GROUND-BASED GAMMA-RAY ASTRONOMY: QUO VADIS ?

Werner Hofmann
MPI für Kernphysik
Heidelberg

2018 Hillas Symposium

www.fabulouspartyware.com

THE TRIVIAL ANSWERS …

THE TRIVIAL ANSWERS …

BIG

Science

CTA 400+ M€
LHAASO 100+ M€

THE TRIVIAL ANSWERS …

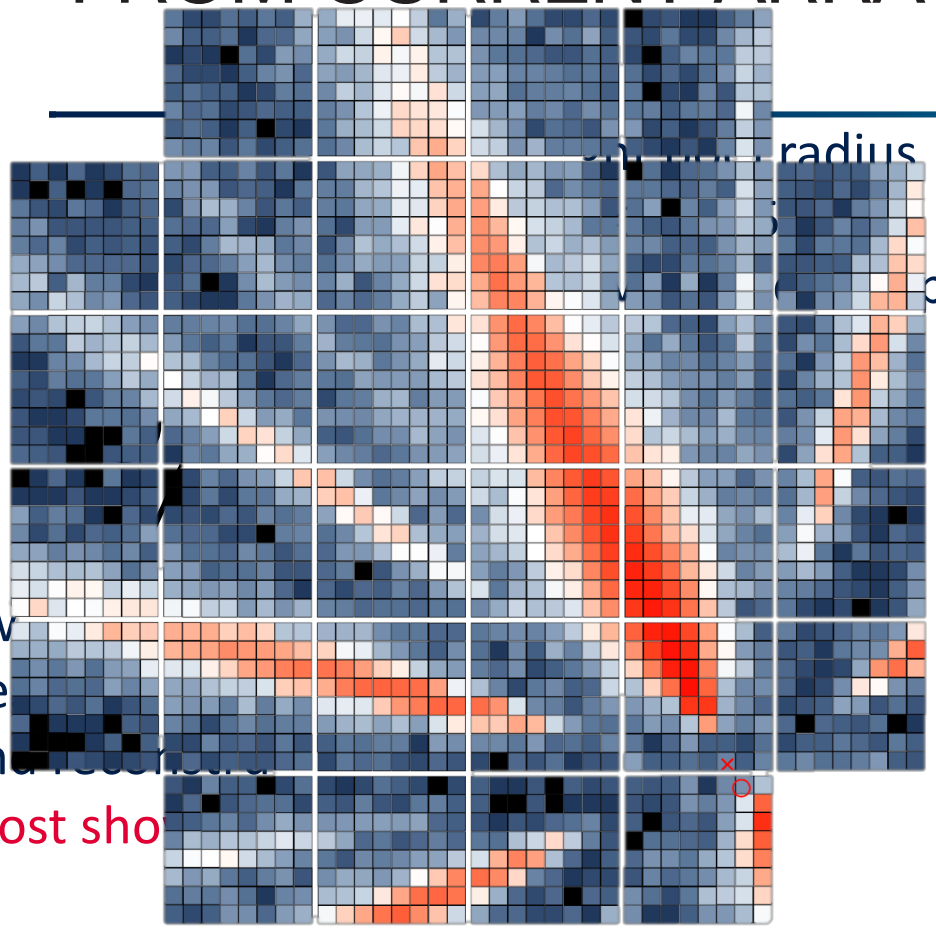
CTA 400+ M€
LHAASO 100+ M€

THE TRIVIAL ANSWERS ..

cta

Agreements regarding southern site to be signed on Dec. 19

FROM CURRENT ARRAYS TO CTA



radius

pe spacing

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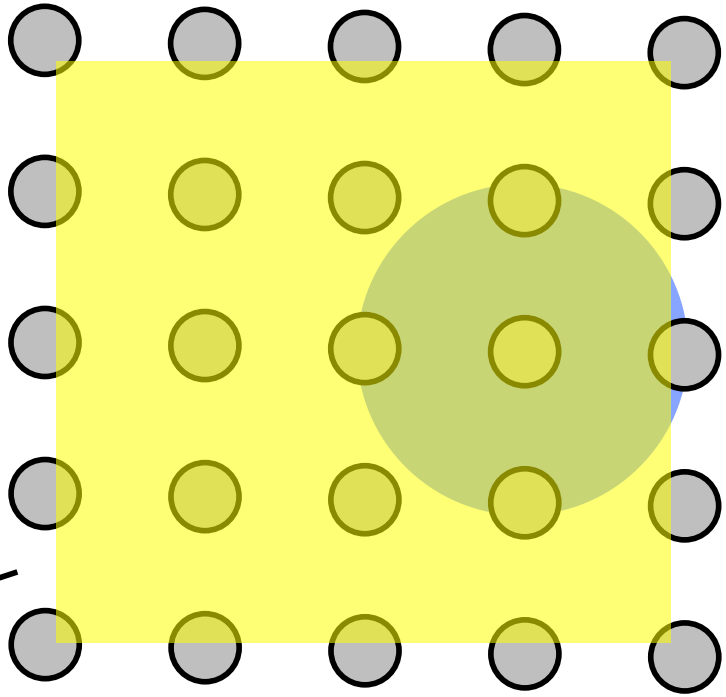
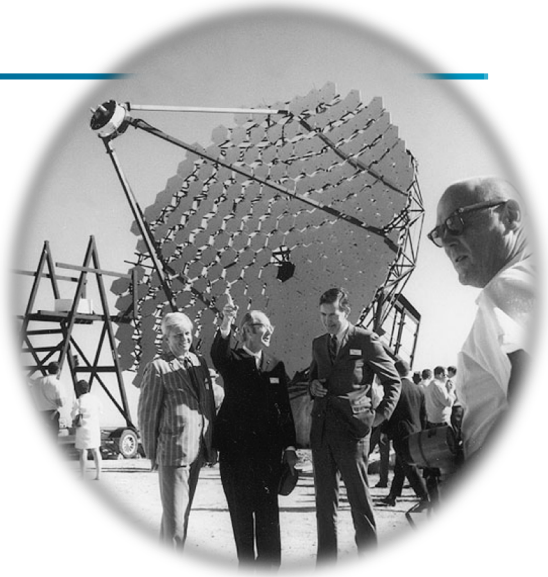


large detection area
more images per shower
lower trigger threshold

CHERENKOV IMAGING IMPROVEMENTS



Improved imaging: larger fov, finer pixels

Large dish

Stereoscopy

Large arrays

High-QE PMTs, silicon sensors

Novel optics concepts

Extremely detailed simulation models

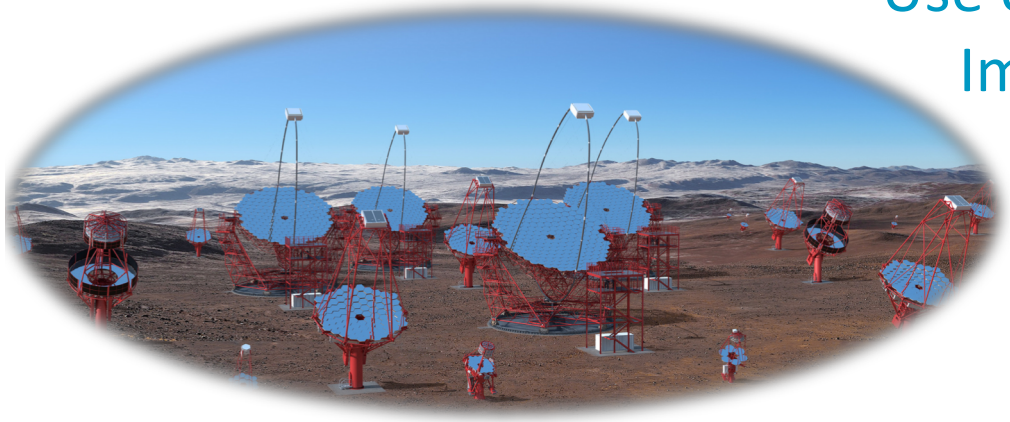
Atmospheric monitoring and modeling

Use of pixel waveforms

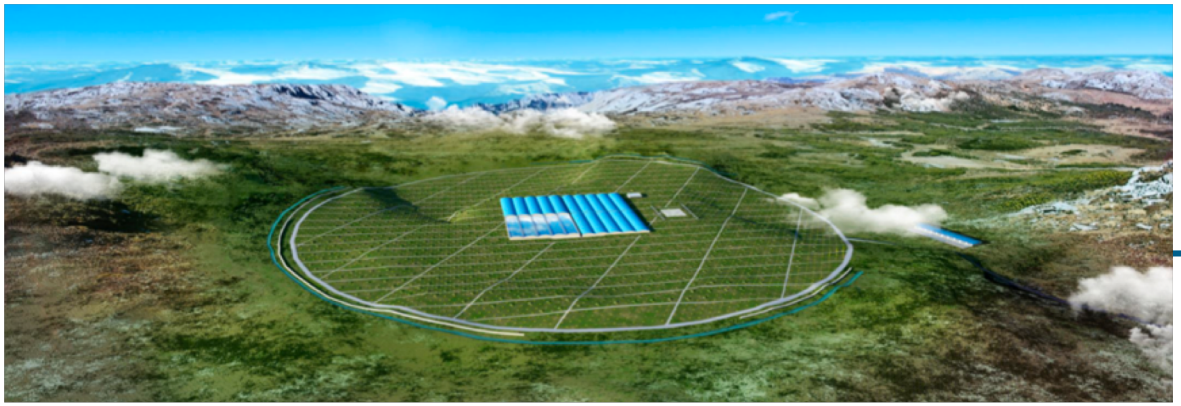
Image fitting

Deep neural networks

Run-wise simulations

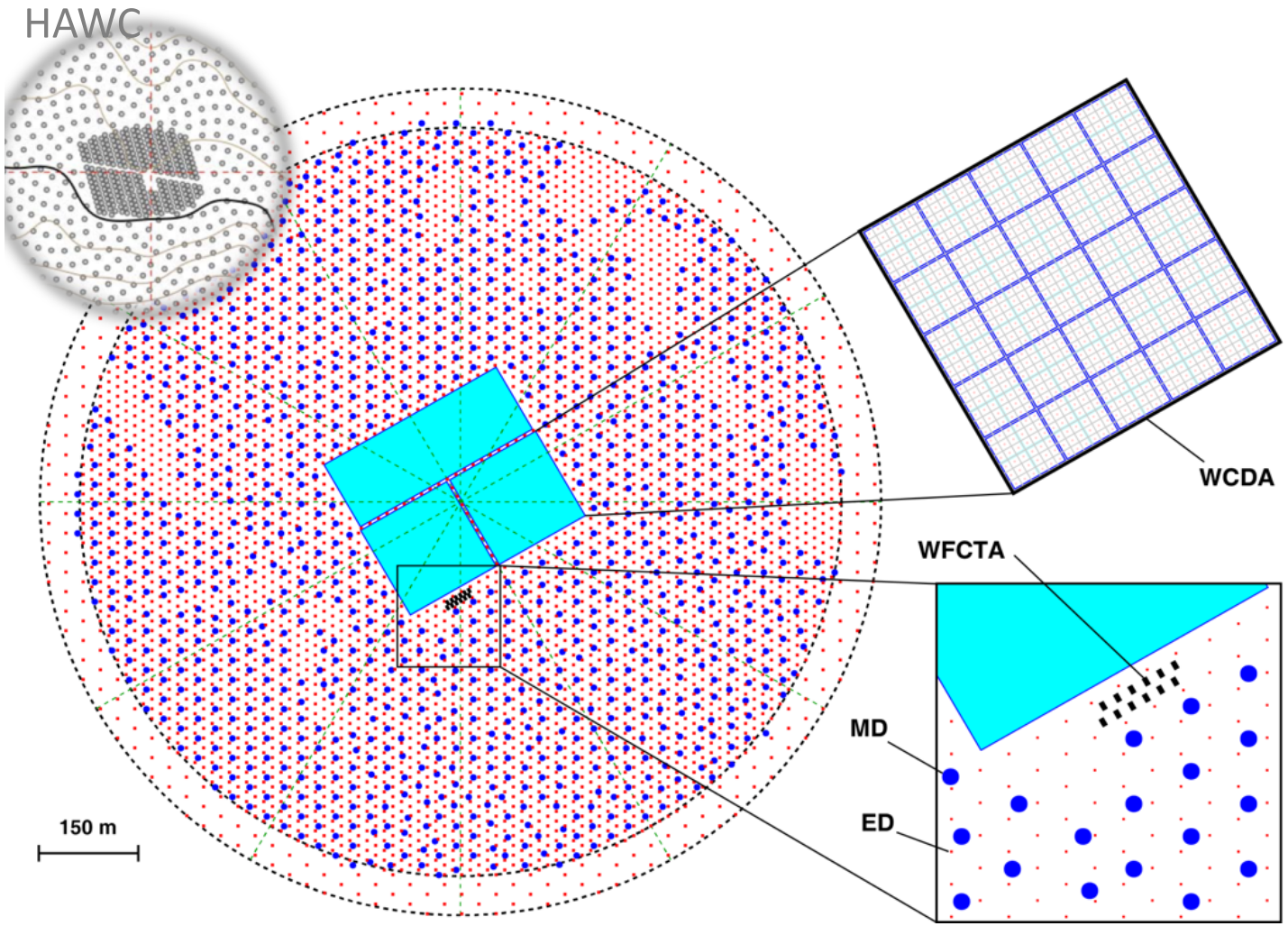


THE TRIVIAL ANSWERS …



LHAASO

Sichuan, China, 4410 m asl



5195 Scintillators
- 1 m^2 each
- 15 m spacing

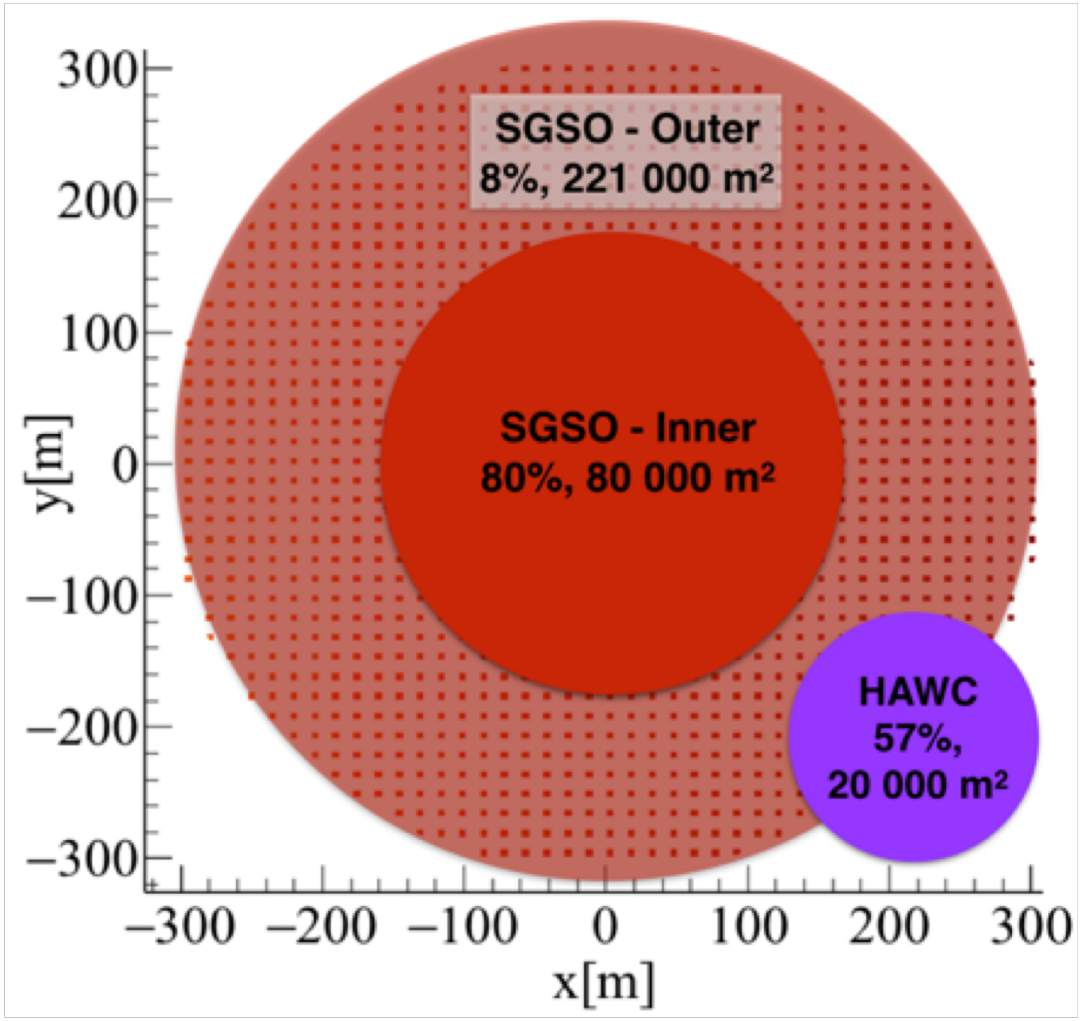
1171 Muon Detectors
- 36 m^2 each
- 30 m spacing

3000 Water Cherenkov Cells
- 25 m^2 each

12 Wide Field Cherenkov Telescopes

THE TRIVIAL ANSWERS (?)

SOUTHERN
GAMMA-RAY
SURVEY
OBSERVATORY

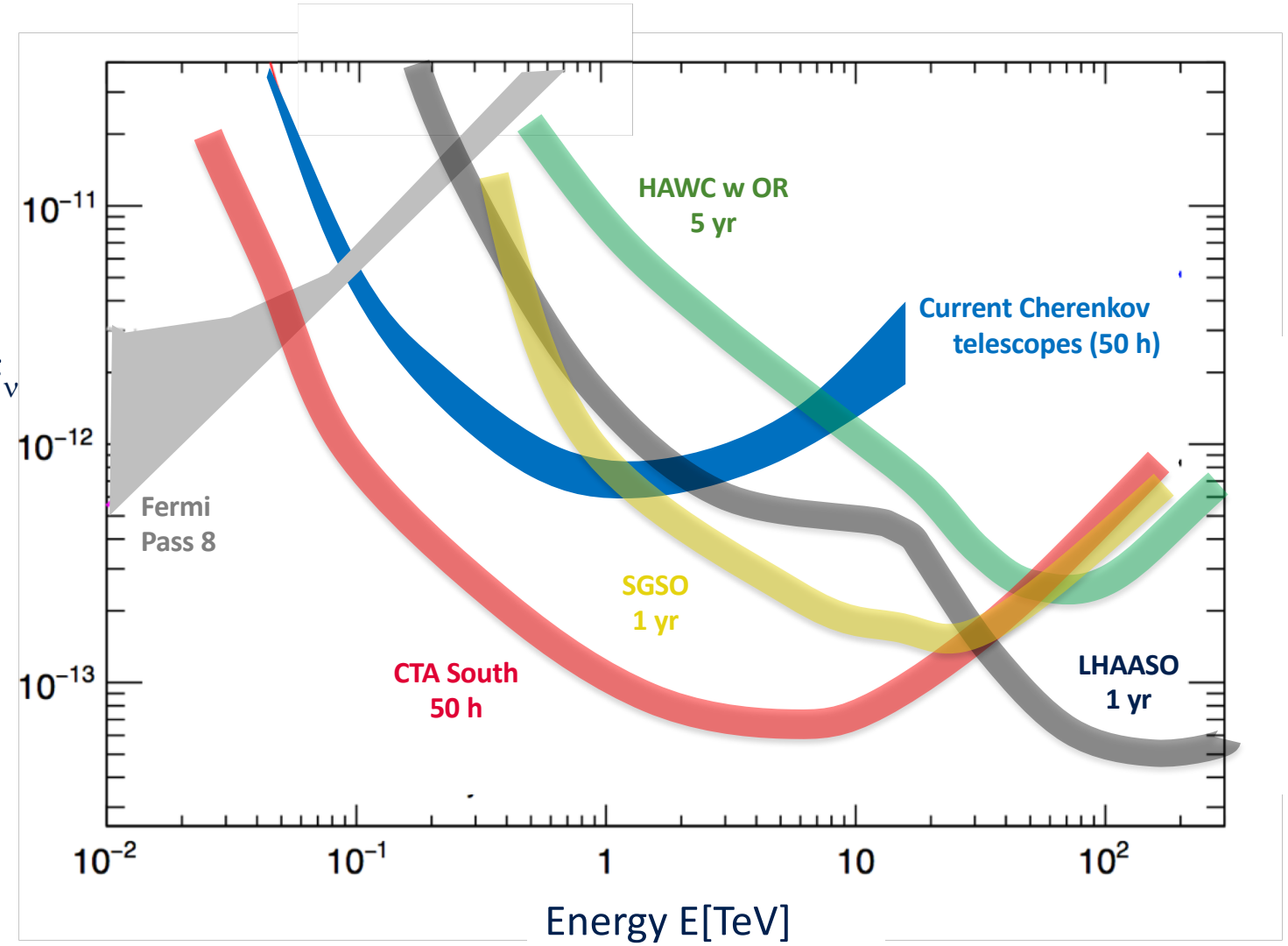


SGSO

an enlarged version
of HAWC in the South

Dense core area ≈ LHAASO

SENSITIVITY (STEADY SOURCES)



adapted from
www.cta-observatory.org;
J. Goodman, COSPAR 2018;
Z. Cao, La Palma 2018

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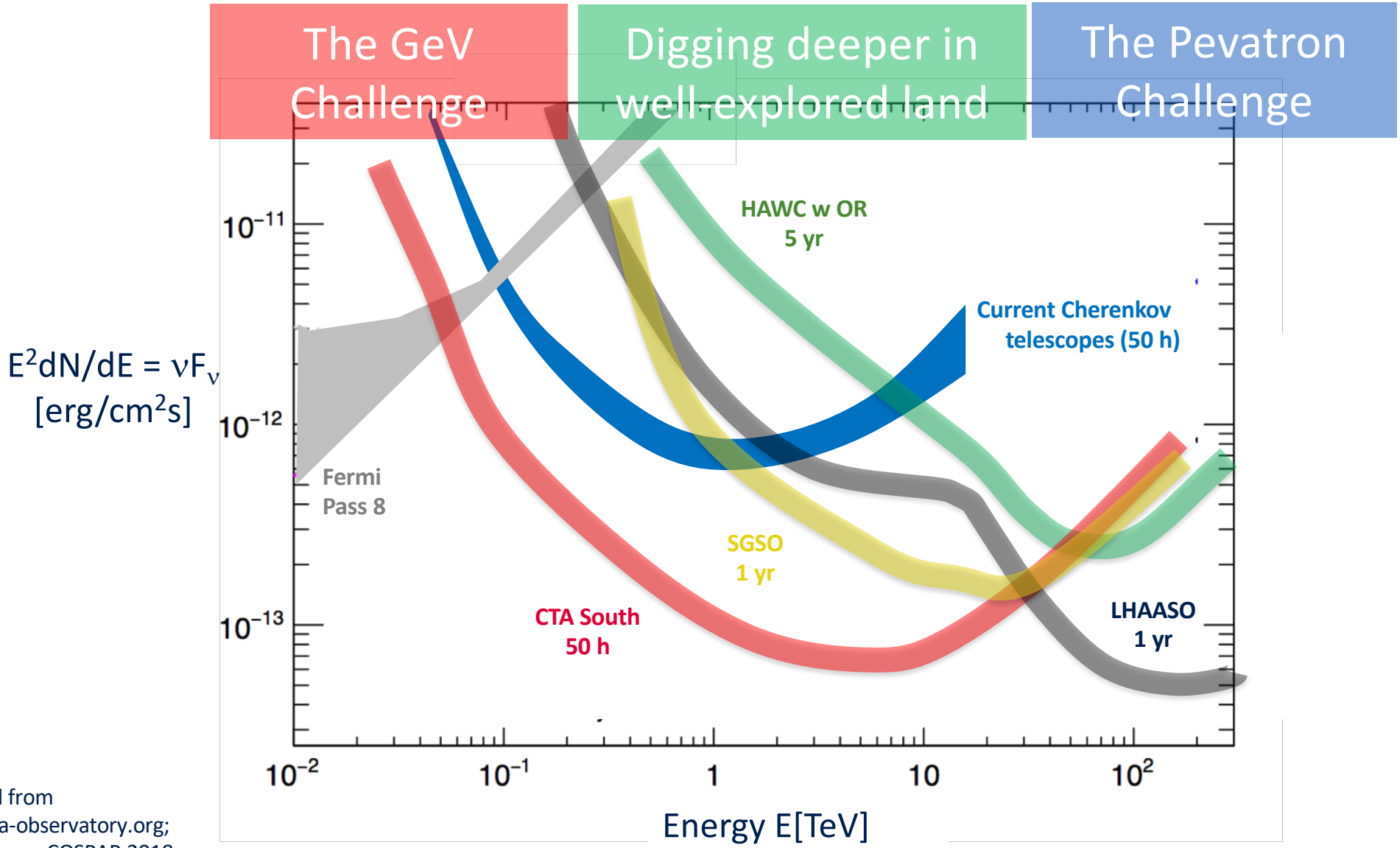

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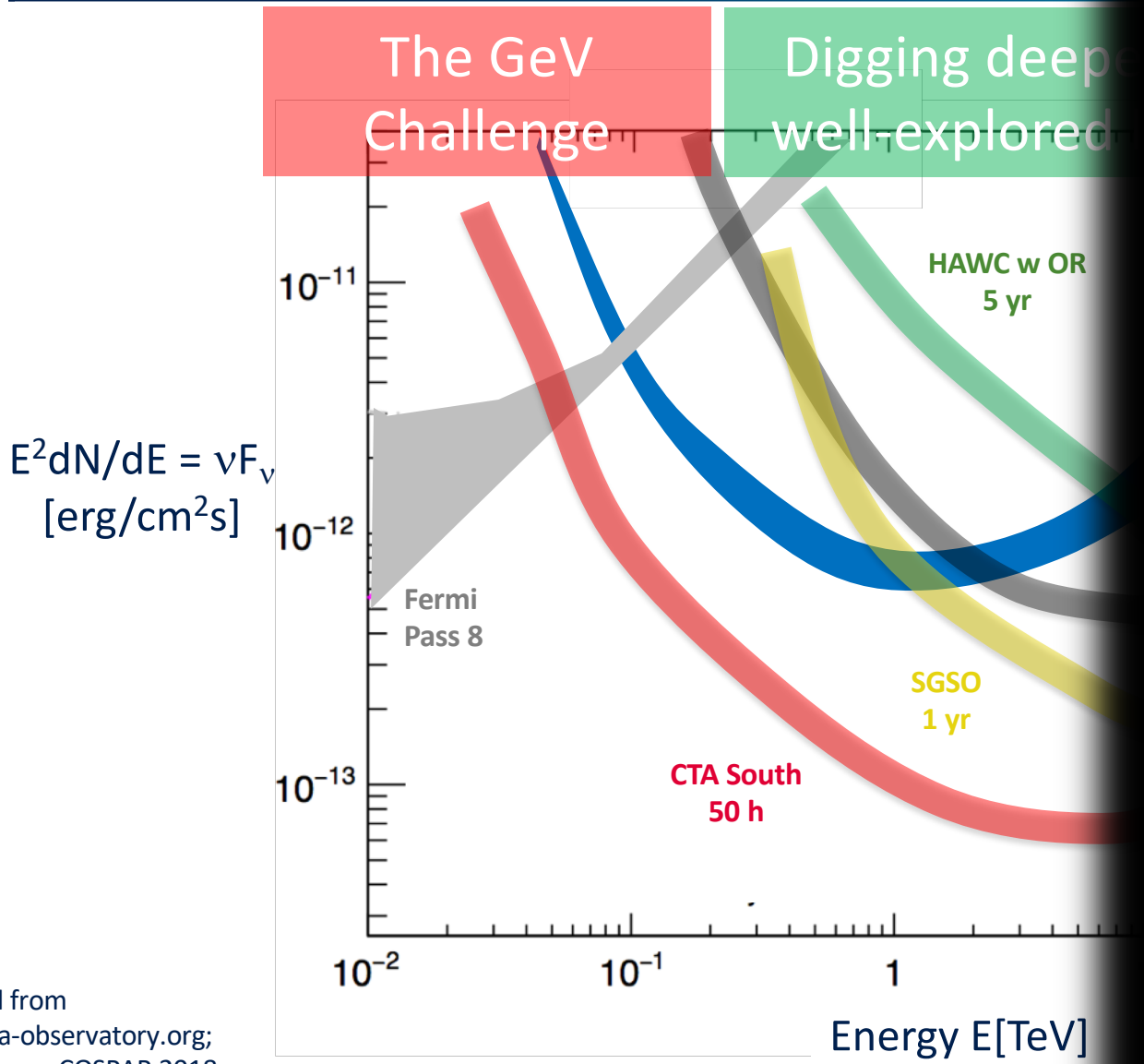
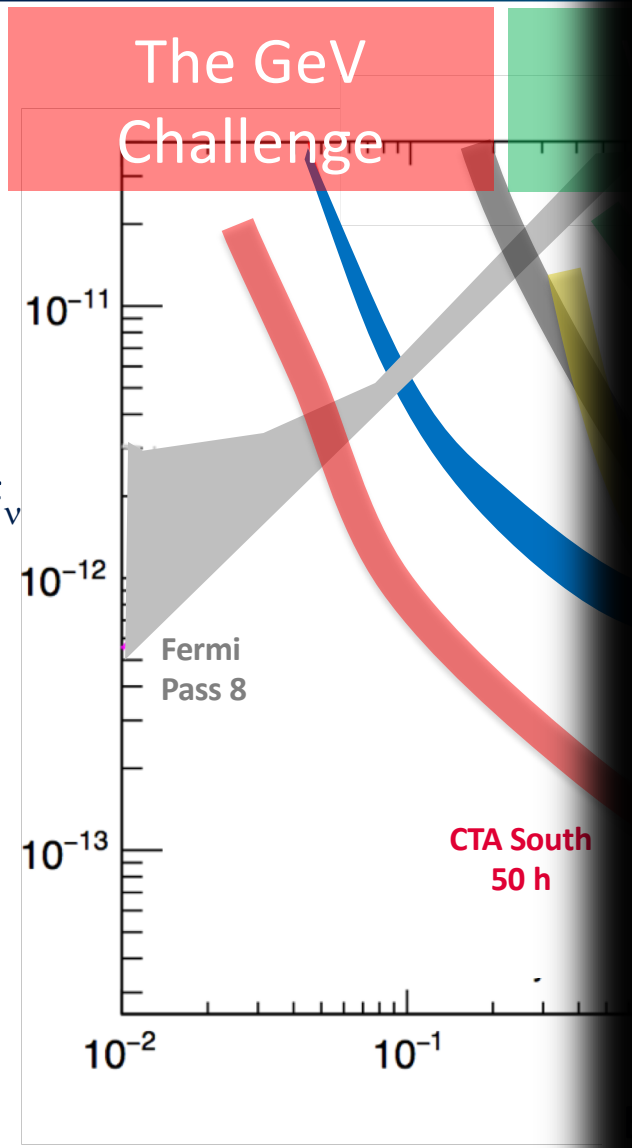


Redshift z=0.1

adapted from
www.cta-observatory.org;
J. Goodman, COSPAR 2018;
Z. Cao, La Palma 2018

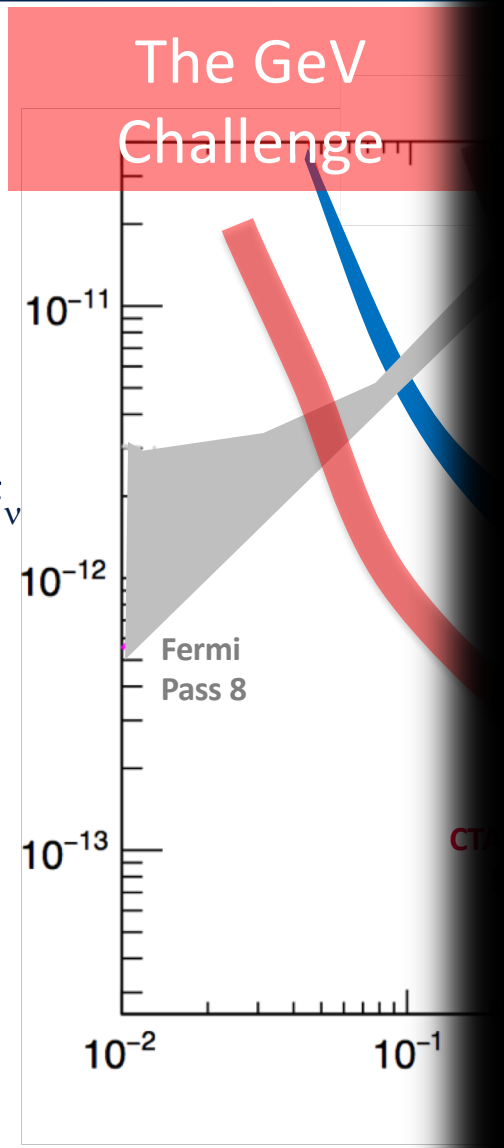
SENSITIVITY (STEADY S



Redshift z=0.3

adapted from
www.cta-observatory.org;
J. Goodman, COSPAR 2018;
Z. Cao, La Palma 2018

SENSITIVITY (STEAD

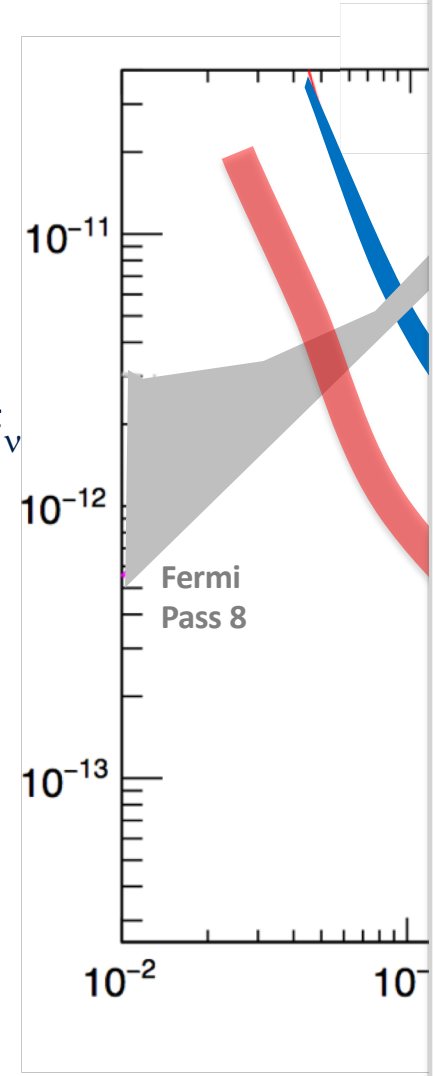


Redshift z=1

adapted from
www.cta-observatory.org;
J. Goodman, COSPAR 2018;
Z. Cao, La Palma 2018

SENSITIVITY (STEA

$E^2dN/dE = \nu F_\nu$
[erg/cm^{2}s]



adapted from
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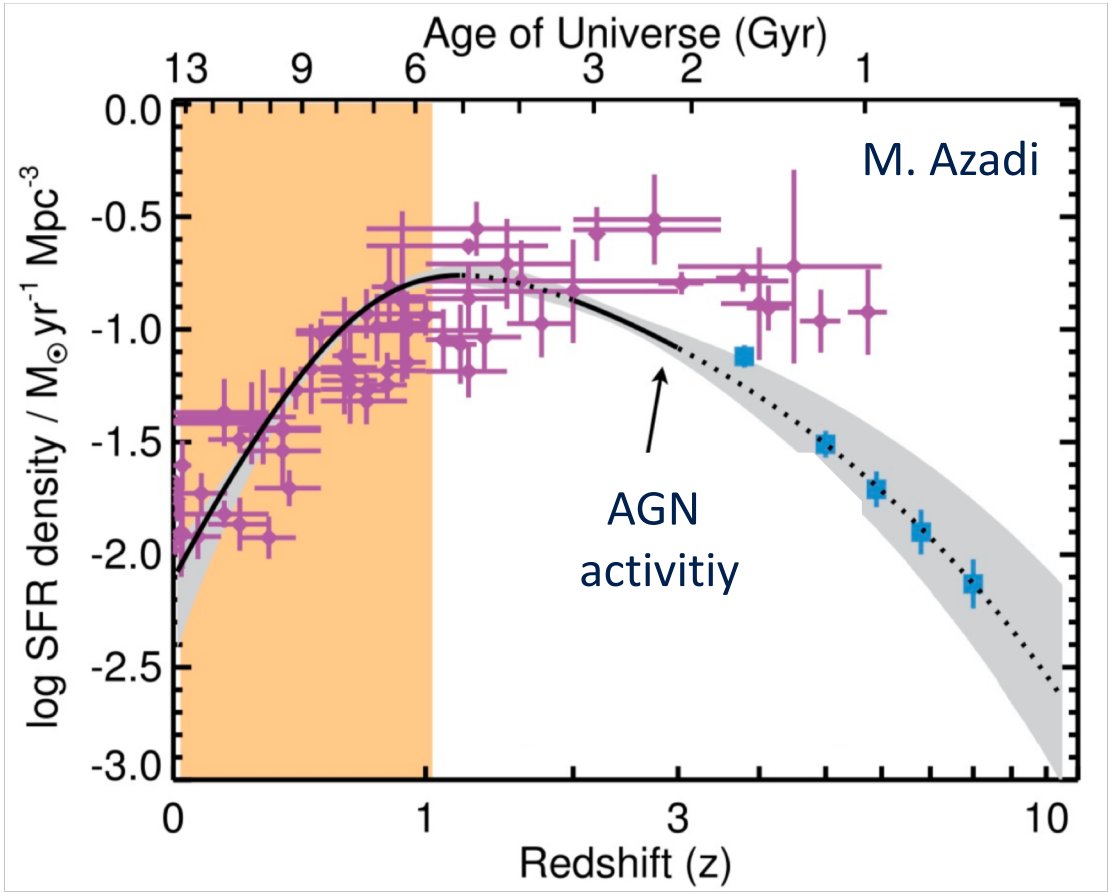
Much information
in the time domain
(transients)



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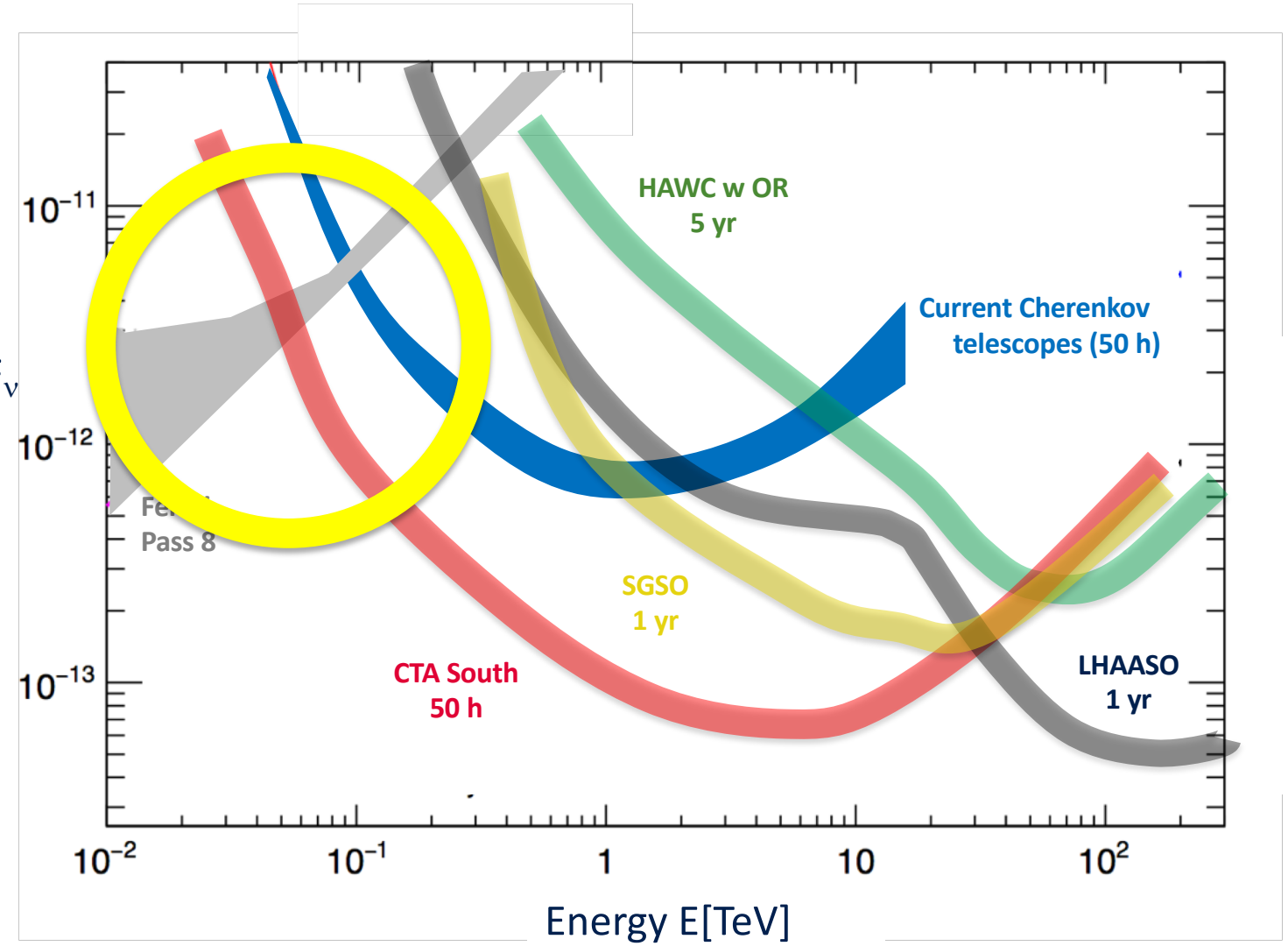

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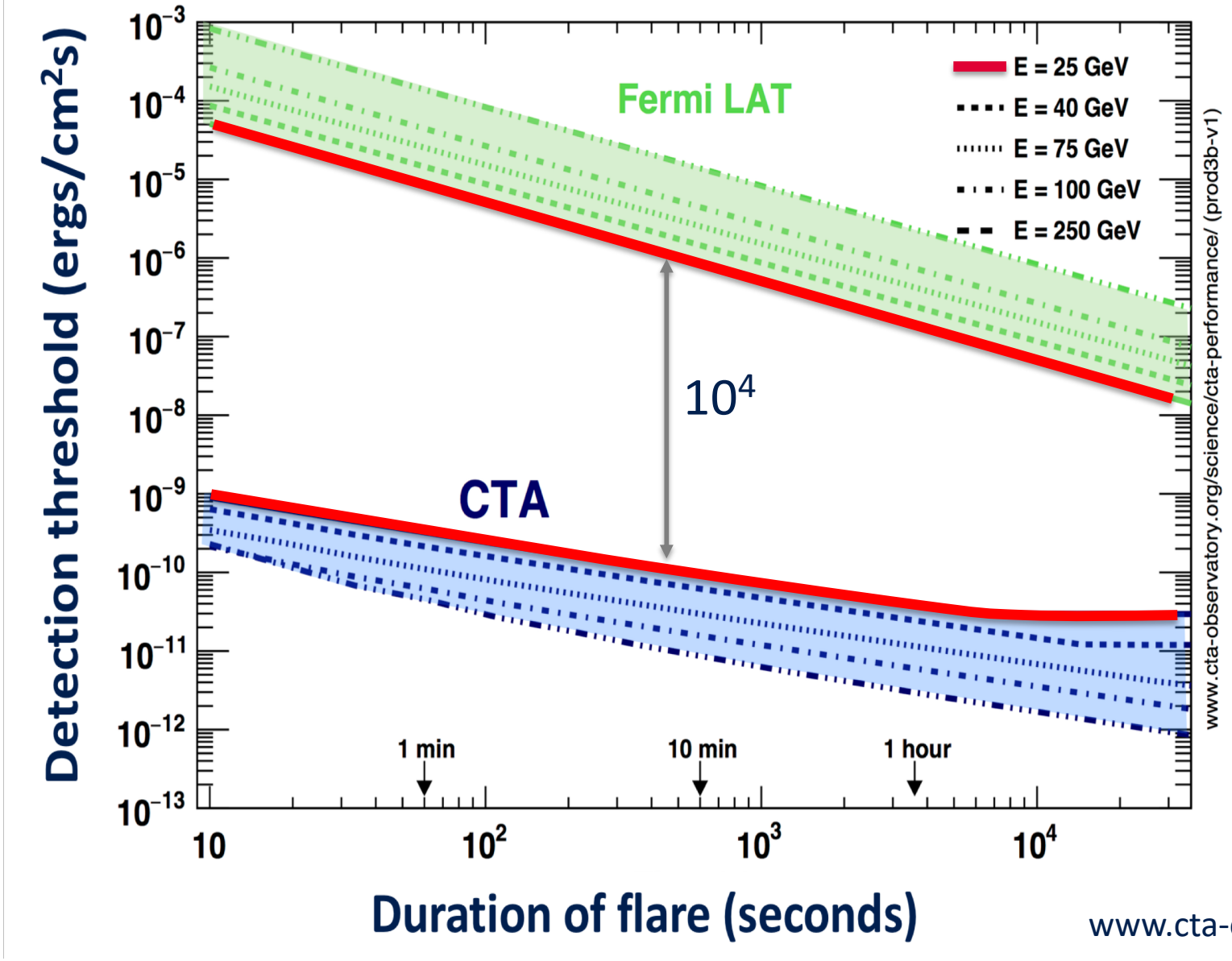
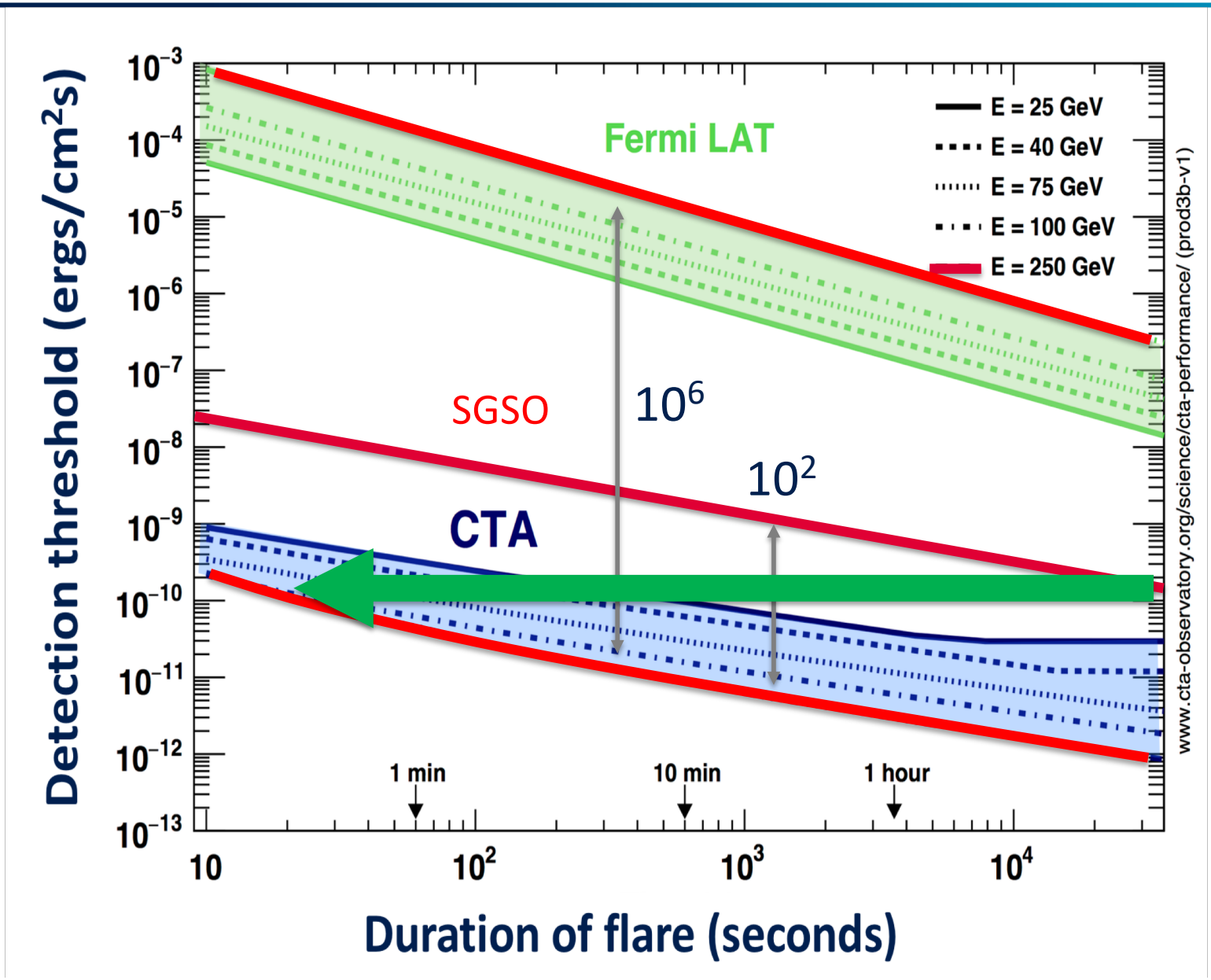
FLARE SENSITIVITY **(25 GEV)**



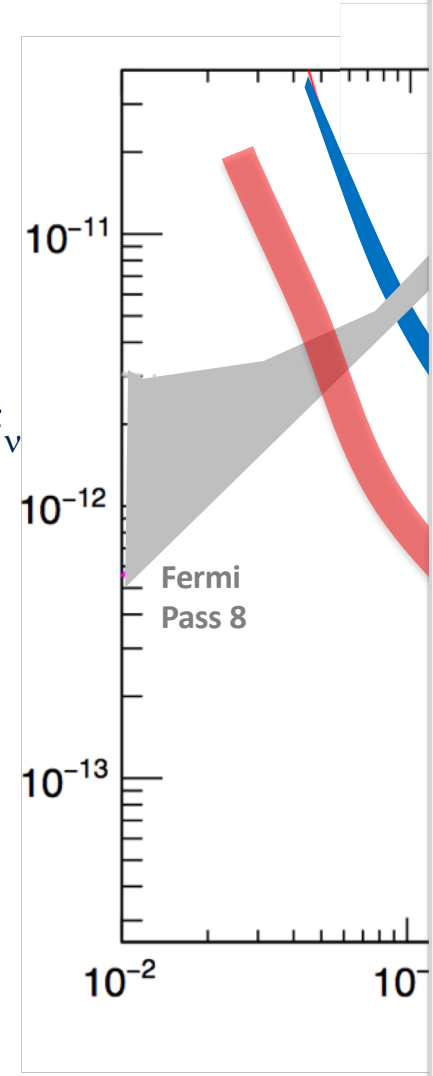
www.cta-observatory.org

FLARE SENSITIVITY **(~300 GEV)**



SENSITIVITY (STEA

$E^2dN/dE = \nu F_\nu$
[erg/cm^{2}s]



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Much information
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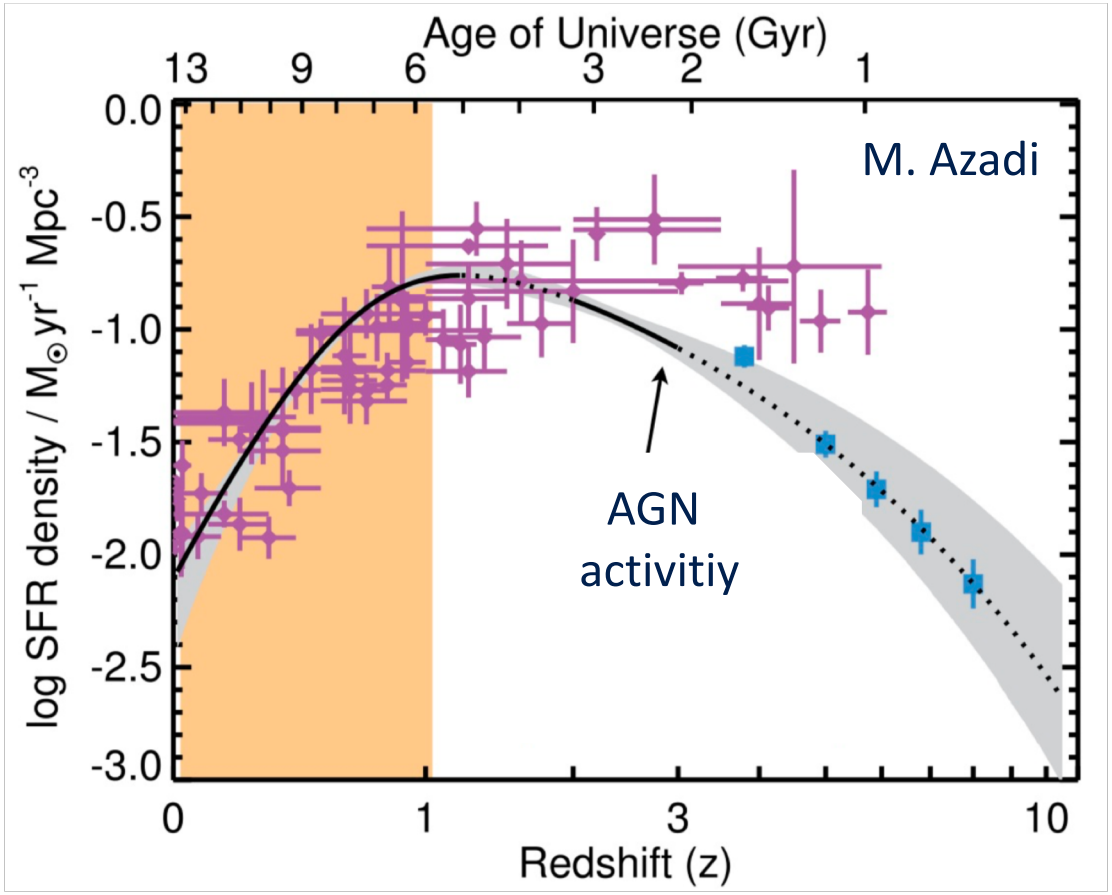
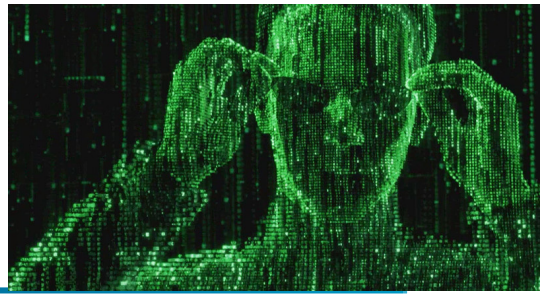


THE MATRIX

THE MATRIX



Source type →

Energy domain ↓

		Galactic Probability that random source in FOV Ground array: 0.3 IACT array: 0.03						Extragalactic Probability that random source in FOV Ground array: 0.2 IACT array: 0.002					
		Steady		Transient				Steady		Transient			
		< deg scale	> deg scale	sec	min	hour	day	< deg scale	> deg scale	sec	min	hour	day
GeV	Search												
	Study												
10s of GeV	Search												
	Study												
TeV	Search												
	Study												
10s of TeV	Search												
	Study												
PeV	Search												
	Study												

Location known? Search or study? ↑

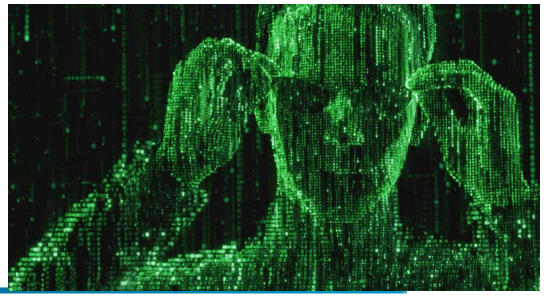
Questions:

- How are these fields covered by current/upcoming instruments?
- Where are improvements conceivable beyond these instruments?
- Is the achievable sensitivity meaningful?
- **Where is the hot science?**

The following slides are highly subjective, and the starting point of a discussion, not the ending point!!

THE MATRIX - COVERAGE

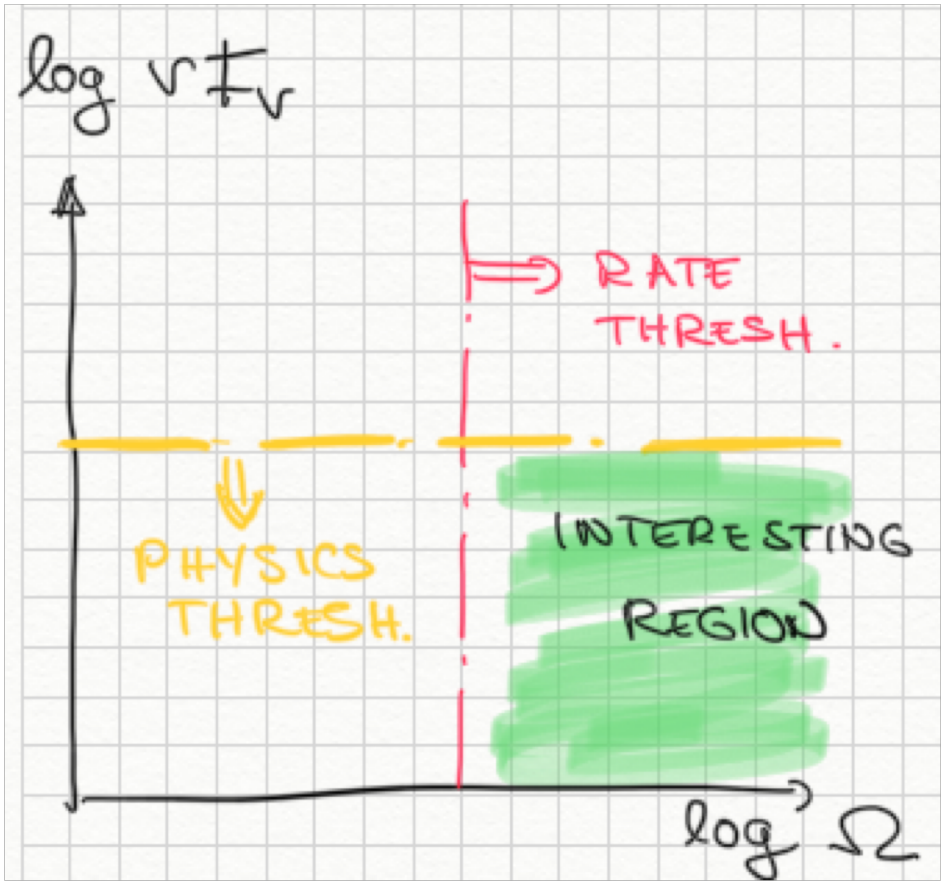
HIGHLY SUBJECTIVE, CORRECTIONS WELCOME!

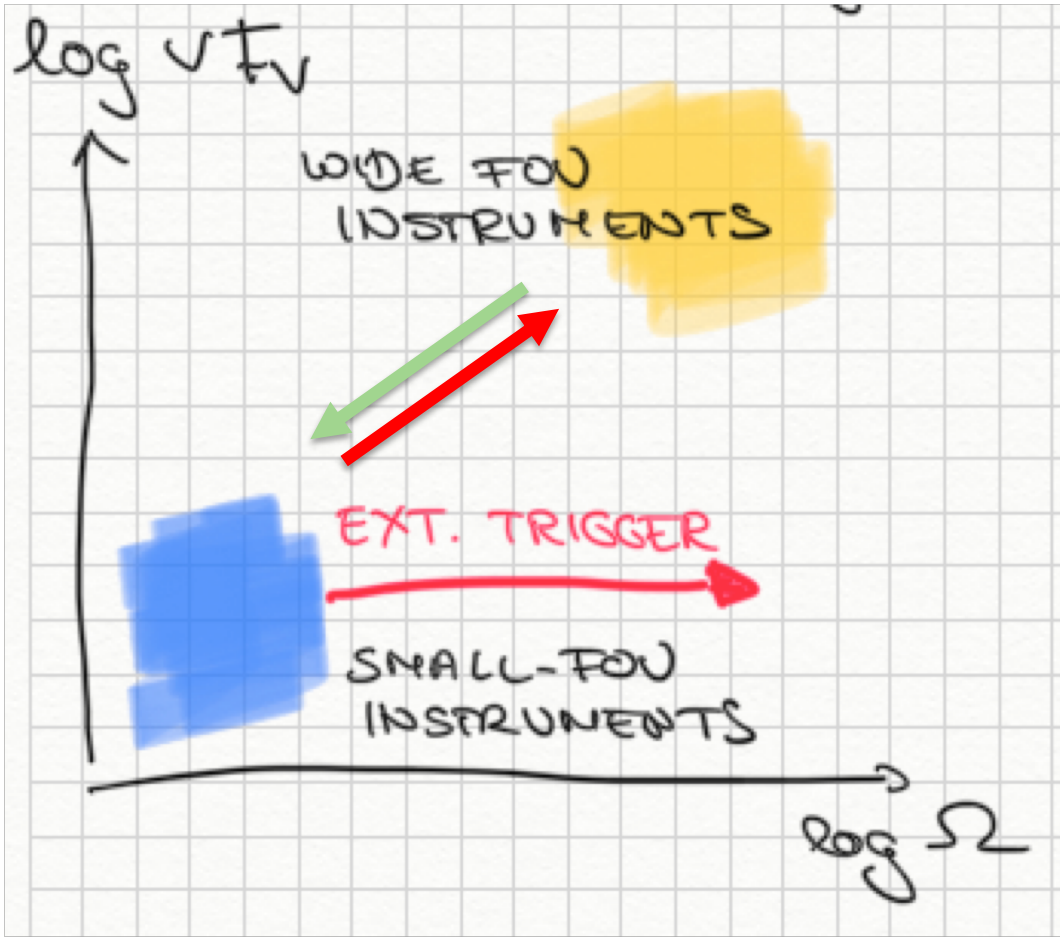


		Galactic Probability that random source in FOV Ground array: 0.3 IACT array: 0.03						**Extragalactic** Probability that random source in FOV Ground array: 0.2 IACT array: 0.002					
		Steady		Transient				Steady		Transient			
		< deg scale	> deg scale	sec	min	hour	day	< deg scale	> deg scale	sec	min	hour	day
GeV	Search	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi
	Study	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi
10s of GeV	Search	Fermi / CTA	Fermi	Fermi	Fermi	Fermi	Fermi / CTA	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi
	Study	Fermi / CTA	Fermi	Fermi	CTA	CTA	CTA	Fermi / CTA	Fermi	Fermi	CTA	CTA	CTA
TeV	Search	CTA	LHAASO / SGSO	LHAASO / SGSO	LHAASO / SGSO	LH/ SGSO/ CTA	CTA / LH / SGSO	LH / SGSO / CTA	LHAASO / SGO	LHAASO / SGSO	LHAASO / SGSO	LHAASO / SGSO	LH / SGSO / CTA
	Study	CTA	LHAASO / SGSO	LHAASO / SGSO	CTA	CTA	CTA	CTA	LHAASO / SGSO	LHAASO / SGSO	CTA	CTA	CTA
10s of TeV	Search	CTA / LH / SGSO	LHAASO / SGSO	LHAASO / SGSO	LHAASO / SGSO	LH / SGSO / CTA	LH / SGSO /CTA						
	Study	CTA	LHAASO / SGSO	LHAASO / SGSO	CTA	CTA	CTA						
PeV	Search	LHAASO	LHAASO	LHAASO	LHAASO	LHAASO	LHAASO						
	Study	LHAASO	LHAASO	LHAASO	LHAASO	LHAASO	LHAASO						

CTA in its energy range whenever
- a steady source fits into the fov
- a transient source can be reached

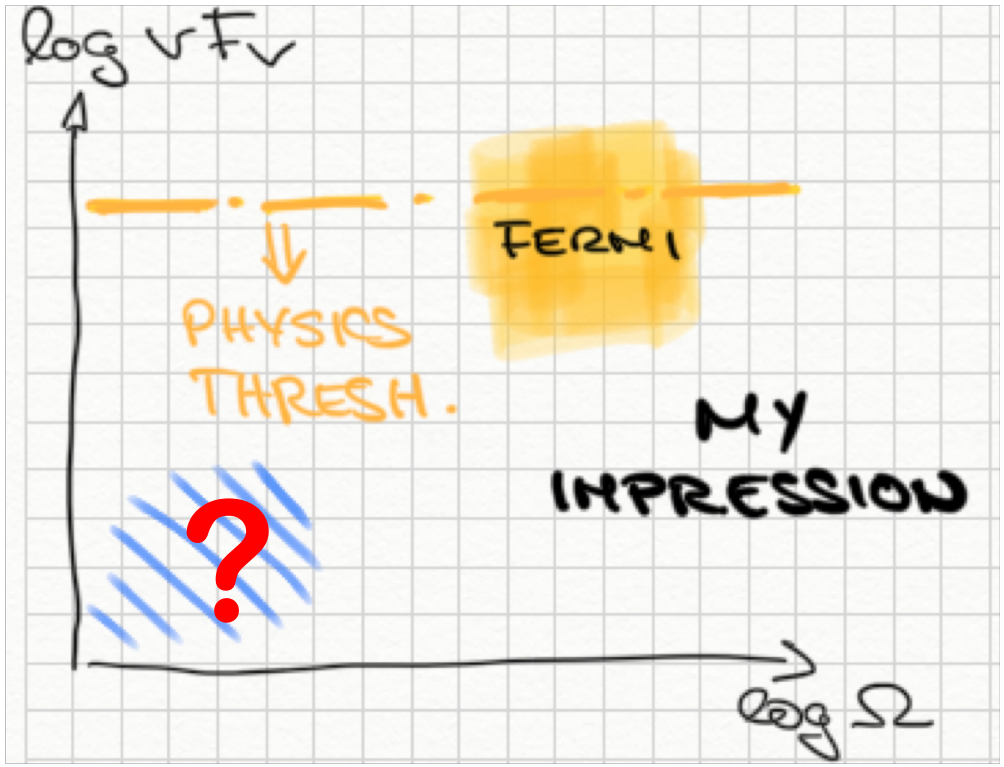
FLARING SOURCES



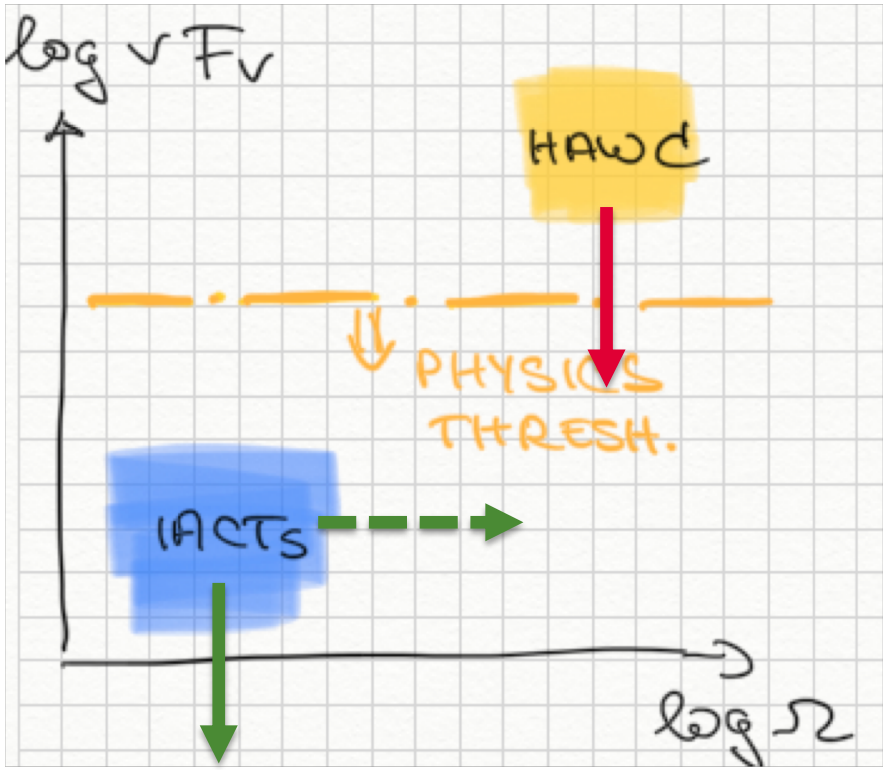


FLARING SOURCES

GeV

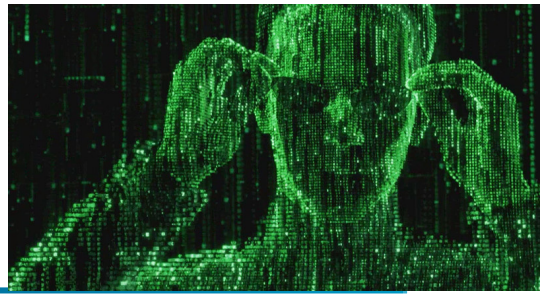


TeV+



THE MATRIX - POTENTIAL

HIGHLY SUBJECTIVE, CORRECTIONS WELCOME!



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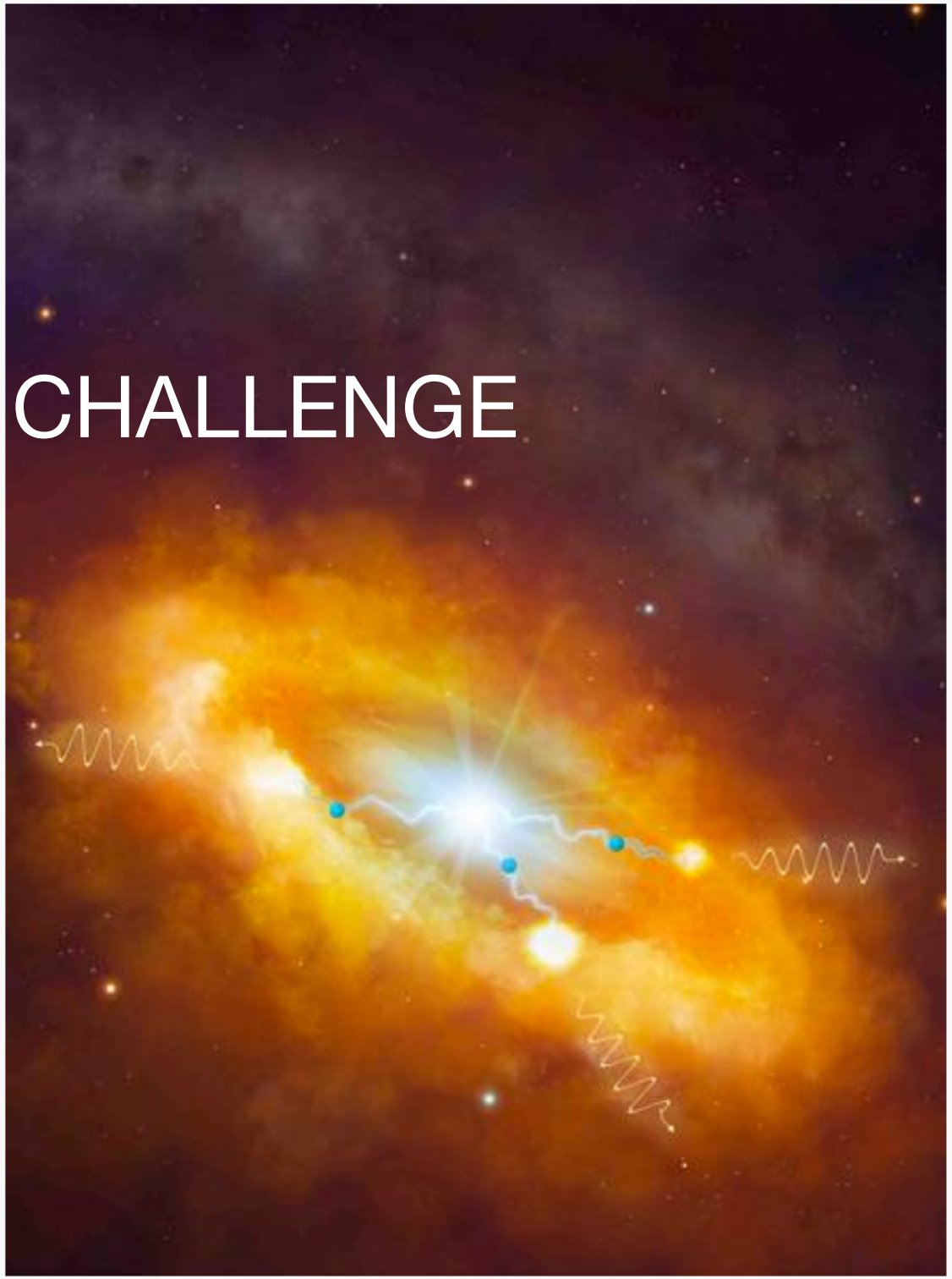
		Steady		Transient				Steady		Transient			
		< deg scale	> deg scale	sec	min	hour	day	< deg scale	> deg scale	sec	min	hour	day
GeV	Search	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi
	Study	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi
10s of GeV	Search	Fermi / CTA	Fermi	Fermi	Fermi	Fermi	Fermi / CTA	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi
	Study	Fermi / CTA	Fermi	Fermi	CTA	CTA	CTA	Fermi / CTA	Fermi	Fermi	CTA	CTA	CTA
TeV	Search	CTA	LHAASO / SGSO	LHAASO / SGSO	LHAASO / SGSO	LH/ SGSO/ CTA	CTA / LH / SGSO	LH / SGSO / CTA	LHAASO / SGO	LHAASO / SGSO	LHAASO / SGSO	LHAASO / SGSO	LH / SGSO / CTA
	Study	CTA	LHAASO / SGSO	LHAASO / SGSO	CTA	CTA	CTA	CTA	LHAASO / SGSO	LHAASO / SGSO	CTA	CTA	CTA
10s of TeV	Search	CTA / LH / SGSO	LHAASO / SGSO	LHAASO / SGSO	LHAASO / SGSO	LH / SGSO / CTA	LH / SGSO /CTA						
	Study	CTA	LHAASO / SGSO	LHAASO / SGSO	CTA	CTA	CTA						
PeV	Search	LHAASO	LHAASO	LHAASO	LHAASO	LHAASO	LHAASO						
	Study	LHAASO	LHAASO	LHAASO	LHAASO	LHAASO	LHAASO						

Will discuss potential for improvement in these areas, @ cost on the 50-500 M€ scale

THE PEVATRON CHALLENGE



THE PEVATRON CHALLENGE

Expected flux:
DAV '94

$$F(>E) \approx 9 \times 10^{-11}\theta \left(\frac{E}{1\,\mathrm{TeV}}\right)^{-1.1} \left(\frac{E_{\mathrm{SN}}}{10^{51}\,\mathrm{erg}}\right) \left(\frac{d}{1\,\mathrm{kpc}}\right)^{-2} \left(\frac{n}{1\,\mathrm{cm}^{-3}}\right) \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

10^{51} erg, θ=0.1, n=1/cm^3, 10 kpc: EF(>E) ≈ E^{2}F(E) ≈ 10^{-13} erg/cm^{2}s

for $\Gamma \approx 2$

Rate-limited sensitivity:

$$(\nu F_\nu)_{min}\left[\frac{\mathrm{erg}}{\mathrm{cm}^2\mathrm{s}}\right] \approx 2 \cdot 10^{-6}\frac{E_{\mathrm{TeV}}}{A_{\mathrm{m}^2} T_{\mathrm{h}}}$$

for ε_γ = 0.5,
min 10 events
per 0.2 DEX

100 TeV, 10^{-13} erg/cm^{2}s : AT ≈ 2×10^9 m^{2}h
1 PeV, 10^{-13} erg/cm^{2}s : AT ≈ 2×10^{10} m^{2}h

THE PEVATRON CHALLENGE

Factor 10 compared to LHAASO possible

Some options, price tag ~ 50 M€; AT given for 1 year
Ballpark estimates!

Importance of fov depends on # of source candidates

Array of small (1 m²) IACTs: 2×10^{10} m²h
- 50 k€/unit -> 1000 units
- 300 m spacing -> 100 km²
- 200 h/year

Very large zenith angle IACTs: 5×10^{9} m²h
- 1 M€ /unit -> 50 units (in a linear config?)
- 10^{6} m²/unit
- 100 h/year (?)

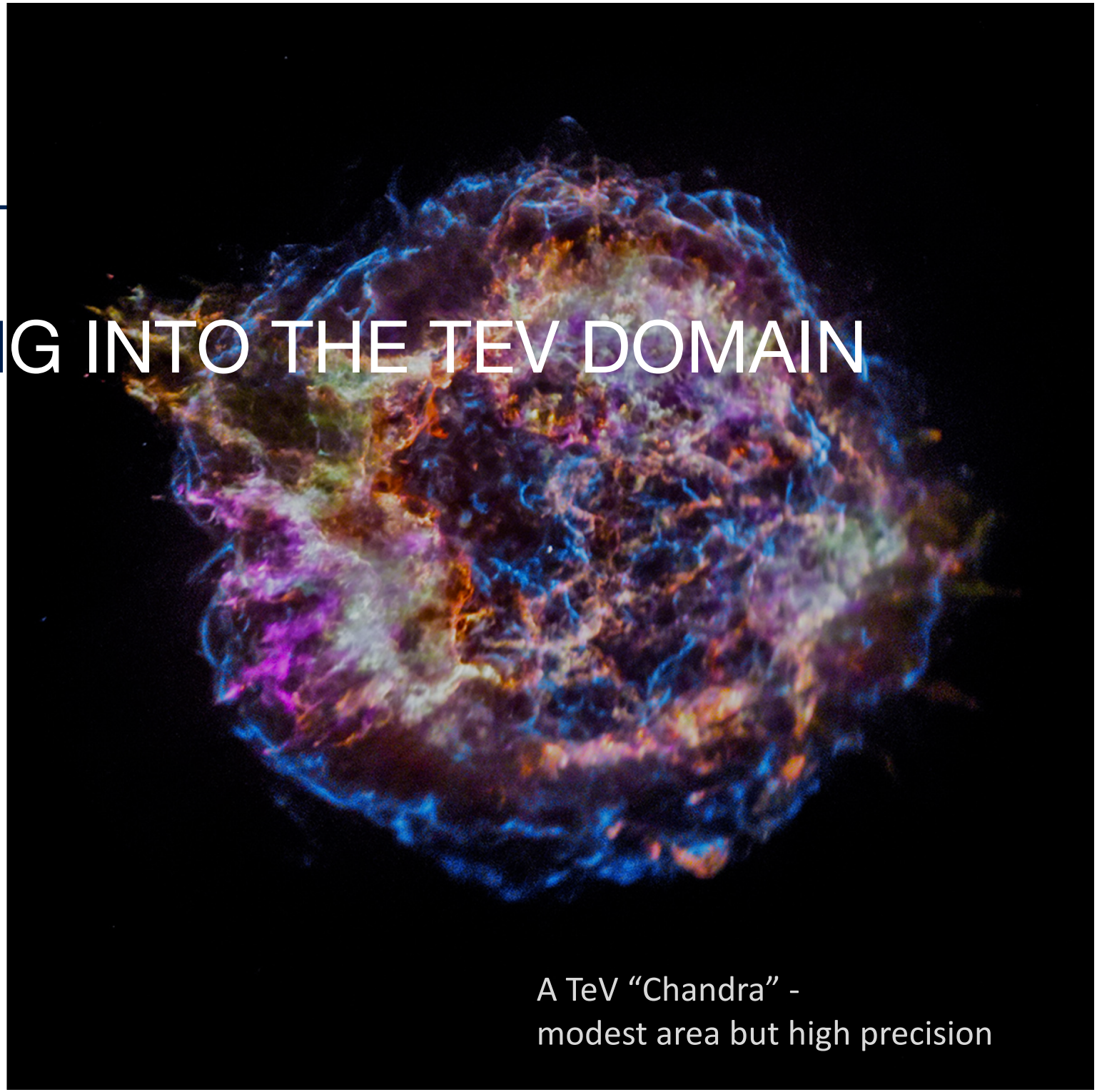
Wide-angle non-imaging Cherenkov: 3×10^{10} m²h
(e.g. HISCORE, arXiv: 1403.5688)
- 15 k€ /unit -> 3000 units
- 200 m spacing -> 100 km²
- 300 h/year

Ground array with muon det.: 3×10^{9} m²h
- LHAASO array, maybe x 2
- 1(- 2) km²
- 2500 h/year

Fluorescence imaging: 3×10^{10} m²h
- @ 1 PeV: need ~100 m² wide FOV tels.
- 2 Stereo clusters of 9 tels, ~10 km spacing
- 300 h/year

Radio 100-200 MHz: 3×10^{11} m²h
- O(PeV) threshold claimed possible in very radio-quiet locations
- 50-100 stations / km²
- 100 km²
- 2500 h/year

DIGGING INTO THE TEV DOMAIN

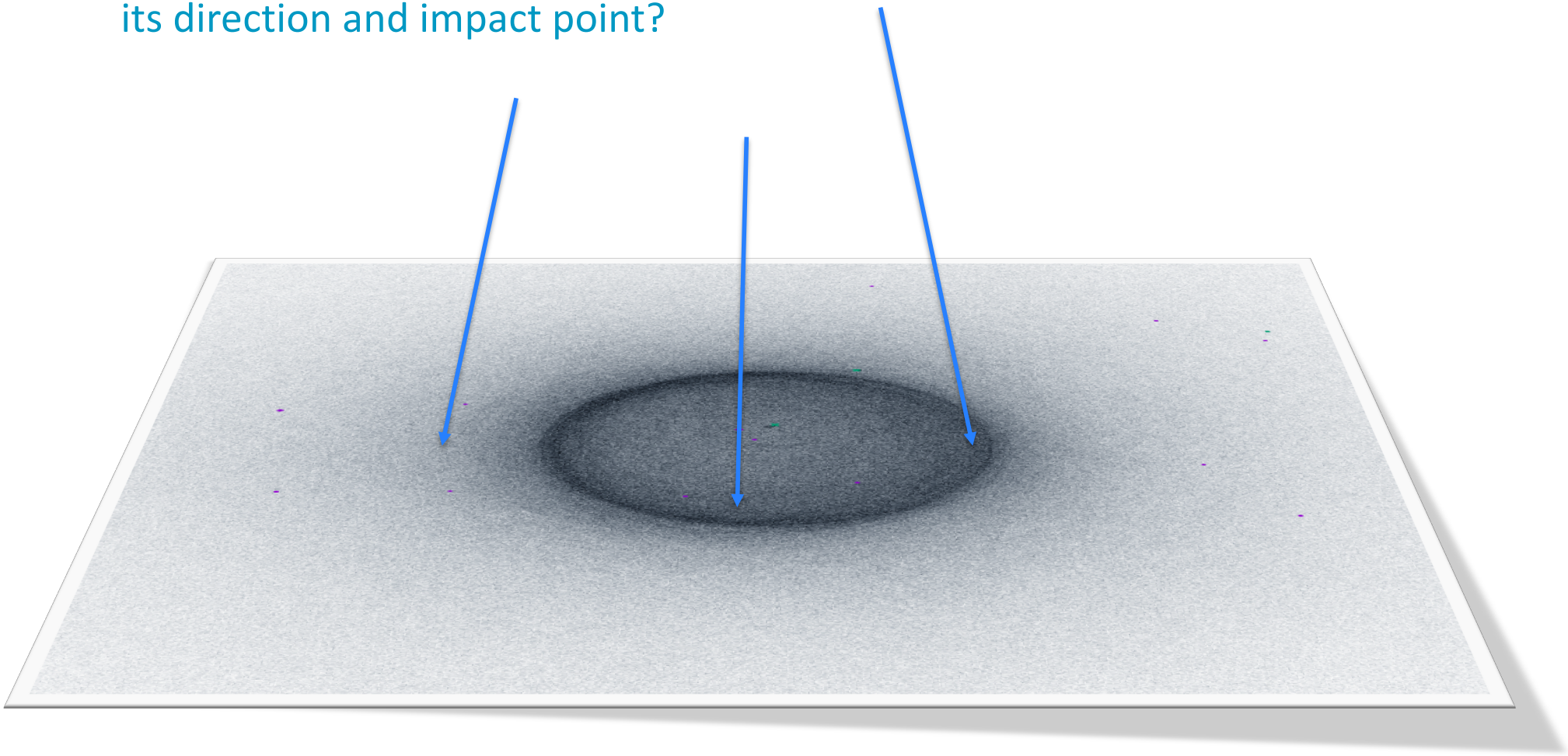


A TeV “Chandra” -
modest area but high precision

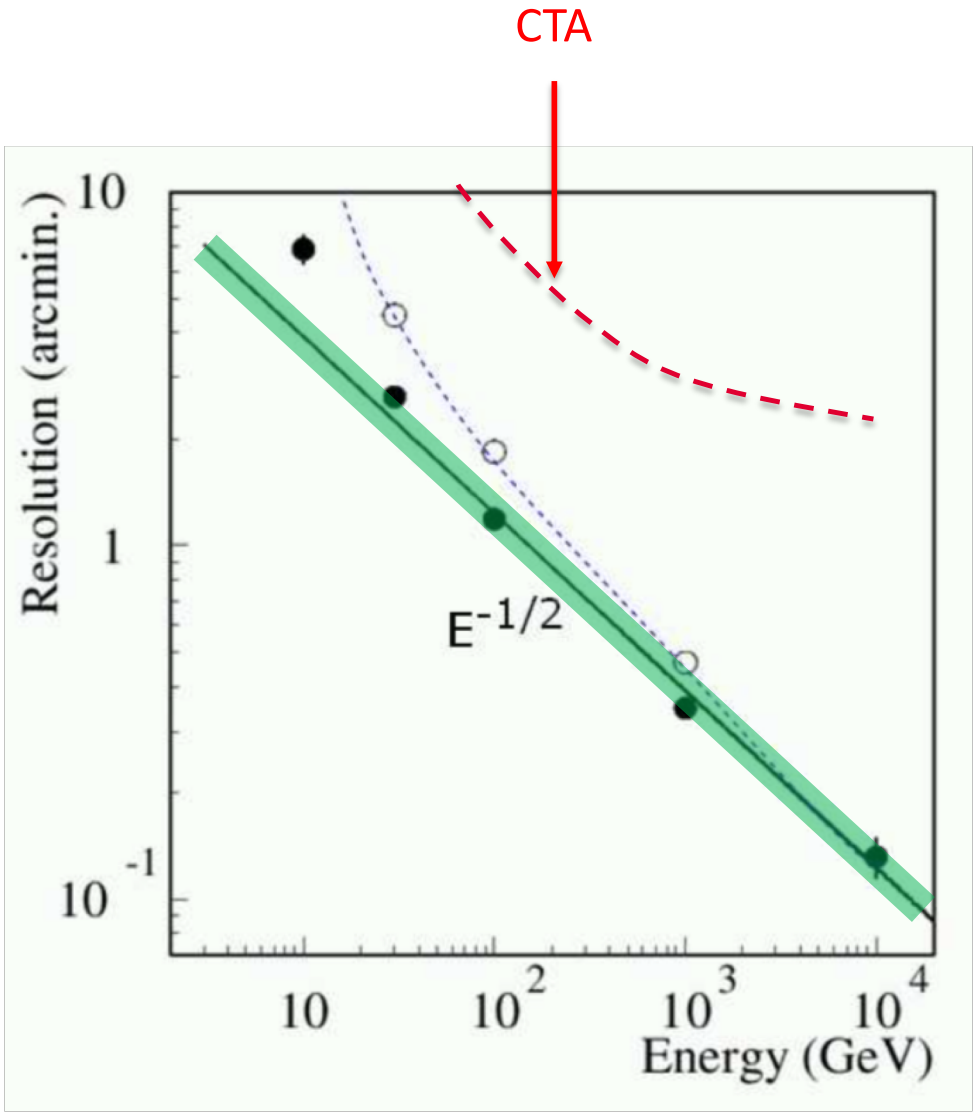
WHAT IF

WH, astro-ph/0603076

we would measure for each
Cherenkov photon
its direction and impact point?



“LIMITING” ANGULAR RESOLUTION



WH, astro-ph/0603076

All photons? How well measured?

Requires **>1% ground coverage** for Cherenkov photons over light pool (with PMT efficiency),

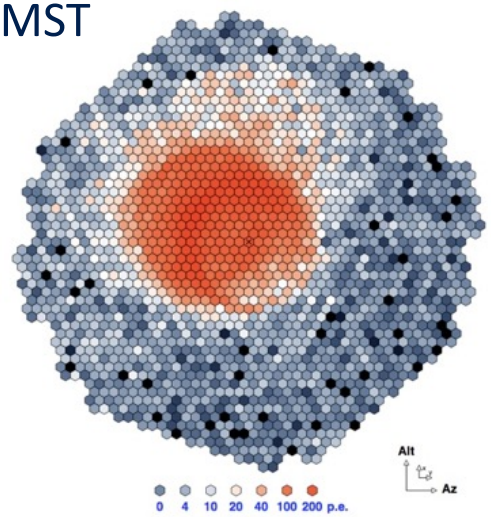
Resolution per photon of better than **0.02° rms (0.07° pixels)**, **4 m rms (15 m dish)**

Algorithm does not use photon arrival time; further improvement may be possible

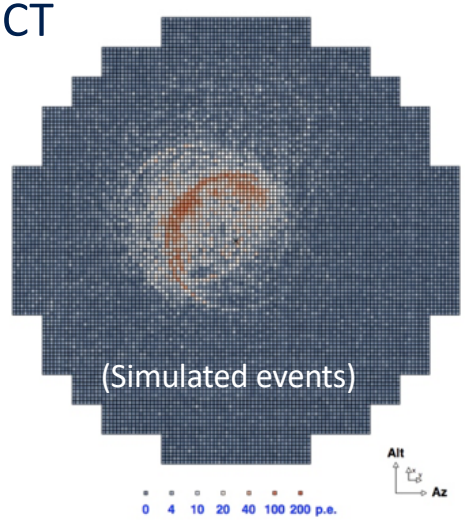
Very high rejection for CR nuclei, $O(10^4)$ at 1 TeV → electron background dominates

SCHWARZSCHILD COUDER TELESCOPE (SCT)

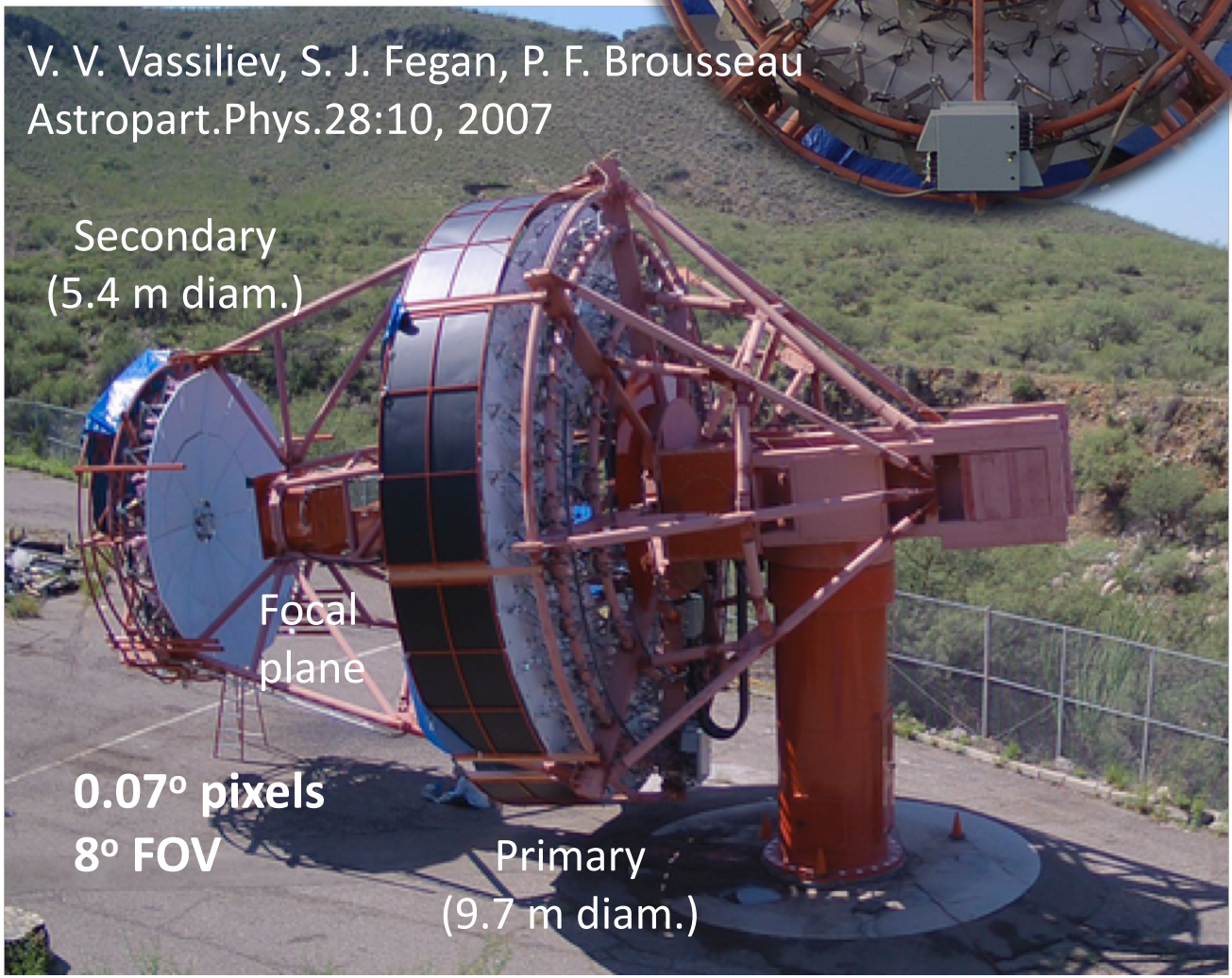
Single-mirror MST



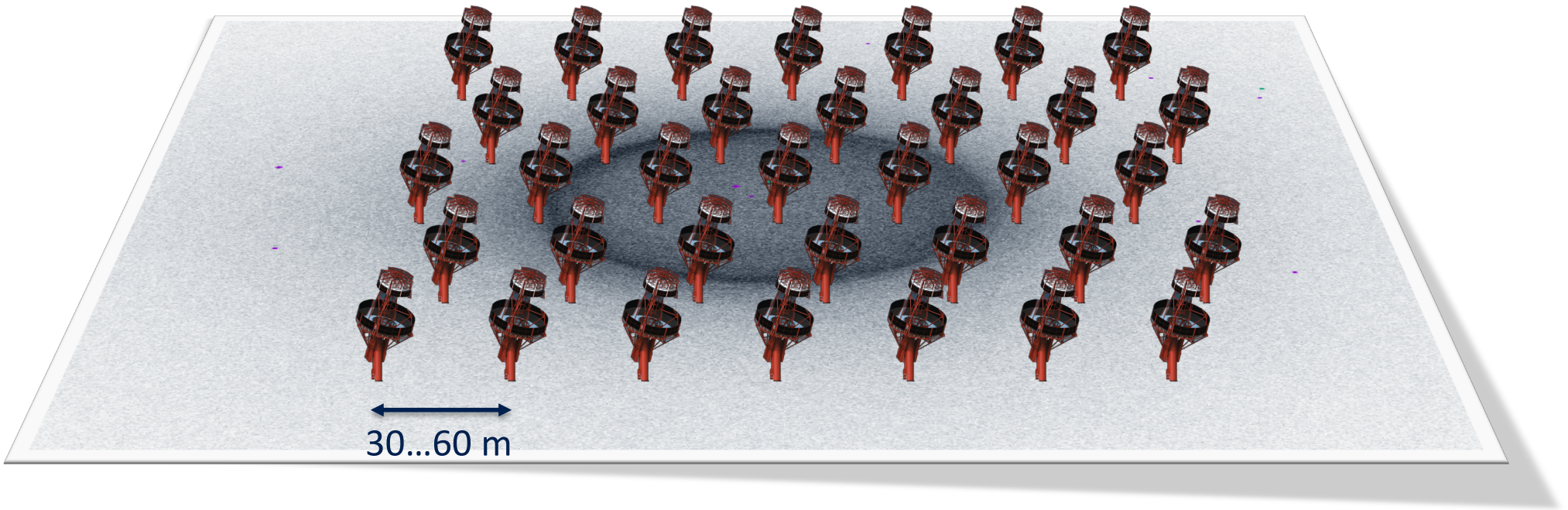
Dual-mirror SCT



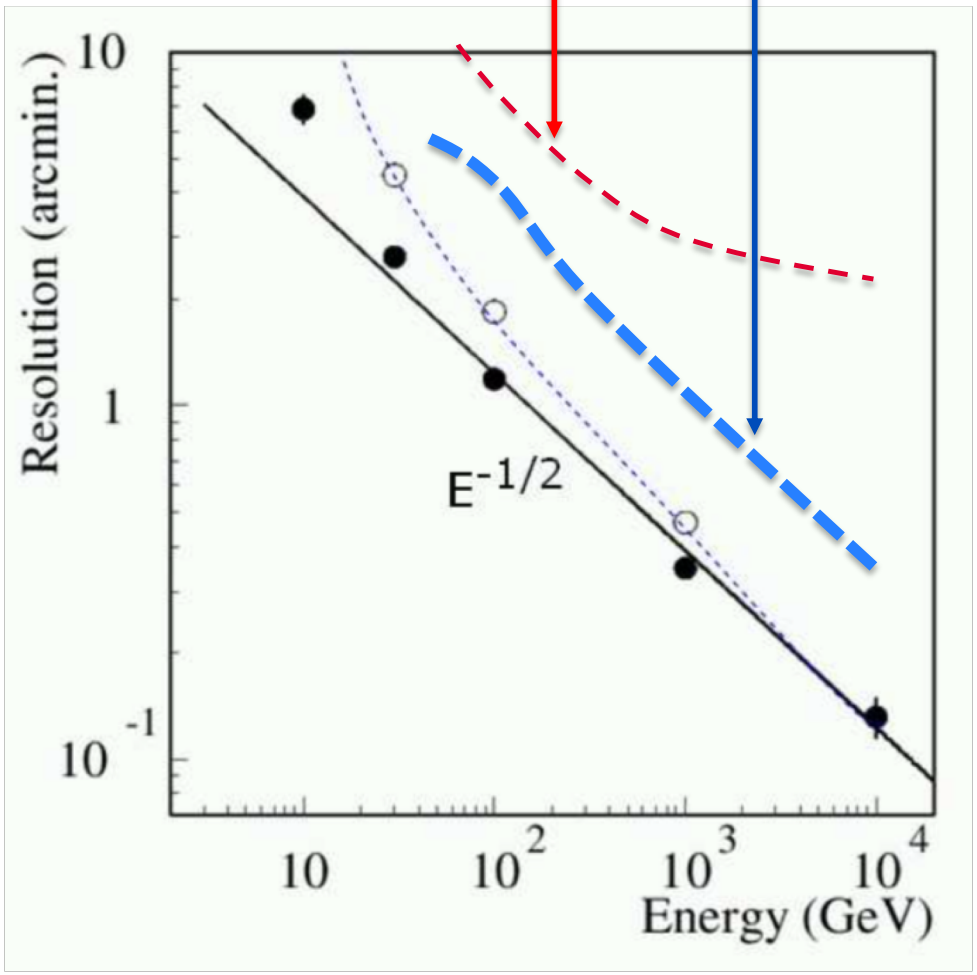
Back side of secondary mirror



WHAT IF



“LIMITING” ANGULAR RESOLUTION

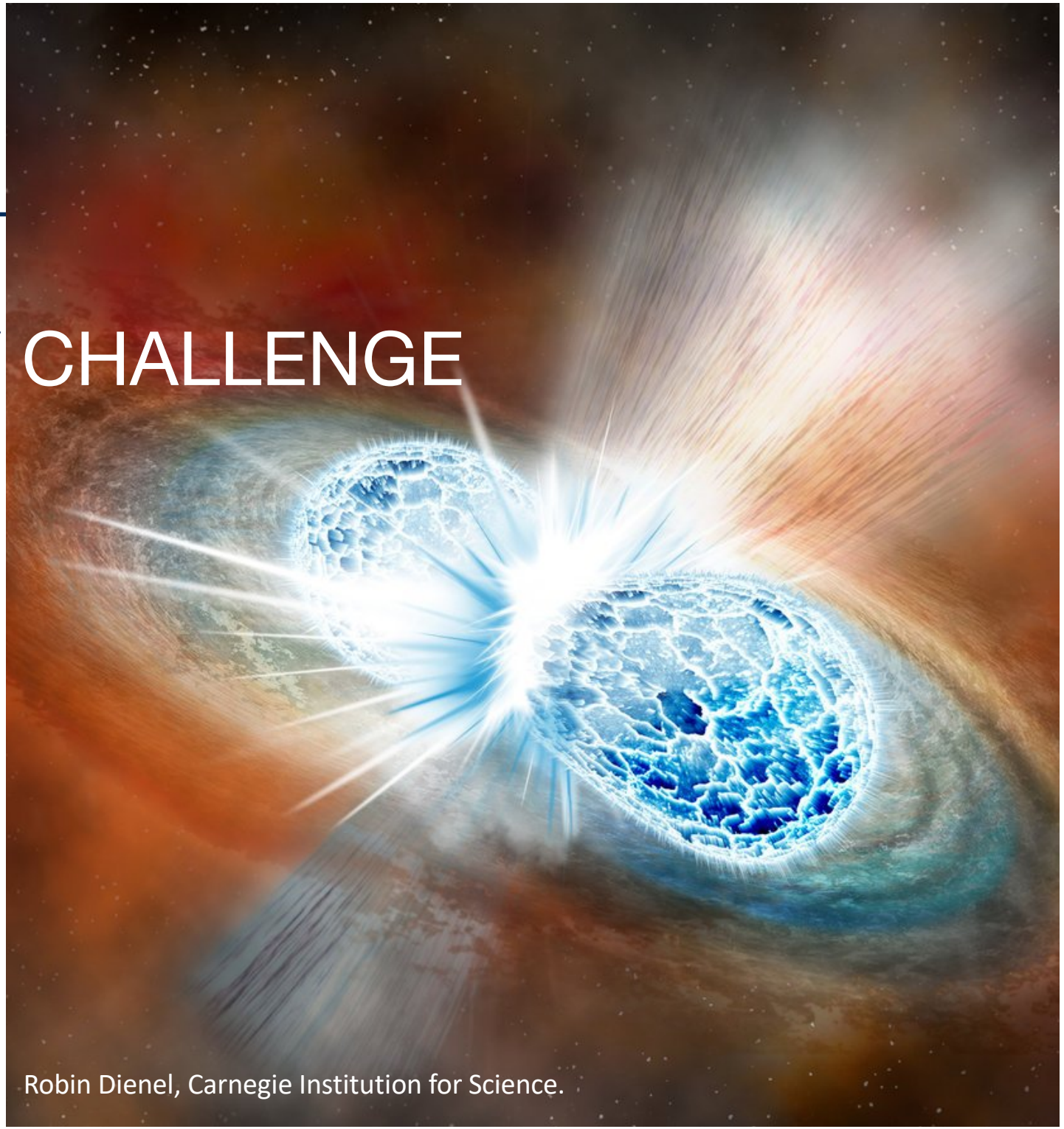


Rejection of electrons

- Height of shower max
- Cherenkov light of primary electron

remains to be quantified

THE GEV CHALLENGE

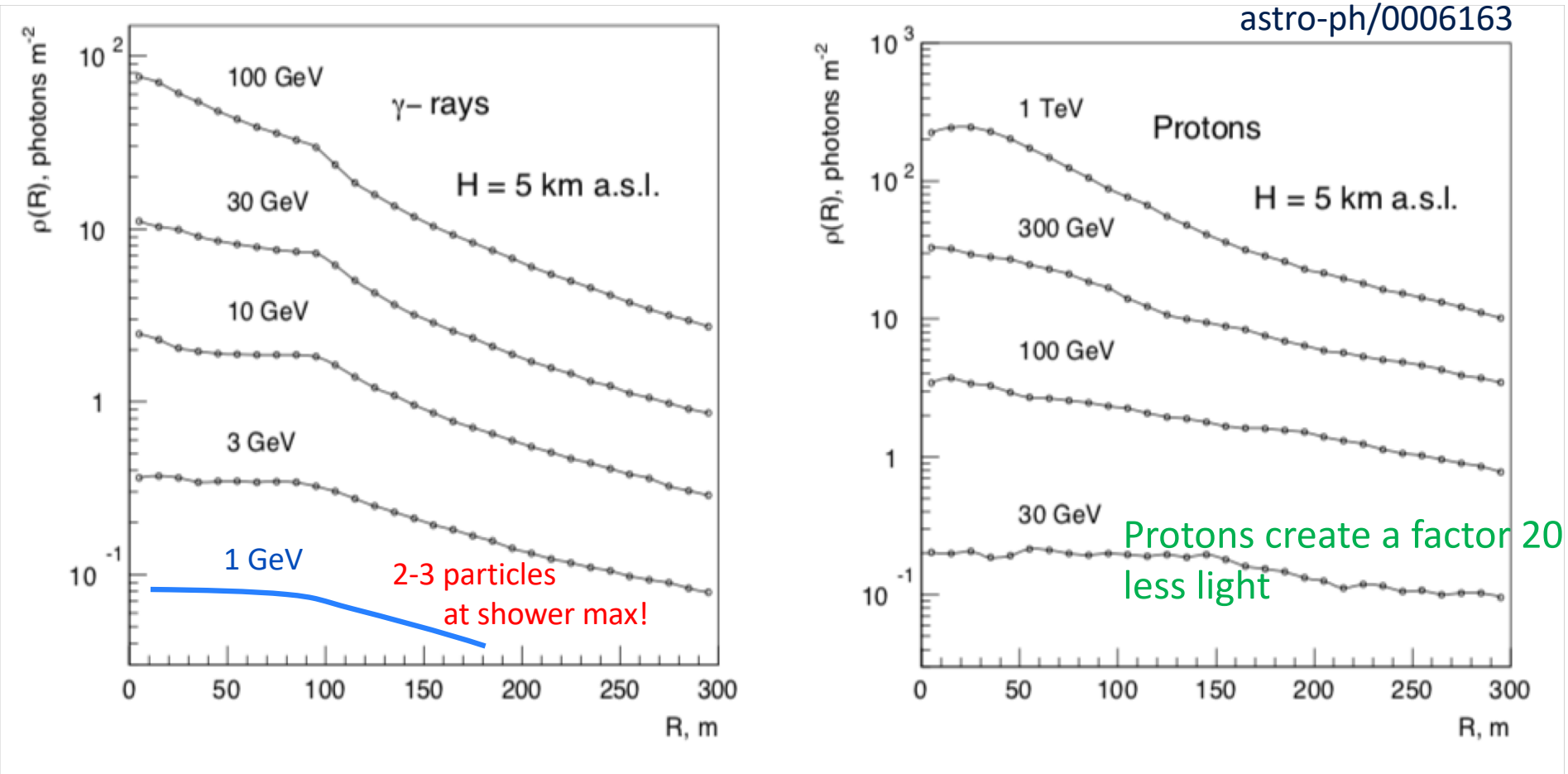


Robin Dienel, Carnegie Institution for Science.

GEV CHERENKOV INSTRUMENT
LIGHT INTENSITY

(Triggered by discussions with Sebastian A. Müller, ETH)

5@5,
F. Aharonian et al.
astro-ph/0006163



for 100 p.e. image need ~10^4 m^2, or about ~10% area coverage, trigger S/N looks ok

GEV CHERENKOV INSTRUMENT

5@5

astro-ph/0006163

Astroparticle Physics, accepted for publication

5@5 - a 5 GeV energy threshold array of imaging atmospheric Cherenkov telescopes at 5 km altitude

F.A. Aharonian, A.K. Konopelko, H.J. Völk

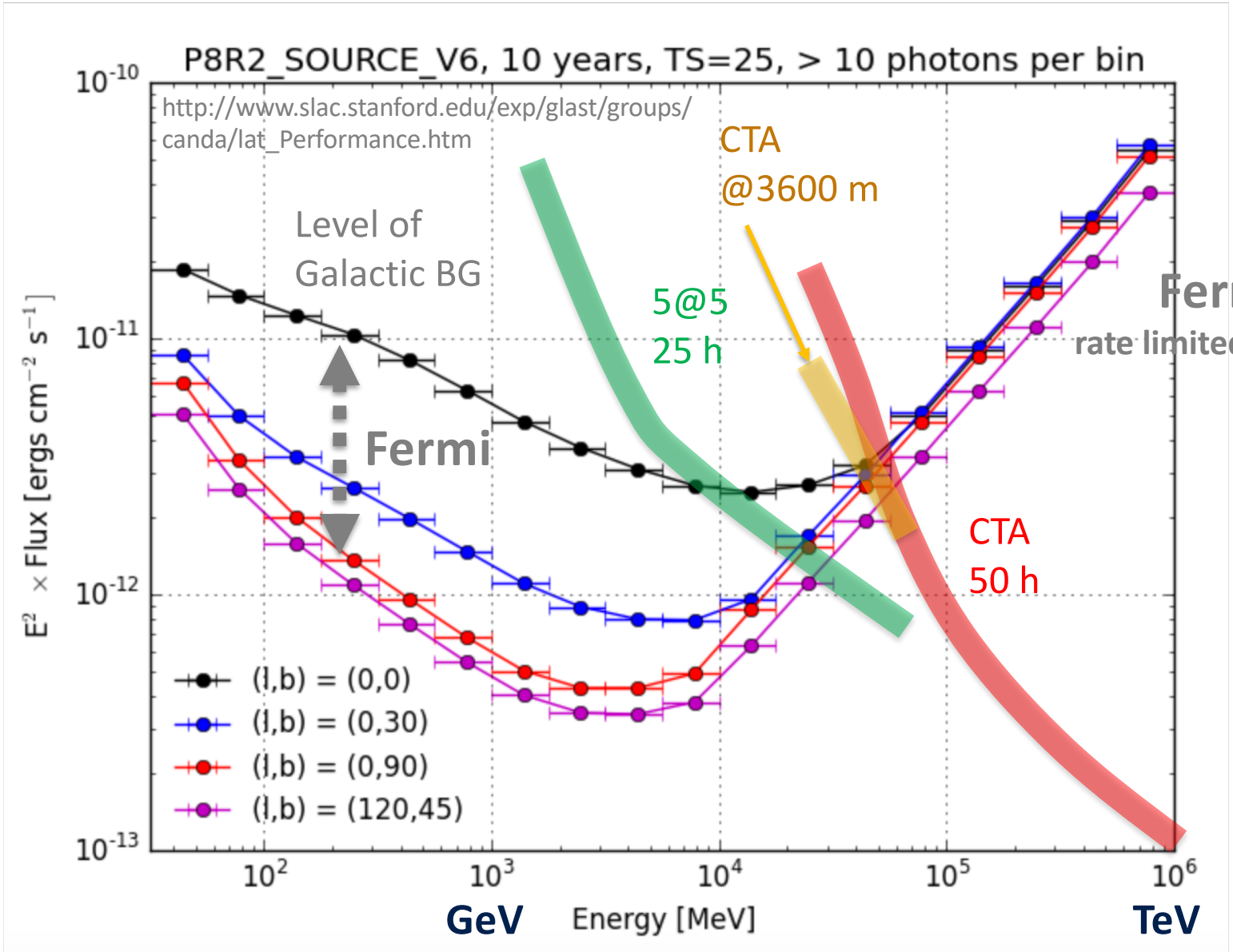
MPI für Kernphysik, D-69029 Heidelberg, Germany

H. Quintana

Astronomy and Astrophysics Department, Pontificia Universidad Catolica de Chile, Casilla 306, Santiago 22, Chile

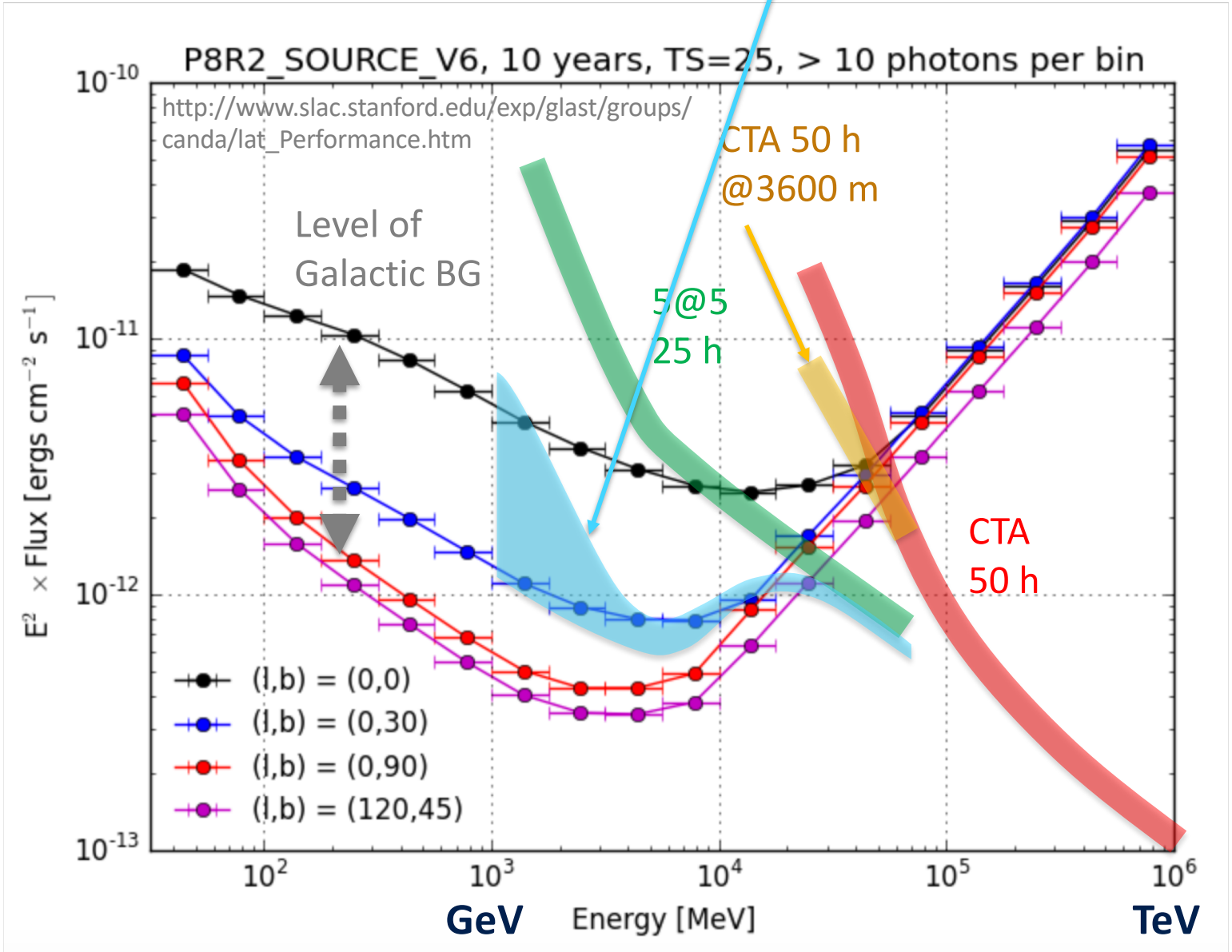
4 x 20 m telescopes, about 2% of 150 m radius pool

THE GEV CHALLENGE



THE GEV CHALLENGE

limiting resolution, 10^4 m^2, 50 h
top: only electron bg + 1% syst.
bottom: only electron bg

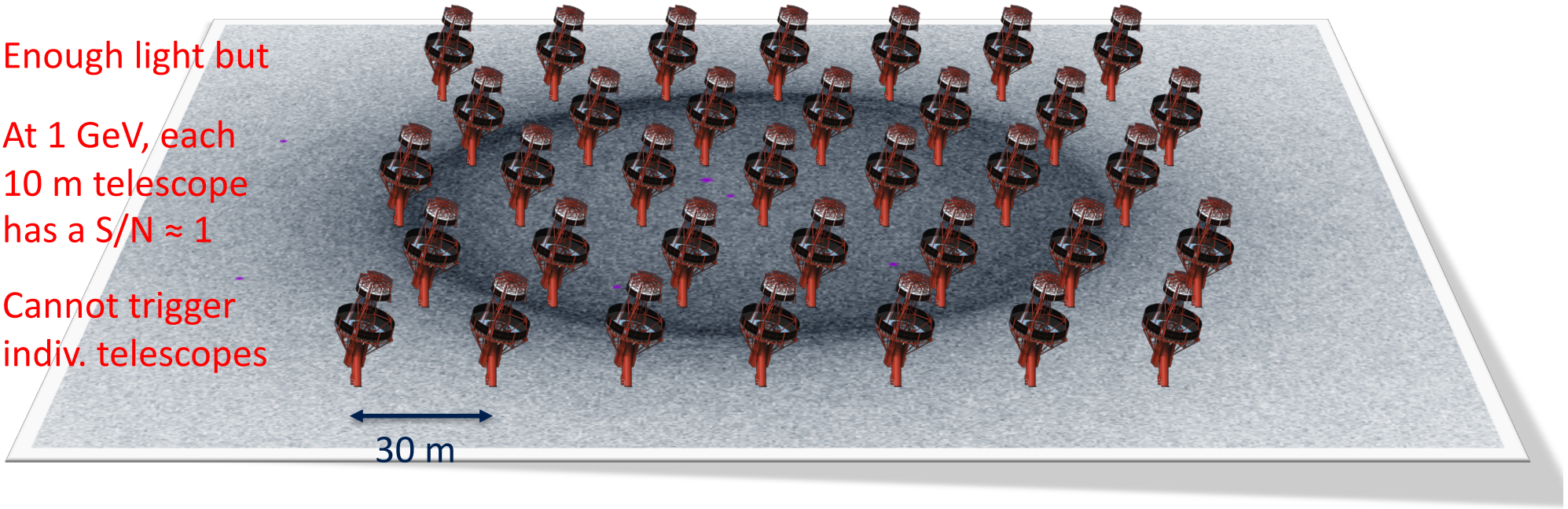


WHAT IF

Enough light but

At 1 GeV, each 10 m telescope has a S/N ≈ 1

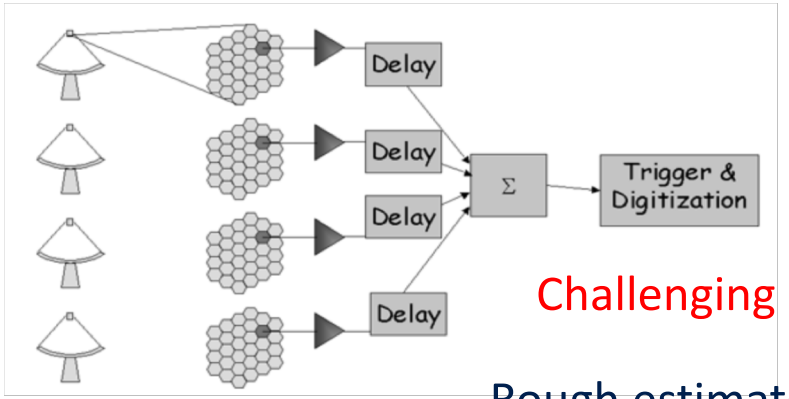
Cannot trigger indiv. telescopes



WHAT IF

"STAR: Very Large Aperture Telescope Array Using Many Small IACTs"
Falcone et al., AIP Conf. Proc. 745 (2005) 748

„An image-based array trigger for Imaging Atmospheric Cherenkov Telescope Arrays"
H. Dickinson et al. NIM 891 (2018) 6



Challenging

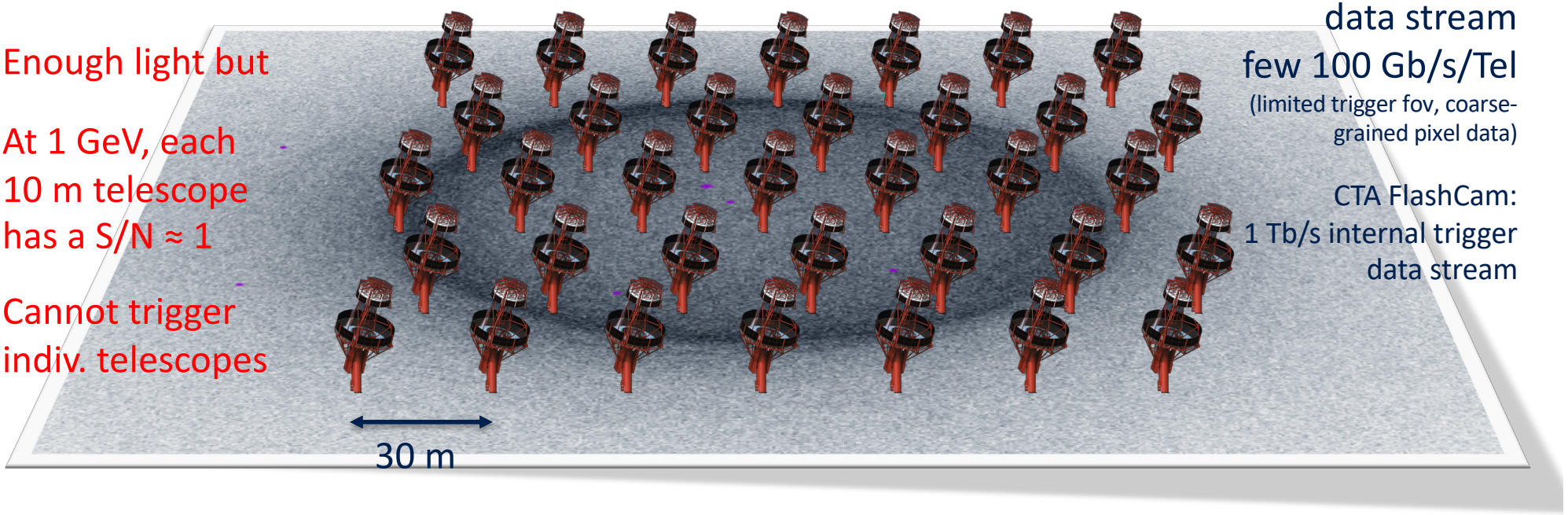
Rough estimate: minimal trigger data stream few 100 Gb/s/Tel
(limited trigger fov, coarse-grained pixel data)

CTA FlashCam: 1 Tb/s internal trigger data stream

Enough light but

At 1 GeV, each 10 m telescope has a S/N ≈ 1

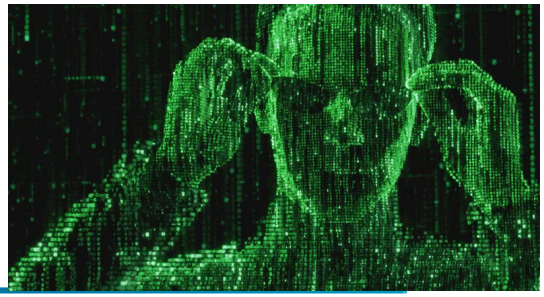
Cannot trigger indiv. telescopes



WHAT IF


see following talk by Sebastian A. Müller
www.seti.org/arecibo-message

QUO VADIS ?



		Galactic Probability that random source in FOV Ground array: 0.3 IACT array: 0.03						Extragalactic Probability that random source in FOV Ground array: 0.2 IACT array: 0.002					
		Steady		Transient				Steady		Transient			
		< deg scale	> deg scale	sec	min	hour	day	< deg scale	> deg scale	sec	min	hour	day
GeV	Search	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi
	Study	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi
10s of GeV	Search	Fermi / CTA	Fermi	Fermi	Fermi	Fermi	CTA	Fermi	Fermi	Fermi	Fermi	Fermi	Fermi
	Study	Fermi / CTA	Fermi	Fermi	CTA	CTA	CTA	Fermi / CTA	Fermi	Fermi	CTA	CTA	CTA
TeV	Search	CTA	LHAASO / SGSO	LHAASO / SGSO	LHAASO / SGSO	LH / SGSO / CTA	CTA	LH / SGSO / CTA	LHAASO / SGO	LHAASO / SGSO	LHAASO / SGSO	LHAASO / SGSO	CTA
	Study	CTA	LHAASO / SGSO	LHAASO / SGSO	CTA	CTA	CTA	CTA	LHAASO / SGSO	LHAASO / SGSO	CTA	CTA	CTA
10s of TeV	Search	CTA / LH / SGSO	LHAASO / SGSO	LHAASO / SGSO	LHAASO / SGSO	LH / SGSO / CTA	CTA						
	Study	CTA	LHAASO / SGSO	LHAASO / SGSO									
PeV	Search	LHAASO	LHAASO	LHAASO									
	Study	LHAASO	LHAASO	LHAASO									

NOT THE END!

In particular the GeV domain is scientifically promising (and technically most challenging) – ”5@5 on steroids”
Would also make a great TeV instrument

QUO VADIS ?

This talk
… evidently did not provide real answers
… likely contains mistakes, invalid assumptions, oversimplifications
… was quite superficial & biased

… primarily serves to point out how much we miss Michael and his deep insights and understanding!

www.fabulouspartyware.com