. Data reduction by 1:10³
=> **recorded data to disk: O(1) TB/day**

10-100 GbE connectivity to remote facilities (permanent storage centres, central data-base, **Multi-messenger alert process stations**)

DAQ: [EPJ Web of Conferences 280, 08004 \(2023\)](#)
DAQ: [Comput. Phys. Commun. 256 \(2020\) 107433](#)
Electronics: [J. Astron. Telesc. Instrum. Syst. 7\(1\), 016001 \(2021\)](#)
DOM: [Eur. Phys. J. C \(2014\) 74: 3056](#)

Intervento di Francesco Benfenati

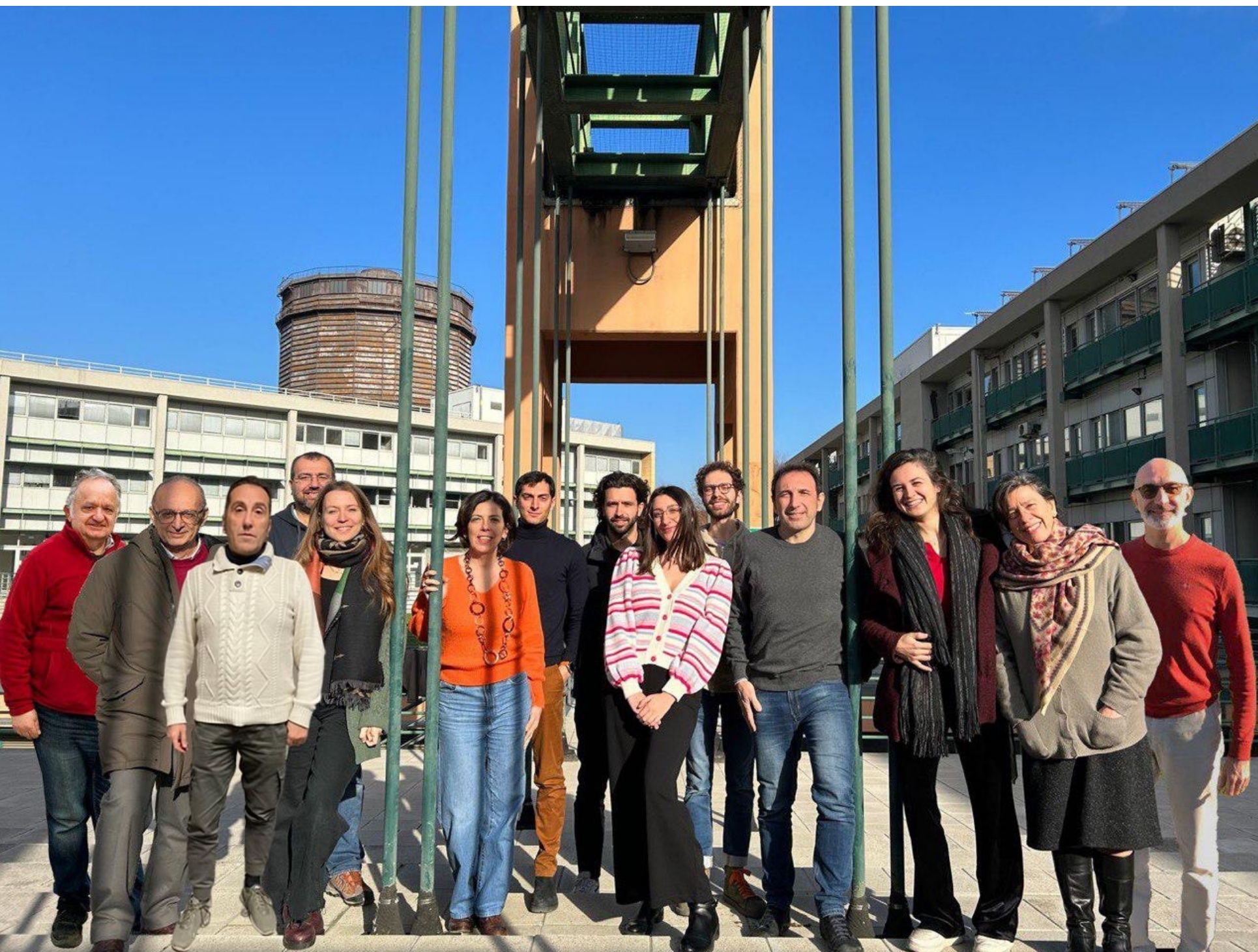
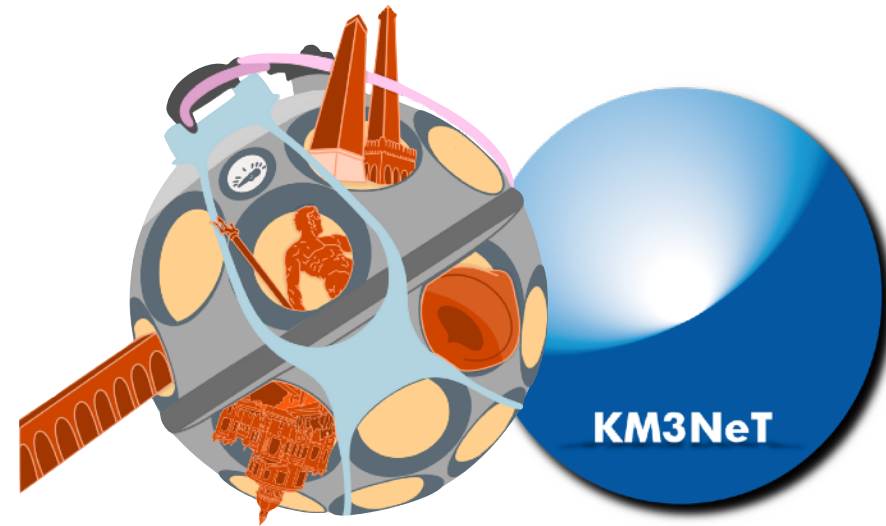


Almost completed the first node ~ 20% ORCA



M01-2024 operations ended 21/10/2024 ~0.14 km³

KM3NeT a Bologna



F. Benfenati	Tecnologo INFN TD PNRR	DAQ - Laboratorio BLU
F. Carenini	Dottorando	Analisi Dati
P. Castaldi	PA UniBO	Posizionamento acustico
T. Chiarusi	Primo ric. INFN	Coord. DAQ
F. Filippini	Post – doc INFN	RAMS (Risk Assessment Method Statement) - Analisi Dati
G. Illuminati	Ric. INFN	Coord. Astronomy & MultiMessenger
G. Levi	Ric. UniBO	KM3DIA – DAQ
A. Margiotta (Resp. Locale)	PA UniBO	Chair PC KM3NeT Resp. Integrazione Base Module
R. Muller	Post-doc INFN	Analisi Dati
M. Spurio	PO UniBO	Dep. Spokesperson ANTARES - Analisi dati
I. Del Rosso	Dottorando	Analisi Dati
<i>Tecnici di sezione INFN:</i> L. Degli Esposti, A. Paolucci, G. Pellegrini, S. Ragonesi (TD PNRR), C. Valieri		



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PIANO NAZIONALE DI RIPRESA E RESILIENZA



KM3NeT4RR

PNRR "Infrastrutture di ricerca"

Data Inizio: 01/12/2022

Durata: 30 mesi (per creare l'infrastruttura)

+10 anni per mantenerla ed utilizzarla

INFN GE
Università di Genova

INFN BO

INFN RM1
Università Sapienza

INFN BA
Politecnico di Bari

INFN NA
Università Federico II
Università della Campania

INFN gruppo collegato SA
Università di Salerno

INAF OA PA

INFN CT
LNS INFN
Università di Catania
INAF OA CT



Principal Investigator:
Giacomo Cuttone (LNS)

PARTNERS



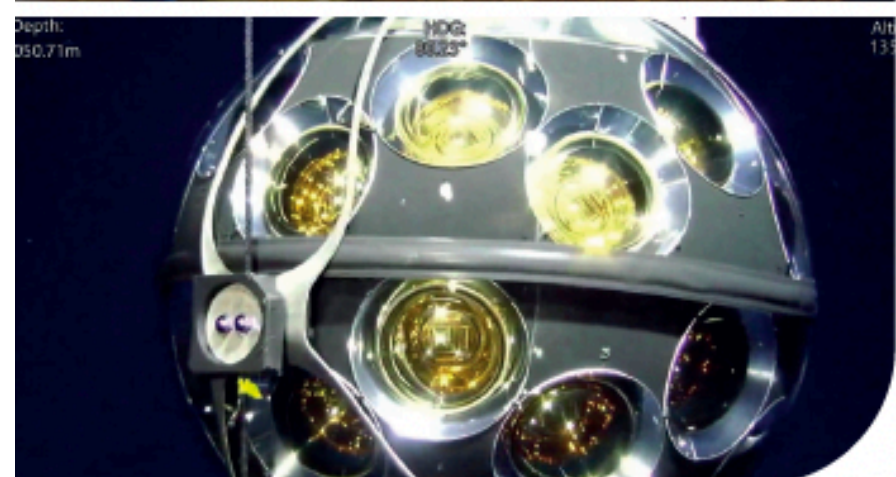
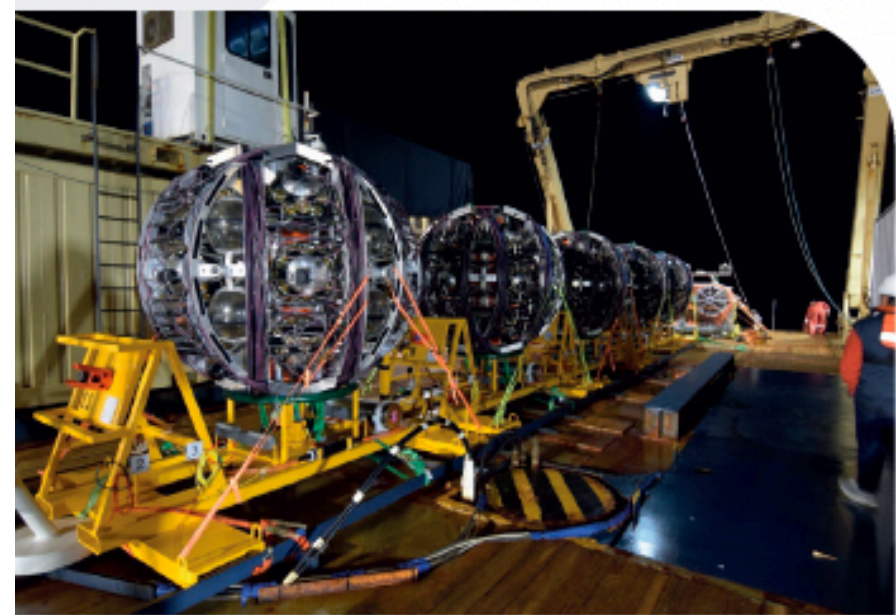
Co-Applicants

- INAF (OA-Catania and OA-Palermo)
- Politecnico Bari
- Università Campania
- Università Catania (DFA - DEI)
- Università Genova
- Università Sapienza Roma
- Università Salerno
- Università Federico II Napoli

Progetto reso possibile perché KM3NeT è:

- ESFRI RI
- PNIR RI
- Strategica RI per la Regione Sicilia

Budget Progetto ~67M€



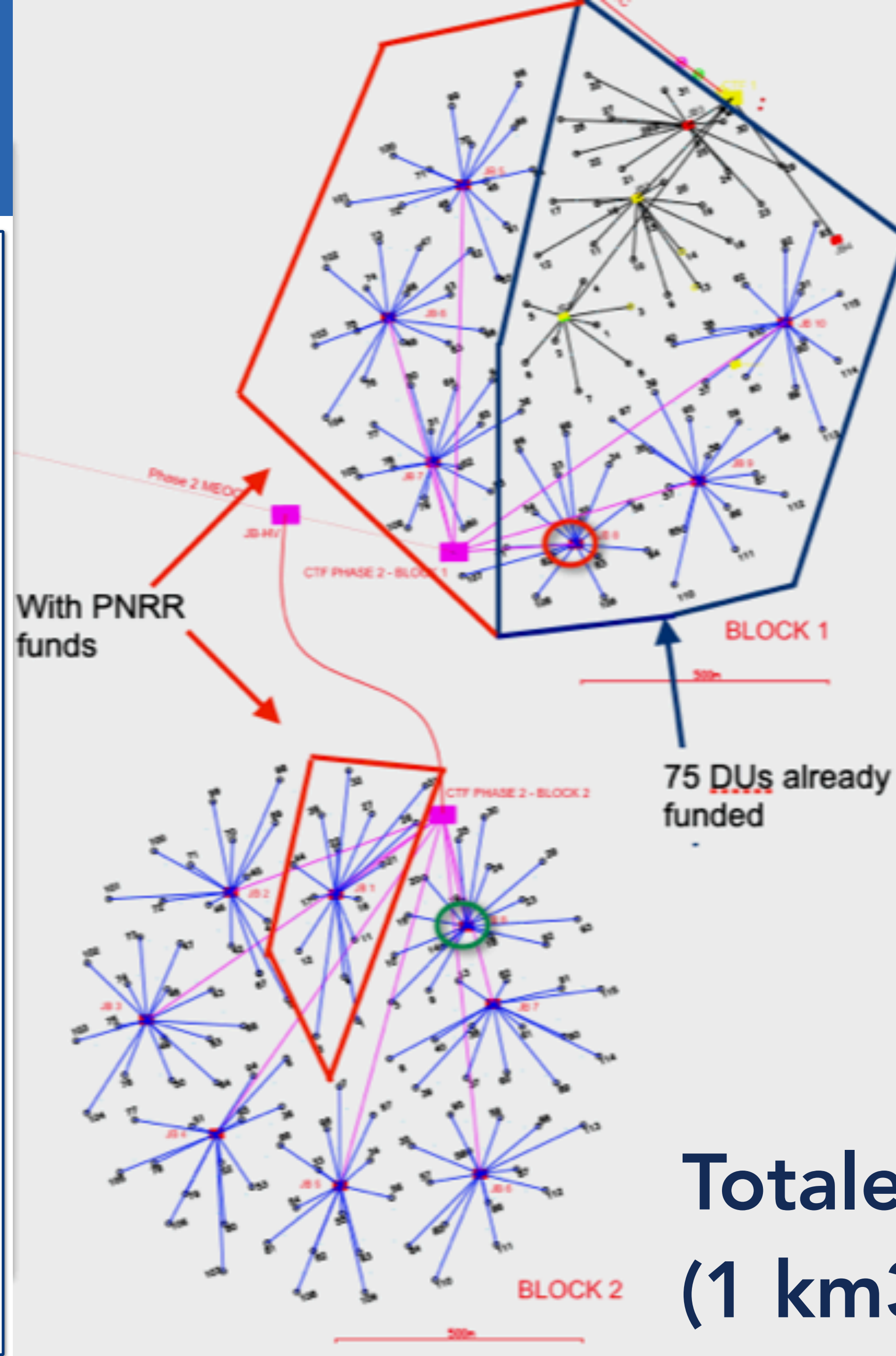
KM3NeT4RR → Potenziamento ARCA

KM3NeT4RR Budget: **67.2 M€** :

- 55 DUs
- Infrastruttura sottomarina (5 JBs + 1CTF + cavi Inter-Link)
- Potenziamento di Laboratori INFN KM3NeT
- Human resources

Quindi:
completamento di ARCA Building Block #1
+ 15 DUs del secondo ARCA Building Block

Un altro progetto PNRR (ITINERIS) → +1JB



~ 63% km³

+

~ 7% km³

Totale = 70% km³
(1 km³ = IceCube)

WP2 (On-shore Infrastructure)

WP6 (Off-shore Detector)

Operating Unit: **INFN-BO**
Contact person: **Tommaso Chiarusi**

Investimento a Bologna ~ 0.8 M€

BB-LAB

Bologna Common Infrastructure (BCI)

DAQ, sincronizzazione temporale, networking, computing, sviluppo tecnologia per acquisizione, sviluppo e test di schede elettroniche

Resp: Tommaso Chiarusi - Francesco Benfenati Gualandi

Bologna Laboratory for User-ports (BLU)

Controllo, sincronizzazione e lettura di apparecchiature per il monitoraggio ambientale ed ancillari, integrazione con DAQ

Resp: Francesco Benfenati Gualandi

Bologna Integration Laboratory Basemodule Objects (BILBO)

Integrazione dei moduli di base delle DU

Resp: Annarita Margiotta

Laboratorio	Obiettivi	Costo totale (k€) - IVA Inclusa
BCI+BLU	2.12	432.4900
LBM	2.3	100.0400
	<i>Totale Laboratori</i>	532.5300
HR		218.288
	<i>Grand Total</i>	750.818

+ costi indiretti (=> estensione contratti)

13 Procedure (+2 annullate):

- 11 Procedure su MEPA (Trattative Dirette)
- 1 Convenzione Consip
- 1 Convenzione RS/INFN

Brainstorming per i capitolati tecnici: Dic.'22/Feb'23

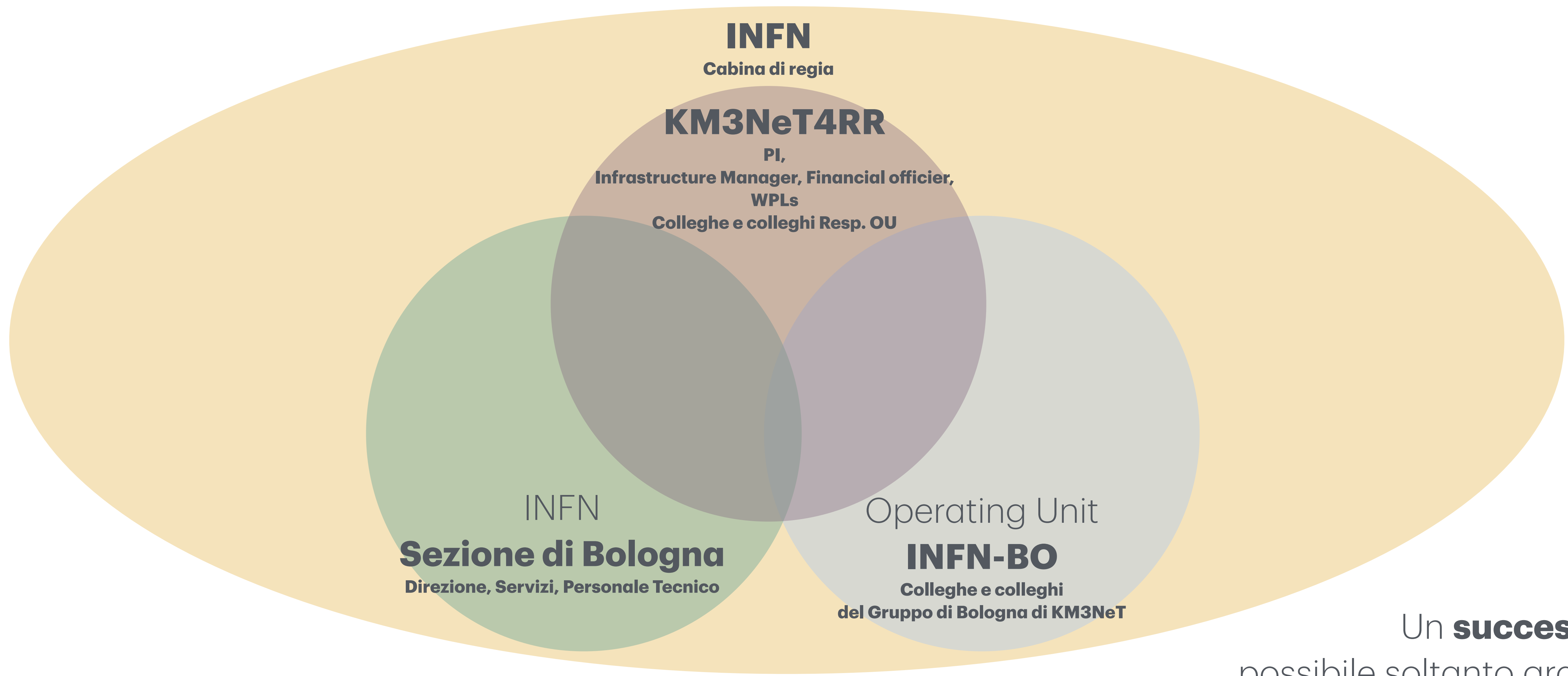
Inizio interpretazione corretta normativa : Marzo 2023

Prima Stipula: maggio 2023

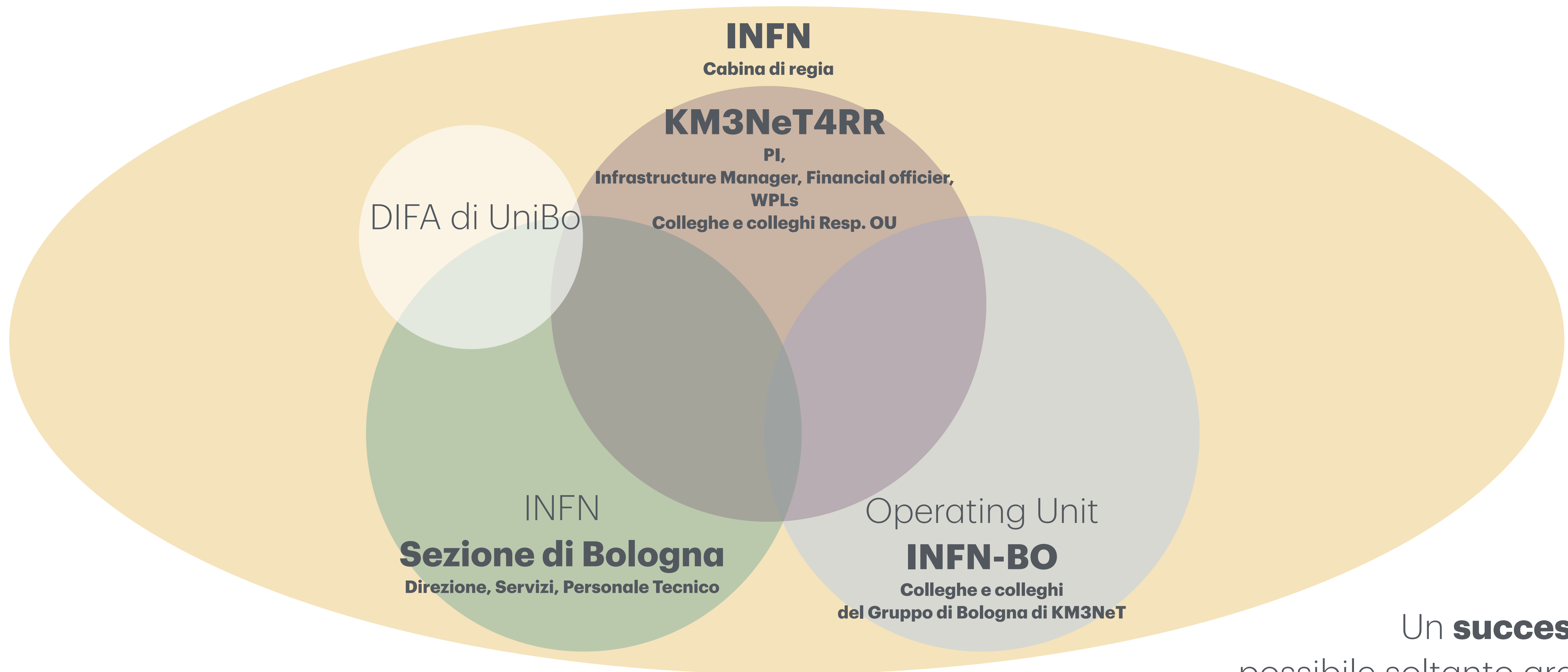
Ultima Stipula: novembre 2023

... 12 mesi intensi ... (ma ovviamente non è tutto...)

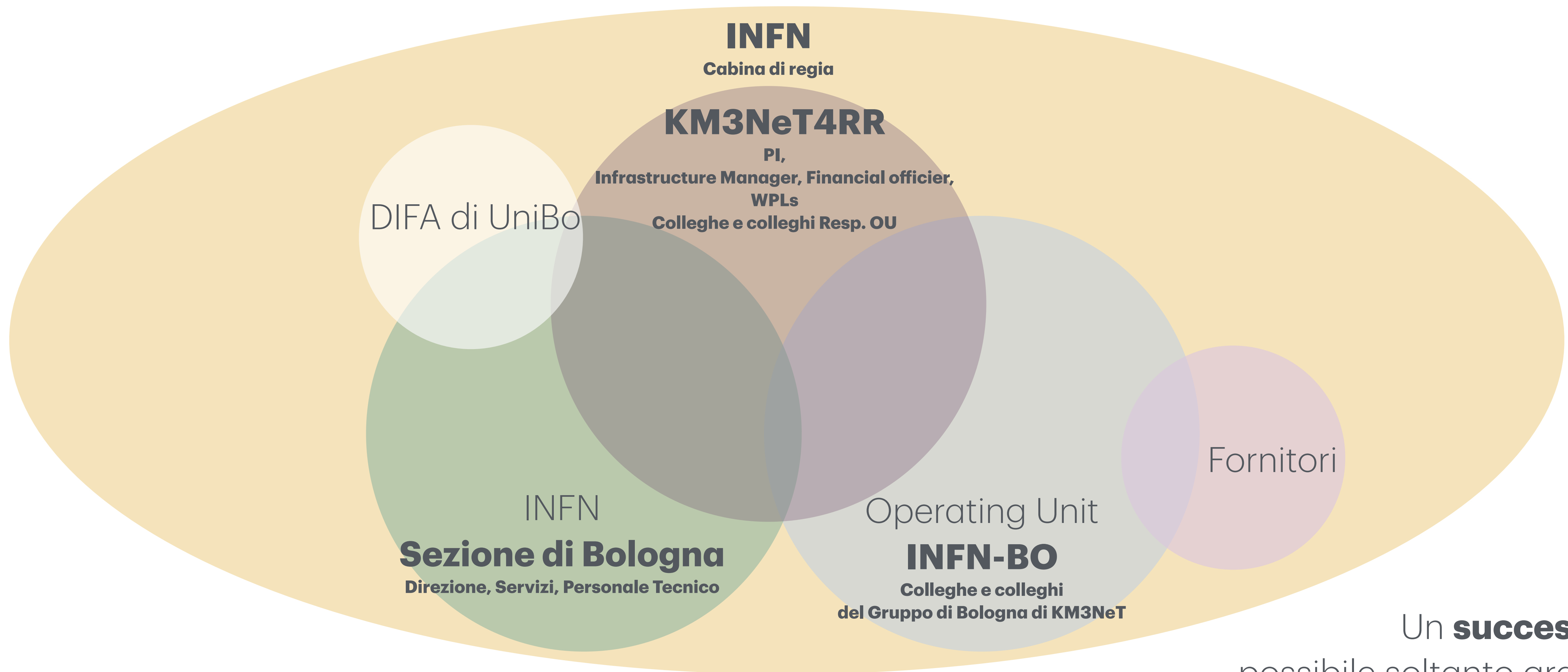
#	Lotto	Totale Lotto (k€) - IVA Inclusa
1	Schede CLB/PB	59.2
2	Schede di potenza	28.8
3	Schede Custom	46.4
4	Infrastruttura White Rabbit	46.7
5	Infrastruttura di rete	13.7
6	Calcolo con GPU	46.3
7	Infrastruttura di calcolo	9.6
8	Oscilloscopi	60.0
9	Attrezzature Elettriche	65.7
10	Attrezzature Ottiche	27.1
11	Monitoraggio Ambientale Sottomarino	40.9
12	Consumo-Laboratorio	7.9
13	Impianti tecnologici dei laboratori	80.2



Un **successo**,
possibile soltanto grazie
ad una collaborazione... globale!



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ad una collaborazione... globale!



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ad una collaborazione... globale!



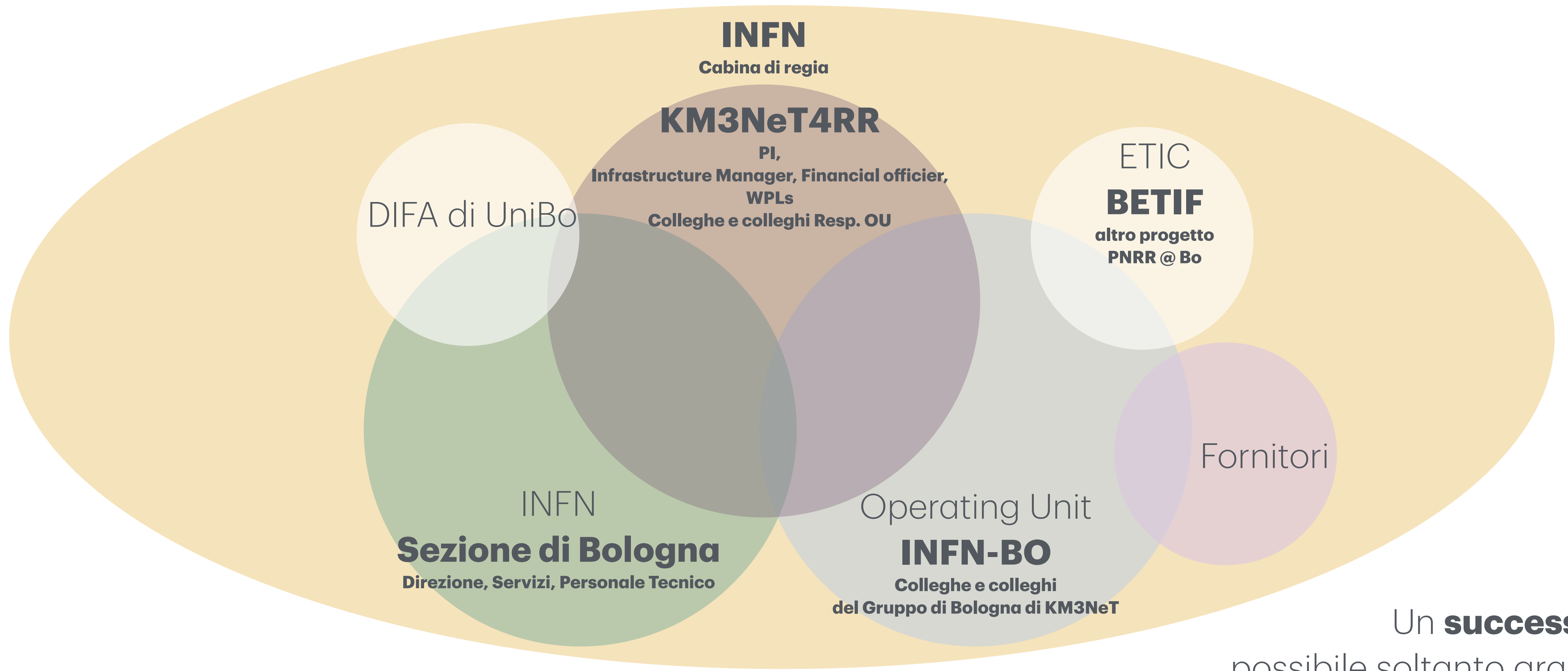
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DI RIPRESA E RESILIENZA



Un **successo**,
possibile soltanto grazie
ad una collaborazione... globale!



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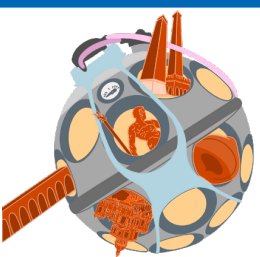
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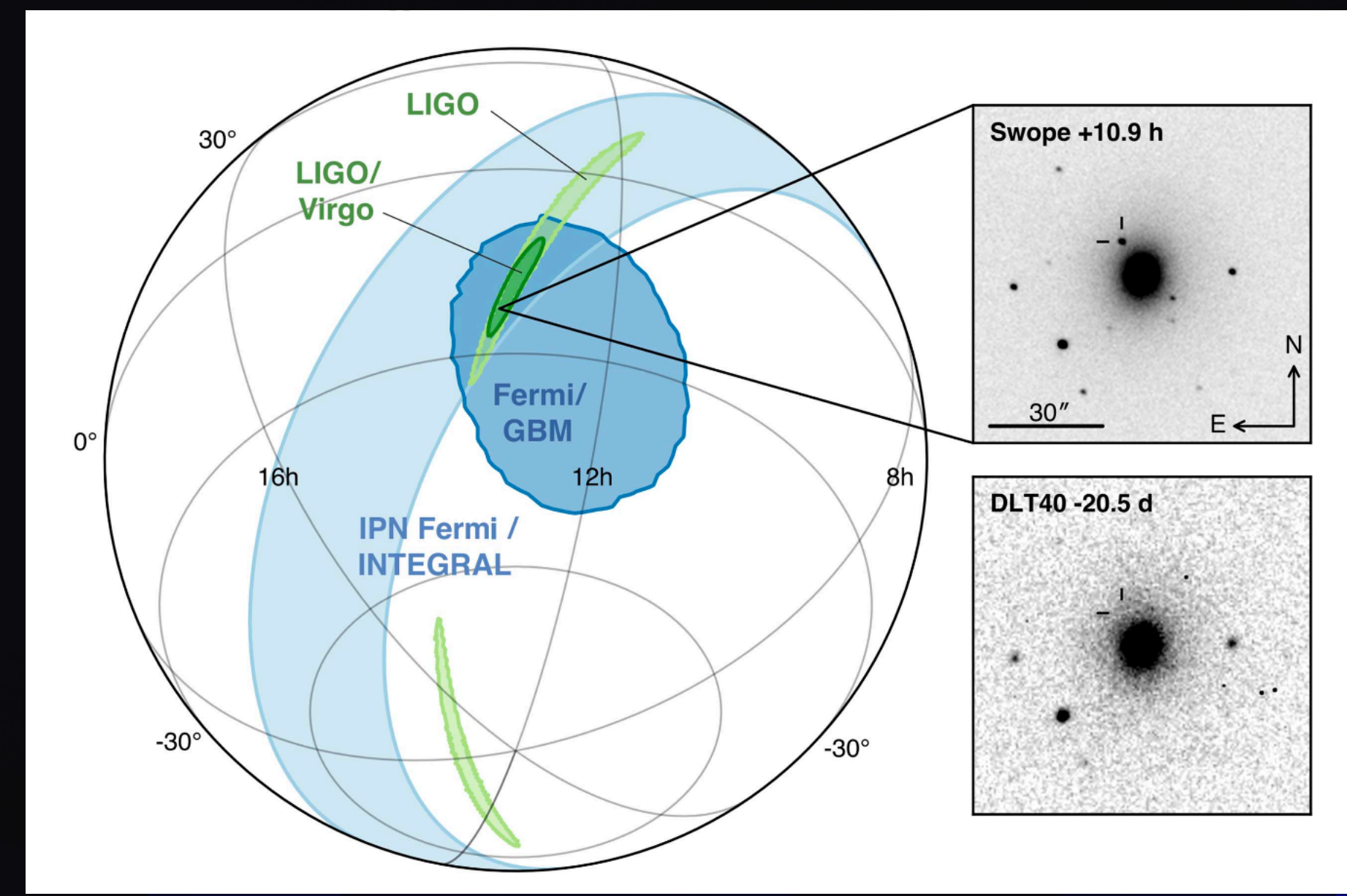
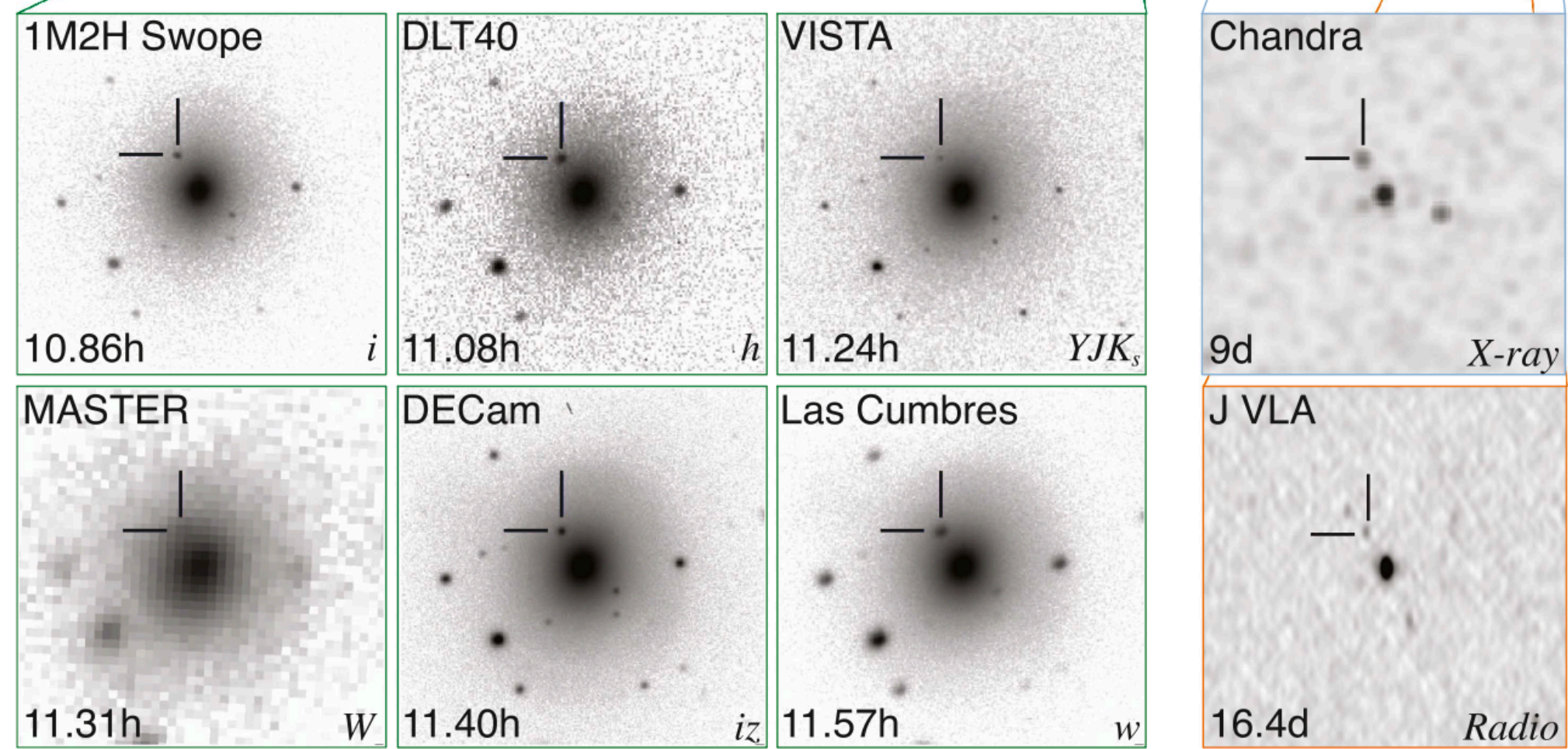
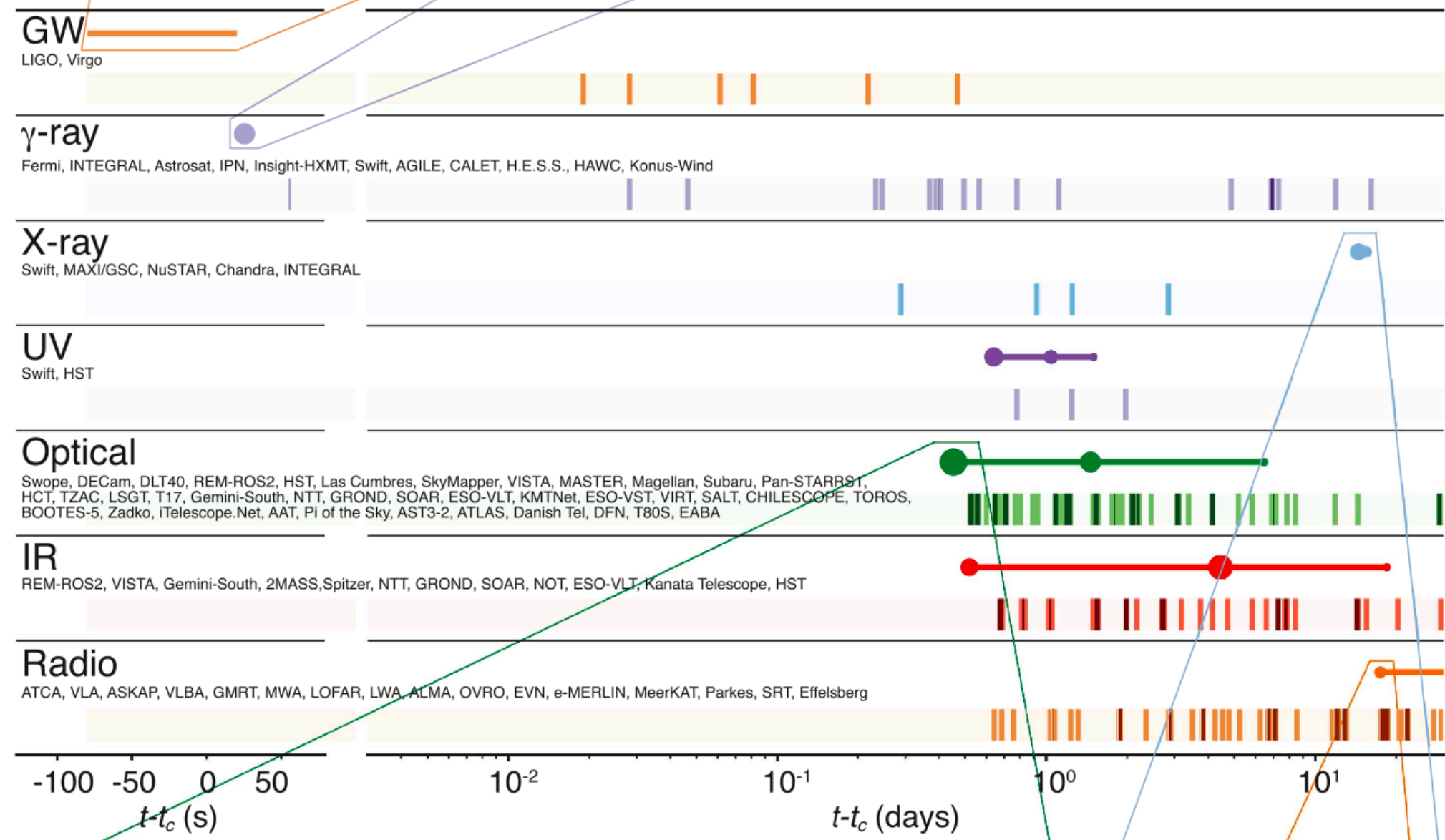
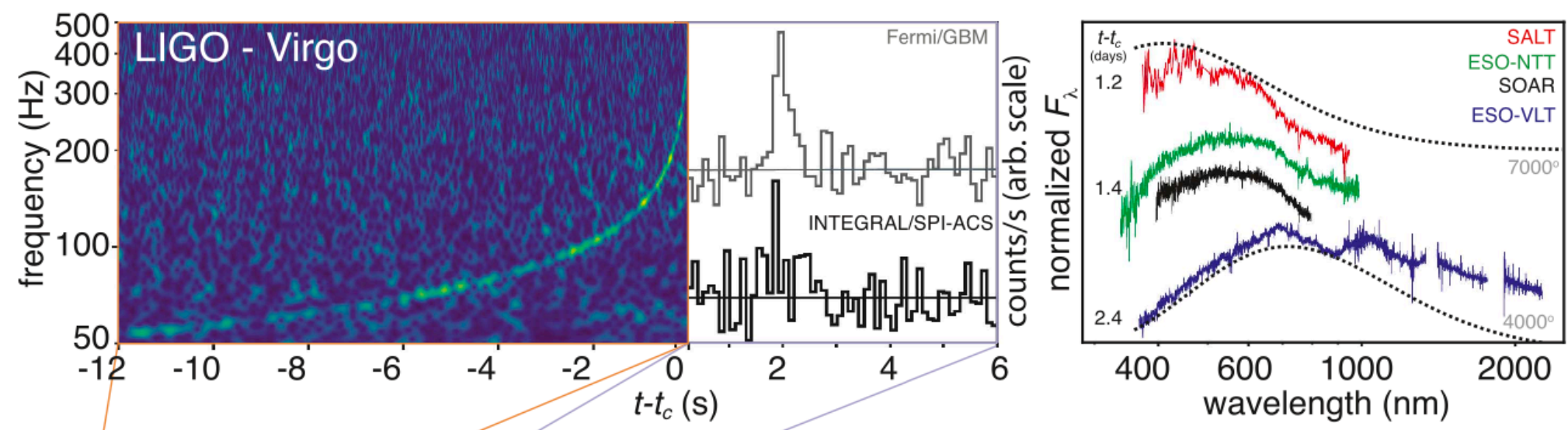


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SPARE





Birth of Multi-Messenger astronomy!

2017, **LIGO + VIRGO** (+ 62 other Collaborations - including **ANTARES** and **ICECUBE**): GW170817 - (*Astrophys.J.Lett.* 848 (2017) 2, L12)

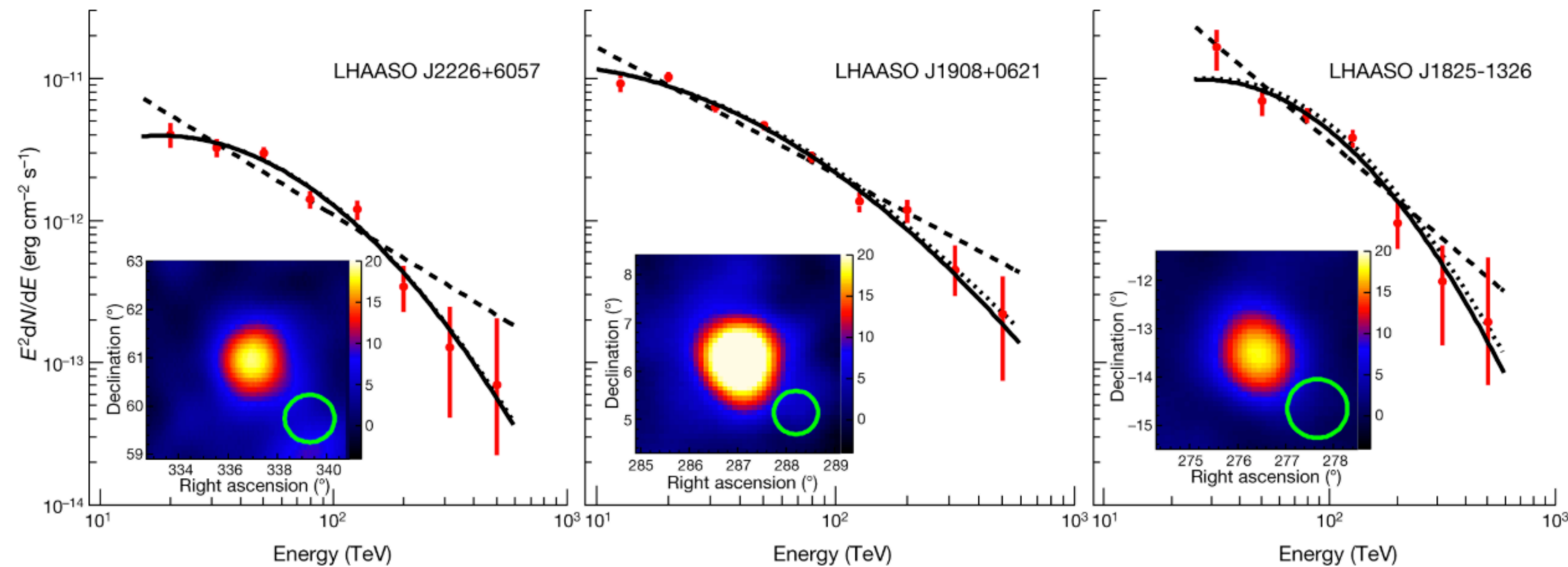
NOT ANY NEUTRINO DETECTED BY "under ice/water" TELESCOPES



Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ -ray Galactic sources

Fig. 1: Spectral energy distributions and significance maps.

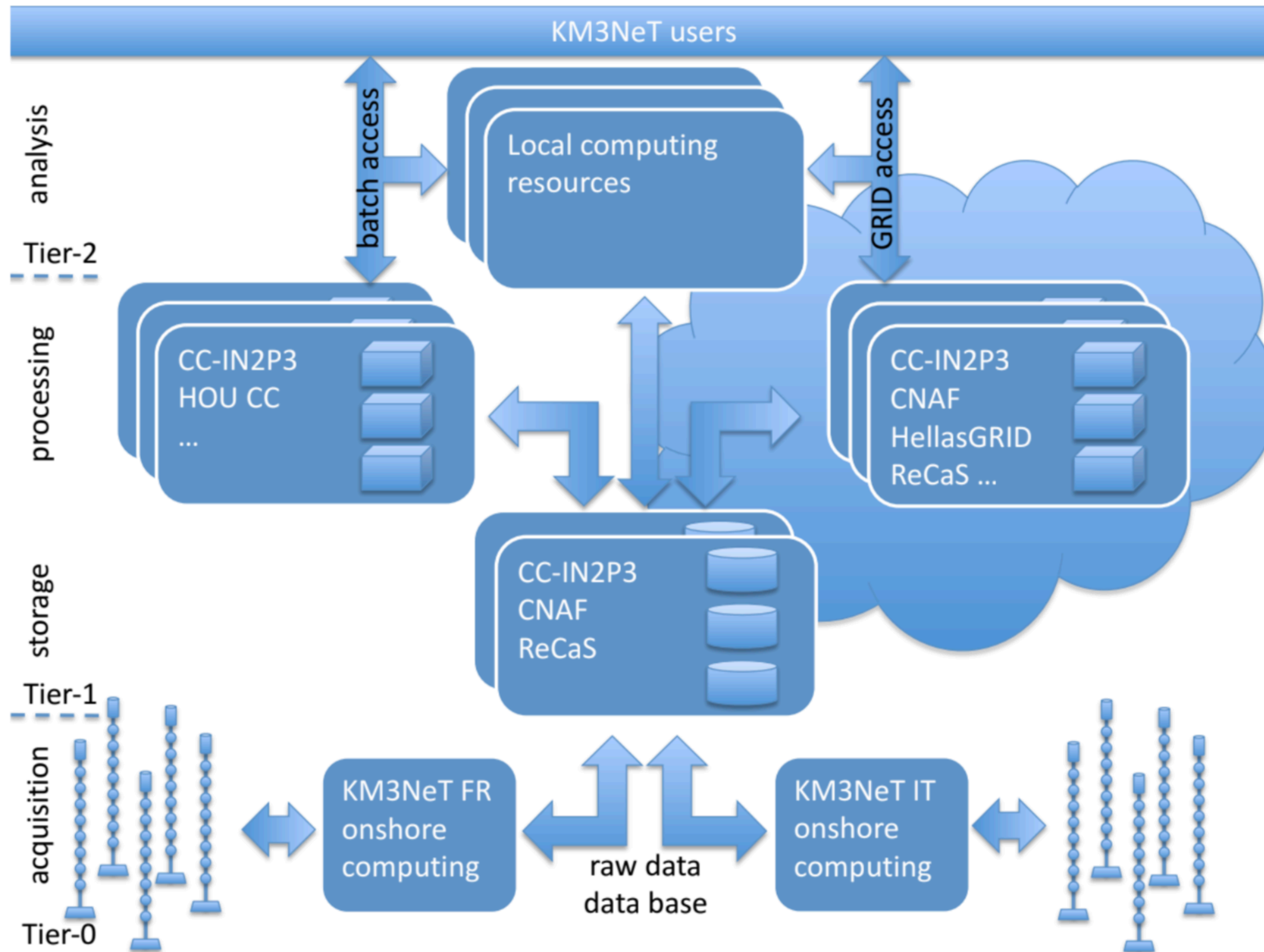
From: [Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 \$\gamma\$ -ray Galactic sources](#)

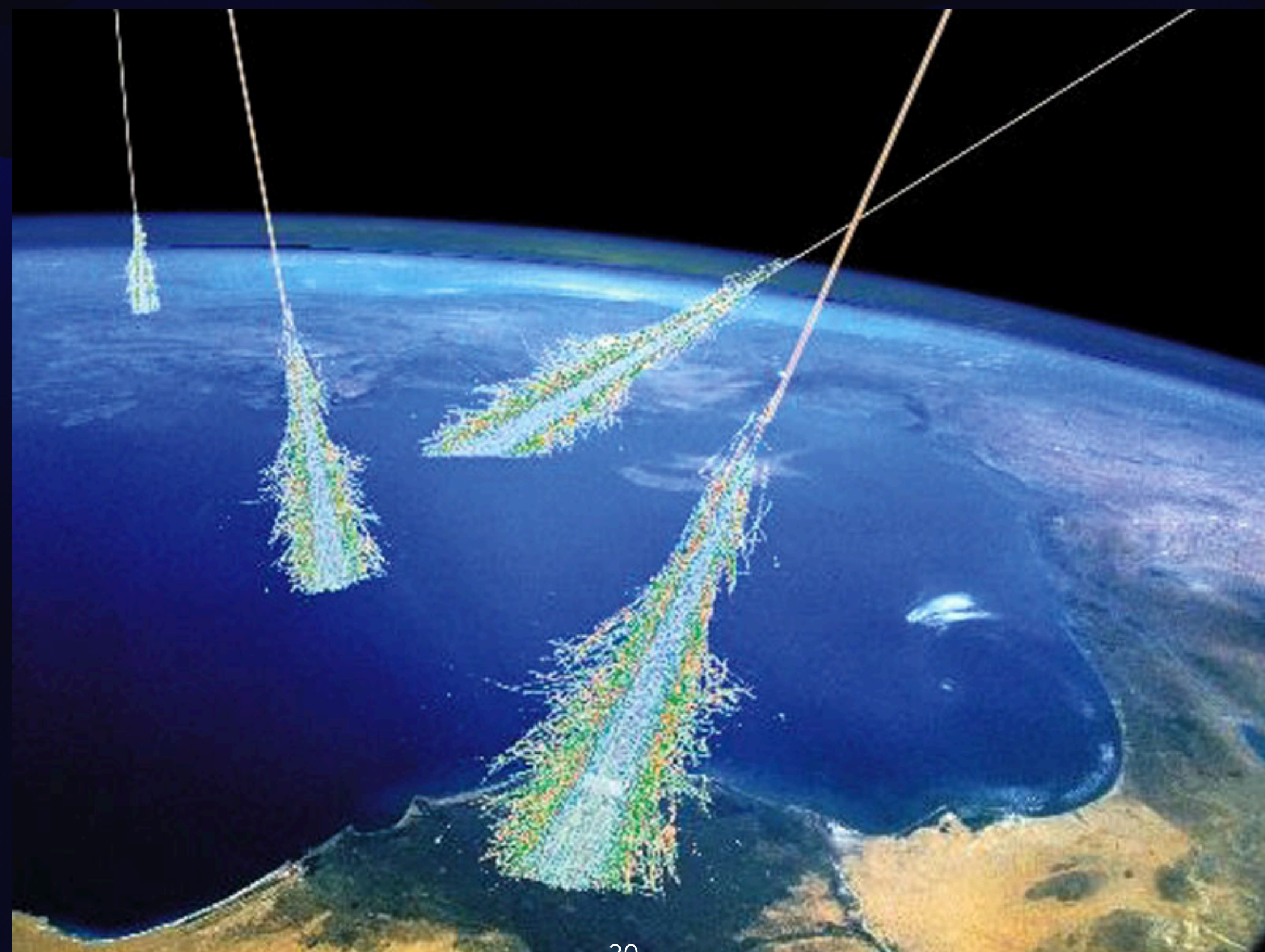
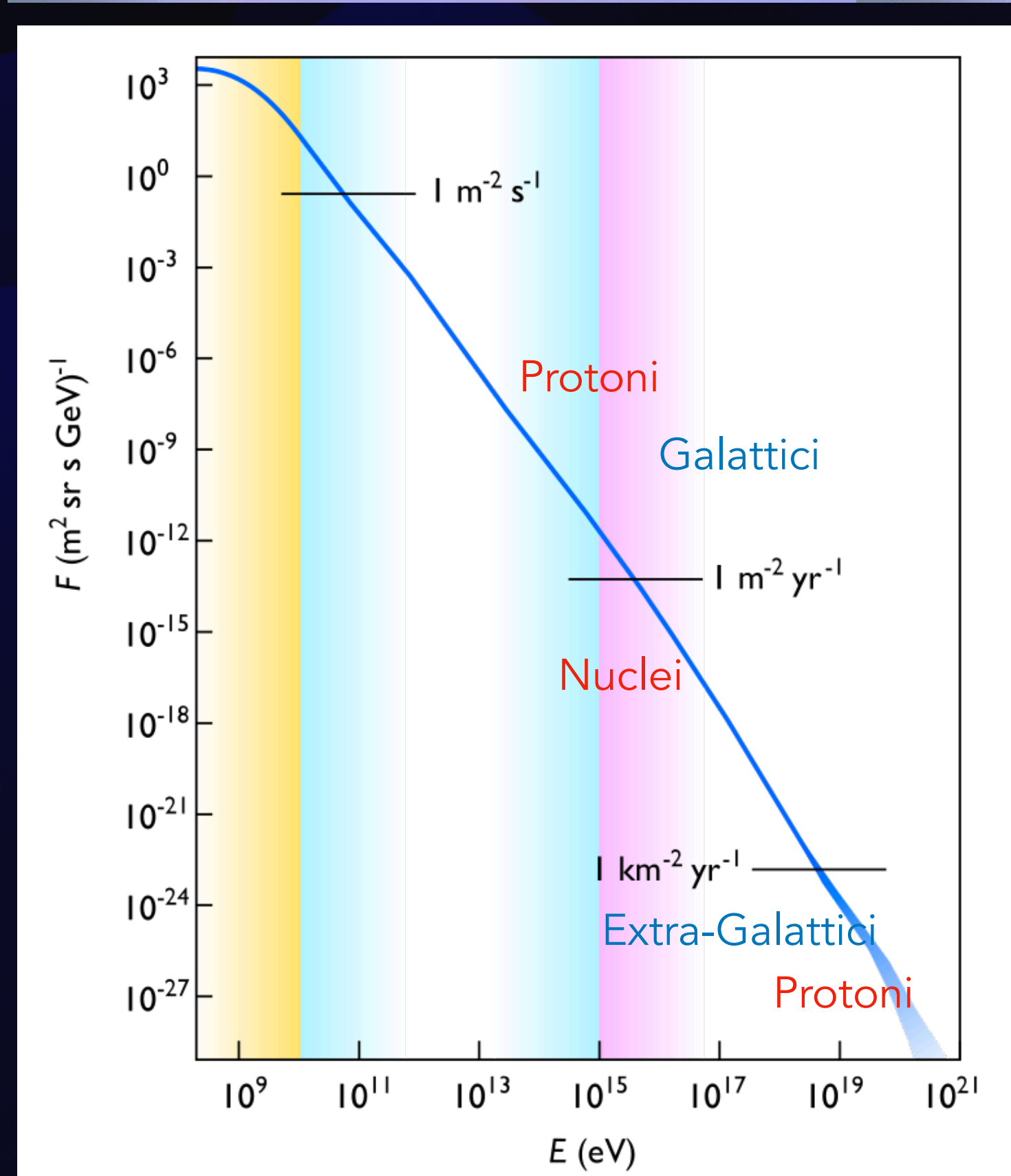
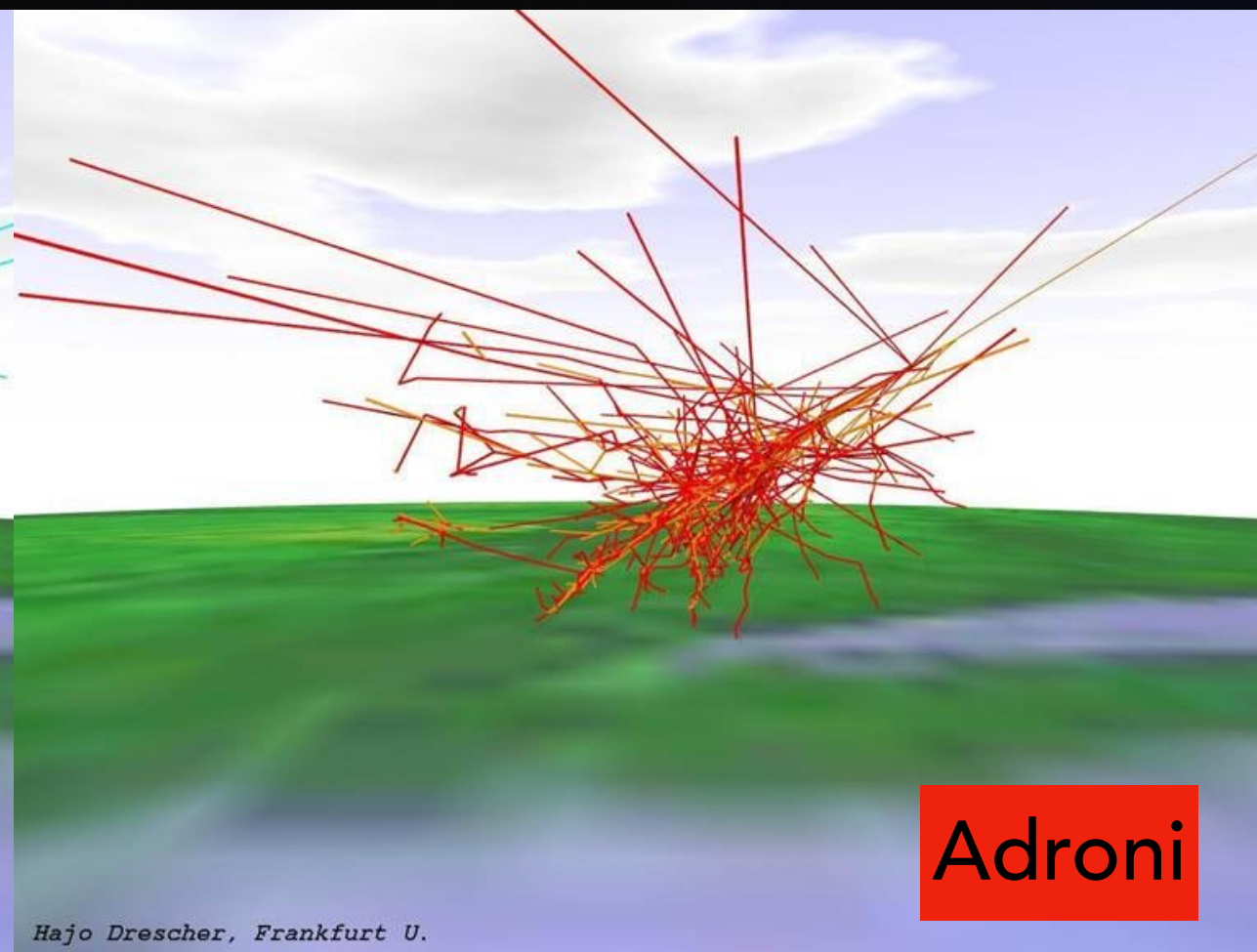
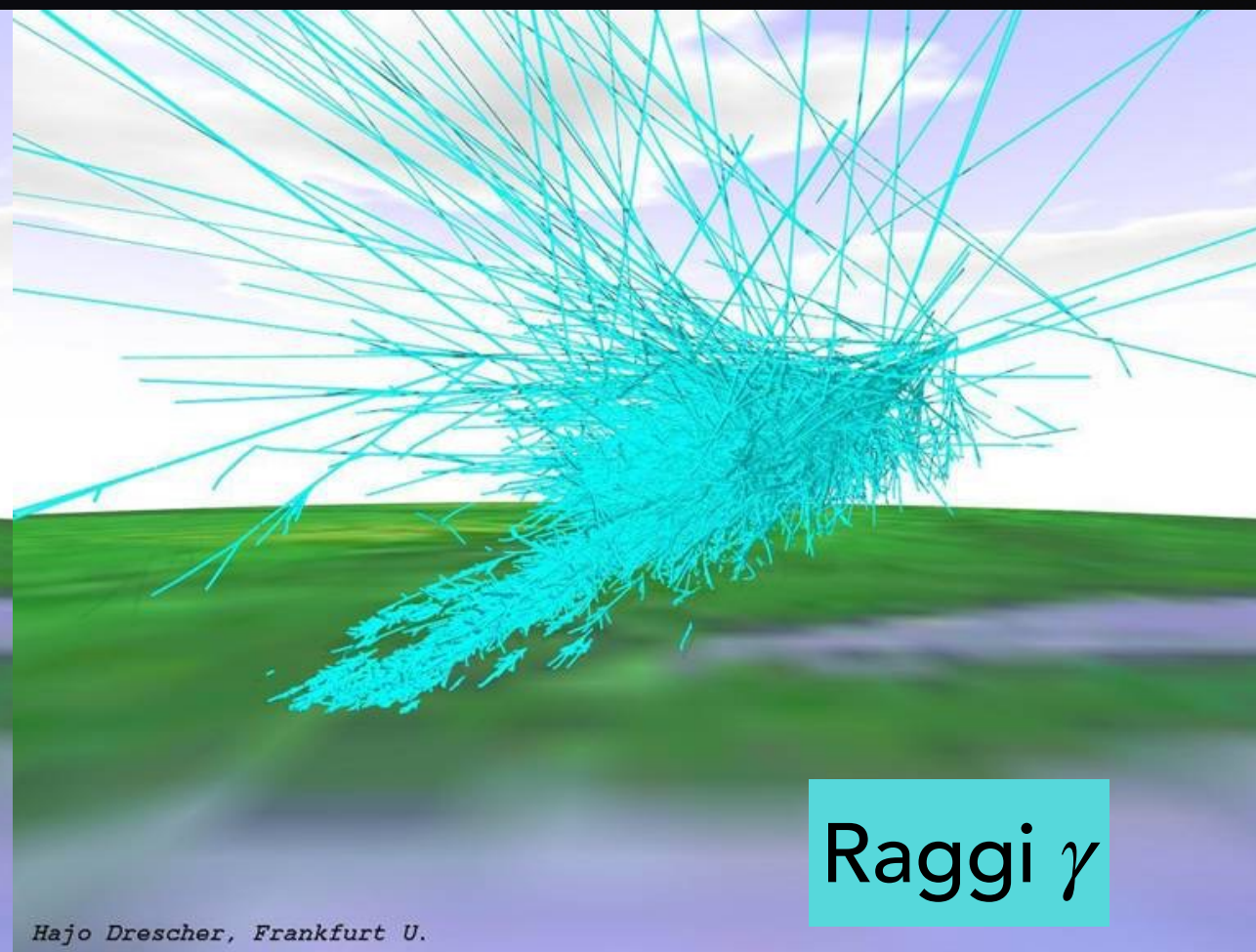
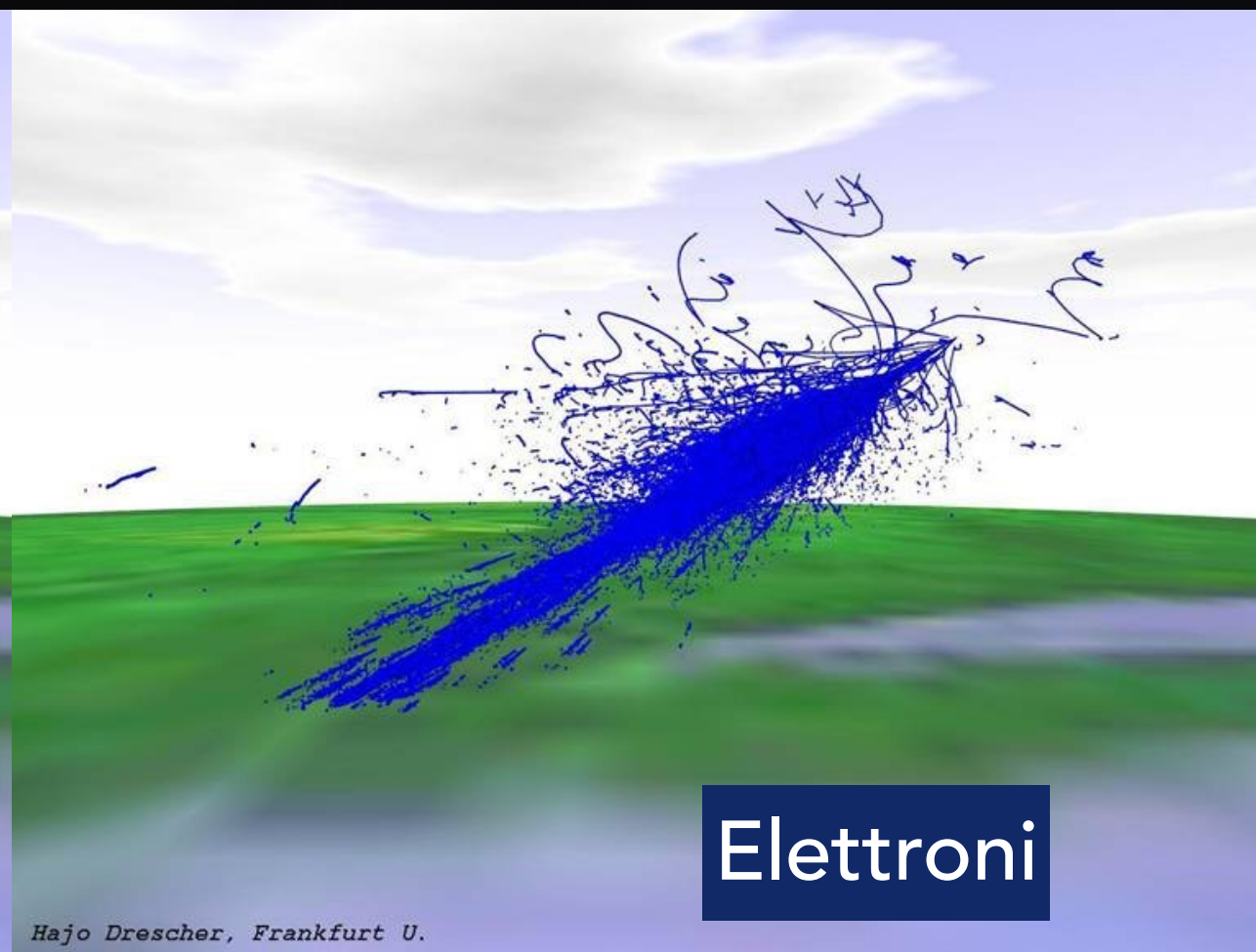
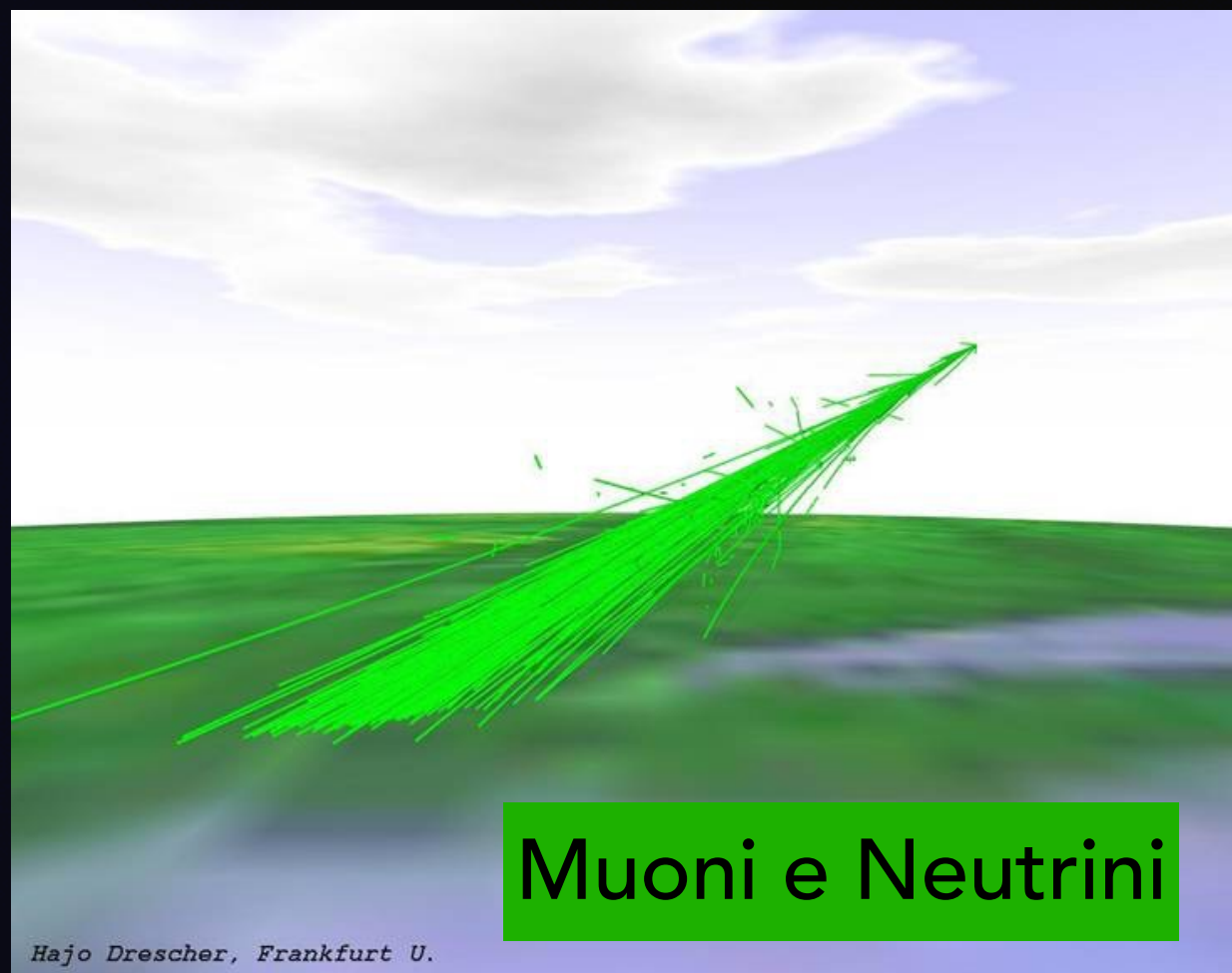


NOT ANY NEUTRINO DETECTED BY "under ice/water" TELESCOPES



KM3NeT Computing Model





To do **Astronomy** => **sub-degree** angular resolution

=> Positioning accuracy ~ **O(10) cm**
 Not trivial for not static structures

=> time synchronisation among sensors ~ **O(1) ns**
 Challenging on a wide area

Angular resolution affected by the light-scattering in the medium

$$L_{sc} = \frac{1}{\mu_b}$$

Energy resolution affected by the light-absorption in the medium

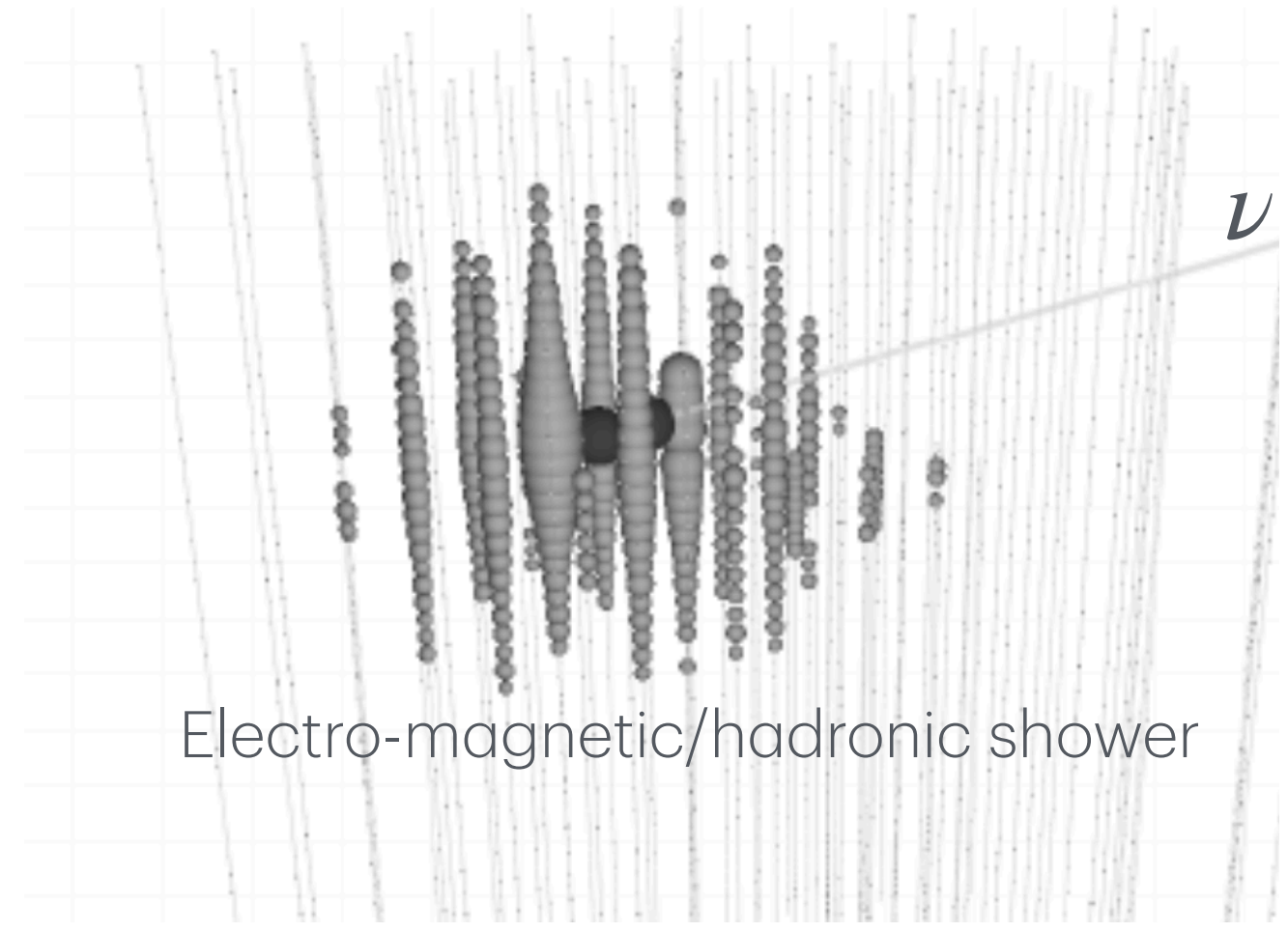
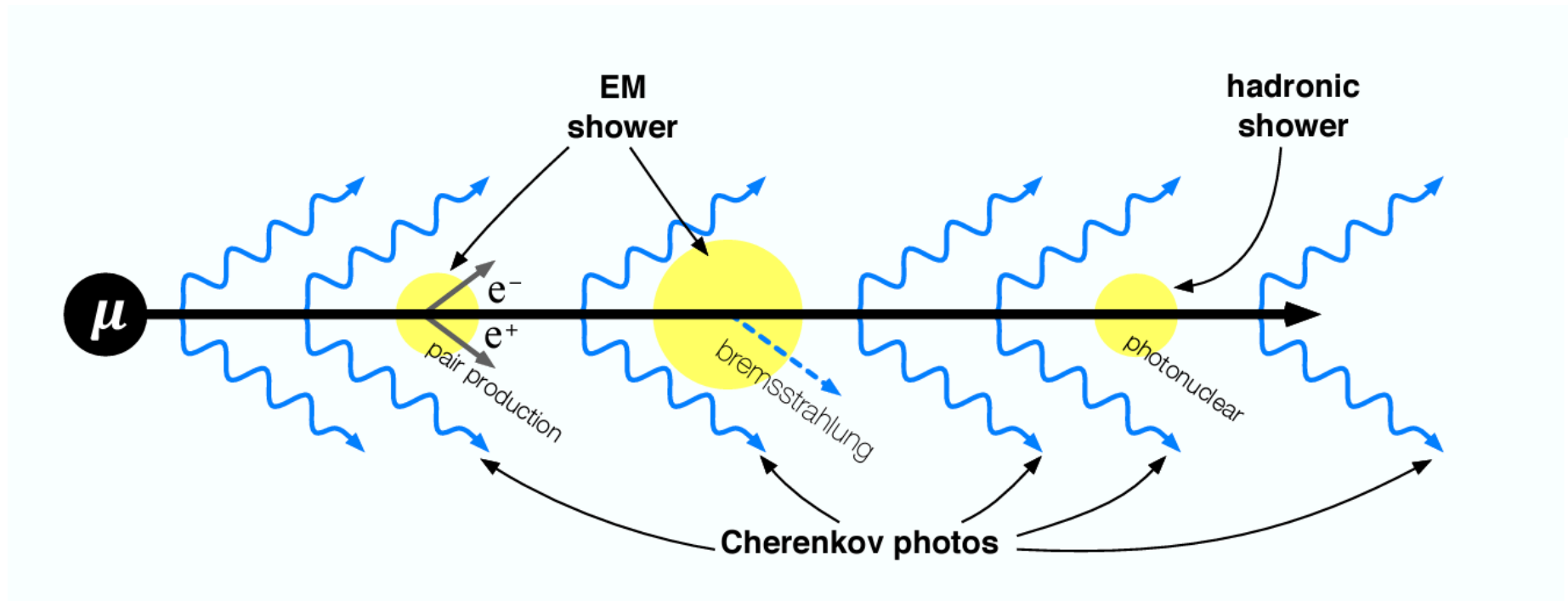
$$L_{abs} = \frac{1}{\mu_a}$$

$$\mu_{att} = \mu_{sc} + \mu_{abs} = \frac{1}{L_{att}}$$

To **study Physical phenomena** => good **energy determination**

Muon tracks (generally not contained):
 underestimated $E_\mu \rightarrow E_\nu$ determination

Showers (generally contained): calorimetry
 => more precise E_ν estimation



Electro-magnetic/hadronic shower



Ilya M. Frank
1908 - 1990



Igor Tamm
1895 - 1971

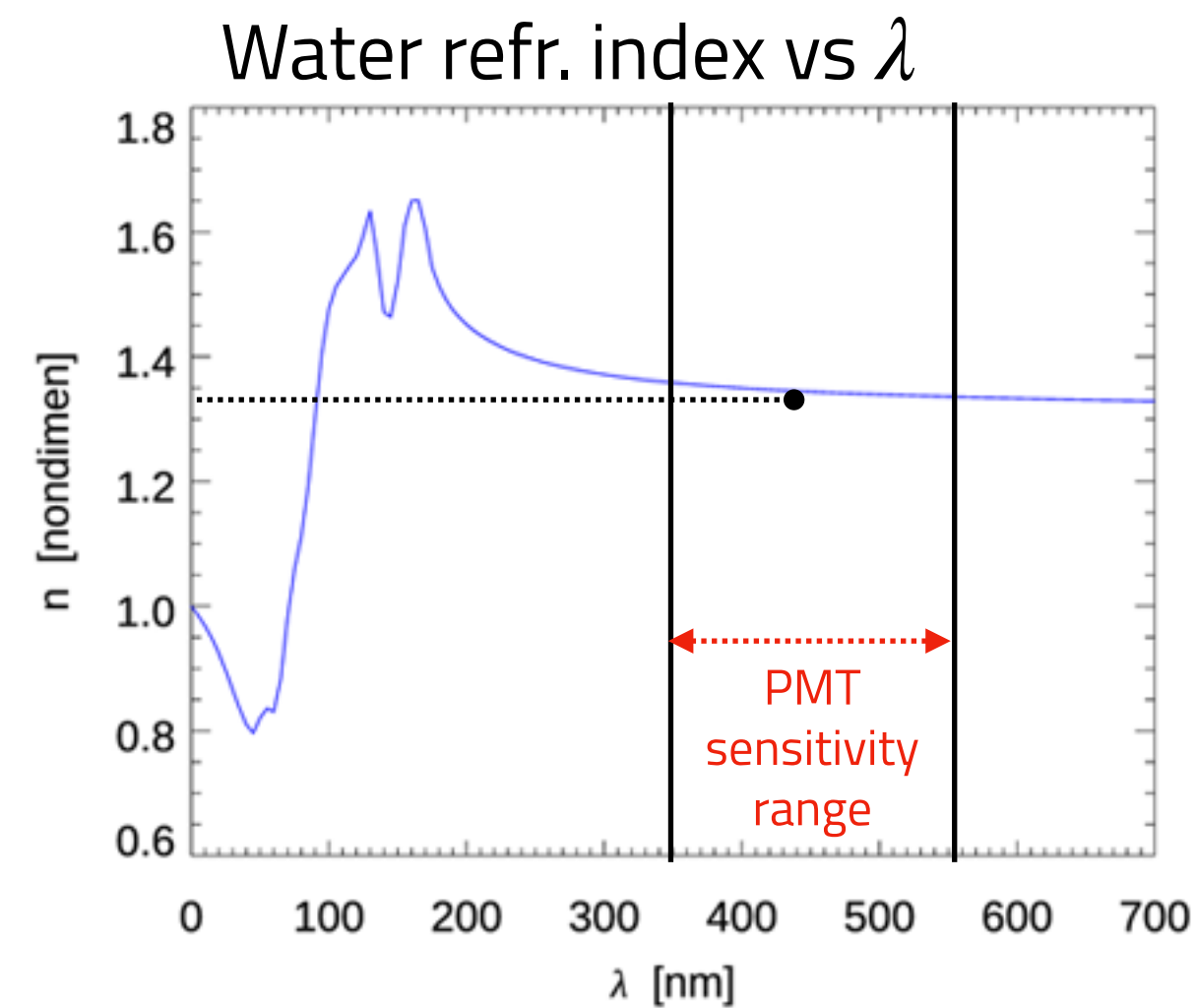
Frank-Tamm formula

$$\frac{\partial^2 E}{\partial x \partial \omega} = \frac{q^2}{4\pi} \mu(\omega) \omega \left(1 - \frac{c^2}{v^2 n^2(\omega)} \right)$$

$$N \cdot \gamma_{Ch}/cm \sim 200$$

Within acceptance range
 $350 \text{ nm} \leq \lambda \leq 550 \text{ nm}$

Assuming $n(\lambda) = \text{constant} = 1.33$ in water



Constraints

$$I = I_0 e^{-\frac{\Delta x}{L_{att}}}$$

PMT Q.E. <30%

PMT \varnothing O(1-10) inches

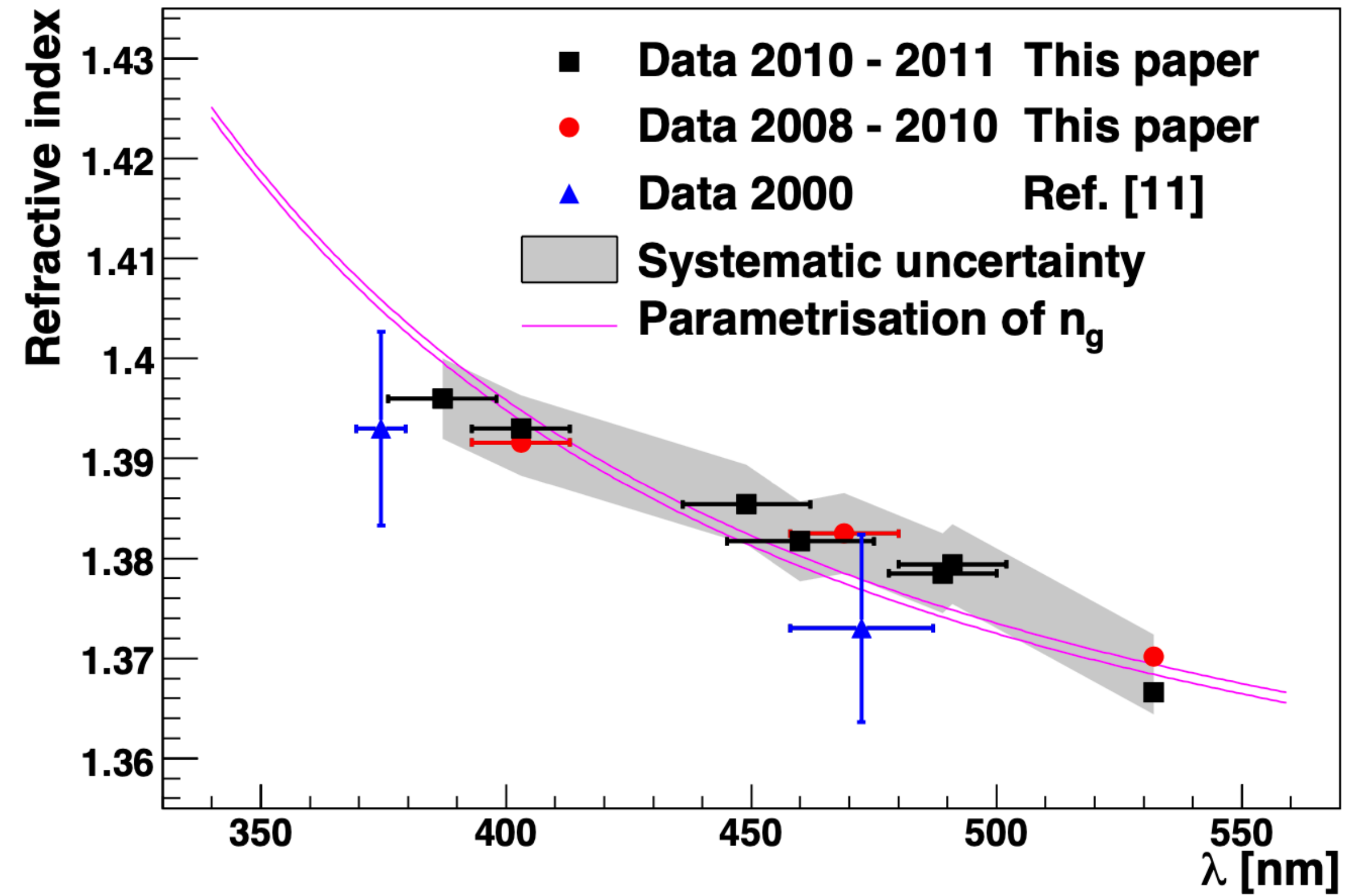
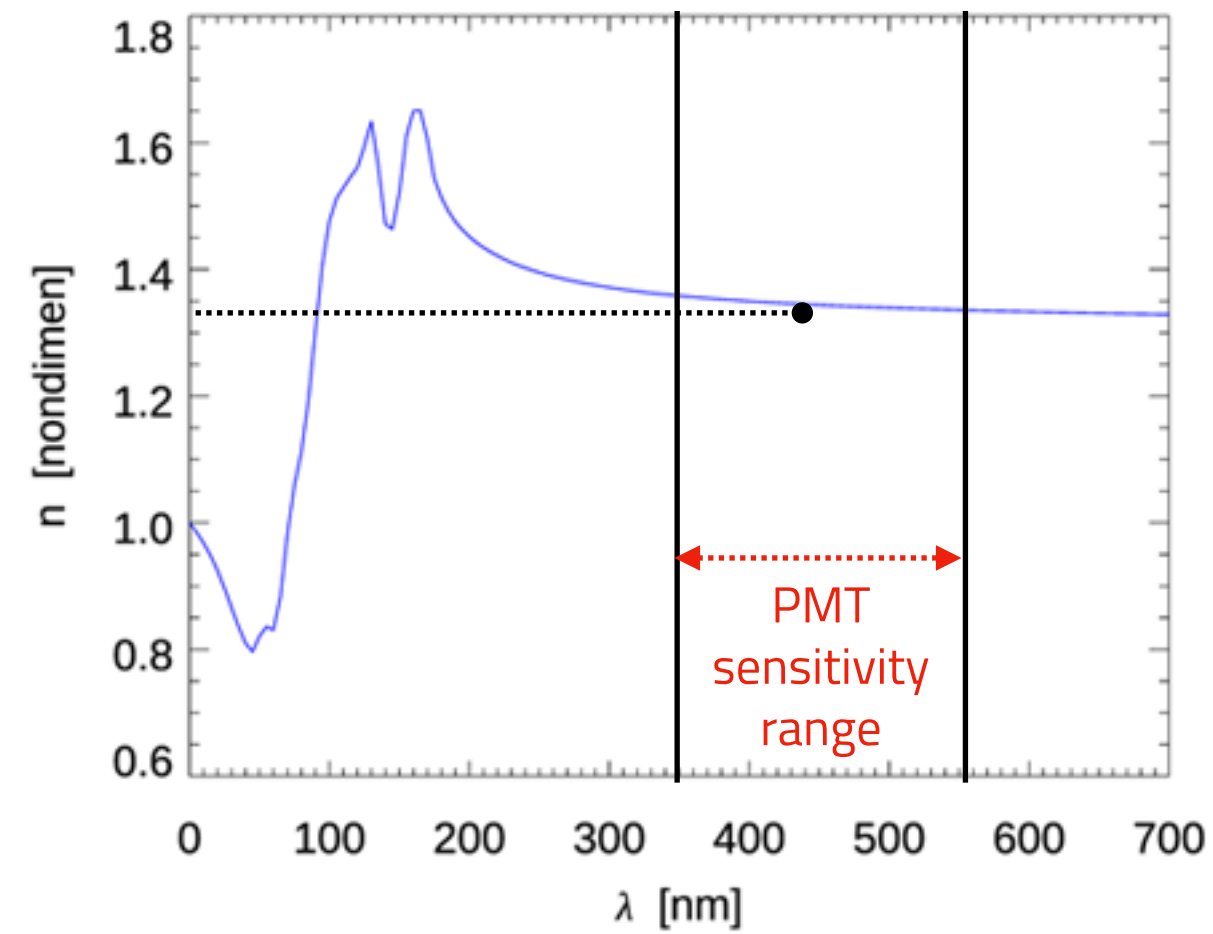
$L_{track} \sim O(1) \text{ km}$

$L_{att} \sim 50\text{m}$

$N_{points} \sim O(100)$

O(5000) of photo-sensors

Water refr. index vs λ



Type of Radiation	Wavelength Range	Frequency Range (Hz)	Energy Range (eV)
Radio Waves	> 1 m (up to ~100 km)	< 300 MHz (down to ~3 kHz)	< 10^{-6} eV
Microwaves	1 mm – 1 m	300 MHz – 300 GHz	10^{-6} – 10^{-3} eV
Infrared (IR)	700 nm – 1 mm	300 GHz – 430 THz	10^{-3} – 1.7 eV
Visible Light	400 – 700 nm	430 – 750 THz	1.7 – 3.3 eV
Ultraviolet (UV)	10 – 400 nm	750 THz – 30 PHz	3.3 – 124 eV
X-rays	0.01 – 10 nm	30 PHz – 30 EHz	124 eV – 120 keV
Gamma Rays (γ)	< 0.01 nm	> 30 EHz	> 120 keV (up to GeV and beyond)