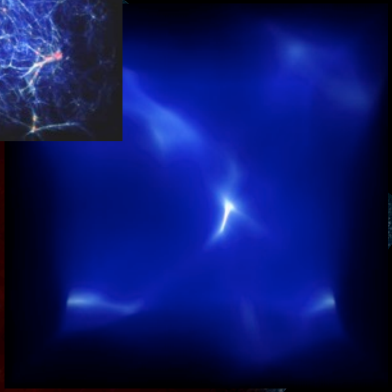
Neutrinos: a major role in astrophysics and cosmology

- High-energy neutrino astronomy
- Neutrinos and cosmological evolution
- Sterile neutrinos



N. Palanque-Delabrouille
(CEA-Saclay)

SFP , July 2017

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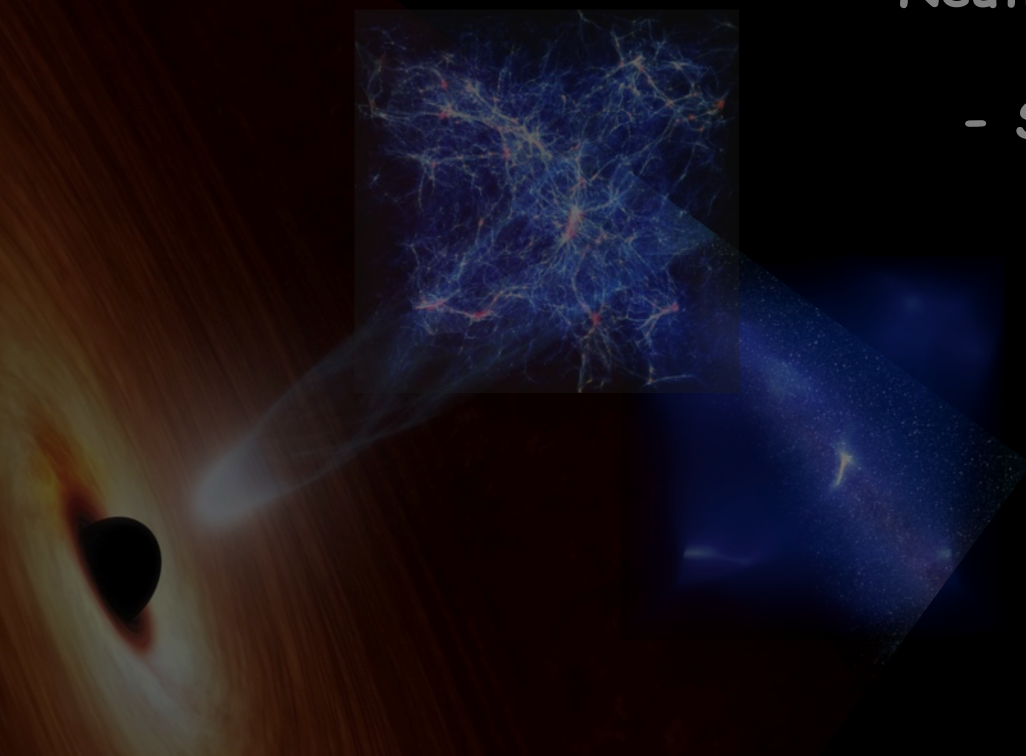

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High-energy neutrino astronomy?

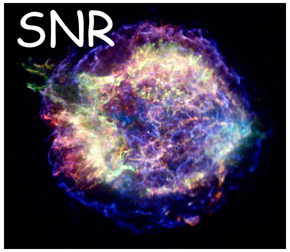
High-energy neutrino production processes

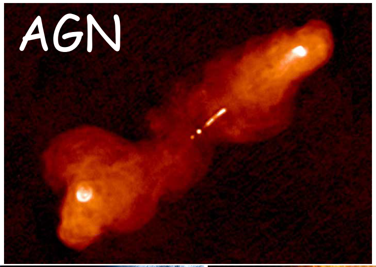
- **Hadronuclear** (e.g. galactic cosmic rays)

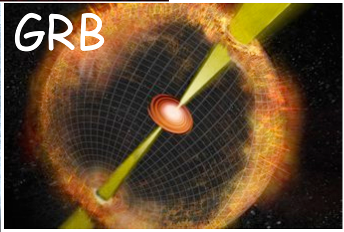
$$pp \rightarrow \begin{cases} \pi^0 \rightarrow \gamma\,\gamma \\ \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \nu_\mu \bar{\nu}_\mu \\ \pi^- \rightarrow \mu^- \bar{\nu}_\mu \rightarrow e^- \bar{\nu}_e \bar{\nu}_\mu \nu_\mu \end{cases}$$

- **Photohadronic** (e.g. gamma-ray bursts, AGNs)

$$p\gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p\,\pi^0 \rightarrow p\,\gamma\,\gamma \\ n\,\pi^+ \rightarrow n\,\mu^+ \nu_\mu \rightarrow n\,e^+ \nu_e \bar{\nu}_\mu \nu_\mu \end{cases}$$







High-energy neutrino astronomy?

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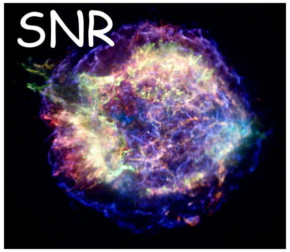
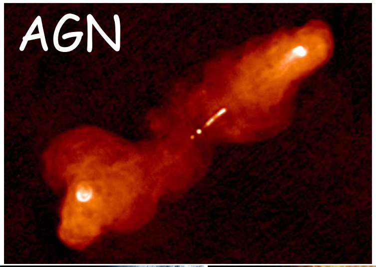
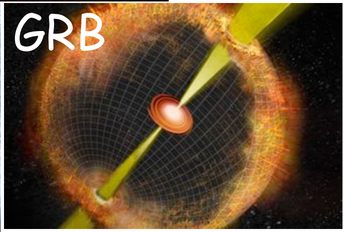
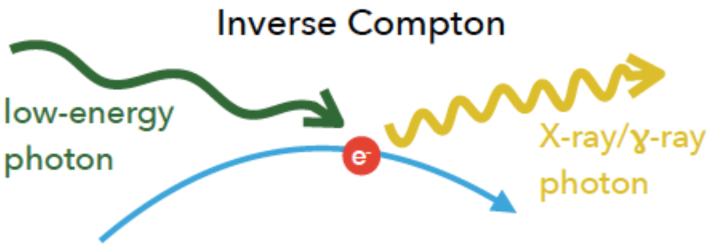
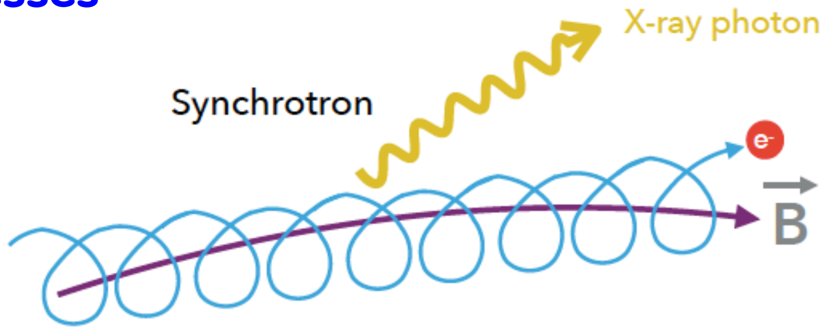




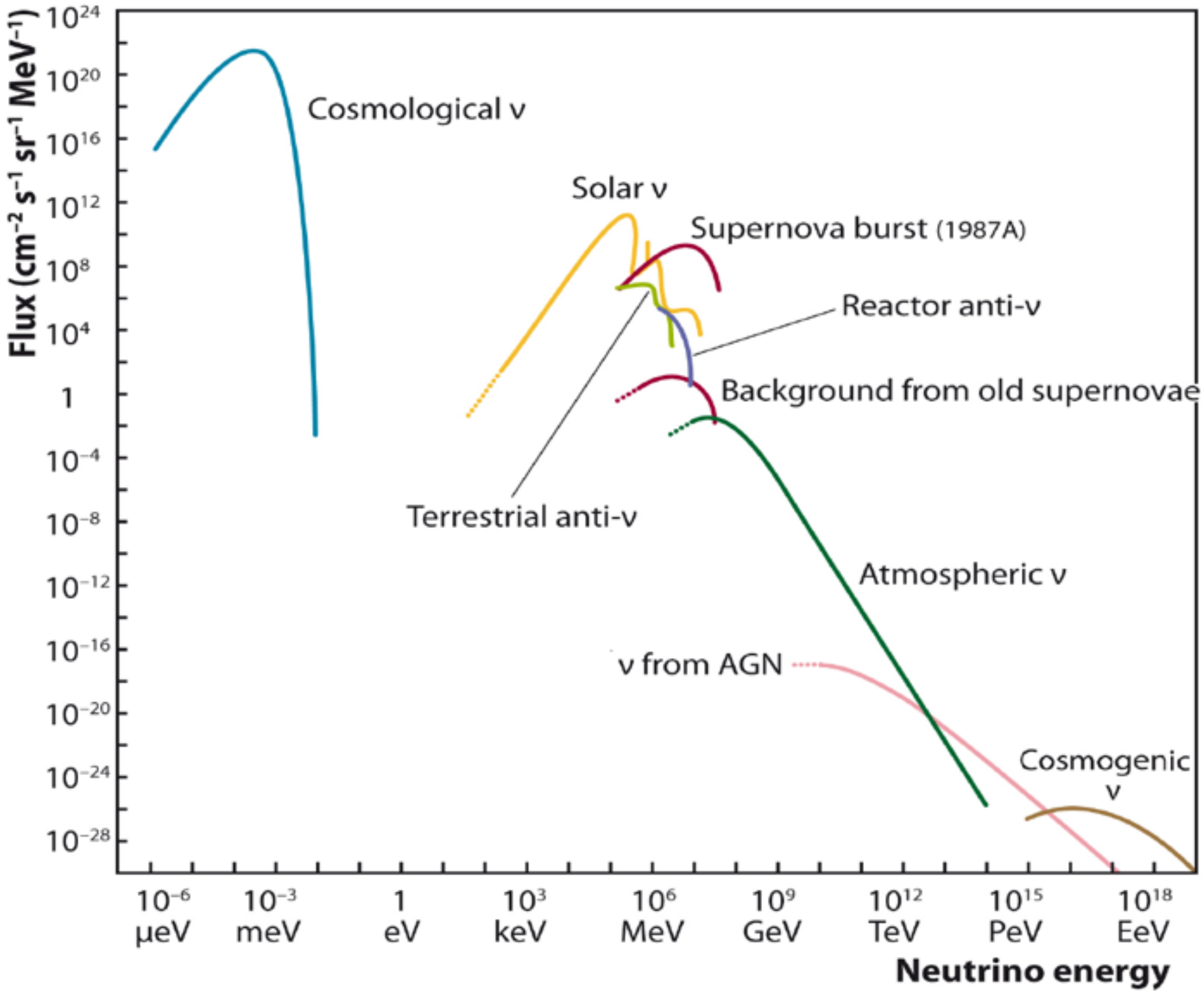


- **But γ-rays also from leptonic processes**

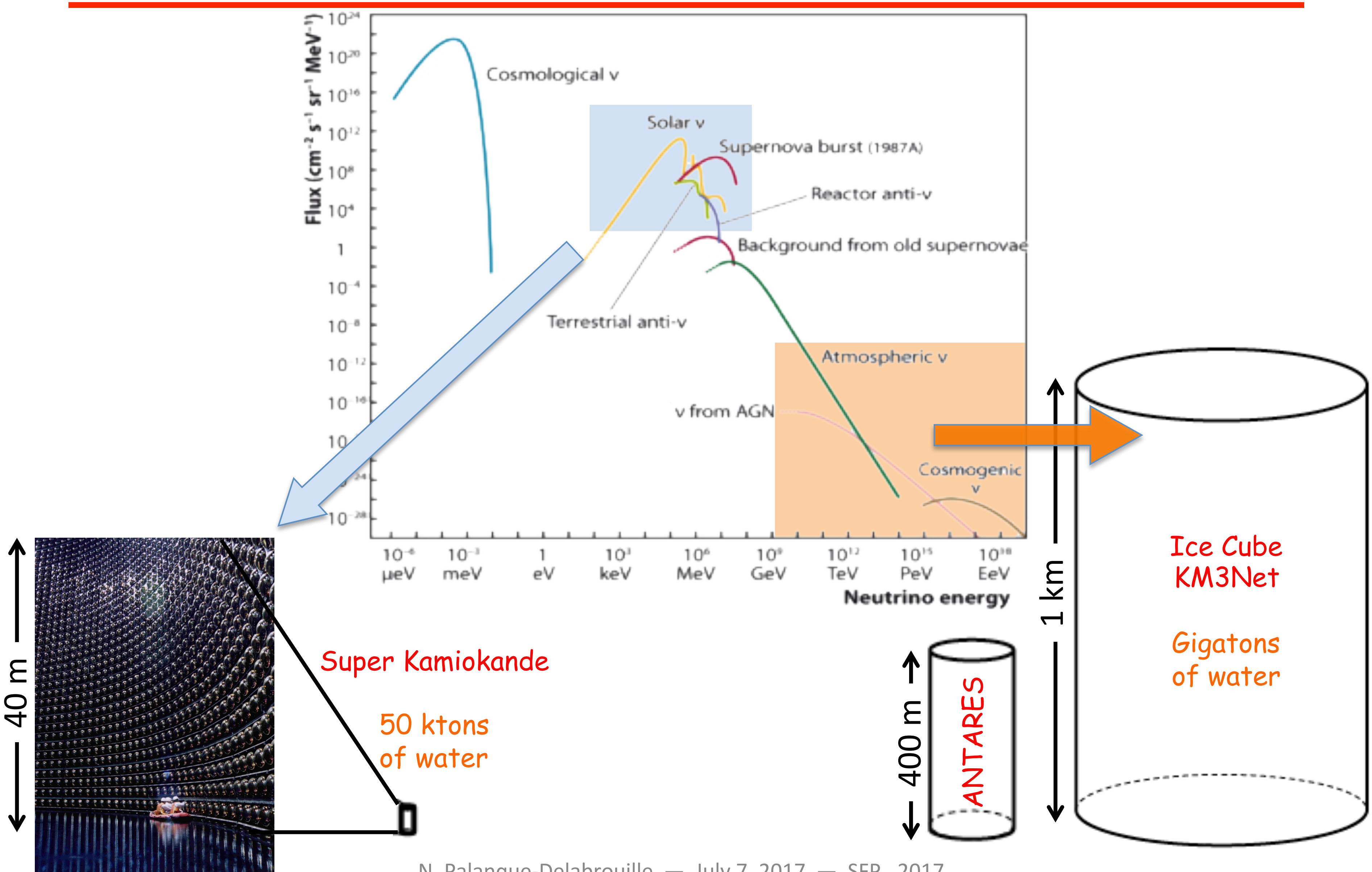


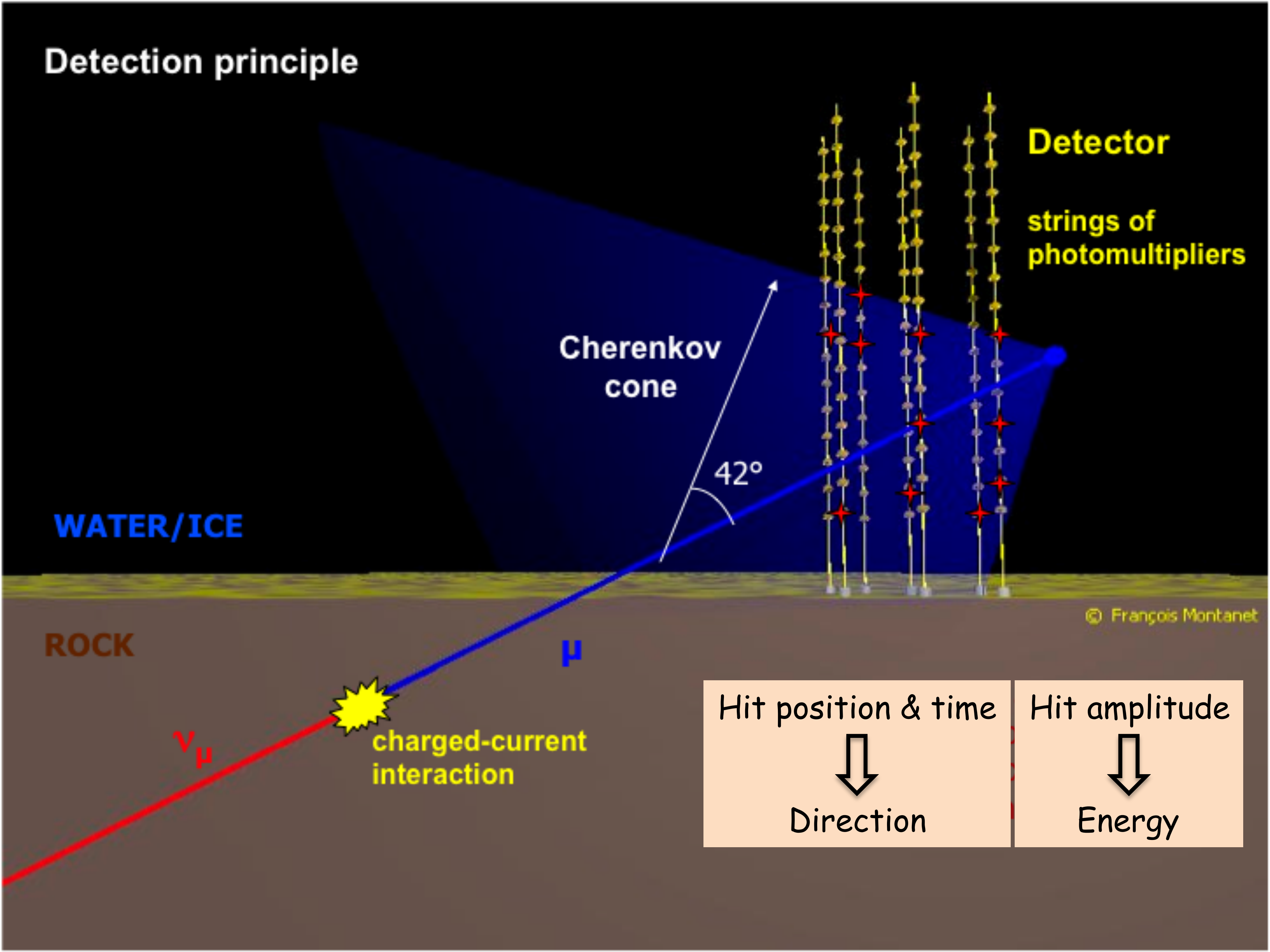


Neutrino spectrum



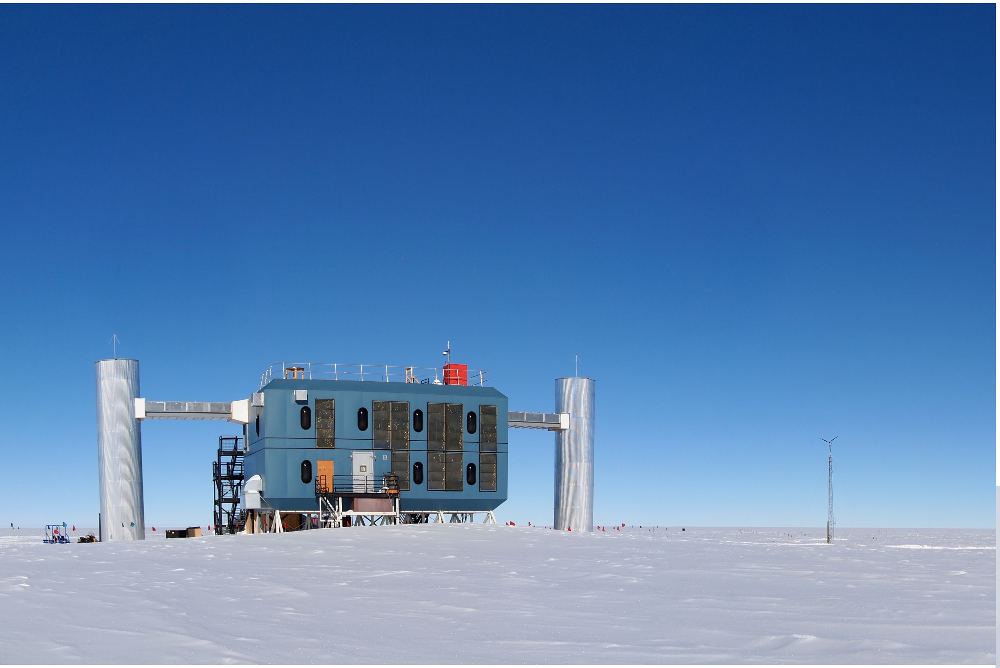
Neutrino spectrum





Detection principle
Detector
strings of
photomultipliers
Cherenkov
cone
42°
WATER/ICE
© François Montanet
ROCK
μ
ν_μ
charged-current
interaction
Hit position & time
Direction
Hit amplitude
Energy

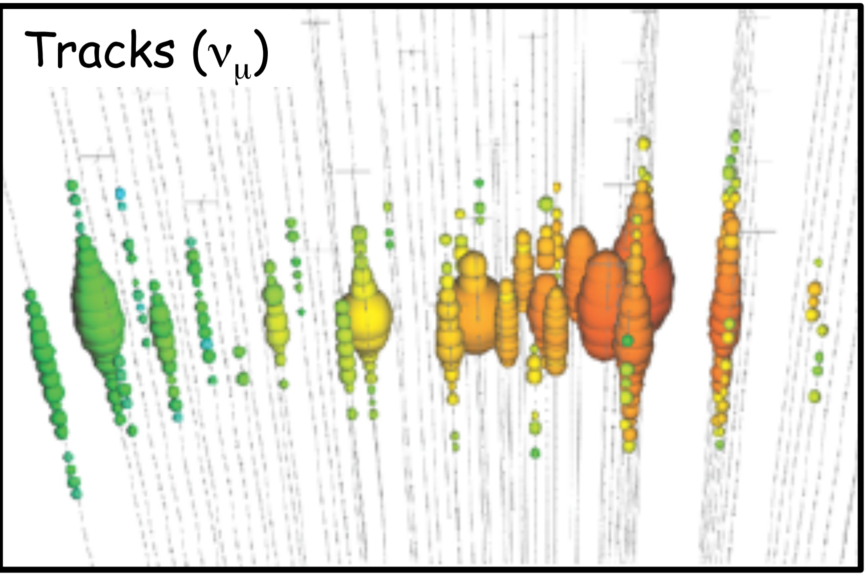
Neutrino telescopes

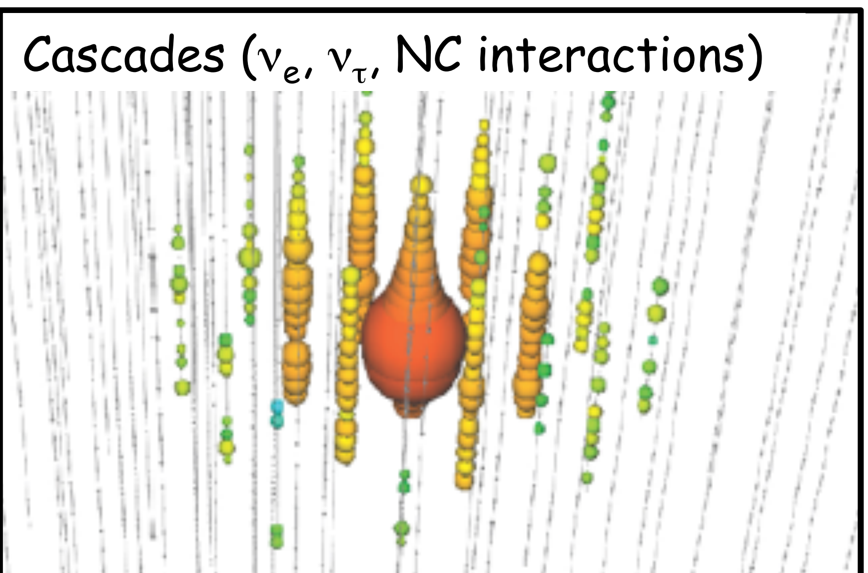


Ice Cube
1 km^2 x 1 km

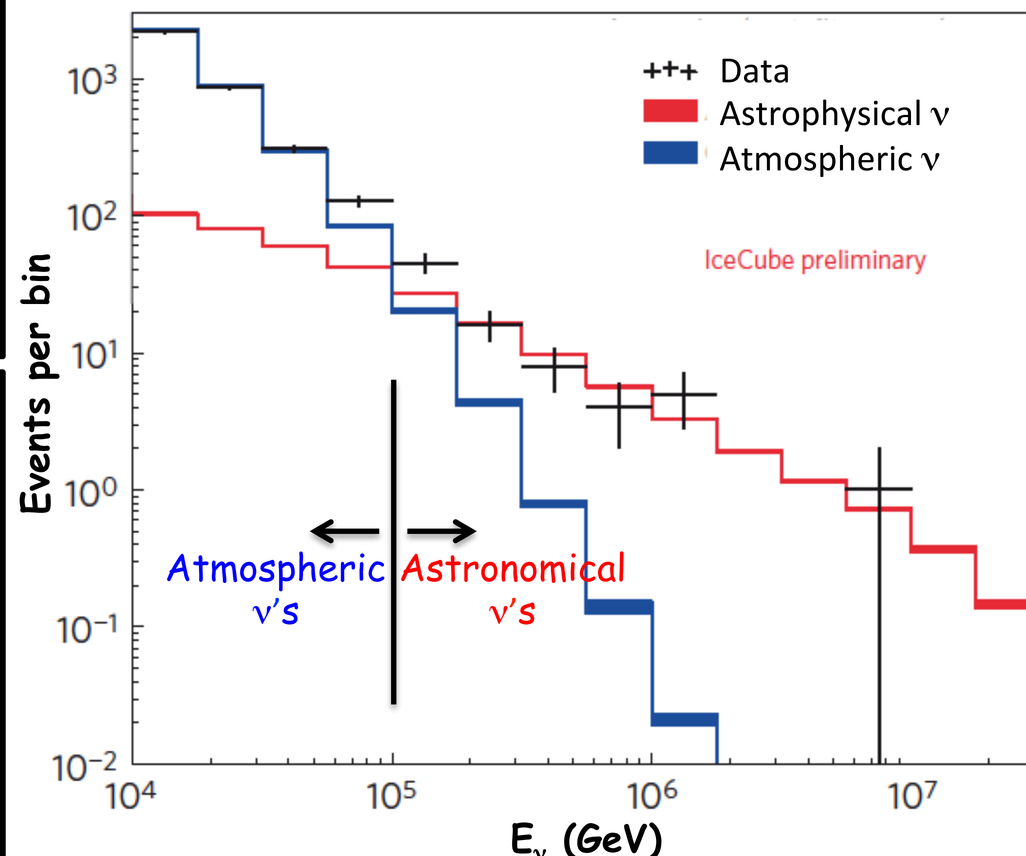
Antares
0.1 km^2 x 400 m

Birth of high-energy neutrino astronomy



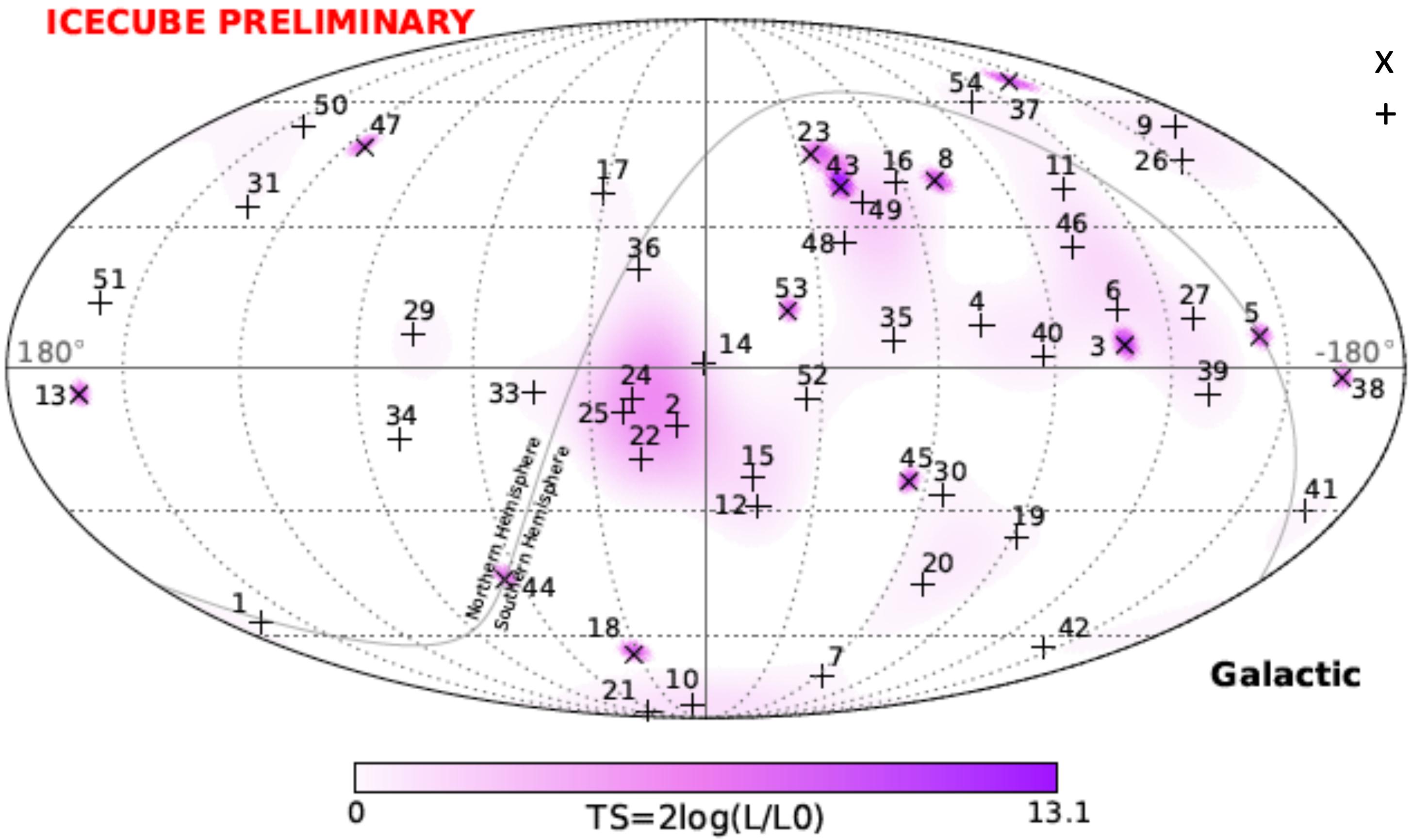


28 events (after 2 years)
Deposited energy from 30 TeV to 1 PeV



Halzen (2016) and refs. therein

Arrival direction

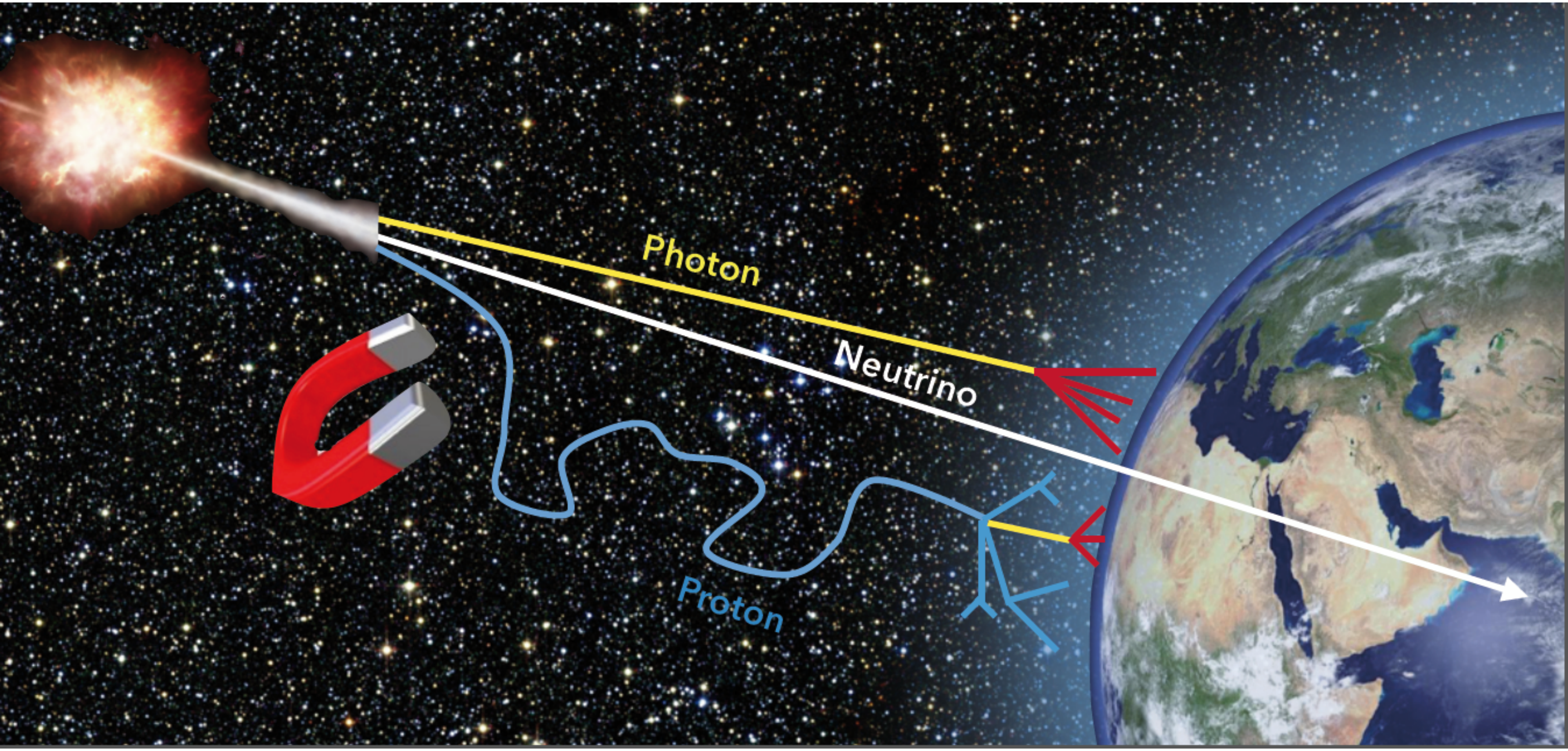


- Compatible with isotropy
- No source identified yet
- Subdominant Galactic component possible

→ Source identification?

Multi-messenger astronomy

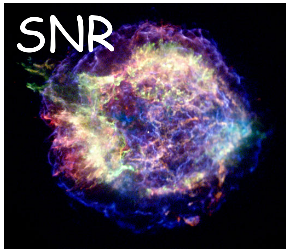
- Correlations at high energy with cosmic ray emitters
- Energy spectrum comparison with (cascaded) high-energy photons



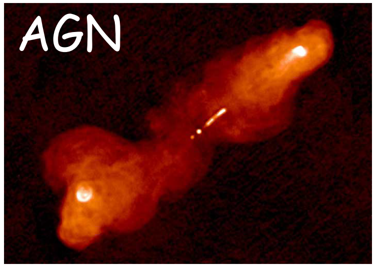
Multi-messenger astronomy

No clear correlation with known classes

whether galactic



or extragalactic

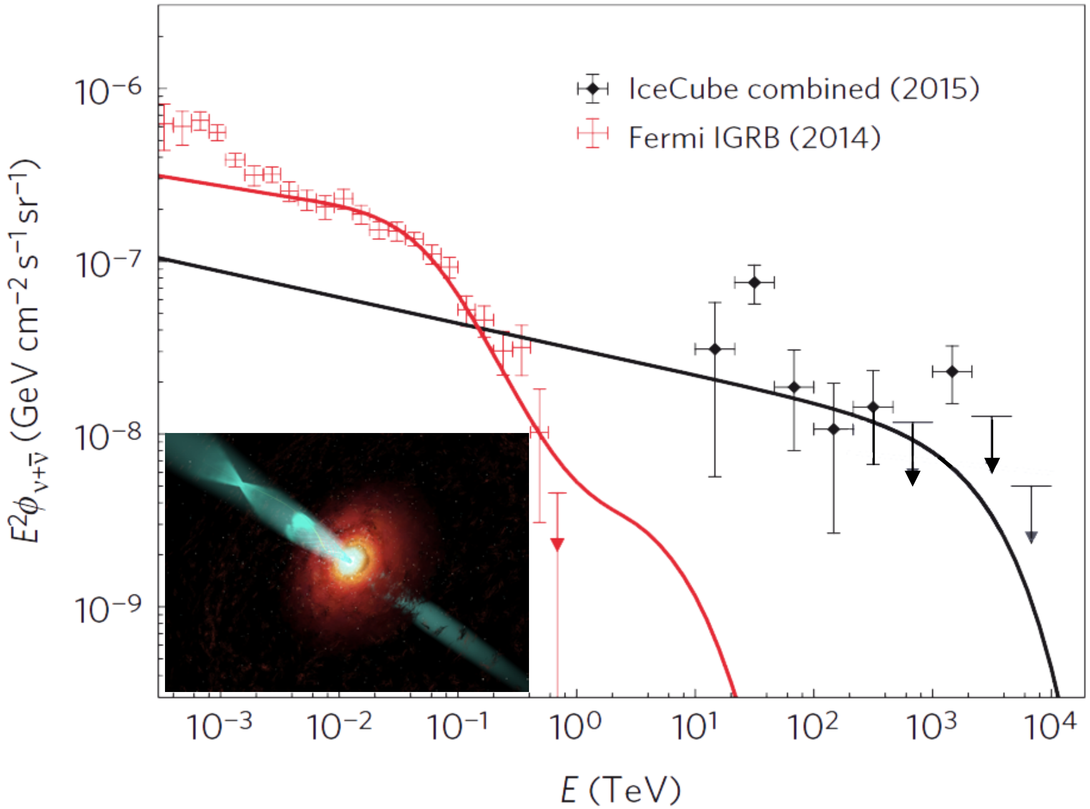


Excellent spectral match with GeV Fermi γ-rays

(accounting for PeV γ cascading on cosmic radiation backgrounds)

Common origin?

Blazars (as hinted by Fermi)?



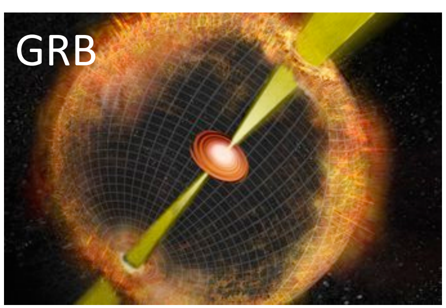
Transient multi-messenger astronomy

Multi-messenger studies of transient & variable sources

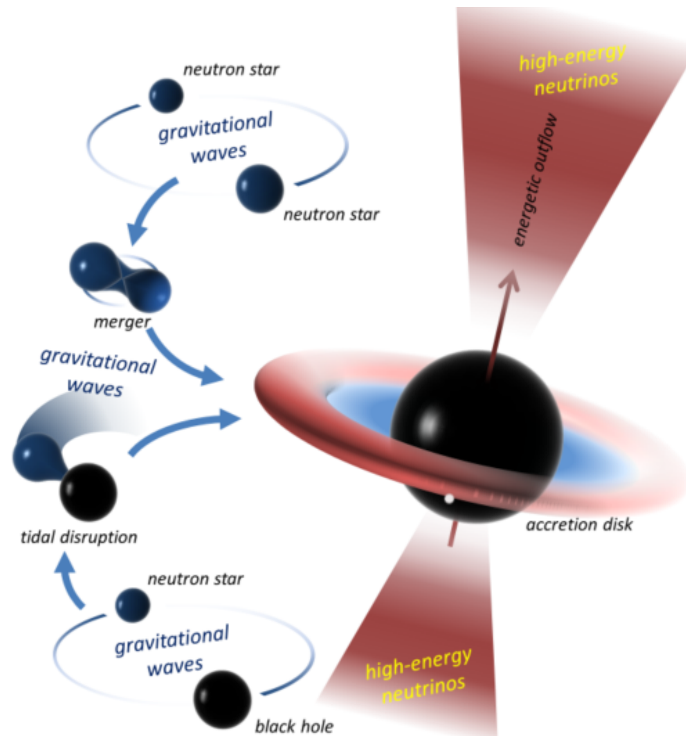
- Increase sensitivity & discovery potential (reduced background)
- Increase statistical significance (joint detection)

TATOO (Antares): Seconds-after follow-up with robotic telescopes

radio	optical	X-ray	GeV γ-ray	TeV γ-ray
MWA (12/yr)	TAROT ZADKO MASTER (30/yr)	Swift (6/yr)	Fermi (offline)	HESS (2/yr)



Search for correlations with gravitational wave events



No correlation identified yet

Future of neutrino telescopes

Bigger

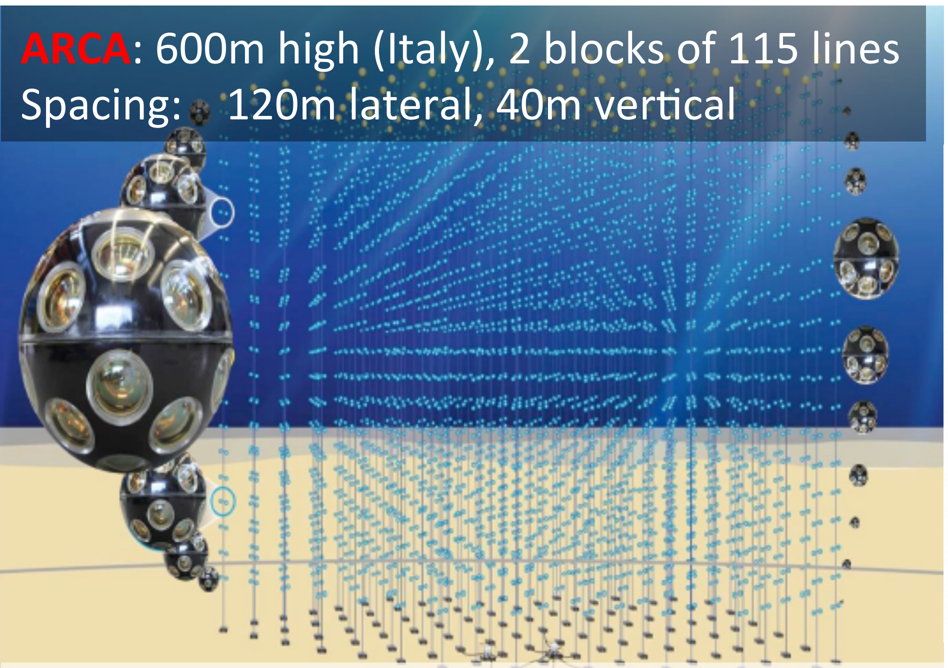
Higher energy
ν astronomy

KM3Net / ARCA
IceCube Gen2

KM3Net / ORCA
IceCube PINGU

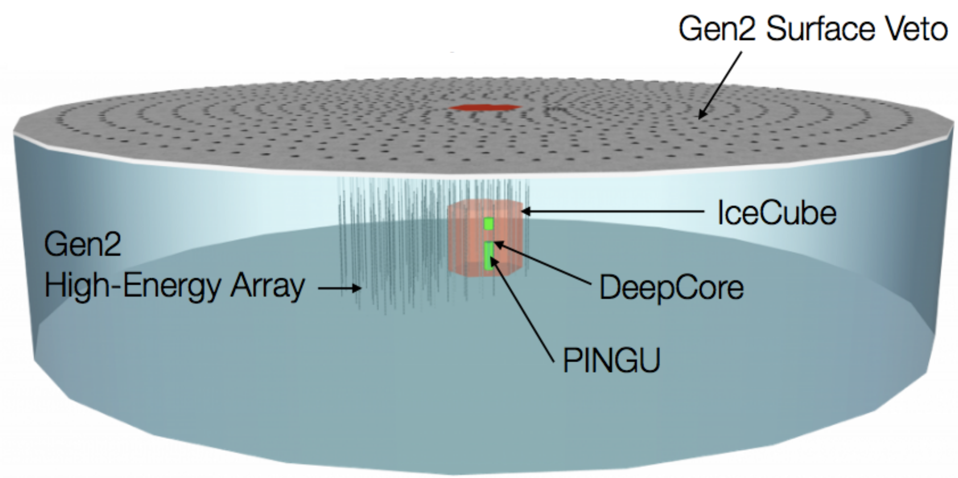
Lower energy: GeV
Neutrino oscillations
Dark matter detection

Denser



ORCA: 100m high (Toulon), 1 block of 115 lines
Spacing: 20m lateral, 6m vertical

IceCube Gen2: 1.25 km high, 120 lines
Spacing: 240m lateral, 15m vertical



Pingu: 1.25 km high, 120 lines
Spacing: 20m lateral, 2m vertical

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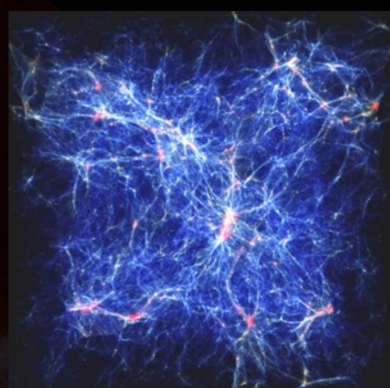
- **Neutrinos and cosmological evolution**
- Sterile neutrinos



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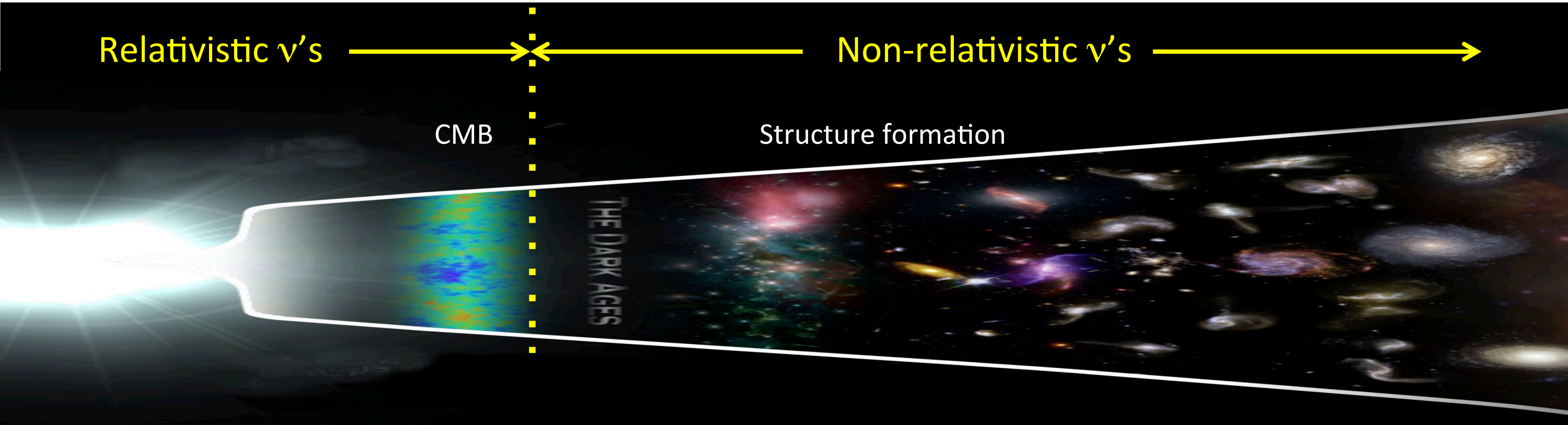
Cosmic neutrino background

$m_\nu \sim$ eV or less

- At early times ($T_\nu \gg m_\nu$), neutrinos contribute as radiation
- At late times ($T_\nu \ll m_\nu$), neutrinos contribute as matter

Non-relativistic transition occurs AFTER CMB for $\Sigma m_\nu < 1.7$ eV
→ negligible impact on CMB primary power spectrum



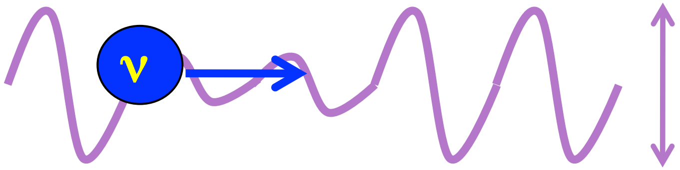
Neutrinos & large-scale structures

While relativistic, neutrinos "free stream" at v=c until t_{nr}

⇒ Destroy perturbations of wavelength $\lambda < ct_{nr}$
although normal clustering on scales $\lambda > ct_{nr}$

- Heavy neutrinos (t_{nr} early)

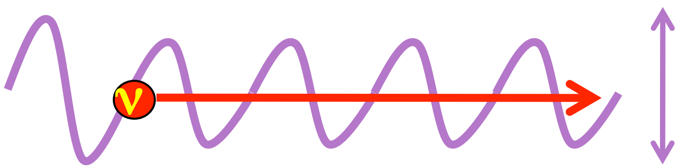
  Strong suppression over short range

  $m_\nu \sim$ keV ⇒ size of dwarf galaxy perturbations smoothed out

- Light neutrinos (t_{nr} late)

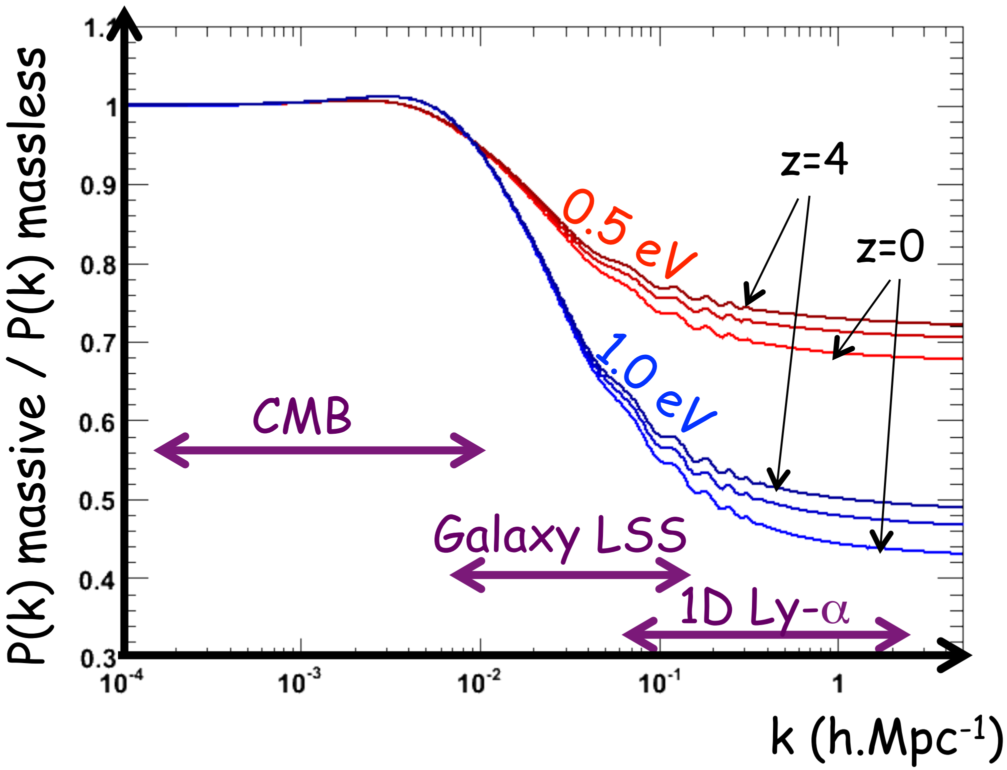
  Weak suppression over long range

  $m_\nu \sim$ eV ⇒ size of galaxy cluster perturbations smoothed out

Neutrinos and large-scale structures

Different probes ⇔ different scales



Large scales

Small scales

- Suppression factor ⇔ Σmν
- Suppression is z-dependent
- Ly-α
  - Small scales, max effect +
  - Large z-range [2.1 ; 4.5] +
  - Non-linear regime & Flux (not mass) P(k) ⇒ Hydro simulations −

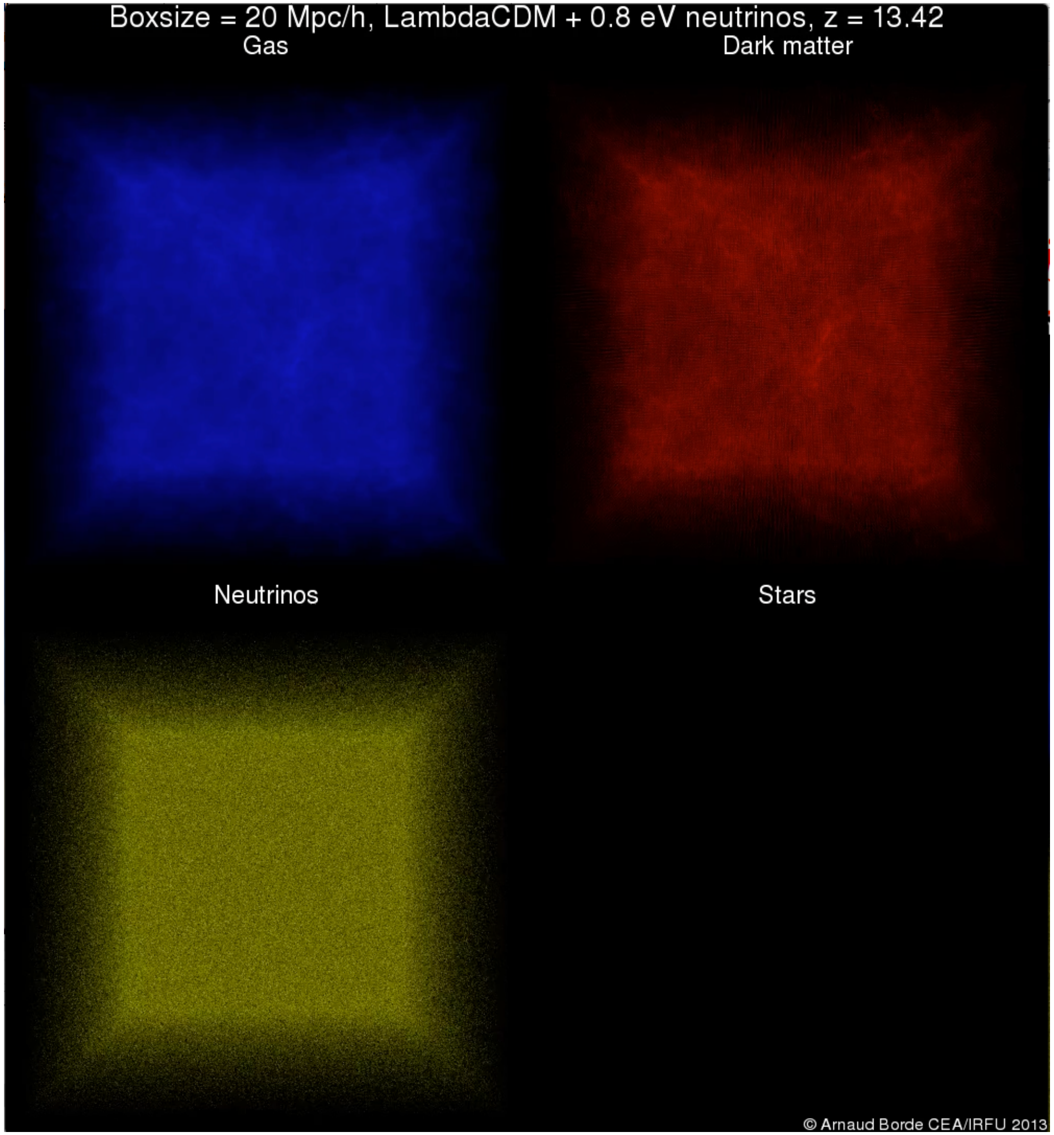
Hydrodynamical simulations

$z = 15$ ($t_{lookback} = 13.5$ Gyr) $\rightarrow 0$

3 species: Baryons
Dark matter
Neutrinos

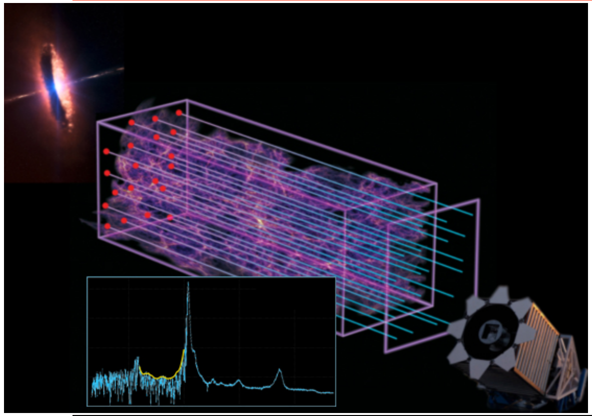
Stars formed from baryons

>10 Million hrs at TGCC



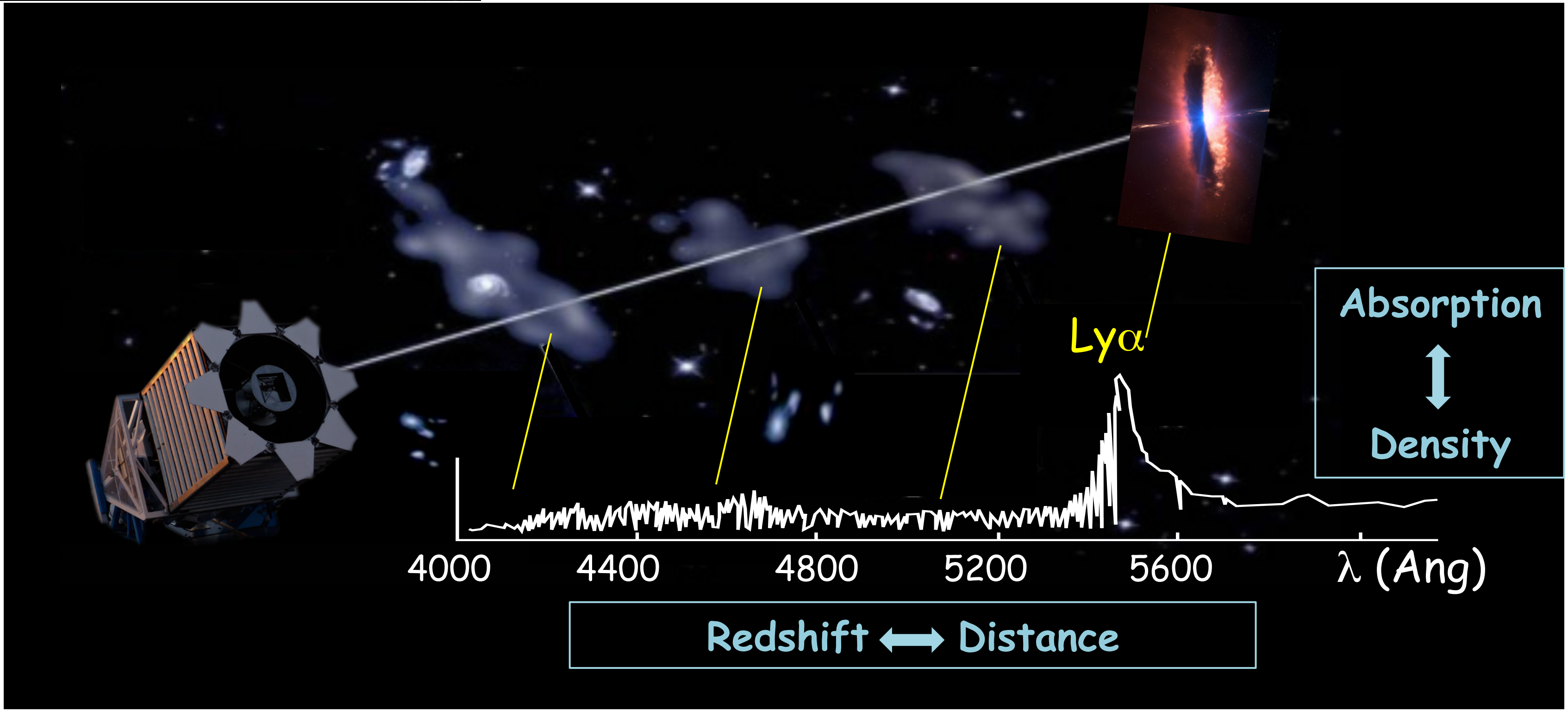
@ A. Borde (CEA-Saclay)

Ly-α forest (BOSS)

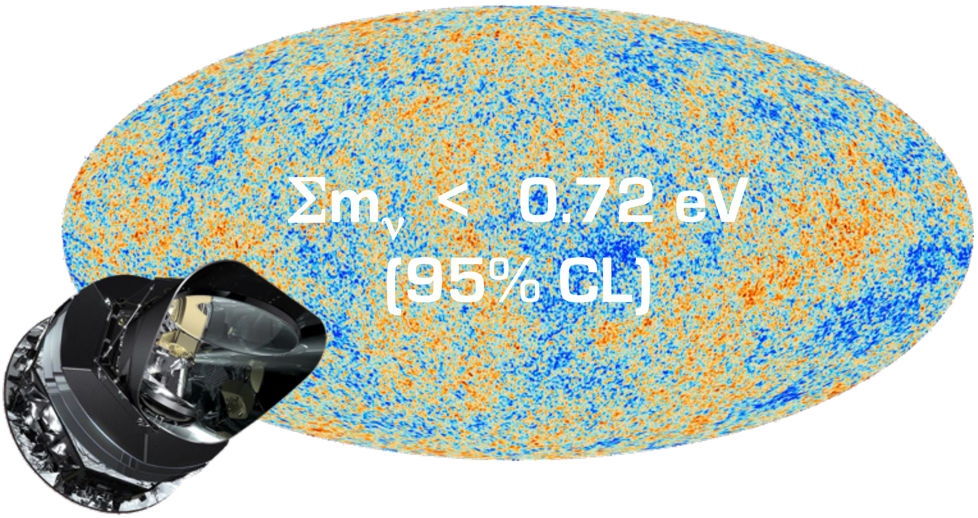


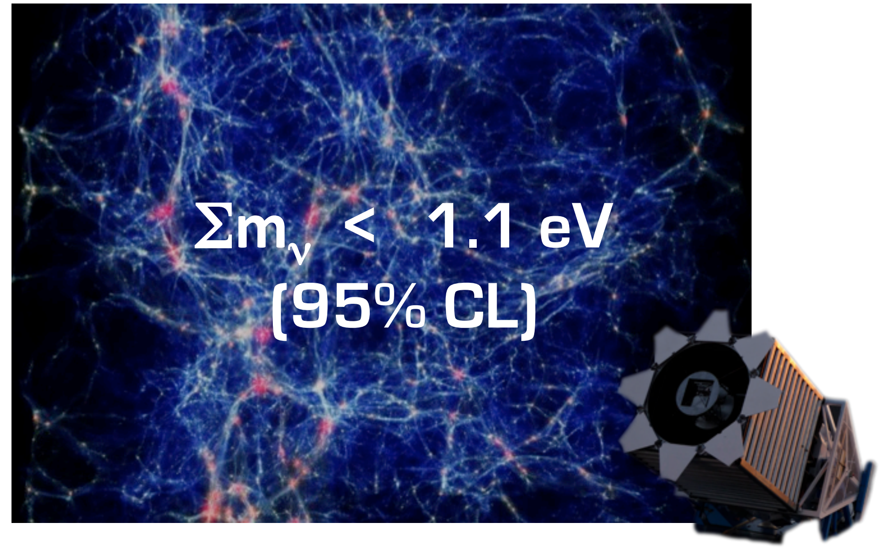
Method

- Quasars visible to **high redshift** (>5)
- Absorption by neutral H (IGM) along line-of-sight
- IGM probes **matter** density
- Matter distribution **on small scales** (ν, ν_s)

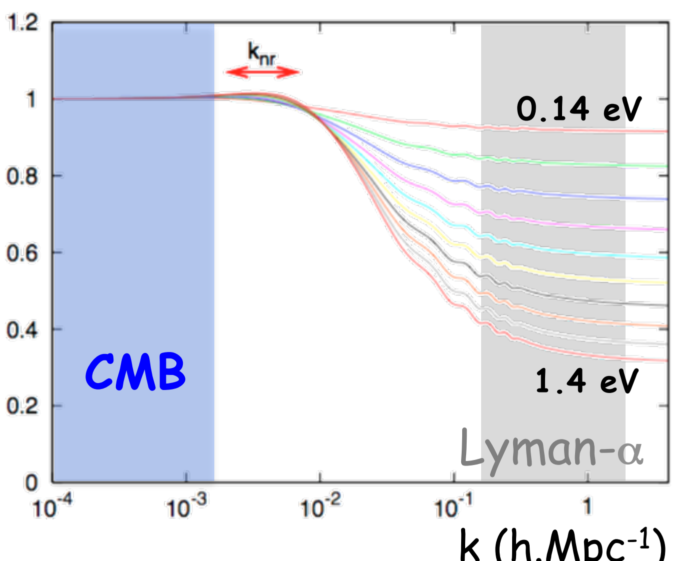


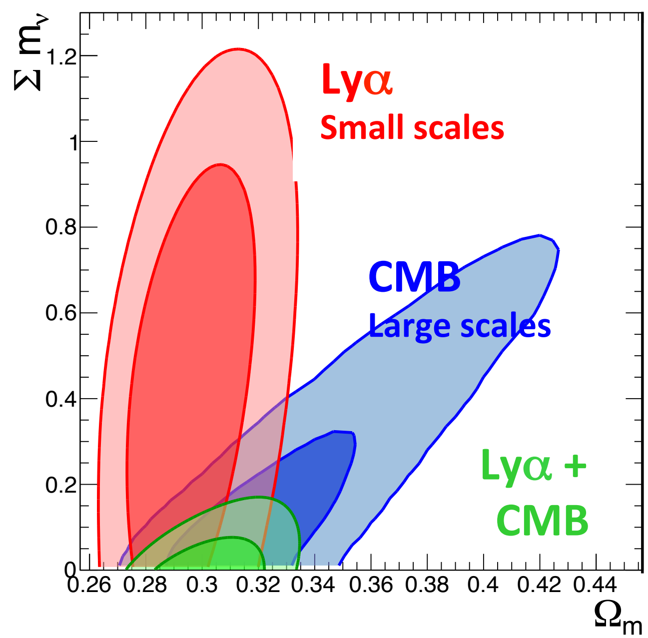
$M\nu$ constraint





P(k) massive / P(k) massless





$\Sigma m_\nu <$ 0.12 eV

NPD, Yèche, Borde et al. (2015)
NPD, Yèche, Baur, et al. (2015)

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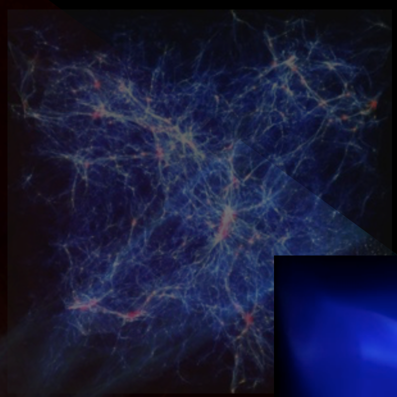
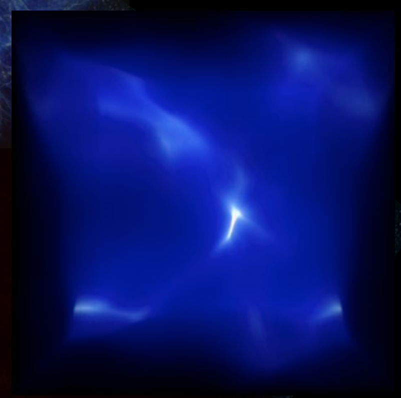
- Neutrinos and cosmological evolution
- **Sterile neutrinos**





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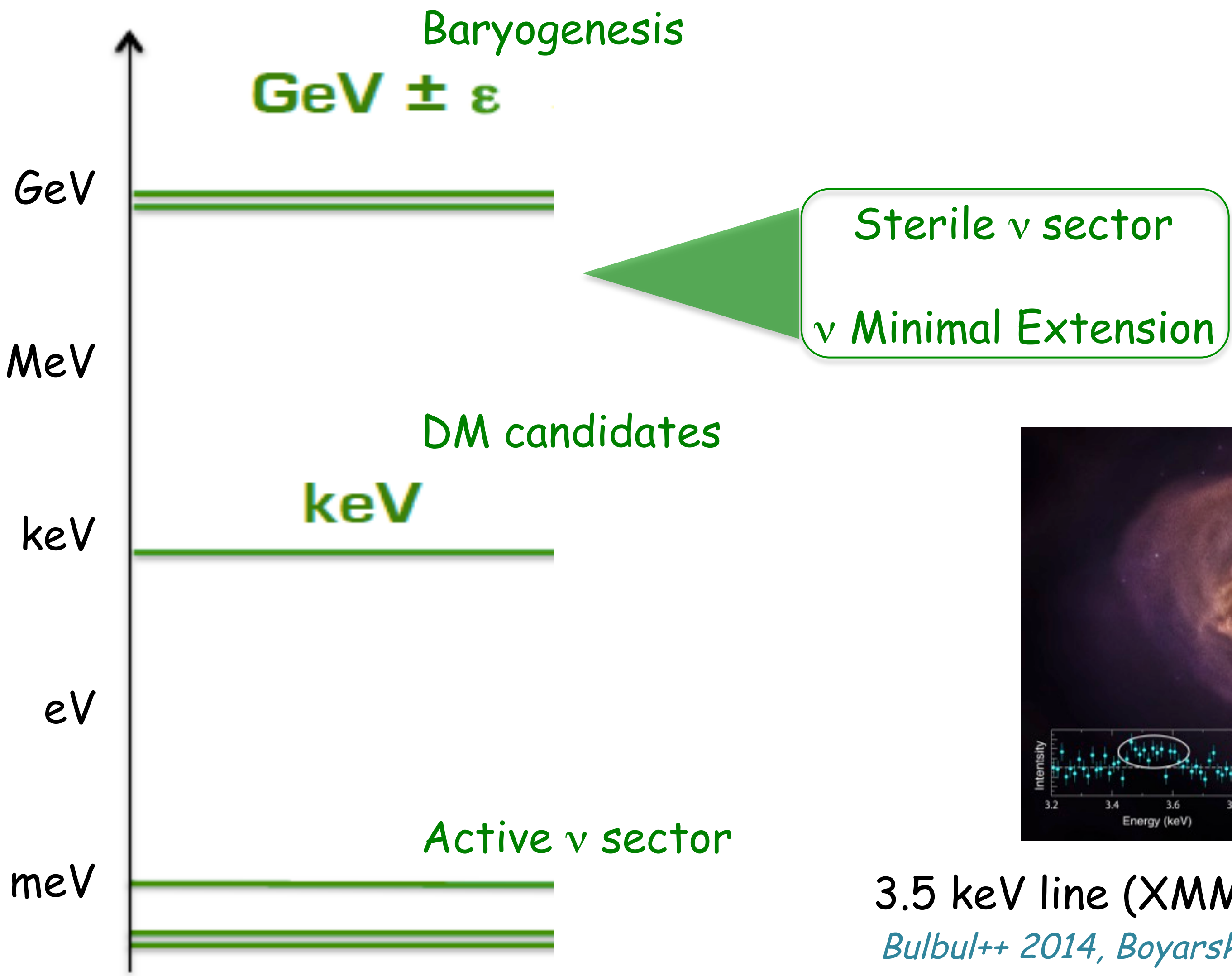
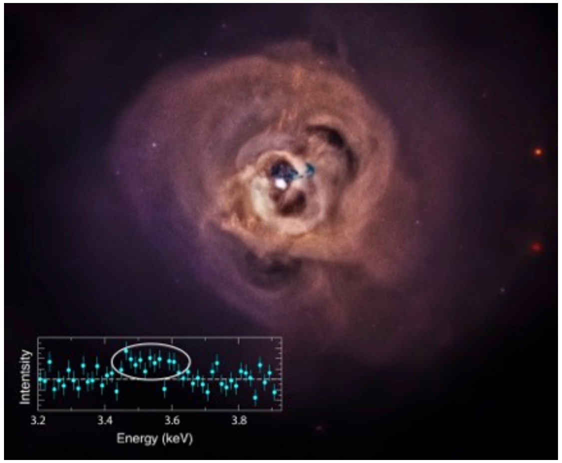
Sterile neutrino sector



Preseus cluster
Andromeda galaxy
XMM clusters



3.5 keV line (XMM): decay of 7 keV ν_s ?

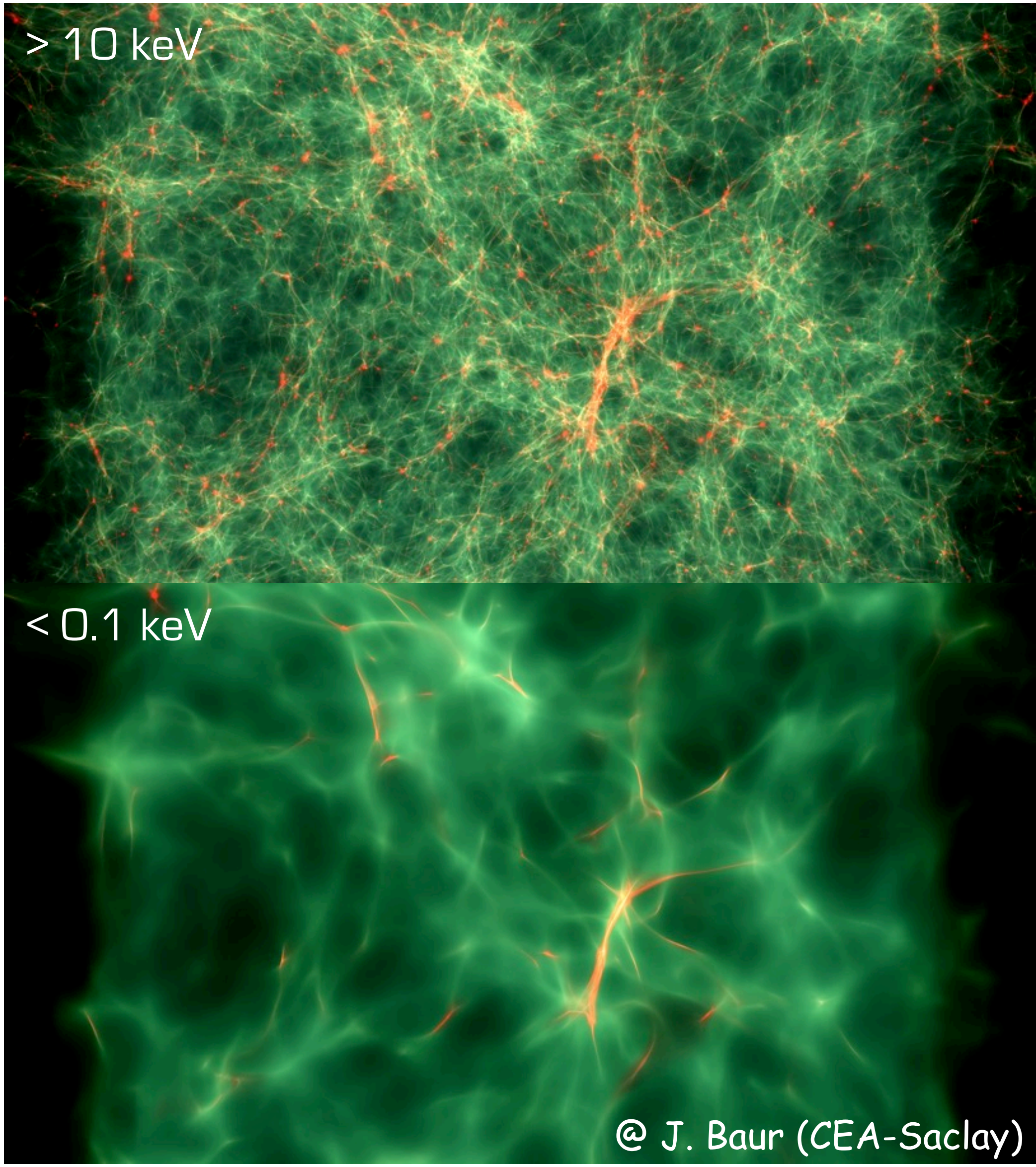
Bulbul++ 2014, Boyarsky++ 2014, Cappelluti++ 2017

Warm Dark Matter

If all dark matter were

Cold Dark Matter

Hot Dark Matter

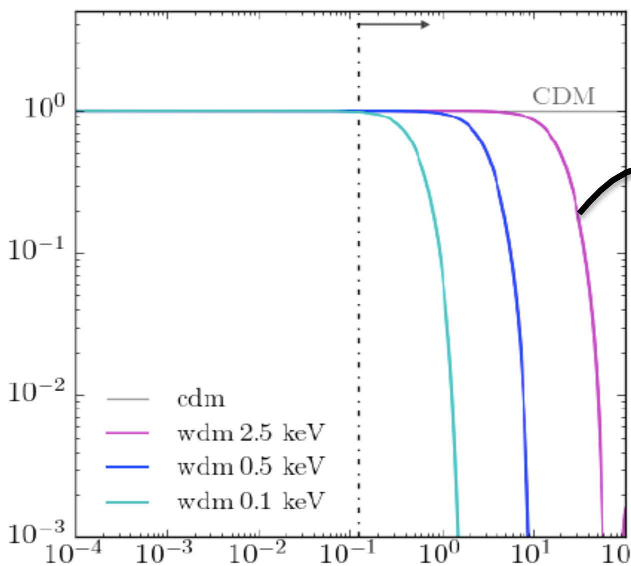


Smooth out of
small-scale structures
by particle free-streaming

Warm Dark Matter: thermal relic & NRP ν_s

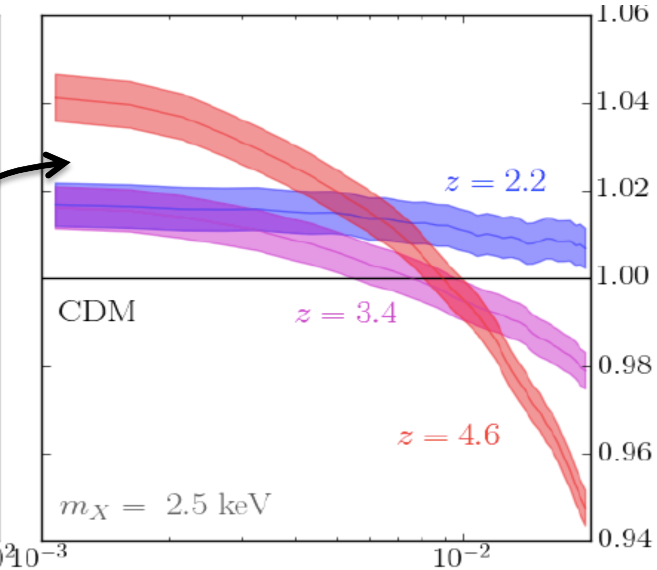
$P_{WDM}(k) / P_{CDM}(k)$ $P_{Ly\alpha}(k) \,.\, k / \pi$

Matter power spectrum



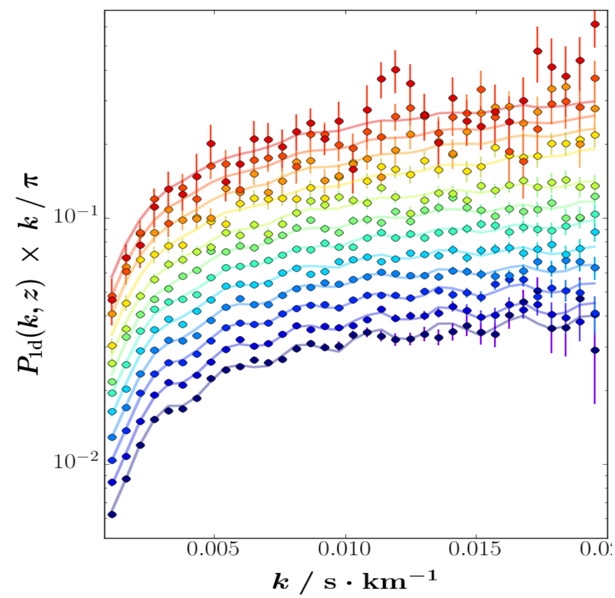
$k\ (h\ Mpc^{-1})$

Lyα flux power spectrum

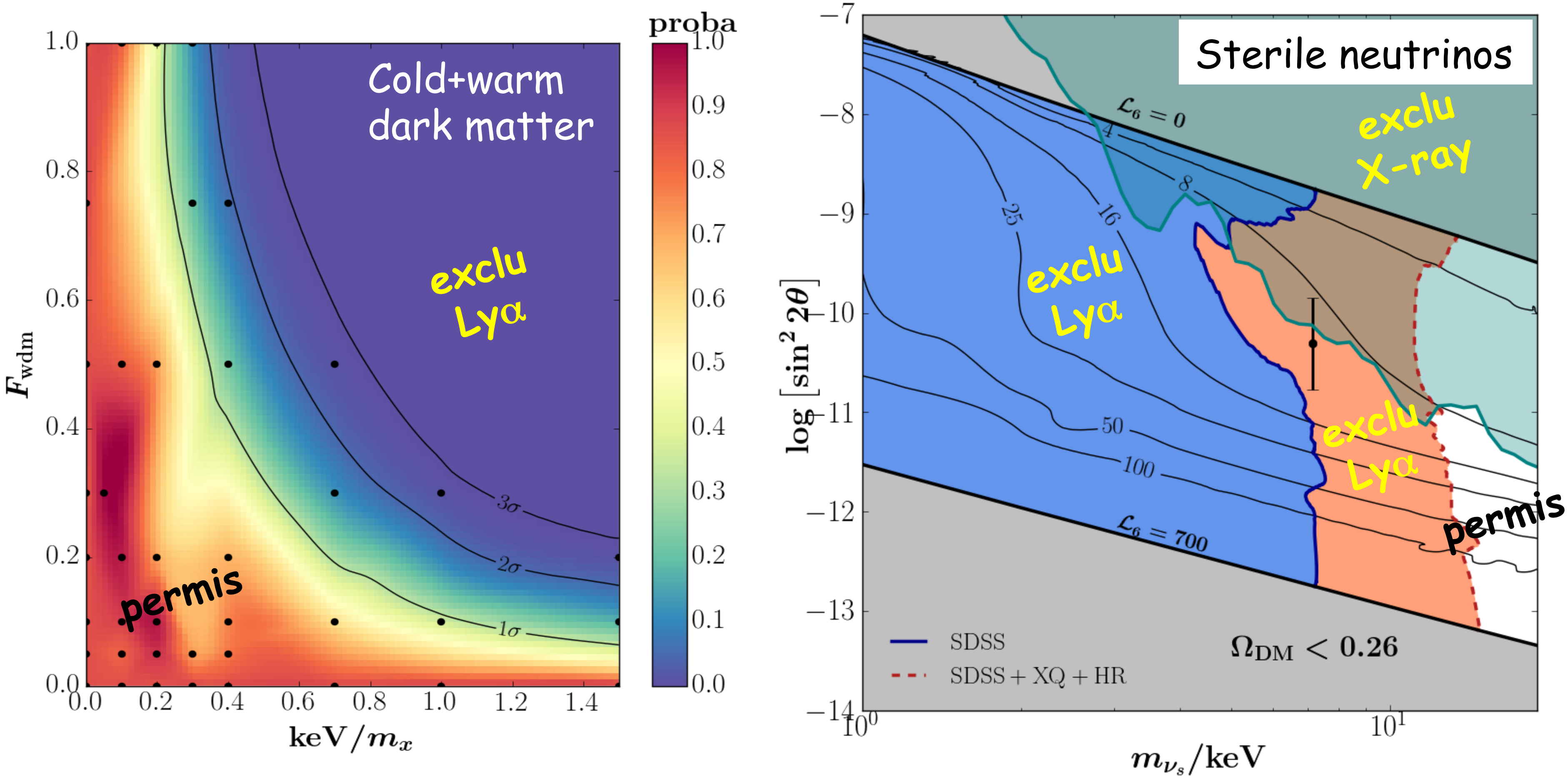


$k\ (s\ km^{-1})$

Fit on data



Cold+Warm or sterile ν Dark Matter



Constraints on cold+warm dark matter & on sterile neutrinos
Lyman-α data in tension with 7 keV sterile ν (X-ray data)

Baur, NPD++ (2017)

Conclusions

- **Neutrino astrophysics**

  Astrophysical origin of HE events confirmed

  No significant anisotropy, Galactic subcomponent possible

  New opening with multi-messenger astronomy

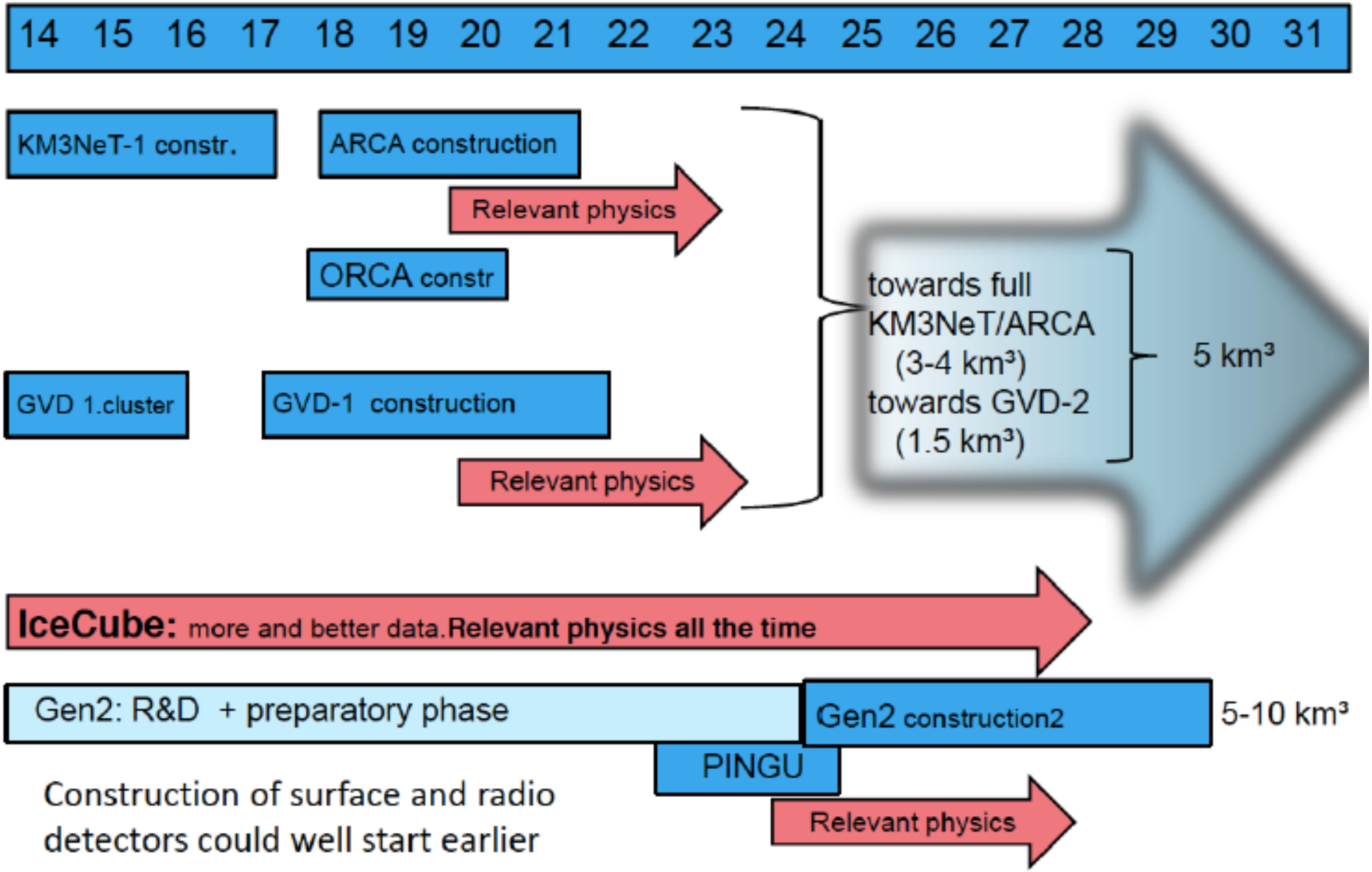
- **Particle physics** bounds on neutrino masses: $0.06 < \Sigma m < 6$ eV

  Cosmology: $\Sigma m_\nu < 0.12$ eV (95% CL) from Lyα+CMB

- **Constraint on warm dark matter & sterile neutrinos**
  - $m_{WDM} > 4.1$ keV (95% CL) for thermal relic
  - $m_{sterile} > 24$ keV (95% CL) for non-resonant production (NRP)
  - Conflict with sterile ν interpretation of 3.5 keV X-ray line

- **Prospects**
  - Next generation surveys (DESI, Euclid) aiming at $\sigma(\Sigma m_\nu) \sim 0.03$ eV

Schedule


14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
KM3NeT-1 constr.
ARCA construction
Relevant physics
ORCA constr
GVD 1.cluster
GVD-1 construction
Relevant physics
towards full KM3NeT/ARCA (3-4 km³)
towards GVD-2 (1.5 km³)
5 km³
IceCube: more and better data. Relevant physics all the time
Gen2: R&D + preparatory phase
Gen2 construction2
5-10 km³
PINGU
Relevant physics
Construction of surface and radio detectors could well start earlier