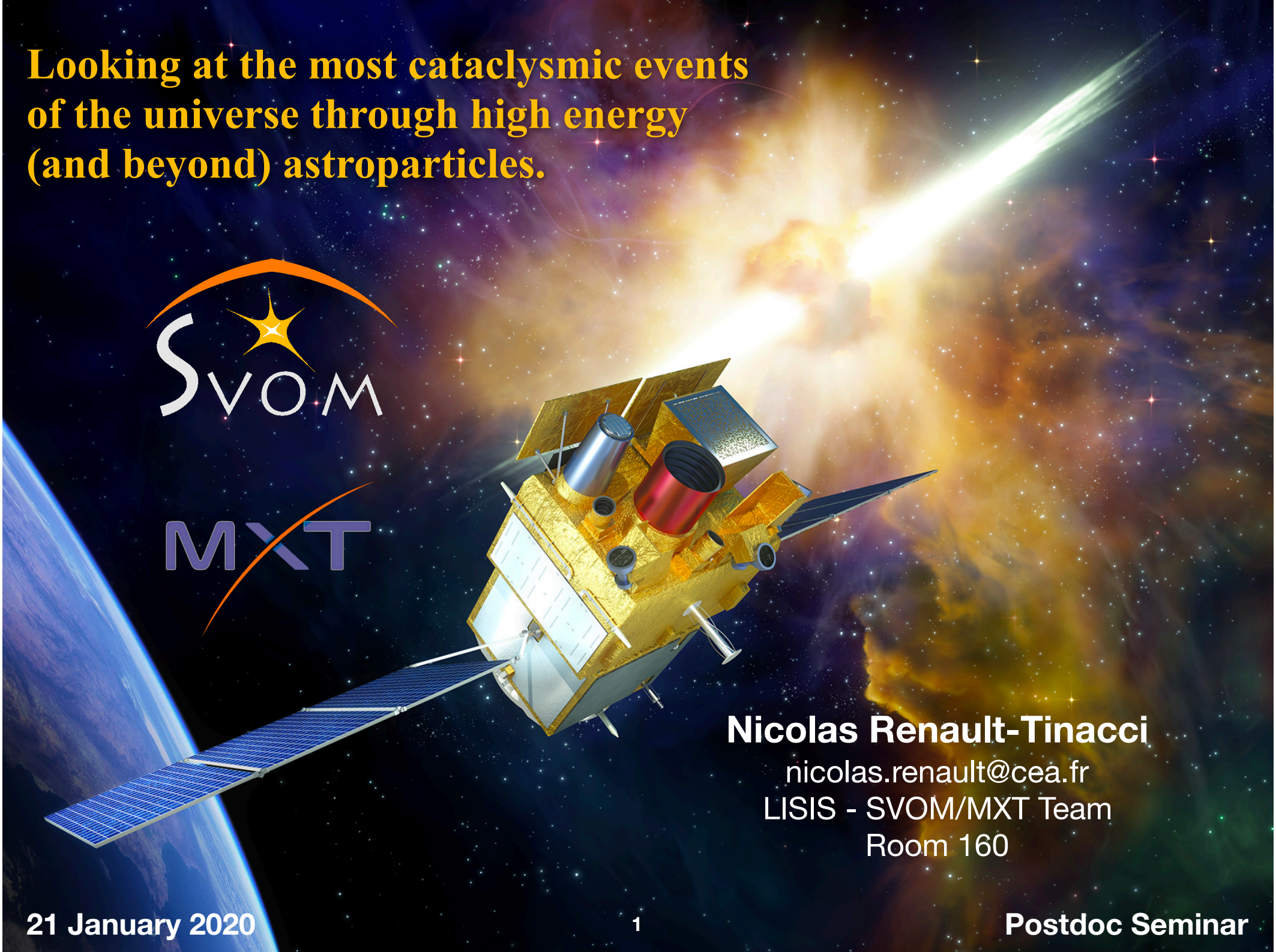
Looking at the most cataclysmic events of the universe through high energy (and beyond) astroparticles.



Nicolas Renault-Tinacci
nicolas.renault@cea.fr
LISIS - SVOM/MXT Team
Room 160

About me in a nutshell

- Engineer and master degrees - Institut d'Optique

2010
- CEA/IRFU/SPP - Internship with F. Schüssler, T. Stolarczyk
  - Data based ANTARES angular resolution estimator

2011-2014
- CEA/IRFU/SAp/LEPCHE - PhD with I. Grenier
  - Phase-resolved spectroscopy of γ-ray MSPs

2015
- Institut d'Astrophysique de Paris - K. Kotera
  - γ-ray searches from super-luminous SNe

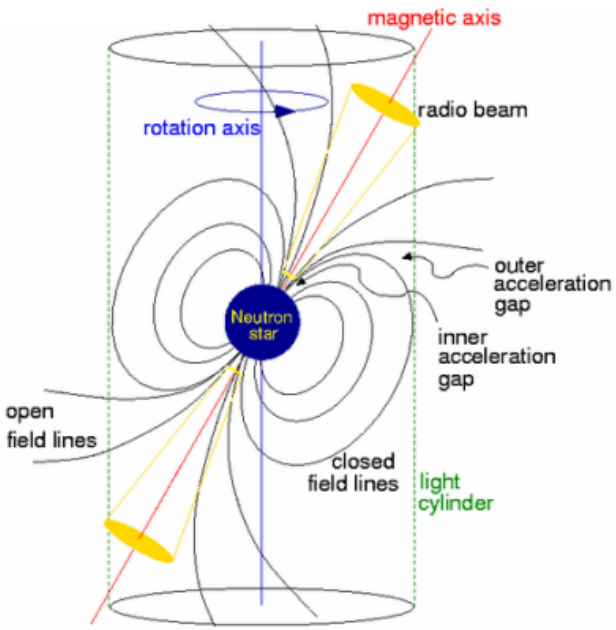
2016
- CEA/DAp/LEPCHE - J. Ballet, F. Acero
  - γ-ray pulsar attenuation

2017
- Institut d'Astrophysique de Paris - K. Kotera, O. Martineau
  - GRAND performances

2018
- Observatoire de Paris/LUTh - C. Boisson, M. Servillat
  - Virtual Observatory - Provenance Standard definition
  - CTA Data Model Definition, CTA SST Prototype

2019+
- CEA/DAp/LISIS - D. Götz, A. Meuris
  - SVOM/MXT Camera Calibration

Outline

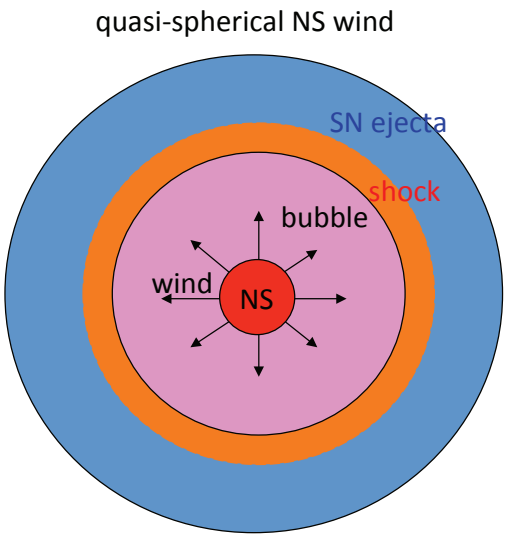


(→2017)

Neutron star, Origin of many phenomena

γ-ray millisecond pulsar phase-resolved spectroscopy

Search for γ-ray signals from super-luminous SNe

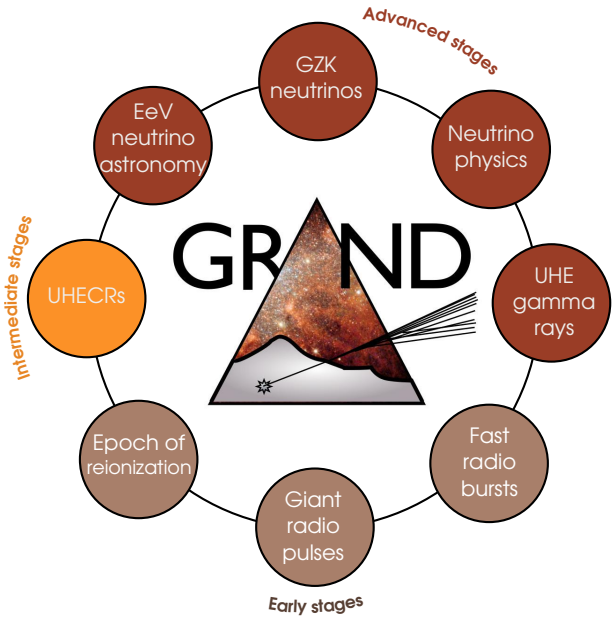


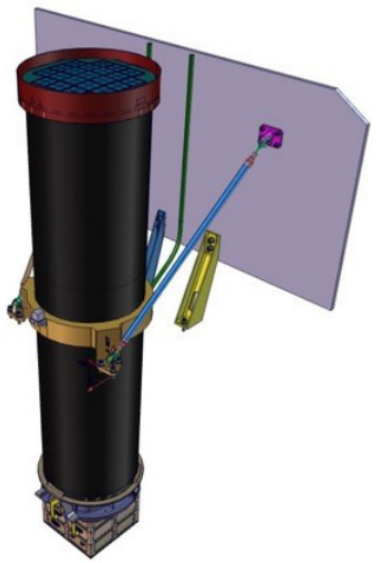
(2017→)

Instruments to observe the cosmic accelerators

GRAND performances Influence of topography

Cosmic-ray sensitivity,…





MXT
Spectral calibration

Instrumental Response Function definition

Softwares, …

What's a neutron star?

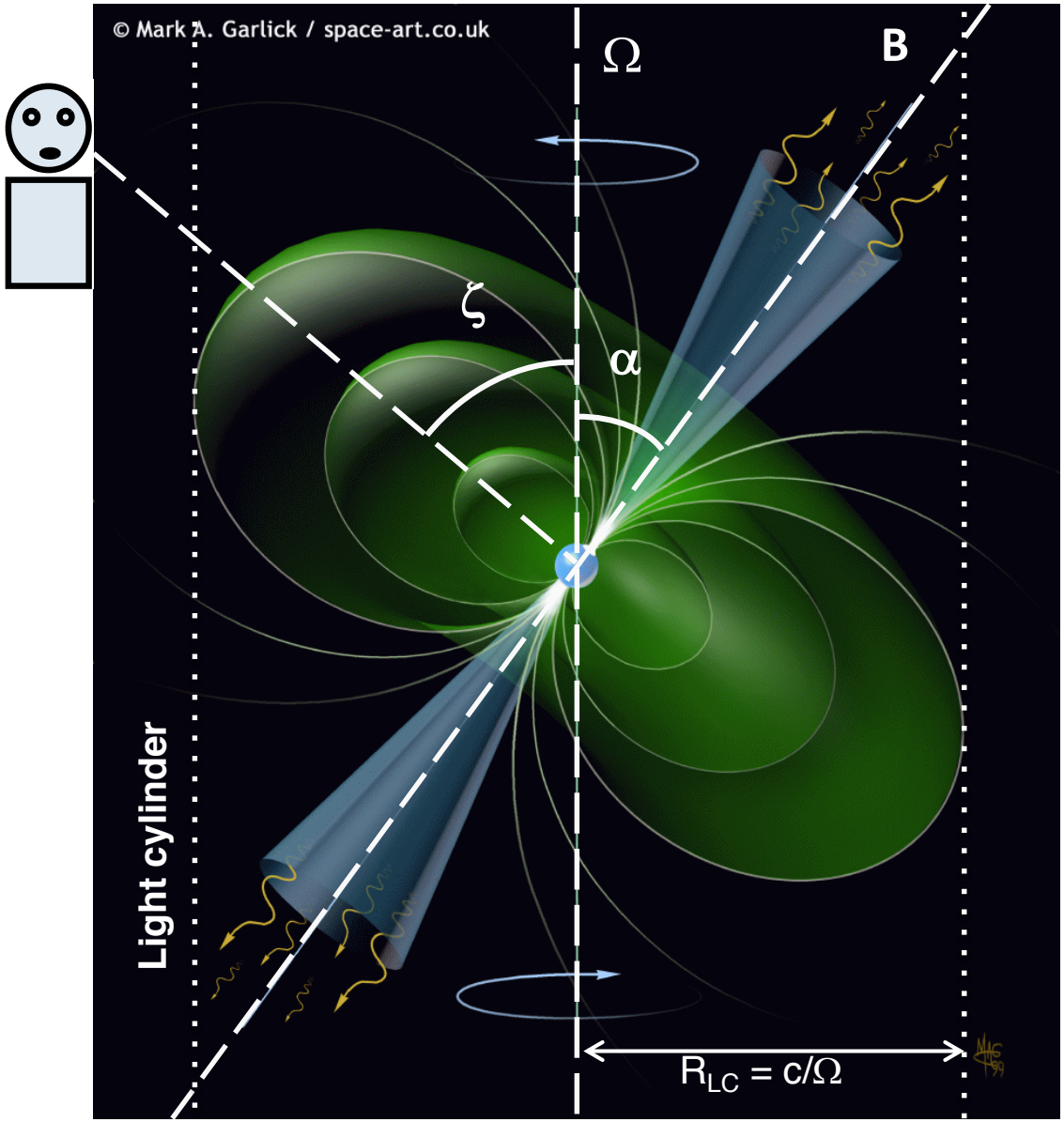
- **Residual of a massive ($M > 8M_\odot$) star gravitational collapse and supernova**

- **Compact object**
  - $M \approx 1.5/2\ M_\odot$
  - $R \approx 10/12$ km

- **Fast rotating**
  - $1\ \text{ms} < P < 10\ \text{s}$

- **Very strong roughly dipolar magnetic field**
  - $10^3\ \text{T} < B_{surface} < 10^{11}\ \text{T}$
  - Magnetosphere in co-rotation with the star up to the light cylinder

- **Pulsar = neutron star whose pulsation is observed on earth**

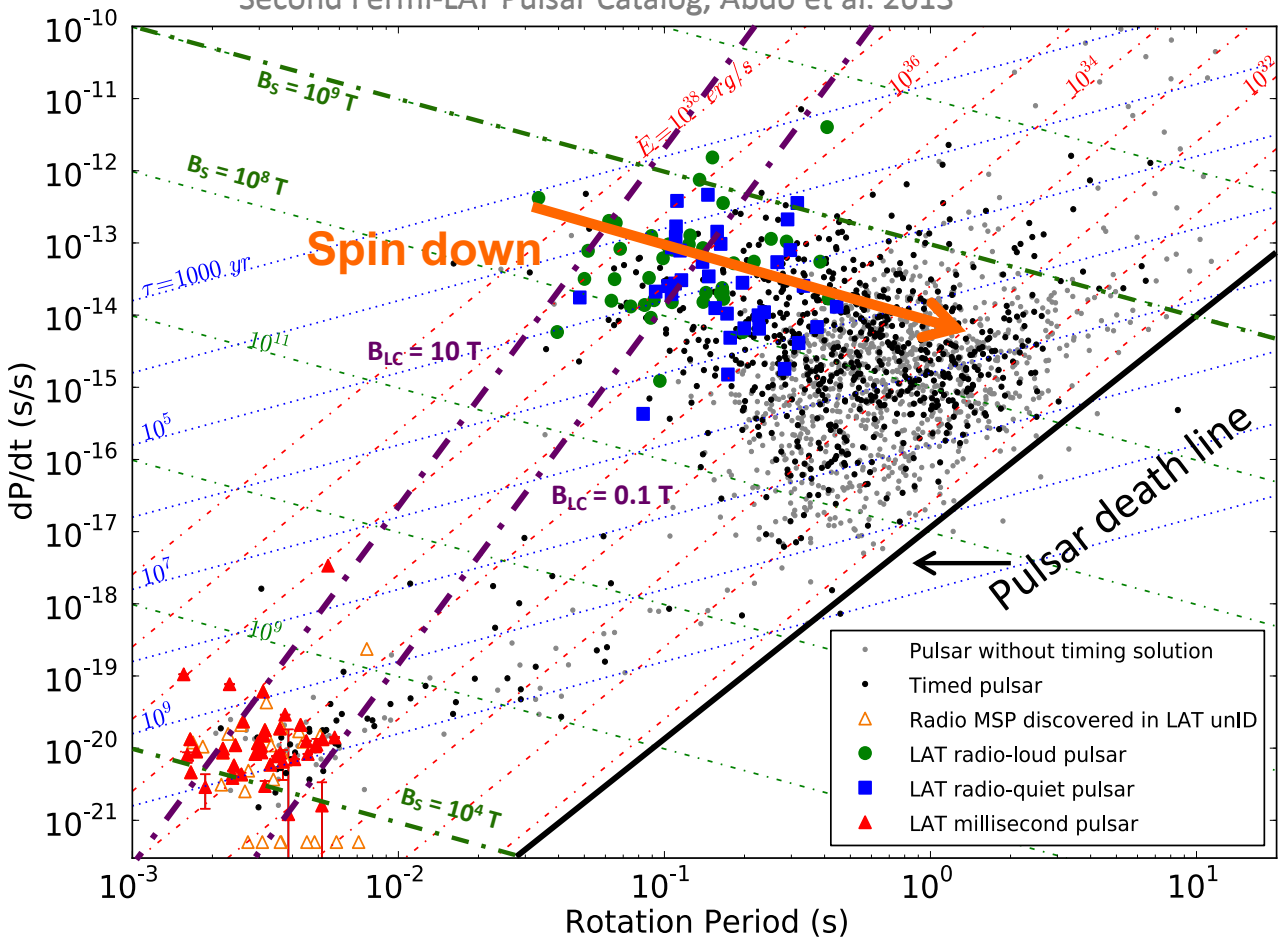


Neutron star's life

- **Spin down :**
  - **Dipolar electromagnetic radiation**
  - **From radio to γ-ray magnetospheric emission**
  - **Gravitational waves**

- **Also characterized by :**
  - **Spin down dP/dt**
  - **Spin-down power, Ė**
  - **B field at light cylinder**

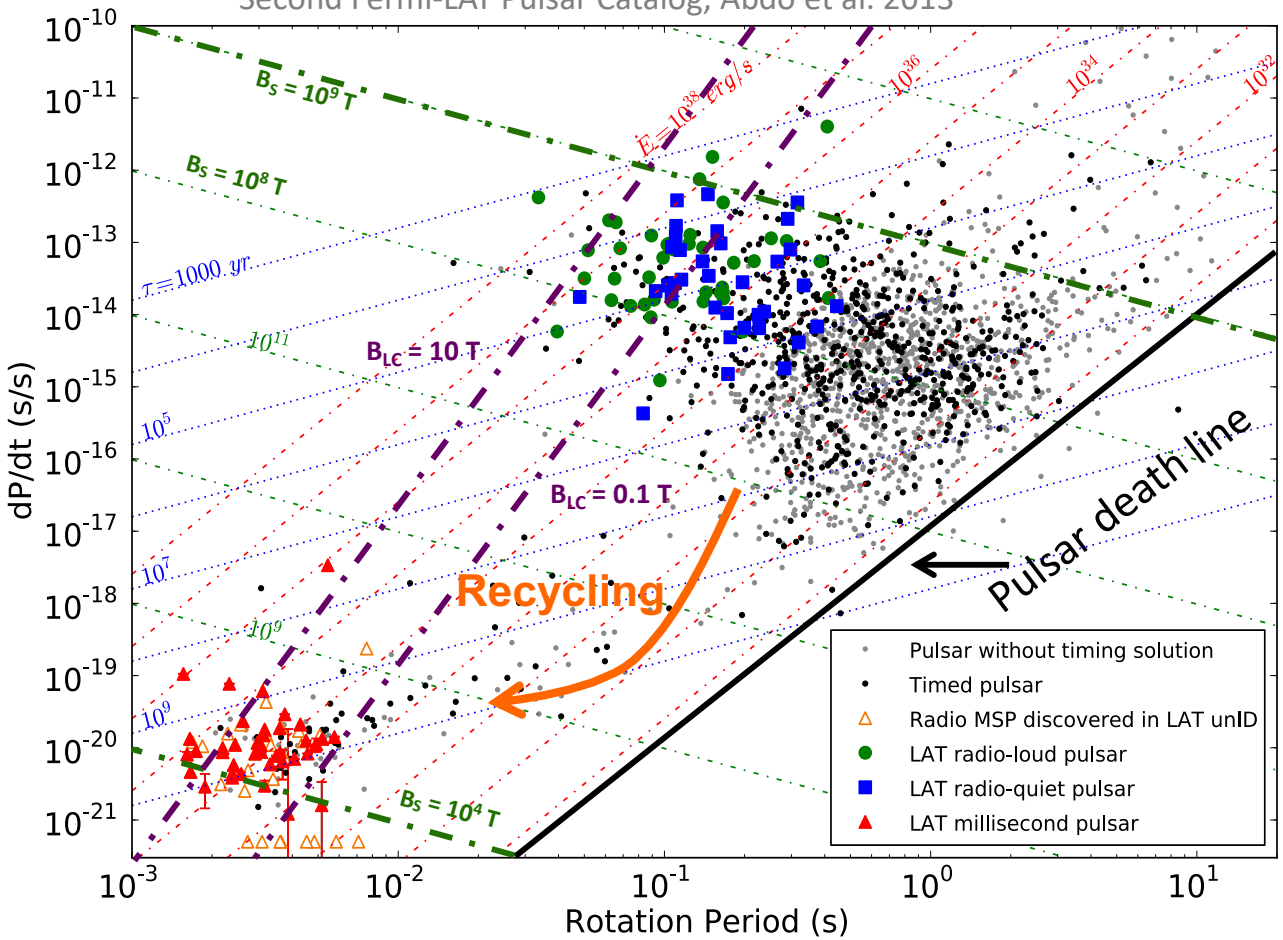
Second Fermi-LAT Pulsar Catalog, Abdo et al. 2013

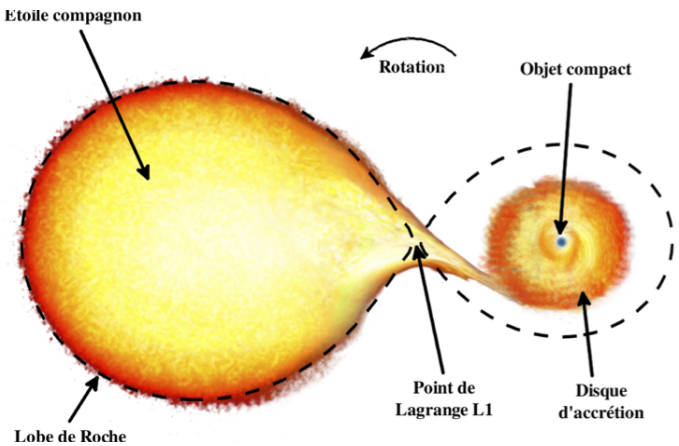


Pulsar's life

- **Spin down :**
  - Dipolar electromagnetic radiation
  - From radio to γ-ray magnetospheric emission
  - Gravitational waves
- **Also characterized by :**
  - Spin down dP/dt
  - Spin-down power, Ė
  - B field at light cylinder

Second Fermi-LAT Pulsar Catalog, Abdo et al. 2013





- **Recycling :**
  - Matter and angular momentum accretion

A cosmic accelerator

- **Pulsar engine:**
  - **Particle acceleration :**
    - **Where ? In wind and/or within the magnetosphere?**
  - **Pulsed emission in different wavelengths (from radio to g-ray emission):**
    - **Processes? Where? Different regions according to wavelength?**
  - **Structure of the magnetosphere (dipolar, multi-polar)**

- **Pulsar wind nebula**
  - **Composition, energy, Poynting flux transfer to particle kinetic energy, …**

- **Source of various signals:**
  - **Ultra High Energy Cosmic Rays (UHECRs)**
  - **Gravitational wave emission**

- **Super-luminous Supernovae (SLSNe) ?**
  (Kotera et al. 2013, Murase et al. 2015)

- **Accreting binary (redback, black widow,…)**

- **Fast Radio Bursts?**

Pulsar, cosmic accelerator

- **Pulsar engine:**
  - **Particle acceleration :**
    - **Where ? In wind and/or within the magnetosphere?**
  - **Pulsed emission in different wavelengths (from radio to g-ray emission):**
    - **Processes? Where? Different regions according to wavelength?**
  - **Structure of the magnetosphere (dipolar, multi-polar)**

- **Pulsar wind nebula**
  - **Composition, energy, Poynting flux transfer to particle kinetic energy, …**

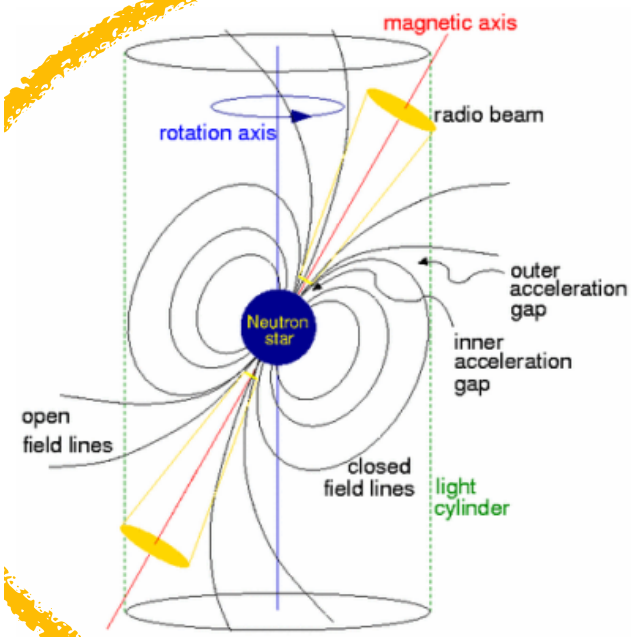
- **Source of various signals:**
  - **Ultra High Energy Cosmic Rays (UHECRs)**
  - **Gravitational wave emission**

- **Super-luminous Supernovae (SLSNe) ?**
  (Kotera et al. 2013, Murase et al. 2015)

- **Accreting binary (redback, black widow,…)**

- **Fast Radio Bursts?**

Outline

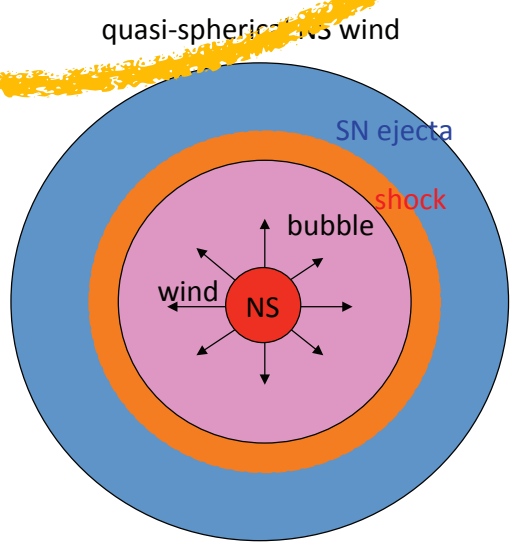


(→2017)

Neutron star, Origin of many phenomena

γ-ray millisecond pulsar phase-resolved spectroscopy

Search for γ-ray signals from super-luminous SNe



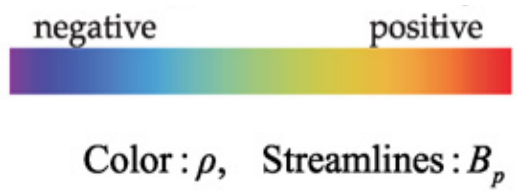
Pulsar Electrodynamics basics

Slot Gap (Arons 1983)
Polar Cap (Sturrock 1971)
Outer Gap (Cheng et al 1986, Romani 1996)

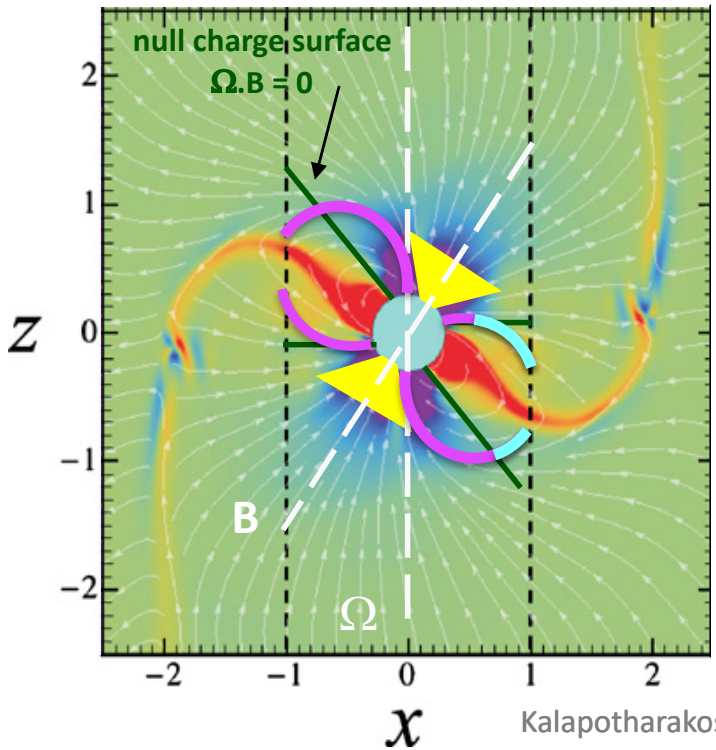
- **Force-free magnetosphere** (Goldreich & Julian 1969)
- **Goldreich-Julian charge density :**

$$\rho_{GJ} = -\epsilon_0 \vec{\Omega} \cdot \vec{B}$$

- **Poisson equation :** $\vec{\nabla} \cdot \vec{E}_{||} = (\rho - \rho_{GJ})/\epsilon$
- **In some specific regions : $\rho \neq \rho_{GJ}$ ➔ $E_{||}$ ➔ acceleration**



- **Few models under force-free assumption:**
  - **each only partly succeeded to reproduce observations (lightcurves, populations,…)**
    (Johnson et al. 2014, Pierbattista et al. 2012,…



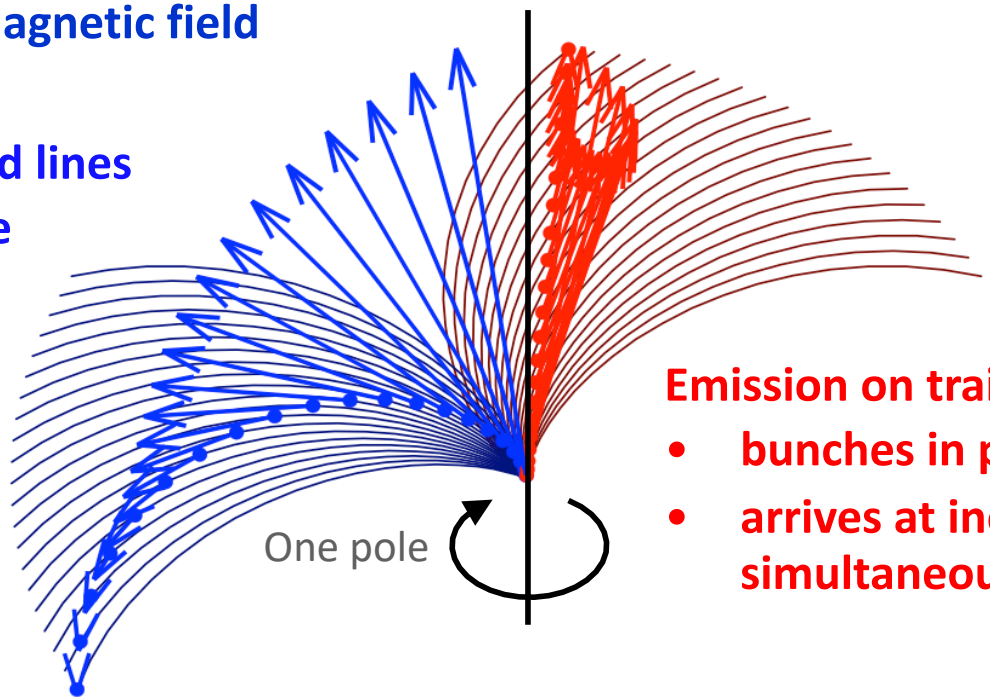
Kalapotharakos et al. 2012

Why “phase resolved spectroscopy” ?

- **Special relativistic effects ➔ phase shifts (Morini 1983)**
  - **time-of-flight delays, light aberration**
  - **retardation of magnetic field**

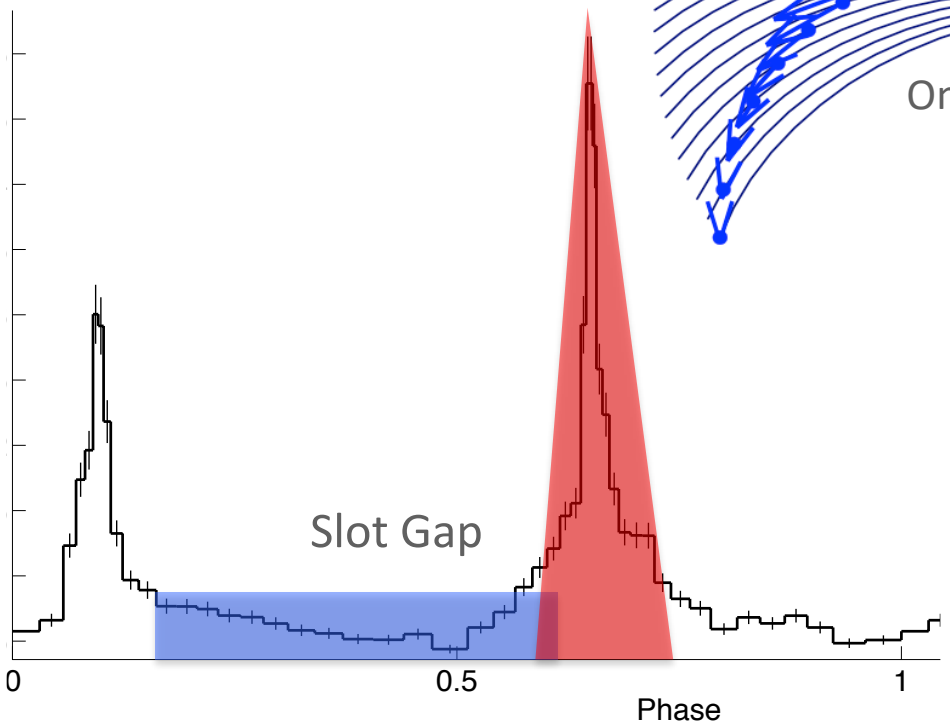
Emission on leading field lines

- **spreads out in phase**
- **arrives at inertial observer at different times**



Emission on trailing field lines

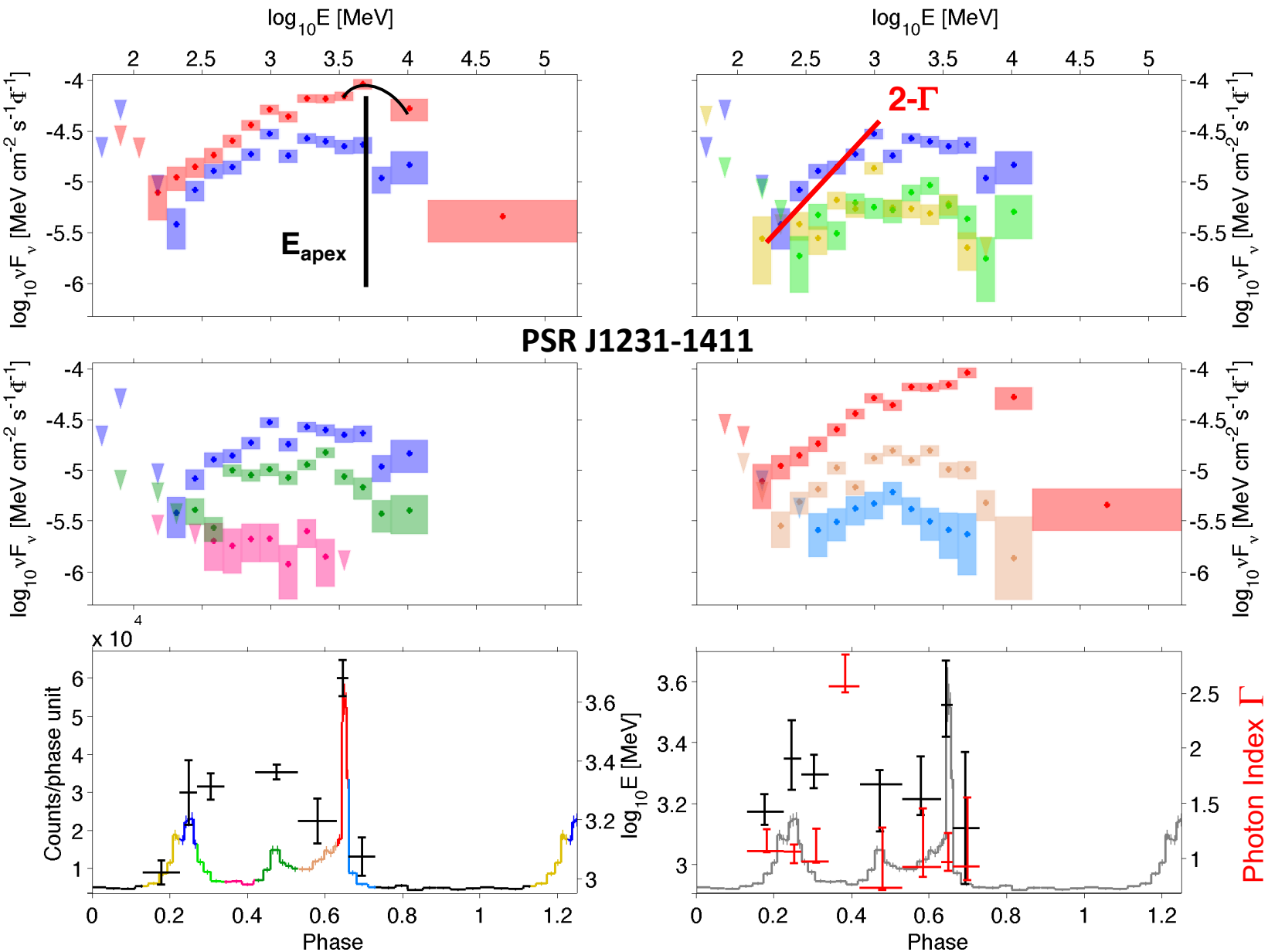
- **bunches in phase**
- **arrives at inertial observer simultaneously**



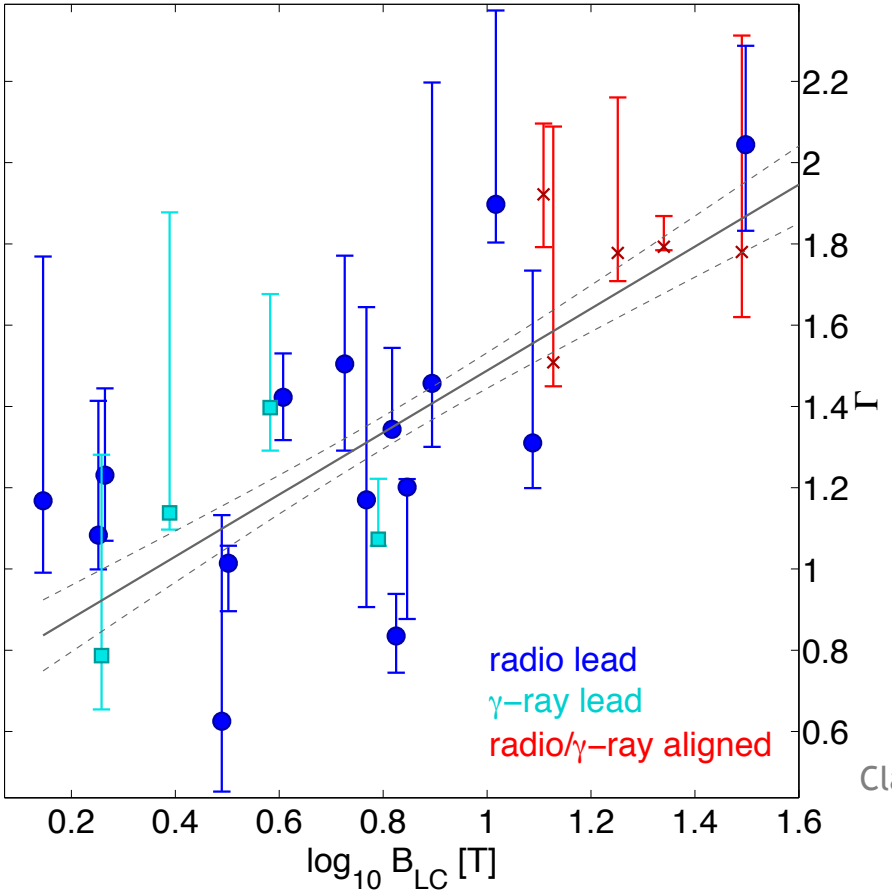
- **Peaks = caustics**
- **Phased resolved spectral analysis**
  - **mapping (in a complex way) processes with altitude and azimuth**

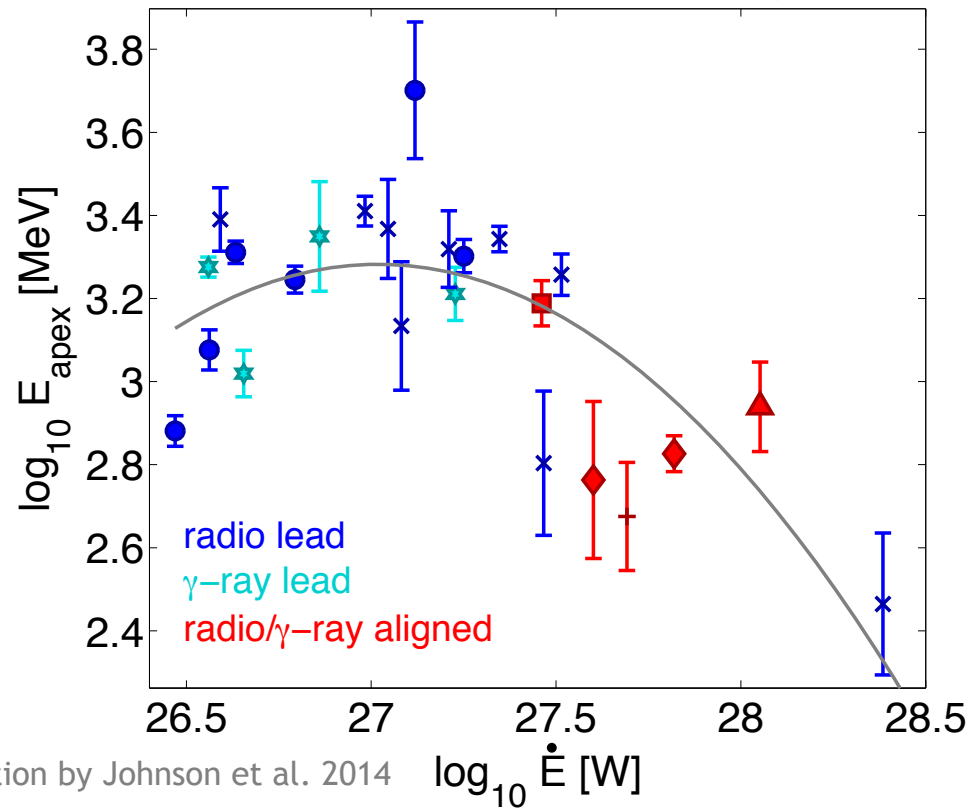
Investigating the pulsar engine

- **Photon index, Γ ⇔ primary particle distribution, cascade development and/or photon pile-up in phase**
- **Apex Energy, E_{apex} ⇔ max radiative power produced in the acceleration/emission regions**
- **Cut-off energy, E_{cut} ⇔ Maximum pair energy or γ-γ pair absorption**



MSP Spectral Sequence





Classification by Johnson et al. 2014

- **Softening with B_{LC} (and $\dot{E}$)**

  Γ constant with B_{LC} rejected at >10σ

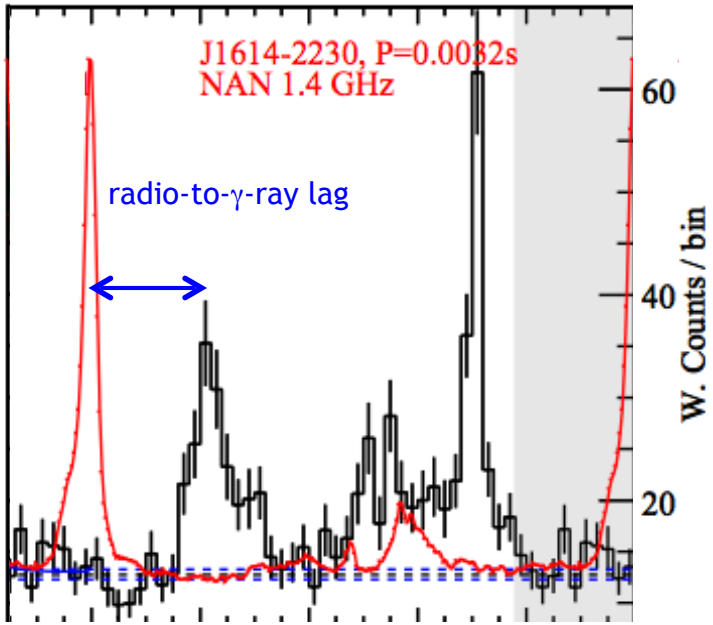
- **Shift in E_{apex} with $\dot{E}$ (and B_{LC})**

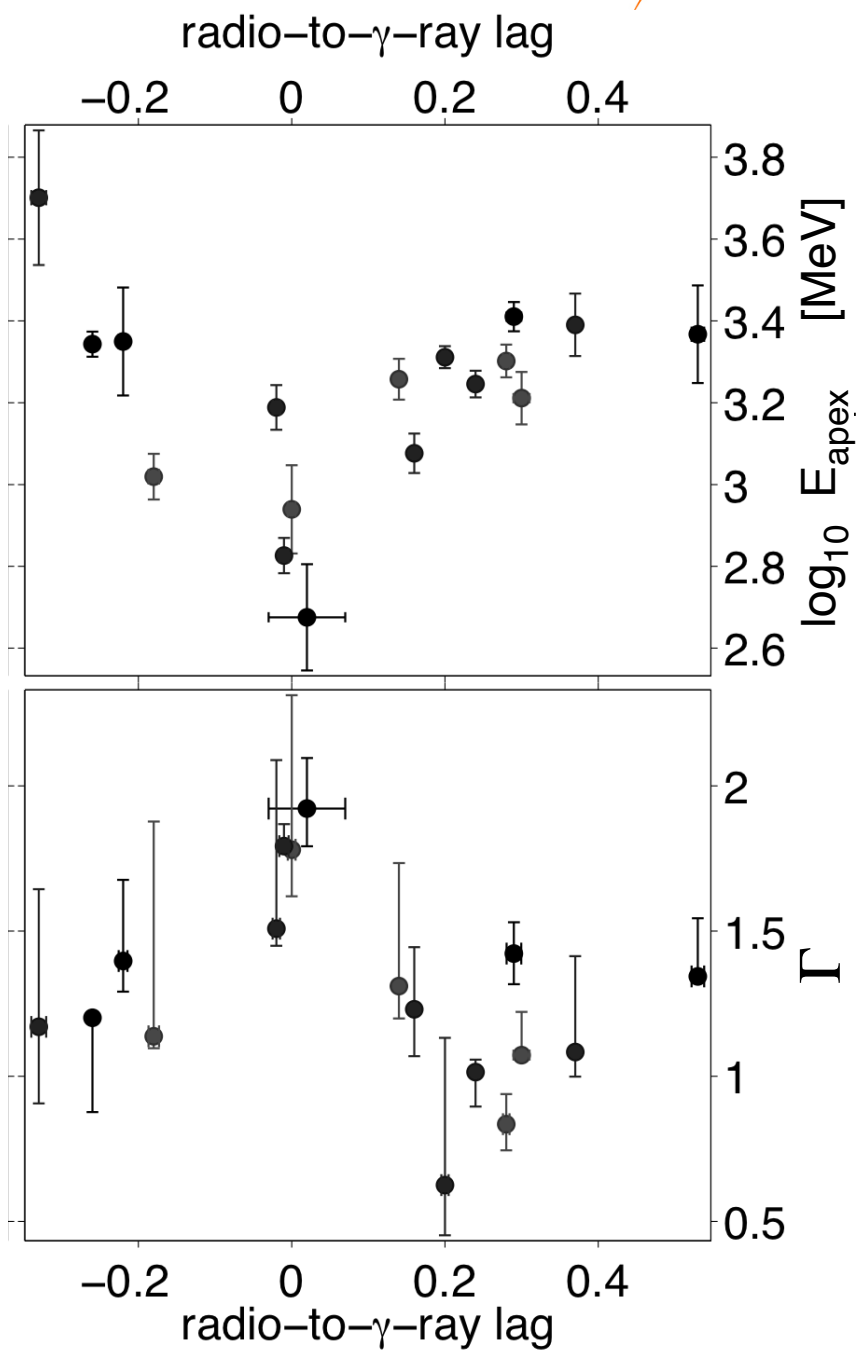
  Curvature testing (« pairwise slope statistics », Abrevaya et Jiang 2003) → **P_{curv} = 99,97 %**

- **Computation (toy model) of the inferred curvature radiation (CR) spectra :**
  - **From primaries near the light cylinder**
  - **$r_c = R_{LC}$ (Hirotani 2011)**
  - **Test with different Γ_{max} distributions**

- **Inability of a single CR component to reproduce the evolution in the sample**
  - **Softer component required**

Influence of radio emission





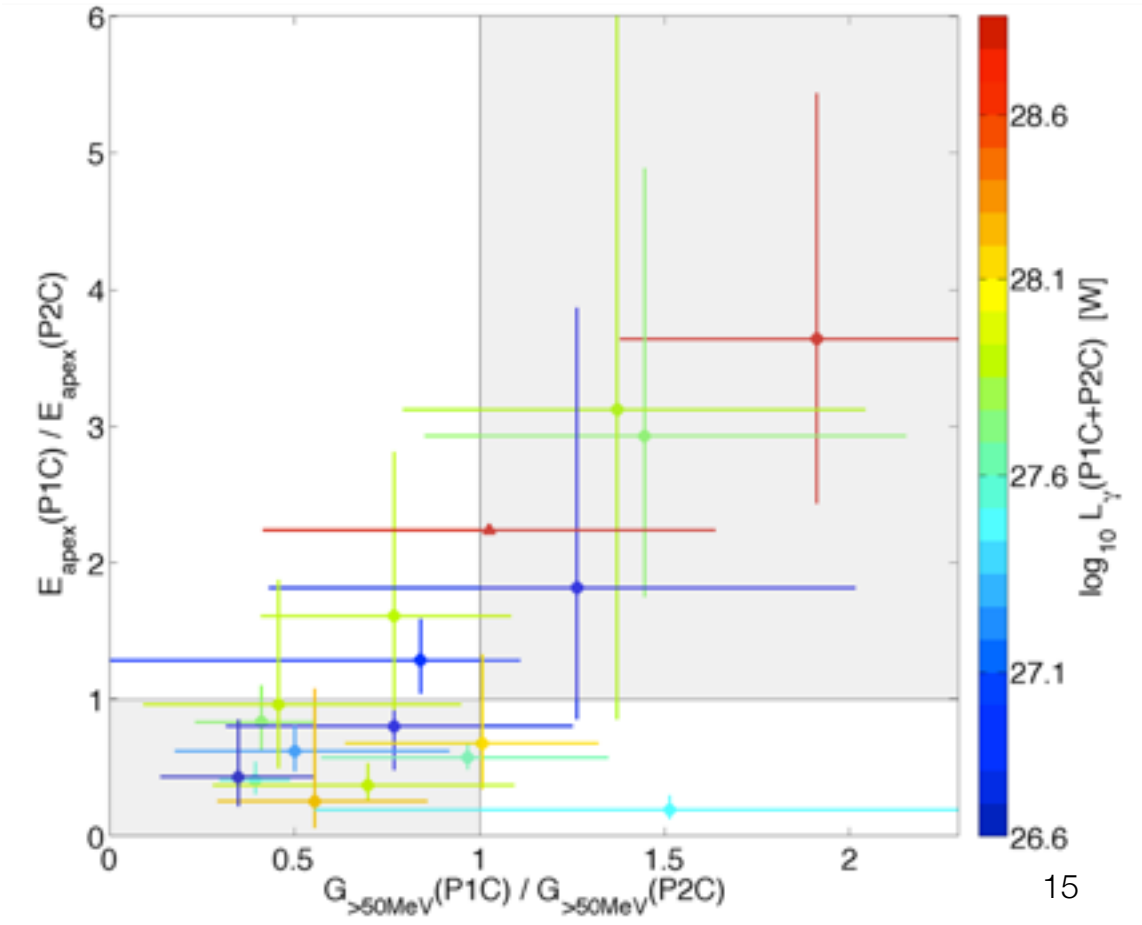
- Softening when radio and γ-ray peaks aligned

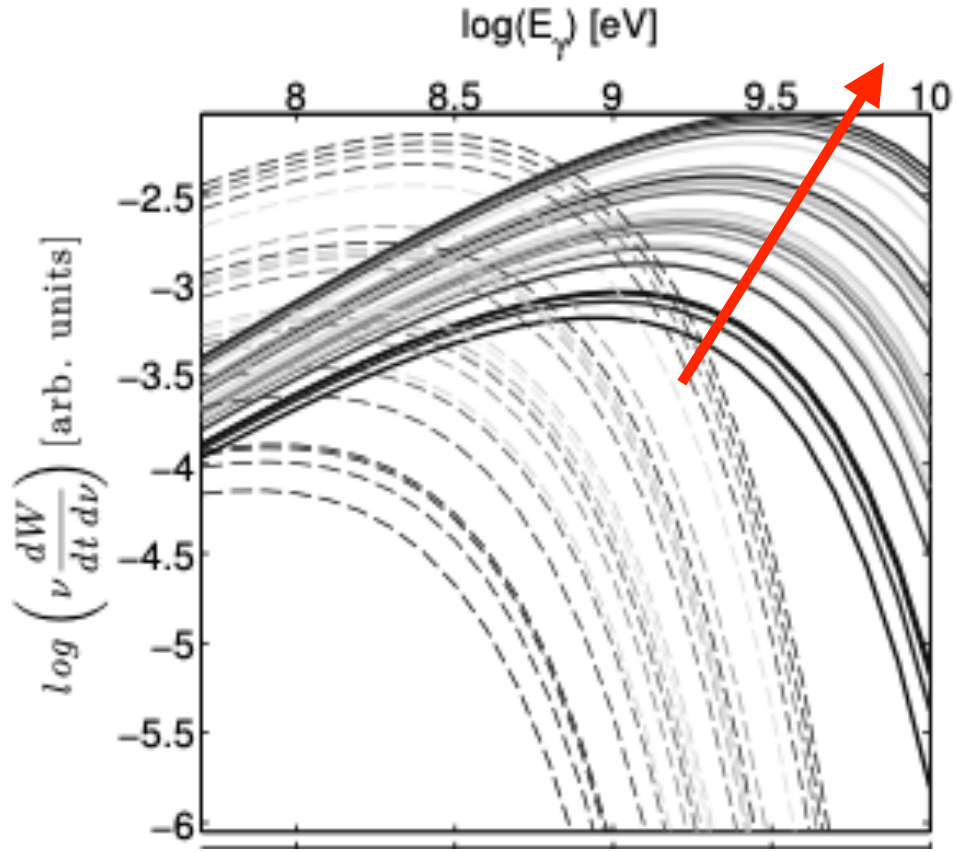
→Synchrotron component from primaries gaining pitch angle by cyclotron resonant absorption of co-located radio photons (Harding et al. 2008)

Spectral pattern with phase

The brighter the core, the higher the apex energy

Irrespective of the peak order





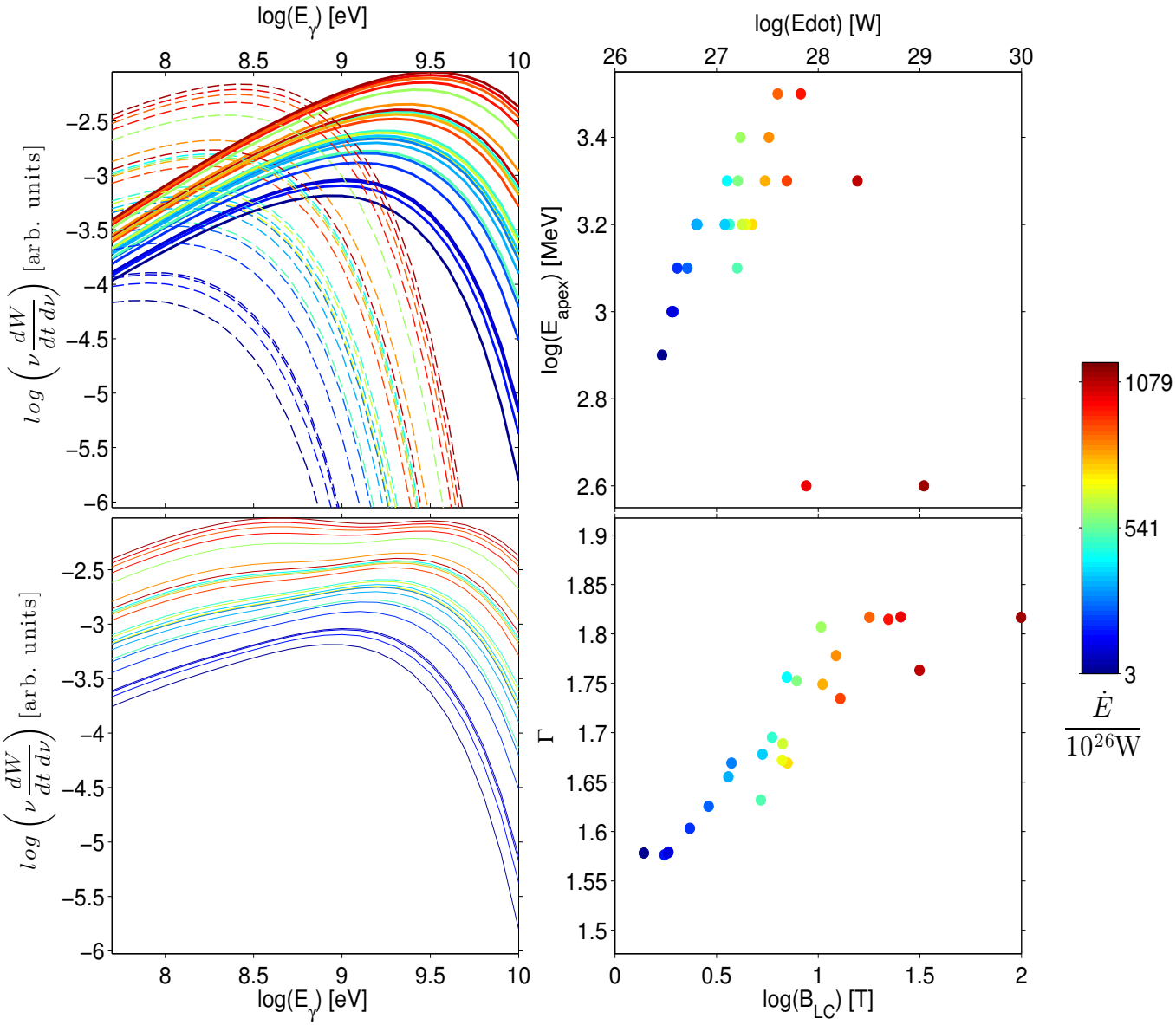
- **Expected for dominant curvature radiation**

MSP Spectral Sequence

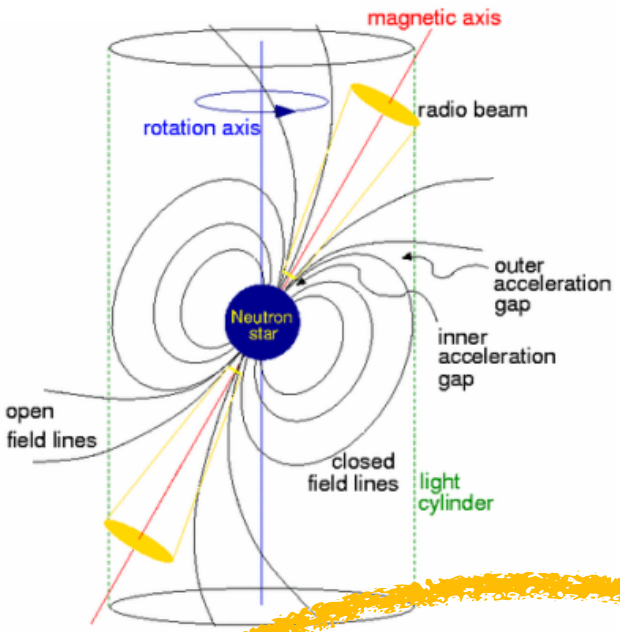
- **MSP spectral sequence with $\dot{E}/B_{LC}$**
  - **Softer emission component required**
- **Transition from $E_{//} \neq 0$ to $E_{//} = 0$ not abrupt ➔CR at few 100MeV**

(Wang et al. 2010, Kalapotharakos 2014)

- **Softening when co-located radio and γ-ray emissions**
  - **synchrotron radiation from primaries** (Harding 2008)
  - **Consistent with the needed softer component**
- **The brighter the core, the higher E_{apex}**
  - **CR dominant**



Outline

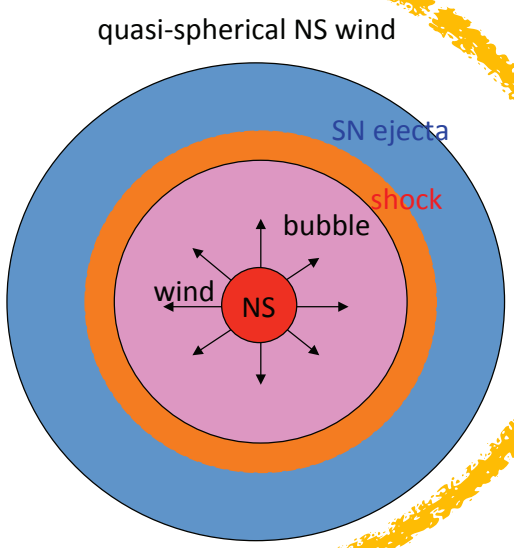


(→2017)

Neutron star, Origin of many phenomena

γ-ray millisecond pulsar phase-resolved spectroscopy

Search for γ-ray signals from super-luminous SNe



What's a SLSNe

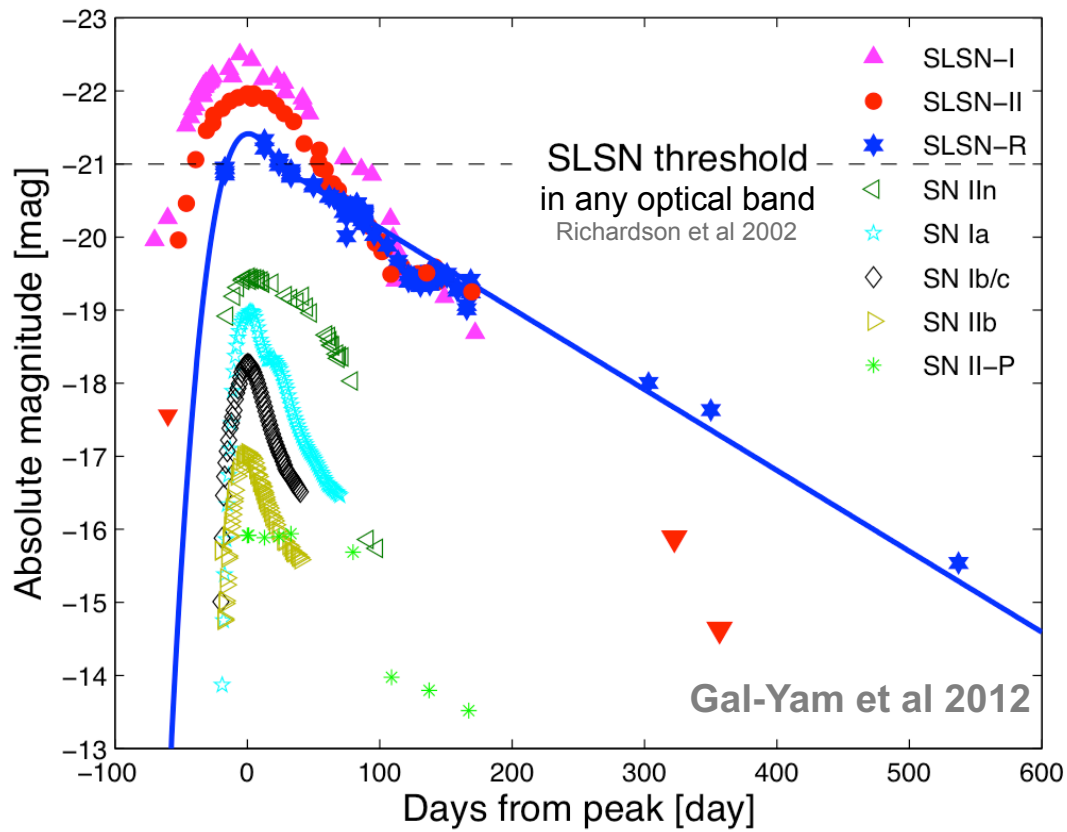
Super-luminous SN are core-collapse SN with $L_{peak} > 5.10^{43}$ erg s^{-1} (≈ x100 brighter than usual SNe)

- **3 main models :**

i) **Neutron-star driven**
(Kotera et al 2013, Murase et al. 2015)

ii) **Powered by interaction of the SN with circumstellar medium**
(Murase et al 2011,2014)

iii) **Pair-instability-driven model**
(Gal-Yam et al 2009)

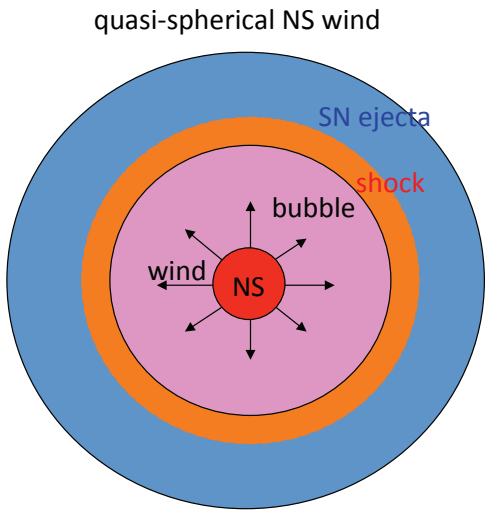


Prediction of γ-ray emission respectively with $L_\gamma = 10^{43} – 10^{45}$ erg.s^{-1}

SLSNe, origin of γ rays?

i) Neutron-star driven (Kotera et al 2013, Murase et al. 2015)

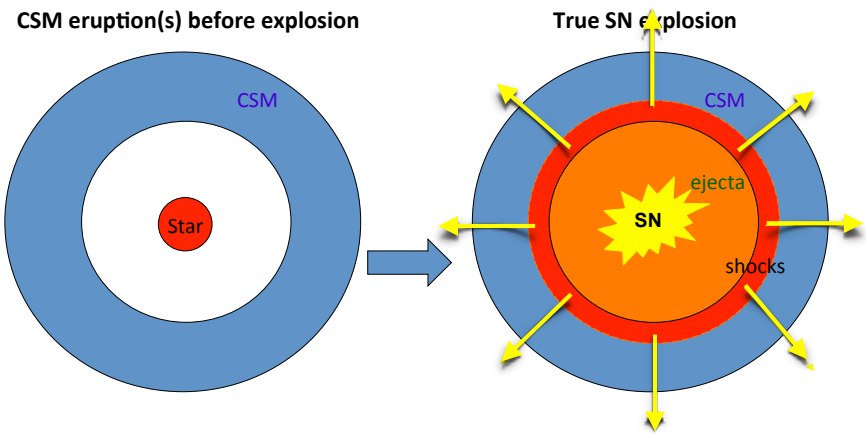
- Fast-rotating (P≈1-10 ms), mildly magnetized (B≈10^{12}-10^{13} G) central neutron star releases its rotational energy into the SN ejecta through the relativistic wind (early PWN)
- X-ray/γ-ray peak predicted after and during few months/years respectively due to synchrotron radiation & Inverse Compton scattering
- γ-ray flux affected above 10s GeV by two-photon attenuation processes

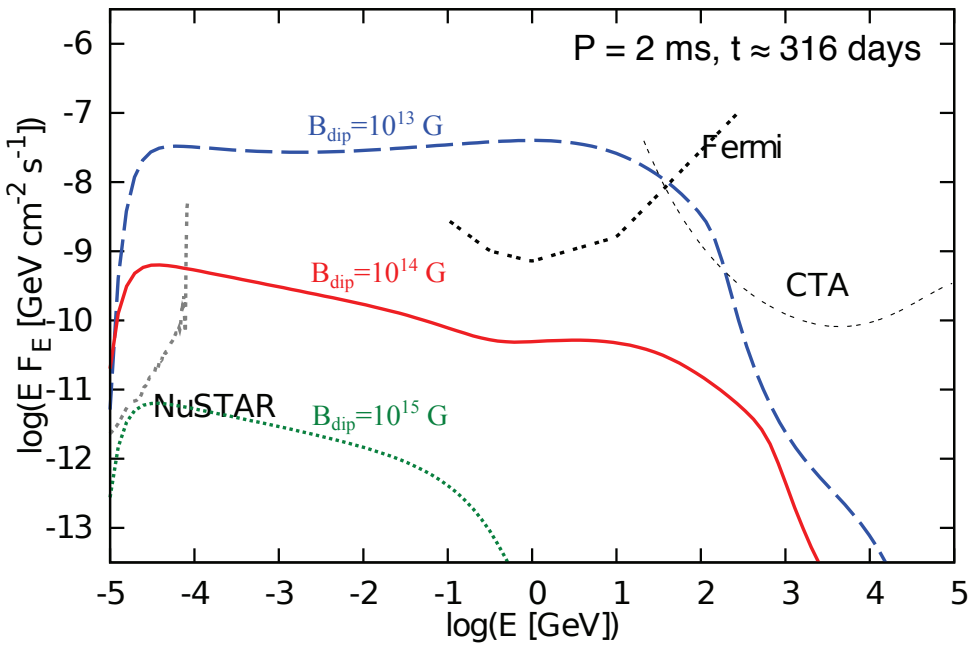


ii) Powered by interaction of the SN with circumstellar material (CSM)

(Murase et al. 2011, 2014)

- γ-ray produced by cosmic ray accelerated at shock between ejecta and dense CSM
- γ-ray absorption but no severe attenuation in the GeV range

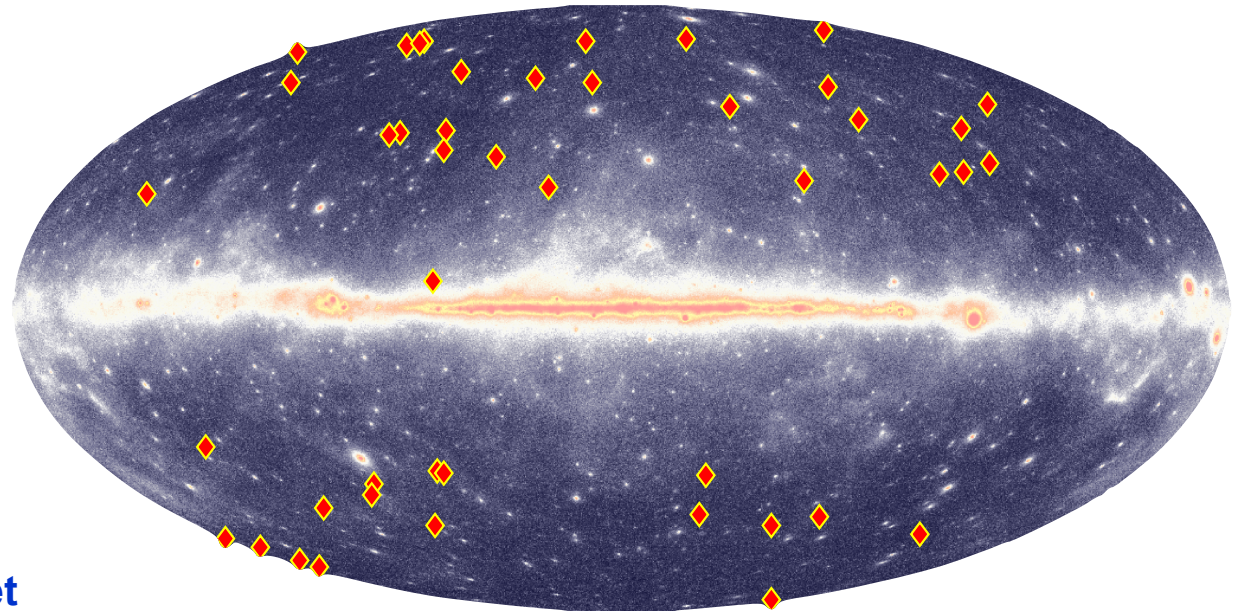




Murase et al 2015

Data and analysis

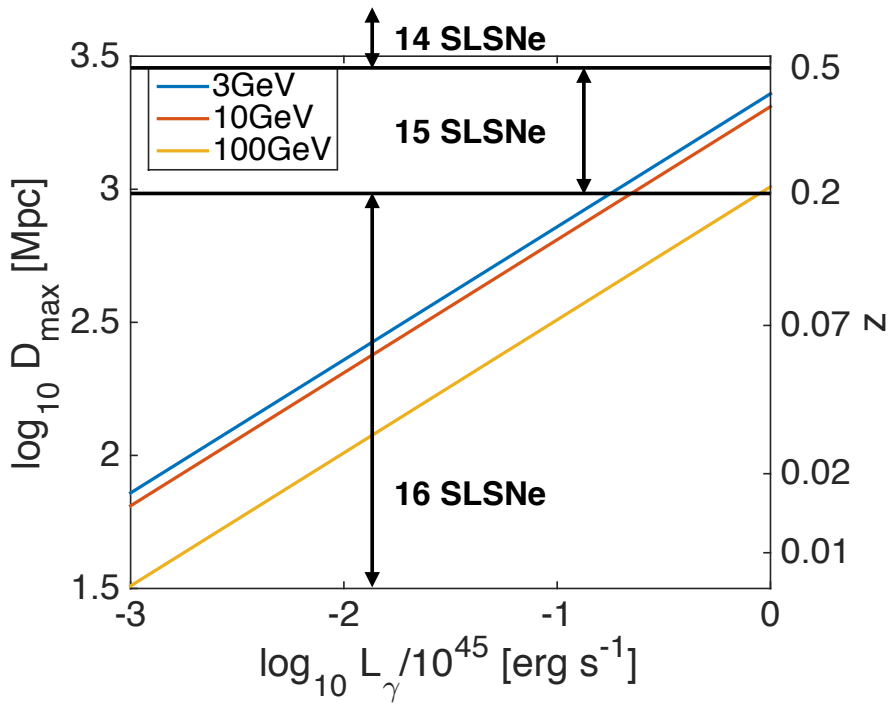
- **Fermi-LAT data:**
  - 85 months
  - $E_\gamma \geq 0.612$ MeV (better resolution)
  - 4 analysis time windows:
    - from t_{peak} - 30d → t_{peak} + 3m
    - from t_{peak} - 30d → t_{peak} + 6m
    - from t_{peak} - 30d → t_{peak} + 1y
    - from t_{peak} - 30d → t_{peak} + 2y



- **Sample:**
  - SN peaking throughout the dataset duration ⇒ 45 SLSNe (0 < z < 1.5)
  - Directions from optical observations
  - 3 groups based on redshift/distance

- **Analyses**
  - Individual analyses
  - Joint-likelihood analysis to search for weak signal:
    - Full sample + 3 groups in redshift
    - Weighting by $1/d^2$ (= assuming an equal γ-ray luminosity for all SLSNe)

(Ackermann et al. 2015)



Pulsars, cradle of SLSNe?

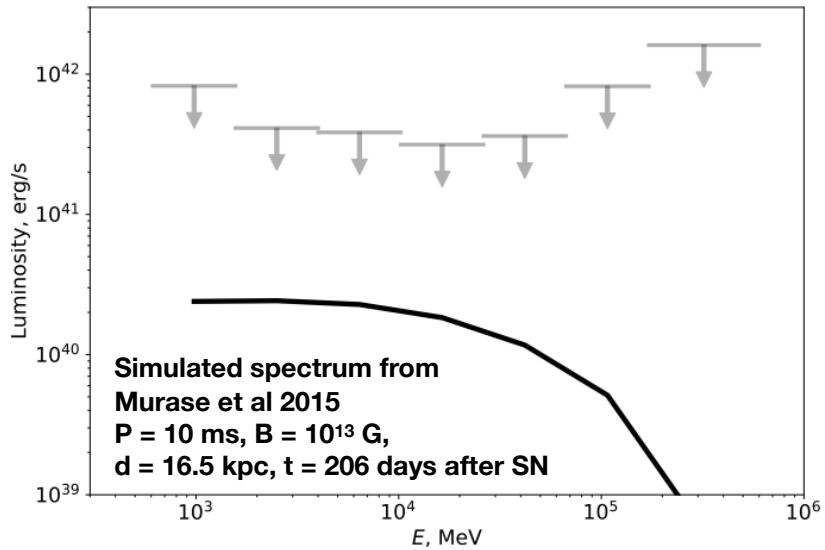
- **Observations :**
  - **No detection above a 3σ-level were reported nor for individual sources nor for samples**
  - **Thin black/white line ➔ 2σ-L_γ upper limits derived from individual and joint analysis flux measurements, respectively**

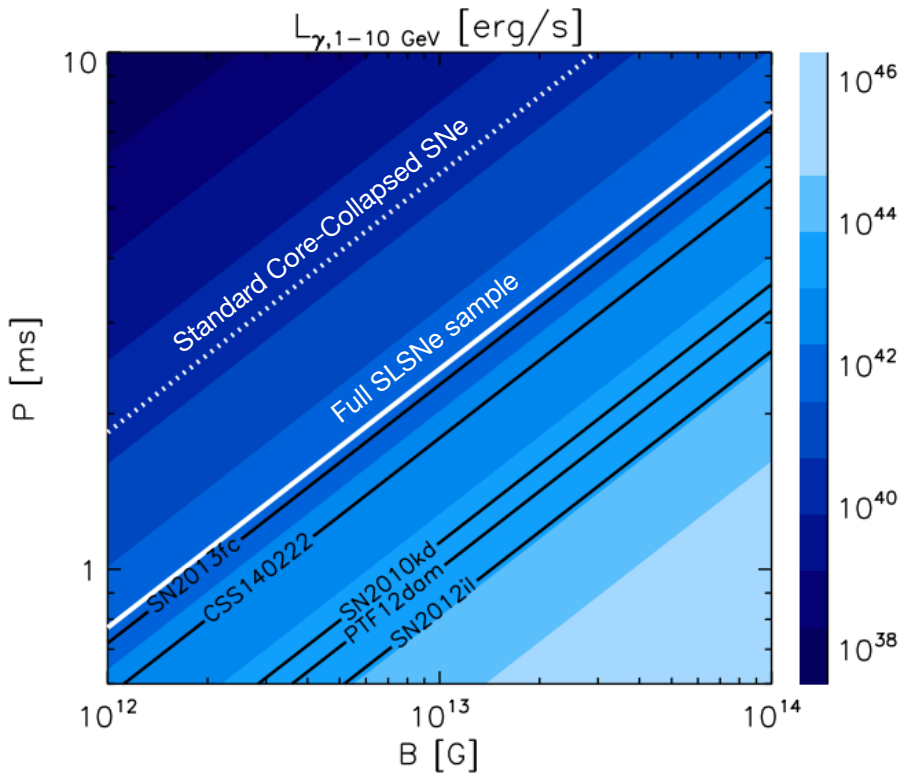
- **Theory :**
  - **Luminosity contours in Period - B_{dip} field space for the neutron-star-powered scenario**
    In the 1-10 GeV band, the IC process is dominant:

$$L_{\gamma,\epsilon} \sim \xi \beta_{\rm ej} \eta_e L_{\rm rot} \qquad \beta_{\rm ej} = (2E_{\rm SN}/M_{\rm ej})^{1/2}(1 + E_{\rm rot}/E_{\rm SN})^{1/2}/c$$

Assuming η_e=1 the fraction of EM luminosity provided by the pulsar into the wind, ξ =0.1 to account for uncertainties on spectral indices and attenuation due to radiation/matter.

- **Exclusion of P-B values below the lines (only slight constrains)**





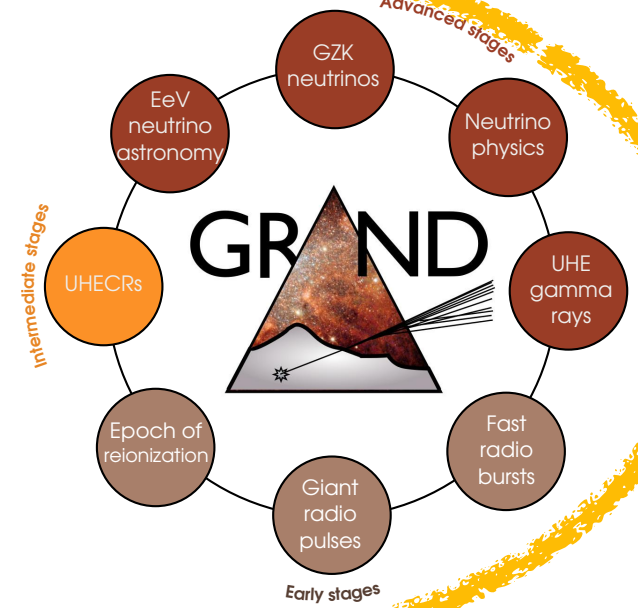
Outline

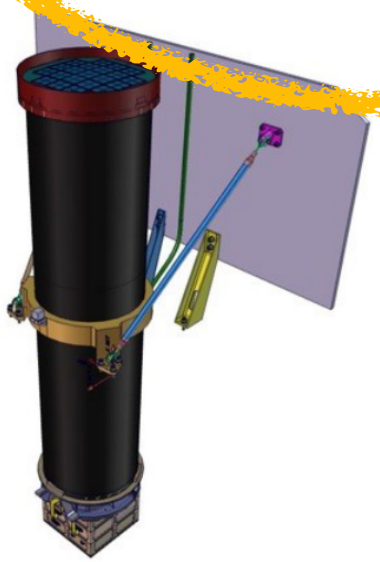
(2017→)

Instruments to observe the cosmic accelerators

GRAND performances
Influence of topography

Cosmic-ray sensitivity,…





MXT
Spectral calibration

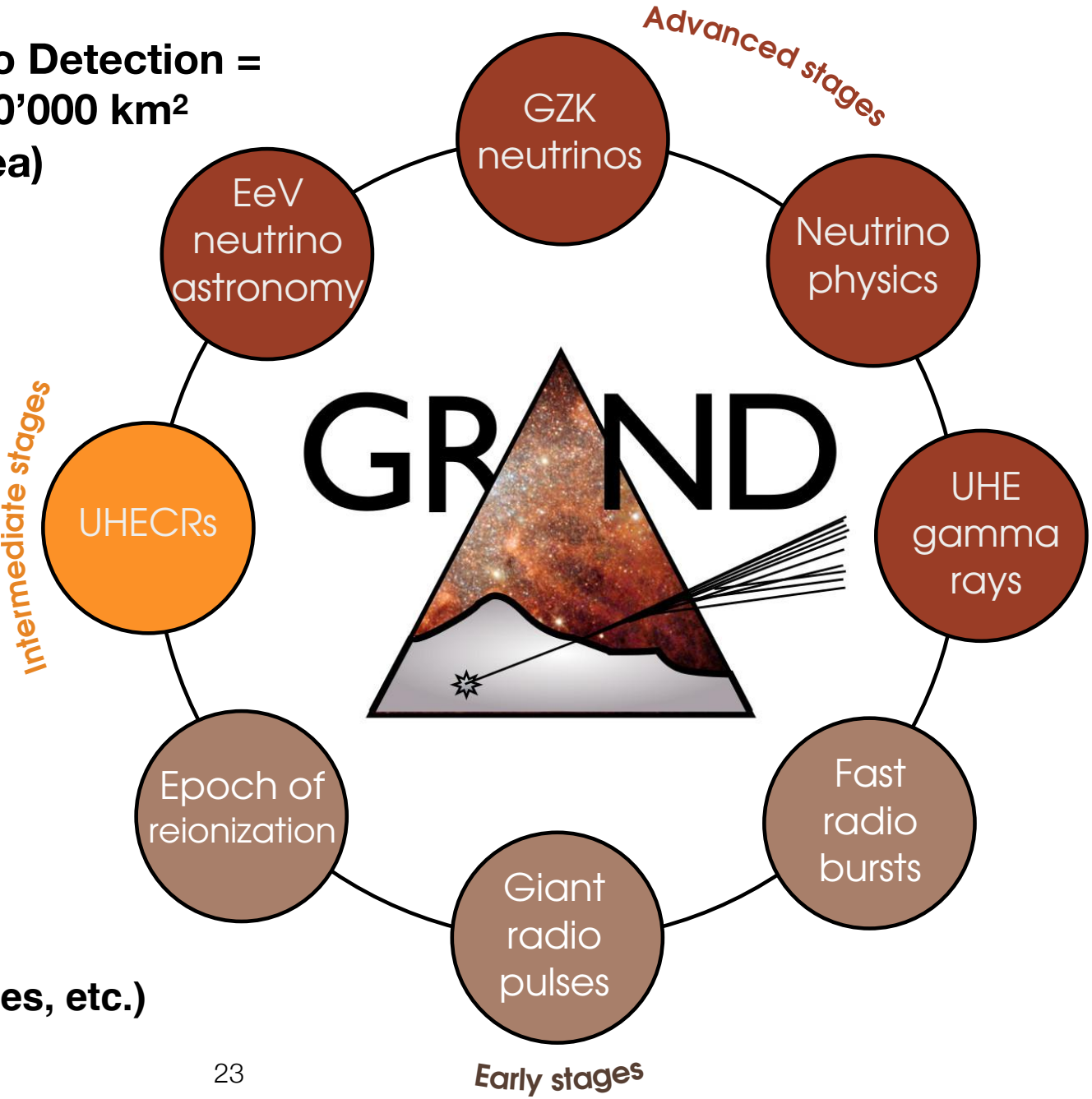
Instrumental Response Function definition

Softwares, …

GRAND science goals

Giant Radio Array for Neutrino Detection = 200'000 antennas over 200'000 km^2 (~ Great Britain area)

Going to be the largest ground-based detector for UHE particles

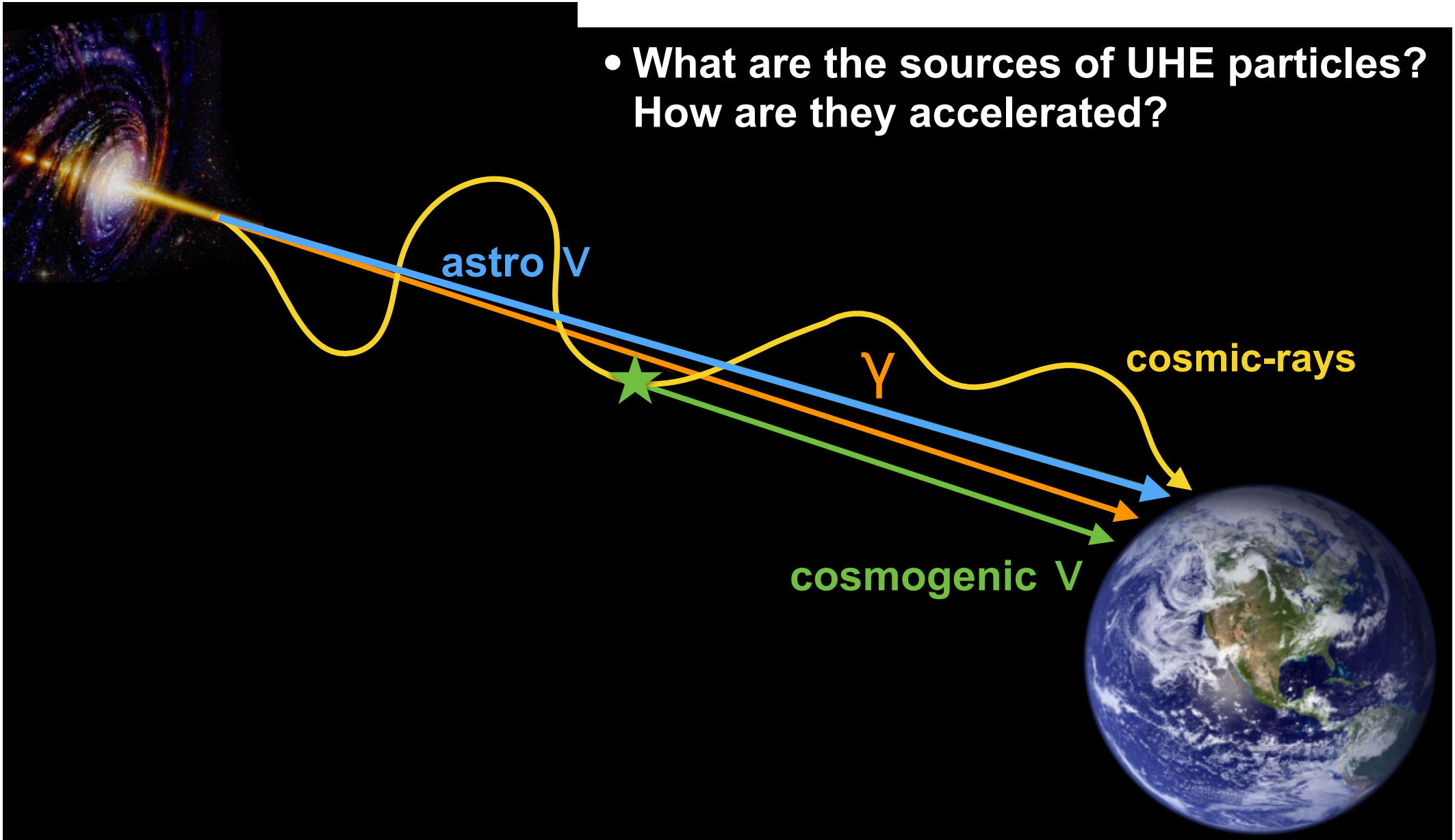


+ EAS physics

+ Extreme electromagnetic atmosphere events (Elfs, Sprites, etc.)

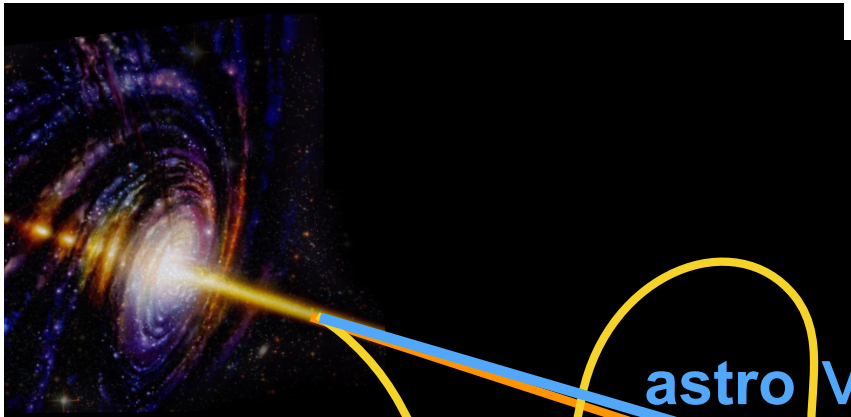
Ultra HE astronomy

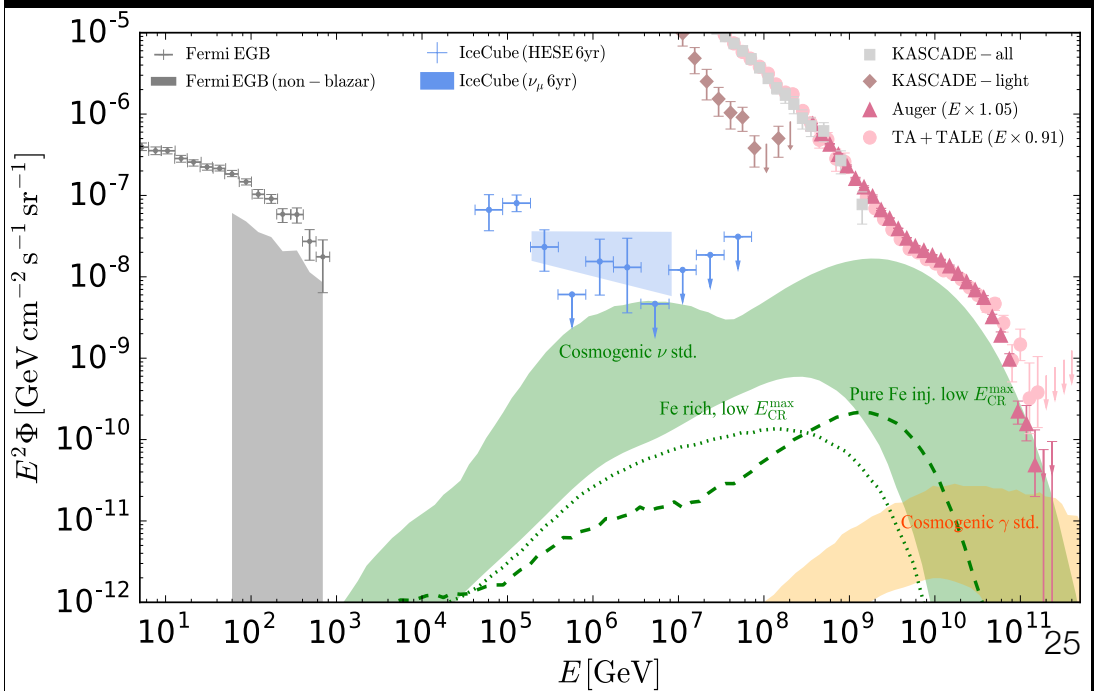
- What are the sources of UHE particles? How are they accelerated?

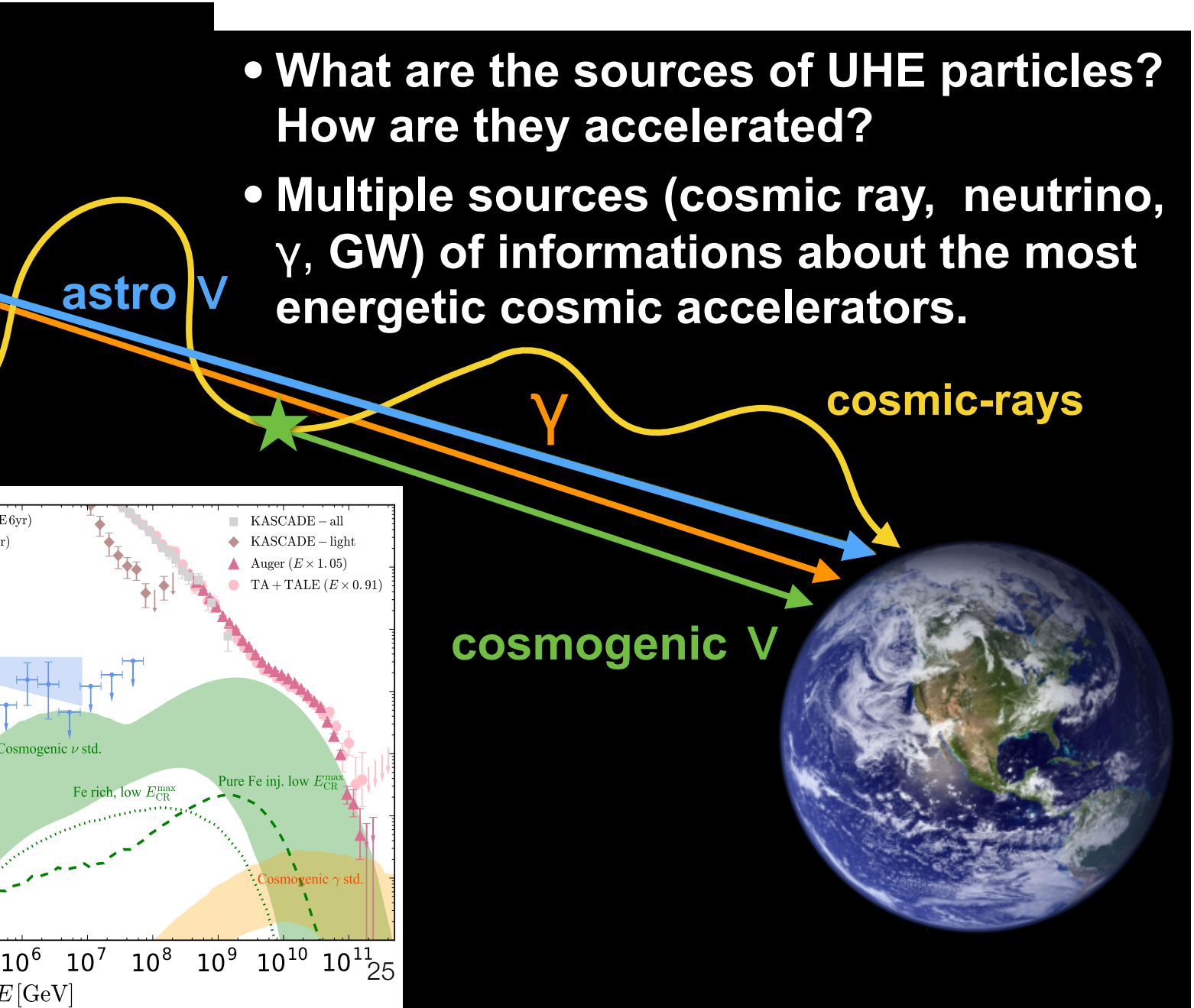


Ultra HE astronomy

- What are the sources of UHE particles? How are they accelerated?
- Multiple sources (cosmic ray, neutrino, γ, GW) of informations about the most energetic cosmic accelerators.

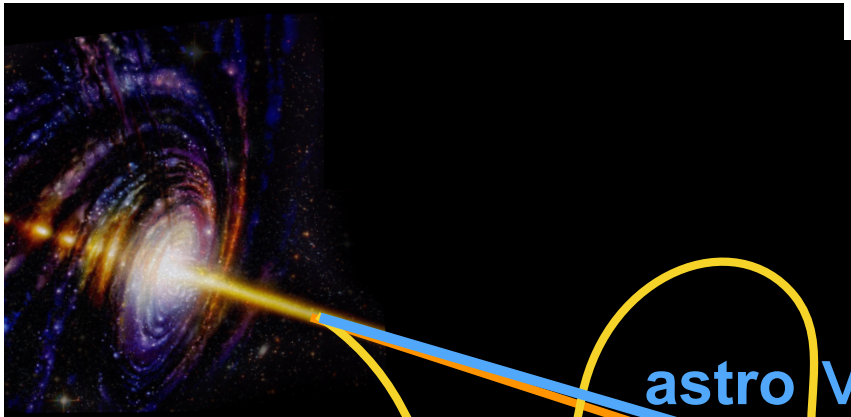


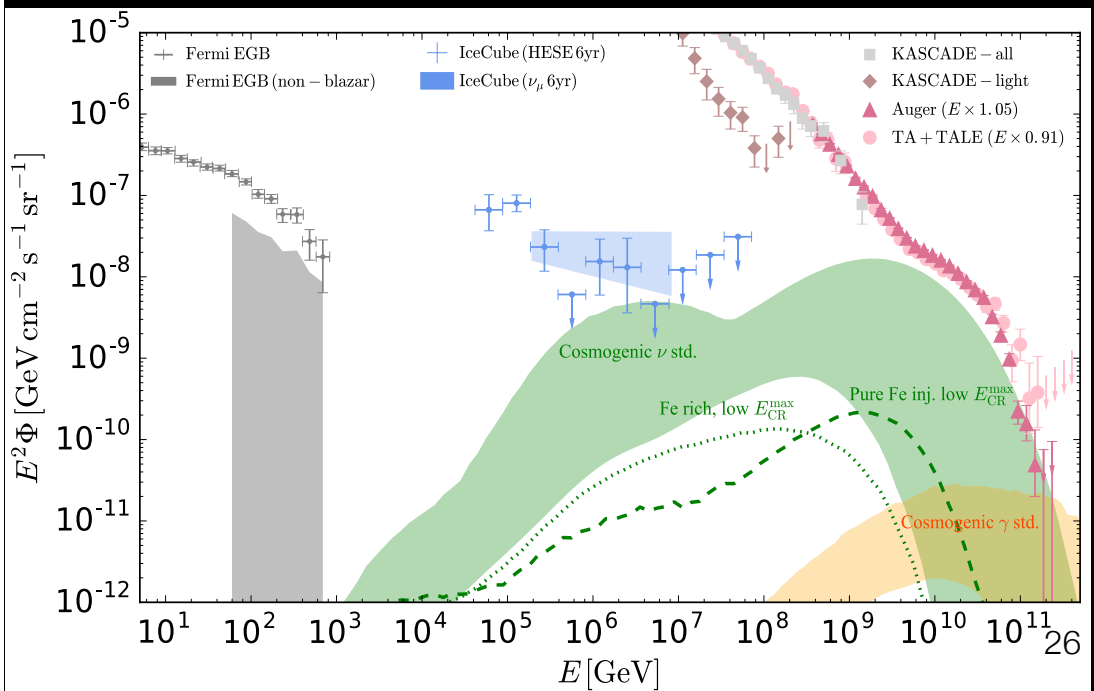


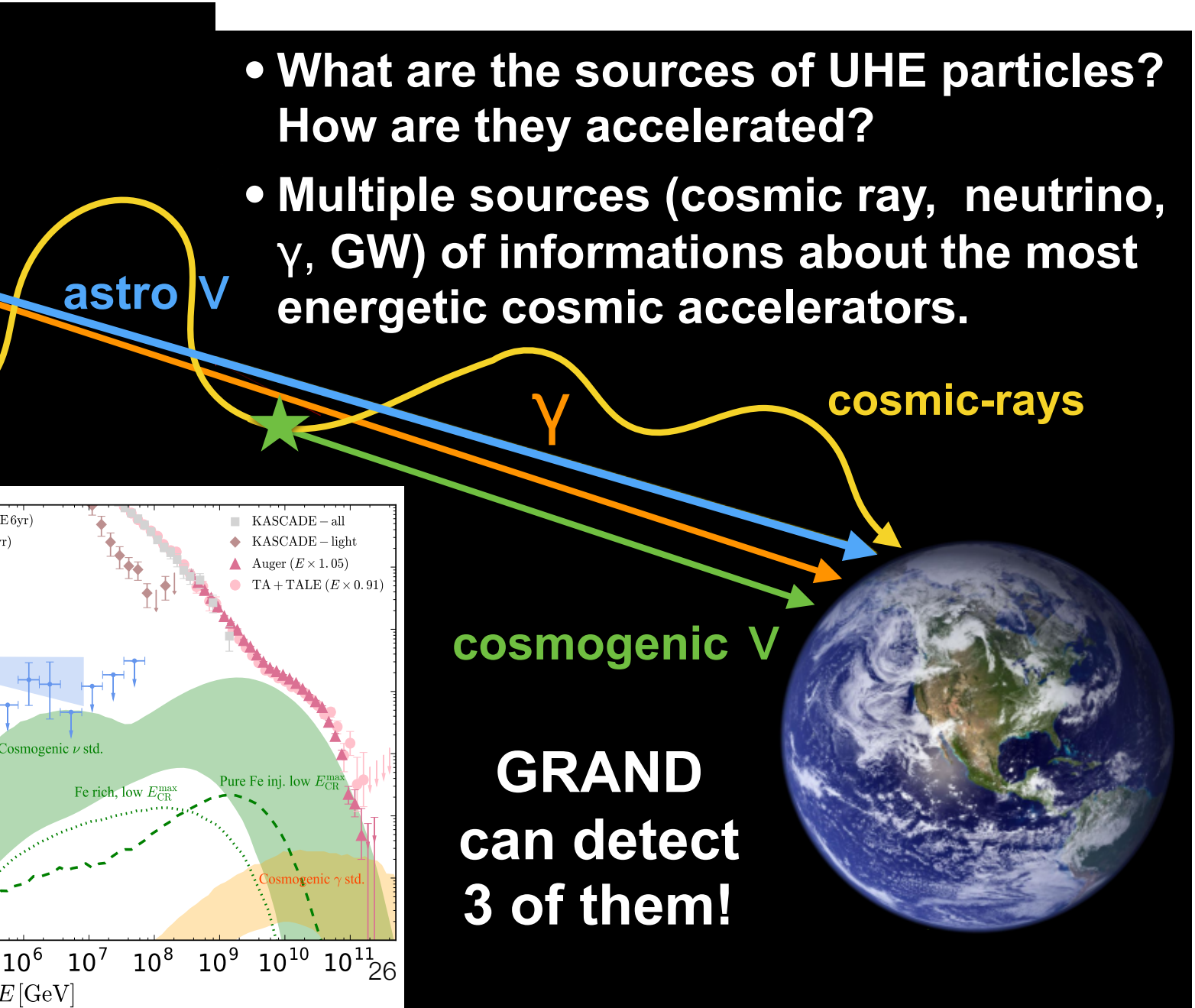


Ultra HE astronomy

- What are the sources of UHE particles? How are they accelerated?
- Multiple sources (cosmic ray, neutrino, γ, GW) of informations about the most energetic cosmic accelerators.

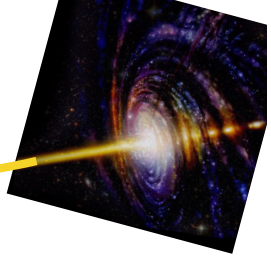






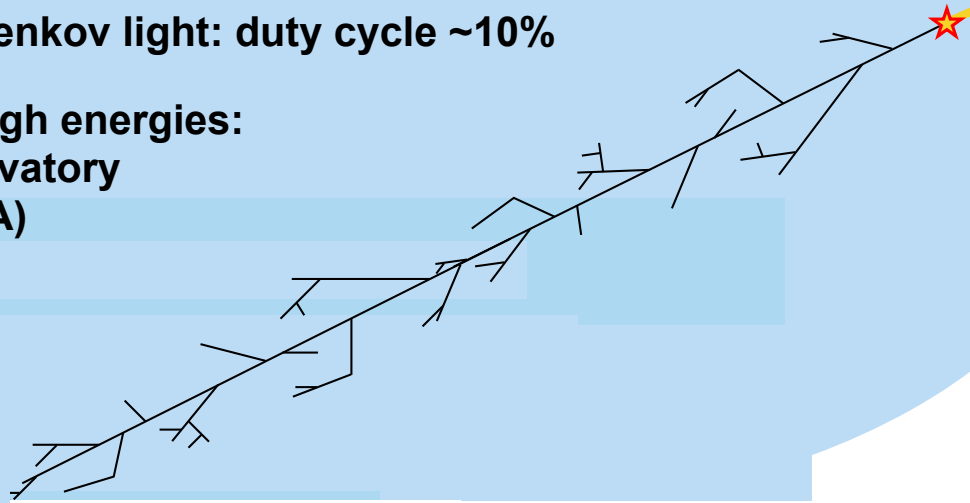
GRAND can detect 3 of them!

How does it work?

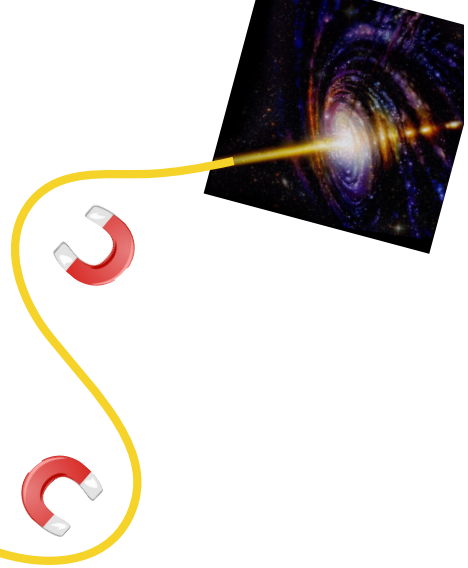


- **Indirect detection techniques via air-shower measurements:**
  - **Particle detectors:**
  muon component → very sensitive to hadronic interaction models
  - **Fluorescence/Cherenkov light: duty cycle ~10%**

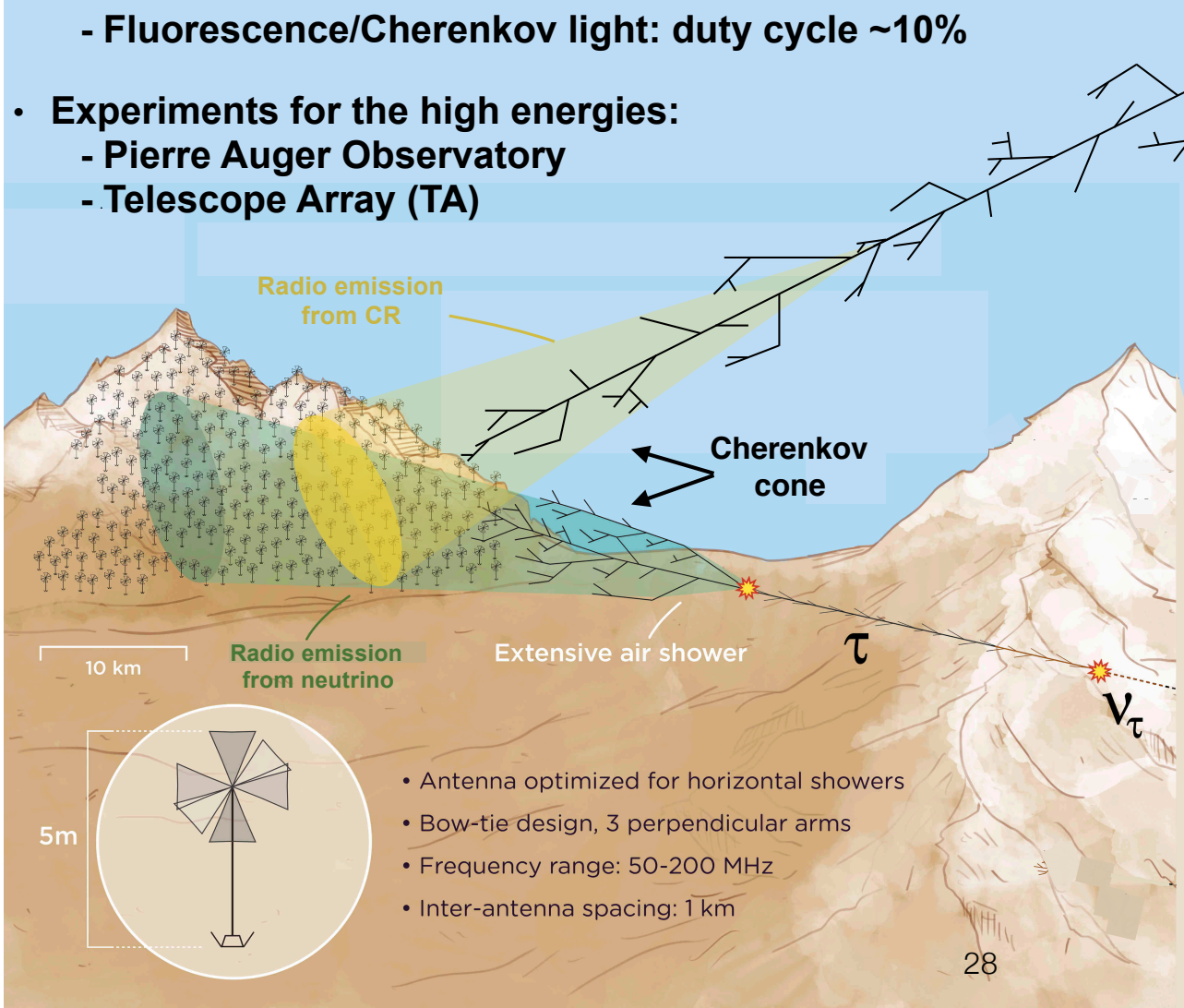
- **Experiments for the high energies:**
  - **Pierre Auger Observatory**
  - **Telescope Array (TA)**



How does it work?

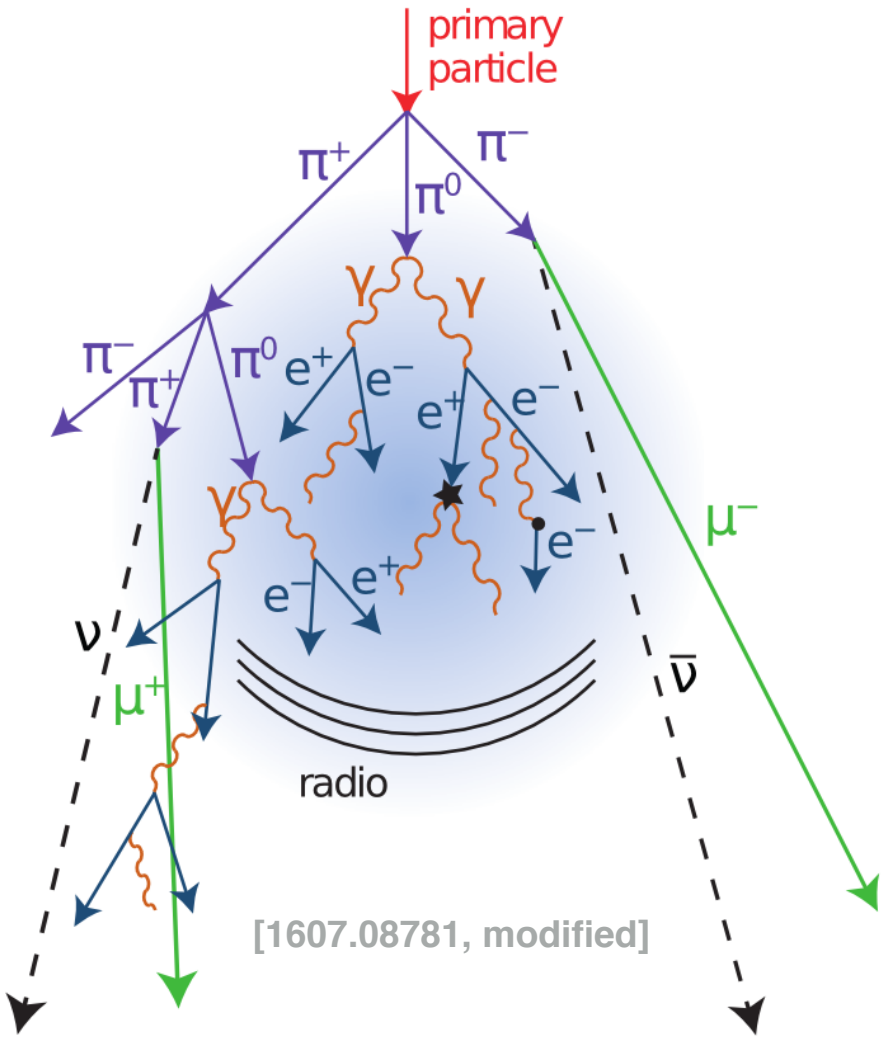


- **Indirect detection techniques via air-shower measurements:**
  - **Particle detectors:**
    muon component → very sensitive to hadronic interaction models
  - **Fluorescence/Cherenkov light: duty cycle ~10%**
- **Experiments for the high energies:**
  - **Pierre Auger Observatory**
  - **Telescope Array (TA)**



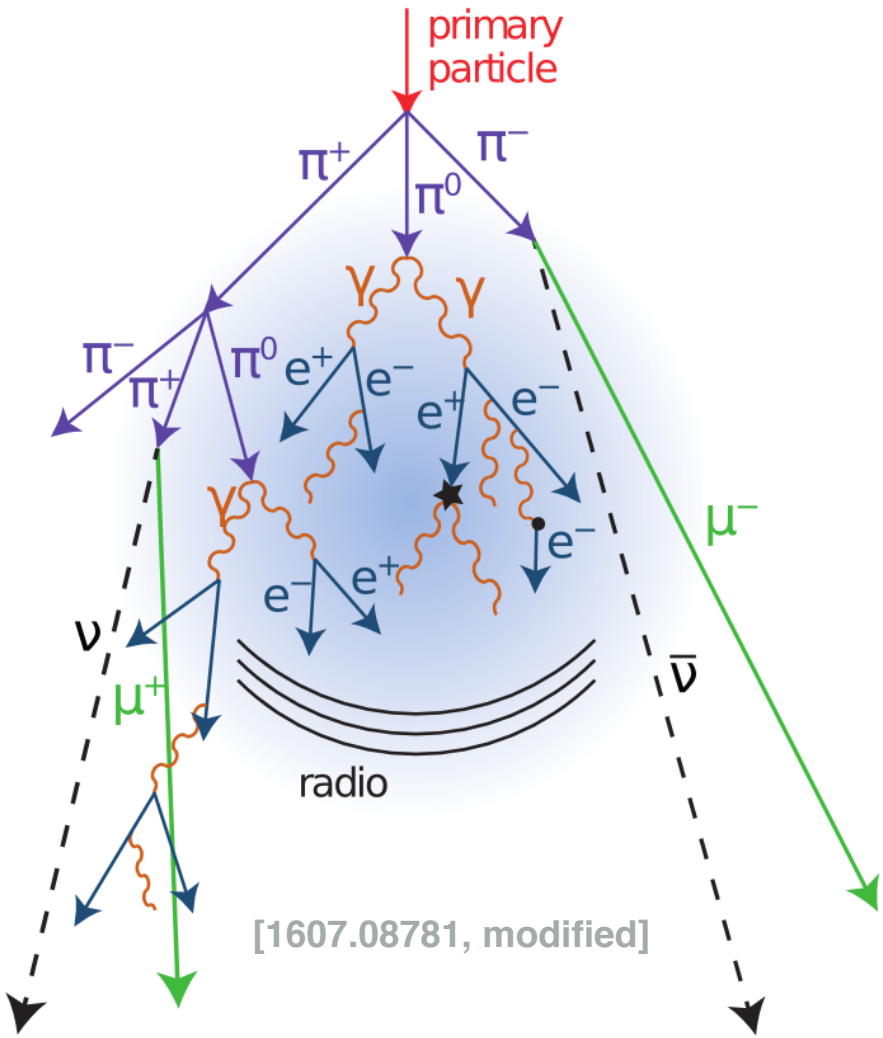
- **Radio detection:**
  - **close to 100% duty cycle + measure EM component → independent on hadronic interaction models**
- **Experiments:**
  - **AERA, LOFAR**
  - **pilot experiments ARA, ARIANNA, ANITA, TUNKA-REX**

Extensive Air Shower



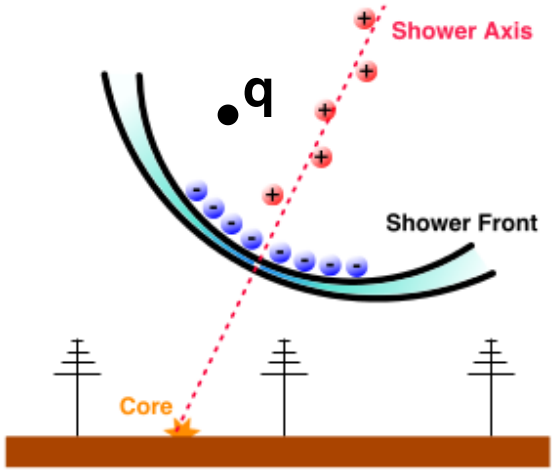
[1607.08781, modified]

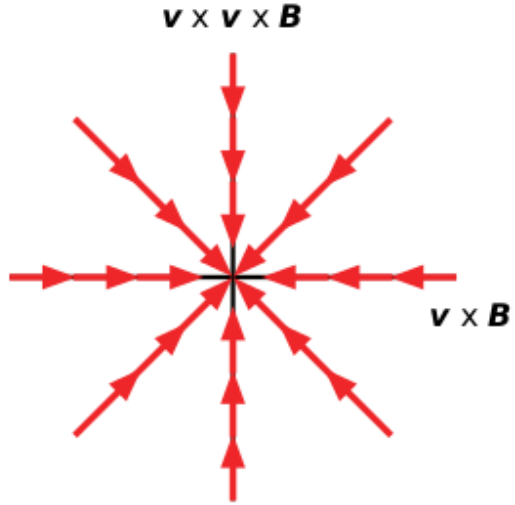
Extensive Air Shower



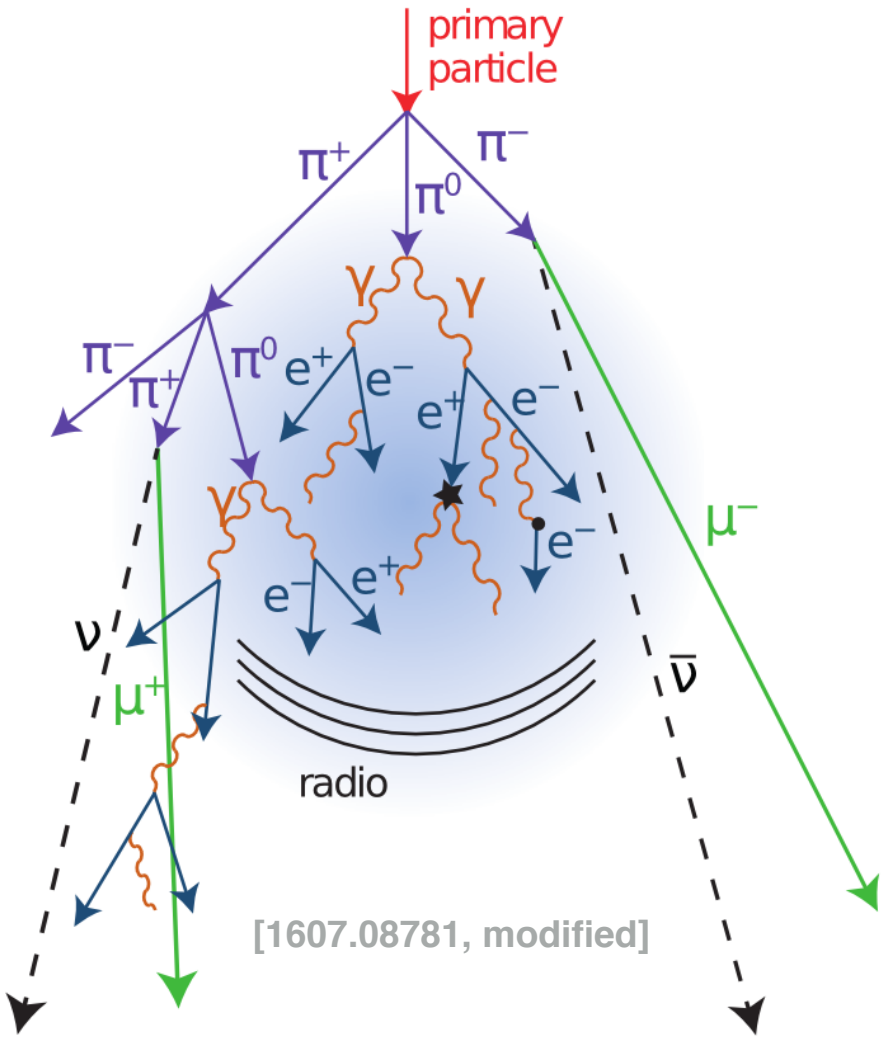
[1607.08781, modified]

Askaryan effect: $E \sim d(n_e - n_p)/dt$
→ time variation of net charge excess



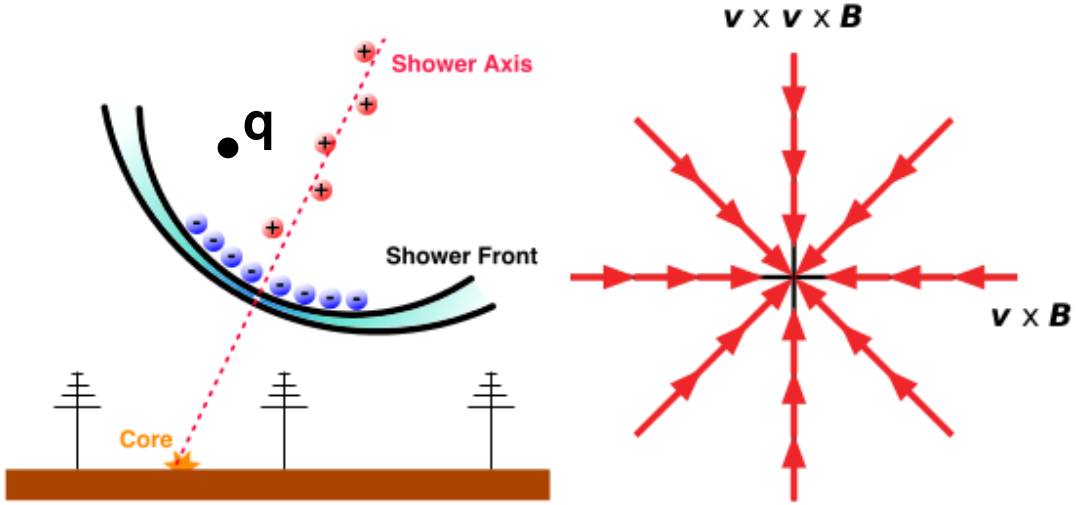


Extensive Air Shower

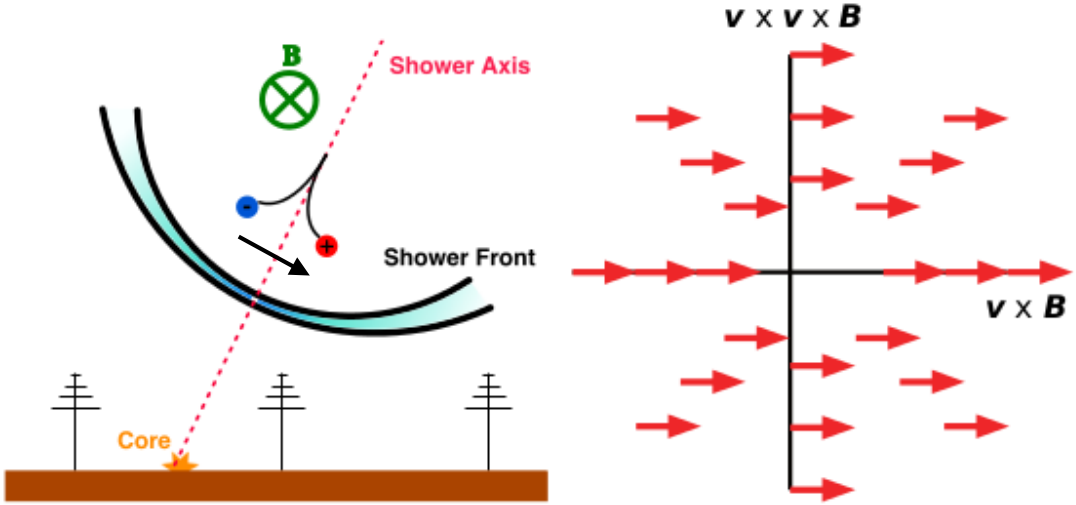


[1607.08781, modified]

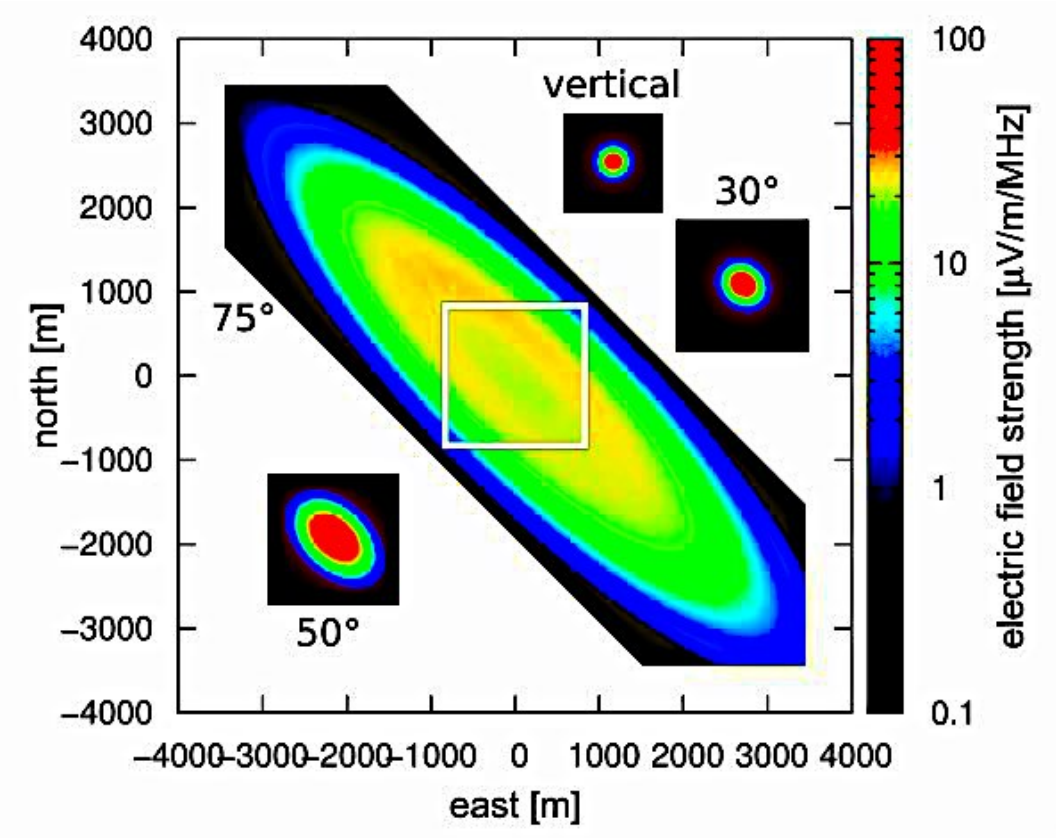
Askaryan effect: $E \sim d(n_e - n_p)/dt$
→ time variation of net charge excess



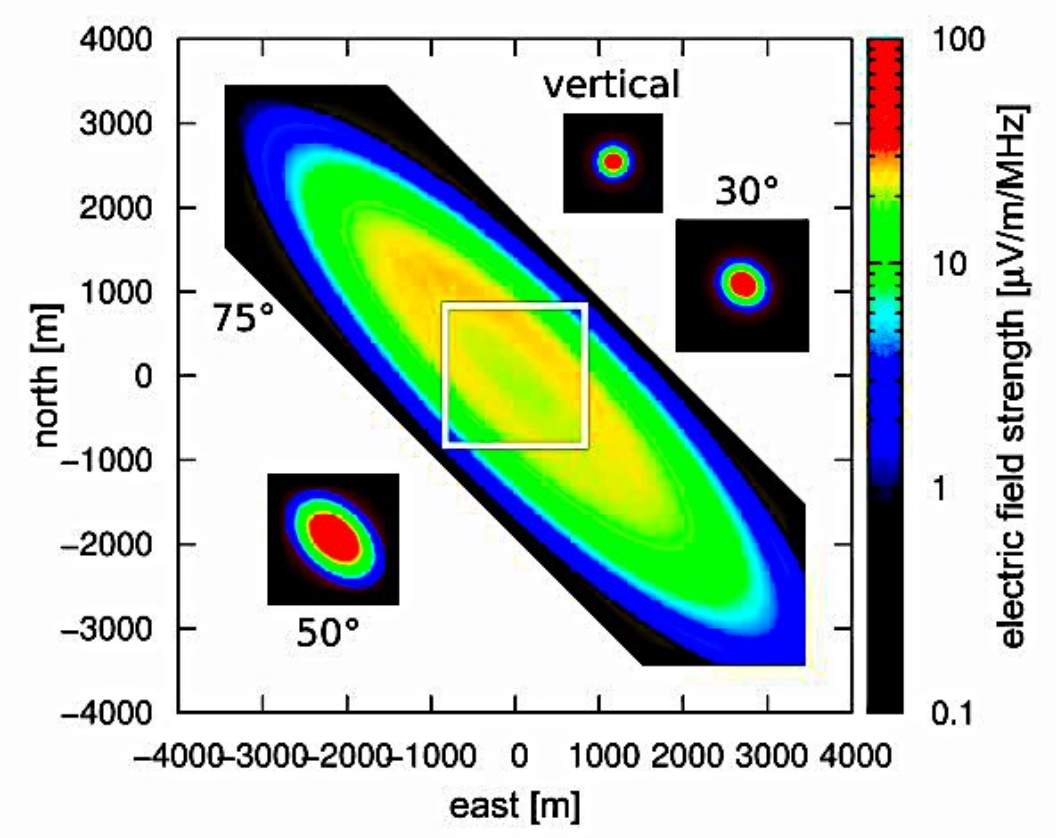
Geomagnetic effect: $E \sim dn_{ch}/dt$
→ time dependent transverse current

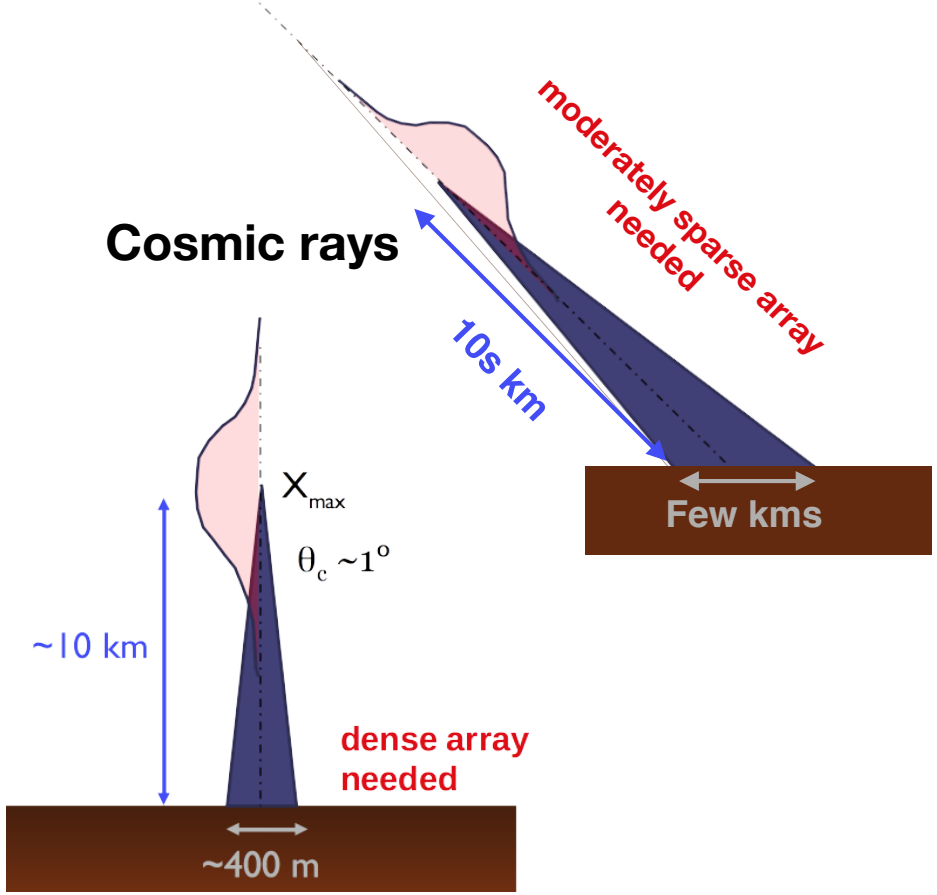


Radio detection of EAS?

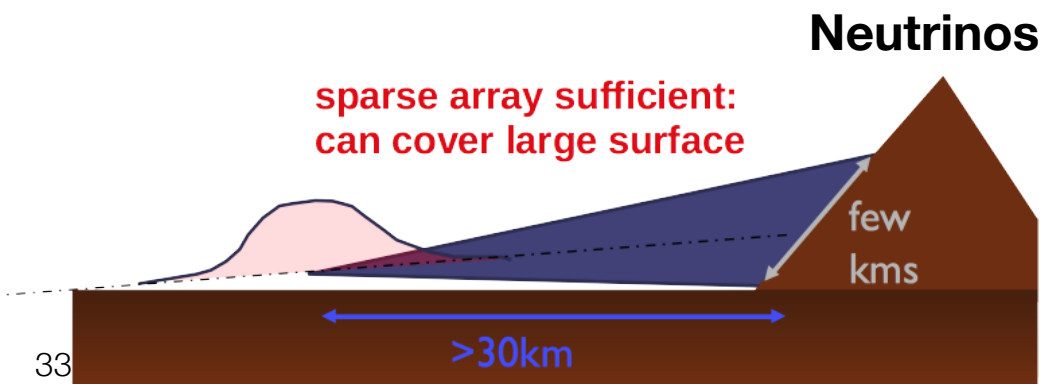


Radio detection of EAS?

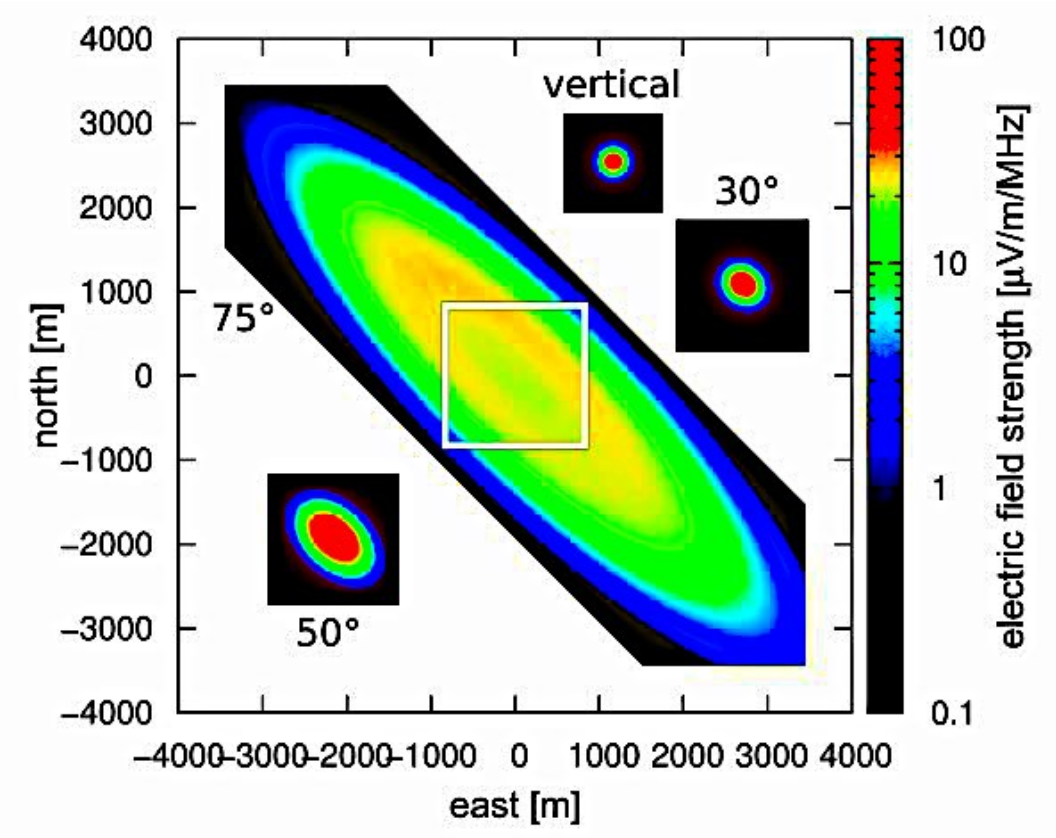


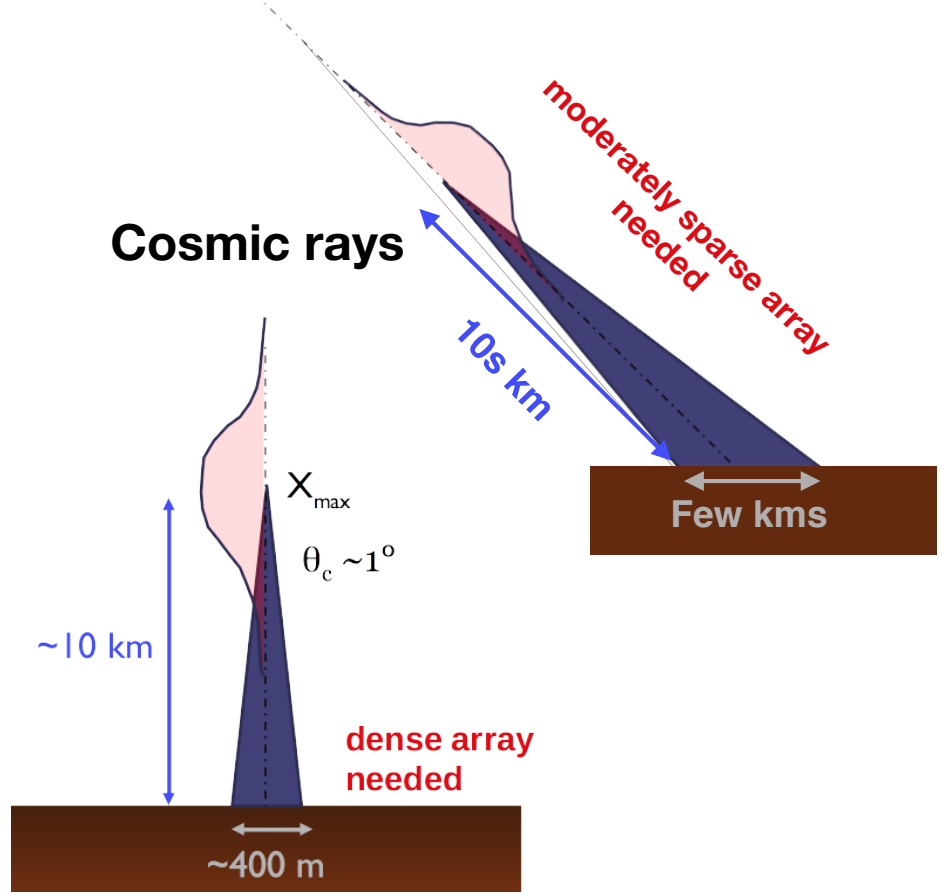


- Footprint becomes large for large zenith



Radio detection of EAS?

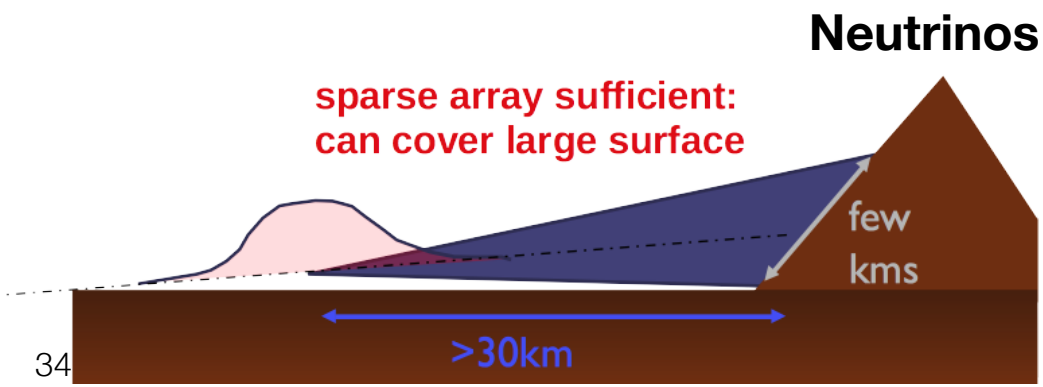




- Footprint becomes large for large zenith
- Radio signal not absorbed by atmosphere
  ⇒ ability to detect horizontal air showers
- radio technique scalable to large areas

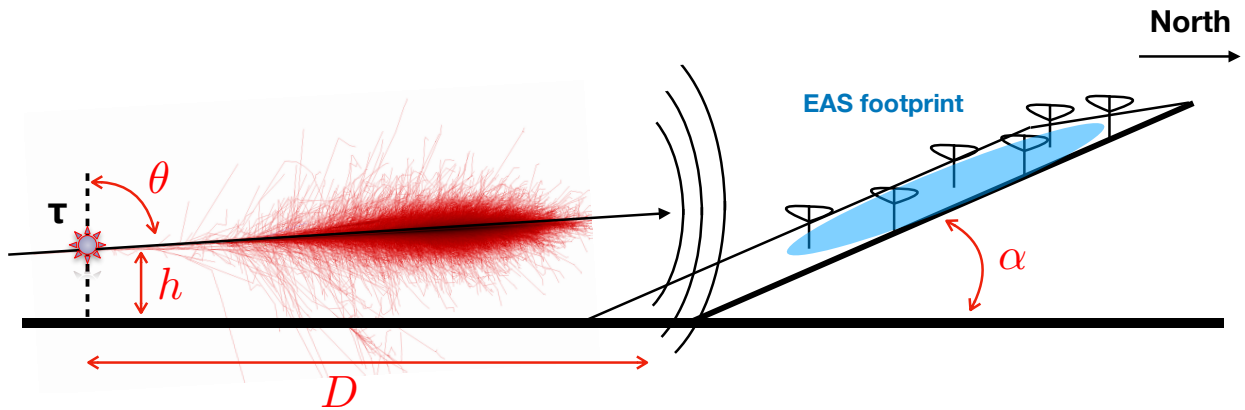
⇒ Antenna array with kms-spacing possible!

- large exposure for moderate costs



Influence of topography

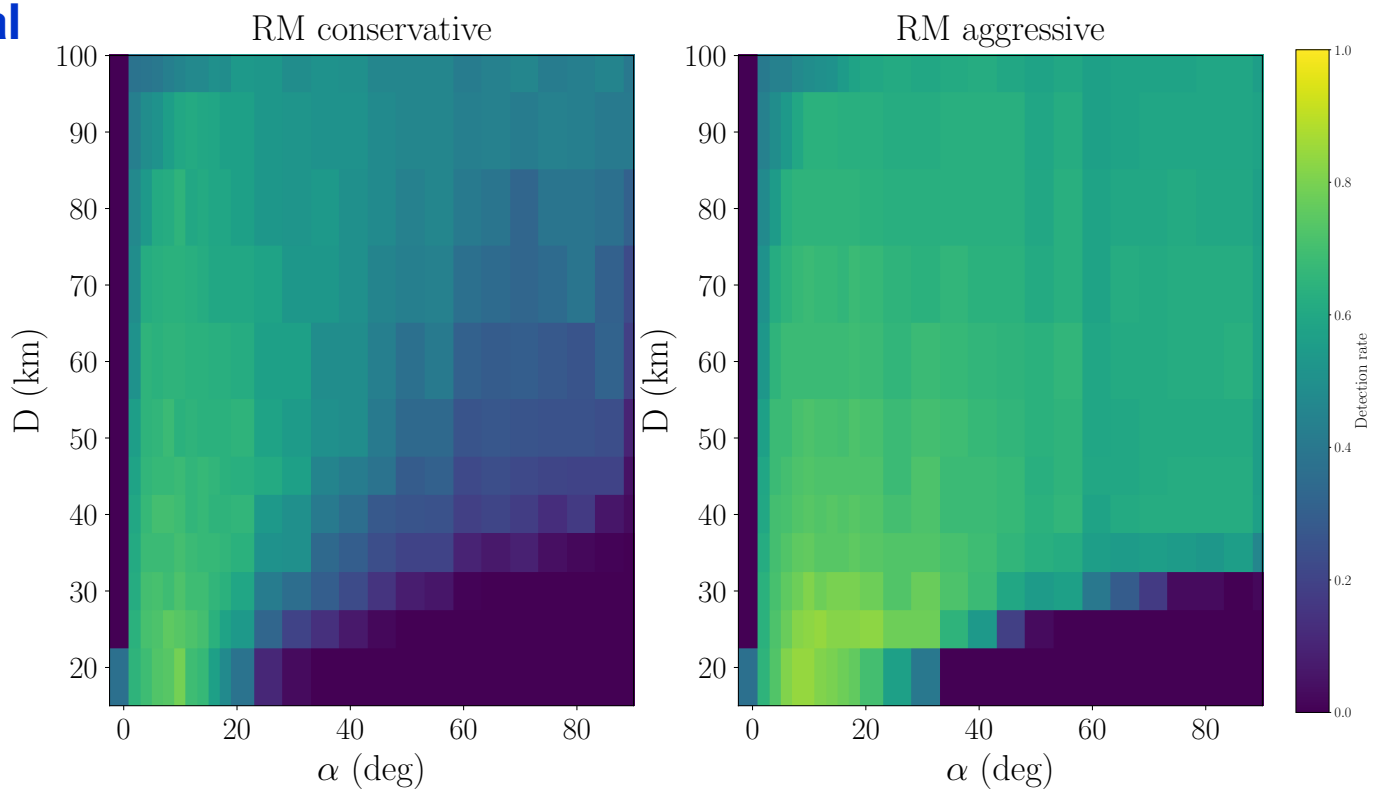
- **Simulations with a ToyModel**
- **Varying parameters :**
  - **Distance between decay point (=start of EAS) and mountain foot**
  - **Slope of the mountain**



- **EAS all flying north**
  - **simulated from physical neutrino flux**
  - **accounting for interactions in Earth**

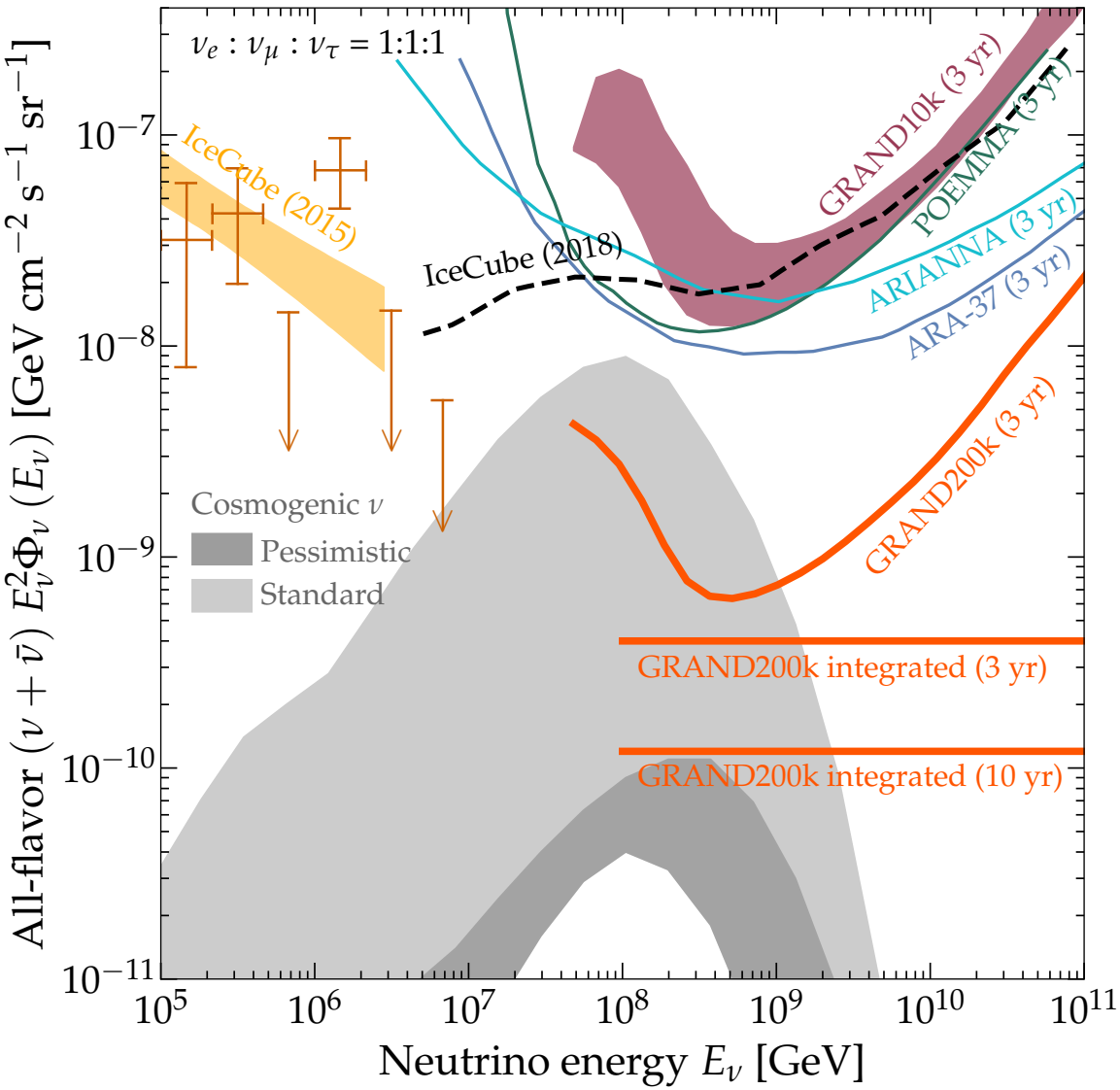
- **Best configuration :**
  - **D,α ~ 20-40km, 10°**
  - **Fraction of detected events ~ 70-90%**

➡ **Search for hotspots with favourable topography to enhance detection rate**



Cosmogenic Neutrino

- **For cosmogenic neutrinos (from interactions of CR with CMB photon field), GRAND =**
  - **discovery and precision instrument for optimistic fluxes**
  - **strong-exclusion instrument for pessimistic cases**

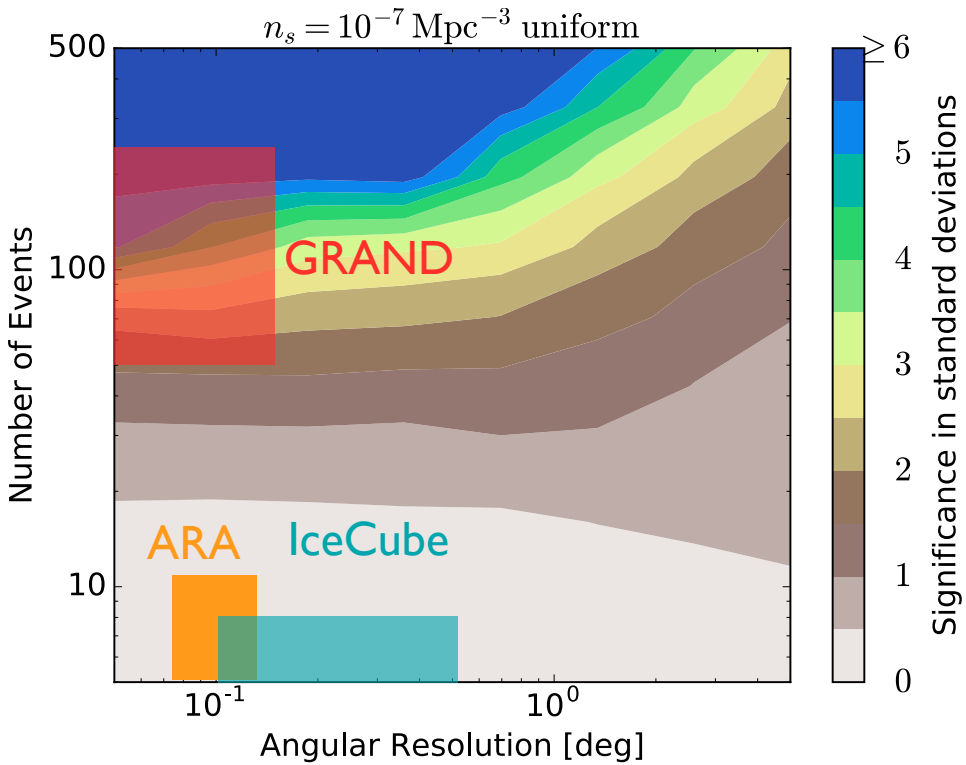


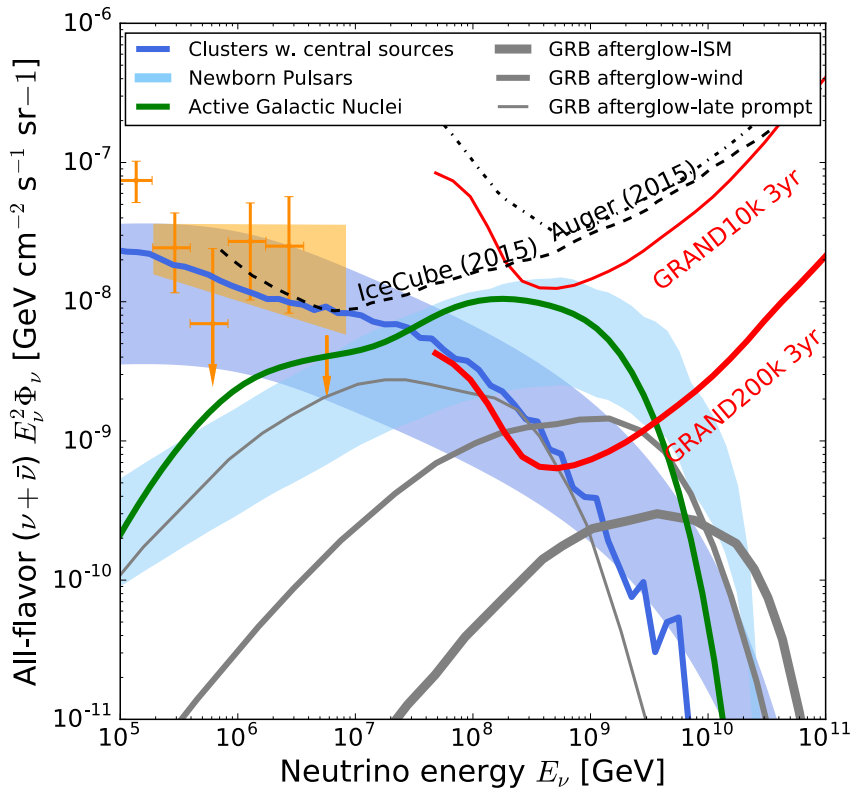
Neutrino Astronomy

To allow point source to stand out of diffuse background, one need

- **good angular resolution (fraction of degree)**
- **number of detected events > 100s**

To estimate neutrino production directly from various sources

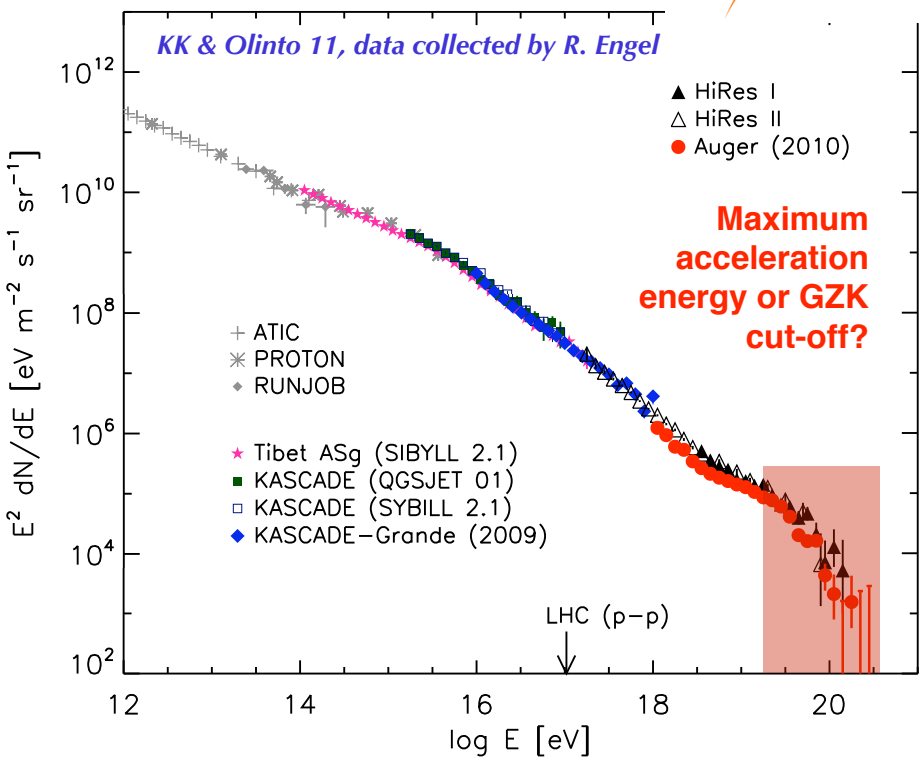




UHECR science

More statistics needed for:

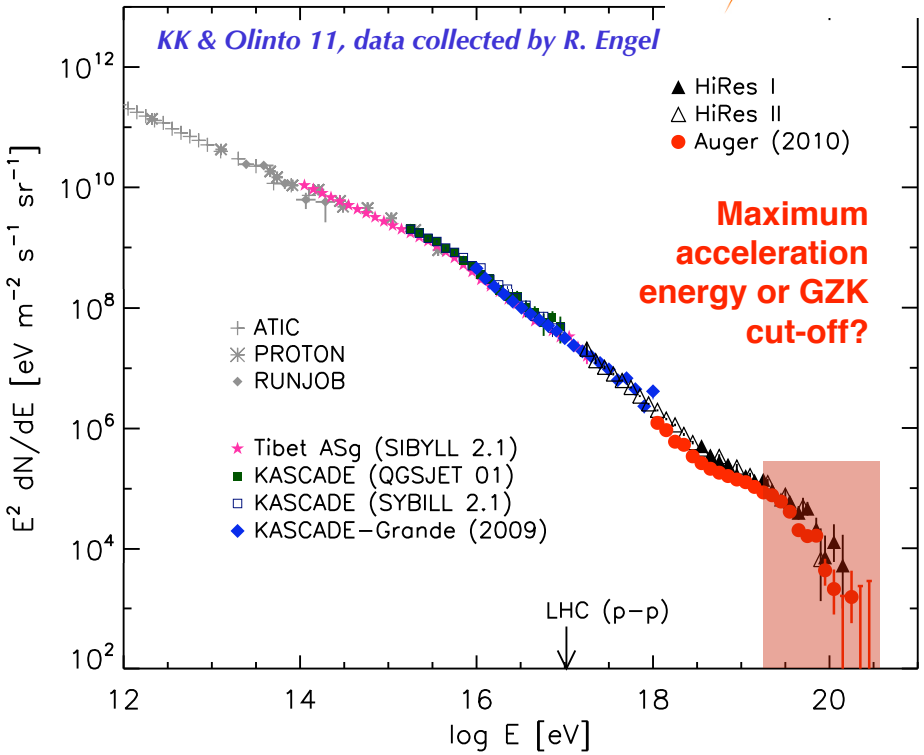
- **Shape of energy spectrum at highest E**

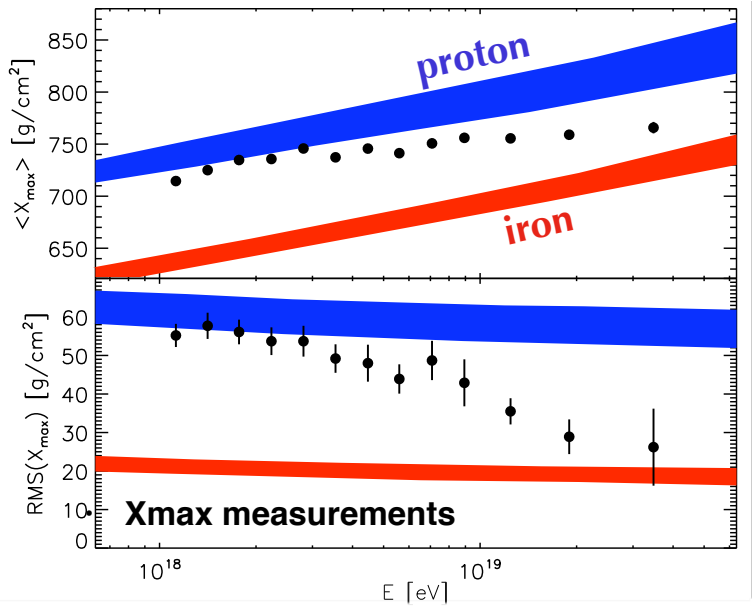


UHECR science

More statistics needed for:

- **Shape of energy spectrum at highest E**
- **Chemical composition at highest E**



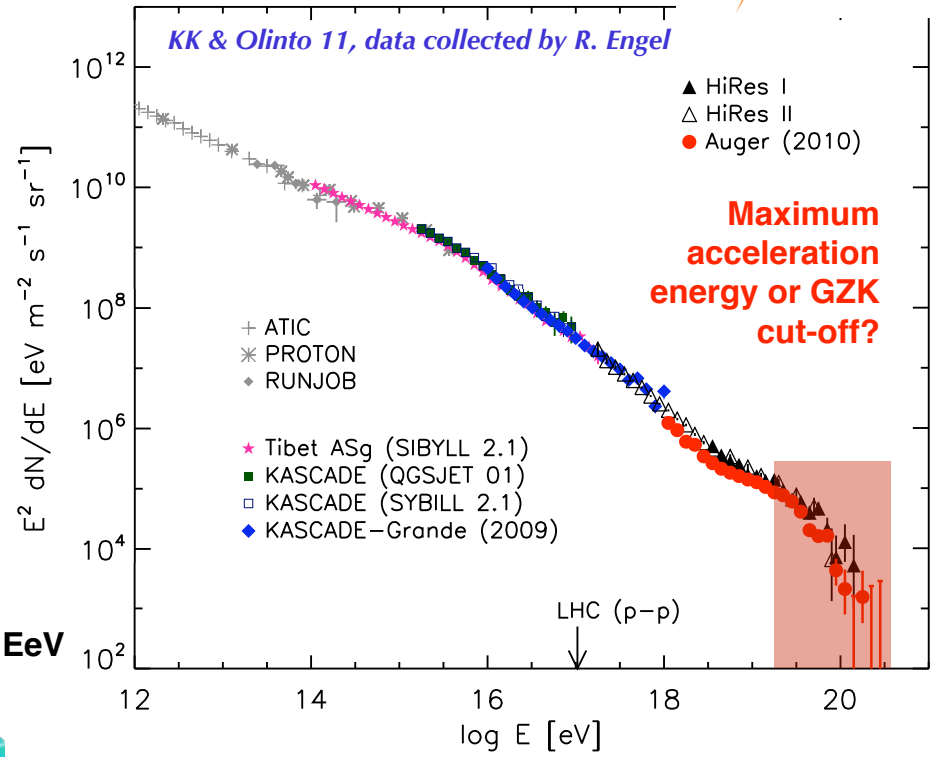


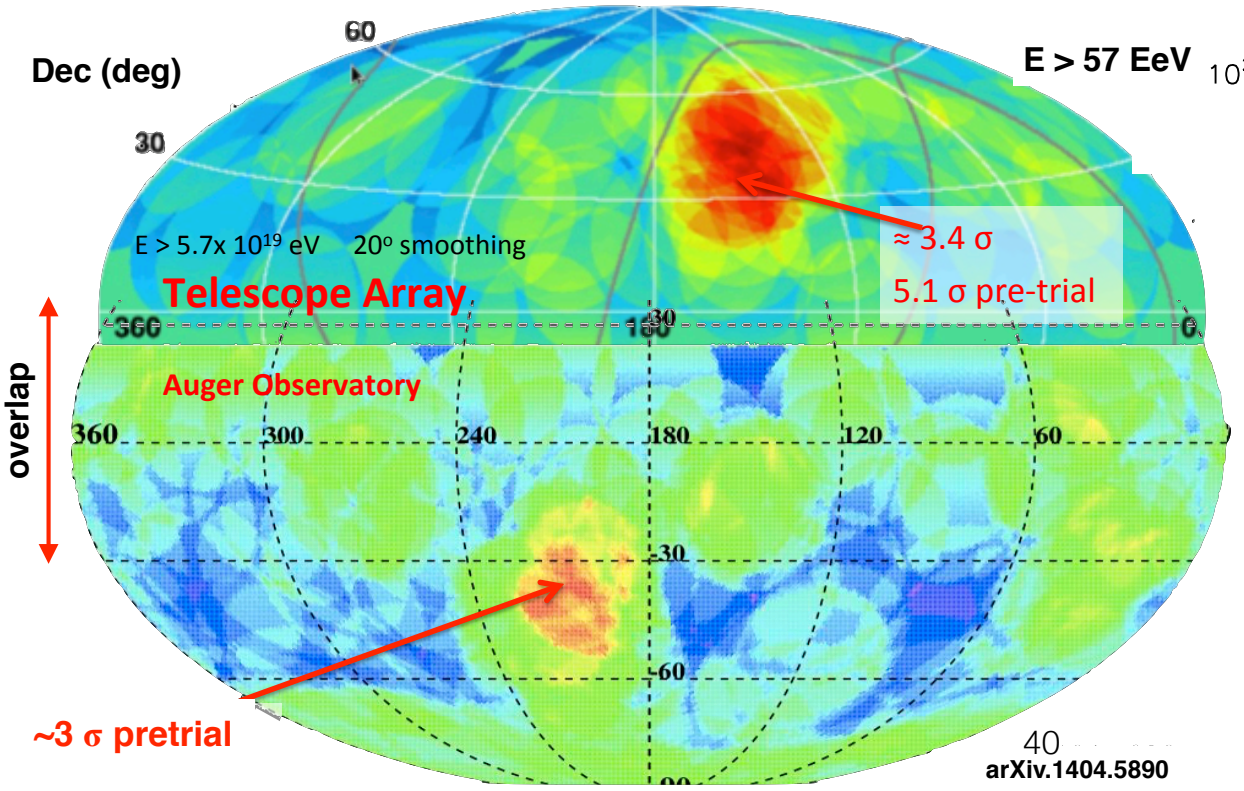
UHECR science

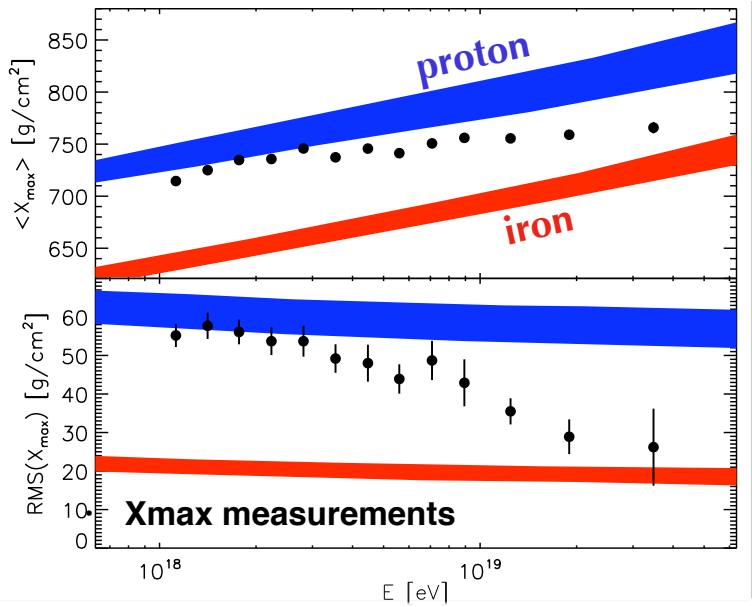
More statistics needed to unravel:

- **Shape of energy spectrum at highest E**
- **Chemical composition at highest E**
- **Anisotropy signatures (steady/transient sources)**

⇒ GRAND will provide such large exposure !







arXiv.1404.5890

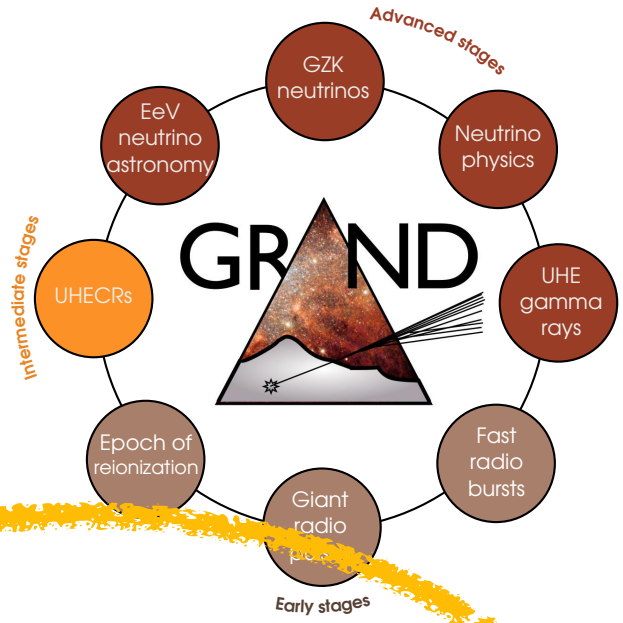
Outline

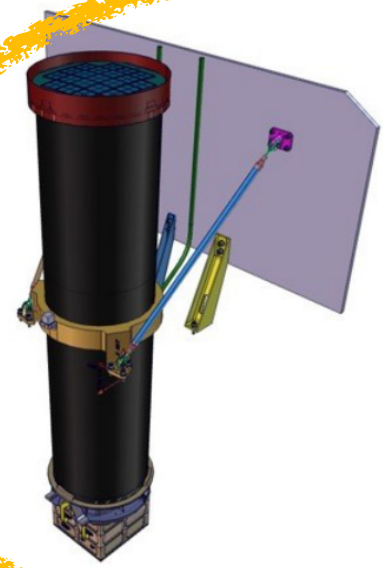
(2017→)

Instruments to observe the cosmic accelerators

GRAND performances
Influence of topography

Cosmic-ray sensitivity,…





MXT
Spectral calibration

Instrumental Response Function definition

Softwares, …

What's SVOM?

Primary goal :
Detection, localisation and spectroscopy of GRBs

ECLAIRs =
Detection of the GRB + 1st localisation in X and soft γ rays

MXT = Microchannel X-ray telescope
2nd localisation + X-ray follow-up of the GRB afterglow

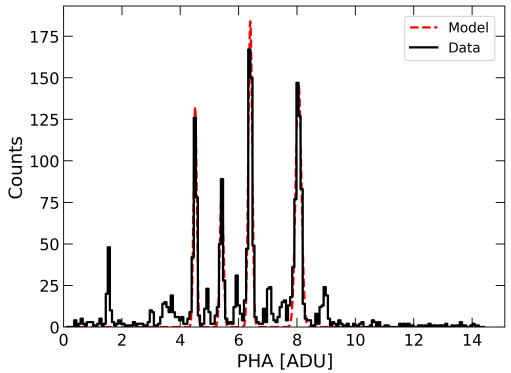
VT = Visible Telescope
3rd localisation + optical and IR follow-up of the GRB afterglow

GRM = γ-Ray Monitor
Localisation + hard X-ray and γ-ray observation of the GRB

GFT = Ground Follow-up Telescope
Optical and IR follow-up on ground

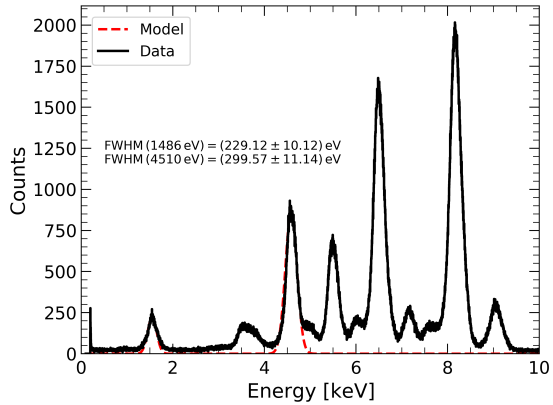
GWAC = Ground-based Wide Angle Camera
Monitor precursor emission in optical

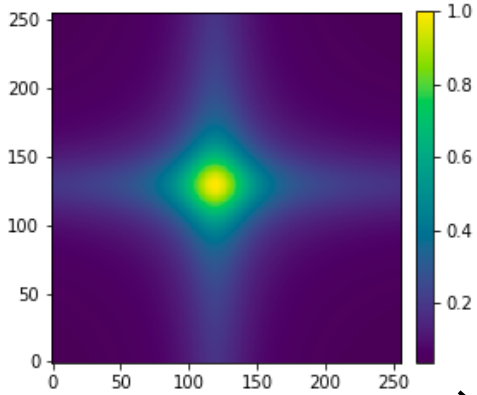
Instrument Responses



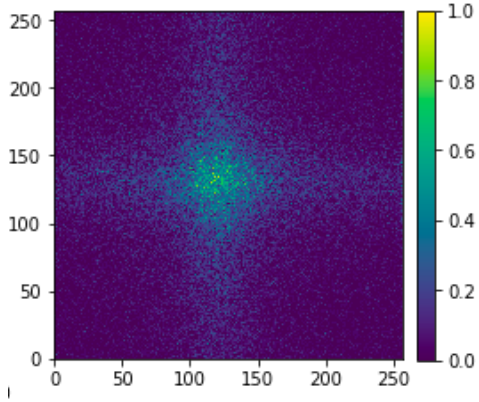
Spectral Calibration

Multi-line X-ray source



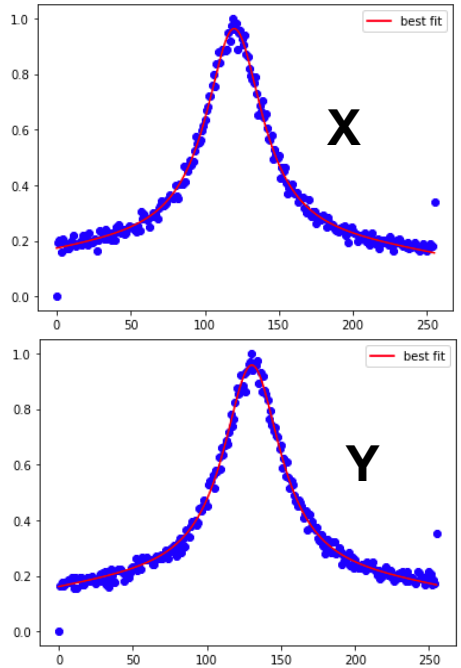


Simulation



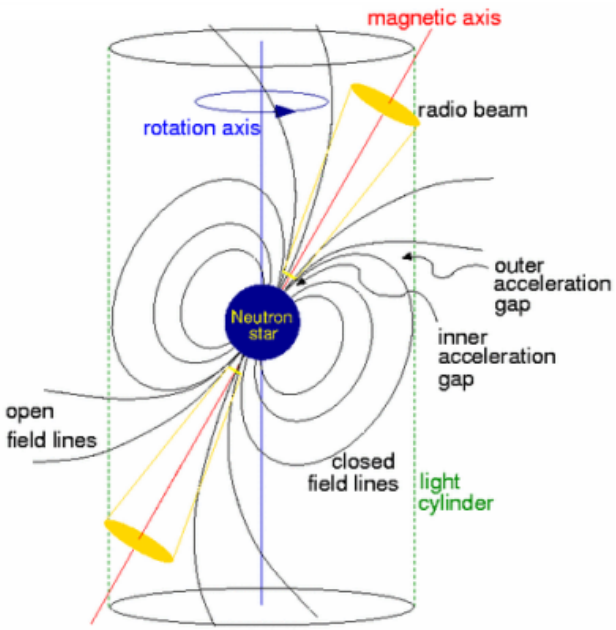
Random draw

Fit



- **In February, upcoming tests at the PANTER facility in Munich with the optic mounted on the camera**
- **And also in the future :**
  - **Ground/Flight Calibration Protocol,**
  - **Software development,**
  - **...**

Conclusion

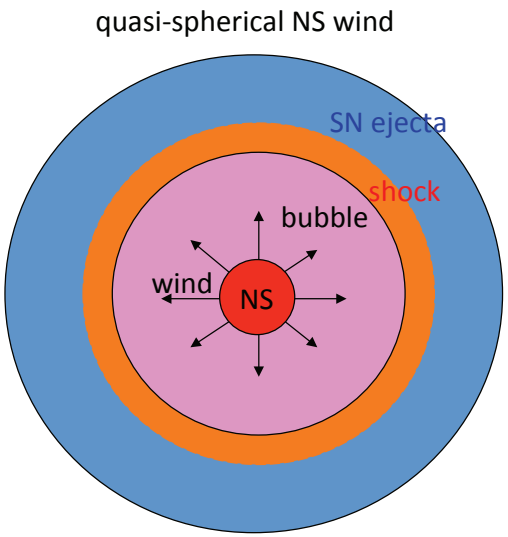


(→2017)

Pulsars, Origin of many phenomena

γ-ray millisecond pulsar phase-resolved spectroscopy

Search for γ-ray signals from super-luminous SNe

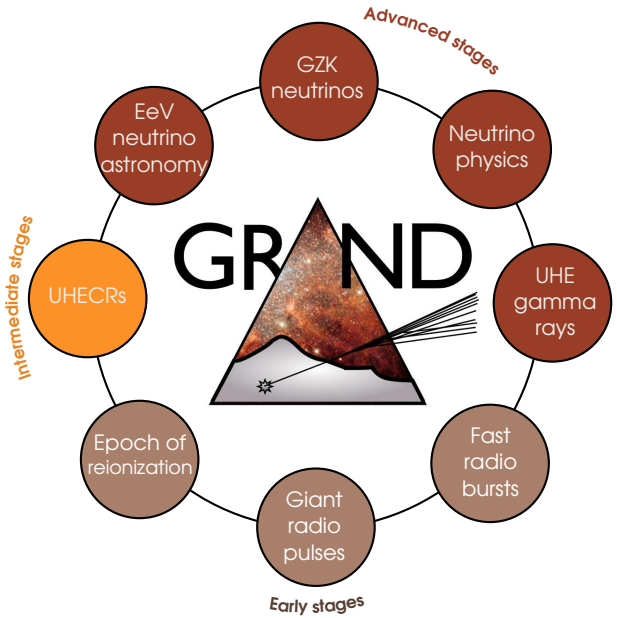


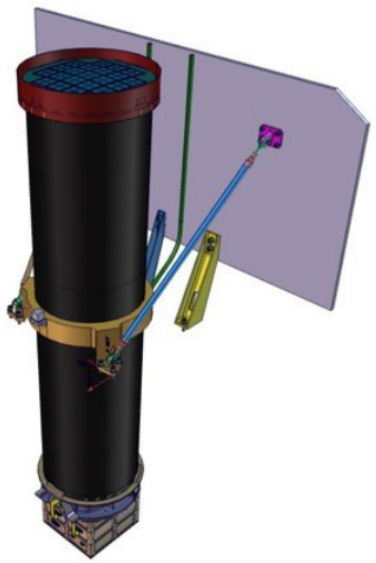
(2017→)

Instruments to observe the cosmic accelerators

GRAND performances Influence of topography

Cosmic-ray sensitivity,…



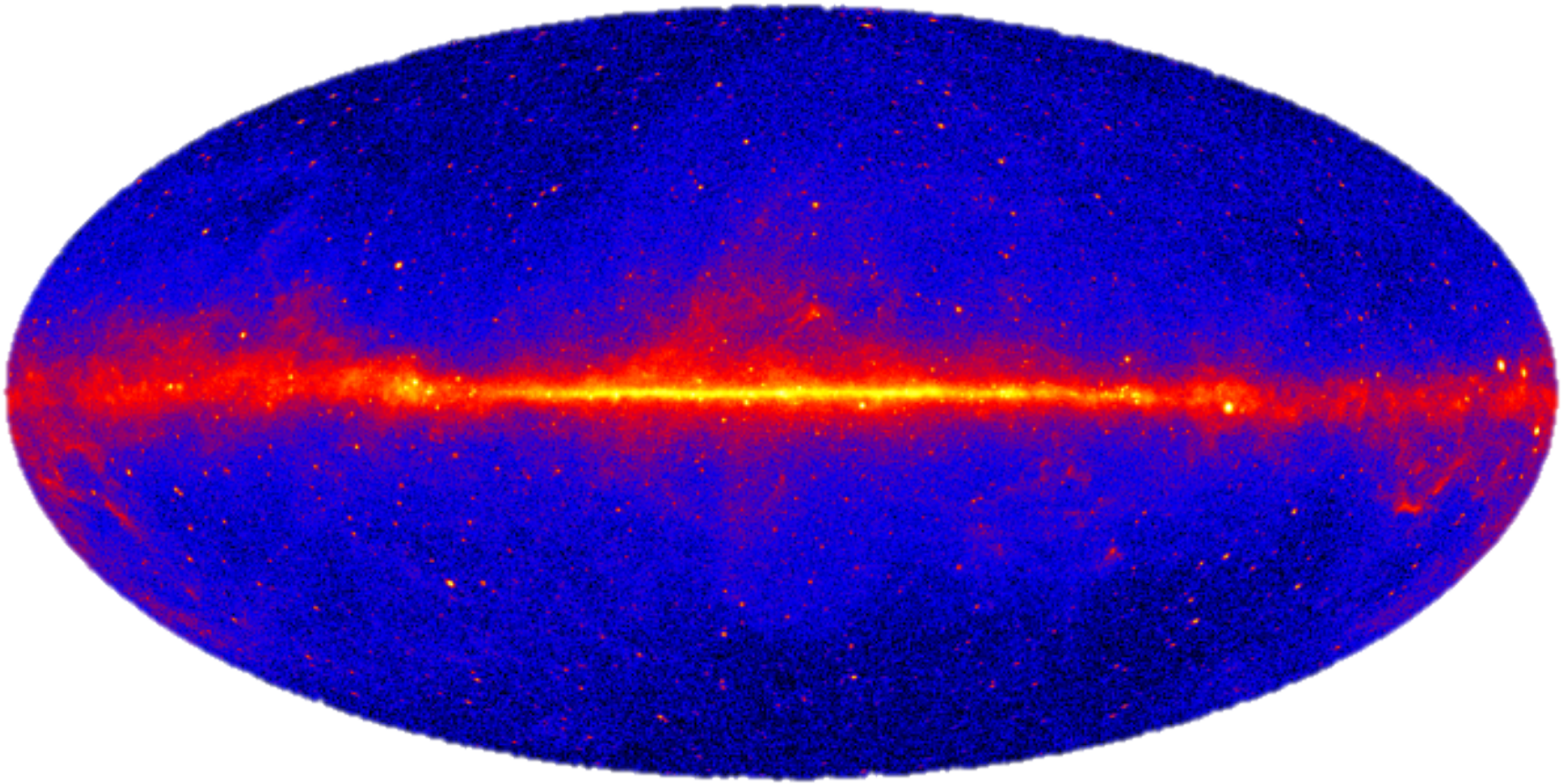


MXT
Spectral calibration

Instrumental Response Function definition

Softwares, …

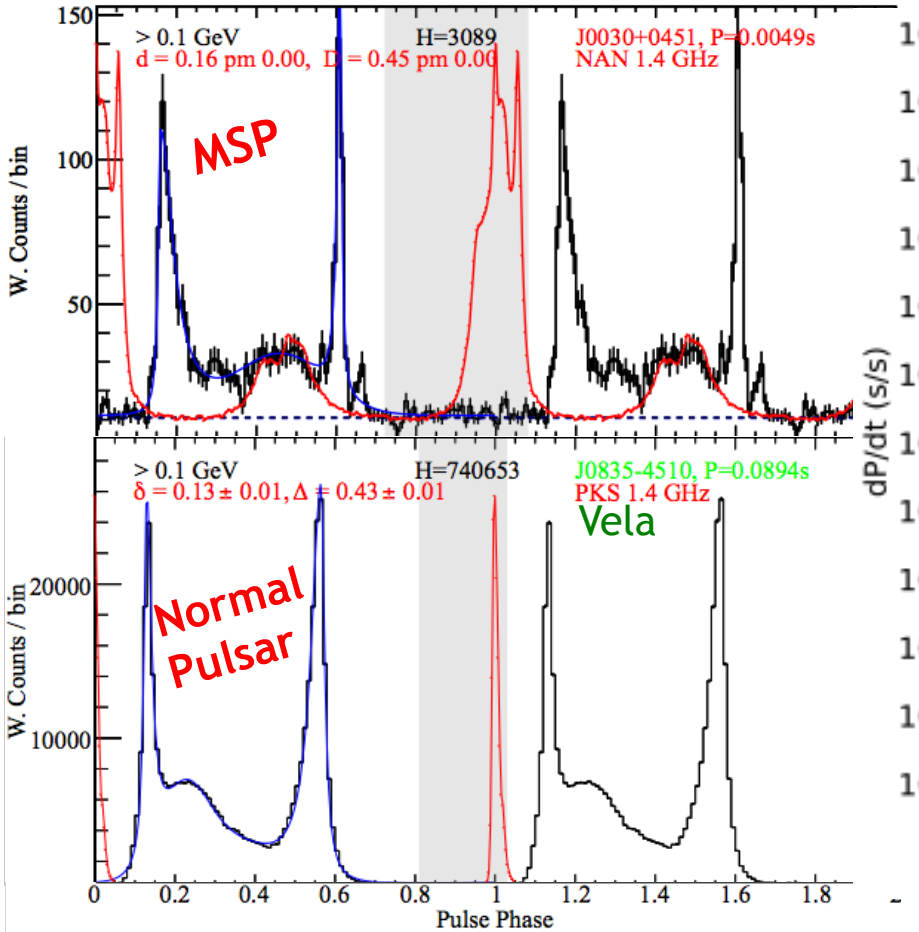
Thank you for your attention

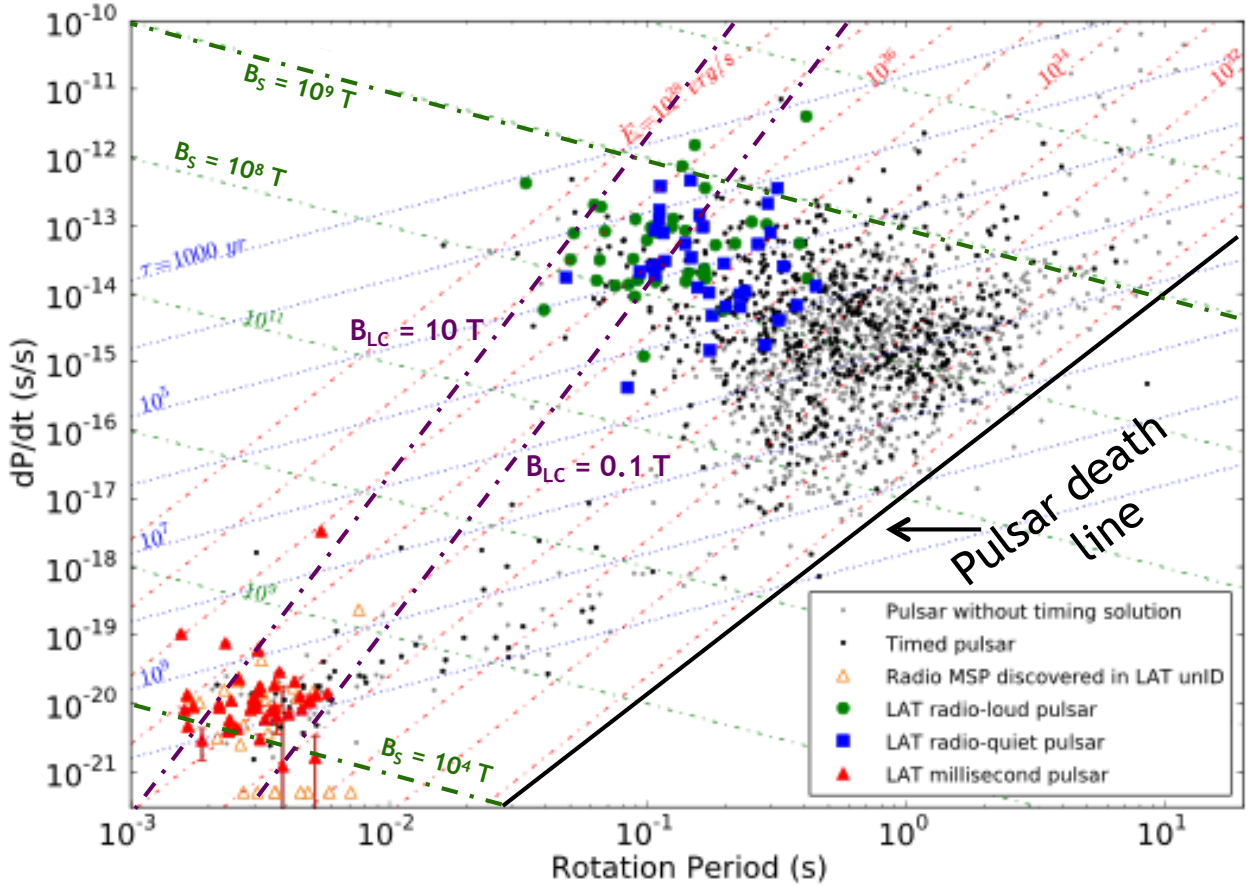


⬇ Back-up ⬇

Why MSPs ?

Second Fermi-LAT Pulsar Catalog, Abdo et al. 2013

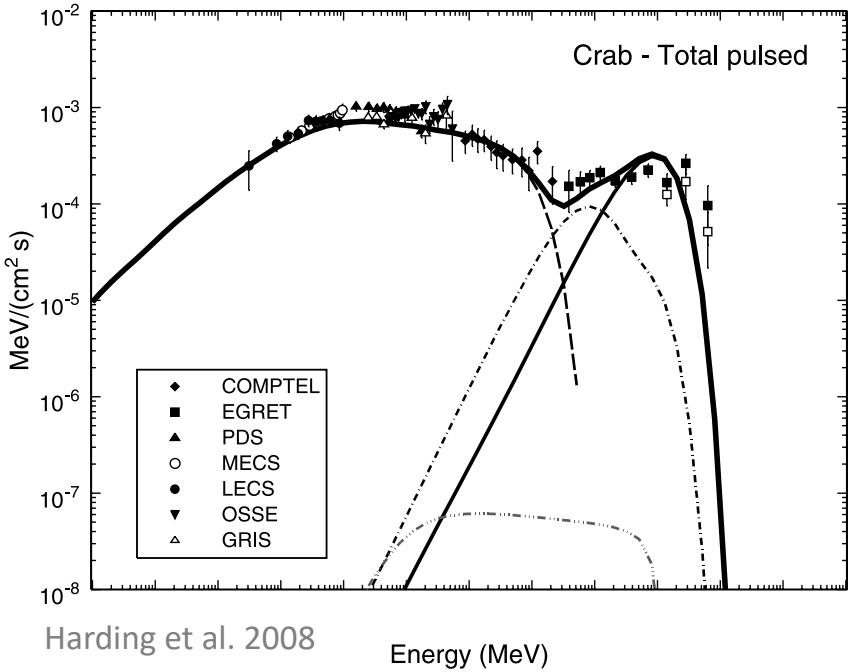




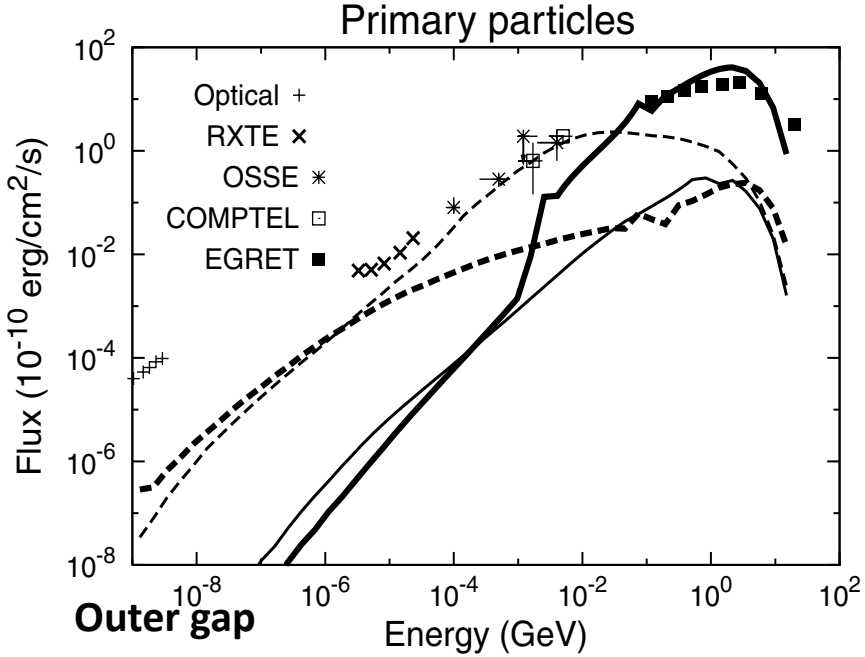
- Growing γ-ray pulsar class
  - (≈45% of detected pulsars)
- Sharp MSP γ-ray profiles
  - → thin gaps → high pair densities
  - similar to young pulsars

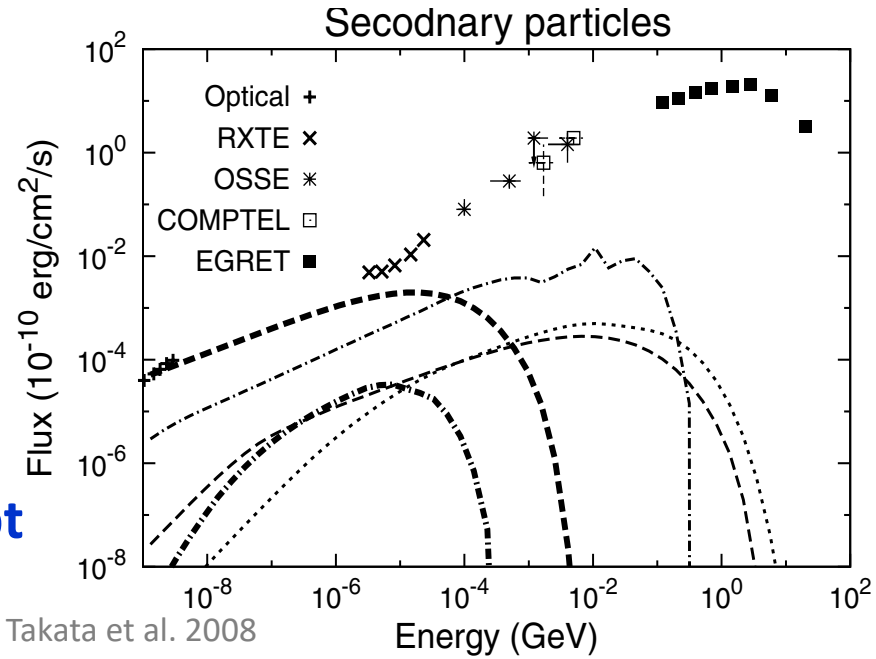
- More compact magnetospheres :
  - same B_{LC} → similar acceleration & radiation processes
- MSP larger stability
- But MSPs are fainter pulsars
  → spectral analyses more difficult

MSP spectral sequence



Harding et al. 2008

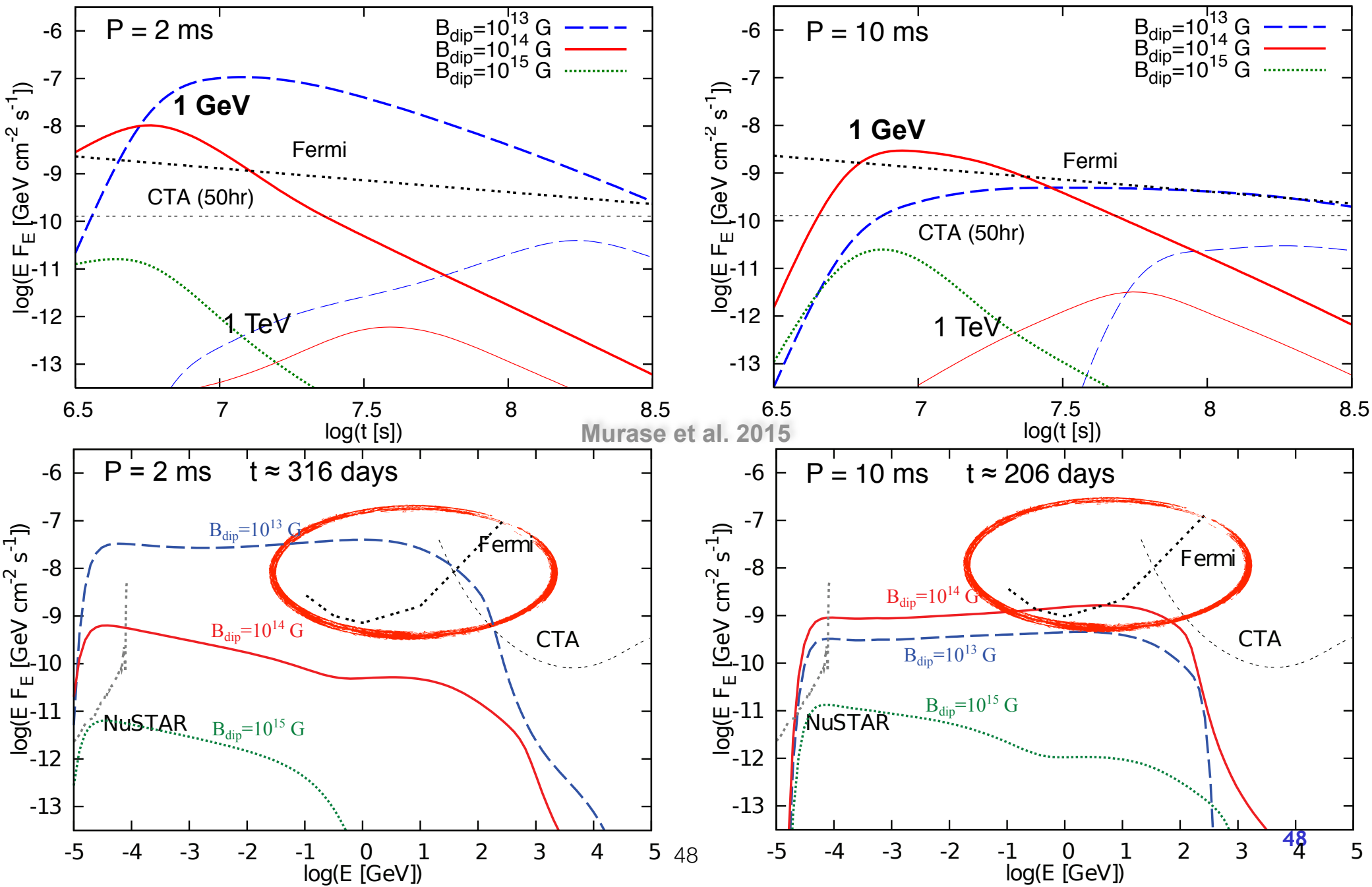




Takata et al. 2008

- **For the Slot Gap or Outer Gap models**
  - **Synchroton component (cyclotron resonant absorption of radio photons)**
    - **from primary pairs**
- **For the Outer Gap (Wang et al. 2010) or the FIDO models (Kalapotharakos 2014)**
  - **Transition from $E_{//} \neq 0$ to $E_{//} = 0$ not abrupt**
    - **➔ CR at few hundreds MeV**

- Super-luminous SN luminosity plateau lasting over few months/years



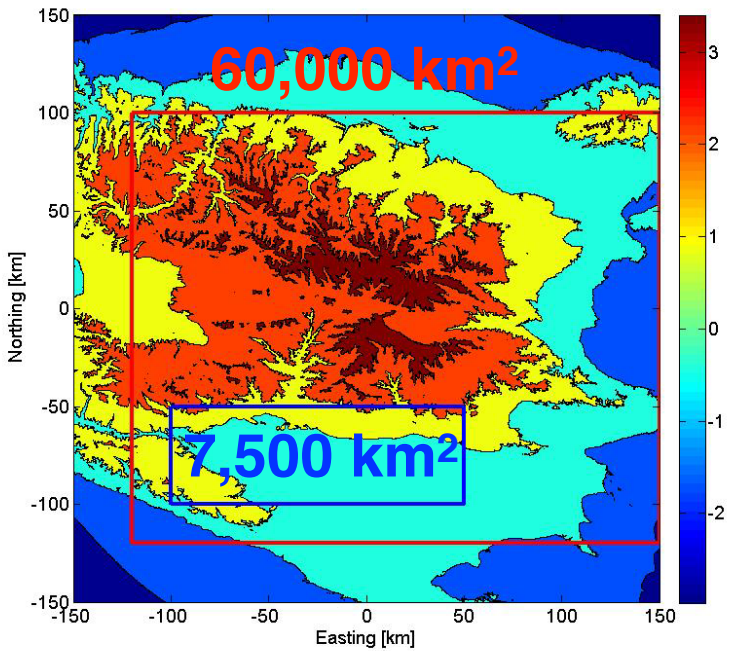
Murase et al. 2015

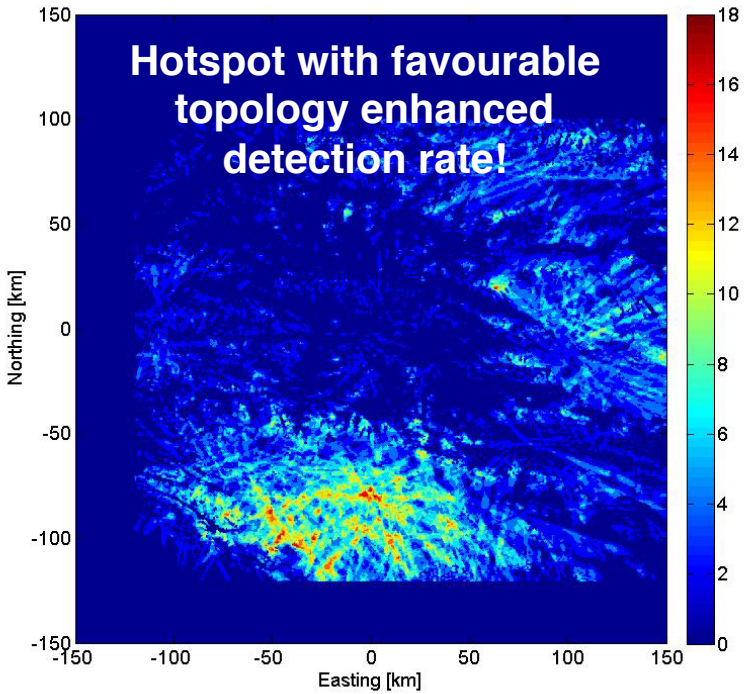
- **Why?**
  - **Growing class of SNe** (Quimby 2012, Gal-Yam 2012, …)
  - **Rarely detected in other wavelengths than optical/UV** (Gezari et al. 2009, Chomiuk et al. 2012, …)
  - **Puzzling objects** (Gal-Yam 2012, …) **despite numerous postulated models**
  - ➡ **Theoretical predictions to test** (Murase et al. 2014, Gal-Yam 2009, Kotera et al. 2013, …)

(1st) search of γ-ray emission from super-luminous supernovae through individual and joint-likelihood analysis

- **Do SLSNe emit in γ-ray ?**
- **What is/are the γ-ray production mechanism(s) ?**
- **What constrains can be put on the pulsar-aided scenario ?**

How to reach the target sensitivity?

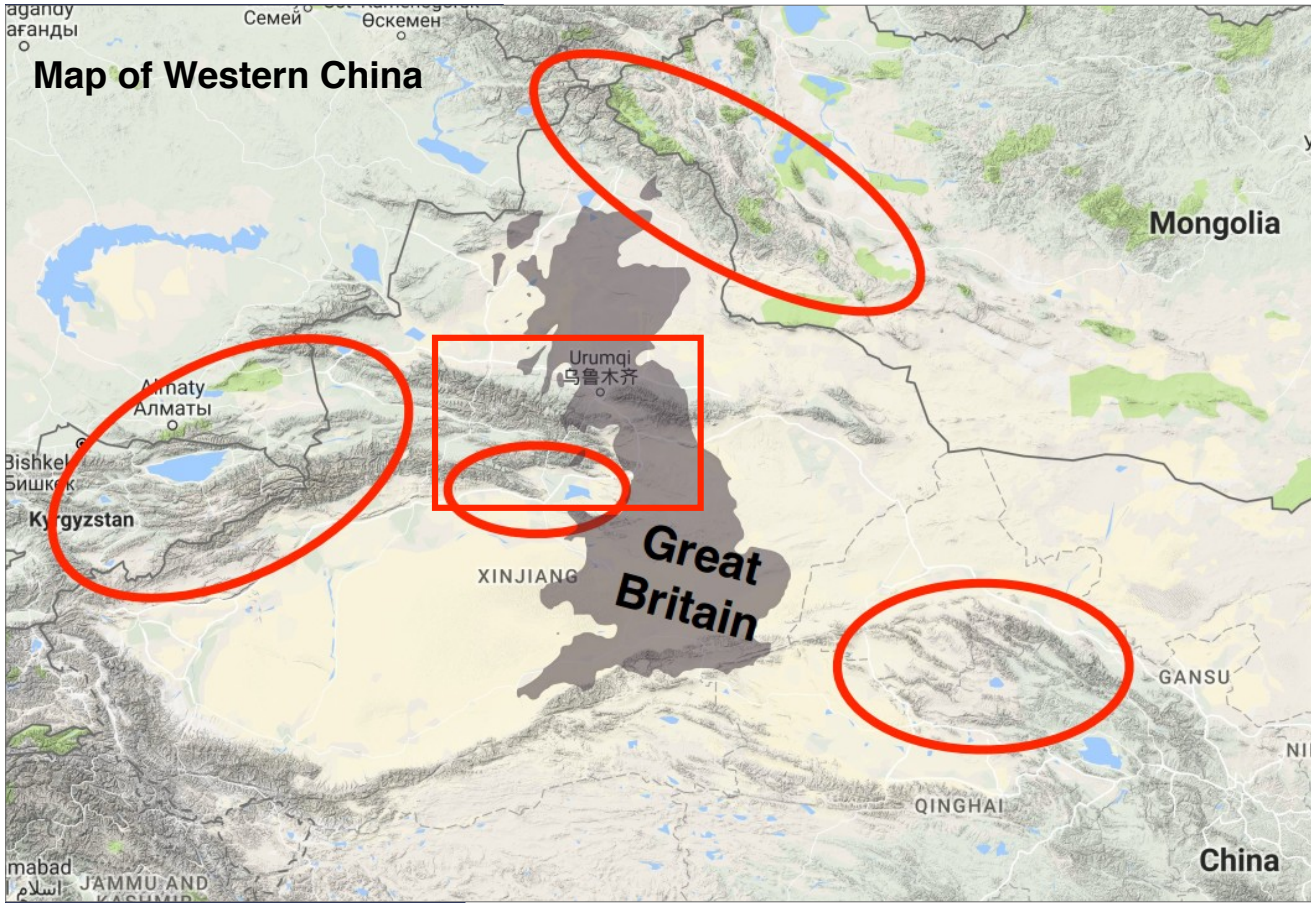




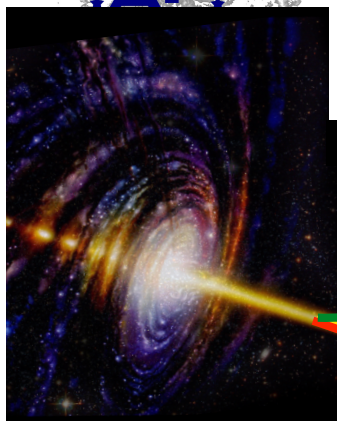
→ Go for hotspots!

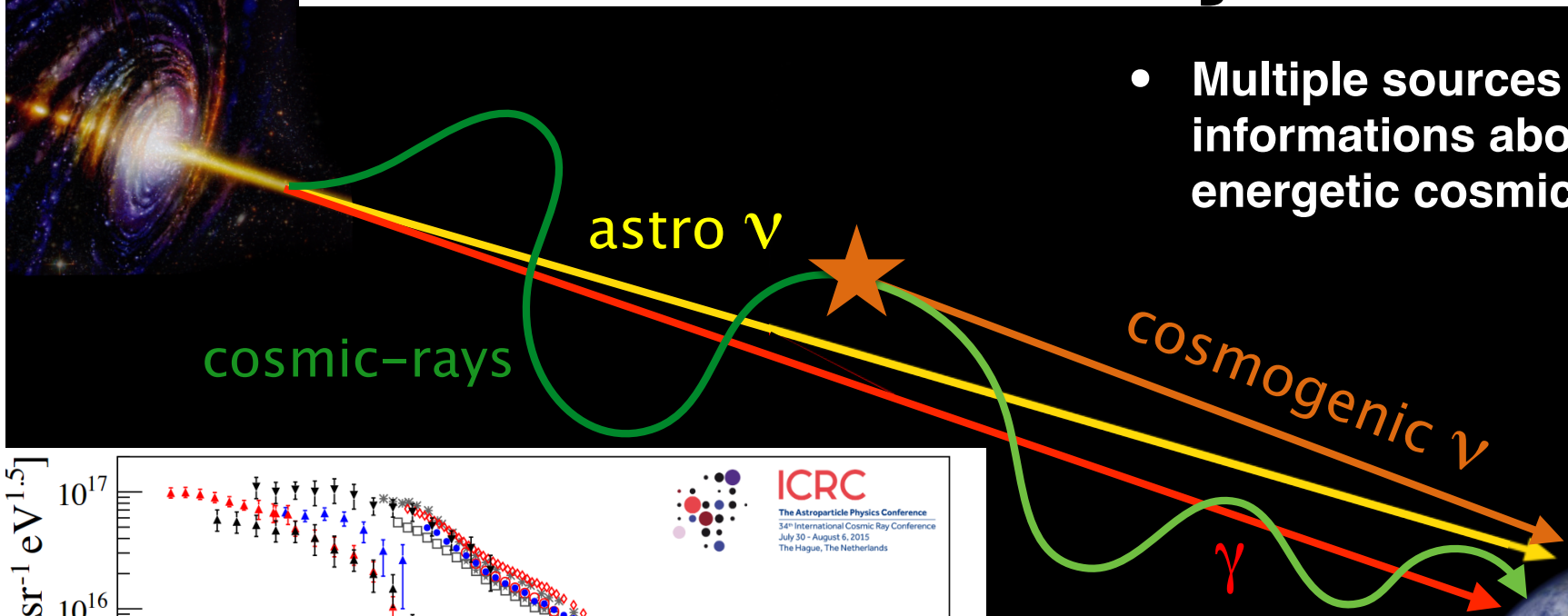
Then 200’000km² may be enough to reach target sensitivity

To be confirmed by full end-to-end simulation.

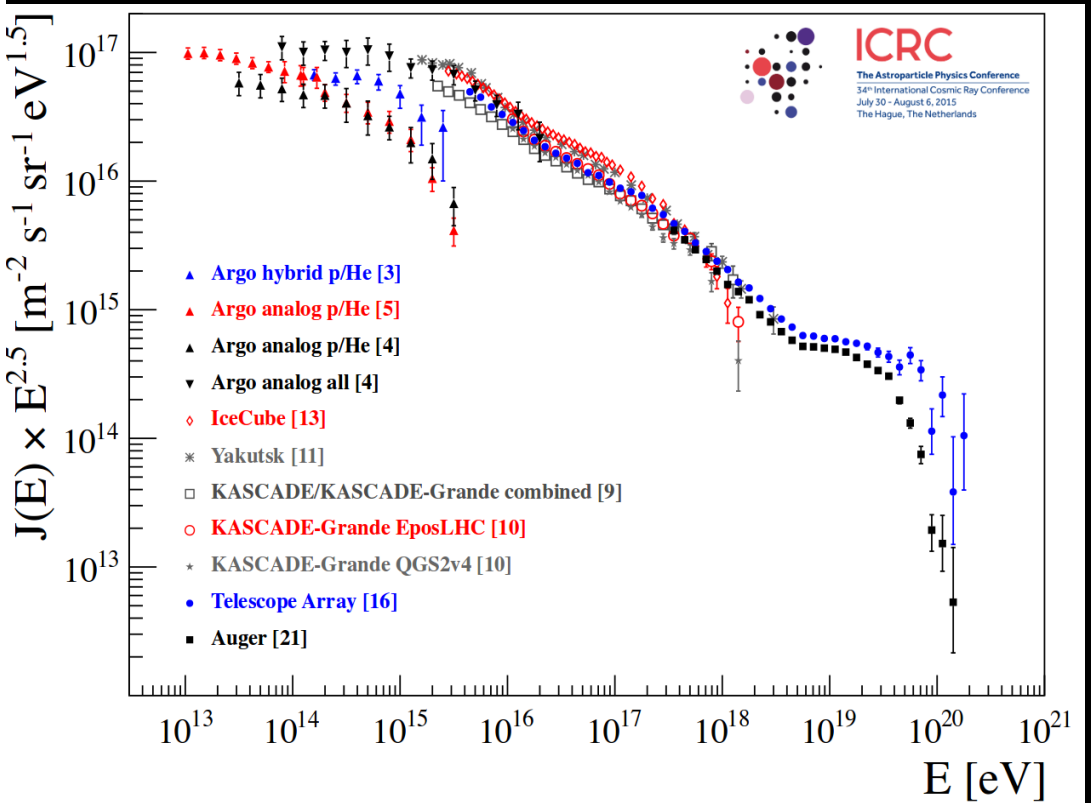


Multi-messenger astronomy





- **Multiple sources (+GW) of informations about most energetic cosmic accelerators.**



Origin of suppression?

- **Maximum energy of sources**
- **GZK effect:**

UHECR flux strongly suppressed by energy-degrading interaction during propagation

[Greisen, Phys. Rev. Lett. 16, 748 (1966)]
[Zatsepin, Kuz'min, ZhETF Pis'ma 4 (1966) 114–117]

GZK effect

Cosmogenic neutrinos

Photo-production

UHE proton with E >4·10^{19} eV $E_p = 10^{20} eV \rightarrow E_\nu = 2 \cdot 10^{18} eV$

$$p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow n + \pi^+$$

Cosmic Microwave Background

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad E_\nu \sim 0.05 E_p$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$n \rightarrow p + e^- + \bar{\nu}_e \qquad E_\nu \sim 10^{-3} E_p$$

Nucleus photo-disintegration + Photo-production

UHE nuclei

$$A + \gamma_{IR/Opt./UV} \rightarrow A' + p$$

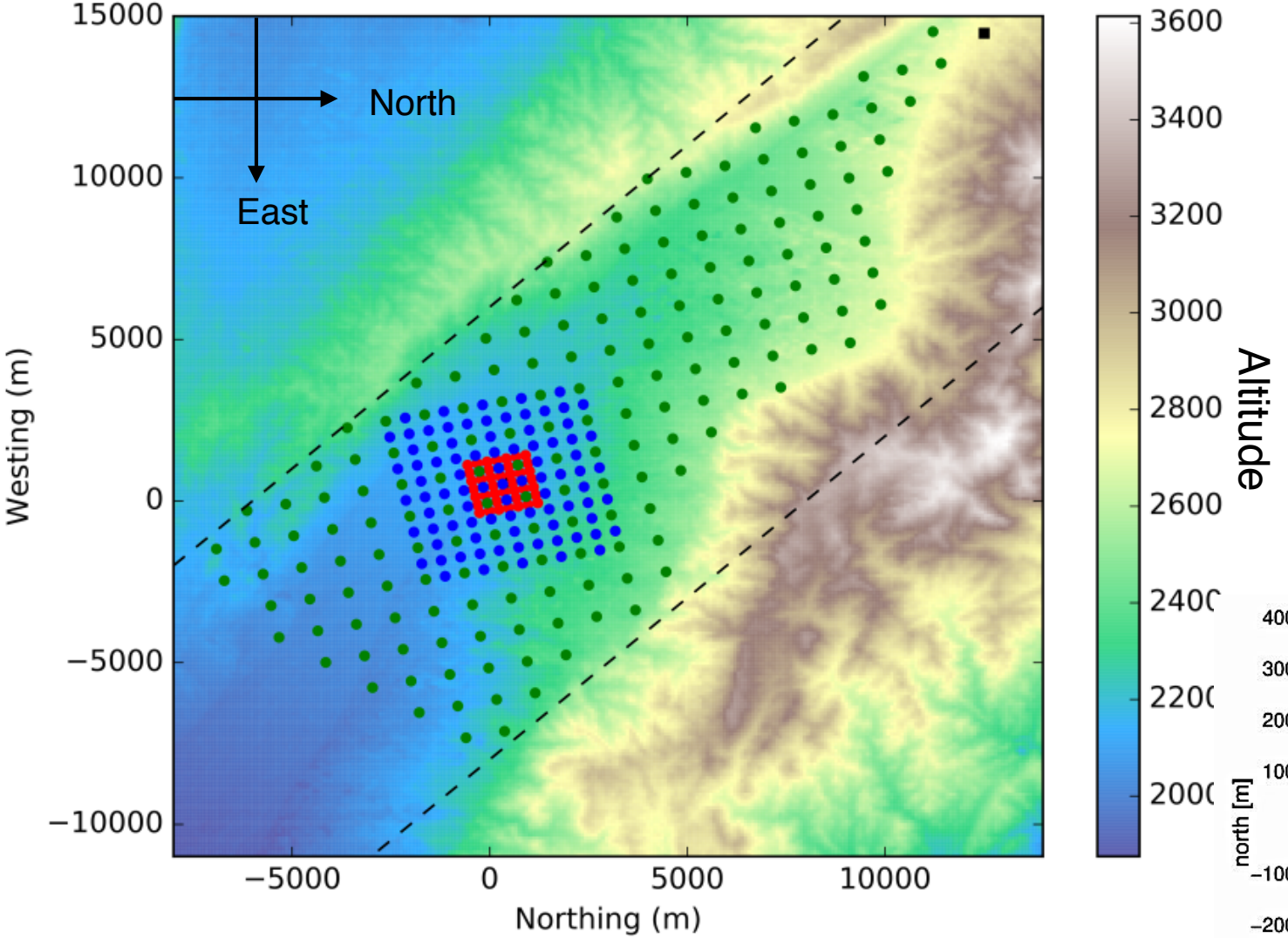
IR/Optical/UB background

$$p + \gamma \rightarrow \nu's \qquad E_\nu \sim 0.05 E_{Nucleus}/A$$

Oscillation over astronomical distances
$\rightarrow \nu_e : \nu_\mu : \nu_\tau \sim 1 : 1 : 1$

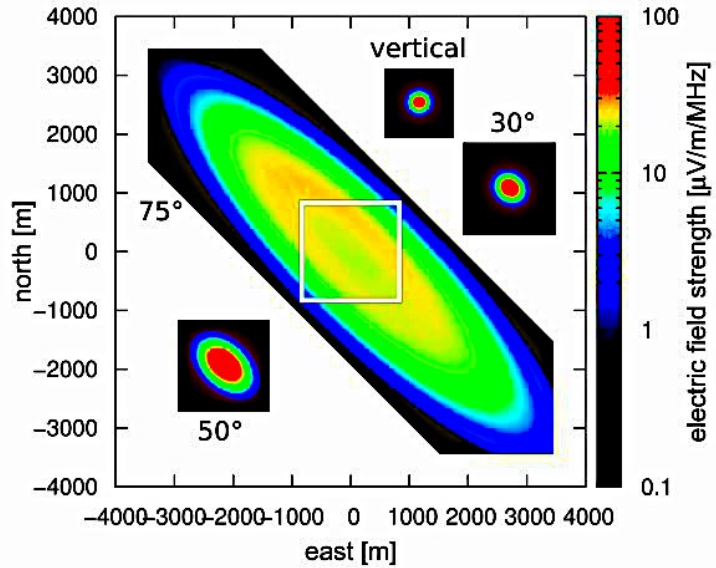
- **"Guaranteed" flux** of cosmogenic neutrinos from the interaction of cosmic rays with the photon fields
- Cosmogenic neutrinos as a **probe for UHECRs**: flux & spectrum strongly depend on UHECRs nature & spectrum (+sources cosmological evolution): powerful tool to better understand it.

Layout of GP300



- **300 antennas positioned on moderate slopes**
- **3-density layout:**

250 m	●	**(49)**
500 m	●	**(+116)**
1 km	●	**(+135)**



➔ **Large energy span**

➔ **Large acceptance at large zenith values**

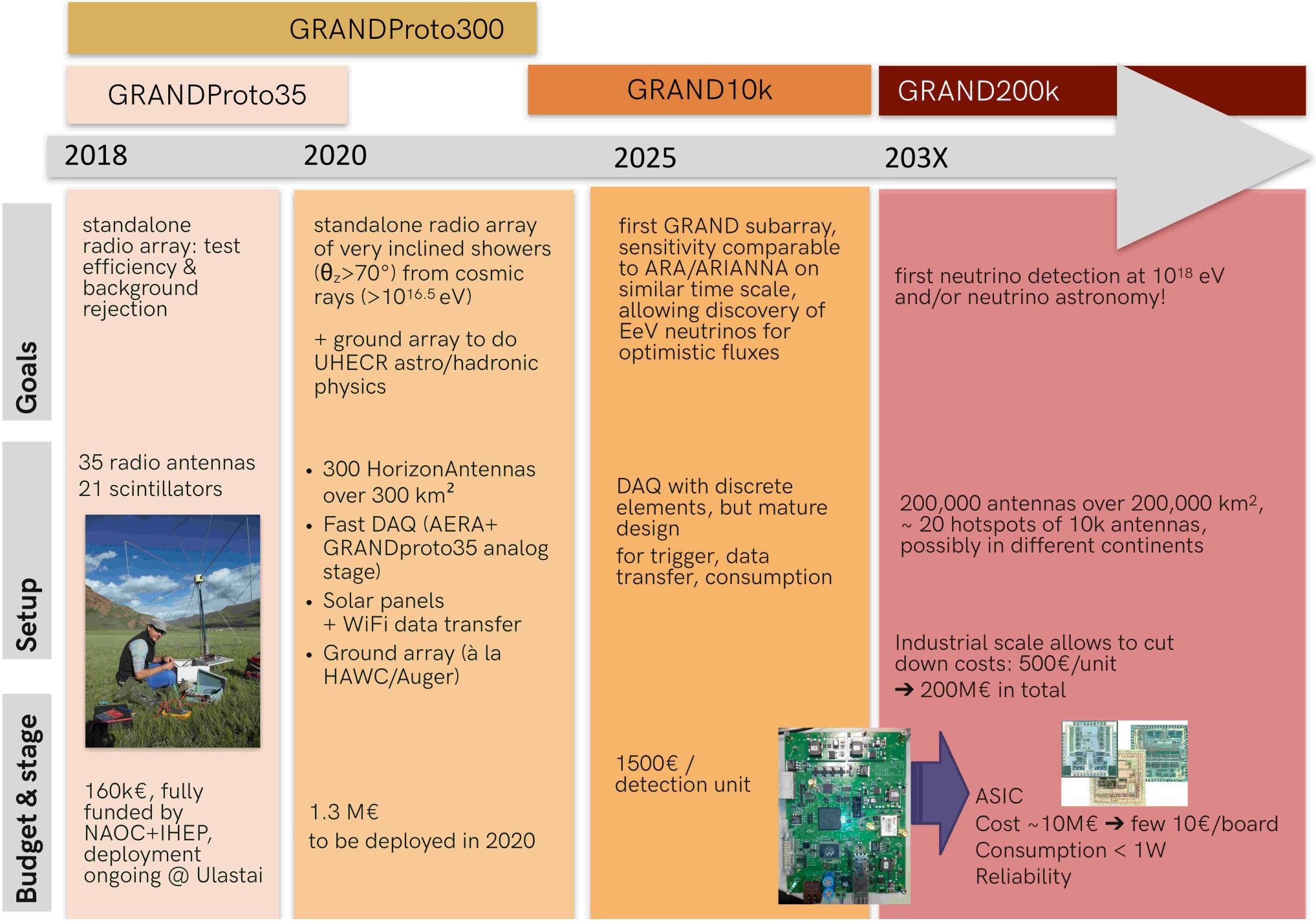


FIG. 29. Timeline of the construction stages of GRAND