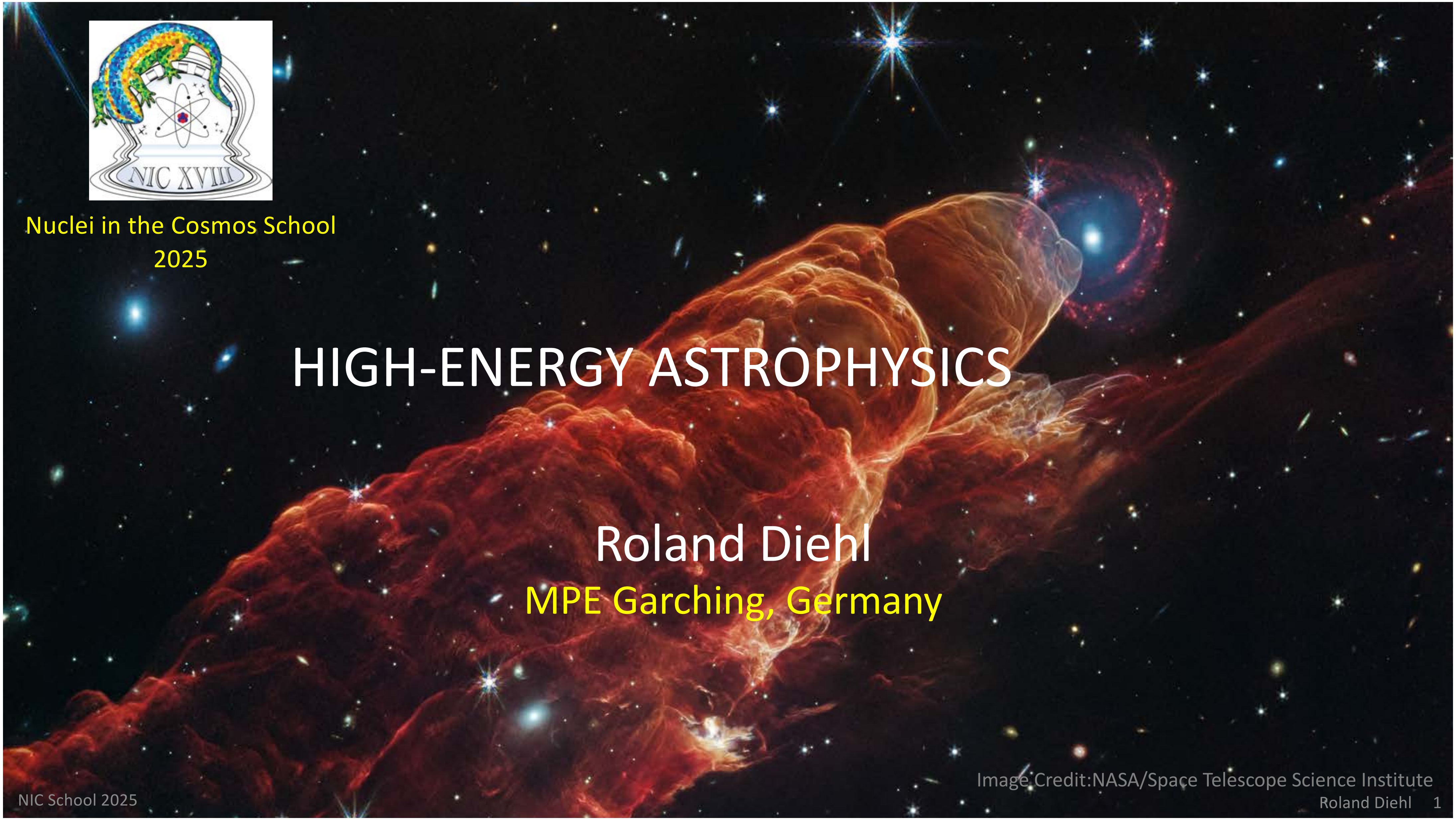
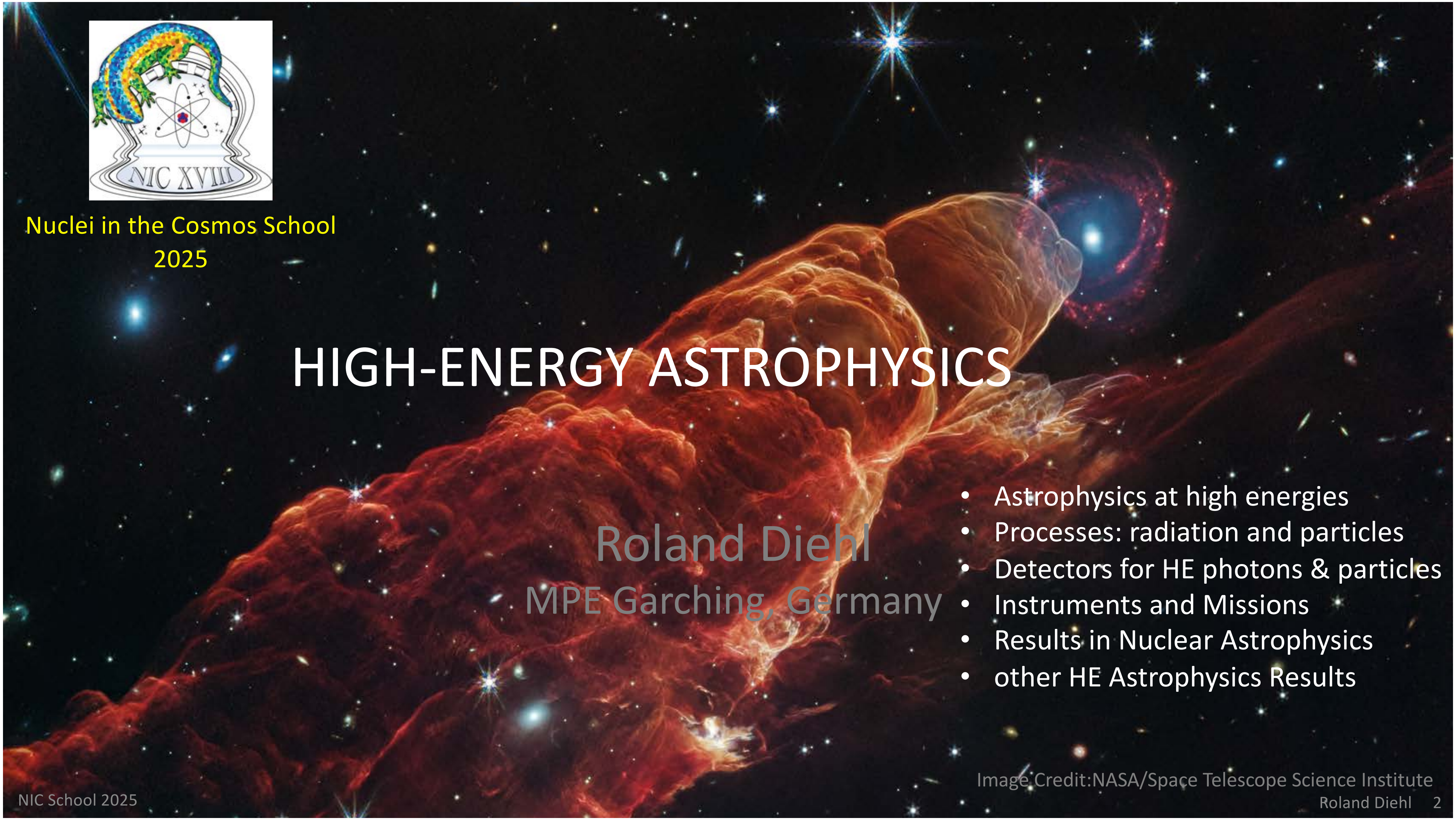


Nuclei in the Cosmos School
2025

HIGH-ENERGY ASTROPHYSICS

Roland Diehl
MPE Garching, Germany

Image Credit:NASA/Space Telescope Science Institute



Nuclei in the Cosmos School
2025

HIGH-ENERGY ASTROPHYSICS

Roland Diehl
MPE Garching, Germany

- Astrophysics at high energies
- Processes: radiation and particles
- Detectors for HE photons & particles
- Instruments and Missions
- Results in Nuclear Astrophysics
- other HE Astrophysics Results

Image Credit:NASA/Space Telescope Science Institute

- Introduction and Overview

(Thermal and) Non-Thermal Emission

- non-thermal radiation is prominent in high-energy astronomy

Radiation Processes in High-Energy Astrophysics

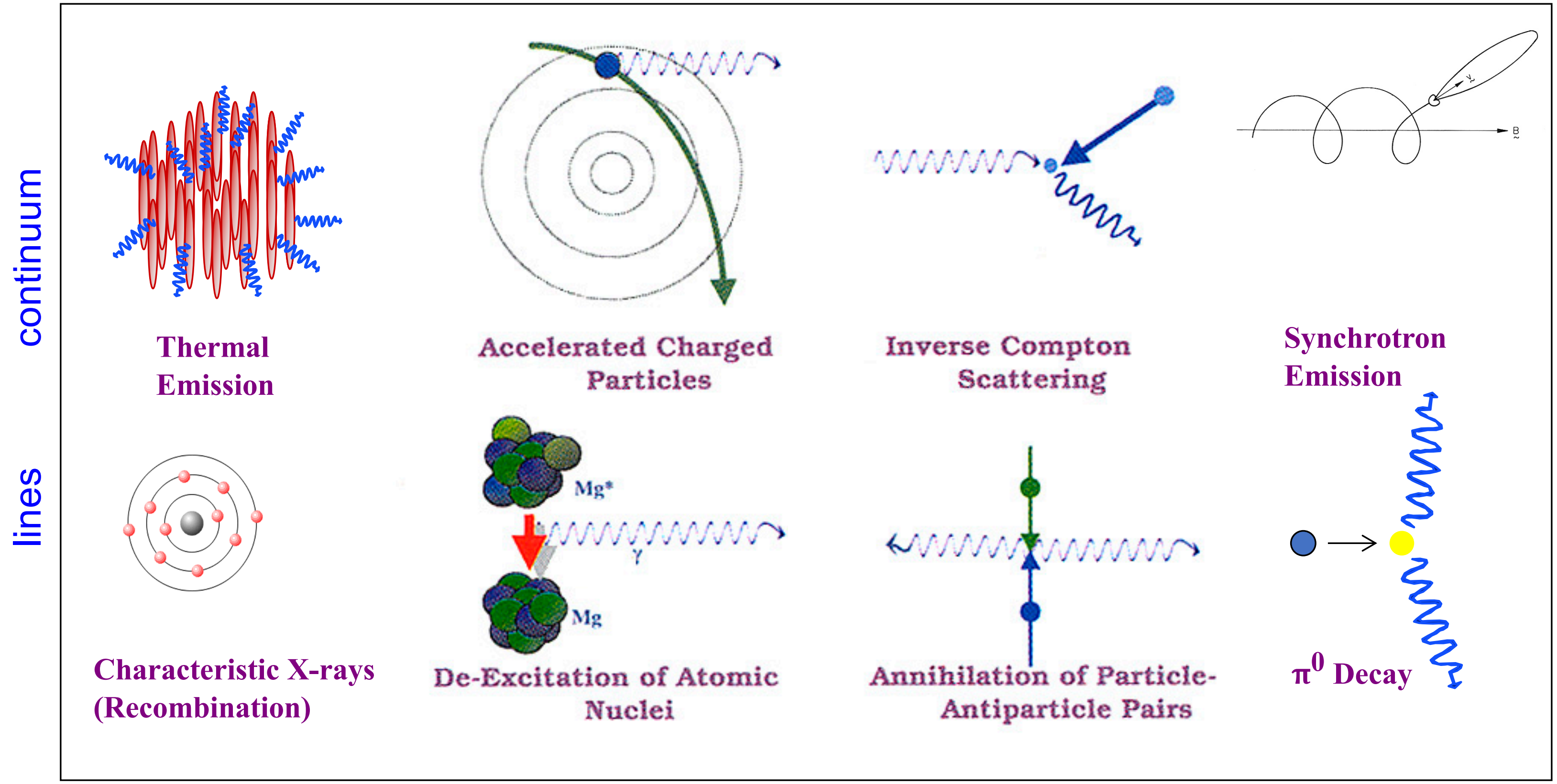
- Thermal Radiation
- Radiation from (Accelerated) Charges
  - ✓ Bremsstrahlung
  - ✓ Synchrotron Radiation
  - ✓ Curvature Radiation
- Electron - Photon Scattering
  - ✓ (Thompson Scattering)
  - ✓ Compton Scattering (inelastic)
- Transitions in QM Systems
  - ✓ Atomic Transitions (partly-ionized atoms)
  - ✓ Nuclear Transitions
- Positron Annihilation
- Pion Decay
- …

Emission and Absorption Processes

Emission	**Absorption**
Thermal emission	Bolometric absorption
Recombination	Photoionization
Line de-excitation	Line excitations (atomic; nuclear)
e-/e+ Annihilation	e-/e+ pair production
Bremsstrahlung	Scattering (electrons; ions; nuclei)
Inverse Compton Scattering	Compton scattering
Synchrotron Emission	Synchrotron self absorption
Nuclear De-Excitation	
Radioactive Decay	Inverse Beta decay, Electron capture
Pion Decay	
...	...

➢ *radiation processes operate in both directions: energy transfers between d.o.f.'s*

Basic Radiation Mechanisms in Astrophysics

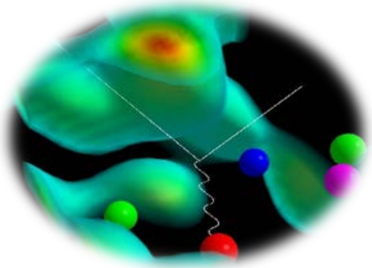
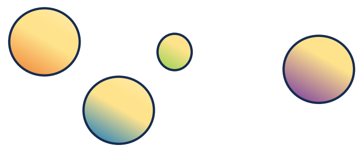
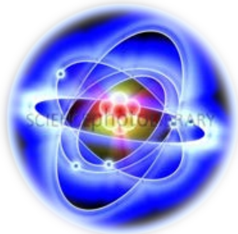
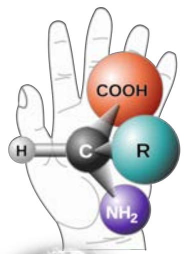


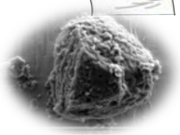
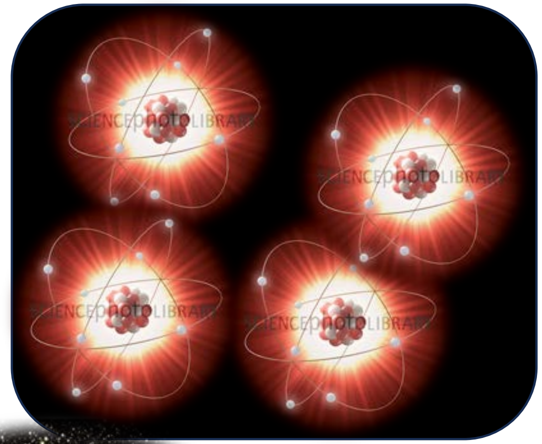
→ apparently, we need to look at

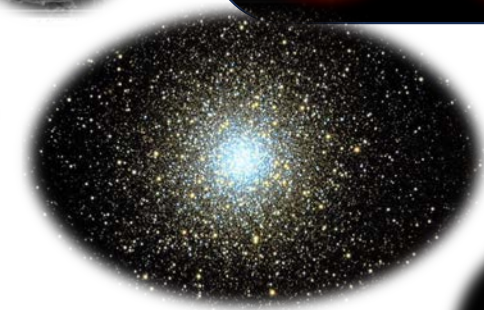
- forms of matter (→ complex systems; intrinsic energies)
- particle and field types, and their interactions and energies

Forms of cosmic matter

- **(elementary) particles**
  - ☞electrons
  - ☞nucleons (p,n)
  - ☞neutrinos, …
- **compound particles**
  - ☞atomic nuclei
  - ☞atoms, molecules
  - ☞dust
- **plasma**
  - ☞elementary particles and atomic nuclei
- **matter in complex larger objects**
  - ☞meteorites, comets, planets
  - ☞stars, stellar groups, galaxies
- **obscure / exotic**
  - ☞black holes
  - ☞dark matter
  - ☞quark stars, other exotica

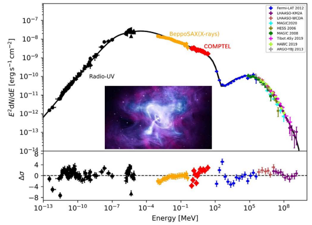


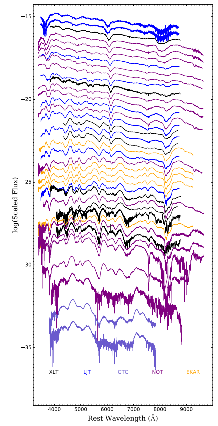
Characteristics of cosmic matter

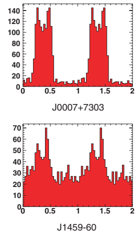
- **Density**
  - ✓ Interstellar medium — *~collisionless, waves & fields control couplings; 10^{-25} g cm^{-3}*
  - ✓ Stars — *collision-coupled multi-component matter; 10^{3} g cm^{-3}*
  - ✓ Compact stars — *extremes: new phases, degeneracy, …; 10^{14} g cm^{-3}*
- **Phase**
  - ✓ plasma, gas — *independent particles of different types*
  - ✓ (liquid — *mutually-attracted but freely-moving particles)*
  - ✓ solid, crystalised — *particles bound in rigid structures; structural d.o.f.*
  - ✓ degenerate — *particles compressed into quantum-limited volume;*
- **Temperature**
  - ✓ cold — *particle energy small wrt. available energy levels, only thermal energy*
  - ✓ hot — *particle energy much larger than available energy level spacings; excitations*
- **Energy**
  - ✓ non-relativistic — *particle kinetic energy much below its rest-mass energy*
  - ✓ relativistic — *particle kinetic energy much larger than its rest-mass energy*

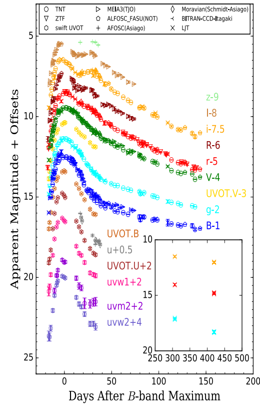
Beyond Images: Characterising radiation from a Source

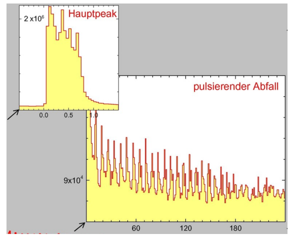
- Intensity and its spectral distribution
  - ✓ Black-body (Planckian; thermal) distributions
  - ✓ Power-law distributions with cut-offs (low-energy, high-energy)
  - ✓ Mixed components with breaks (linear, power law, Planckian,...)
  - ✓ Spectral lines (Gaussian, Lorentzian; narrow, broadened)
- Time of arrival
  - ✓ photon propagation differs for different energies → dispersion
  - ✓ light curves, rise and fall times
  - ✓ periodicities, power spectra, oscillations
- Polarisation
  - ✓ Stokes parameters
- Angular distribution
  - ✓ Dipole and multipole radiation
  - ✓ Forward beaming, backscatter

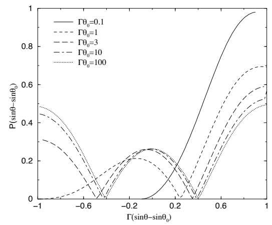
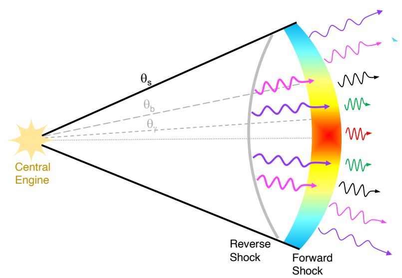










Energy Scales

- **Rest-Mass Energy**
  - ✓ Energy Equivalent of Mass of Matter Constituents

$$E = mc^2 \qquad E_{tot} > mc^2 \Leftrightarrow relativistic$$

$$E = N \cdot m_i c^2 \qquad m_e c^2 \approx 0.5[MeV] \quad m_p c^2 \approx 1[GeV]$$

- **Thermal Energy**
  - ✓ Kinetic-Energy Distribution with Mean

$$\varepsilon \approx k_B T \qquad k_B = 8.6132 \cdot 10^{-11}[MeV/K]$$

- **Gravitational-Binding Energy**
  - ✓ Gravitational Potential Energy (N particles)

$$E_{grav} \approx \frac{G \cdot (N m_i)^2}{R} \qquad G = 6.6726 \cdot 10^{-8}[cm^3 g^{-1} s^{-2}]$$

$$E_{Grav,NS} \approx 200\left[\frac{10km}{R}\right]\left[\frac{mc^2}{1GeV}\right][MeV]$$

- **Atomic-Binding Energy**
  - ✓ Electromagnetic Potential Energy (Coulomb Potential)

$$a_0 = \hbar^2 / m_e q^2 \qquad E_C \approx \frac{m_e \cdot q^4}{2\hbar^2} \approx 13.6[eV]$$

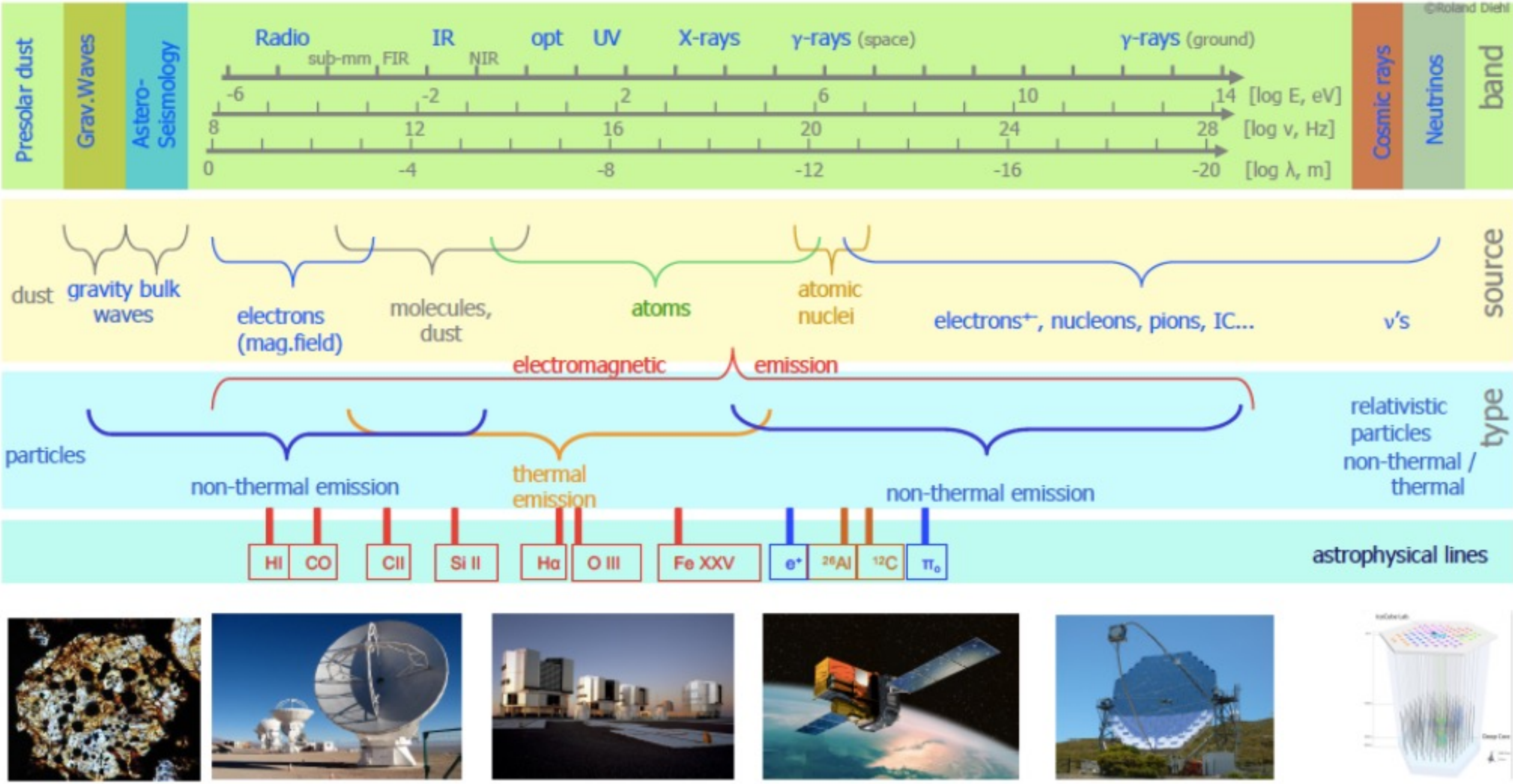
- **Molecular-Binding Energy**
  - ✓ Electromagnetic Energy (oscillations in potential well)

$$E_{vib} \approx \left(\frac{m_e}{\mu}\right)^{1/2} \cdot E_C \approx 0.25[eV] \qquad E_{rot} \approx \left(\frac{m_e}{\mu}\right) \cdot E_C \approx 10^{-2}[eV]$$

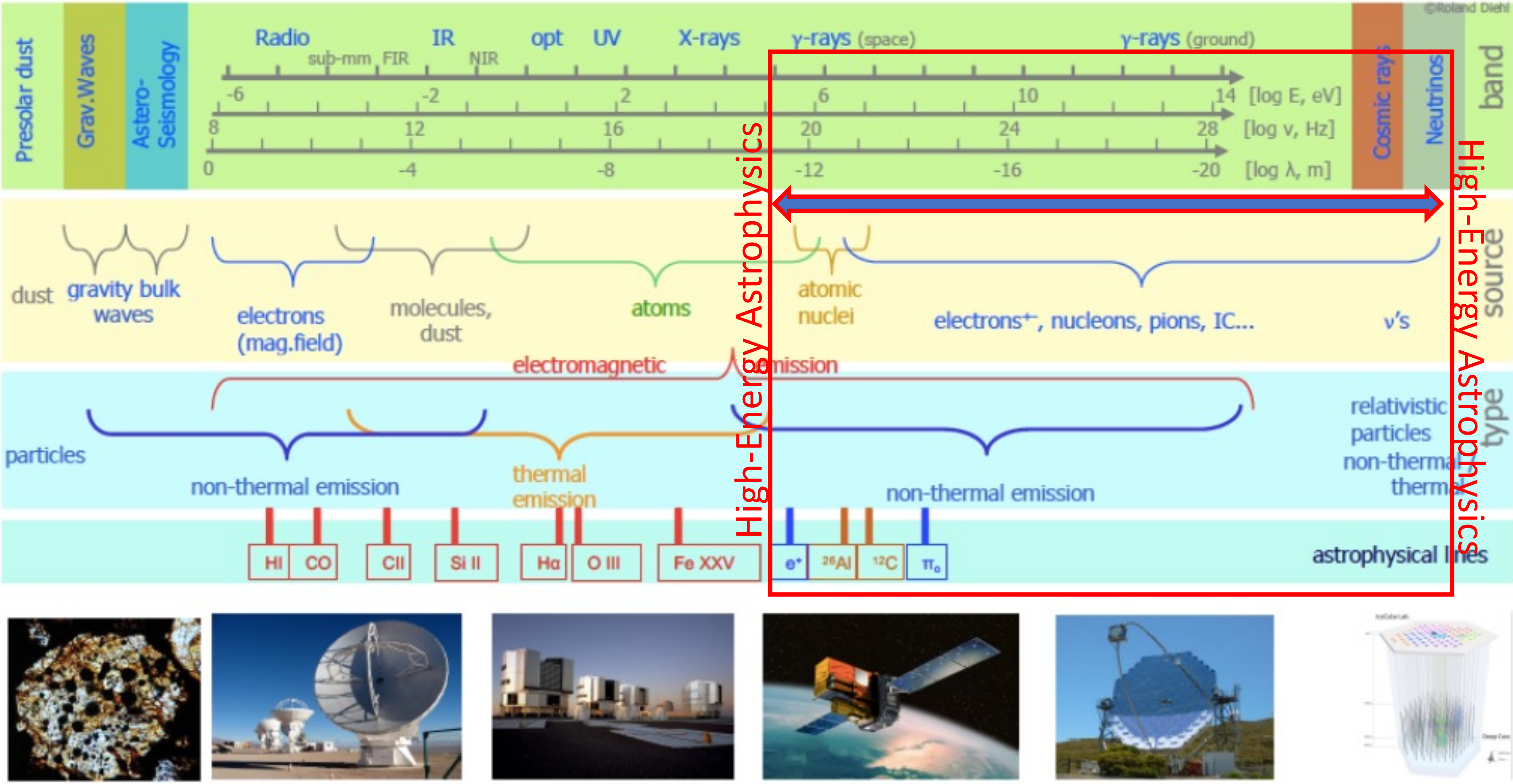
- **Nuclear-Binding Energy**
  - ✓ Nuclear Potential Energy {Nucleon Binding)

$$r_0 \approx 1\text{fm} \qquad E_C \approx \frac{m_p \cdot q^2}{1\,fm} \approx 1[MeV]$$

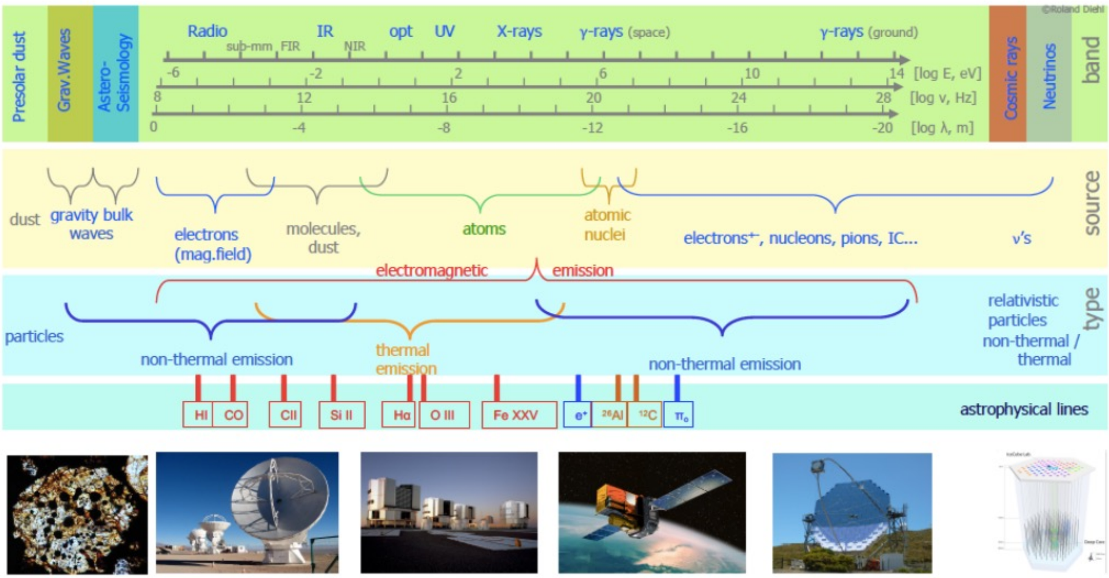
Astronomy: a Multi-Messenger Enterprise



Astronomy: a Multi-Messenger Enterprise



Astronomical 'Windows'



- Optical Astronomy ~ancient.. 17 century+
- “New Astronomies” 1930+
  - ☞Radio Astronomy >1930
  - ☞UV & X-Ray Astronomy > 1970 (IUE, Uhuru)
  - ☞Gamma-Ray Astronomy >1970 (OSOIII,SASII)
  - ☞Infrared Astronomy >1980 (IRAS)
  - ☞TeV Astronomy >2000 (MAGIC, HESS)
- High-Energy Astronomy: > 100 eV … TeV (range >10 decades!)

young!

- Review/reminder of physical processes

Blackbody Radiation

1. Planck functions (Brightness of a blackbody)

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

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

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

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

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

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

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

3. Wien displacement law

Maximizing B_ν:

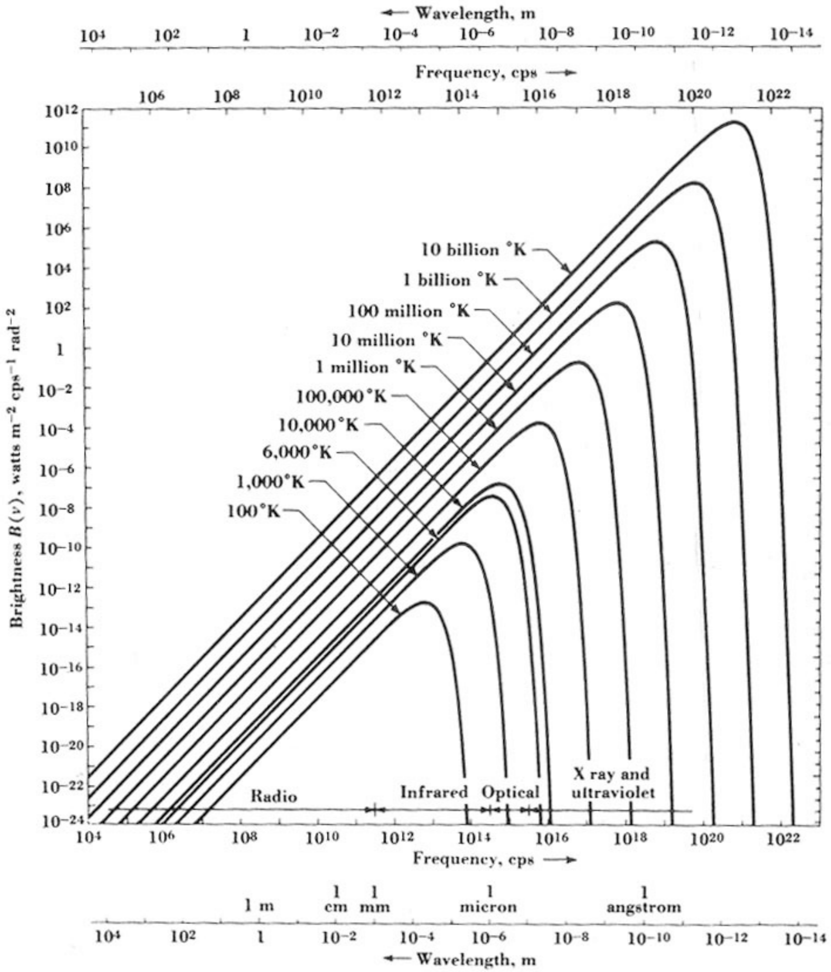
$\nu_m = 5.9 \times 10^{10}\ T$ Hz

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

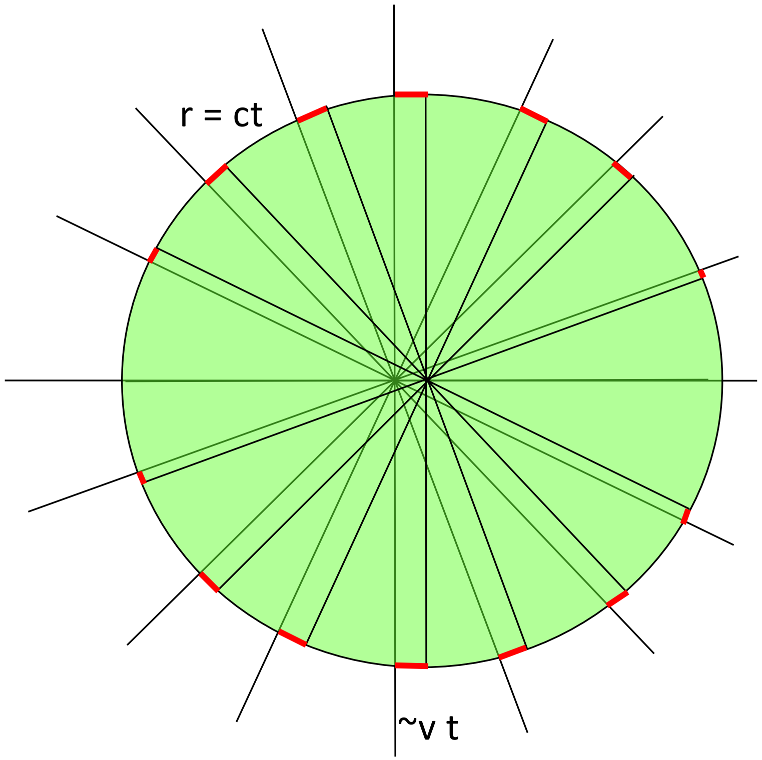
Maximizing B_λ:

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

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



Radiation from an accelerated charged particle (general case)



- The information about the charge acceleration is transmitted as a *pulse of electromagnetic radiation, with velocity c*
- The total radiation is approximated by the *Larmor formula (1897)*

$$\frac{dP}{d\Omega} = \frac{q^2 \left|\ddot{r}\right|^2 \sin^2\Theta}{4\pi c^3} \qquad P = \left.\frac{2q^2\left|\ddot{r}\right|^2}{3c^3}\right|_{t'=t-R/c}$$

(p = dipole moment qr of charge q, a= $\ddot{r}$ = acceleration)

- The radiation pattern is of *dipolar form*, i.e. the power radiated varies as $\sin^2\Theta$. There is no radiation along the acceleration direction
- The radiation is *polarized* with the electric field vector in the direction of the acceleration vector of the particle

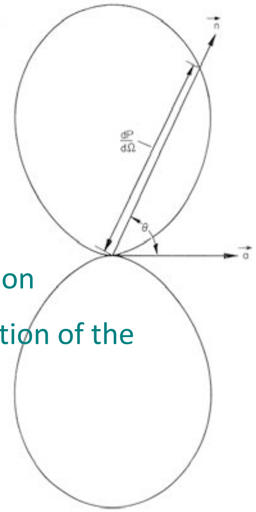
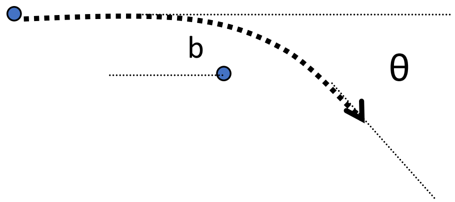


Fig. 3.1. The angular distribution of the power radiated by a non-relativistic charge undergoing an acceleration **a**. The power per unit solid angle radiated in the direction of the vector **n** is proportional to the radius vector as indicated in the figure.

Evaluate the 'retarded'
electric (scalar) and magnetic (vector)
Potentials at observer...
→ Liénard,Wiecher ~1900

Bremsstrahlung



- Bremsstrahlung of Deflected Charge in Coulomb Fields of Nuclei in a Gas

- Bremsstrahlung Cross Section
  - ✓ High-energy e- on unshielded charge Ze -> 'cross section':

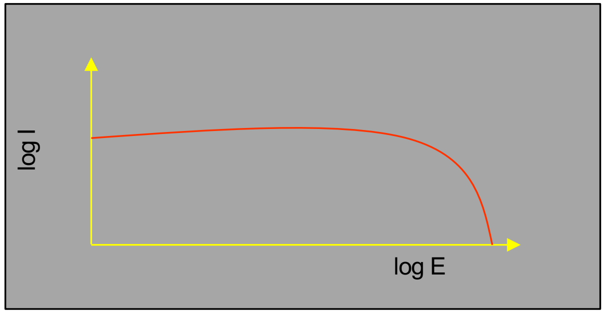
$$\sigma_r = 4Z^2 \frac{e^2}{\hbar c}\left(\frac{e^2}{mc^2}\right)^2 \frac{1}{\hbar\omega}\frac{1}{E_i^2}\left(E_i^2 + E_f^2 - \frac{2}{3}E_i E_f\right)\left[\ln\left(\frac{2E_i E_f}{mc^2\hbar\omega}\right) - \frac{1}{2}\right]$$

  - ✓ In a plasma:
    screening corrections
    Gaunt factor (b_{max}/b_{min}) encodes properly-averaged collisional parameters

  - ✓ Radiated Spectral Power:

$$P(v,v)dv = N_i v \frac{16Z^2e^6}{3m^2c^3v^2}\int_{b_{min}}^{b_{max}} \frac{db}{b}\cdot dv = N_i v \frac{16Z^2e^6}{3m^2c^3v^2}\cdot \ln\left(\frac{b_{max}}{b_{min}}\right)\cdot dv$$

see Bethe & Heitler (1964), Koch & Motz (1959)



$$\tan\frac{\Theta}{2} = \frac{Ze^2}{mv^2 b}$$

Synchrotron Radiation

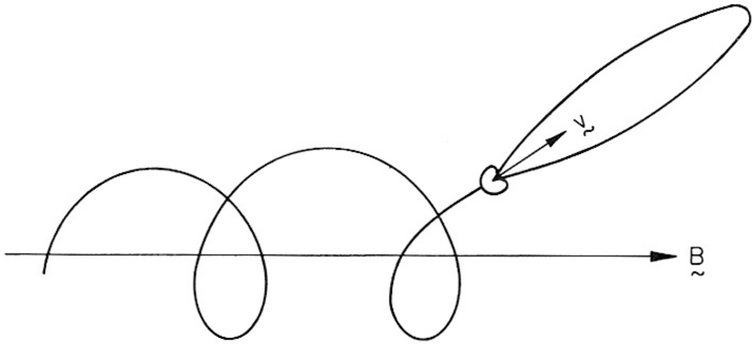


Fig. 3.2. A relativistic particle spiraling in a magnetic field emitting synchrotron radiation with the angular pattern as indicated.

Particle in magnetic field **B**
→ Acceleration perpendicular to B
→ Gyration

Gyration frequency:
ω=eB/γmc = 1.8x10^{7} B **γ^{-1}**
=14.4 B/E [Hz]
with Lorentz factor γ

Radiation Characteristics:

Power per solid angle: $$\frac{dP}{d\Omega} = \frac{e^2\dot{v}^2}{4\pi c^3}\frac{\sin^2\vartheta}{(1-\beta\cos\vartheta)^5}$$ b=v/c, δ=angle v←→observer

Radiation Cone Opening Angle: $$\alpha = \gamma^{-1} = \left[1-\beta^2\right]^{1/2} = \frac{mc^2}{E} = 8.2\cdot10^{-7}E^{-1}rad$$

Radiation Spectrum of a Pulse Sweeping by an Observer: $$2\pi\nu_{crit} = \frac{c\beta}{\rho} \approx 6\cdot10^{28}\frac{E^3}{\rho}Hz$$

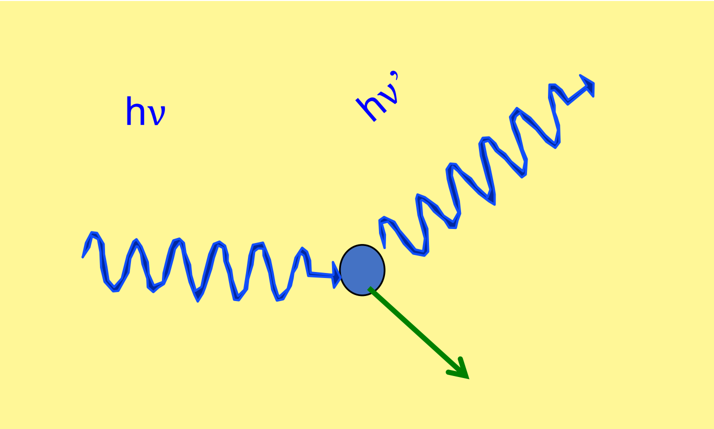
(e$^-$ gyrating with orbit radius r) or expressed as (with ψ pitch angle B-v) -> γ>10^{3} for X/γ rays!

$$\nu_{crit} \approx 6.3\cdot10^{18}\sin\psi\frac{B}{\mu G}\frac{E^2}{GeV^2}Hz$$

Total Power of Synchrotron Radiation (a||v): $$P_{\parallel} = \frac{2e^2}{3c^3}\dot{v}^2\gamma^6$$

Compton Scattering

- ➢E field of photon accelerates the charged electron → photon emission
- ➢Momentum and energy transfer to e-



$$\frac{1}{\nu'} - \frac{1}{\nu} = \frac{h}{m_e c^2}(1-\cos\theta)$$

$$\frac{h}{m_e c} = \lambda_C = 2.426\times 10^{-10}\,cm$$

- ➢Compton Cross Section: $\sigma_C = \sigma_{KN} = \frac{3}{8}\sigma_T \frac{1}{\varepsilon}\left\{\left[1-\frac{2(\varepsilon+1)}{\varepsilon^2}\right]\ln(2\varepsilon+1)+\frac{1}{2}+\frac{4}{\varepsilon}-\frac{1}{2(2\varepsilon+1)^2}\right\}$

  - ✓ Arthur Holly Compton (1892-1962), 1927 Nobel Prize (particle concept of em)
  - ✓ Klein Nishina Cross Section, from Q.M. Corrections

$\varepsilon = \frac{\hbar\omega}{mc^2}$

Inverse Compton Scattering

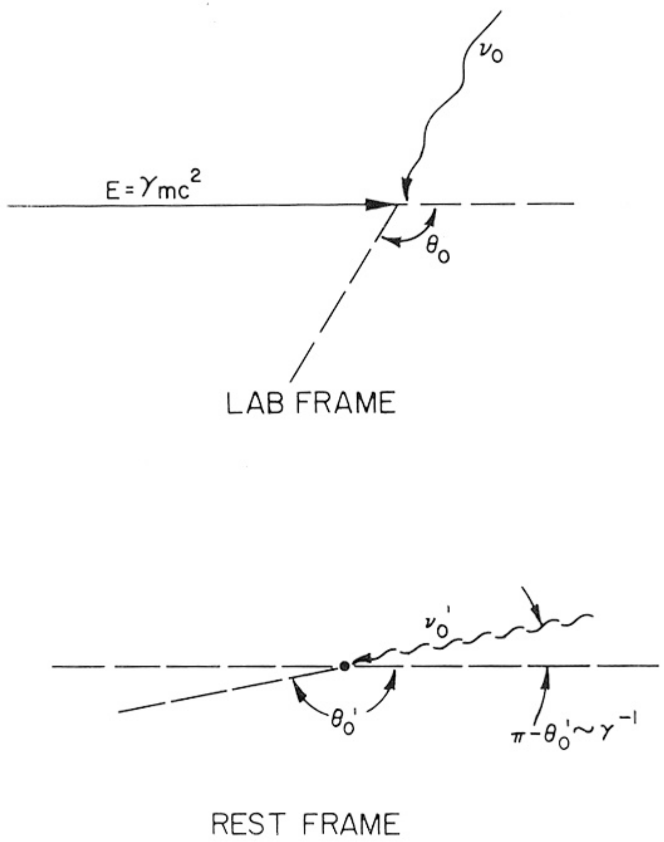


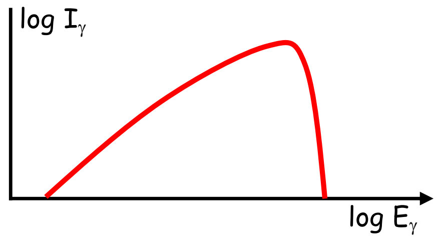
Fig. 3.10. Compton collision between a relativistic electron and low frequency photon as viewed in both the laboratory and the rest frame of the electron.

- **Energy gain of photon in a collision**
  - ✓ $E_\gamma = \gamma^2 h\nu$ for lower energies
  - ✓ $E_\gamma = \gamma^2 mc^2$ for high (relativistic) energies

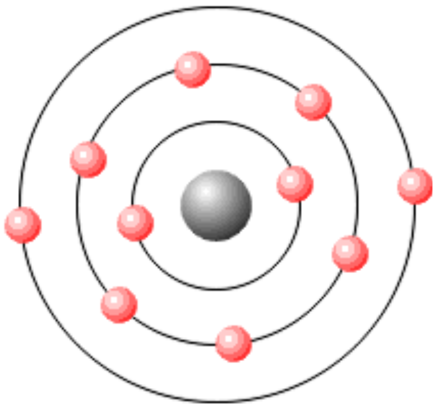
- **Total Power**
  (= Energy Loss of e^-)
  - ✓ $$-\frac{dE}{dx} = \int \sigma_c(E_\gamma, h\nu) N(h\nu) E_\gamma dE_\gamma d(h\nu)$$ $$\sigma_c = \sigma_{Th}$$
  - ✓ low-energy situation: Thompson scattering
  - ✓ High energy ($\gamma h\nu >> mc^2$): Klein-Nishina, ~1/hν

$$\sigma_c \approx \frac{3}{8}\sigma_{Th}\left(\frac{mc^2}{\gamma h\nu}\right)\left[\ln\left(\frac{2\gamma h\nu}{mc^2}\right) + \frac{1}{2}\right]$$

  - ✓ Energy spectrum ~ $h\nu$ N($h\nu$)
  - ✓ Max Energy ~ $4\gamma^2 E_{photons}$



Characteristic X-rays



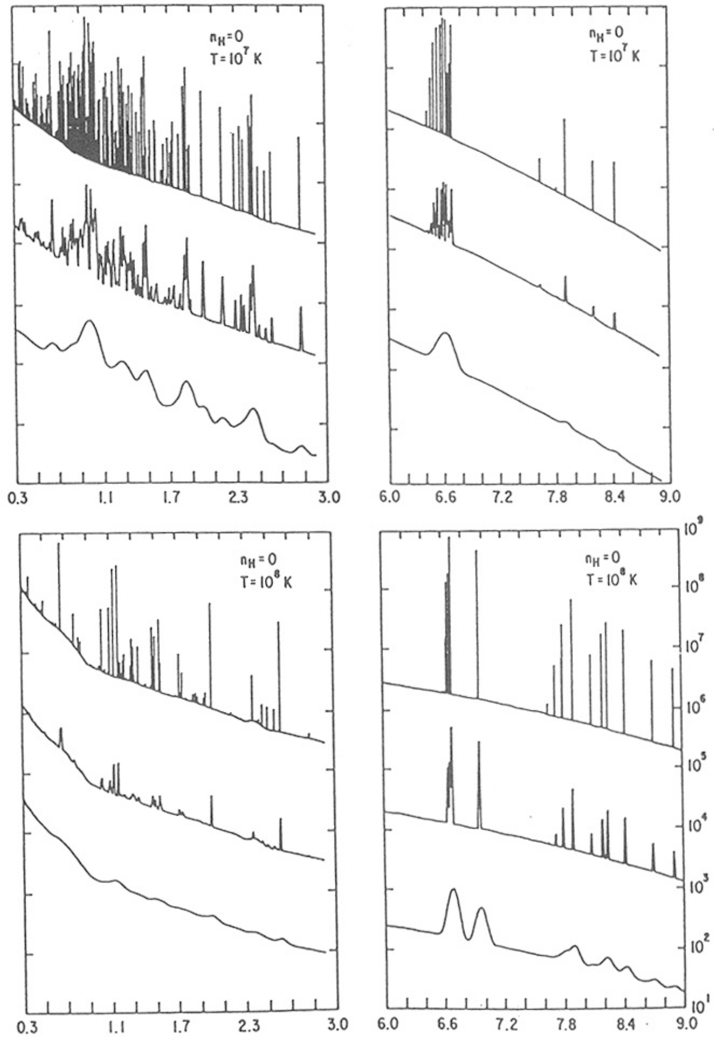


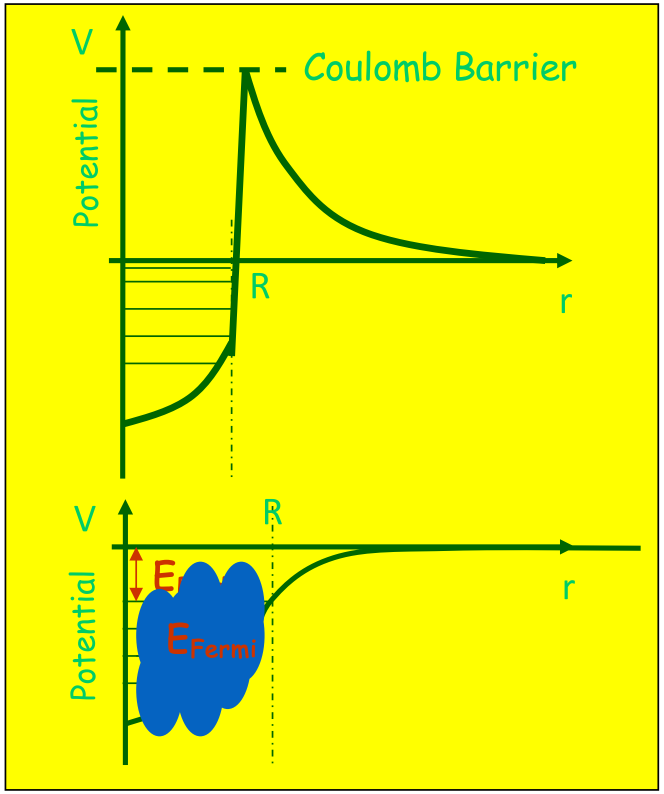
Figure 3. Coronal equilibrium spectra (arbitrary logarithmic intensity) of plasmas with solar abundances, in the energy bands (keV) containing Fe L- and Fe K-emission, as viewed with detectors having FWHM resolutions of 1, 10 and 100 eV (upper, middle and lower trace of each panel).

Atomic Nuclei: Potential Well for Nucleons

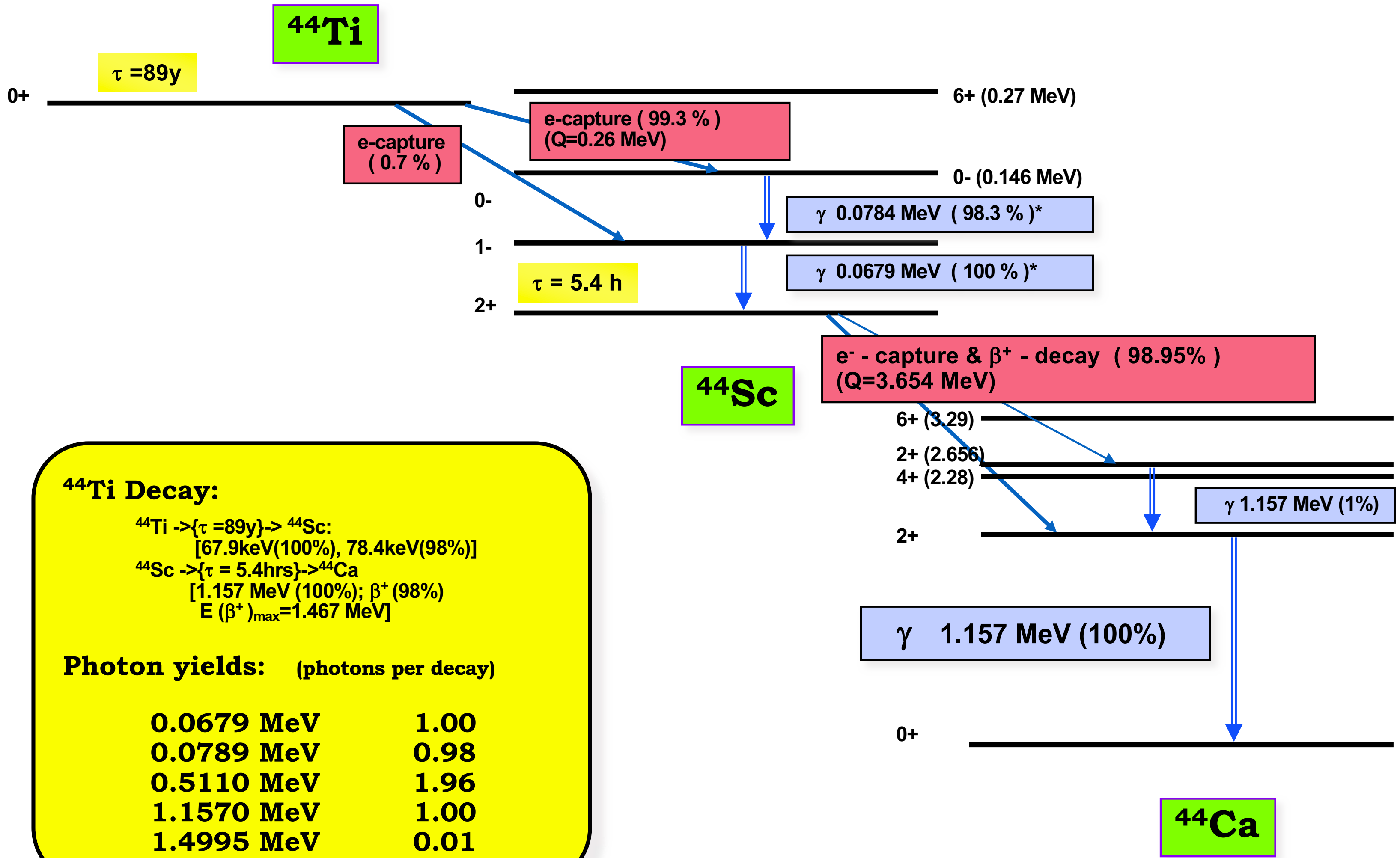
- **Nucleons**
  - ✓ Neutrons
  - ✓ Protons
- **Nuclear Radius**
  - ✓ From Rutherford Scattering -> ~ 1 fm
- **Nuclear Density**
  - ✓ ~10^{13} g cm^{-3}
- **Number of Nucleonic Levels:**
  - ✓ From above, plus Phase Space Considerations: $\hbar^3 = V_{state}$

$$\frac{dn}{dp} = \frac{4\pi p^2}{h^3}V \quad \text{->} \quad n = \int \frac{4\pi p^2}{h^3} V \cdot dp = \frac{p^3 V}{6\pi^2 \hbar^3}$$

$$E_{fermi} = \frac{p_f^2}{2m} \approx \frac{250^2}{2 \cdot 938} = 33[MeV]$$



^{44}Ti Decay and Transitions between Nuclear Energy Levels



^{44}Ti Decay:

^{44}Ti ->{τ =89y}-> ^{44}Sc:
[67.9keV(100%), 78.4keV(98%)]
^{44}Sc ->{τ = 5.4hrs}->^{44}Ca
[1.157 MeV (100%); β^+ (98%)
E $(\beta^+)_{max}$=1.467 MeV]

Photon yields: (photons per decay)

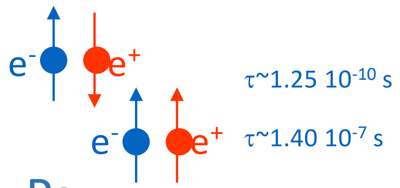
0.0679 MeV	**1.00**
0.0789 MeV	**0.98**
0.5110 MeV	**1.96**
1.1570 MeV	**1.00**
1.4995 MeV	**0.01**

Positron Annihilation

- Annihilations when merging with its anti-particle: e-

→Directly,
or forming an "atom" with e^- and e^+ → Positronium

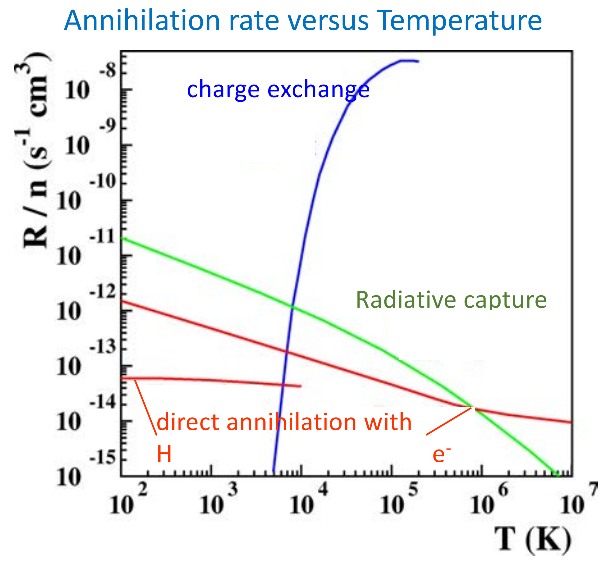
- ➢Relative Spin Orientations ➔
  - ✓Singlet State $^1S_0$/ Para-Positronium
  - ✓Triplet State $^3S_1$/ Ortho-Positronium



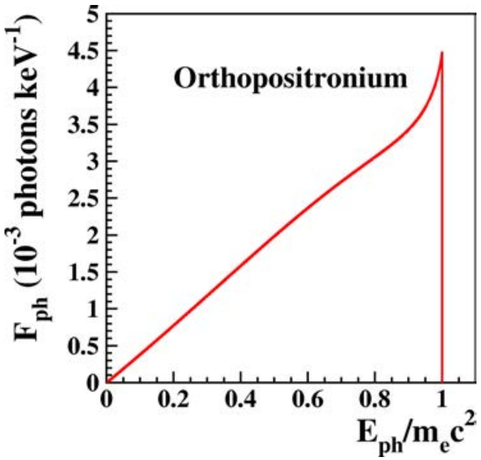
- ➢2-Photon Annihilation Only for Para-Ps:

2 γ at ~511 keV

- ➢3-Photon Annihilation from Ortho-Ps: s=1 to s=1



- ➢Annihilation Spectrum:
  - ✓Line/Continuum γ Ratio 1.45
  - ✓2.75 Annihilation γ's per e^+



Pion Decay

- Pion production occurs in hadronic collisions at high energies

$\boxed{\pi^\pm}$

$I^G(J^P) = 1^-(0^-)$

Mass $m = 139.57039 \pm 0.00018$ MeV (S = 1.8)
Mean life $\tau = (2.6033 \pm 0.0005) \times 10^{-8}$ s (S = 1.2)

π^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\mu^+\nu_\mu$	[b]	(99.98770 ± 0.00004) %		30
$\mu^+\nu_\mu\gamma$	[c]	$(2.00 \pm 0.25) \times 10^{-4}$		30
$e^+\nu_e$	[b]	$(1.230 \pm 0.004) \times 10^{-4}$		70
$e^+\nu_e\gamma$	[c]	$(7.39 \pm 0.05) \times 10^{-7}$		70
$e^+\nu_e\pi^0$		$(1.036 \pm 0.006) \times 10^{-8}$		4
$e^+\nu_e e^+ e^-$		$(3.2 \pm 0.5) \times 10^{-9}$		70

$\boxed{\pi^0}$

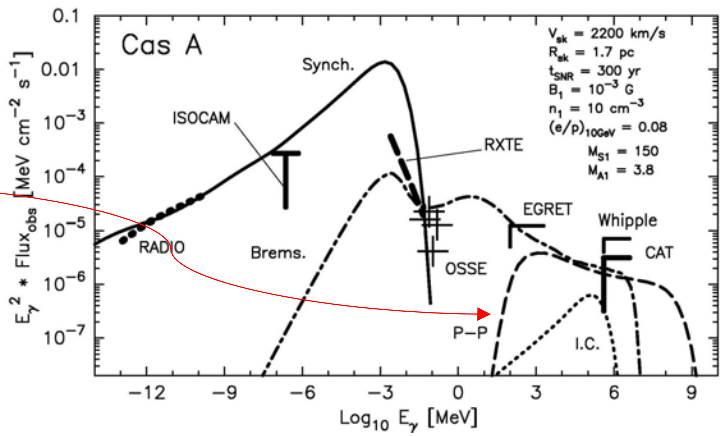
$I^G(J^{PC}) = 1^-(0^{-+})$

Mass $m = 134.9768 \pm 0.0005$ MeV (S = 1.1)
$m_{\pi^\pm} - m_{\pi^0} = 4.5936 \pm 0.0005$ MeV
Mean life $\tau = (8.43 \pm 0.13) \times 10^{-17}$ s (S = 1.2)

π^0 DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
2γ	(98.823 ± 0.034) %	S=1.5	67
$e^+e^-\gamma$	(1.174 ± 0.035) %	S=1.5	67
γ positronium	$(1.82 \pm 0.29) \times 10^{-9}$		67
$e^+e^+e^-e^-$	$(3.34 \pm 0.16) \times 10^{-5}$		67
e^+e^-	$(6.46 \pm 0.33) \times 10^{-8}$		67
4γ	$< 2 \times 10^{-8}$	CL=90%	67

➢ Creation of Gamma-Ray Photons of ~67 MeV (in restframe of decay)

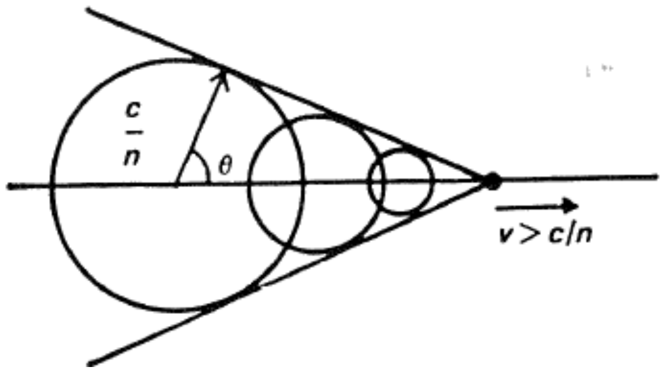
☞ i.e. Doppler-broadened with cosmic-ray energies



Čerenkov radiation

- charged particle motion with v>c/n=c_{local_medium}
  → Čerenkov radiation
- photon flash emitted at angle θ wrt motion

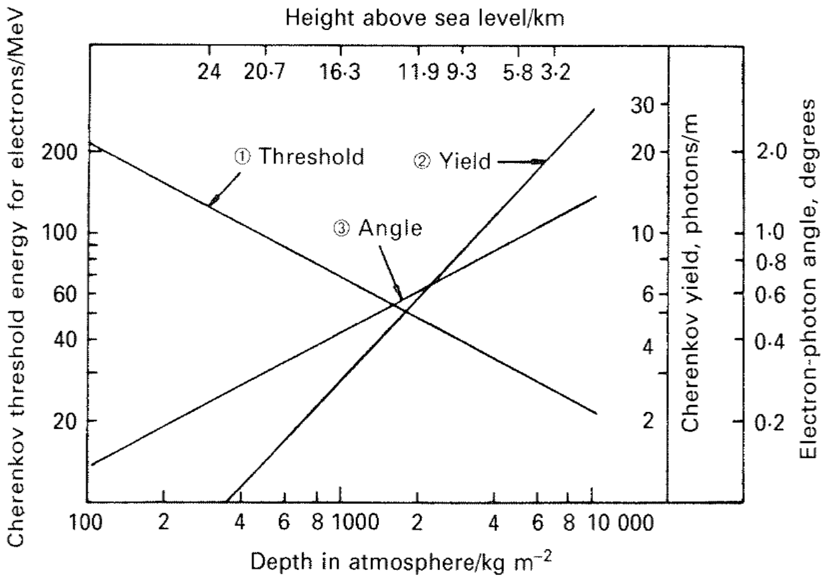
$$\cos\Theta = c/nv$$



- Energy emitted (per band):

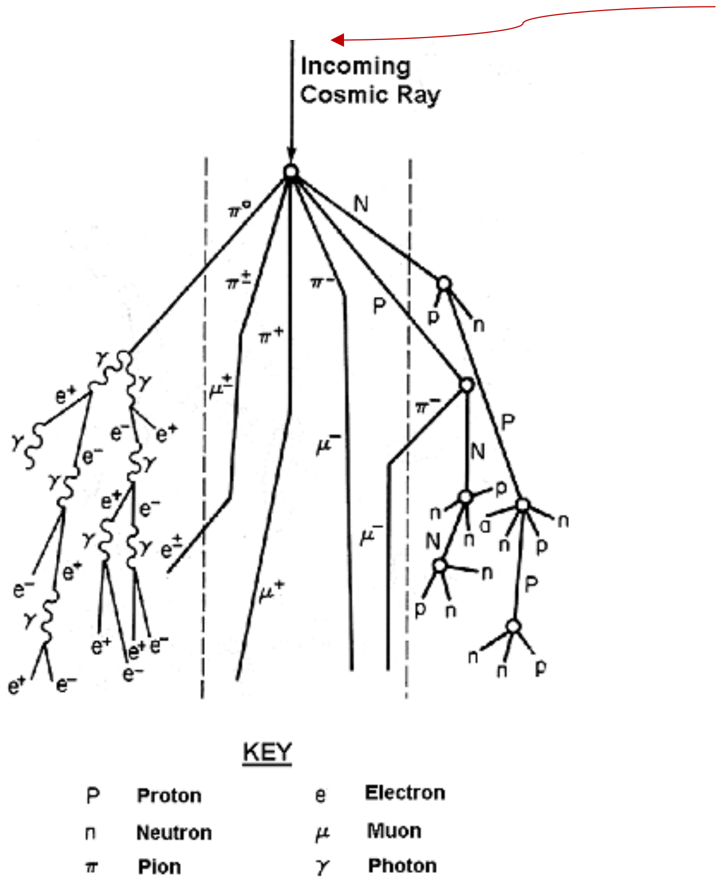
$$\frac{dU(\omega)}{dx} = \frac{\omega e^2}{4\pi\varepsilon_0 c^3}\left(1 - \frac{c^2}{n^2 v^2}\right)$$

→ determine radiation characteristics from integrating over path in the atmosphere



- HE-Processes beyond electromagnetic radiation

Cosmic Rays – rays of relativistic particles



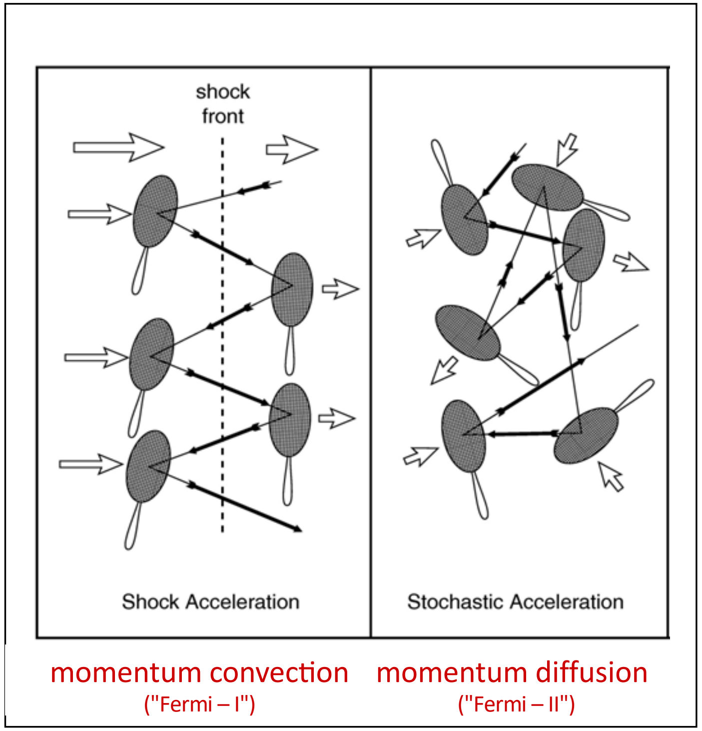
Entering Earth Atmosphere, Cosmic Rays produce an avalanche of Secondaries, an "Air Shower"

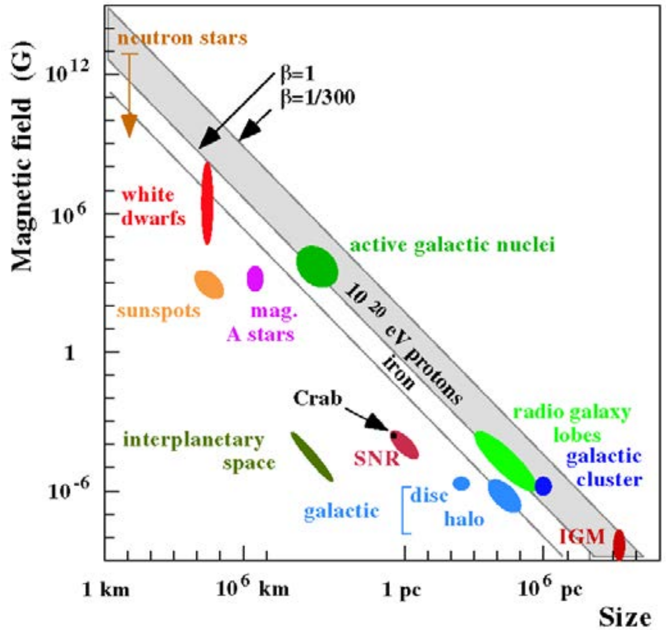
Air showers consist of 3 components:

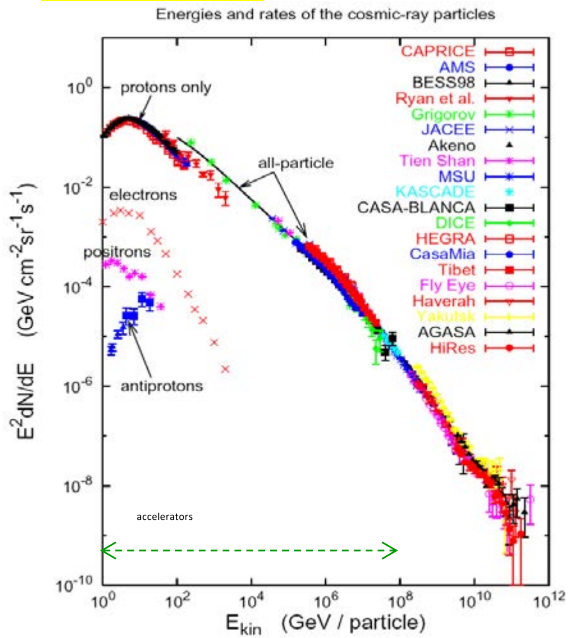
- hadronic component
  primary proton scatters off atmospheric nuclei, thereby producing protons, neutrons, pions, kaons, ...
- myonic component
  the decay of charged pions and kaons generates myons
- electromagnetic component
  the decay of neutral pions generates γ`s, which initiate electromagnetic cascade through pair creation and bremsstrahlung

Cosmic Particle-Acceleration Sites

- No electrostatic accelerators because of short-circuiting plasma currents
- Shocks provide a "Fermi accelerator"
  - ➢ Magnetic-field scatterings confine particle to bounce between regions before/behind shock
  - ➢ Need to Confine CRs within their Acceleration Regions
    - ✓ Larmor Radius < Source Extent → $E_{\max} \propto \beta \cdot ZeB \cdot L$

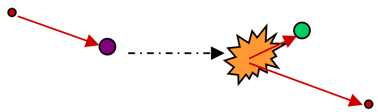






Positron Production Processes

✓ Cosmic-Ray Nuclear Reactions



- e.g. $^{12}C(p,pn)^{11}C(\beta^+)$, or $^{16}O(p,\alpha)^{13}N(\beta^+)$
- Pion Production in HE Collisions

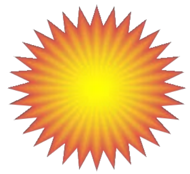
$$p + p \rightarrow \pi^+ + X$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad (\tau = 2{,}6 \cdot 10^{-8}\ s)$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu \quad (\tau = 2{,}2 \cdot 10^{-6}\ s)$$

✓ Hot-Plasma Pair Production

- 'kT>MeV'-Plasma
  - ✓ Accretion Columns & Disks
  - ✓ Jet Bases

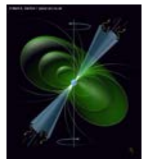
$$\gamma + \gamma \rightarrow e^+ + e^-$$



✓ E.M.-Cascade Pair Production

- Strong Magnetic Fields
  - ✓ Pulsars
  - ✓ Jets

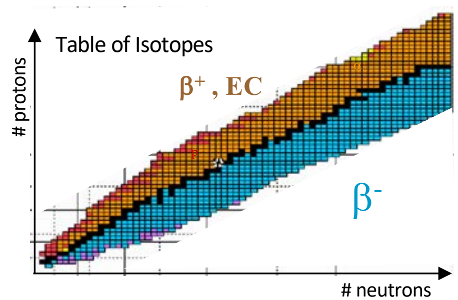
$$\gamma + B \rightarrow e^+ + e^-$$



✓ Nucleosynthesis

- e.g. $^{56}Ni(\beta^+)$, $^{44}Ti(\beta^+)$, $^{26}Al(\beta^+)$, $^{22}Na(\beta^+)$, $^{13}N(\beta^+)$, $^{14}O(\beta^+)$, $^{15}O(\beta^+)$, $^{18}F(\beta^+)$

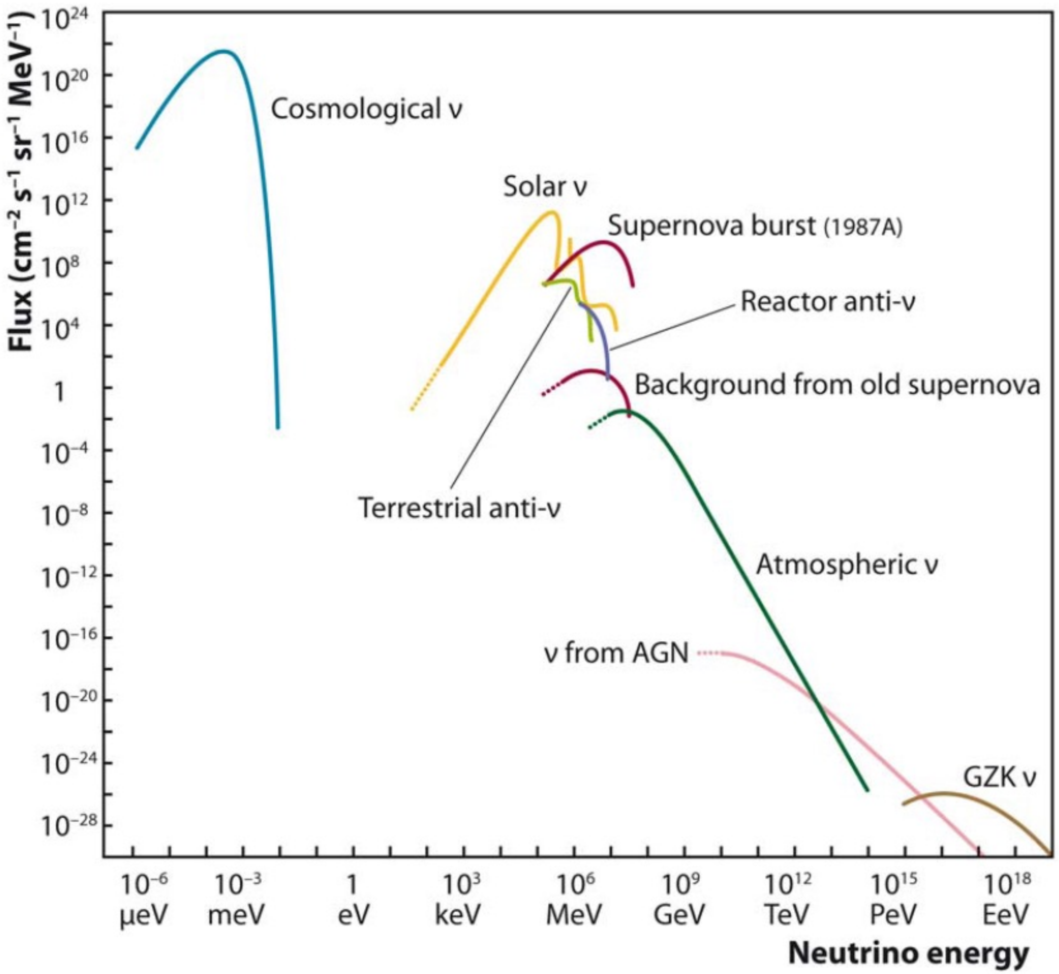
$$^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + e^+ + \nu_e$$



Neutrinos from Cosmic Sources

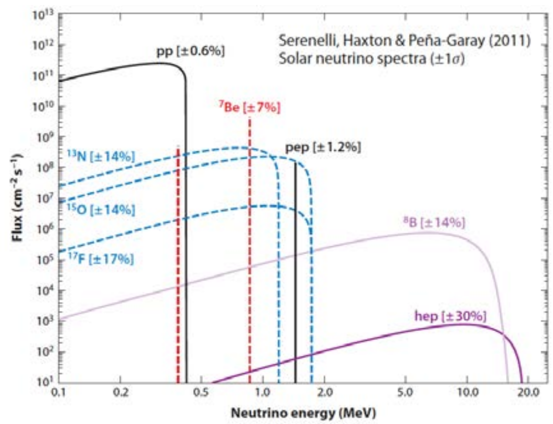
- Weak Interaction Particle

$$n \to p + e^- + \bar{\nu}_e$$
$$\pi^\pm \to \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$$



✓ from nuclear interactions, e.g.

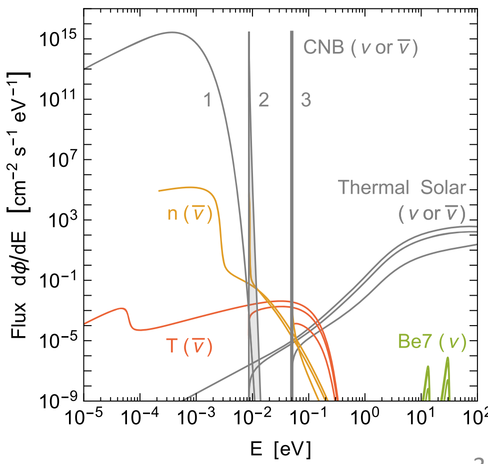
☞ solar:



✓ from high-temperature plasma, e.g.

☞big bang:

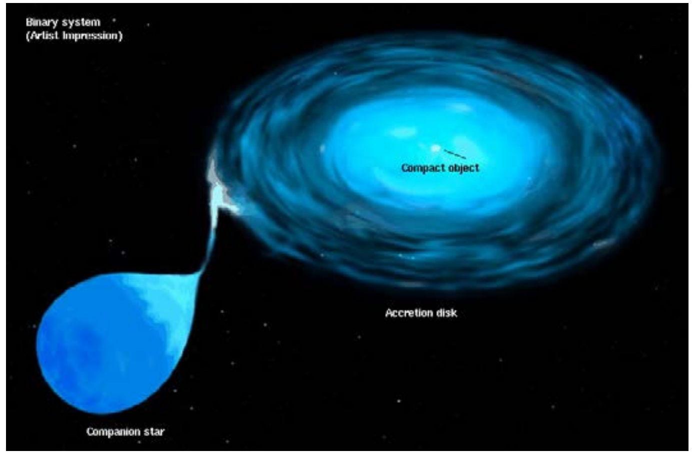
☞solar:



Accretion: Modeling Conversion from Gravitational Energy to Photons

(Shakura&Sunyaev 1973)

$$E_{Grav,NS} \approx 200 \left[\frac{10km}{R}\right]\left[\frac{mc^2}{1GeV}\right][MeV]$$

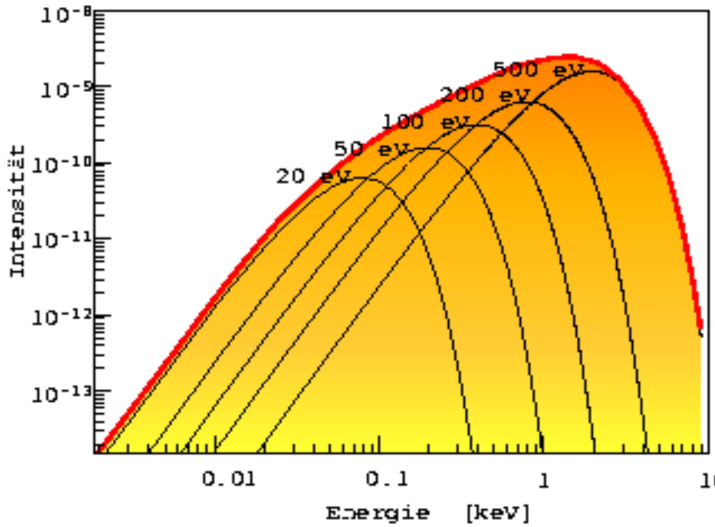


- Potential energy of infalling matter → Heating
- Angular momentum → Accretion Disk
- Virial Theorem:
  1/2 of Energy → Radiation, 1/2 → Heat of Gas

$$L = \frac{1}{2}\dot{U} = \frac{GM_\bullet \dot{M}_\bullet}{2r} = 2\pi r^2 \sigma T^4 \;\Rightarrow\; T = \left(\frac{GM_\bullet \dot{M}_\bullet}{4\pi\sigma r^3}\right)^{1/4}$$

- Temperature Distribution

$$T(r) \approx \left[\frac{3GM_\bullet \dot{M}_\bullet}{8\pi\sigma R_S^3}\right]^{1/4}\left(\frac{r}{R_S}\right)^{-3/4} = 6.3\times10^5\,\mathrm{K}\left(\frac{\dot{M}_\bullet}{\dot{M}_E}\right)^{1/4} M_8^{-1/4}\left(\frac{r}{R_S}\right)^{-3/4}$$



- 2 Regions:

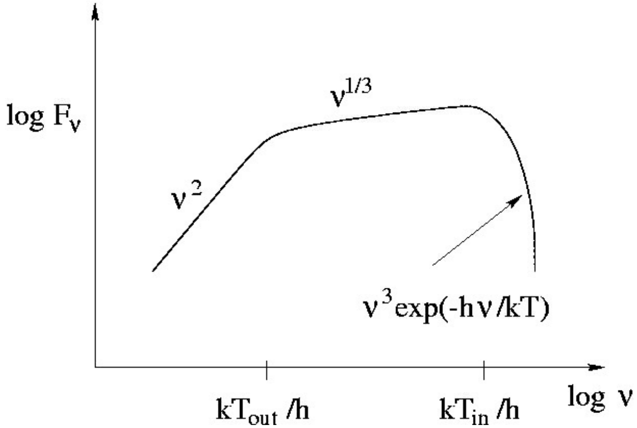
  Radiation Pressure > Gas Pressure

  inner Region; Torus-like

  Gas Pressure > Radiation pressure

  optically-thin, geometrically-thick Disk

- Innermost radius = 6 R_g = 6 GM/c^2

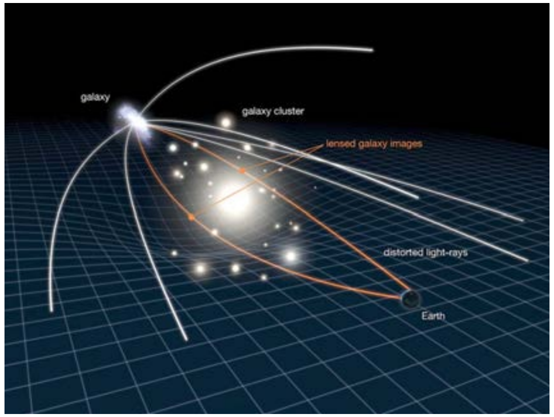


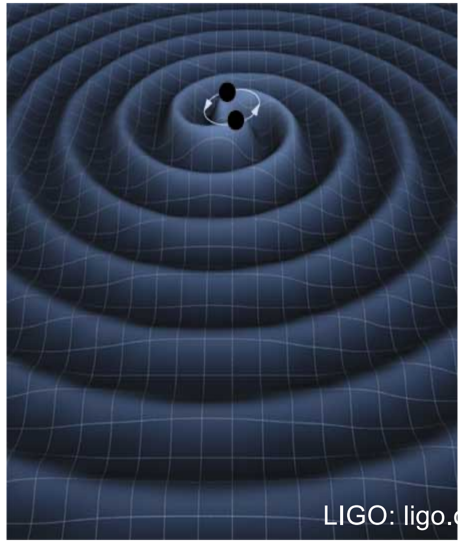
Gravitational Waves

- Photon Propagation: Gravity Effects

  Gravitational Redshift

  Gravitational Lensing





- Dynamical Space Distortions → Gravitational Waves

illustration, though largely exaggerated