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Stellar entropy and stellar evolution

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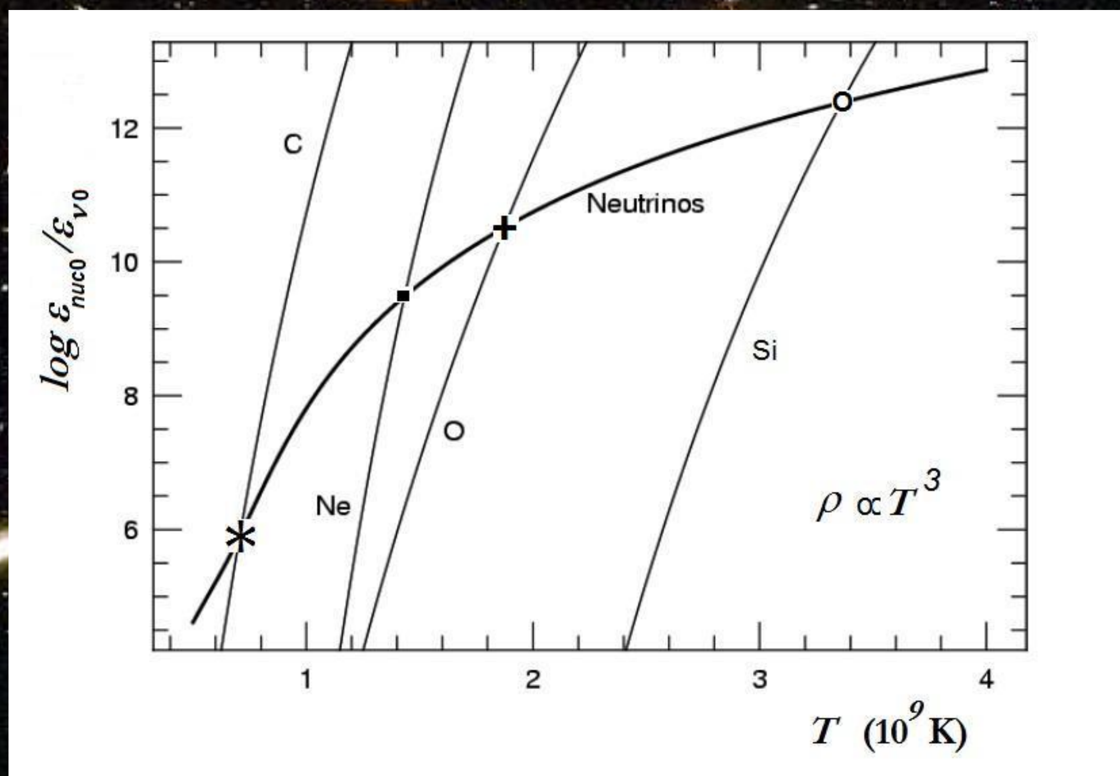
"Digging an entropy hole" (massive stars) :

The entropy per baryon decreases at the core along stellar evolution



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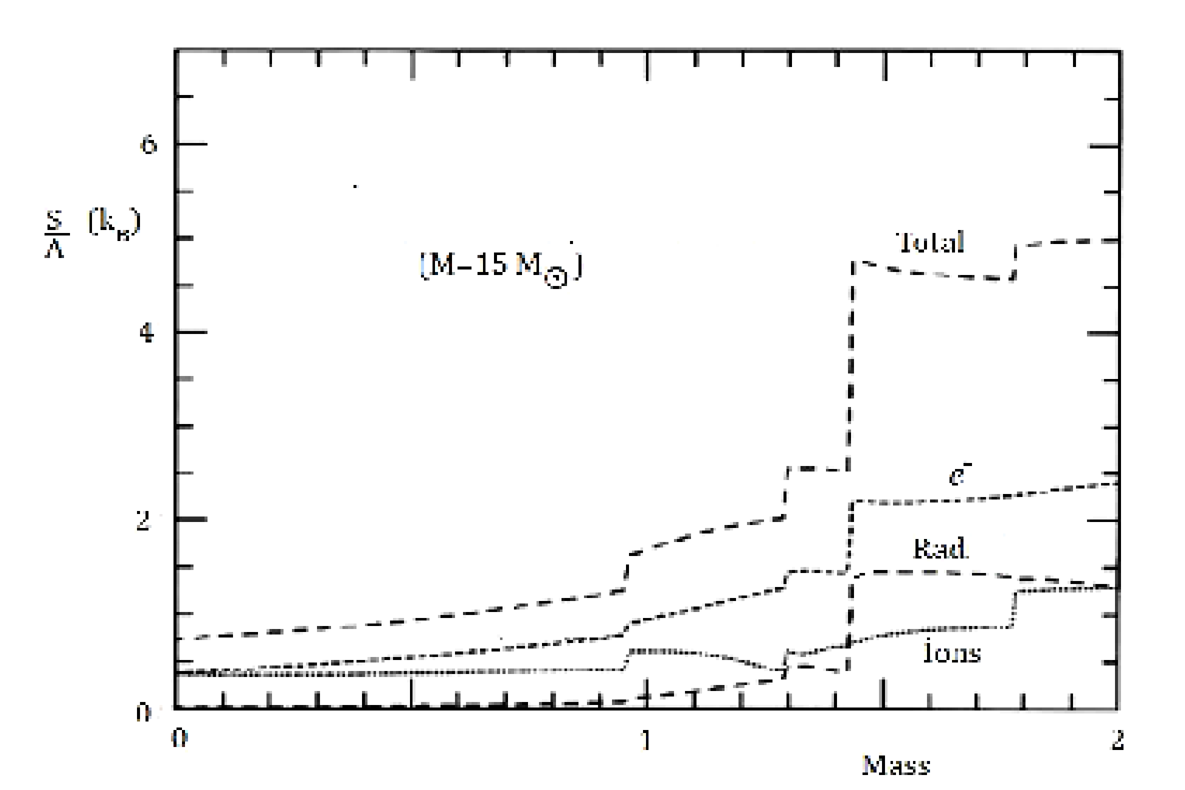

Entropy per baryon inside the stellar core (Woosley)

$$S = C + \frac{N_o k_B}{\bar{\mu}} \ln\frac{T^{3/2}}{\rho} + \frac{4a}{3}\frac{T^3}{\rho}$$

Gas + radiation

But virial equilibrium guarantees $\frac{GM^2}{R} \approx \frac{N_o}{\bar{\mu}} M k_B T$, hence

$$T \sim \frac{G\bar{\mu}}{N_o k_B} M^{2/3} \rho^{1/3}$$

because of the ln, entropy decreases if T increases

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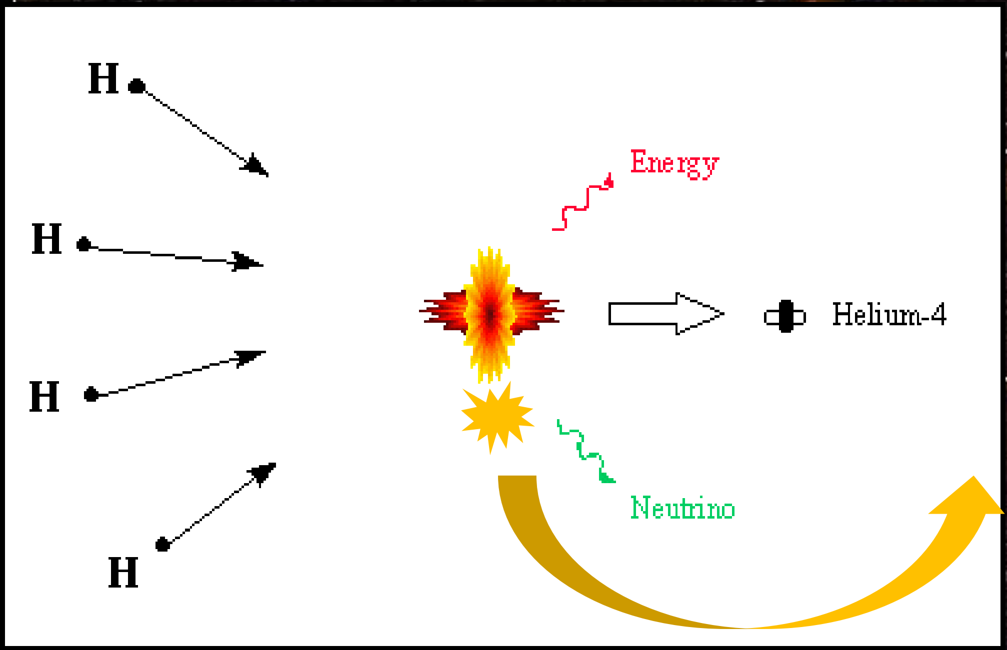
Very well known, but not very well appreciated facts

Weak interactions control nuclear reaction rates p-p ➡ 10^9 yr (?!)



Something very important happens here: one of the protons should decay into a neutron to allow a deuteron bound state s

$$H + H \rightarrow {}^{2}D + \beta^{+} + \nu$$

If a diproton bound state would exist, stars would explode very promptly and we would not be here in Havana…

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The Big synthesis of Stellar Evolution

$$\tau_{ff} \sim \left(\frac{3}{8\pi G \rho} \right)^{1/2}$$

Free-fall timescale

$$\tau_{th} \sim \frac{R^2}{D_{th}}$$

Thermal diffusion timescale

$$\tau_{KH} \sim \frac{GM^2}{RL}$$

Kelvin-Helmholtz timescale

$$\tau_{nuc} \sim \left(\frac{1}{X} \frac{dX}{dt} \right)^{-1}$$

Nuclear fuel consumption timescale

$$\tau_{ff} < \tau_{th} < \tau_{KH} < \tau_{nuc}$$

Condition for a stationary state

Violation implies redajustment (contraction/collapse)

→ Matter changes induced (e.g. degeneracy)

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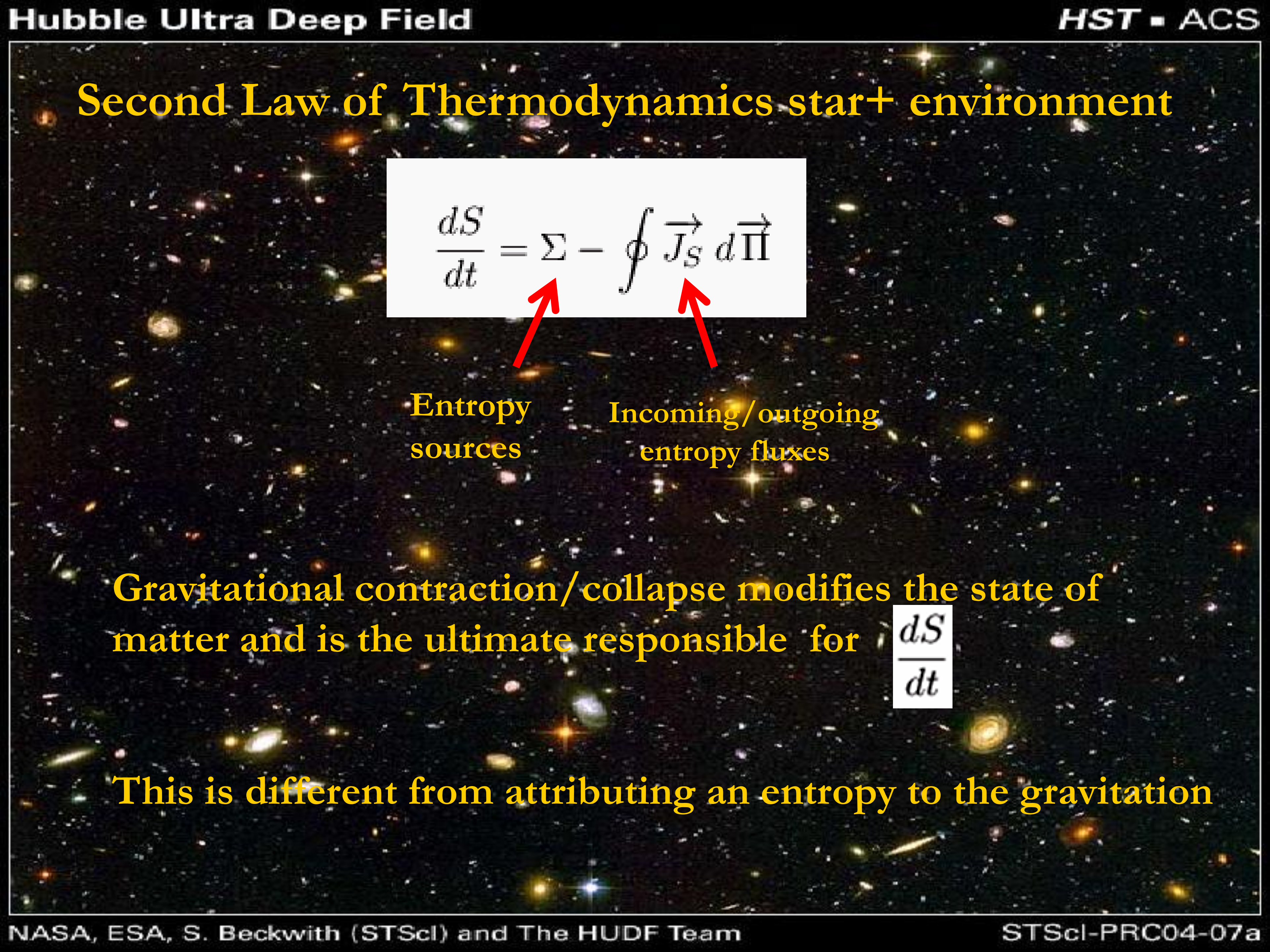

Second Law of Thermodynamics star+ environment

$$\frac{dS}{dt} = \Sigma - \oint \overrightarrow{J_S}\, d\overrightarrow{\Pi}$$

Entropy sources

Incoming/outgoing entropy fluxes

Gravitational contraction/collapse modifies the state of matter and is the ultimate responsible for $\frac{dS}{dt}$

This is different from attributing an entropy to the gravitation

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Calculations

Comparing different phases of stellar evolution for the same baryon number

Choice: 1.6 x 10^{57} corresponding to M= 1.35 $M_\odot$

Assumptions : $E_{tot} = E_{int} + E_{kin} + E_{pot}$: conserved

$E_{pot} = -2 \times E_{kin}$ holds

equilibrium particle distributions

We generate endpoints (WD, NS, BH) with 1.35 $M_\odot$ and trackback their progenitors to whatever mass have

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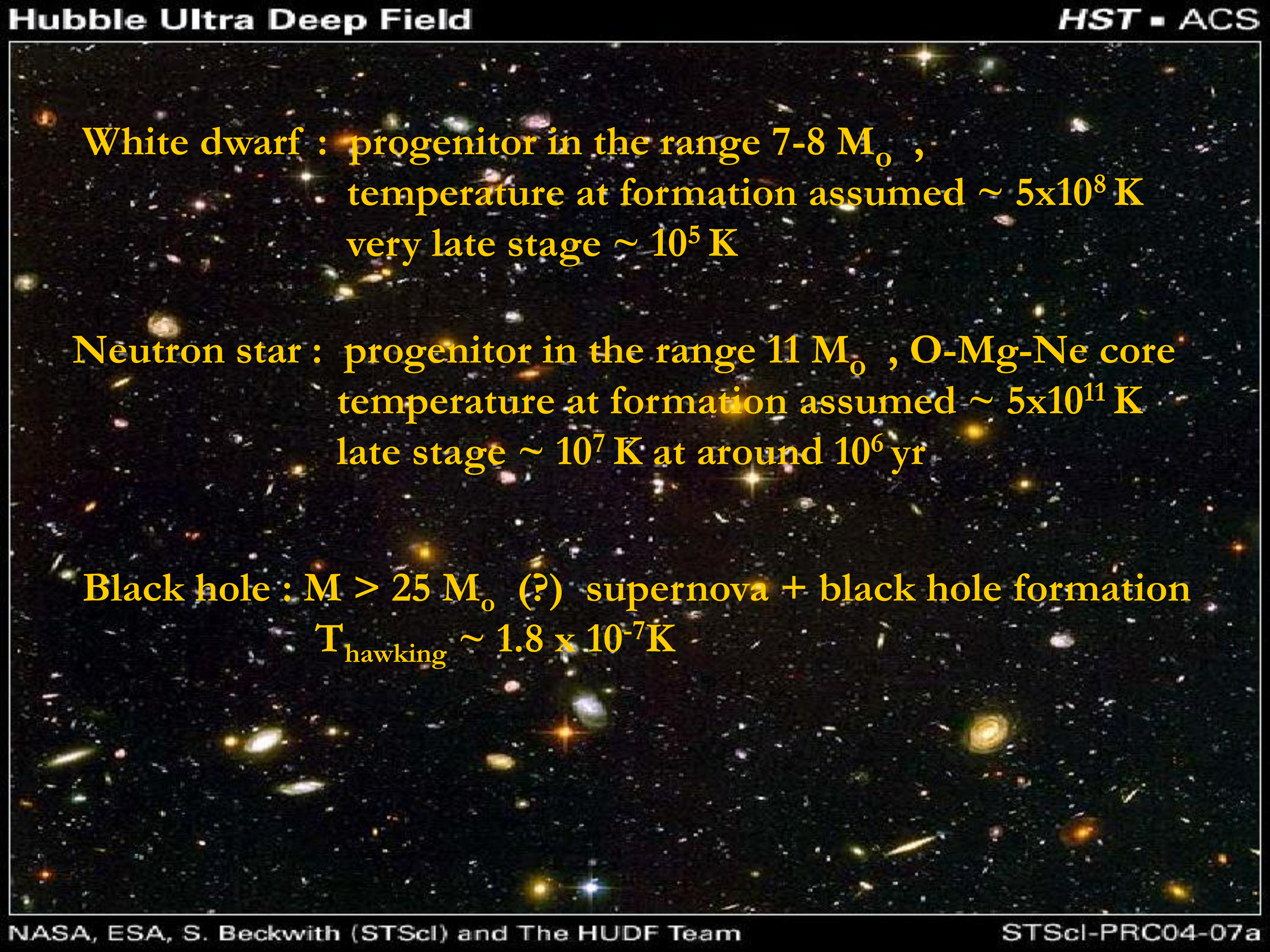
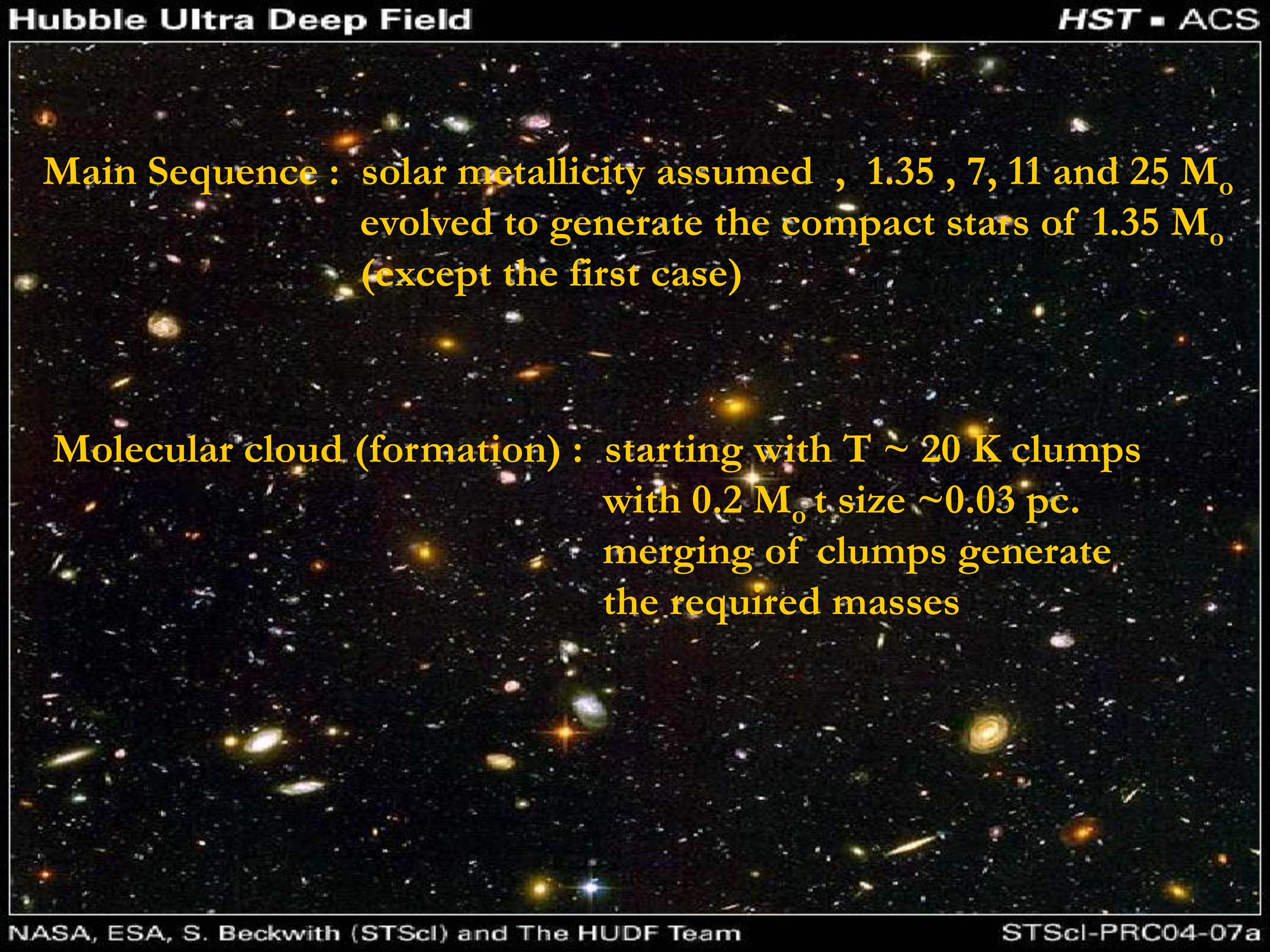


White dwarf : progenitor in the range 7-8 M_o ,
temperature at formation assumed ~ 5×10^8 K
very late stage ~ 10^5 K

Neutron star : progenitor in the range 11 M_o , O-Mg-Ne core
temperature at formation assumed ~ 5×10^{11} K
late stage ~ 10^7 K at around 10^6 yr

Black hole : M > 25 M_o (?) supernova + black hole formation
$T_{hawking} \sim 1.8 \times 10^{-7}$K



Main Sequence : solar metallicity assumed , 1.35 , 7, 11 and 25 M_o evolved to generate the compact stars of 1.35 M_o (except the first case)

Molecular cloud (formation) : starting with T ~ 20 K clumps with 0.2 M_o t size ~0.03 pc. merging of clumps generate the required masses

Results

ideal gas only (enough for a molecular cloud)

$$S_{MC} = \sum S_{SMCbaryons} = \sum N_{SMC,b} k_b \left(ln\left(\frac{V_{SMC}}{N_{SMC,b}}\right) + \frac{3}{2} ln\left(\frac{E_{inSMC}}{N_{SMC,b}}\right) + const \right)$$

MS and beyond

$$S_{stars} = S_{baryons} + S_{electrons} + S_{rad} = N k_b \left(ln\left(\frac{V}{N}\right) + \frac{3}{2} ln\left(\frac{E_{in,b}}{N}\right) + const \right)$$

$$+\frac{7}{8} N k_b \left(ln\left(\frac{V}{7N/8}\right) + \frac{3}{2} ln\left(\frac{E_{in,e}}{7N/8}\right) + const2 \right) + \frac{4}{45} \frac{\pi^2 k_b^4}{c^3 \hbar^3} V T^3$$

WD

$$S_{WDe^-} = \frac{1}{2} \frac{\pi^2 (x_e^2 + 1)^{1/2} N k_b \left(\frac{k_b T_{WD}}{m_e c^2}\right)}{x_e^2}$$

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later, at $\sim 10^5 K << \theta_D$ and a Coulomb lattice must be added

$$S_{WDcold-ions} = \frac{16N\pi^4 k_b}{15}\left(\frac{T}{\theta_D}\right)^3 \sim 10^{33} erg/K$$

NS initially Boltmann gas assumed (very hot), later Fermi gas expression

BH Bekenstein-Hawking entropy ~A/4

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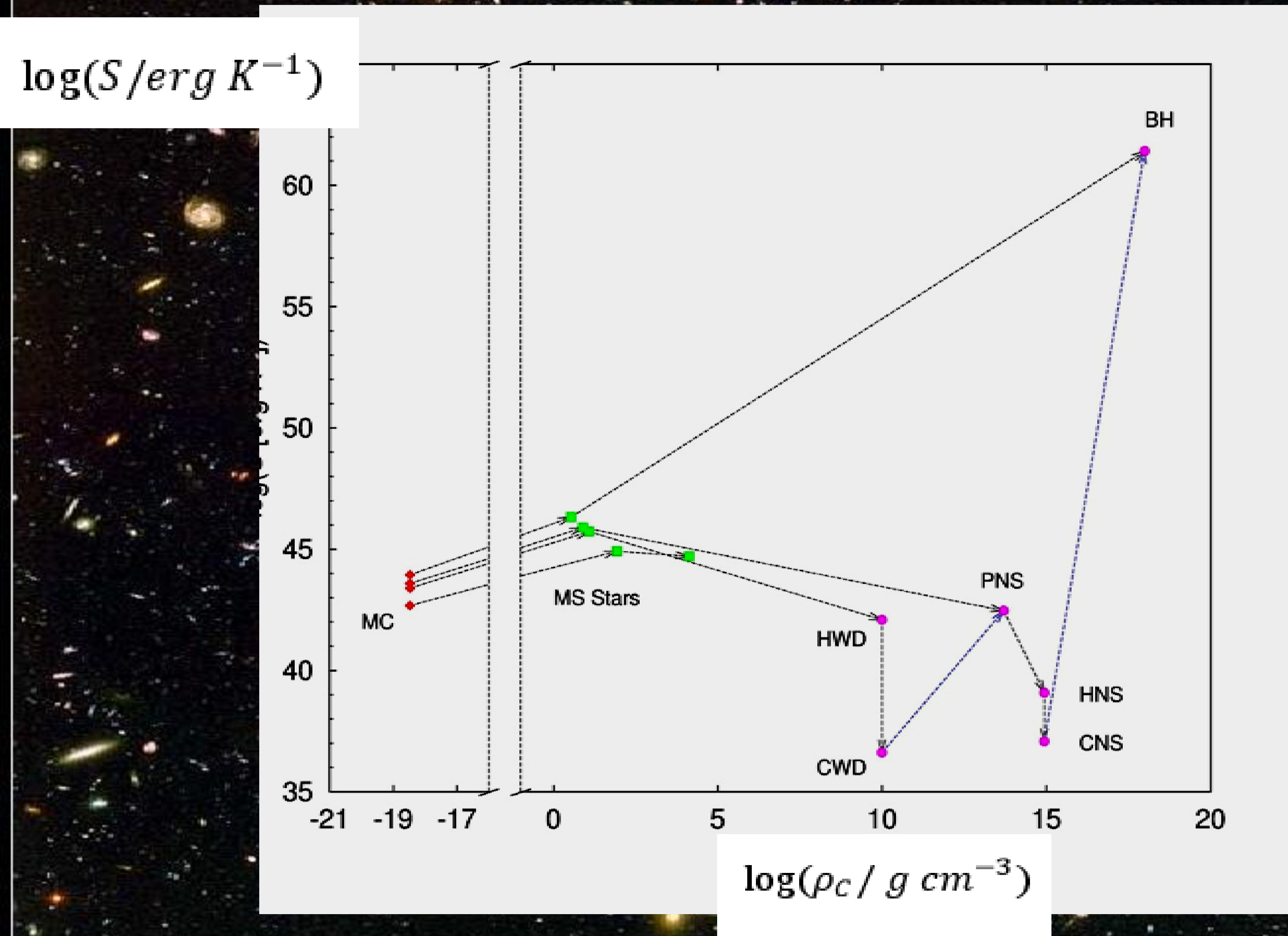
Results



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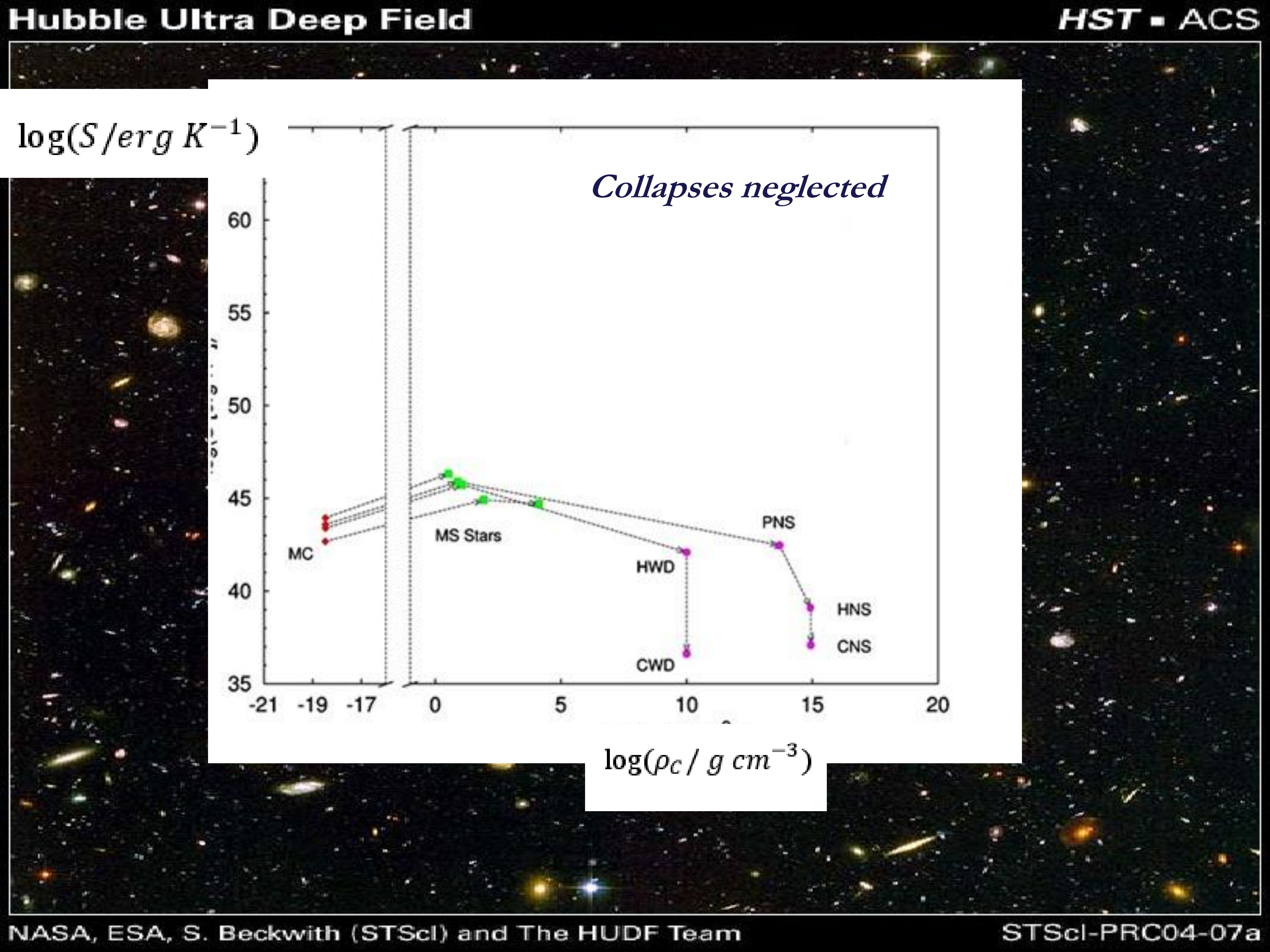
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$\log(S/erg\,K^{-1})$
Collapses neglected
60
55
50
45
40
35
-21
-19
-17
0
5
10
15
20
MC
MS Stars
PNS
HWD
HNS
CNS
CWD
$\log(\rho_C/\,g\,cm^{-3})$
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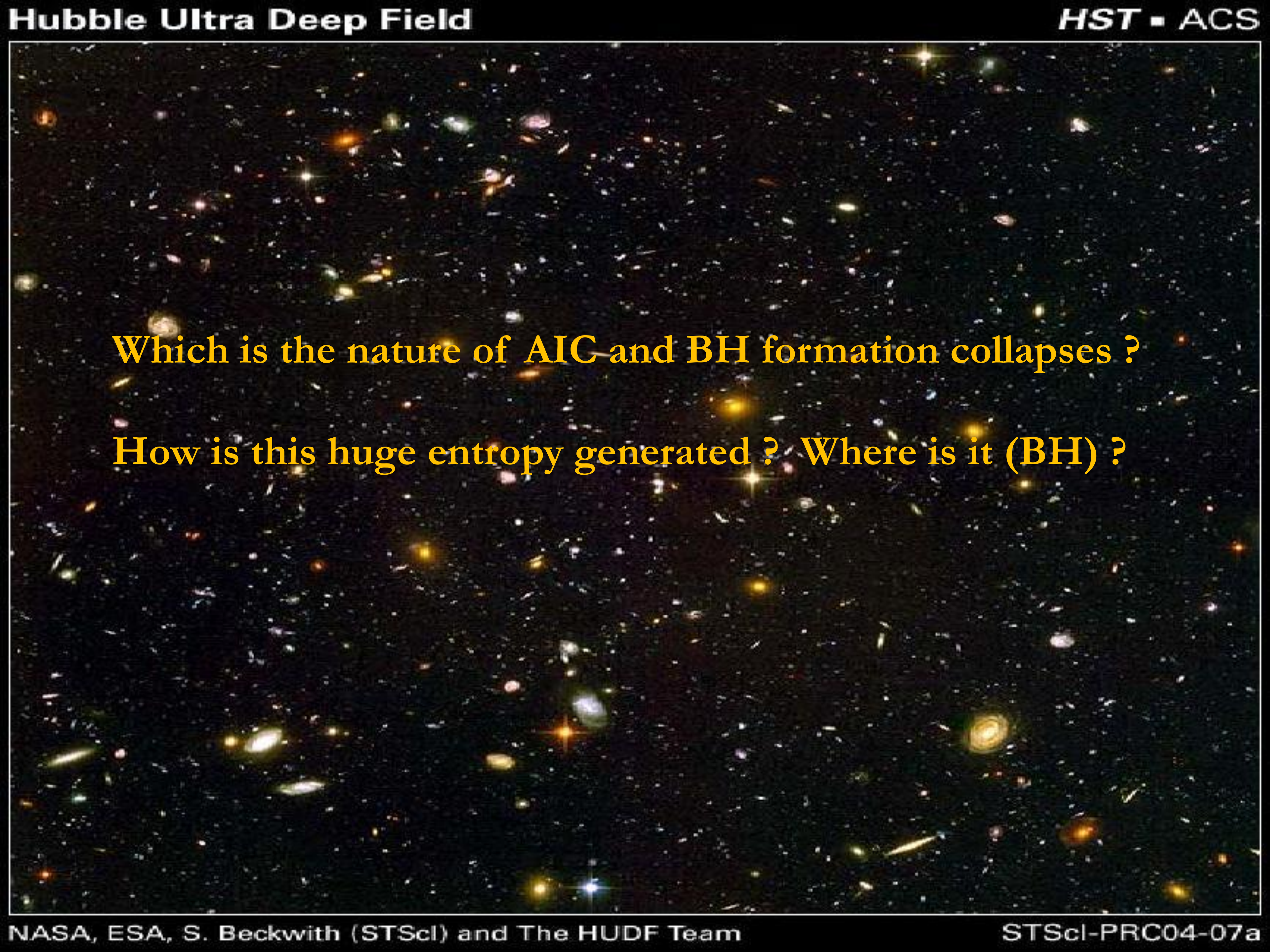
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Which is the nature of AIC and BH formation collapses ?
How is this huge entropy generated ? Where is it (BH) ?
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Conclusions

- Stars can be thought as machines that process the matter leaving an entropy-per-baryon which decreases systematically. Collapses act the other way around

- It remains to be discussed whether an entropy has to be assigned to the gravitational field…what is entropy after all ?

- Tracking of entropy may reveal the "entropy path" of the stellar evolution, there may be a synthesis to be done here

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