Multimessenger strategies for the study of the macrocosm and microcosm

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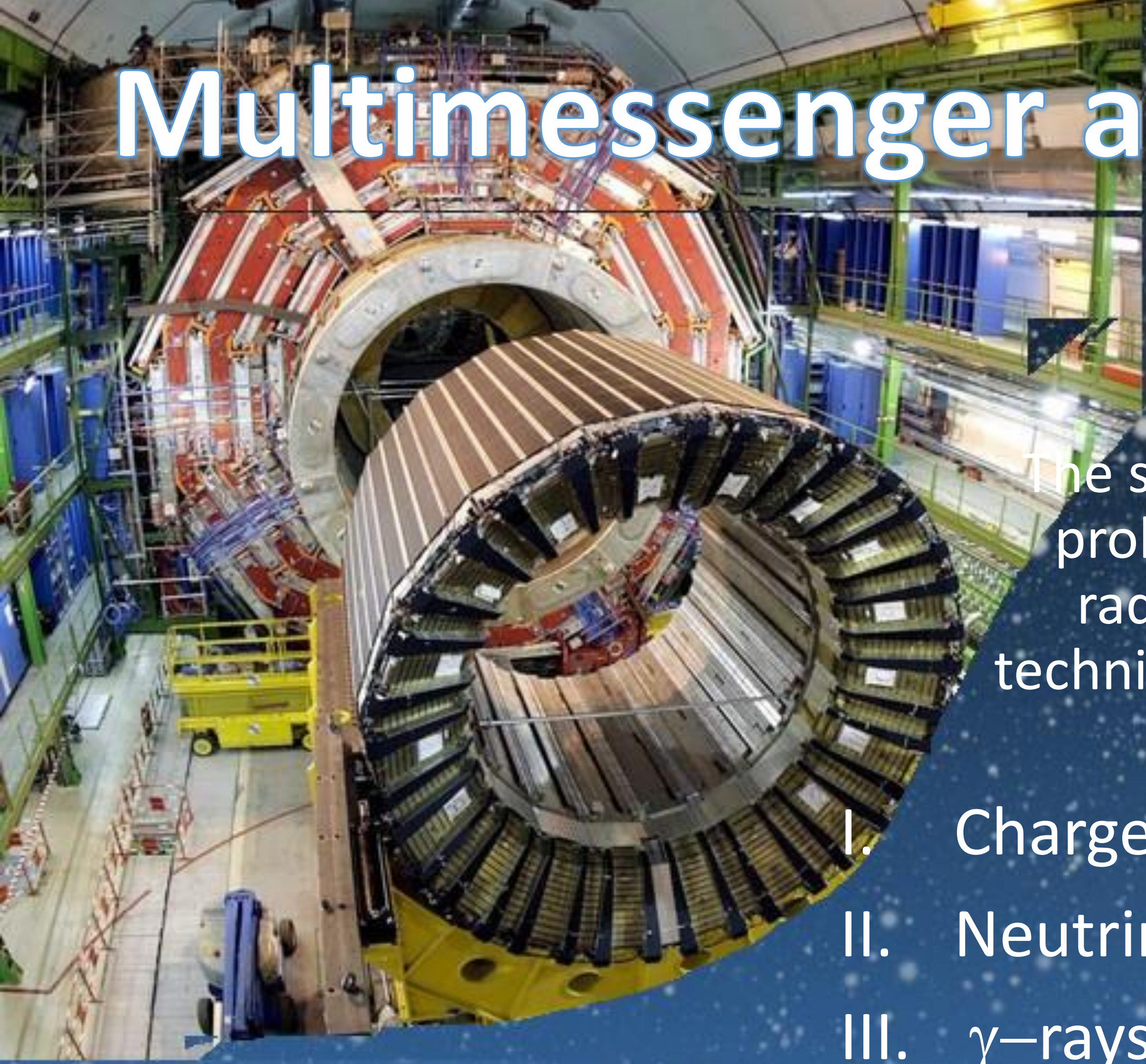
Multimessenger astrophysics



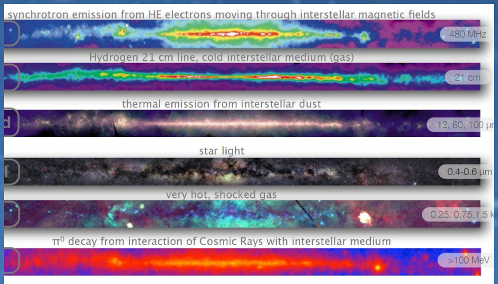
The study of the Universe with probes different from the EM radiation, with experimental techniques mainly developed in particle physics

I. Charged cosmic rays

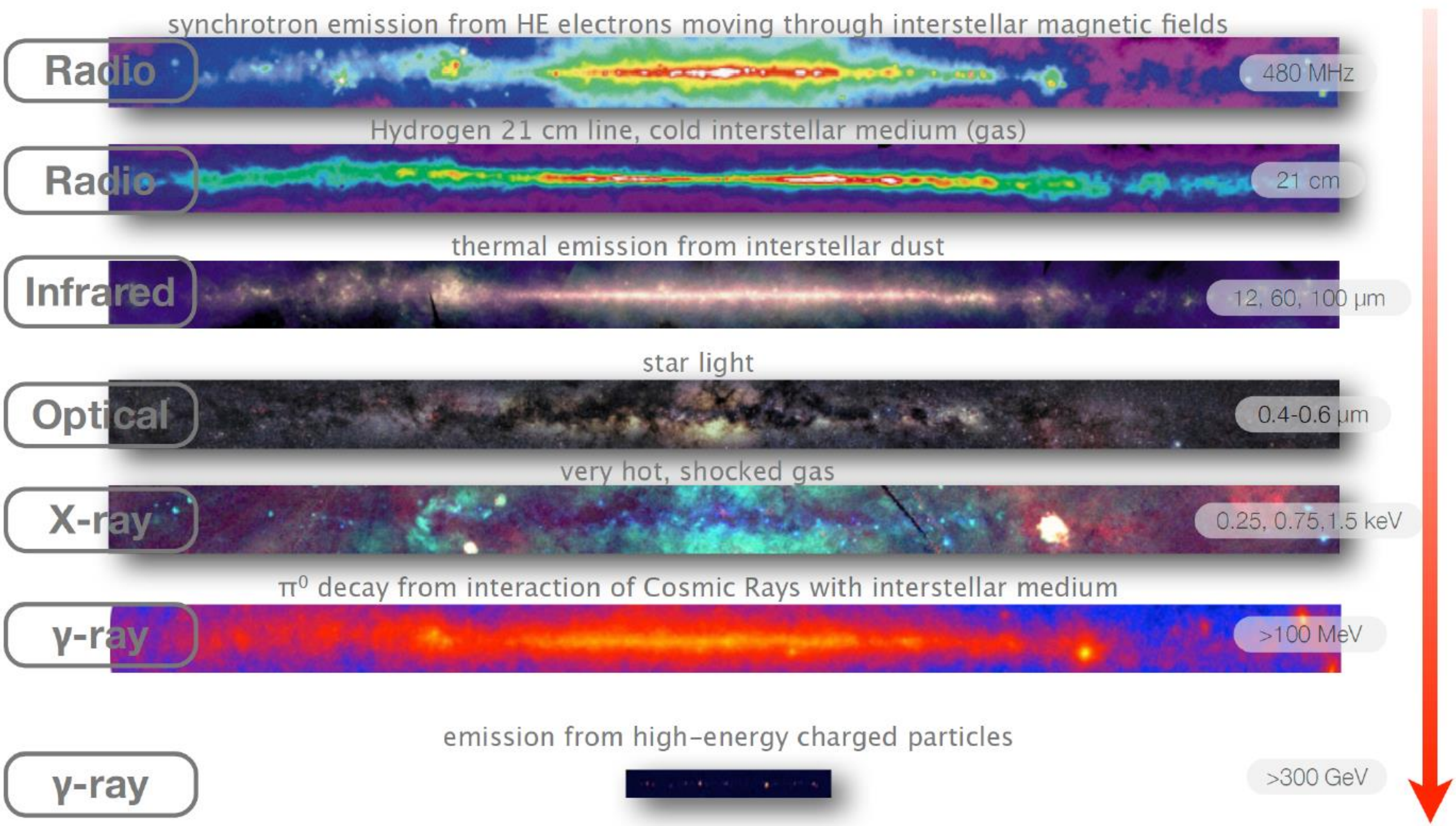
II. Neutrinos

III. γ–rays

IV. Gravitational waves

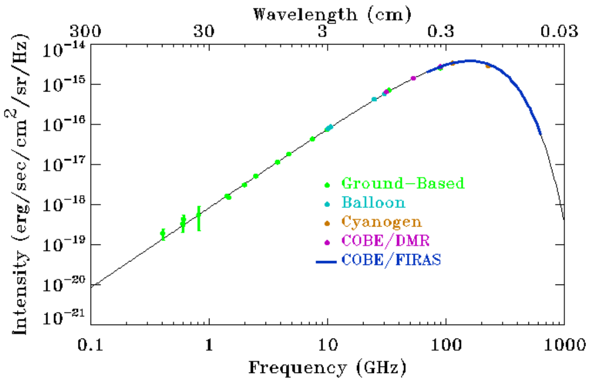


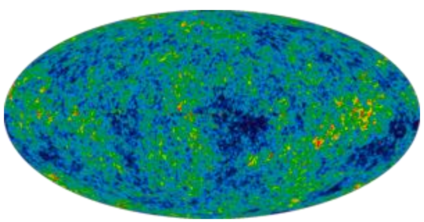
«Traditional» Astronomy



The thermal universe: the black-body spectrum

CMBR: 2.7 K



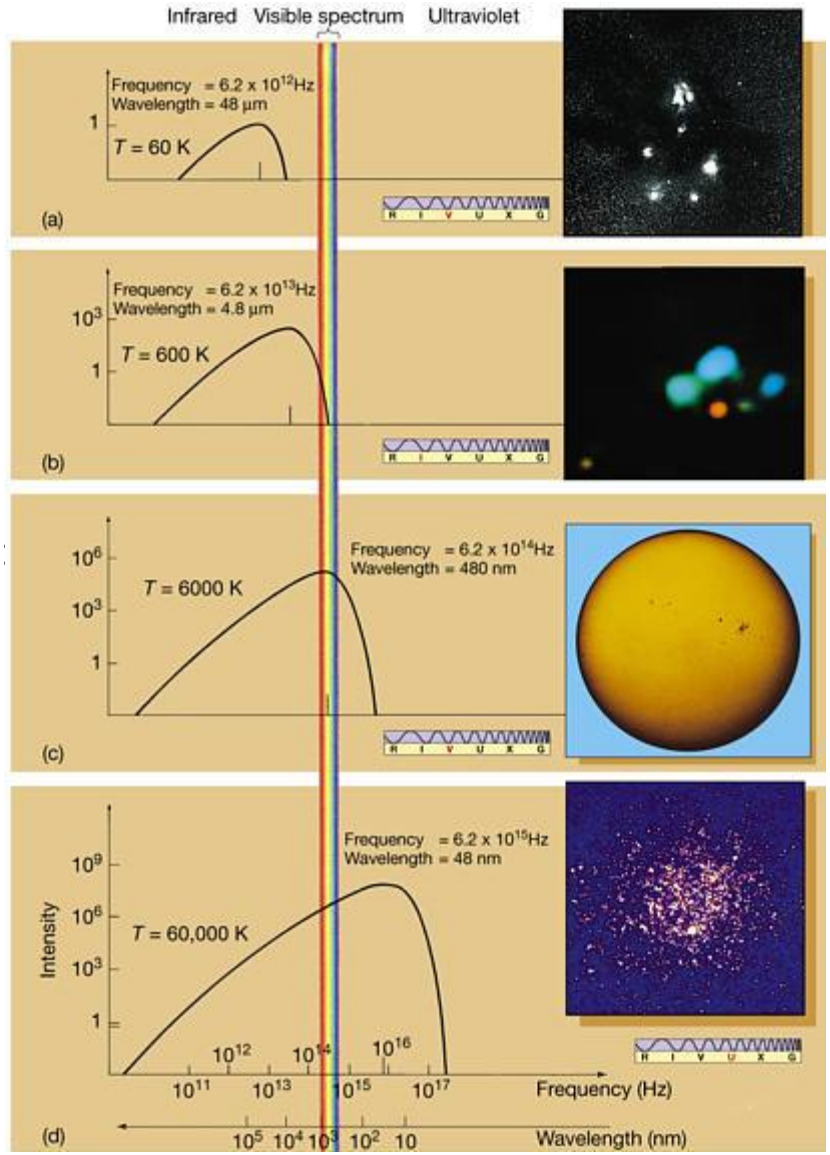


A Galactic gas cloud: 60 K

Star in the Orion Nebula: 600 K

The Sun surface: 6000 K

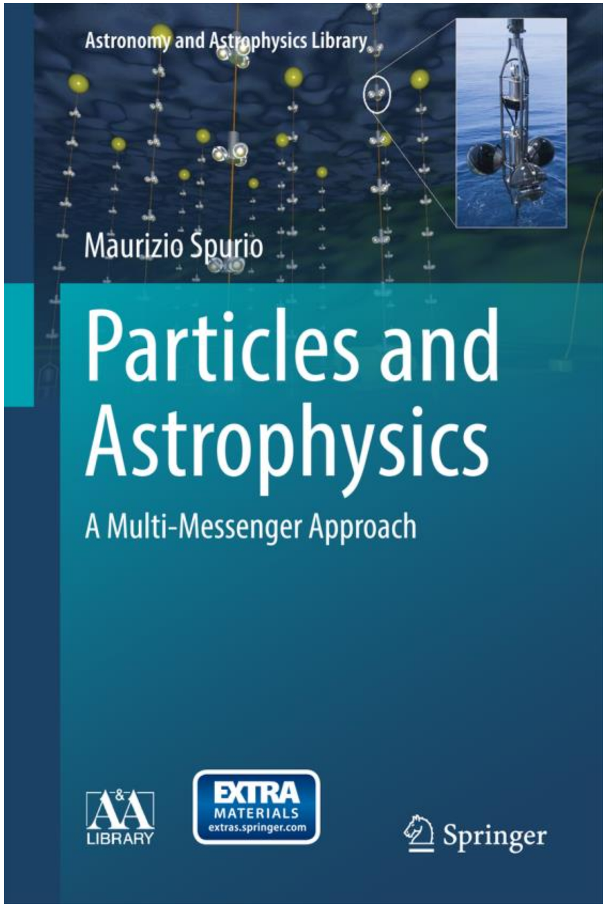
Cluster of very bright stars, Omega Centauri 60,000 K



Disclamers

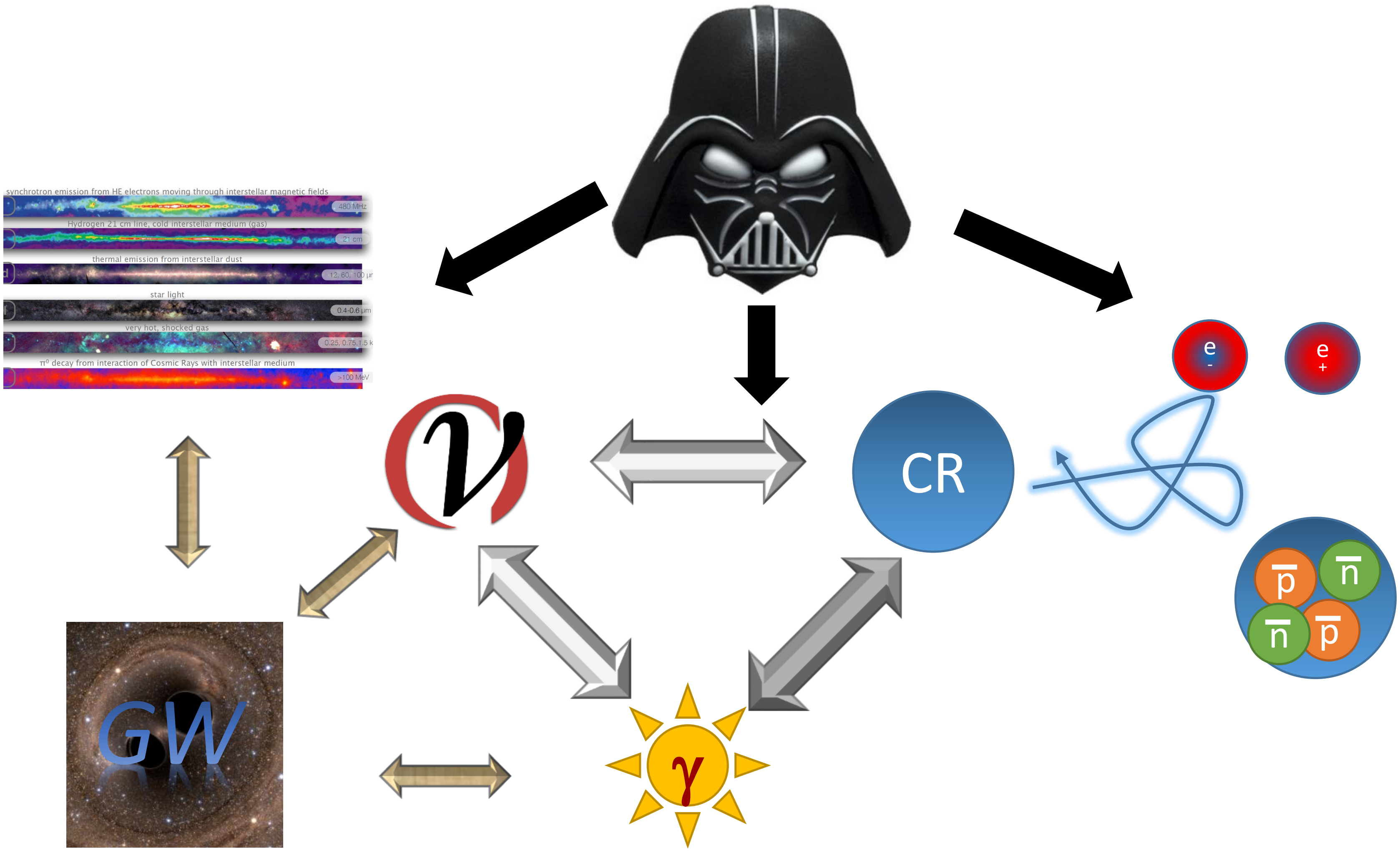
- These 3h are the synthesis of a 48 h lectures on «Astroparticle physics» for master students in Bologna
- It is a summary of a 580 pages book, printed in 2014
- A new edition (that includes GWs) available soon in 2018 (immediately for you)

1. An Overview of Multimessenger Astrophysics
2. Charged Cosmic Rays in Our Galaxy
3. Direct Cosmic Ray Detection
4. Indirect Cosmic Ray Detection
5. Diffusion of Cosmic Rays in the Galaxy
6. Galactic Accelerators and Acceleration Mechanisms
7. The Extragalactic Sources and UHECRs
8. The Sky Seen in γ-rays
9. The TeV Sky and Multiwavelength Astrophysics
10. High-Energy Neutrino Astrophysics
11. Atmospheric Muons and Neutrinos
12. Low-Energy Neutrino Physics and Astrophysics
13. Basics on the Observations of GravitationalWaves
14. Microcosm and Macrocosm



The multimessenger physics

Part I

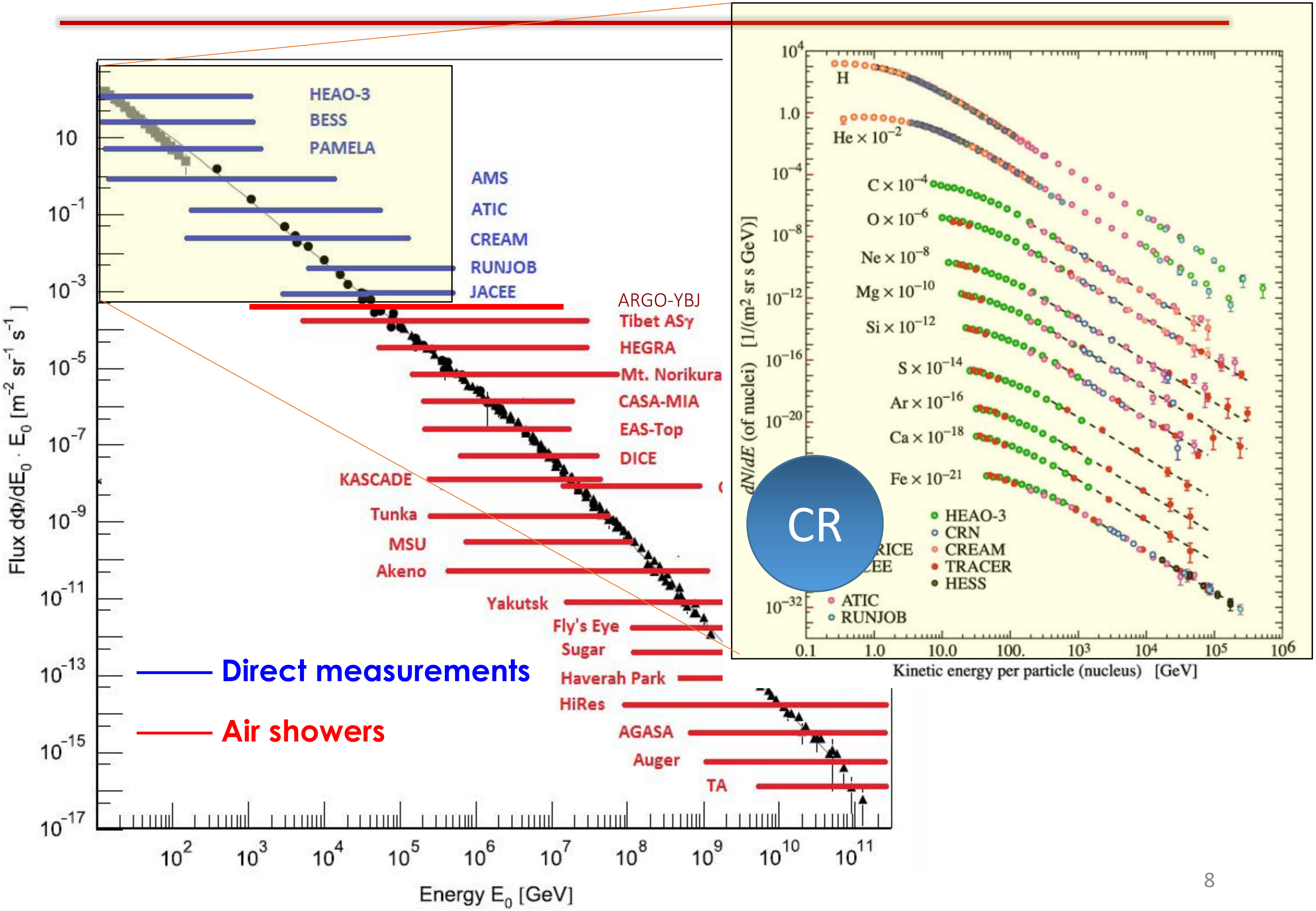


1) The origin of the «cosmic» radiation

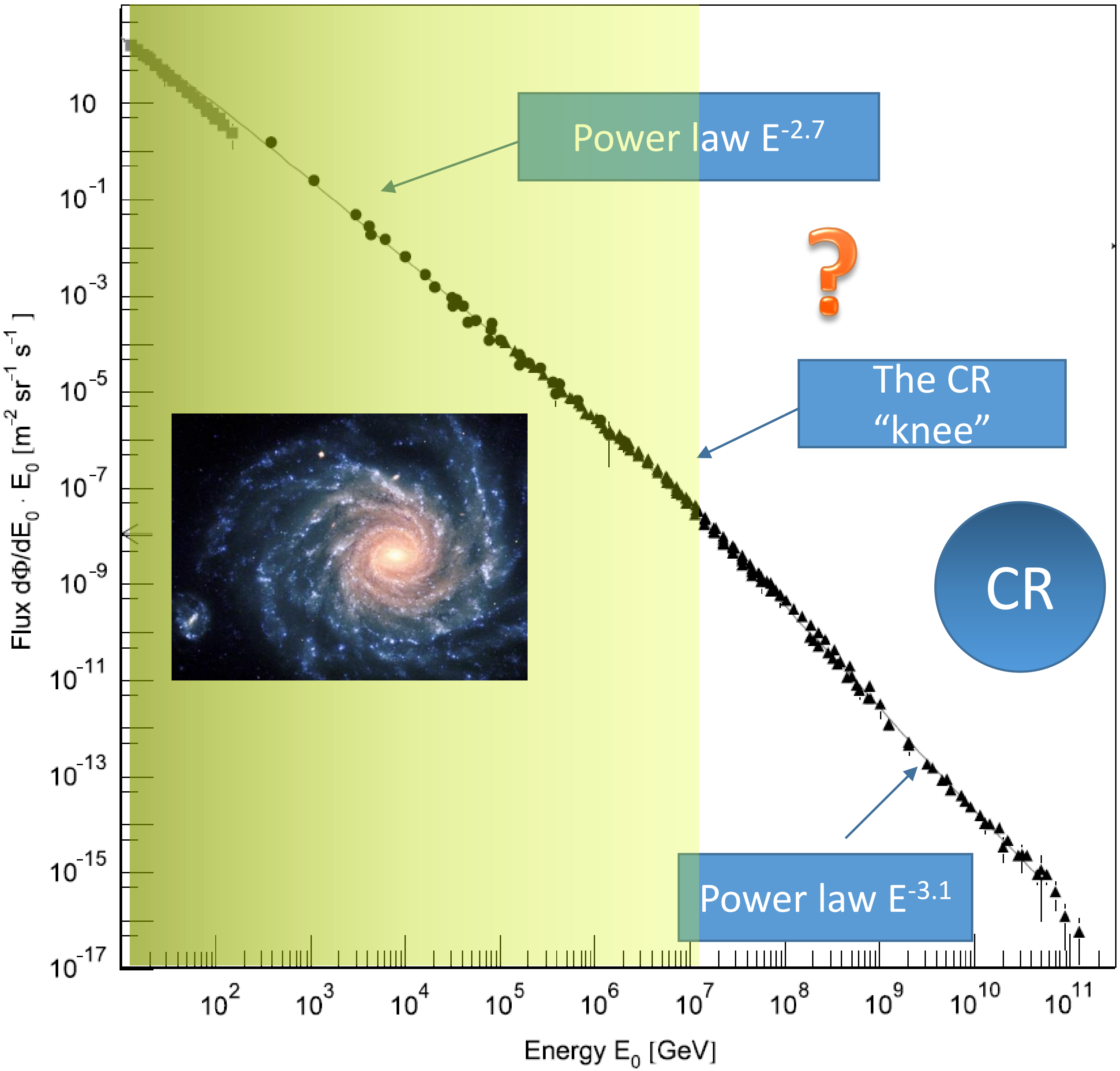
Charged cosmic rays

- Origin
  - Galactic: SN remnants, origin of heavy elements
  - Extragalactic (?)
- Composition
  - Protons
  - Nuclei
- Highest energy?

The measured CR spectrum



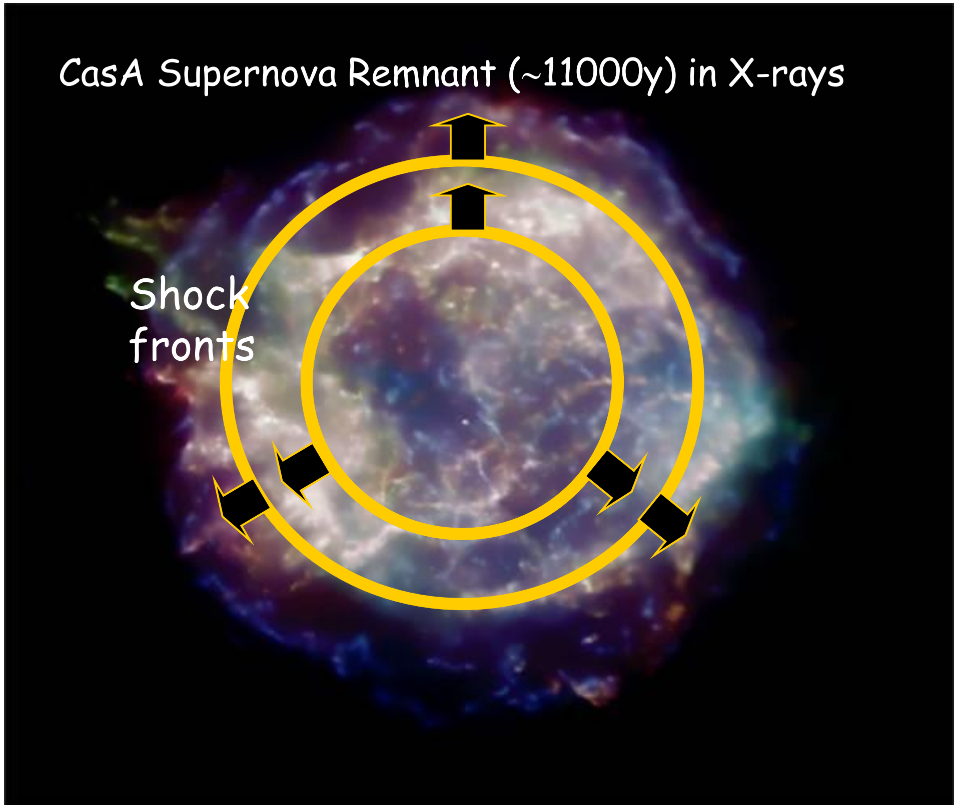
The sources of CRs



Galactic (SuperNova Remnants- SNRs)

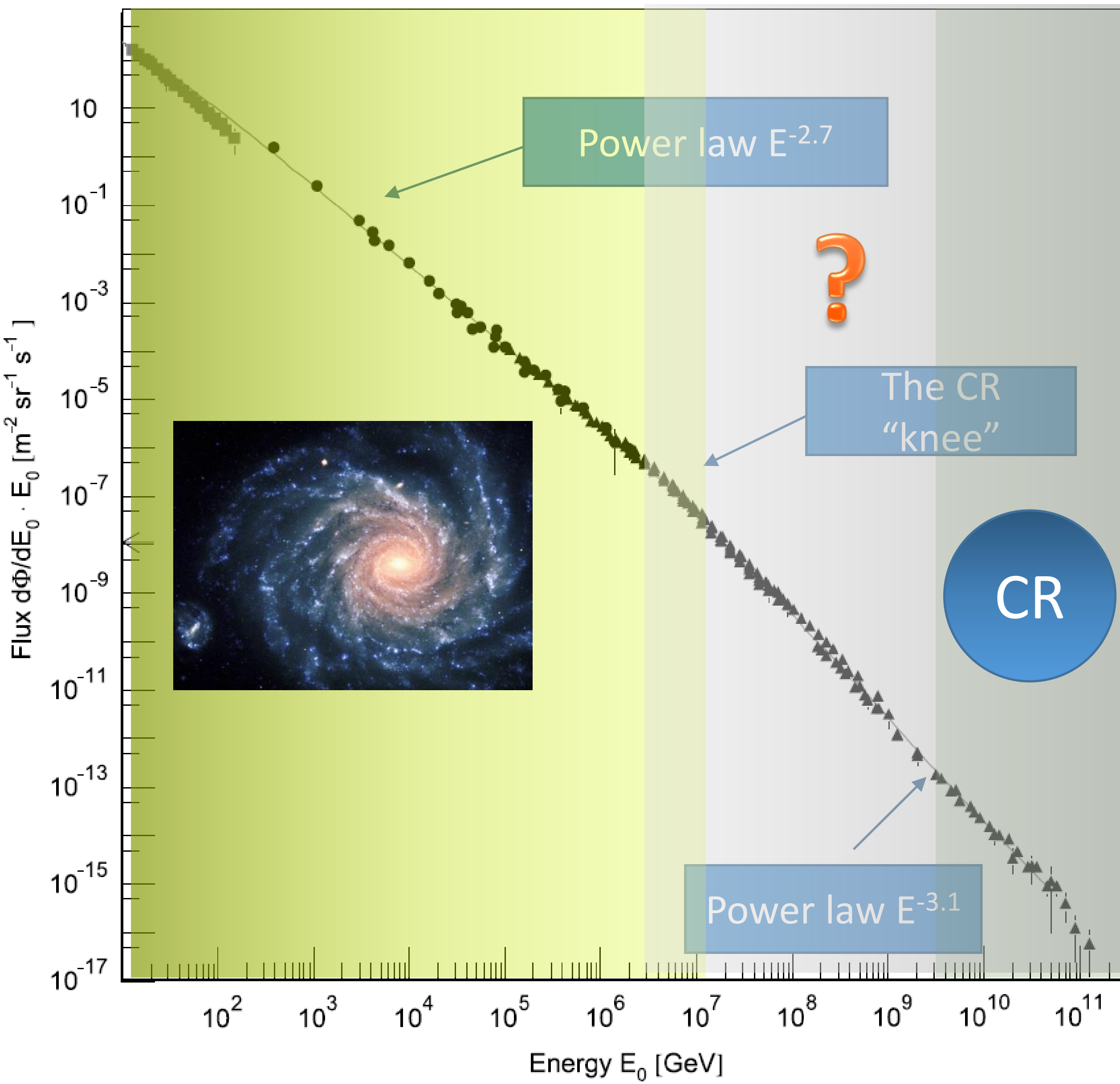
The «Fermi» acceleration process

- Supernova explosion
- Shock waves with speed $v_s=10^{-2}$ c
- Energy gain for head-on interaction: $\Delta E=\beta E$
- $\beta\sim v_s/c \sim 10^{-2}$
- Recursive process: energy gained after k processes is: $E = \beta^k E_0$
- It provided a power-law energy spectrum:
$$\frac{dN}{dE} \propto E^{-\gamma}$$



- Under reasonable assumptions, $\gamma \cong 2$
- Maximum attainable energy in the case of a SN: $\boldsymbol{E_{max} \approx 300\ Z\ (TeV)}$

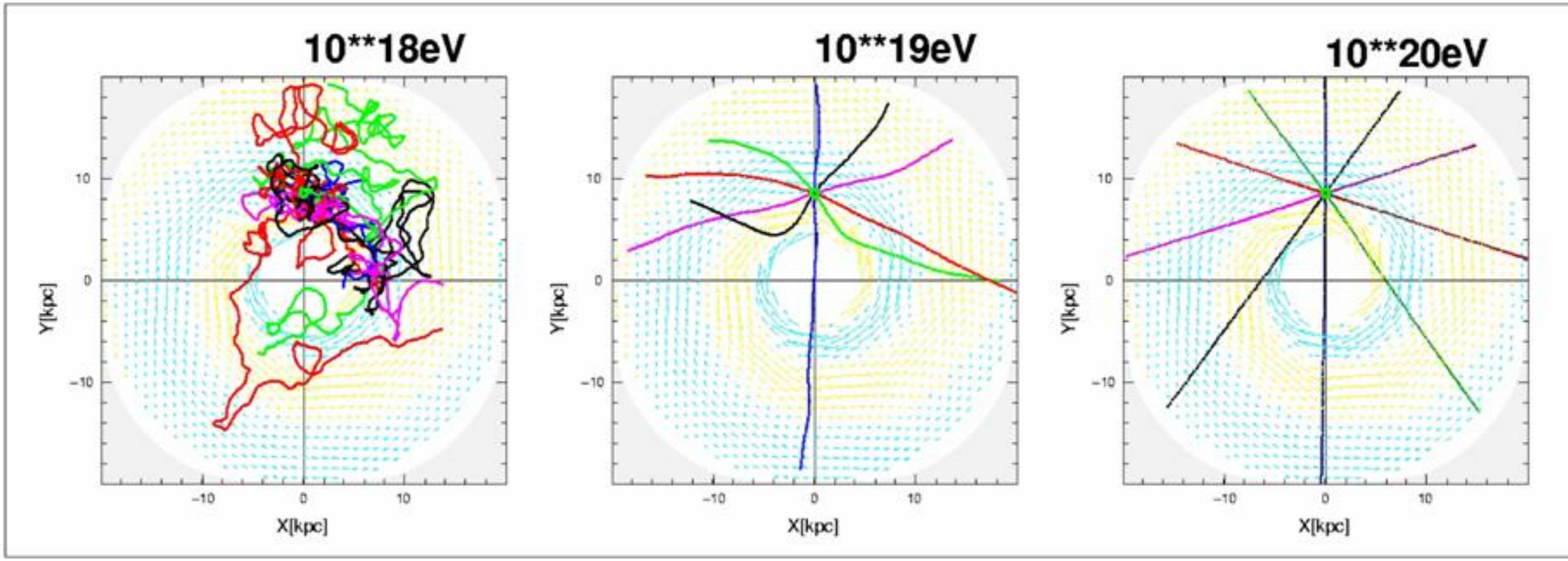
Beyond the SN energy bound



Galactic (SuperNova Remnants- SNRs)

ExtraGalactic (AGN, GRBs)

CR confinement in our Galaxy

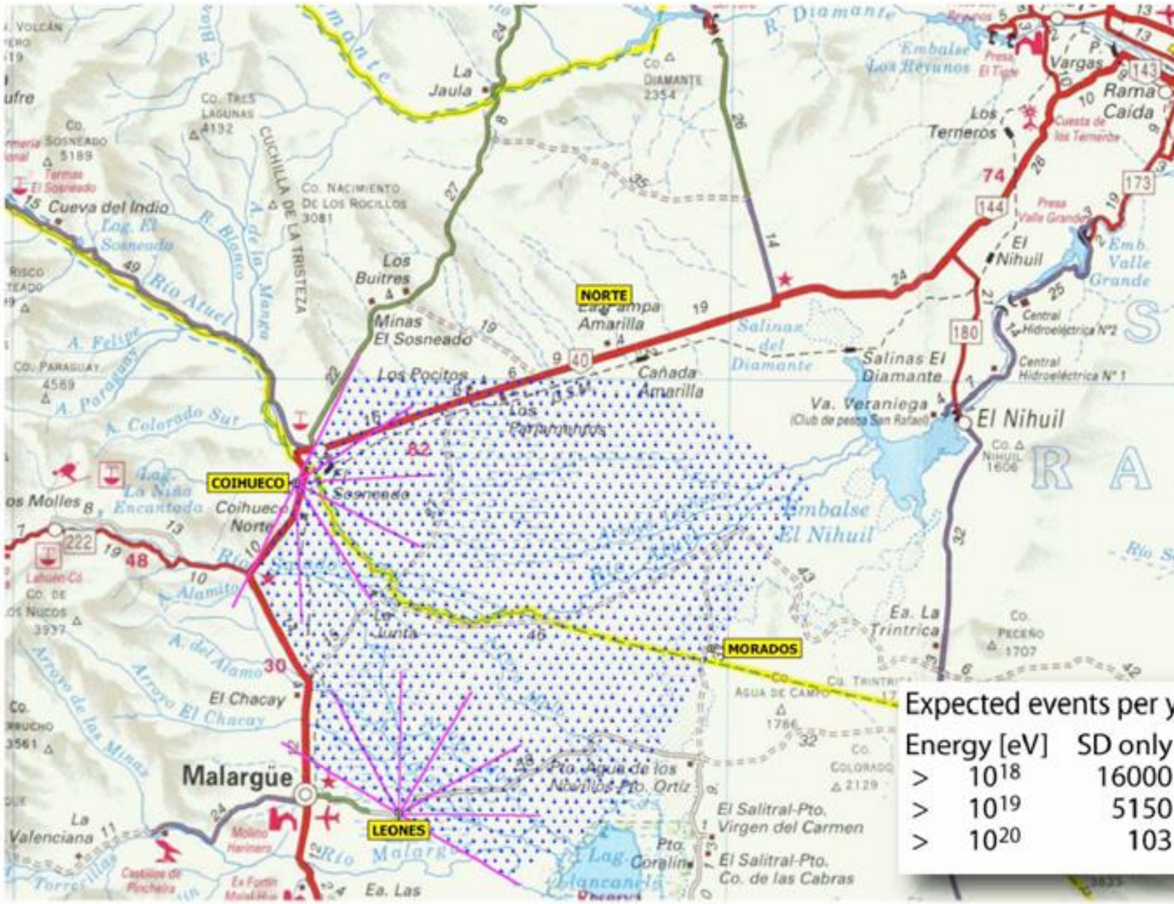


~ 10^{18} eV: RC well confined within our Galaxy
≳ 10^{19} eV: probably of extragalactic origin (@ 10^{20} eV deviation in our Galaxy smaller than 1°)

$$\boxed{r(kpc) \cong \frac{E(EeV)}{ZB(\mu G)}}$$

- At the highest energies, huge experiments are necessary to detect few CRs
- Flux @10^{20} eV ~ **1 particle/century/km²** .

The P. AUGER Observatory

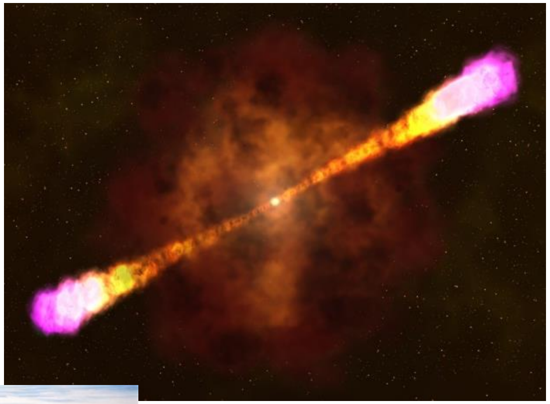


Expected events per y

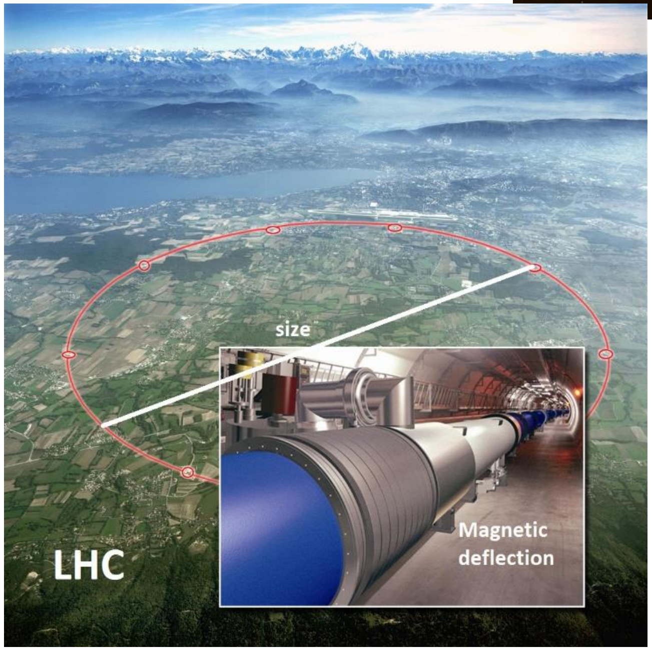
Energy [eV]	SD only
> 10^{18}	16000
> 10^{19}	5150
> 10^{20}	103

Cosmic vs. terrestrial particle accelerators

- Faraday law mechanism → $E_{max} \cong (Ze) \cdot B \cdot L$
- «Hillas» plot

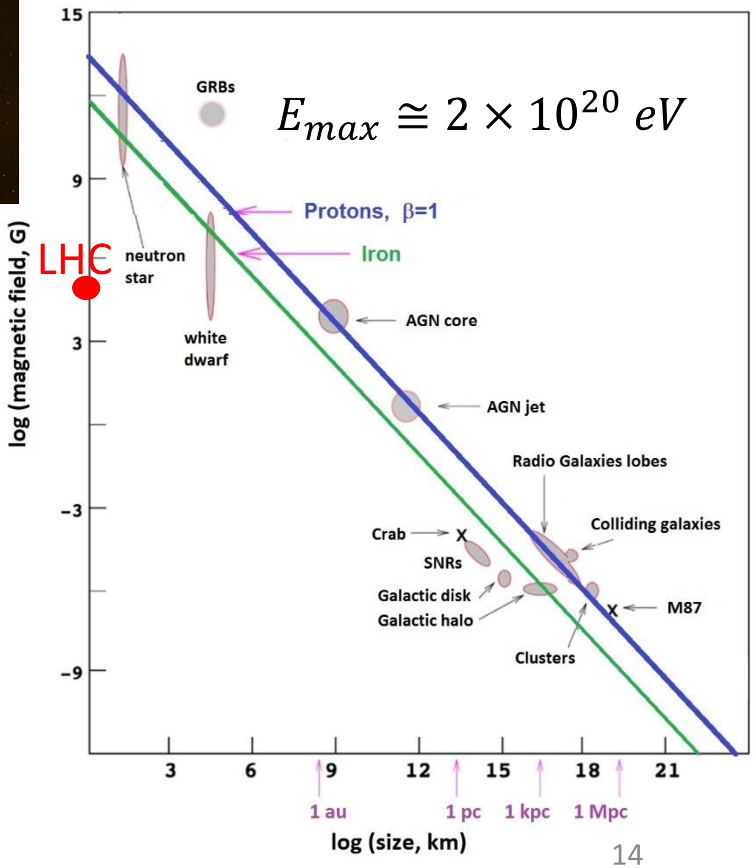


B$\sim 8\ T$
$R \sim 4.3\ km$
$E_{max} \cong 7 \times 10^{12}\ eV$

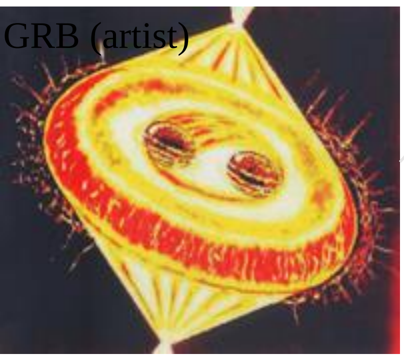


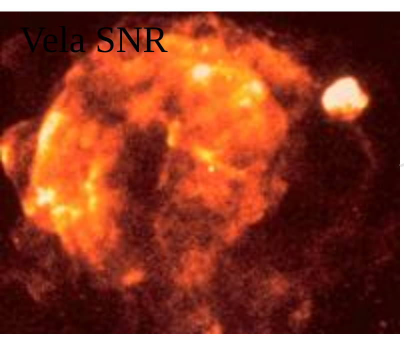
CR

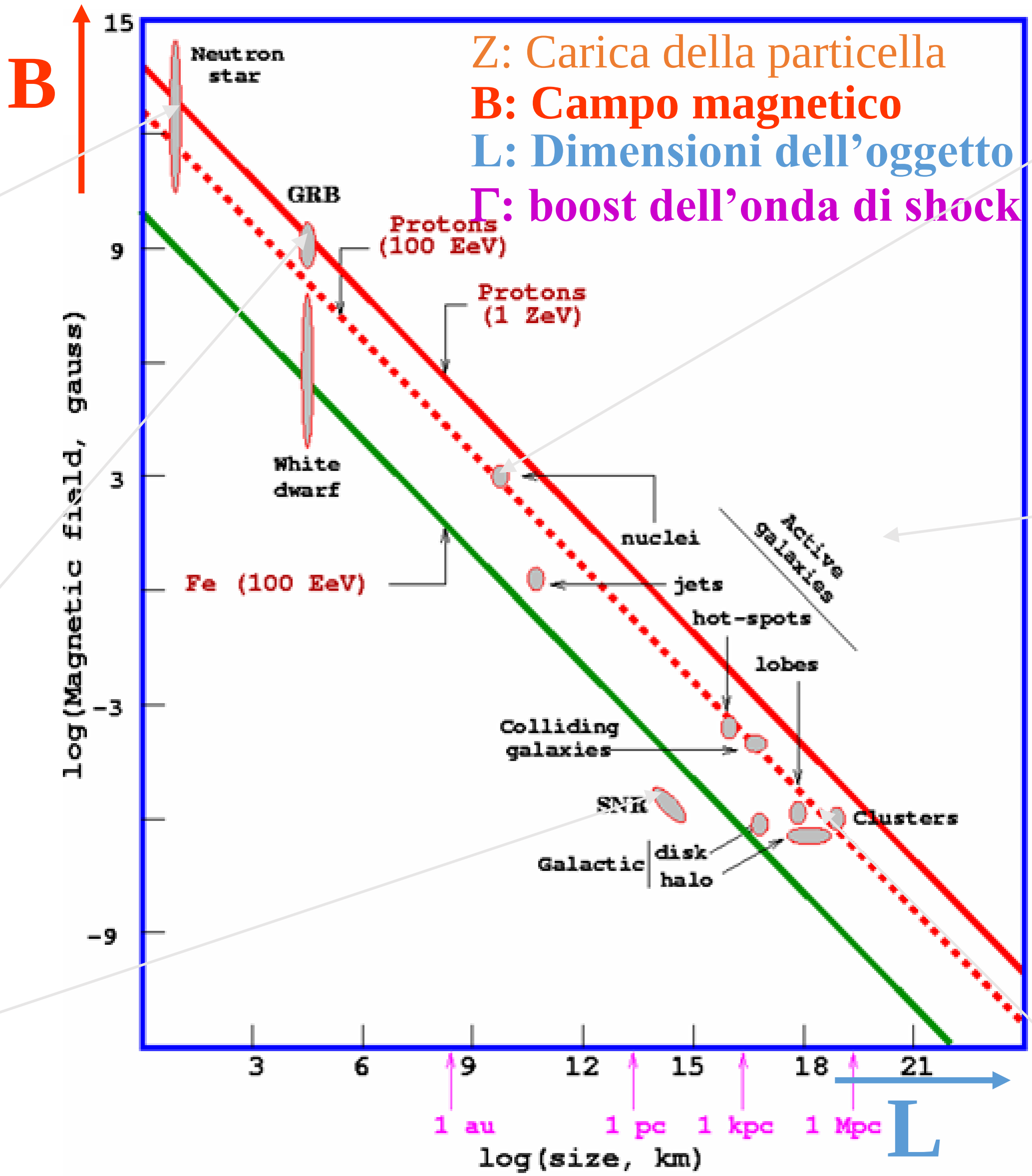
$E_{max} \cong 2 \times 10^{20}\ eV$

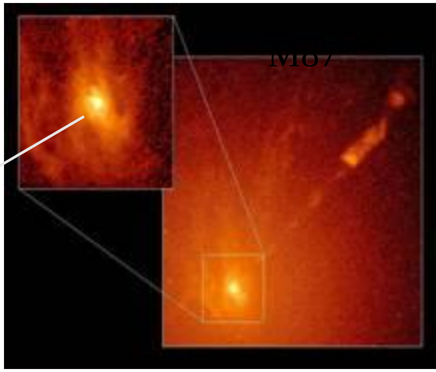


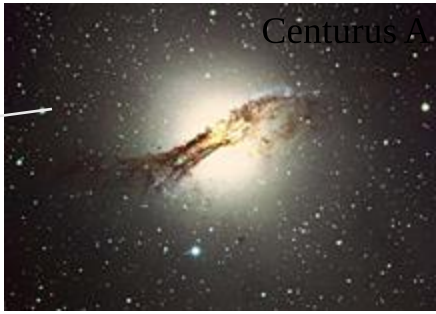
See: (M. Pimenta) **The Extreme Universe. High Energy Cosmic Rays**

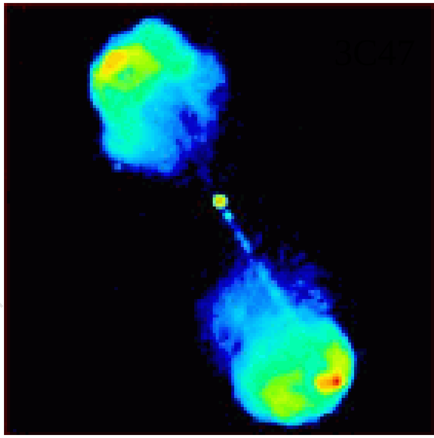












2) Cosmic Rays: matter and antimatter

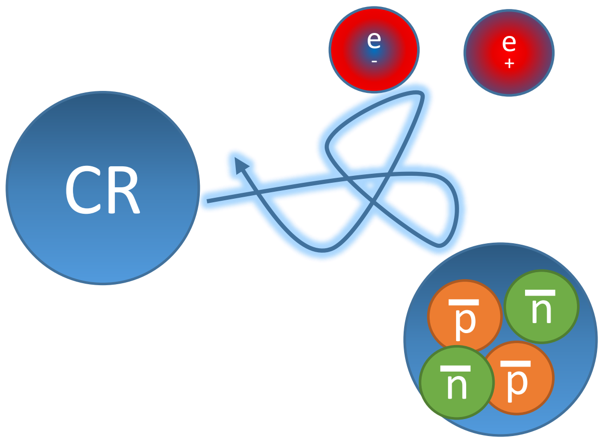
Antimatter in the Universe

- CRs Propagation
  - $\bar{p}/p \sim 10^{-4} - 10^{-5}$
  - $e^+/e^- \sim 10^{-1}$
- Positron anomaly (?)
- Antinuclei ?

Propagation of CRs

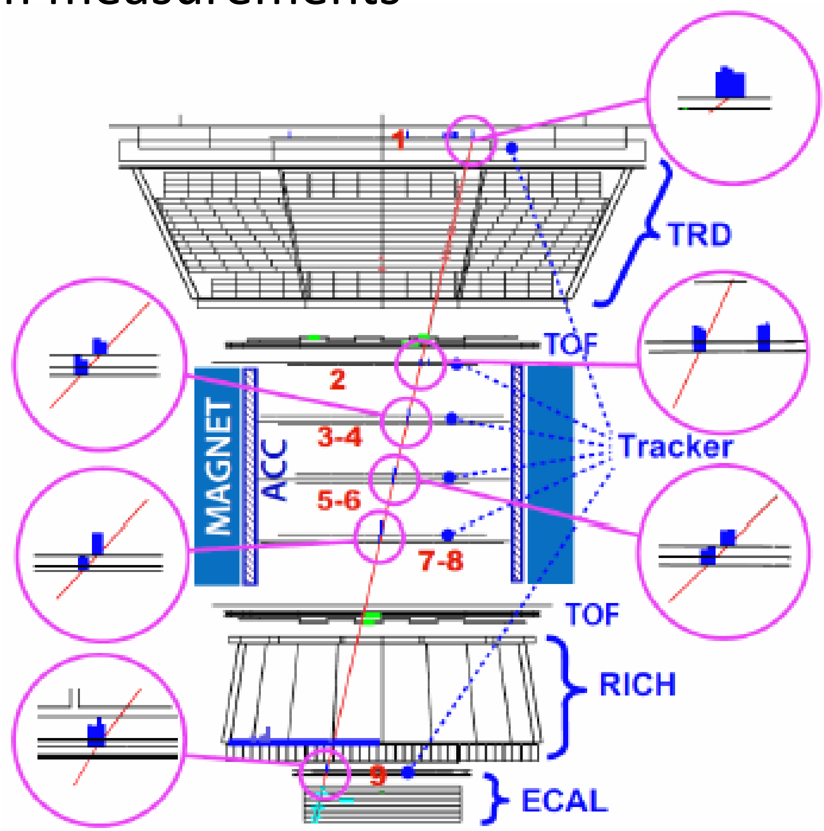
- Knowledge of the Galaxy
  - Matter distribution
  - Radiation fields
  - Magnetic fields

The primordial anti-matter suppression mechanism



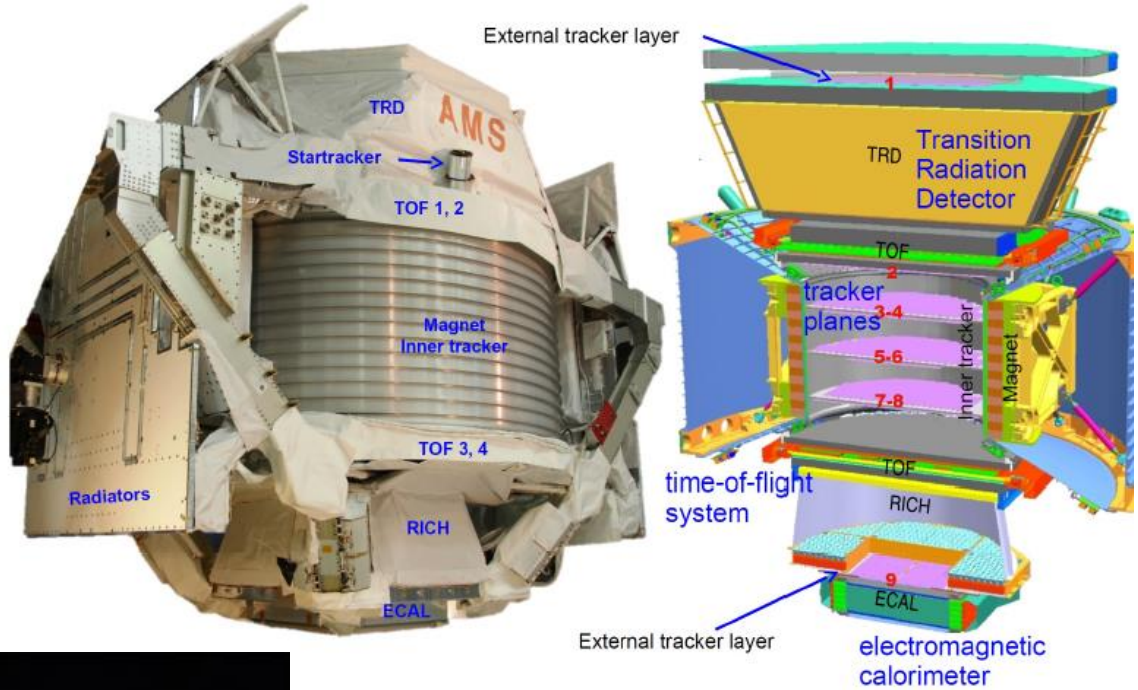
Antimatter in the Universe?

- No **primary antimatter** (e^+, $\bar{p}$) observed in the Universe
- Needs for a magnetic spectrometer in space
- Particle ID/ energy and momentum measurements

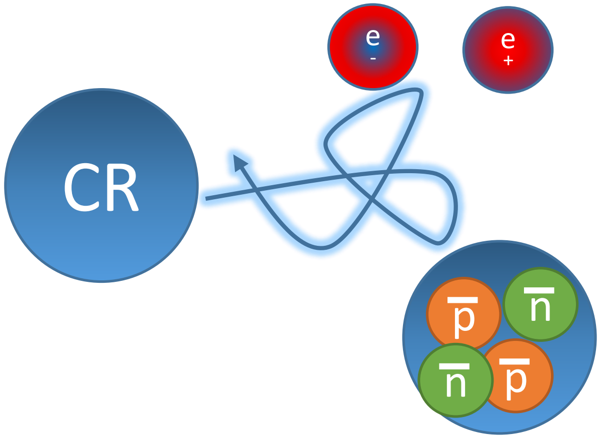


- **Secondary antiparticles** produced during propagation of CRs
- Determined with computer codes modelling the CR density and Galaxy structure (magnetic field, matter density…)
- **Experiments**:
    - BESS (Balloon)
    - PAMELA (Satellite)
    - AMS-02 (ISS)

AMS-02

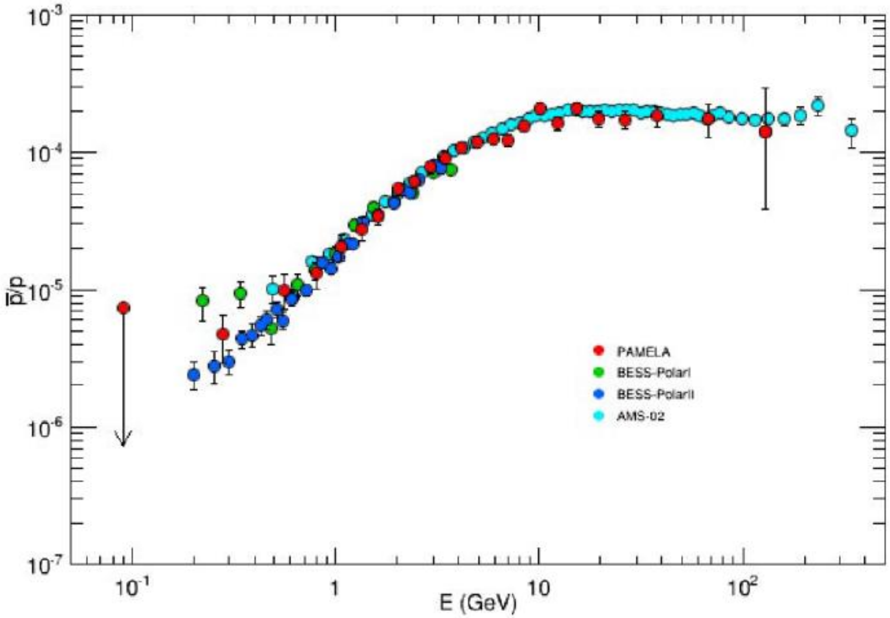


TRD
AMS
Startracker
TOF 1, 2
Magnet
Inner tracker
TOF 3, 4
Radiators
RICH
ECAL
External tracker layer
1
TRD
Transition
Radiation
Detector
TOF
2
tracker
planes
3-4
5-6
7-8
Inner tracker
Magnet
TOF
time-of-flight
system
RICH
9
ECAL
External tracker layer
electromagnetic
calorimeter



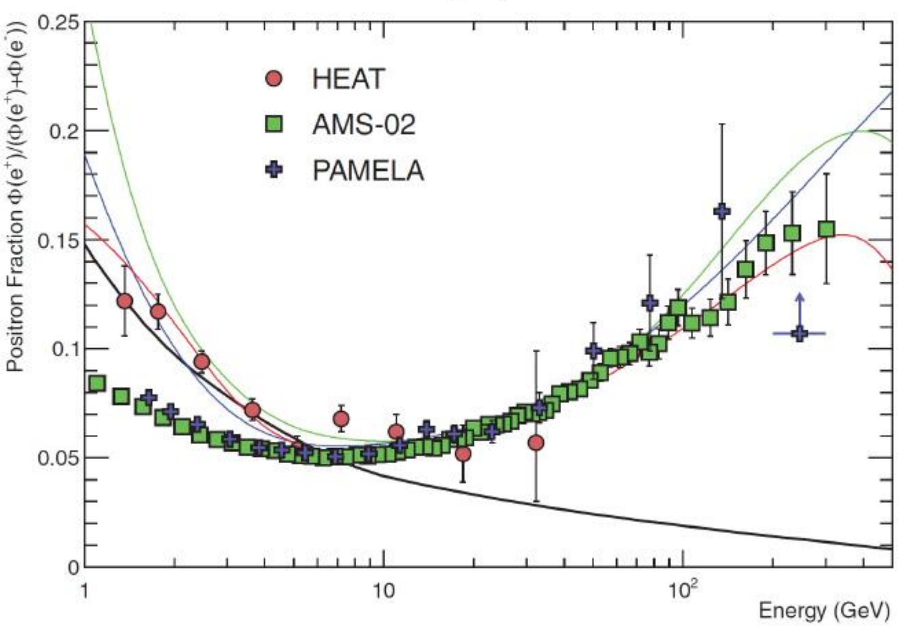
e -
e +
CR
p̄
n̄
n̄
p̄

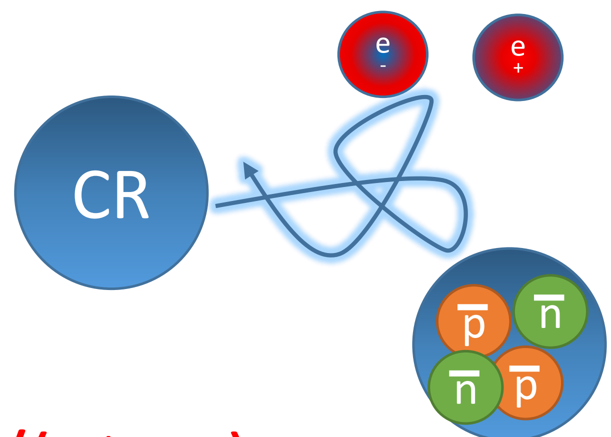
Antiprotons and positrons



$\bar{p}/p$

~ok

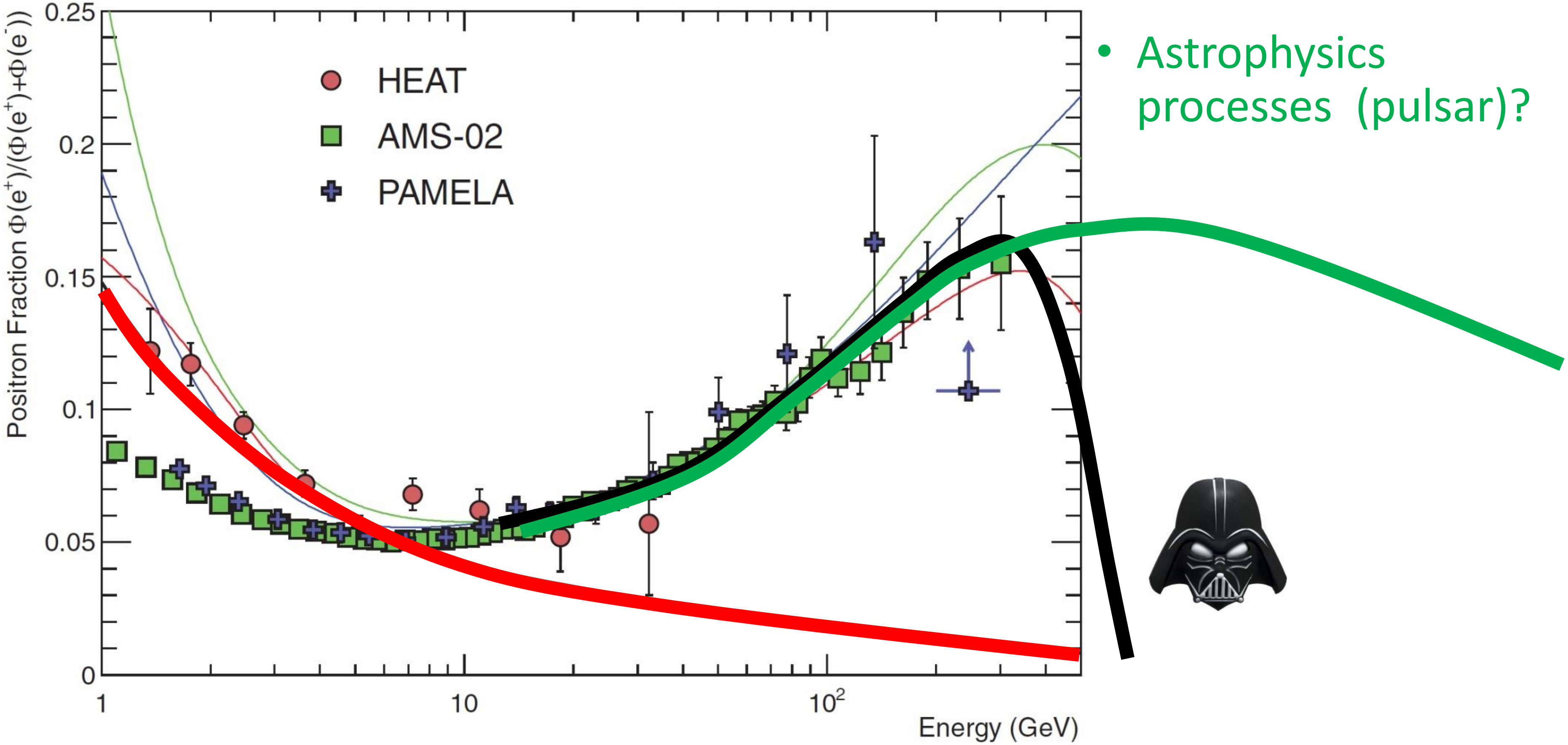




$e^+/(e^++e^-)$

anomaly (**under study**)

AMS02: interpreting the positron excess



- «Conventional» propagation nodel
- Dark matter ?
- Astrophysics processes (pulsar)?

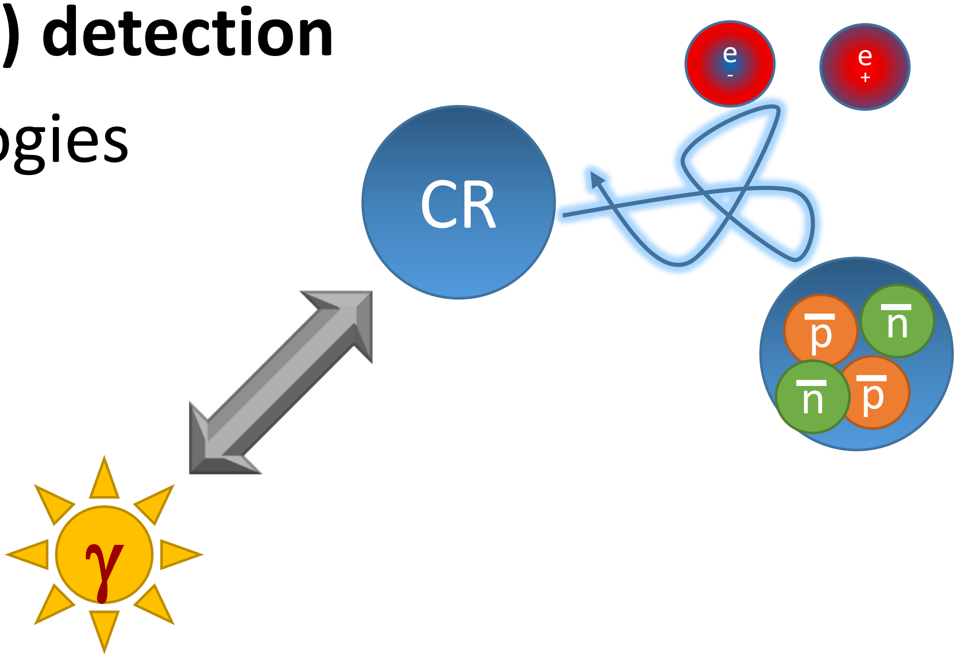
3) Astrophysics with γ-rays

1. Astrophysical production

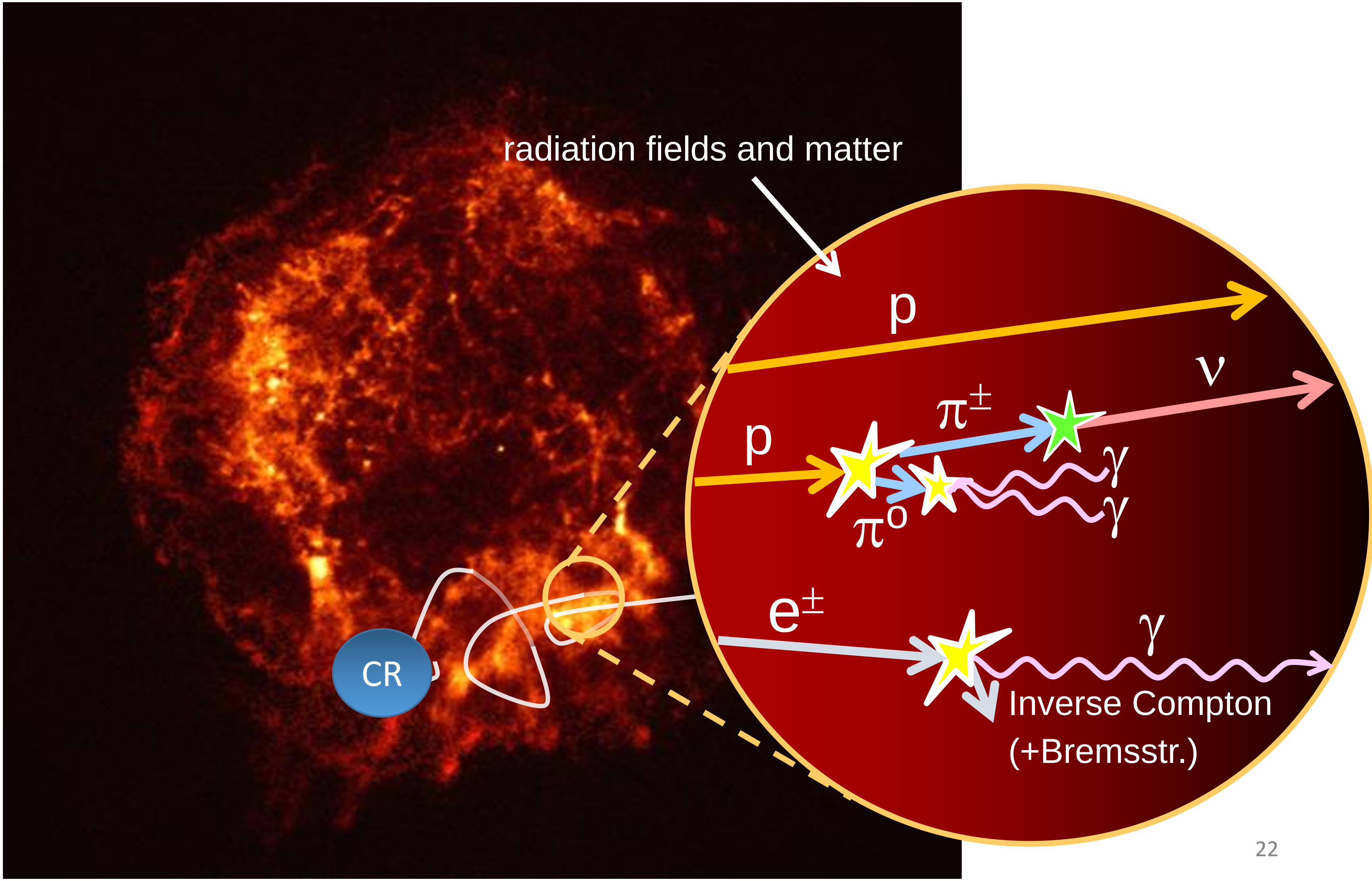
- Leptonic mechanism
- Hadronic mechanism
  - Baryon fraction

2. γ-rays (GeV-TeV) detection

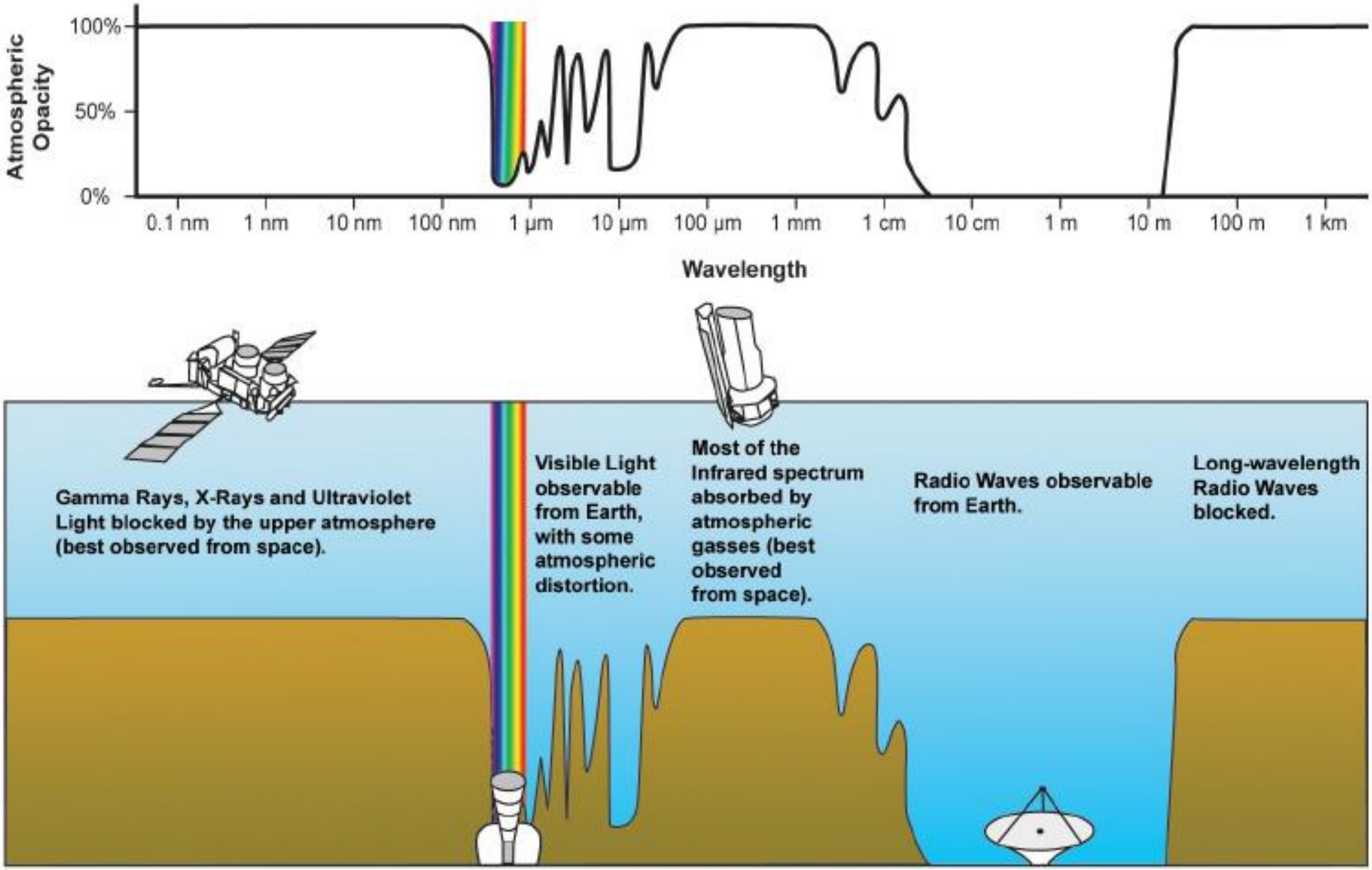
- Satellites technologies
- IACTs



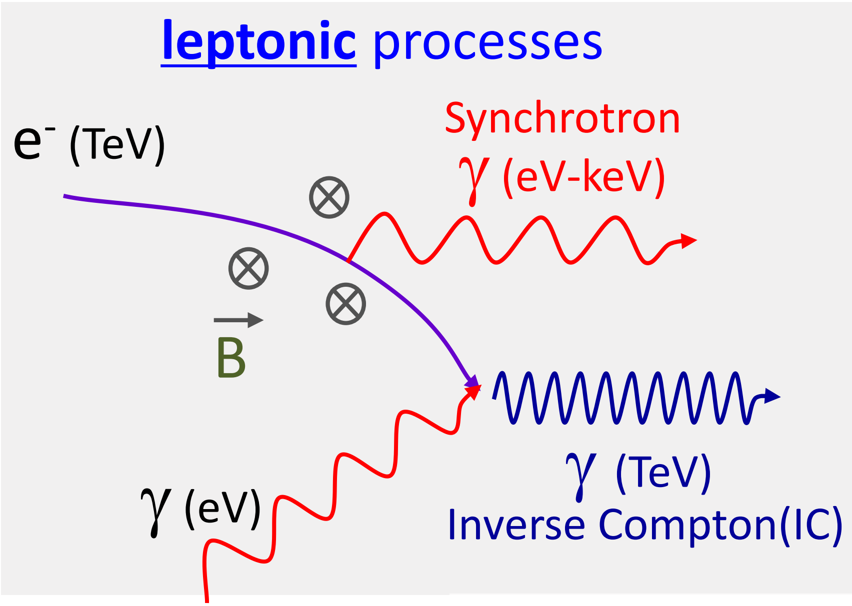
Cosmic Accelerators

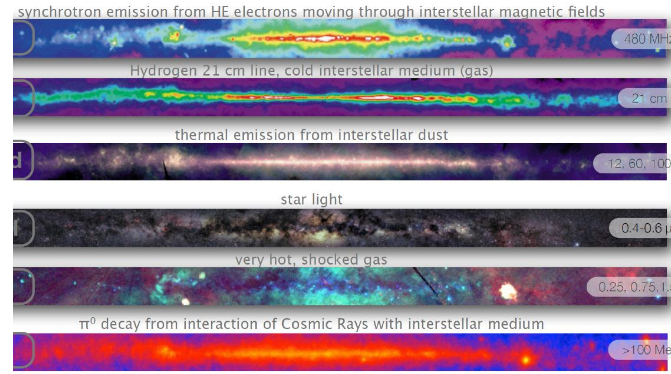


Atmospheric opacity to the EM radiation

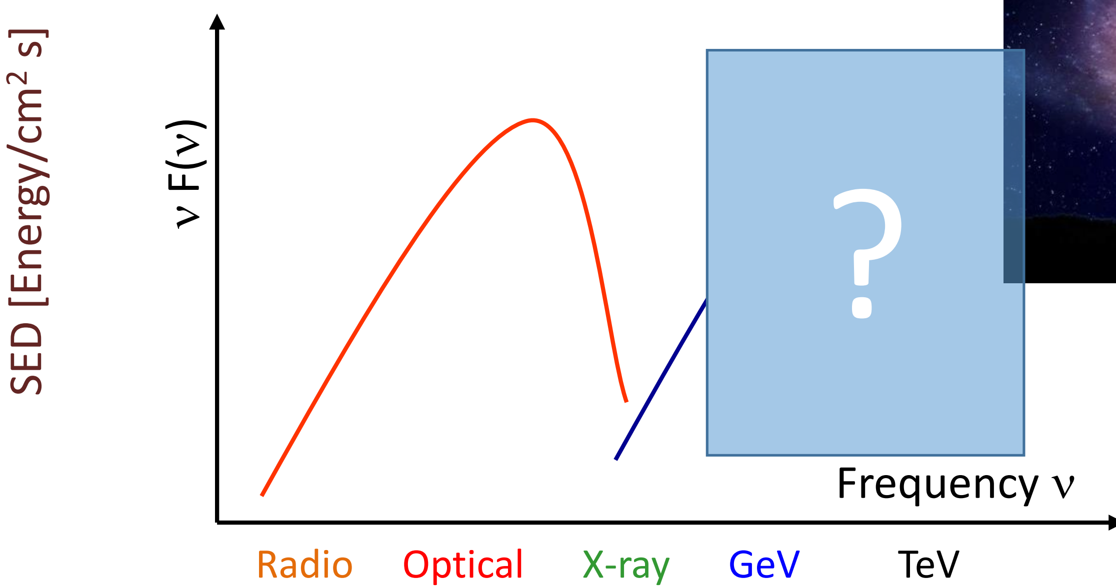


Non-thermal Universe

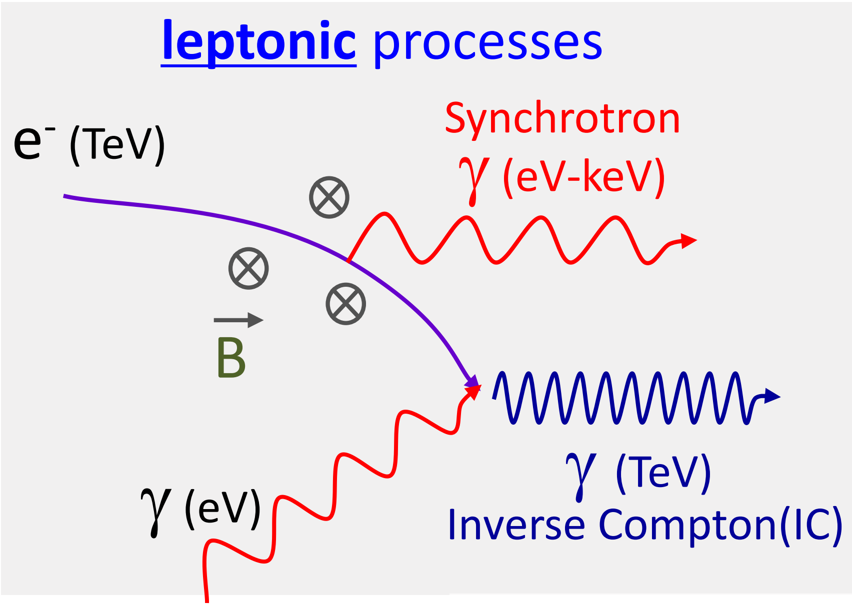


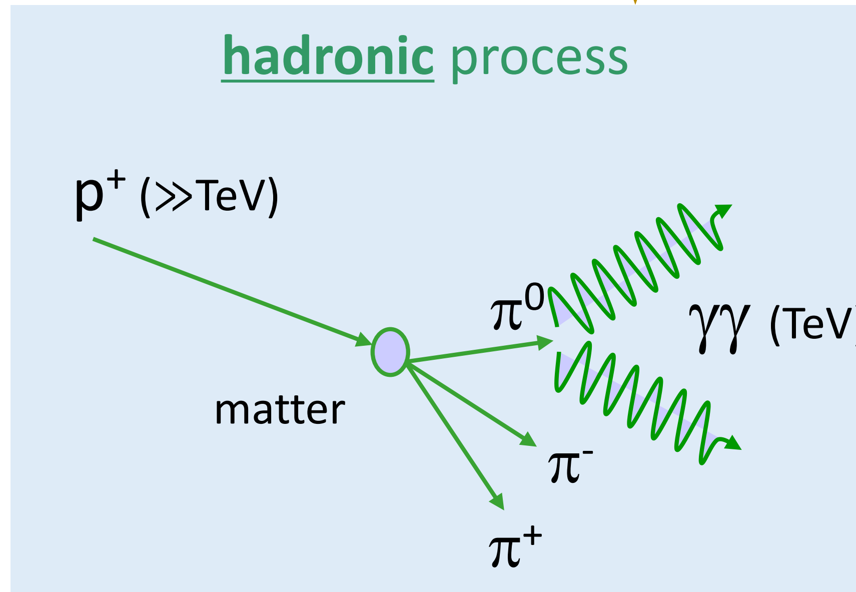


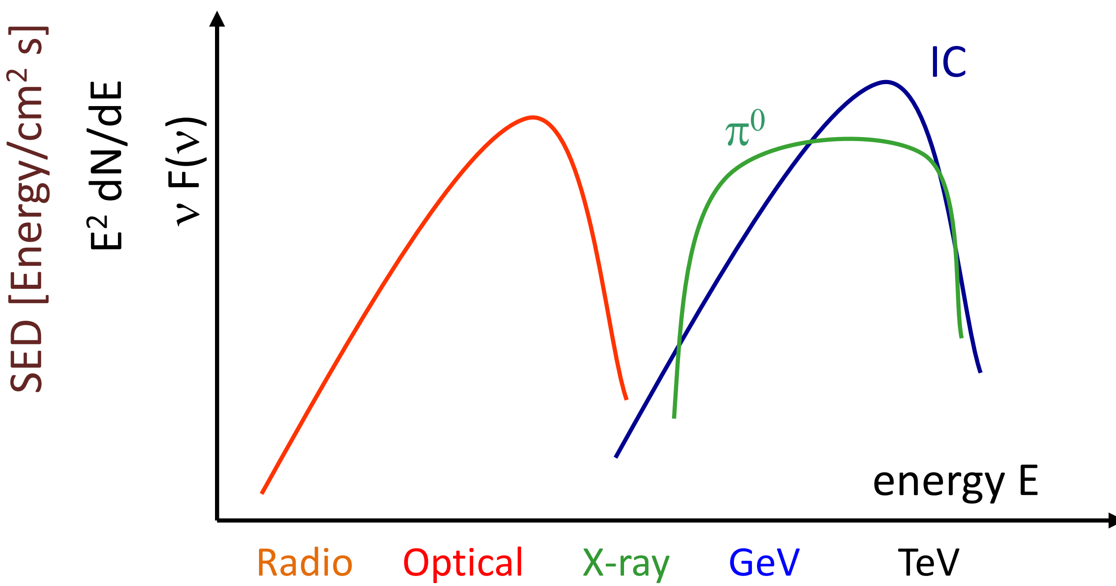
Traditional Astronomy



Non-thermal Universe

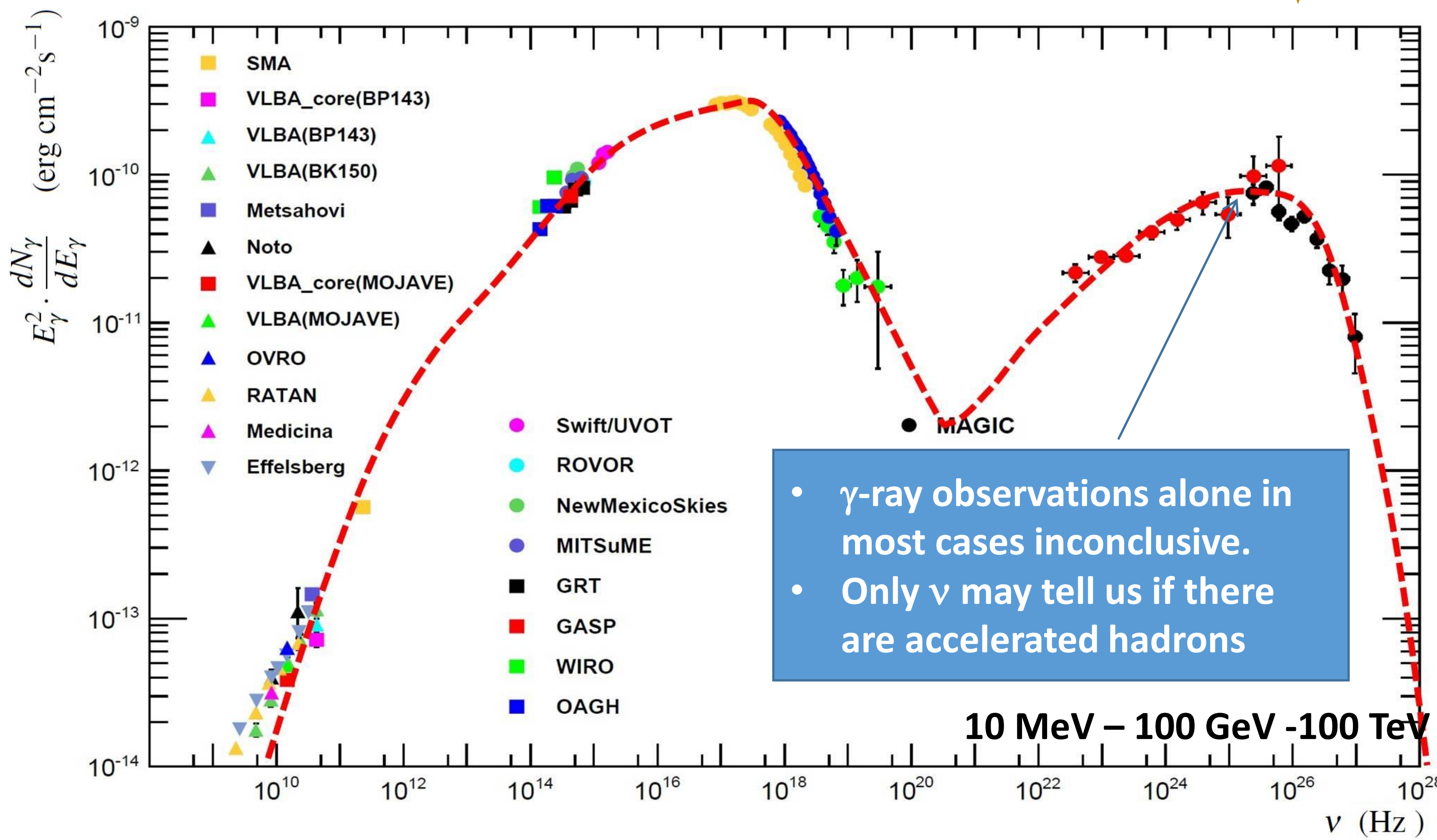






To distinguish between **hadronic/leptonic** origin the Spectral Energy Distribution **(SED)** must be studied with different experimental techniques.

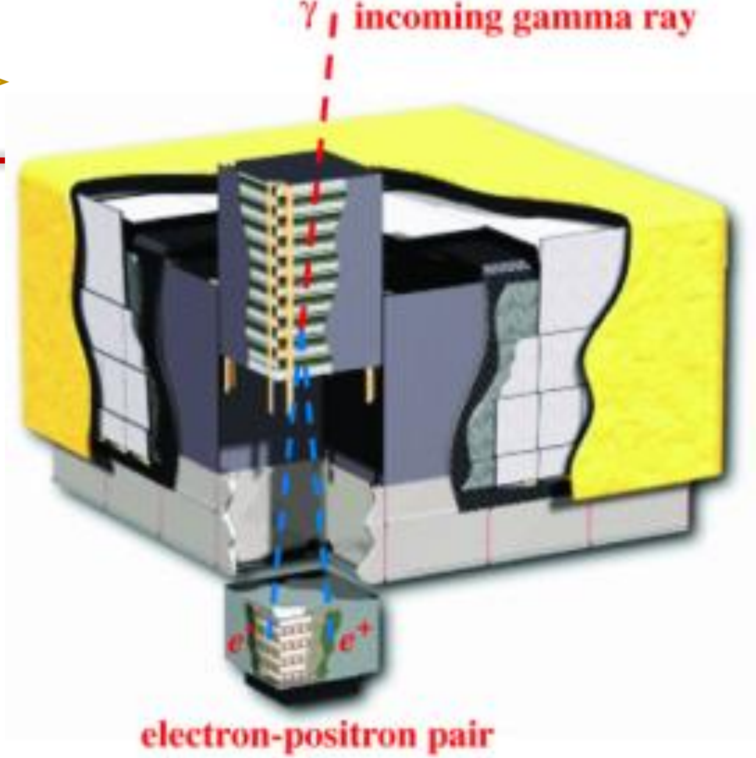
Multi-wavelength observation

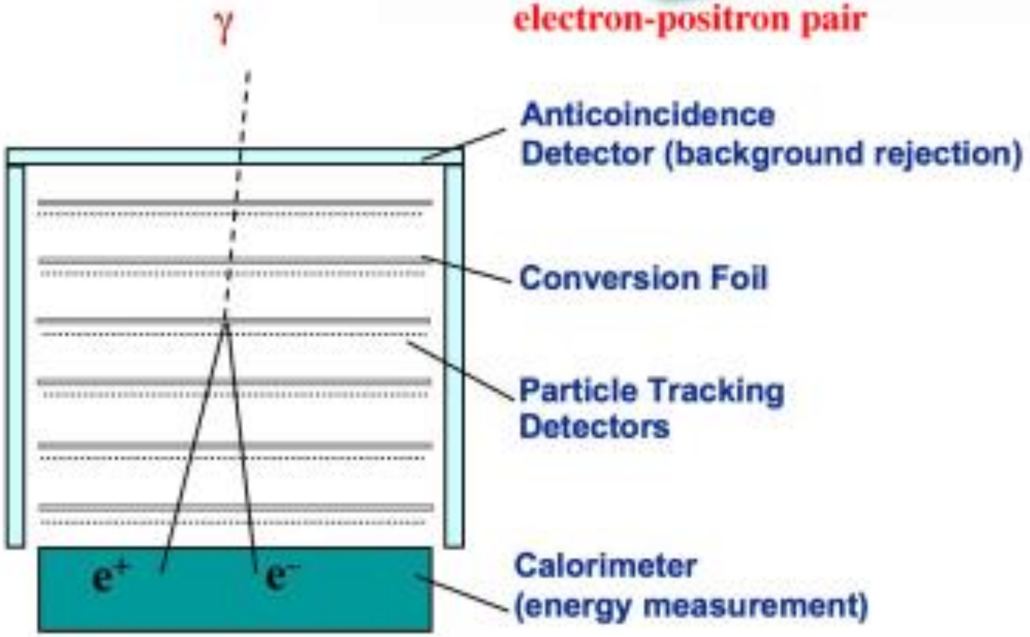


Extensive multi-wavelength measurements showing the spectral energy distribution ***(SED)*** *of* ***Markarian 421 from*** *observations made in 2009. The dashed line is a fit of the data with a leptonic model. Abdo et al. ApJ 736(2011) 131 for the references to the data*

The Fermi-LAT satellite

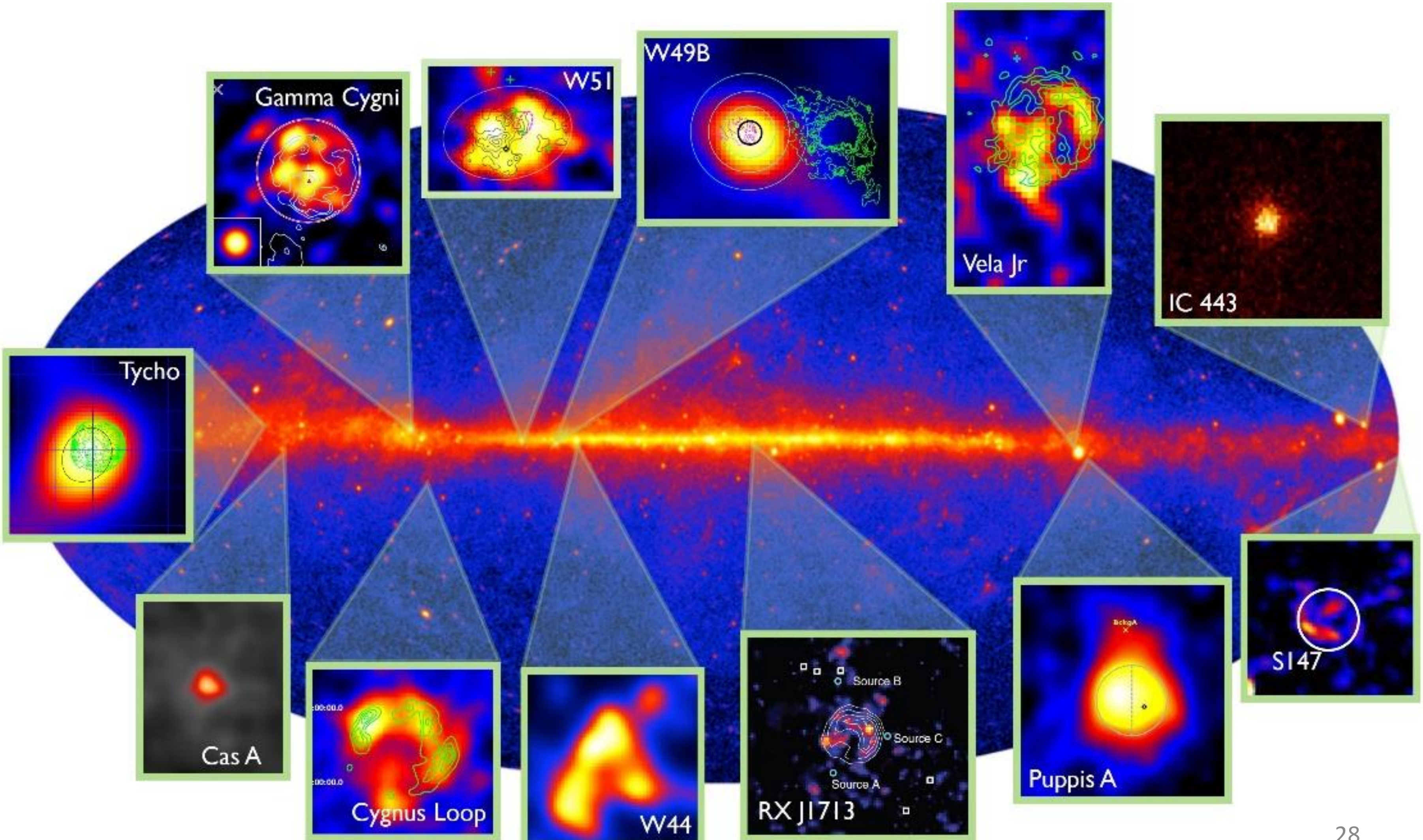
- A γ conversion (into e+e- pairs) detector
- Calorimetric measurement of e+e- pairs (E_γ up to 300 GeV)
- Launch: 11/6/2008





The GeV γ-ray sky https://fermi.gsfc.nasa.gov/

γ-ray = **Diffuse** + cosmic sources



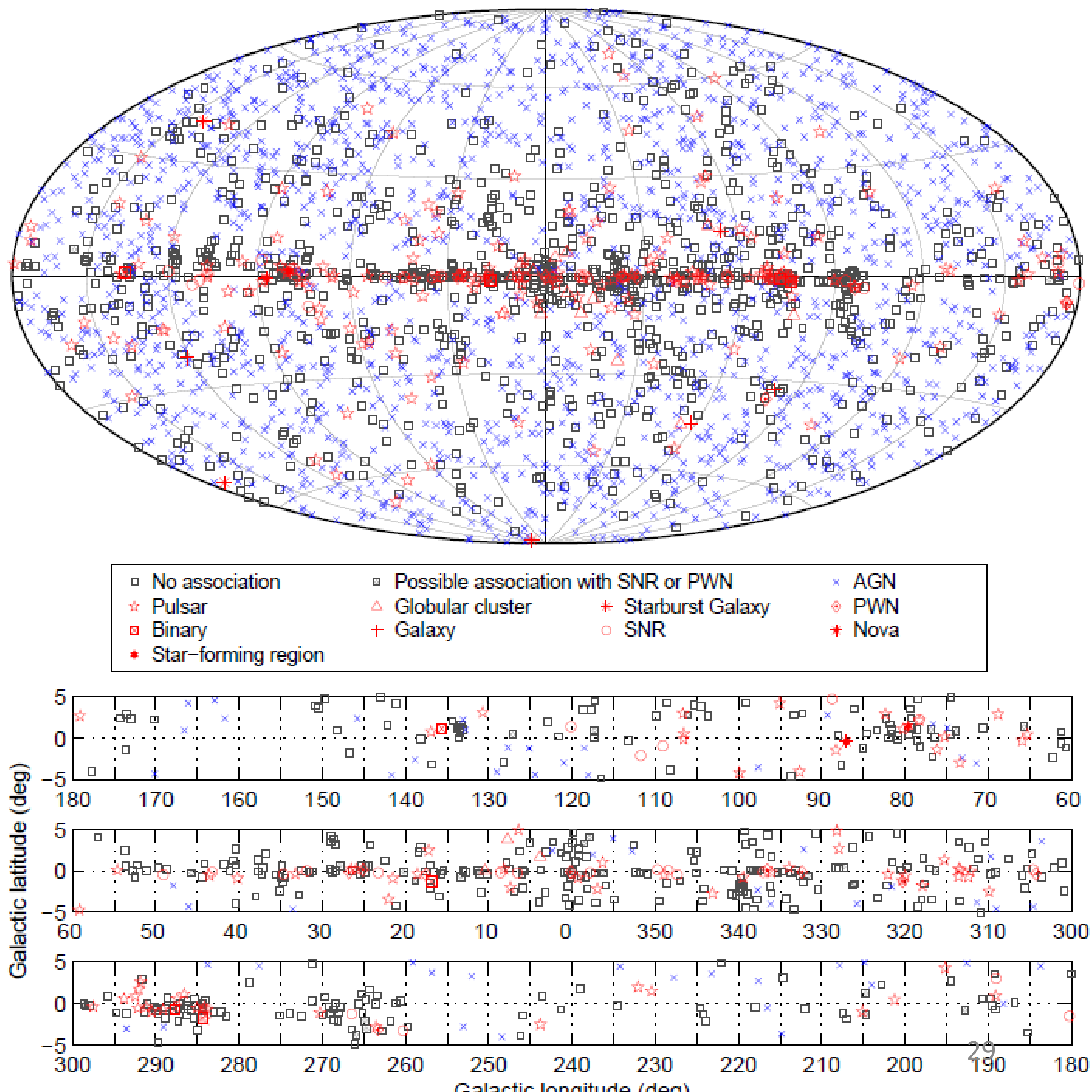
Fermi-LAT Point Source Catalog (3FGL)

Fermi LAT Third Source Catalog (4y)
arXiv:1501.02003

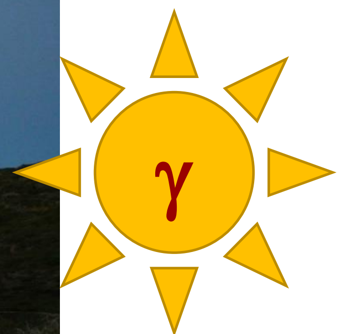
Table 6. LAT 3FGL Source Classes

Description	Identified		Associated	
	Designator	Number	Designator	Number
Pulsar, identified by pulsations	PSR	143	...	...
Pulsar, no pulsations seen in LAT yet	...	...	psr	24
Pulsar wind nebula	PWN	9	pwn	2
Supernova remnant	SNR	12	snr	11
Supernova remnant / Pulsar wind nebula	...	...	spp	49
Globular cluster	GLC	0	glc	15
High-mass binary	HMB	3	hmb	0
Binary	BIN	1	bin	0
Nova	NOV	1	nov	0
Star-forming region	SFR	1	sfr	0
Compact Steep Spectrum Quasar	CSS	0	css	1
BL Lac type of blazar	BLL	18	bll	642
FSRQ type of blazar	FSRQ	38	fsrq	446
Non-blazar active galaxy	AGN	0	agn	3
Radio galaxy	RDG	3	rdg	12
Seyfert galaxy	SEY	0	sey	1
Blazar candidate of uncertain type	BCU	5	bcu	568
Normal galaxy (or part)	GAL	2	gal	1
Starburst galaxy	SBG	0	sbg	4
Narrow line Seyfert 1	NLSY1	2	nlsy1	3
Soft spectrum radio quasar	SSRQ	0	ssrq	3
Total	...	238	...	1785
Unassociated	...	...	...	1010

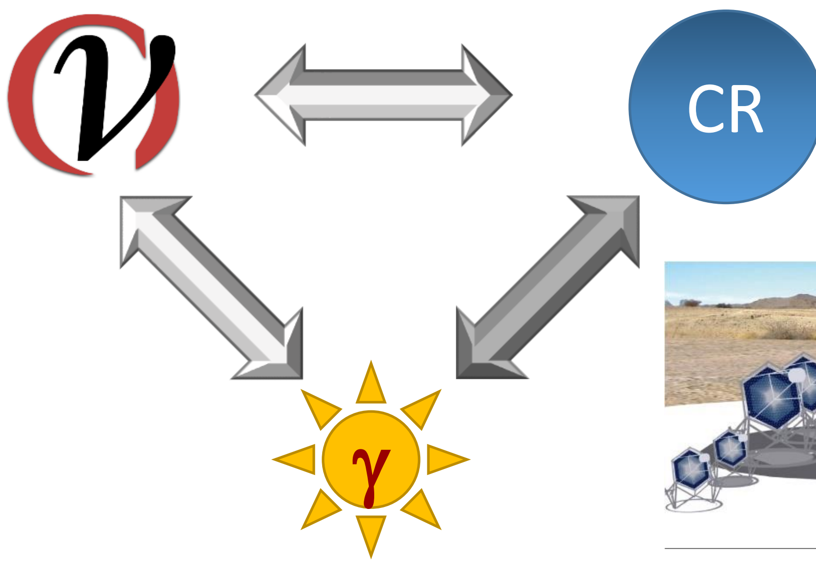
Note. — The designation 'spp' indicates potential association with SNR or PWN (see Table 7). Designations shown in capital letters are firm identifications; lower case letters indicate associations. In the case of AGN, many of the associations have high confidence. Among the pulsars, those with names beginning with LAT were discovered with the LAT.



Higher energies: TeV γ-ray sky: IACTs

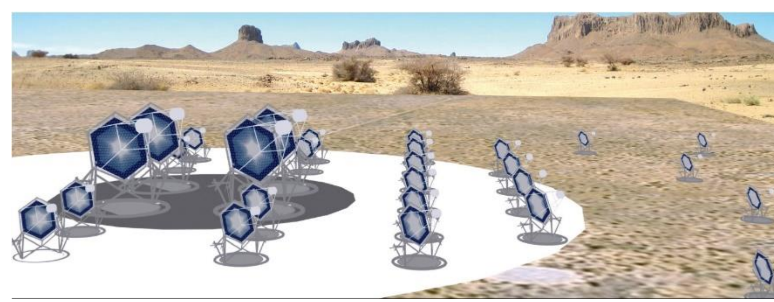


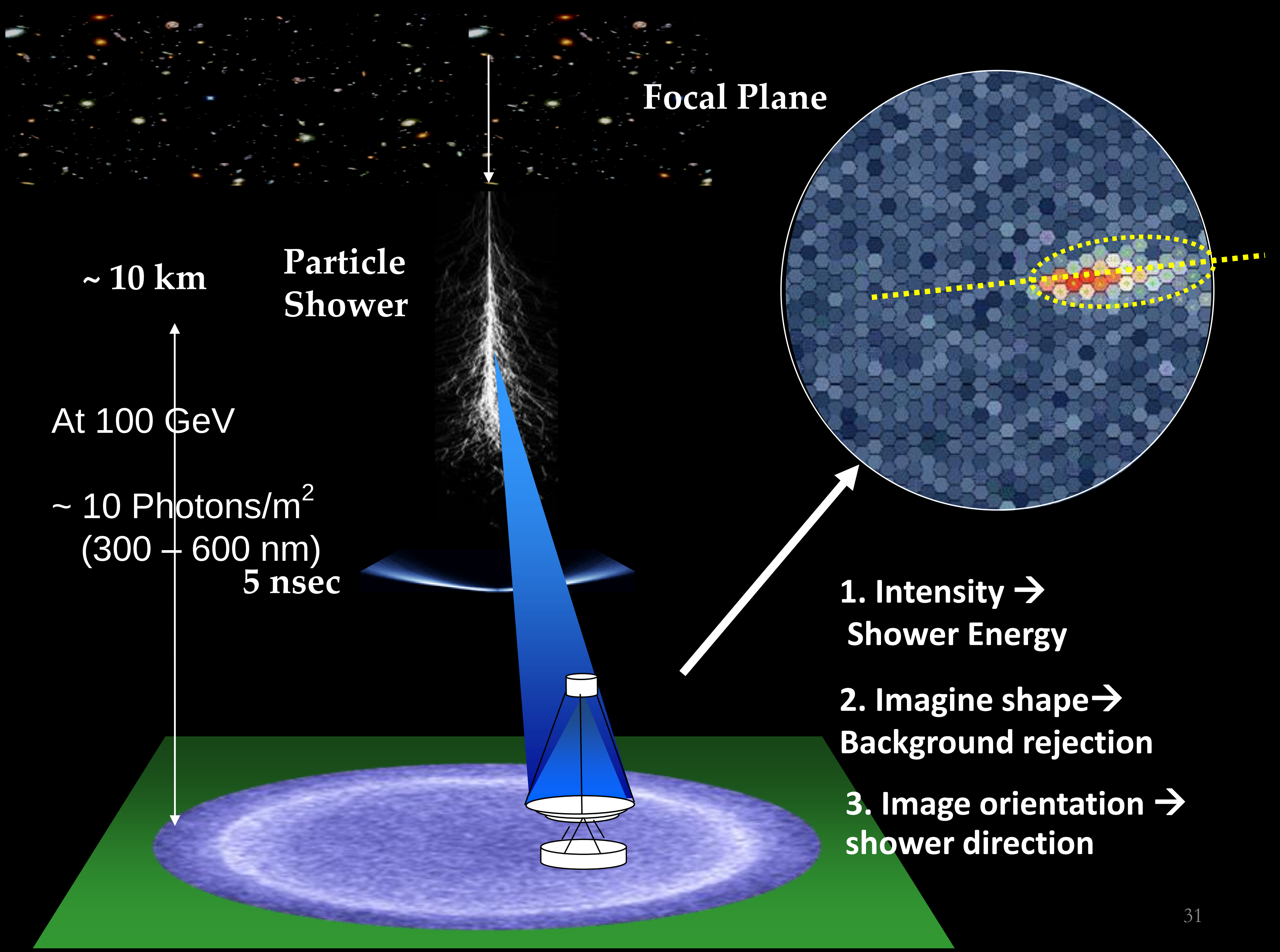
- MAGIC
- HESS
- VERITAS



The future:

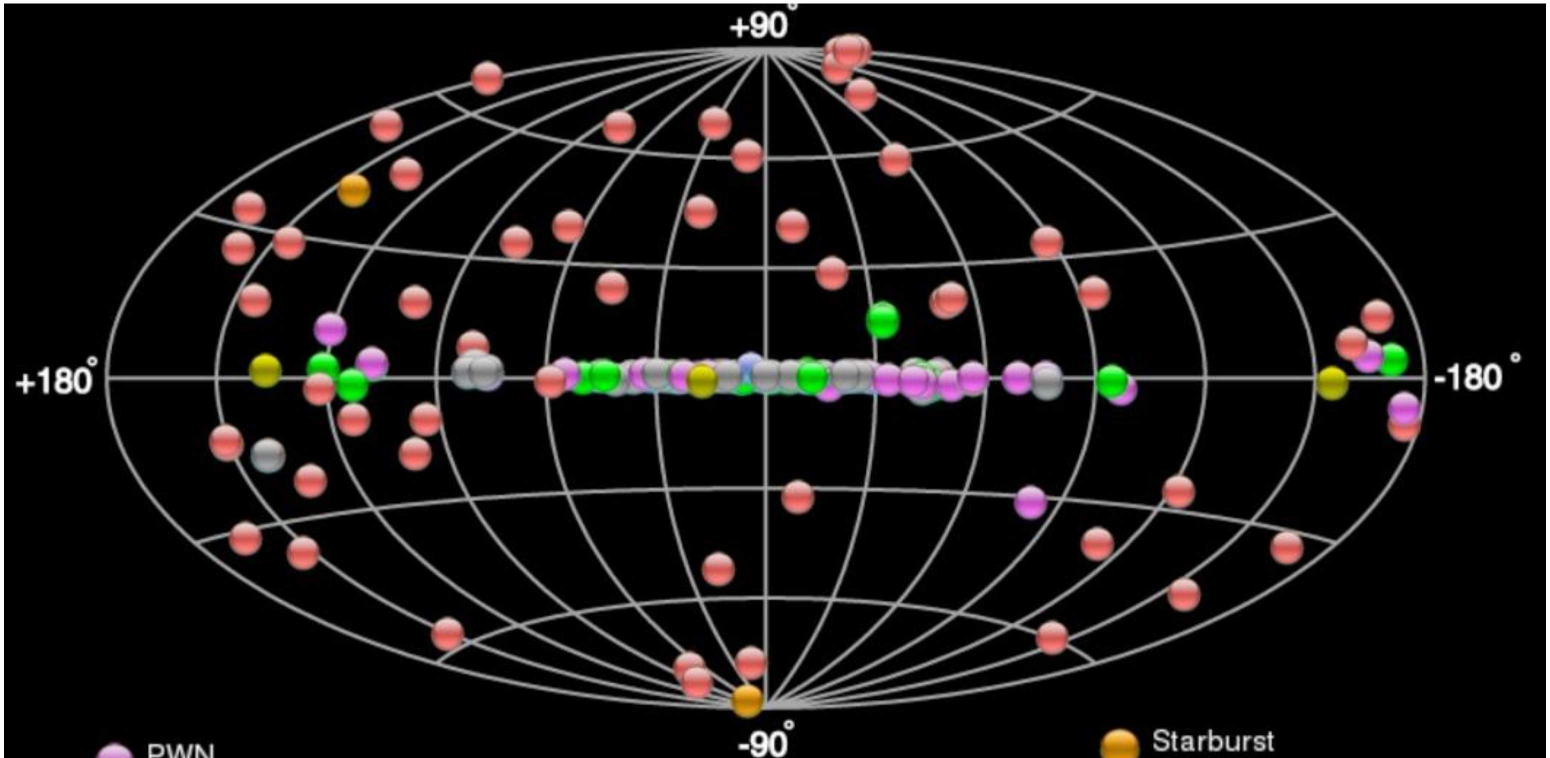
- CTA

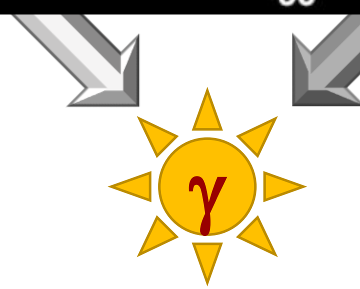




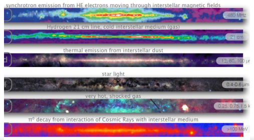
Focal Plane
~ 10 km
Particle Shower
At 100 GeV
~ 10 Photons/m^2
(300 – 600 nm)
5 nsec
1. Intensity → Shower Energy
2. Imagine shape→ Background rejection
3. Image orientation → shower direction

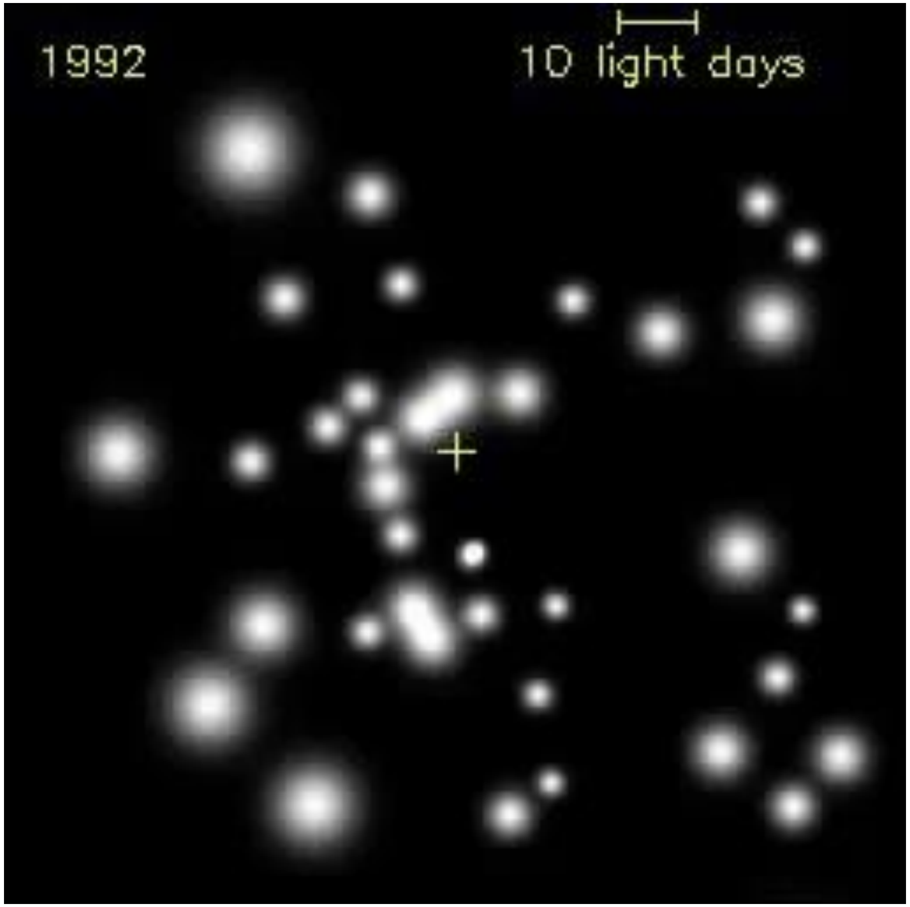
TeV γ-ray sky: IACTs





The black hole in our Galaxy



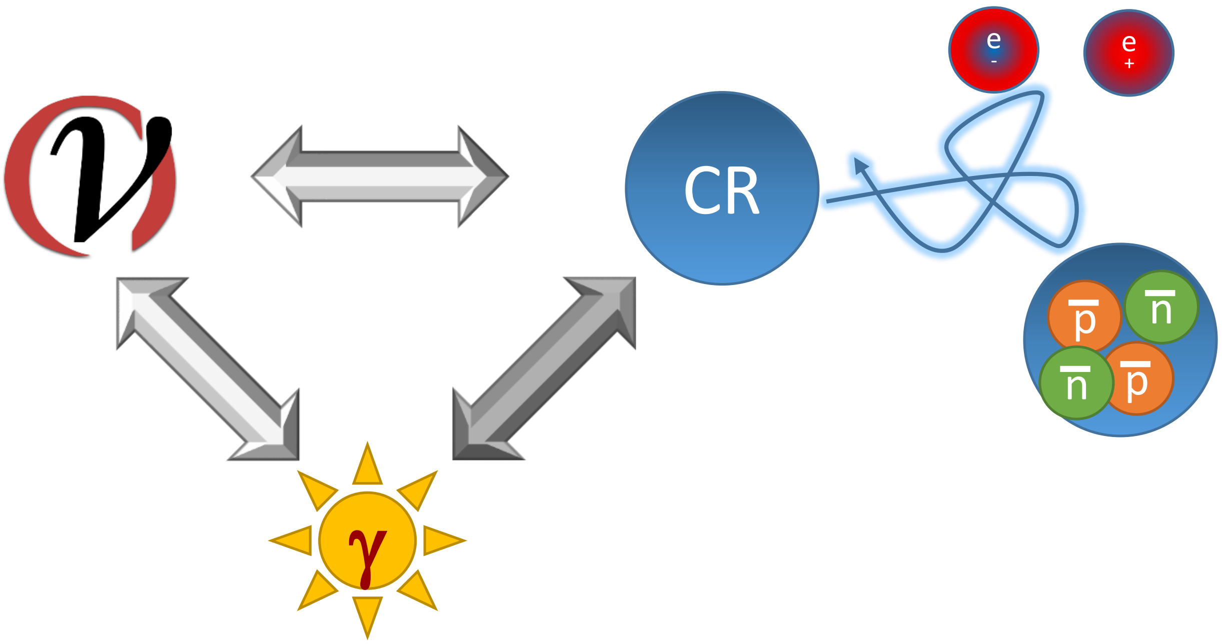


- **Question**: Evaluate the BH mass from the movie

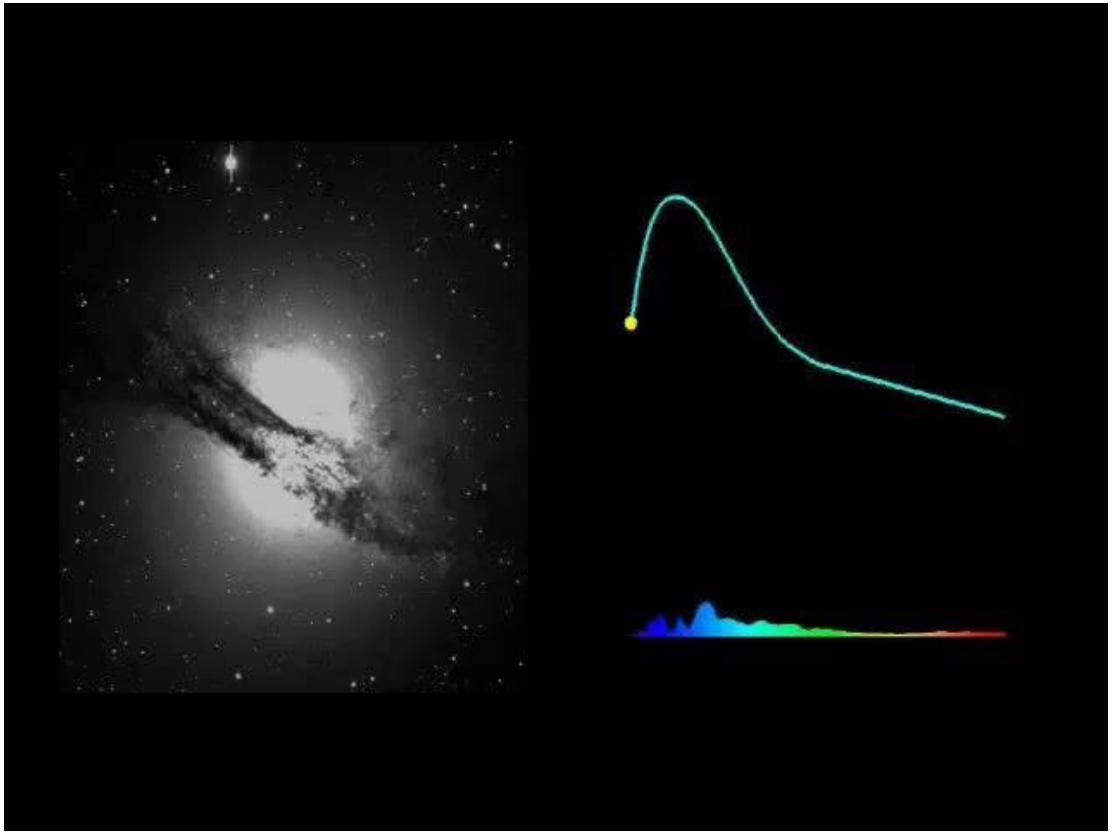
4) Astrophysics with low-energy neutrinos

Low energy ν's detected

- 4.1) Astrophysics of core collapse SNe
- 4.2) Astrophysics of stars



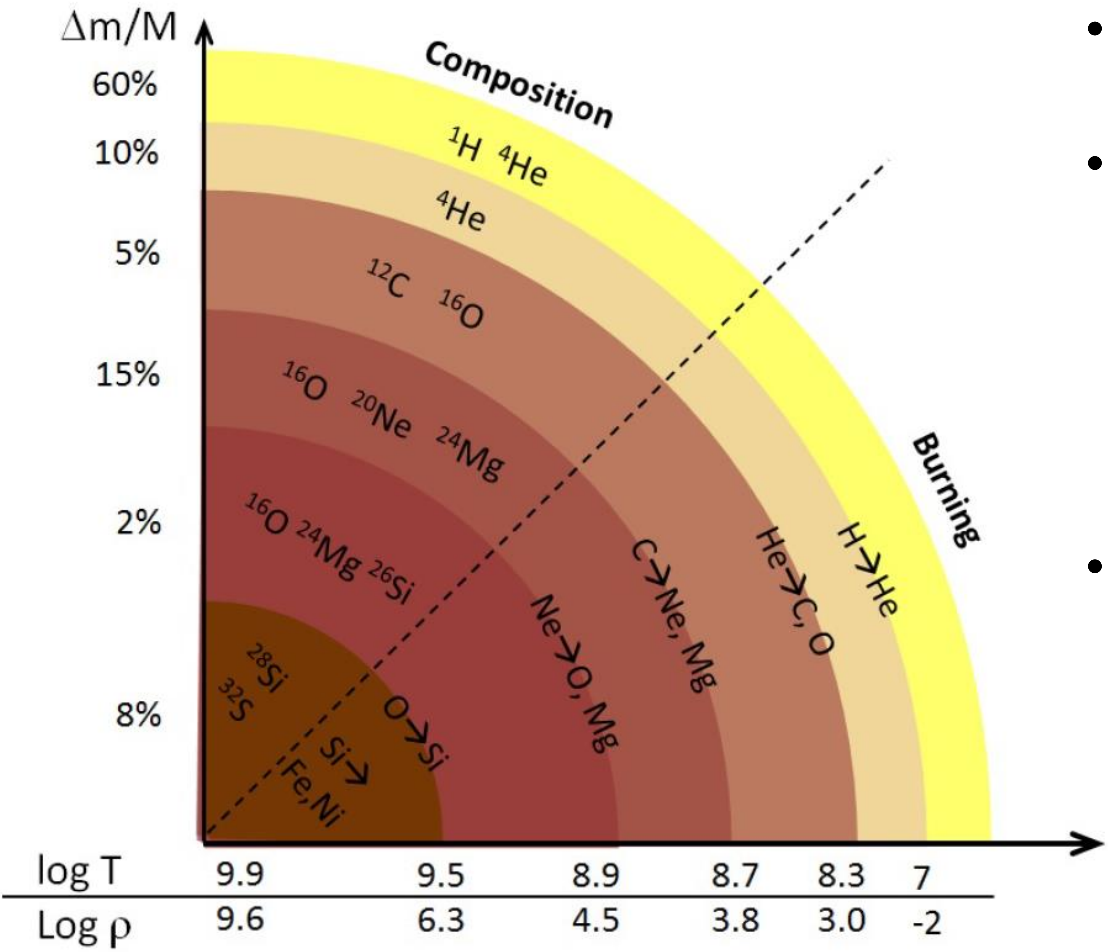
4.1) Neutrinos from Supernovae



Type Ia Supernova in the Centaurus A Galaxy. The clip has prepared by the “Supernova Cosmology Project” (P. Nugent, A. Conley) with the contribution of the Lawrence Berkeley National Laboratory's Computer Visualization Laboratory (N. Johnston: animation)“ National Energy Research Scientific Computing Center”

For a recent review: Supernova neutrinos: Production, oscillations and detection
A. Mirizzi, et al. Rivista del Nuovo Cimento 39, N1-2: 10.1393/ncr/i2016-10120-8

Heavy elements in massive stars



- Onion-like structure in the final stage of massive stars (25M).
- The outermost envelope is composed of H and He, and progressively heavier nuclei (up to Fe) are layered, due to successive fusion reactions.

- Are massive stars the production site of **trans-iron nuclei?**

- Typical values of mass, density ρ (in g/cm^3) and T (in K) of the different shells are indicated along the axes

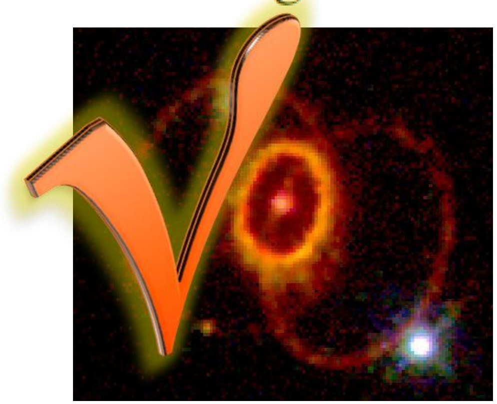
Massive star evolution

- Stars with masses above eight solar masses undergo ***gravitational collapse***.
- Once the core of the star becomes constituted primarily of iron, further compression of the core does not ignite nuclear fusion and the star is unable to thermodynamically support its outer envelope.
- As the surrounding matter falls inward under gravity, the temperature of the core rises and iron dissociates into α particles and nucleons.
- Electron capture on protons becomes heavily favored and electron neutrinos are produced as the core gets neutronized (a process known as ***neutronization***).
- When the core reaches densities above 10^{12} g/cm^3, neutrinos become trapped (in the so-called neutrinosphere).
- The collapse continues until 3 – 4 times nuclear density is reached, after which the inner core rebounds, sending a shock-wave across the outer core and into the mantle.
- This shock-wave loses energy as it heats the matter it traverses and incites further electron-capture on the free protons left in the wake of the shock.
- During the few milliseconds in which the shock-wave travels from the inner core to the neutrinosphere, electron neutrinos are released in a pulse. This neutronization burst carries away approximately **10^{51} ergs of energy**.

Core-Collapse Supernovae (Type-II)

- The work U done by gravity in compressing a star of mass M and radius R in the core (neutron star) of radius R_{NS} and mass M_{NS} is given by

$$U = \left| \frac{3GM^2}{5R} - \frac{3GM_{NS}^2}{5R_{NS}} \right| \simeq \frac{3GM_{NS}^2}{5R_{NS}} \simeq 3 \times 10^{53} \text{erg}$$



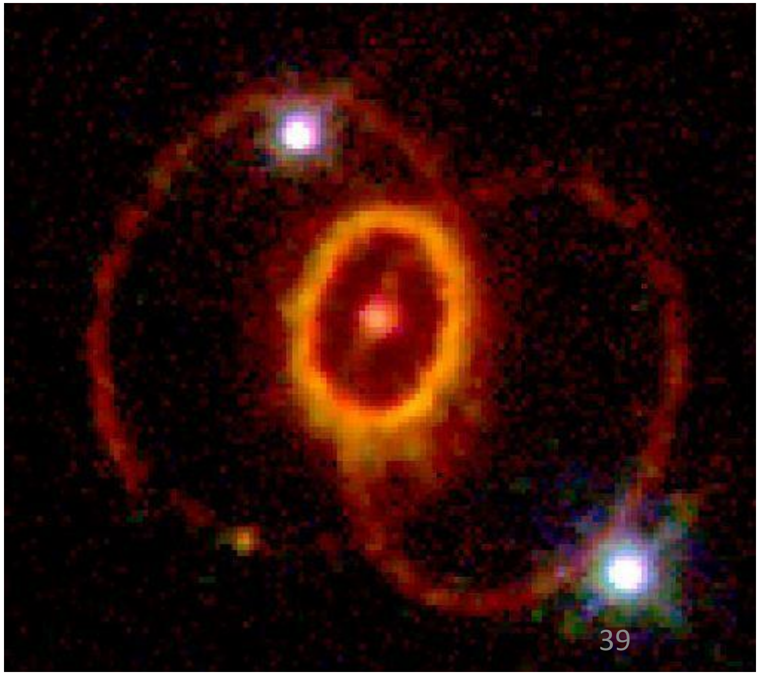
- This shows up as
  - 99% Neutrinos
  - 1% Kinetic energy of the explosion
    (few % of this into Cosmic Rays)
  - 0.01% Photons (outshine host galaxy)

- Neutrino luminosity (while it lasts) outshines the photon luminosity of the entire Universe
  - $L_\nu = 3\times10^{53}$ erg/3 sec $= 3\times10^{19}\ L_{Sun}$

SN1987A: birth of multimessenger astrophysics

- SN1987A was the first SN since 1604 visible with the naked eye
- The progenitor was a main-sequence star of mass $M = (16–22)M_{sun}$
- Located in the Large Magellanic Cloud at a distance of about 50 ± 5 kpc
- Two water Cherenkov detectors, Kamiokande-II (2.2 kton) and IMB (5 kton in USA), observed 12 and 8 neutrino interactions respectively, over a 13 s interval
- The signals of the two experiments were almost simultaneous (for the technology of 1987)
- Two smaller scintillator detectors, LSD and Baksan also reported observations
  - Baksan reported five counts
  - The LSD is controversial because the events were recorded several hours early

- **Question**: Evaluate the expected signal in Kamiokande for the SN1987A



Answer: how many events from SN1987A.

1- Energy released 2.5 10^{53} erg
2- Average $\bar{\nu}_e$ energy ≈ 16 MeV = 2.5 10^{-5} erg
3- N_{source}= (1/6) × 2.5 10^{53}/ (2.5 10^{-5})= 1.7 10^{57} $\bar{\nu}_e$

4- LMC Distance : D=52 kpc = 1.6 10^{23} cm
5- Fluency at Earth: F = $N_{Source}/4pD^2$ = 0.5 10^{10} cm^{-2}
6- Targets in 1 Kt water: N_t = 0.7 10^{32} protons
7- cross section: **$\sigma(\bar{\nu}_e+p) \sim 2x10^{-41}$ cm^2**

8- N_{e^+} = F (cm^{-2})× σ (cm^2)× N_t (kt^{-1})= 0.5 10^{10} × 2x10^{-41}× 0.7 10^{32}
= 7 positrons/kt
9 – M(Kam II) = 2.1 kt, efficiency ε~ 80%
10 – Events in Kam II = 7 x 2.1 x e ~ 12 events

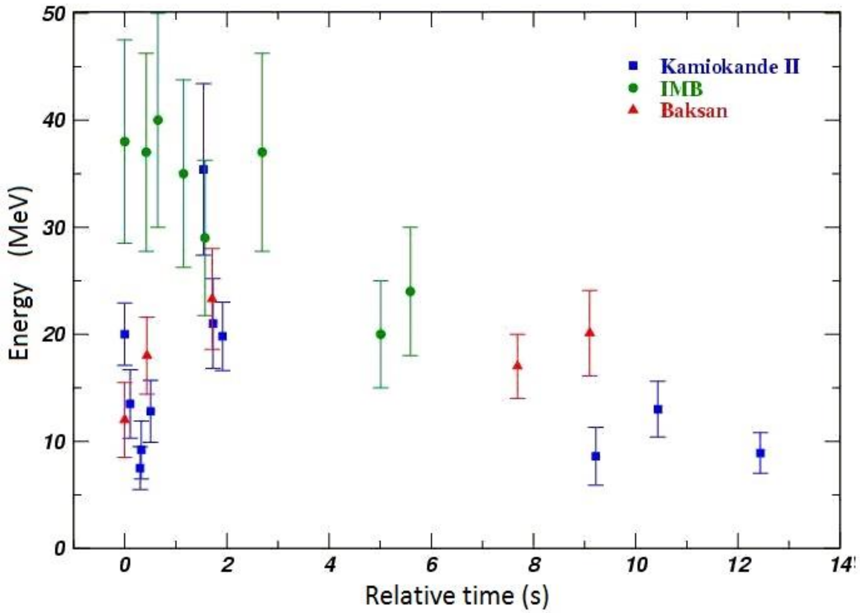
For a SN @ Galactic Center (8.5 kpc) :
N_{events}= 7x$(52/8.5)^2$ = 260 e^+/kt

Neutrinos from SN1987A

- Although Kamiokande and IMB collected a small sample of ν's, they were sufficient to give an exact time for the start of the explosion to which the light curve can be normalized and to confirm the baseline model of core-collapse. In particular:
  - the time distribution of the observed events is in agreement with predictions of a ~10 s burst;
  - their energy distribution gives a measure T ~ 4.2MeV of the neutrino-sphere and an average energies of detected neutrinos of~15MeV;
  - the number of the observed events is in agreement with ~ 3 × 10^{53} erg luminosity of a core-collapse burst

- **Question**: Estimate an upper limit on the neutrino mass from SB1987A

Relative time and energy of SN1987A neutrinos observed by Kamiokande, IMB and Baksan. The time of the first event was arbitrarily set = 0



Answer: Neutrino mass limit from SN1987A

- The observation of SN ν's brings a better understanding of the core collapse mechanism from the feature of the time and energy spectra;
- Moreover, an estimation of the neutrino masses could be done in the following manner. The velocity of a particle of energy *E* and mass *m*, with *E* >> *m*, is given by (with c = 1):

$$v_i = \frac{p_i c}{E_i} = \frac{\sqrt{E_i^2 - m^2 c^4}}{E_i^2} \sim 1 - \frac{m^2 c^4}{2E_1^2}$$

- Thus, for a SN at distance *d*, the delay of a ν from the highest/lowest energy neutrino, ΔE, due to its mass is (in proper units)

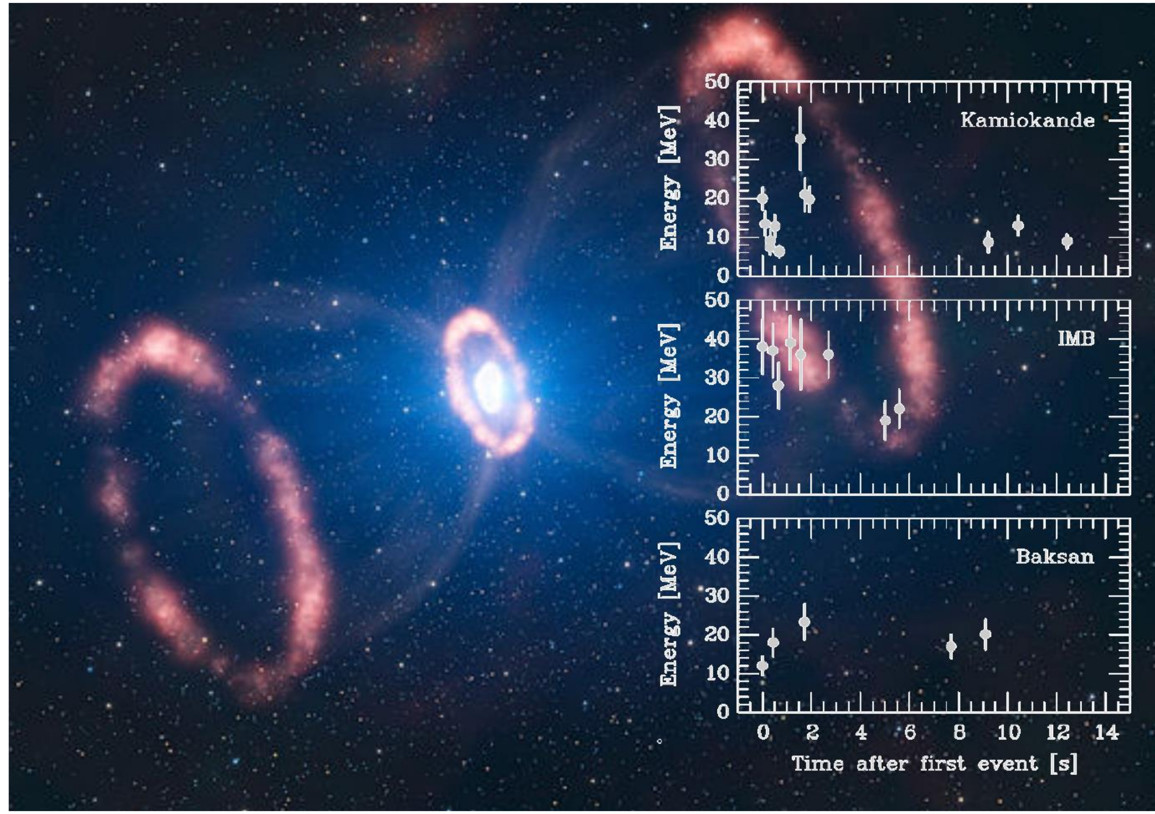
$$\Delta t_{[s]} \sim 0.05 \frac{m^2_{[eV^2]}}{\Delta E_{[MeV]}} d_{[kpc]}$$

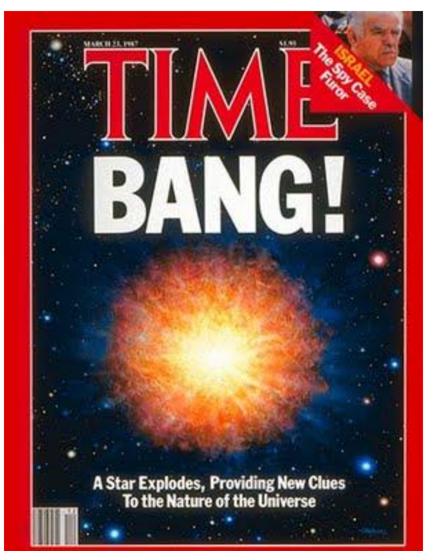
- Therefore, neutrinos of different energies released at the same instant should show a spread in their arrival time. For SN1987A, assuming Kam data and Δt=13 s, ΔE=30 MeV and d=50 kpc, we get:

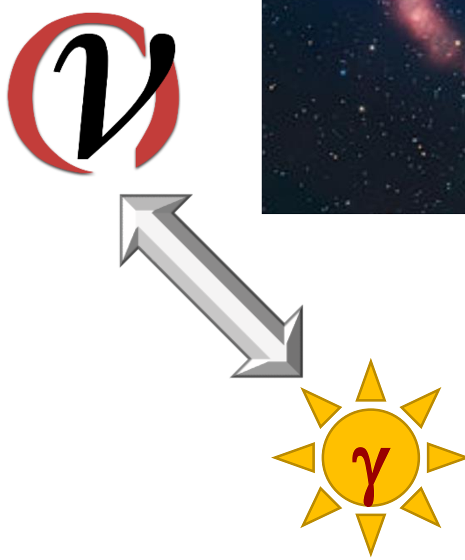
$$mc^2 < 12\ eV$$

Low energy neutrinos and photons

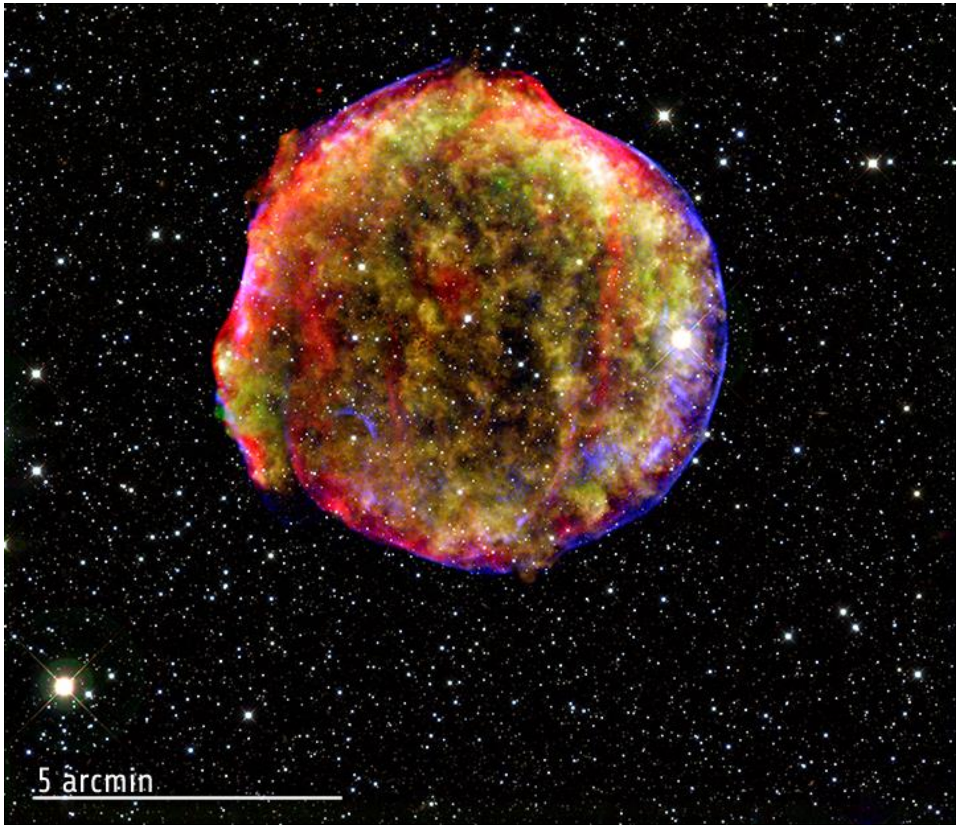
- SN1987A
- 99% of the energy of the collapsing star into neutrinos







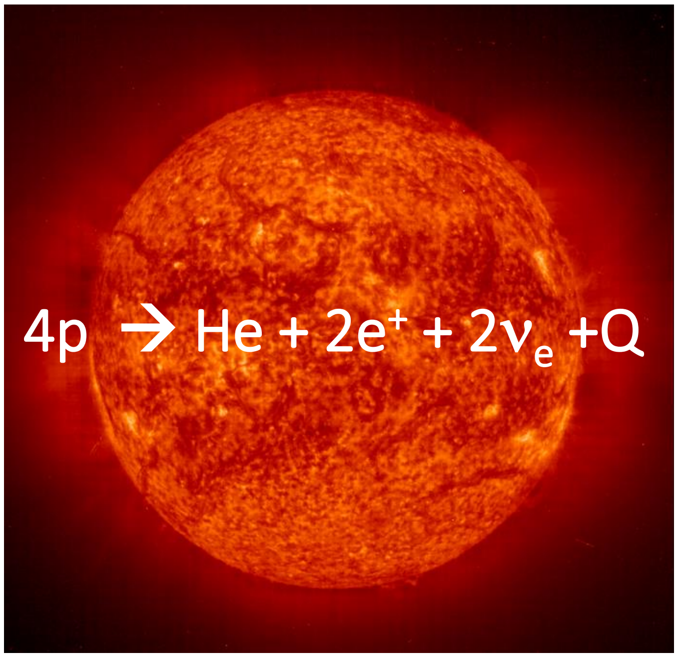
SN1572 (Tycho Brahe) today



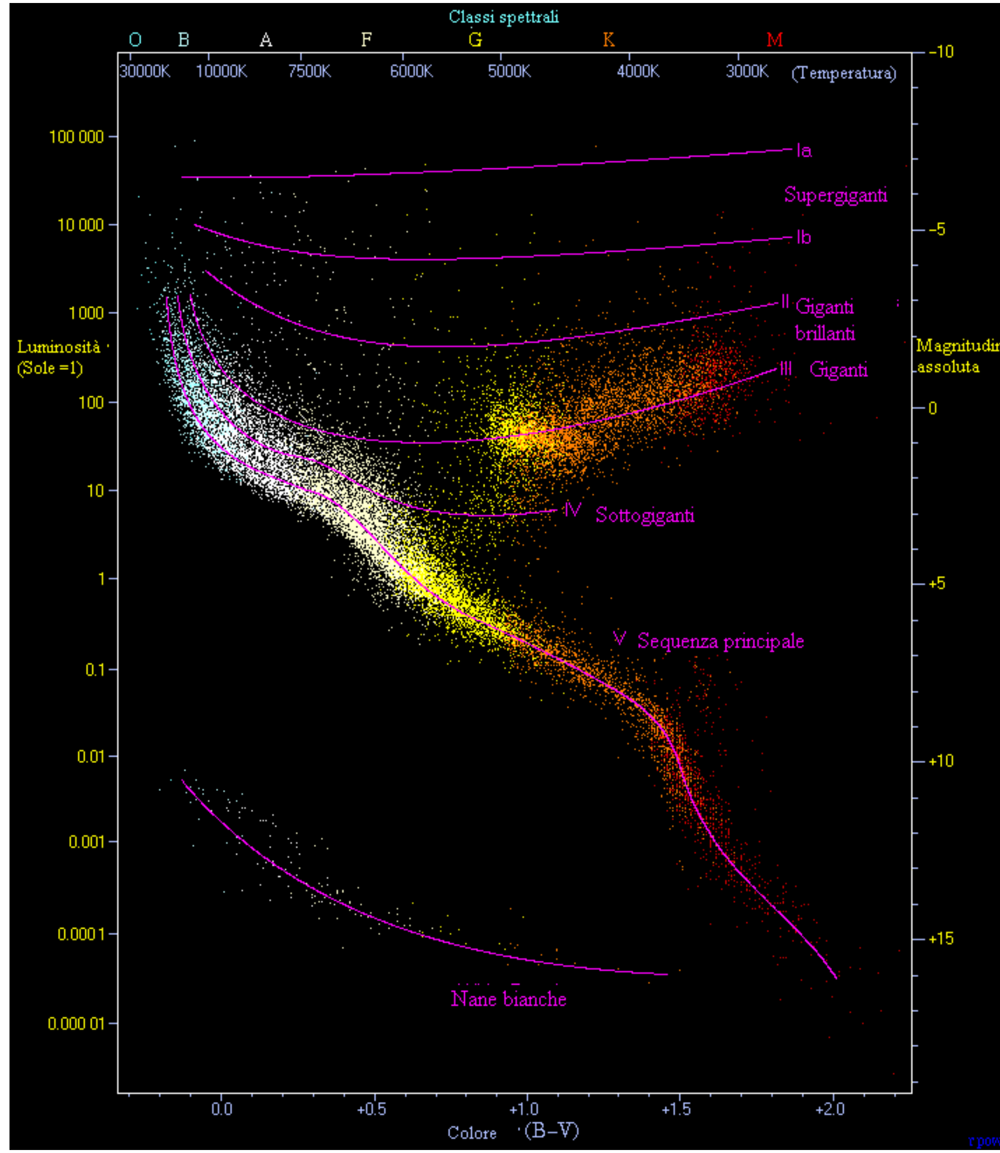
Exercize: The distance of the Tycho SN from the Earth is 3 kpc (1 pc=3 10^{18} cm)

- Estimate the size of the SN remnant in the picture
- Evaluate the speed of the shock wave

4.2) Neutrinos from the Sun



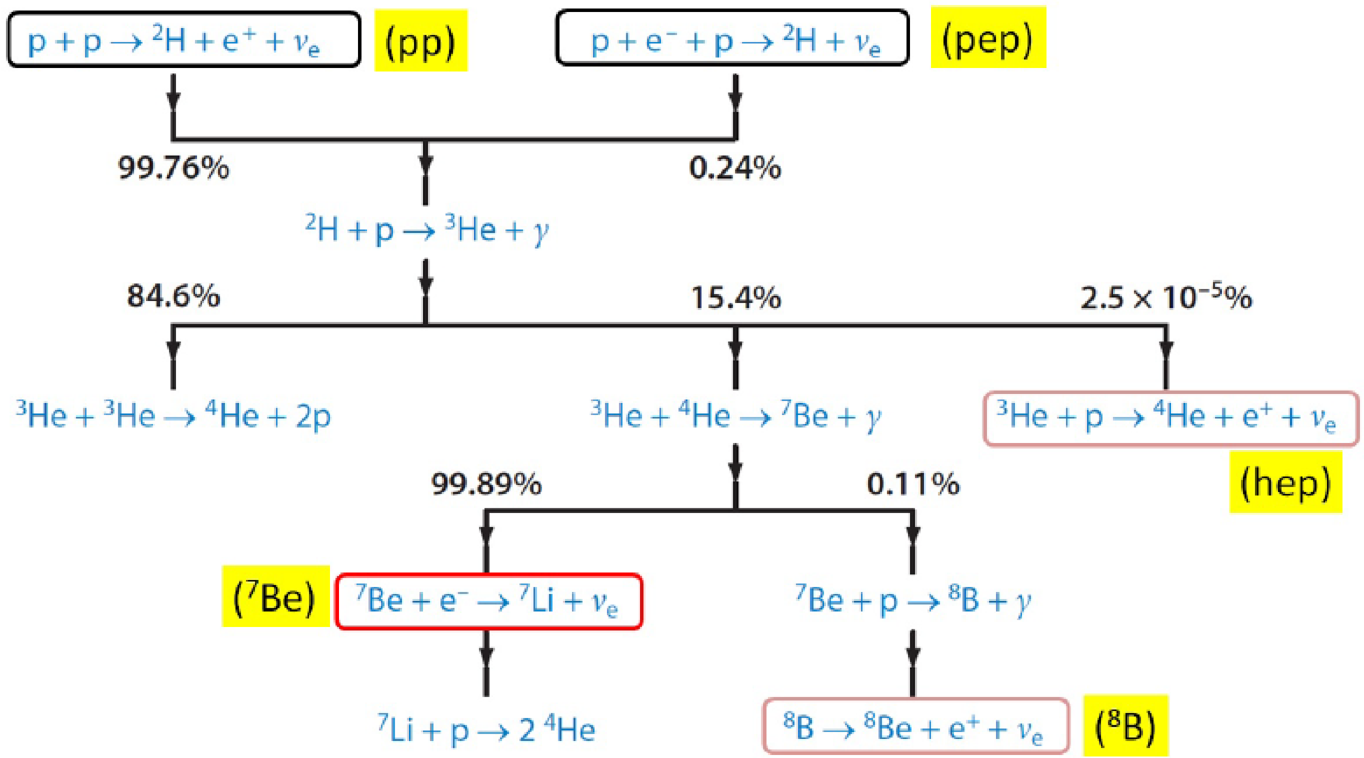
$4p \rightarrow He + 2e^+ + 2\nu_e + Q$



Solar constant: ε=0.136 W/cm^2

→ Luminosity: L_{sun}= 3,84 10^{26} W

ν from the Sun: the pp chain



$$4p \rightarrow {}^4\mathrm{He} + 2e^+ + 2\nu_e \qquad Q = 26.73\ \mathrm{MeV} \qquad \langle E_\nu \rangle \cong 0.53\ \mathrm{MeV}$$

$$\boxed{\Phi_{\nu_e} \simeq \frac{1}{4\pi D_\odot^2}\frac{2L_\odot}{(Q - \langle E_\nu \rangle)} = 6 \times 10^{10}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}}$$

The Standard Solar Model (SSM)

- **J. Bahcall**: The initial author of the SSM
- Derived from the conservation laws and energy transport equations of physics, applied to a spherically symmetric gas (plasma) sphere

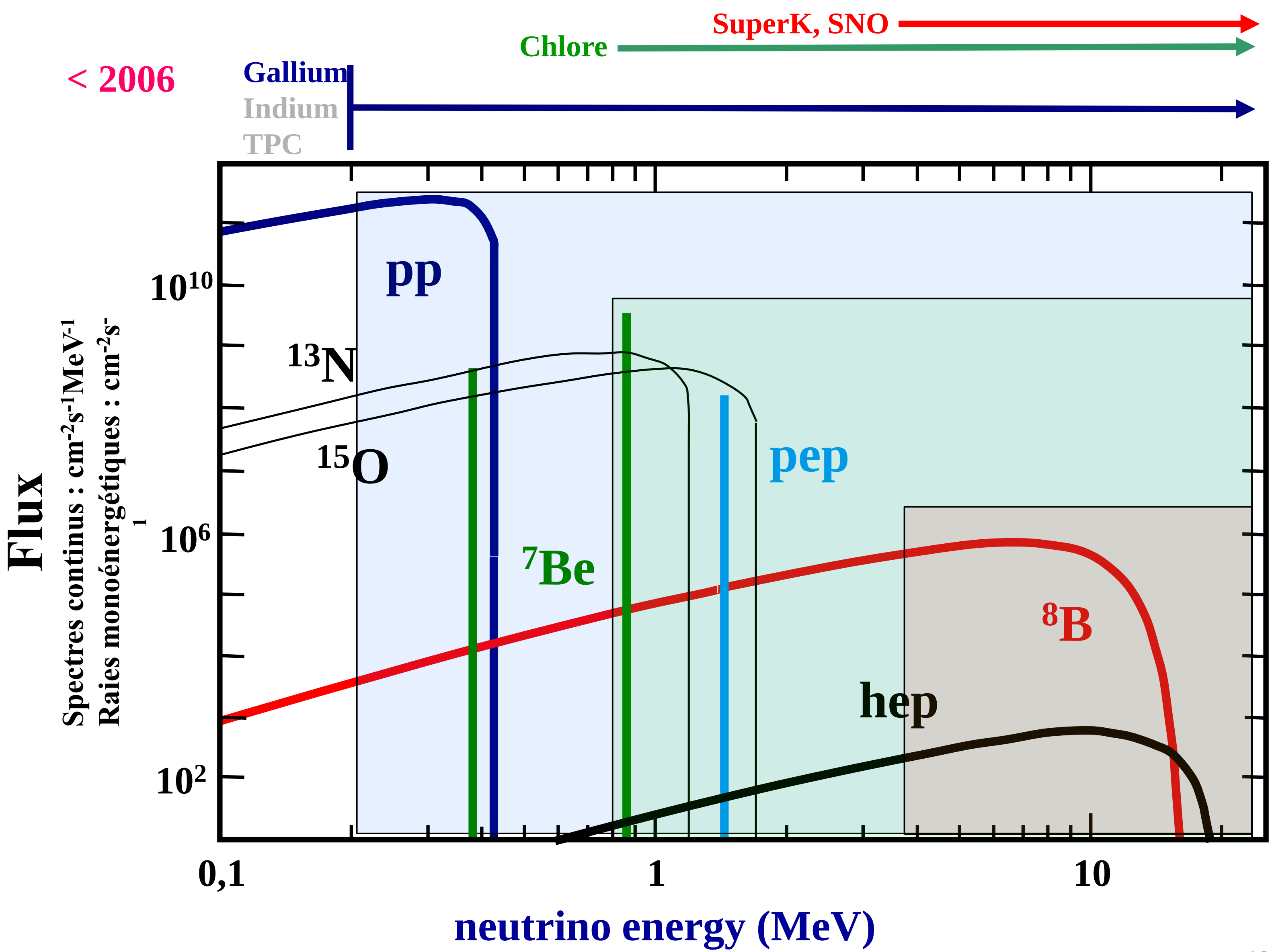
- **Input of the SSM:**
  - Mass, Age, Luminosity, Radius
- **Assumptions of the SSM**
  - Hydrostatic equilibrium
  - Spherical symmetry, no rotation, no magnetic field
  - Energy generation by H burning
- **Free parameters**:
  - initial relative mass abundances:

  X_{in} (H), Y_{in}(He), Z_{in}(metals)=1-X_{in} – Y_{in}
- **Tested by helioseismology**

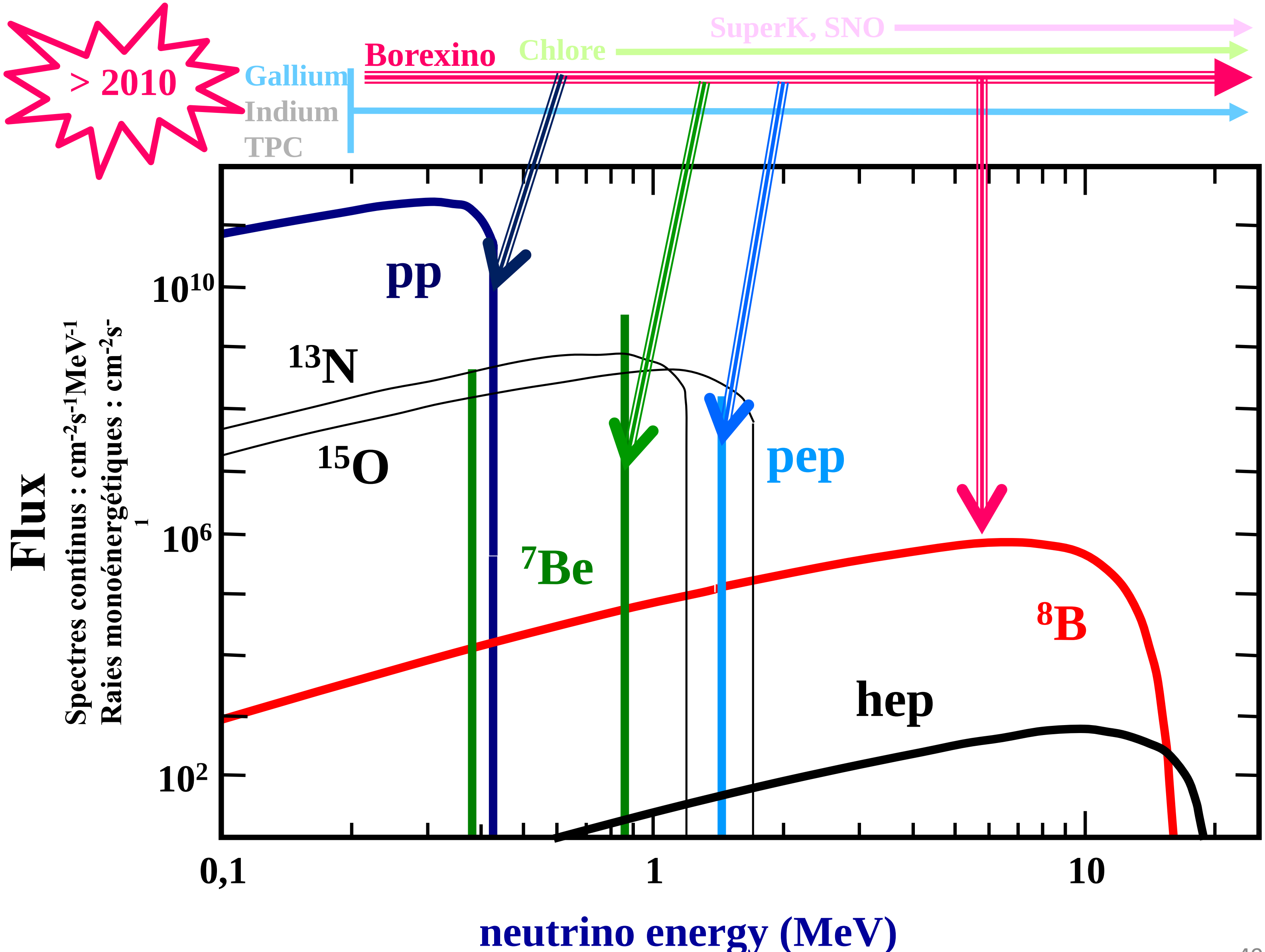
http://www.sns.ias.edu/~jnb/

Note: Read the paper (tradotto anche in italiano)
http://www.sns.ias.edu/~jnb/Papers/Popular/Nobelmuseum/italianmystery.pdf

Differential ν_e flux (from SSM)



Differential ν_e flux (from SSM)



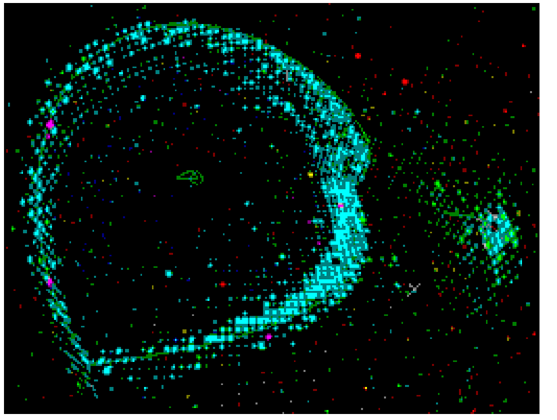
Experimental Techniques

Detection techniques for solar neutrinos:

1- elastic scattering

$$\nu_e + e \rightarrow \nu_e + e$$

SK



2- Neutron capture

$$\nu_e + n \rightarrow e + p$$

No free neutrons in nature:

$$(Z,A) + \nu_e \rightarrow e + (Z+1,A)$$

Examples:

$^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$

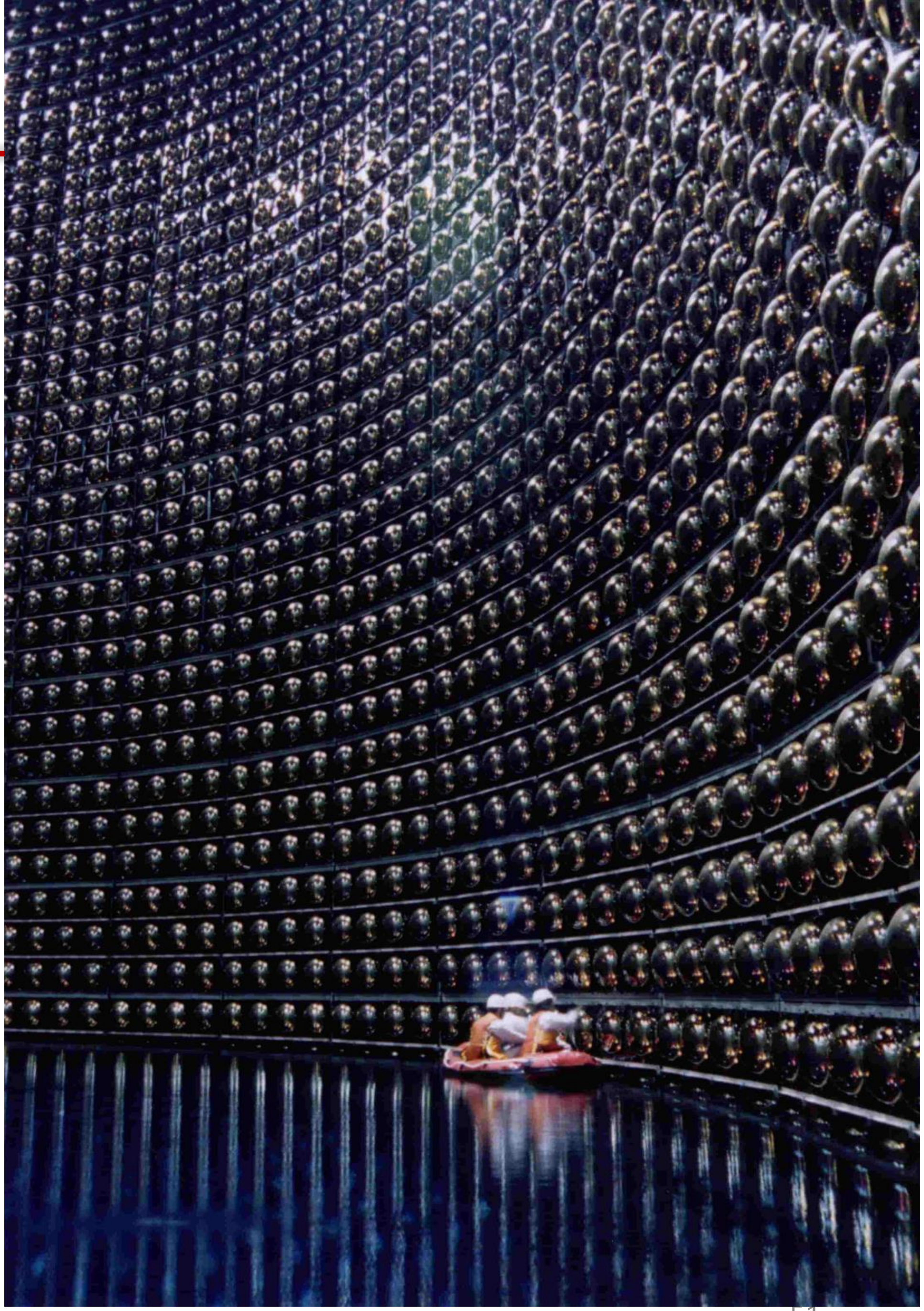
$^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e$

3- The SNO way:

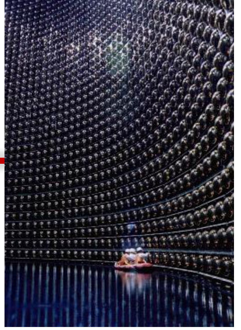
- $\nu_e + d \rightarrow e + p + p$
- $\nu_x + d \rightarrow \nu_x + n + p$

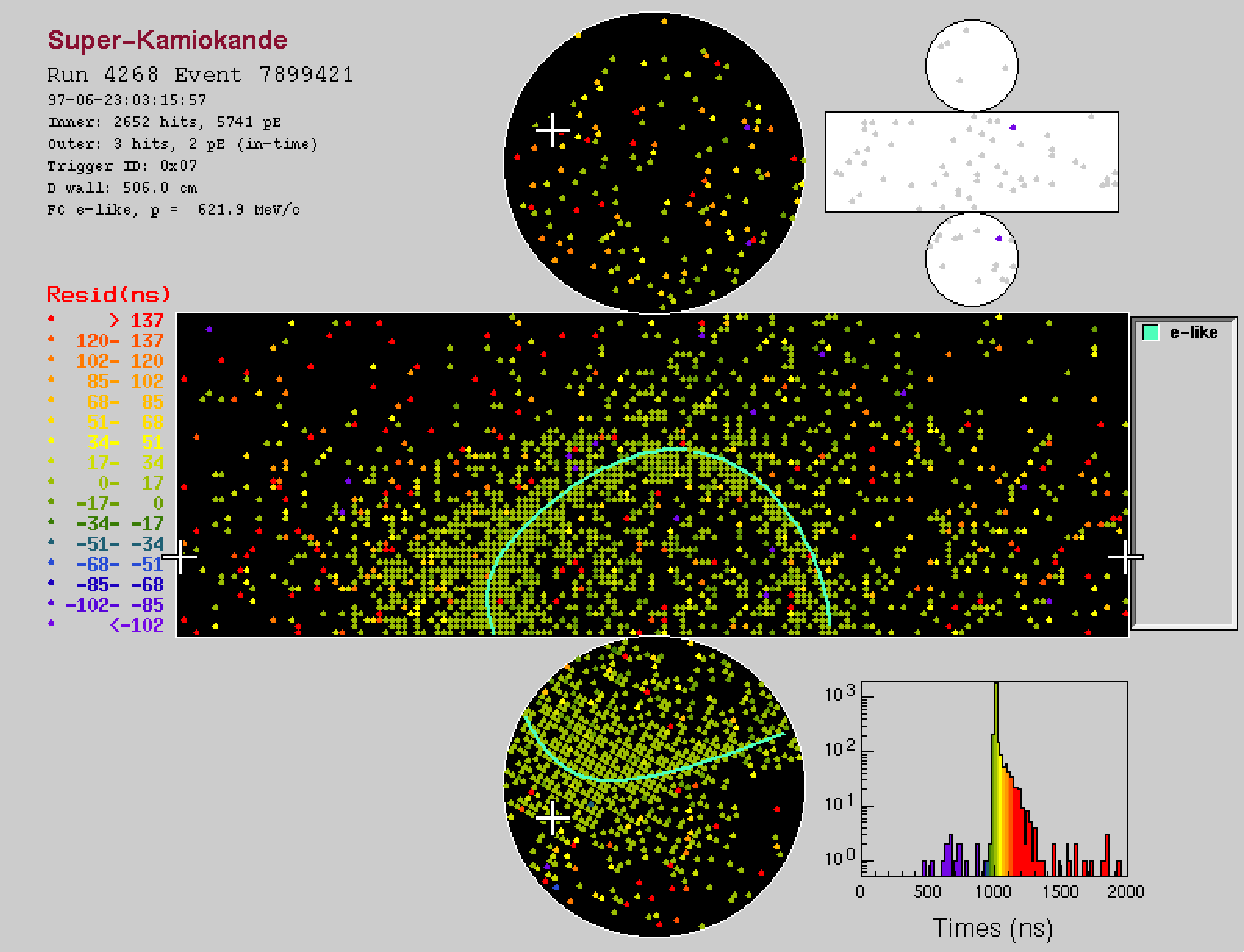
A huge detector

- Super-Kamiokande (SK) in Japan
  - 1000 m Underground
  - 50.000 ton of purified water
  - 11000 (+2000) PMTs
  - Running since 1996

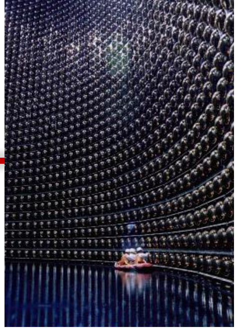


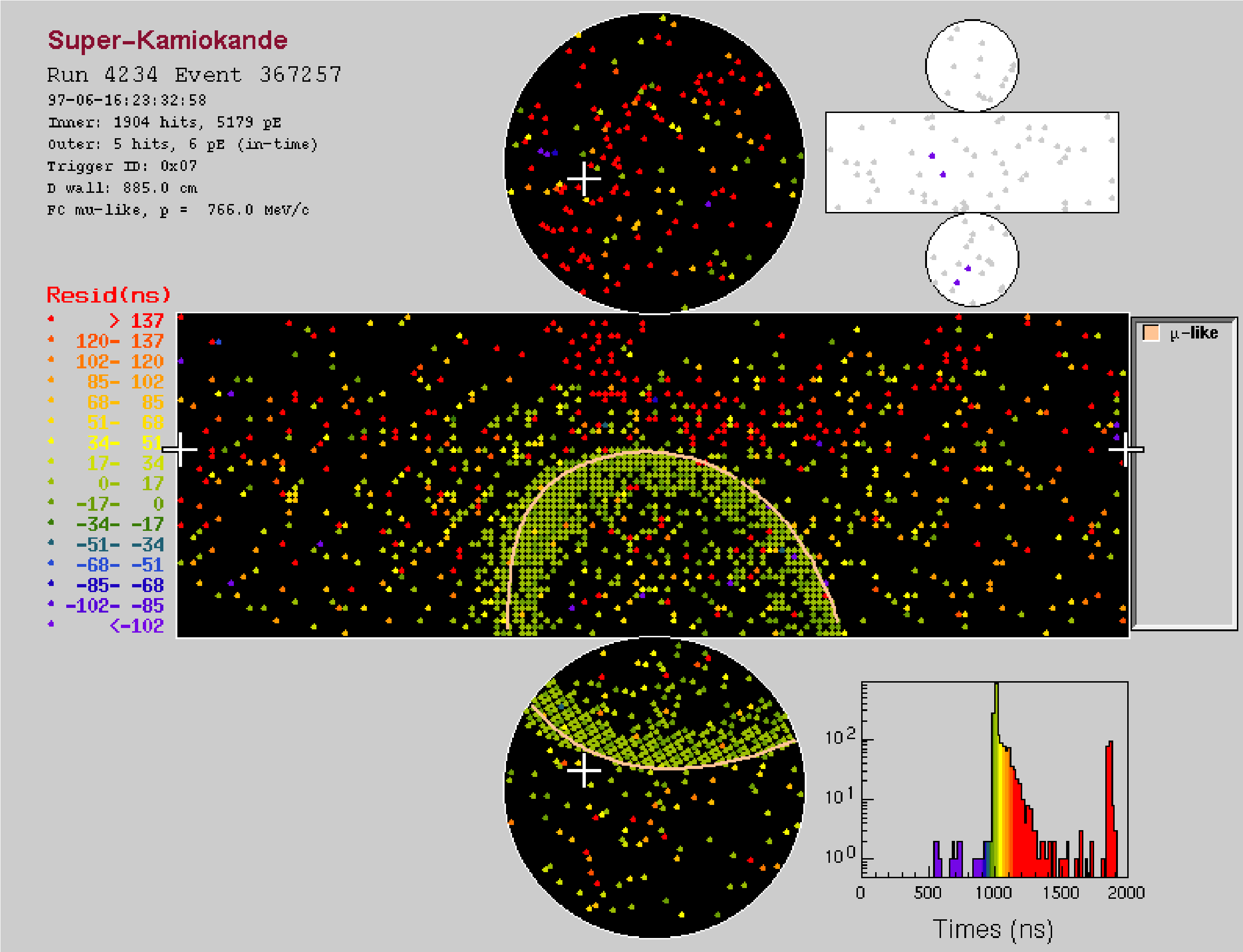
SuperKamiokande: ν_e



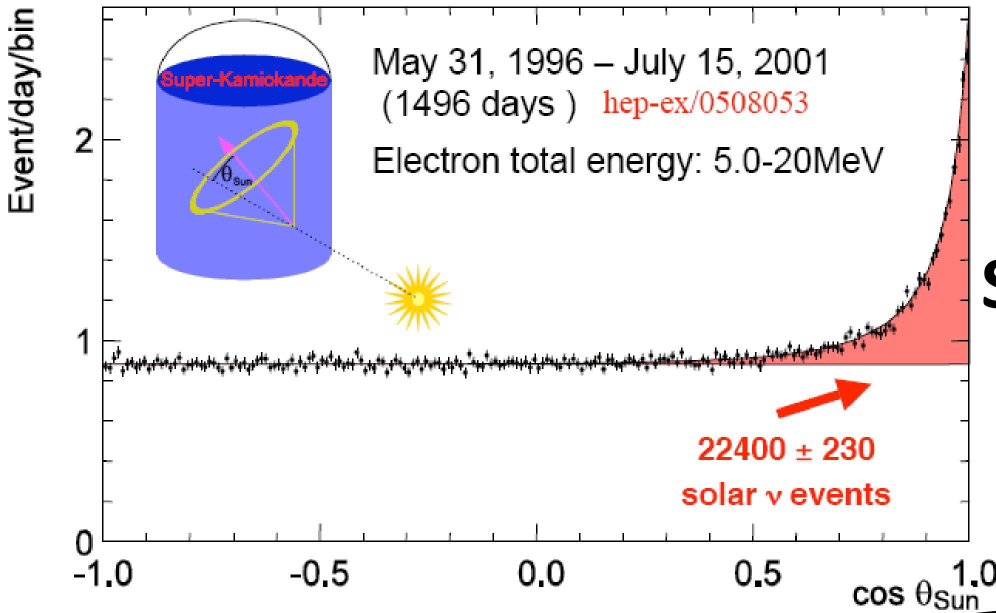


SuperKamiokande: ν_μ

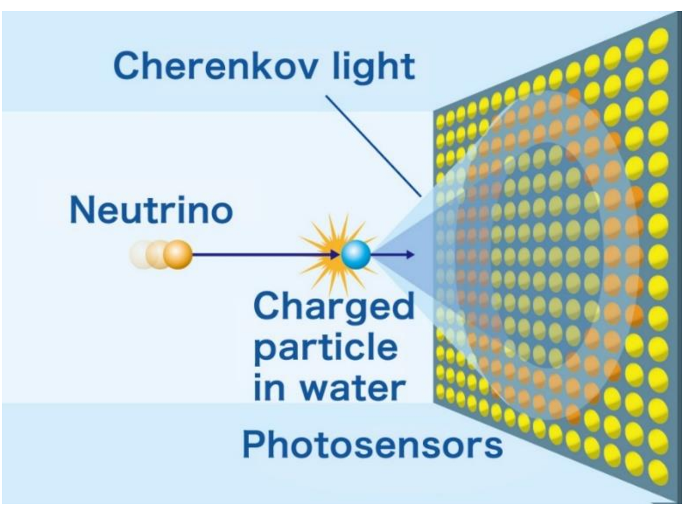


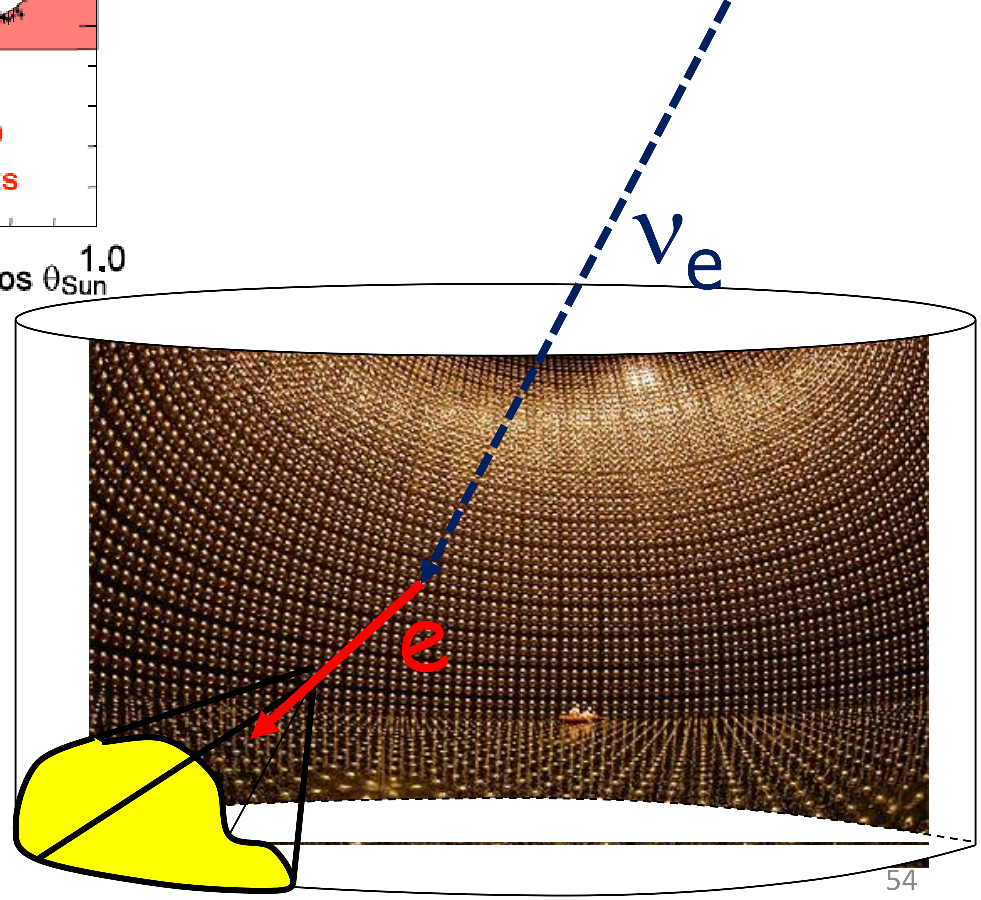


Elastic scattering ($\nu_e\, e \;\rightarrow \nu_e e$) in SK



See: «Neutrino» talks





The decisive results: SNO (1999 –2006)

- 18 m sphere underground (~2.5km), in Ontario - Canada
- Heavy water (D_2O) inside a transparent acrylic sphere (12m diameter)
- 10,000 photomultiplier tubes (PMTs)
- Each PMT collect Cherenkov light photons
- Pure salt is added to increase sensitivity of NC reactions (≥2002)
- Flux of all flavors '$\Phi(\nu_x)$' from NC and electron neutrinos '$\Phi(\nu_e)$' with CC
- The flux of non-electron neutrinos is

$$\Phi(\nu_\mu, \nu_\tau) = \Phi(\nu_x) - \Phi(\nu_e)$$

3- The SNO way:

- $\nu_e + d \rightarrow e + p + p$
- $\nu_x + d \rightarrow \nu_x + n + p$

Latest SNO Solar ν Results

The SNO-I/II and SNO-III results are in generally good agreement, and both separately and in combination established the following:

- The total flux of active neutrinos $\nu_f = \nu_e + \nu_\mu + \nu_\tau$ from ^{8}B decay measured through NC interactions corresponds to

$$\boxed{\Phi_{SNO}^{NC} = \Phi_{\nu_f}(^8\mathrm{B}) = (5.25 \pm 0.16_{stat} \pm 0.13_{sys}) \times 10^6\ \mathrm{cm}^{-2}\mathrm{s}^{-1}\ .}$$

$\nu_e + \nu_\mu + \nu_\tau$

in good agreement with SSM predictions, see Table 12.2.

- The flux of the ν_e flavor producing CC interactions is (SNO-II)

$$\boxed{\Phi_{SNO}^{CC} = \Phi_{\nu_e}(^8\mathrm{B}) = (1.68 \pm 0.06_{stat} \pm 0.09_{sys}) \times 10^6\ \mathrm{cm}^{-2}\mathrm{s}^{-1}\ .}$$

ν_e *only*

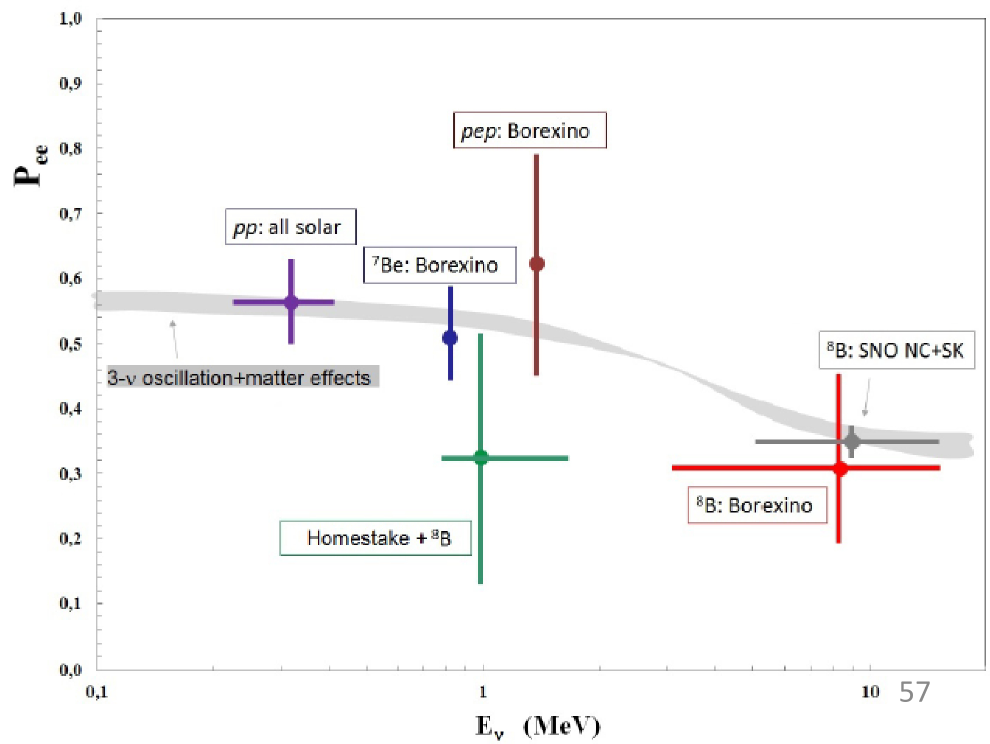
$$\boxed{\text{Bahcall et al. – SSM} = \mathbf{(5.1 \pm 0.7)} \times 10^6\ \mathrm{cm}^{-2}\mathrm{s}^{-1}}$$

Theory, *SSM*

Neutrino oscillations and the Sun

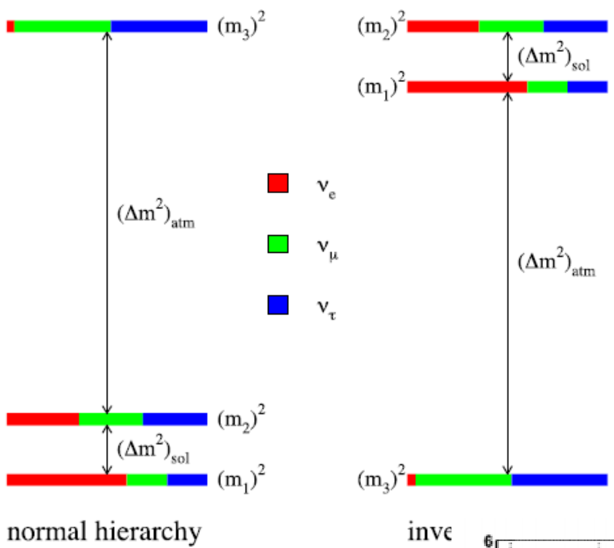
ν React.	Interaction rate counts (day 100 ton)$^{-1}$	$(\frac{Data}{SSM})$ ratio	$\Phi_{\nu_e}(E)$ $(10^8\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1})$	$(\frac{Data}{SSM})/P_{ee}$ ratio
pp	$144 \pm 13 \pm 10$	0.64 ± 0.12	$(6.6 \pm 0.7) \times 10^2$	1.10 ± 0.22
^{7}Be	$46.0 \pm 1.5 \pm 1.6$	0.51 ± 0.07	48.4 ± 2.4	0.97 ± 0.09
pep	$3.1 \pm 0.6 \pm 0.3$	0.62 ± 0.17	1.6 ± 0.3	1.1 ± 0.2
^{8}B	$0.22 \pm 0.04 \pm 0.01$	0.31 ± 0.15	0.05 ± 0.01	0.91 ± 0.23
CNO	< 7.9	-	< 7.7	< 1.5

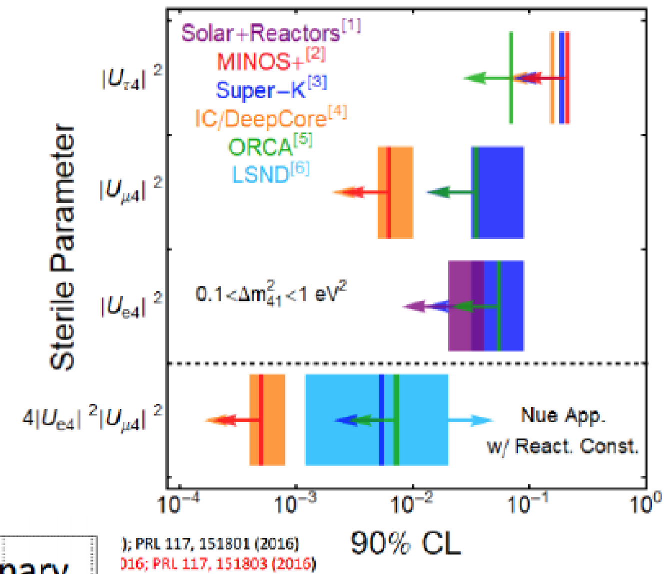
Table: Summary of the interaction rates of the different neutrino species measured by the **Borexino experiment at the Gran Sasso Lab** and the ratios with respect to SSM (column 3)

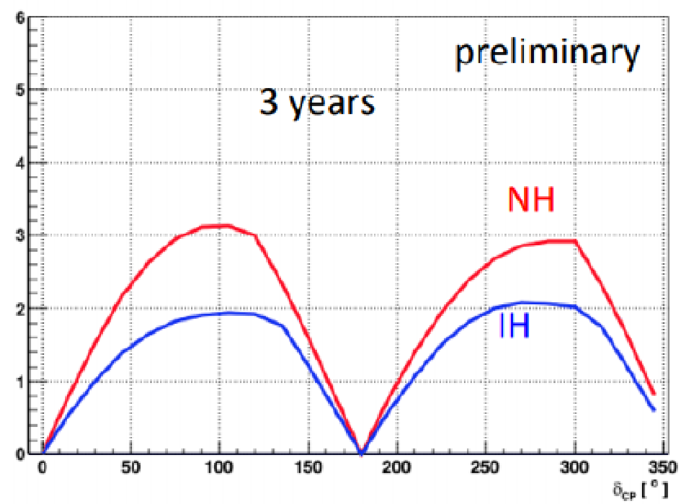


The «neutrino problem» in the SM:

opened by astroparticle physics experiments

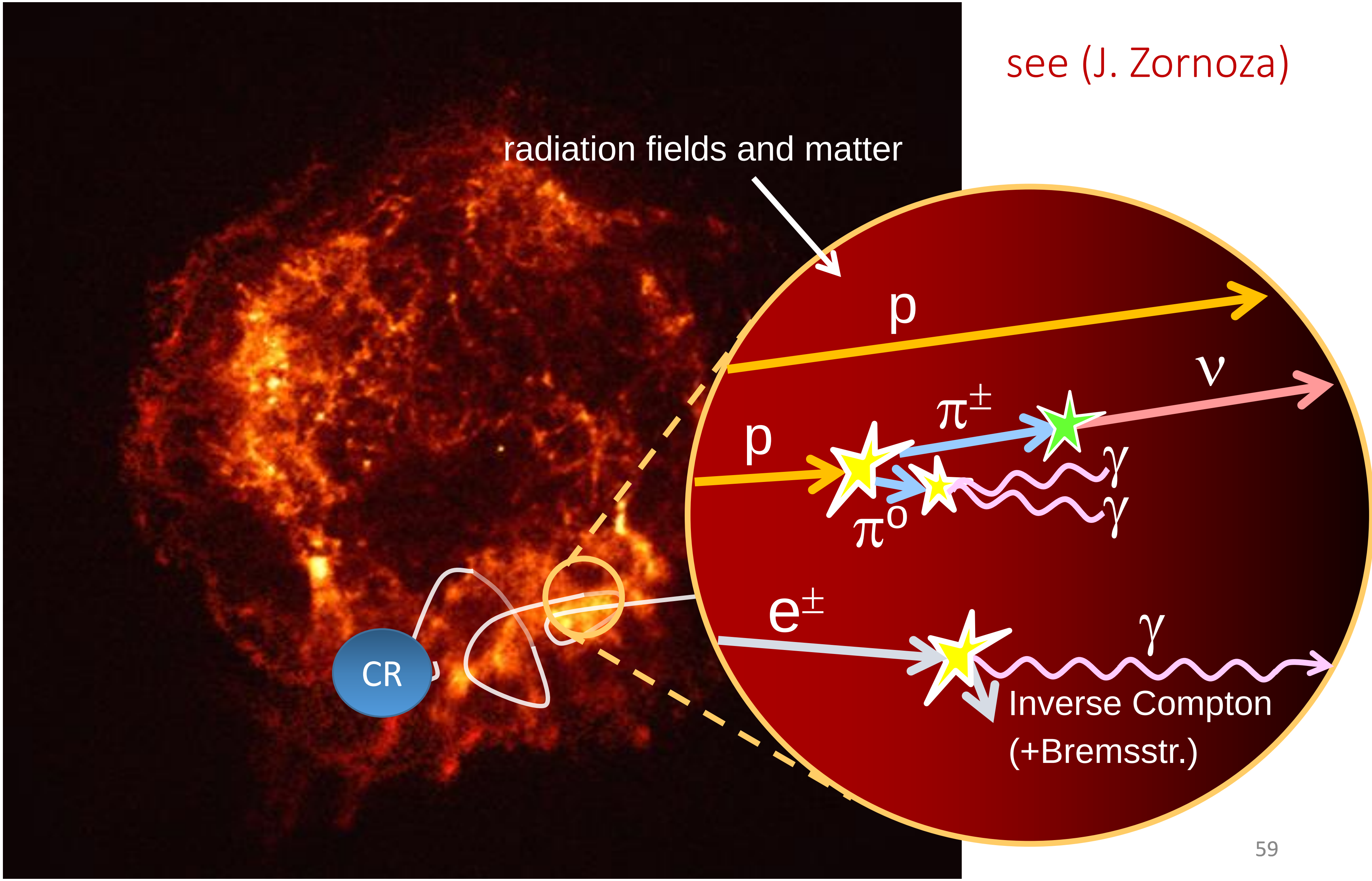




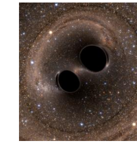


5) High-energy neutrinos and n telescopes

see (J. Zornoza)

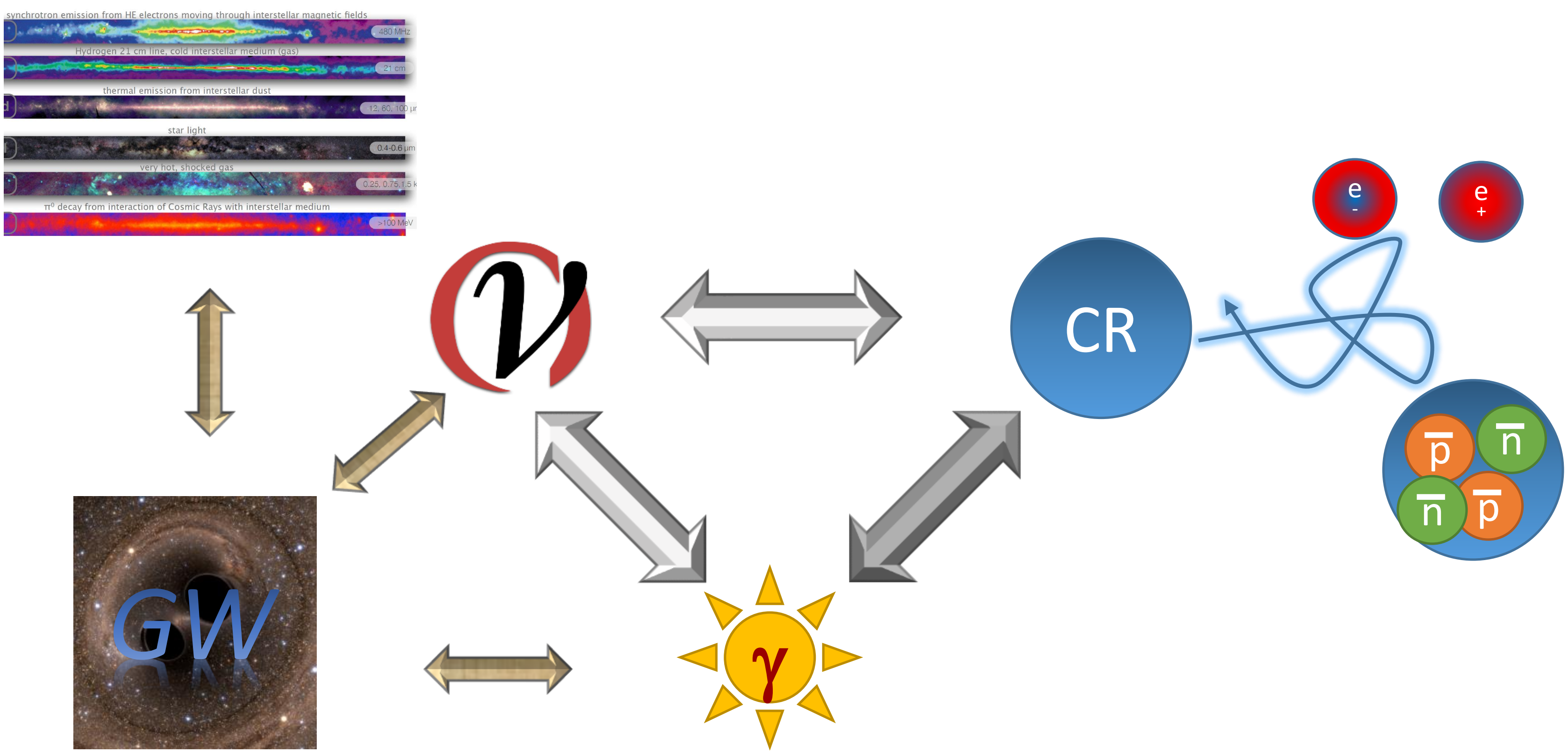


6) Other probes: gravitational waves



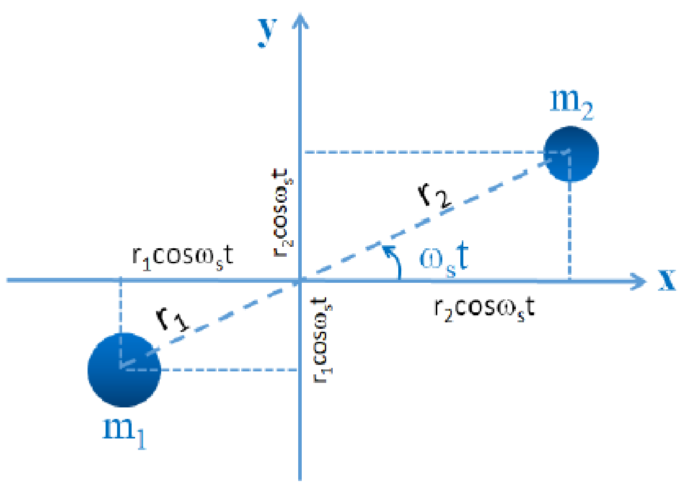
Gravitational waves (see lectures J. A. Font)

- Breakthrough discovery
- New windows in the observational universe

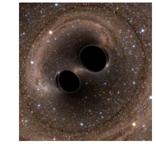


EM vs Gravitational waves

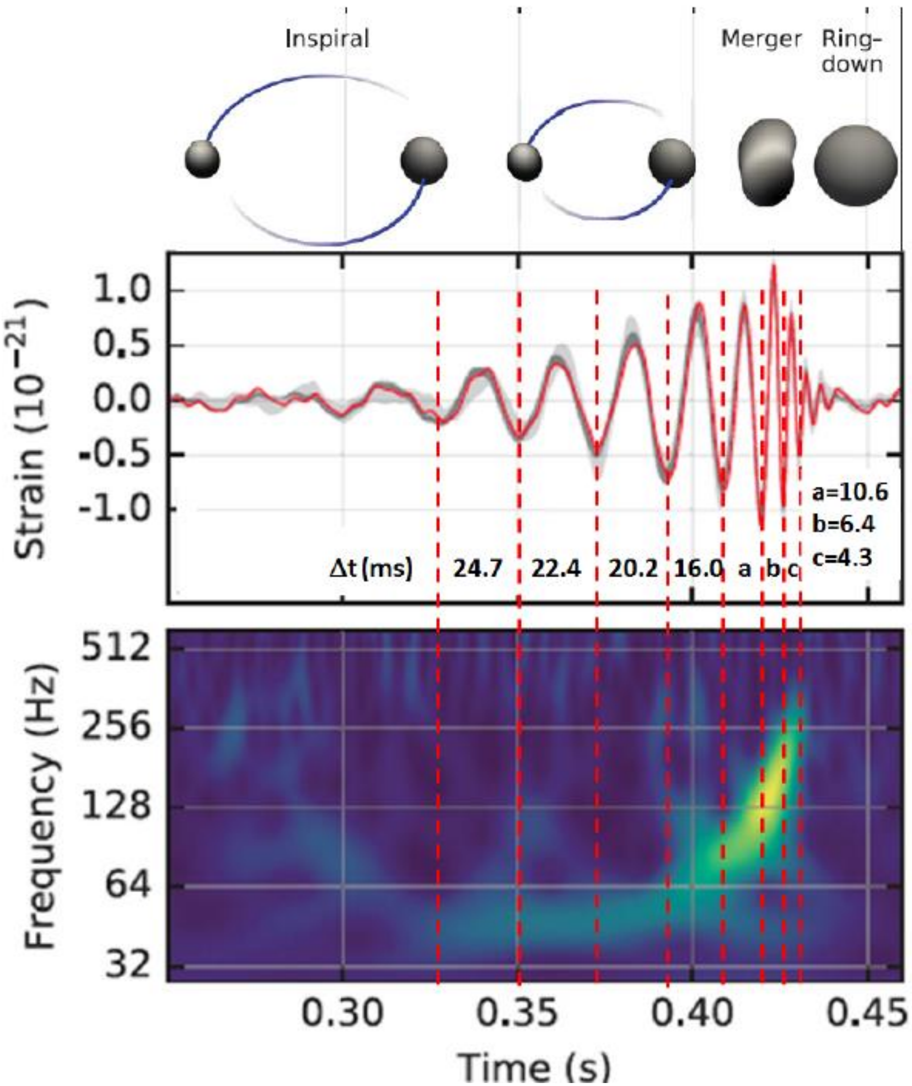
- The **EM radiation** emitted is an incoherent superposition from sources >> λ;
- **GW radiation** comes from systems with sizes R << λ. Hence, the signal reflects the coherent motion of extremely massive objects.
- Effect of EM radiation falls as **$1/r^2$ (intensity)**. GWs as **1/r (phase)** .
- GWs suffer a very small absorption when passing through ordinary matter.
- **Experimental methods** complementary to that developed in particle physics and traditional astronomy
- The **observables** contain direct information on **mass, distance, spin**



The derived quantities



- Observables → Physical properties

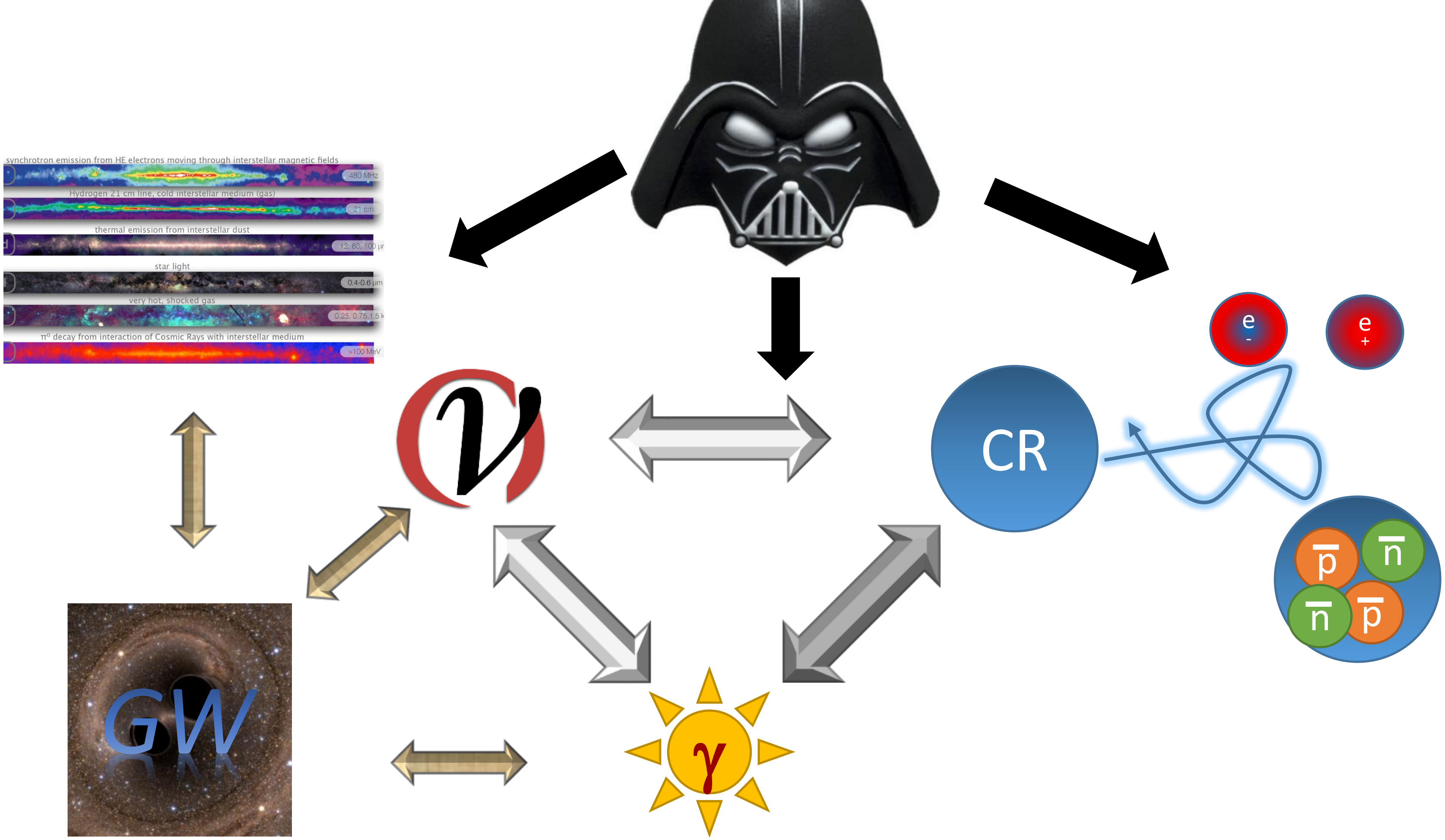


Δt (ms)	ν_{gw} (Hz)	$\dot{\nu}_{gw}$ (Hz s^{-1})	$\nu_{gw}^{11}\ \dot{\nu}_{gw}^{3}$	$\mathscr{M}$ (kg)	$\mathscr{M}/M_{\odot}$	R (km)
24.7	40	-	-	-	-	630
22.4	45	186	4.6E-12	6.0E+31	30	590
20.2	50	241	3.2E-12	5.6E+31	28	550
16.0	63	812	9.4E-12	7.0E+31	35	470
10.6	94	3004	5.1E-12	6.2E+31	31	360
6.4	156	9673	6.7E-13	4.1E+31	21	255
4.3	233	17746	5.2E-14	2.5E+31	12	200

- Individual masse of two BHs
- Luminosity Distance and Cosmological Effects
- Total Emitted Energy as GWs
- Spin of the BHs

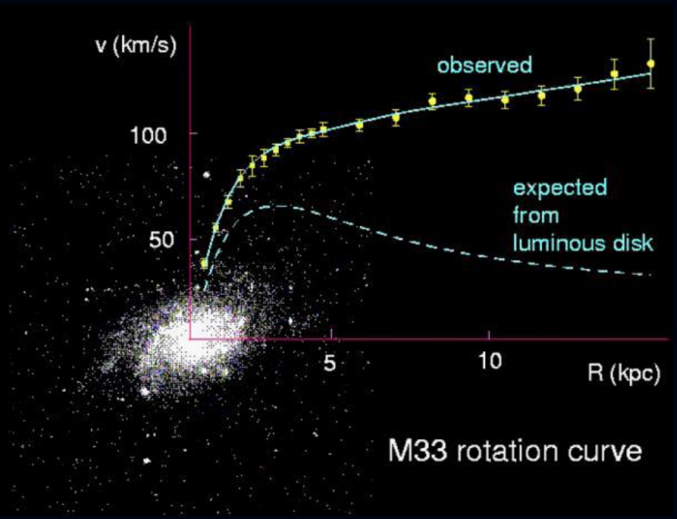
7) The dark side

- **Dark Matter (see:** *Sergio Palomares-Ruiz)*
  - Indirect searches

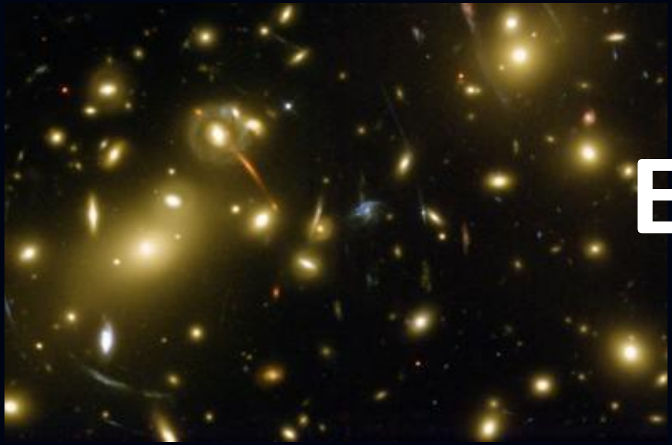


- Starting from 1933, when the astronomer Zwicky realized that the mass of the luminous matter in the Coma cluster was much smaller than its total mass implied by the motion of cluster member galaxies:

Rotation curves of galaxies

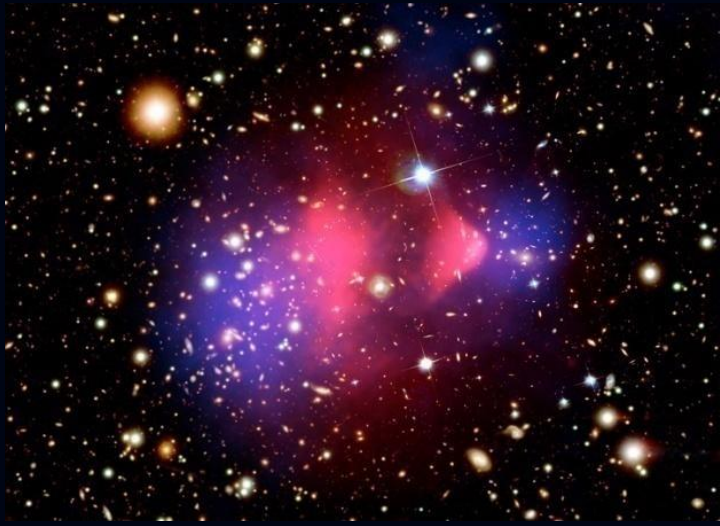


Gravitational lensing

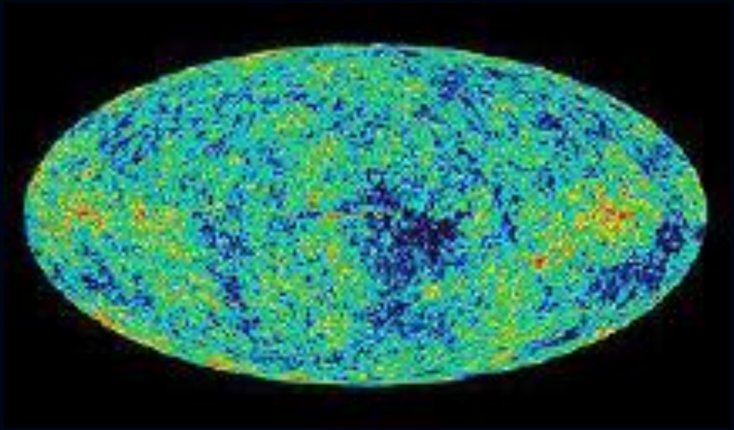


Evidences

Bullet cluster



Structure formation as deduced from CMB

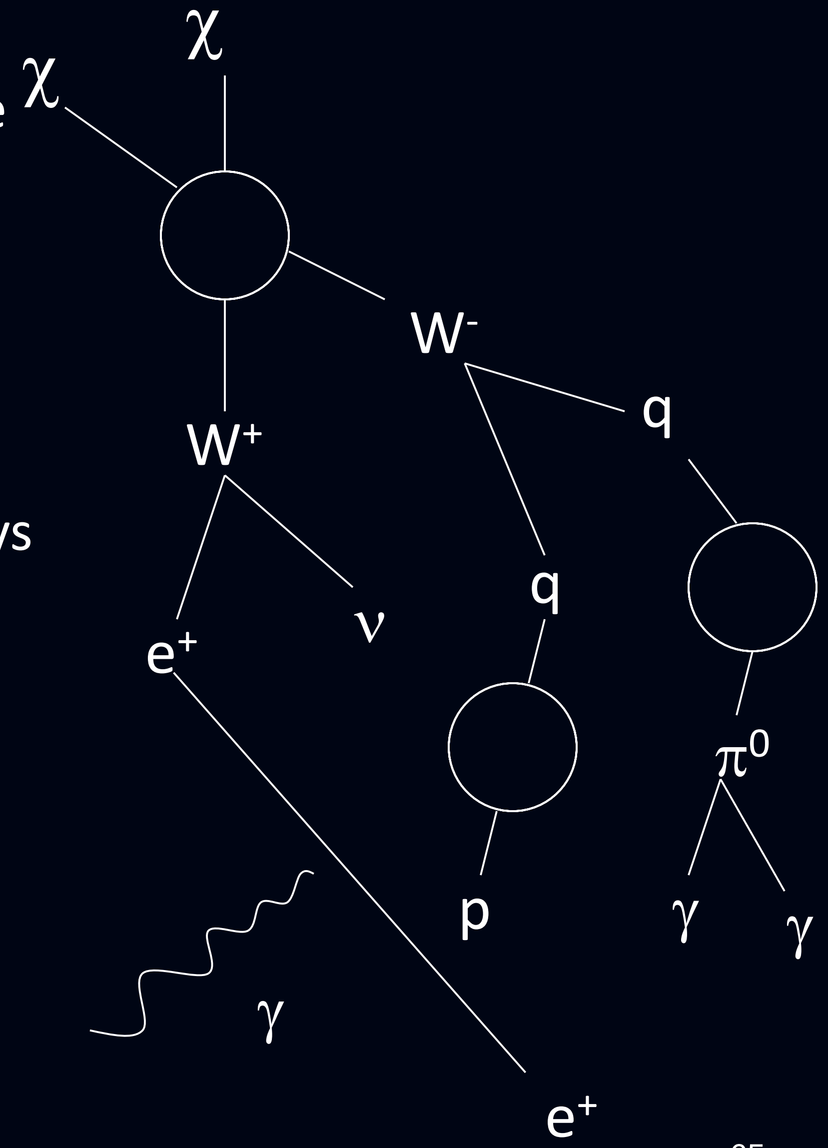


The Indirect Detection of DM

- **WIMP Annihilation** Typical final states include heavy fermions, gauge or Higgs bosons

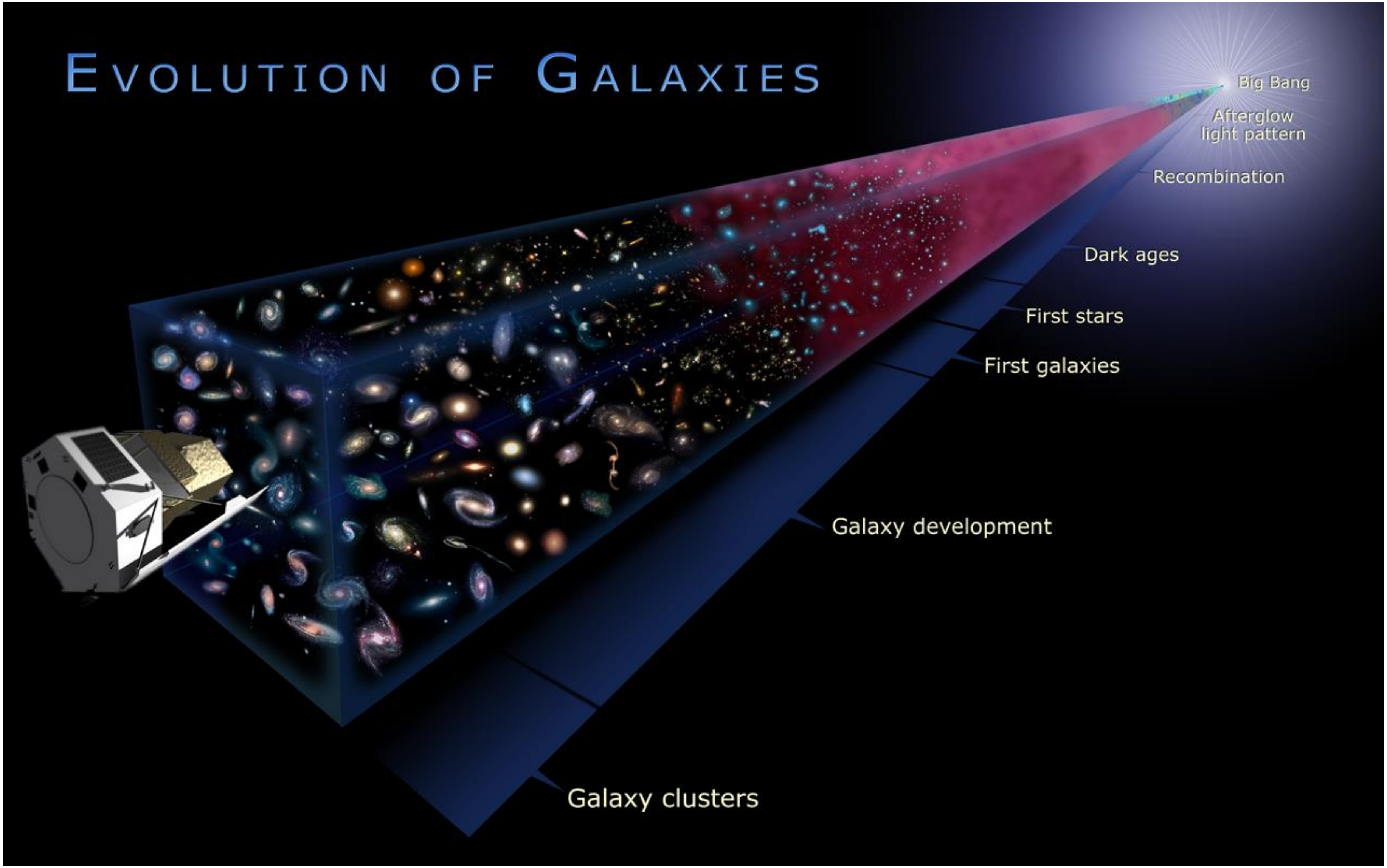
- **Fragmentation/Decay** Annihilation products decay and/or fragment into combinations of electrons, protons, deuterium, neutrinos and gamma-rays

- **Synchrotron and Inverse Compton** Relativistic electrons up-scatter starlight/CMB to MeV-GeV energies, and emit synchrotron photons via interactions with magnetic fields



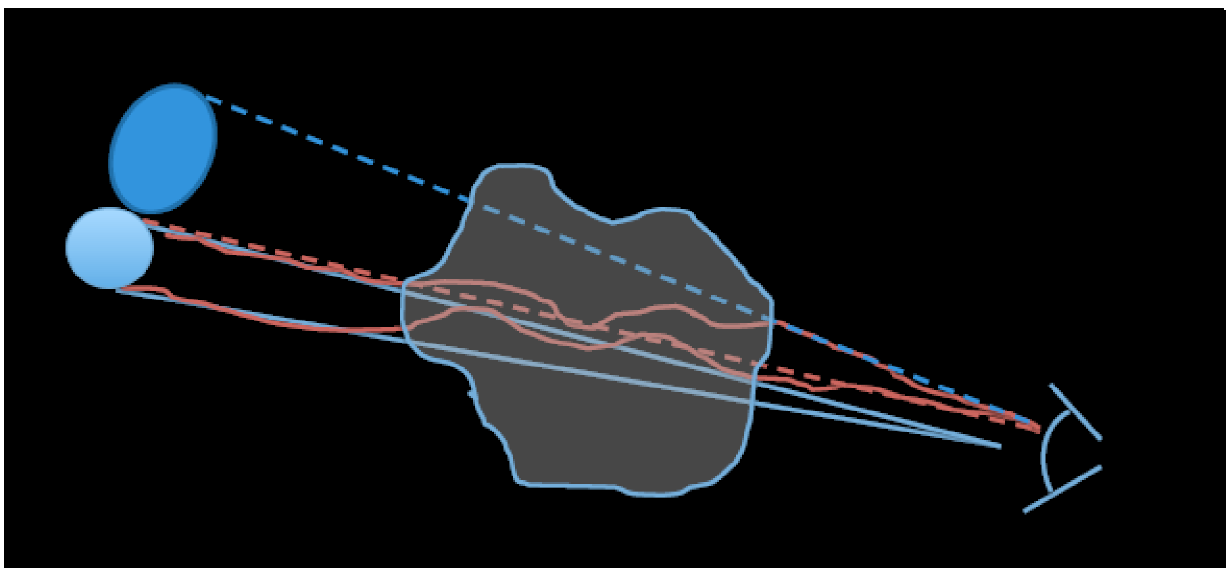
8) … and Dark Energy. See: Cosmology (O. Mena)

The EUCLID mission



The EUCLID mission

- Derive properties/nature of dark energy, test gravity using a unique combination of independent but complementary probes.
- **Galaxy clustering:**
  - 30 millions galaxies with redshifs between 0.7 and 2
  - Spectroscopic surveys can extract the 3D galaxy clustering information
- **Weak Lensing**



The image of the galaxy is related to its true shape via convergence (modifies the size) and shear (distorts the shape)