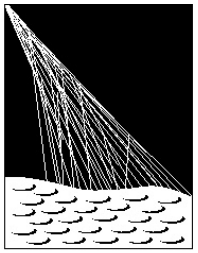


PIERRE AUGER OBSERVATORY

Multimessenger Working Group

UHE Neutrinos & Photons

1. Neutrinos and photons as *MM*
2. Photons
3. Neutrinos
4. Conclusion

CERN
13-16 February 2012

International Symposium on Future Directions in UHECR Physics

Working Group Messengers

Jaime Alvarez-Muniz
Santiago de Comp., Spain
Auger, neutrino

Grigory I. Rubtsov
Moscow, Russia
TA (Yakutsk), photon/neutrino

Markus Risse
Siegen, Germany
Auger, photon

Benjamin T. Stokes
Salt Lake City, USA
TA, neutrino/photon

multi-messengers → 2 speakers

The charge of the working group

review current situation w.r.t. future directions: physics and techniques

... many aspects,
e.g. compare:

neutrinos *vs* **photons**

neutrinos, photons *vs* **charged CR**

EAS observation *vs* **other techniques**

ground EAS *vs* **EAS from space**

ground EAS techniques *vs* **each other**

data *vs* **models**

various models *vs* **each other**

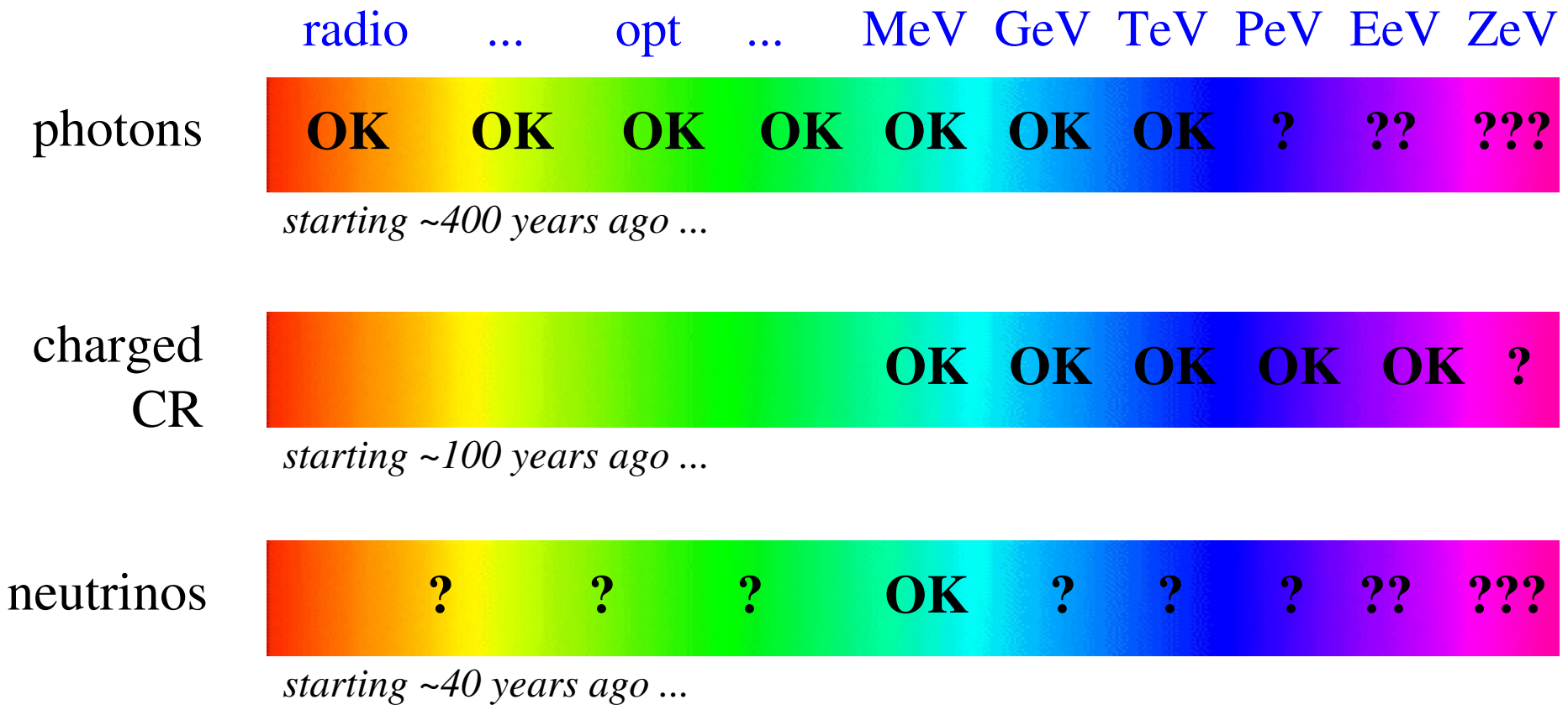
present status *vs* **future directions**

disclaimer: neither complete nor finished

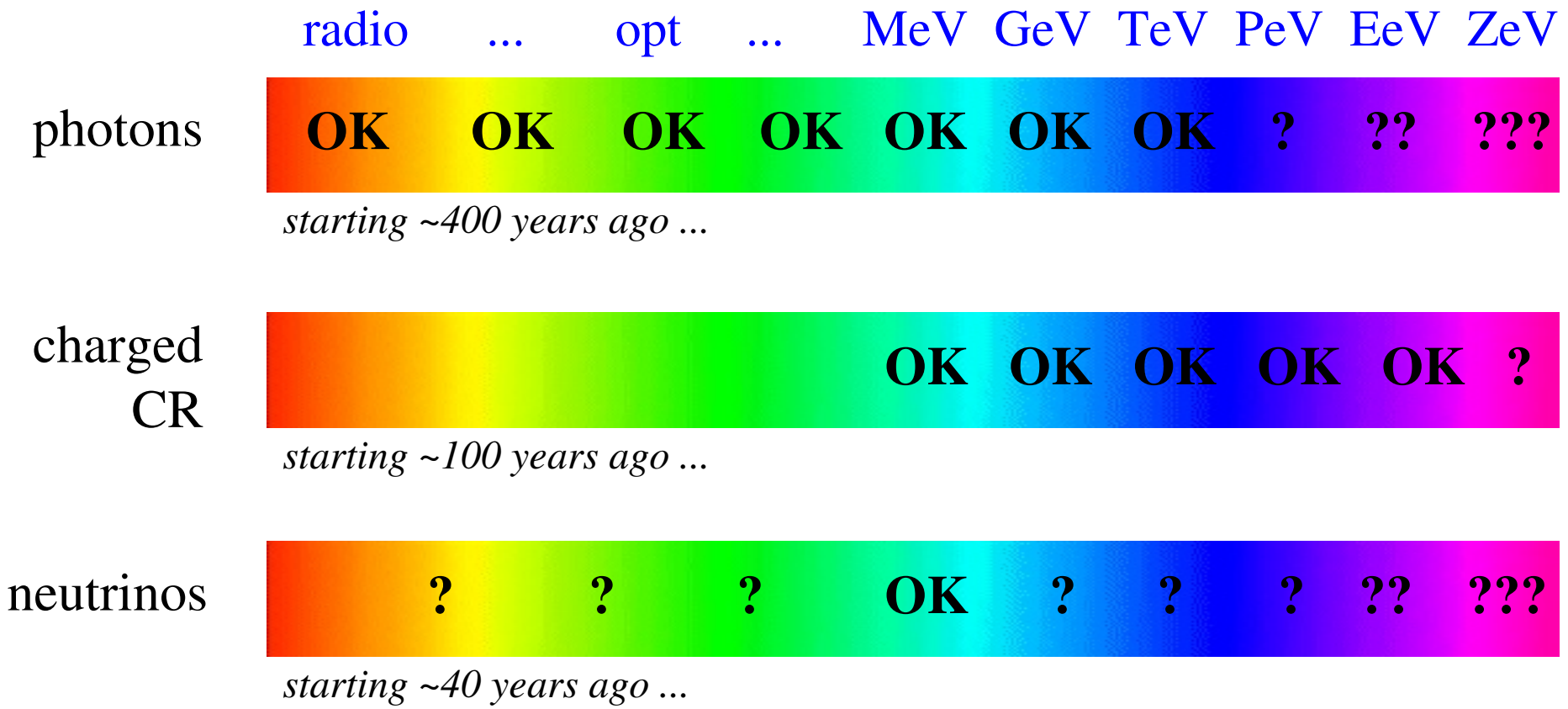
→ **certain aspects compiled and highlighted**

1. Neutrinos and photons as Multimessengers

MM windows to the Universe



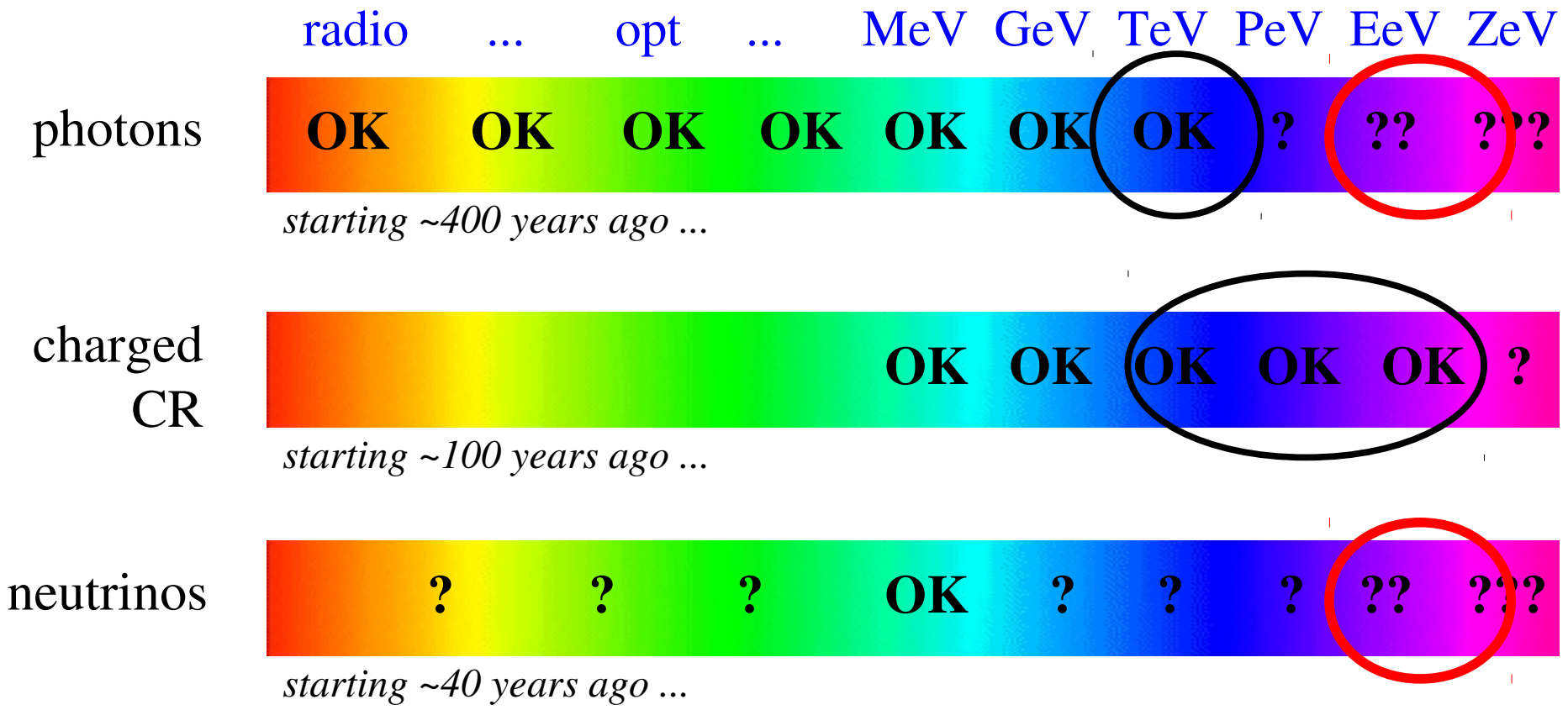
MM windows to the Universe



from history: **new windows - new discoveries**

- e.g. CMB, γ-ray bursts, muon, neutrino oscillation
- sometimes completely unexpected
- impact on different fields of physics *(astro /particle /cosmo / fundamental ...)*

MM windows to the Universe



current **observations** using air showers

here: ***MM* searches** using air showers at UHE (above ~0.1 EeV)

Production of UHE neutrinos and photons

Typically as **decay secondaries** (i.e. needs higher energy CR):

UHE-CR (nucleon or nucleus) interacts
- with matter, e.g. with gas around source
- with background photons, e.g. CMB or photon fields around source

➔ **pions:** neutral → photons, charged → neutrinos

example: GZK neutrinos and photons: >50 EeV proton and CMB

$$p + \gamma_{2.7K} \rightarrow \Delta(1232) \rightarrow \begin{cases} n + \pi^+ \rightarrow \mu^+ + \nu_\mu \\ \qquad\qquad\quad \searrow e^+ + \bar{\nu}_\mu + \nu_e \\ p + \pi^0 \rightarrow \gamma + \gamma \end{cases}$$

3ν, each ~5% E_p

2γ, each ~10% E_p

alternative **top-down** (but see later)

➔ pions from decay or annihilation of exotic particles

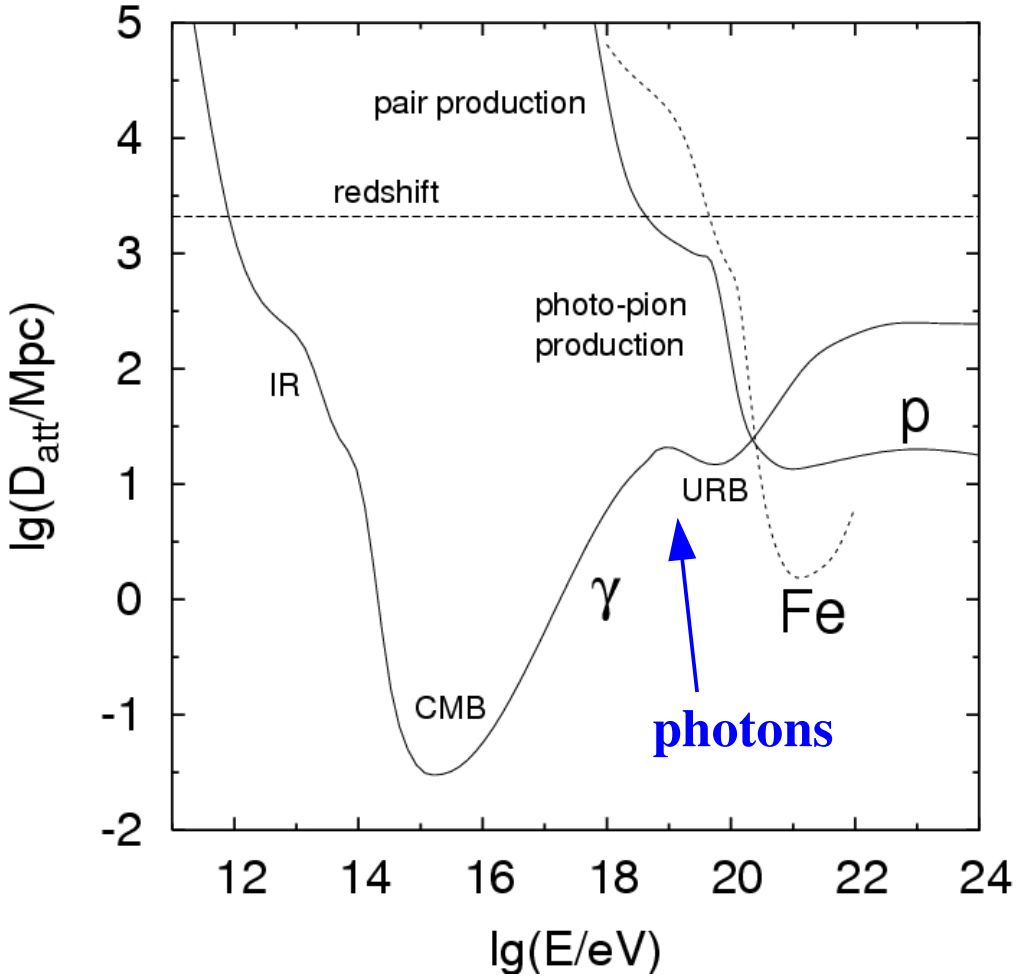
➔ both: same type of initial process, finally from (pion) decay

Propagation of UHE neutrinos and photons

both: along straight line (different from charged CR! "Astronomy")

neutrinos: ~no interaction (max. mixing over cosmol. distance $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$)

photons: initiate EM cascade (into GeV-TeV)



→ **10-20 Mpc** @ UHE

Universal Radio Background
large uncertainty !

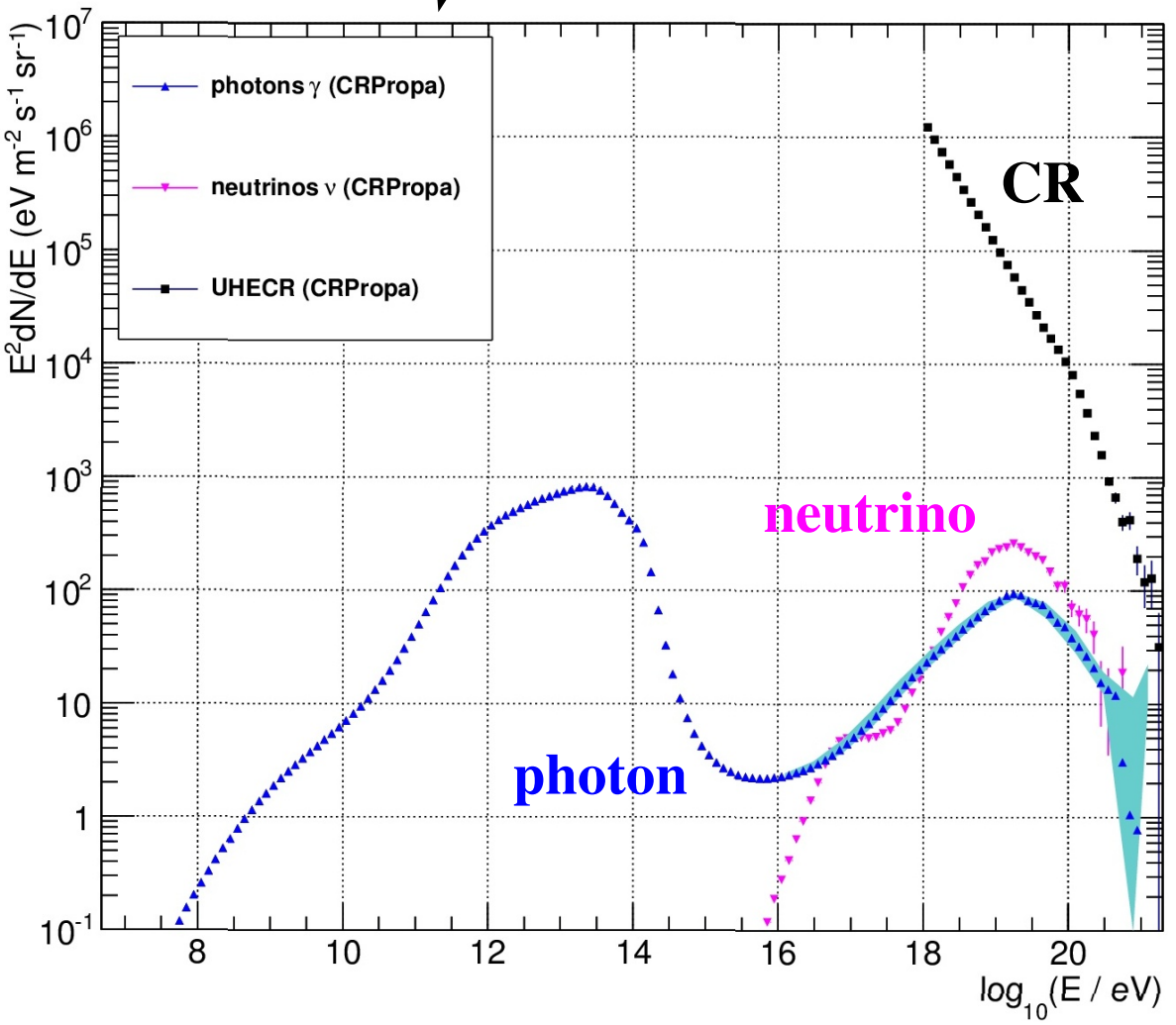
complementary: **photons - local, neutrinos - all universe**

Complementarity of neutrinos and photons: an illustration

(N. Nierstenhöfer, A. van Vliet)

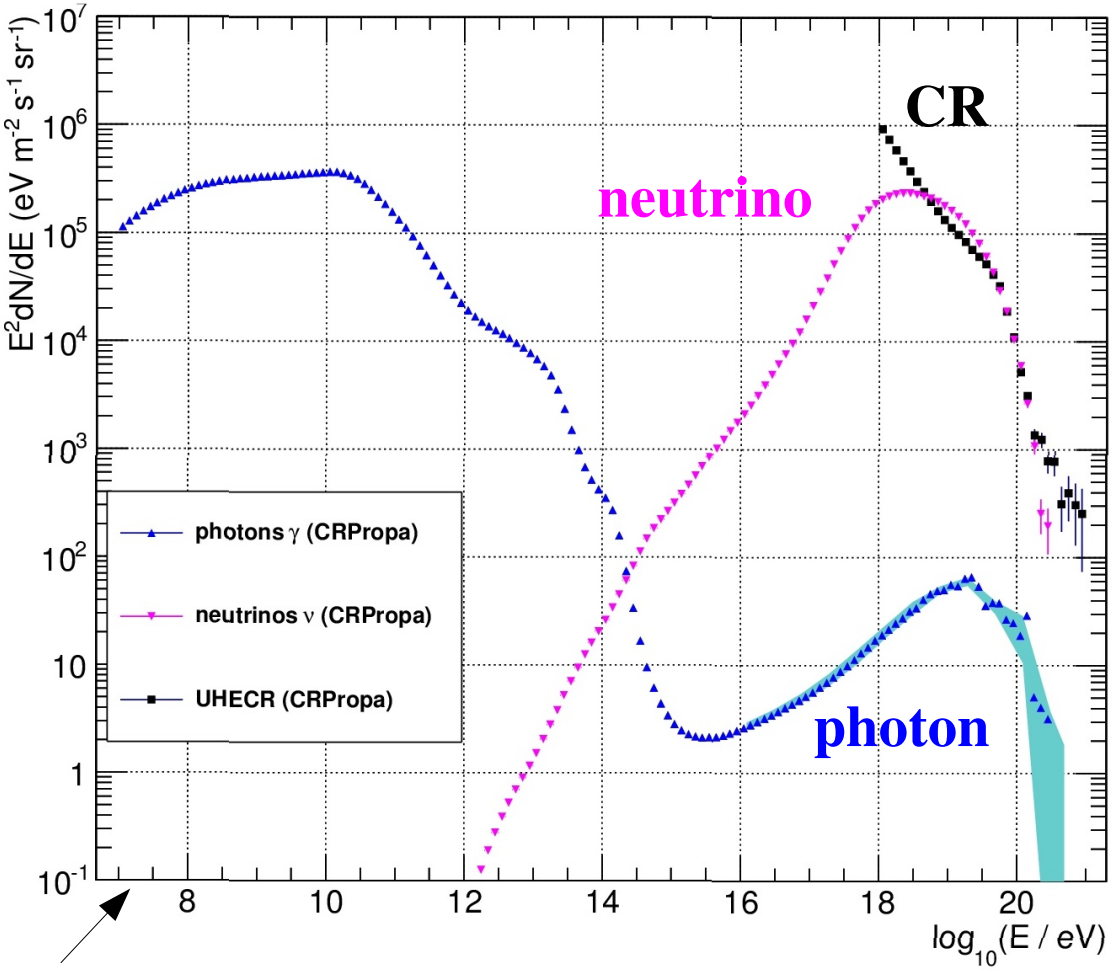
(1) nearby source (10 Mpc) :

neutrino ~ photon ~ 1% CR



Complementarity of neutrinos and photons: an illustration

(N. Nierstenhöfer, A. van Vliet)



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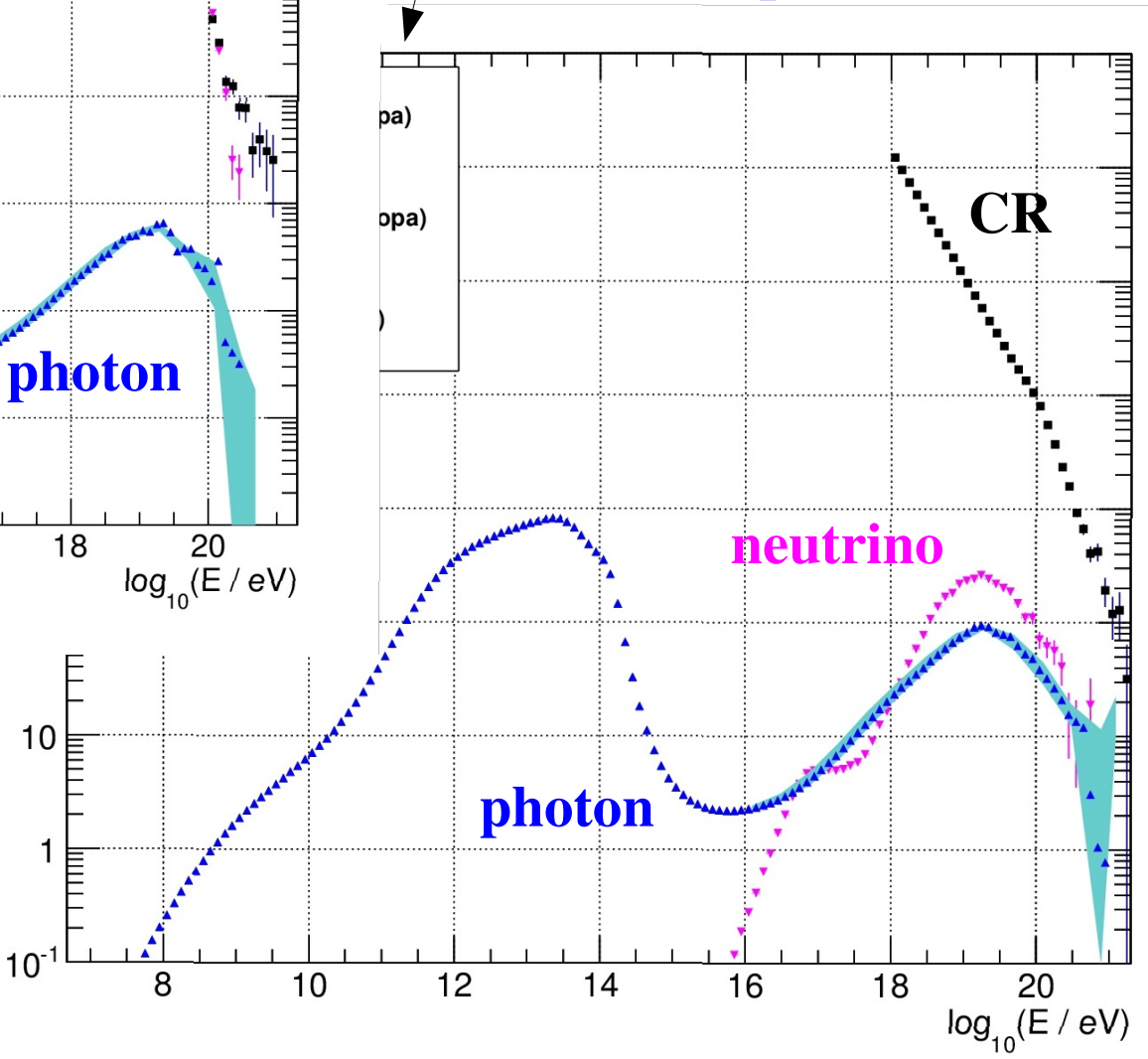


(2) distant sources:

neutrino ~ CR

photon ~ 0.1% CR

GeV-TeV increased

Search for UHE neutrinos & photons with EAS (overview-1)

photons:

- "normal" showers (similar to hadron showers): use typical EAS detectors
- separation based on composition sensitive EAS observables
  challenge for space EAS observation ? (Medina-Tanco 2011)
- no competitive technique to EAS detectors so far

neutrinos:

- probability ~10^{-5} for EAS (1000 g cm^{-2}, 1 EeV)
- but if EAS: can populate also extreme phase space
  near-horizontal EAS starting deep, upward-going starting in Earth's crust
- strong background reduction (but trying to keep large exposure)
  space EAS observations may significantly add exposure ?
- competition with other techniques, e.g. ν telescopes (ice/water)

Search for UHE neutrinos & photons with EAS (overview-2)

both: no discovery yet → upper limits !

photons: candidates (usually close to threshold), compatible with bkg

conservative: no subtraction of (hadron) bkg to avoid uncertainties

neutrinos: no candidates, search NOT limited by bkg but by exposure

both: **fairly robust EAS interpretation** with regard to theory uncertainties:

photons -- mostly EM showers (QED)

neutrinos -- cross section & tau energy loss uncertainty

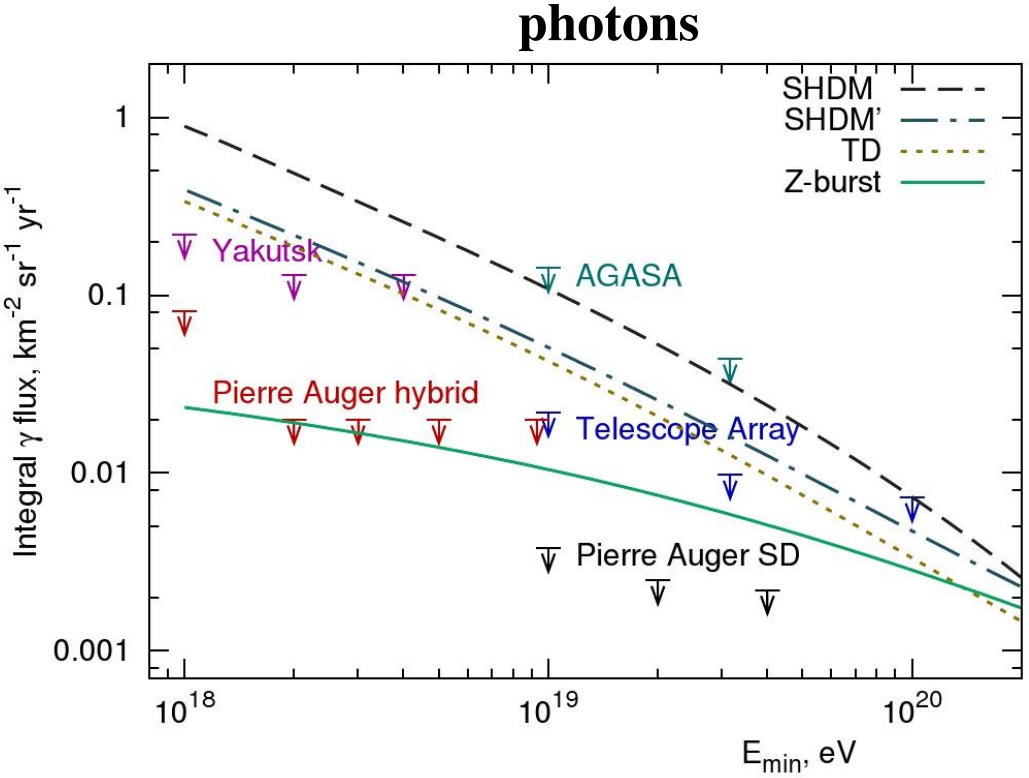
uncertainty in shower development less important

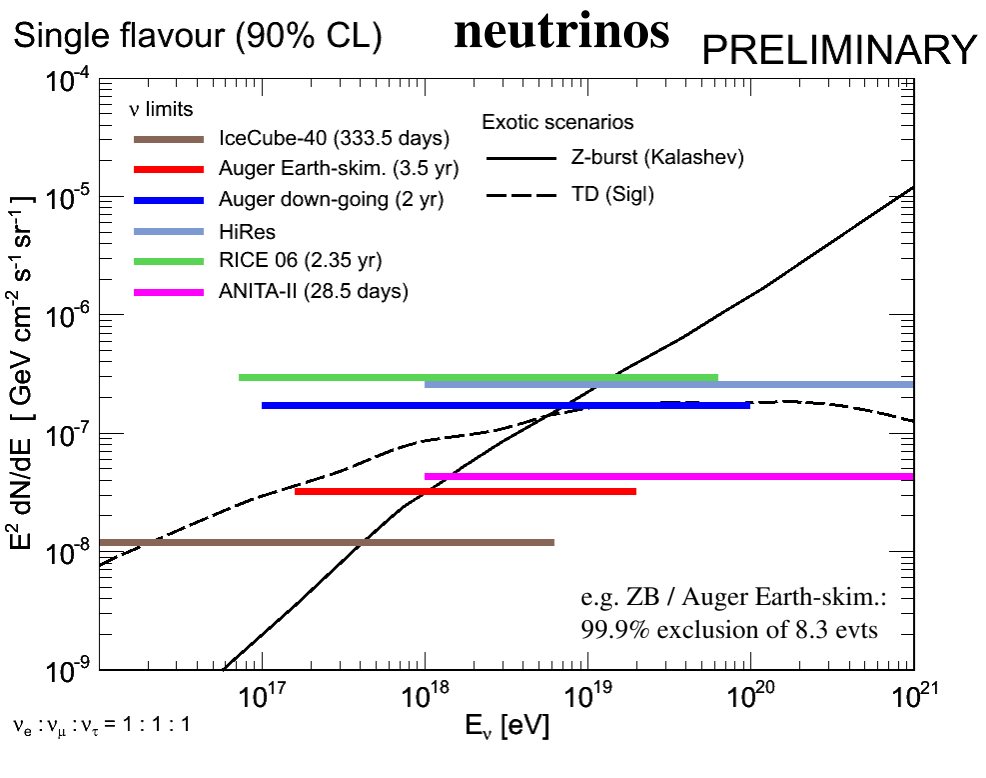
(identification relies on EM component of shower)

different from (uncertain) interpretation of hadron showers !

Impact of current UHE neutrino and photon limits

(1) strong constraints on top-down models:





(2) tests of LV (Galaverni & Sigl 2008)

(3) reduce systematics for other analyses (cross-section, spectrum, mass)

(4) start constraining astrophysical source scenarios (see later)

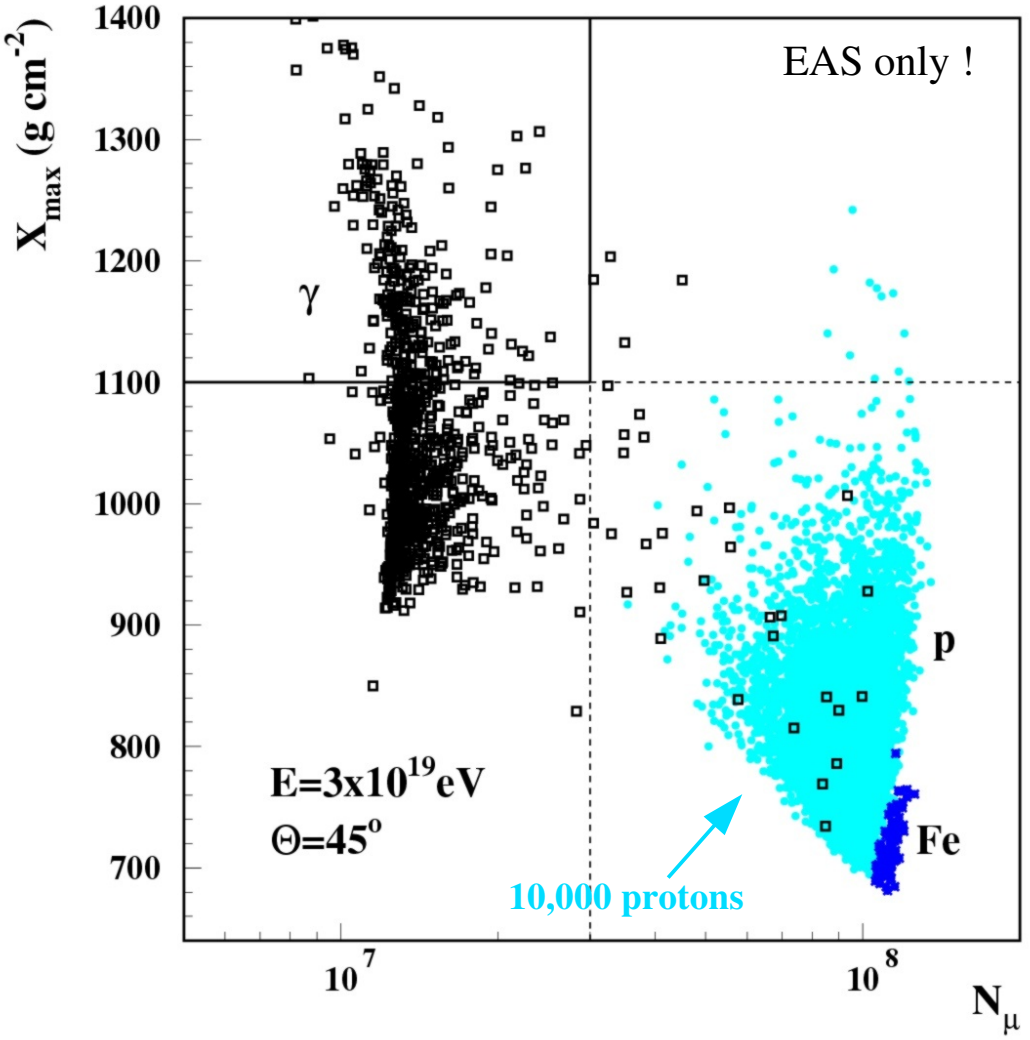
➔ ***MM*** **searches using EAS are (already) useful !**

2. Photons

Photon EAS in a nutshell

mostly **EM showers**, minor photo-nuclear or muon pair production;
above few EeV: **LPM**, above few 10 EeV: **preshower***

➔ larger X_{max}, fewer muons (and related: risetime, curvature ...)



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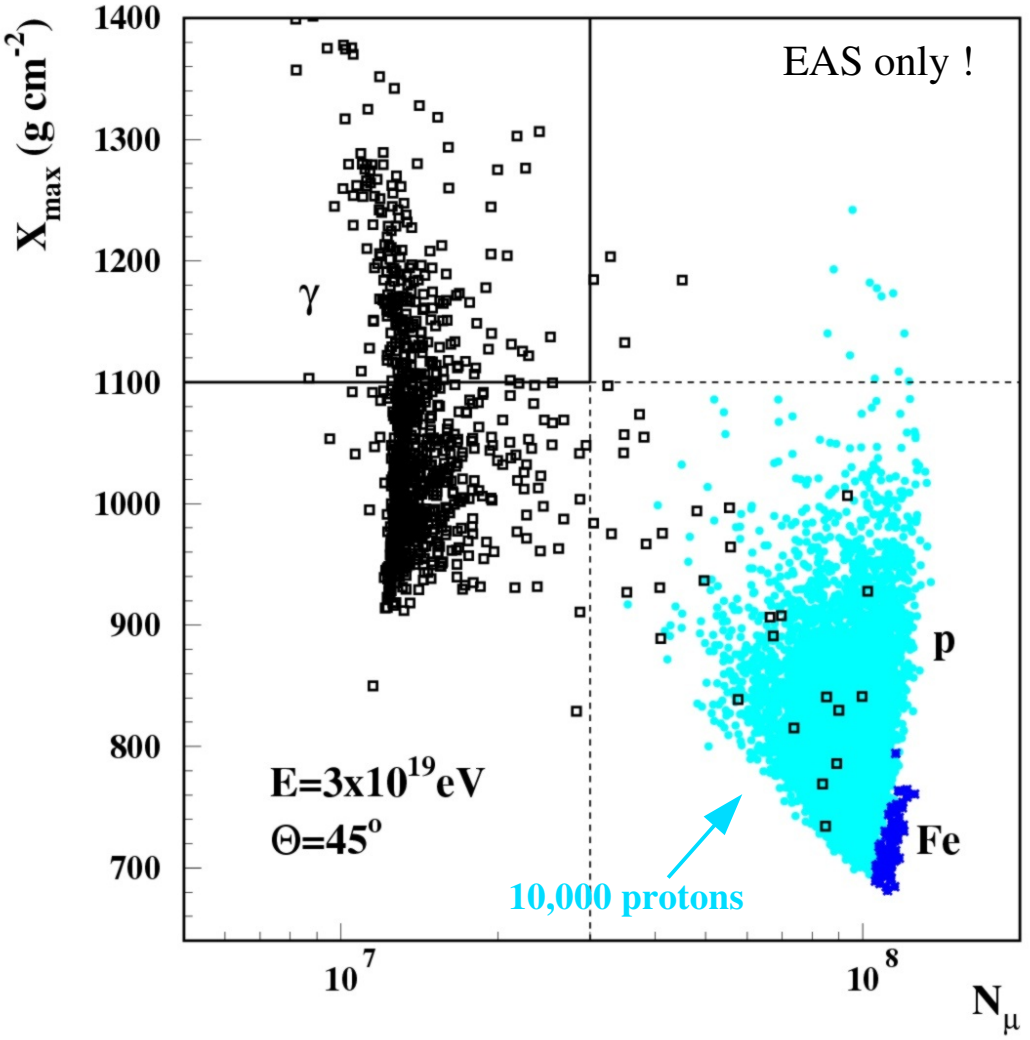

challenge ...
- not: γ looking like p
- but: **p looking like γ**

few p above cut in **X_{max}: very good !**

no p below cut in **muons: excellent !**

caveat: p fluctuations uncertain
(hadron interactions; here QGSJET 01)

***unique photon signature !**

large X_{max} change, direction dependent

Photons: comparison of observables / techniques

Experiment	Technique	Observables	Ref
Haverah Park	SD: water Cherenkov	attenuation of inclined showers	[2]
AGASA	SD: scintillator & muon	muon density	[3, 6]
Yakutsk	SD: scintillator & muon	muon density	[4, 5, 7]
Pierre Auger	SD: water Cherenkov	front curvature, rise time	[9]
	hybrid: fluorescence + SD	X_{max}, particle density far from the core	[8, 10]
Telescope Array	SD: scintillator	front curvature	[11]

details on posters !

What technique is best?

maximize ***Q*** **~ (separation power) / (price per exposure)**

e.g. muon detectors: separation power ! (but shower geometry??)
SD: price per exposure !
fluorescence: clean EM measurement ! (but shower geometry?)

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details on posters !

What technique is best?

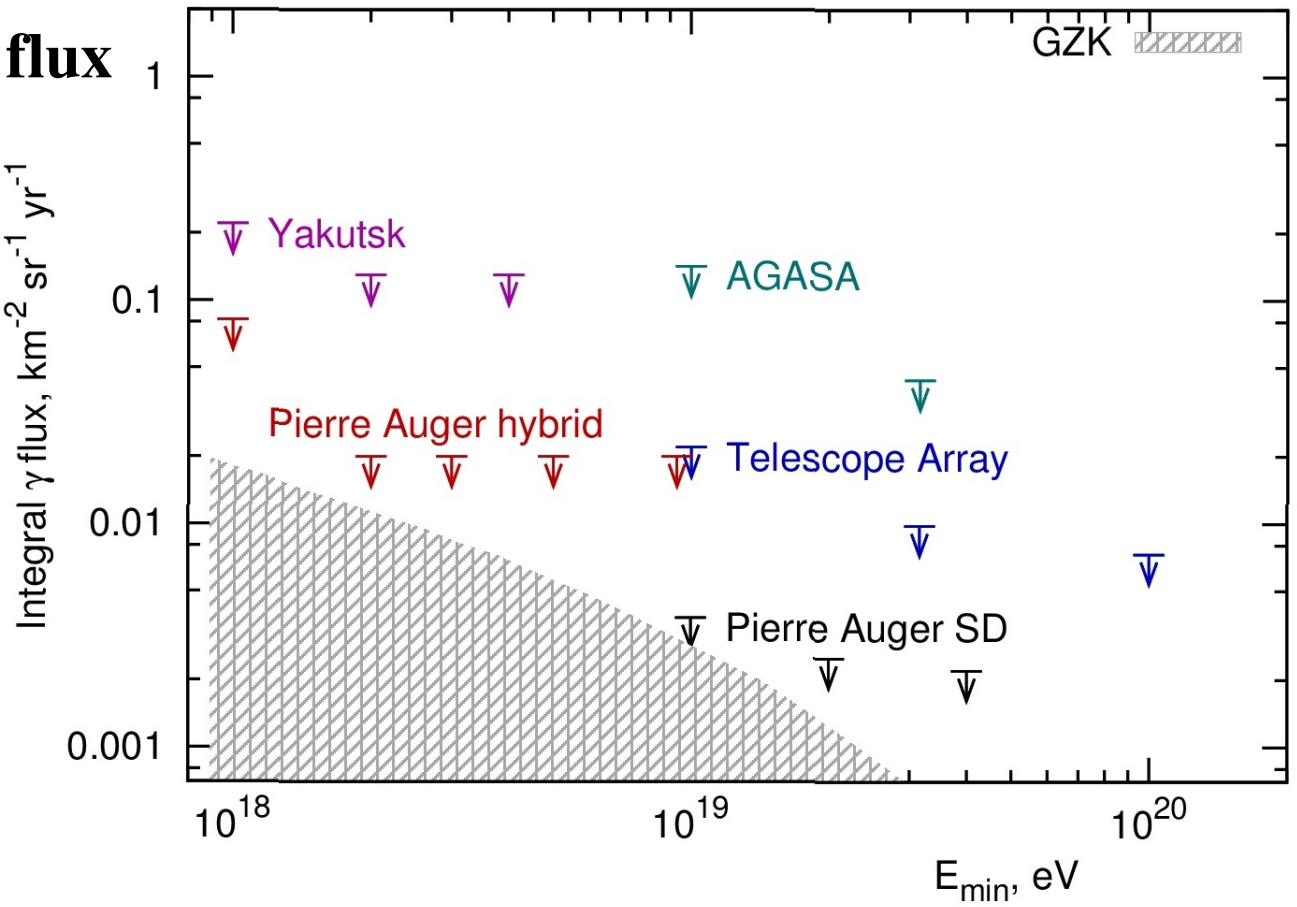
maximize ***Q*** **~ (separation power) / (price per exposure)**

e.g. muon detectors: separation power ! (but shower geometry??)
SD: price per exposure !
fluorescence: clean EM measurement ! (but shower geometry?)

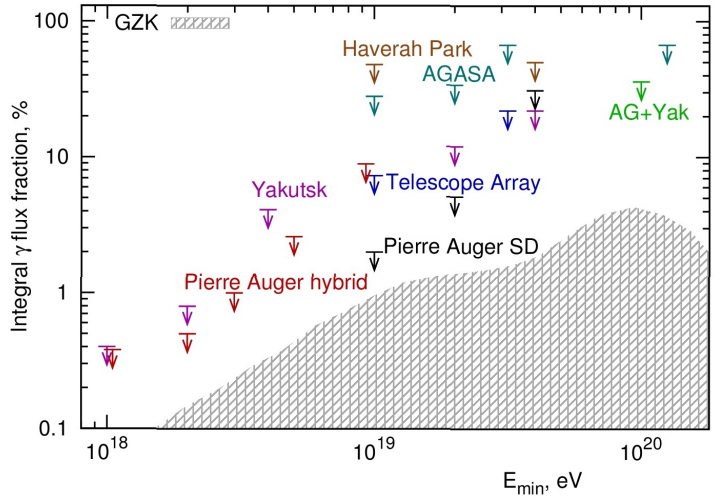
➔ each one **OK**, with **+-**. **Complementary**. **Combination ideal**.

➔ *link to composition WG:* ***what is good for composition, is fine for photons!***
(if EM component can trigger)

Photons: current limits



fraction

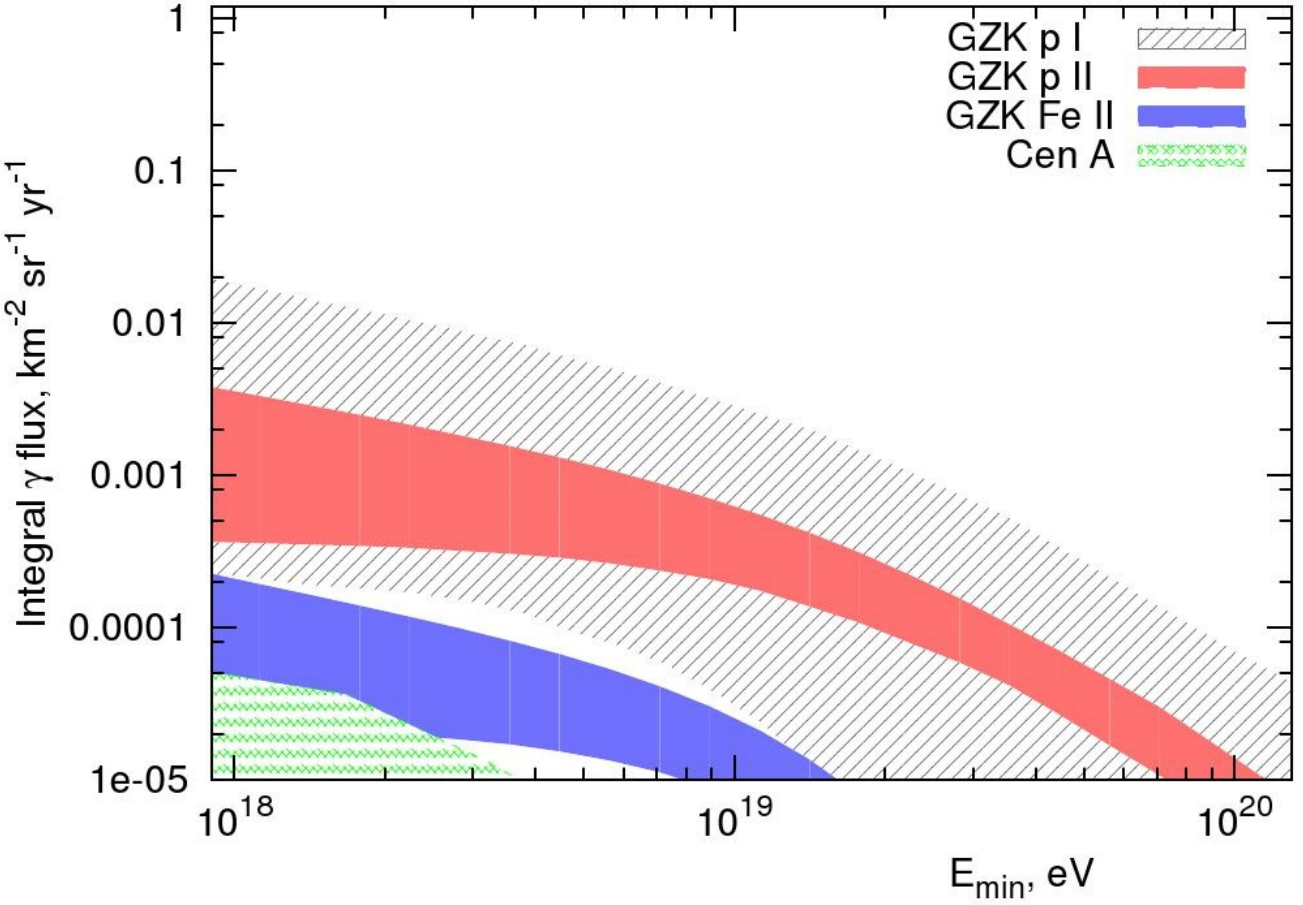


➔ **different techniques, similar findings**

- limits went down and towards lower energy
  due to growing exposure and improved analyses
- typically no candidate at high energy, bkg at threshold

➔ **most optimistic GZK scenarios not far**

Photons: (some) models



Gelmini et al. 2008
B. Sarkar et al. 2011
Kachelriess et al. 2010

➔ **large uncertainty !**

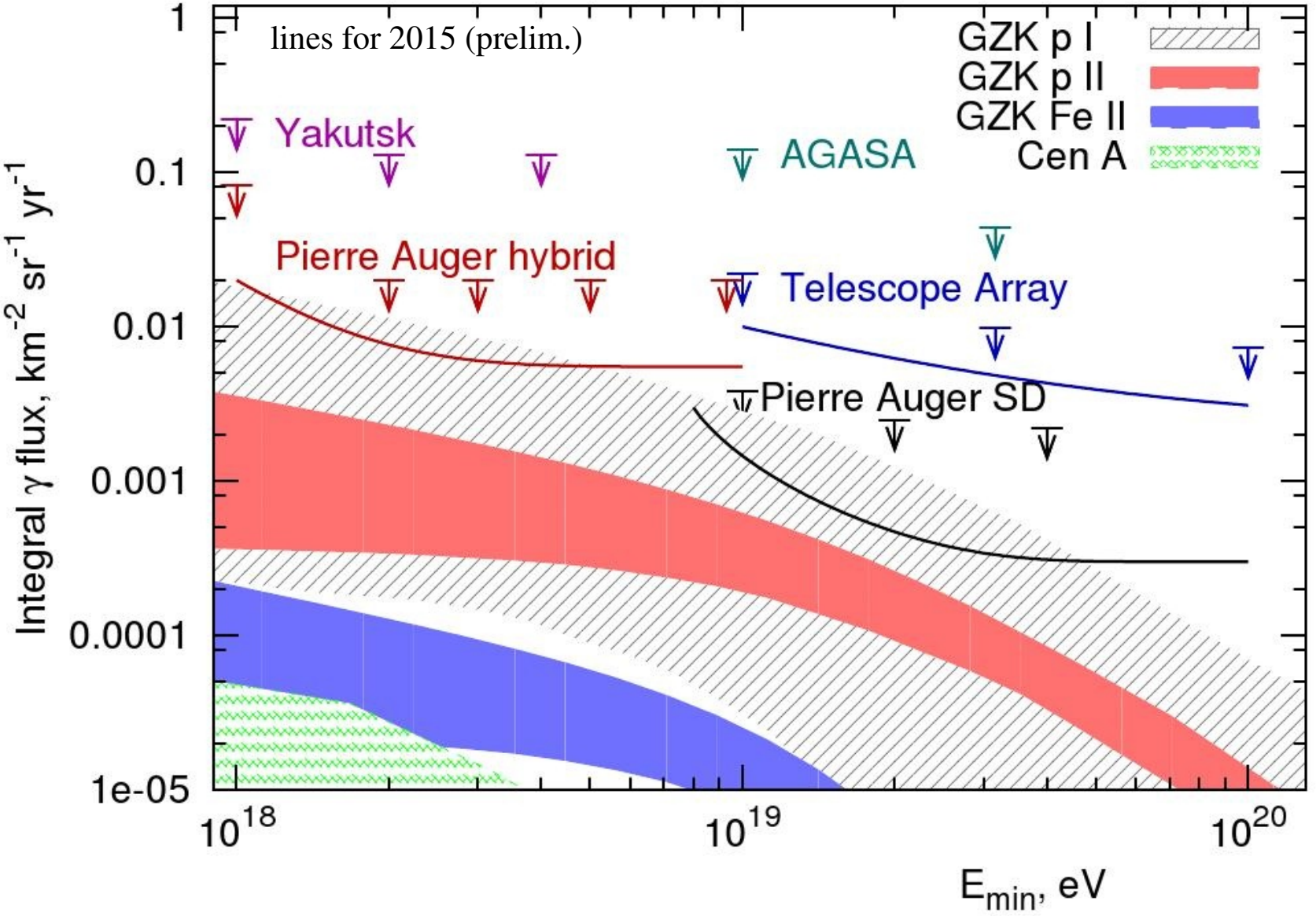
composition (**p**, **Fe**), E_{max} and slope at source, bkg & magn fields ...

source photons in addition to propagation photons?

➔ **photon searches (even limits) may help constrain phase space**

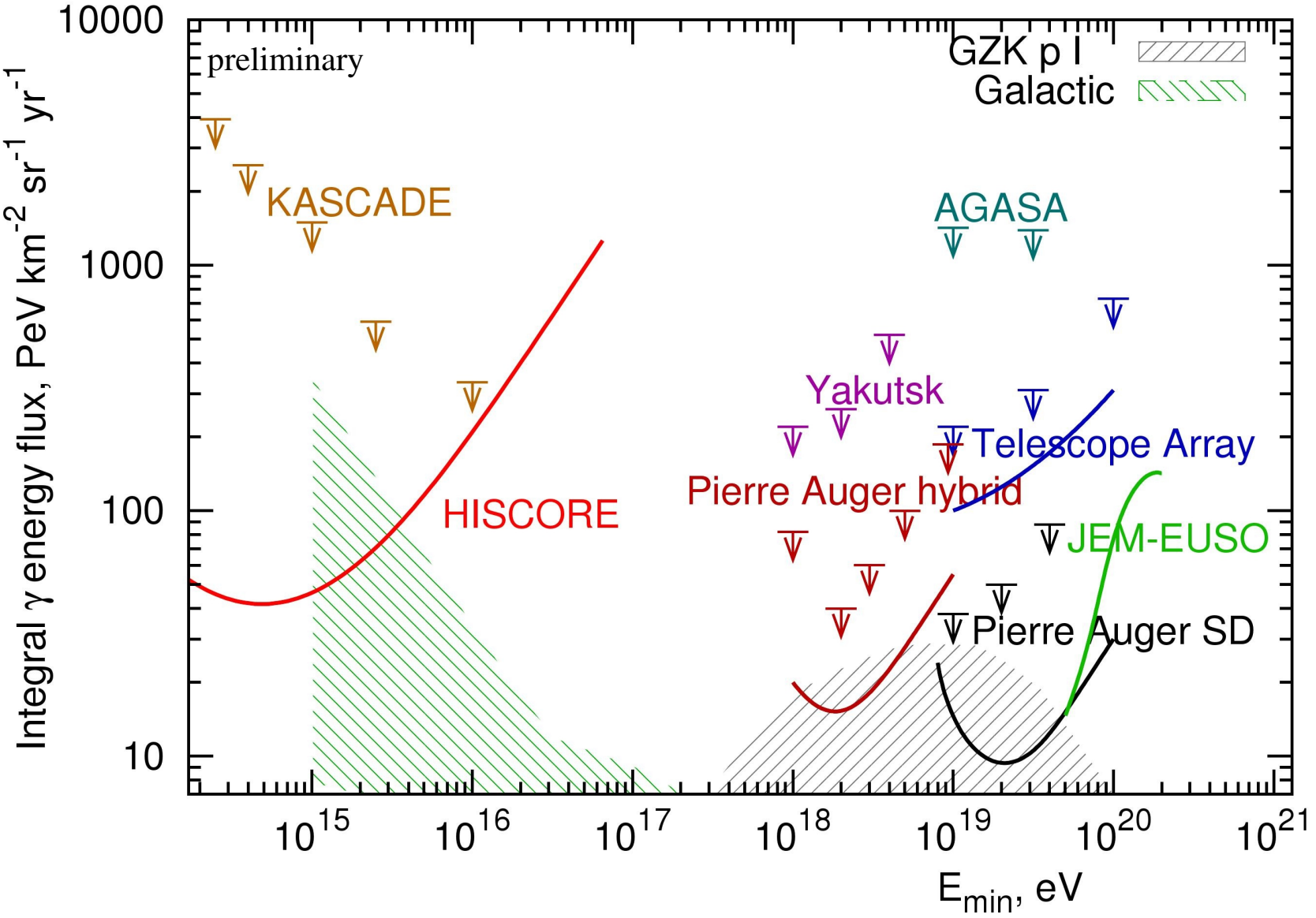
➔ task for phenomenology: **combine various constraints** to reduce phase space

Photons: ~2015 sensitivity estimates



➔ **photon observation possible but not guaranteed** (of course) **!**

Photons: a broader view



experimental gap between 10^{16} – 10^{18} eV

expanding coverage by low-energy extensions (AMIGA, HEAT, TALE ...)

Photons: (some) possible impacts

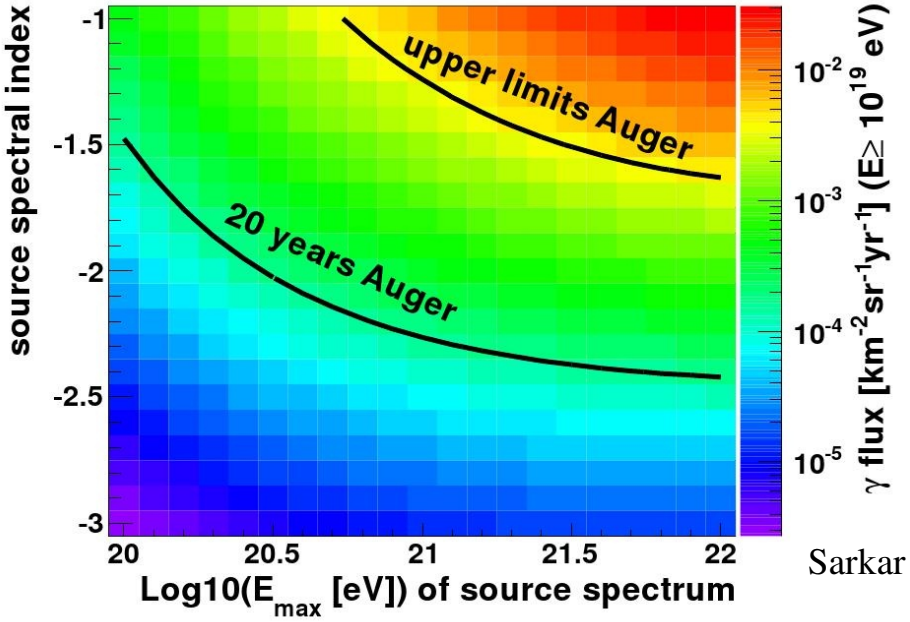
If discovery:

... and the unexpected !

- **astrophysics !** incl. smoking guns
  - source pointing
  - GZK messenger (p interaction with E/m ~ 10^{11} !)
- **fundamental physics !** LV, spacetime fluct., ... one is enough!
- **particle physics !** photon showers@UHE
  - test QED incl. LPM, preshower effect
  - test QCD photonuclear interactions

If no discovery:

- **astrophysics** constraints (source param., composition)
- further **LV** constraints



Sarkar 2011

3. Neutrinos

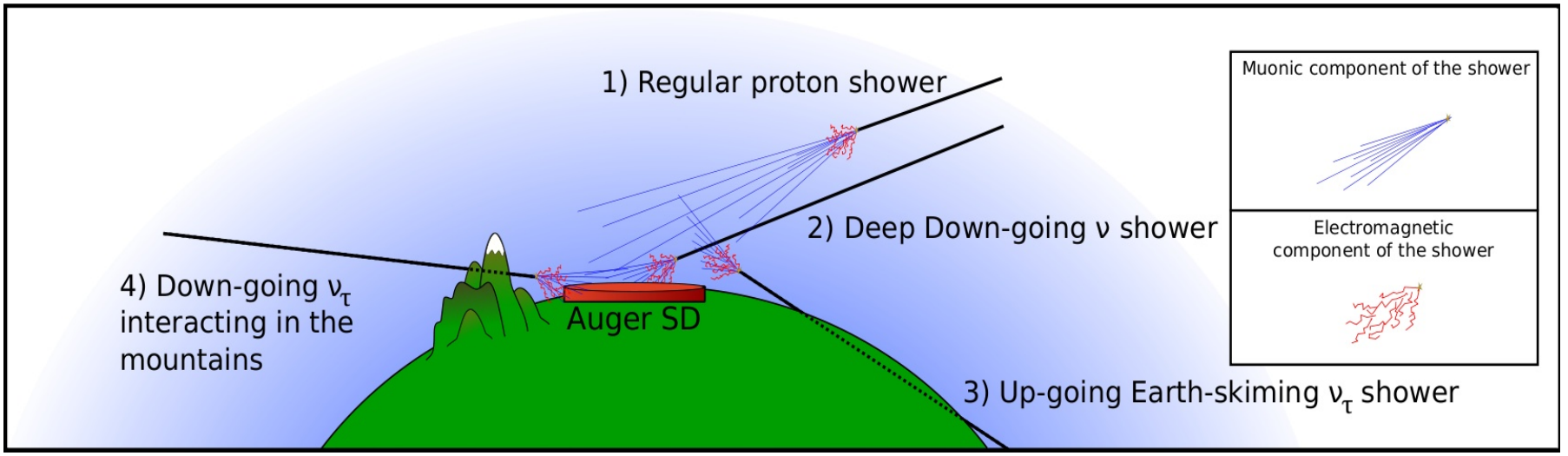
Neutrino EAS in a nutshell

Identification in ground arrays: young (deep) & inclined showers

Main observable: (Broad) time structure of shower front

Channel	Earth-skimming	Downward-going
Flavours & Interac.	ν_τ Charged Current	ν_e, ν_μ, ν_τ & CC + NC
Angular range	90° -> ~ 95°	~ 65° -> 90°
Target	Earth's crust $\rho \sim 2 - 3$ g cm^{-3}	Atmosphere $\rho \sim 10^{-3}$ g cm^{-3}
Relative sensitivity	~ 2.5 - 3	1

details on posters !



Neutrinos: comparison of observables / techniques

Experiment	Technique Flavours Target	Observables	Limit [GeV cm^{-2} s^{-1} sr^{-1}] K x E^{-2} flux (90% CL – single) Livetime/Energy range
Pierre Auger	Array water stations Earth-skimming tau ν Earth's crust	Shower incidence Time spread sh. front	K = 3.2 10^{-8} 3.5 yr full SD / ~0.16 - 20 EeV
Pierre Auger	Array water stations Down-going all flavours Atmos., mountains	Shower incidence Time spread sh. front	K = 1.7 10^{-7} 2.0 yr full SD / ~1 – 100 EeV
HiRes	Fluorescence telesc. Earth-skimming tau ν Earth's crust	Shower incidence Upward-going shower	K ~ 2.6 10^{-7} ~ 6.5 yr data / ~ 1 – 100 EeV
Telescope Array	Array scintillators Down-going all flavours Atmos., mountains	Shower incidence Time spread sh. front	N/A ~ 3 yr data / ~ 1 – 100 EeV
ANITA-II	Antenna Balloon Up-going all flavours Antarctic Ice	Shower incidence MHz-GHz Cherenkov	K = 4.3 10^{-8} 28.5 days / ~ 1 – 3.1 10^{5} EeV
IceCube	Array buried PMTs Up/horizontal all flavours Antarctic Ice	Shower or μ incidence Amount of Cher. light	K = 1.2 10^{-8} 333.5 days / 2 PeV – 6.3 EeV
RICE	Array buried antennas Up-going all flavours Antarctic Ice	Shower incidence MHz-GHz Cherenkov	K = 2.6 10^{-7} 2.35 yr / 0.1 – 100 EeV
Lunar expts. RESUN – LUNASKA - NuMoon	Radio telescopes Moon-skim. all flavours Moon Regolith	MHz-GHz Cherenkov from Moon	K = 7.5 10^{-6} – 10^{-5} – N/A 200, 33.5, 50 h / > 100 EeV

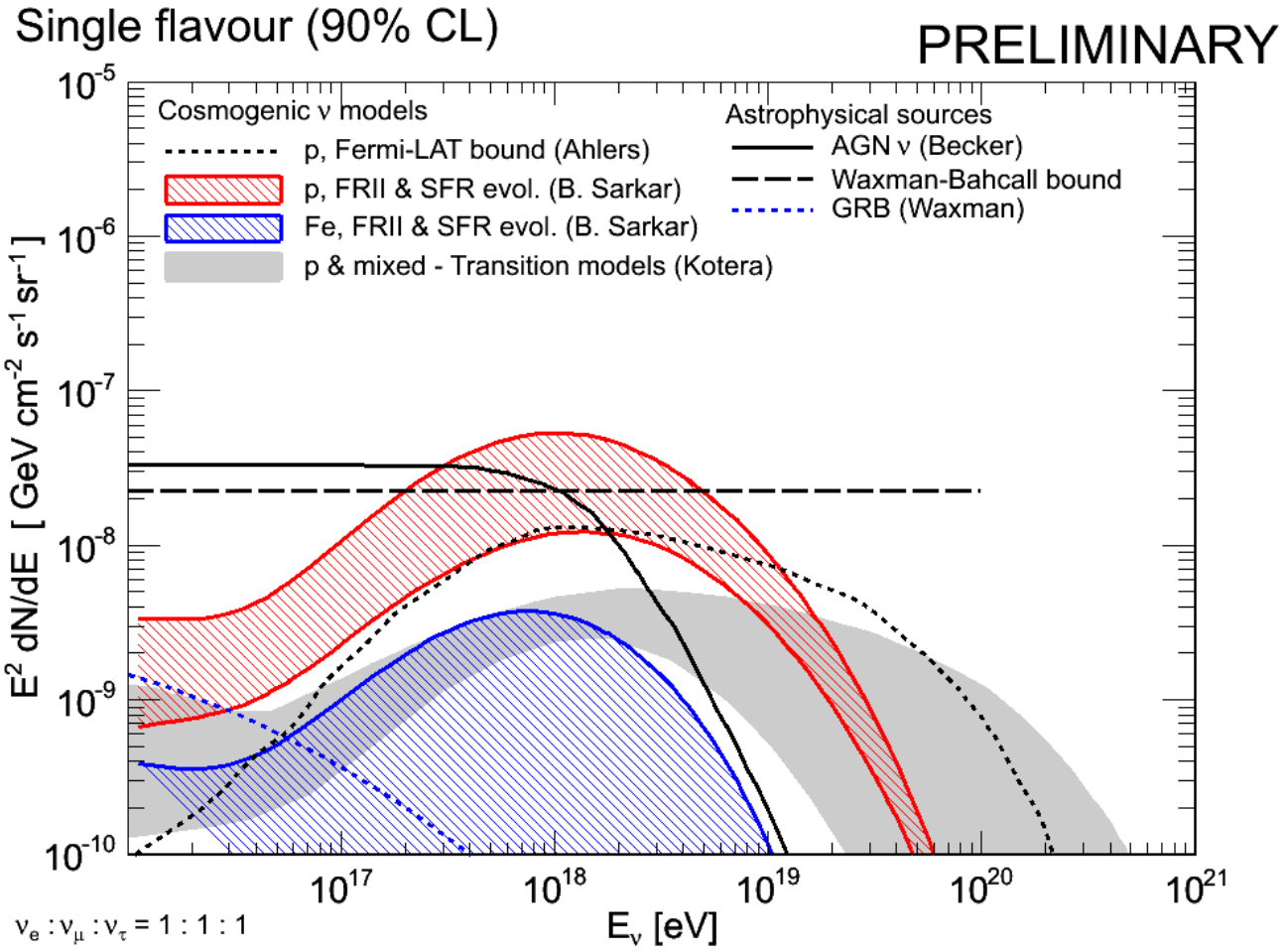
In short: conclusions & highlights from table

- **ground arrays** devoted to EeV CR detection:
  - all arrays currently apply similar ideas to UHE ν search
    (measure time structure of shower front to identify young inclined showers)
  - sensitivities peak where cosmogenic ν is expected to peak (see later)
  - earth-skimming channel more sensitive than downward-going
  - arrays have reached sensitivities comparable to ν-dedicated experiments
    IceCube-40 & ANITA-II (but see later...)

- higher duty cycle of ground arrays compared to **fluorescence detectors**

- **ν-dedicated experiments:**
  typically more sensitivity in less time (larger target density)

Neutrinos: (some) models

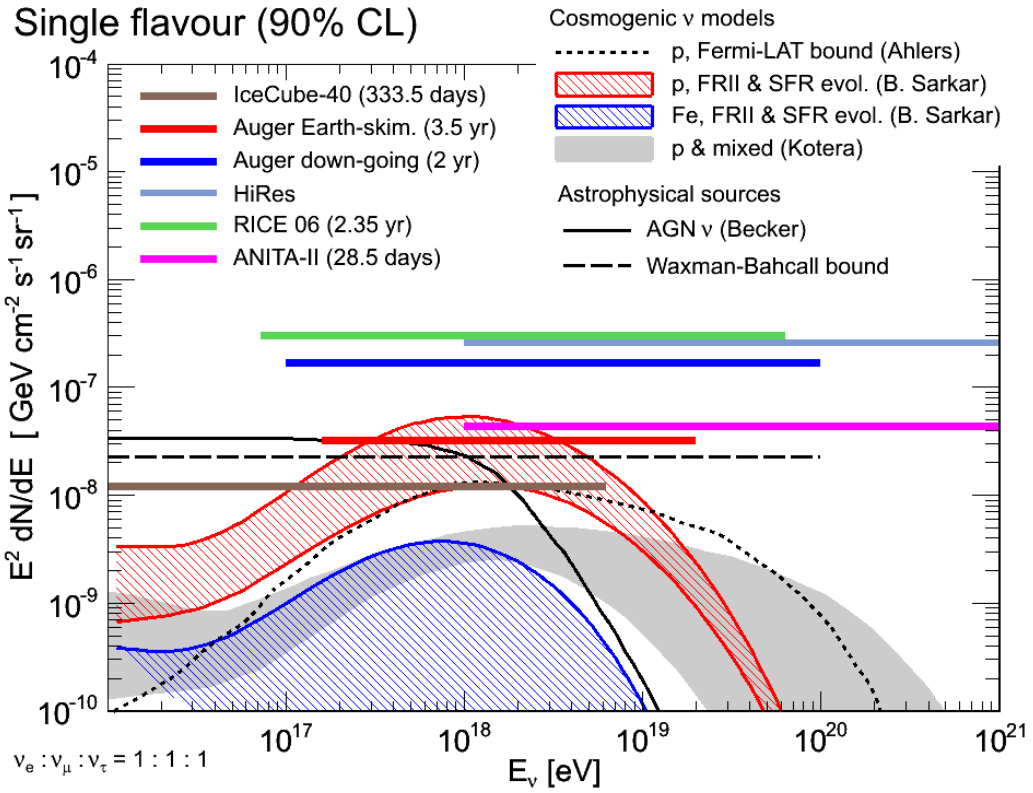


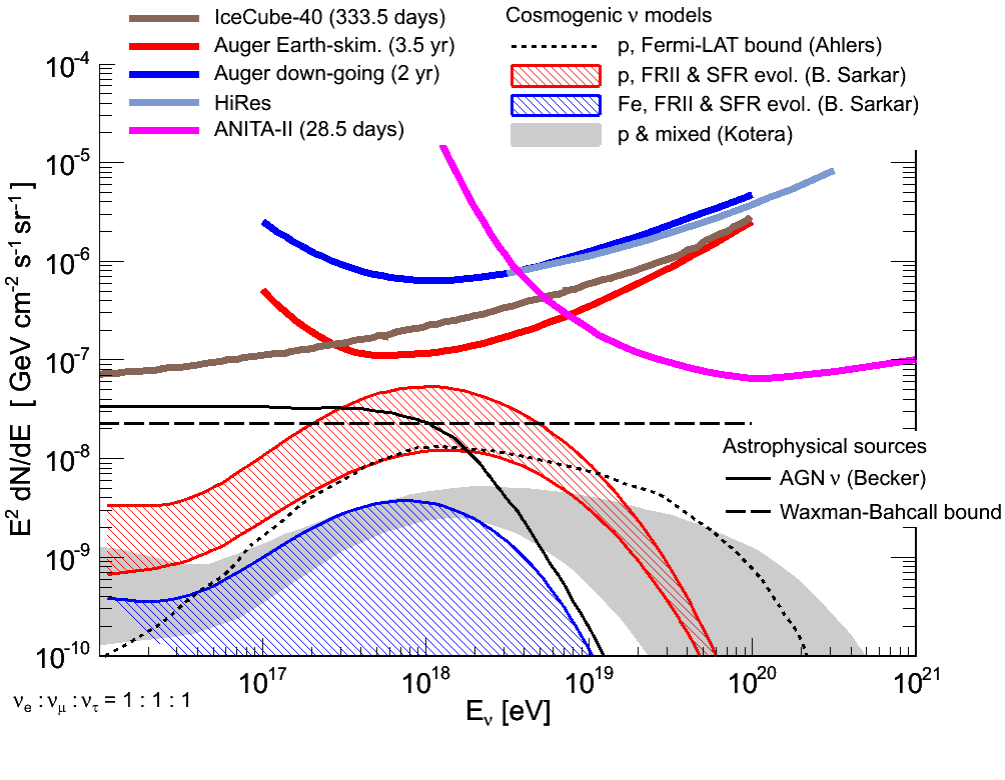
➔ **large uncertainty !**

composition (**p**, **mixed**, **Fe**), E_{max} and slope at source, source evolution with z (strong - FR II, weaker - SFR), transition galactic to extragal. CR source neutrinos (AGN, GRB) in addition to cosmogenic neutrinos

➔ **task for phenomenology: combine various constraints** to reduce phase space (incl. ν limits, GeV γ-ray bounds, ...)

Neutrinos: current limits





integral limits: assume E^{-2} ν flux & find normalization needed to detect ~ 2.4 events

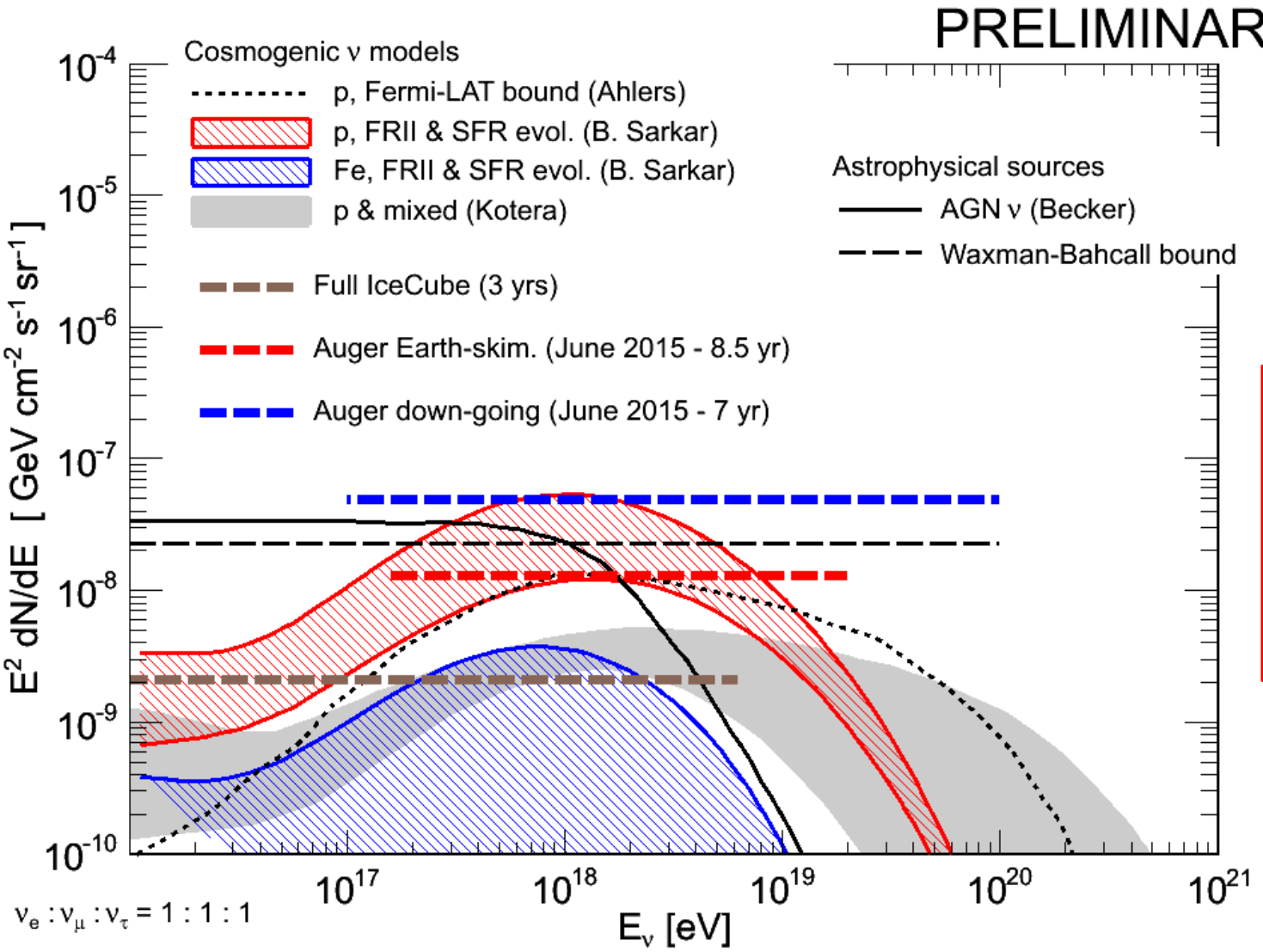
differential limits: assume E^{-2} ν flux in energy bins & find normalization to have 2.4 events in each bin

EAS ground array sensitivity peaks at peak of cosmogenic fluxes (~EeV)

→ event rates (estimated):

ν Model	IceCube-40	Auger (Earth-skim.)	
GZK - p, Fermi-LAT (dashed black line)	~ 0.4	~ 0.6	Poorly constrained
GZK - p, FRII evolution (top edge red band)	~ 1.8	~ 2.2	Starts to be constrained
AGN (solid black line)	~ 5.5	~ 1.2	Strongly constrained

Neutrinos: ~2015 sensitivity estimates



if ν not discovered by 2015, proton models constrained !

ν Model	IceCube-86 (3 yrs)	Auger (Earth-skim.) 2015	
GZK - p, Fermi-LAT (dashed black line)	~ 2.3	~ 1.5	Starts to be constrained
GZK - p, FRII evolution (top edge red band)	~ 10.3	~ 5.4	Strongly constrained

Neutrinos: future EAS detector

What is best for neutrinos? (from the experience with Auger)

- **large area array** (large exposure, $\gg 3000$ km^2):
  size & design (distance between detectors) probably determined by what ν-dedicated expts. detect ... or do not detect ...

- **individual detector stations:**
  acceptance to very inclined directions:
  - water tanks
  - scintillators less suitable

  capability to distinguish young from old showers
  - time structure of EAS front

    and / or
  - particle identification

- higher duty cycle of ground arrays compared to **fluorescence detectors**

- **other technologies** to detect EAS: radio MHz, microwave ... too soon to tell ...

EeV Neutrinos: possible impacts (EAS observation)

If discovery:

- smoking gun of **CR acceleration** to EeV energies
- possible identific. of **sources of CR** (could be transients ! GRB, ...)

and/or

- **GZK messengers** (confirmation that depletion of CR flux is indeed from GZK effect)
- if detected events are identified as Earth-skim. tau neutrino then:
  observation of **oscillations over cosmological distances**
- if tens of events detected then:
  ratio (Down-going rate / Earth-skim.) sensitive to **x-section @ EeV**
  small ratio => small x-section; huge x-section => new physics (TeV black holes etc)
- …

… and the unexpected !

If no discovery:

- **astrophysics constraints** on relevant parameters:
  - source evolution/distribution & injection spectra of UHECR
    (UHECR spectrum alone is too degenerate)
  - info on opacity of sources,...
- hints on **CR composition** at EeV

4. Conclusion

WG charge:
review current situation w.r.t. future directions: physics and techniques

neutrinos
vs
photons

production: (pion decay) **secondaries**, same initial processes
propagation: **photons - local, neutrinos - all universe**

photons: **~normal EAS** (large X_{max}, few muons), small bkg
neutrino: ~10^{-5} prob, **extreme EAS** (deep, upward), no bkg
effective apertures ratio ~10^4 (ground array, 10 EeV)

neutrinos, photons
vs
charged CR

neutral! **source pointing** (astronomy)
GZK messengers
EAS interpretations more robust

data
vs
models

EAS-*MM* searches (already) useful
constraints on top-down, LV, (starting:) astrophysics
neutrino & photon **discovery possible**, not guaranteed

various models
vs
each other

large uncertainty
task for phenomenology: **combine various constraints**

EAS observation
vs
other techniques

photons: **no competition** to EAS
neutrinos: competition, (presently) **comparable**
findings can strongly impact future ν-plans

ground EAS
vs
EAS from space

separation of primaries better from ground
some balance if large **exposure** from space?
(see talks on Thursday)

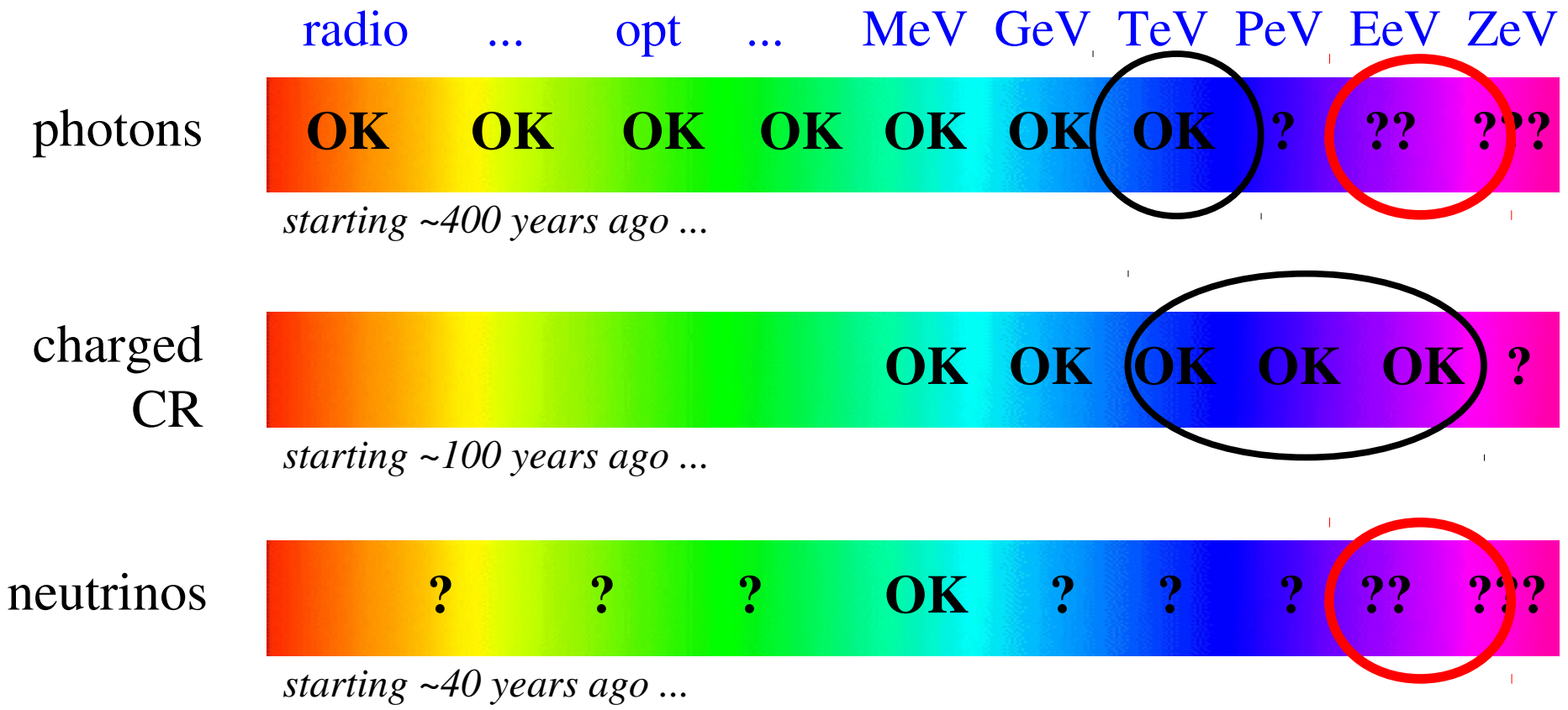
ground EAS techniques
vs
each other

photons: **each OK with +-, complementary** (best: combine)
"good for composition - fine for photons!"
neutrinos: **large exposure to inclined EAS!**
e.g. large array of water det.

present status
vs
future directions

(see next slide)

Present status *vs* future directions

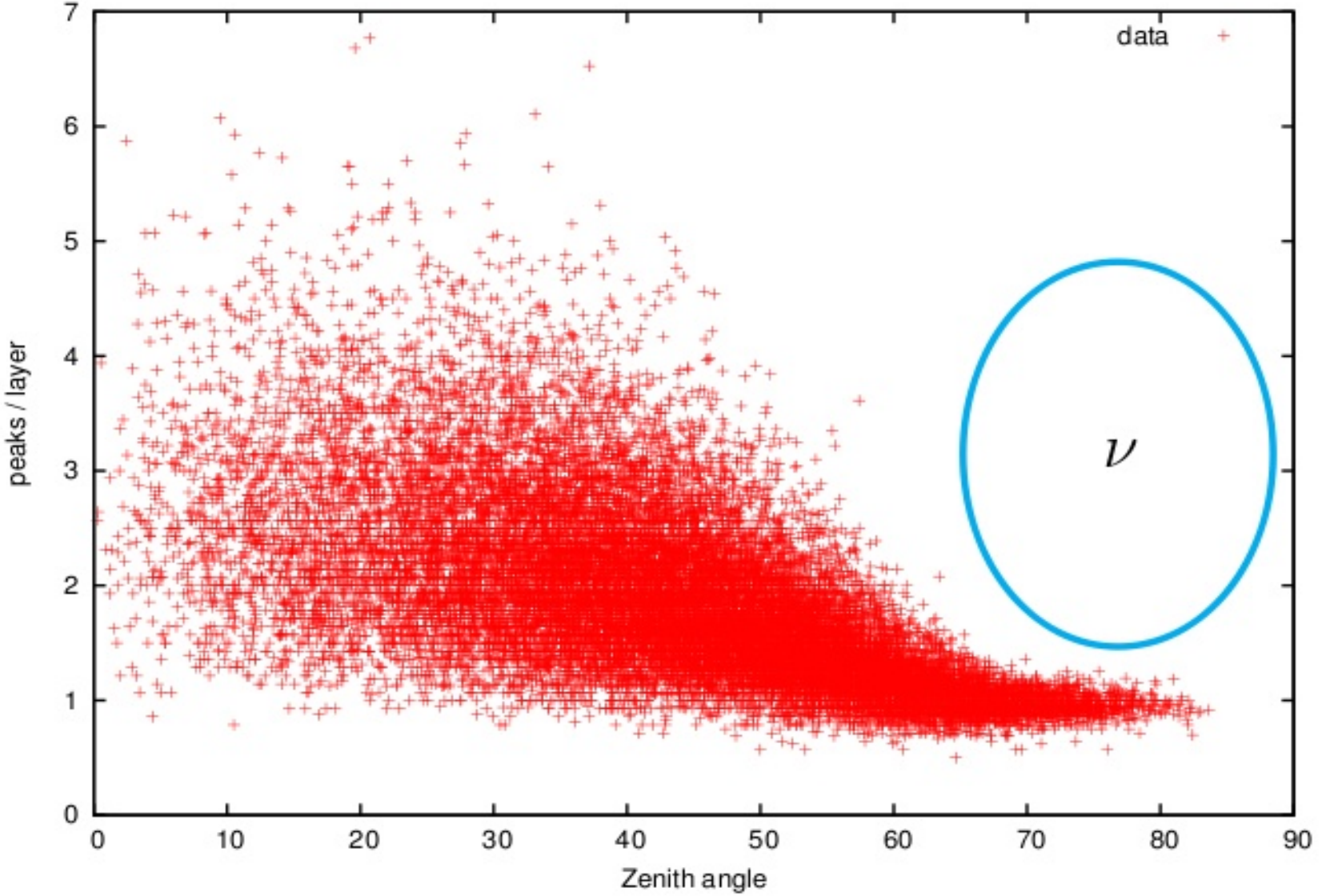


new windows - new discoveries
large impact, also beyond astroparticle physics

Question to EAS community:
How do we want this to look like in 10-15 years ?

Appendix

TA neutrino search



- No young inclined showers => no neutrino candidates