Short Course on High Energy Astrophysics

Exploring the Nonthermal Universe with High Energy Gamma Rays

Lecture 1: Introduction

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High Energy Astrophysics?

High Energy Astrophysics as a part of more general interdisciplinary area called *Astroparticle Physics*

Astro-Particle Physics

modern interdisciplinary research field at the interface of
astronomy, physics and cosmology

HE Astrophysics	X-, gamma-ray astronomies, cosmic rays neutrino (but also also R,O, UV, …)
Relativistic Astrophysics	black holes, gravitational waves
HE Physics/ Cosmology	"non-accelerator particle physics" Early Universe, Dark Matter, Dark Energy

both experiment/observations and theory

Golden Age of Astroparticle Physics

- ✓ traditionally is treated as a top priority research activity within the *Astronomy/Astrophysics Community*

- ✓ is strongly supported by the *Particle Physics Community* for different objective and subjective reasons:

subjective - it is not clear what can be done with accelerators after LHC;
in general, APP projects are dynamical and cost-effective;
can be realized by small groups on quite short timescales, …

objective - (huge) discovery potential *in fundamental (particle) physics*
("particle physics without accelerators")

Major Objectives of Astroparticle Physics

No 1: **Universe** - its content ("what is the Universe made of"), history/evolution; how (why) it was created? formation of large-scale structures, magnetic and radiation fields,…

good concepts/ideas - Big Bang, inflation, …
established facts: existence of Dark Matter (DM) and Dark Energy (DE), fluctuations of MBR

combined efforts of astronomers and (particle) physicists - to clarify missing "details" - e.g. *nature of DM* and *origin of DE*, or reason(s) of asymmetric creation of the Universe

HE astrophysicists are "*high-flyers*" (as well)

at first glance HE astrophysics community has more modest objectives; e.g. for them the study of *astrophysics and physics of black holes* is not "too boring" and they can discuss over and over "minor" issues like "which particles - e or p ? - produce γ-rays in Supernova Remnants"

but, in fact, HE astrophysicists also are "*high-flyers*" with a (the) major scientific objectives - study the "*Nonthermal Universe*". For example they try to understand the origin of Gamma-Ray Bursts - "mini Big Bangs" with a very attractive features (advantage) compared to Big Bang - gamma-ray astronomers detect such explosions every day! These enormous events with energy release 10^{51}erg (or more) over seconds contain also huge cosmological information, e.g. about *First Stars*

High Energy Astrophysics

a (the) major objective: study of *nonthermal* phenomena in

most energetic and violent forms in the Universe

many research topics are related, in one way or another, to exploration of Nature's perfectly designed machines:

Extreme Particle Accelerators

Cosmic Rays from up to 10^{20} eV

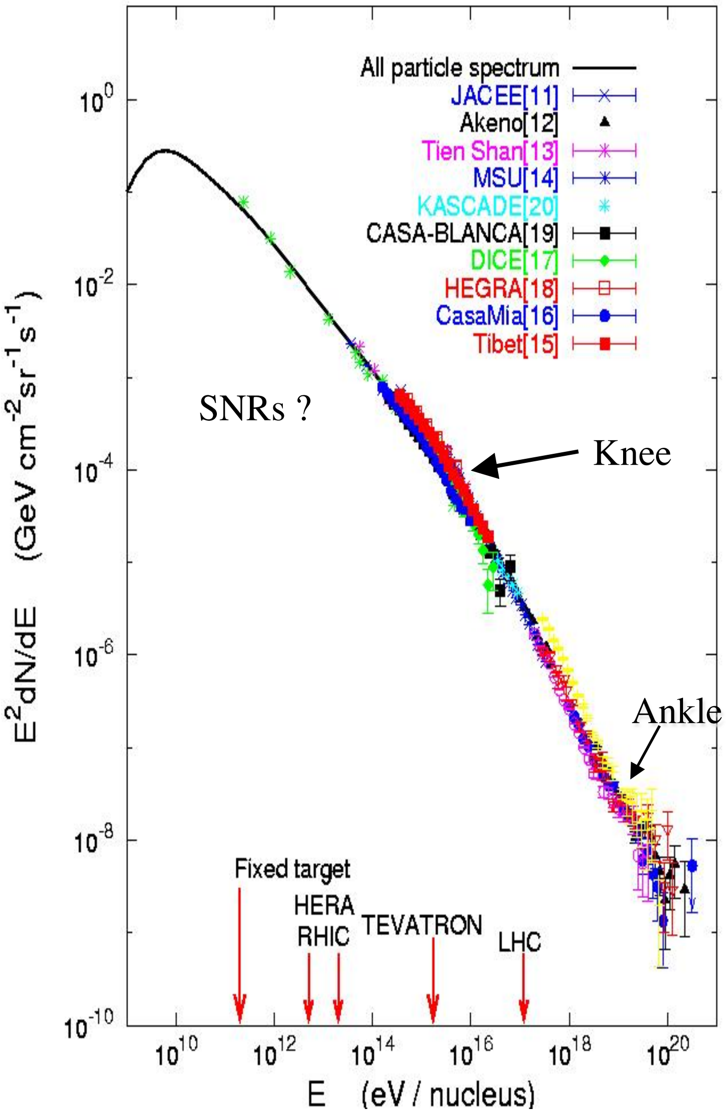
up to $10^{15\text{-}16}$ (knee) - Galactic
most likely sources: Supernova Remnants

SNRs: $E_{max} \sim v_{shock}\, Z \times B \times R_{shock}$

"standard" DSA theory: $E_{p,max} \sim 10^{14}$ *eV*
solution? amplification of B-field by CRs

10^{16} eV to 10^{18} eV:
a few special sources? Reacceleration?

above 10^{18} eV (ankle) - Extragalactic
10^{20} eV particles? : two options
"top-down" (non- acceleration) origin
or *Extreme Accelerators*



T. Gaisser

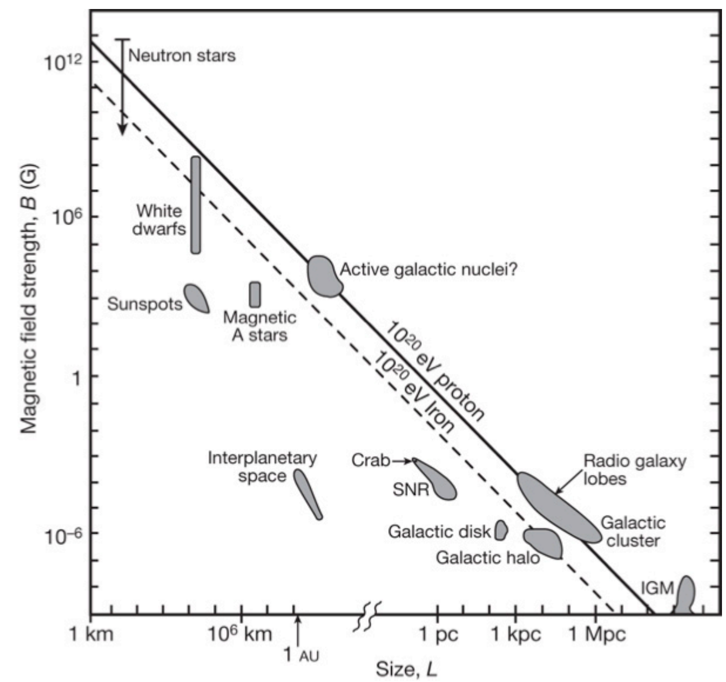
1. Particles in CRs with energy 10^{20} eV

the very fact of existence of such particles implies existence of extragalactic extreme accelerators…

the "Hillas condition" - $l > R_L$ - a necessary but not sufficient condition…

(i) maximum acceleration rate allowed by classical electrodynamics $t^{-1} = \eta q B c$ or c/R_L with $\eta \sim 1$ and $\sim (v/c)^2$ in shock acceleration scenarios

(ii) B-field cannot be arbitrarily increased - Synch. and curvature radiation losses become a limiting factor, unless … perfect linear accelerators!



only few options survive from the original Hillas ("l-B") plot:
$>10^9\ M_o$ BH magnetospheres, small and large-scale AGN jets, GRBs

High Energy Astrophysics

addresses an impressively broad range of topics related to the high energy processes in the Universe, including acceleration, propagation and radiation of relativistic particles on all astronomical scales: from compact objects like (neutron-stars and black holes) large-scale cosmological structures (galaxy clusters)

basic areas

Research Areas of High Energy Astrophysics

- ✓ *X-ray astronomy*
- ✓ *gamma-ray astronomy*
- ✓ *neutrino astronomy*
- ✓ *Cosmic Rays*

Gamma-Ray Astronomy

High Energy Astrophysics - in the context of studies of **high energy nonthermal** processes in Universe

Astroparticle Physics - (1) as one of the **cosmic messengers** (together with cosmic rays, neutrinos, gravitational waves)
(2) in the context of indirect search of **Dark Matter**,
(3) **fundamental physics** (challenging basic laws)

Relativistic Astrophysics - the parents of gamma-rays – relativistic electrons, protons, nuclei are related, in one way or another, to **particle acceleration** close to **relativistic objects**: black holes, neutron stars/pulsars, SN explosions …
In many cases gamma-ray sources associate with **relativistic outflows** (pulsar winds and BH jets)

this course

after general introduction of the field, the major nonthermal high energy phenomena in different astrophysical environments related to electromagnetic messengers* - *X-rays* and *gamma-rays* will be described with emphasis on Very High Energy** domain. The lectures will cover several major topics, in particular

- *Origin of Galactic and Extragalactic Cosmic Rays*
- *Physics and Astrophysics of Relativistic Outflows*
- *Observational Cosmology*

*) Cosmic Rays and Neutrinos will be covered in separate lecture blocks

**) *low and high energy gamma-rays will be covered my separate lectures*

Gamma-Ray Astronomy

provides crucial window in the cosmic E-M spectrum for exploration of non-thermal phenomena in the Universe in their most energetic, extreme and violent forms

'the last window' *in the spectrum of cosmic E-M radiation* …

the last E-M window ... 15+ decades:

LE	or	MeV :	0.1 -100 MeV	(0.1 -10 + 10 -100)
HE	or	GeV :	0.1 -100 GeV	(0.1 -10 + 10 -100)
VHE	or	TeV :	0.1 -100 TeV	(0.1 -10 + 10 -100)
UHE	or	PeV :	0.1 -100 PeV	(*only hadronic*)
EHE	or	EeV :	0.1 -100 EeV	(*unavoidable because of GZK*)

low bound - nuclear gamma-rays, upper bound - highest energy cosmic rays

the window is opened in MeV, GeV, and TeV bands:

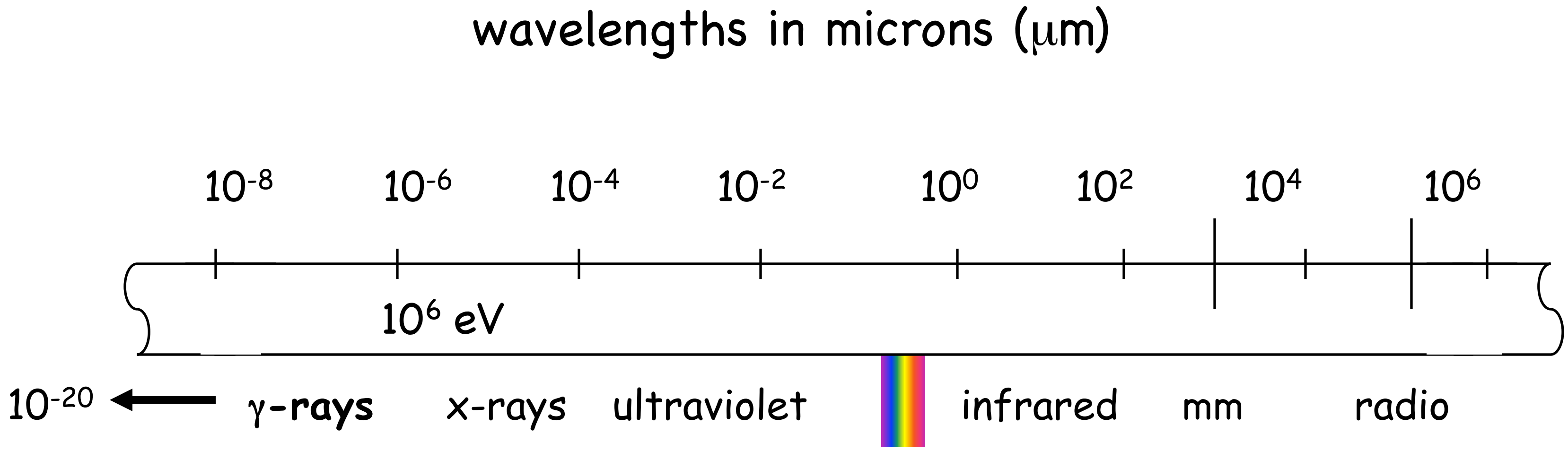
LE,HE — *domain of space-based astronomy*

VHE, ... — *domain of ground-based astronomy*

potentially 'Ground-based γ-ray astronomy' can cover five decades (from 10 GeV to 1 PeV) , but presently it implies 'TeV γ-ray astronomy'

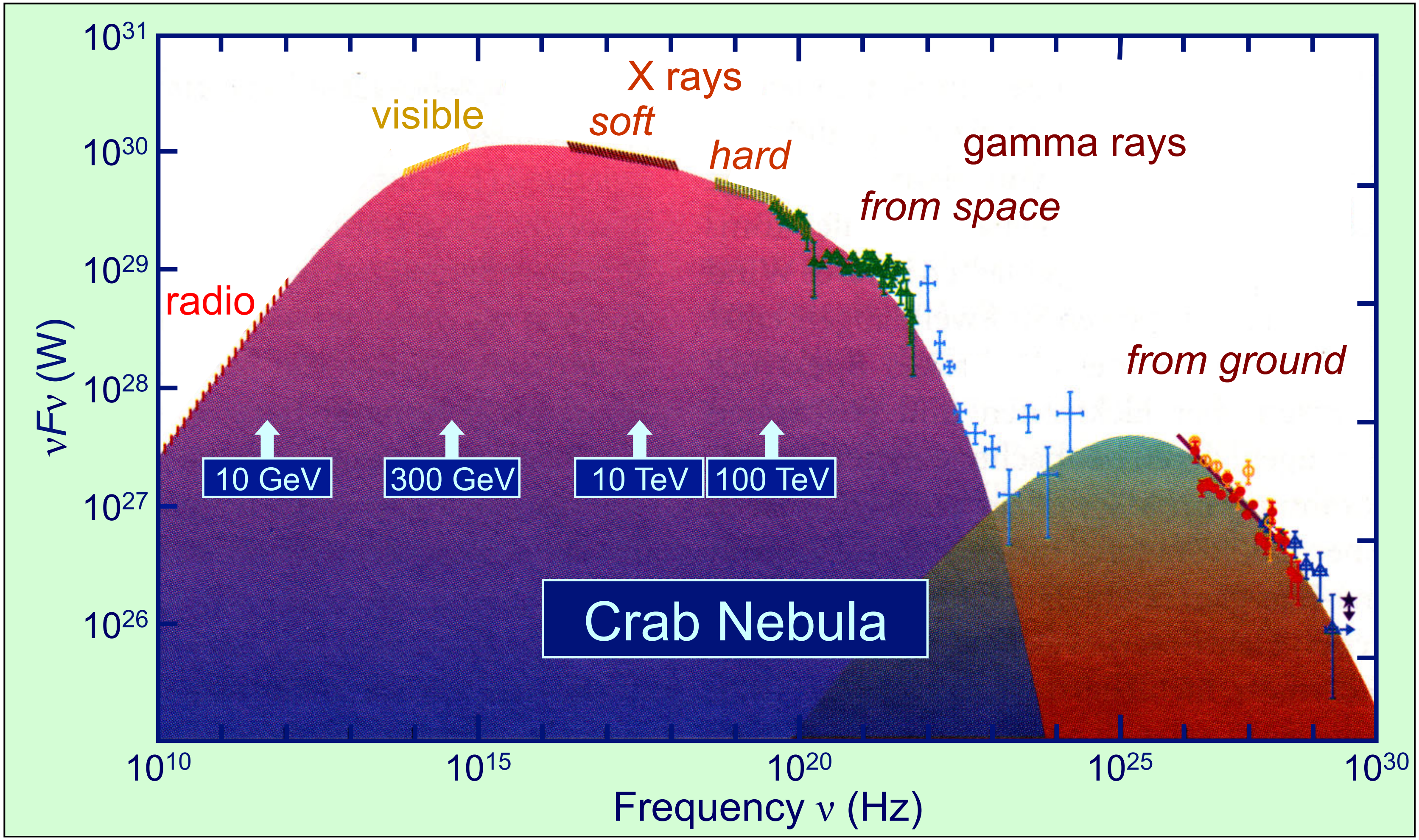
1MeV=10^6 eV, 1GeV=10^9 eV, 1TeV=10^{12} eV, 1PeV=10^{15} eV 1EeV=10^{18} eV

γ-rays: photons with wavelengths less than 10^{-6} μm



gamma-rays are detected from 10^5 eV to 10^{14} eV

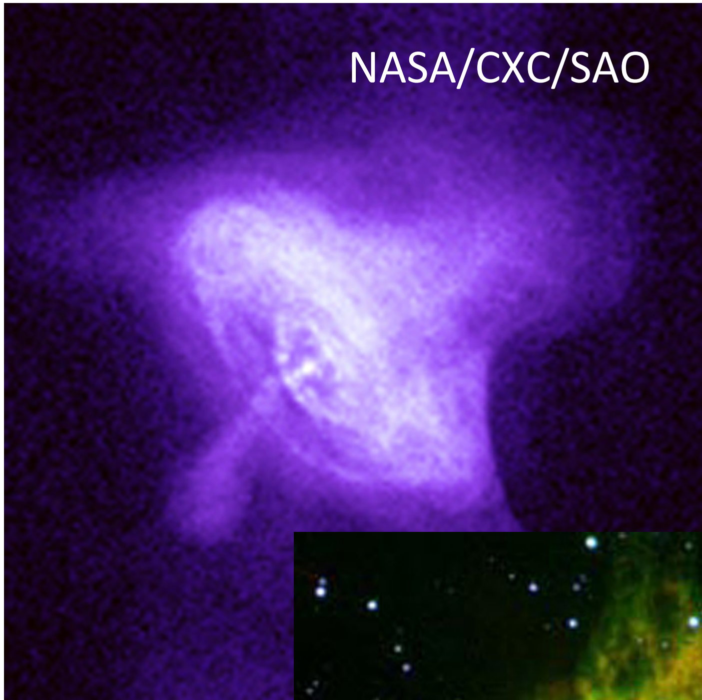
a non-thermal astrophysical object seen over 20 energy decades

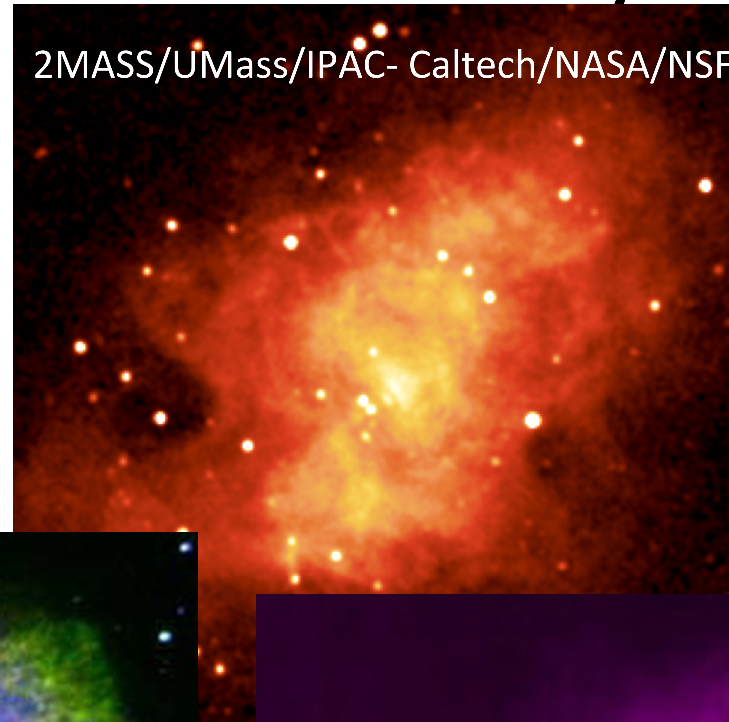


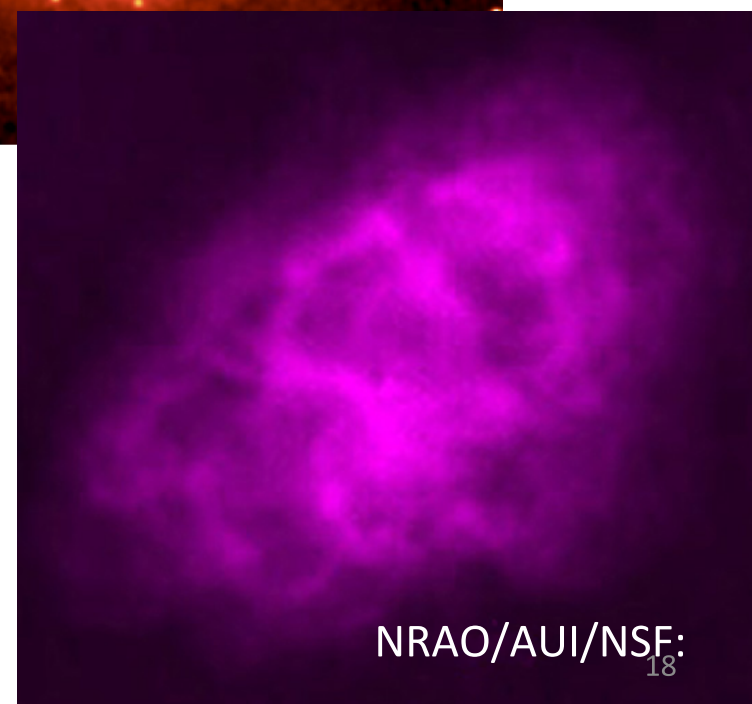
R, mm, IR, O, UV,X

gamma-rays

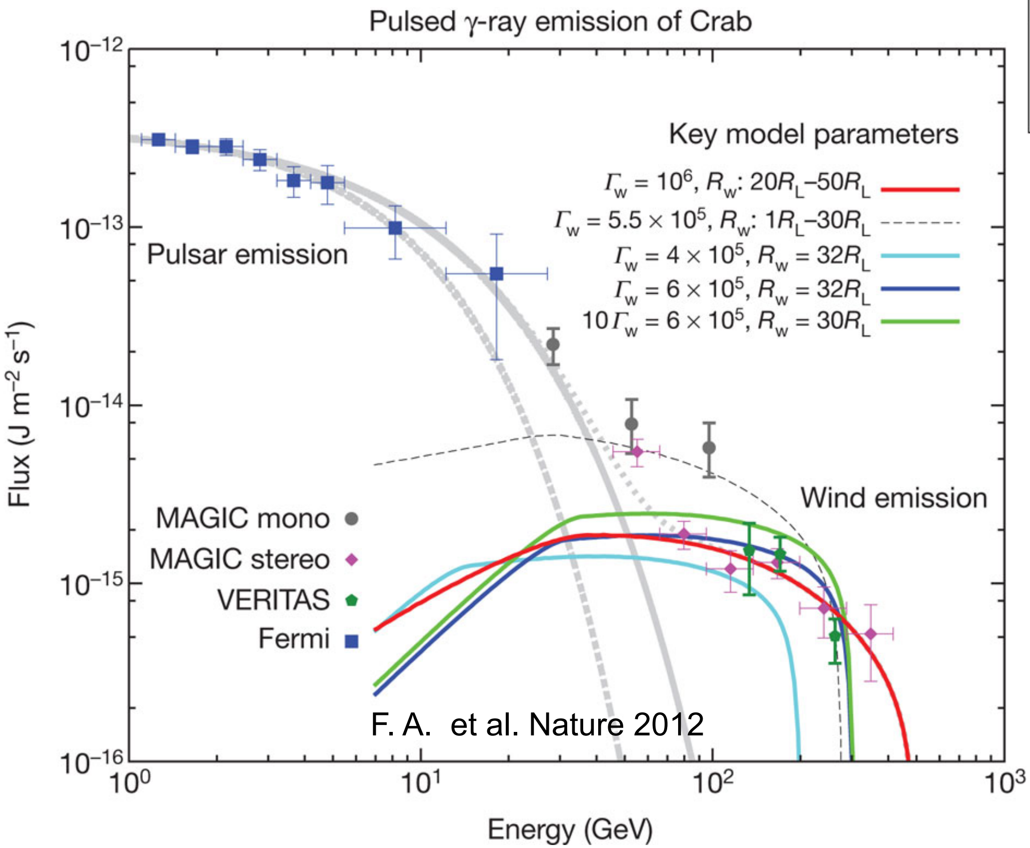
The Crab Pulsar and Nebula System

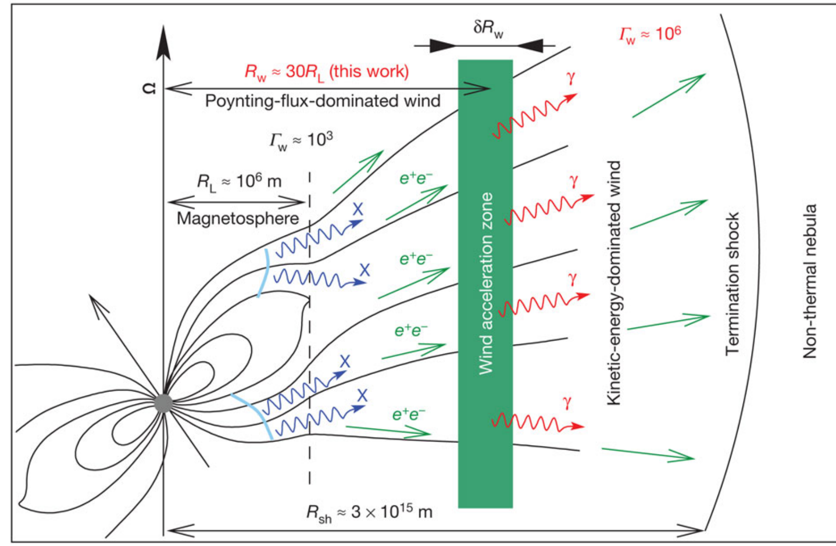


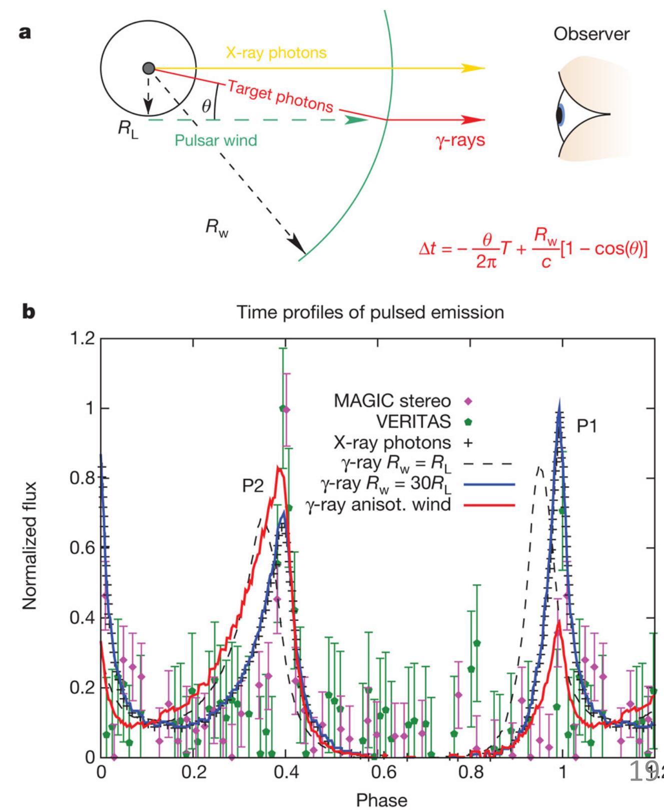




Crab Nebula: powered by rotational energy of the pulsar transported through a cold ultrarelativistic wind







gamma-rays – unique carriers of information about high energy processes in the Universe

- ✓ are effectively produced
  in both electromagnetic and hadronic interactions
- ✓ penetrate (relatively) freely throughout
  intergalactic and galactic magnetic and photon-fields
- ✓ are effectively detected
  by space-based and ground-based detectors

high energy cosmic gamma-rays

a few general remarks …

extreme physical conditions

generally the phenomena relevant to HEA generally proceed under extreme physical conditions in environments characterized with

- *huge gravitational, magnetic and electric fields,*
- *very dense background radiation,*
- *relativistic bulk motions (black-hole jets and pulsar winds)*
- *shock waves, highly excited (turbulent) media, etc.*

any coherent description and interpretation of phenomena related to high energy cosmic gamma-rays requires knowledge and deep understanding of many disciplines of experimental and theoretical physics, including

nuclear and particle physics,
quantum and classical electrodynamics,
special and general relativity,
plasma physics, (magneto) hydrodynamics, etc.

and (of course) Astronomy&Astrophysics

Extreme Accelerators

machines where acceleration proceeds with efficiency close to 100%

(i) fraction of available energy converted to nonthermal particles

in PWNe and perhaps also in SNRs and AGN <u>*can be as large as 50 %*</u>

(ii) maximum energy achieved by individual particles

acceleration rate close to the <u>*maximum (theoretically) possible rate*</u>

sometimes efficiency can even “exceed” 100% ?

(due to relativistic and non-linear effects)

radiation and absorption processes

any interpretation of an astronomical observation requires

- ✓ unambiguous identification of radiation mechanisms and
- ✓ good knowledge of radiation and absorption processes

gamma-ray production and absorption processes:
several but well studied

E-M: VHE

bremsstrahlung: e N(e) => e' γ N (e) * $E\gamma \sim 1/2E_e$

pair production γ N(e) => e^+e^- N (e) *

e+e- annihilation e^+e^- => $\gamma\,\gamma$ (511 keV line)

Strong/week: pp (A) => π, K, Λ, … ** $E\gamma \sim 1/10E_p$

π, K, Λ => γ, ν, e, μ

μ => ν

also in the low energy region

Nuclear: p A => A* => A' γ, n

n p => D γ (2.2 MeV line)

interactions with radiation and B-fields

Radiation field **VHE**

E-M:

inverse Compton:	$e\,\gamma\,(B) \Rightarrow e'\,\gamma$	**	$E\gamma \sim \varepsilon(Ee/mc^2)^2$ (T) to $\sim Ee$ (KN)
$\gamma\gamma$ pair production	$\gamma\,\gamma\,(B) \Rightarrow e^+e^-$	**	
Strong/week	$p\,\gamma \Rightarrow \pi, K, \Lambda, \ldots$	*	
	$\pi, K, \Lambda \Rightarrow \gamma, \nu, e, \mu$		$E\gamma \sim 1/10 Ep$
	$\mu \Rightarrow \nu$		
	$A\,\gamma \Rightarrow A^* \Rightarrow A'\,\gamma$	*	$E\gamma \sim 1/1000A\ Ep$

B-field

synchrotron	$e\,(p)\,B \Rightarrow \gamma$	*	$E\gamma \sim BE_e^2$; $h\nu_{max} \sim \alpha^{-1} mc^2$
pair production	$\gamma\,B \Rightarrow e+e-$	*	

** - very important!

leptonic or hadronic?

gamma-rays produced in interactions of electrons and protons/nuclei often are called leptonic and hadronic interactions
but it is more appropriate to call them as E-M (electromagnetic) and S (strong)

examples:

(i) synchrotron radiation of protons - pure electromagnetic process
interaction of hadrons without production of neutrinos

(ii) photon-photon annihilation => μ+μ- => neutronos, antineutrinos
production of neutrinos by photons as parent particles

E-M are calculated with high accuracy and confirmed experimentally
S are well studied experimentally and explained theoretically

often several processes proceed together =>
cascades in matter, radiation and B-fields