Particle Astrophysics : *Future Facilities for Multi-Messenger Astronomy*

Jim Hinton

University of Leicester

IOP HEPP 2010 *UCL 31st March 2010*

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2 Multi-messenger Astronomy?

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- Traditional astronomy (pre 1980s)
  - 10^{-7} – 10^{10} eV photons (radio – gamma-ray)
- Now - the new photon astronomy
  - VHE gamma-rays 10^{11}-10^{14} eV

  (+ neutrinos from SN 1987a and the sun)
- Soon (within ~10 years)
  - Charged particle astronomy (>10^{19} eV protons)
  - VHE-UHE neutrino astronomy
  - Gravitational wave astronomy

Particle Astrophysics

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Particle Astrophysics

See also talks by Werner Hofmann, Malcolm Fairbairn, Martin Hendry, Andrew Jaffe, Henrique Araujo

4 Major Themes

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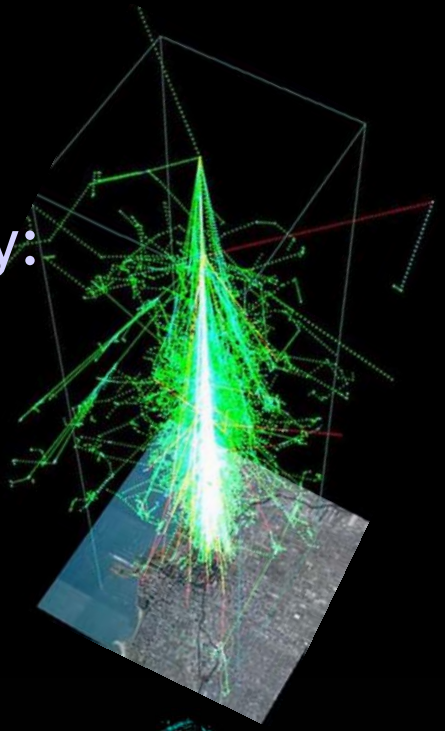
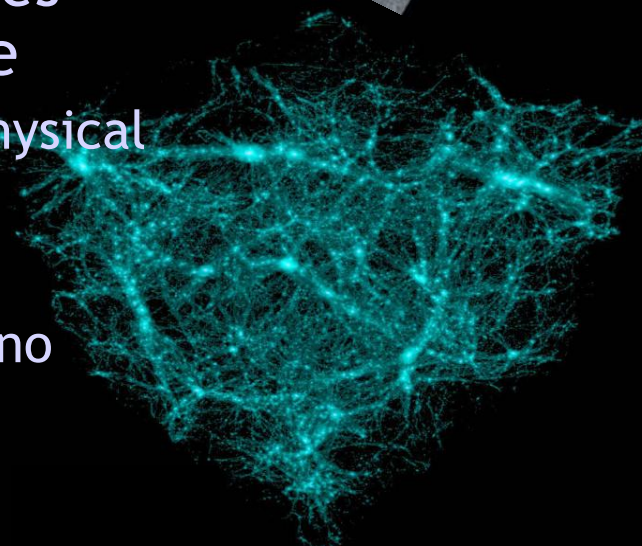
- "Cosmic Rays"
  - Acceleration, propagation and radiation of ultra-relativistic particles, specifically:
    - Where and how are particles accelerated to very high energies in the universe?
    - Overlap with high energy astrophysics
- Dark Matter
  - Identifying the nature (mass, cross-section) of the non-baryonic particles which make up most of the universe
    - Indirect measurement in-situ in astrophysical environments
  - + Other fundamental physics
    - tests of Lorentz Invariance, UHE neutrino interactions/cross-section, ...





5 Dark Matter Detection

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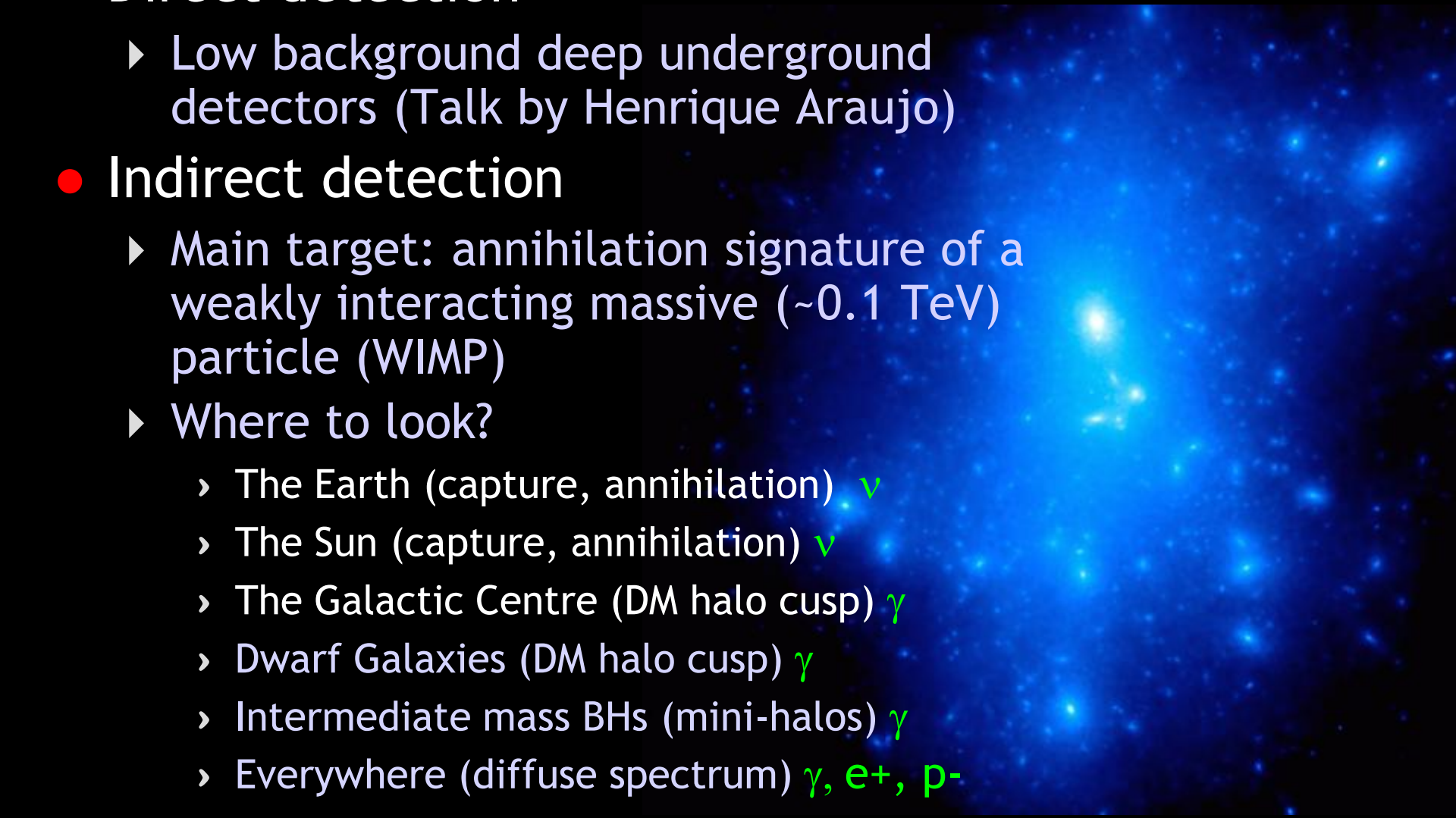
- Direct detection
  - Low background deep underground detectors (Talk by Henrique Araujo)
- Indirect detection
  - Main target: annihilation signature of a weakly interacting massive (~0.1 TeV) particle (WIMP)
  - Where to look?
    - The Earth (capture, annihilation) ν
    - The Sun (capture, annihilation) ν
    - The Galactic Centre (DM halo cusp) γ
    - Dwarf Galaxies (DM halo cusp) γ
    - Intermediate mass BHs (mini-halos) γ
    - Everywhere (diffuse spectrum) γ, e^+, p^-



Simulated DM density, Moore et al 2005

6 Dark Matter Detection

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    - Everywhere (diffuse spectrum) γ, e+, p-

Multi-messenger (+direct & accelerator) to tie-down astrophysics & PP

Simulated DM density, Moore et al 2005

7 Cosmic rays

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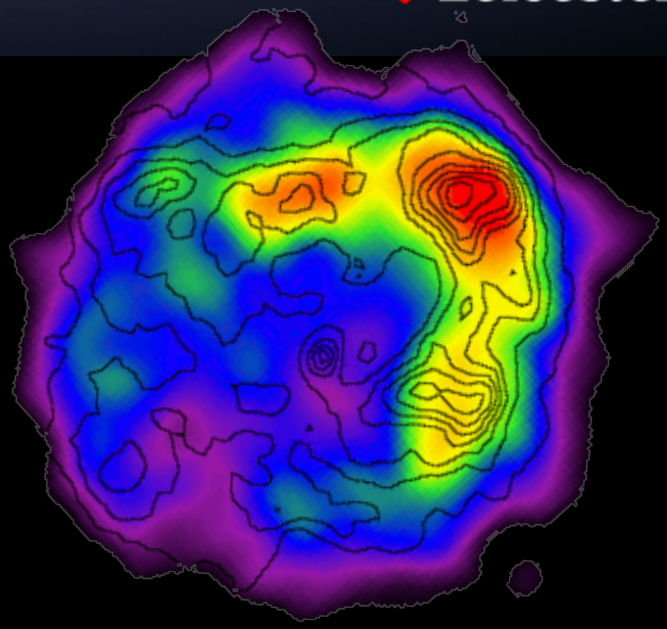
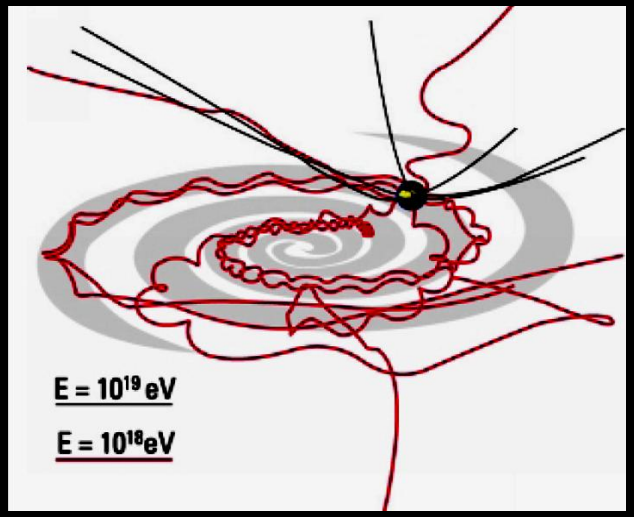


- Sources
  - Galactic (below PeV): Many - SNRs may dominate, Extragalactic (above 10^{19} eV): Unknown – AGN may dominate
- Composition
  - Protons + nuclei, electrons (<10 TeV), mixture well known only at low E, Fe may dominate at highest E
- Deflections
  - Galactic deflection ~$3^\circ \times Z/(E/10^{20}$ eV)
    - Diffusion inside galaxy for E<10^{18} eV
  - Extragalactic
    - Very uncertain, a few deg for 10 Mpc?
- Charged particle astronomy may be possible >6x10^{19} eV



8 Interactions in Sources

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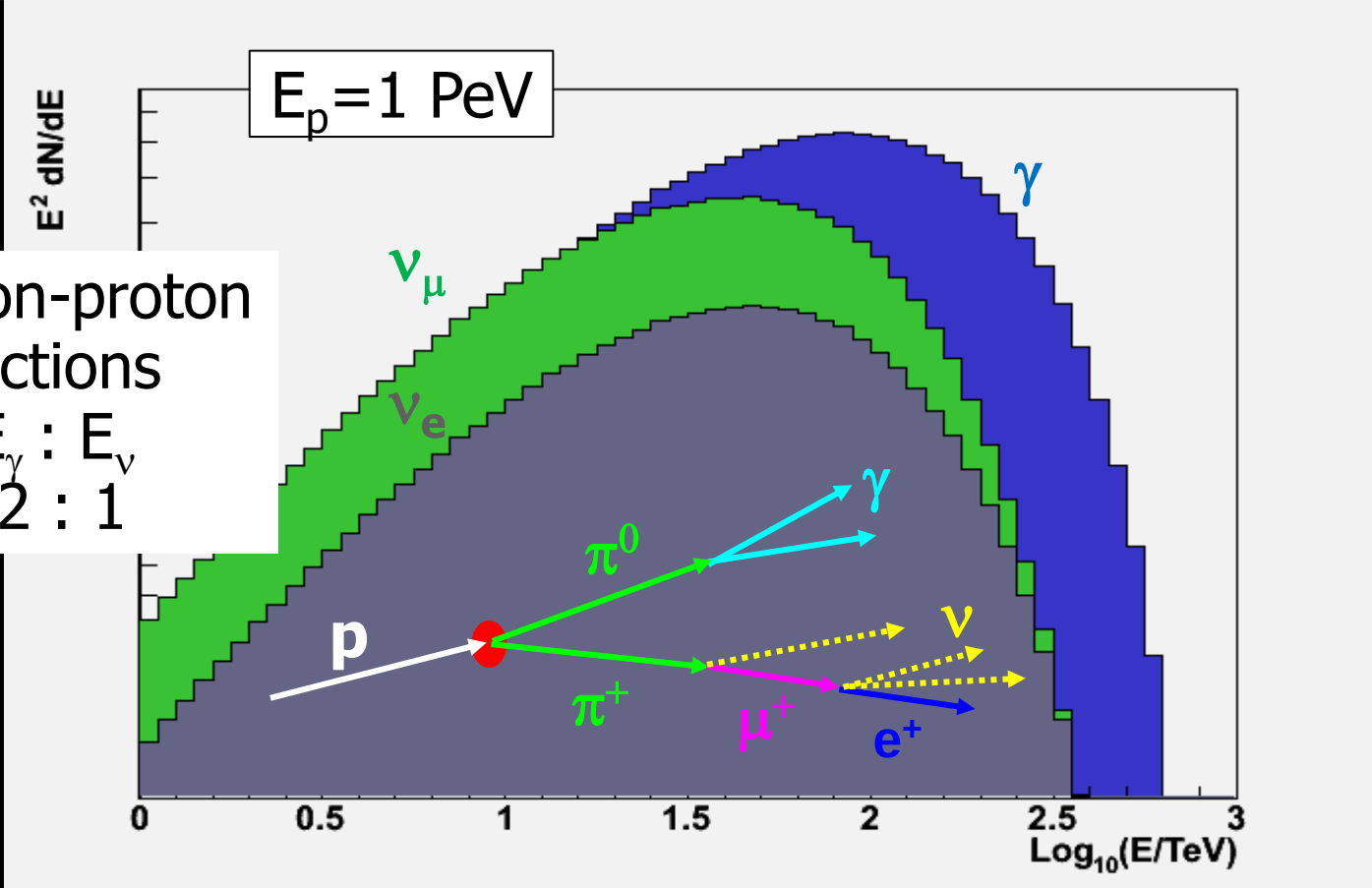
e.g. proton-proton Interactions

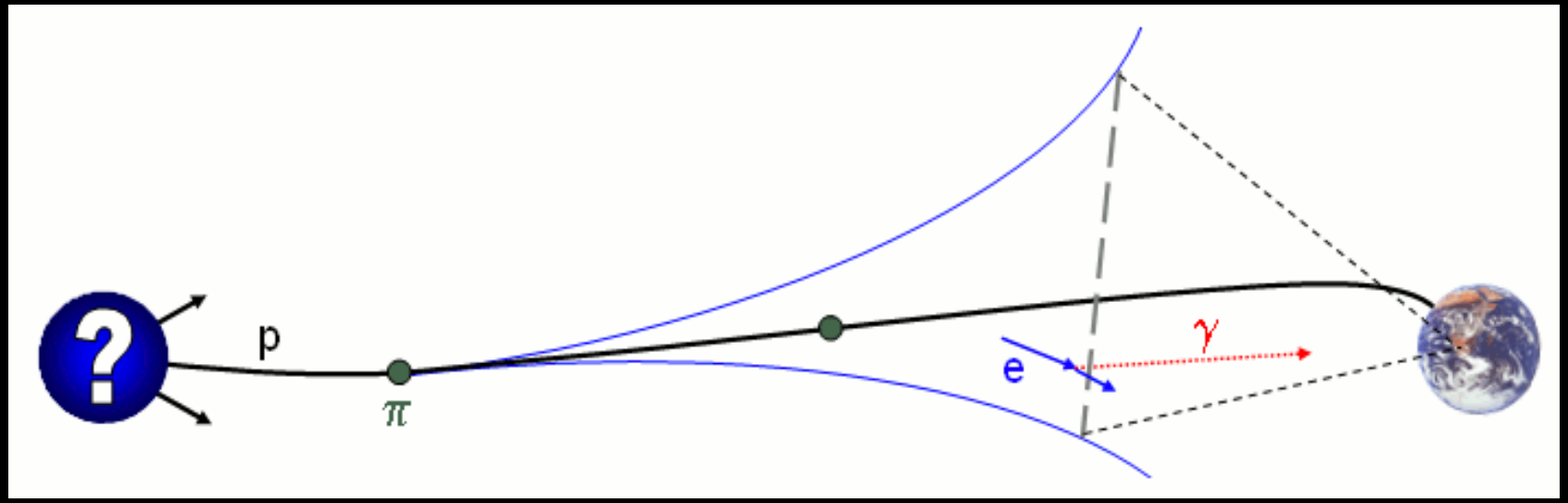
$E_p : E_\gamma : E_\nu$

20 : 2 : 1



- Gamma+neutrino to identify parent particles
  - Removes ambiguity with IC scattering
  - Challenge – expect very few neutrino events/km^3.year

9 ..and during propagation



- GZK effect for protons above 6 x 10^{19} eV
  - Interaction with CMBR, pion (and hence neutrino and gamma-ray) production
  - Electromagnetic part cascades on radio/CMBR
    - Windows for EG photon astronomy <100 TeV and >10 EeV
- Gamma-rays and neutrinos as signatures
  - Diffuse γ+ν signal + γ-ray halos around sources

10 Towards Observatories

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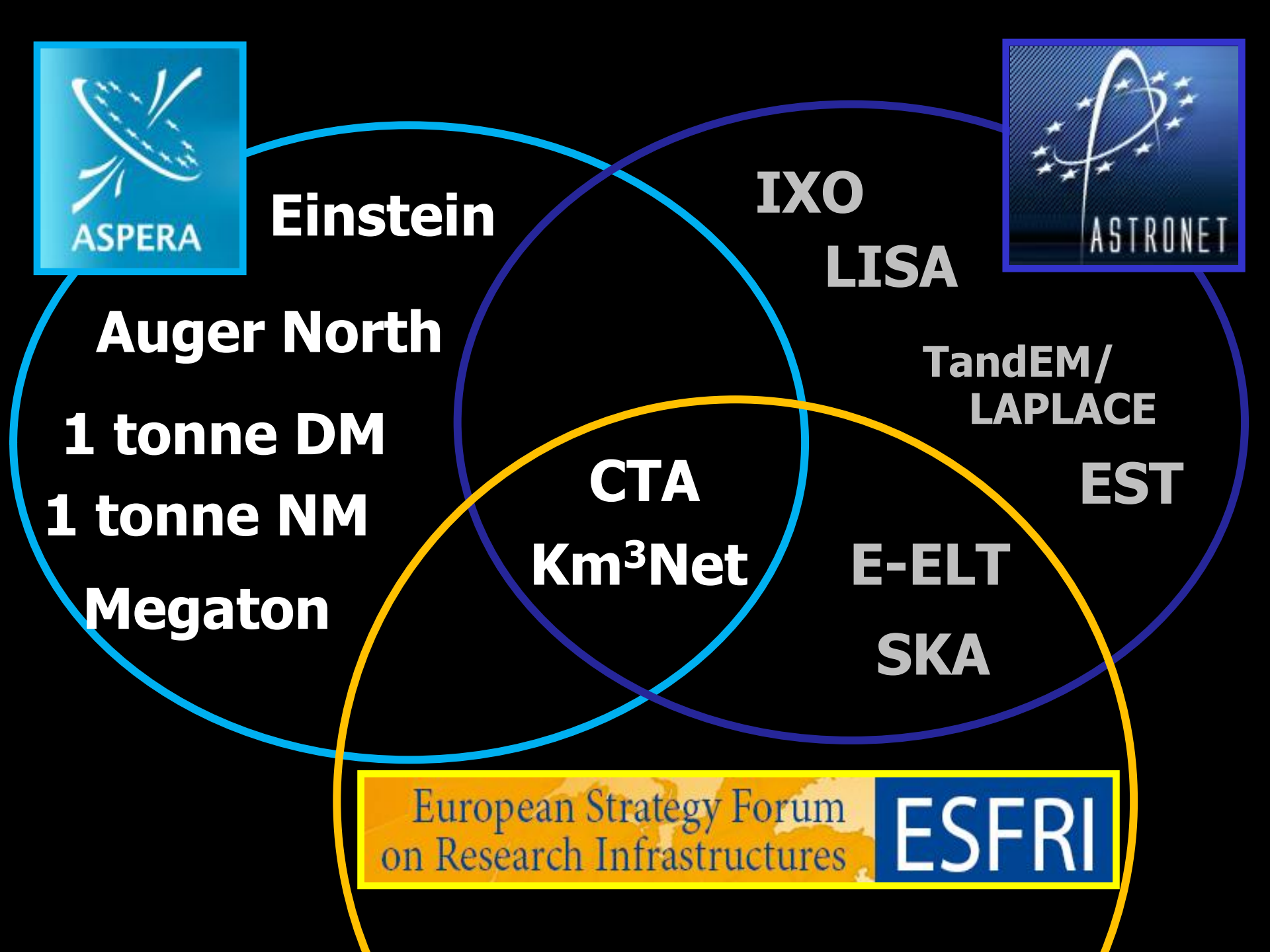
- AGASA, HiRes → Auger S+N, JEM-EUSO
  - Technique: Fluorescence and ground particle detection
  - Goals: charged particle astronomy, UHE ν det., UHE γ det.
- ANTARES, AMANDA → KM3, IceCube
  - Technique: Water/Ice Cherenkov
  - Goals: diffuse signatures of ν sources, individual ν sources, dark matter detection
- ANITA, ACORNE → ARA, ARIANNA ....
  - Technique: Radio, Acoustic shower detection
  - Goals: Diffuse (GZK) UHE neutrino flux, neutrino physics
- HESS, MAGIC → CTA (and VERITAS → AGIS)
  - Technique: Imaging Air Cherenkov
  - Goals: >1000 γ sources, detailed study of cosmic ray sources, Dark Matter detection


ASPERA
Einstein
Auger North
1 tonne DM
1 tonne NM
Megaton
IXO
LISA
ASTRONET
TandEM/
LAPLACE
EST
CTA
Km3Net
E-ELT
SKA
European Strategy Forum
on Research Infrastructures
ESFRI

12 Pierre Auger Observatory

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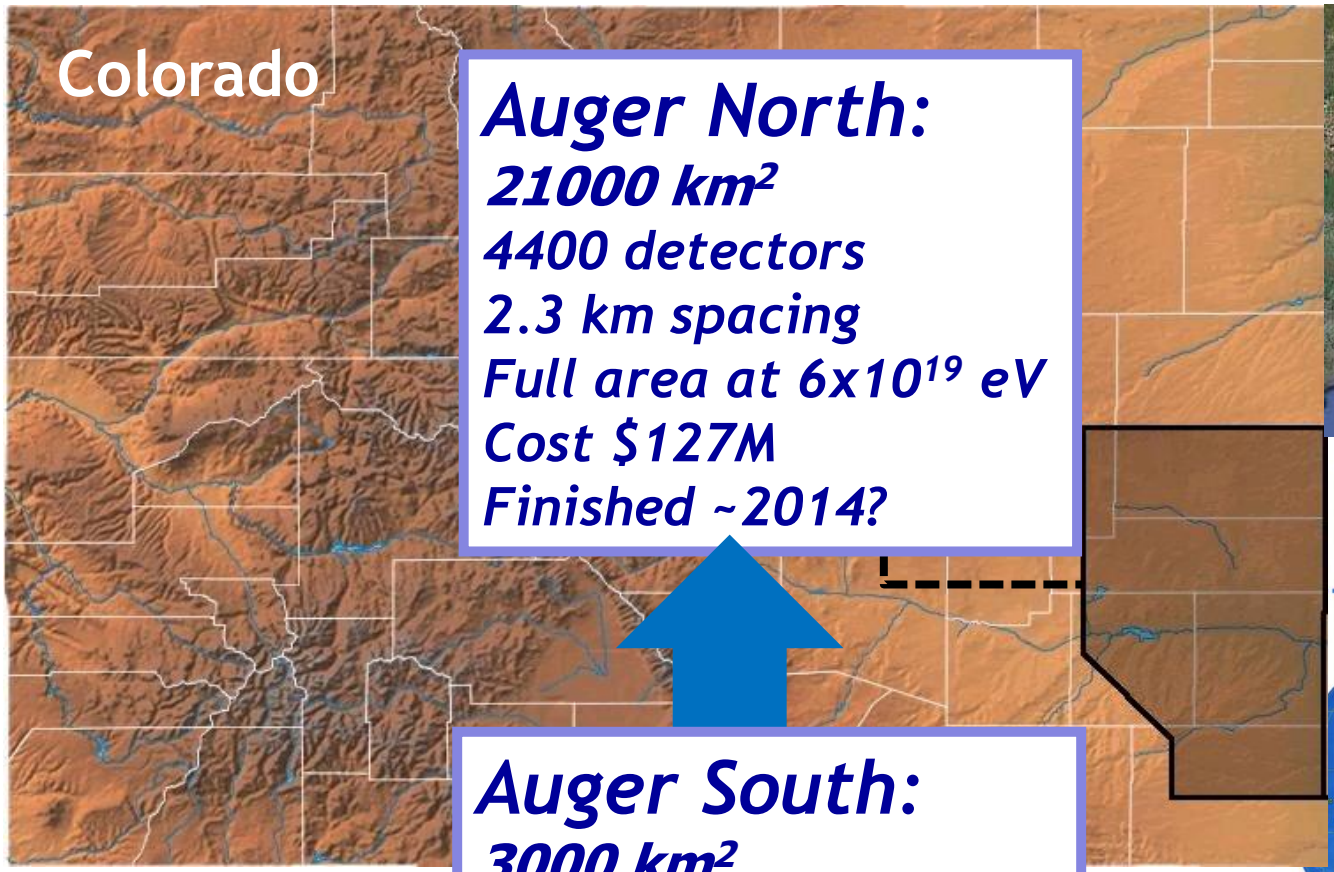
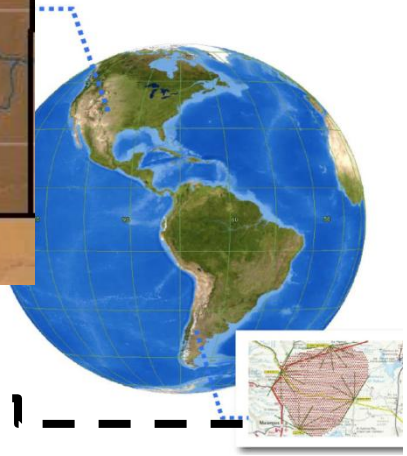


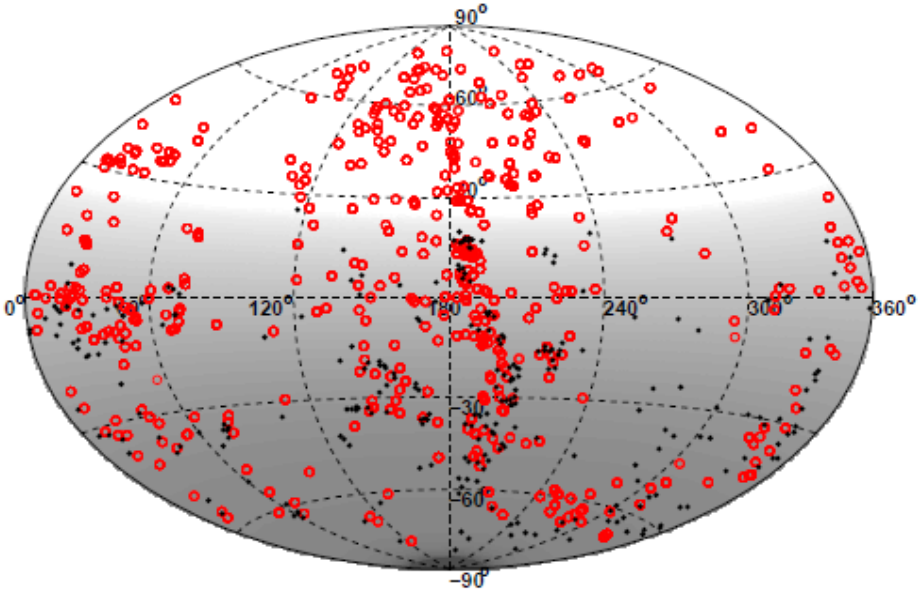
Auger North:
21000 km²
4400 detectors
2.3 km spacing
Full area at 6×10^{19} eV
Cost $127M
Finished ~2014?



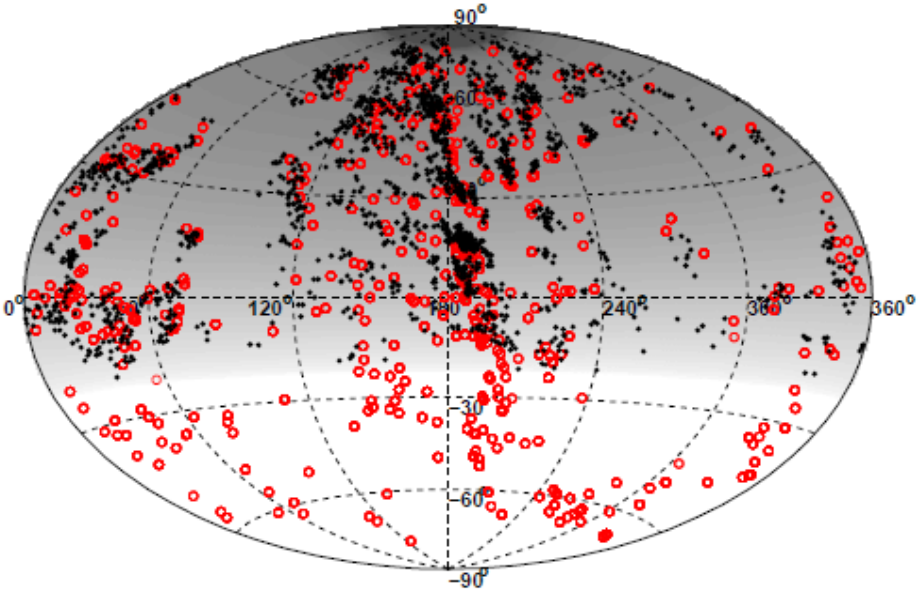
Auger South:
3000 km²
1600 detectors
1.5 km spacing
Full area at 10^{19} eV
Cost $54M
Finished 2008

Example: Events E>55 EeV, t=10 years

Auger South, N=270



Auger North, N=1890



simulation with sources $\sim$ VCV, BSS and protons

- full FD coverage, $t = 10$ years, $\tau = 13\%$
  $\rightarrow$South: 35 events above 55 EeV
  $\rightarrow$North: 246 events above 55 EeV

Micheal Unger
Karlsruhe

14 UHECRs from space

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- JEM-EUSO
  - Fresnel lens based system
  - Installed on ISS 2015
  - 5 years of operation
  - >400 km altitude

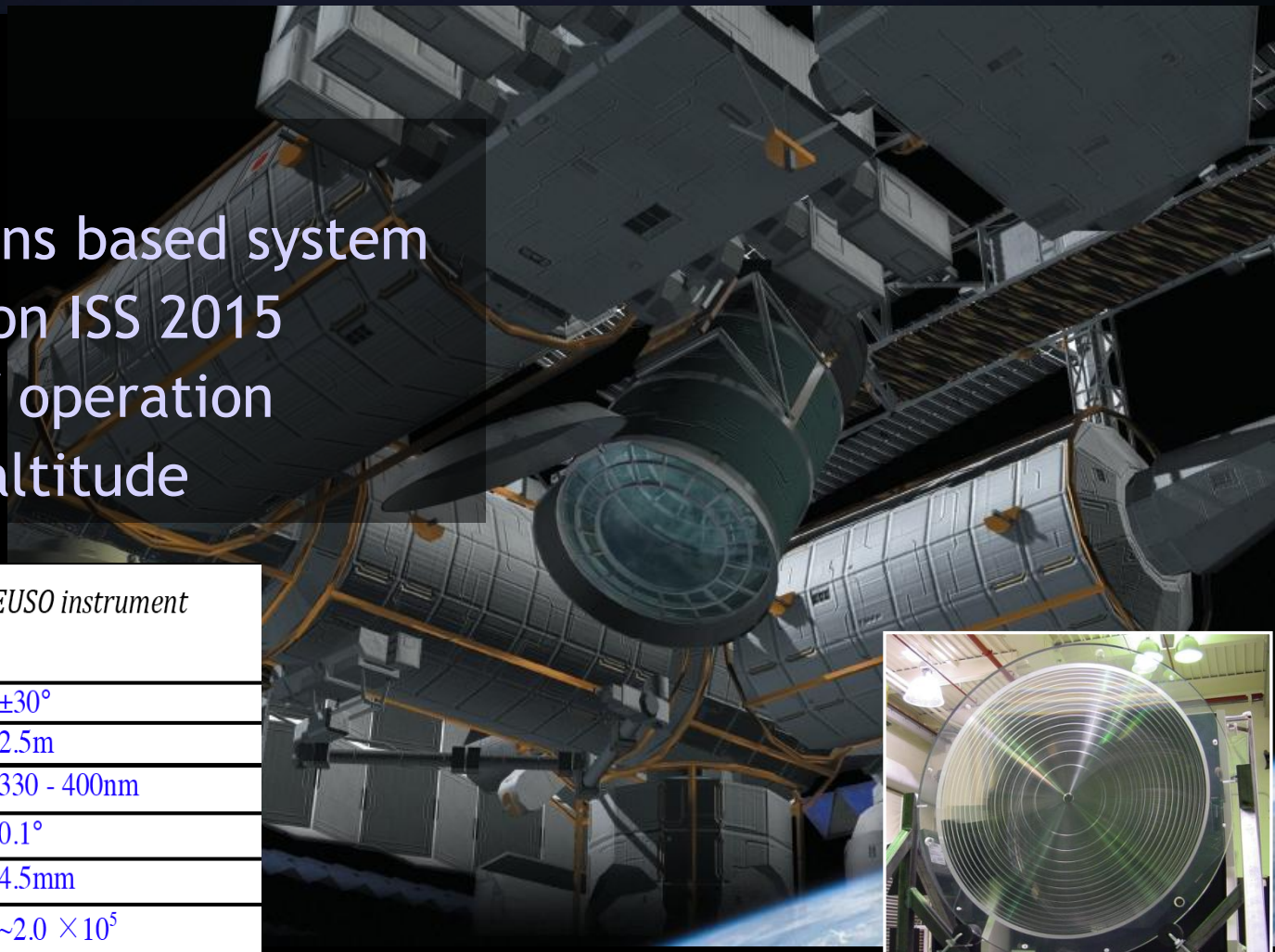
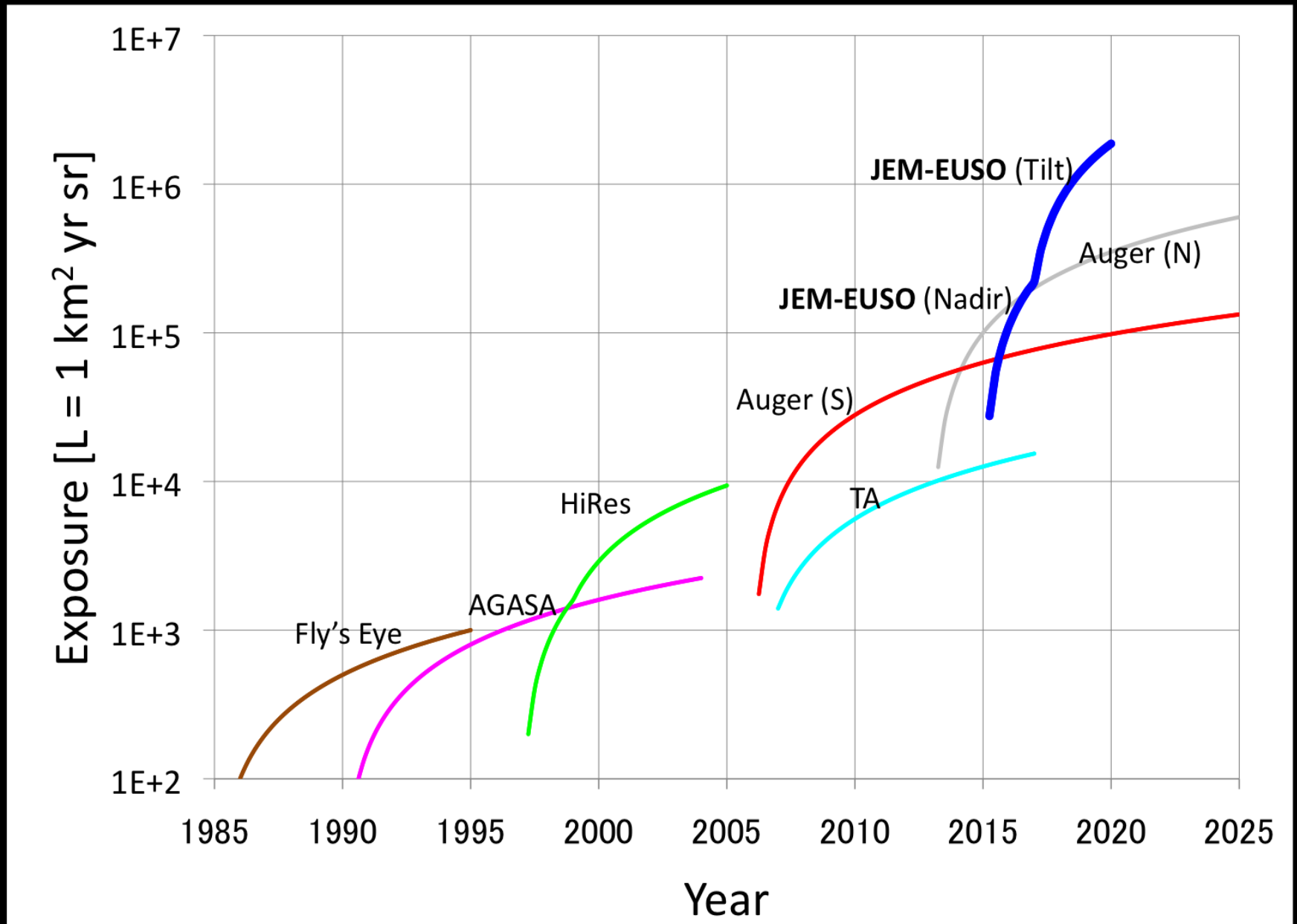


Table 1. *Main parameter of the JEM-EUSO instrument*

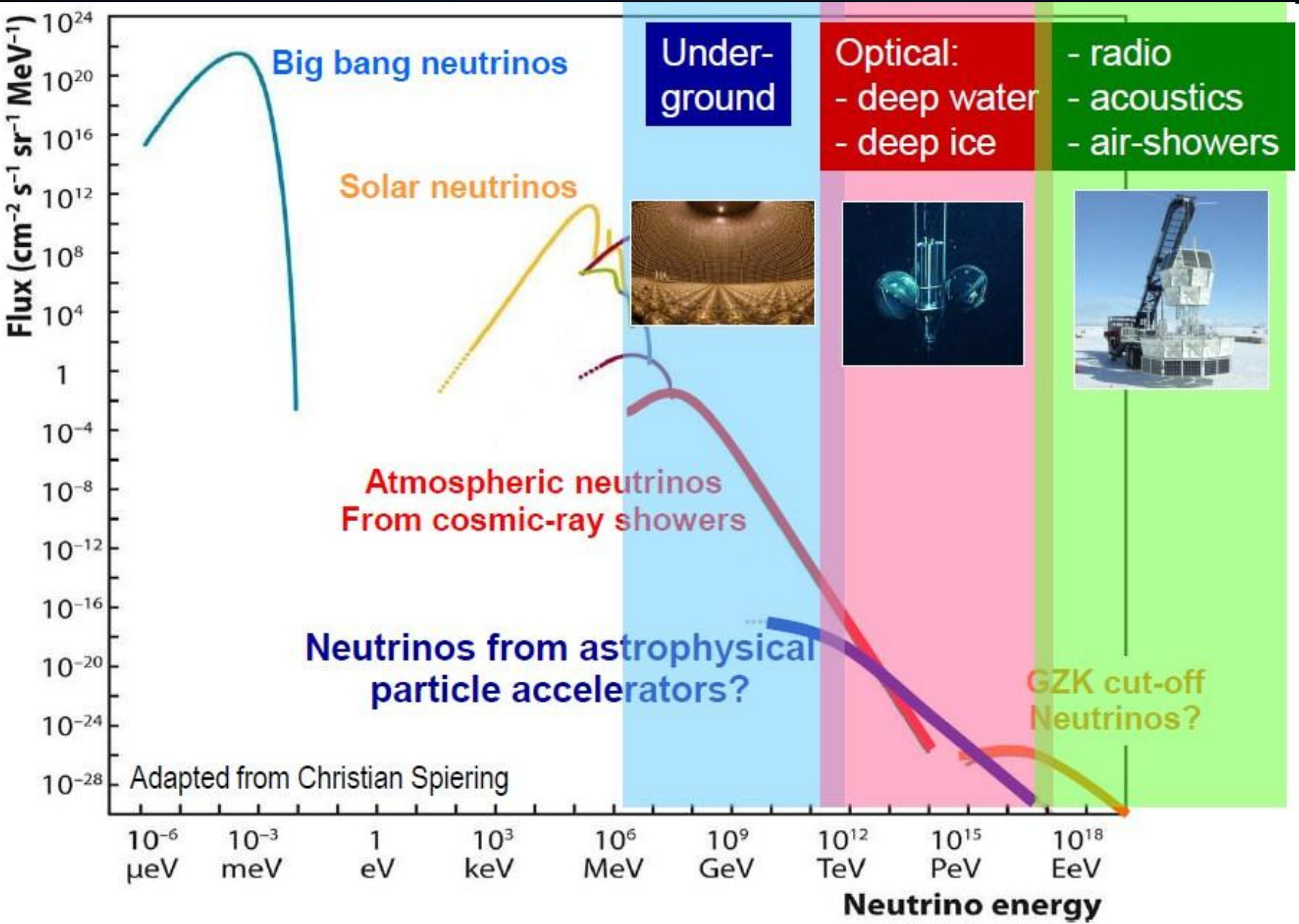
Field of View	±30°
Aperture Diameter	2.5m
Optical bandwidth	330 - 400nm
Angular granularity	0.1°
Pixel Size	4.5mm
Number of Pixels	~2.0 $\times 10^5$
Pixel Size at the ground	750m
Duty Cycle	~20 - 25%
Observational Area	~2 $\times$ 10^5 km^2

(NB – full efficiency only at 10^{20} eV)

UHE Exposure



Neutrino Astronomy



SNO+

Leeds, Liverpool, Oxford, QMUL, Sussex

SUPERNOVA NEUTRINOS

Variety of interactions in scintillator with unique tags and sensitivities to ν_e, $\bar{\nu}_e$ & ν_x

$$\bar{\nu}_e + p \longrightarrow e^+ + n$$

$$\bar{\nu}_e + {}^{12}C \longrightarrow {}^{12}B + e^+$$
$$\hookrightarrow \bar{\nu}_e + {}^{12}C + e^-$$

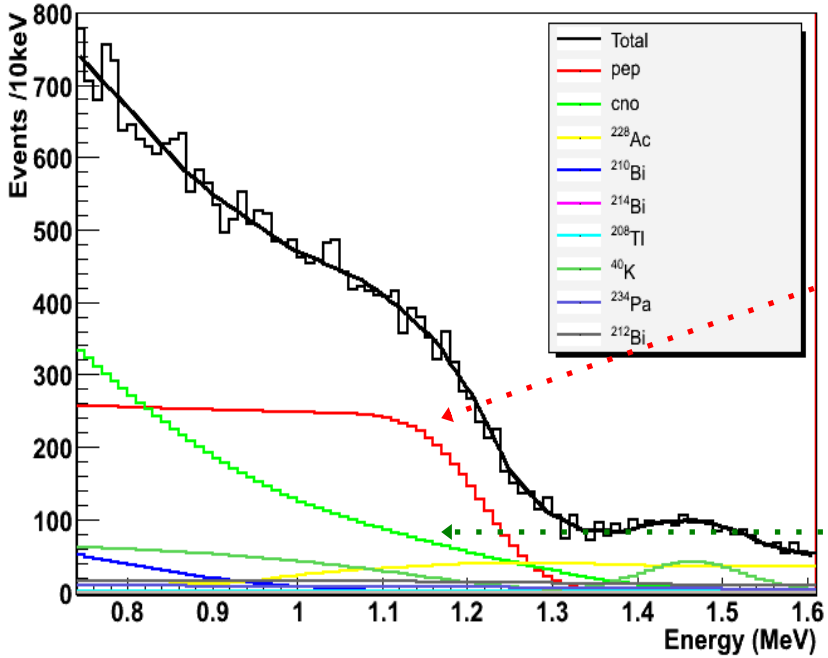
$$\nu_e + {}^{12}C \longrightarrow {}^{12}N + e^-$$
$$\hookrightarrow \nu_e + {}^{12}C + e^+$$

$$\nu_x + {}^{12}C \longrightarrow {}^{12}C^* + \nu_x$$
$$\hookrightarrow {}^{12}C + \gamma \text{ (15.1 MeV)}$$

$$\nu_x + p \longrightarrow \nu_x + p$$

$$\nu_x + e^- \longrightarrow \nu_x + e^-$$

Simulated SNO+ Energy Spectrum



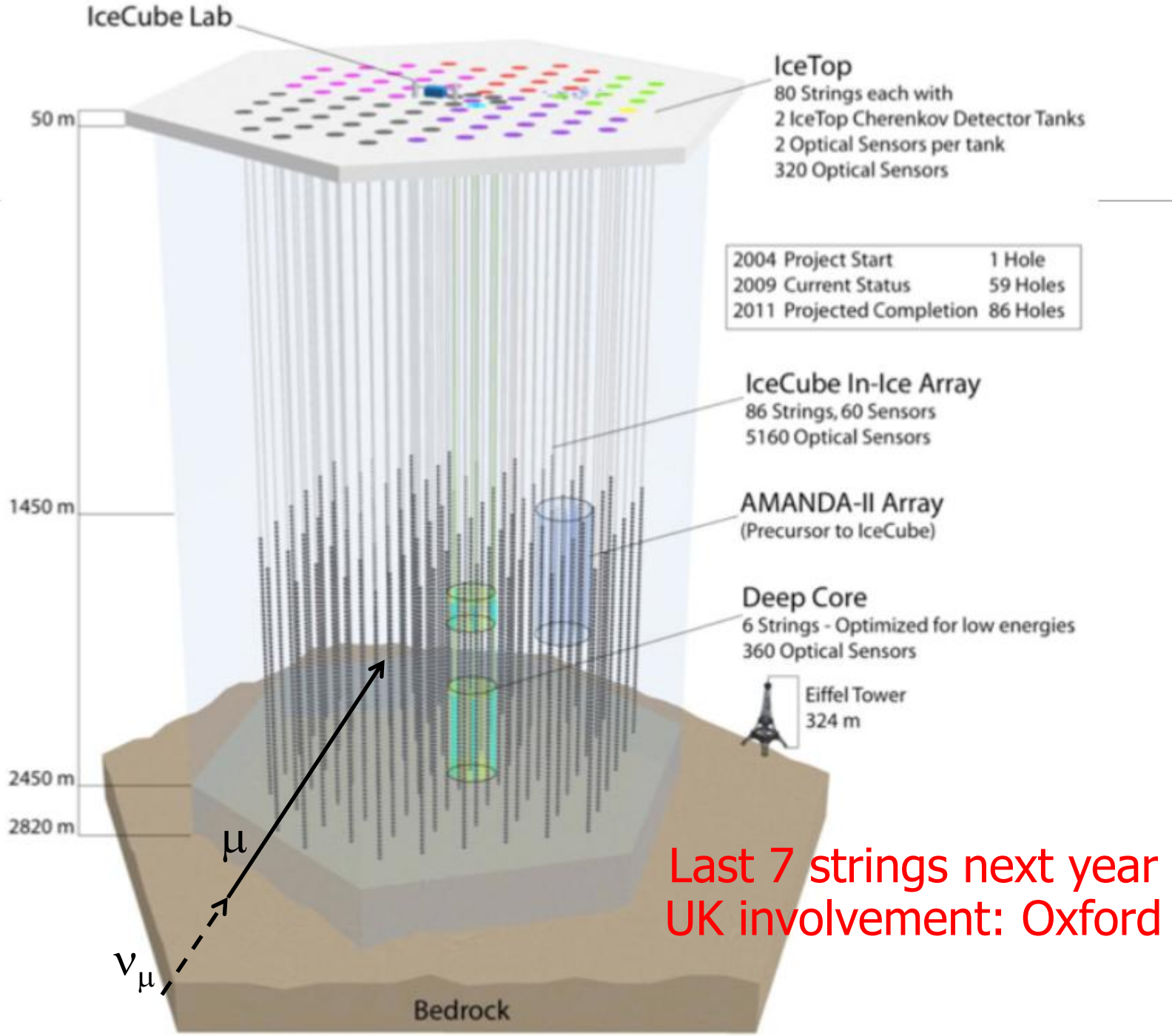
pep Solar ν

Test solar luminosity constraint

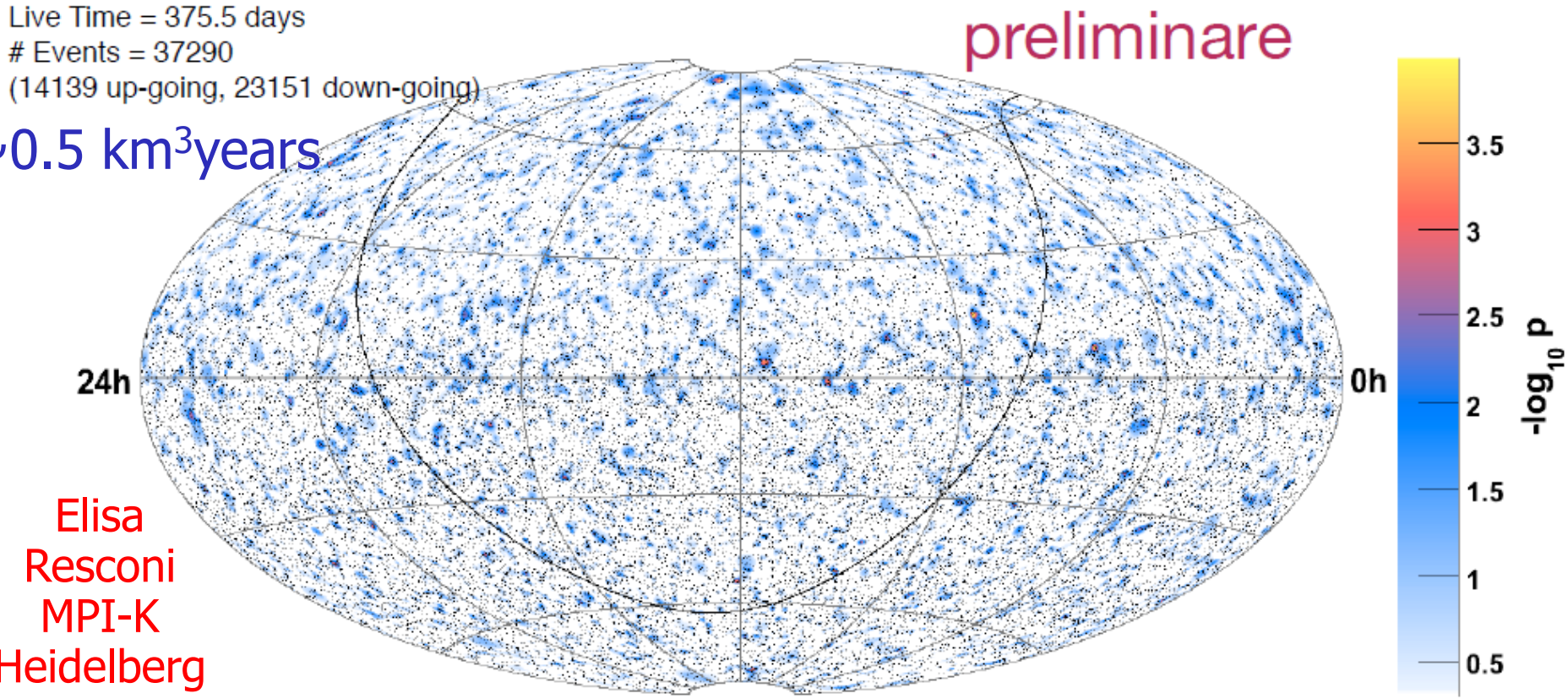
Study vacuum/MSW transition

CNO Solar ν

Resolve solar metalicity problem


IceCube Lab
IceTop
80 Strings each with
2 IceTop Cherenkov Detector Tanks
2 Optical Sensors per tank
320 Optical Sensors
50 m
2004 Project Start 1 Hole
2009 Current Status 59 Holes
2011 Projected Completion 86 Holes
IceCube In-Ice Array
86 Strings, 60 Sensors
5160 Optical Sensors
1450 m
AMANDA-II Array
(Precursor to IceCube)
Deep Core
6 Strings - Optimized for low energies
360 Optical Sensors
Eiffel Tower
324 m
2450 m
2820 m
μ
νμ
Bedrock
Last 7 strings next year
UK involvement: Oxford

Point Source Search: IC40 just starting



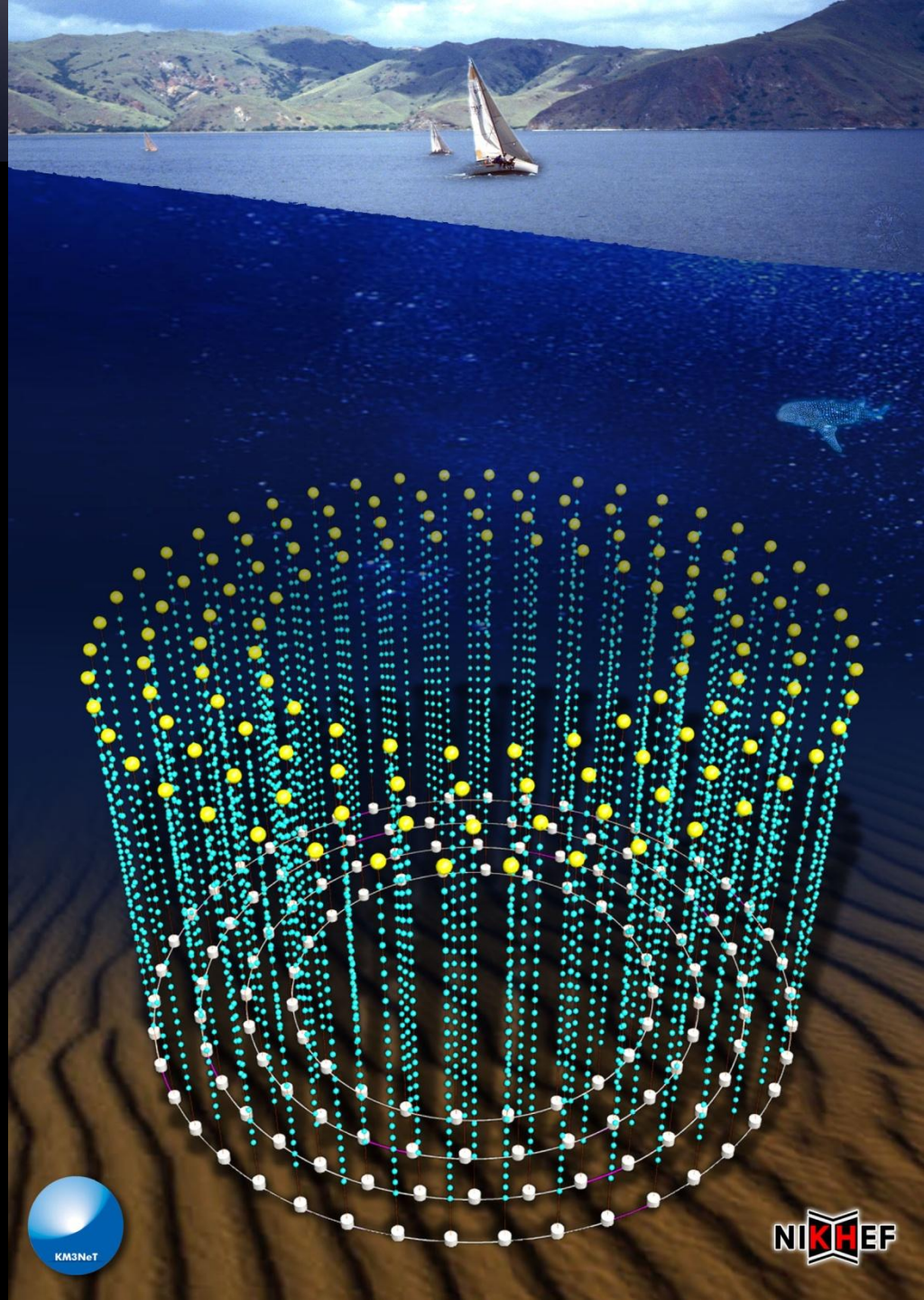
Elisa Resconi MPI-K Heidelberg

IC40, Northern sky & Southern sky

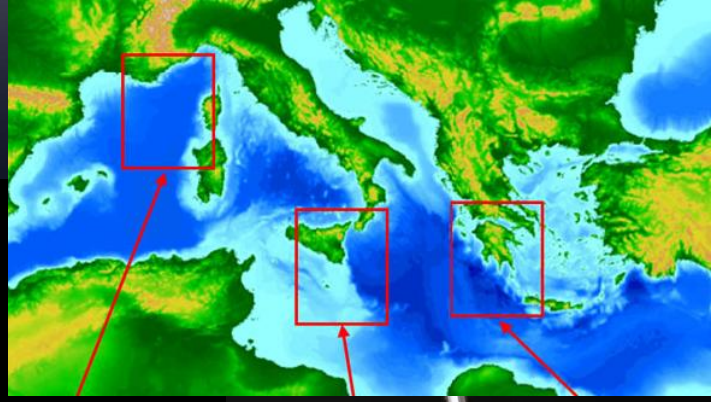
No evidence yet for Neutrino-sources

20 KM3Net

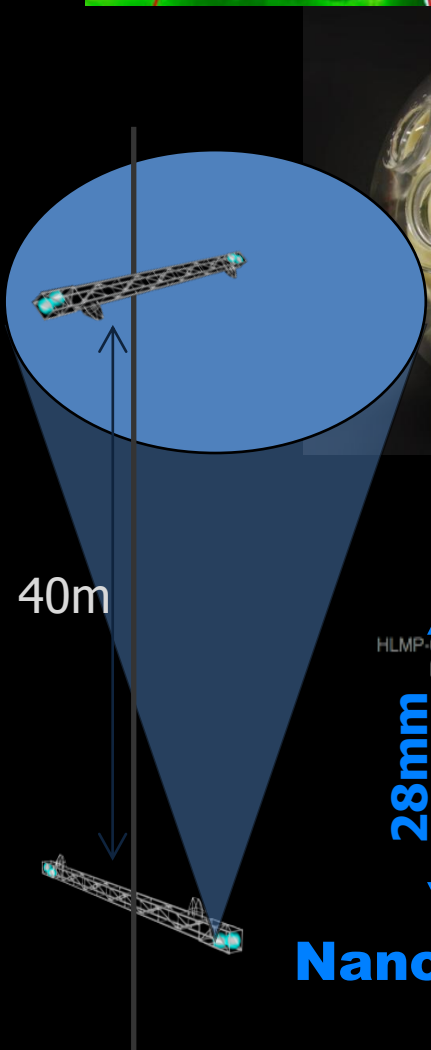
- Project to build a >2 km^3 neutrino detector in the Mediterranean
  - Sensitivity a factor of 3 better than IceCube for €150M
    - ~2×10^{-12} $erg/cm^2/s$ (90% conf. 3 years)
  - Better access to inner galaxy
    - Views southern sky
  - Better angular resolution
    - 0.1° at high energies



21 KM3Net



- Status
  - EU funded Preparatory Phase
  - Site decision in ~1 year
    - 3 candidate sites
  - Construction 2013-2017
  - Ongoing studies to optimise OM design, deployment method and string layout
- UK groups
  - Sheffield, Leeds, (Liverpool)
  - Involvement in calibration system
    - Nanobeacon - compact/low-cost nanosecond blue light flasher



Nanobeacon

UHE neutrinos

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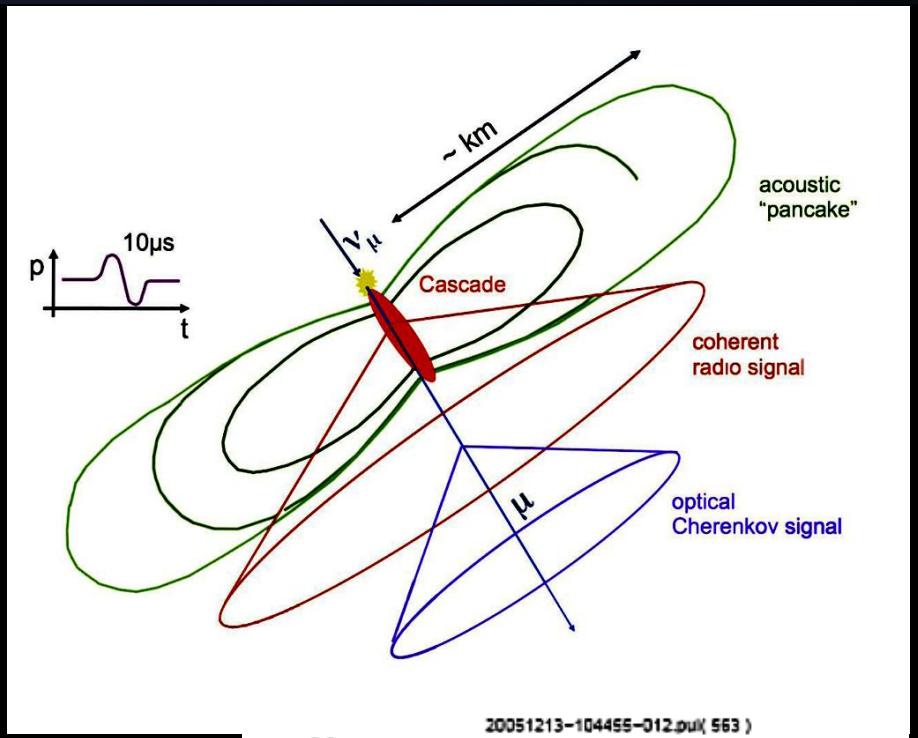
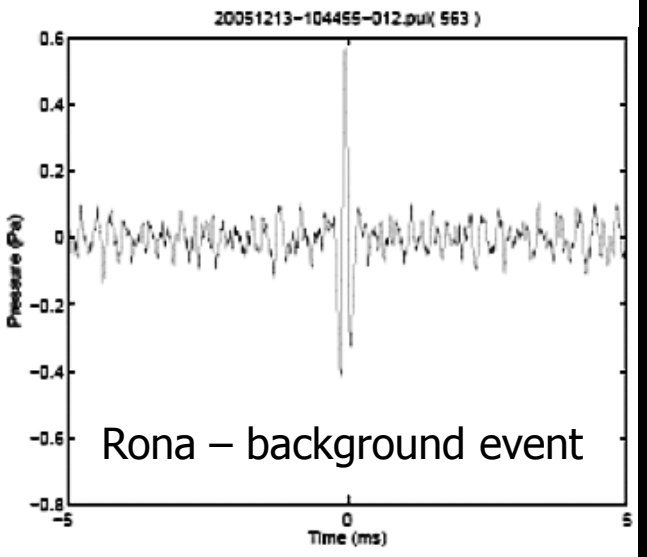
- Radio and acoustic signals are coherent
  - Power $\propto E^2$
  - +larger propagation distance than optical
  - Promising for UHE
- Acoustic
  - In ice
    - SPATS within IceCube
  - In water
    - AMADEUS System of ANTARES
    - ACORNE pilot project in Scotland, see talk from Terry Sloan yesterday
      - Sheffield, Lancaster, UCL, Northumbria





23 UHE neutrinos - Radio

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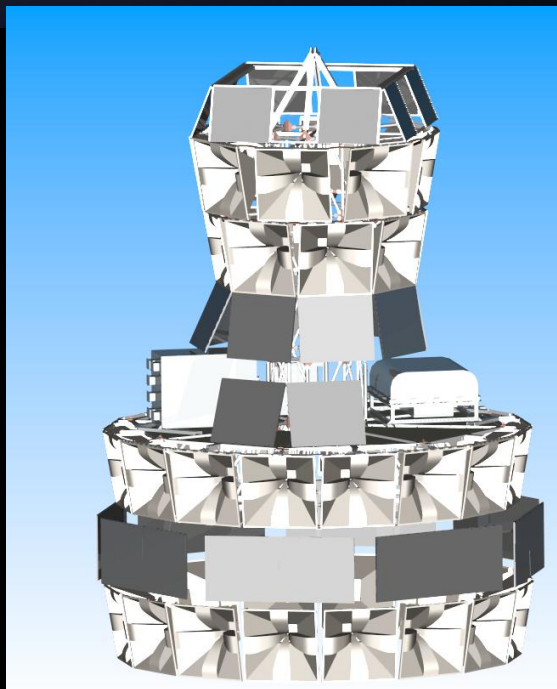
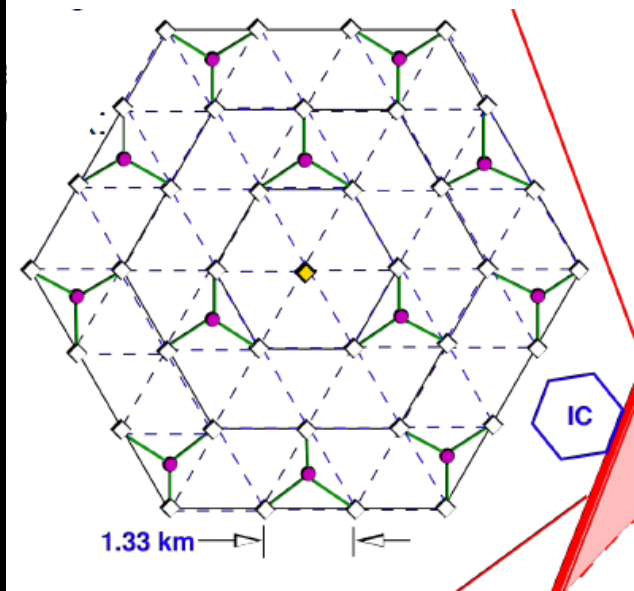
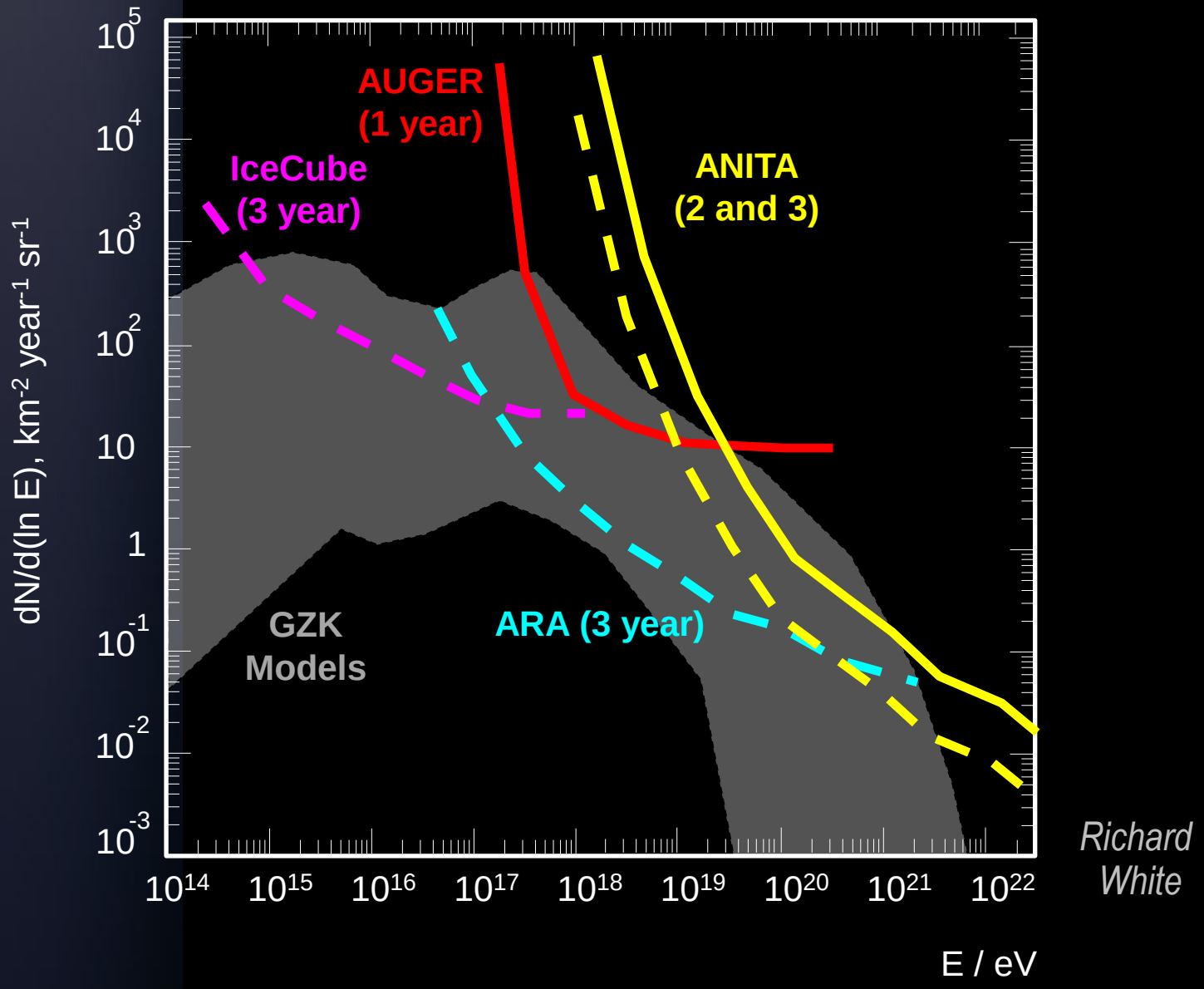
- ANITA
  - 1 million km^3 ice volume monitored
    - Best limit so far at UHE (ANITA-2)
    - See summary of ANITA-1 and -2 by WH
  - ANITA-3 – factor 3-5 improvement
    - Flight 2012-2013, UK involvement: UCL
- ARA
  - 80 km^2 array 200m under the South Polar ice (next to IceCube)
  - Lower threshold – should see GZK neutrinos at 10^{18}eV – and better energy resolution
  - UK involvement: UCL

(several other radio array concepts)





24 Limits


AUGER
(1 year)
IceCube
(3 year)
ANITA
(2 and 3)
GZK
Models
ARA (3 year)
dN/d(ln E), km-2 year-1 sr-1
E / eV
Richard
White

25 Don't forget the photons

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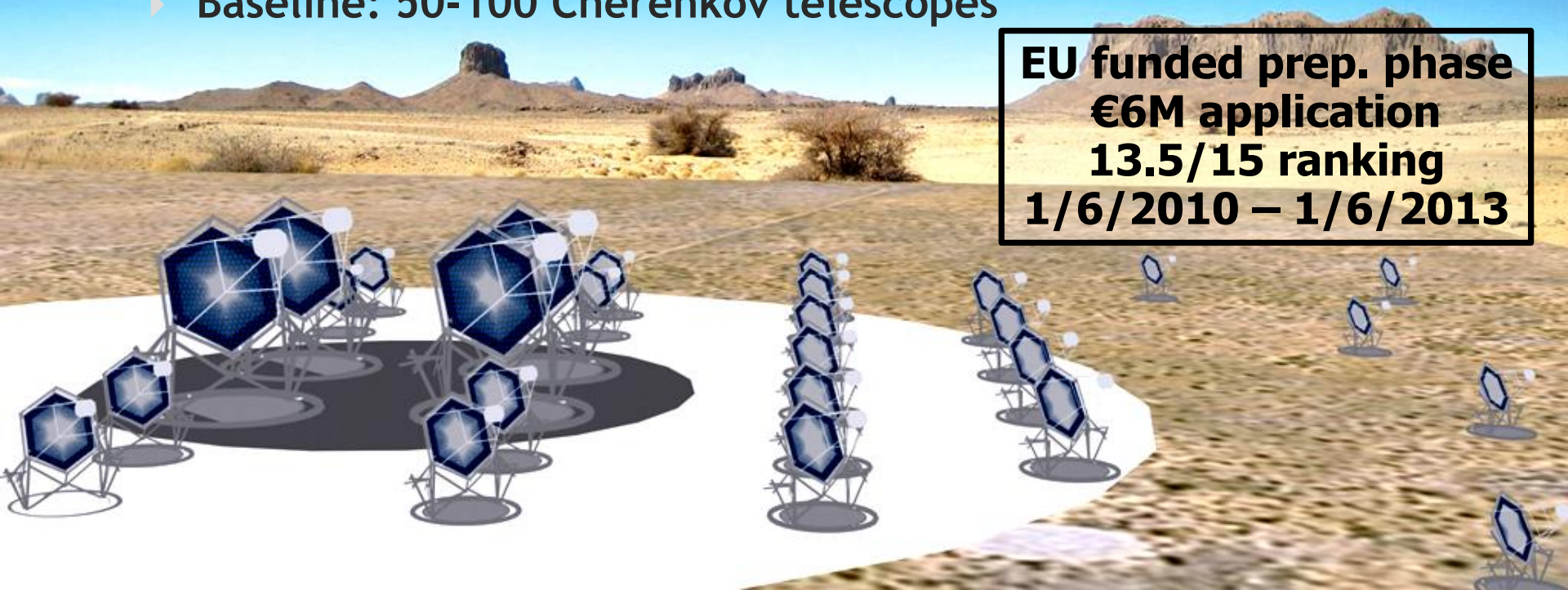
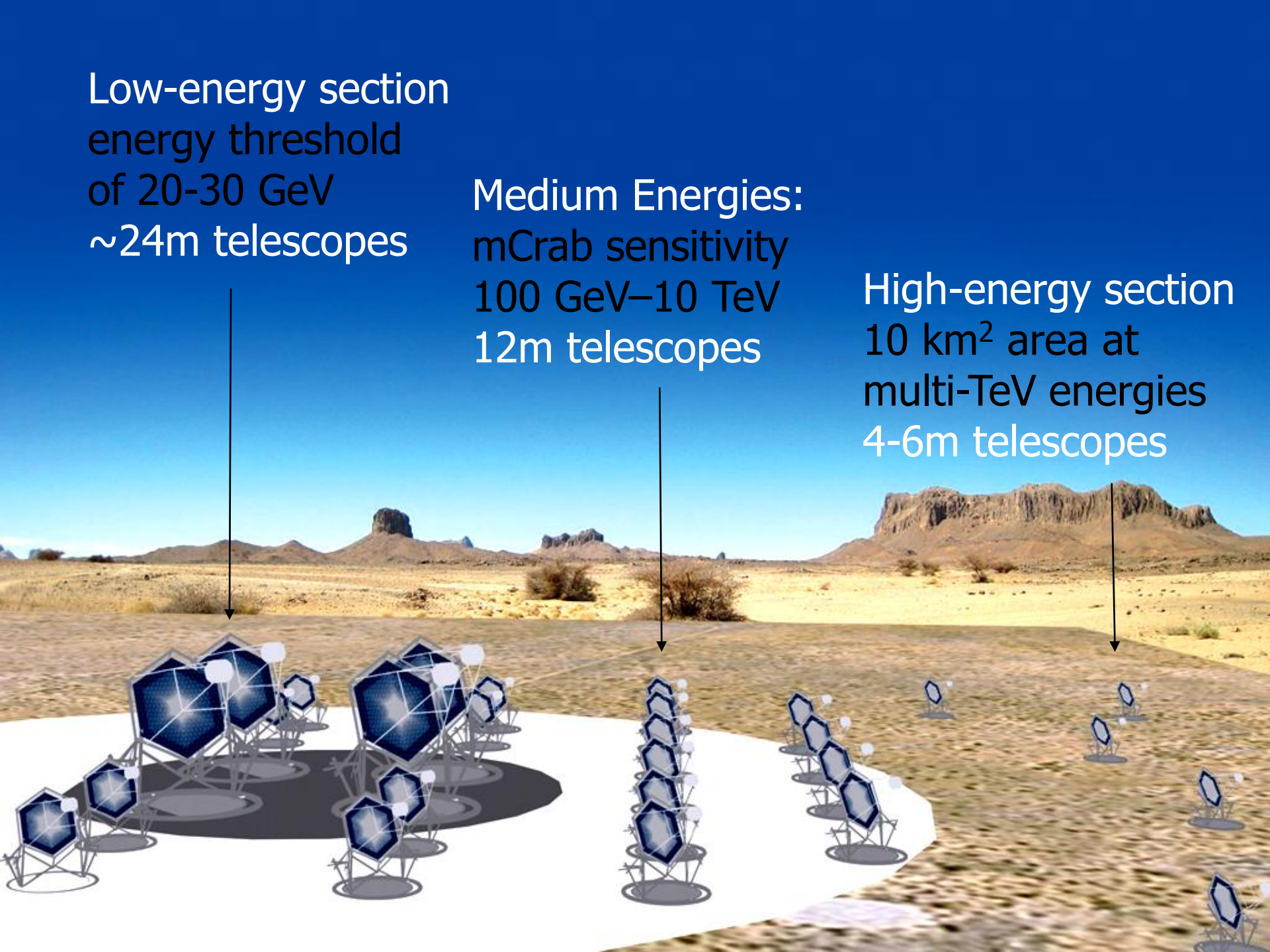
- Very high energy (~TeV) gamma-rays
  - Huge collection area (km^2 cf m^2) $\rightarrow$ statistics (e.g. >1000 photons/hour in recent AGN flare)
  - Best angular resolution (0.02°)
  - 100 sources now – expect >1000 with next generation
- HAWC
  - Water Cherenkov detector under construction
  - Modest area, sensitivity and resolution – but 100% duty cycle and several steradian field of view
- AGIS (US) and CTA (European)
  - >=1 km^2 precision air-Cherenkov instruments
  - AGIS aims to merge with CTA in near future

The Cherenkov Telescope Array

- A factor 10 more sensitive than current instruments
  - Plus - much wider energy coverage, substantially better angular and energy resolution & wider field of view
- A ~£130M European led project
  - 100 institutes in 22 countries signed MoU
  - Design 2008-2011, Prototyping 2011-13, Construction 2013-18
  - Baseline: 50-100 Cherenkov telescopes

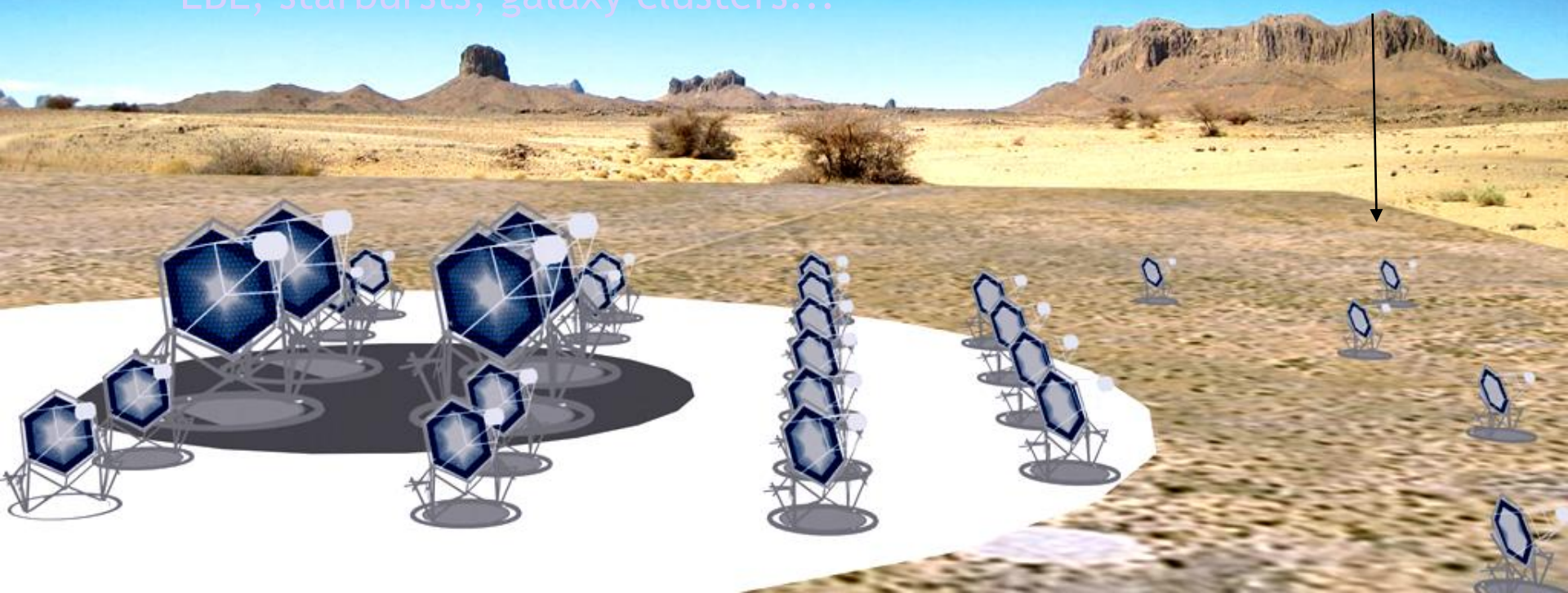
EU funded prep. phase
€6M application
13.5/15 ranking
1/6/2010 – 1/6/2013




Low-energy section
energy threshold
of 20-30 GeV
~24m telescopes
Medium Energies:
mCrab sensitivity
100 GeV–10 TeV
12m telescopes
High-energy section
10 km^2 area at
multi-TeV energies
4-6m telescopes

- UK is focussed on high (3-300 TeV) energies (Talk by Richard White)
  - The best performance e.g. angular resolution, energy resolution
  - The biggest potential improvement (>>factor 10)
  - Science case: cosmic ray acceleration to high energies, X-ray synergies, nearby radio galaxies, the evolution of the FIR EBL, starbursts, galaxy clusters...

High-energy section
10 km^2 area at
multi-TeV energies
4-6m telescopes



29 CTA in the UK

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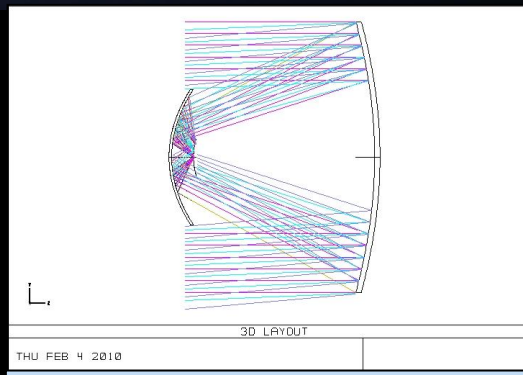
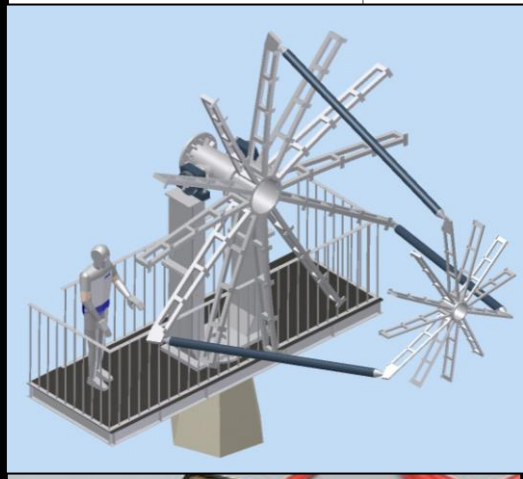
- UK-Consortium
  - Durham, Hertfordshire, Leeds, Leicester, Liverpool, Northumbria, Nottingham, Oxford, RAL, Sheffield, Southampton
- Science-based optimisation of the array
  - MC simulations and analysis (Talk Dan Parsons)
  - Science case studies: GRBs, DM annihilation...
- Design of the array of small-sized telescopes (SSTs)
  - UK idea: a two reflector solution with a compact (SiPM, MAMPT, MCP...) camera for the small CTA telescopes (Talk Tim Greenshaw)
  - Conceptual design by May 2010, towards prototyping 2011-2012
  - UK coordinates SST in prep. phase

International Collaboration Meeting RAL/Oxford this November





30 Point-source Sensitivity

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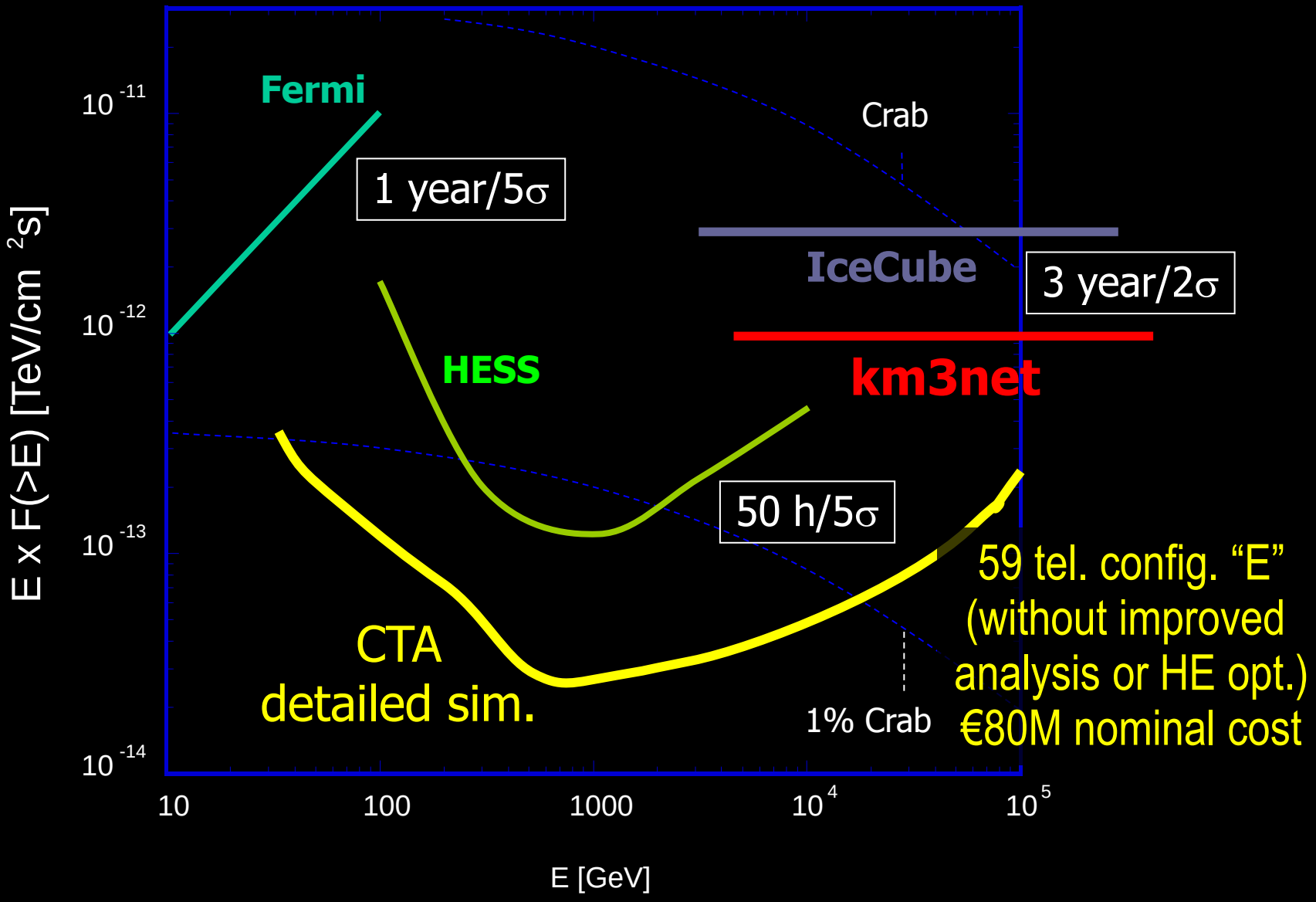

31 Don't forget the photons II

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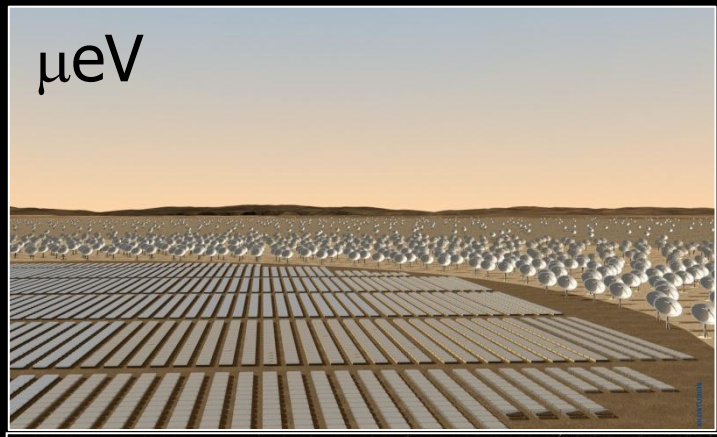
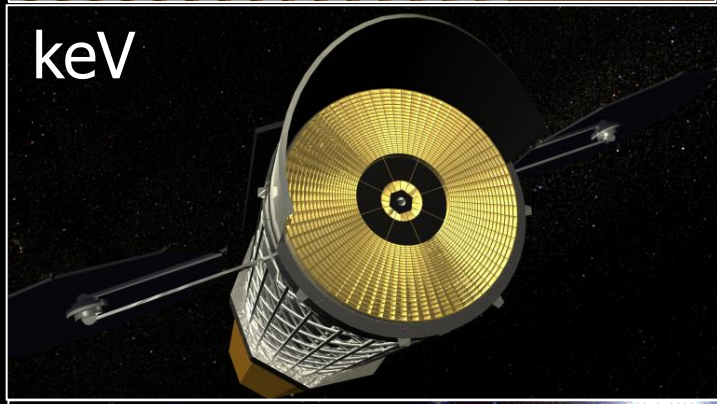
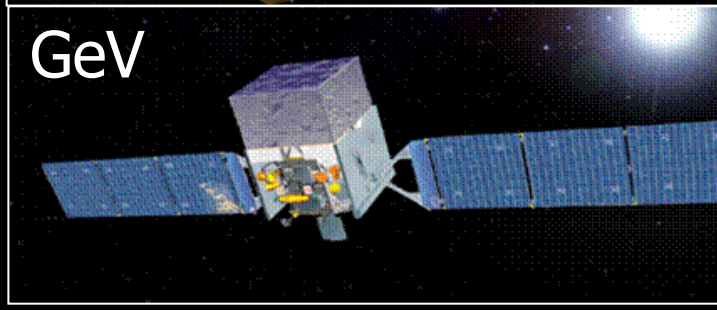
- Radio
  - ***The*** Future Facility is SKA
- Optical
  - E-ELT, JWST, ...
- X-rays
  - Astro-H, SVOM, IXO ...
- HE Gamma-rays
  - Fermi, AMS

- We (particle astrophysicists) need (many of) these facilities as well



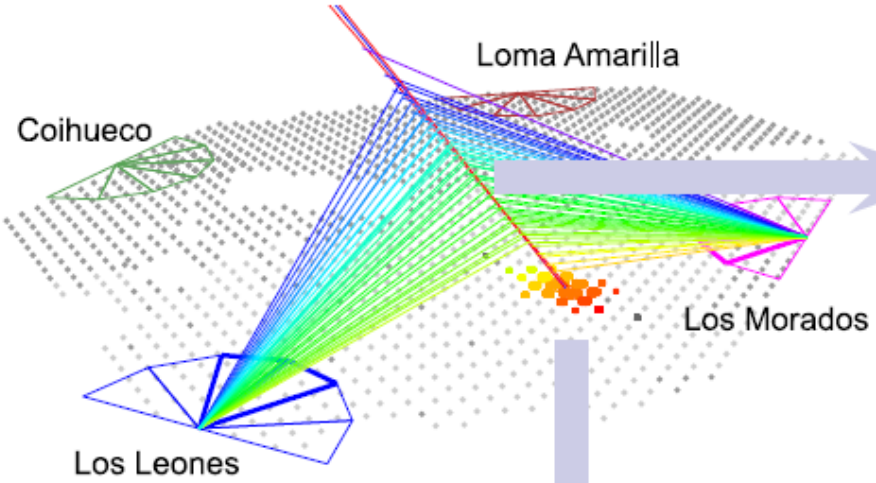


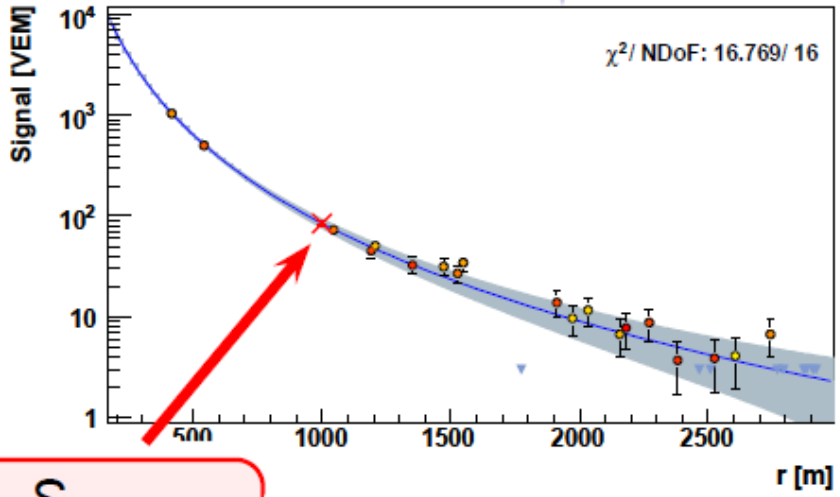


Conclusions

- Big projects (and big science) are on the way
- Multi-messenger astronomy is not just a nice phrase
  - It is likely that some of the biggest discoveries in physics & astronomy in the next decades will come in this area
- The UK is well positioned to play a major role
  - Unfortunately almost zero (small amount for SNO+) support from STFC for the projects described here (at the moment)...

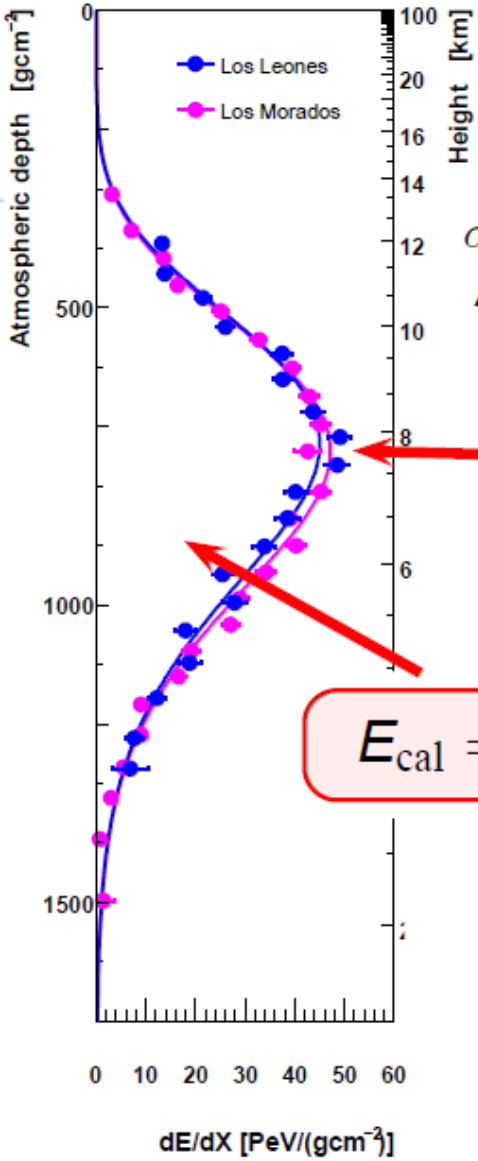
Hybrid Measurement of Air Showers in Auger





S_{1000}

$E_{surface} = f(S_{1000}, \theta)$



$\sigma_{X_{max}} < 20\ \mathrm{g/cm^2}$

$\Delta_{sys} \approx 15\ \mathrm{g/cm^2}$

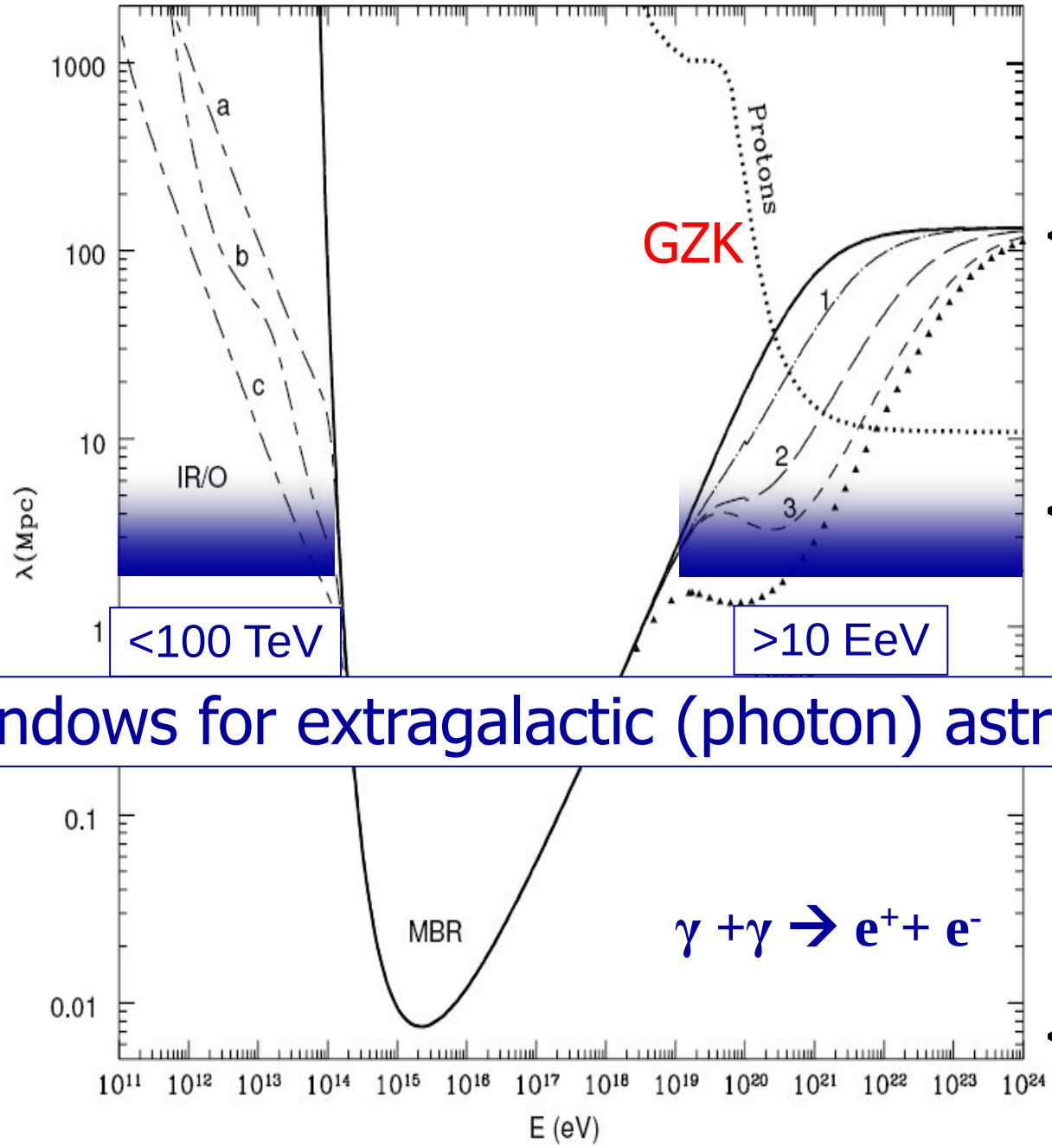
X_{max}

$E_{cal} = \int \frac{dE}{dX}\, dX$

$\sigma_E/E \sim 8\,\%$

$\Delta_{sys} \approx 22\,\%$

(R. Ulrich, APS meeting 2010)



nearest blazar

nearest AGN

Galactic centre

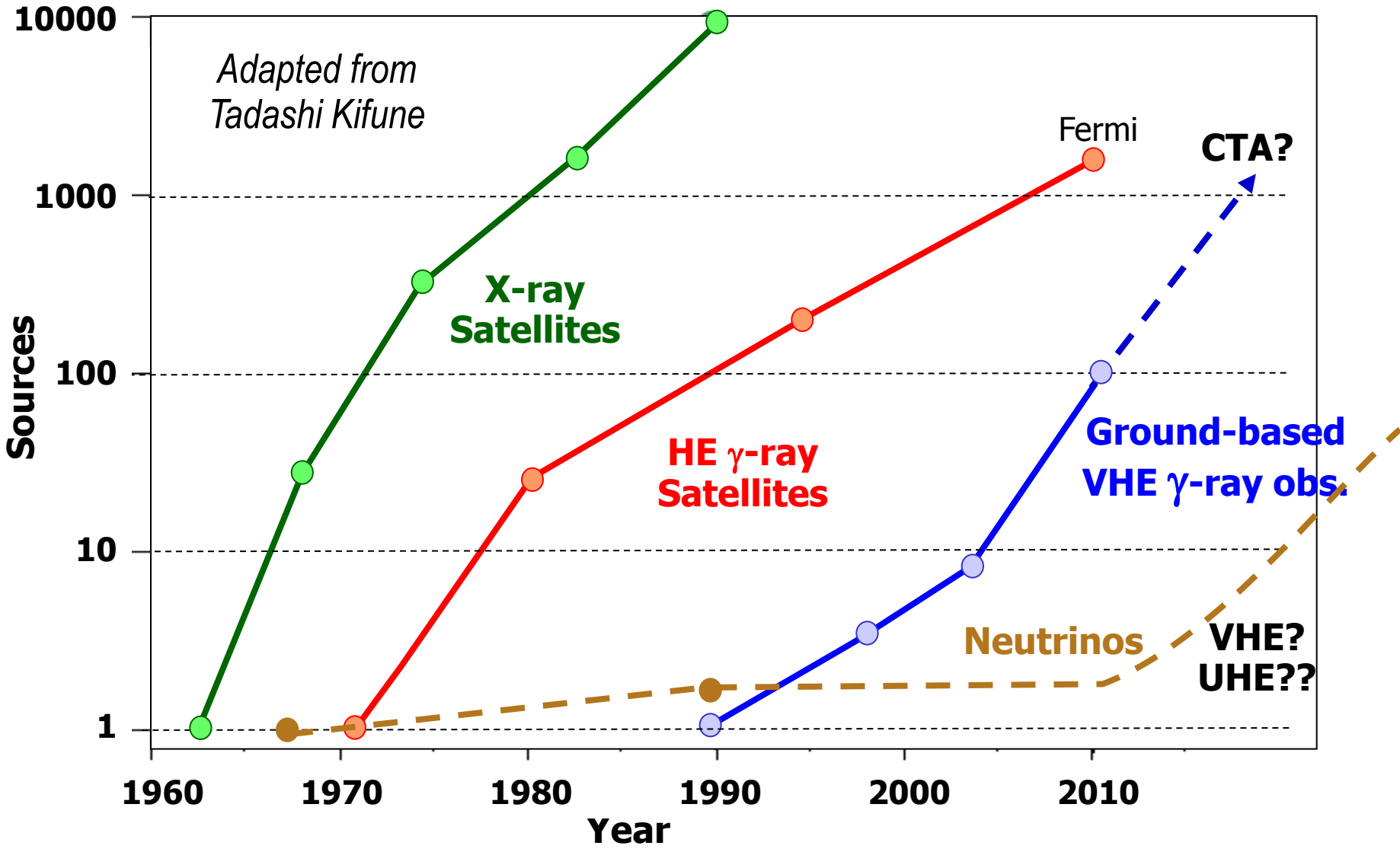
<100 TeV

>10 EeV

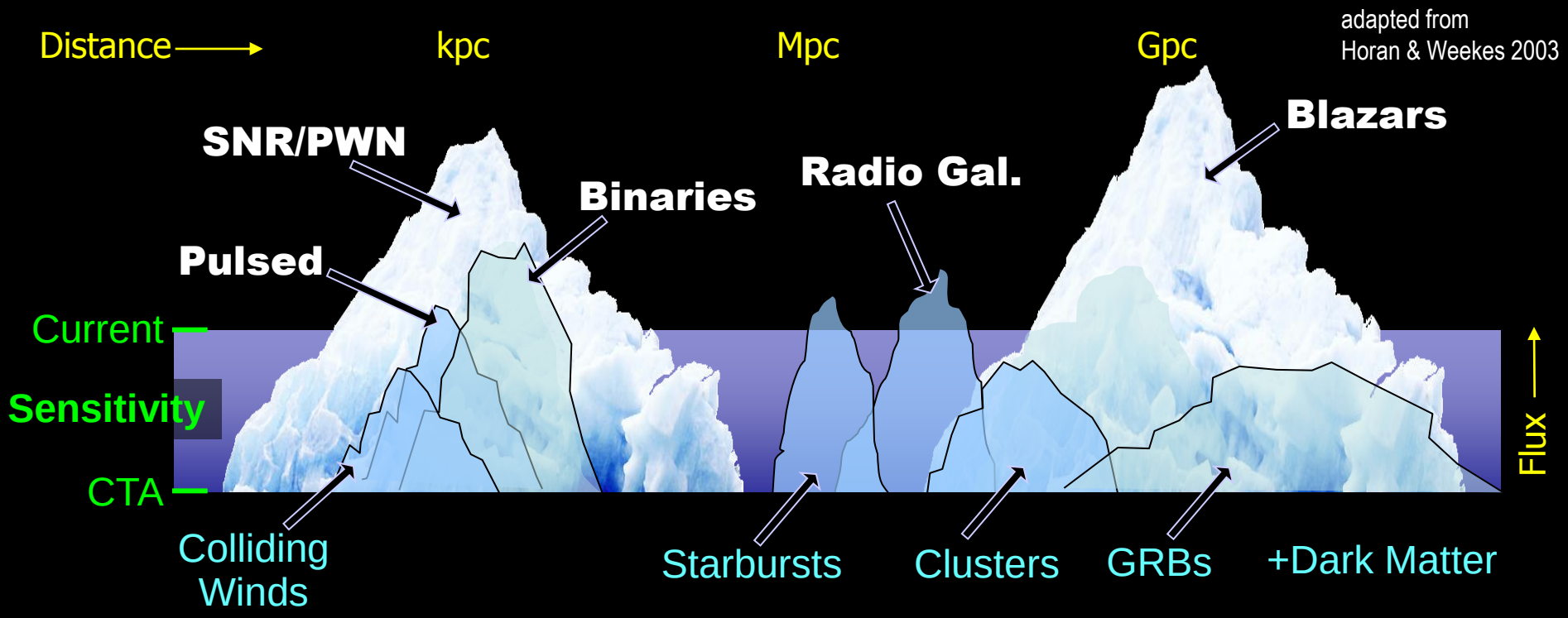
Windows for extragalactic (photon) astronomy

36 Source Numbers

University of Leicester



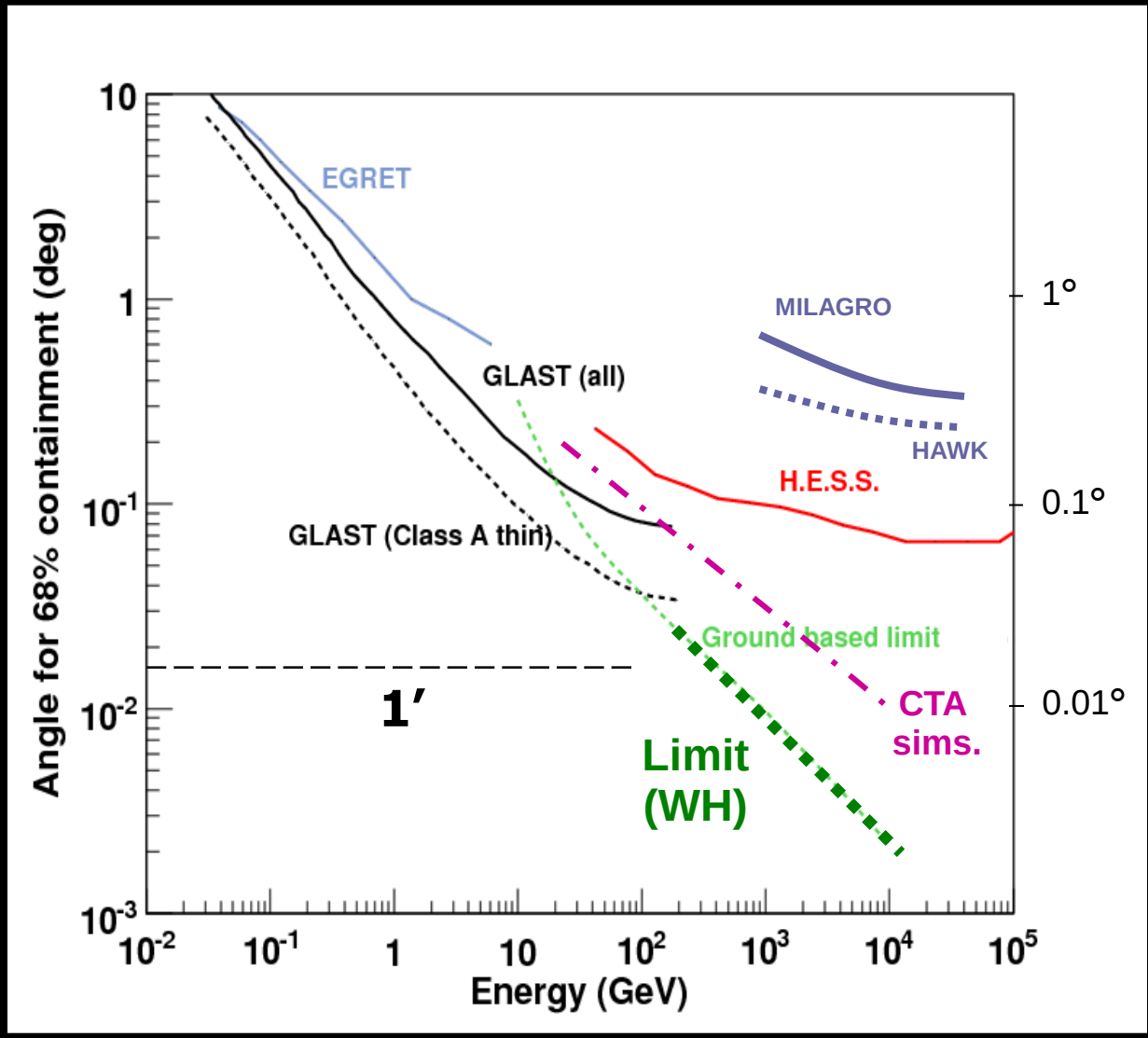
CTA Science Potential



- Current instruments have passed the critical sensitivity threshold and reveal a rich panorama, but this is clearly only the tip of the iceberg
- Broad and diverse program for CTA, combining guaranteed astrophysics with significant discovery potential

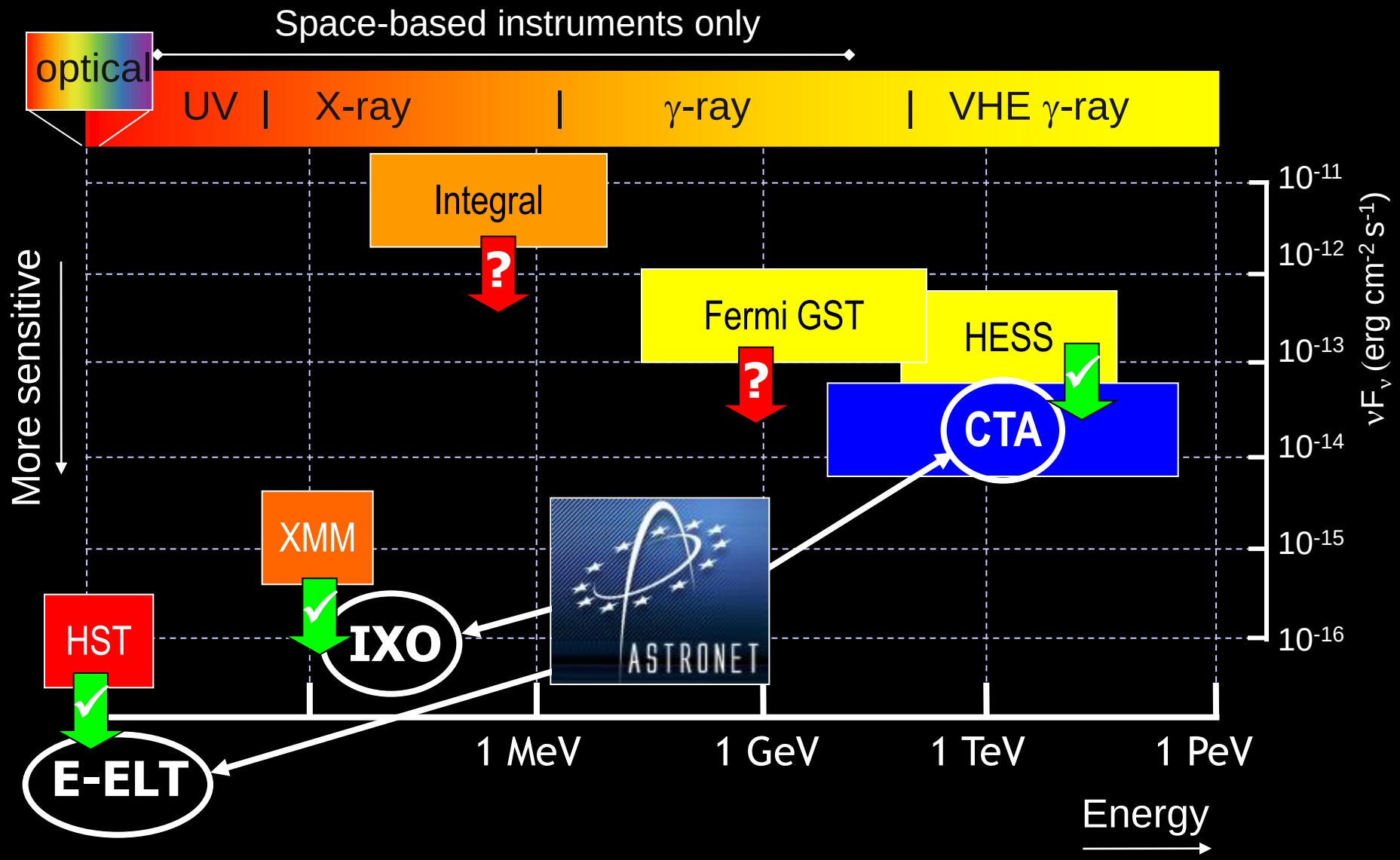
Angular resolution

- ~1’ resolution achievable with next generation ground-based detectors
- Fundamental limit is ~10” above a few TeV

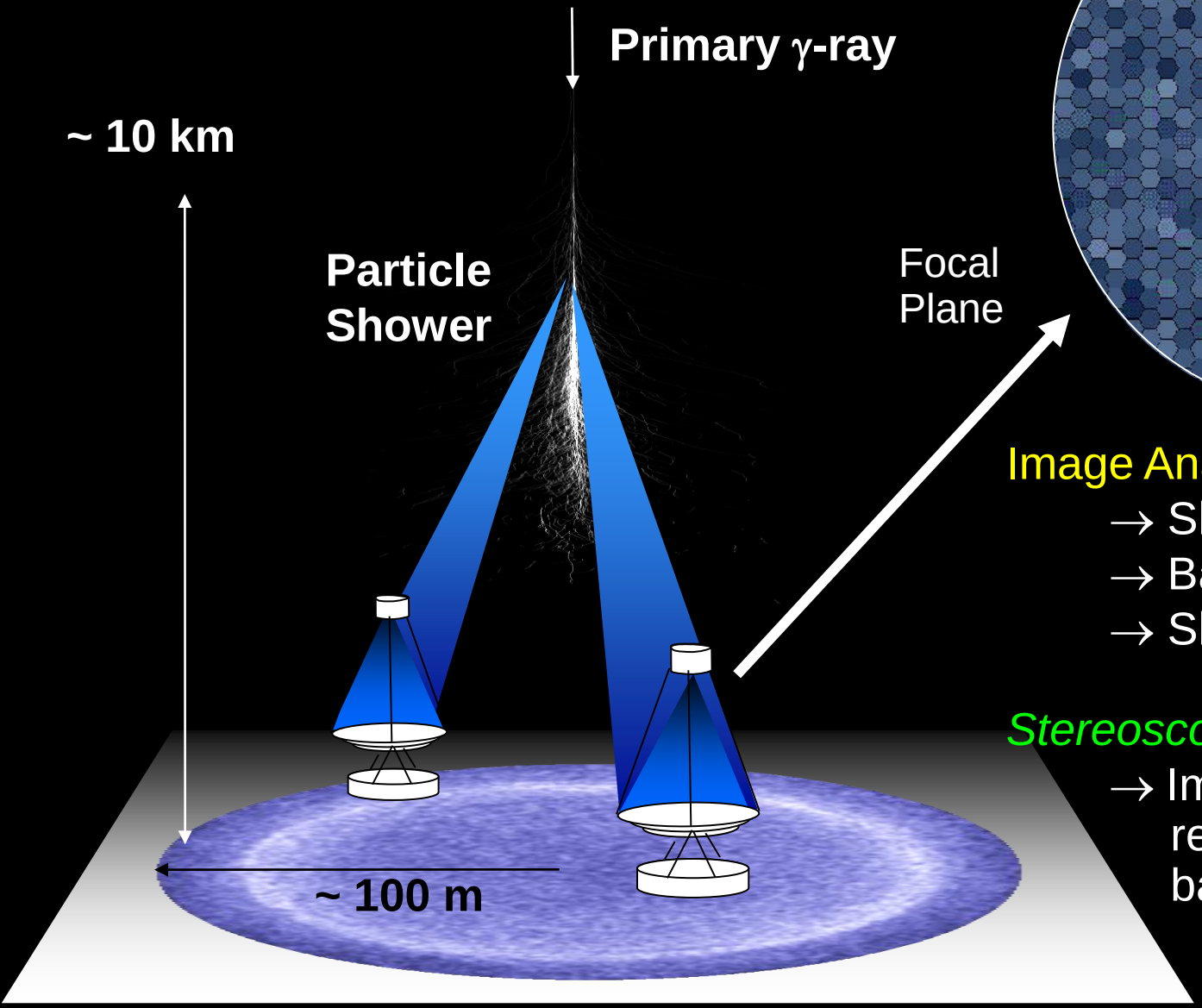


39 High Energy Sensitivity

University of Leicester



40 Technique



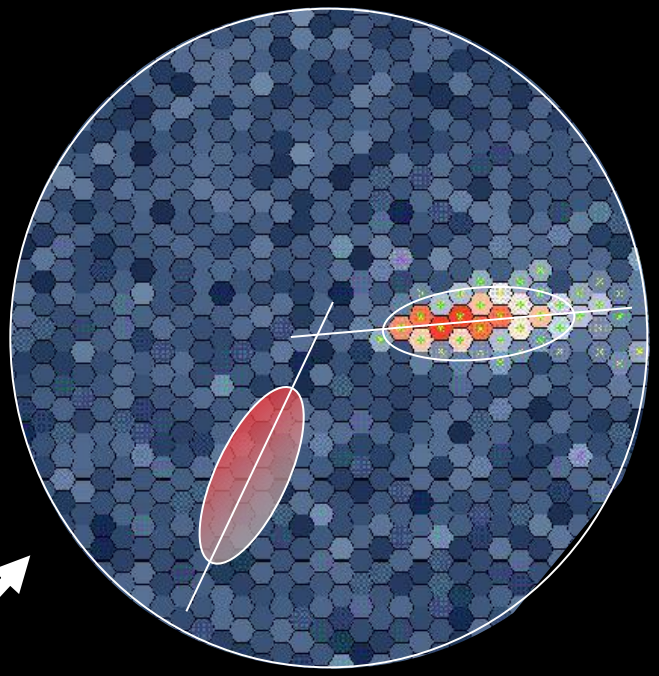
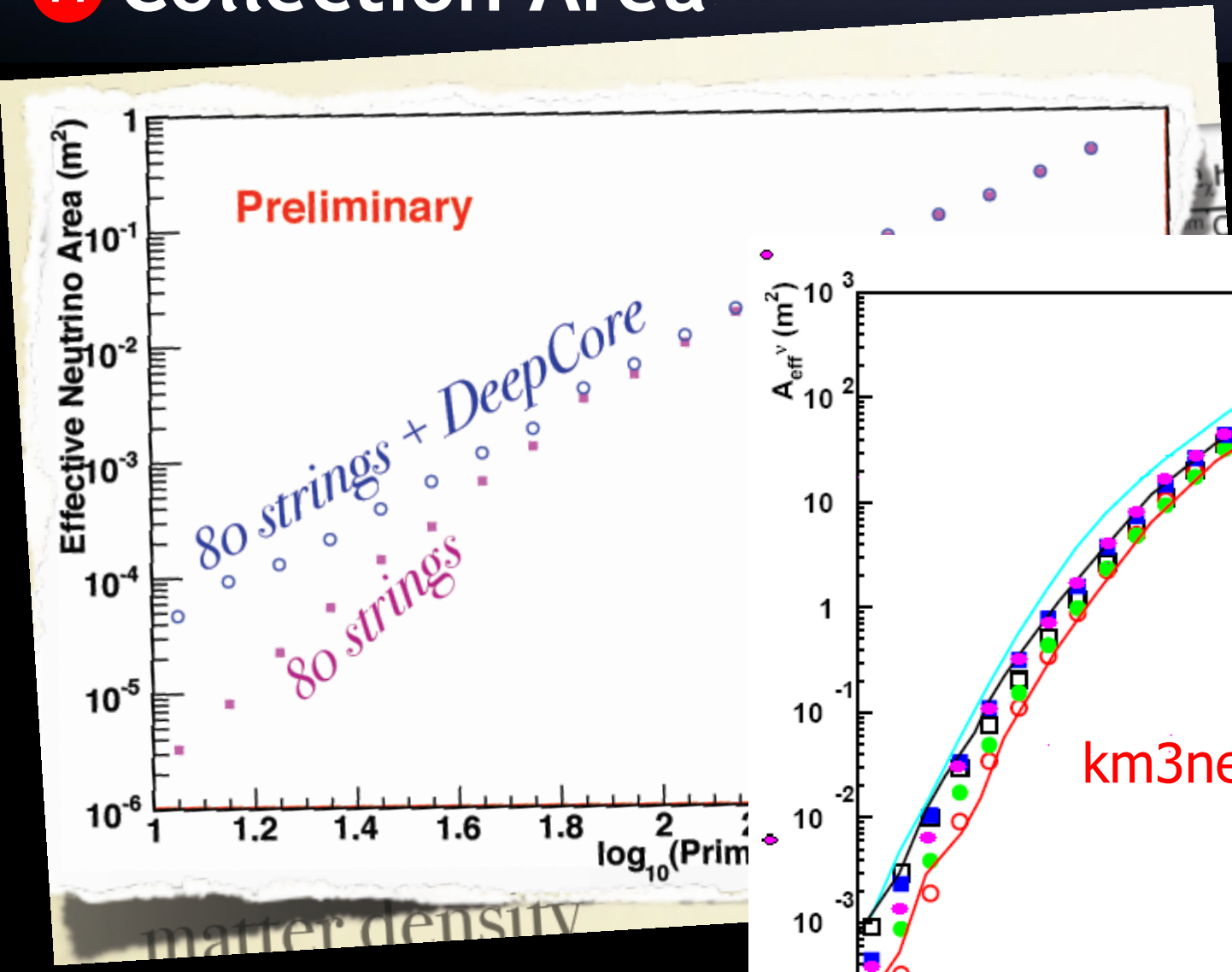
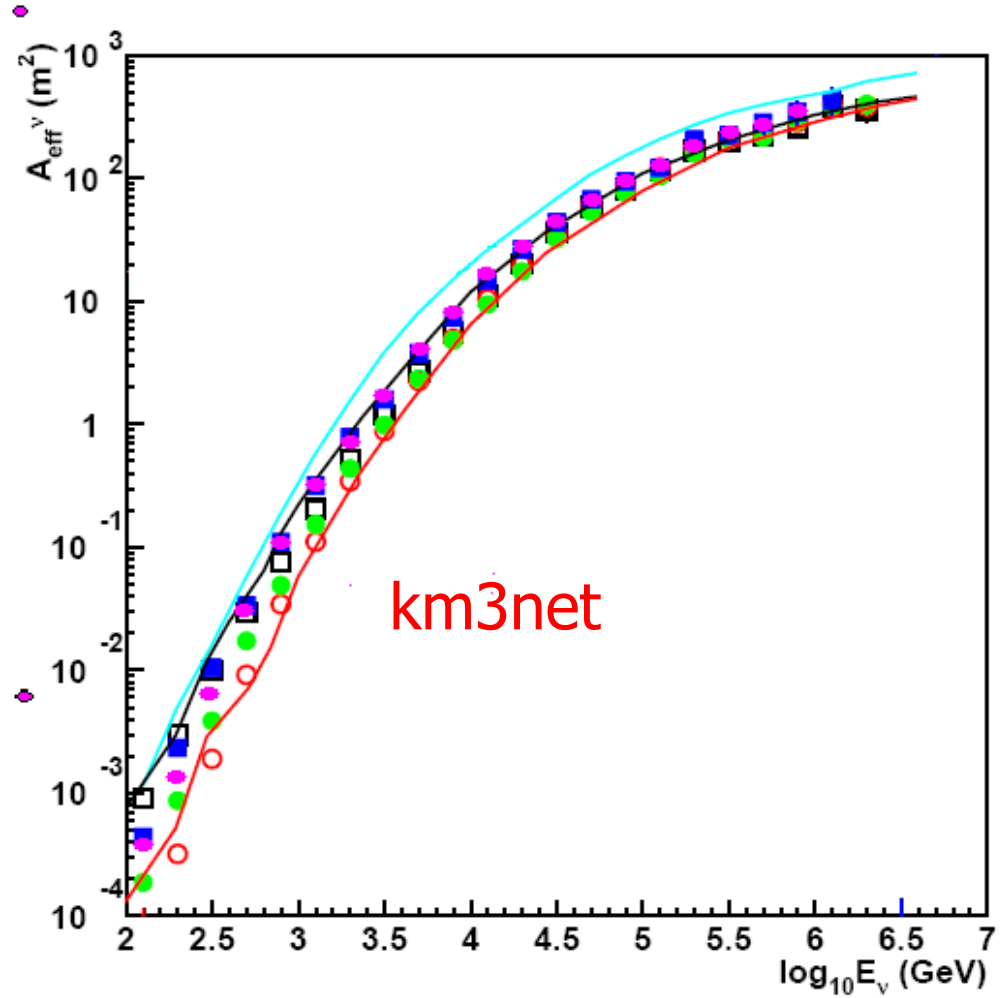


Image Analysis gives
- → Shower Energy
- → Background rejection
- → Shower Direction

Stereoscopic views
- → Improved angular resolution and background rejection

Collection Area



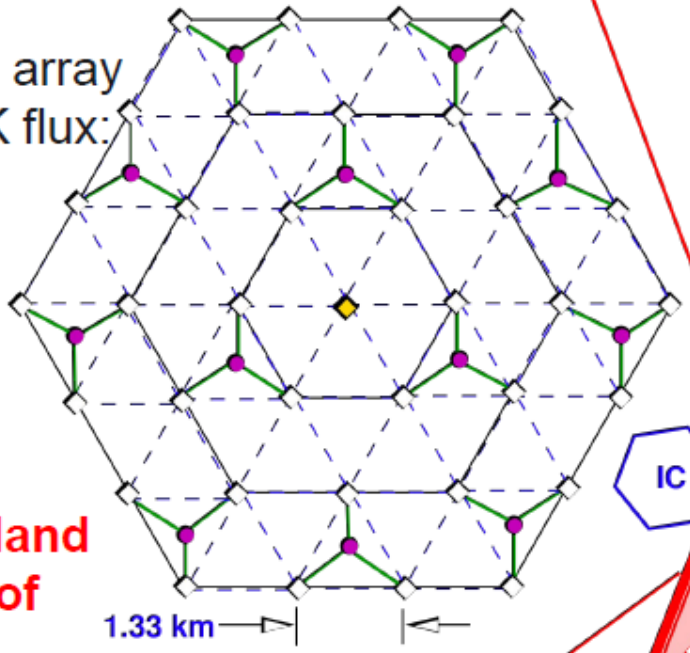


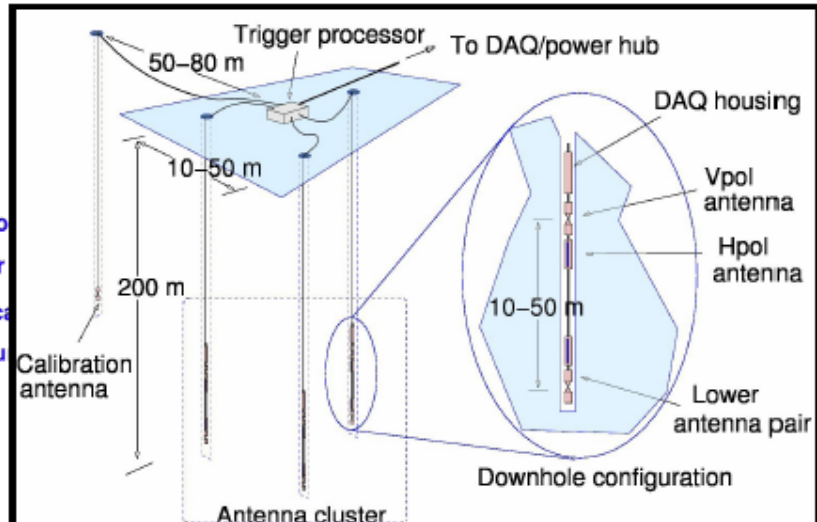
Askaryan Radio Array (ARA)

"Intermediate" scale array to establish the GZK flux: 80 km^2

Proposal submitted to US recovery act "stimulus funds" jointly from the **University of Maryland** and the **University of Wisconsin** for $4M

Total Price of ARA: $7.7M





Other collaborating & interested institutions: U of Kansas, U of Hawaii, National Taiwan U, U of Delaware, Colorado State U, U Libre de Bruxelles, U College London, U of Chiba, **U of Wuppertal, DESY Zeuthen ?**