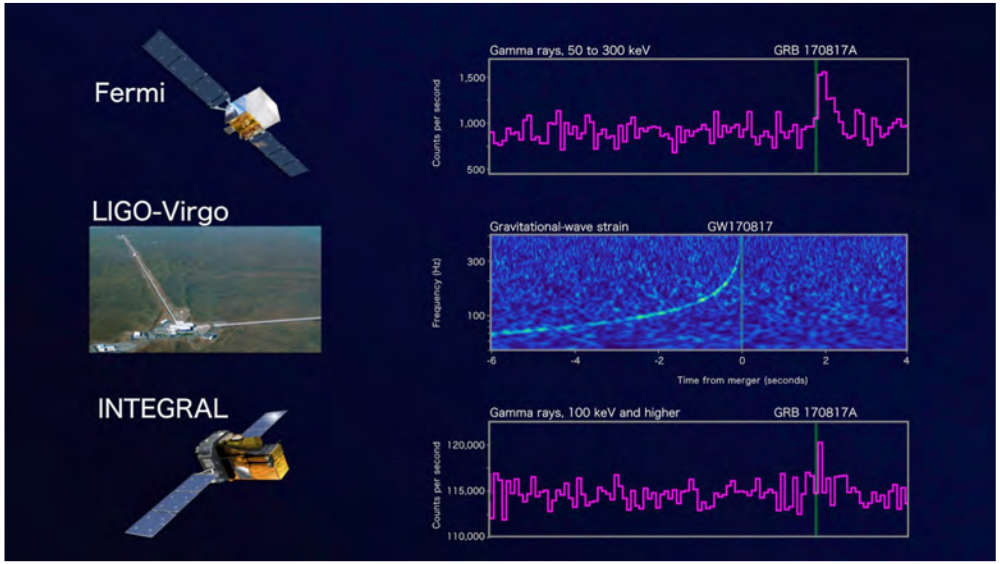
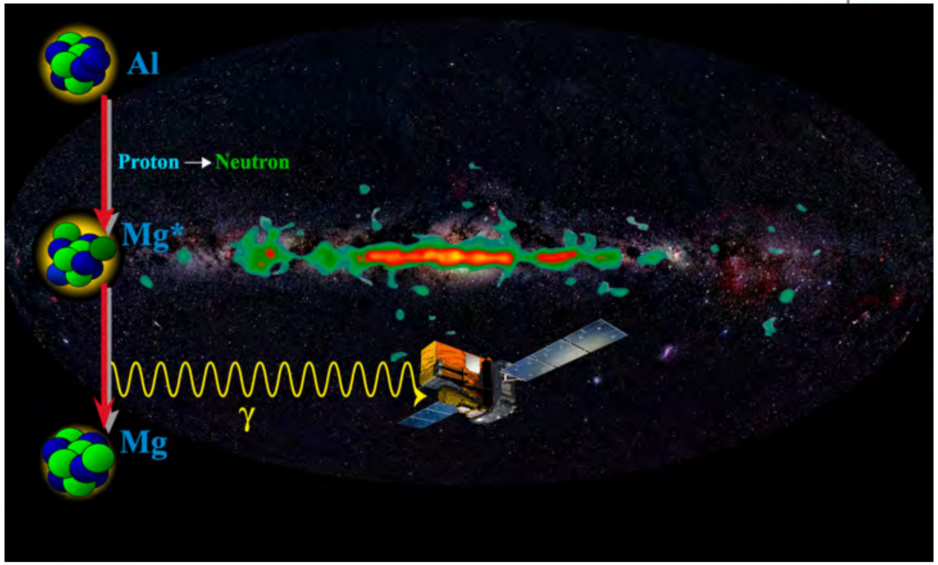
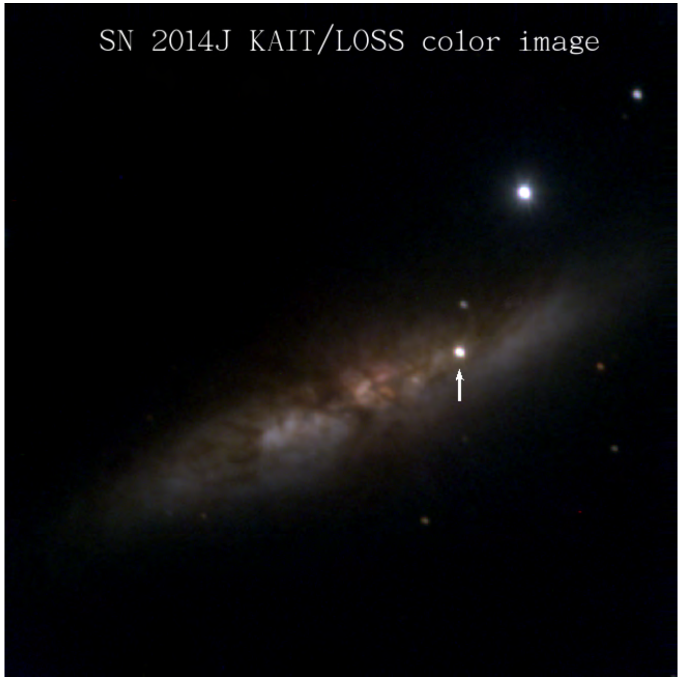
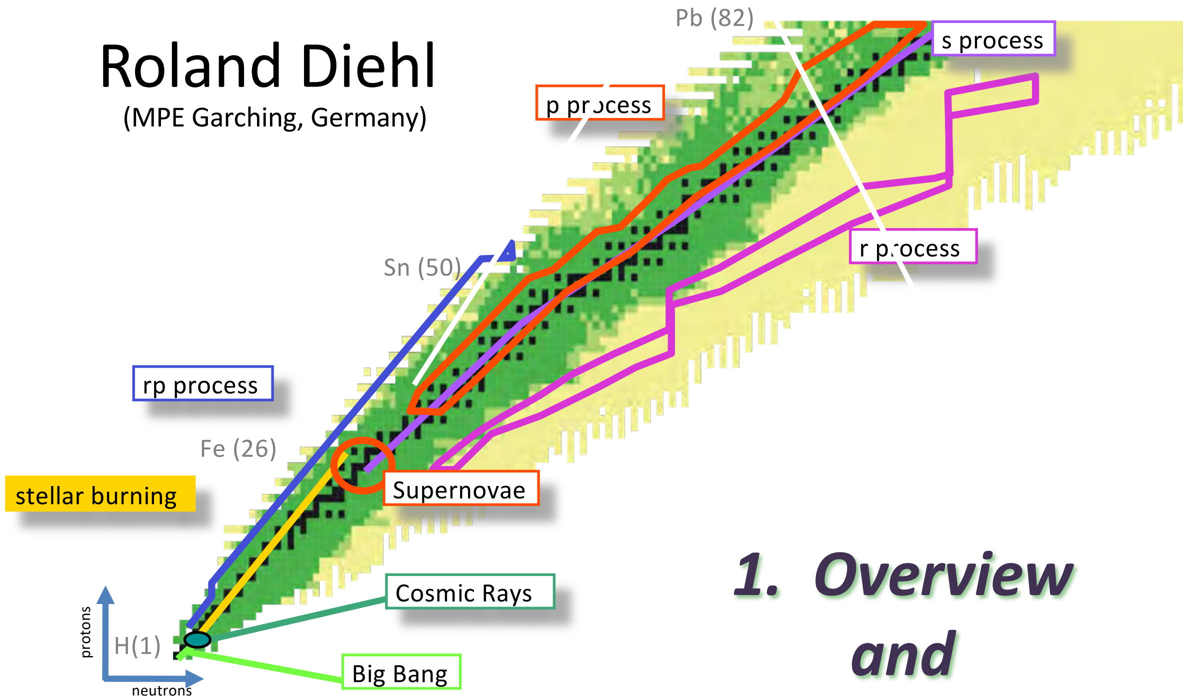
Gamma-ray spectroscopy from cosmic nuclei







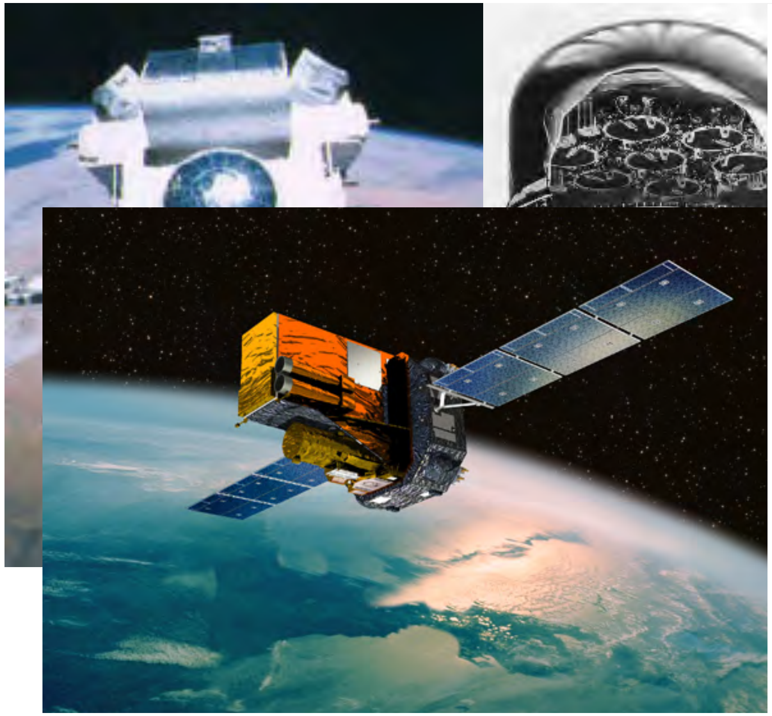
Roland Diehl
(MPE Garching, Germany)

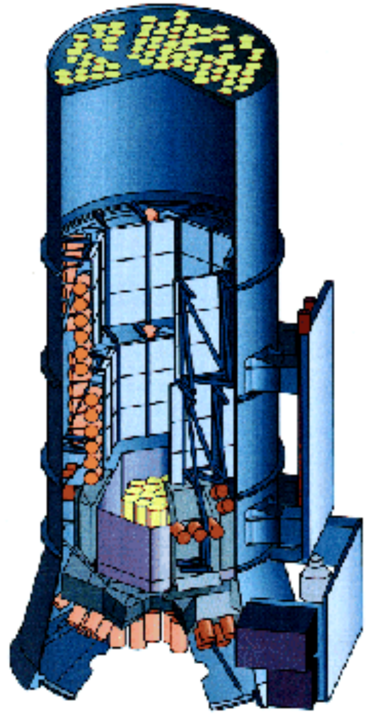


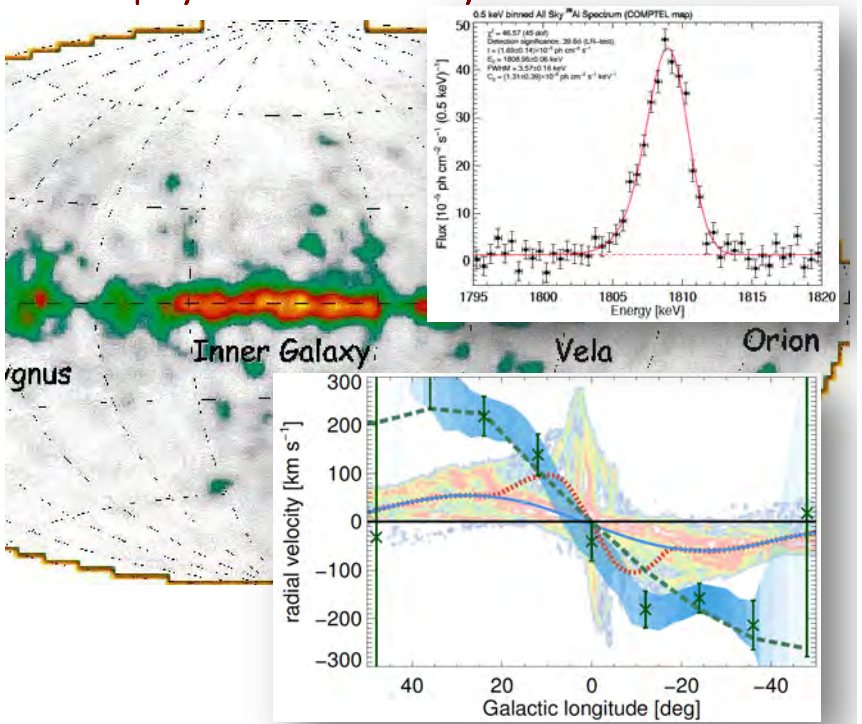
1. Overview and Context

Profile: Roland Diehl

- ☆ Nuclear-Physics Background
- ☆ Gamma-Ray Telescopes: Design, Response & Data Analysis Aspects
- ☆ Gamma-Ray Spectroscopy: Radioactivities; Nucleosynthesis Sources
- ☆ Massive Stars, Supernovae, ISM, Relativistic Particle Acceleration
  - ☞ Projects: Compton Gamma-Ray Observatory / COMPTEL; INTEGRAL / SPI; GRIPS
  - ☞ ESF EuroGenesis; Universe Cluster; Nuclear Astrophysics Community







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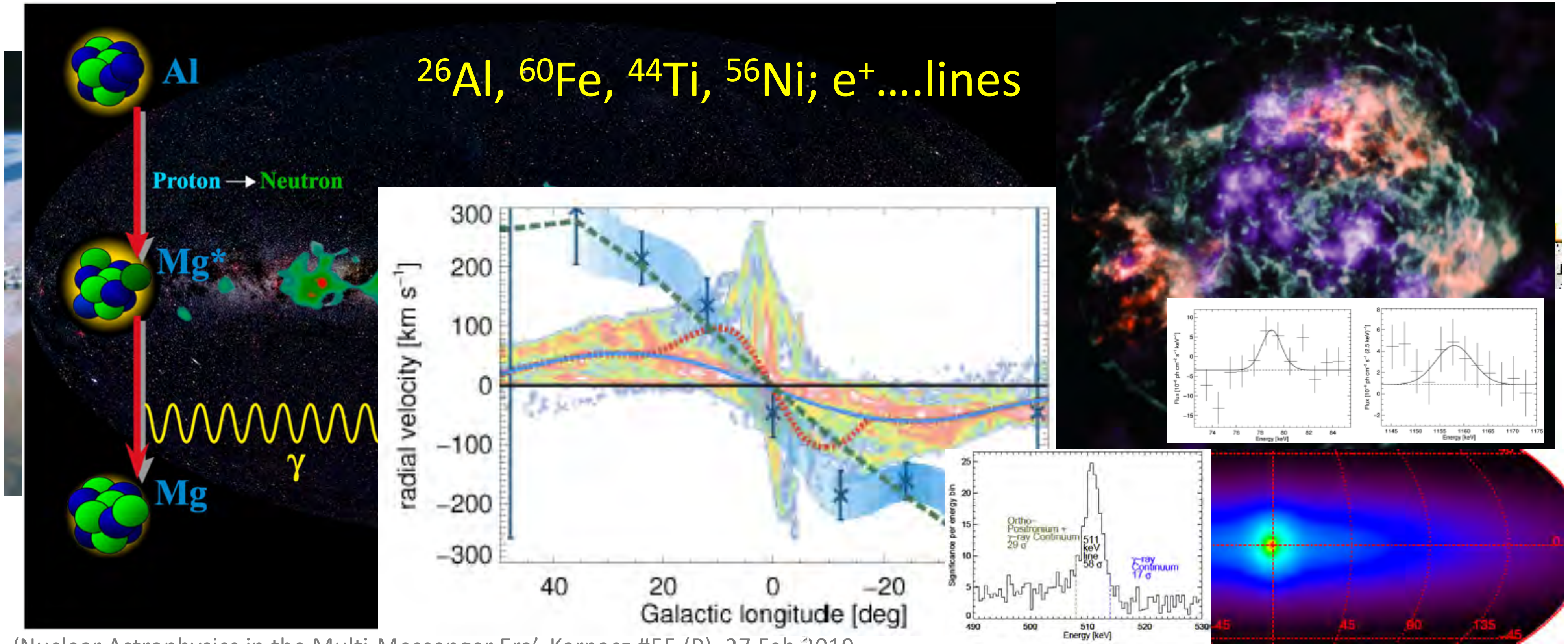

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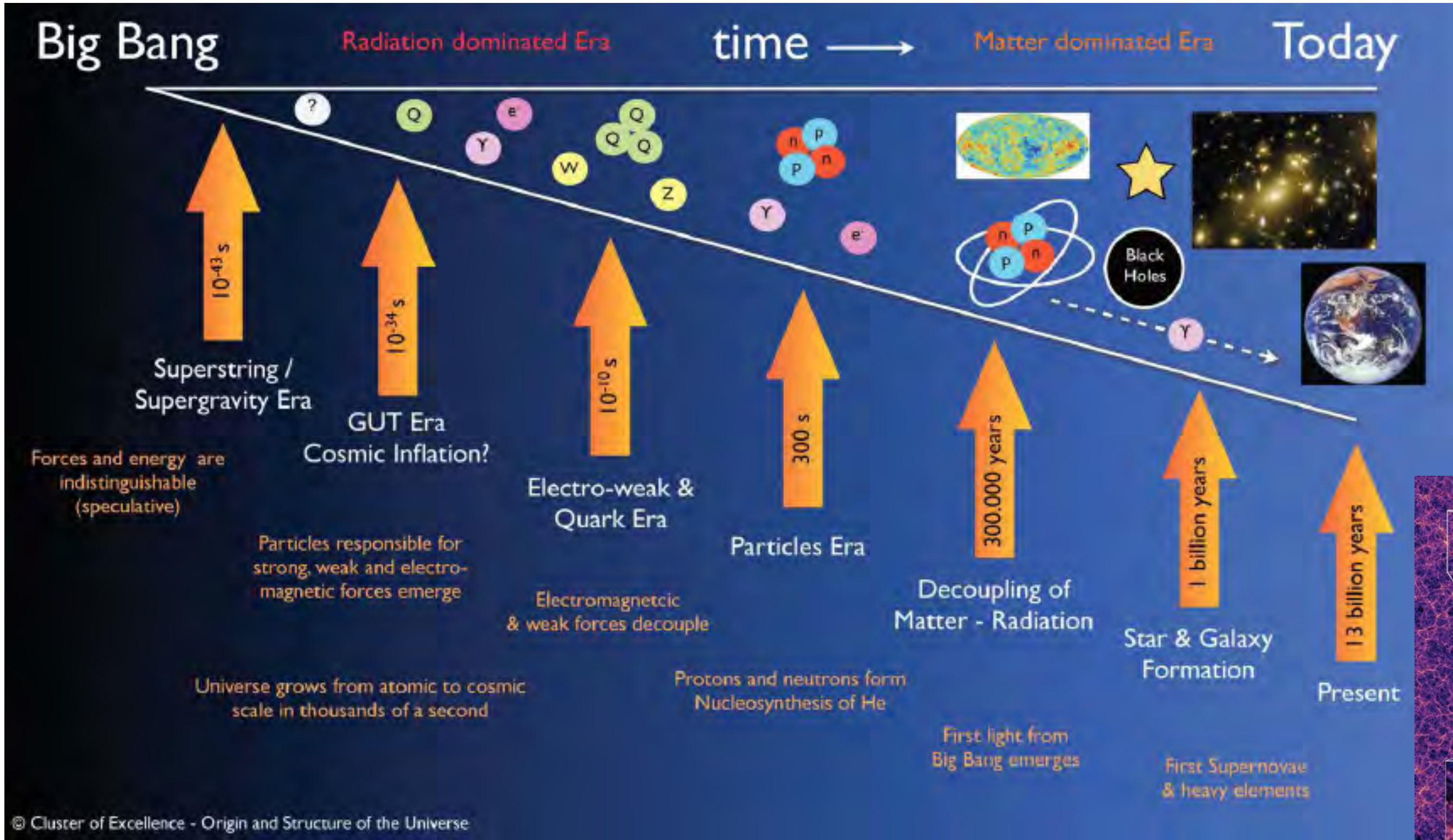
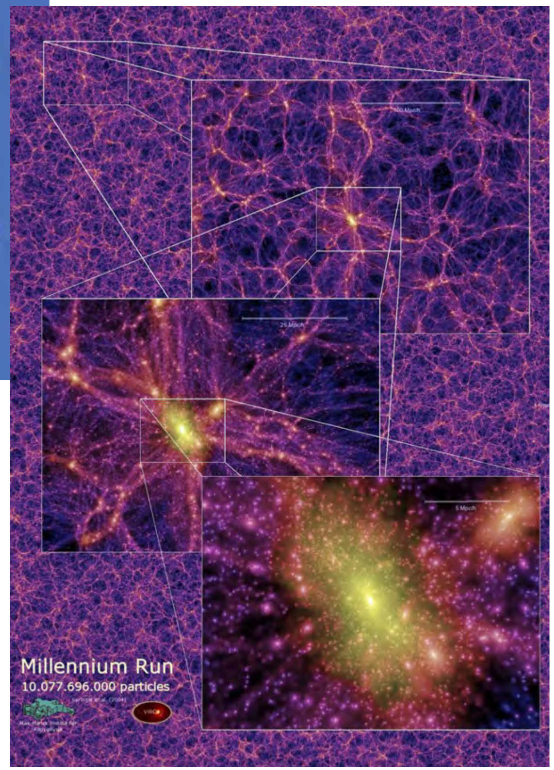
1. The context of gamma-ray spectroscopy
   - Astronomy
   - Astrophysics
   - Multi-Messenger Astronomy and Astrophysics

2. Techniques and issues in gamma-ray spectroscopy
   - Instrument Concepts
   - Detectors
   - Background handling
   - Line parameters

3. Results and lessons, and still-open issues
   - Specific sources
   - Diffuse emission

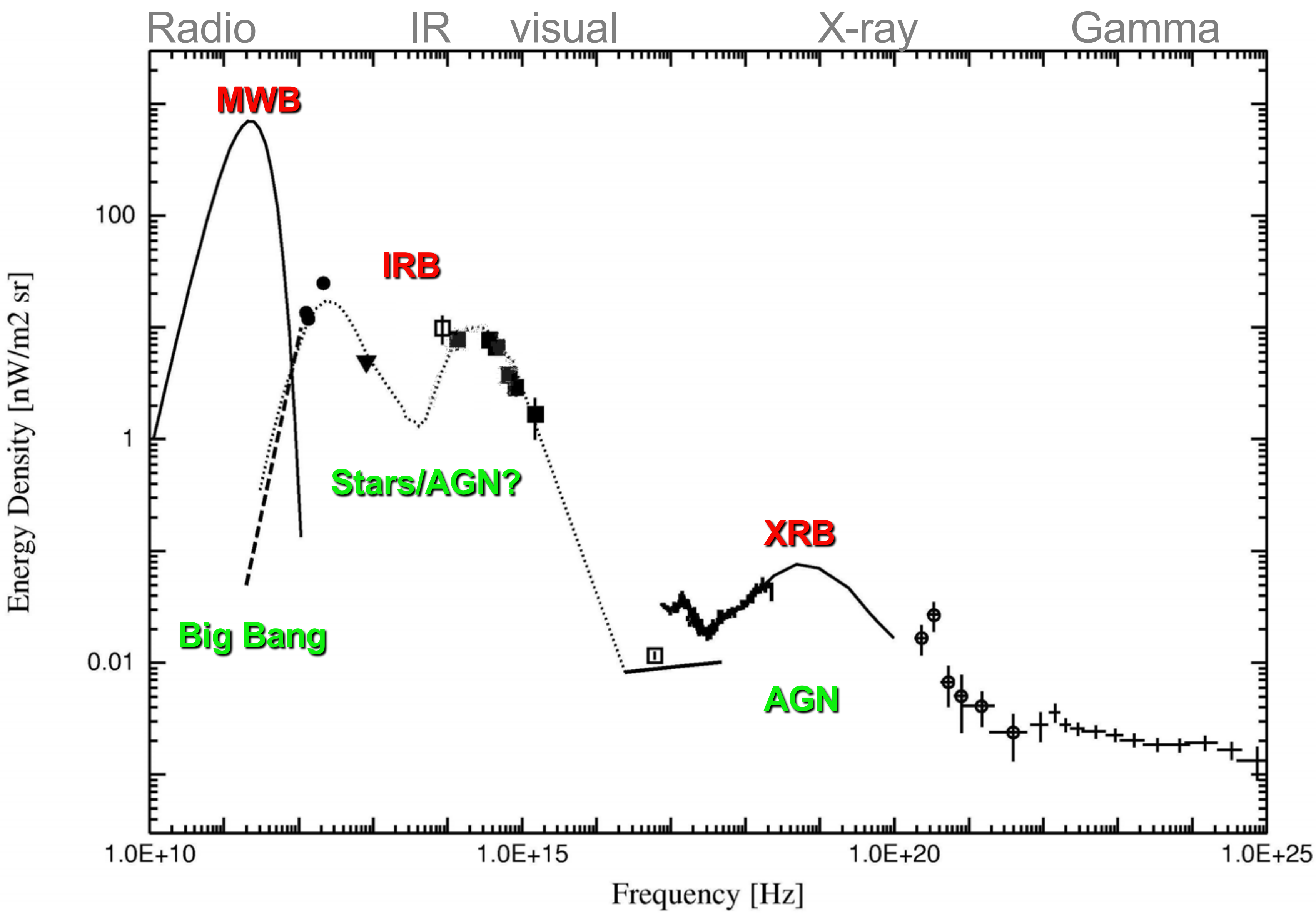
Radiation from objects in the evolving universe





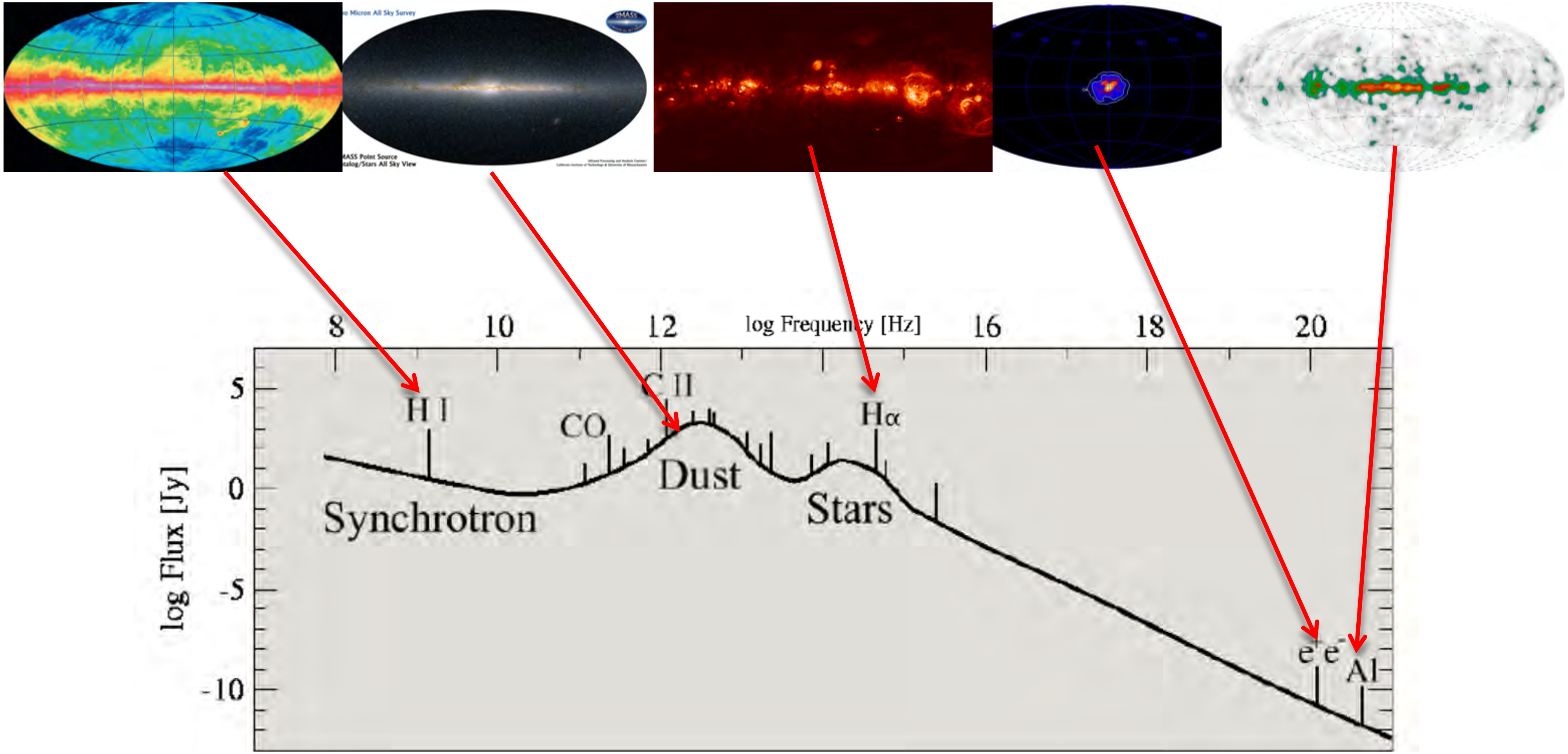
- ☆ Formation of galaxies around dark-matter concentrations
- ☆ Evolution of galaxies, often around central supermass black holes
- ☆ Evolution of gas composition from stellar nucleosynthesis

The Energy Spectrum of Diffuse Cosmic Radiation

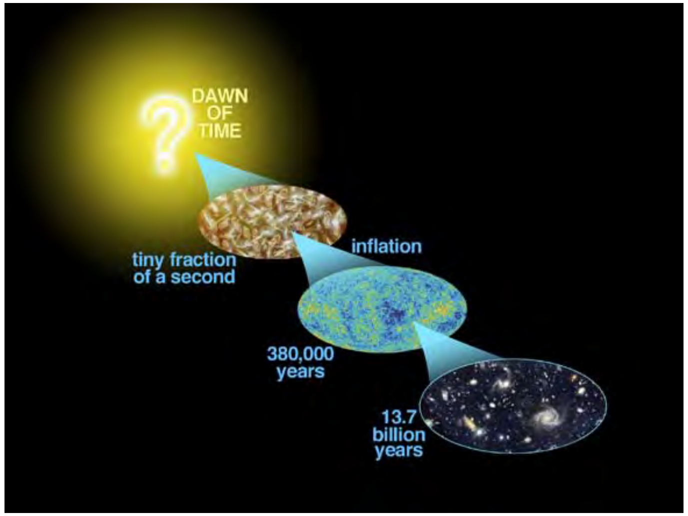


Emission from Galaxies

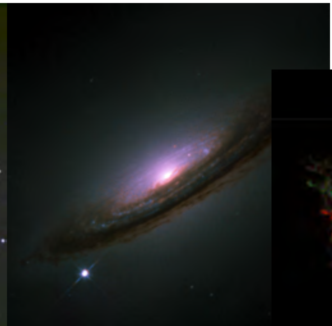
☆ Normal Galaxies (Milky Way)

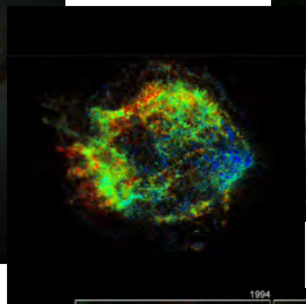


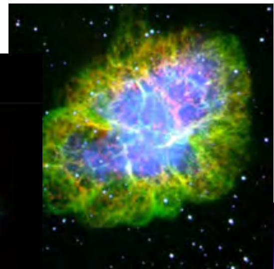
Cosmic Objects

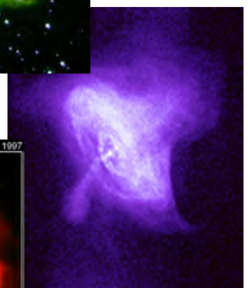


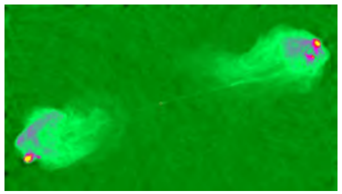
- Galaxies
- Stars
- Interstellar Gas

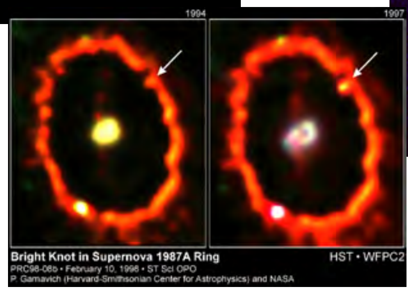


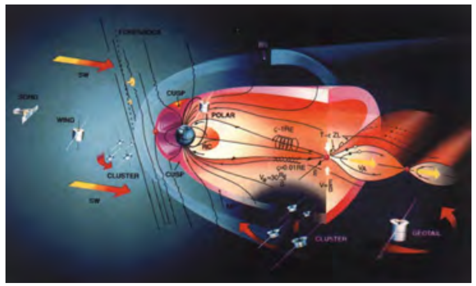












Blackbody Radiation

1. Planck functions (Brightness of a blackbody)

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{(\exp\frac{h\nu}{kT}-1)} \quad \text{erg cm}^{-2}\text{sec}^{-1}\text{Hz}^{-1}\text{ster}^{-1}$$

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5}\frac{1}{(\exp\frac{hc}{\lambda kT}-1)} \quad \text{erg cm}^{-2}\text{sec}^{-1}\text{cm}^{-1}\text{ster}^{-1}$$

$$B_{\tilde\nu}(T) = \frac{2hc^2\tilde\nu^3}{(\exp\frac{hc\tilde\nu}{kT}-1)} \quad \text{erg cm}^{-2}\text{sec}^{-1}(\text{cm}^{-1})^{-1}\text{ster}^{-1}$$

$$B_\nu(T)\,d\nu = B_\lambda(T)\,d\lambda = B_{\tilde\nu}(T)\,d\tilde\nu$$

Rayleigh-Jean's law

$h\nu / kT \ll 1$

$$B_\nu(T) = 2\left(\frac{\nu}{c}\right)^2 kT$$

Wien's law

$h\nu / kT \gg 1$

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\exp\frac{-h\nu}{kT}$$

2. Stefan-Boltzmann law

$$\text{total emittance} = \pi\int_0^\infty B_\nu(T)\,d\nu = \sigma T^4 \text{ ergs cm}^{-2}\text{sec}^{-1}$$

$$\sigma = \frac{2\pi^5 k^4}{15c^2h^3} = 5.67 \times 10^{-5} \text{ erg cm}^{-2}\text{ deg}^{-4}\text{ sec}^{-1}$$

3. Wien displacement law

Maximizing B_ν :

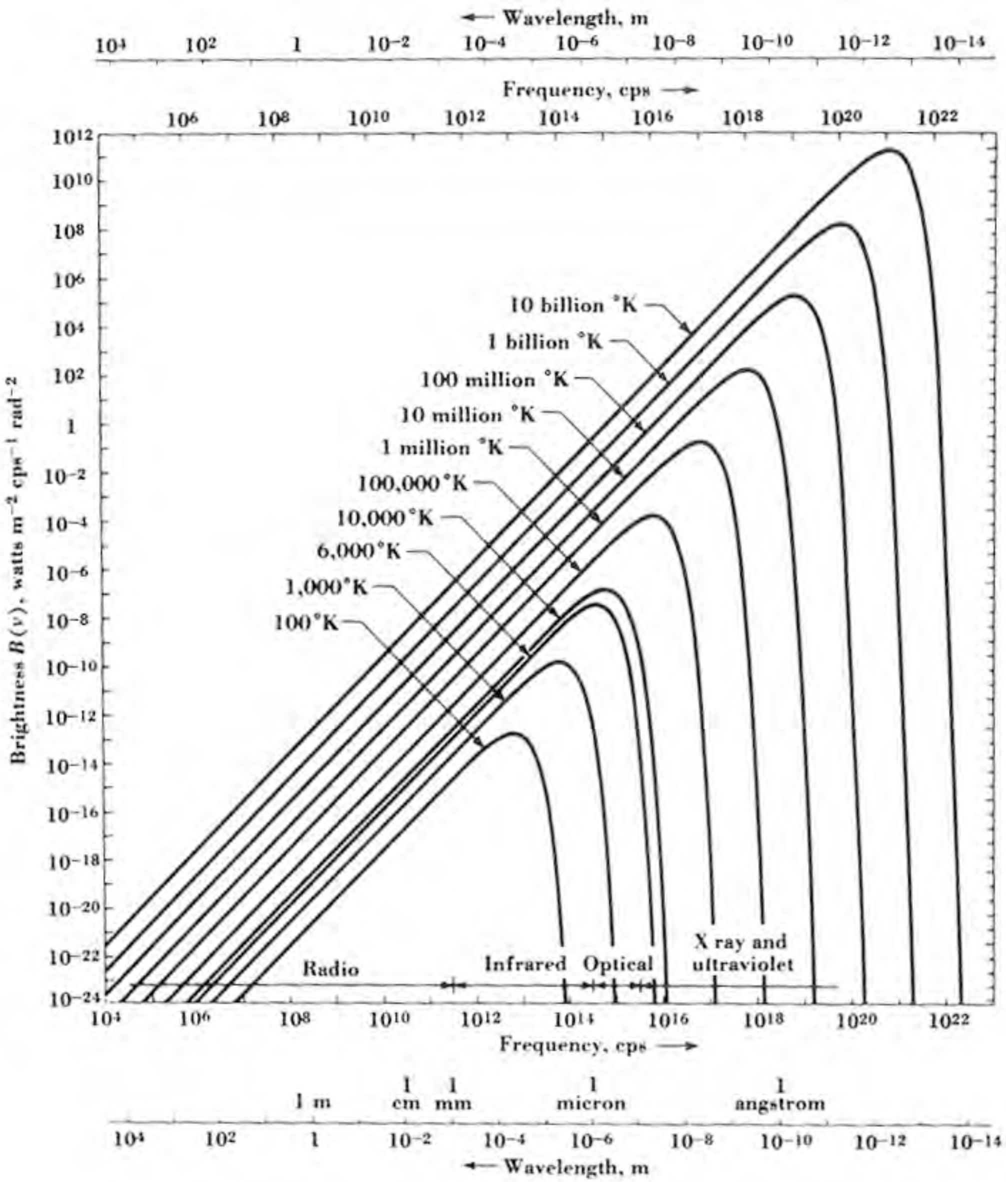
$\nu_m = 5.9 \times 10^{10}\ T$ Hz

$\lambda_m = 0.51\ T^{-1}$ cm

Maximizing B_λ :

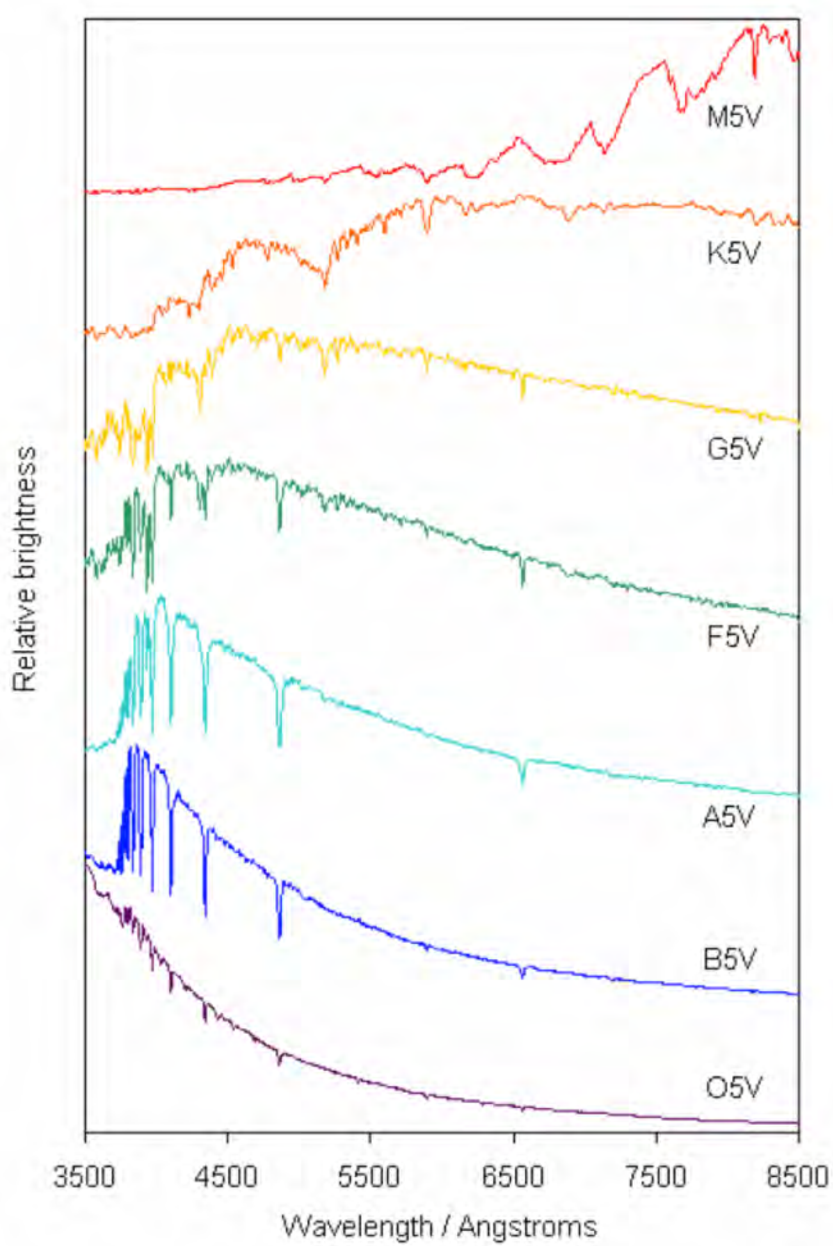
$\nu_m = 10.3 \times 10^{10}\ T$ Hz

$\lambda_m = 0.29\ T^{-1}$ cm



Stars: Typical Emission Signature

- ☆ Thermal Spectrum, Close to Black-Body Shape
  - ☞ Harvard Classification
    - – OBAFGKM
  - ☞ T_{eff}~2000...40000K
- ☆ Characteristic Lines
  - ☞ Absorption from Gas above Photosphere
  - ☞ Emission from Recombining Gas
- ☆ HE Phenomena:
  - ☞ Wind Interactions
    - » Be Systems, O Stars, WR Stars
  - ☞ Coronal Flare Emission
    - » TTau Stars, ...
  - ☞ Compact Stars
    - » Accretion → Release of Gravitational Energy
    - » Nuclear Explosions → Release of Nuclear Energy
    - » NS Surface; Pulsars

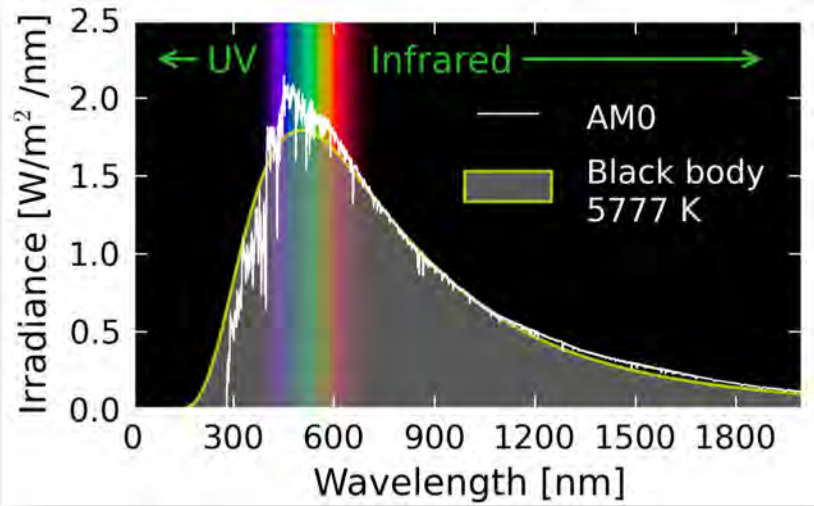


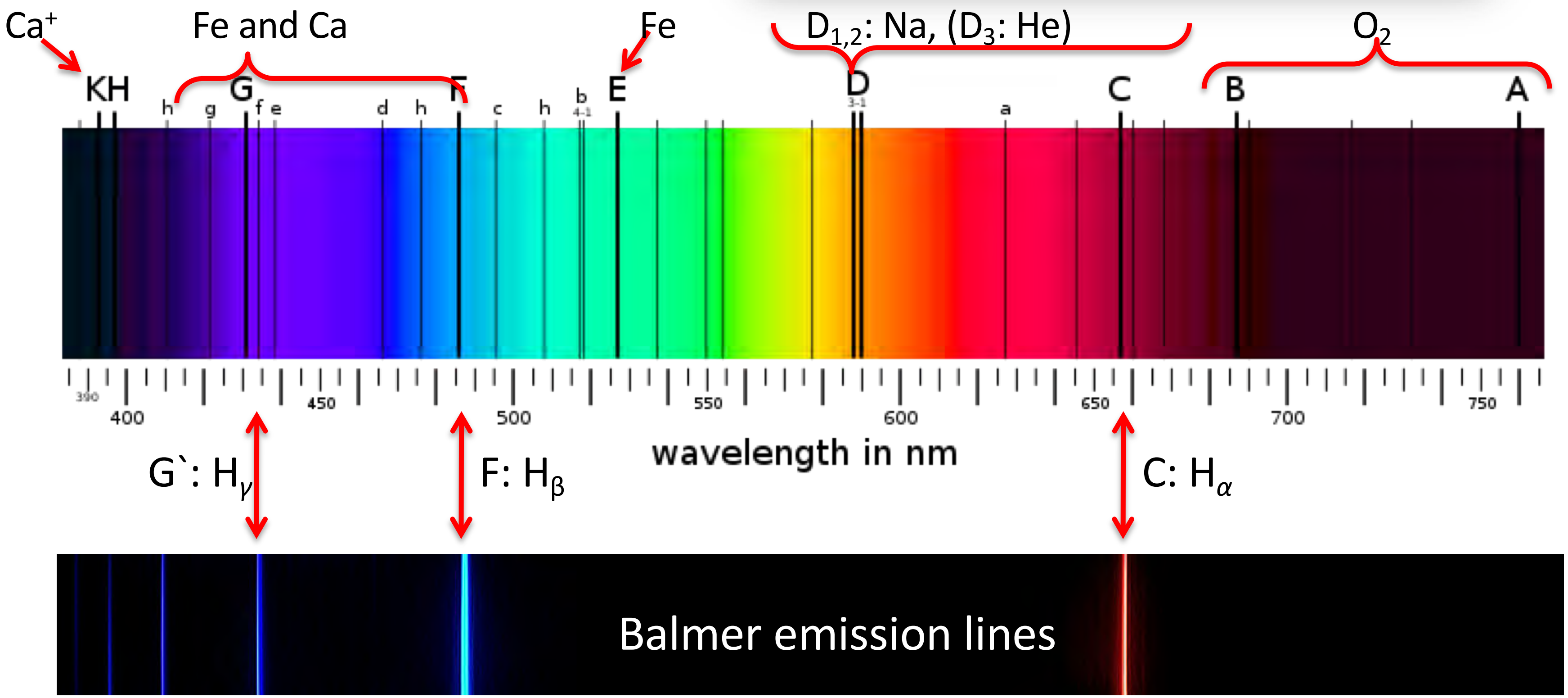
Non-Thermal Radiation

- ☆ non-thermal radiation is important in astronomy
  - recombination
  - fluorescence
  - magnetic field interactions of charged particles

Spectral Lines in Radiation from the Sun

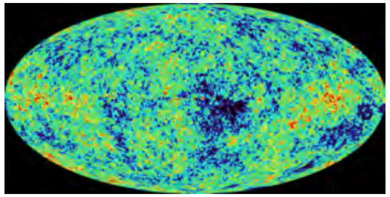
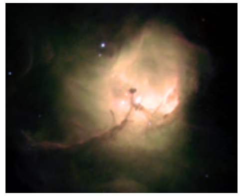
- Joseph von Fraunhofer *(1787-1826)*
  - ☆ *In years up to !1814:*
    - ☞ 570+ „dark lines“ found in the solar spectrum;
    - ☞ Identification with atomic species

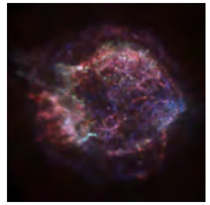




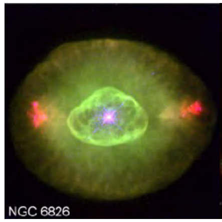
Electromagnetic Radiation from Cosmic Sources

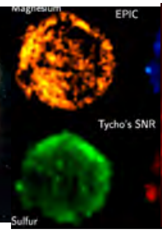
Thermal Radiation

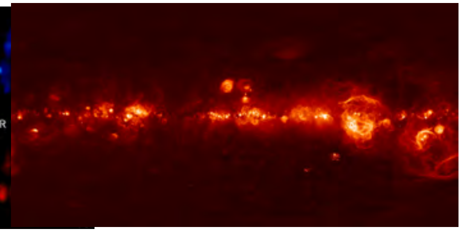





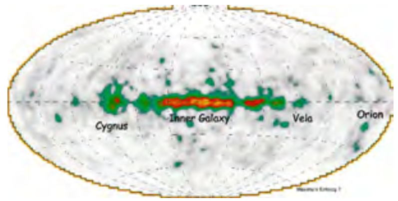
Atomic Transitions



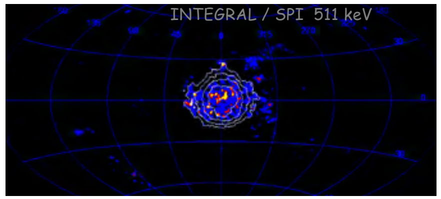





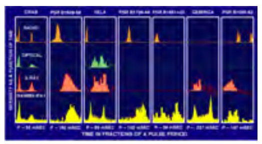
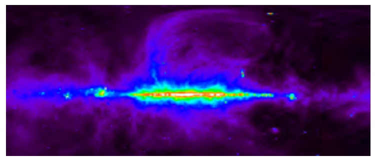
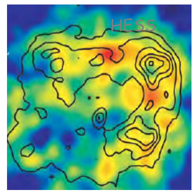
Nuclear Transitions



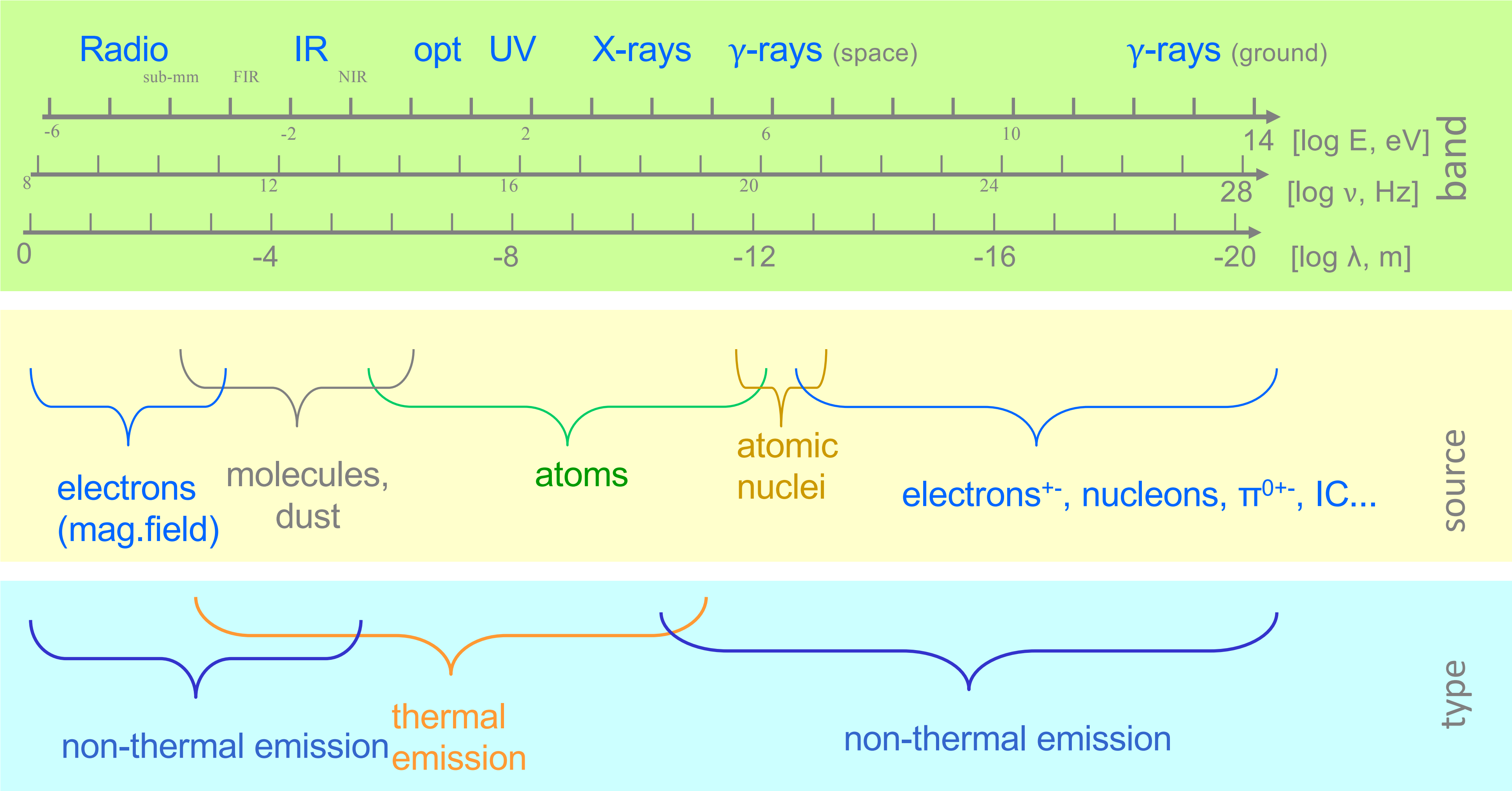
Matter/Antimatter Annihilation



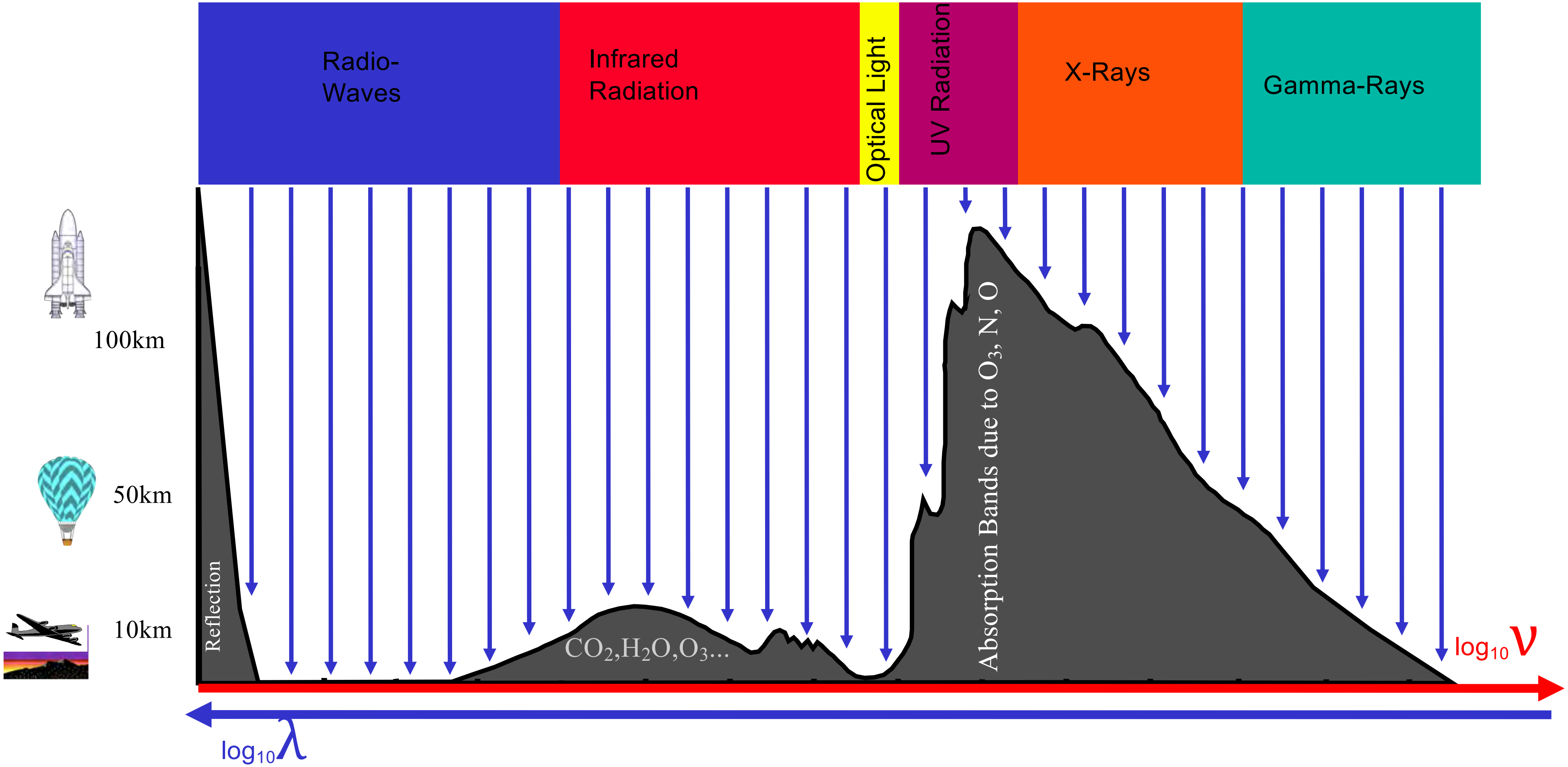
Non-thermal Continuum Processes

Astronomy across the Electromagnetic Spectrum

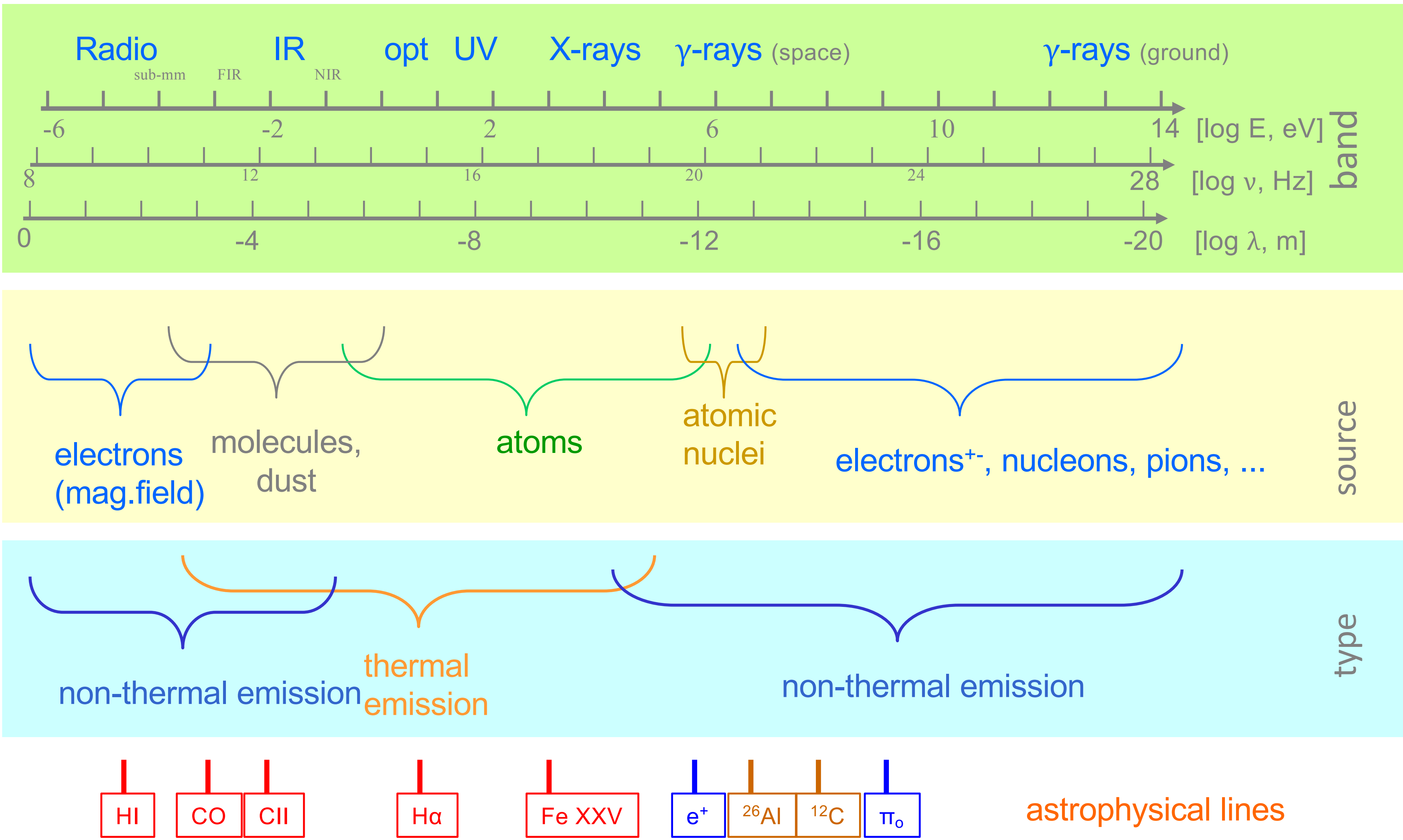


Observational Windows in Astronomy



→ Need a Combination of Ground-Based and Space Satellite Observations

Line Spectroscopy across the Electromagnetic Spectrum



Nuclear Gamma-Ray Lines

Isotope	*Mean Lifetime*	*Decay Chain*	*γ-Ray Energy (keV)*
^{7}Be	77 d	$^{7}Be \rightarrow {}^{7}Li^*$	478
^{56}Ni	111 d	$^{56}Ni \rightarrow {}^{56}Co^* \rightarrow {}^{56}Fe^* + e^+$	158, 812; 847, 1238
^{57}Ni	390 d	$^{57}Co \rightarrow {}^{57}Fe^*$	122
^{22}Na	3.8 y	$^{22}Na \rightarrow {}^{22}Ne^* + e^+$	1275
^{44}Ti	85 y	$^{44}Ti \rightarrow {}^{44}Sc^* \rightarrow {}^{44}Ca^* + e^+$	78, 68; 1157
^{26}Al	$1.04\ 10^6 y$	$^{26}Al \rightarrow {}^{26}Mg^* + e^+$	1809
^{60}Fe	$3.8\ 10^6 y$	$^{60}Fe \rightarrow {}^{60}Co^* \rightarrow {}^{60}Ni^*$	59, 1173, 1332
e^+	.... $10^5 y$	$e^+ + e^- \rightarrow Ps \rightarrow \gamma\gamma..$	511, <511

individual object/event

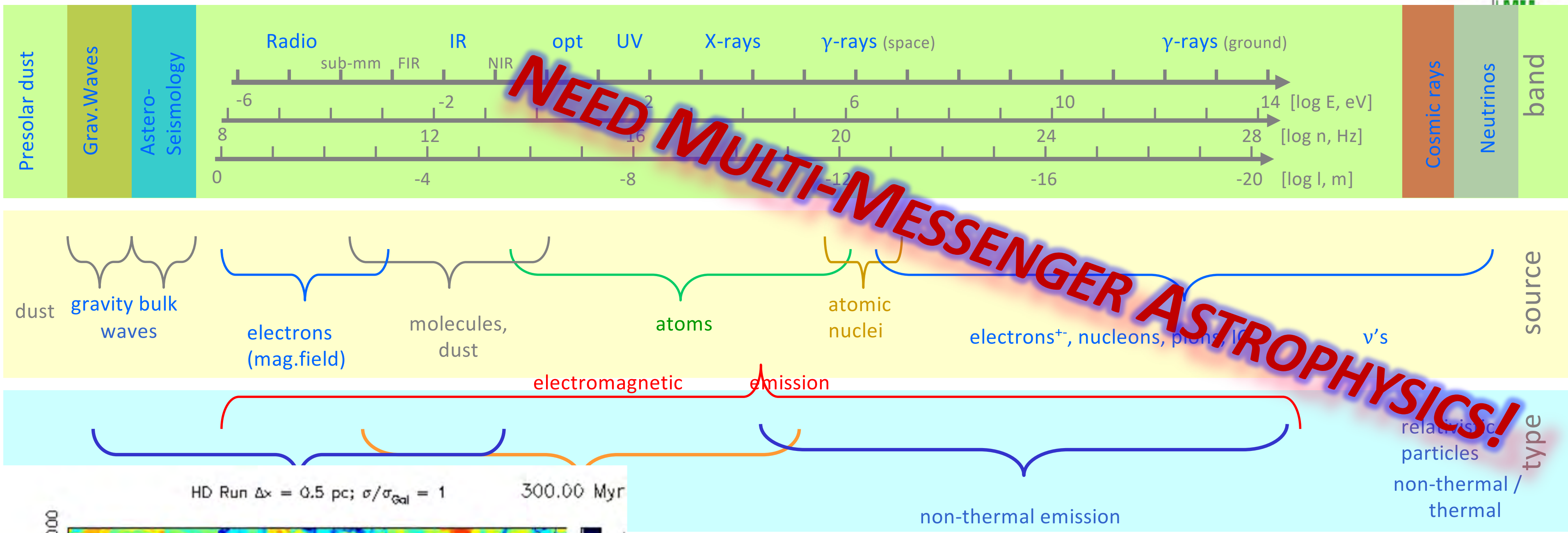
cumulative from many events

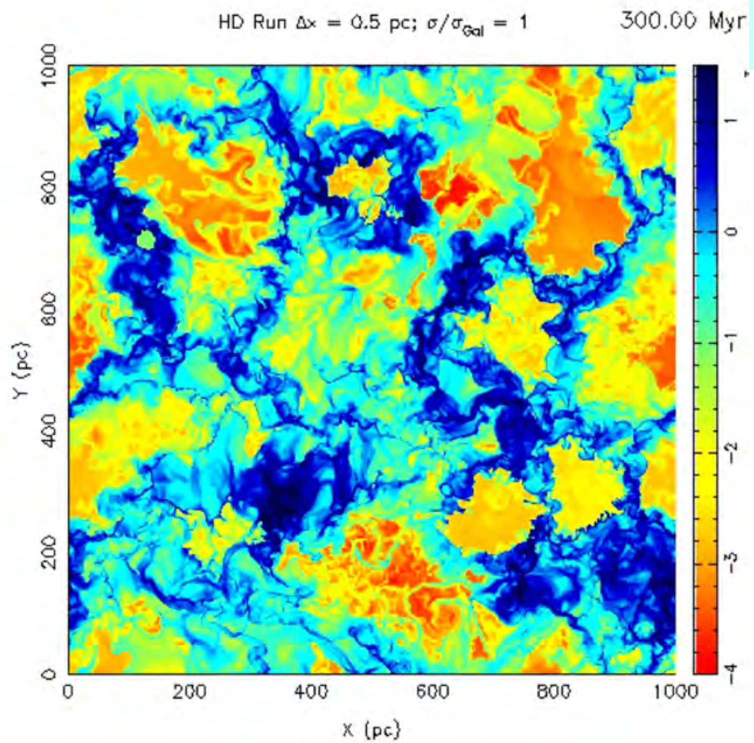
Radioactive trace isotopes are by-products of nucleosynthesis

For gamma-ray detections we need:

- ☞ Decay Time > Source Dilution Time (~weeks) (→ no < days lifetimes)
- ☞ Yields > Instrumental Sensitivities (10^{-5} ph cm^{-2} s^{-1}) (→ no elements > Fe)

Gamma-rays and the variety of astronomies



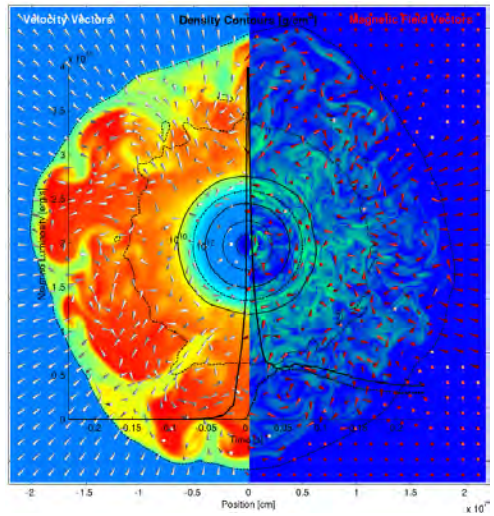


Nuclear astrophysics: How nuclear energy shapes cosmic objects

Directly through γ's:

stellar explosions

cosmic matter cycle



Roland Diehl

Nuclear Energy and Stars: Modeling our Sun

- Core hydrogen burning, Hydrostatic equilibrium
- Input physics:
  - Nuclear reactions
  - Hydrodynamics
  - Energy transport by radiation, convection, diffusion
- Parameters:
  - Y (He abundance), Z
  - Mixing length α
- Outputs:
  - Luminosity (energy)
  - Structure → sound velocity profile
  - …
- Agreement within ~1%
  - Improved (3D) solar abundances worsen the agreement

NEED MULTI-MESSENGER ASTROPHYSICS!

Helioseismology (1962+)

Bahcall+2005

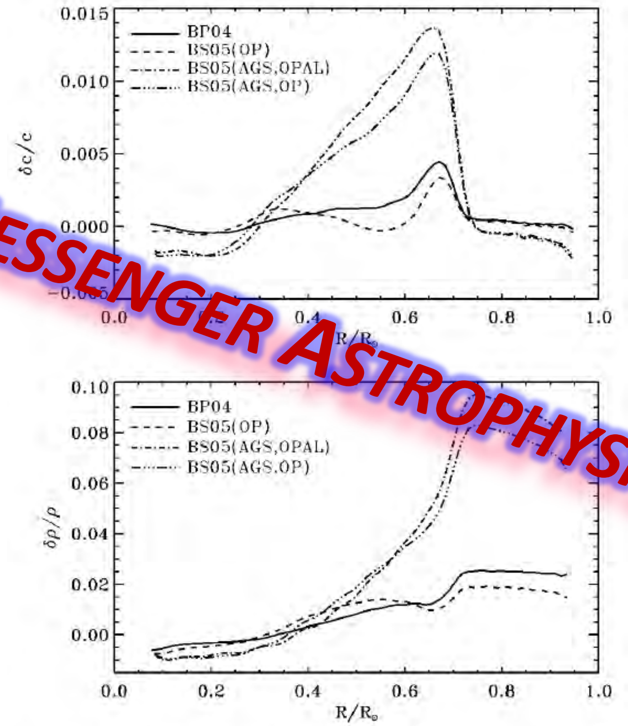
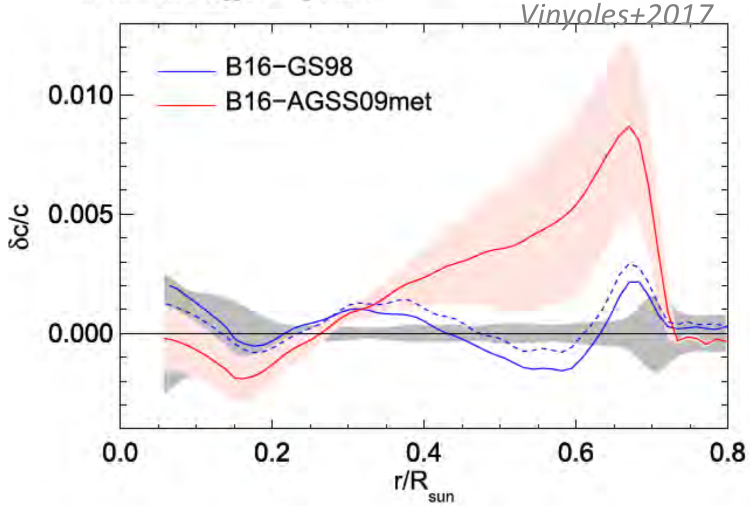


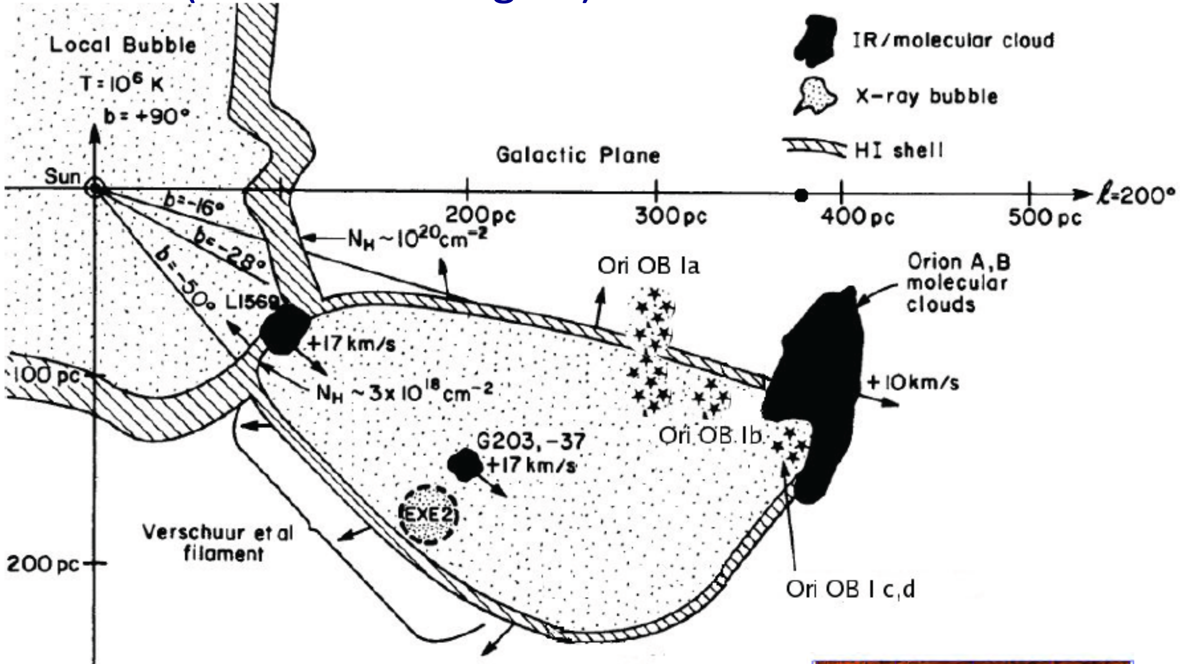
FIG. 1.—Relative sound speed differences, $\delta c/c = (c_{\odot} - c_{model})/c_{model}$, and elative densities, $\delta\rho/\rho$, between solar models and helioseismological results rom Michelson Doppler Imager data.

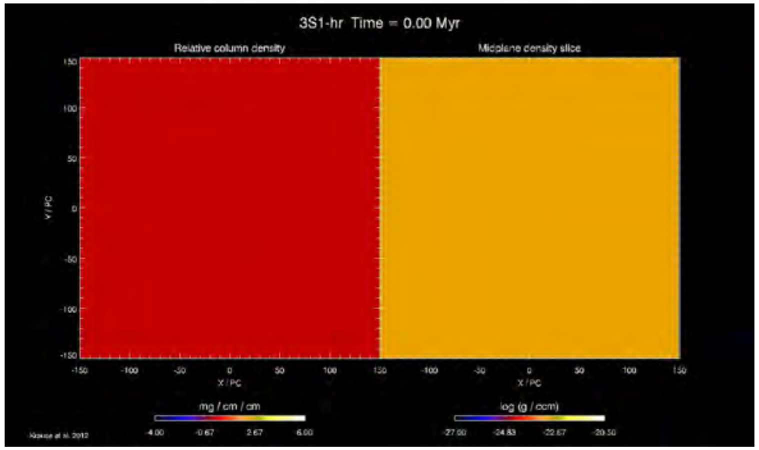
Vinyoles+2017

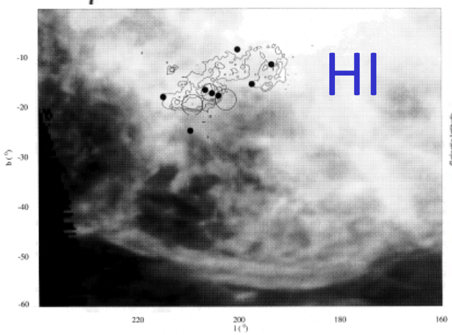


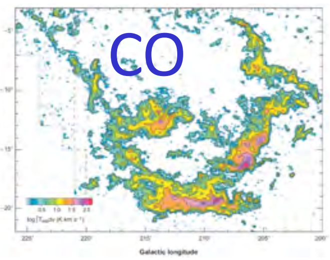
Example in Nuclear Astrophysics:
Nucleosynthesis Ejecta and the Dynamic Interstellar Medium

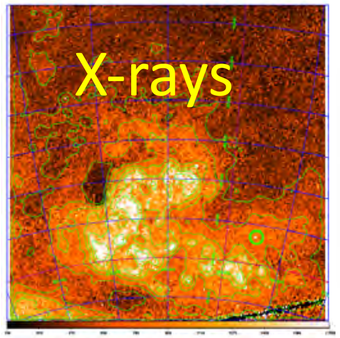
- ISM is Driven by Stars and Supernovae → Ejecta in (Super-)Bubbles
  - ☆ Study Multi-Messenger Observations, also through Simulations
    (here: Orion Region)

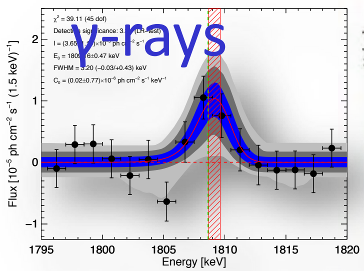


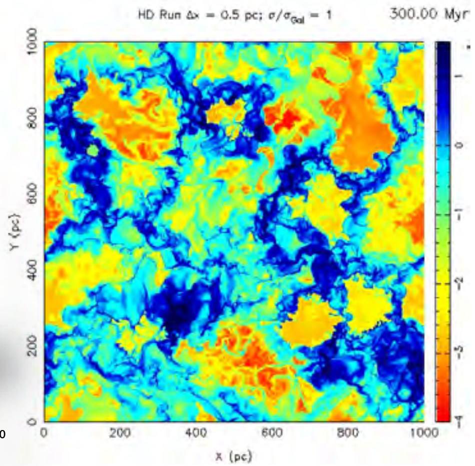












Current Nuclear-Astrophysics Issue: r Process Origin

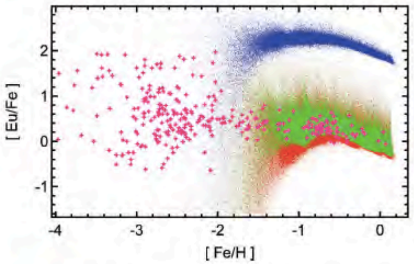
- Can we identify the sources of r process isotopes?

NEED MULTI-MESSENGER ASTROPHYSICS!

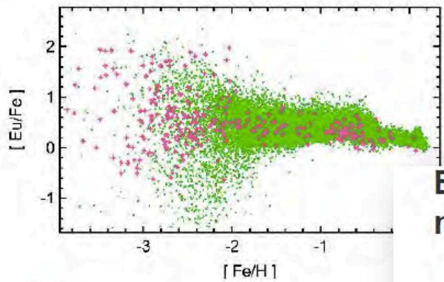
How are nucleosynthesis ejecta represented in stellar photospheres??

Introduction: Summary

- The r process is a primary process operating in a site that produces both neutrons and seeds. Large neutron densities imply a site with extreme conditions of temperature and/or density.
- There is strong evidence that the bulk of r-process content in the Galaxy originates from a high yield/low frequency events.
- Neutron star mergers may account for most of the r-process material in the galaxy. However, due to the coalescent delay time they may not contribute efficiently at low metalicities. Magneto-rotational supernova may contribute at low metalicities.



- Red dots: 10^8 yr coalescence time
- Green dots: 10^6 yr coalescence time
- Blue dots: larger merger probability.



- Including MHD-jet supernovae

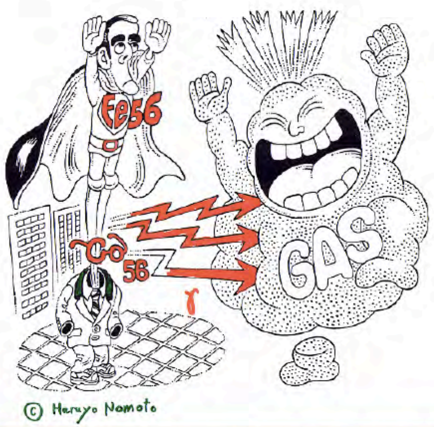
Wehmeyer, B., M. Pignatari, and F.-K. Thiel, Mon. Not. Roy. Astron. Soc. 452, 1970 (2

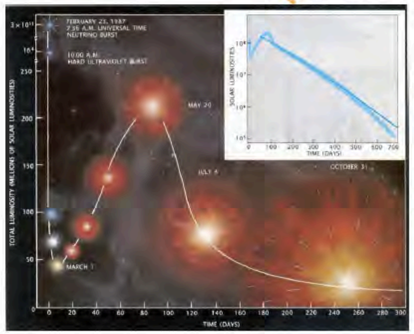
- How is radioactive energy re-radiated at optical/IR?

  ☞ How can be obtain the original energy from the absorbed & re-radiated fraction of light??

Electromagnetic signatures of nucleosynthesis

Supernova light curves follow the decay of ^{56}Ni ($t_{1/2} = 6$ d) and later ^{56}Co ($t_{1/2} = 77$ d)

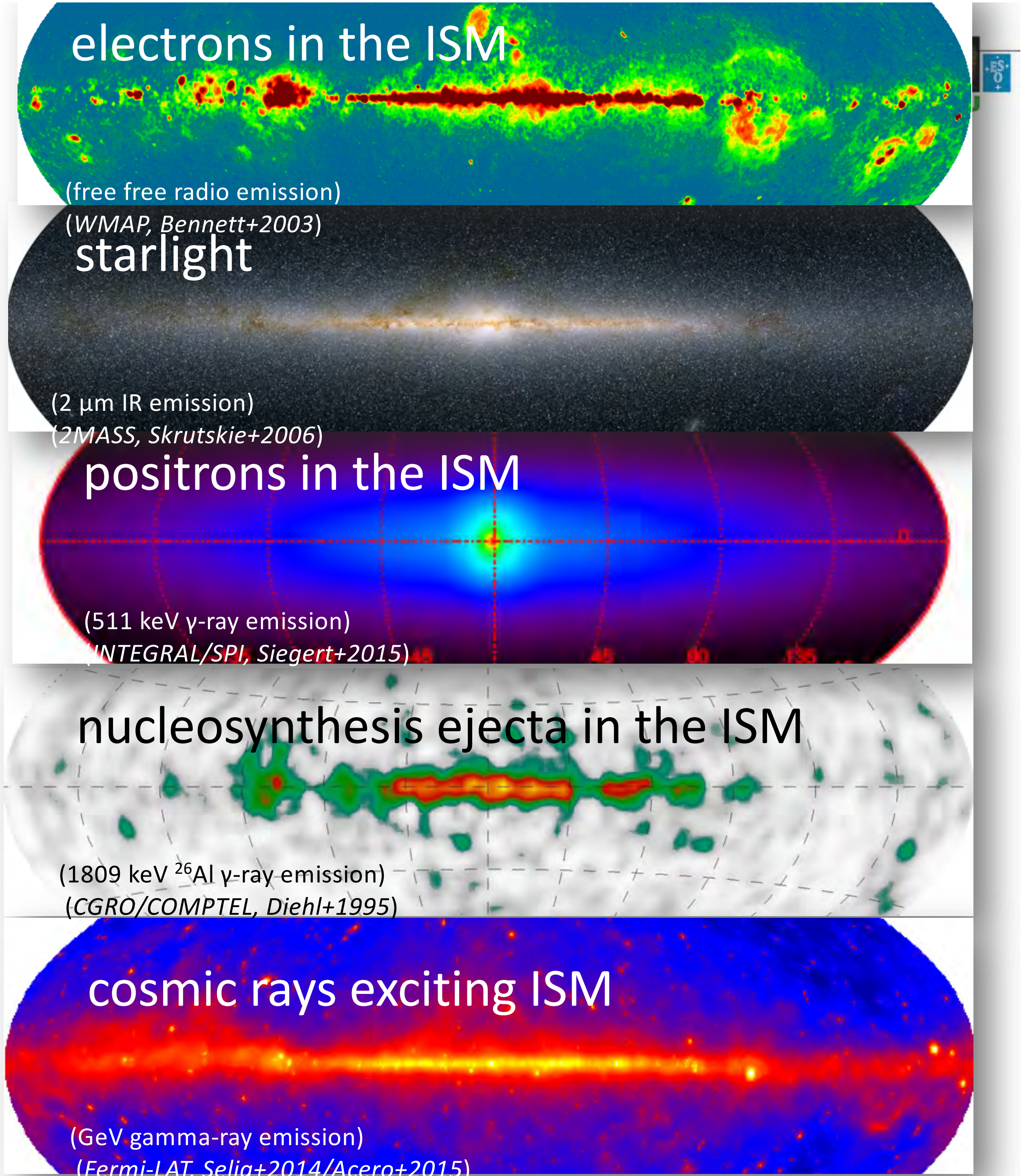




The Galaxy in Our Messengers

- The stars and gas in galaxies shows a variety of characteristic light

- We need to understand the origin of such emission, so we can avoid misinterpretation and learn about astrophysical origins

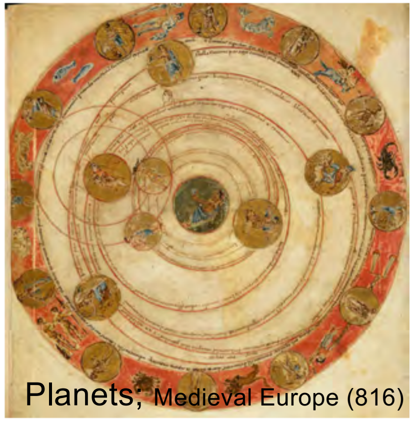


Astronomical Measurements

Astronomy: Telescopes

Astronomy and "new astronomies"

- Optical astronomy: understanding the sky of stars
  - Babylonian/Greek/India/China/Maya… studies (<3000 BC)
  - pre-socratic philosophers: *"all observed events must have rational, discoverable causes"*
  - The "telescope" >1608/9 (Galilei/Lipperhey)



Planets; Medieval Europe (816)

Sun, Moon, Stars; Nebra, Europe (~1600BC)

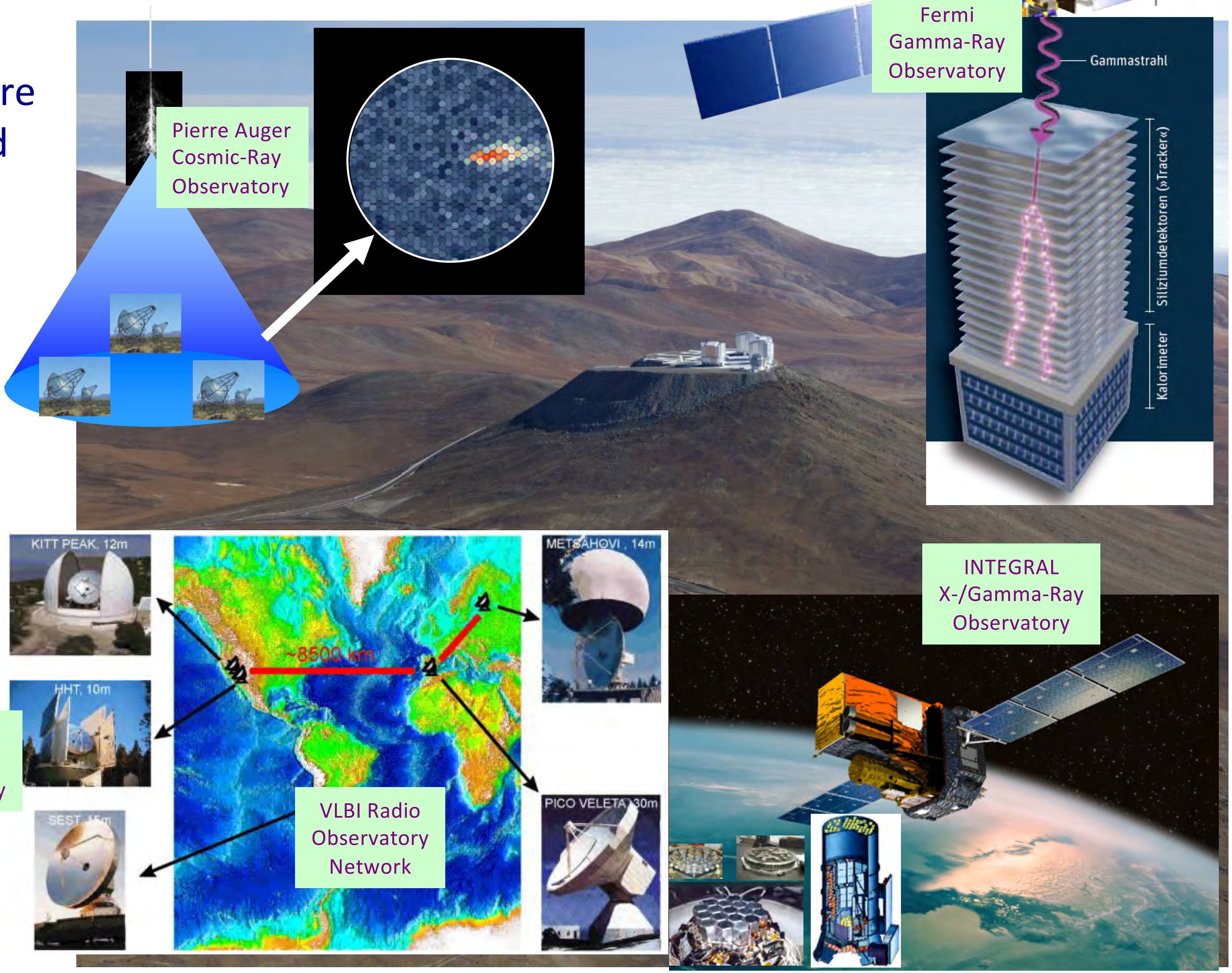
- "New astronomies" 1900+
  - Radio astronomy >1930 (Jansky)
  - UV & X-ray astronomy > 1970 (IUE, Uhuru)
  - GeV,MeV gamma-ray astronomy >1970 (OSOIII,SASII, HEAO)
  - Infrared astronomy >1980 (IRAS)
  - Presolar grains (from meteorite studies) >1980 (nanoSIMS)
  - Cosmic rays, EeV (Whipple, >1980
  - TeV gamma-ray astronomy >2000 (MAGIC, HESS)
  - Neutrinos > 2000 (Amanda, IceCube)
  - Asteroseismology > 2010 (Kepler, Corot)
  - Gravitational Waves >2015 (Ligo, Virgo)

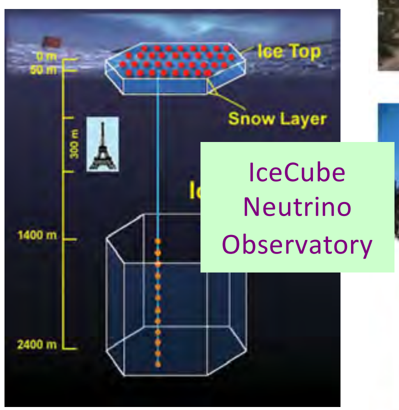
young!

☆ *expanding from Europe & Asia to Africa & America, and Space*

Today's Astronomy Tools

- Conventional "Telescopes" are complemented by a Suite of Detectors for Cosmic Messengers





Radio Astronomy: Historical Developments

- First discovery of cosmic radio waves ~1930
  - ☆ Karl G. Jansky
    - ☞ Bell Labs / Oklahoma → Sgr A* radio emission (1933)
- Pioneering years (up to ~1950ies)
    - ☞ Grote Reber: amateur radio receiver → sky survey
    - ☞ James Stanley Hey, George Clark Southworth → solar radio emission
    - ☞ Radio observation group at Cambridge university: John A. Ratcliffe: → Mullard Radio Observatory (MRAO); Martin Ryle, Anthony Hewish: Cavendish Lab. (50ies) → Nobel Prize 1974
- Technological Advances and Current Status
  - ☆ Steerable Antennae
  - ☆ Interferometry
    - → VLA 1980+
    - → ALMA 2011+
    - → SKA 2018+

X-ray Astronomy: Historical Developments

- Early and Pioneering Stages
  - ☆ Rocket flights (~1960ies) → discovery of cosmic X-rays
  - ☆ UHURU/SAS-I (1970-73): First orbiting satellite with an X-ray telescope → First source catalogue 4U with 339 sources
  - ☆ Einstein satellite (1978-81): first deep imaging and spectroscopy

- Recent & Current Space Facilities
  - ☆ ROSAT (1990-1999): all-sky survey, 0.1-2 keV
  - ☆ XMM-Newton (1998-current): imaging and spectroscopy, 0.15-15 keV
  - ☆ Chandra (1999-current): fine imaging and spectroscopy, 0.2-10 keV
  - ☆ ASCA (1993-2001): X-ray survey, 0.1-12 keV
  - ☆ Suzaku (2005-2015): (High resolution spectroscopy), 0.2-600 keV
  - ☆ Swift (2004-current): Gamma-ray bursts, X-ray transients, AGN, 0.3-150 keV
  - ☆ Astrosat (2015-current): X-ray transients/binaries, AGN, SNRs,…; 3-80 keV
  - ☆ HXMT (2017-current): X-ray transients/binaries, AGN, SNRs,…; 20-200 keV

Gamma-ray Astronomy: Historical Developments

Early and Pioneering Stages

- ☆ Balloon detectors (Rice/Haymes 1964) → discovery cosmic γ-rays
- ☆ OSO, SAS, COS-B (1970ies-80ies): First gamma ray sky info
- ☆ HEAO-3 (1978/79): First radioactivity lines, 26Al
- ☆ SMM (1985): Solar gamma-ray flares; SN1987A lines

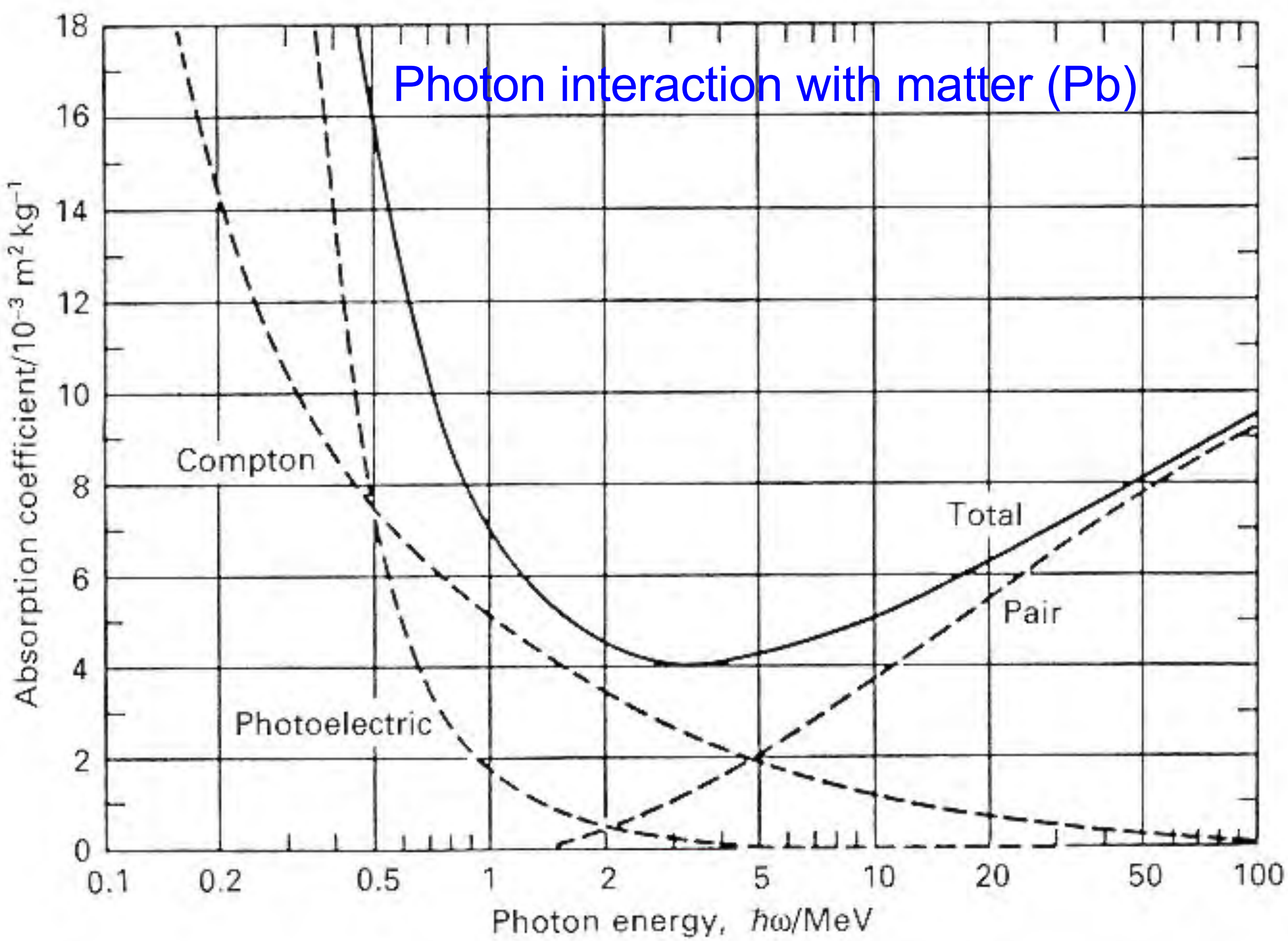
Recent / Current Space Facilities

- ☆ Compton Gamma-Ray Observatory (1991-2000): all sky survey 1-30 MeV
- ☆ INTEGRAL (2002-current): Imager & line spectroscopy 0.01-8 MeV
- ☆ FERMI (2006-current): High energy sky, 100 MeV – 30 GeV

Recent / Current Ground Facilities

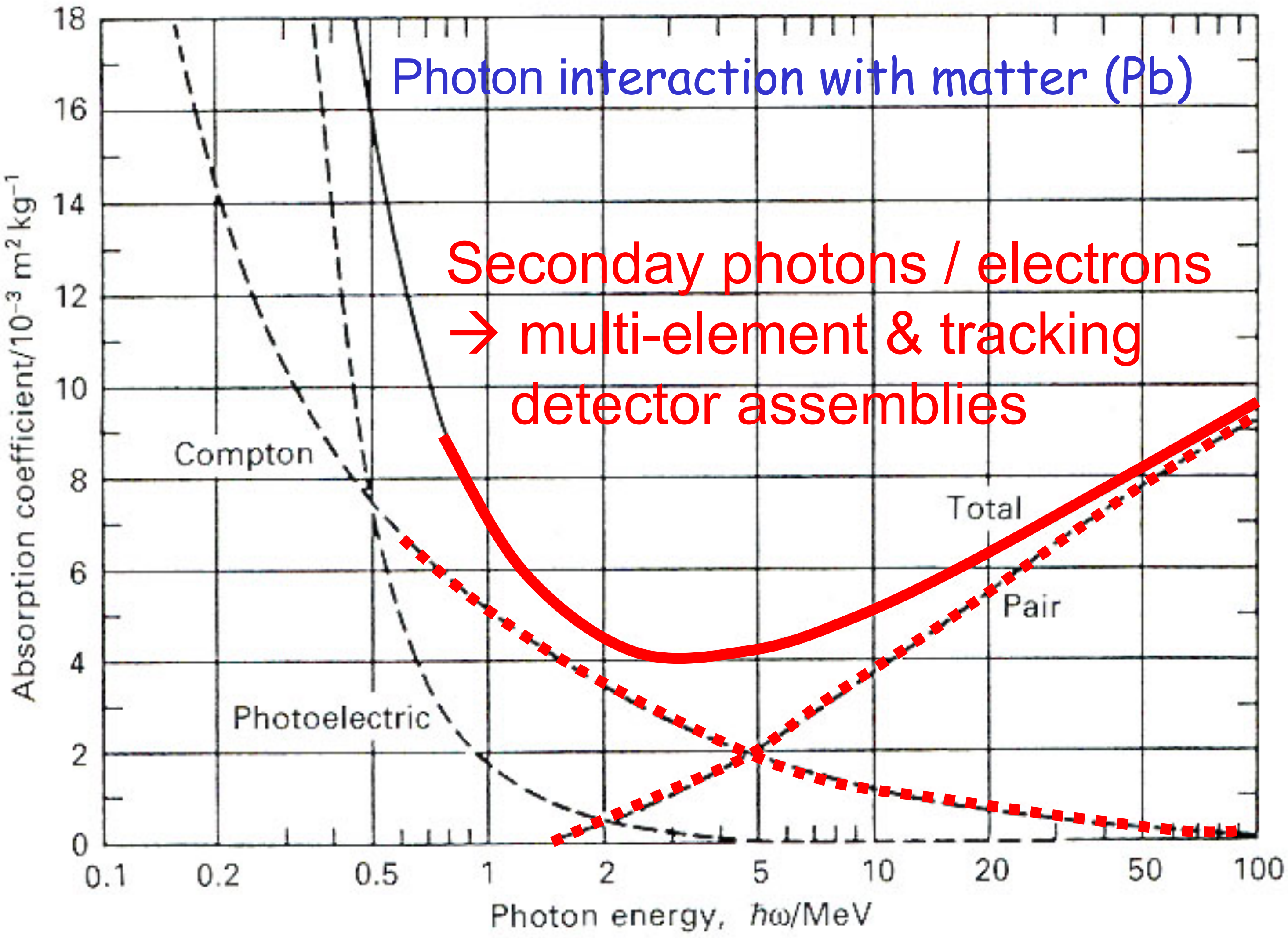
- ☆ MAGIC (2004 – current): 0.5–30 TeV observations
- ☆ H.E.S.S. (2003 – current): 0.1–10 TeV high imaging resolution

Interaction of high-energy photons with matter



Gamma-Ray Astronomical Telescopes:

Interaction of high-energy photons with matter



→ Secondary Particles … → e.m. cascade

Current Nuclear Gamma-Ray Line Telescopes

INTEGRAL

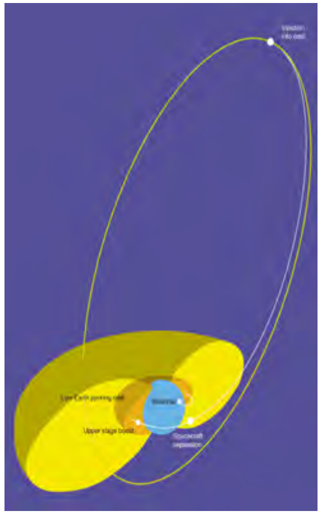
2002-(2021+..2029)

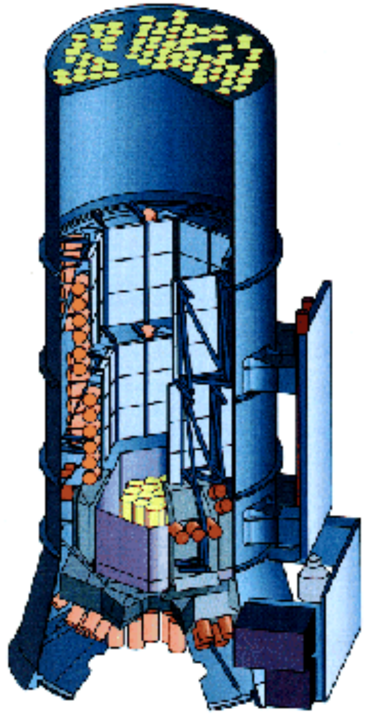
ESA

high E resolution

Ge detectors

15-8000 keV





NuSTAR (<80 keV!)

2012-(2020+) …

NASA

hard X ray

imaging <80 keV

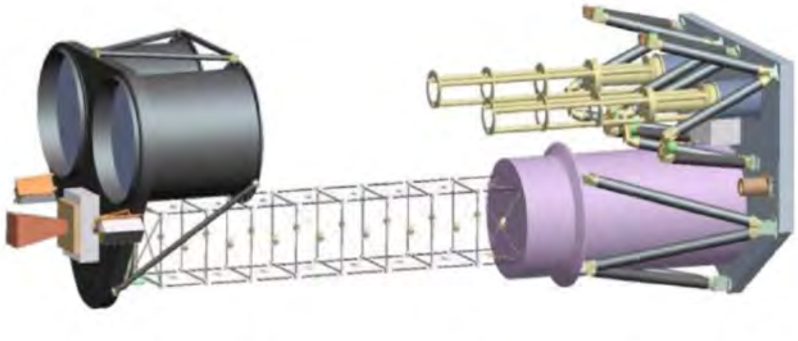


Fig. 1. NuSTAR telescopes in deployed configuration

Detectors in Gamma-Ray Astrophysics

High Sensitivity

HESS, MAGIC, CANGAROO, VERITAS

Energy Range .05-50 TeV
Area > 10^4 m^2
Background Rejection > 99%
Angular Resolution 0.05°
Aperture 0.003 sr
Duty Cycle 10%

High Resolution Energy Spectra
Studies of known sources
Surveys of limited regions of sky

Low Energy Threshold

EGRET/GLAST

Energy Range 0.1-100 GeV
Area: 1 m^2
Background Free
Angular Resolution 0.1° - 0.3°
Aperture 2.4 sr
Duty Cycle > 90%

Unbiased Sky Survey (<100 GeV)
Extended Sources
Transients (AGN, GRBs) <100 GeV
Simultaneous ν Observations

Large Aperture/High Duty Cycle

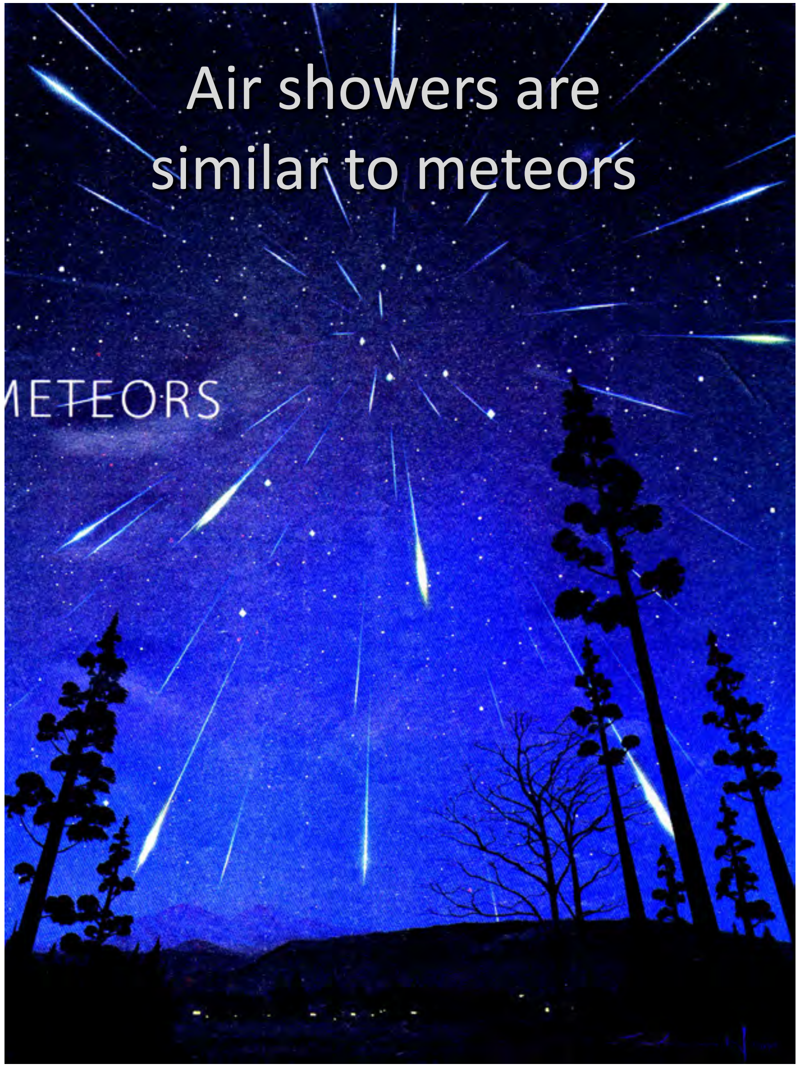
Milagro, Tibet, ARGO, HAWC

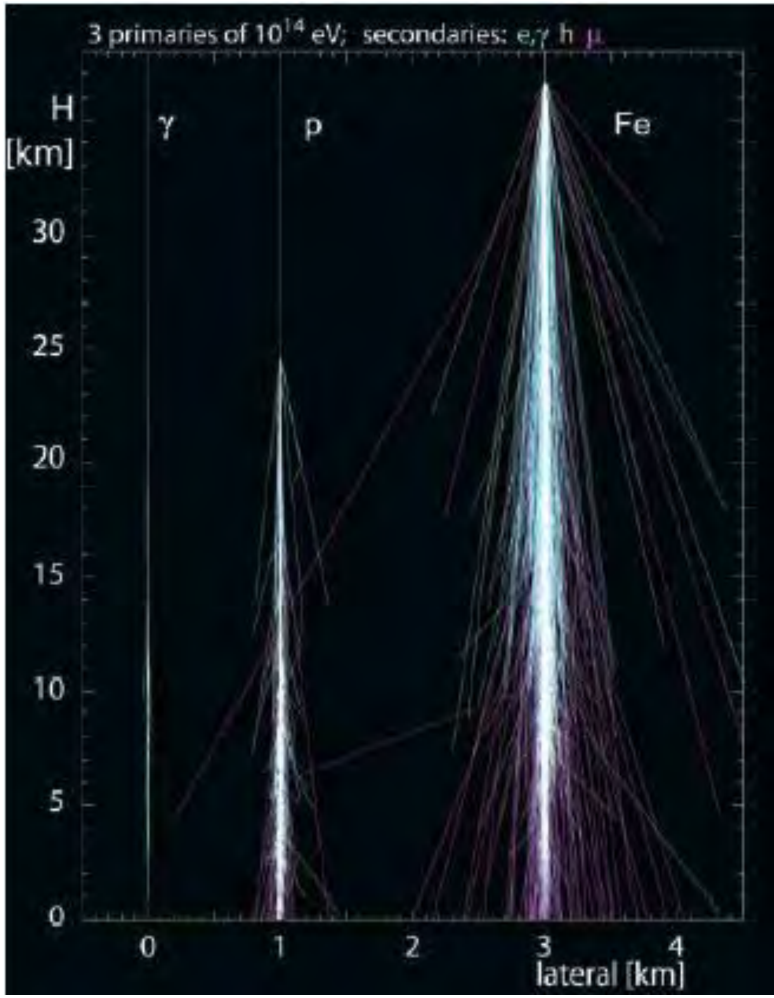
Energy Range 0.1-100 TeV
Area > 10^4 m^2
Background Rejection > 95%
Angular Resolution 0.3° - 0.7°
Aperture > 2 sr
Duty Cycle > 90%

Unbiased Sky Survey
Extended Sources
Transients (GRB's)
Simultaneous ν Observations

Earth's atmosphere as a detector:

→ What is measured?





- appearance of shower
  - ➢ primary particle (photon or hadron)
- penetration depth
  - ➢ heavy or light particle
- particles detected on ground
  - ➢ e.g. mass estimate (from ratio of myon to electon number)

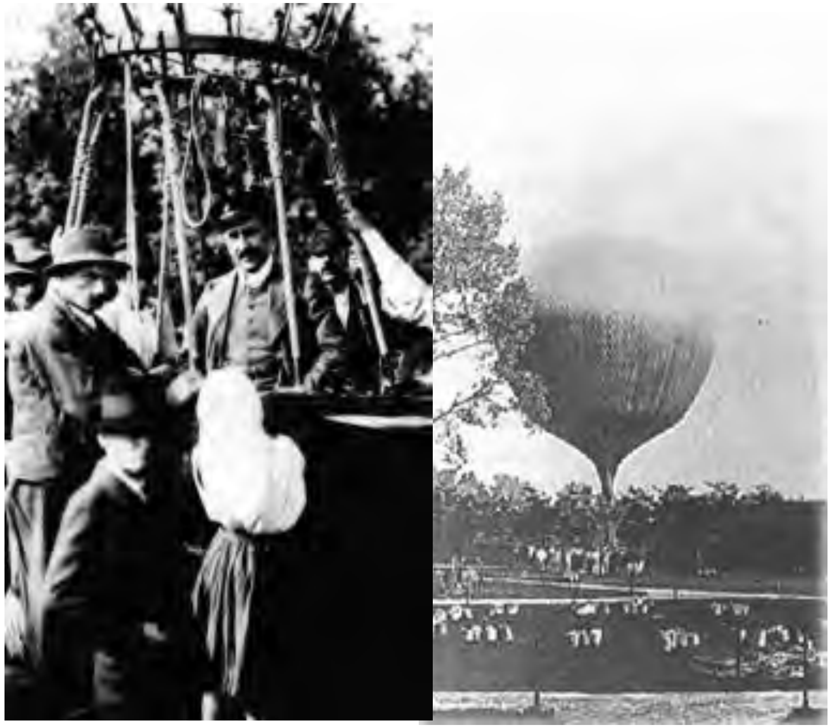
Cosmic Rays

Discovery 1912 - VICTOR HESS (Nobel Prize 1936)

- Balloon flights as part of exploring the earth atmosphere and air travel
  → Measurement of the ''Höhenstrahlung'' with an ionisation chamber

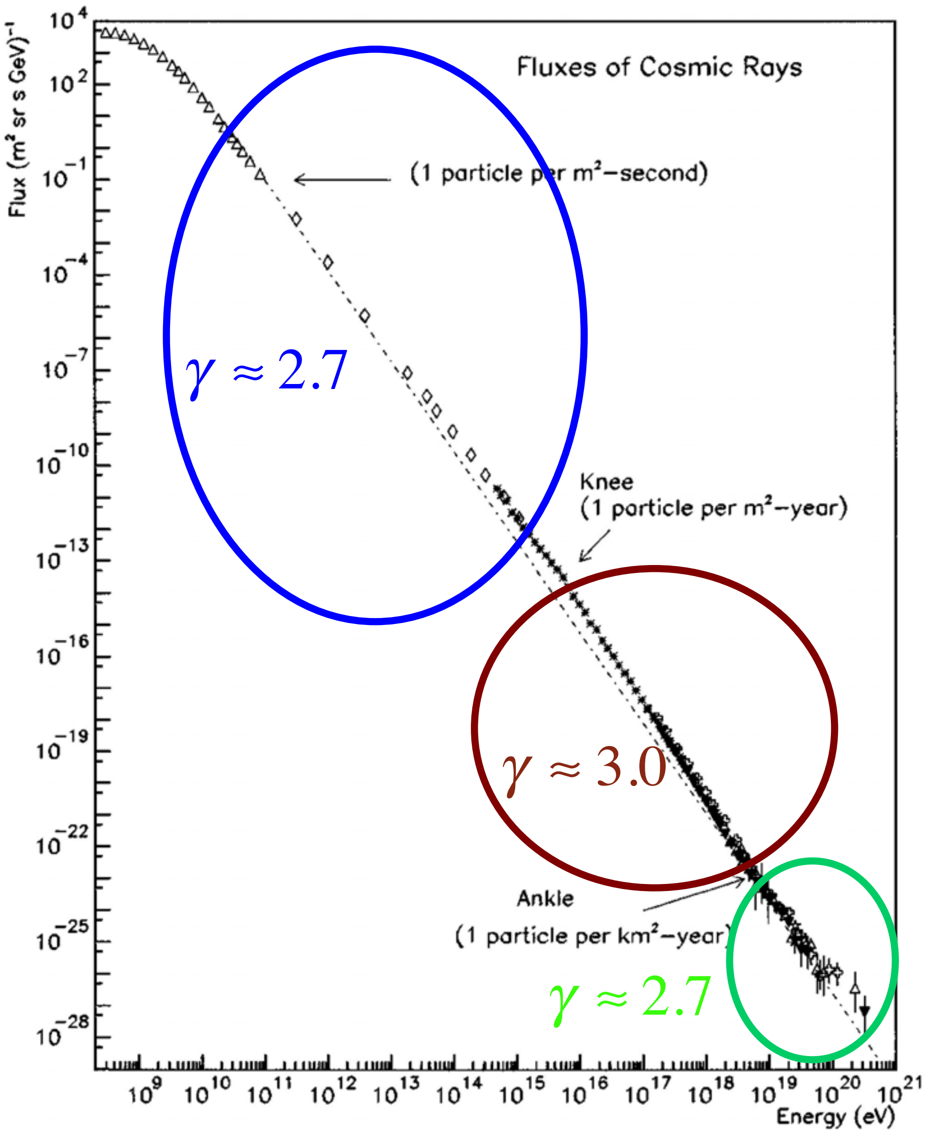
- Results:

  - up to 2000 m: a small decrease of ionisation (soil radioactivity)
  - but then, above: dramatic increase (Hess reached a maximum height of 5300 m)



- **Confirmation of extraterrestrial origin of such a "cosmic radiation"**

The energy spectrum of cosmic rays



- CRs are observed across a wide energy range from 10^6 eV up to 10^{21} eV
- Intensity falls rapidly with increasing energy:

$$\frac{dN}{dE} \propto E^{-\gamma}$$

"power law"

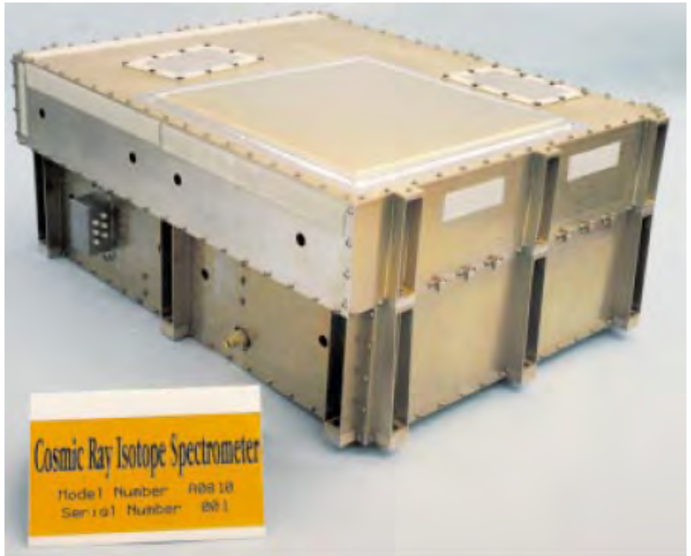
Characteristic changes in the spectrum:

- "Knee":
  1. Galactic magnetic field can keep only particles which Lamor radius is smaller or similar to dimension of Milky Way
     - > 10^{15} eV particles leave Milky Way
  2. Maximum acceleration in supernovae

- "Ankle":
  contribution of extragalactic origin

ACE/CRIS: Isotopes in Cosmic Rays

- ☆ High-Resolution Mass Spectrometry



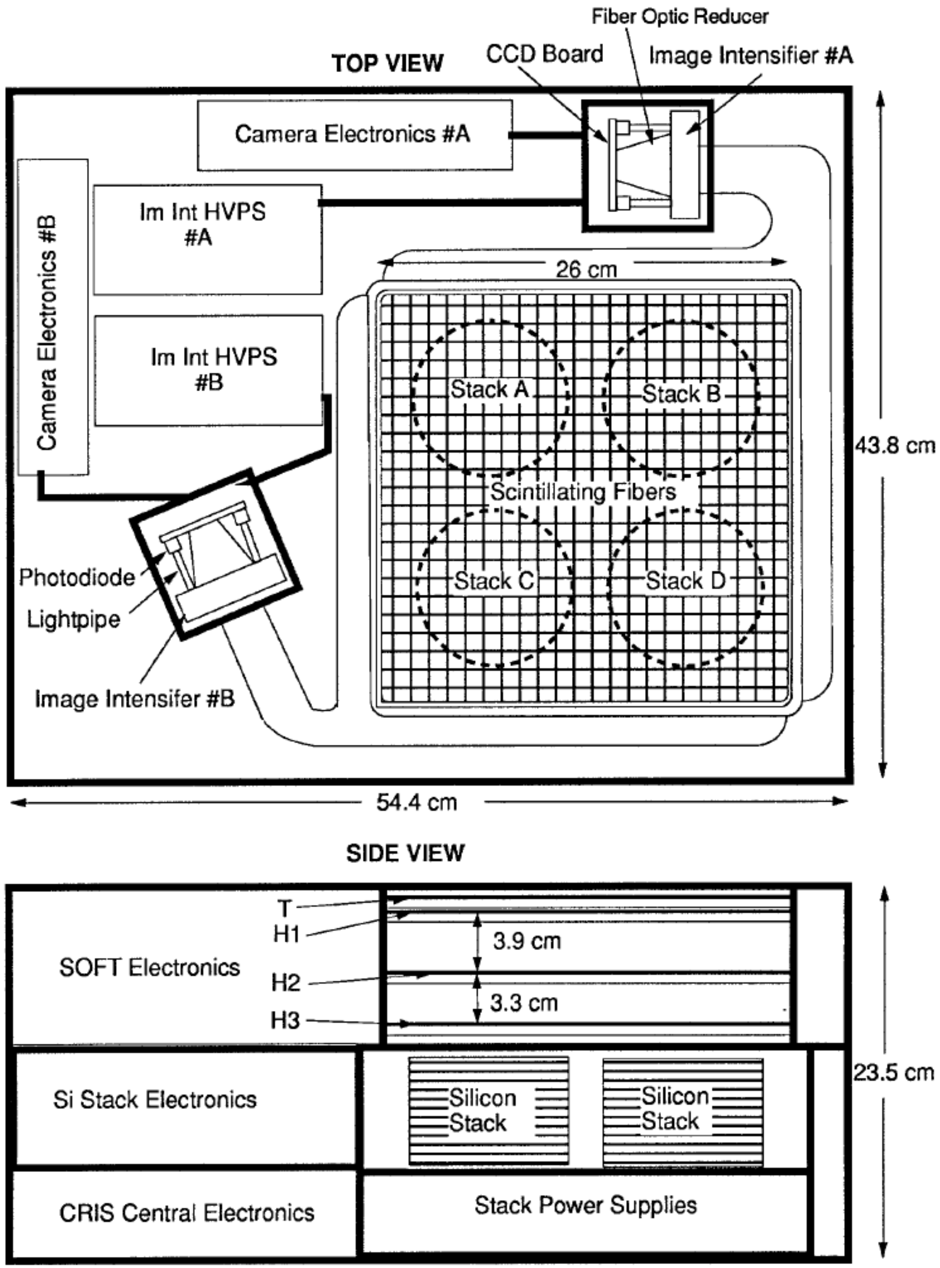


Figure 6. CRIS instrument cross section. The side view shows the fiber hodoscope which consists of three hodoscope planes (H1, H2, H3) and one trigger plane (T) which are located above the four stacks of silicon detectors. The top view shows the fiber readout which consists of two image intensified CCDs at either end of the fibers and the four stacks of silicon detectors.

Applications: Isotopes in CR's

- ☆ Spallation Reactions along Cosmic-Ray Trajectories Produce Secondary Isotopes
  - ☞ Include New Radioactive Isotopes
- ☆ Cross Sections of Nuclear Spallation Reactions are Well-Known
  - ☞ Can be Measured in Accelerators
  - ☞ High-Energy Situation is 'easy'
- ☆ Abundances of Radioactive Species Encode the Path Length of the CR Trajectory
  - ☞ Deconvolve Energy Spectra
  - ☞ Compare Different Isotopes' Results

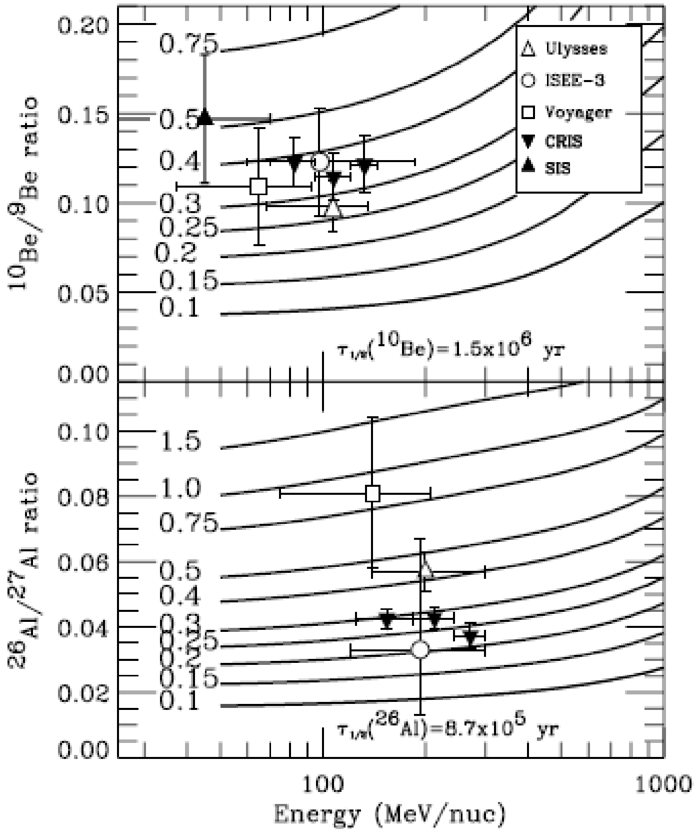
Radioactive nuclides

Nuclide	Decay Mode	Partial Half life[a]
^{7}Be	ec	53 days
^{10}Be	β^-	1.5 Myr
^{14}C	β^-	5730 yr
^{26}Al	β^+	0.87 Myr
	ec	4.0 Myr
^{36}Cl	β^-	0.30 Myr
^{37}Ar	ec	35 days
^{41}Ca	ec	0.10 Myr
^{44}Ti	ec	49 yr
^{49}V	ec	330 days
^{51}Cr	ec	28 days
^{53}Mn	ec	3.7 Myr
^{54}Mn	ec	312 days
	β^+	400 Myr
	β^-	0.8 Myr[b]
^{55}Fe	ec	2.7 yr
^{56}Ni	ec	6.1 days
^{56}Ni	β^+	$\gtrsim$ 1 yr
^{57}Co	ec	270 days
^{59}Ni	ec	76000 yr

[a]Laboratory half lives.
[b]Estimated value (Zaerpoor et al., 1997).

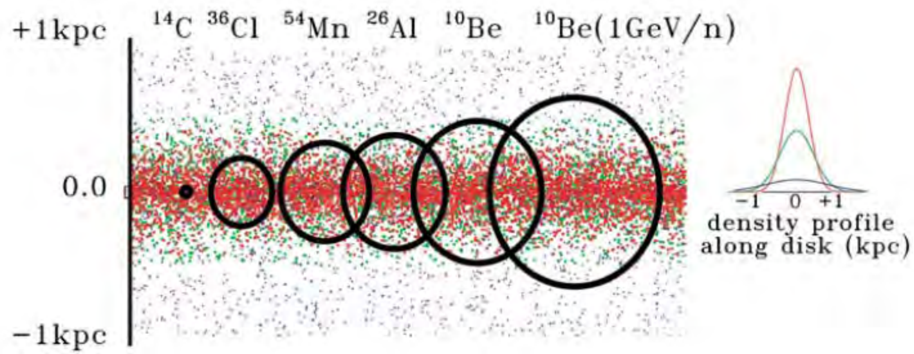
Radioactive Isotopes: Propagation of Cosmic Rays in the Galaxy

- ☆ Spallation reactions produce radioactive isotopes as Cosmic-Rays collide with atomic nuclei in the ambient ISM
- ☆ Spallation cross sections are determined from lab measurements
- ☆ Abundances of unstable isotopes → CR path length in Galaxy
  - ☞ Compare isotope ratios to 'leaky-box' models for CR propagation:



→ Density of Confinement Region [H atoms cm^{-3}]

Size of Galactic-disk region 'sampled' by different isotopes:

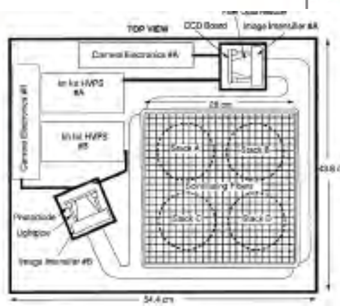


Roland Diehl

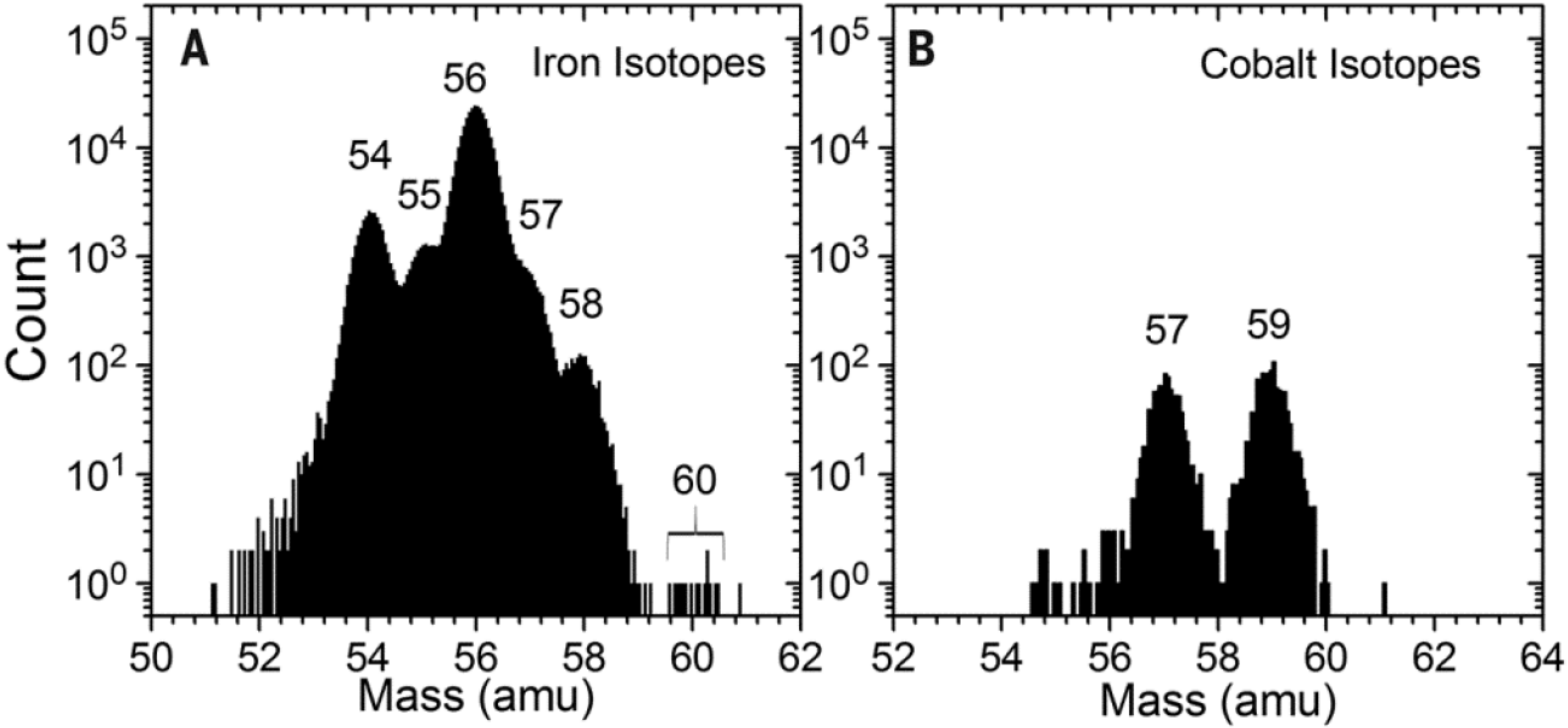
^{60}Fe in Local Galactic Cosmic Rays

- Direct sampling of GCRs with ACE/CRIS
- ^{60}Fe cannot come from spallation!

High-Resolution Mass Spectrometry



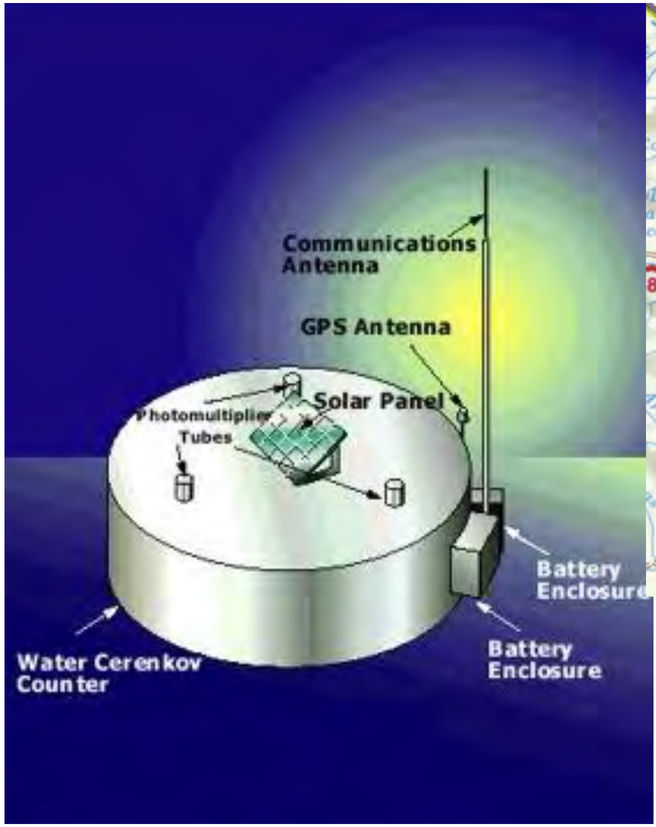
Israel+ 2016; Binns+ 2016

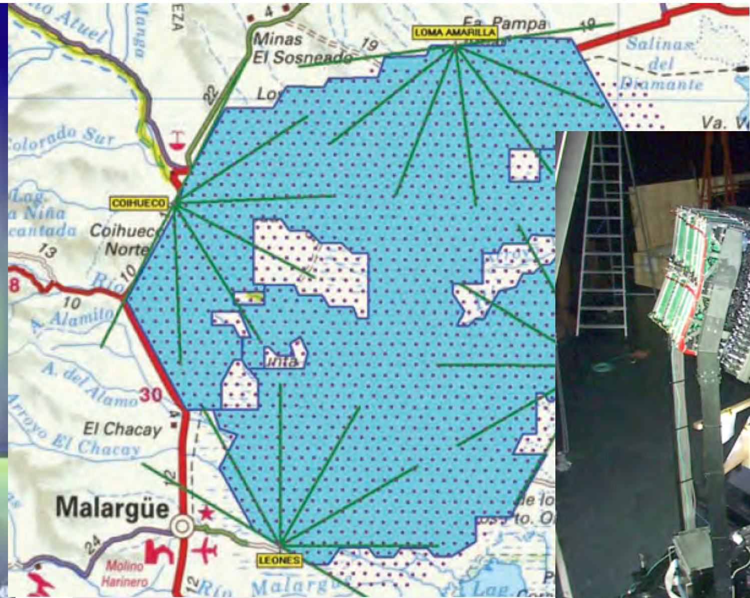


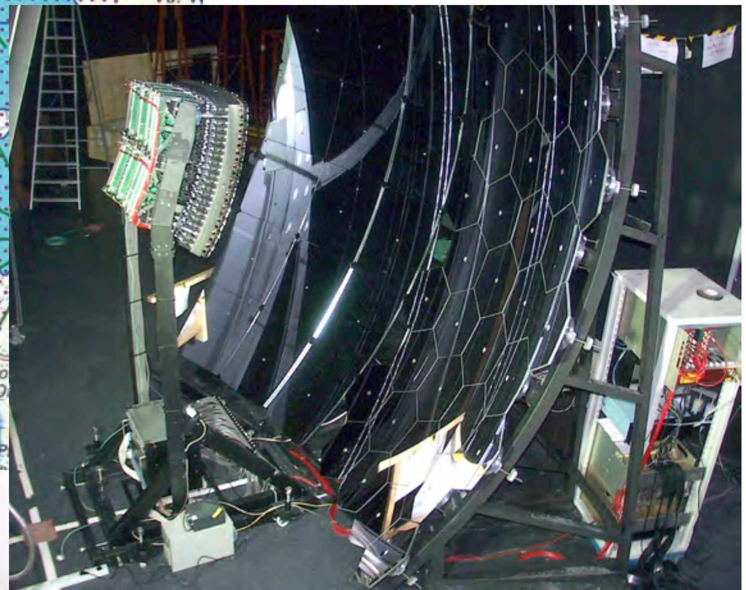
Cosmic Rays: PIERRE AUGER – MENDOZA (ARGENTINIA)

1600 Water-Čerenkov-detectors, distributed over area of 3000 km^2

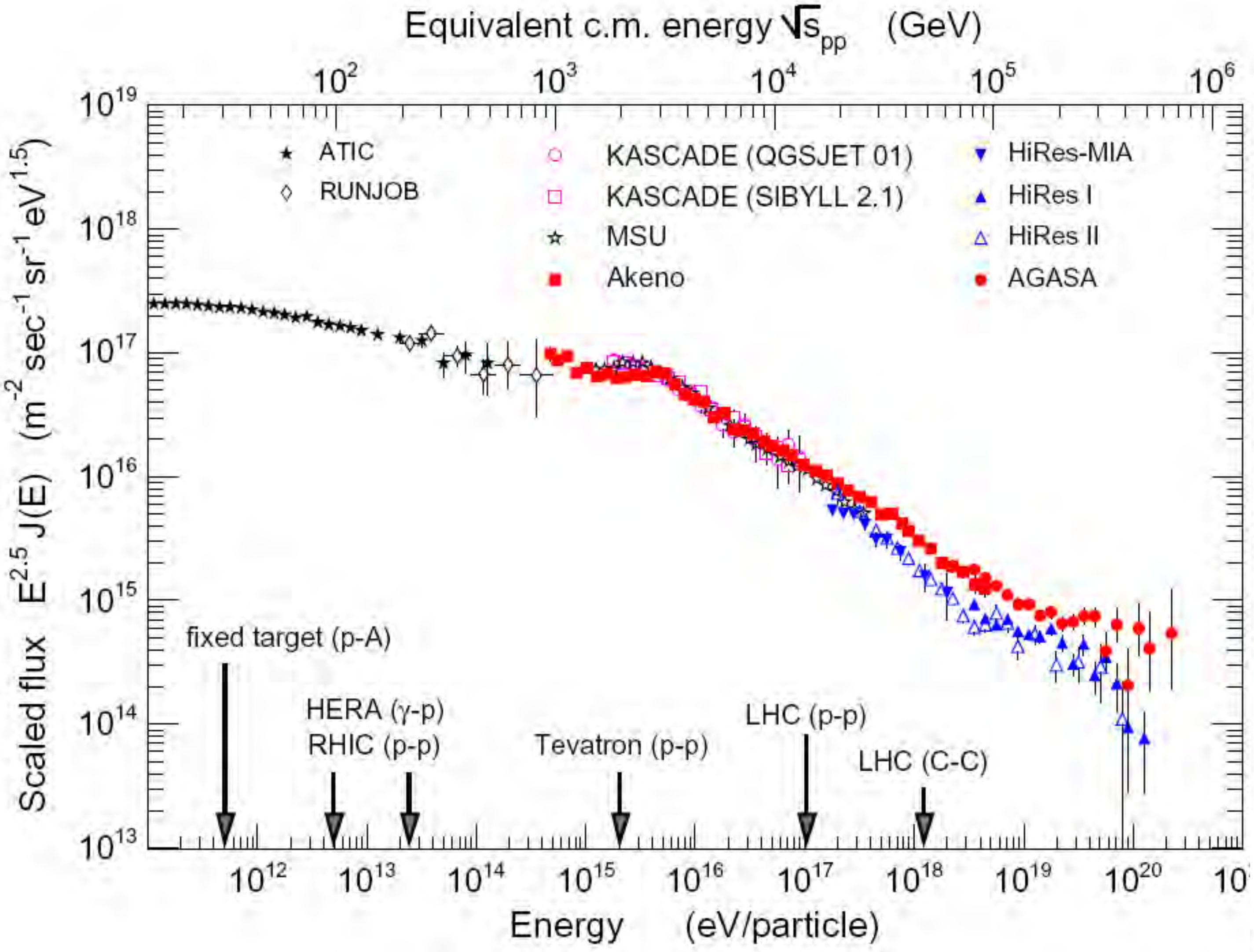
One of 4 fluorescence light detectors (in total 30 telescopes)





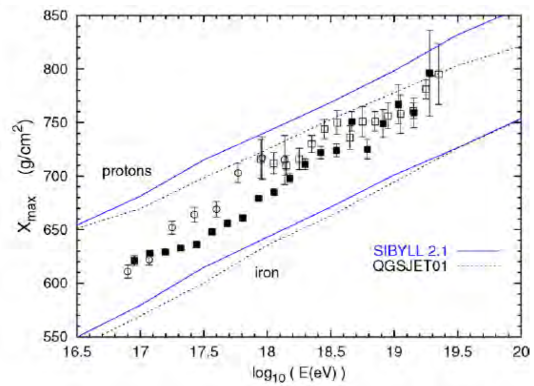


Highest-Energy Cosmic Rays



☆ Transition from Galactic to Extragalactic Origin?

☆ GKZ Cut-off? (Absorption by IC on CMB)



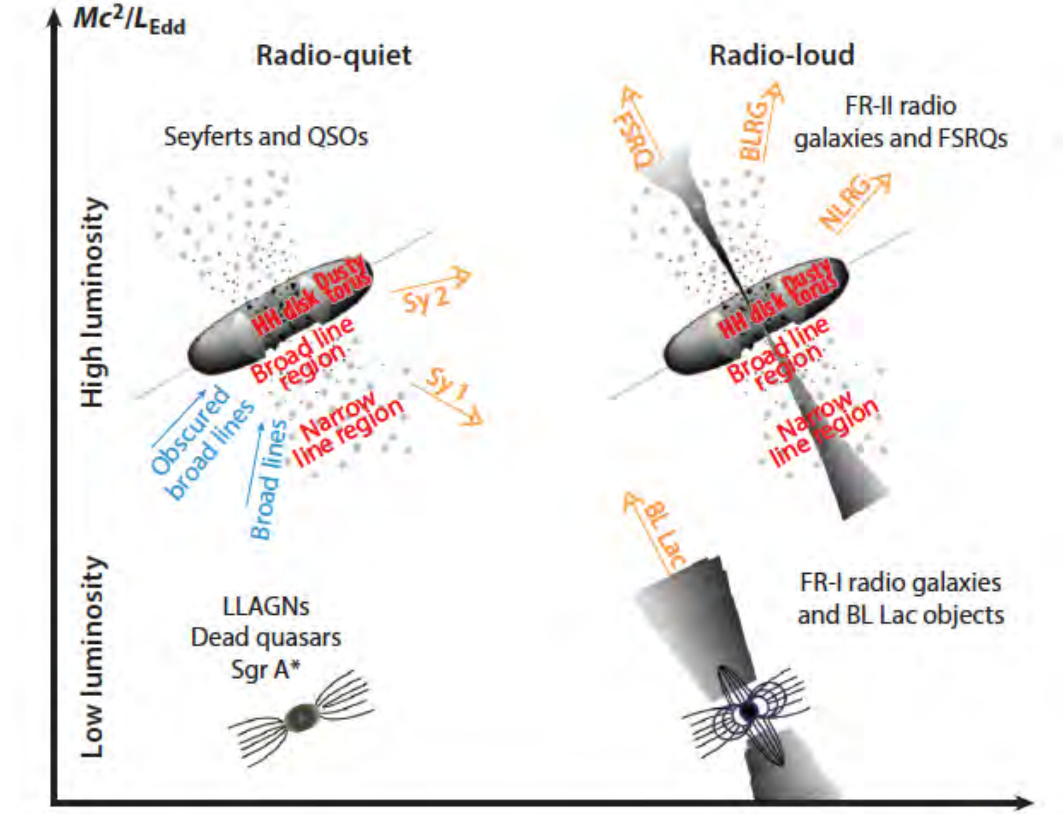
☆ Around ~10^{18} eV, the composition changes from heavy-nuclei-dominated to (pure) protons

☞ (from shower properties)

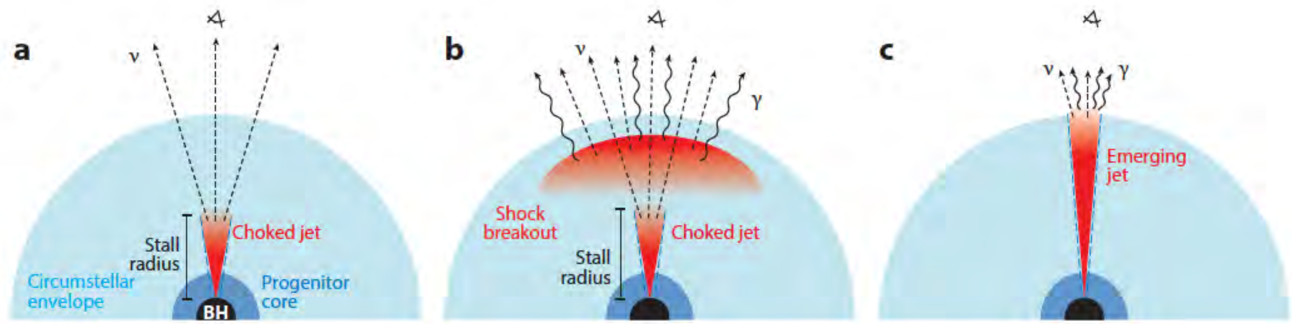
AGN as Highest-Energy Particle Accelerators

Power: ← Accretion onto black holes

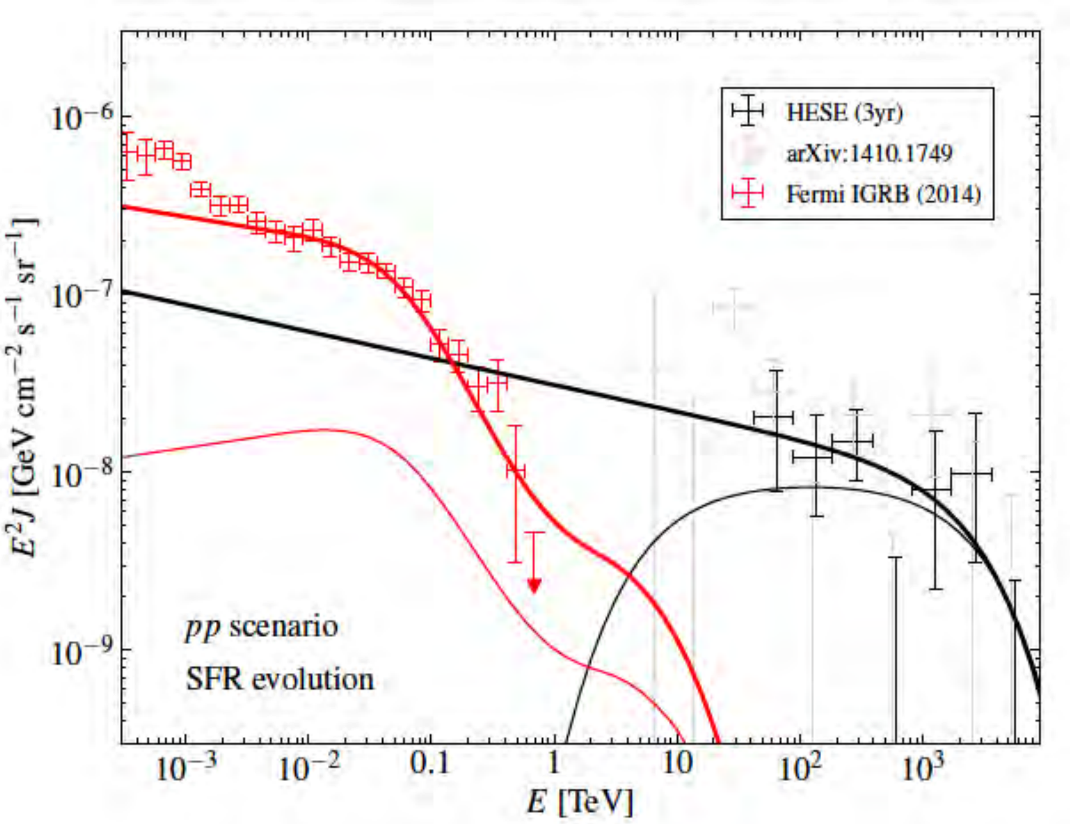
- AGN?



- GRB Jets?

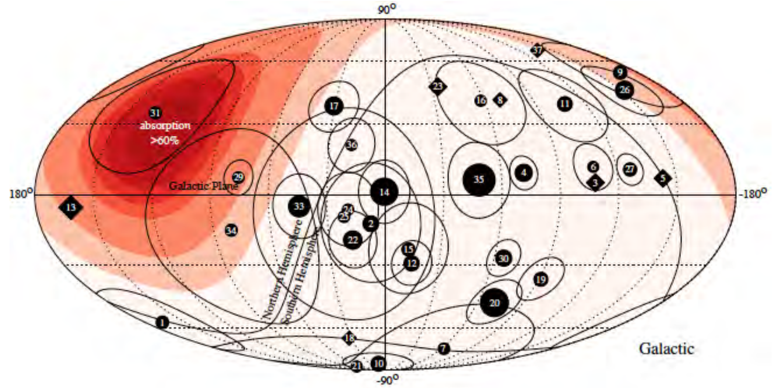


Neutrino Discovery from Cosmic Sources



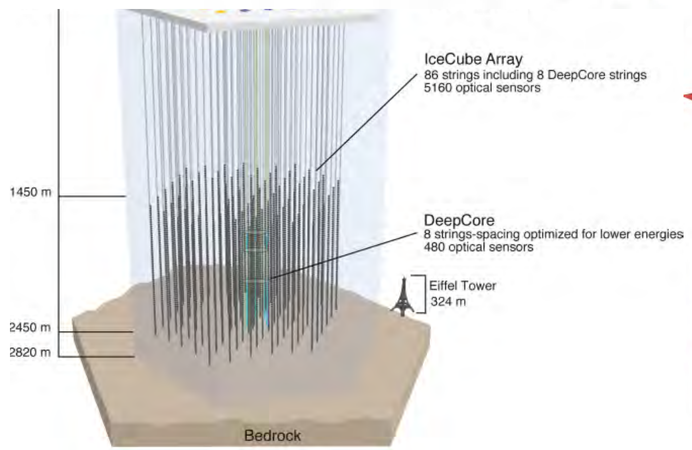
IceCube 2015

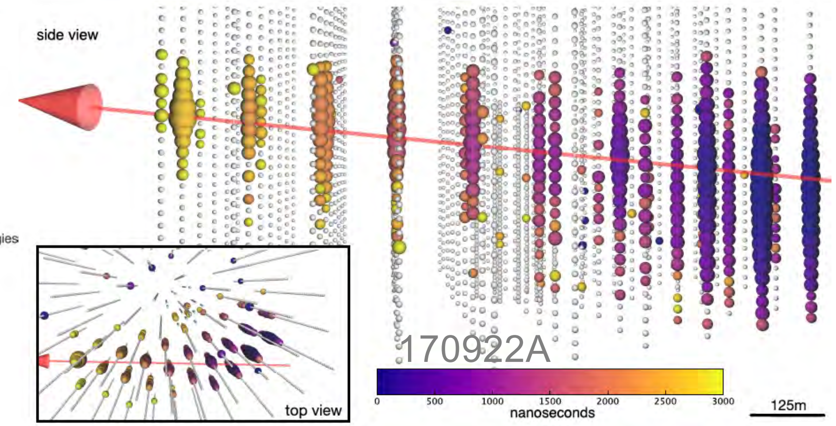
- Excess at highest energies
- Wide scatter of arrival directions

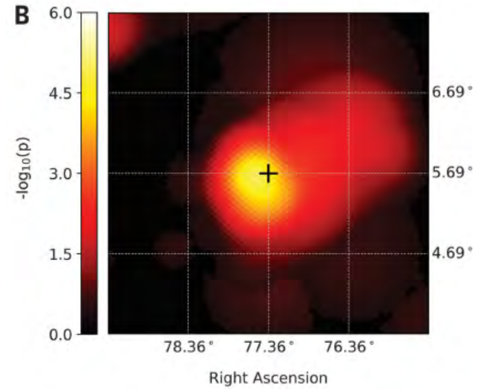


- Source unclear: a Blazar?
  - TXS 0506+056

    (IceCube Collab, 2018)

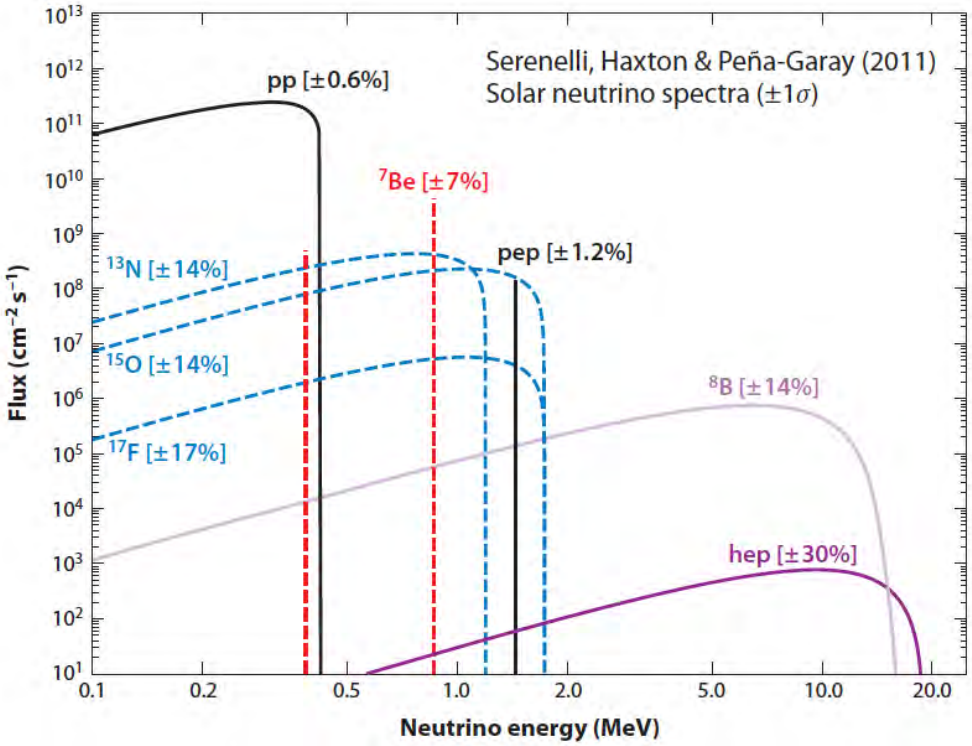




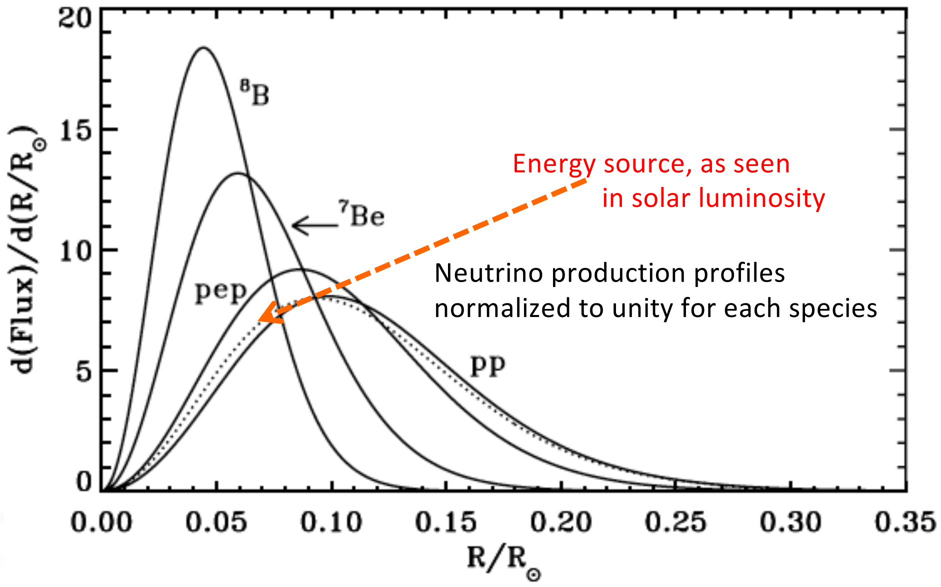


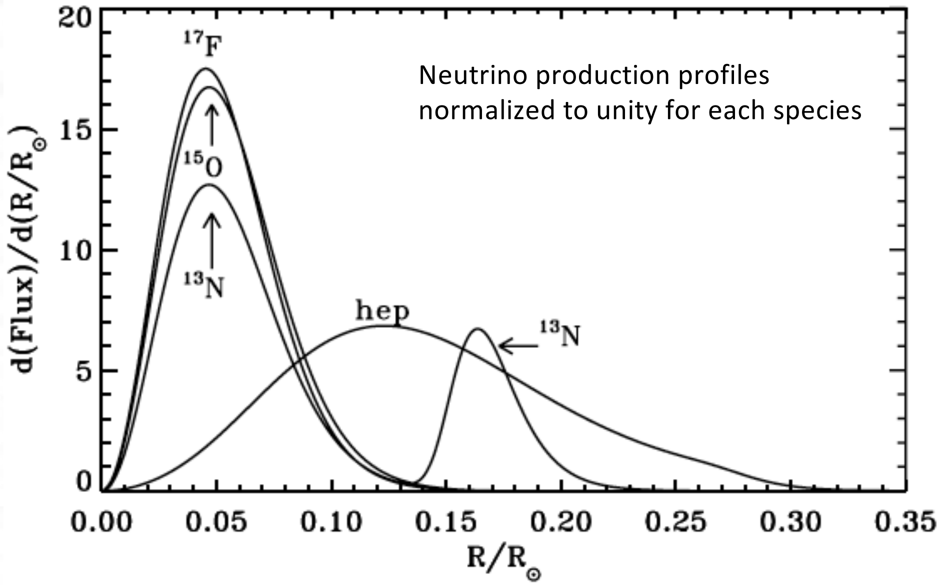
Modeling our Sun

- Core hydrogen burning, hydrostatic equilibrium
- Parameters:
  - Y (He abundance), Z (metallicity)
  - Mixing length α
- Outputs:
  - Luminosity (energy), neutrinos



Bahcall+2006

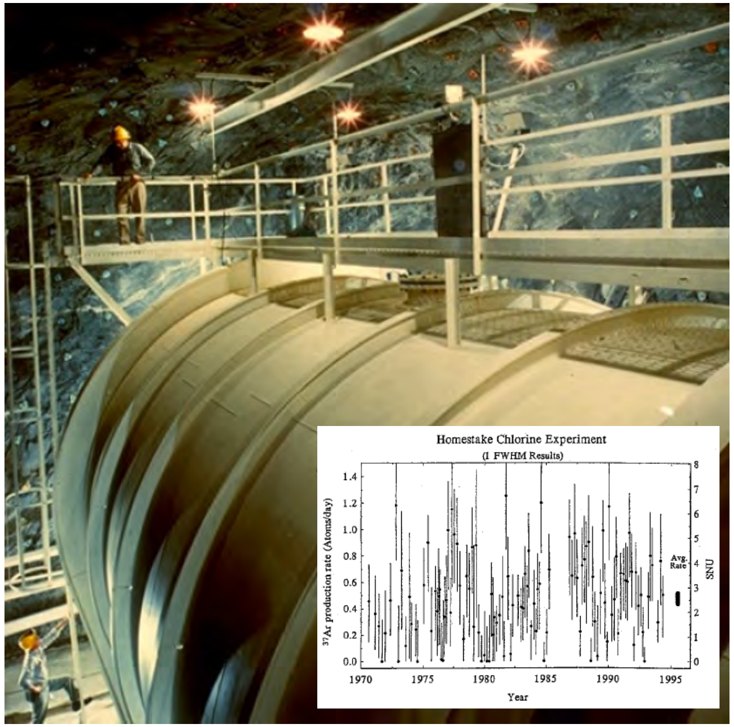




Neutrino production profiles normalized to unity for each species

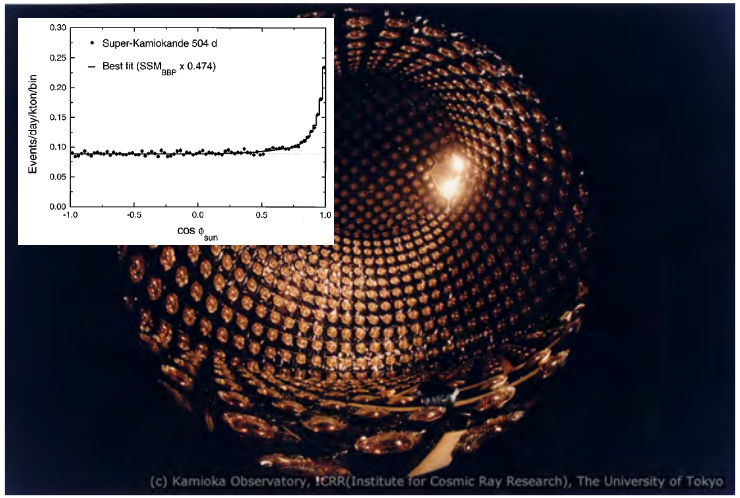
Detecting Low-Energy (~MeV) Neutrinos

- Homestake Gold Mine,
  Dakota: Ray Davis Jr. et al. (1968)
  - ☆ 650 tons C_2Cl_4 → $^{37}\mathrm{Cl} + \nu_e^{solar} \rightarrow {}^{37}\mathrm{Ar} + e^-$
    $^{37}Ar \rightarrow {}^{37}Cl$ decay measurement
    (after 2 days exposure; off line)
    - ☞ n_{obs} ~ 0.3 $n_{predicted}$
      → "solar neutrino problem"
    - ☞ Nobel prize 2002



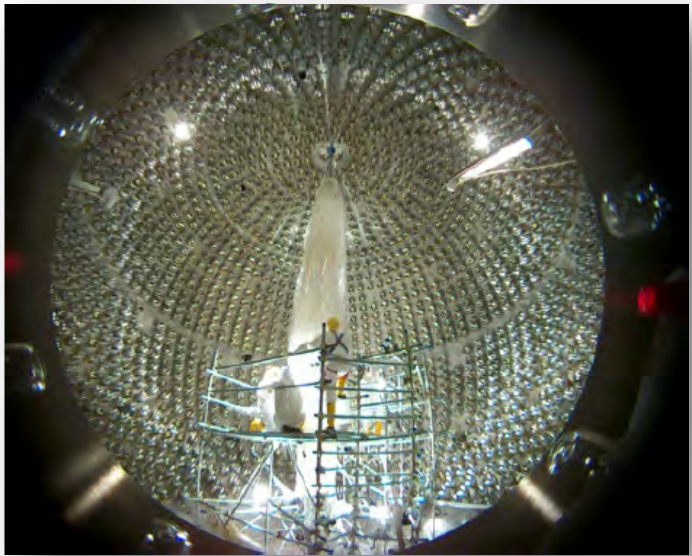
- GALLEX/GNO
  - ☆ ^{71}Ga as ν target material, → $^{71}GeCl_4$

- Kamiokande
  - ☆ event by event measurement
    $\nu_e + e^- \rightarrow \nu'_e + e^{-\prime}$
    Cherenkov radiation measurement

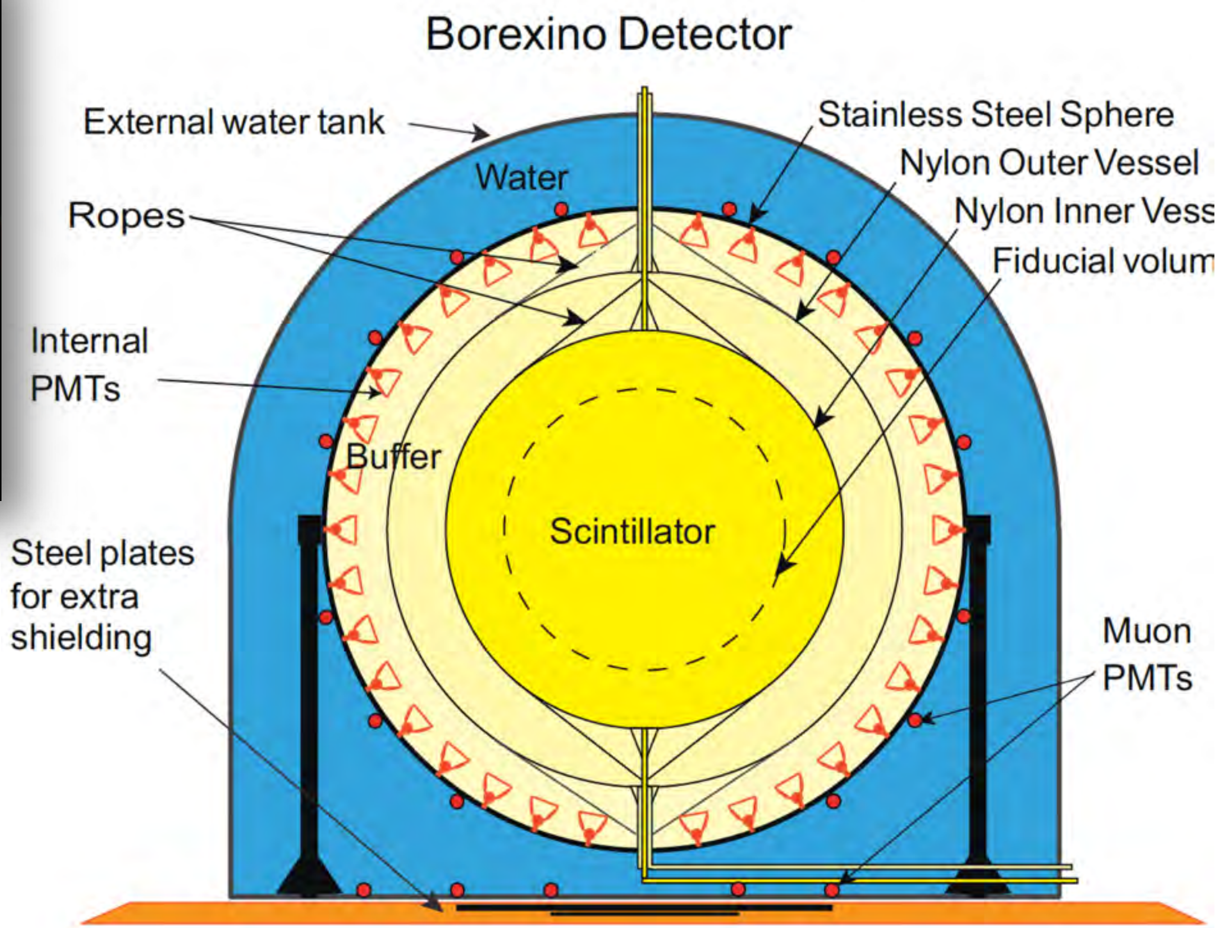


Borexino: lower energy neutrinos (<^{8}B)

- Underground Scintillation Detector in Gran Sasso (LNGS, Italy)



operated since May 2007



☆ Principle:

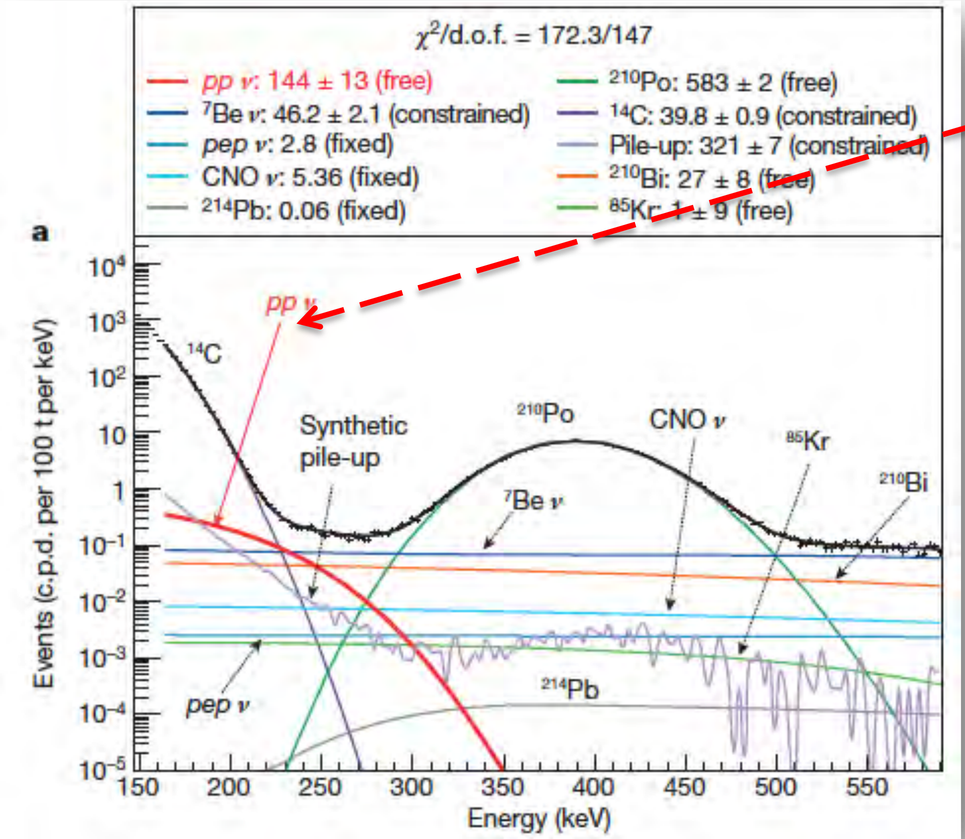
- ☞ search for events without external trigger, creating recoil e-, protons, or C nuclei (detect scintillation)
- ☞ suppress very efficiently other background

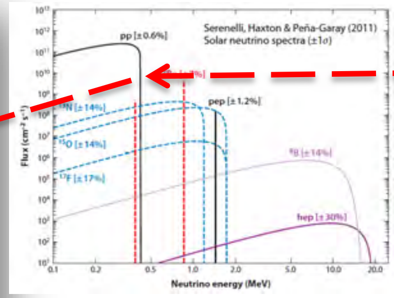
Neutrinos from the Sun

Solar Interior Probe; compare to oscillations, composition, luminosity

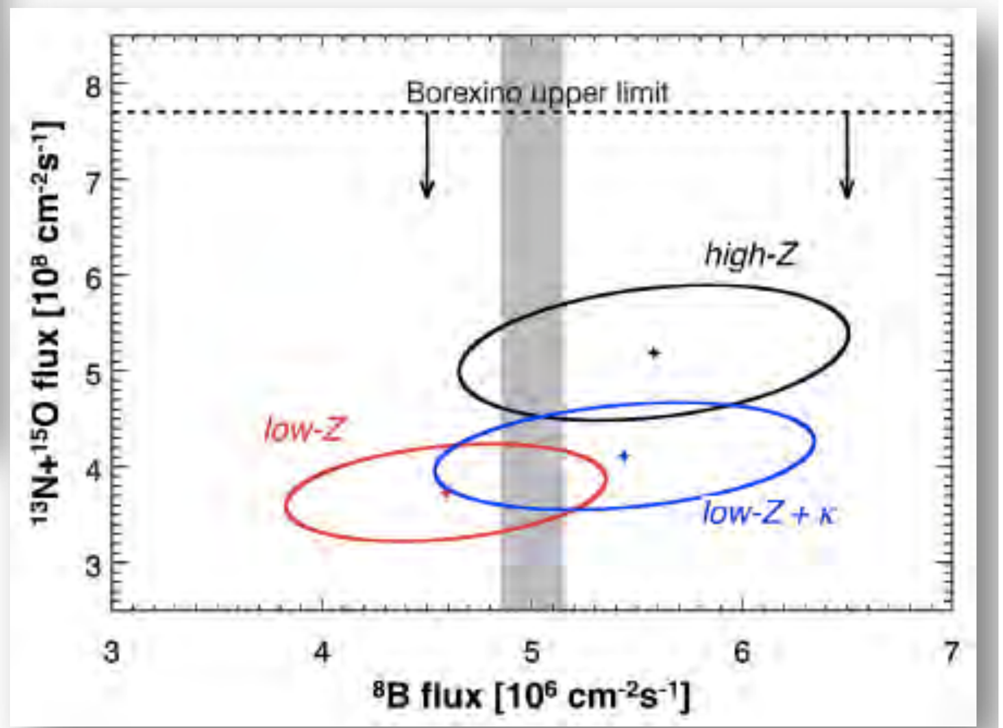
☆ Neutrinos from full pp chain in hydrogen burning now measured (Borexino)

$$p + p \longrightarrow {}^{2}\mathrm{H} + e^{+} + \nu_e$$





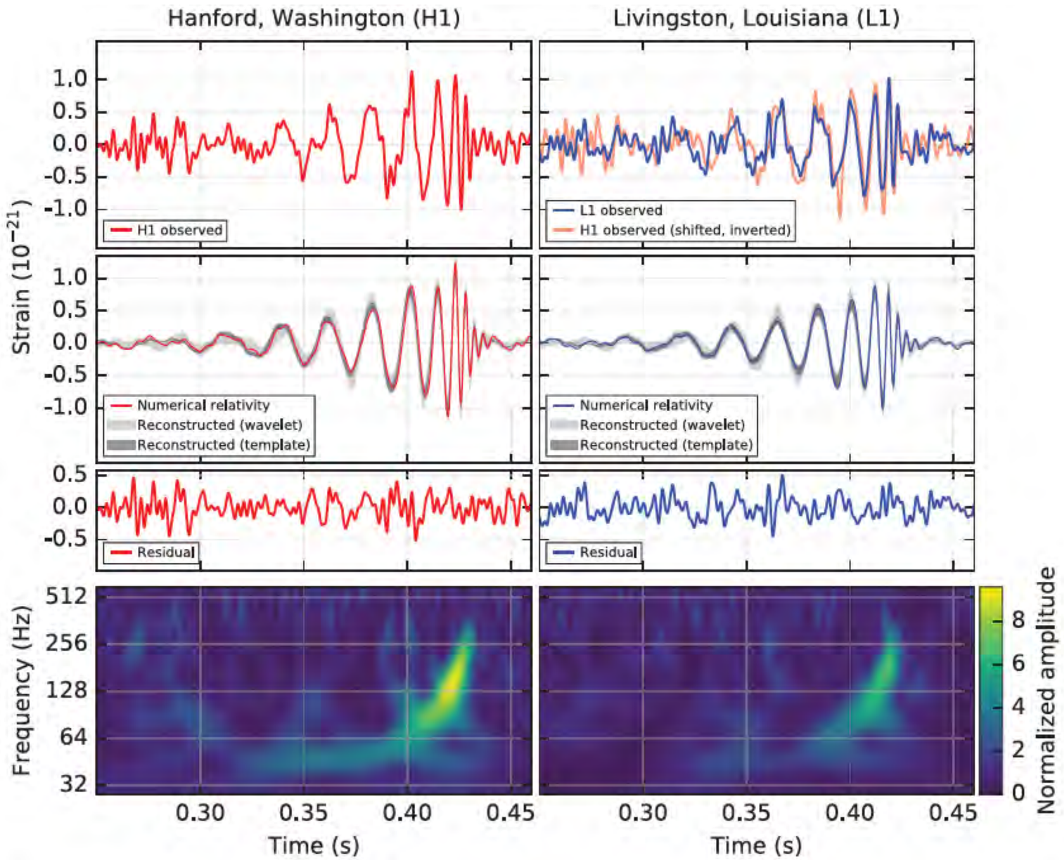
☆ Prospect: Composition constraint from pp versus CNO neutrinos →

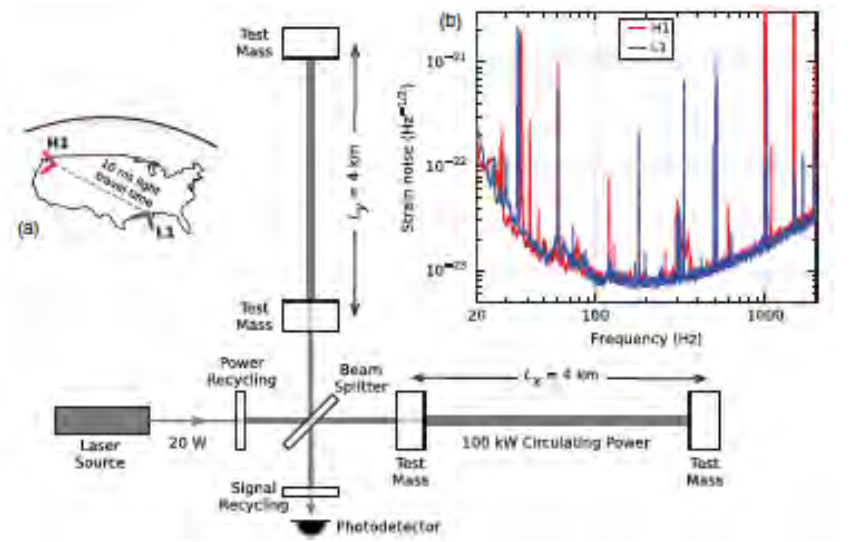


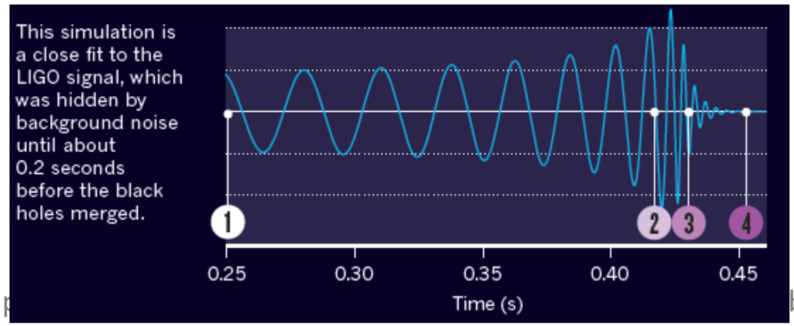
2014+ Astronomy Window: Gravitational Waves

- First source: BH binary merger

☞ *Abbott et al. 2016*



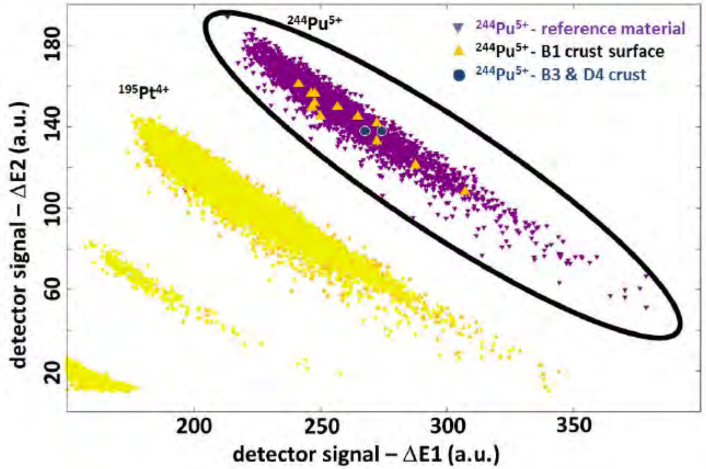


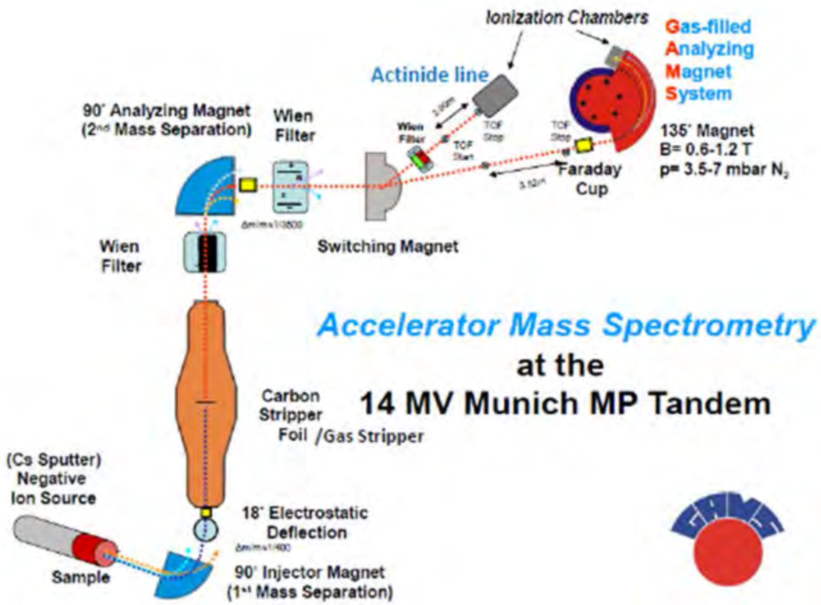


90% credible level). In the detector frame, the chirp mass[1] is $30^{+2}_{-2}\,M_\odot$ and the total mass is $71^{+5}_{-4}\,M_\odot$; the mass ratio is $0.82^{+0.16}_{-0.21}$ and the luminosity distance is determined to be 410^{+160}_{-180} Mpc (redshift $0.09^{+0.03}_{-0.04}$). The two BH masses in the source frame then are $36^{+5}_{-4}\,M_\odot$ and $29^{+4}_{-4}\,M_\odot$, and the chirp mass in the source frame is $28^{+2}_{-2}\,M_\odot$. The source-frame mass and spin of the final BH are $62^{+4}_{-4}\,M_\odot$ and $0.67^{+0.05}_{-0.07}$ and the source is localized to a sky area of 600 deg^2 (see also LVC16d;

r process ejecta on Earth?

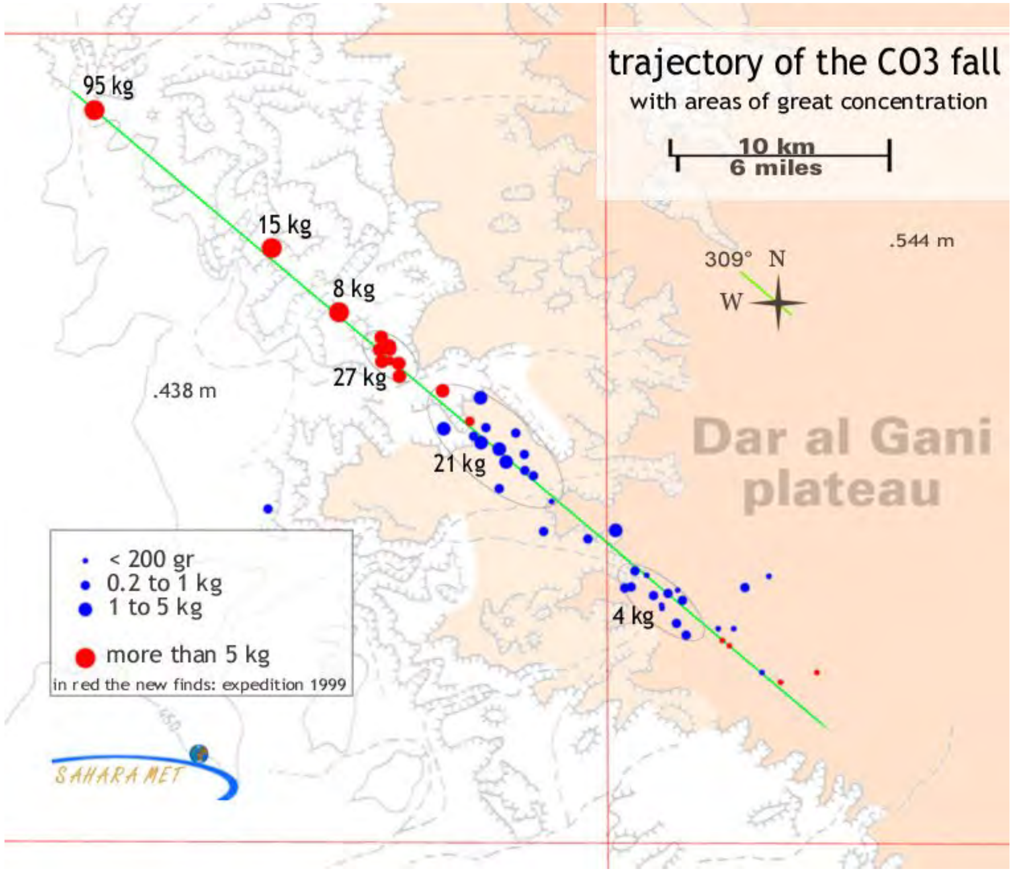
- If r process occurs nowadays → interstellar material should bring this to Earth
  - ☆ search for typical r-process isotopes in deep-ocean sediments with Accelerator Mass Spectroscopy
    - ☞ Precision level ~10^{-15}

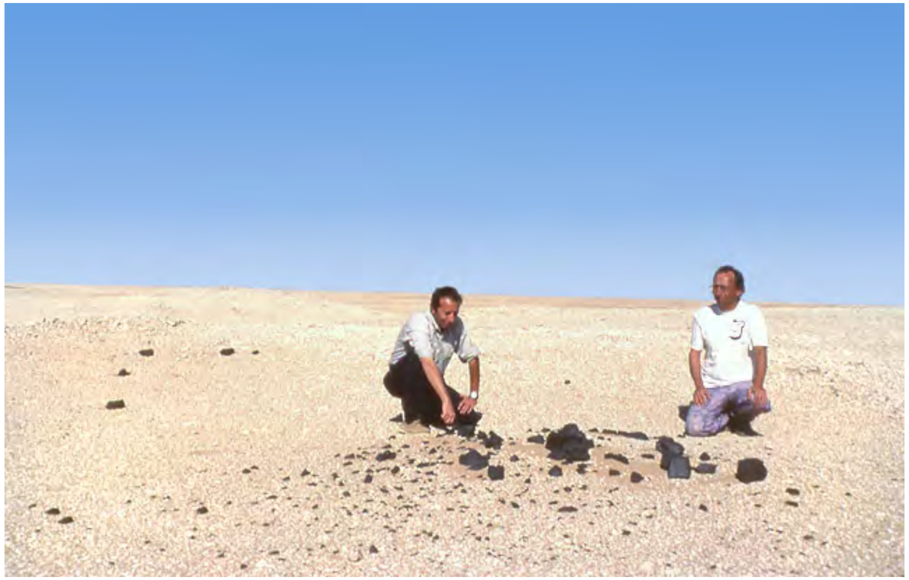




Meteorites

- ☆ "Falls":
  - ☞ Meteorite is Observed While Falling
- ☆ Debris Scattered Over Trajectory

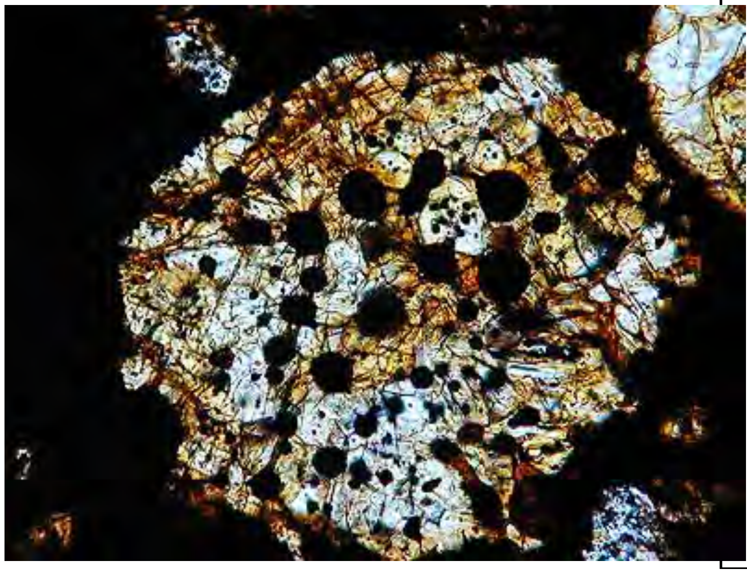


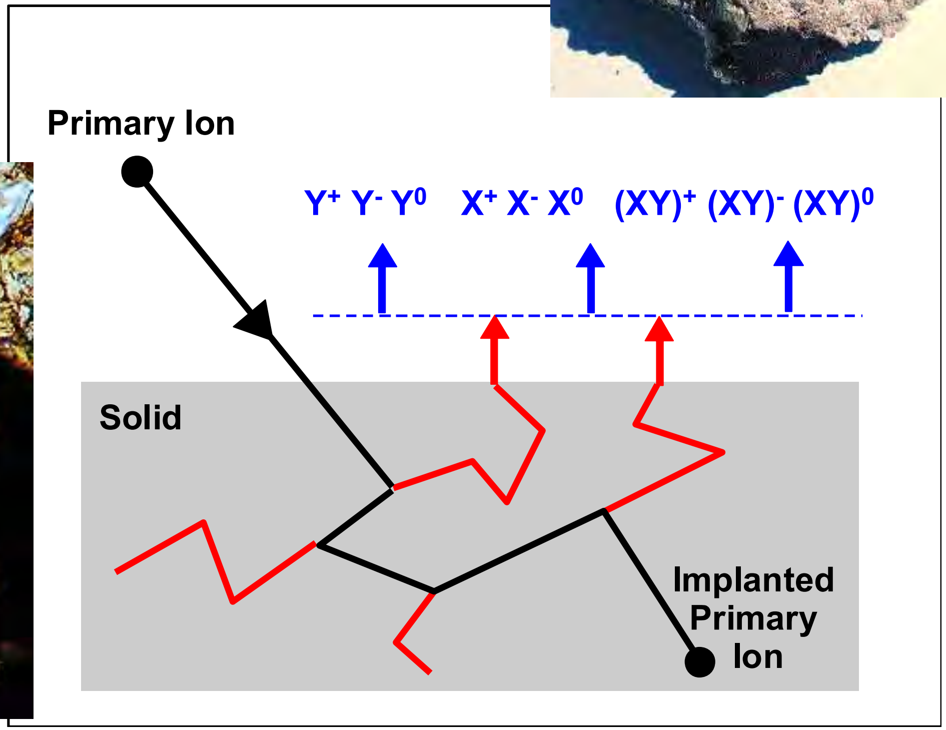


Laboratory Technologies for Isotopic-Composition Analyses

☆ Physical & Chemical Preparation of Meteorite

☞ Dissolve Meteoritic Matrix through Acids
-> Hardest Component (most refractory, oldest)





☆ Secondary-Ion Analysis

☞ Secondary-Ion Mass Spectroscopy

- » nanoSIMS with Ion Microprobes
- » TOF-SIMS
- » Resonant IMS (RIMS)