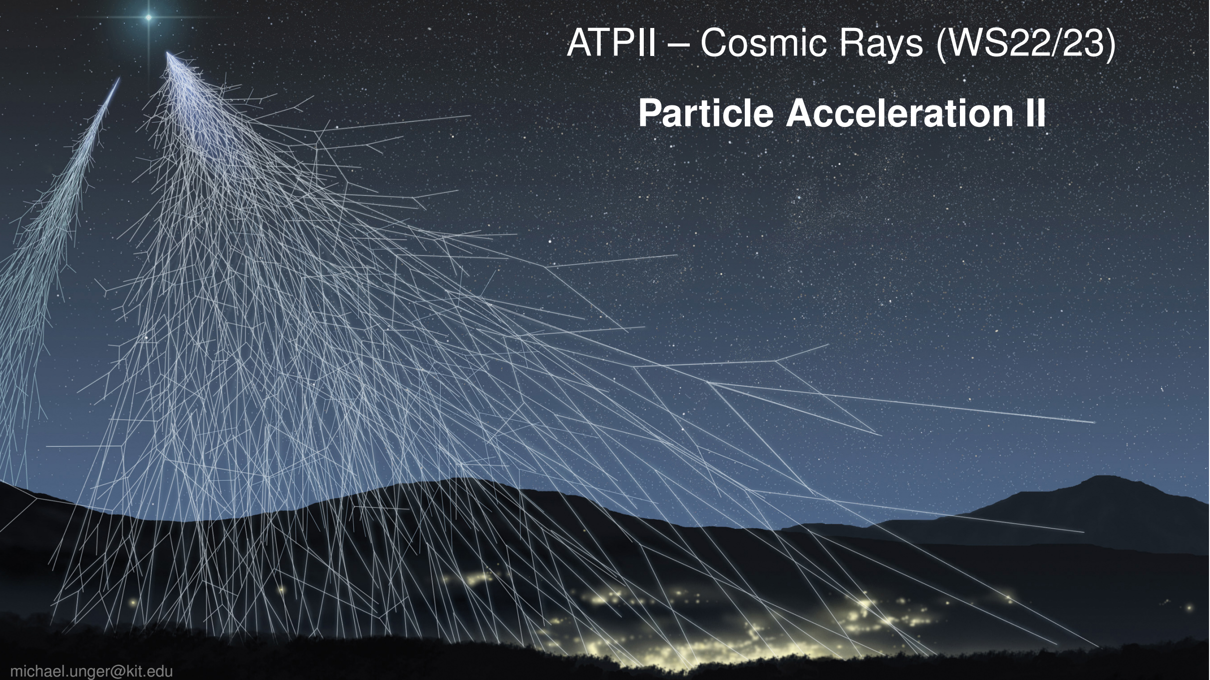


ATPII – Cosmic Rays (WS22/23)

Particle Acceleration II

michael.unger@kit.edu

Cosmic-Ray Energy Spectrum

- origin of power laws? $(\Phi \propto R^{-\alpha-\delta})$
  $\rightarrow$ stochastic acceleration (α) + escape (δ) ✓
- value of spectral index? $(\alpha \sim 2.1\ldots 2.4)$
  $\rightarrow$ diffuse shock acceleration ✓
- maximum rigidity?
- features? (knee, 2nd knee,...)

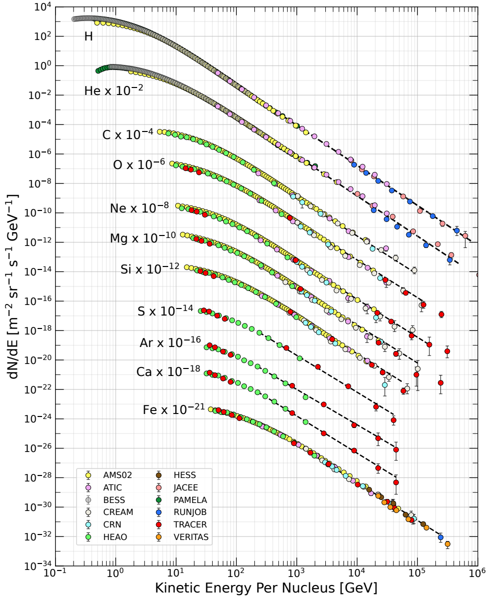
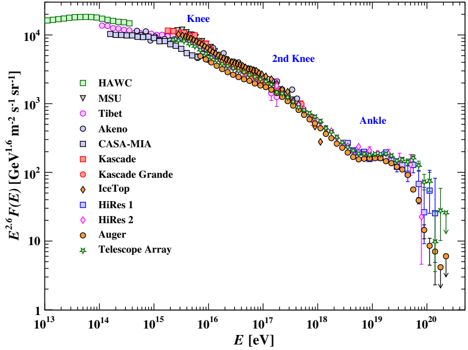


Figure 30.1: Fluxes of nuclei of the primary cosmic radiation in particles per energy-per-nucleus are plotted vs energy-per-nucleus using data from Refs. [1–15] The inset shows the H/He ratio as a function of rigidity [1,3].

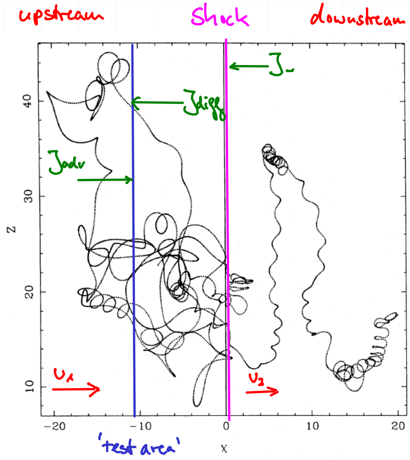


Maximum Energy in DSA

- lecture 6: $E(t) = E_0(1+\varepsilon)^n$, $n = \frac{t}{T_{cycle}}$
- but limit due to finite acceleration time T_A!
- acceleration rate: $\frac{dE}{dt} = \frac{\varepsilon \cdot E}{T_{cycle}}$ (using $\ln(1+\varepsilon) \approx \varepsilon$)
- flux through test area:
  - advective flow $J_{adv} = n(x)u_1$ (lecture 4)
  - diffuse flow $J_{diff} = -D_1 \frac{dn}{dx}$ (Fick's law, see lecture 4)
- stationary:

$$J_{adv} + J_{diff} = n u_1 - D_1 \frac{dn}{dx} = 0$$

$$\rightarrow n(x) = n_0 e^{\frac{u_1 x}{D_1}} \rightarrow N/A = \int_{-\infty}^{0} n(x)\,dx = \frac{n_0 D_1}{u_1}$$



K.R. Ballard and A.F. Heavens, MNRAS **259** (1992) 89

- average time upstream: (lecture 6: $J_- = \frac{n_0 c}{4}$)

$$\underline{\langle t_1 \rangle = (N/A)/J_- = \frac{4D_1}{u_1 c}}$$

Maximum Energy in DSA

- average time upstream: $\langle t_1 \rangle = \frac{4D_1}{u_1 c}$
- Similar for particles returning from downstream (see Drury 1983): $\langle t_2 \rangle = \frac{4D}{u_2 c}$
- $T_{cycle} = \frac{4}{c}\left(\frac{D_1}{u_1} + \frac{D_2}{u_2}\right)$
- $\left.\frac{dE}{dt}\right|_{accel} = \frac{E \cdot \varepsilon}{T_{cycle}}$

scattering length

Larmor radius

- minimum diffusion coefficient: $\lambda_D \sim r_L = \frac{p}{ZeB}$, $D = \frac{1}{3}\lambda_D \cdot v$
- $v \simeq c$, $p \cdot c \approx E$ $\Rightarrow D_{min} \sim \frac{1}{3}\frac{E}{ZeBc}$ ('Bohm diffusion')
- $D_1 \approx D_2 = D_{min}$ $(\vec{B} \parallel \vec{n}_{shock} \rightarrow B_1 = B_2)$, $u_2 = \frac{u_1}{4}$ (ideal gas, strong shock) → lecture 6

$$\Rightarrow T_{cycle} = \frac{20 D}{c \cdot u} = \frac{20}{3}\frac{E}{ZeBuc}$$

$$\Rightarrow \frac{dE}{dt} = \frac{3}{20}\,\varepsilon\, ZeBuc \neq f(\varepsilon)\,!!$$

Fermi 1st order: $\varepsilon = \frac{4}{3}\beta$

$\beta = V/c = \frac{u_1 - u_2}{c} = \frac{3}{4}\frac{u_1}{c}$

$$\Rightarrow \boxed{E(t) = \frac{3}{20}\, u_1^2\, B\, Z e\, t} \quad (u = const)$$

typical t, u_1, B in SNR ?? ⇒ detour:

- limited acceleration time T_A

$$E_{max} = E(T_A)$$

- but: energy losses during acceleration

e.g. synchrotron

very important for $e^{+/-}$!

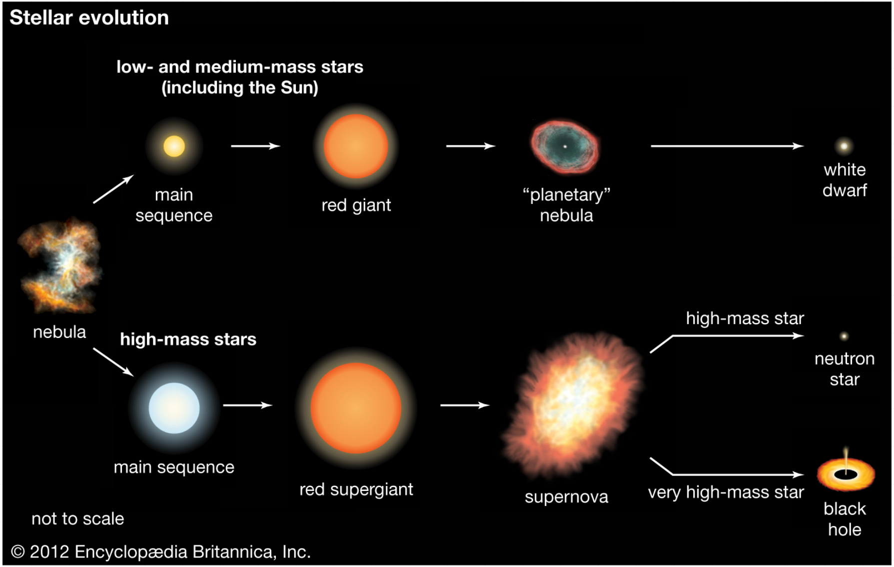
$$-\left.\frac{dE}{dt}\right|_{syn} \approx 1.6 \cdot 10^{-3}\,\frac{erg}{s}\left(\frac{Z}{A}\frac{m_e}{m}\right)^4 E^2 B^2$$

→ see ATP II $\gamma + \nu$ in summer!

- $dE/dt|_{accel} = -\left.\frac{dE}{dt}\right|_{syn}$

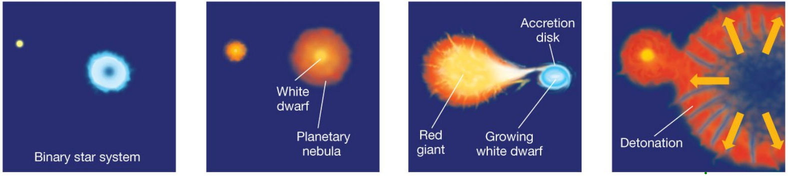
$$\Rightarrow E_{max}^{e^{+/-}} = 23\,\text{TeV}\,\frac{u_1}{c}\,\frac{1}{\sqrt{B/G}}$$

Detour: Stellar Evolution, Supernovae (SNe), Supernova Remnants (SNRs)



Thermonuclear Supernova (Type Ia)

runaway carbon fusion



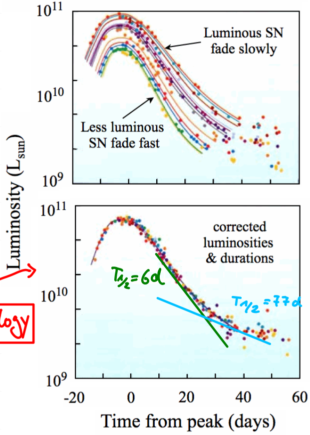
E. Chaisson, S. McMillan "Astronomy Today"

or WD-WD merger or ignition of shell

$L_{peak} \sim 5 \cdot 10^9 \, L_\odot$, $E \sim 1.5 \cdot 10^{51}$ erg

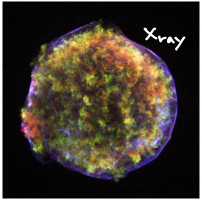
standard candle for cosmology

Lightcurves



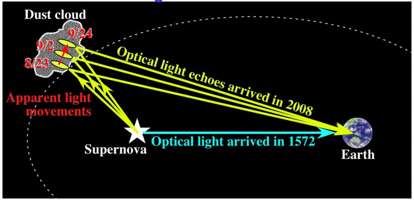
$^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$

Tycho SN1572



chandra.harvard.edu

measurement of light curve: (for historical SNRs)



subarutelescope.org

hydrogen lines?

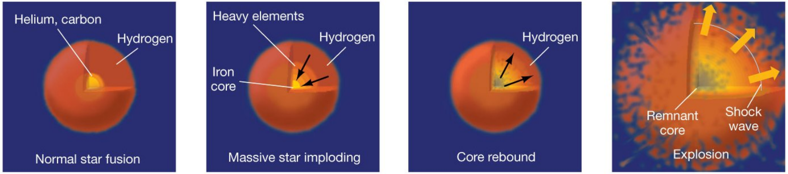
no → Type I

yes → Type II

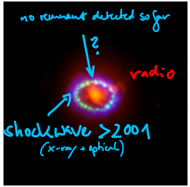
Core-Collapse Supernova (Type II, Ib, Ic)

collapse to neutron star after nucl. burning → Fe

(ejecta hit circumstellar ring of material)

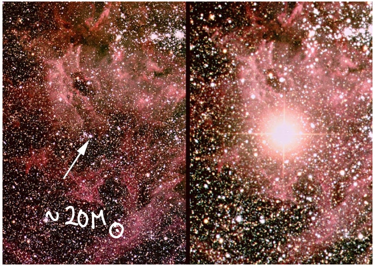


E. Chaisson, S. McMillan “Astronomy Today”

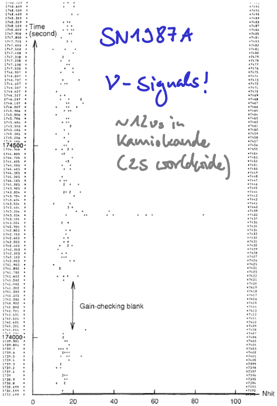


ALMA/Hubble/Chandra

$L_{peak} \sim 10^8 L_\odot$, $E \sim 10^{53}$ erg (ca. 100% in ν!)



SN1987A: GMC (d=50kpc) before + after



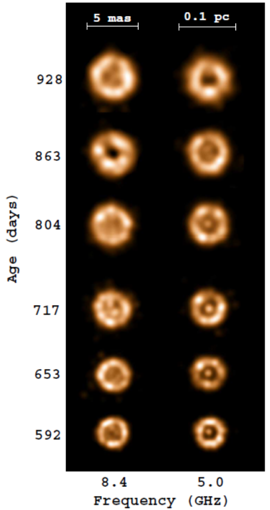
SN1987A

ν-Signals!

~12 νs in Kamiokande (25 worldwide)

M. Koshiba, Phys.Rept. **220** (1992) 229

SNR Evolution: Free Expansion



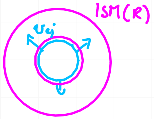
SN 2008iz in M82 ($d \sim 3.5$ Mpc), A. Brunthaler et al, arXiv:1011.5316

- ≈ undisturbed by swept-up material

$$M_{ej} \approx M_\odot \gg M_{sw}$$

- $v_{ej} = \left(\frac{2E_{SN}^{kin}}{M_{ej}}\right)^{\frac{1}{2}} \approx 10^4$ km/s ≈ const

- slow-down once $M_{sw} \approx M_{ej}$



$$M_{sw} = \frac{4}{3}\pi R^3 \rho_{ism}$$

- sweep-up radius

$$R_{sw} = \left(\frac{3M_{ej}}{4\pi\rho_0}\right)^{\frac{1}{3}} \qquad t_{sw} \sim M_{ej}^{5/6}\sqrt{E_{SN}^{kin}}\,\rho^{-\frac{1}{3}}$$

→ t_{sw} of several 100 years

SNR Evolution: Sedov-Taylor & Snow-Plow Phase

dimensional analysis:

unknown: $R(t)$ $\quad [R] = L$

initial conditions: E_{SN}^{kin} $\quad [E] = M L^2 / T^2$

ρ_{ISM} $\quad [\rho] = M / L^3$

$$\boxed{R(t) = \text{const} \left(\frac{E_{SN}^{kin}}{\rho_{ISM}} \right)^{\frac{1}{5}} t^{2/5}}$$

$\text{const} = O(1)$

Ansatz: $[R] = L = [E]^{\alpha} [\rho]^{\beta} [t]^{\gamma}$

$$= M^{\alpha+\beta} L^{2\alpha-3\beta} T^{-2\alpha+\gamma}$$

$\Rightarrow$ ① $\alpha + \beta = 0 \Rightarrow \alpha = -\beta$ $\quad \Rightarrow \beta = -\frac{1}{5}$

② $2\alpha - 3\beta = 1$ $\quad \Rightarrow \alpha = \frac{1}{5}$

③ $-2\alpha + \gamma = 0$ $\quad \Rightarrow \gamma = \frac{2}{5}$

$$v(t) = \frac{dR}{dt} \sim t^{-3/5}$$

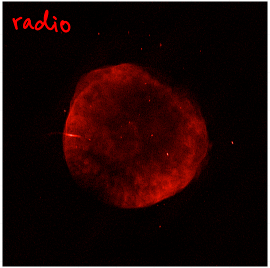
Snow-Plow: radiative cooling

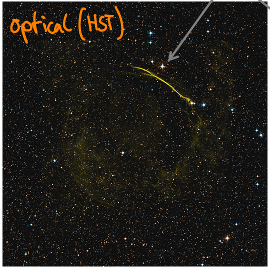
- $T < T_{recomb}$ → recombination, transparent, cooling via line-emission
- once $v \approx a_{ISM}$ → SNR merges with ISM

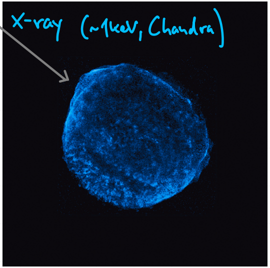
Shell-Emission from SN 1006

filaments $\Delta x \approx 10^{-2}\,\mathrm{pc}$

$\Delta x \approx \sqrt{D(E)\,\tau_{loss}(E)} \approx 0.04\,\mathrm{pc}\left(\frac{B}{100\,\mu G}\right)^{-\frac{3}{2}}$

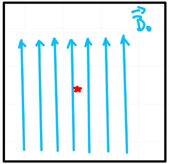


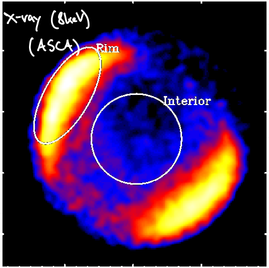


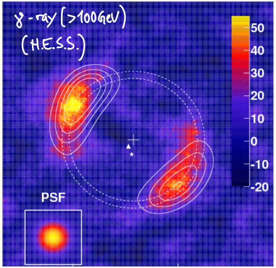


$B \gg B_{ISM}$!!

⇒ compression ?



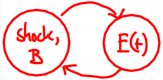




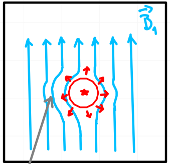
⇒ selfgenerated magnetic field ?

non-linear DSA:

accel. charged particles



amplify magnetic field

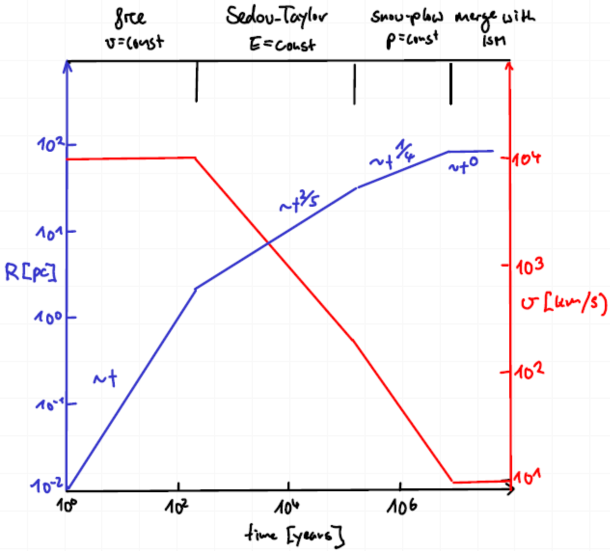


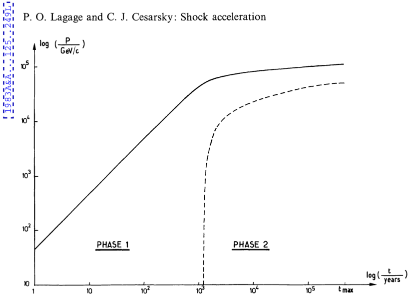
compressed $\vec{B}_1 > \vec{B}_0$

asymmetric limb brightening

⇒ non-thermal emission from SNR shock!

Maximum Energy





$$\boxed{E(t) = \frac{3}{20} u_1^2 B Z e t} \approx 5\cdot 10^{13}\,\mathrm{eV}\left(\frac{u_1}{10^4\,\mathrm{km/s}}\right)^2 \frac{B}{\mu G}\,\frac{t}{10^3\,\mathrm{yr}}$$

- SNRs: a) Sedov-Taylor : $v \sim t^{-3/5}$
  b) free expansion : $v = \mathrm{const}$
  → E_{max} at t_{sw} when $M_{sw} \sim M_{ej}$
- example: $t_{sw} = 500$ yr, $u_1 = 10^4$ km/s
  $B_{ISM} = 3\mu G$ → $E_{max} \approx Z \cdot 7 \cdot 10^{13}$ eV
  $B_{shock} = 100\mu G$ → $E_{max} \approx Z \cdot 2 \cdot 10^{15}$ eV

Standard Paradigm of Galactic Cosmic Rays

'Peters' cycle

$$\boxed{E_{max} \sim Z \cdot R_{max}}$$

B.Peters 1961

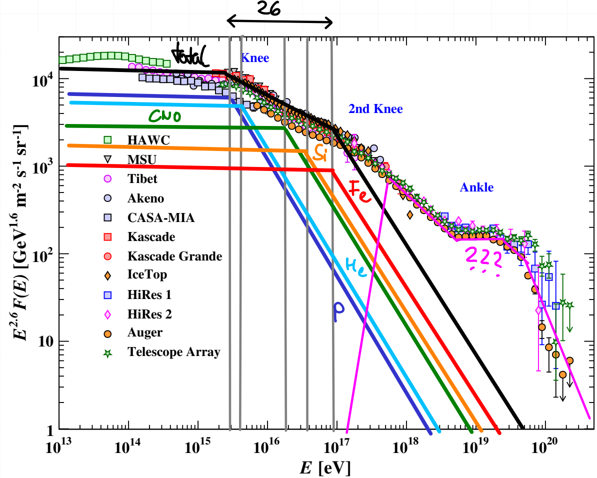


Figure 30.9: The all-particle spectrum as a function of E (energy-per-nucleus) from air shower measurements [106–119]

Particle Data Group 2022

Standard Paradigm of Galactic Cosmic Rays

Observation:

- mass abundance $\sim$ solar
- Li-B, F, Sc-Mn overabundant
- $\lambda(R) \propto R^{-\delta}$, $\delta \sim 1/3 \ldots 1/2$
- cosmic clocks: $c\,\tau_{\mathrm{esc}}\,\rho_{\mathrm{ISM}} > \lambda_{\mathrm{esc}}$
- energy density: $u_{\mathrm{CR}} \approx 1\ \mathrm{eV}/\mathrm{cm}^3$
- power law: $J \propto E^{-\alpha-\delta}$
- $\alpha = \gamma - \delta = 2.1 \ldots 2.4$
- spectral features (knees)
- energies up to $\sim 10^{17}\ \mathrm{eV}$

Explanation:

- stellar origin, ISM
- secondary fragments
- diffusive propagation in turbulent B-field
- diffusion in disk and halo
- SNRs, $\sim 1 - 10\%$ of L_{SN}
- stochastic acceleration and escape
- diffuse shock acceleration (DSA)
- $E_{\mathrm{max}} = ZeR_{\mathrm{max}}$, 'Peters Cycle'
- $Z = 26$, nonlinear DSA, B-field amplification

power spectrum

$E(k) \sim k^{\delta-2}$

Happy Cosmic Holidays!