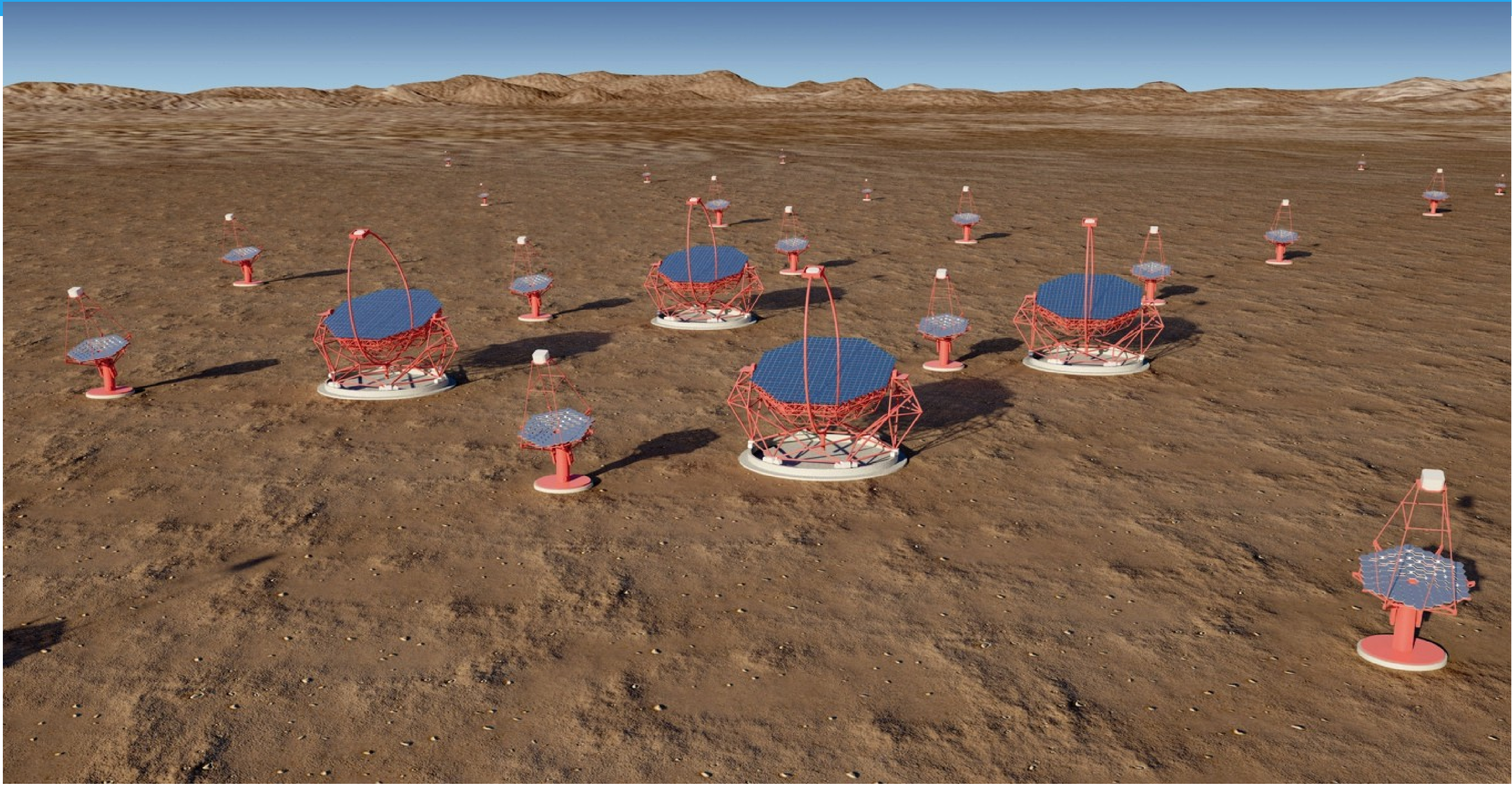
Optimization of Cherenkov telescope Array performances with NectarCAM



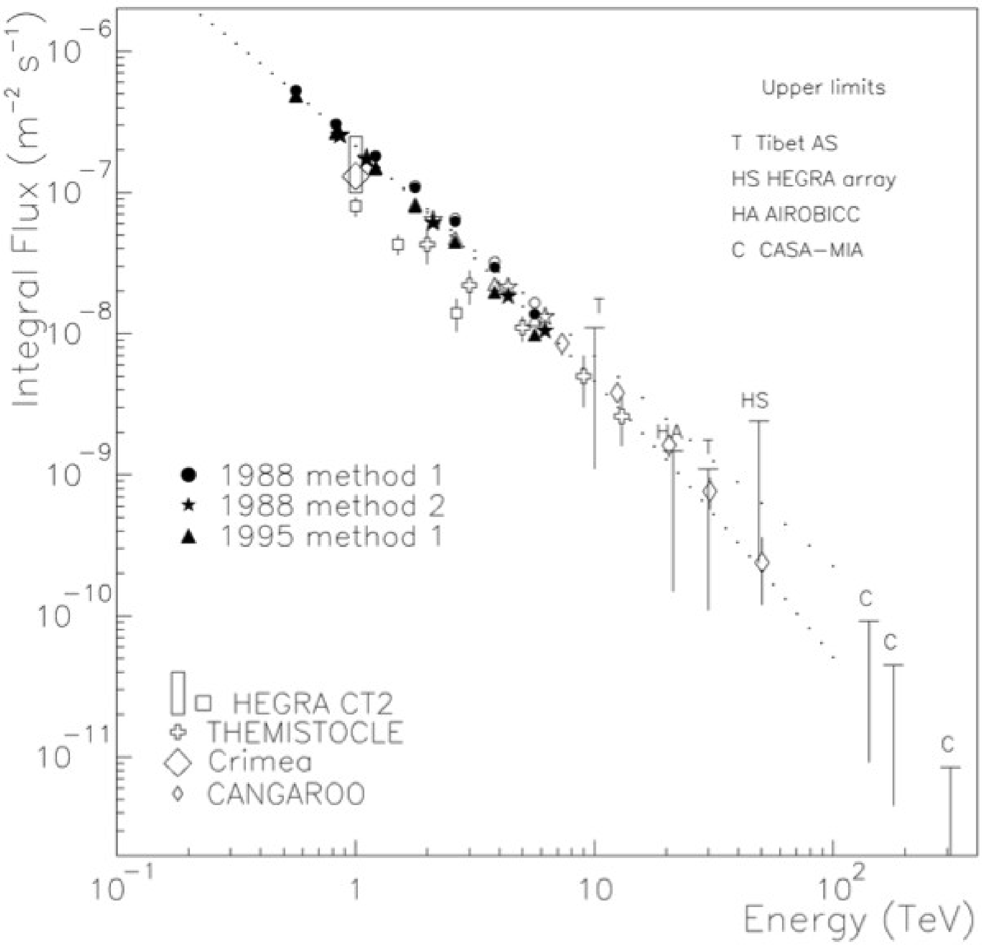
Maxim Shayduk

irfu cea saclay

Overview:

- Introduction to Imaging Atmospheric Cherenkov Telescopes (IACTs)
- Next-generation IACT facility: Cherenkov Telescope Array (CTA)
- How to optimize CTA performance with camera hardware design?
- CTA physics: Young Supernova Remnants as seen by CTA
- CTA physics: Pulsars in Very High Energy domain
- NectarCAM integration at Irfu

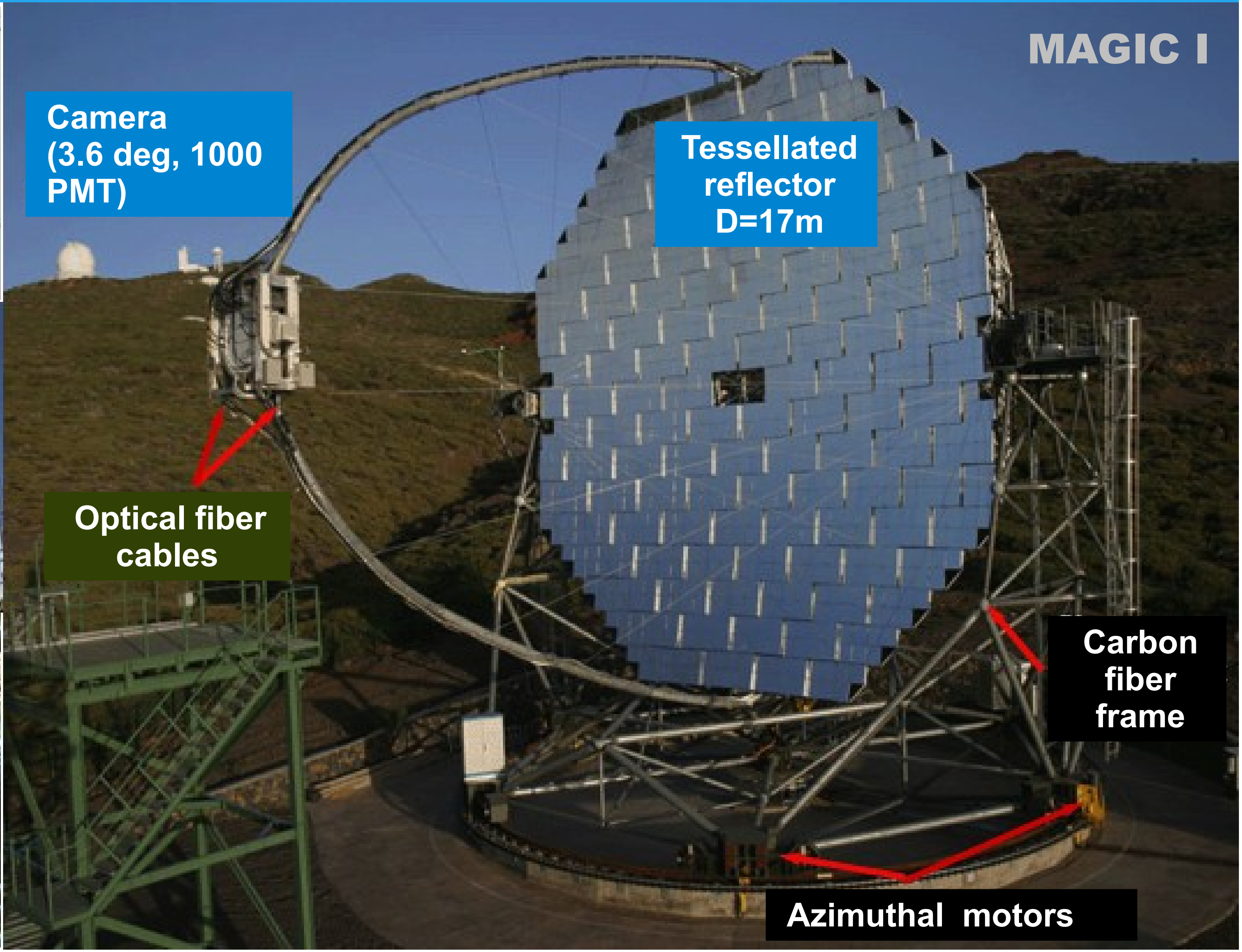
Ground-based gamma-ray astronomy



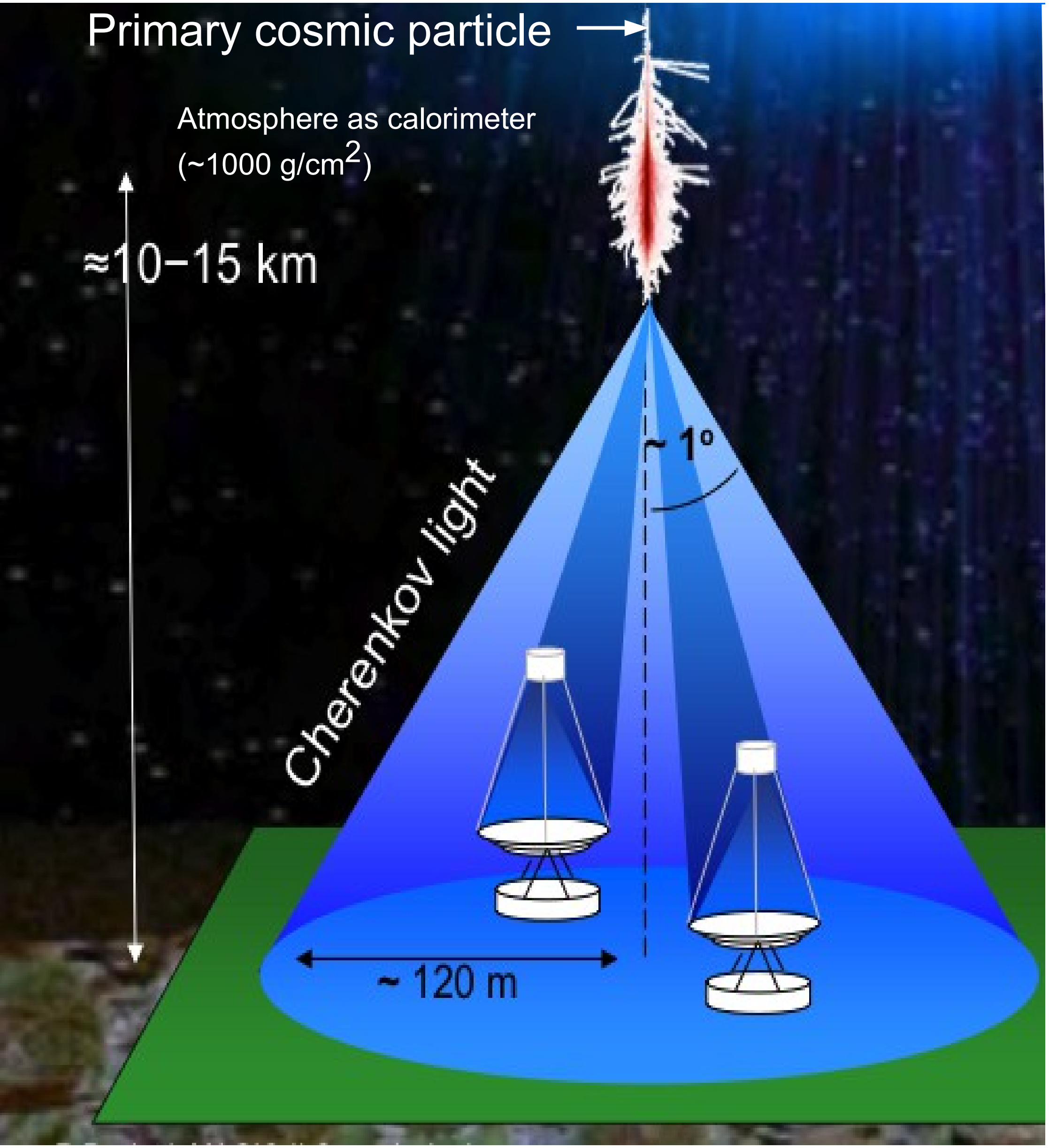
Crab Nebula Energy Spectrum
(Whipple, 10m)

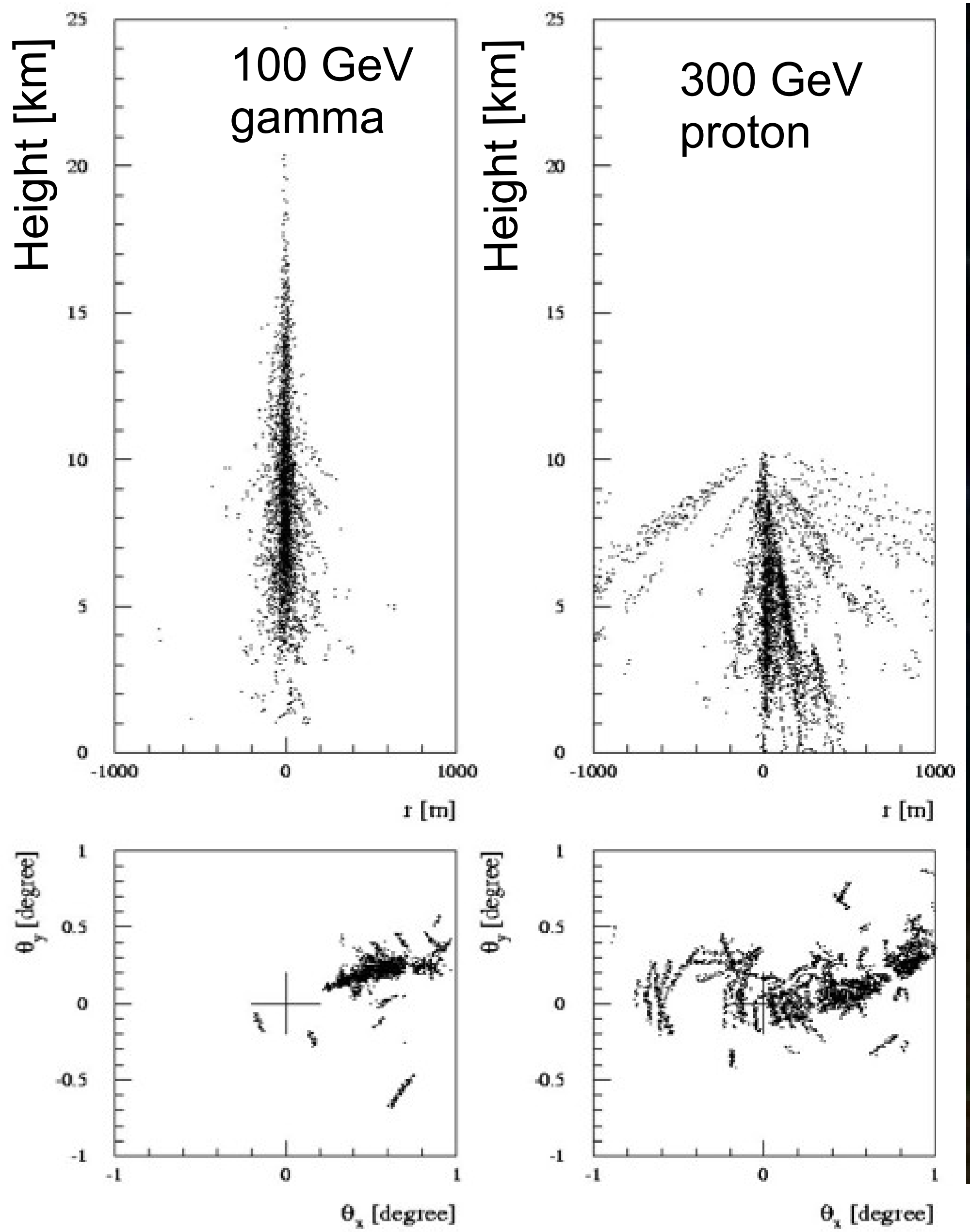
started operation in 1968
first source in 1988
retired in 2011

Cherenkov telescope design



Imaging Cherenkov telescope technique





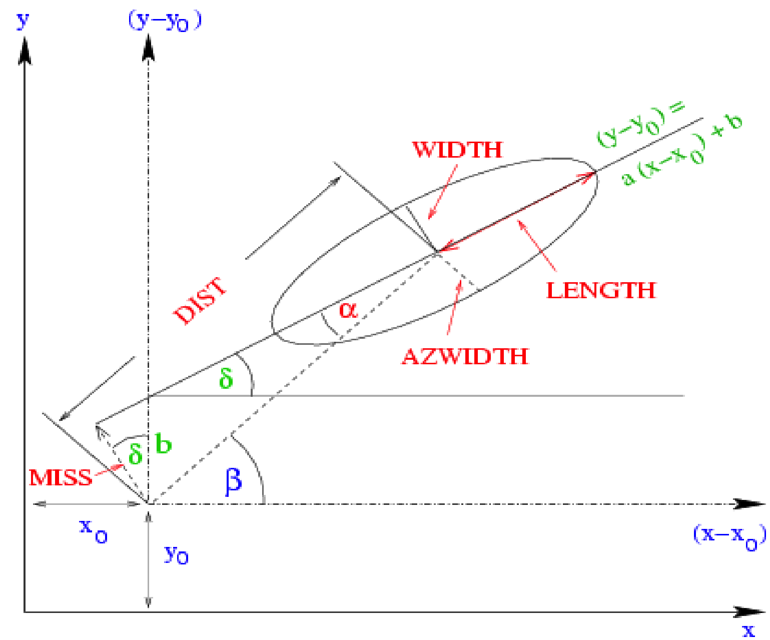
Imaging Cherenkov telescope technique

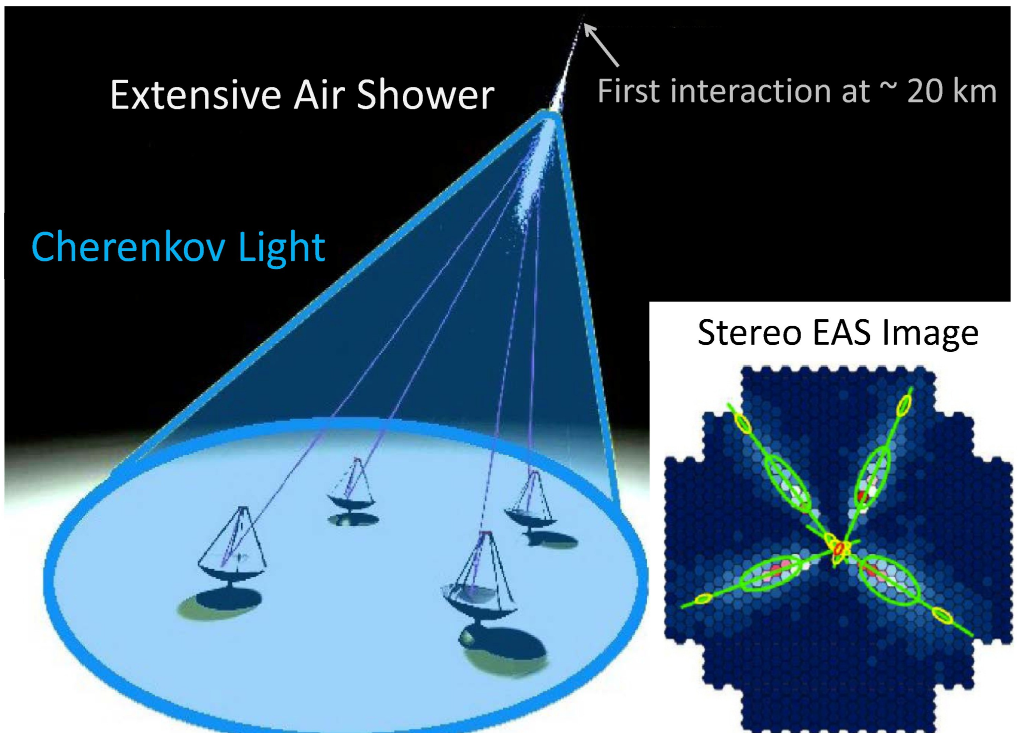
Gamma-ray/background separation:

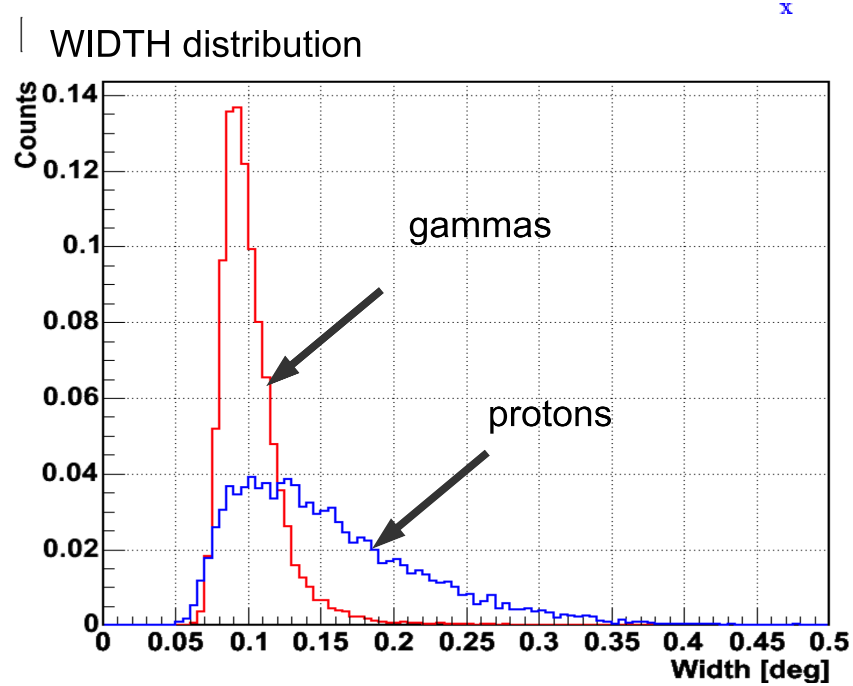
1. Getting the shower signals: Trigger and Image cleaning.

2. Parametrization of images by Hillas parameters (2-d covariance matrix)

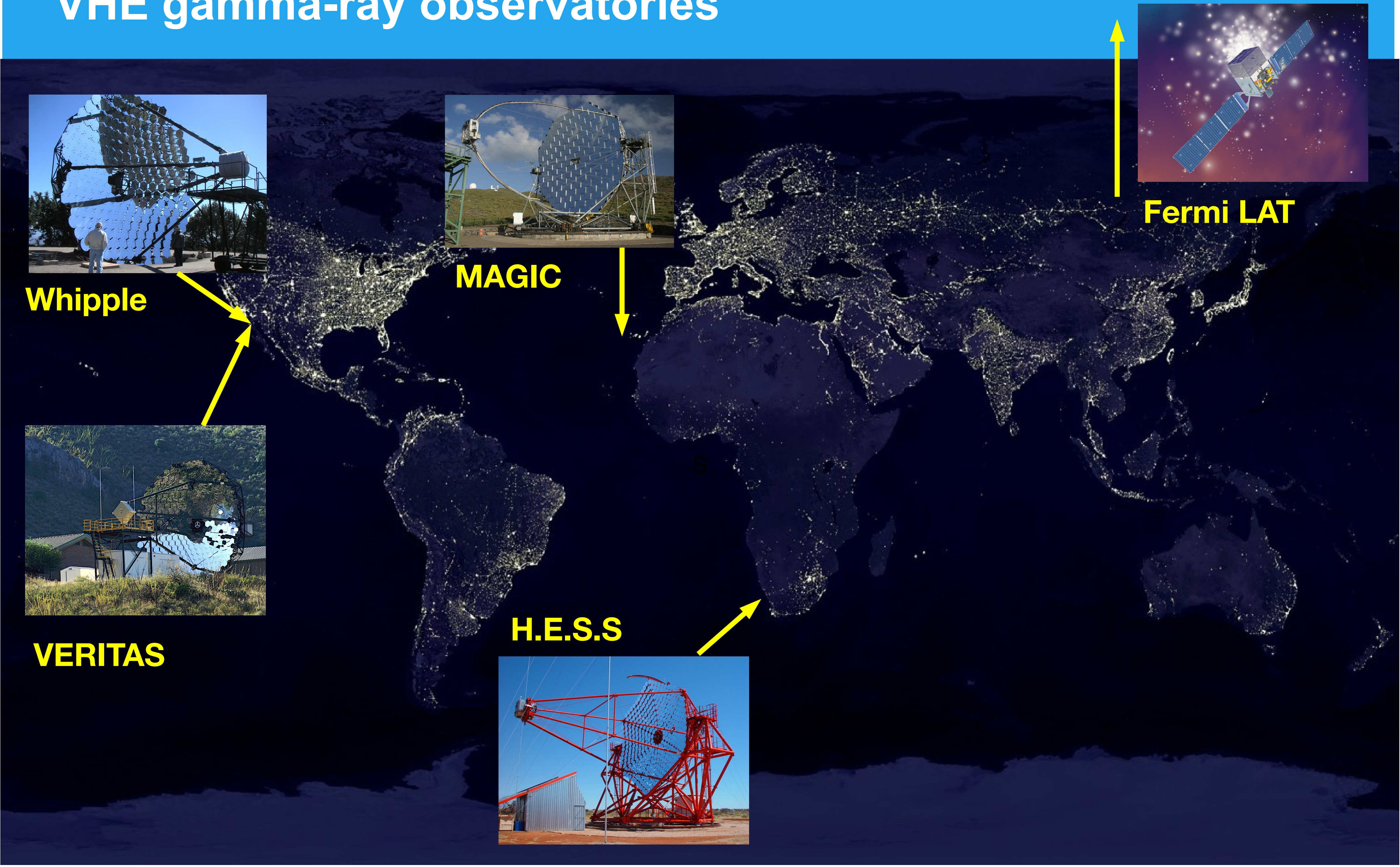
3. Multivariate analysis in multi-dimensional image features space: Neural networks, Random Forest, Boosted Decision Trees, 3D-shower model analysis







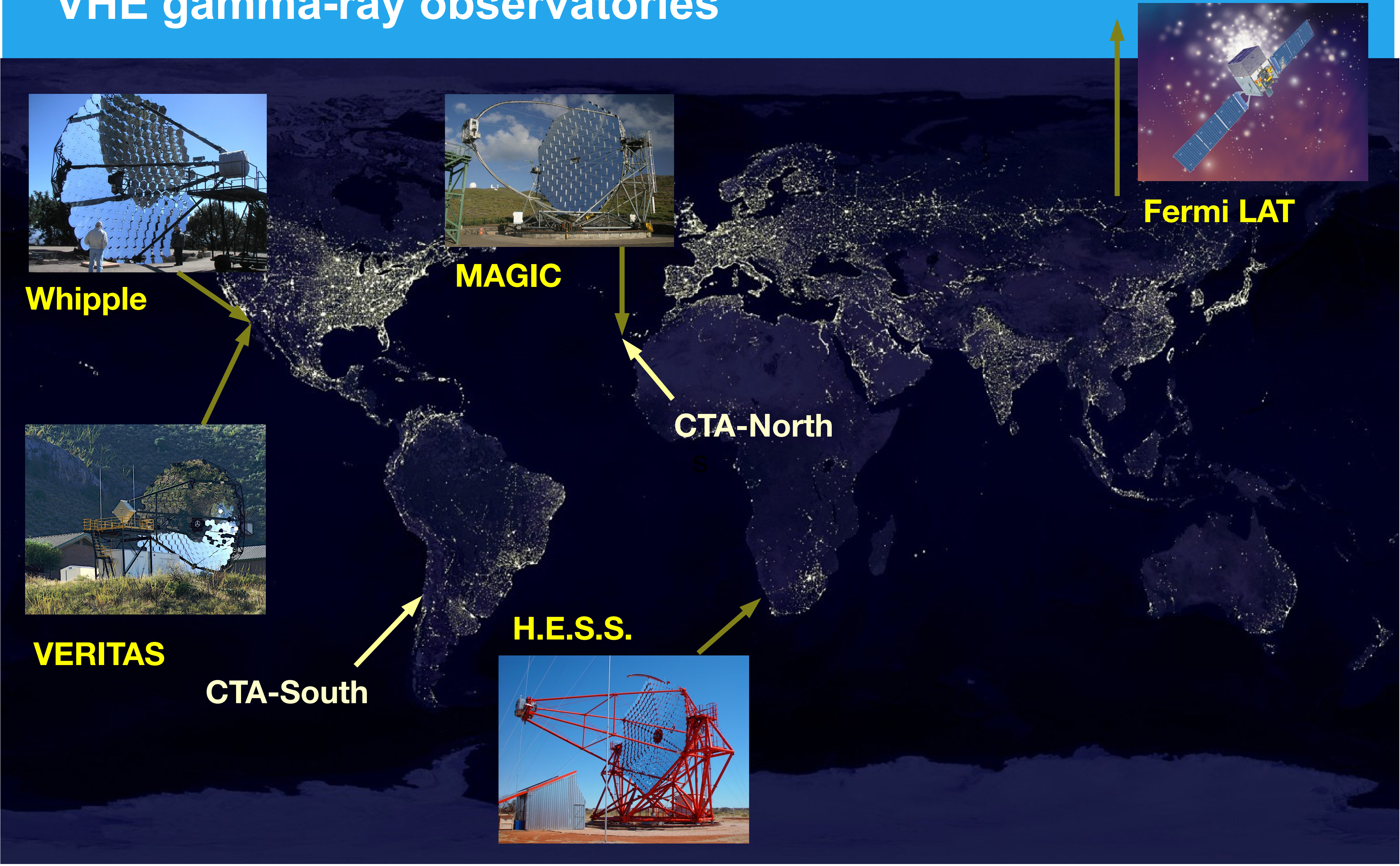
VHE gamma-ray observatories



Next-generation IACT facility:

Cherenkov Telescope Array (CTA)

VHE gamma-ray observatories

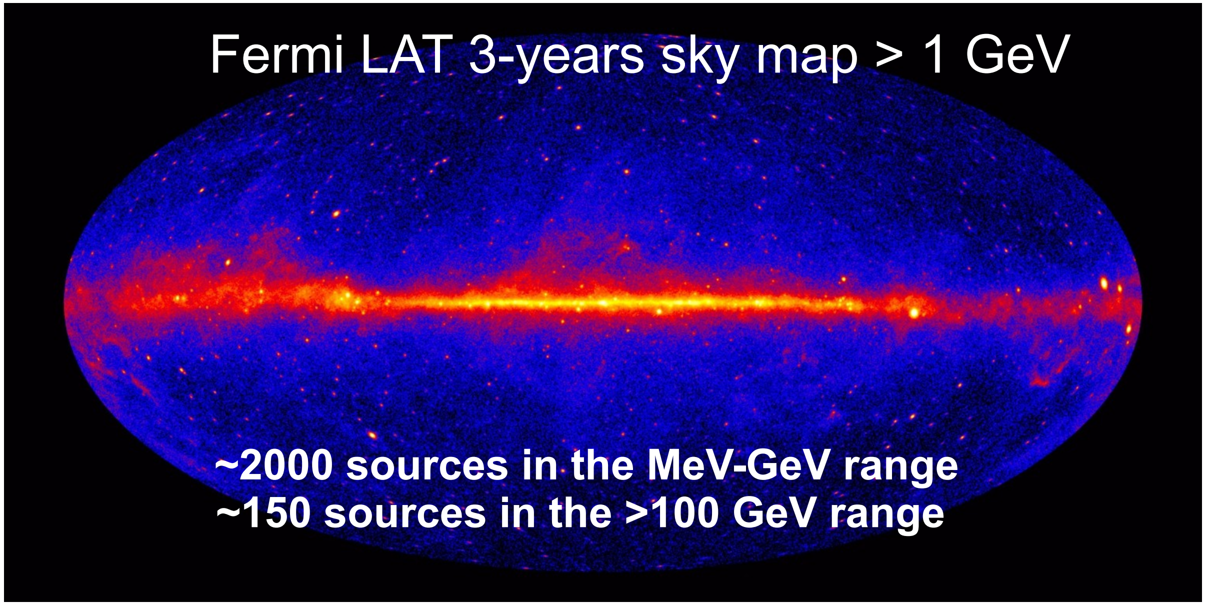


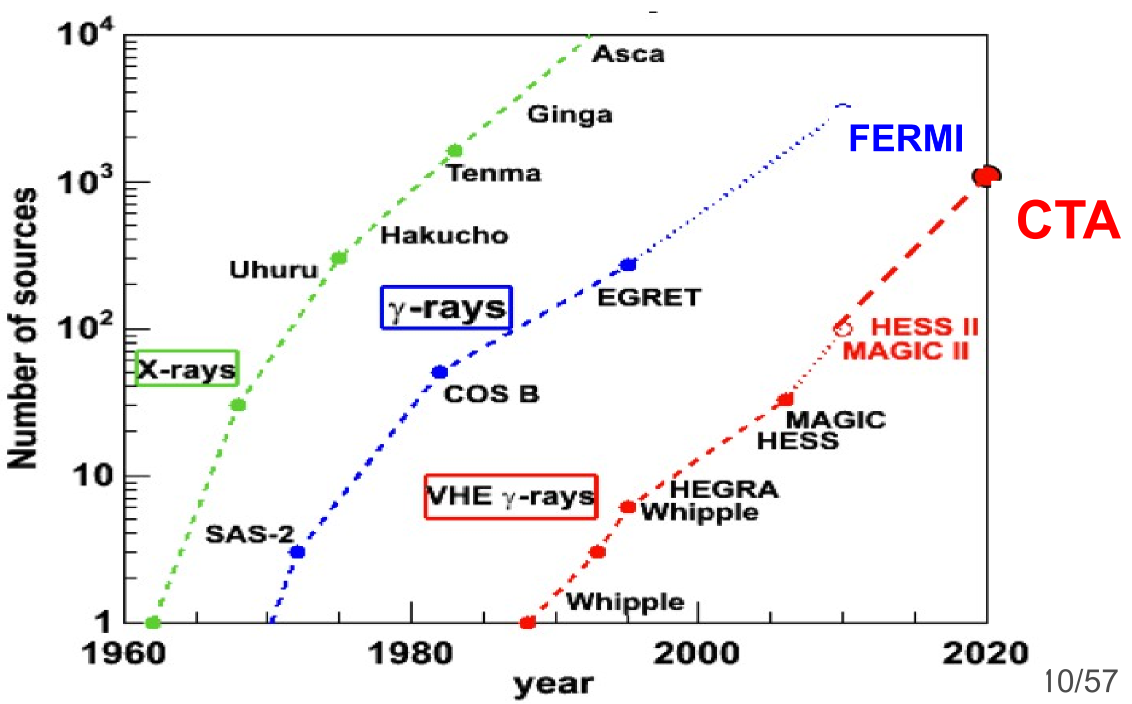
Next generation observatory: CTA

CTA Consortium:

- Collaboration of many experiments: MAGIC, H.E.S.S., Veritas, Fermi-LAT...
- >1000 members
- ~10 times higher sensitivity
- Enhanced angular resolution
- Improved energy resolution
- Widened energy range

Design Prototyping 2008-2015,
Construction 2017-2022





CTA Physics targets

1. Galactic Gamma-Ray Sources:

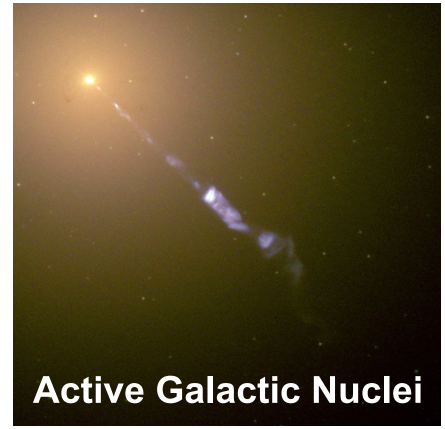
Supernova Remnants
Pulsars, Pulsar Wind Nebulae
X-Ray Binaries & Micro-quasars
Star-Formation Regions
The Galactic Centre

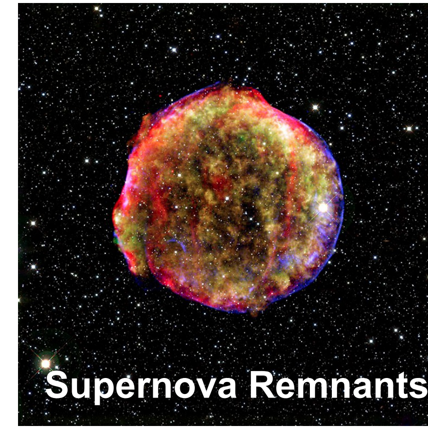
2. Extragalactic Gamma-Ray Sources:

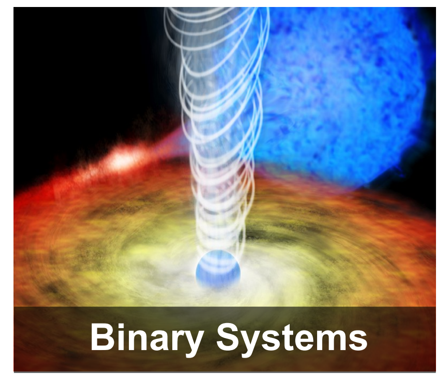
Active Galactic Nuclei
Extragalactic Background Light
Gamma-Ray Bursts
Galaxy Clusters

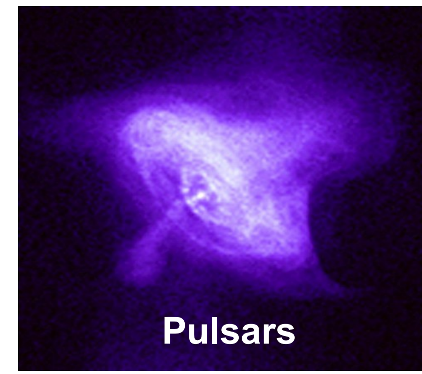
3. Fundamental Physics:

Dark Matter
Quantum Gravity
Charged Cosmic Rays .... and more

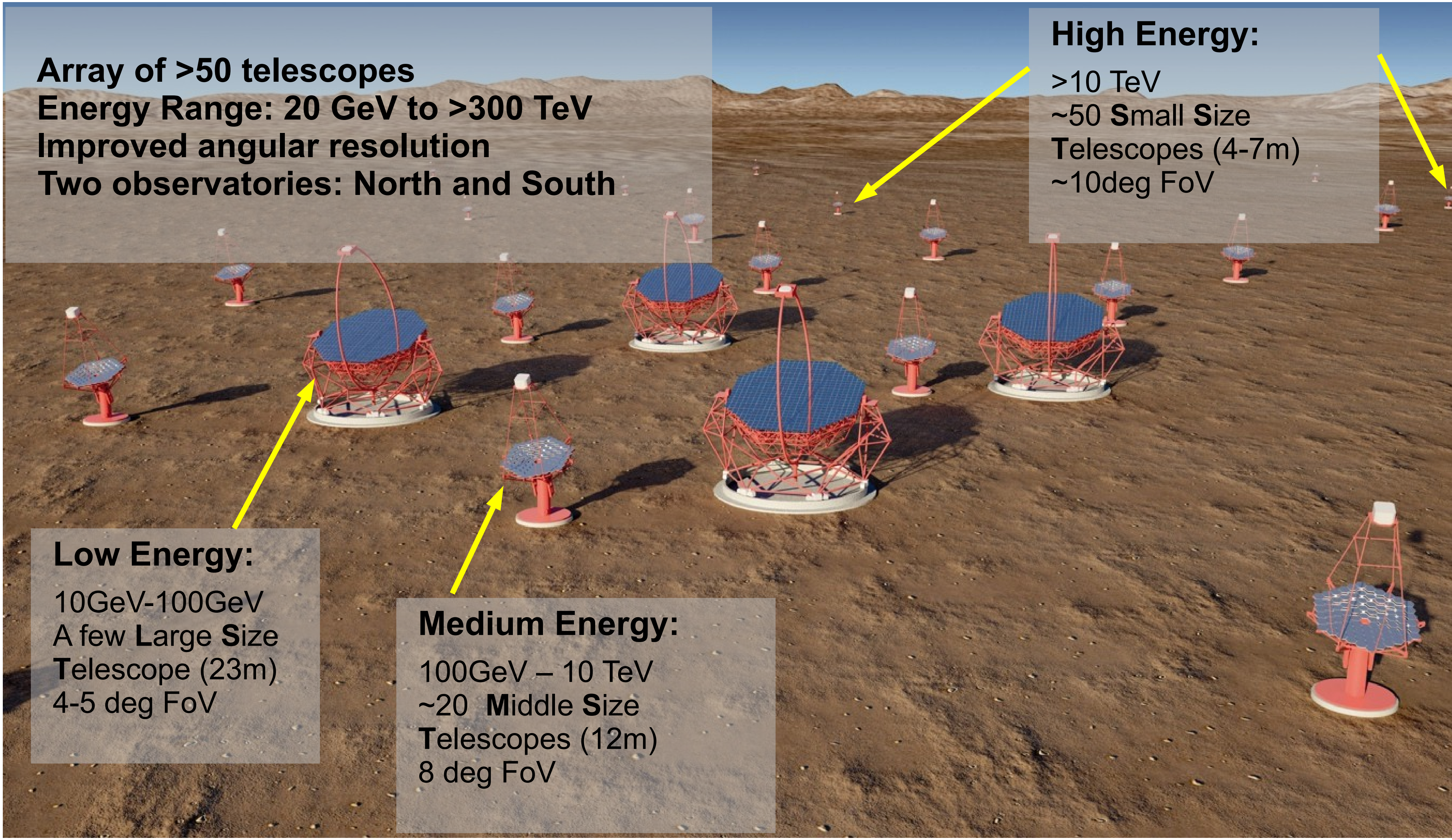




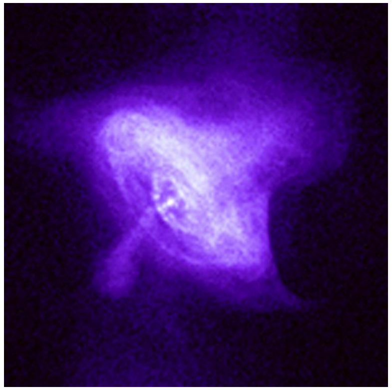




Next generation observatory: CTA

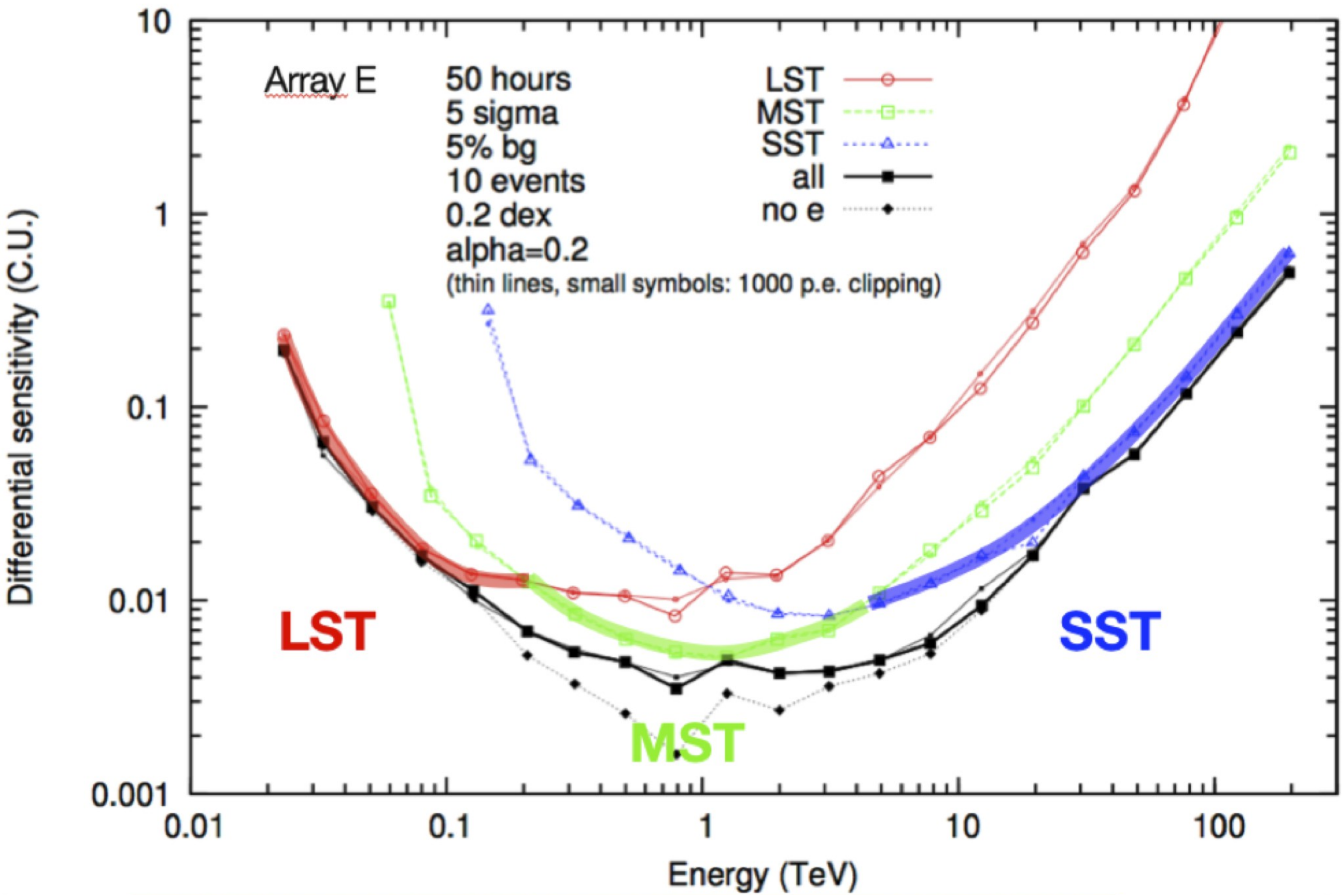


CTA performance: Telescopes energy domains



Crab Nebula "Standard candle" of ground-based gamma-ray astronomy)

C.U. - flux in Crab Nebula units



How to optimize CTA performance with the camera design?

Performance simulation. How to optimize?

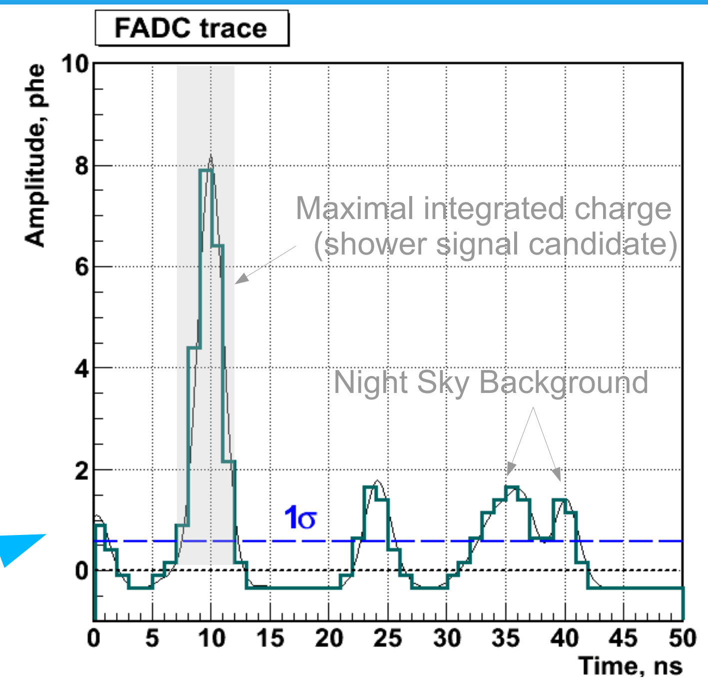
Night Sky Background noise:

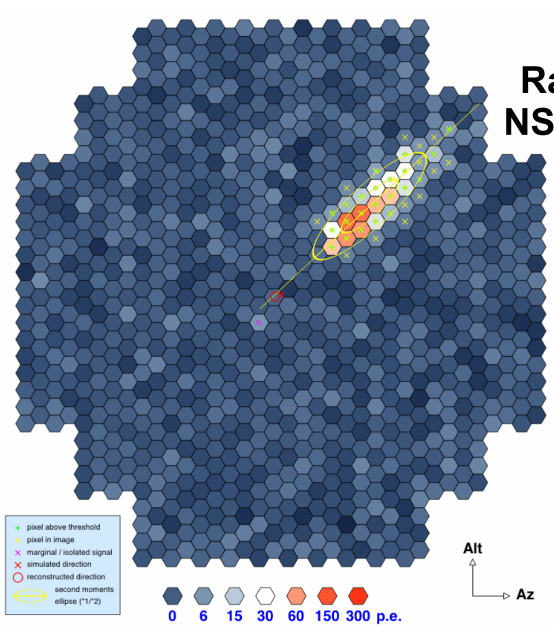
1. Cherenkov telescopes operate under the condition of Night Sky Background (NSB) light: noise rate of O(100 Mhz)/pixel.

2. Due to the photoelectrons (p.e.) induced by NSB and PMT after-pulsing, some charge is always found in EVERY pixel !
=> to distinguish between shower signal and NSB noise **Trigger and Image Cleaning** procedure are needed.

How to Improve signal to noise?

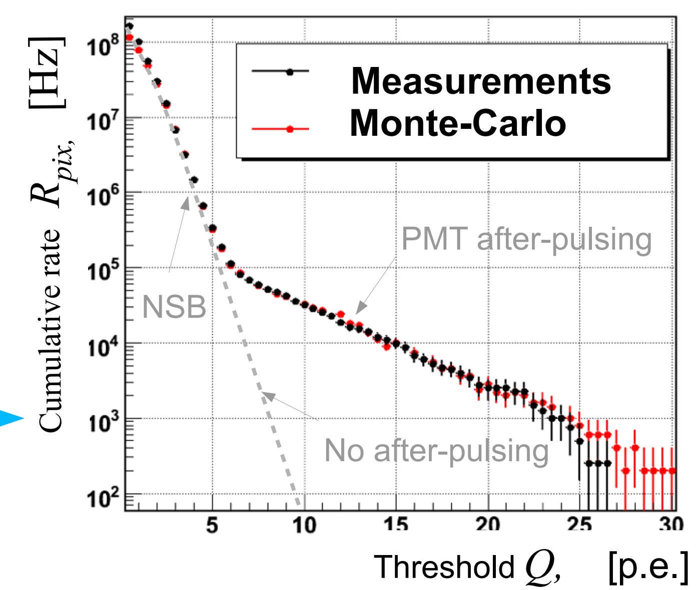
Shower signal waveforms should be recorded to properly select the region of interest => extract the maximum charge within the small window. **What electronic bandwidth should be used?**





Raw image with NSB and shower signals

Cumulative charge spectrum in one pixel: $R_{pix}(Q)$ (no shower signal)



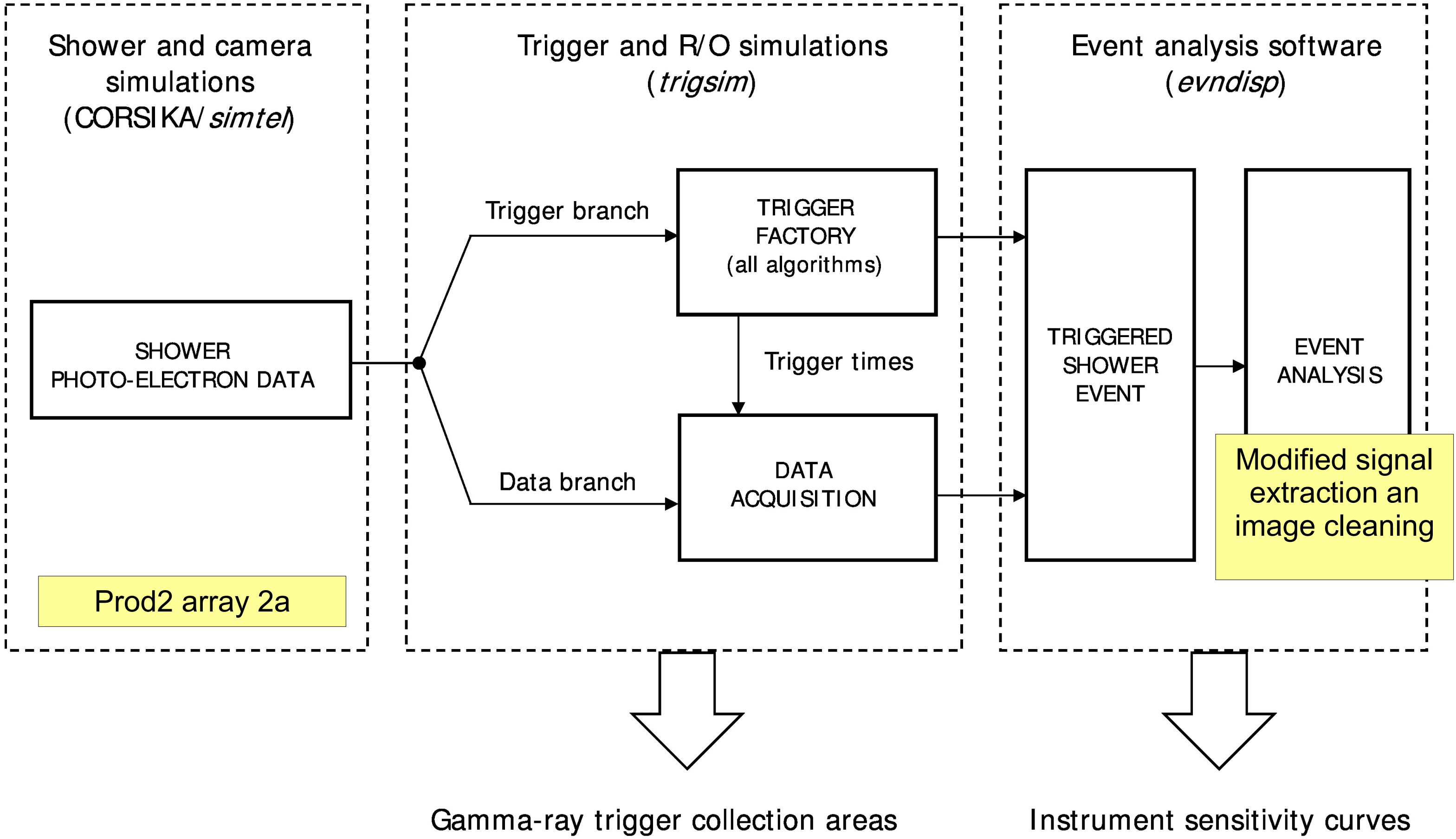
Performance Simulations:

Camera options:

1. High-BW (fwhm<6ns**)**
2. Low-BW (fwhm>6ns)
3. Mixed (Trigger/Data)

Mixed:

Trigger and data analog signals are simulated independently => can possess different BW within one camera option



Trigger simulations

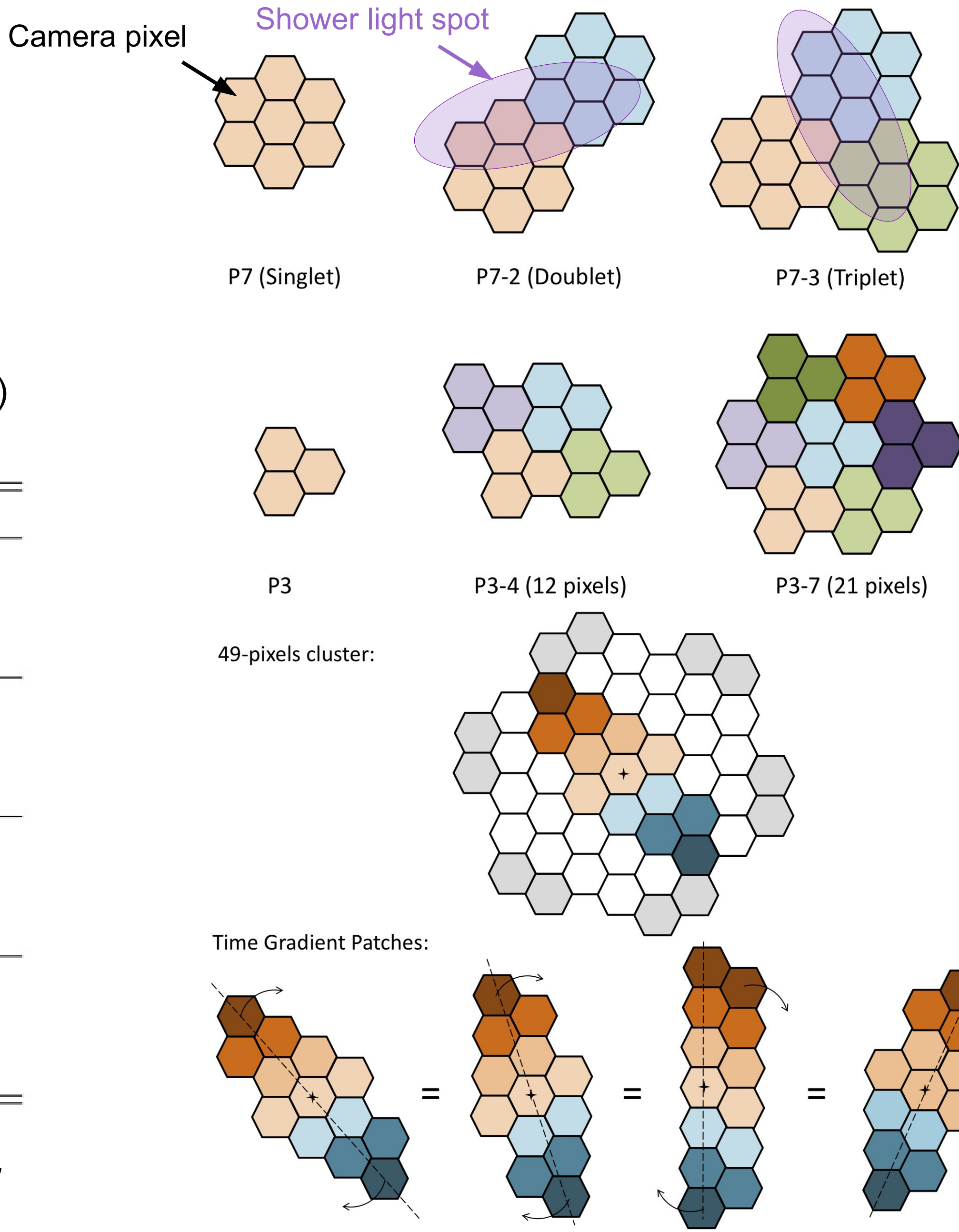
Trigger Algorithms:

1. Two options for signal processing: digital and analog
2. Various trigger patches (7-, 14-, 21-pixels areas)
3. Smart triggers: “Time Gradient”, etc...

Overall ~ 70 trigger scenarios evaluated.
Figure of Merit: Triggered γ–rate (the higher the better) versus energy

Concept	Algorithm
Majority Trigger	Majority 3/7
	Majority 4/7
	Majority 5/21
Analogue Sum Trigger	*SumSinglet*
	SumDoublet
	SumTriplet
Digital Trigger	P7-2
	P7-3
	P3-4
Binary Trigger	Maj. 3/7 OR Maj. 4/7
	Maj. 5/21 OR Maj. 7/21
	Time Gradient

Published in: U. Schwanke, M. Shayduk et.al., "A versatile digital camera trigger for telescopes in the Cherenkov Telescope Array", NIM A 782, (2015), 92-103



Sensitivity comparison

NSBx1 sensitivities:

Analysis steps:

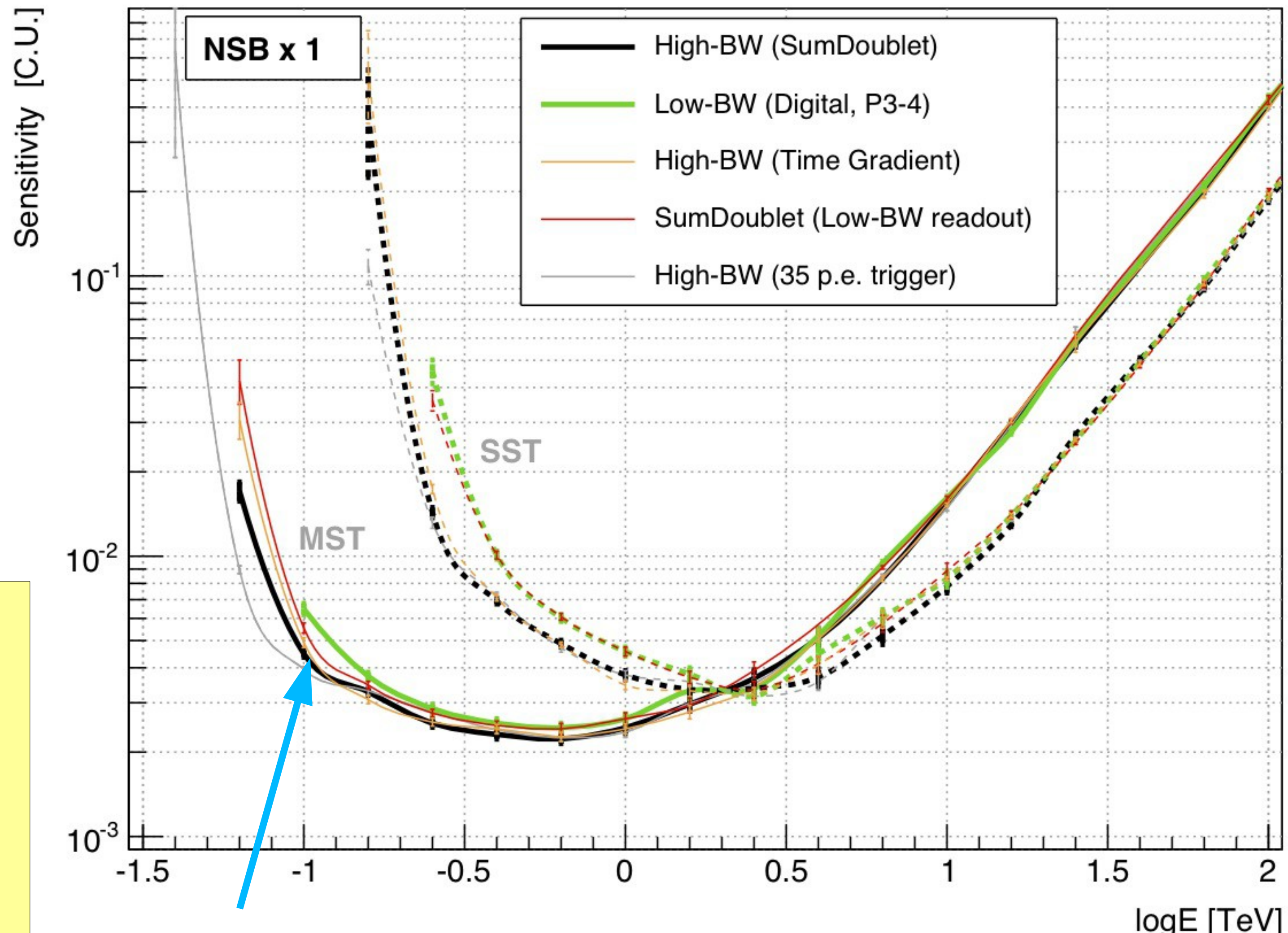
1. Signal extraction:
dynamic integration window (ToT, all slices above 5σ are integrated) Minimal length: 4ns (High-BW)
and 12ns (Low-BW)

2. Optimized Next-neighbor image cleaning (*M.Shayduk, ICRC2013*)

3. Standard analysis chain.

Design of the readout system influence the array performance:

Faster (High-BW) readout yields better performance



We aim to reach this performance with NectarCAM

Sensitivity comparison (brighter background)

NSBx4.5 sensitivities:

Analysis steps:

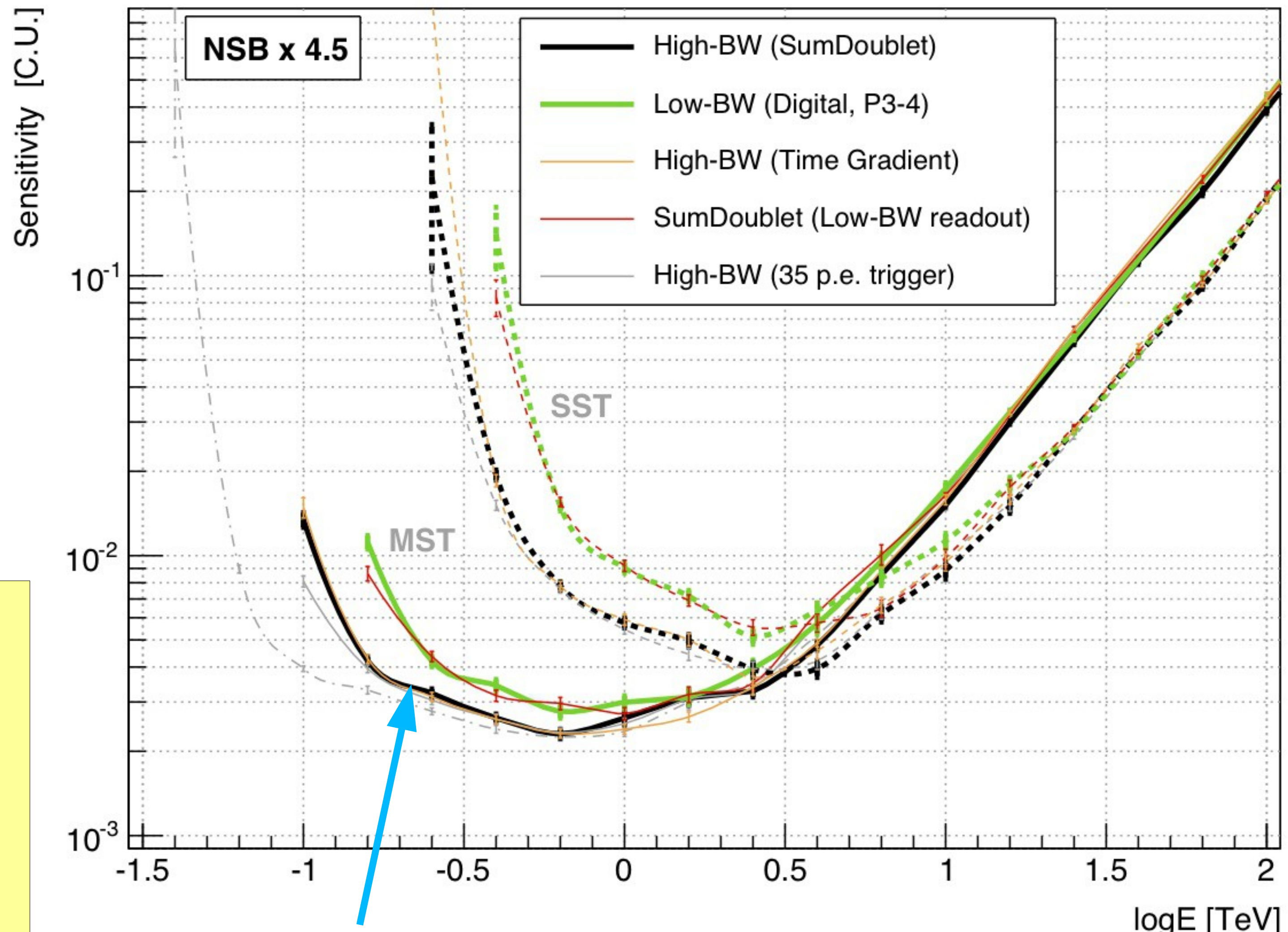
1. Signal extraction:
dynamic integration window (ToT, all slices above 3σ are integrated) Minimal length: 4ns (High-BW)
and 12ns (Low-BW)

2. Optimized Next-neighbor image cleaning (*M.Shayduk, ICRC2013*)

3. Standard analysis chain.

Design of the readout system influence the array performance:

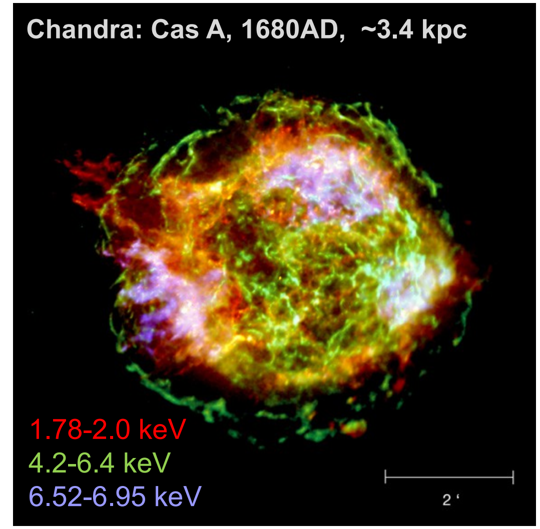
Faster (High-BW) readout yields better performance

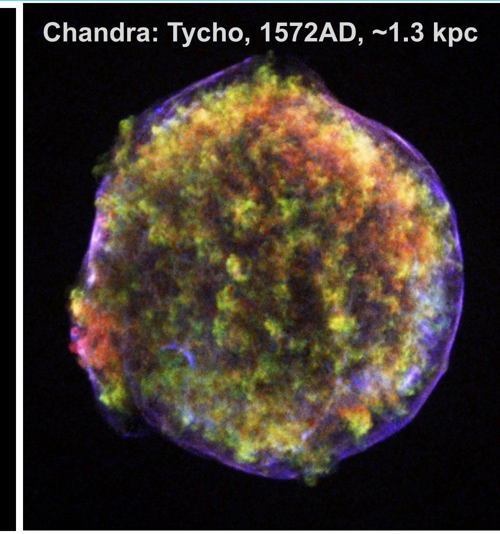


We aim to reach this performance with NectarCAM

CTA physics: Young Supernova Remnants as seen by CTA

Young SNRs variety as "seen" by CTA





Supernova Remnants (SNRs) are believed (established: *Ackermann et al., 2013*) to be the acceleration sites of the bulk of cosmic rays:

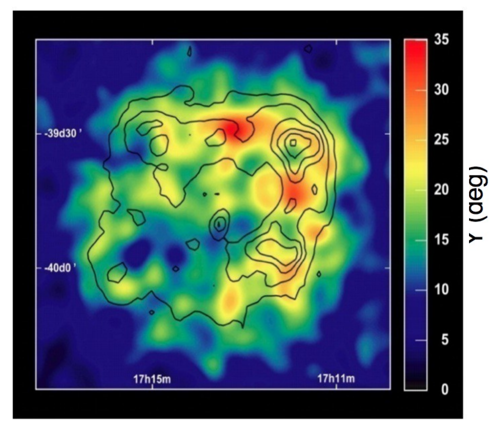
=> Long-term challenge of "Origin of Cosmic Rays".

Most efficient CR acceleration: When SNR is young! (i.e. shock is most energetic)

Overview:

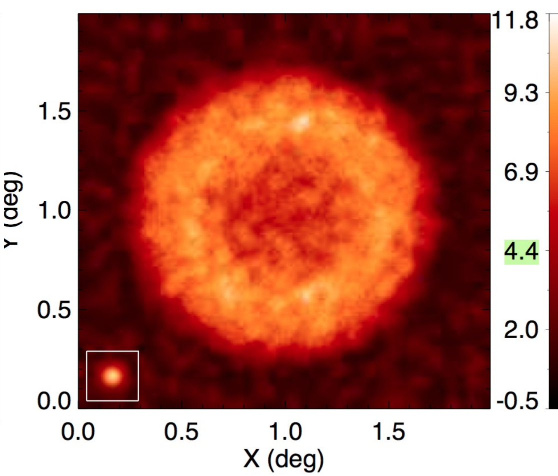
- Explosion types
- Input:
  - SNR models
  - Diffuse Astrophysical Background
  - CTA response matrices
- Results:
  - Detectability and resolvability study
  - Radii reconstruction
  - Morphology hints
  - Model recovery

RX J1713.7-3946, H.E.S.S.



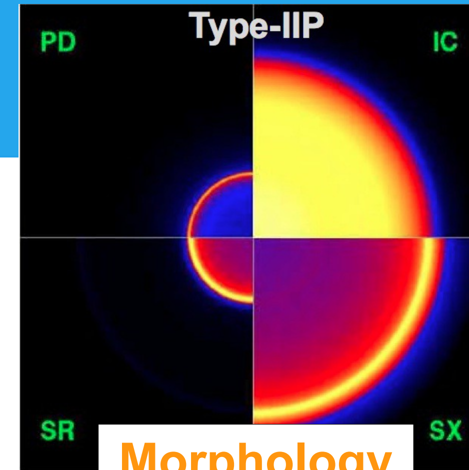
Aharonian et.al. Nature (2004)

RX J1713.7-3946-like "measured" by CTA

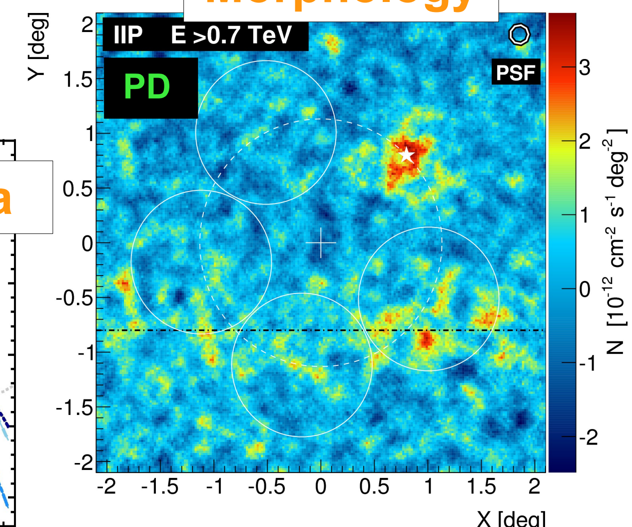


M. Renaud for CTA, arXiv:1109.4326v1,(2011)

Young SNRs variety as "seen" by CTA



Morphology

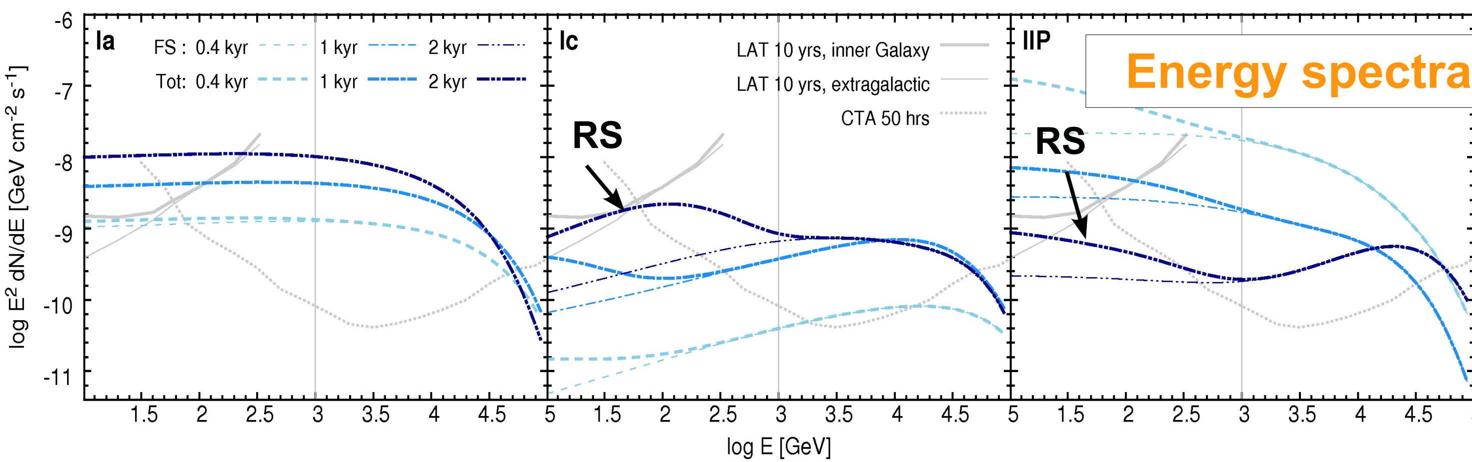


Overview:

1. Theoretical models of young (<2000years) SNR (**Type-Ia, Type-Ic, Type-IIP**) are build based on time-dependent simulations of hydrodynamics and magnetic field evolution and the CR acceleration in both forward (**FS**) and reverse shocks (**RS**).

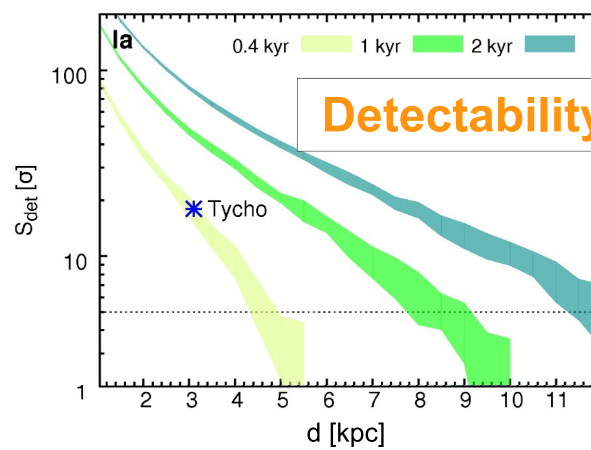
2. Theoretical skymaps and energy spectra convolved with CTA response functions.

3. Simulated Background: structured astrophysical (diffuse gamma-rays) and residual background from cosmic rays (hadrons and electrons)

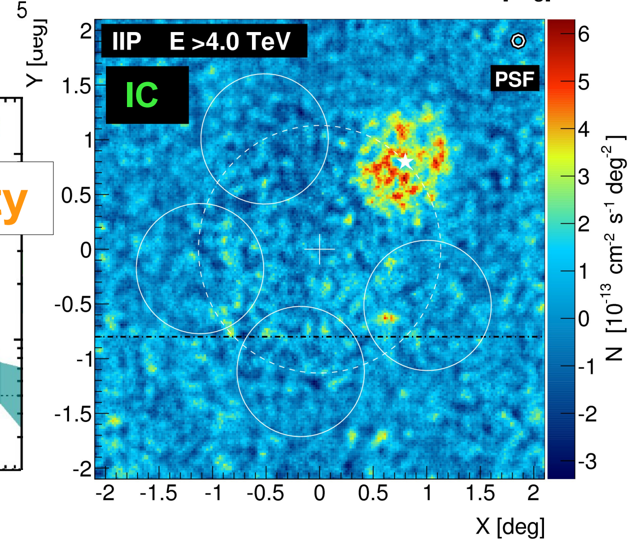


Energy spectra

Published in: M.Shayduk, I.Telezhinsky et. al, "The Cherenkov Telescope Array potential for the study of young supernova remnants": 10.1016/j.astropartphys.2014.08.005

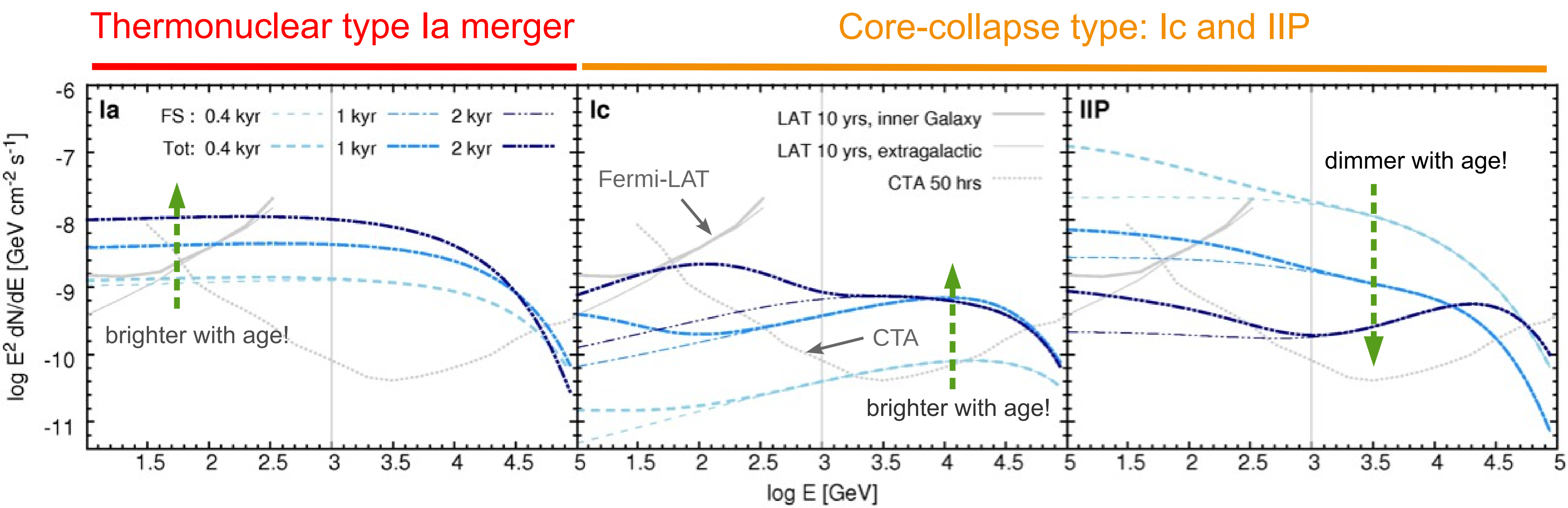


Detectability



Emission spectra of young SNRs

SNR gamma-ray emission: Tot = Forward (FS) + reverse shock (RS),   FS = forward shock only



Evolution of gamma-ray emission spectra from type-Ia, type-Ic and type-IIP SNRs due to pion-decay (PD) and inverse Compton (IC) radiation.

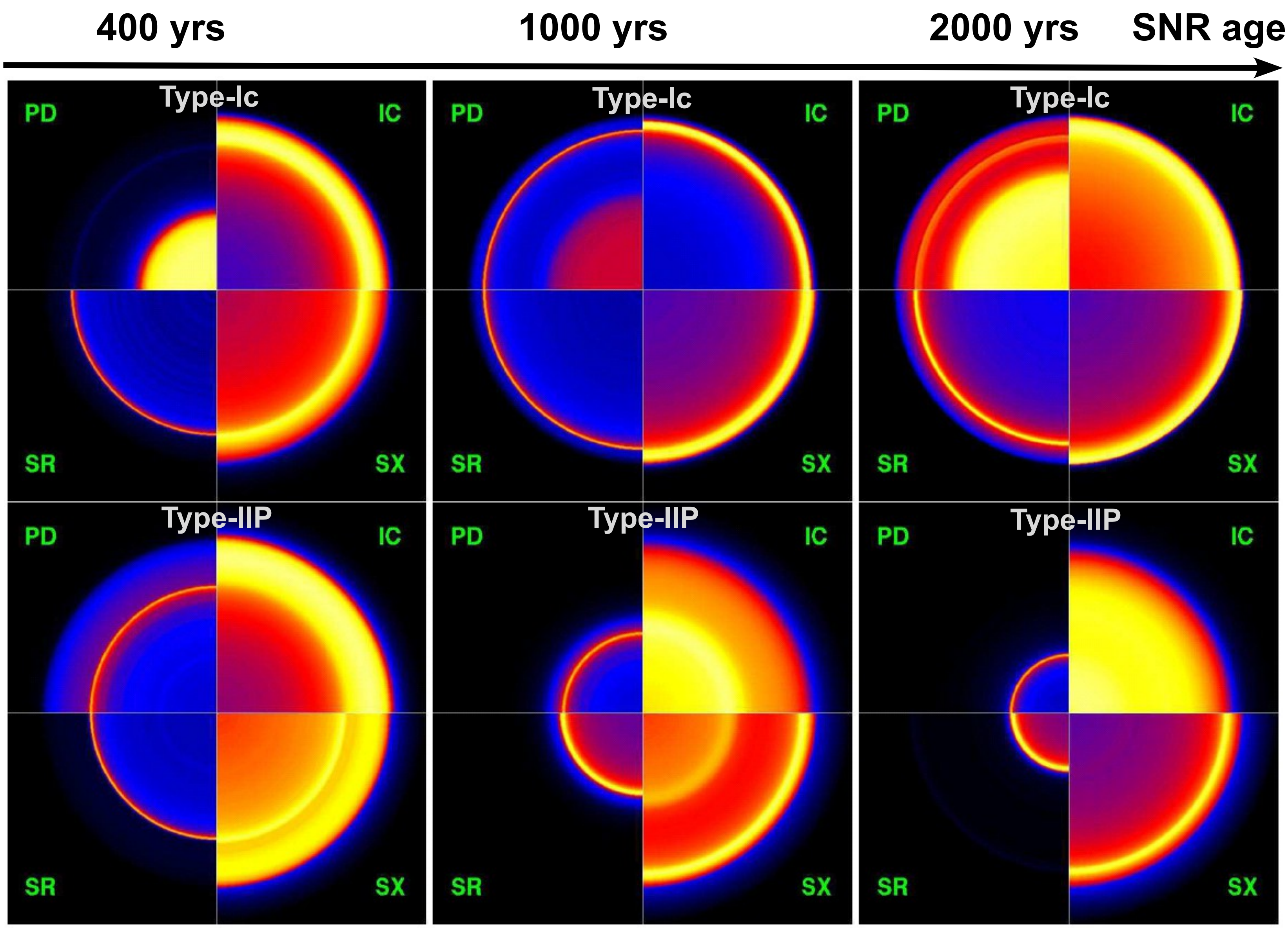
I.Telezhinsky, V.Dwarkadas, M.Pohl APh 35, 300 (2012)
I.Telezhinsky, V.Dwarkadas, M.Pohl A&A 552, A102 (2013)

Input: Energy and Age dependent intensity maps

PD: 1TeV
IC: 1 TeV
SX: 3keV
SR: 1.4GHz

Intensities normalized to maximum in each image.

All images are normalized by the Forward Shock (FS) radius.

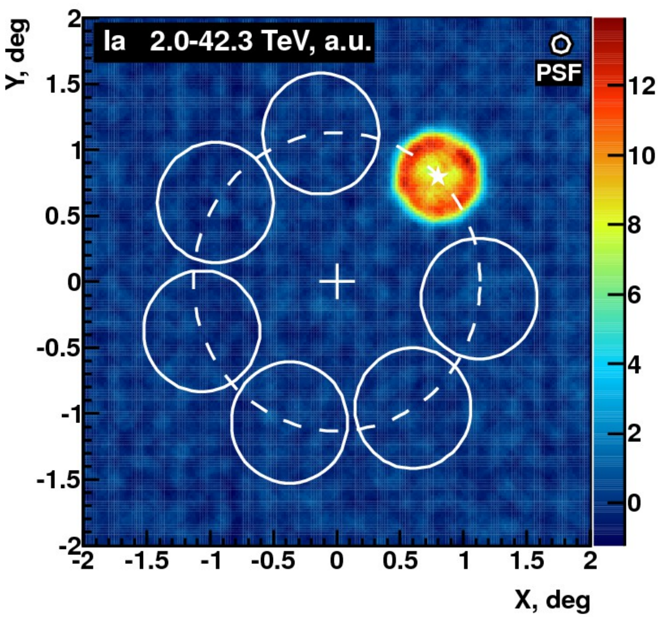


Taken from: *I.Telezhinsky, V.Dwarkadas, M.Pohl A&A 552, A102 (2013)*

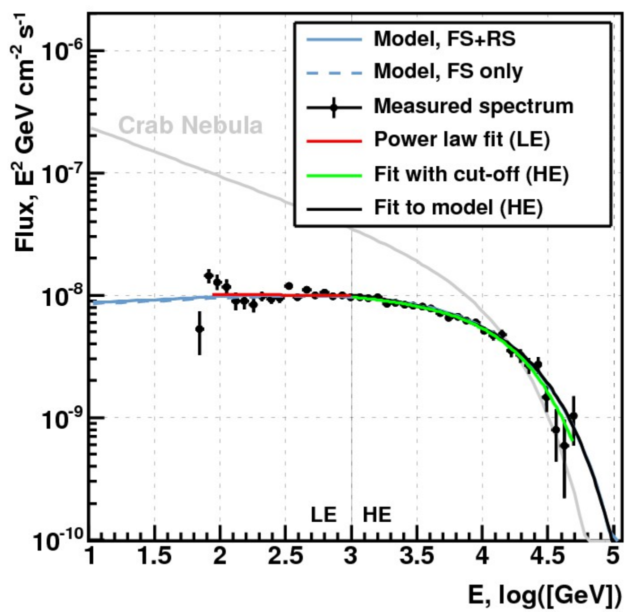
Simulation example: young SNR “seen” by CTA

Type-Ia

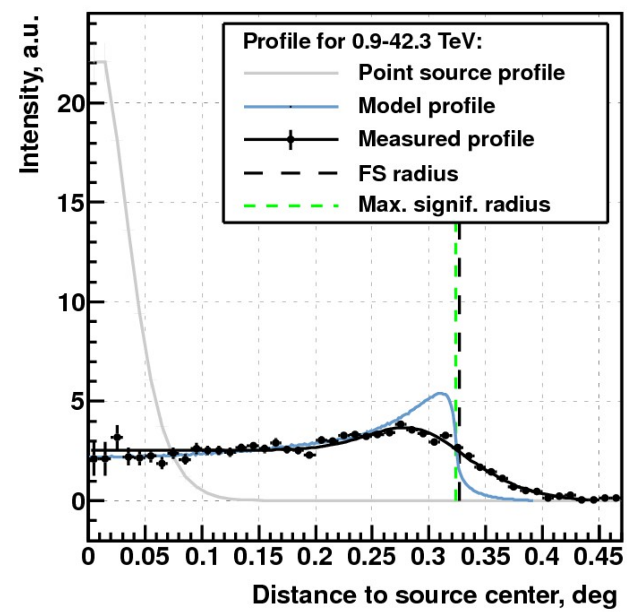
Simulated(!) sky map



Spectrum “measured” by CTA



SNR profile “measured” by CTA



- **Fit for two energy ranges:**

<1TeV (LE, possible contribution from RS):

$$F_{\rm LE}(E)\cdot E^2 = A_{\rm LE}\cdot E^{2-\alpha}$$

>1TeV (HE):

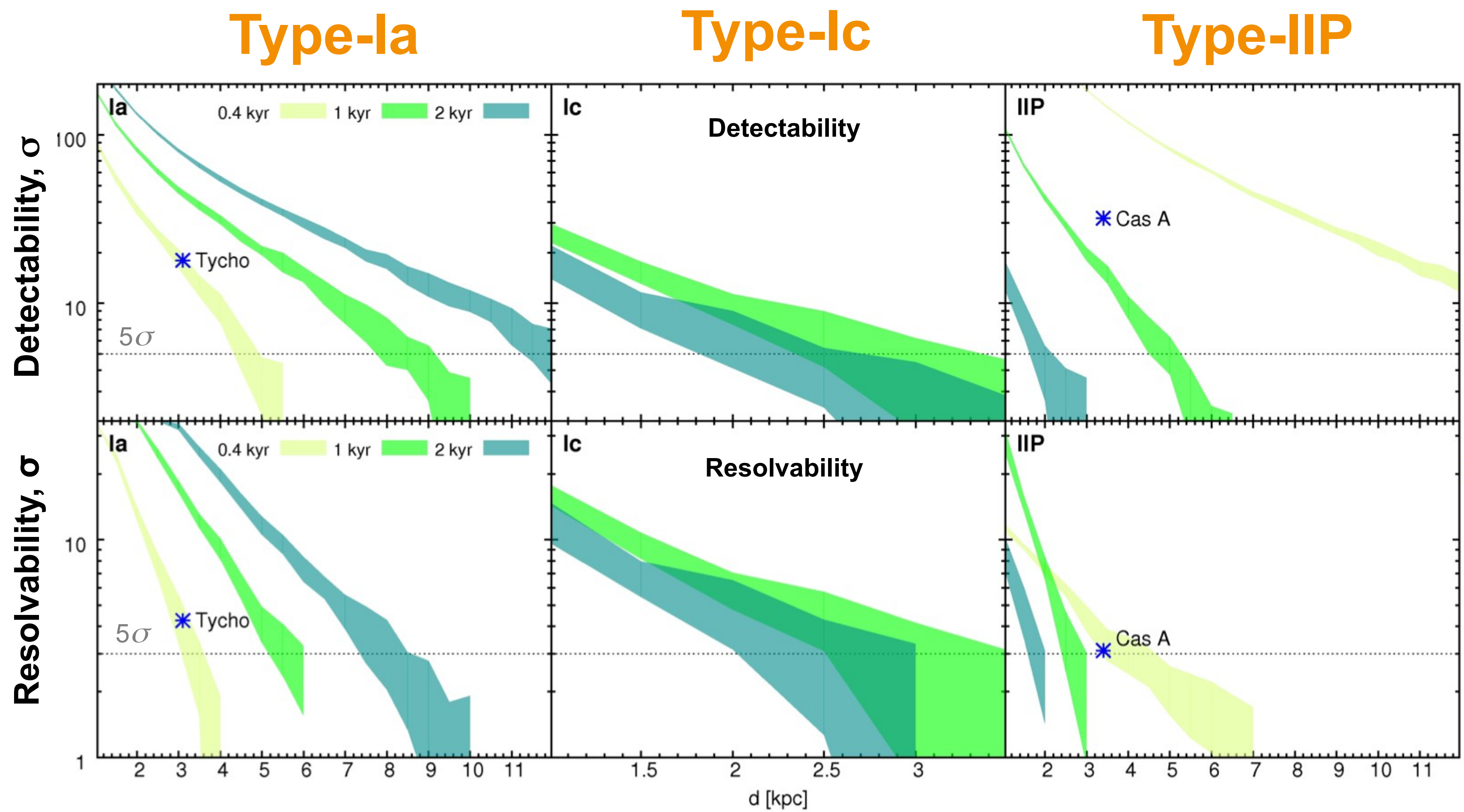
$$F_{\rm HE}(E)\cdot E^2 = A_{\rm HE}\cdot E^{2-\alpha}\cdot \exp(-E/E_{\rm c})$$

Profile fit function (smeared disc + gauss shell):

$$I(r) = I_0\cdot\left[\mathrm{erf}\left(\frac{R_p - r}{\sqrt{2\cdot\sigma_d^2}}\right) + \mathrm{erf}\left(\frac{R_p + r}{\sqrt{2\cdot\sigma_d^2}}\right) + \phi(r)\right]$$

gauss shell

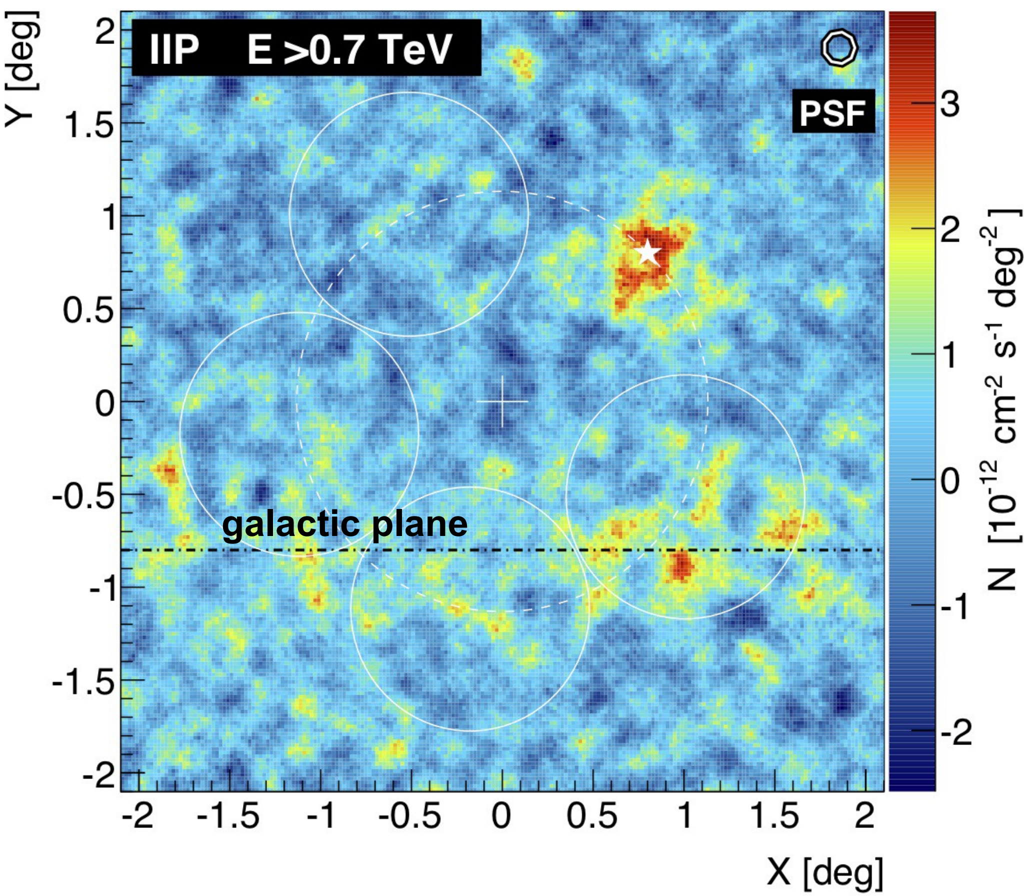
Detectability and resolvability



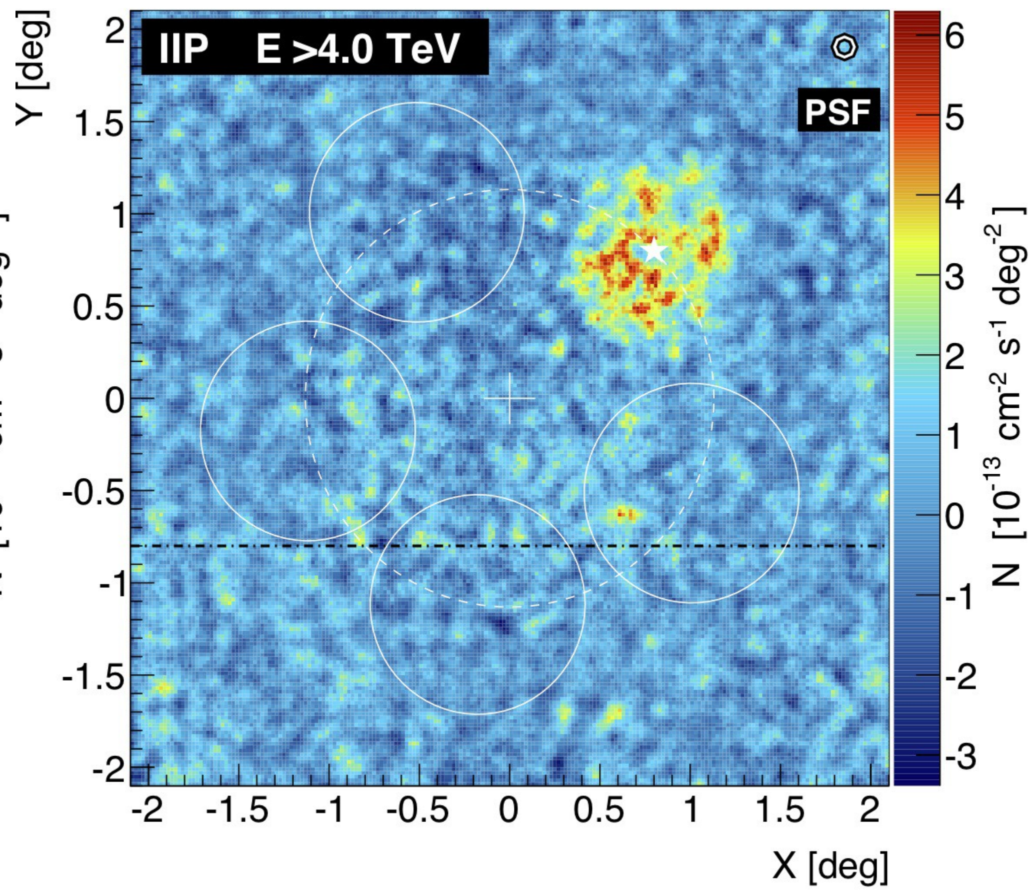
- **Best observables:** Ia are detectable throughout the galaxy
- Tycho-like SNRs resolved (compared to point-source) up to 3.5 kpc

Type-IIP: 2000yr, 1kpc, 200h

PD emission from high-density central part:



IC emission on uniform CMB:



Type-Ic: 2000yr, 1kpc, 200h

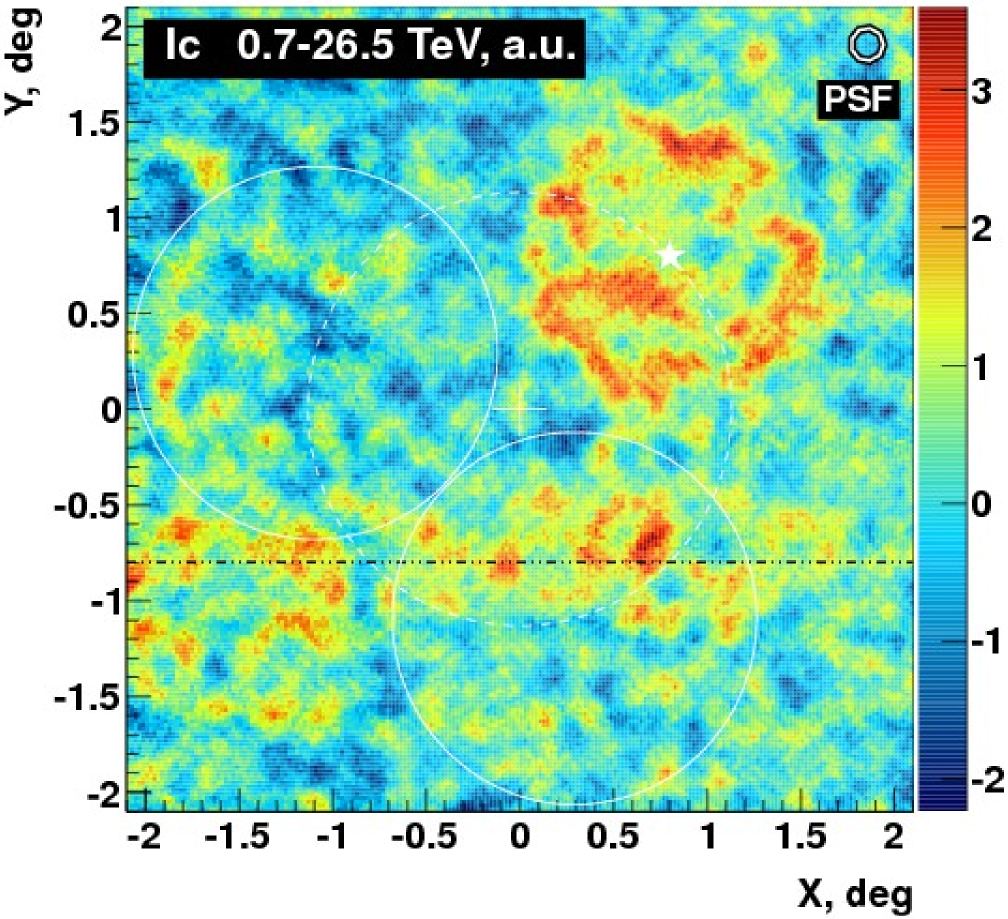
- "Minimal" diffuse gamma-ray BG:
  - Can affect morphology studies for low energies
  - Careful BG treatment is needed:
    limited wobble position choice,
    detailed BG modeling…etc.

Total SNR flux: ~7% C.U. (at 0.7TeV)

flux within PSF circle: ~0.03% C.U.

NB: Diffuse gammas from unresolved sources :

K. Egberts et. al. for H.E.S.S. collaboration. arXiv:1308.0161



Summary

- There is no “standard” *young* SNR (even among generic!):
  - emission and morphology are type and age dependent
- The best observable are type-Ia SNRs (brighter with age).
- Type II core-collapse SNRs become dim with age but are interesting:
  - spectral features and pronounced energy-dependent morphology
- If reverse shock acceleration is present spectra will give a hint!
- Astrophysical background is an issue for low-energy (<1TeV) analysis of faint sources
- Next: VHE emission from SNR swept-up shell and nearby molecular clouds

To increase the CTA capabilities to reveal the physics of various types of SNR an effort must be put into improving low and high energy sensitivity

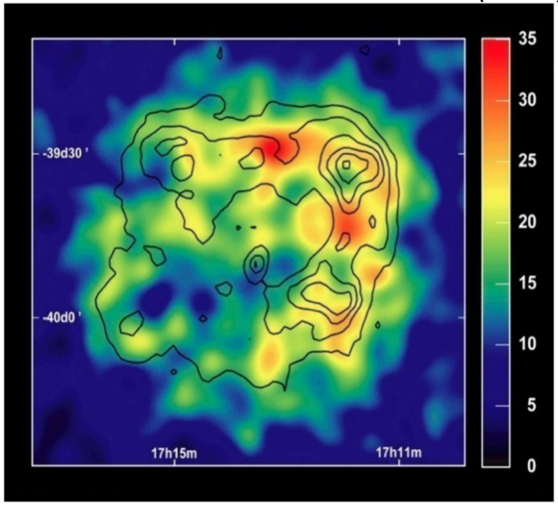
High energies: Sensitivity is statistically limited => larger arrays

Low energies: γ/background separation and NSB limited =>

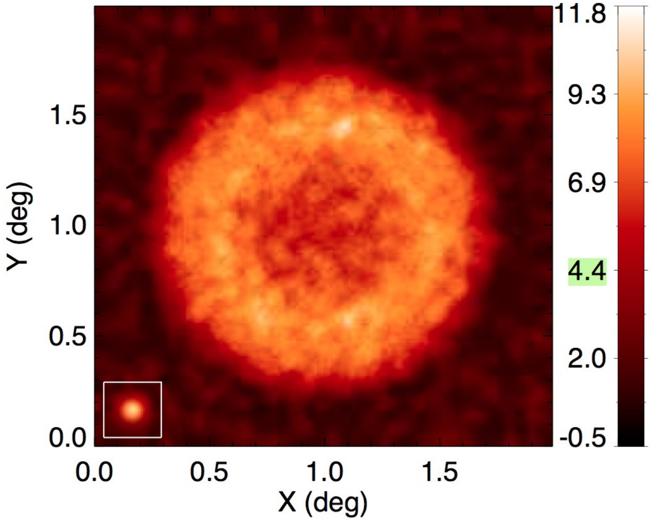
high performance (i.e low threshold) trigger and readout are required

SNR RX J1713.7-3946

H.E.S.S., Aharonian et.al. Nature (2004)



RX J1713.7 “measured” by CTA



M. Renaud for CTA, arXiv:1109.4326v1, 2011

CTA physics: Pulsars in VHE

Observation of Pulsars in VHE range

Models:

Pulsar: Compact, conductive, rotating object (i.e. neutron star (NS) and it's magnetic dipole).

High surface E-field: ~10^{13} V/m
(accelerating particles in very short time)

Many models, differing by acceleration and radiation “geometry”:

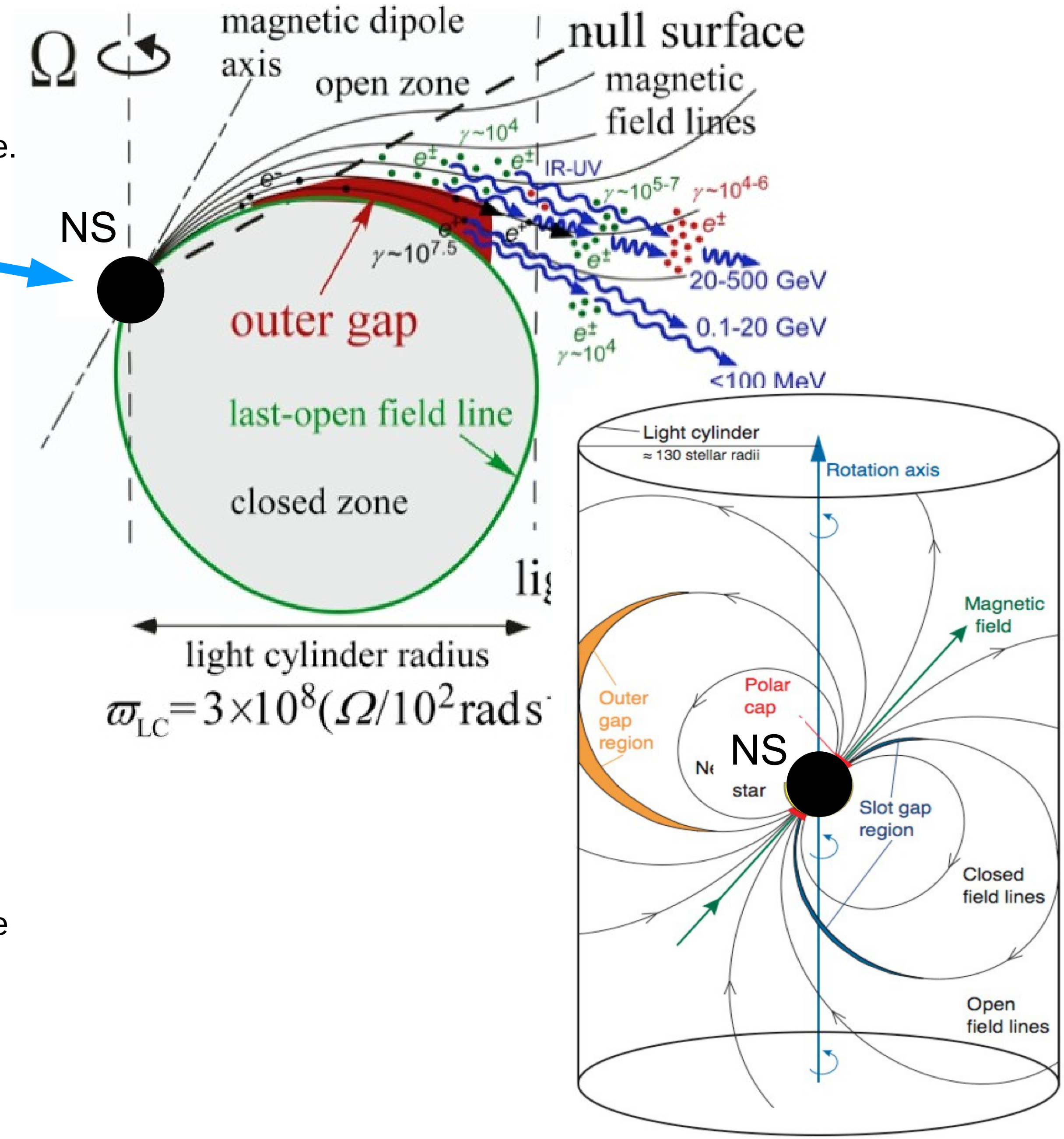
Polar Cap: acceleration and radiation near magnetic poles of the NS

Outer Gap: acceleration and radiation near (inside) the Light Cylinder

Slot Gap/TPC (Two Pole Caustic) : acceleration and radiation from NS surface up to the Light Cylinder

Striped wind: acceleration and radiation outside Light Cylinder in the wind zone

Magnetospheric Cascade Model (Crab Pulsar).
K. Hirotani & MAGIC, Apj 742 43, 2011



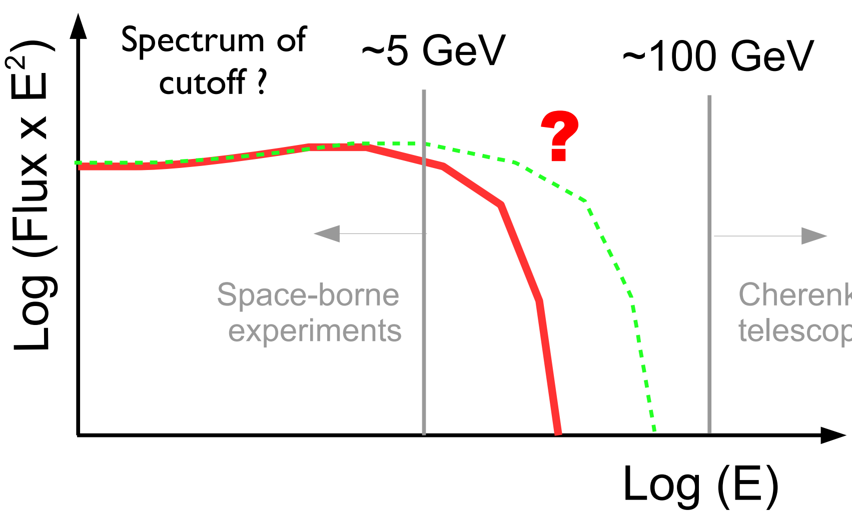
Pulsar's energy spectra cutoffs:

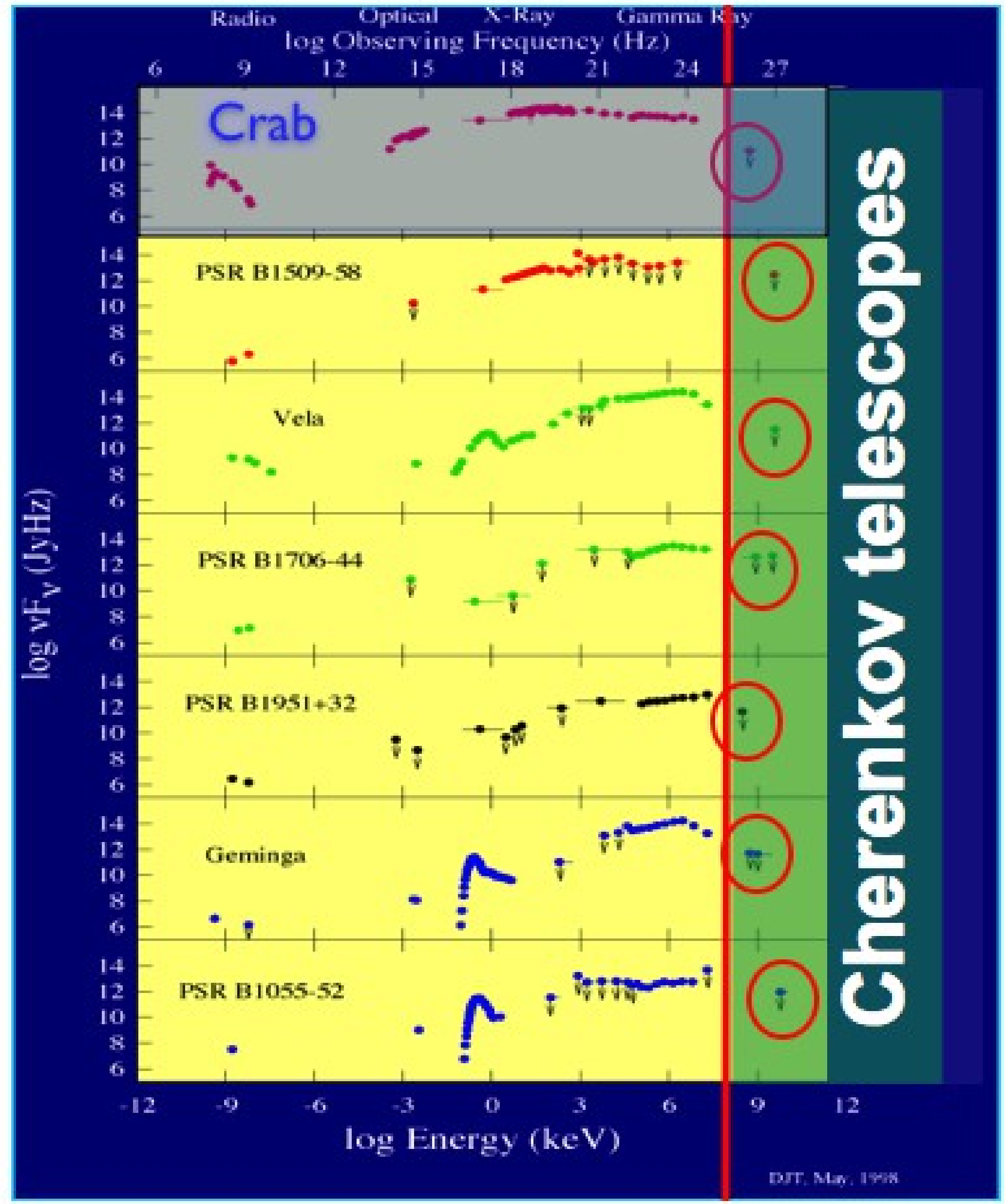
Observational challenge since many years!
Space-borne experiments lack statistics at VHE.

Cutoff shape and energy contains a lot of information about the acceleration and radiation mechanisms of pulsars: allows to distinguish between different models.

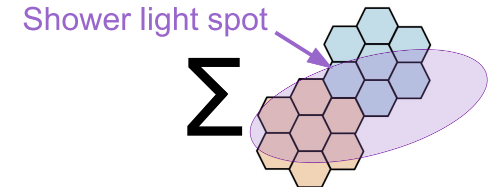
For Cherenkov telescopes: Sensitivity below 100 GeV needed => this was provided **for the first time** by the new Analog Sum Trigger and high efficiency image cleaning!

Before Fermi-LAT results!





First Detection of Crab Pulsar above 25 GeV by MAGIC



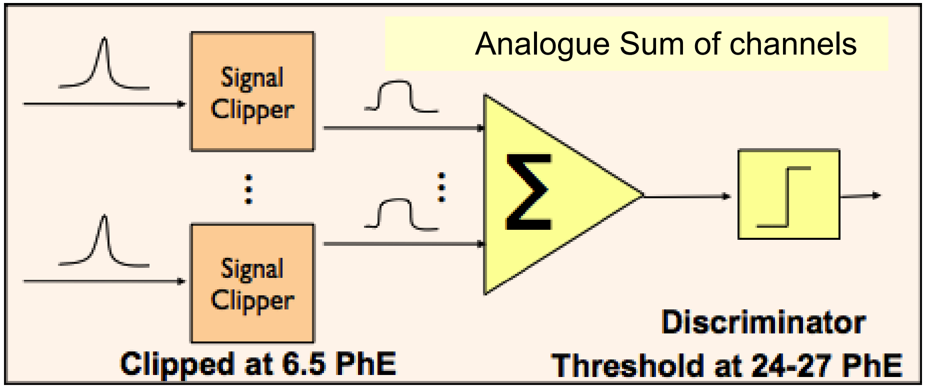
Concept of Analog Sum Trigger:

Sum of analog signals in some patch (~18 pix):

Advantage:

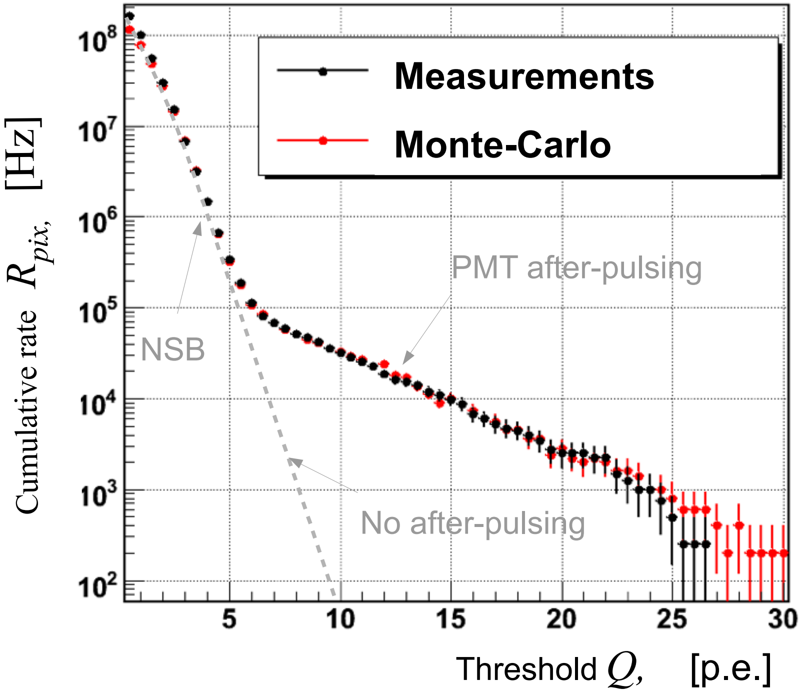
Sums up **all** signals from shower in the patch, even those that would be below discriminator threshold in conventional trigger schemes => **increases signal to noise ratio !**

=> lower light intensities can be triggered and lower energy threshold can be achieved compared to conventional triggers.



Problem:
Too high noise rate at large signal amplitudes due to PMT after-pulses. One noise pulse can dominate the sum and pass the final discriminator.

Solution:
Clip signal in every pixel at the certain amplitude (5-6 p.e.) Small signals are unaffected and still contribute to the trigger decision.



Development of the low-threshold trigger

Energy Threshold:

Analog Sum Trigger:
Provided twice lower energy threshold compared to next-neighbor triggers!

Hardware Implementation:
Simple concept and flexible design of MAGIC telescope allowed to develop, produce and commission the new trigger system in less then half a year !
(joint effort with electronic engineers)

M. Shayduk et. al., AIP Conference Proceedings, 2009, 1112(1): 72-78

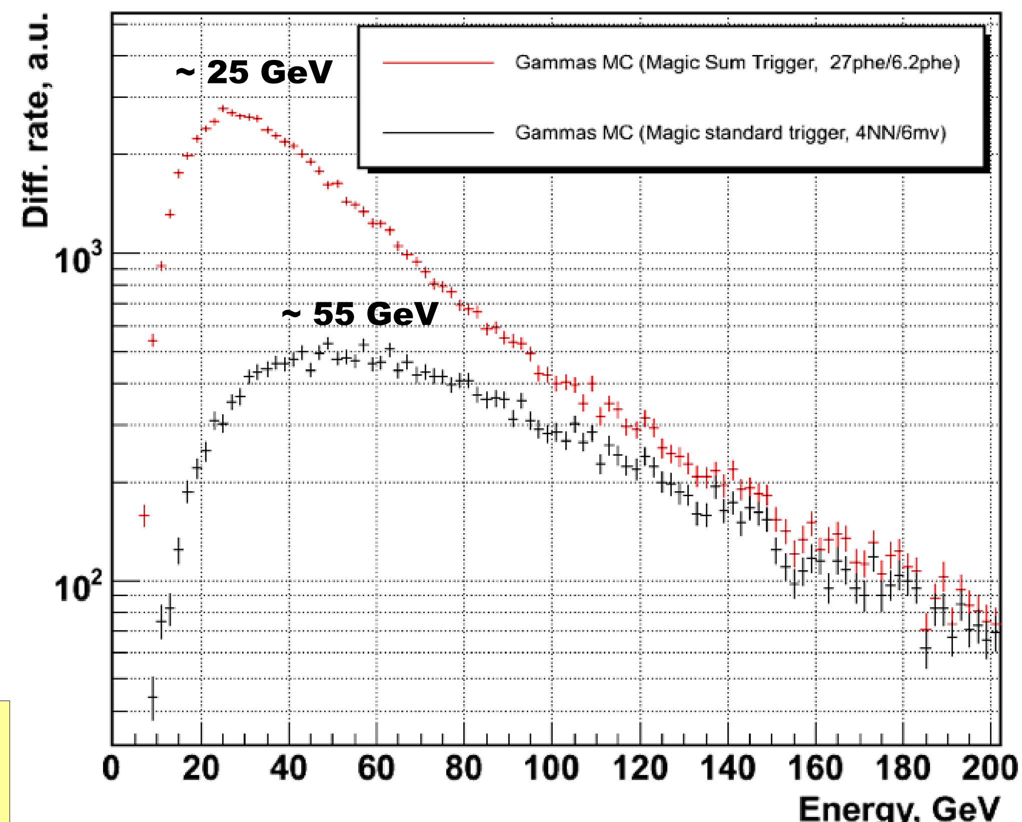
M. Rissi, N. Otte, T. Schweizer, M. Shayduk, IEEE Transactions on Nuclear Science, 2009, 56(6): 3840-3843,

Concept influence:

This successful concept is one of the main design options for CTA camera trigger!

Figure of Merit:

Triggered γ–rate (the higher the better) vs γ–energy



Detection of Crab Pulsar above 25 GeV

NEW light curves !

Pulsar's energy spectra cutoffs:

For the first time Crab Pulsar was detected above 25 GeV:
1. **Rejected Polar Cap model**.
2. Revealed unexpectedly shallow cutoff
3. Opened new window for Cherenkov telescopes
4. Inspired future observations of pulsars by ground-based instruments

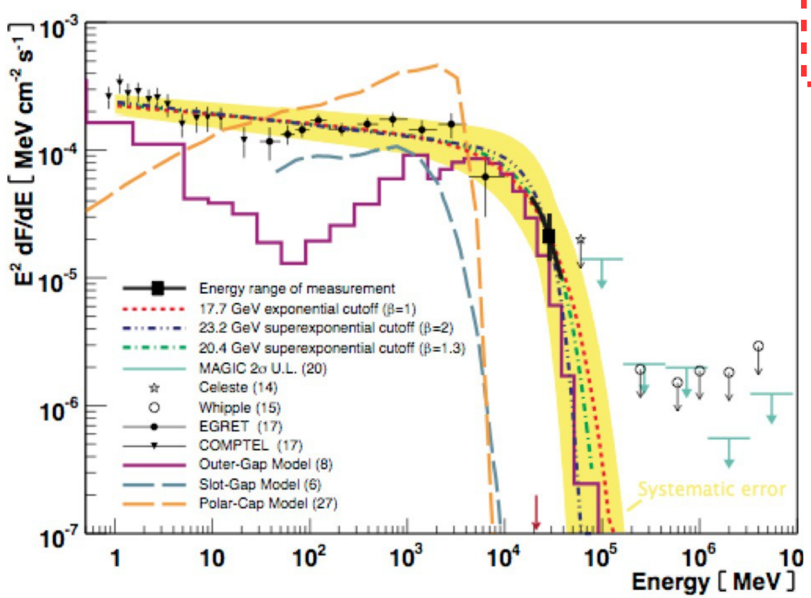
M.Shayduk, N. Otte, M. Rissi, T. Schweizer, M. Lopez for MACIC,
***Science 322 (2008) 1221-1224**, "Observation of pulsed gamma-rays above 25 GeV from the Crab pulsar with MAGIC"*

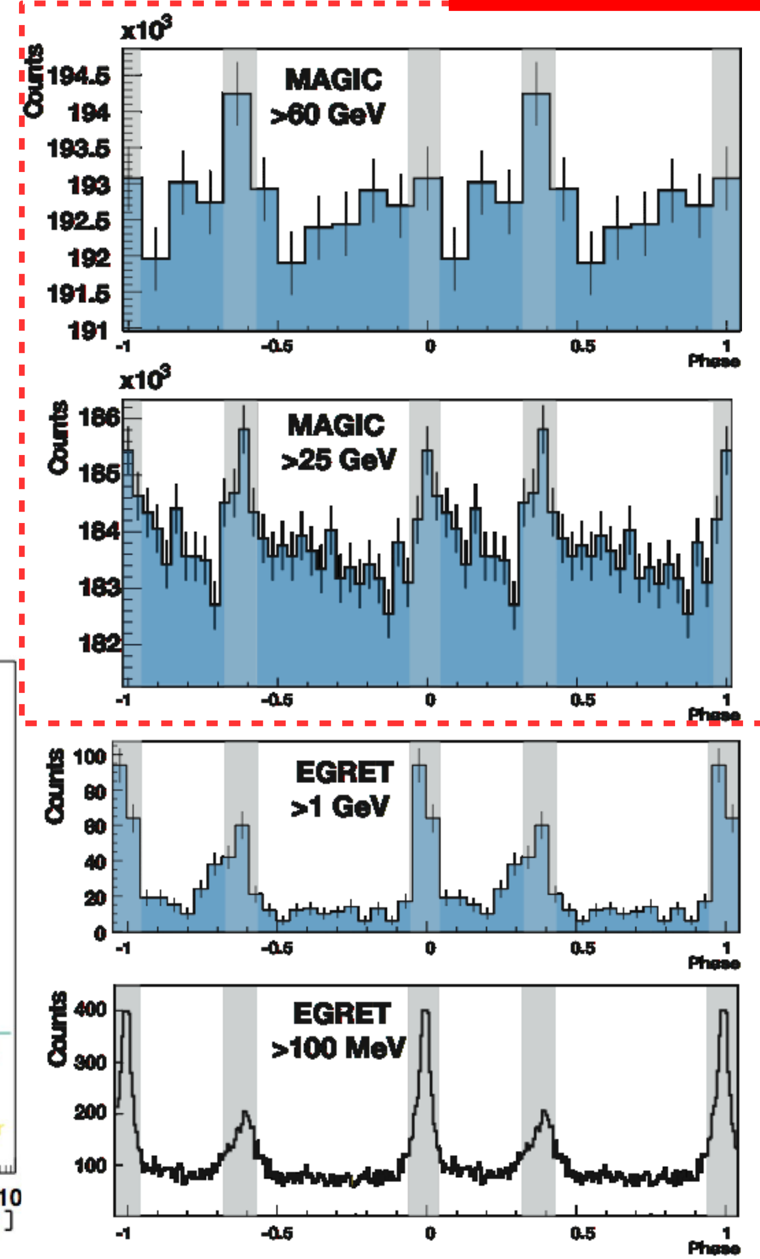
$$F(E) = A \cdot E^{-\alpha} \cdot \exp\left(E/E_0\right)^{\beta}$$

$\alpha = 2$ (fixed parameter)

$\beta = 1$	17.7
$\beta = 2$	23.2
$\beta = 1.2$	20.4

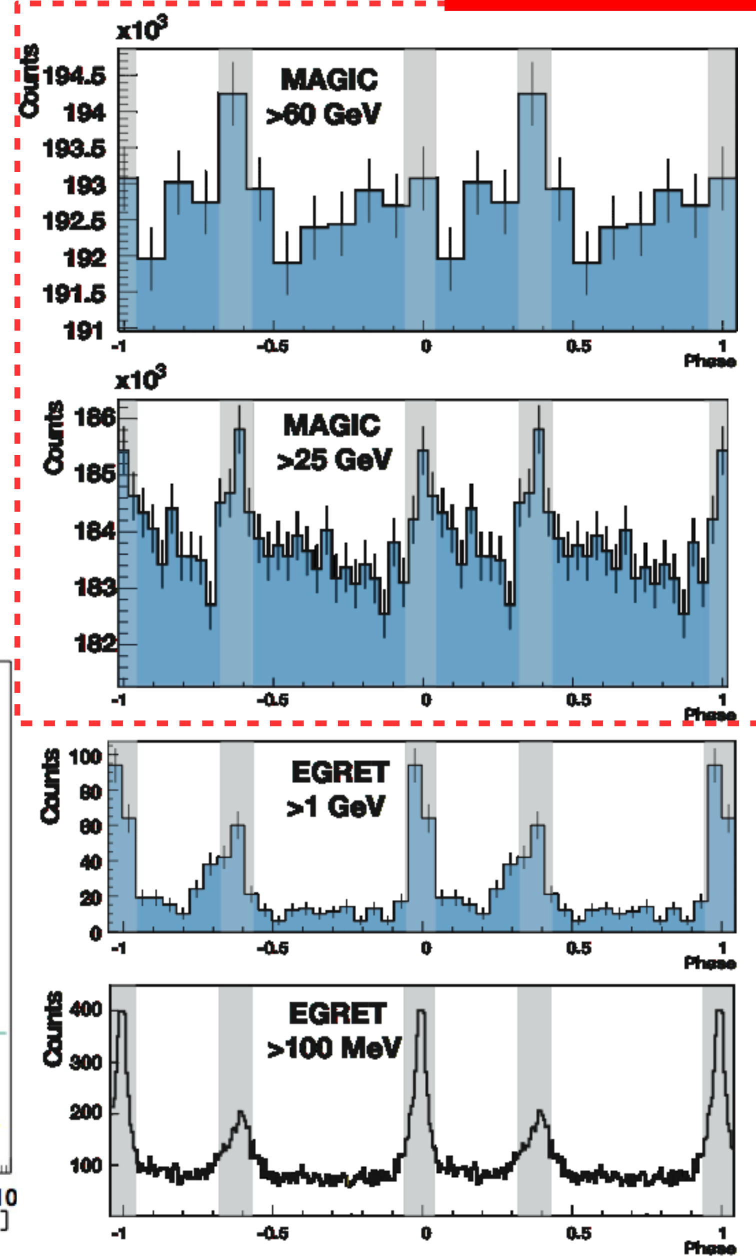
$\beta = 1$ (exponential cutoff)





Detection of Crab Pulsar above 25 GeV

NEW light curves !



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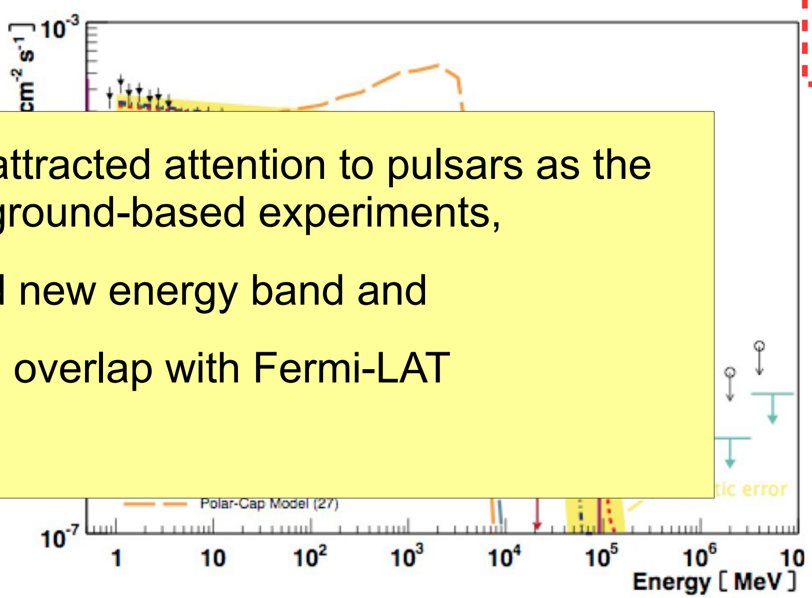
$\alpha = 2$ (fixed parameter)

β



This detection (re)attracted attention to pulsars as the targets for ground-based experiments,

Opened new energy band and

Provided overlap with Fermi-LAT

Pulsars in VHE: current status

Energy band	Number of Pulsars
Radio	~2000
Fermi, > 100 MeV	~150
Fermi, >25 GeV	13
IACTs, > 50 GeV	**Crab, Vela**

Only two pulsars are detected above 50 GeV:

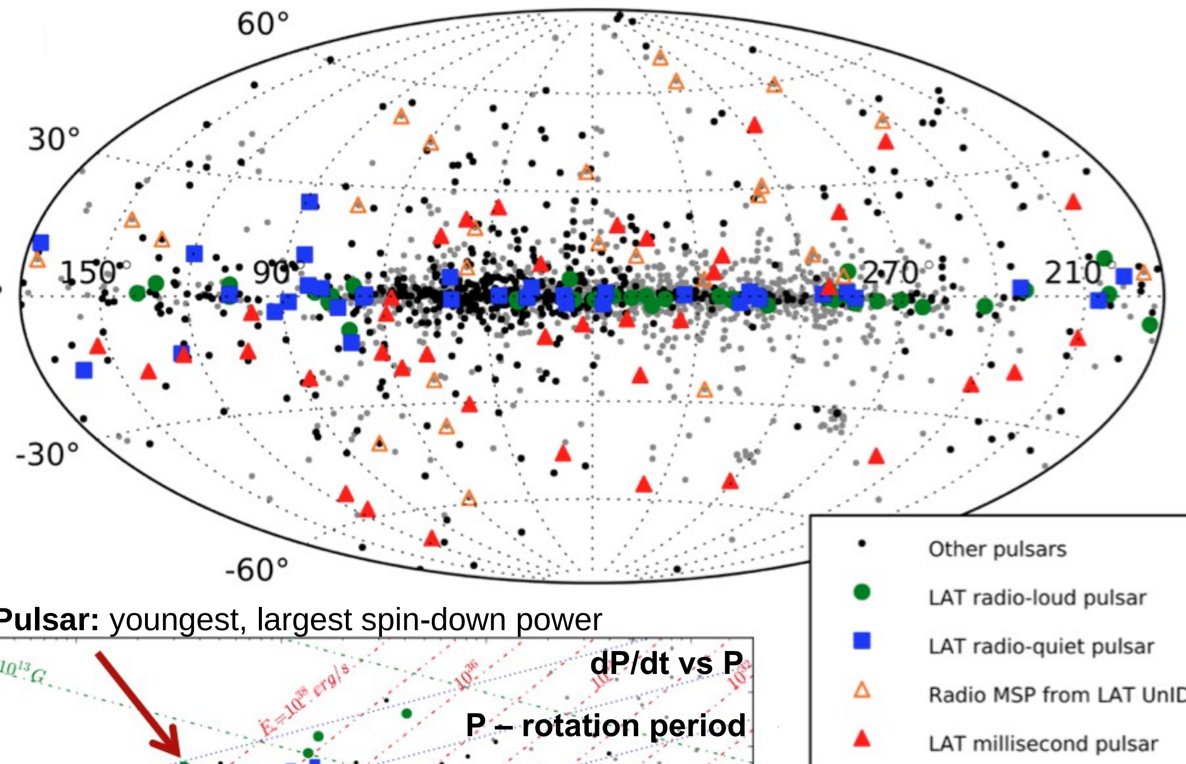
=> Fermi-LAT lacks statistics above 20-30 GeV.

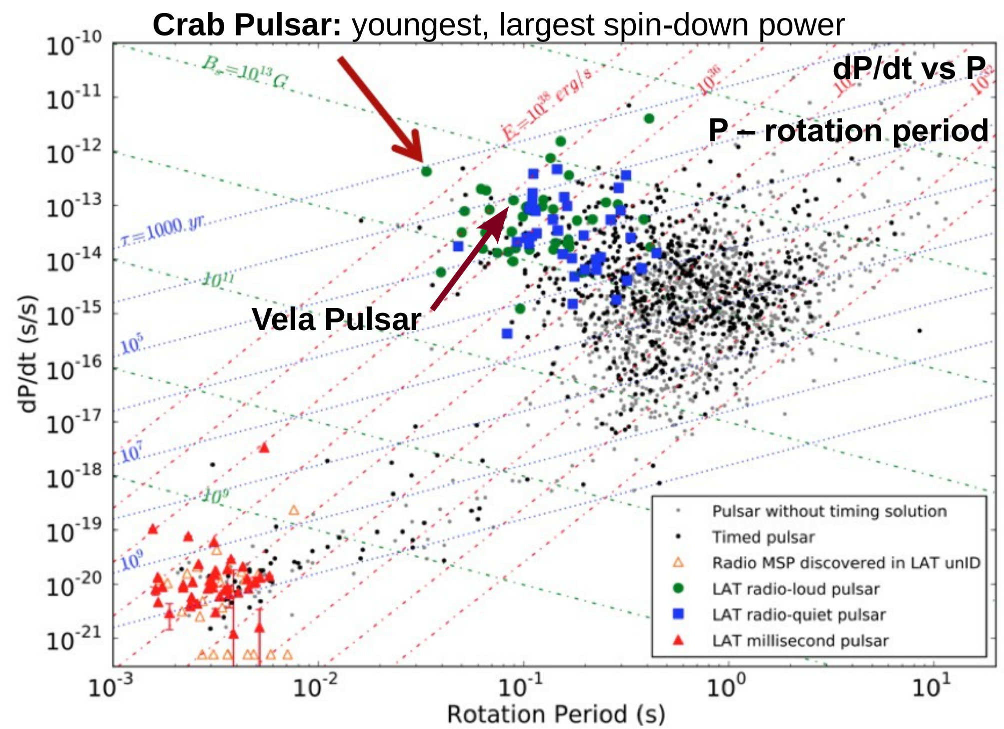
Spin-down power due to magnetic dipole radiation:

$$\dot{E} = \frac{d}{dt}\left(\frac{1}{2} I\Omega\right) = I\Omega\dot{\Omega} = \frac{2}{3c^3} |m_B|^2 \, \Omega^4 \sin^2 \alpha$$

α - the angle between the rotation and magnetic axis

Fermi 2[nd] catalogue



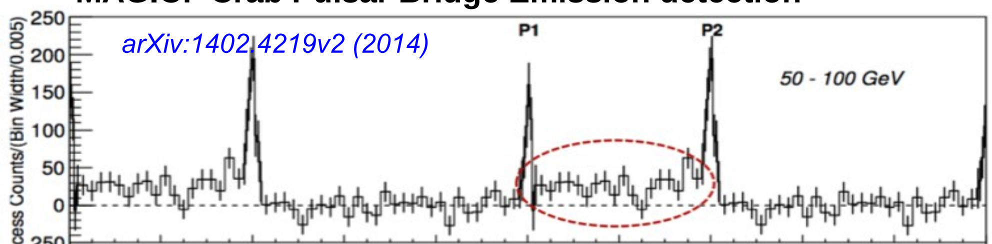


Pulsars in VHE: current status

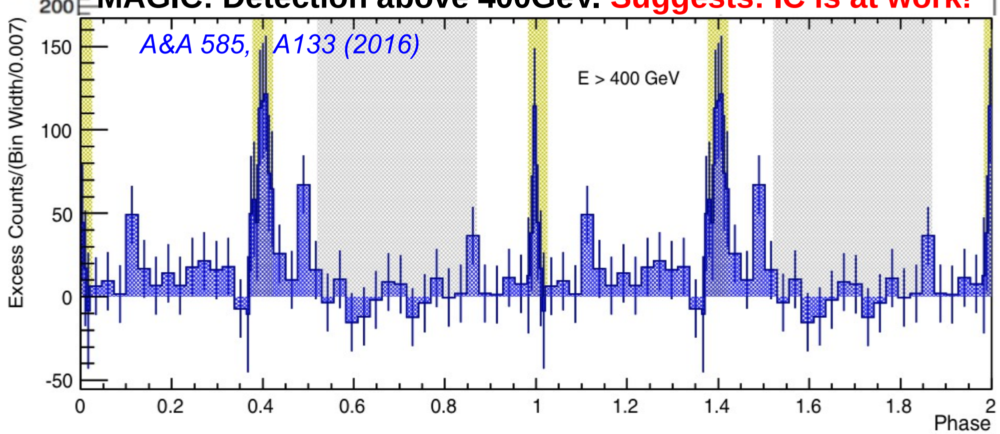
Energy band	Number of Pulsars
Radio	~2000
Fermi, > 100 MeV	~150
Fermi, >25 GeV	13
IACTs, > 50 GeV	Crab, Vela

Pulsar observations in VHE bring an important input to constrain pulsar models. More and more details learned:

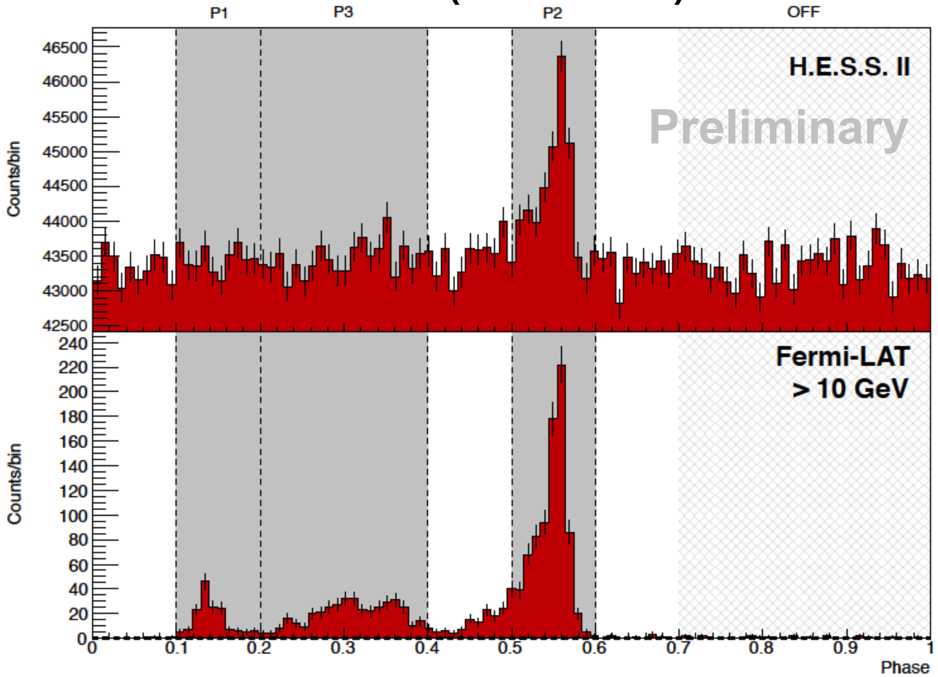
MAGIC: Crab Pulsar Bridge Emission detection



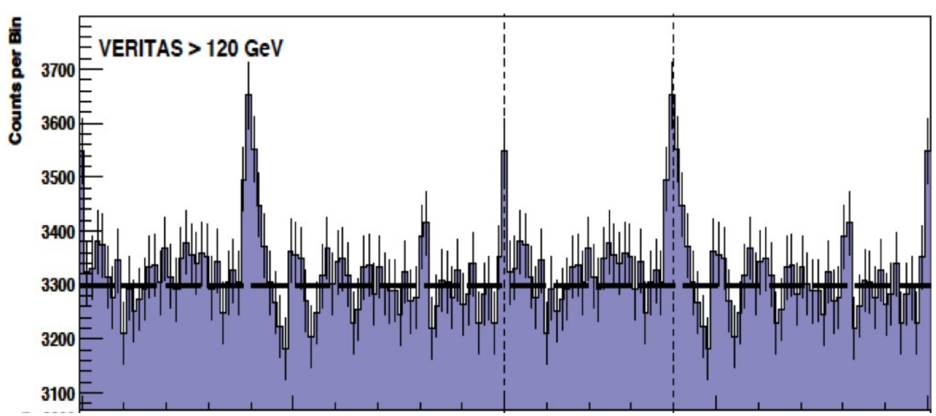
MAGIC: Detection above 400GeV. Suggests: IC is at work!



H.E.S.S. II Vela Pulsar (PSR B0835-45)



VERITAS Crab Pulsar (PSR B0531+21)

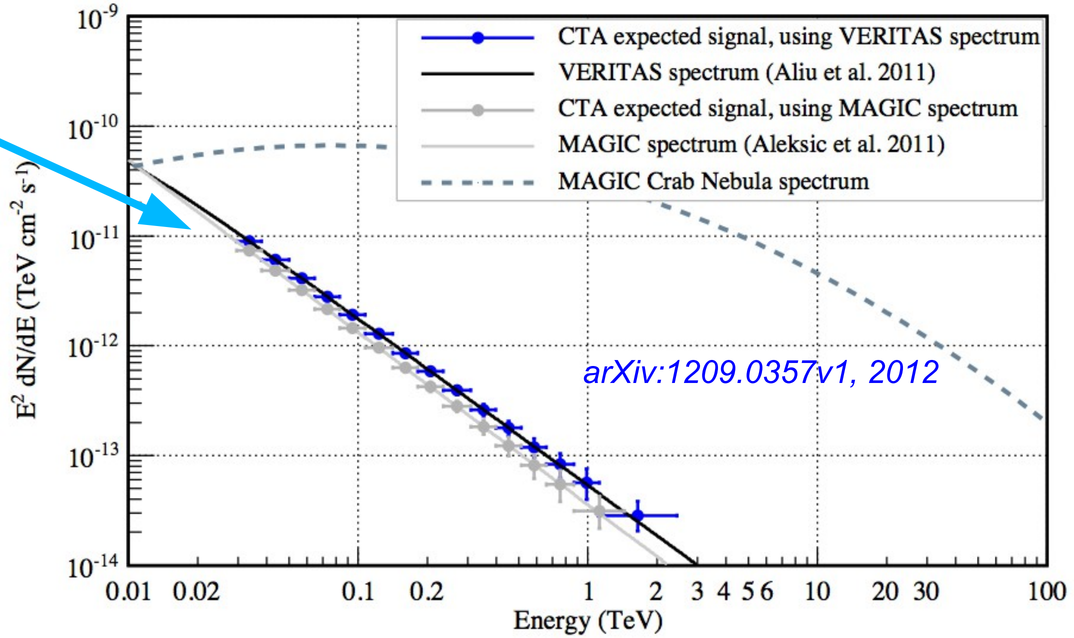


Prospects for CTA

Given the high sensitivity of CTA:

1. CTA will perform precise measurement of VHE pulsed emission >30 GeV for power-law “cut-off” scenarios
2. CTA will extend and complement Fermi-LAT and current IACTs (1/10 of the CTA sensitivity) for exponential cut-offs
3. CTA low energy sensitivity starts to significantly cover the energy domain of Fermi VHE pulsars

Simulated(!) Crab Pulsar spectrum “measured” by CTA



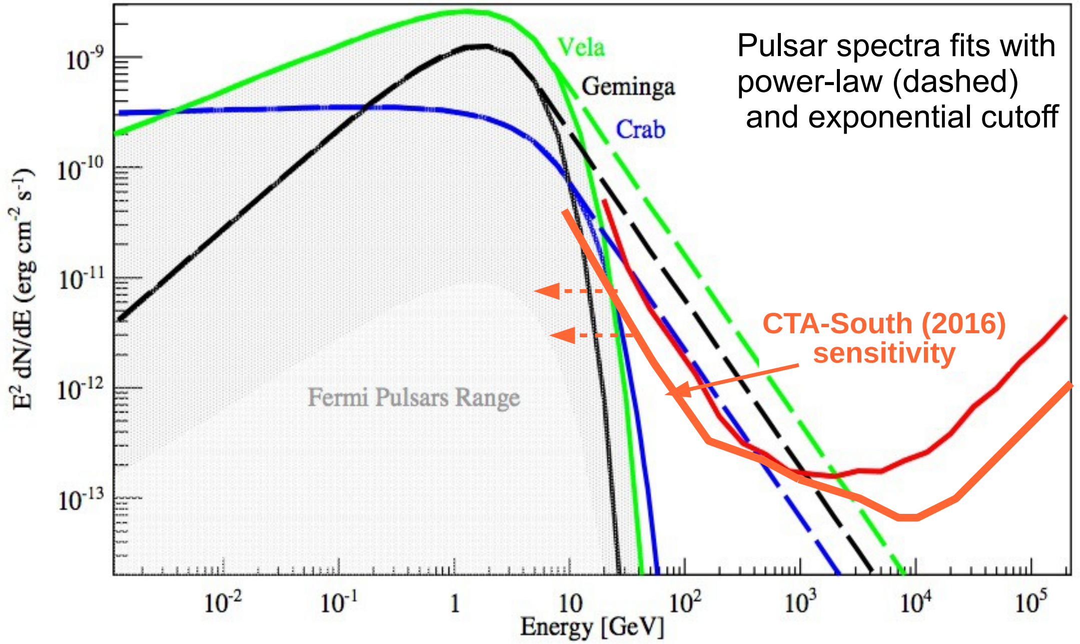
Again (like in SNR case):

An effort must be put into improving CTA low energy sensitivity to increase the scientific outcome.

High energies: Sensitivity is statistically limited => larger arrays

Low energies: Sensitivity is limited by γ/background separation and NSB =>

Optimizations of trigger (i.e lowering threshold) and readout are required



NectarCAM integration at Irfu

NectarCAM to optimize CTA performance

NectarCAM:

Designed to provide **the balanced CTA sensitivity in both low and high gamma-ray energy domains.**

Integration hall at CEA-Irfu:

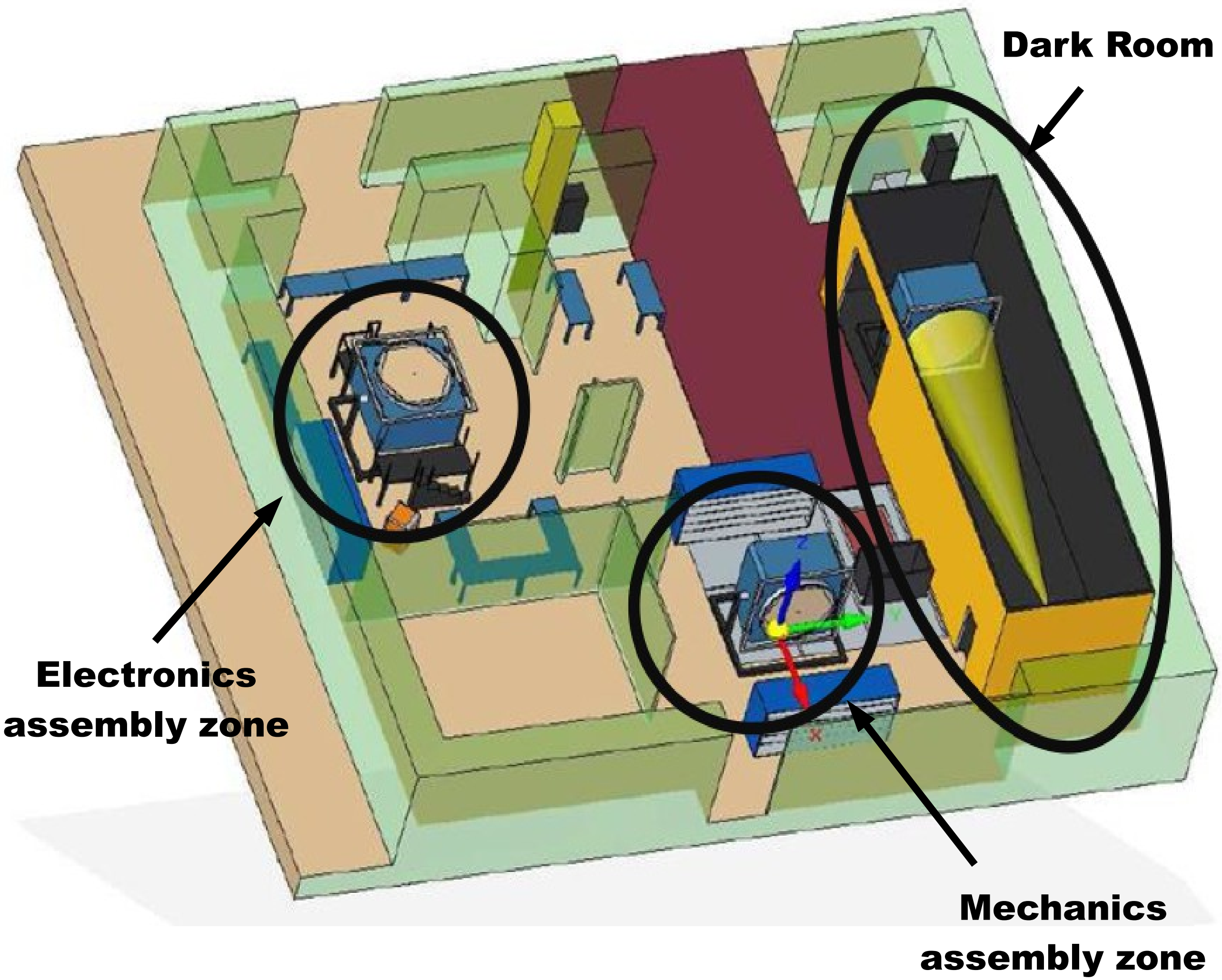
1. 19-modules demonstrator (7x19 channels)

2. Integration of full-scale MST camera prototype

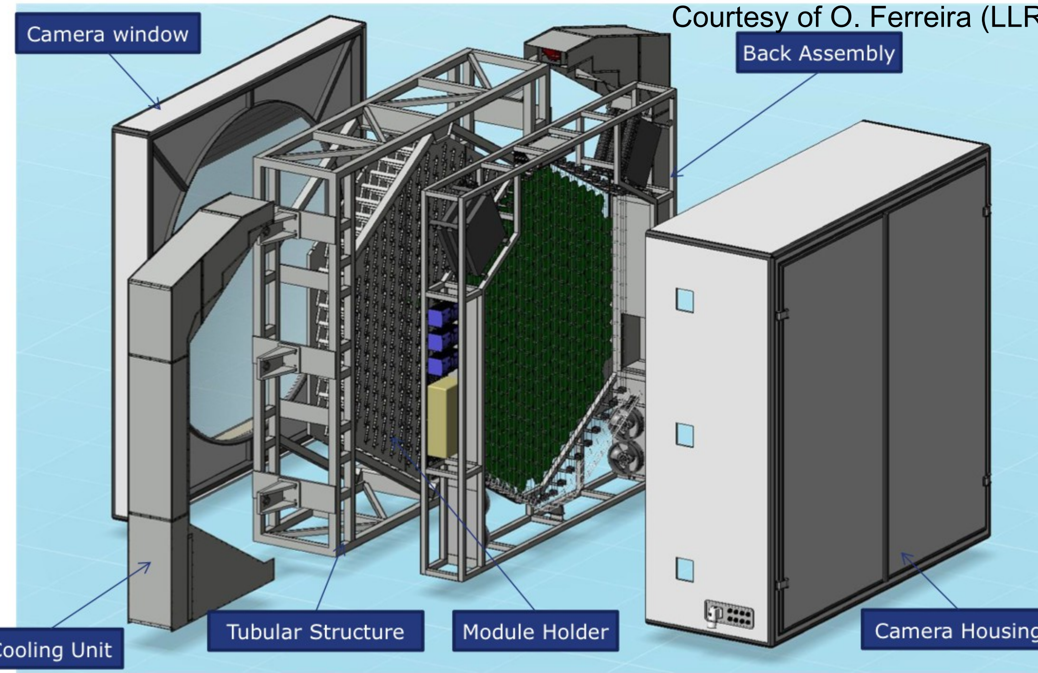
Prototype will be deployed in the dark room.

Trigger and DAQ tests will be performed

NectarCAM Integration site. Courtesy of F. Louis (Irfu)



NectarCAM integration at CEA-Irfu

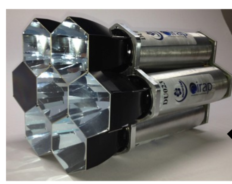


Full-scale NectarCAM:

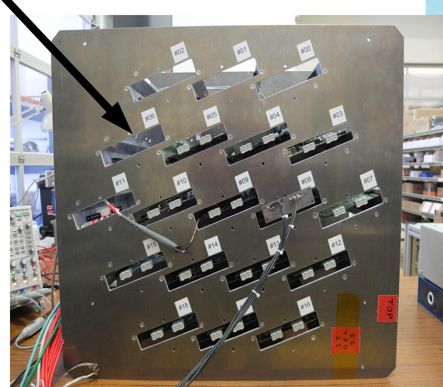
- Integration of full-scale camera prototype (1855 channels) will be performed in the dark room at CEA-Irfu.

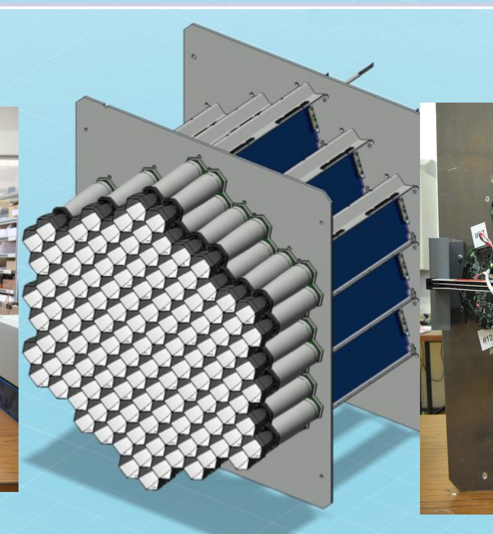
19-drawers camera demonstrator:

1-drawer: 7 channels

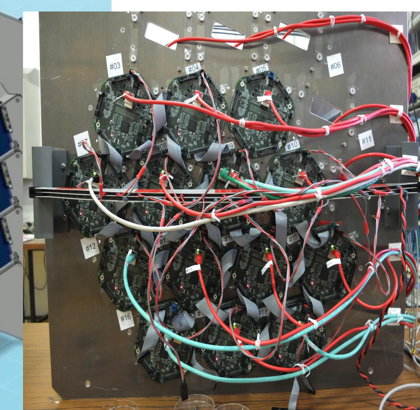


Focal plane





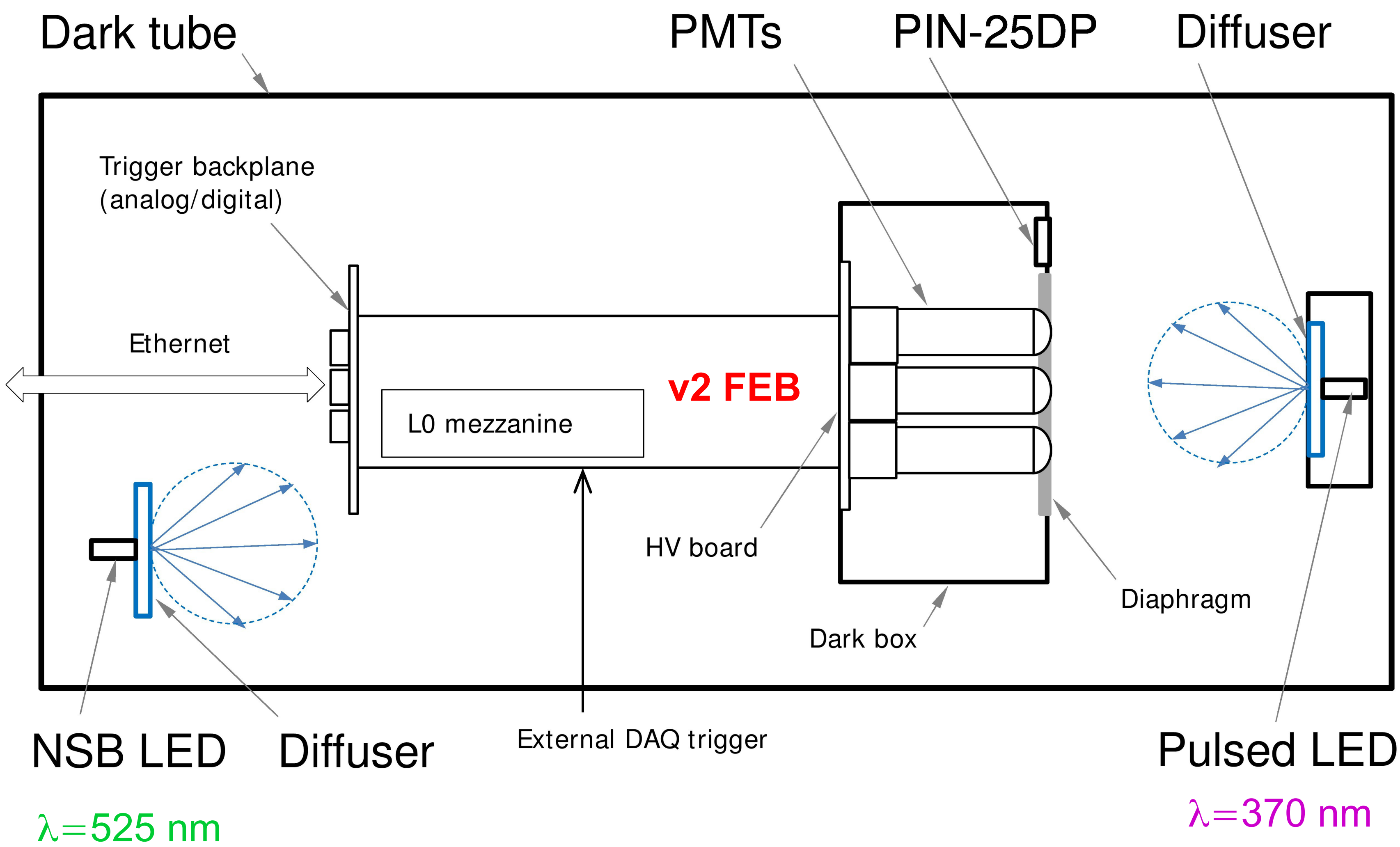
Backplane



Comprehensive tests:

1. Trigger with two options (digital and analog)
2. Readout
3. Camera control, etc...

Single drawer optical test



Single drawer optical test: single p.e. spectra

Conversion to p.e. (peak) :

FADC/p.e. (5ns) = 58 cnts/p.e.

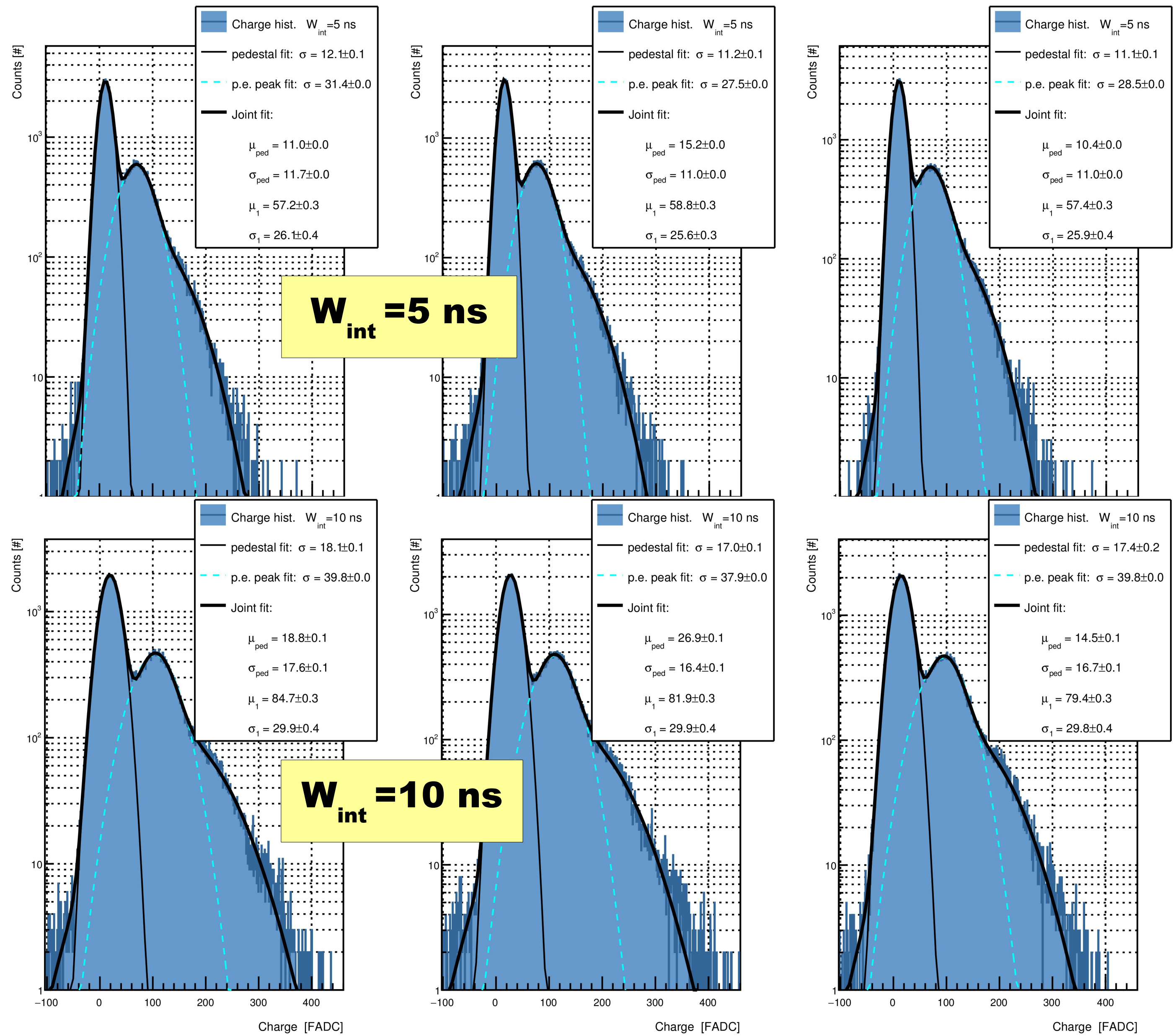
FADC/p.e.(10ns) = 82 cnts/p.e.

FADC/p.e.(16ns) = 90 cnts/p.e.

Pedestal noise(<16ns): < 0.25 p.e. for all channels

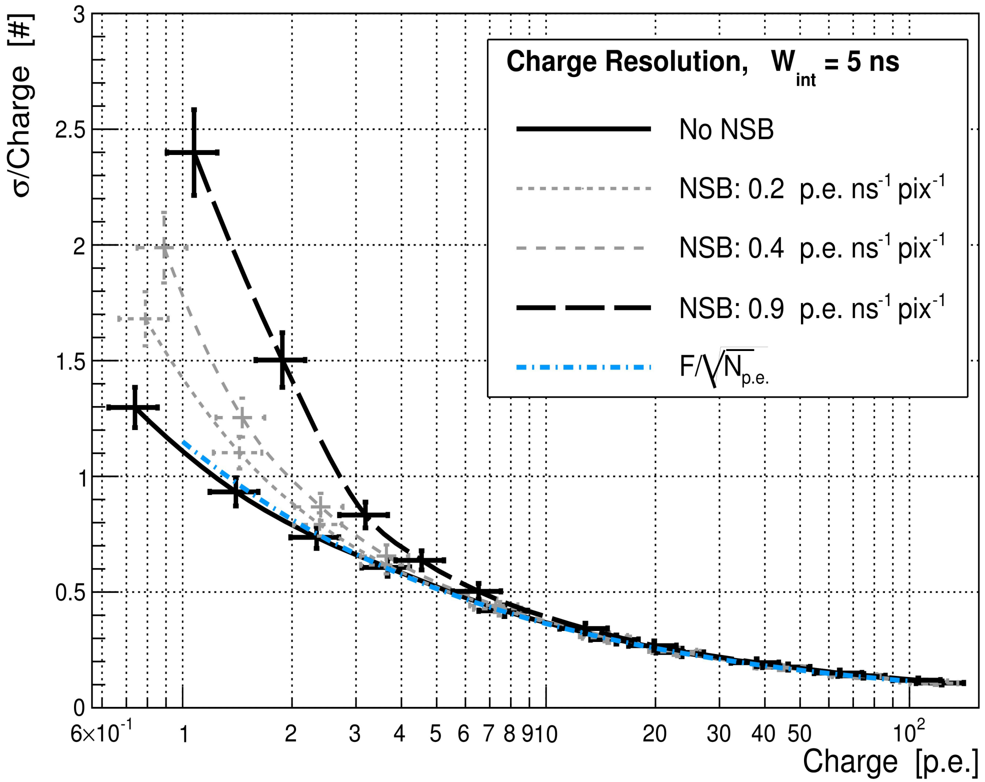
Noise (RMS over 1ns): ~7 cnts (might be improved by better grounding)

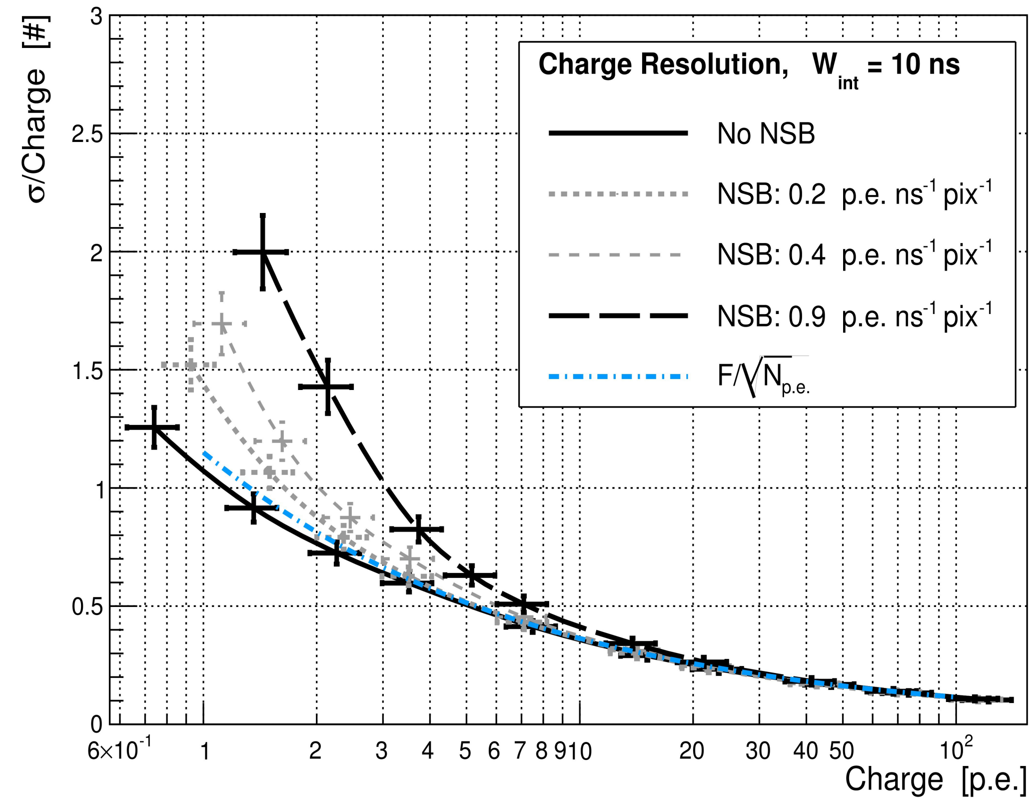
FADC/p.e.(Ampl) ~ 21 cnts/p.e.



Single drawer optical test

Charge resolution:



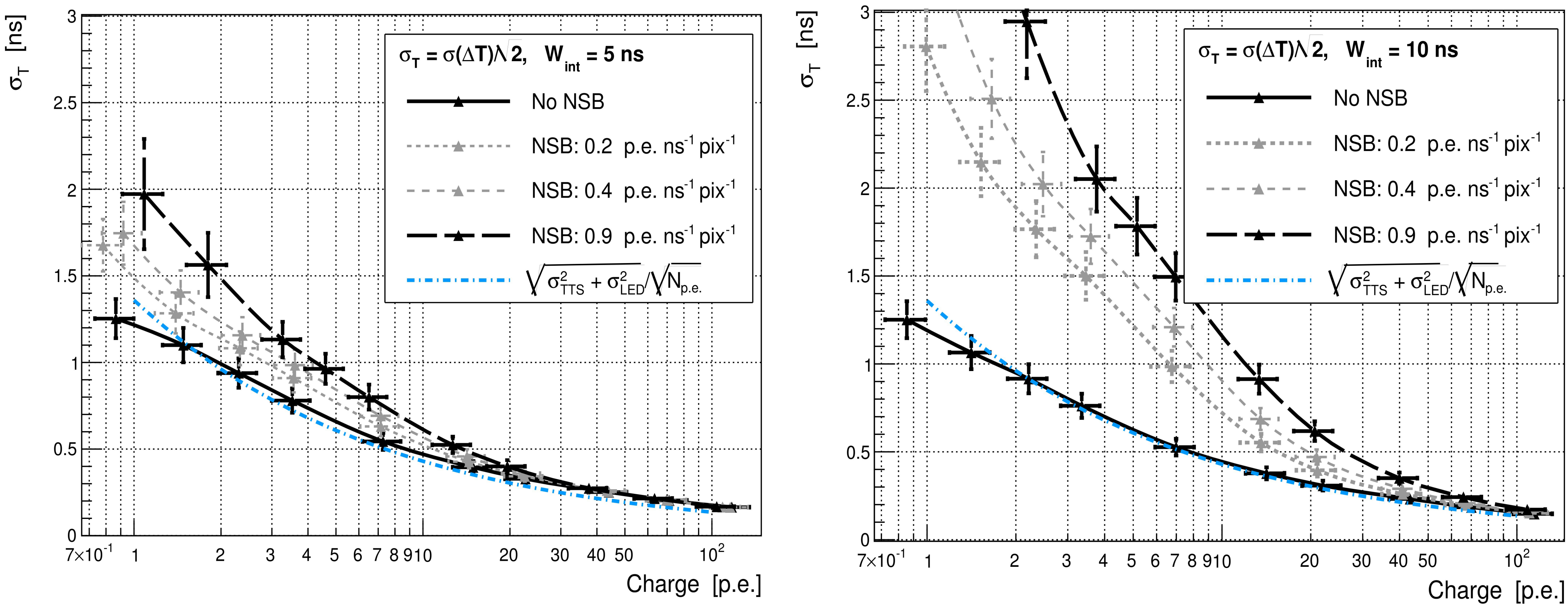


Blue curve is the physical limit for the setup used: **σ/Charge = F/ sqrt($N_{p.e.}$),**

F ~1.15 is the excess noise factor of R11920-100 at 40k gain

Single drawer optical test

Time resolution:



Blue curve is the physical limit for the setup used: $\sigma_T = \mathrm{sqrt}(\sigma^2_{TTS} + \sigma^2_{LED}) / \mathrm{sqrt}(N_{p.e.})$,

σ_{TTS} - PMT transit time spread, σ_{LED} - pulsed LED intrinsic time spread (estimated on Slide 16)

Many tests performed:

L1 trigger mezzanines:

1. Calibration of discriminators.
2. Amplitude flat-fielding (att. at L0-mez.)

L0 trigger mezzanines:

1. Calibration of discriminators
2. Time flat-fielding

PPS/trigger distribution:

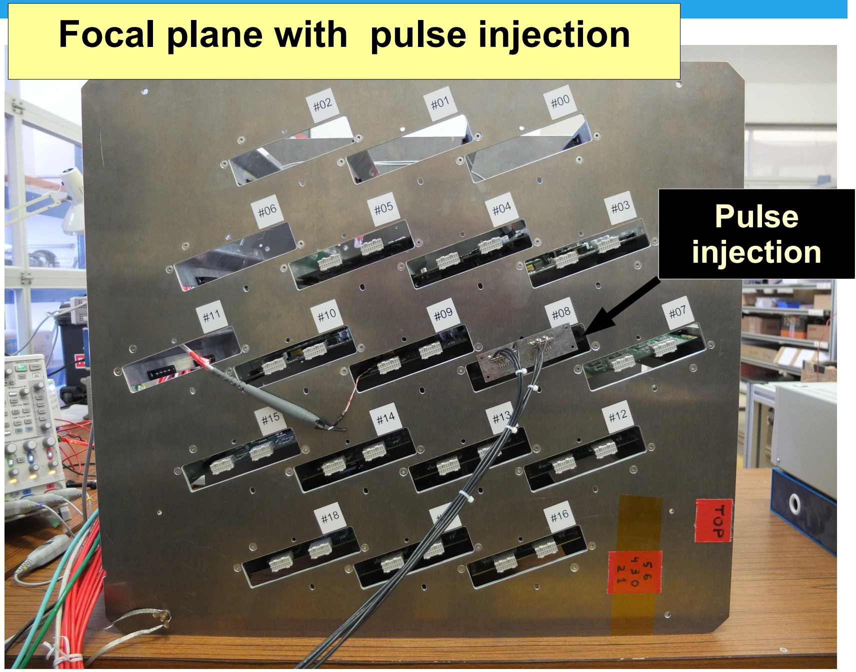
1. PPS time flat-fielding (PPS from TIB)
2. L1 daisy chain configuration
3. L1 time flat-fielding

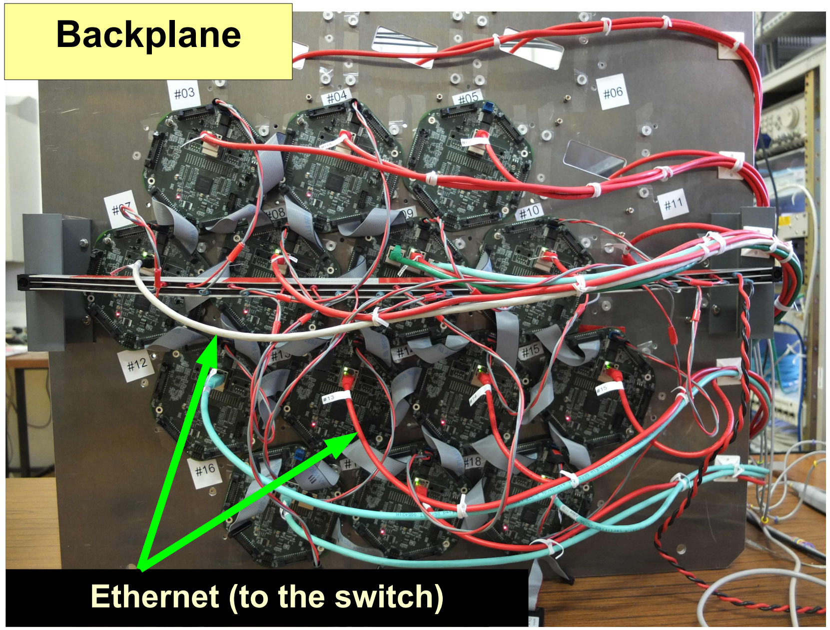
Burst trigger test:

1. Event buffering demonstration

Random trigger readout test:

1. Dead-time measurement with the Poisson event rate





Poisson trigger test

Readout Rate:

Testing the readout of the NectarCAM readout chain:

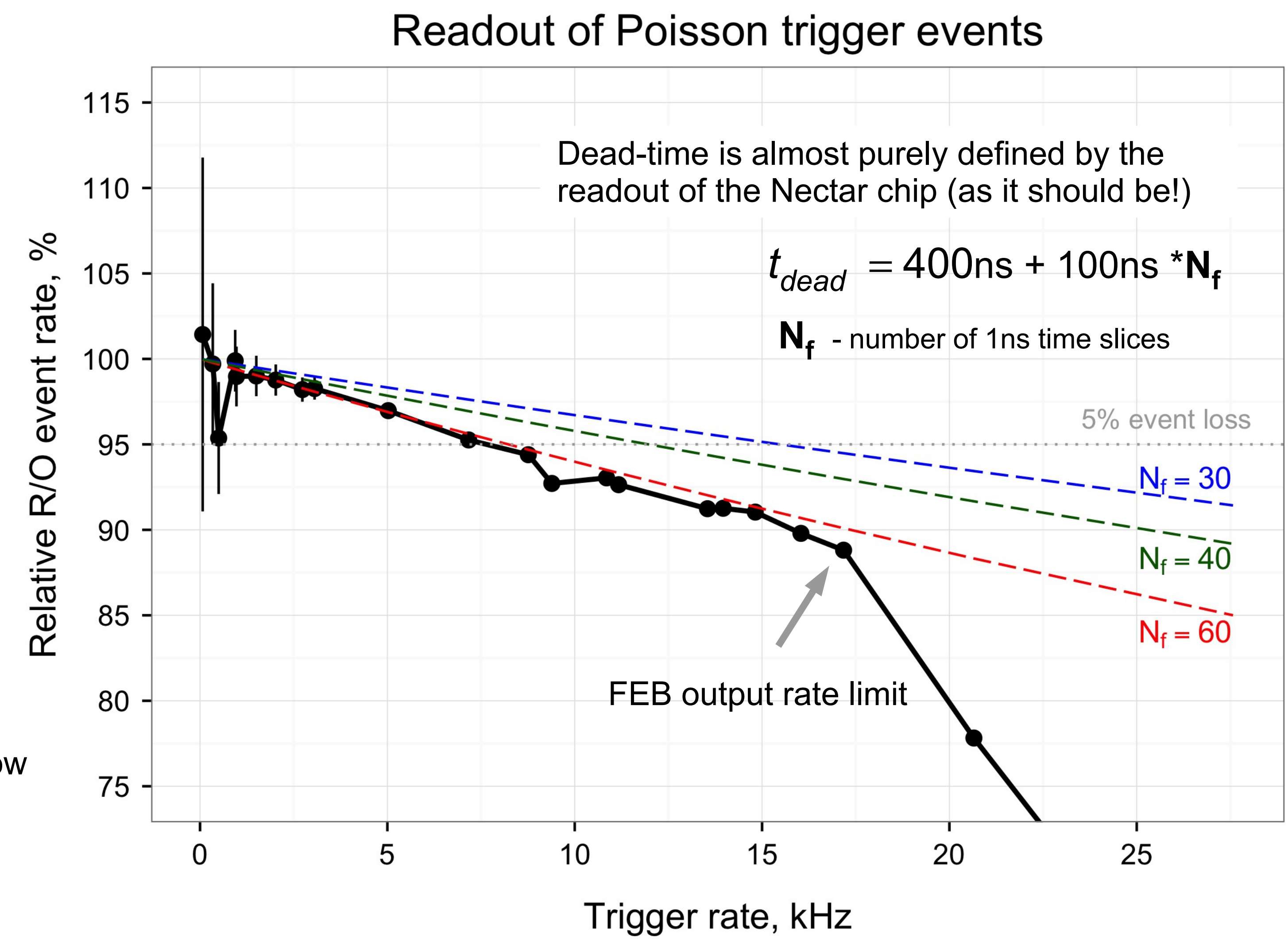
1. 12-drawers mini-camera is triggered with Poisson signals

2. Readout with Event Builder with $\mathbf{N_f}$**=60** slices.

3. Trigger rate is measured independently with two counters

Results:

For $\mathbf{N_f}$**=40** the event loss is below 5% for trigger rates up to 12 kHz (fullfills the CTA requirements)



Summary

Single drawer:

- Optical tests: NectarCAM electronics chain fulfills CTA requirements for time and charge resolution

19 modules demonstrator: (currently 12)

- L1/L0 mezzanines: discriminators calibrated and analog signal are flat-fielded in amplitude
- Analog Sum trigger: PPS/L1 distribution through daisy chain is done for 12 drawers
- Events recording with Event Builder and storage in ZFits format.
- Dead time of the current version of NectarCAM allows to fulfill 5% event loss limit up to 12.5 kHz. Reading out of 40 slices does not affect the CTA performance.
- Ready for optical tests in the dark room (given the components delivery to Irfu)

(Near)Future plans:

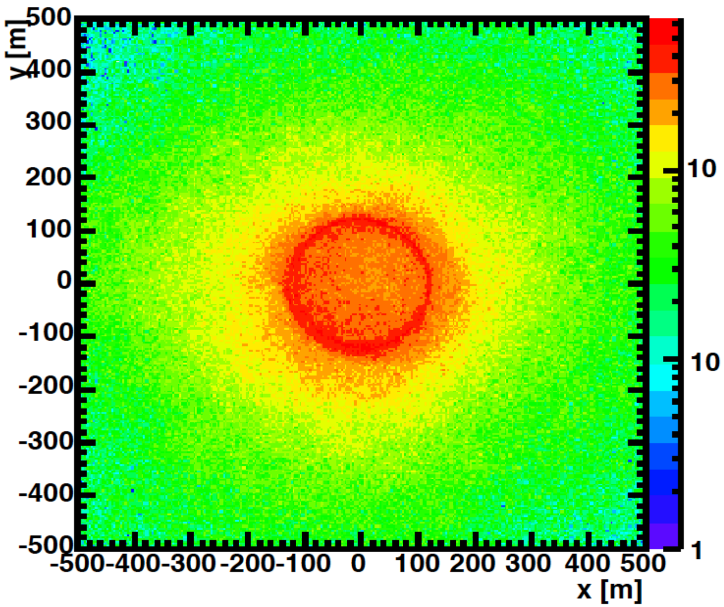
- Digital (DESY) trigger tests (this week:)).
- First optical tests of fully equipped drawer (with DUs and IRAP HV interface board)

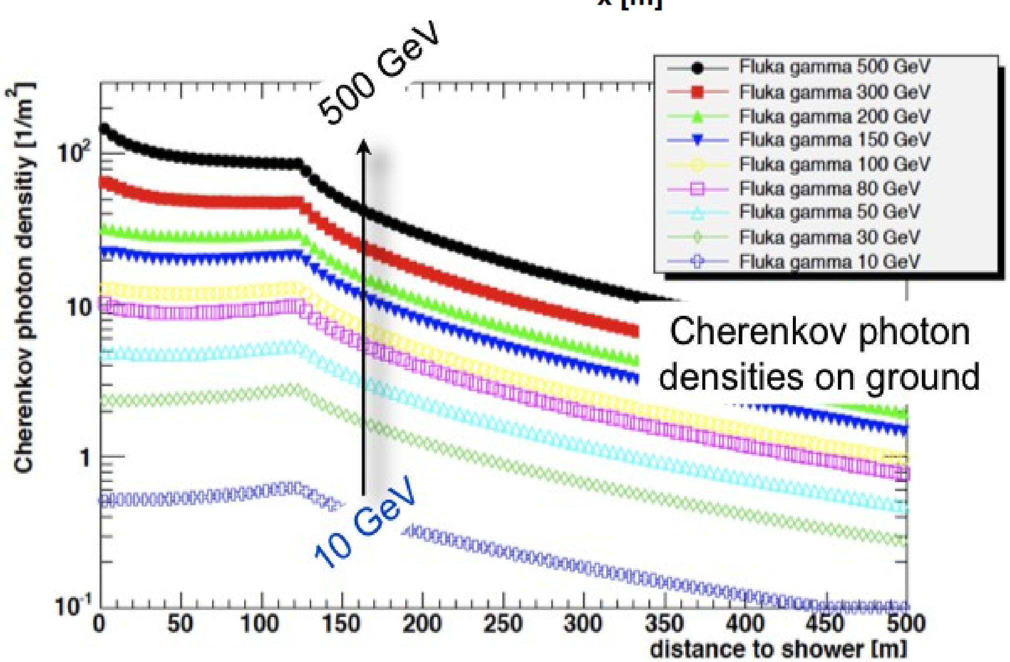
NectarCAM in on the right track to provide the best CTA performance!

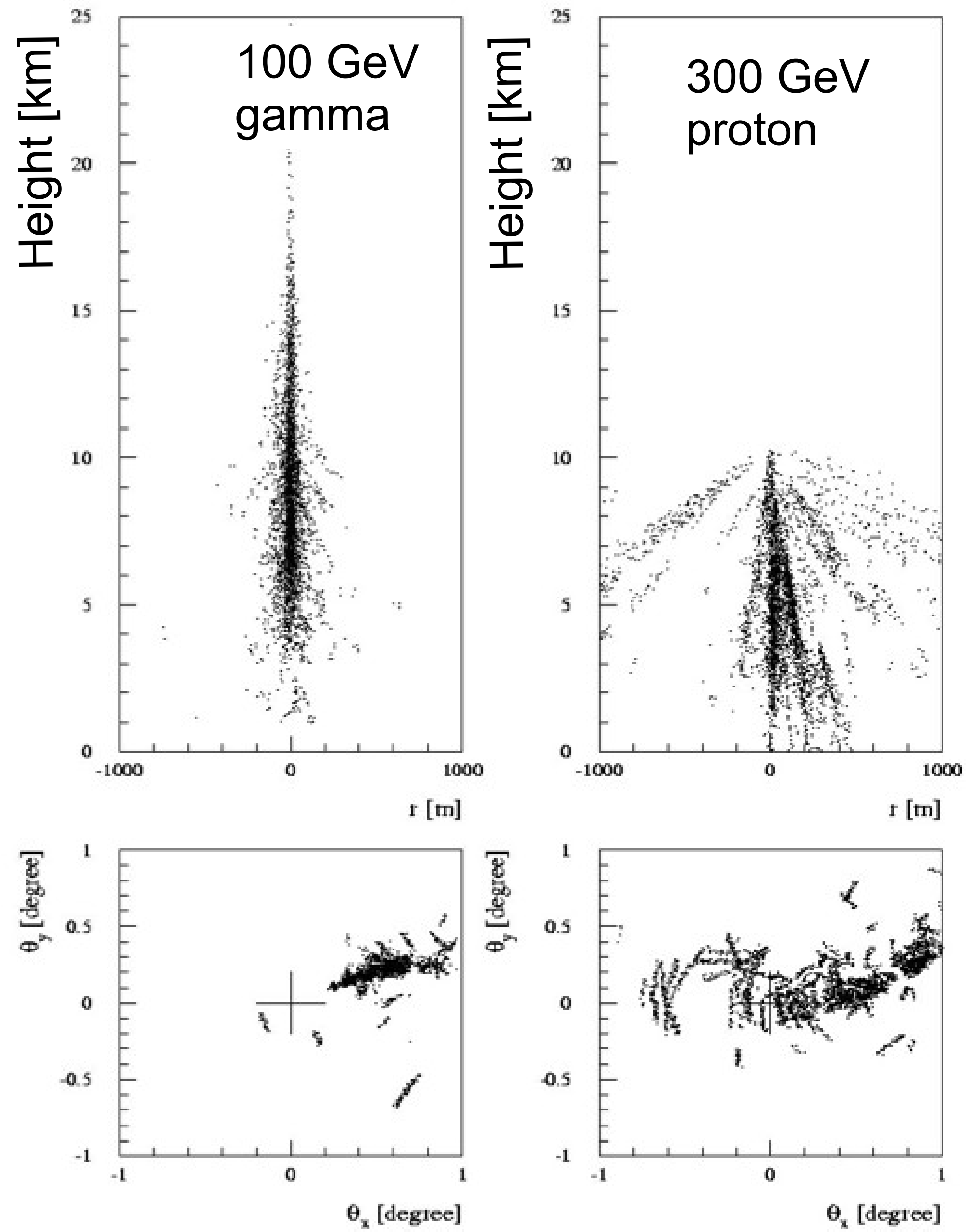
Thank you for your attention

Back-up: Imaging Cherenkov telescope technique

Cherenkov light Intensity distribution on ground







Back-up: Imaging Cherenkov telescope technique

Secondary particles detected through Cherenkov light=>should not necessarily reach ground=>low detection threshold

Rate of γ-rays ~1000 times smaller compared to hadron rate
=> very effective methods of gamma/hadron separation are needed.

Hadron-induced showers:

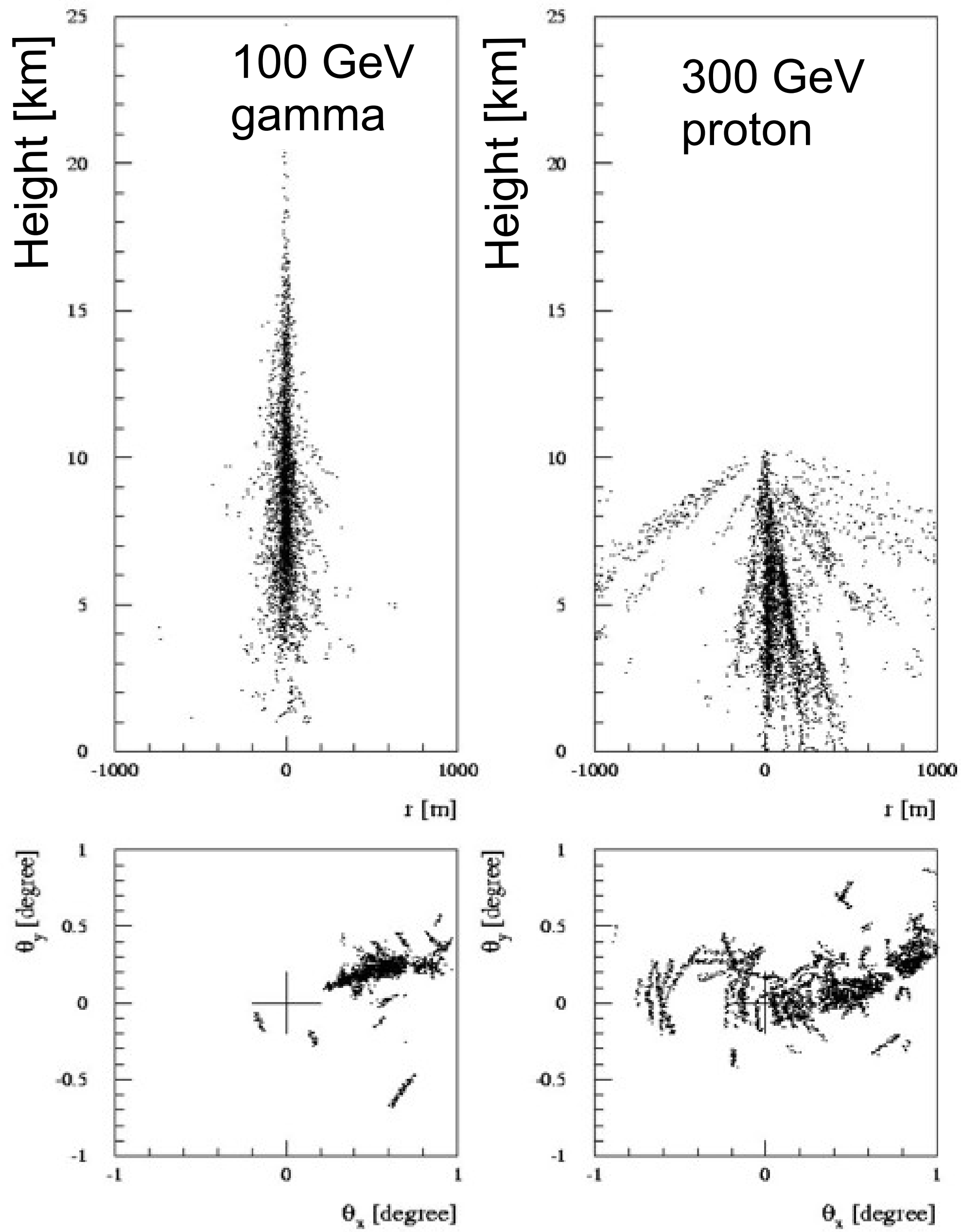
1. Larger transverse momentums.
   Wider angular spread of secondary particles

2. Higher intrinsic particle density fluctuations.

3. Sub-showers.

4. Muon component.

etc..



Back-up: SNR modeling

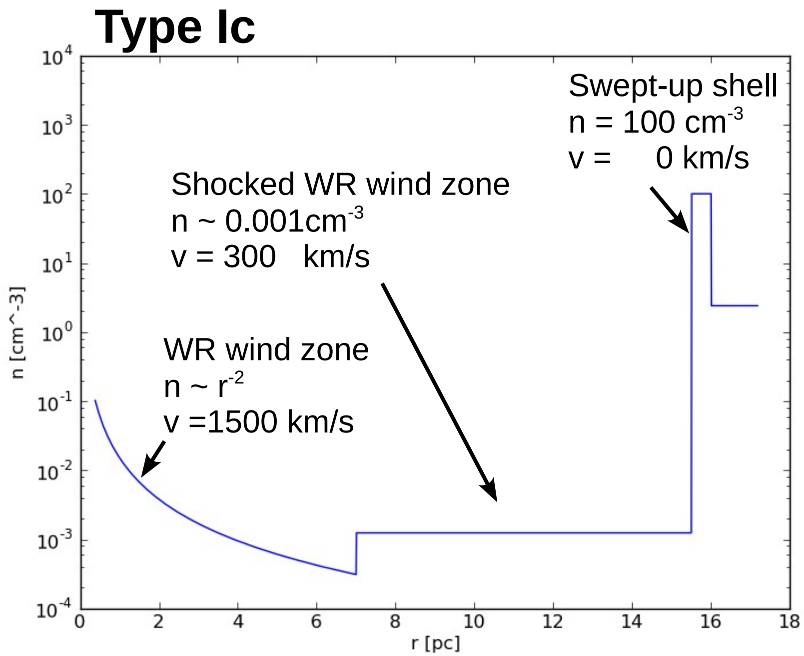
- **SNR models:**
  - Early SNR evolution and detailed hydro-dynamics is taken into account. No „generic“ Sedov-like explosion.
  - Complex ISM density profiles **before explosion** are assumed.
  - Acceleration in the reverse shock (RS) is considered
  - Test-Particle approach.
  - VHE emission from pion-decay (PD) and inverse Compton (IC):

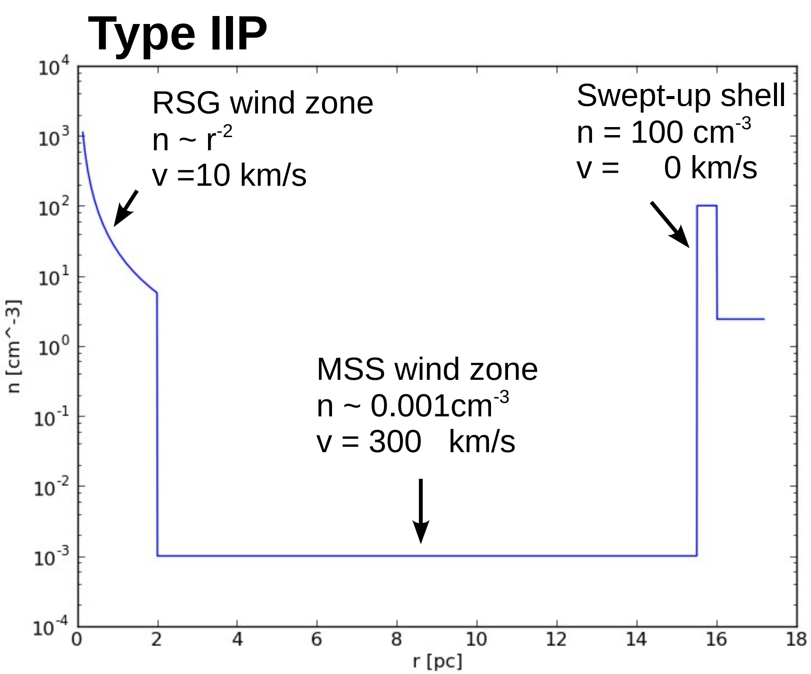
PD: $\sim n_{CR}(r,E,t) \times n_{p/He}(r,t)$

IC: $\sim n_{CR}(r,E,t)$ (IC on CMB)

For models details see:

I.Telezhinsky, V.Dwarkadas, M.Pohl APh 35, 300 (2012)
I.Telezhinsky, V.Dwarkadas, M.Pohl A&A 552, A102 (2013)

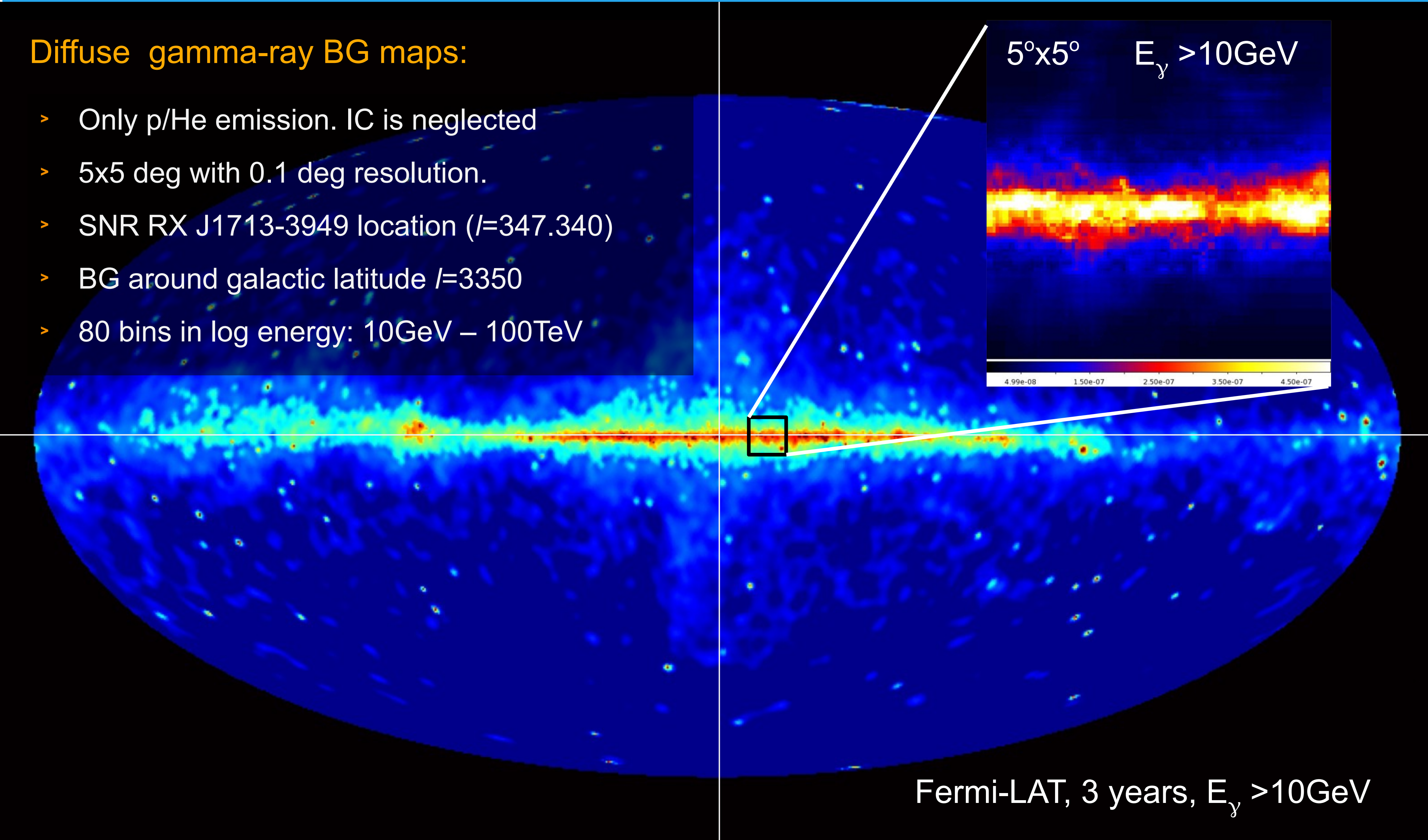




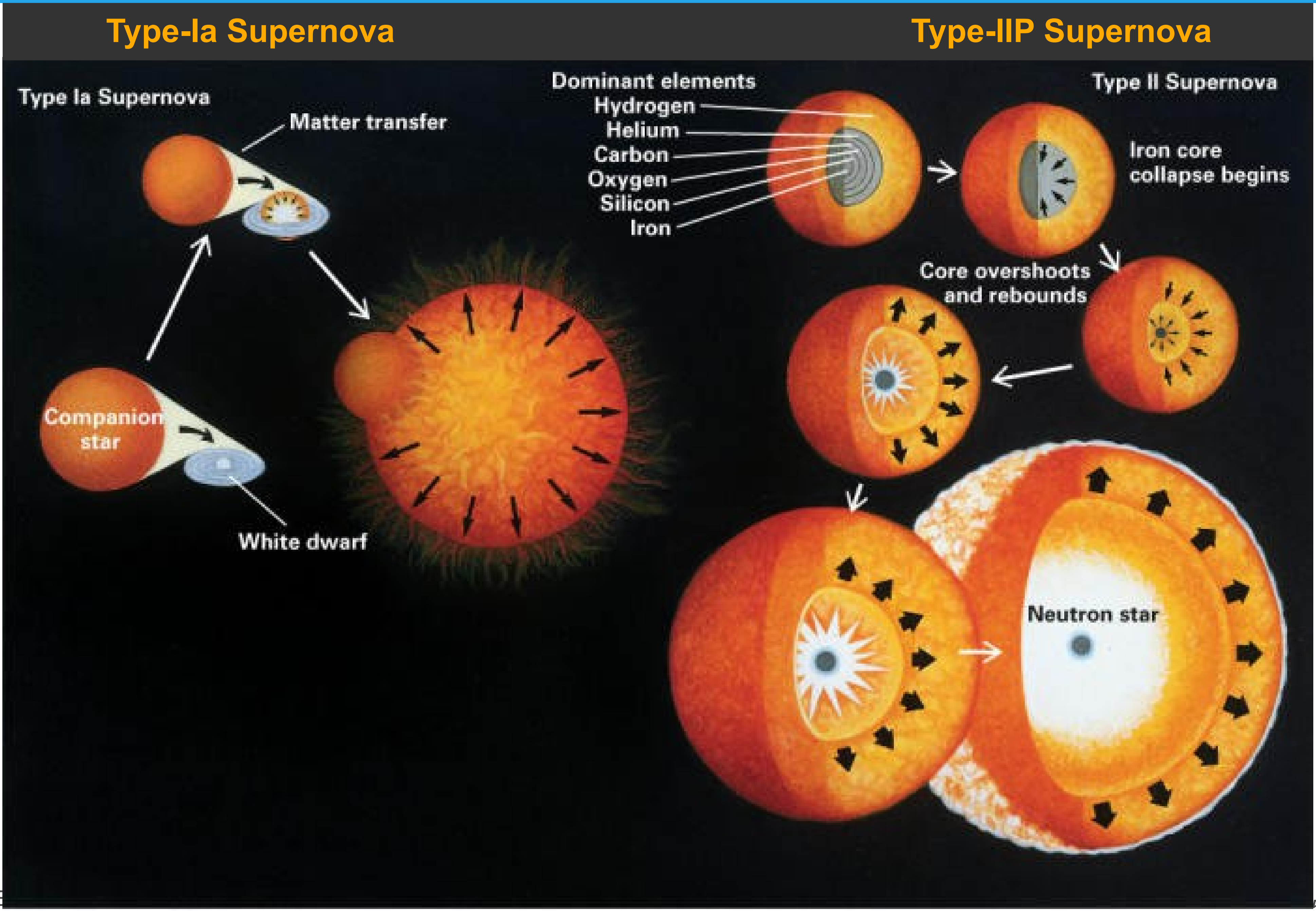
Back-up: Structured gamma-ray background

Diffuse gamma-ray BG maps:

- Only p/He emission. IC is neglected
- 5x5 deg with 0.1 deg resolution.
- SNR RX J1713-3949 location (*l*=347.340)
- BG around galactic latitude *l*=3350
- 80 bins in log energy: 10GeV – 100TeV



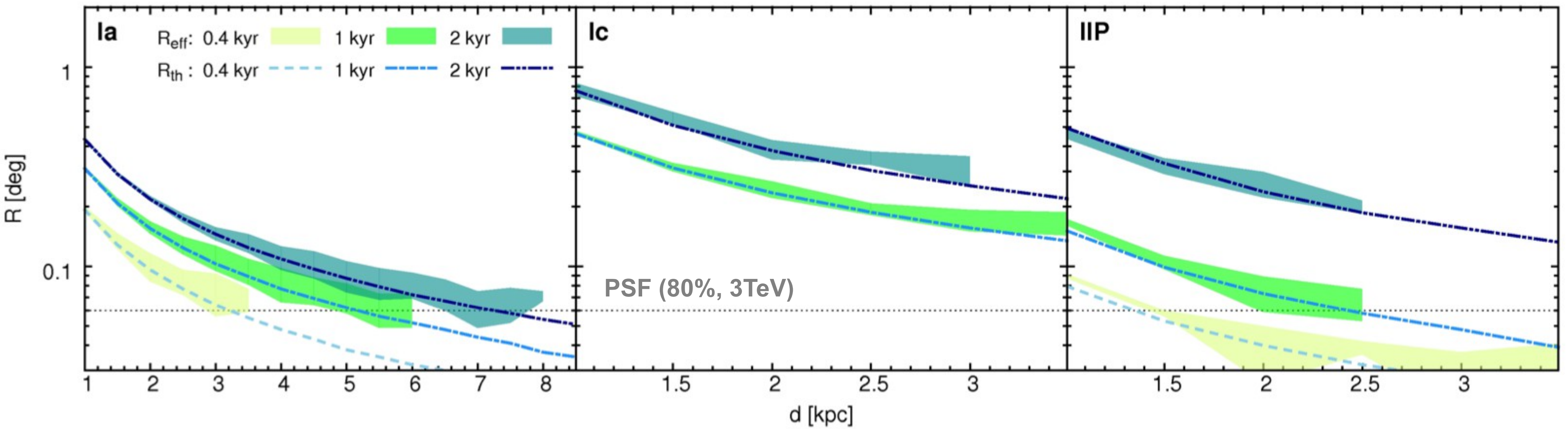
Back-up: SNR progenitors



Courtesy of Encyclopaedia Britannica, Inc.; from the 1989 Britannica Yearbook of Science and the Future; illustration by Jane Meredith

Backup: Reconstructed effective radii

Type-Ia Type-Ic Type-IIP



- SNR radii are reasonably reconstructed up to resolvability horizons
- Additional important parameter for multi-wavelength studies

age: 400 1000 2000

r(Ia): 3.6 5.7 7.9

r(Ic): 4.3 8.7 14.0

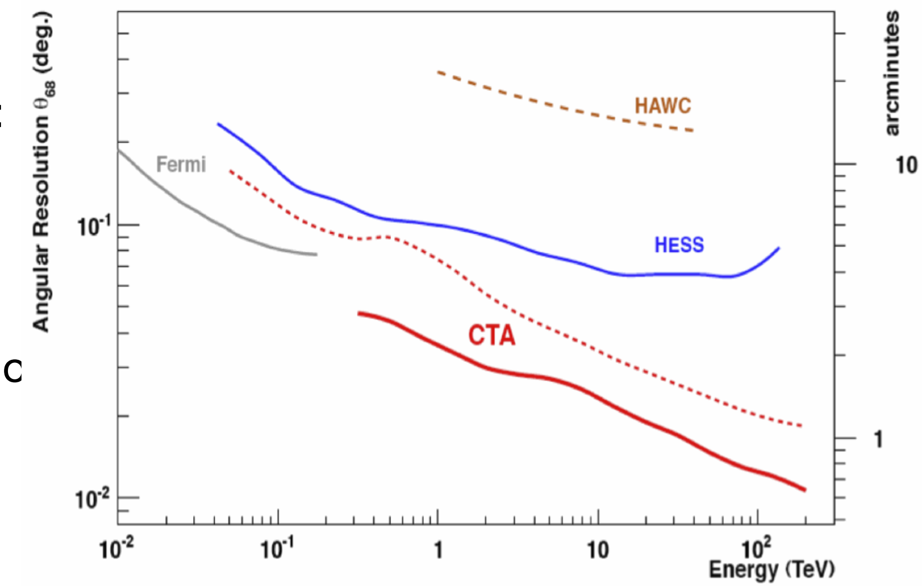
r(2p):1.4 4.1 8.5

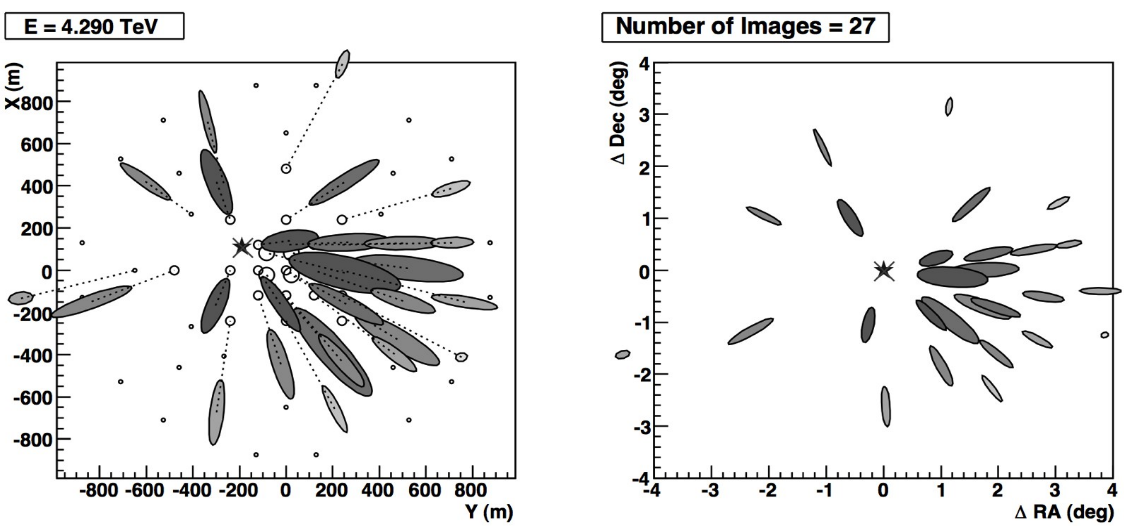
Backup: CTA angular resolution

Enhanced angular resolution together with high sensitivity:

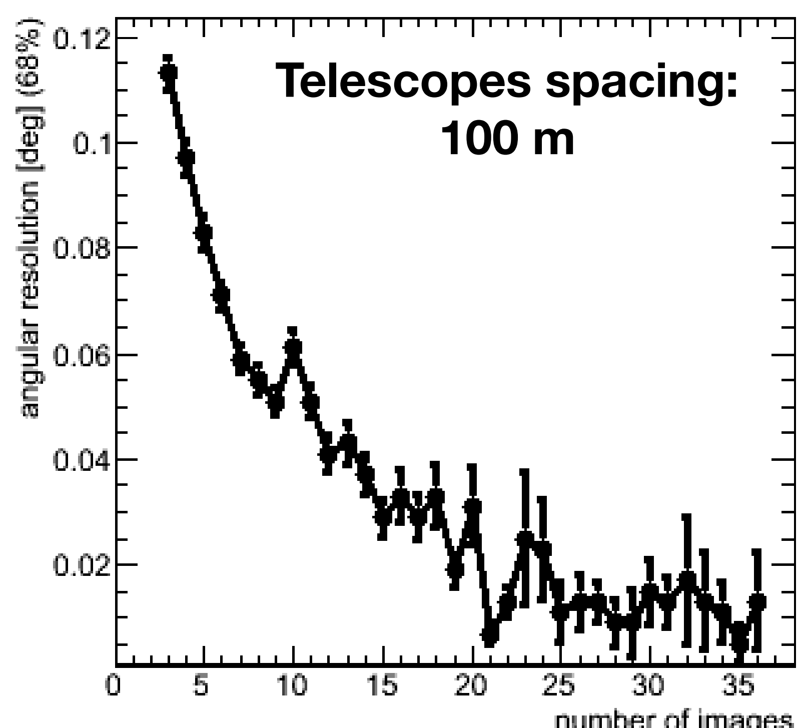
1. Improve sources morphology studies
(important almost for any CTA physics goals!)

2. With strong background discrimination cuts: Possibility c
“golden events” selection





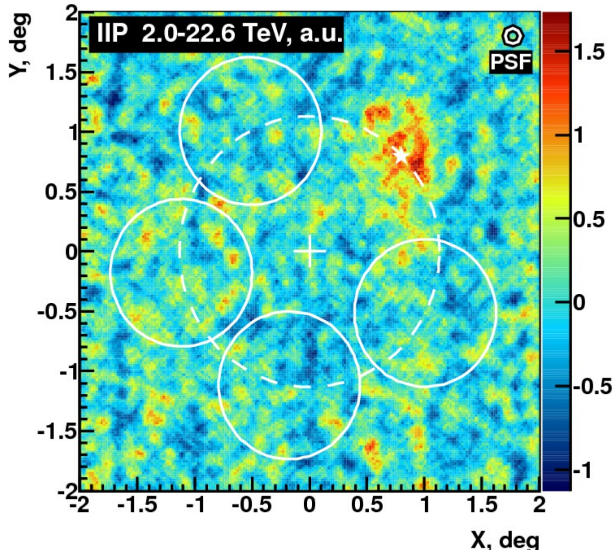
4.3 TeV gamma ray



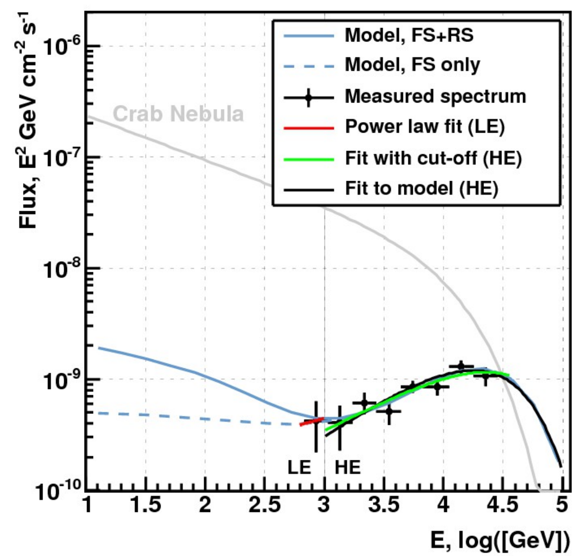
Backup

Type-IIP

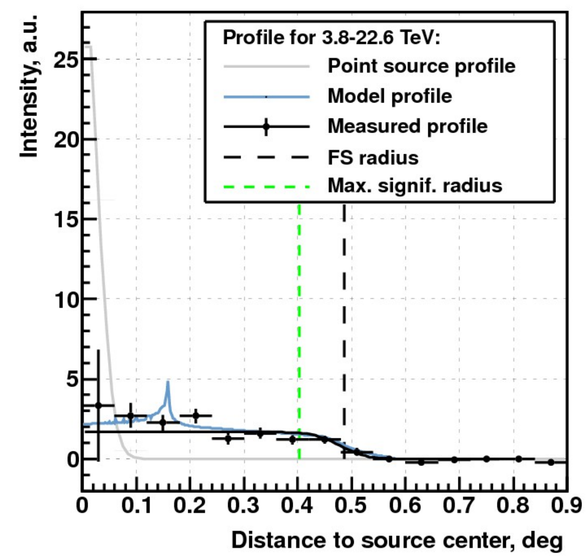
Simulated(!) sky map



Spectrum “measured” by CTA



SNR profile “measured” by CTA



Type-Ic