Colors of the Universe

- **Nebulae / emission (H_{II} regions)**
- **reminders on microphysics of light emission**
- (+ some bonus sideways :-))

→ *Let's start with the reminders*

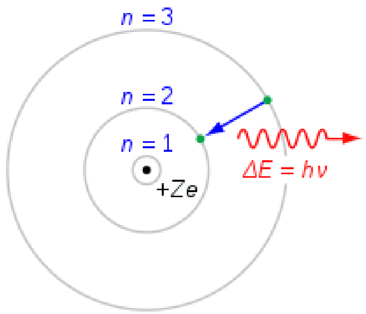
(Nebulae color's : [next week]())

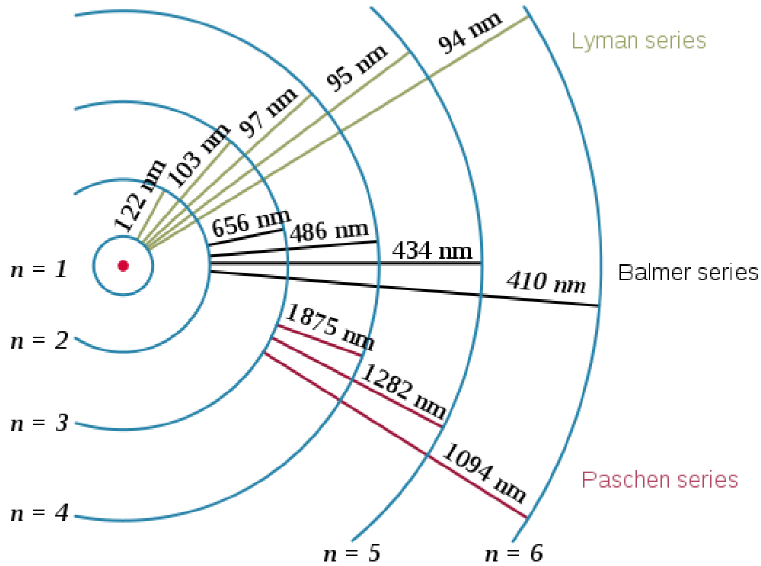
Reminders on **microphysics of light emission**

1: Atom ; electronic shell → de-excited electron + photon

shell = stationary electron wave
as if captured photon

$E = mc^2$, $E = h\nu \rightarrow$ *Compton* $\lambda = \dfrac{h}{mc}$





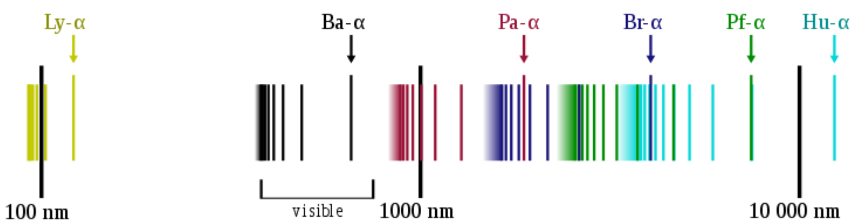
$$E_n = -\frac{Z^2 e^4 m_0}{2\hbar^2 n^2}$$

(for Hydrogen)

ionized / recombination = goto ∞ *(91nm) ~ highest excited*

→ *Rydberg formula:* $\nu = \dfrac{c}{\lambda} = cRZ^2 \left(\dfrac{1}{n'^2} - \dfrac{1}{n^2}\right)$ → ***line spectrum***

91 $H_\alpha = Ba_\alpha =$ pink



Hydrogen spectral series

UV *visible* *IR* *far IR…*

NB: not really Diracs (mvt → Doppler , + uncertainty principle / Fourier)

Anyway, isolated atoms are rare !

→

1b: Molecules, complex molecules, metals, crystals

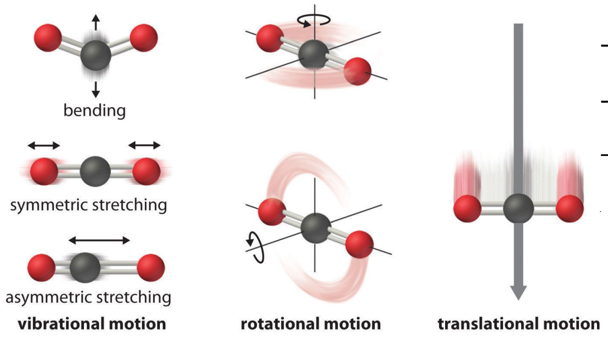
Very weak bands (far IR -> microwave -> radio) *e.g.,* H_2 *(µw oven)*

Then break to atoms → totally different emission look $H : H_I$

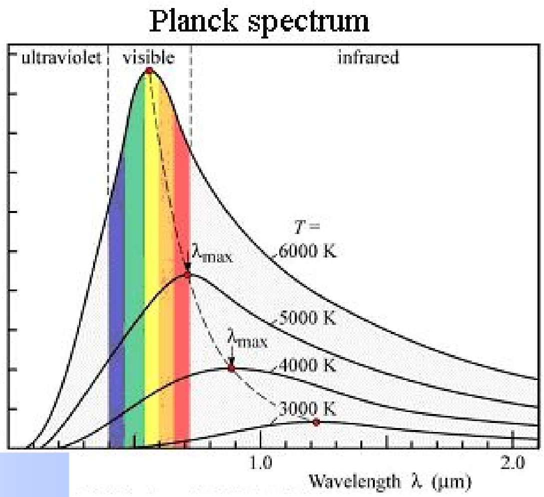
Then ionize → yet totally different emission look $H^+ : H_{II}$

2: Black Body spectrum

Molecular mechanical DOF (~T): de-excited + photon



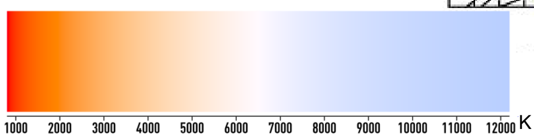
→ accelerated dipoles (~ oscillating EM field)
→ can emit
→ cf: charge acceleration (↗, ↘, ↷)
⇒ synchrotron radiation



In fact, quantized too.
But numerous modes + non-linearities +
*macroscopic balance → **continuous spectrum***
A lot more energy !

Sideway: perception:

no green star :-)



peak ≠ in λ vs ν

3: forbidden modes (Nature >> lab)

- *In practice, continuous exchanges btw DOF (including electron level).*
- *E.g.: inelastic collision → excited DOF or electron → inelastic collision*
  (→ emerging notion of T, unique global scalar at balance).
- *Deep vacuum: electron might de-excite before next (rare) collision*
  (once mysterious "Nebulium", "Coronium" → forbidden transition)

Equivalences and reciprocities

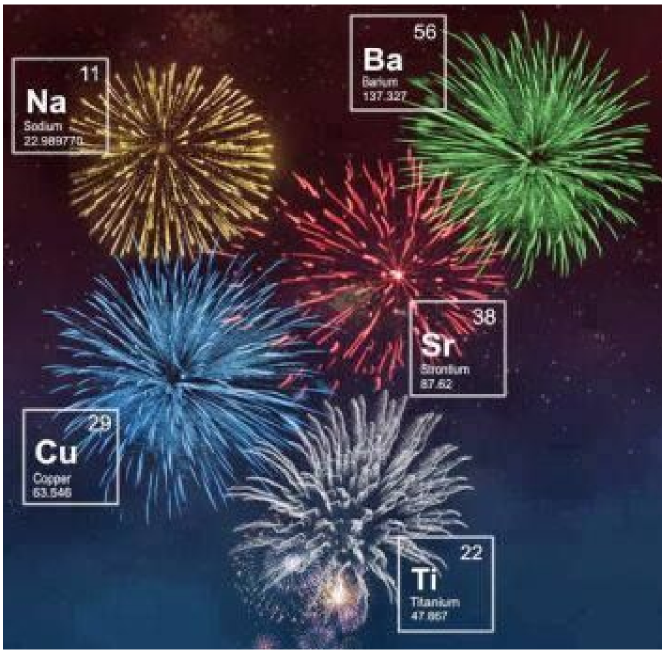
weak emitter ⇒ weak absorber ⇒ transparent *(e.g., H_2 . c/: BB)*
⇒ hard to heat (with radiations) + hard to cool.

Sideway:

- *Collapsing gas clouds into star requires dust*
  collapse: heats→ (2ble)pressure → balance gravity
  dust: radiates → cools → P↘ → gravity win over pressure
- *Reason why black matter is diffuse*

Sideway | application: fire & fireworks

- *very hot → ionized → line emission*
- *kitchen gas, + throw salt etc.*
- *fireworks: black powder + added "salt"*

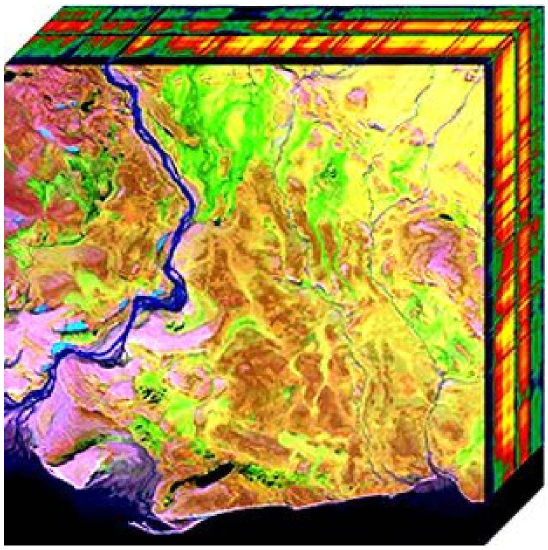


… + one "special case": (only happens to be ultra frequent)

carbon material + oxygen → partial combustion → soot (= nanopartic)

- *BlackBody continuous spectrum (~ 1000°C)*
- *ultra-bright (masks lines)*
- *ultra-opaque (→ heats a lot, + oven effect)*
- *smoke (same, if undispersed)*

Sideway: hyperspectral images + a world in a pixel



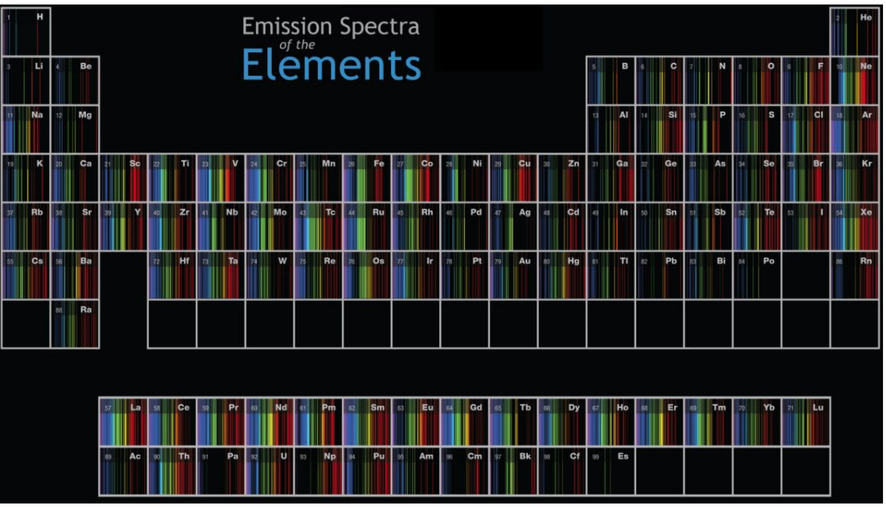
Hyperspectral: *a spectrum per pixel*
Look at surfaces (usually)
→ directly “read” materials (reflect. spectrum)
→ separating lighting easy

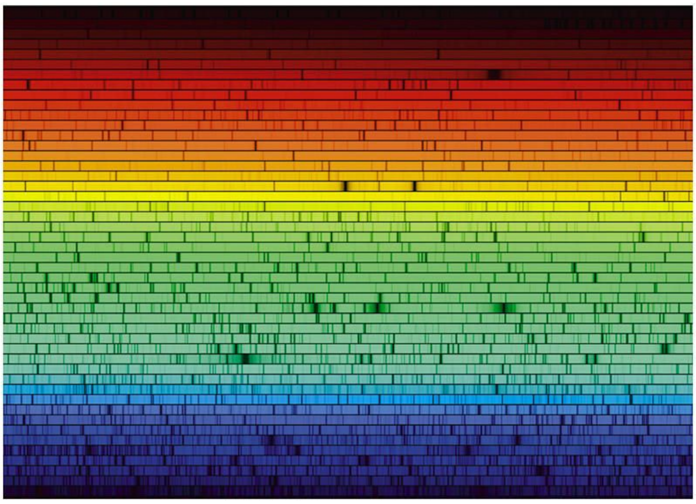
Multispectral: *some discrete bands*

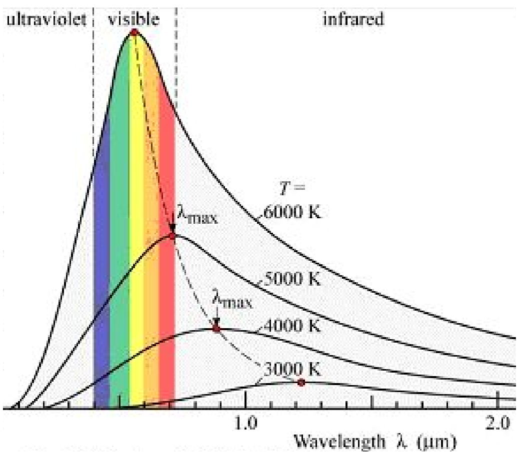
Astronomy:
- *nebulae quite homogeneous*
- *lighting simple (no shadows ; direct emission lines…)*
- *stars = points, + planets & binaries ; transparent medium*

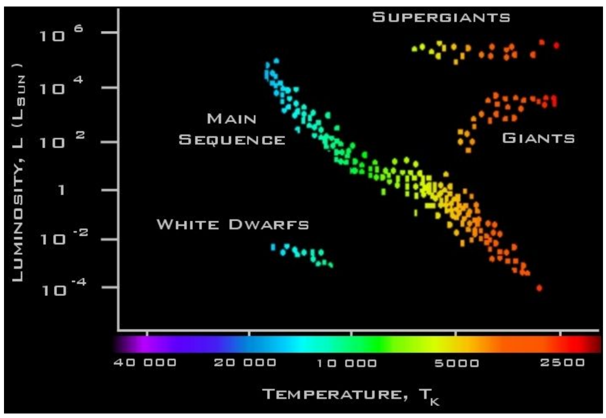
But: many things along ray (vol) / in the pixel

→ analyzing one pixel.
trick: recognize lines pattern (=material) in spectrum
or BB(T) (+ we know absL(T)) + absorption lines



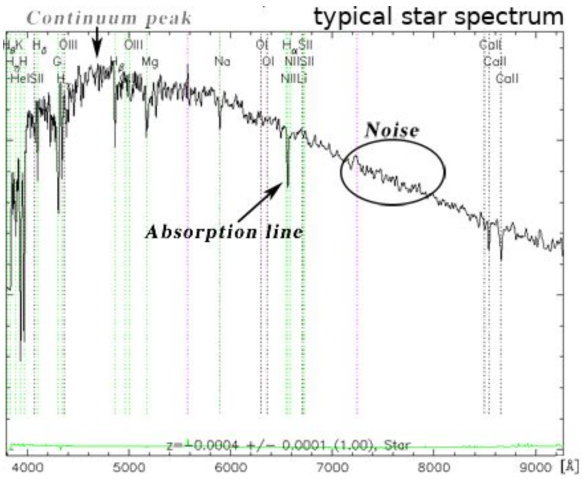


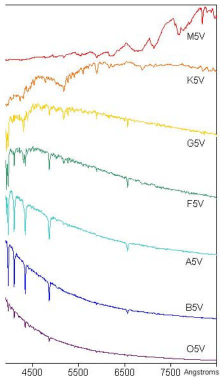


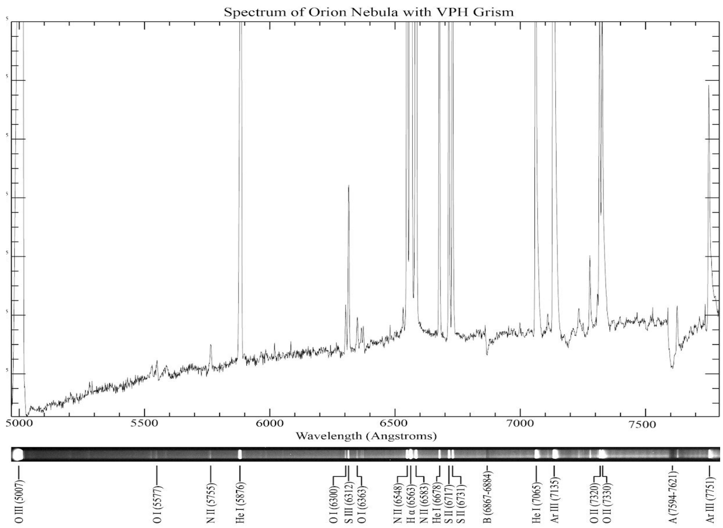


A world in a pixel

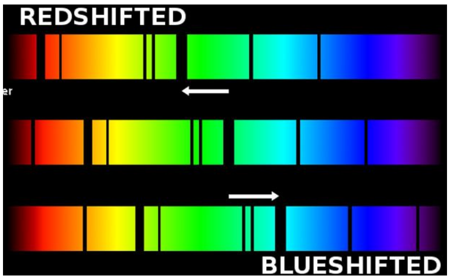
- *material mix (+ correlation: e.g. CO for H_2) : pattern*
- *temperature (BB/IR ; + lines of split molecules / ionization): shape, presence*

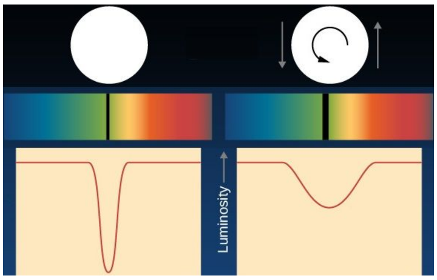


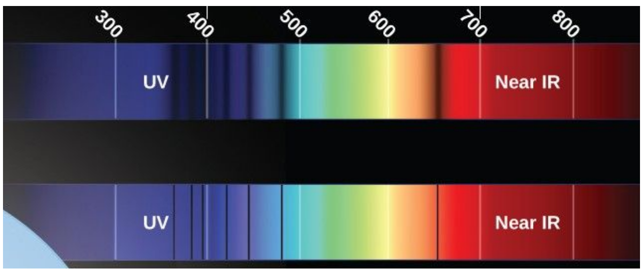




- *radial velocity / high distance (via expansion): red/blue shift of pattern*
- *rotating: blurry pattern*
- *binary stars: doubled pattern*
- *photosphere temperature: blurry absorption lines*







- *separating distant objects along ray: different shifts superimposed*
- *magnetic field (+ orientation) : polarization*

- *planet/binary + period : variation of L in time*

  + atmosphere composition: variation of spectrum in time

… all this from one pixel !

Disclaimers

I'm not physicist ;-)
just my understanding & memory + fast sketching

Other emission types reducing to previous:
laser (sync de-excitation), auroras, airglow (ionization, etc) , lightning & electric arcs (plasma), photoluminescence [=fluo+phospho] (de-excitation), "neon" tubes (ionization+fluorescence), bio/chemio-luminescence (Δmolec→Δshells) ...

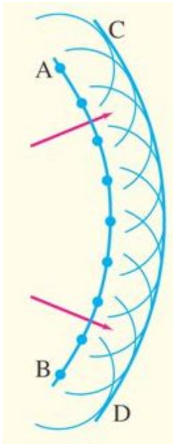
Emission modes not covered:
LED (gap - e^- annihilation), laser-LED (quantum box), Cherenkov radiation (Vpartics > light), Unruh effect (referential-dep. photons), sonoluminescence (unknown), various particle decays and interactions...

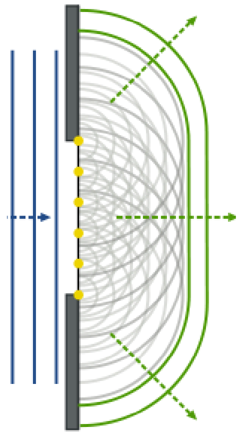
+ passive effects:
effects of diffractions (includes refrac & reflec), scatterings (Rayleigh,Mie,...), interferences & irisations, + everything in materials [+ scale matters]...

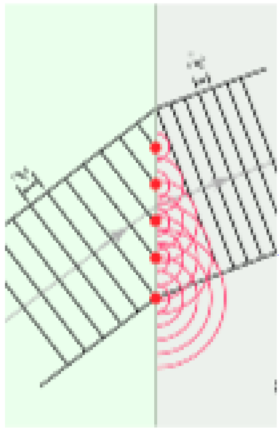
Sideway: Refraction as a subset of diffraction
Microphysics of refraction

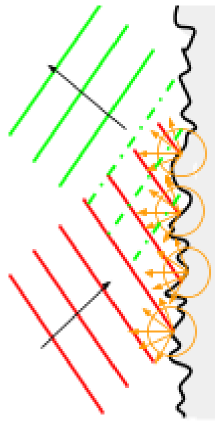
1. Huygens principle

Diffraction everywhere
Forget ray / photon "particle"
→ all waves
→ whole geometrical optic emerges.



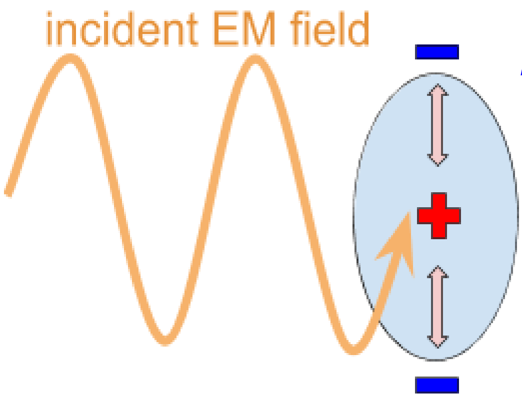






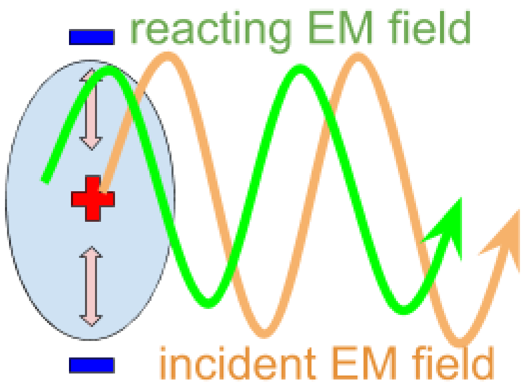
2. Microphysics of refraction: dipole reacting EM field

(= coherent Rayleigh)



Dielectric:

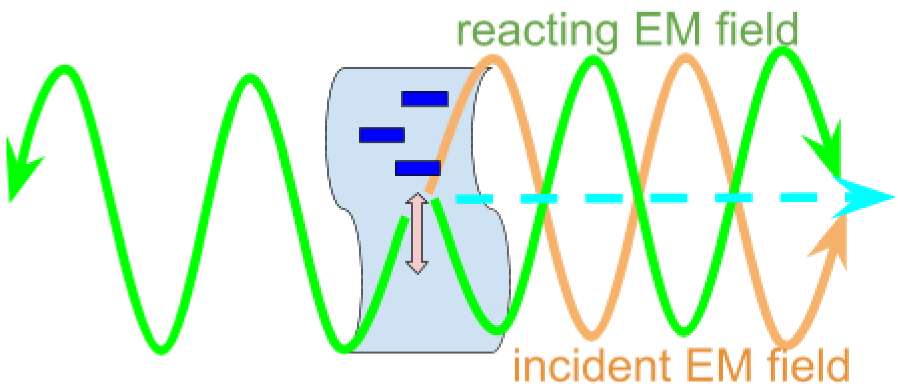
- *dielectric deforms in EM wave plane*
- *reacts with a delay (analogous mass-spring)*
- *charge motion → induced EM field (all dirs)*
  → Huygens : fronts (partic dist << λ)



- *sum: resulting field = late-phased*
- *accumulation: closer fronts, slower phases*
  "slower light" $v = \frac{c}{n} = \frac{1}{\sqrt{\mu\varepsilon}}$
- *but E (group velocity) keeps c speed*
  Where is the photon ? :-)
  (could induce miss-predictions)

***Conductor** (ideal) :*

- *electrons very mobiles*
- *kills incident wave*
- *reflect all (th: no color)*



Sideway: microphysics of c

For whole kinds of waves, $c = \sqrt{\frac{reactivity}{inertia\,factor}}$

reason: just the differential equation :

<u>Harmonic oscillator</u>: e.g.: mass - spring

Newton: ma = F

$$(m)\,\frac{\partial^2 X}{\partial t^2} = -(k)\,X \;\rightarrow\; X = A\,\cos(\sqrt{\tfrac{k}{m}}\,t + \phi)$$

(BTW: + forcing term = EM waves → dielectric dipole reaction → refr. index)

<u>Wave equation:</u> medium = chained oscillators

$$(m')\,\frac{\partial^2 X}{\partial t^2} = (k')\,\frac{\partial^2 X}{\partial x^2} \;\rightarrow\; X = A\,cos(\tfrac{2\pi}{\lambda}(x - c_\varphi t) + \phi),\; c_\varphi = \sqrt{\tfrac{k'}{m'}}$$

$$\rightarrow c_\varphi = \sqrt{\frac{elasticity(Young)}{density}}$$

is the speed of information in a medium (sound, Froude, seism…)

<u>EM</u> (Maxwell): $\mu\,\frac{\partial^2 E,B}{\partial t^2} = \frac{1}{\varepsilon}\,\frac{\partial^2 E,B}{\partial x^2}$ *(permittivity*$^{-1}$ $1/\varepsilon$ *~ F between 2 charges , like k)*

$\rightarrow c_\varphi = \sqrt{\frac{1/\varepsilon}{\mu}} = \frac{1}{\sqrt{\mu\varepsilon}}$ *(material permeability* μ *& permittivity* ε *)*

Vacuum: $c_0 = \frac{1}{\sqrt{\mu_0\varepsilon_0}}$ *Vacuum is a dielectric medium:*

has properties: <u>vacuum permittivity</u> ε_0 *= 8.85... 10*$^{-12}$ *F/m*

<u>vacuum permeability</u> $\mu_0 = 4\pi\;10^{-7}$ *H/m*

<u>free space impedance</u> $Z_0 = \mu_0 c$ *= 376.73...* Ω

<u>vacuum energy</u> $= 10^{-9} - 10^{113}\;J/m^3$ *:-)*

→ fluctuations, creation/annihilation of <u>"virtual" particles</u> +-

→ <u>QM vacuum</u> is <u>polarizable</u> (i.e.: dielectric-like dipole)

+ Casimir effect, shifts in material properties (Lamb shift, …),
causes of <u>spontaneous</u> photon emission, ~ van der Waals force, etc.

→ c is not about "light".

***Relativity**: "c = max speed, speed of massless, speed of information"*

***QM**: "c = characteristic of the vacuum 'medium' (speed of info) " (?)*