Colors of the Universe

I've seen things you people wouldn't believe. Attack ships on fire off the shoulder of Orion. I watched C-beams glitter in the dark near the Tannhäuser Gate. All those moments will be lost in time, like tears in rain.

more specifically:

- Nebulae / emission (H_{II} regions)

- reminders on microphysics of light emission (prev week)
- (+ some bonus sideways :-))

Motivations:

- Galaxy / veRTIGE collaboration (is small bit)

- emission (ionized) nebulae more beautiful;
reflection & absorption nebulae too ordinary CG :-)

Galaxy / veRTIGE project ~ 2011-2015

RSA-Cosmos , GEPI+LERMA / Obs.Meudon , INRIA

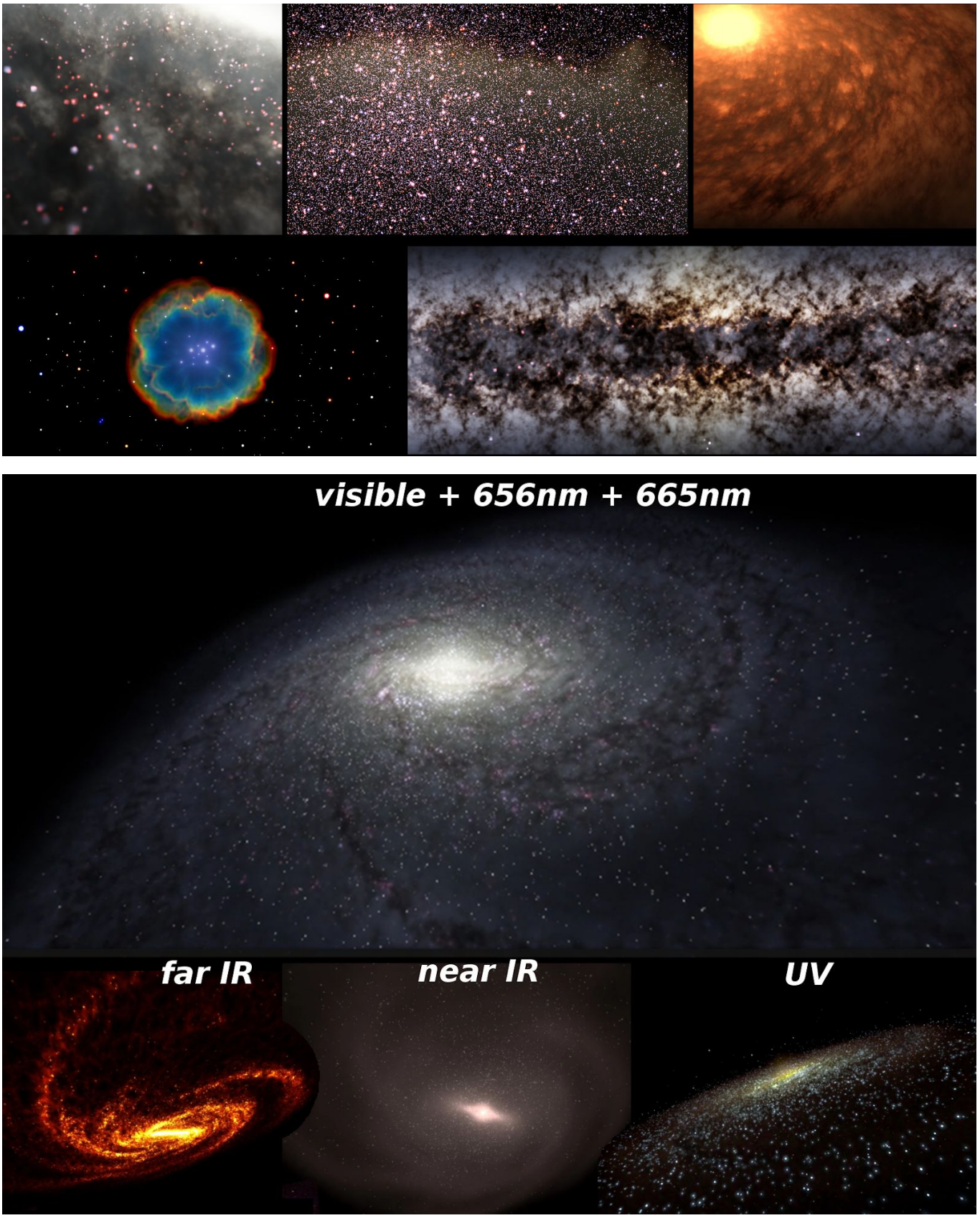
virtual Galaxy exploration *(inside & outside, all scales)*
- *photo-realistic* *(Hubble-like images)*
- *multispectral* *(~ Hubble imager, 48 filters, large to peak)*
- *hard real-time, in highres*

M51

Mixes galaxy simulation, astro catalogs,
(uncomplete) astrophys + phys knowledge *= laws + empirics + data*
procedural amplification, GPU voxel rendering (GigaVoxels).

→ $H_{||}$ Nebulae was just a very small bit.

Galaxy / veRTIGE project: Results



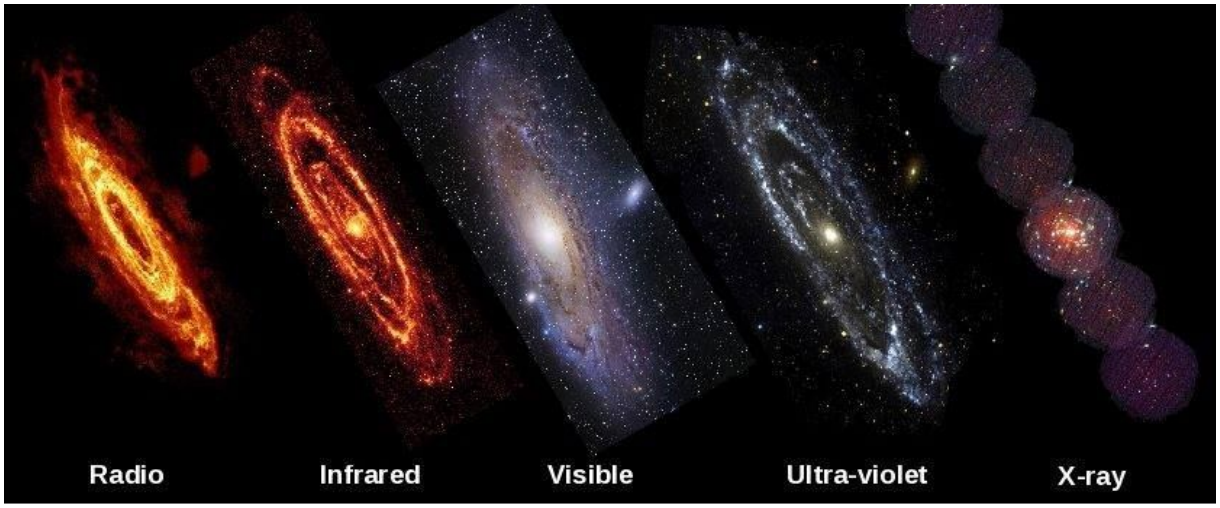
[article + video]

What are nebulae: the big figure

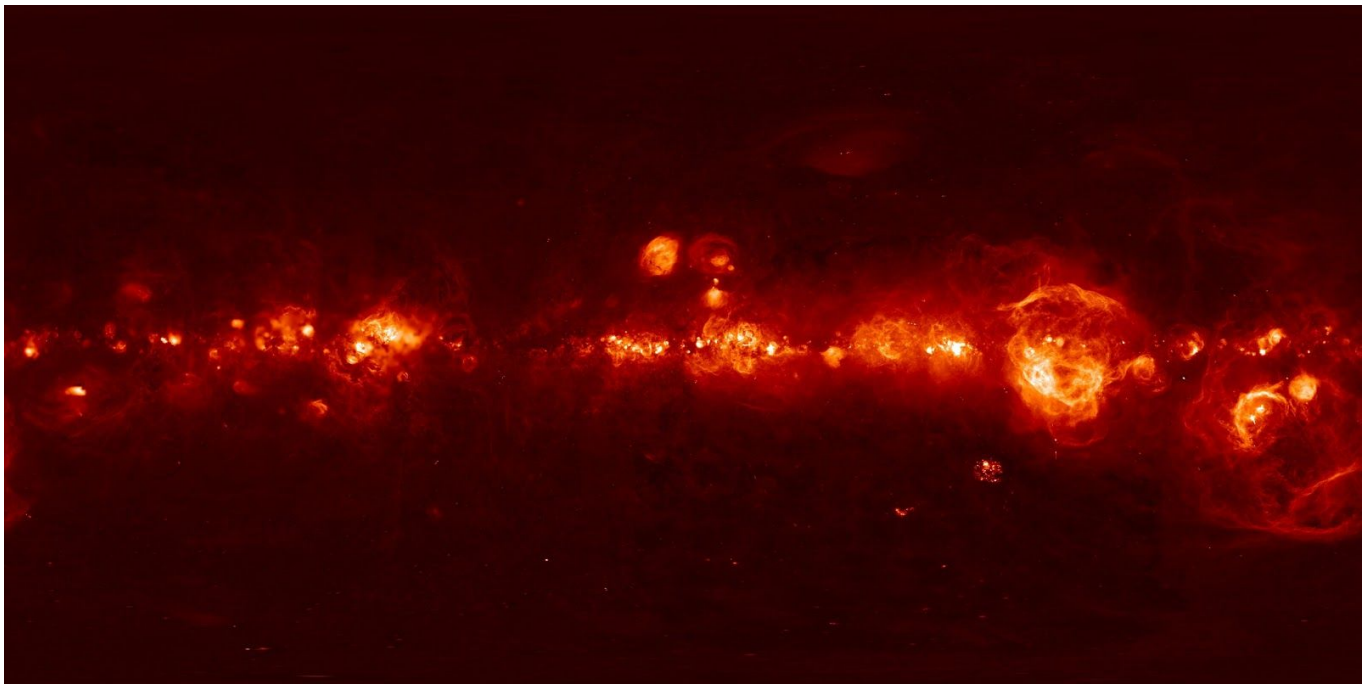
- *dark clouds (H+dust)*
- *spiral gravity waves*
- *concentrate/collapse*
- *new stars. Blue giants (O,B)*
- *UV (ionize,dissolve) +pressure*
- *bubble phase I,II*
- *supernova*
- *phase III: big/super bubbles*

visible (RGB) : all pink (boring)

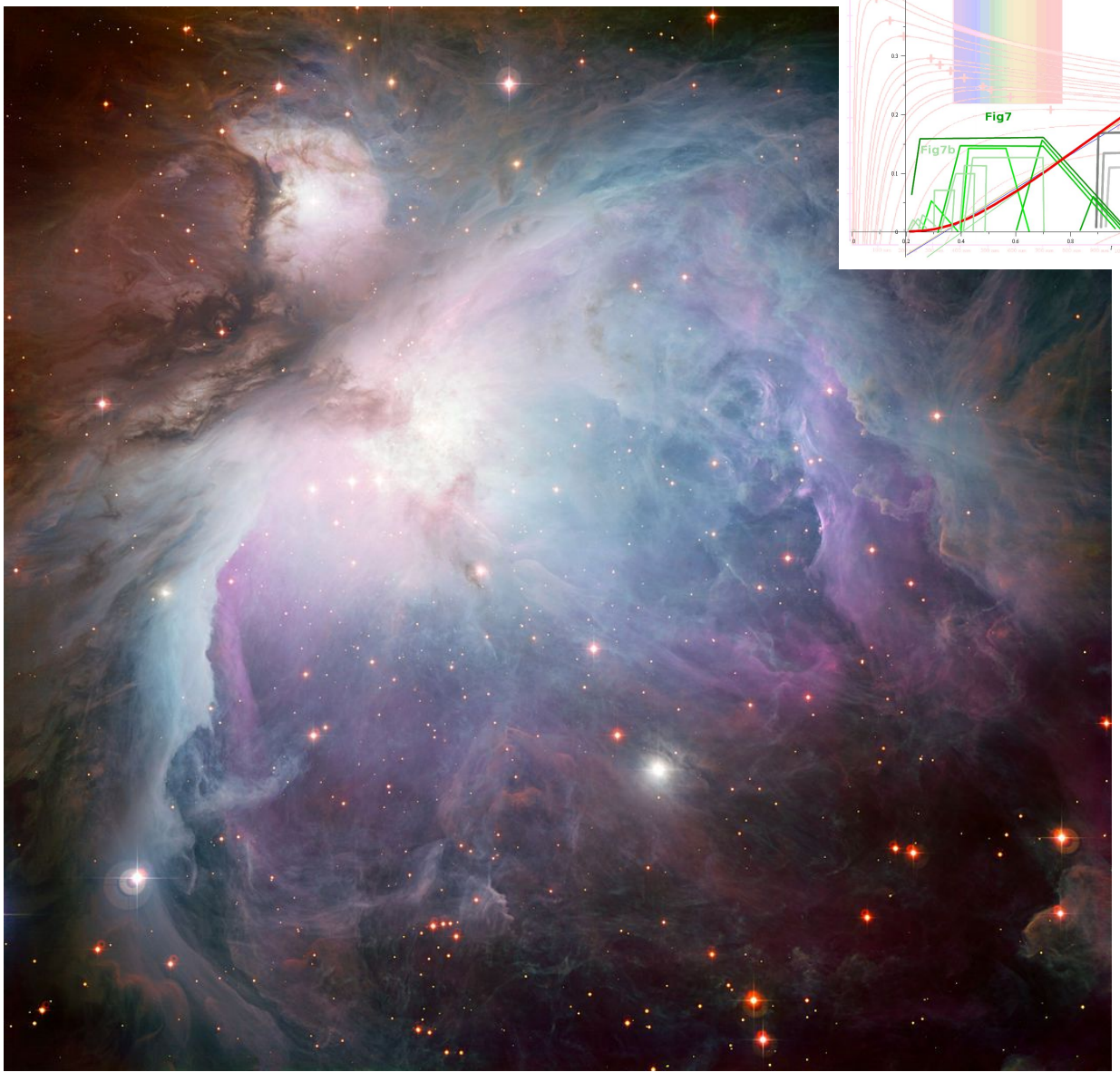
EM spectrum so much richer ! (3D vs ∞D)

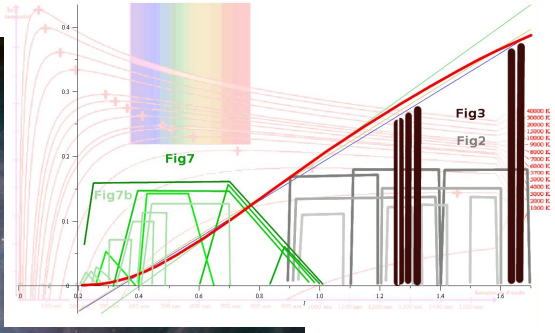


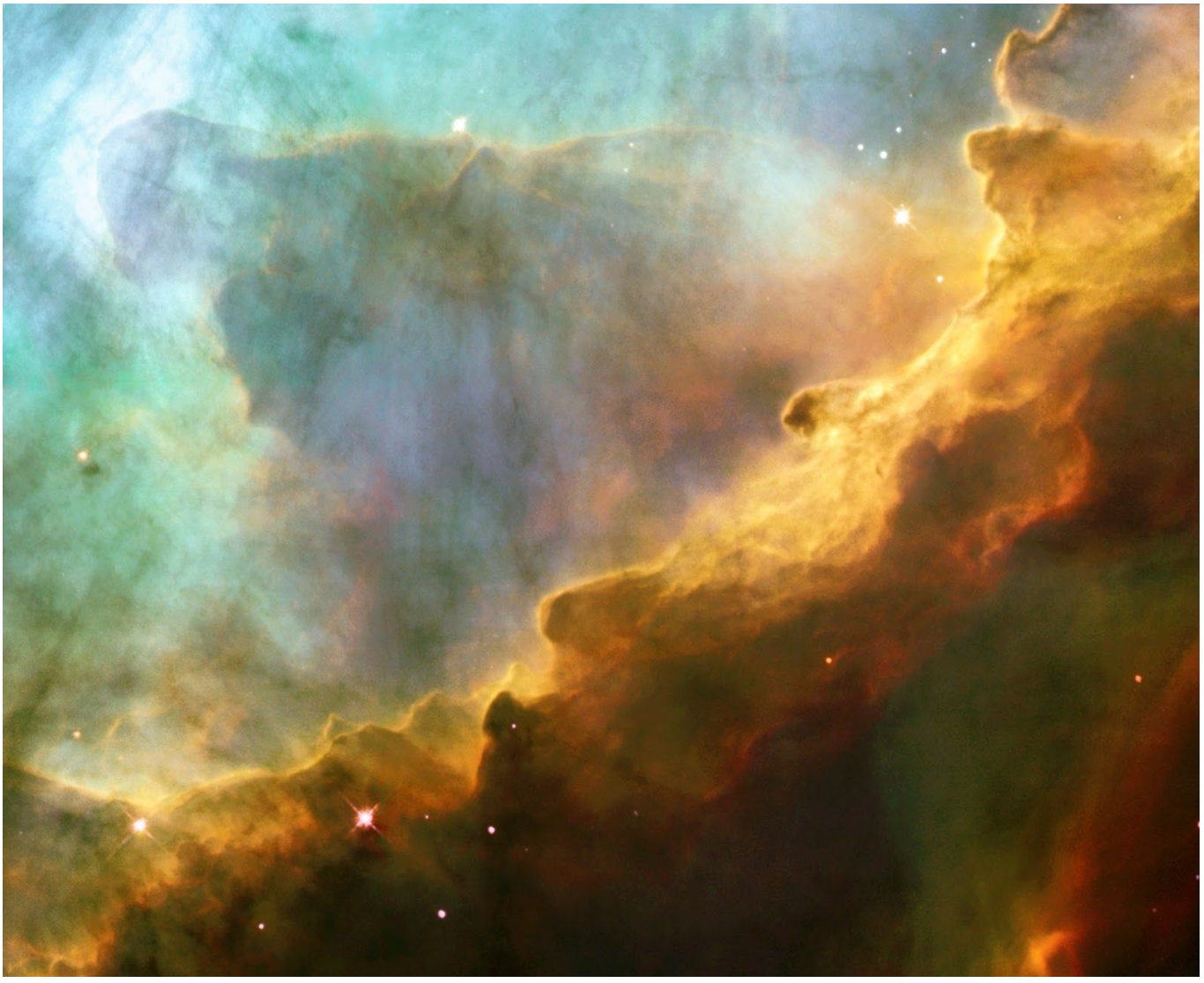
Filters from IR to UV + bands → peep spectrum in false colors



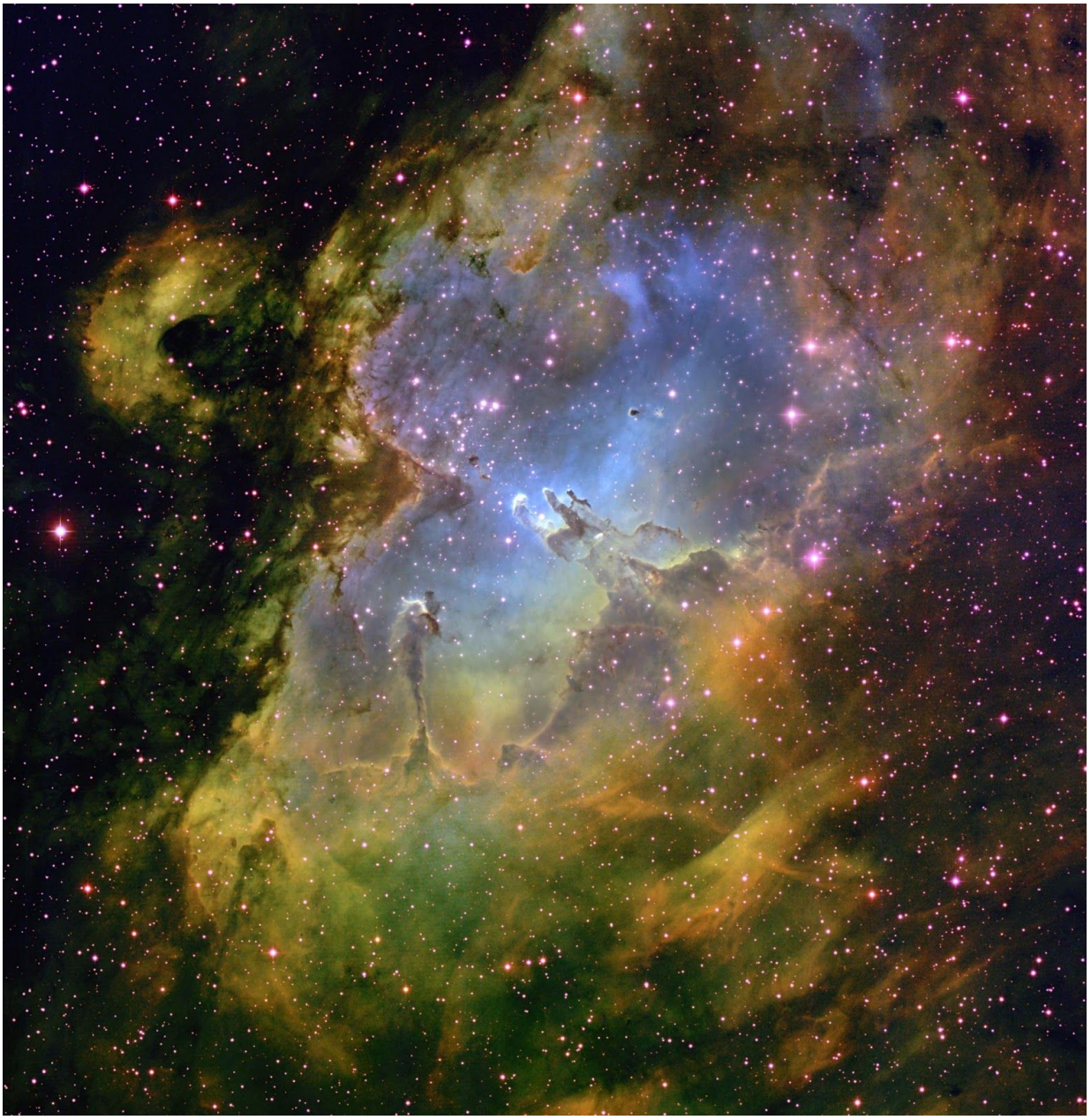
MilkyWay explorer @ GalaxyMap project - Sky-map (v2) - Chromoscope







Eagle



Pillars of creation

→ *let now explain all these colors (goal: synthesize nebula)*

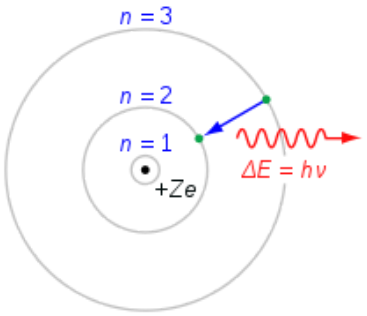
Raw story:

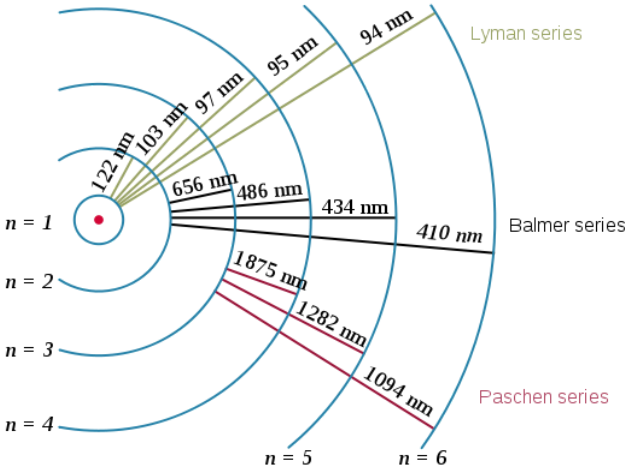
- *(Super)giant blue star (O/B)*
  15-150 M_S , 30-50k °K , BB: 10k-10M l_S
  → *UVs Hell*
- *Gas around (mostly H_2) ionized→H_{II}*
  → *ionize↔recombination+photon*
  → *+ other species: spectral lines*

Simple figure: homogeneous ionized Hydrogen

Atom ; electronic shell → de-excited electron + photon

(cf reminders on microphysics of light emission)





(for Hydrogen)

ionized / recombination = goto ∞ ~ highest excited

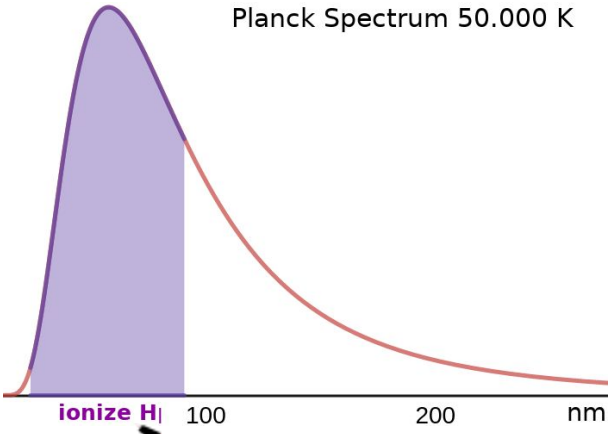
Ionization Energy ≡ E photon ≤ 91nm

Efficiency: ionization cross section ~ $\frac{1}{\nu^3}$

→ Star's UV within 10-40 … 91 nm :

absorbed into $H_{|}$ ionization

rest: pass through



Once ionized, $H_{||}$ transparent → 1st front

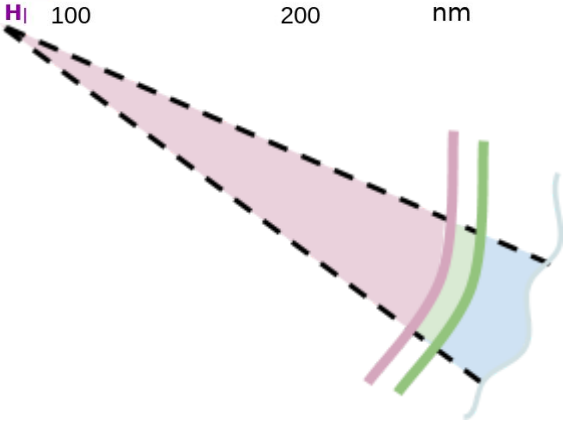
But: recombinations (gas of e^- around H^+→rate)

- *emit light*
- *H to be broken again → absorb UV again*

→ some column of H eats 100% UVs

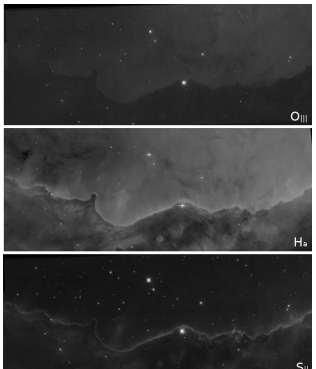
→ ***Strömgren sphere****: N recomb/s = flux photons*

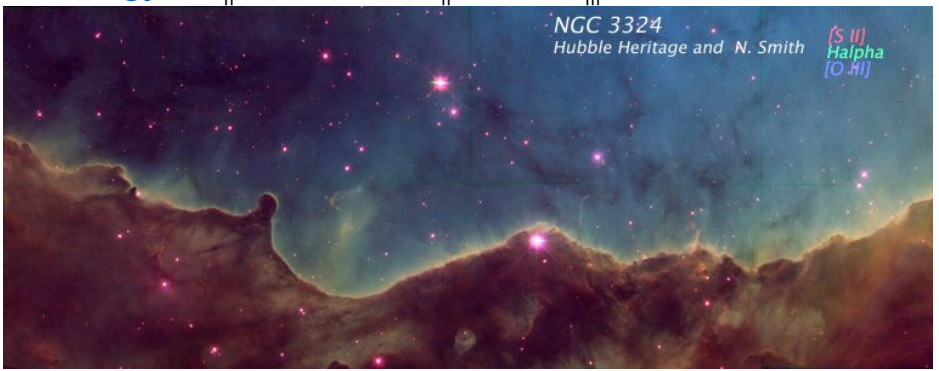
lum cst, not in 1/r² ! *bottleneck = matter, not photons*



Other species: (a lot rarer)

- *can eat weaker star photons; emit different peaks*
- *yield different Strömgren radius → colored shells*
- *depends on Ionization energy : $H_{||}$: 1312 kJ/mol, $S_{||}$: 1000 $O_{|||}$: 3388*

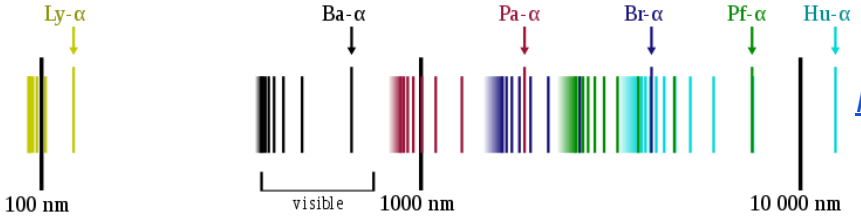




More realistic figure: spectrum

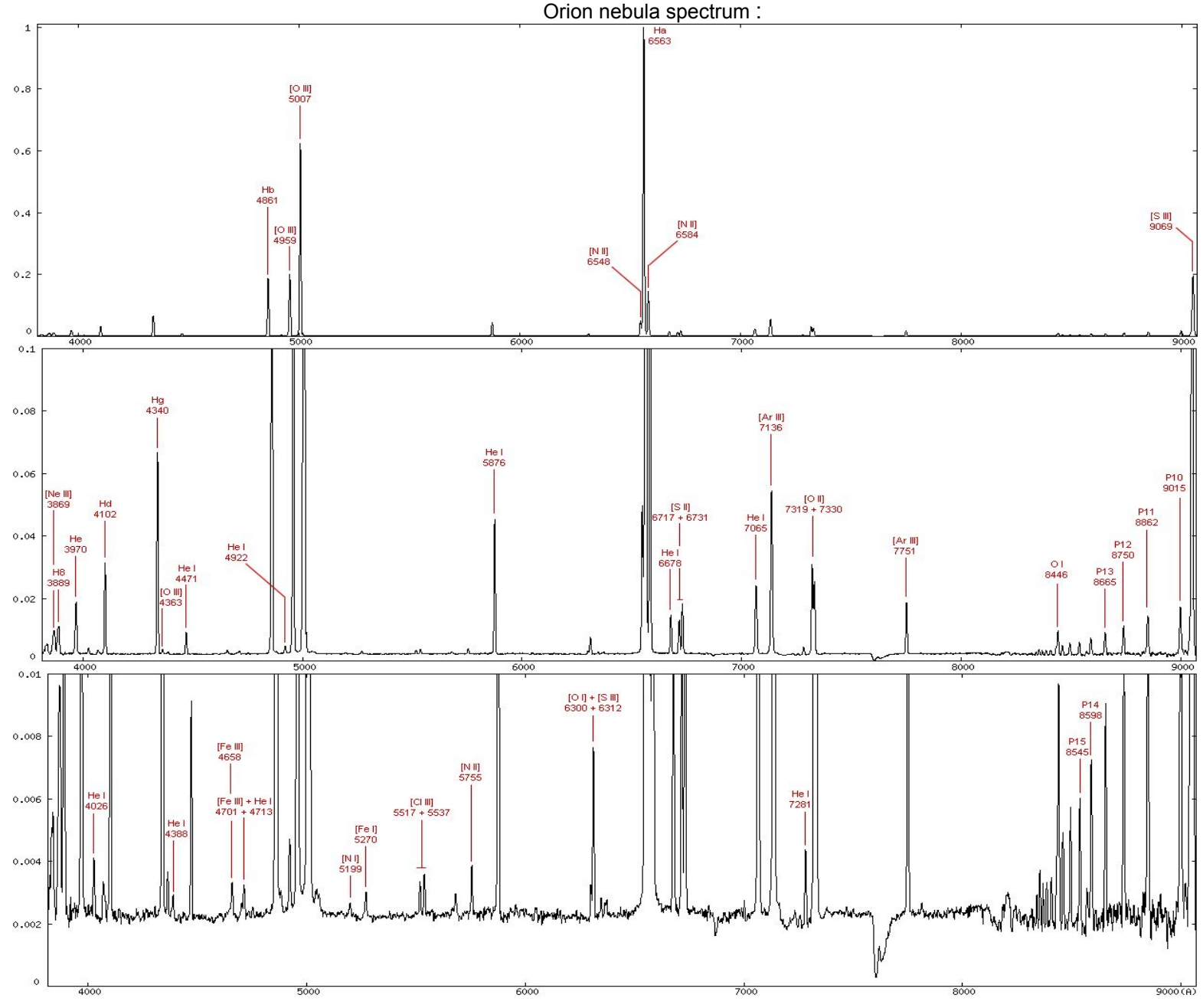
- *H reemit most in UV → reabs → lines not visible ; ~ UV diffusion*
- *99% E used to heat e⁻ → de-excitations → spectral series (collisional lines)*
  *→ **99% E re-emitted as fluorescence**, not recombination*
  → H_α , S_{II} , O_{III} … (collisional excitation , forbidden transitions)

$H_\alpha = Ba_\alpha = 3 \rightarrow 2$ = pink



Hydrogen spectral series

Orion nebula spectrum :



More realistic figure: shape

- *Strömgren radius: H assumed uniform, but:*

  proba recombination = $\rho_{ion}\ \rho_{e^-}\ \alpha_{n,T}$. *H:* $\sim\rho^2$ *: non linear !*

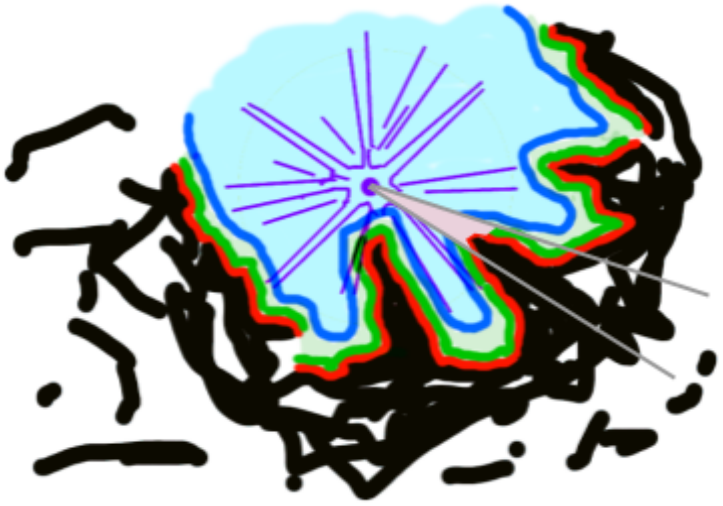
  → *matter distrib change everything !* (*denser → bright++, opaque++*)

  … and matter really not homogeneous (*prev cloud, bubble, pillars*)

  NB: loc more linear for other species (<< *H →* e^- *provided by H*) *but correl*

  → ***not spheres*** *!*

  ~topological Strömgren sphere/shells: (¬ *lin:* ***eqv cone of same*** $\int \rho^2(l)$)



Sideway: another ρ^2 *situation: sky ("Rayleigh")* *Sideway2: why sky not violet ?* [4]

N_2 molecules… + transcients N_2 doublets & triplets (+...)

More realistic figure: misc

- *Several OB stars / dust nest + windows / long distance UV* (*then* $1/r^2$)
- *species interaction*
- *super-radiance at border (?) …*
- *stars creation in pillars / strong O may shuffle protoplanetary disk*
- *...*

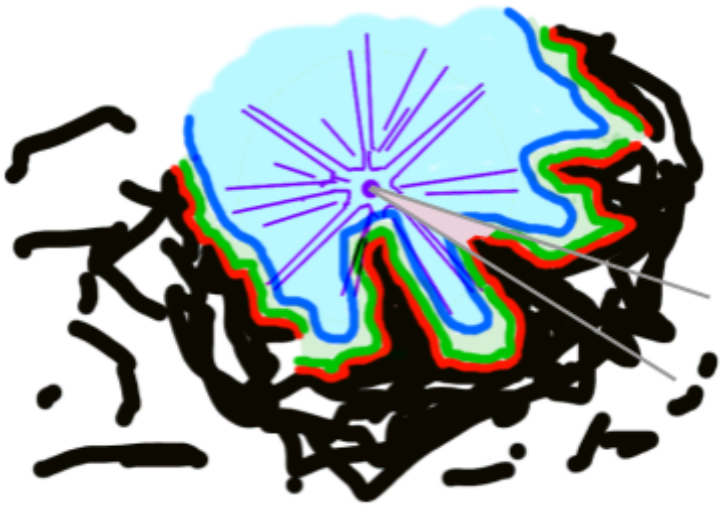
More realistic figure: dynamics

Very dynamic picture, ~ front flame:

- *startup: ionize → make transp → front go further (up to $R_{Strömgren}$)*

- ***Photodissociation**:*
  dust grains (+H_2 , 10K) → molecules → atoms (+H_I) → ions (+ H_{II} , 10^5K)
  → different lines & opacity
  → erodes shell & pillars ("evaporation")

- *High heating + more moles → volume↗ (H: × 100 × 2) → gas jets (wisps)*
- *Pressure → pushes front & crushes pillars*

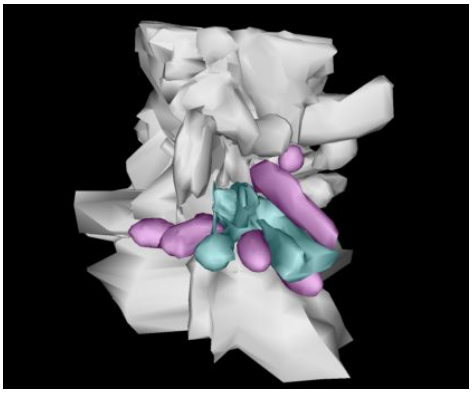


→ Shock wave 20 km/s (>> sound) , draw momentum

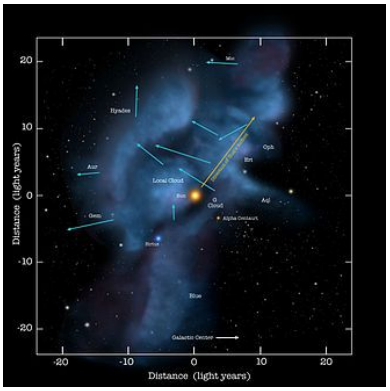
- *bubble stages: 1: UV,growth 2: inertia 3: SN explosion (1-10 My)*

- *macro picture: Δ pressures, winds, bubbles foam, super-bubbles…*

Sideway: *our local bubble (Sun pass through)*



our local cloud



Wrap-up model (simplified)

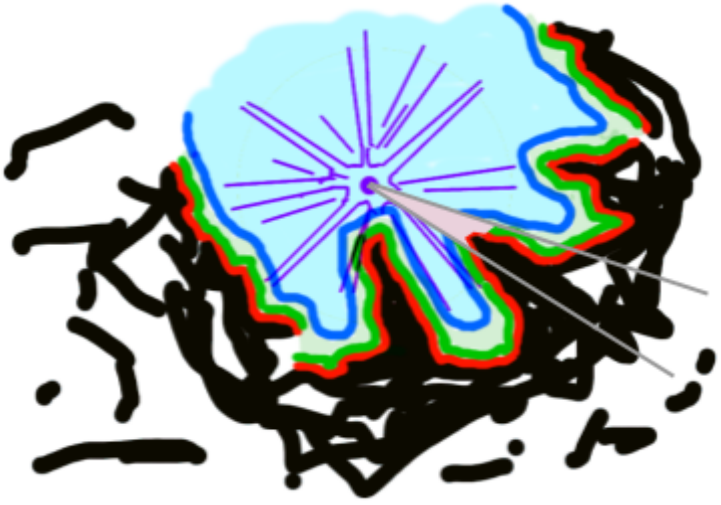
[disclaimer: from memory + mix rev. ing. Coherency not guaranteed :-/]

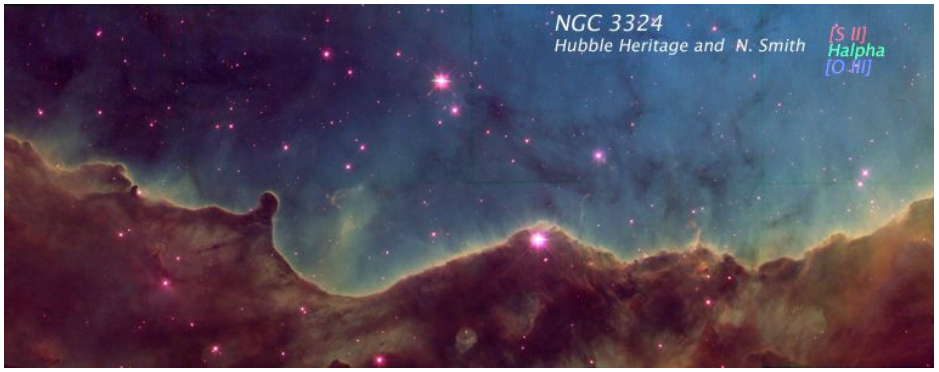
- *Shell$_i$ at* $L \mid \Phi(L) = \int_{cone}^{l<L} \rho^2(l)\, l^2\, dl = \alpha_i I_{star}$
- *in practice, most* ρ *within skin of pillar / propagating shell (phase1)*
- *Typical markers:*

  $O_{|||}$ *[mapped blue] :* *in bubble, stop before pillar / border*

  $S_{||}$ *[mapped red] :* *in fringe, just 1 scatter: silverlining*

  H_α *[pink, mapped green] : bubble + skin + wisps*





- *procedural* ρ *field:*
  - *noise, low in bubble, increasing (highly) from front*
  - *close-form integral* $\Phi(p) \rightarrow$ *front location*

  $\rightarrow \quad \rho_{in} + (e^{k_i \max(r - r_i, 0)} - 1) \ , \ r_i = R(t) + noise(R(t))^n$

- *rendering:*

  $I_{loc} = \alpha I_{star} \rho^2 \ \Sigma_i$ *smooth_in (* $range_i, \Phi(p)$ *)* C_i *(sum shells)*

  real-time volume ray-tracing (spectral) + extinction

Sideway: our spectral rendering: Finite Elements → I_S, I_{loc}, *T, sensor =* $P_3(\lambda)e^{k\lambda}$ *(closed family)*

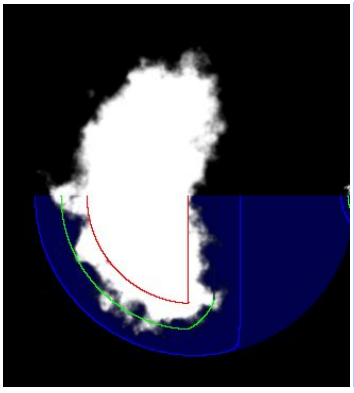
just compute up to 5 values per channel

Results

@RSA Cosmos:

(but not integrated in Sky Explorer: perfs...)

Shadertoys:



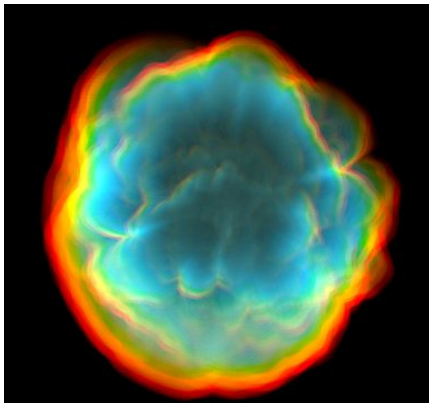
shaping noise https://www.shadertoy.com/view/lssSRn

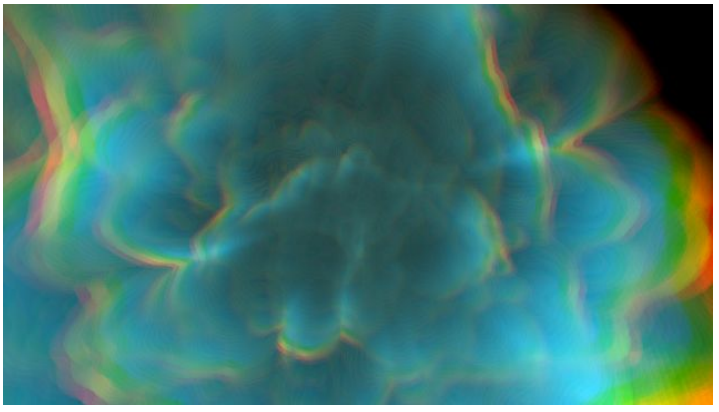
3D noise + lighting + volume rendering

https://www.shadertoy.com/view/4sfSz4

H_{II} region https://www.shadertoy.com/view/Md2GWR

. [https://www.shadertoy.com/view/4siGDR]





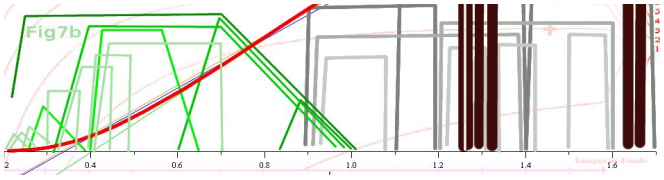
Back in context

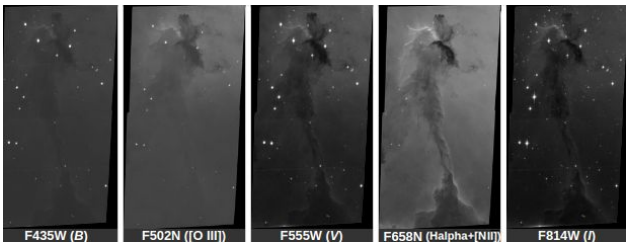
(H_{II} nebulae were just a small part of the project)

if zoom on pink areas + set filters

Sideway: the art of Nasa Hubble Images

- *Scientists choose a filter set (and look only these outputs)*





& choose pause time

- *Comm scientists prepare images for public:*
  - *mapping channels to RGB colors [std ? ethic ?]*
  - *may: gain, contrast, log, substract bg…*

Delusions behind project purpose "just simulates Hubble wandering in galaxy":

- *no automatic std mapping to RGB colors*
- *filter choice depends on target [→ let operator set from its pedagogical scenario]*
- *pause time hugely differs for stars vs nebulas*
- *view angle very different dep. on target (zoom vs mosaic)*
- *sensor PSF (ring+cross around stars) depends on sensor pixel size*

Zoom ≠ get closer ≠ wide angle

https://www.shadertoy.com/view/XdsGWs

- *astrophysics / astronomic data far from complete, not always consensus*
- *dialog with physicists not always easy (cultural gaps, even between them)*

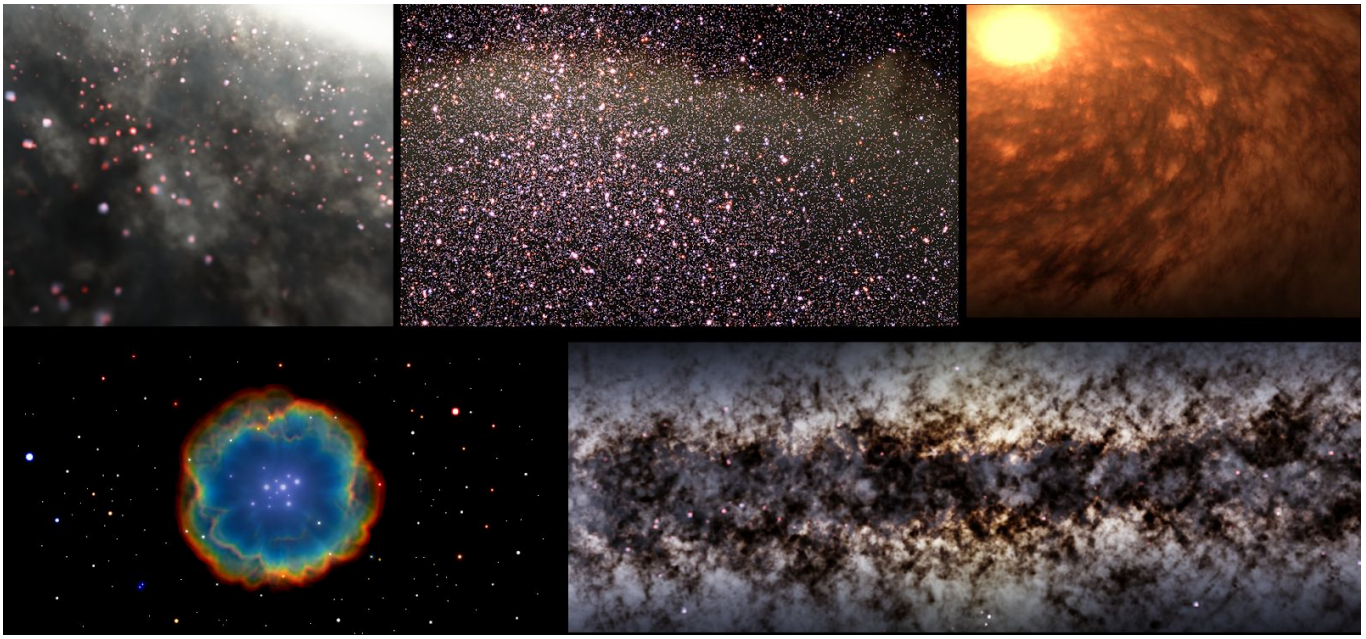
Some side messages:

→ think longer about "does the question makes sense"
*or "what is *exactly* the request (or concept)" "si c'est flou, ya un loup" :-p*
question the full real pipe-line (not isolated scientific end-concept)

→ CG as an integrative + re-modeling science
+ stochastic extrapolation: instantiating high-res fields obeying global prop.

Popularization article & video on whole Galaxy / veRTIGE project

Highres part: (not fast enough for integration)



hard real-time: integrated in Sky Explorer