

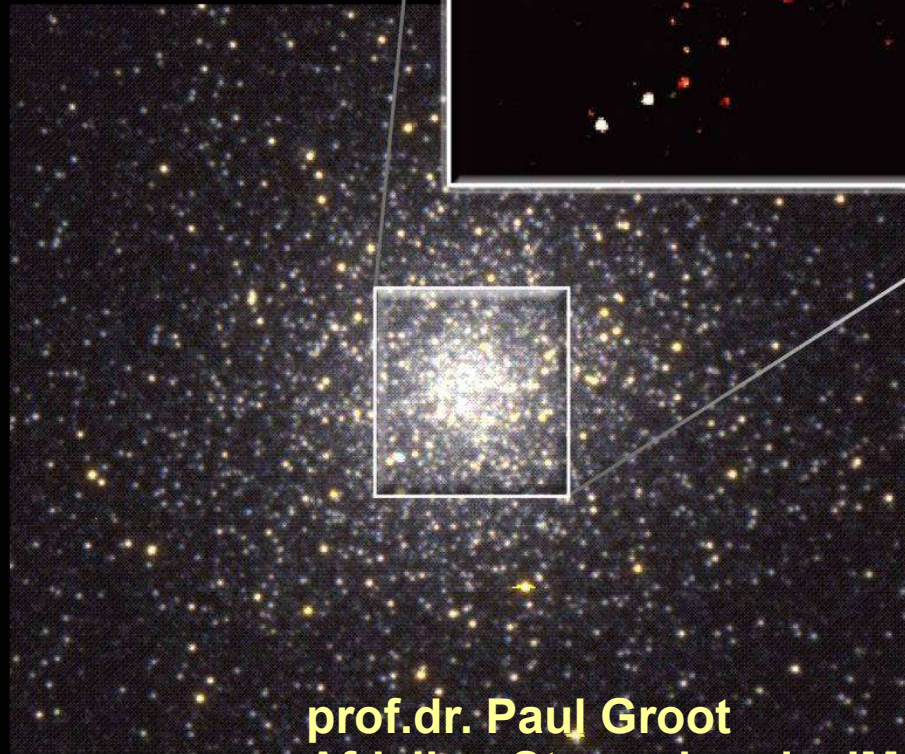
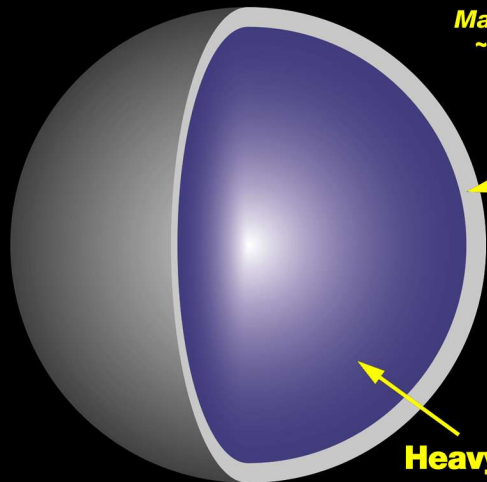
Het Quantummechanisch Heelal

Neutron Star

Mass ~ 1.5 times the Sun
~12 miles in diameter

Solid crust
~1 mile thick

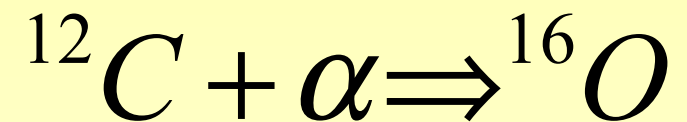
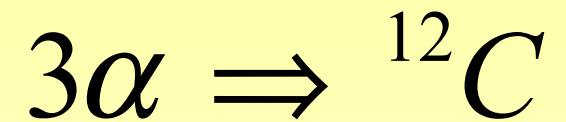
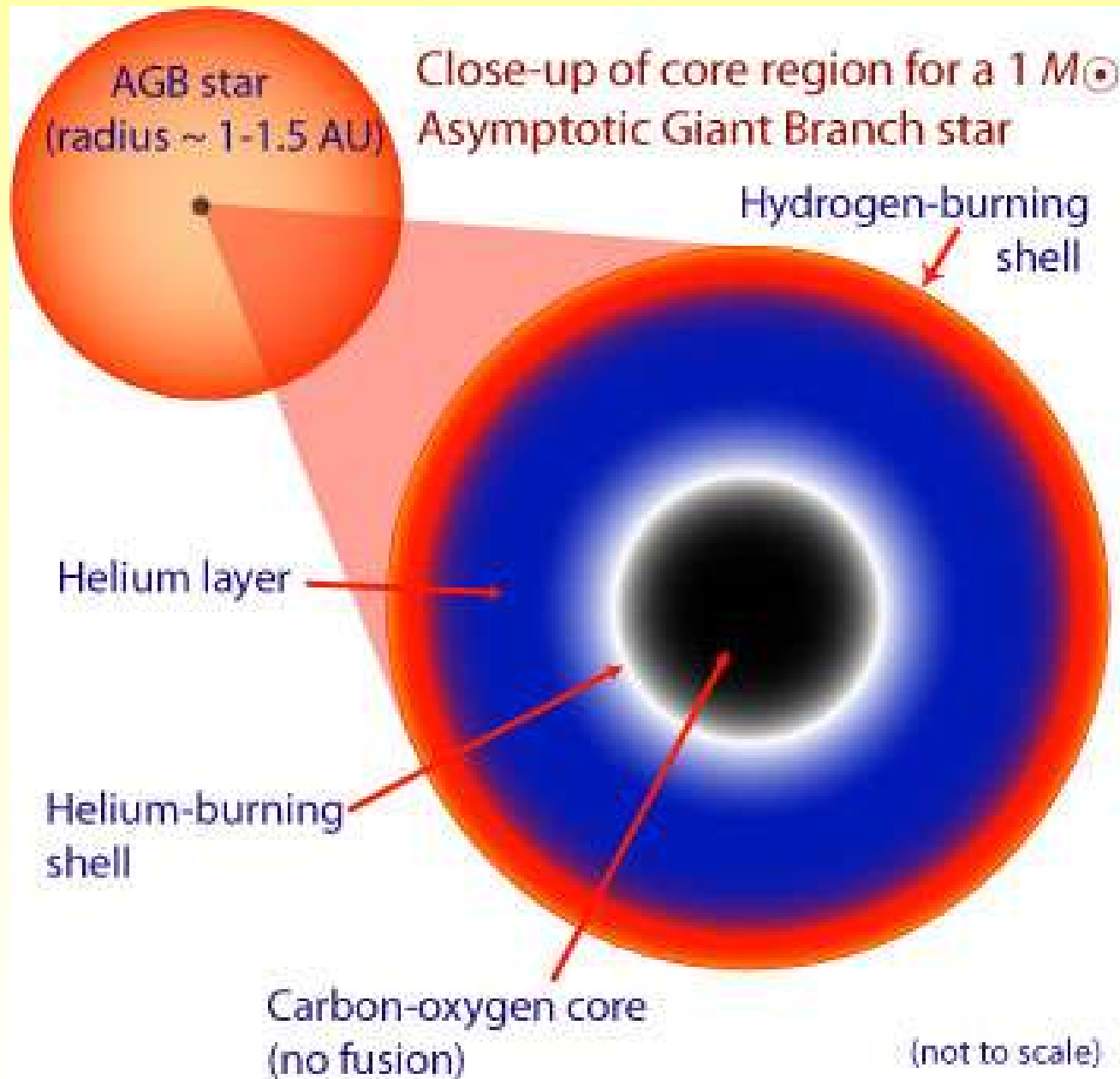
Heavy liquid interior
Mostly neutrons,
with other particles



prof.dr. Paul Groot
Afdeling Sterrenkunde, IMAPP
Radboud Universiteit Nijmegen

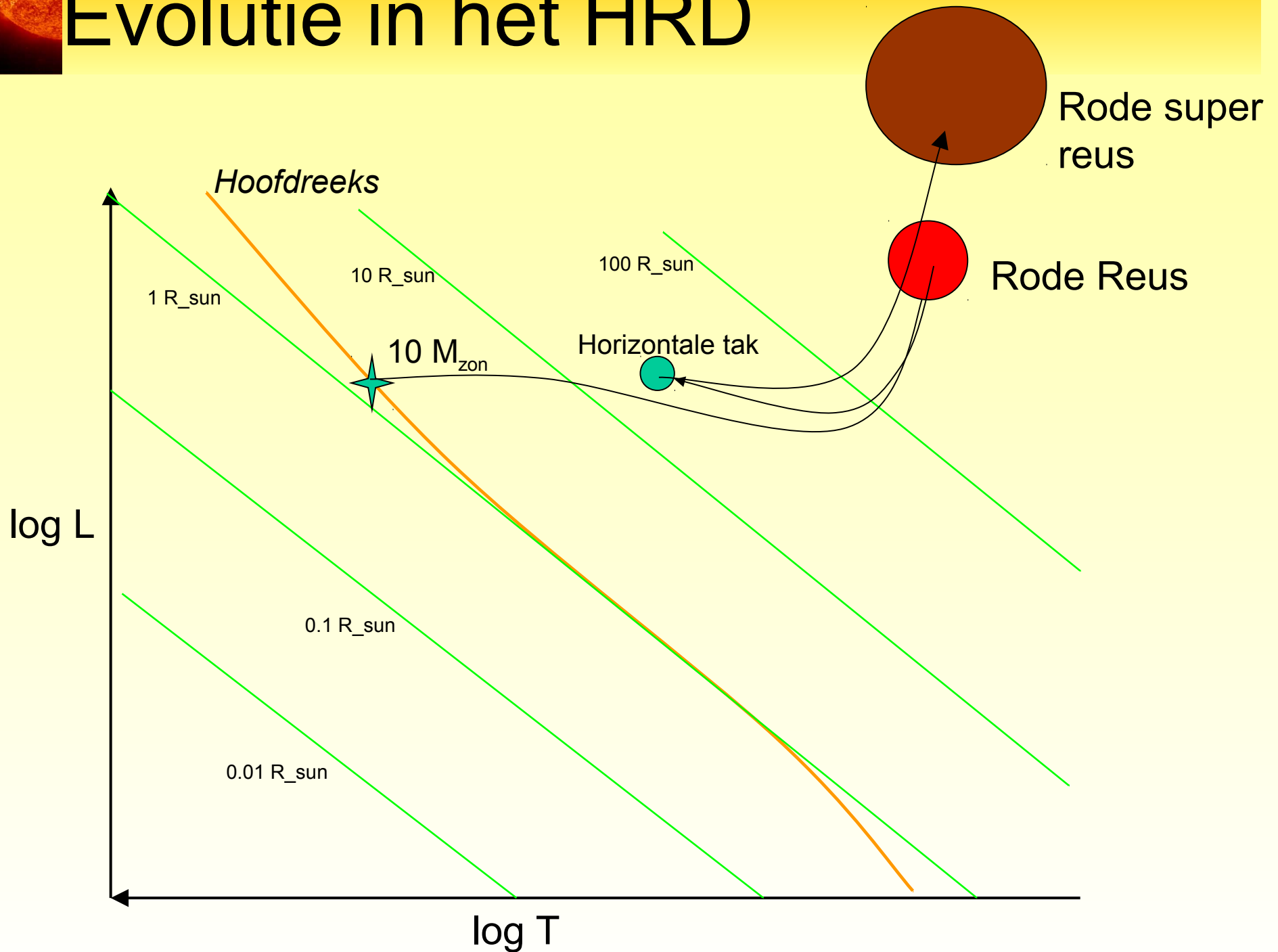


Late evolutionary stages



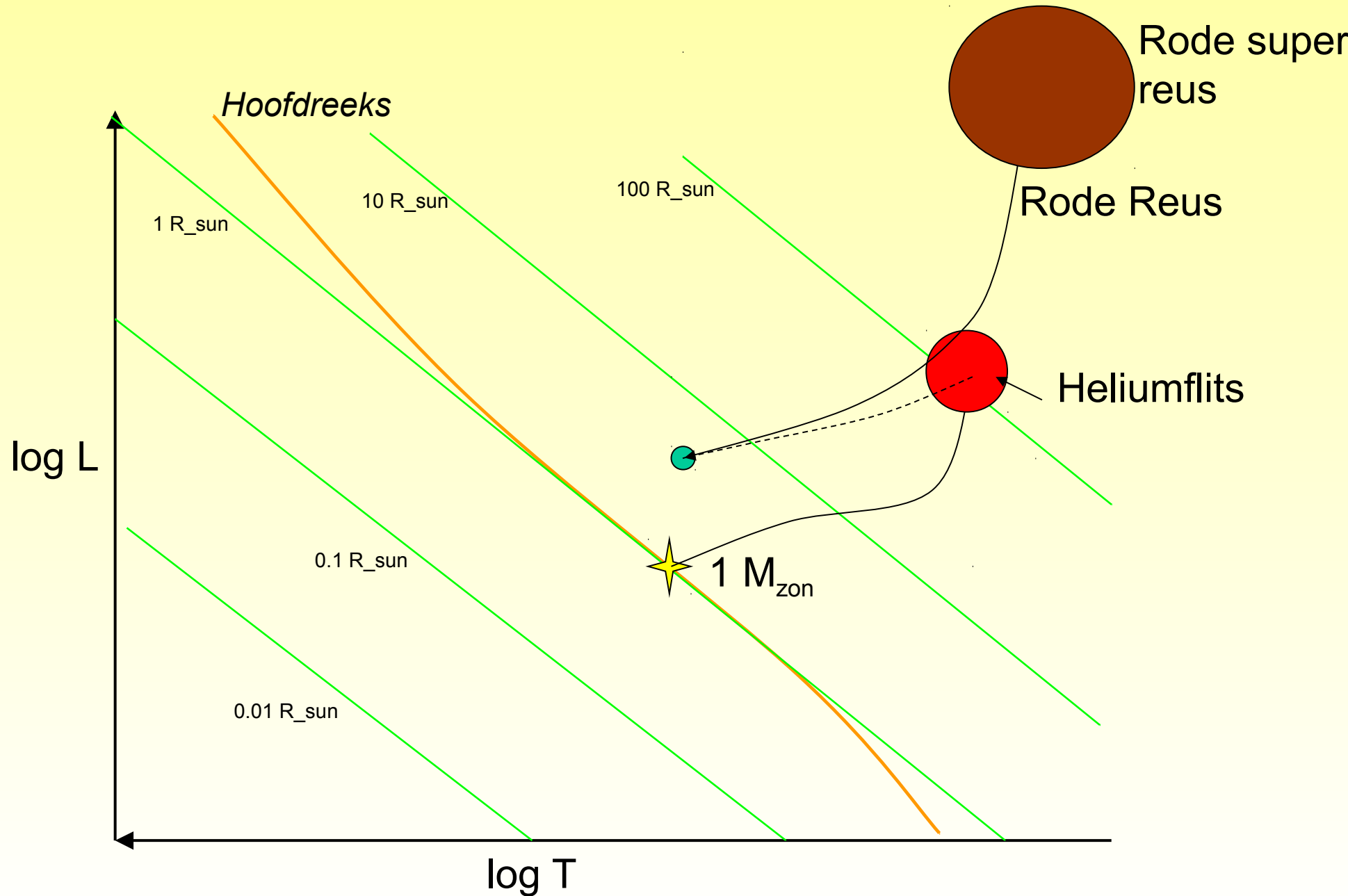


Evolutie in het HRD



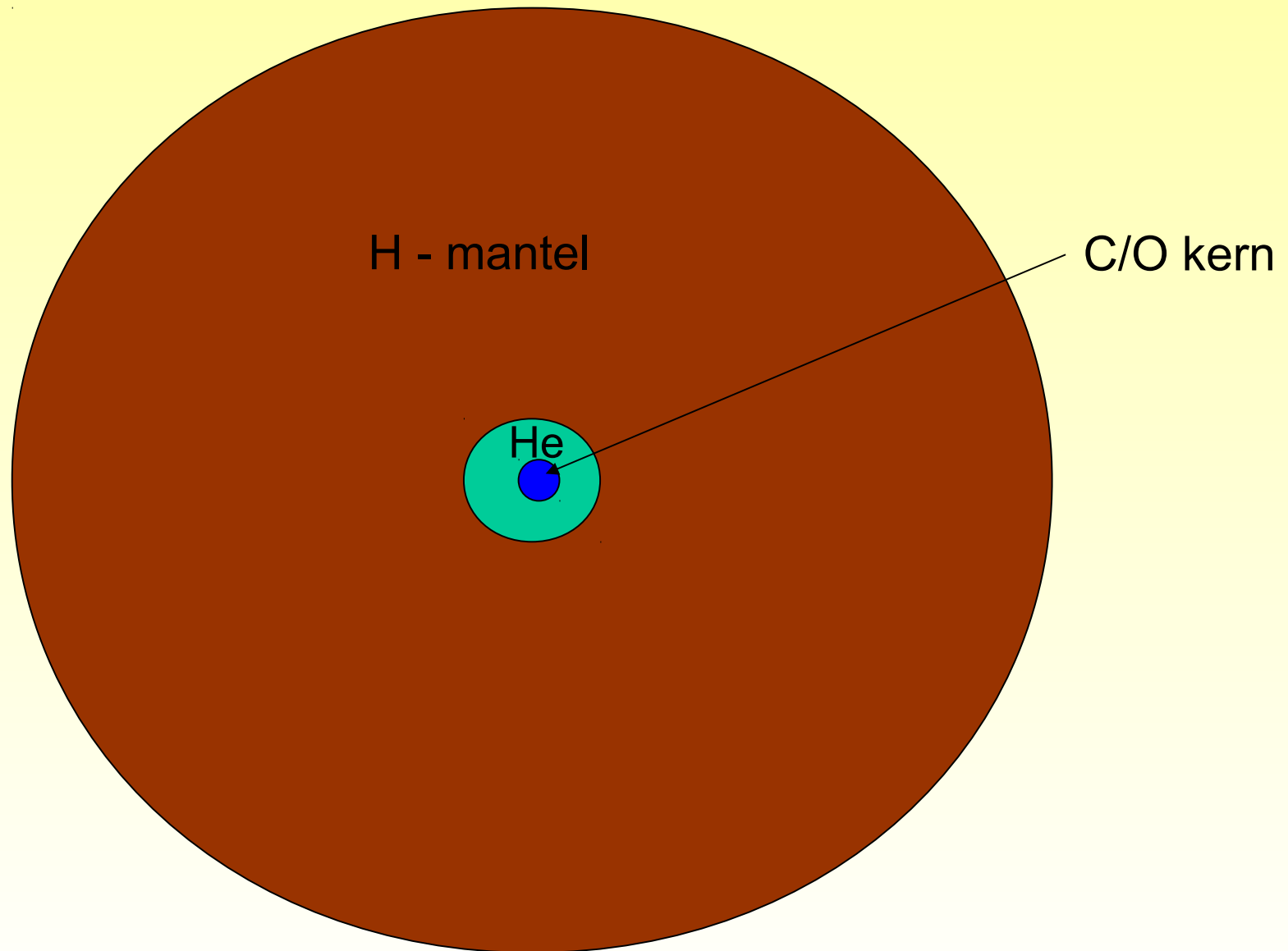


Een lichte ster ($< 8 M_{\text{zon}}$)





Interne structuur





AGB fase

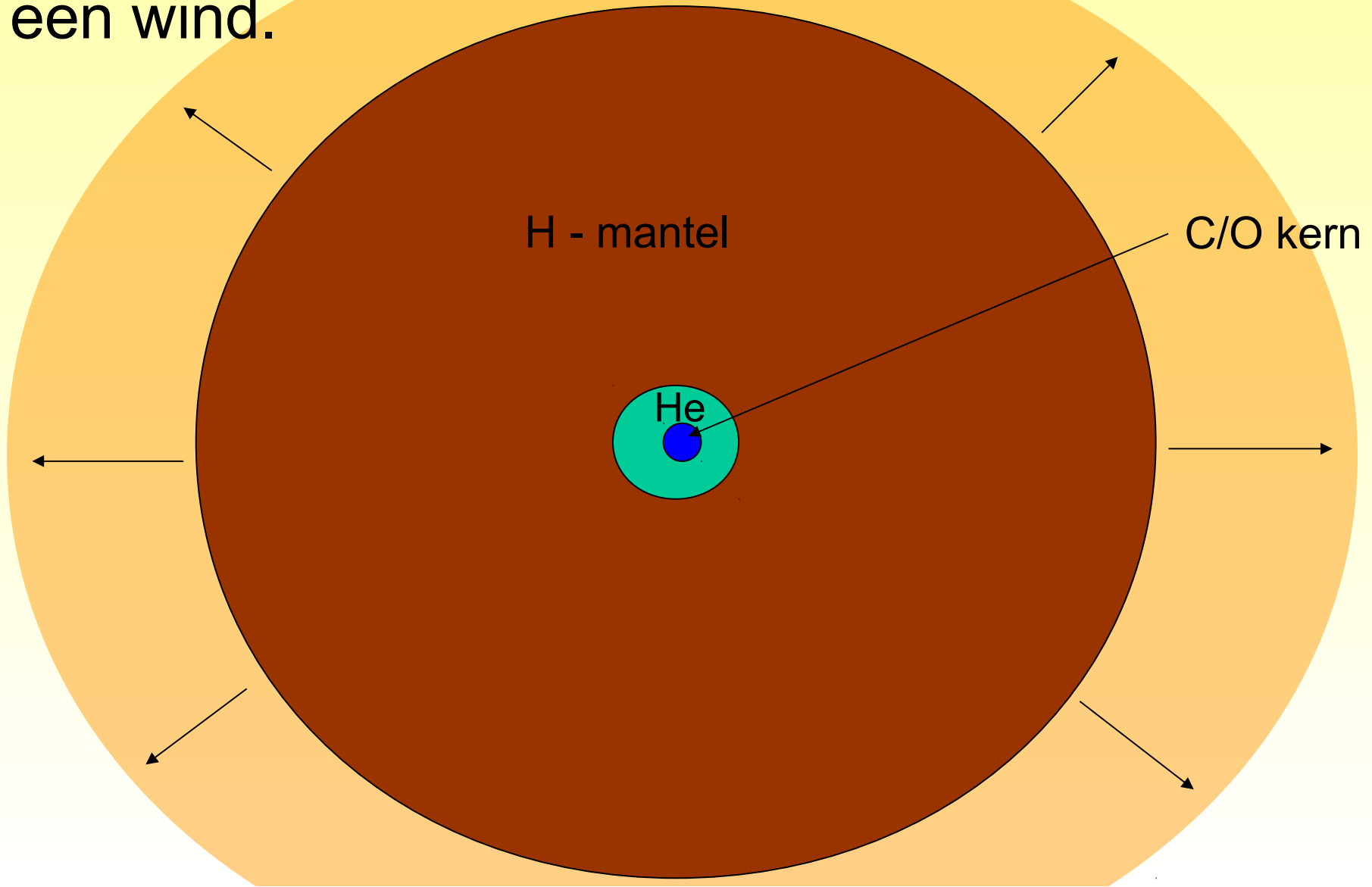
Nadat He in de kern op is, gaat de ster He en H fuseren in schilverbrandingen en gaat hij de Asymptotische reuzentak op.

De kortdurende He schil verbranding fases en de langerdurende H schil verbranding zorgen voor thermische pulsen.



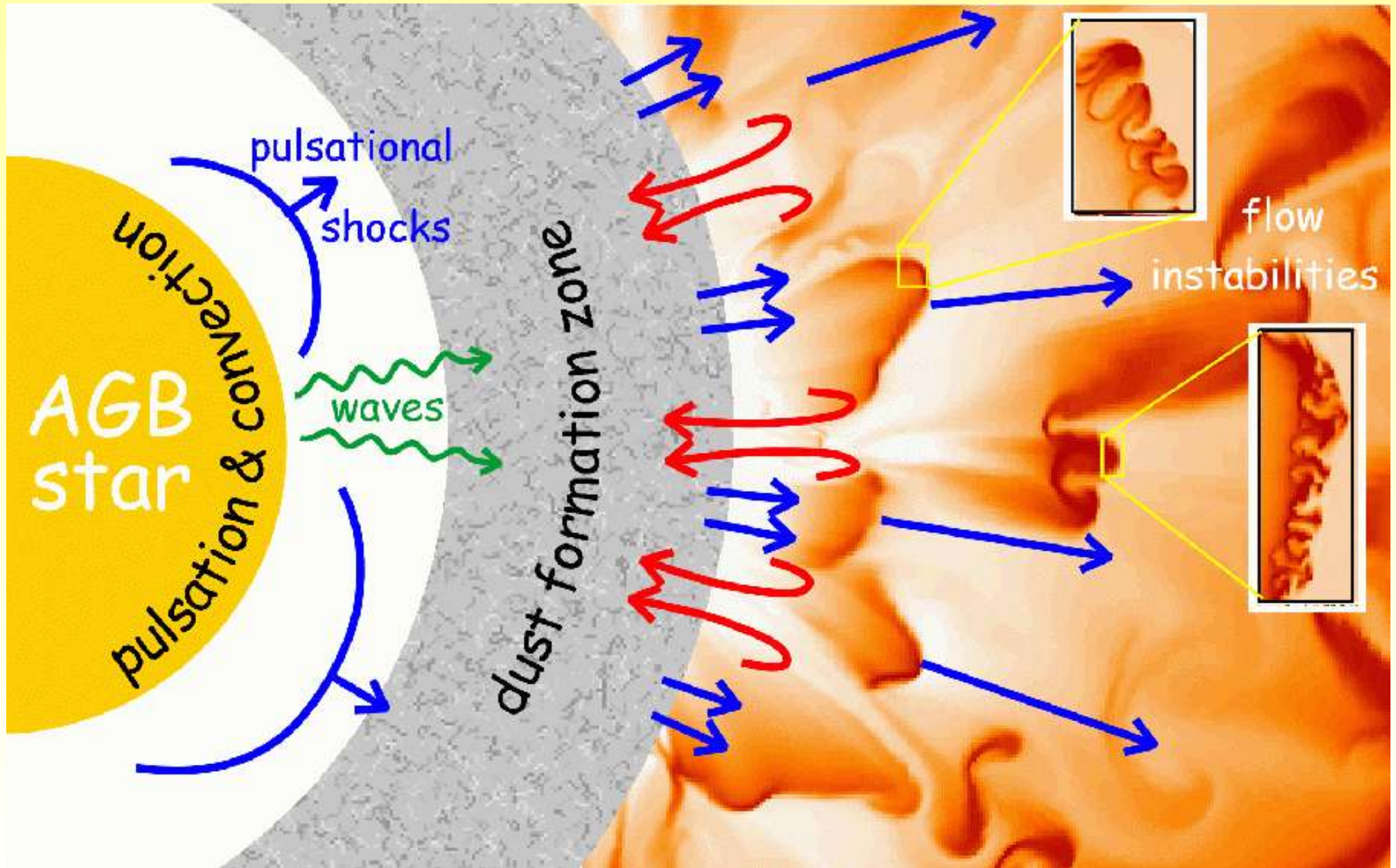
Aan de buitenkant

De ster verliest in deze fase heel veel massa in een wind.



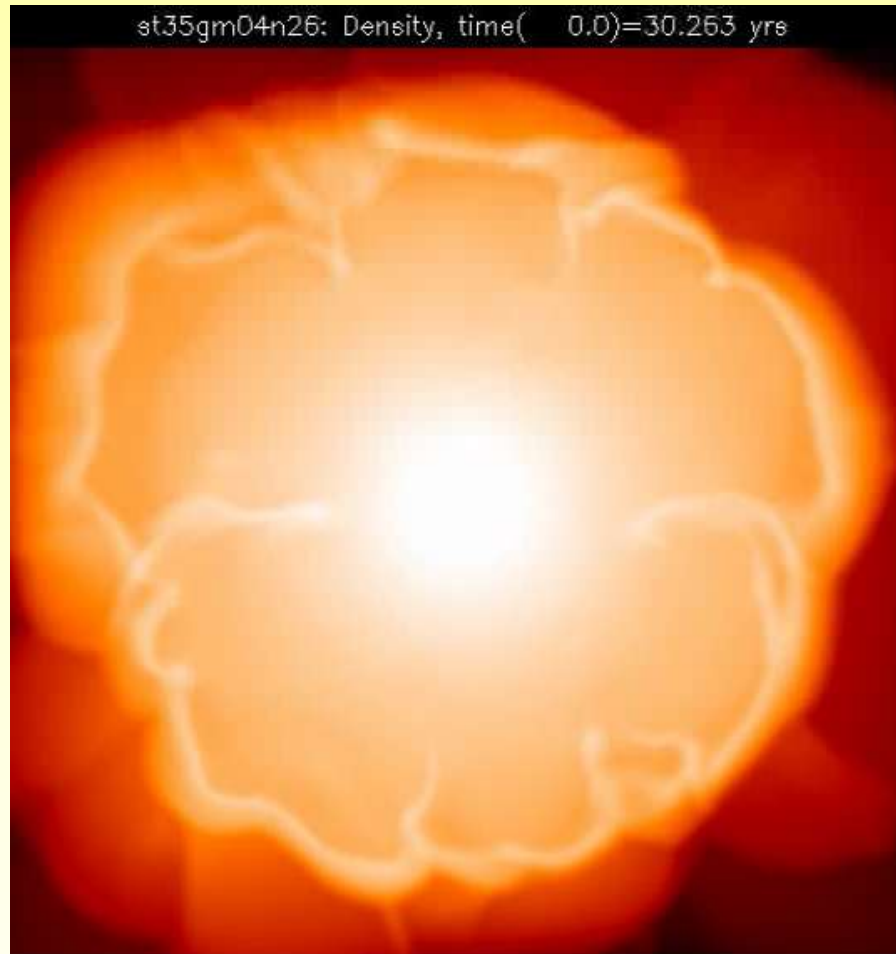


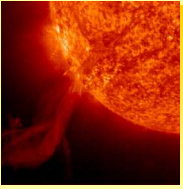
Aan de buitenkant





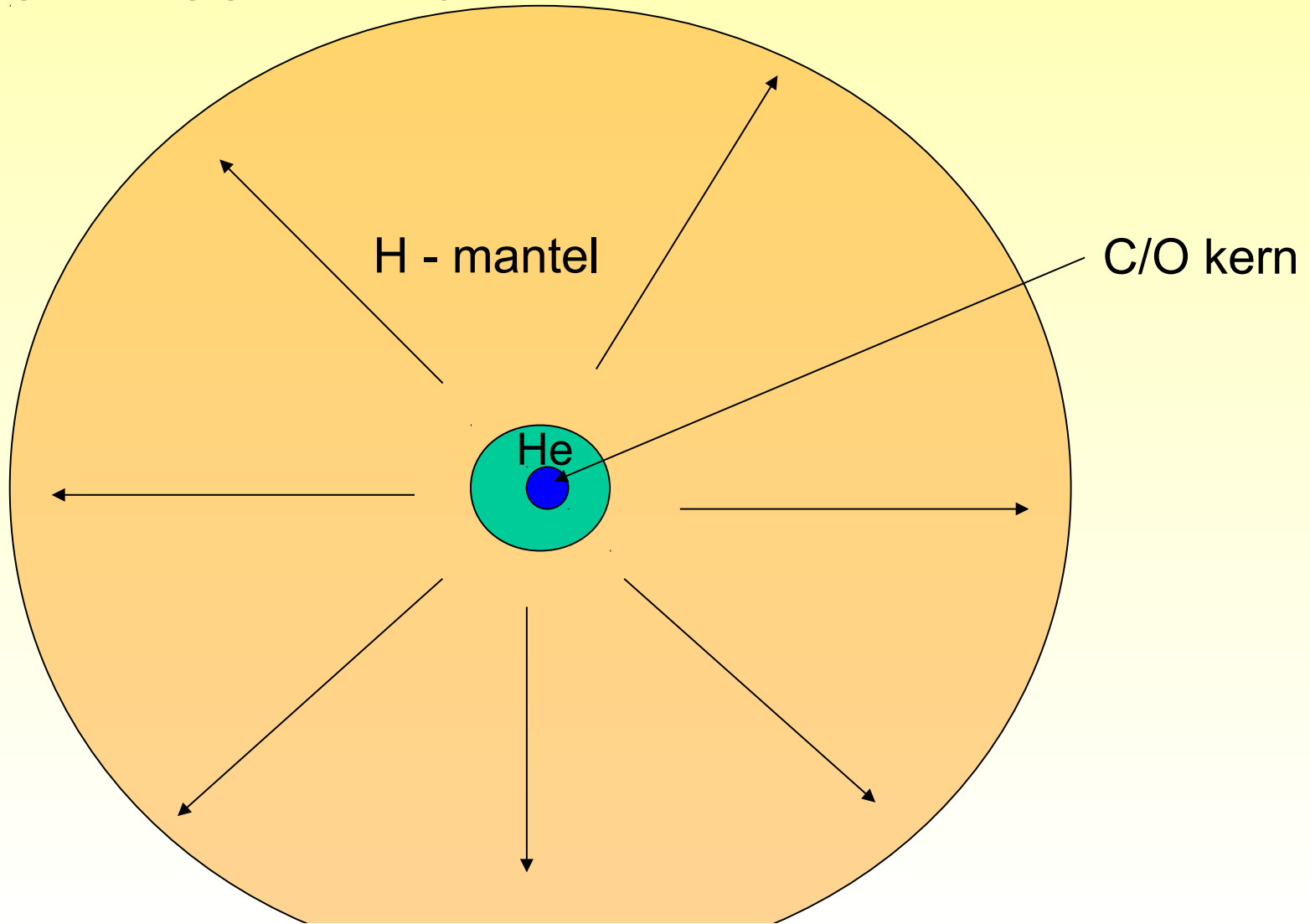
Aan de buitenkant





Na de AGB fase

Uiteindelijk zal de ster zijn hele mantel verliezen in een 'wind'.





Na de AGB fase

Als de mantel verwaait is, wordt de hete kern zichtbaar.

Het stof wordt door de UV straling weer ontbonden en het gas wordt geïoniseerd.

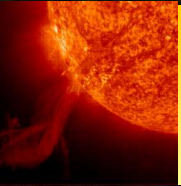
Planetaire nevel





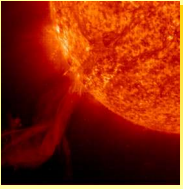
Ring nevel



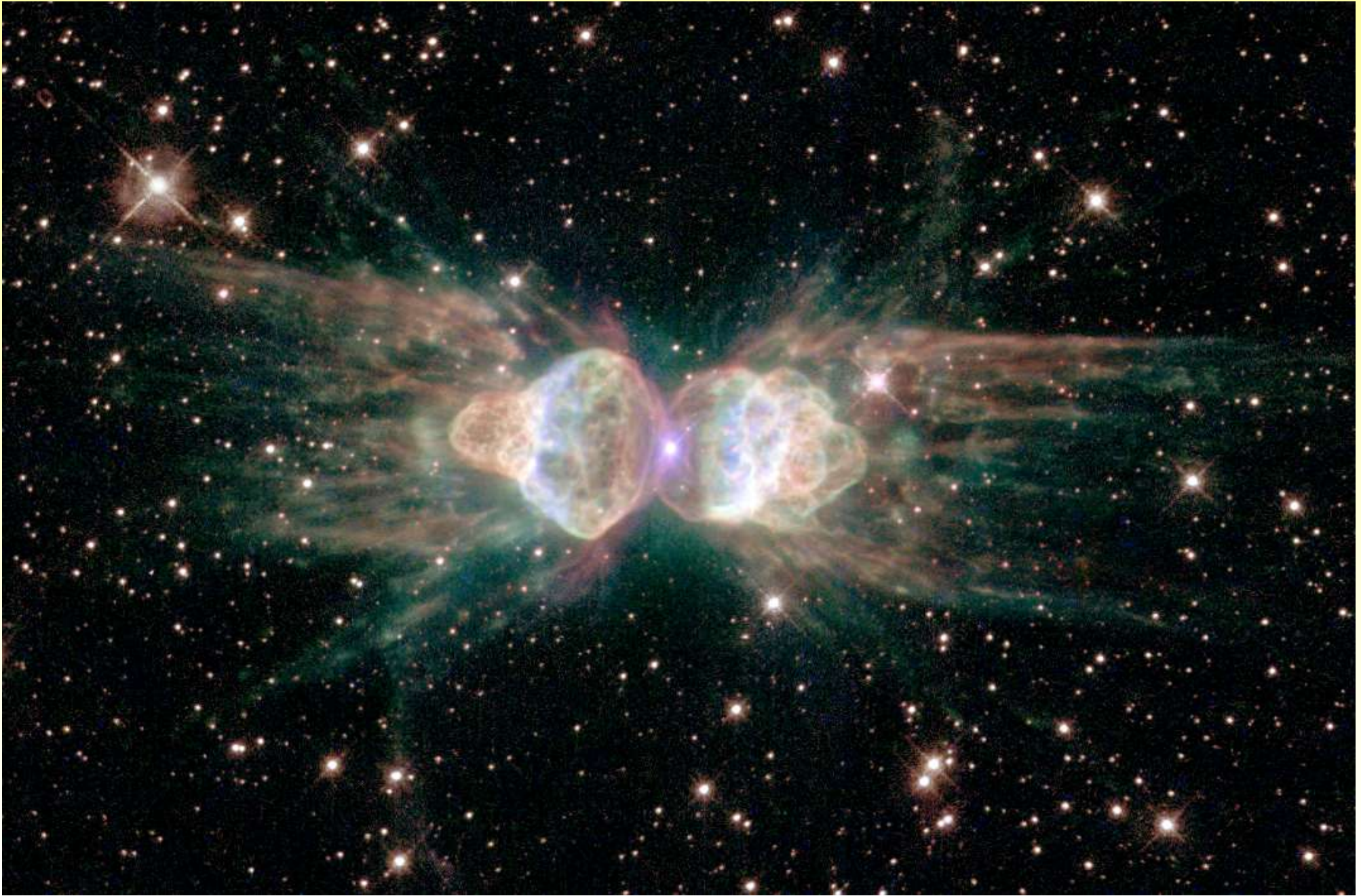


Zandloper nevel



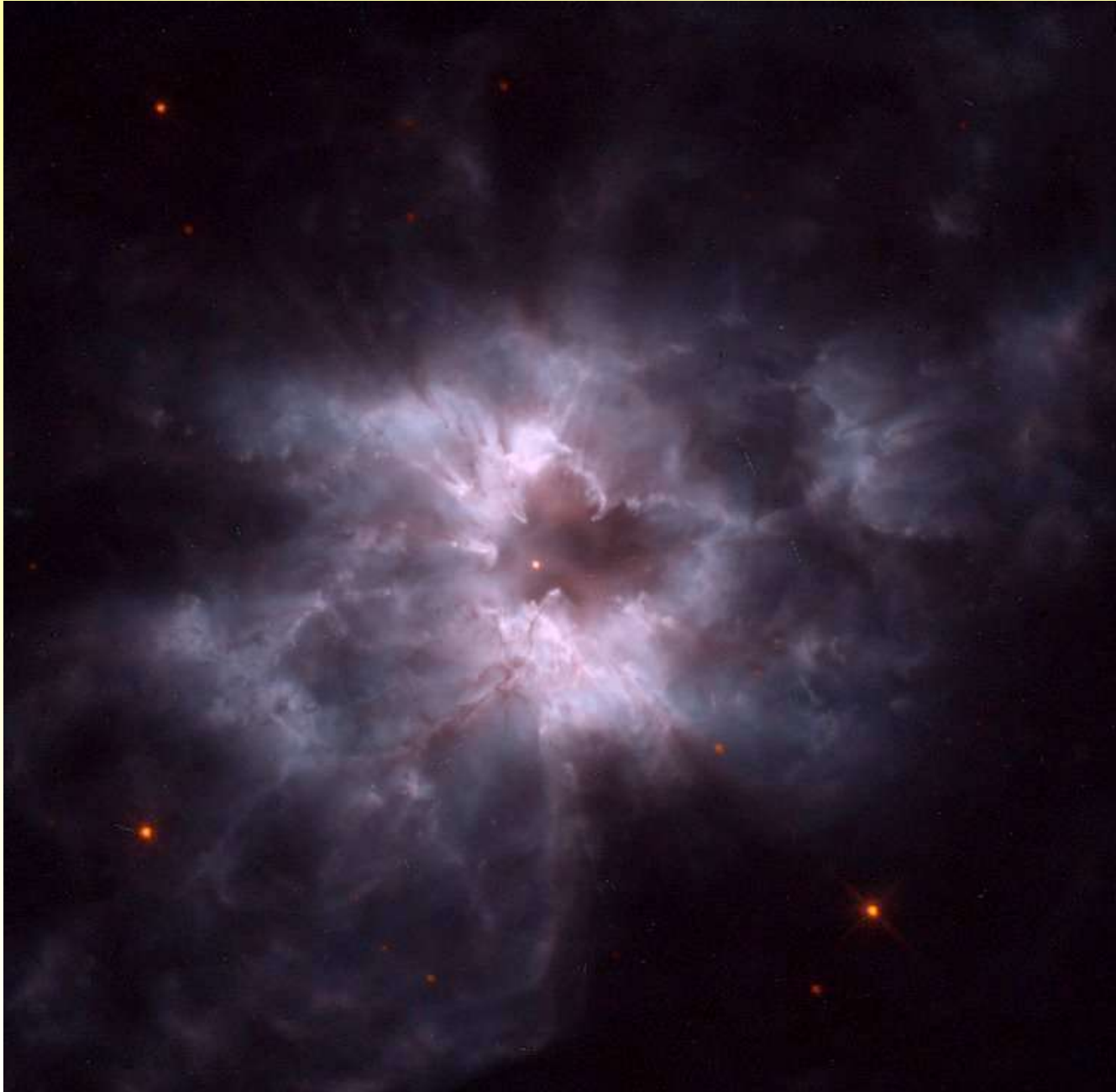


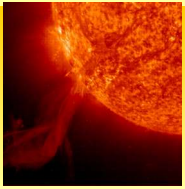
Jet nevel: Mz 3





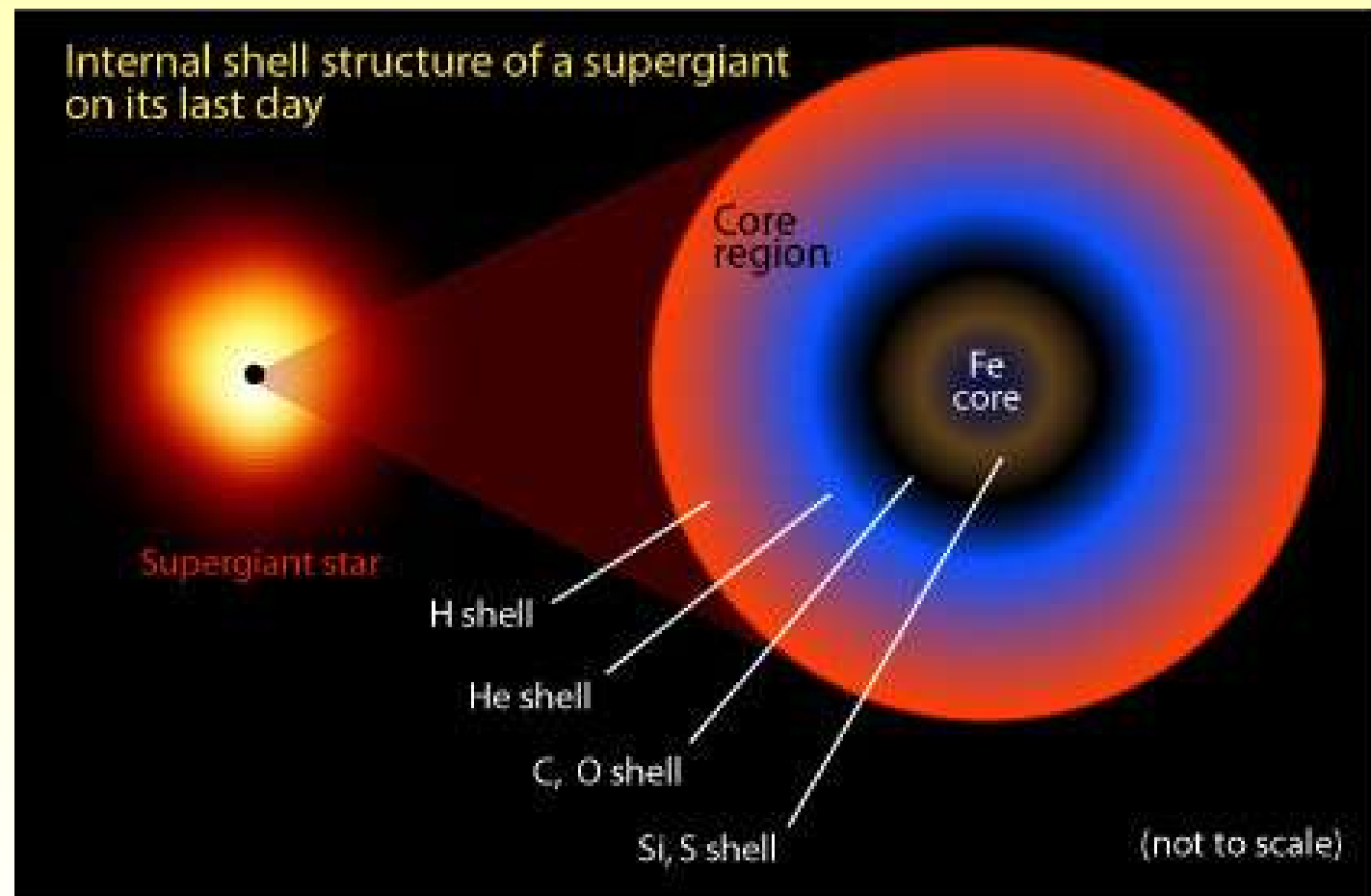
Verwaaien van de nevel.

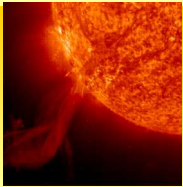




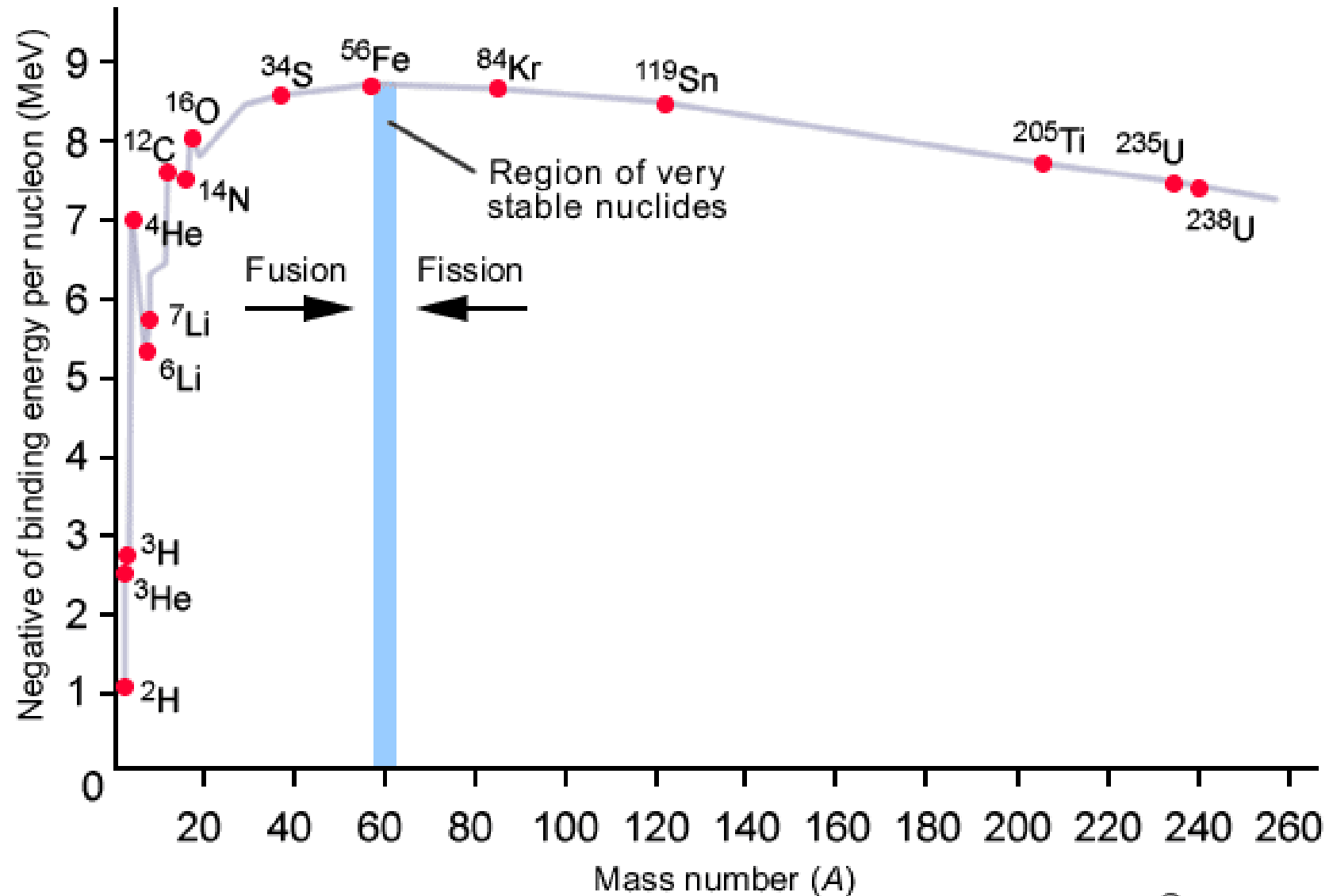
Zware jongens

Wat gebeurt er met de zware jongens
($M > 8 M_{\text{zon}}$)?



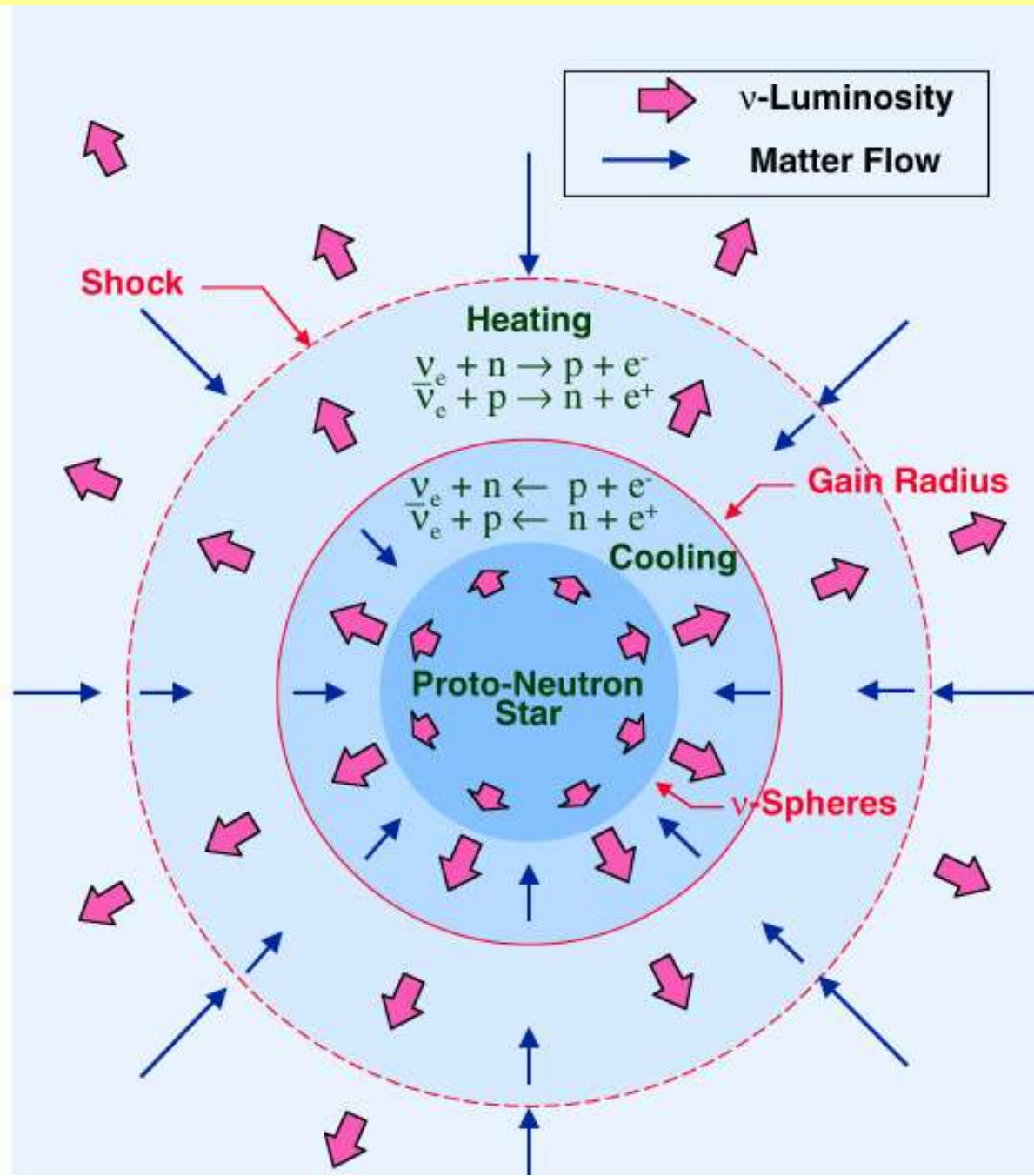


Implosie van ijzerkern



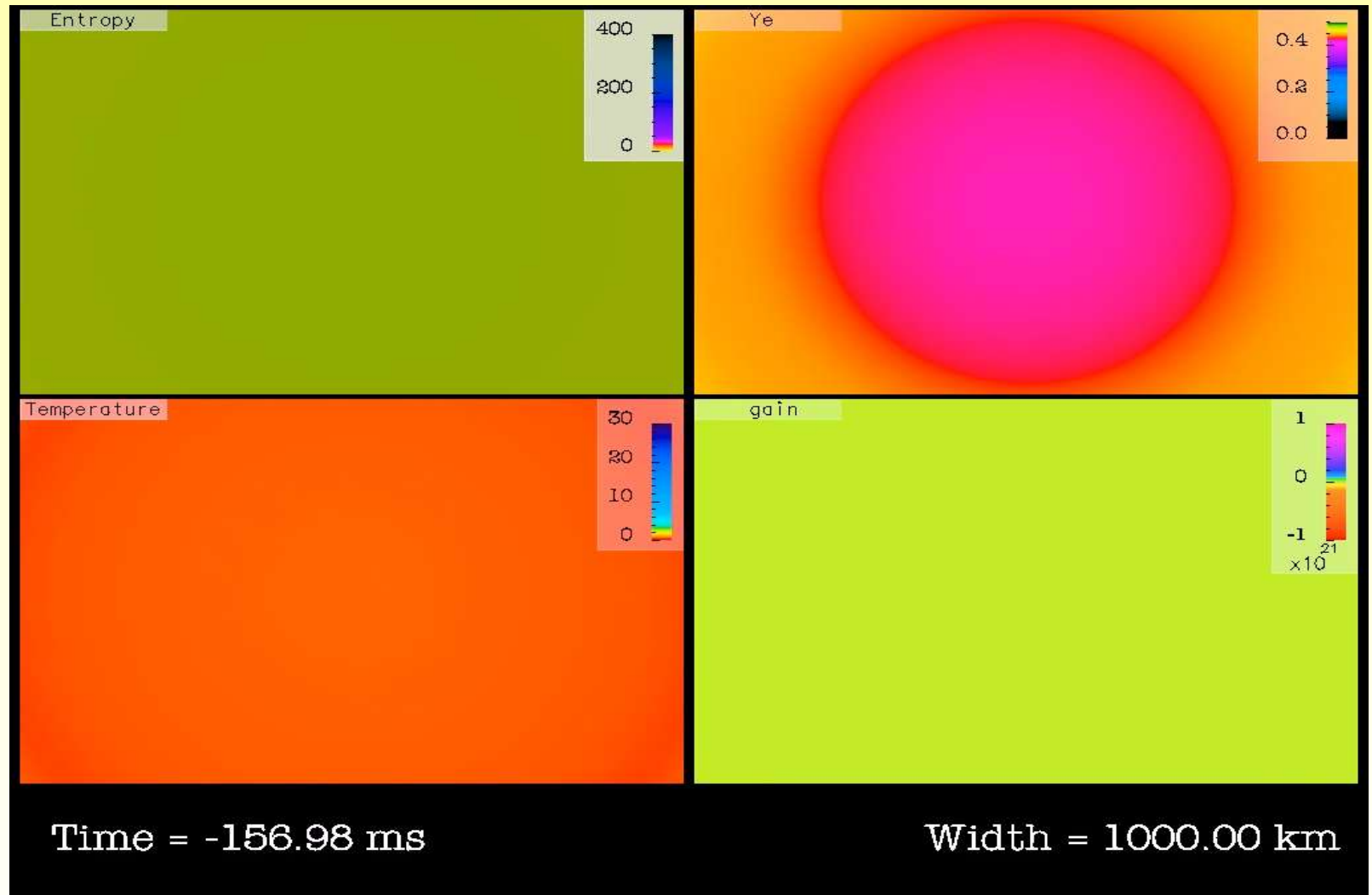


Kern vormt proto-neutronen ster

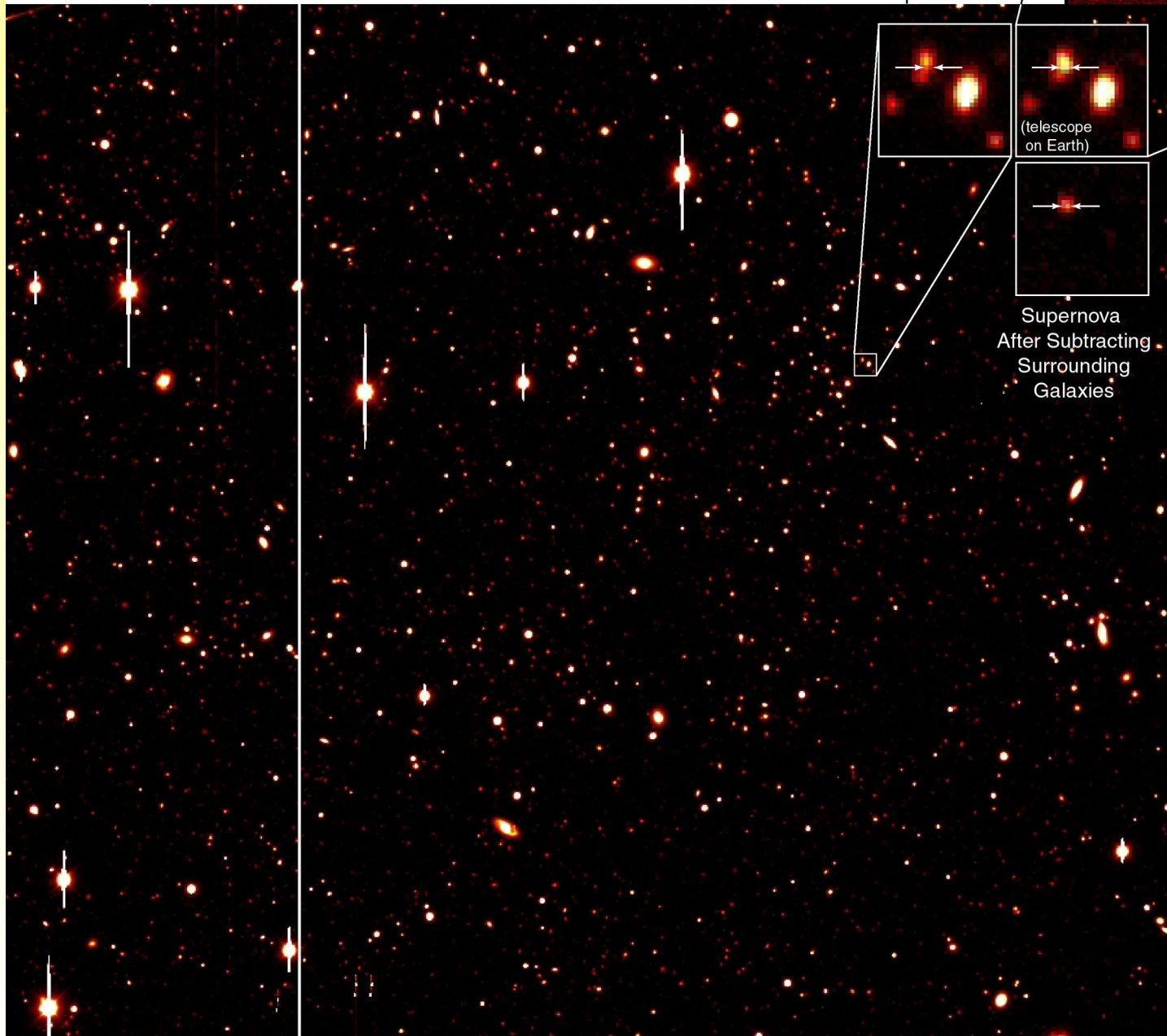




Simulations by Adam Burrows et al.

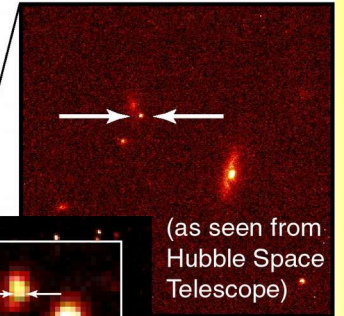


Zo helder als stelsel

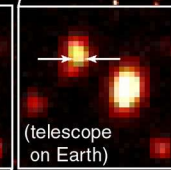
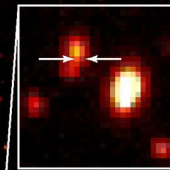


Before
Supernova

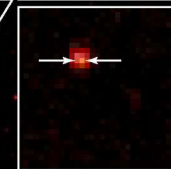
During
Supernova



(as seen from
Hubble Space
Telescope)



(telescope
on Earth)



Supernova
After Subtracting
Surrounding
Galaxies



Historische supernovae

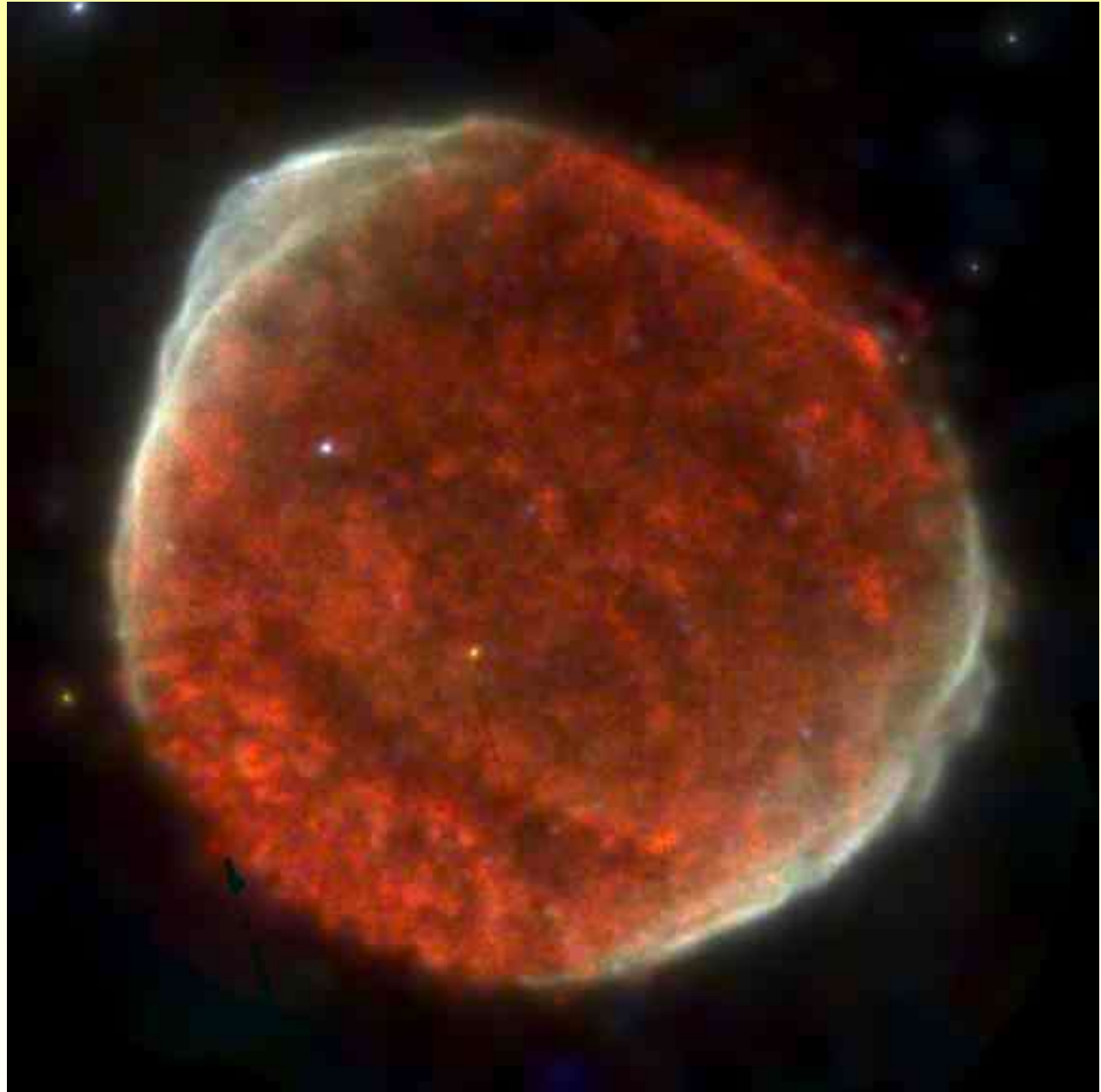
1572 Tycho

SN 1006

1680 Cas A

Crab 1054

1604 Kepler





Historische supernovae

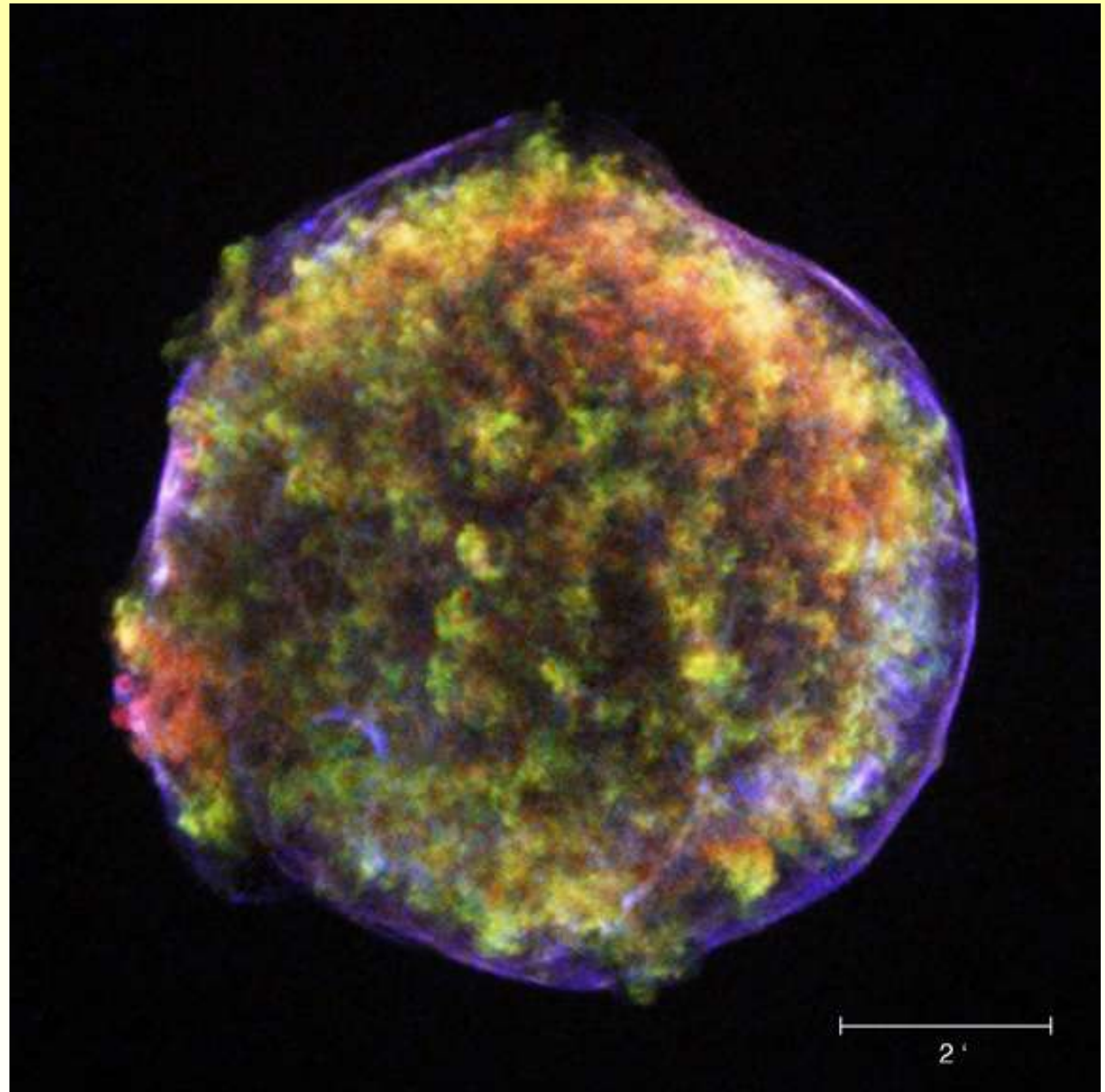
1572 Tycho

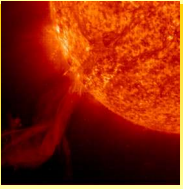
SN 1006

1680 Cas A

Crab 1054

1604 Kepler





Historische supernovae

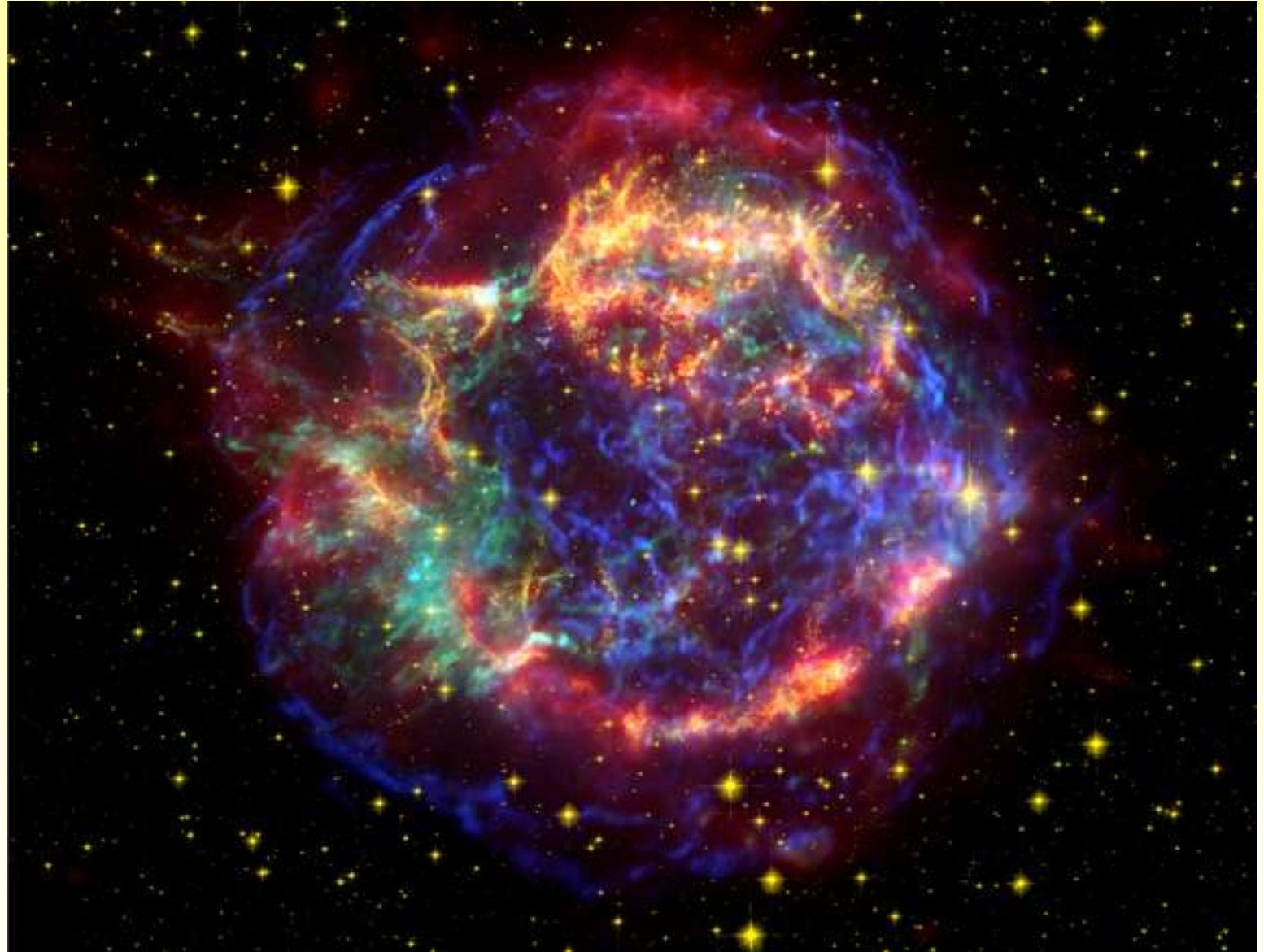
1572 Tycho

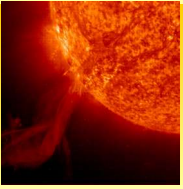
SN 1006

1680 Cas A

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1604 Kepler





Historische supernovae

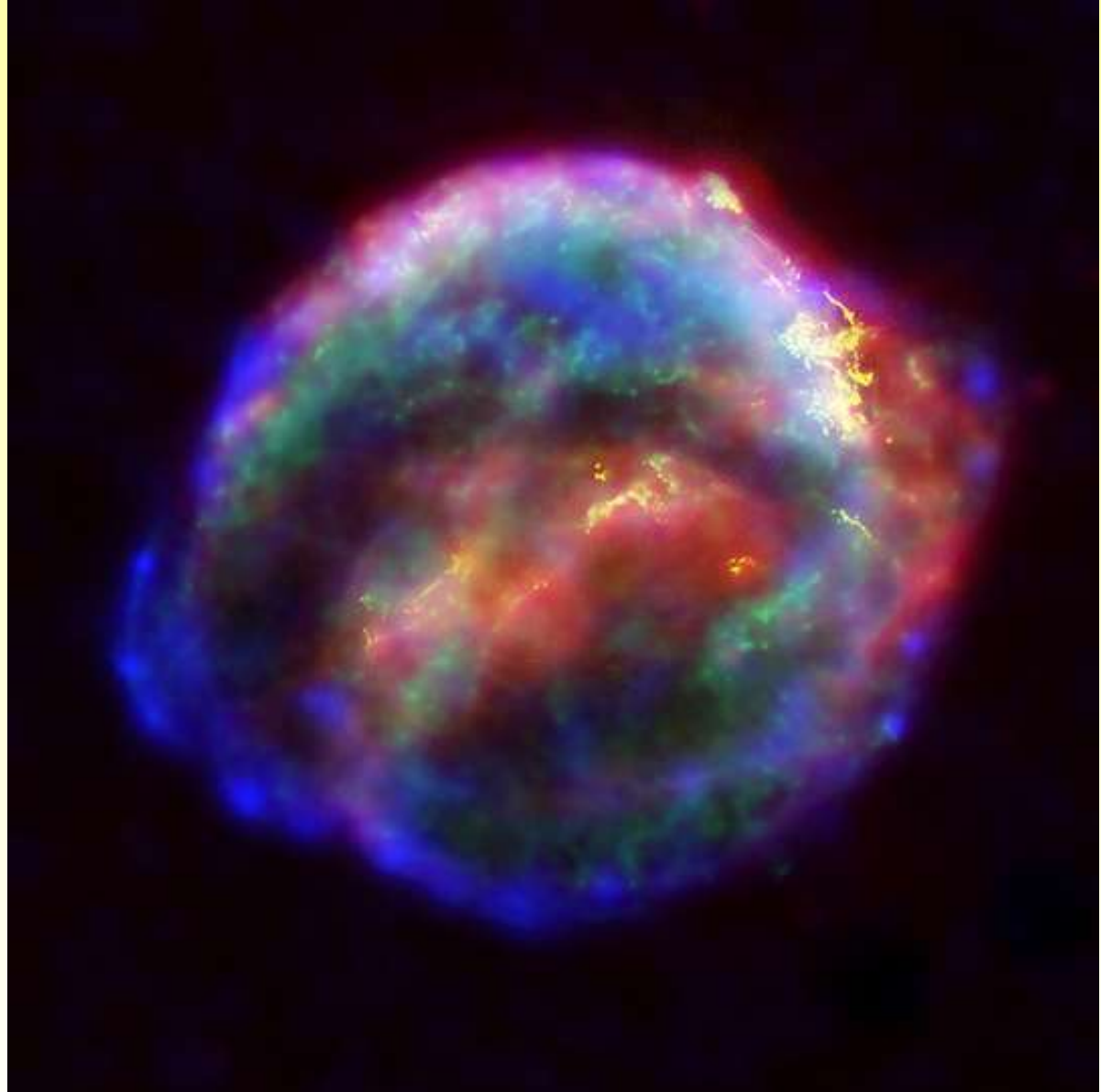
1572 Tycho

SN 1006

1680 Cas A

Crab 1054

1604 Kepler





Historische supernovae

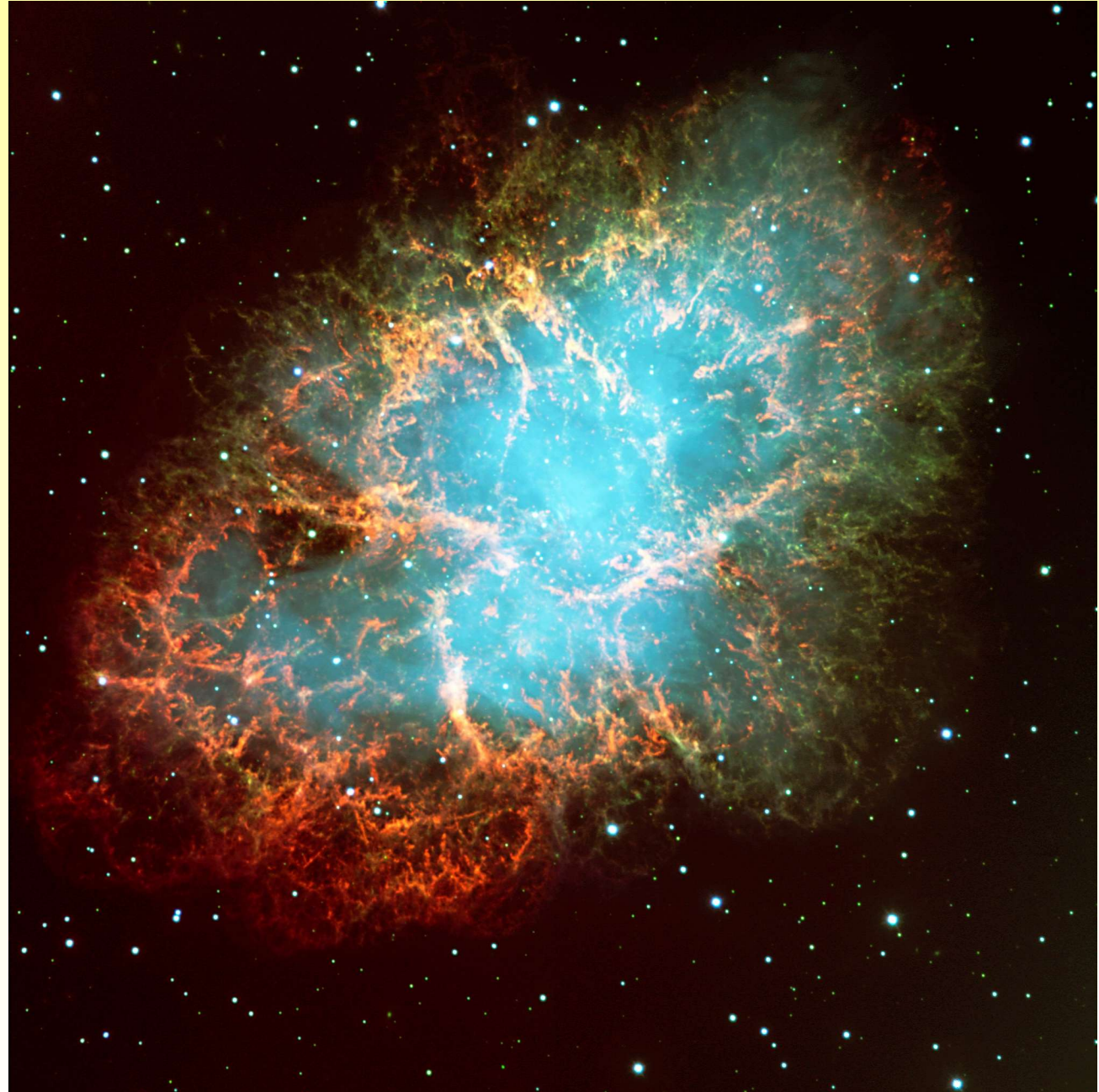
1572 Tycho

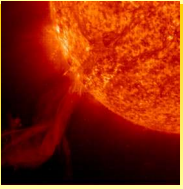
SN 1006

1680 Cas A

Crab 1054

1604 Kepler





Binnenste van Crab nevel

1572 Tycho

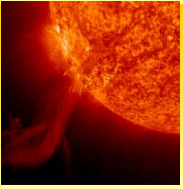
SN 1006

1680 Cas A

Crab 1054

1604 Kepler





De pulsar in de Crab nevel

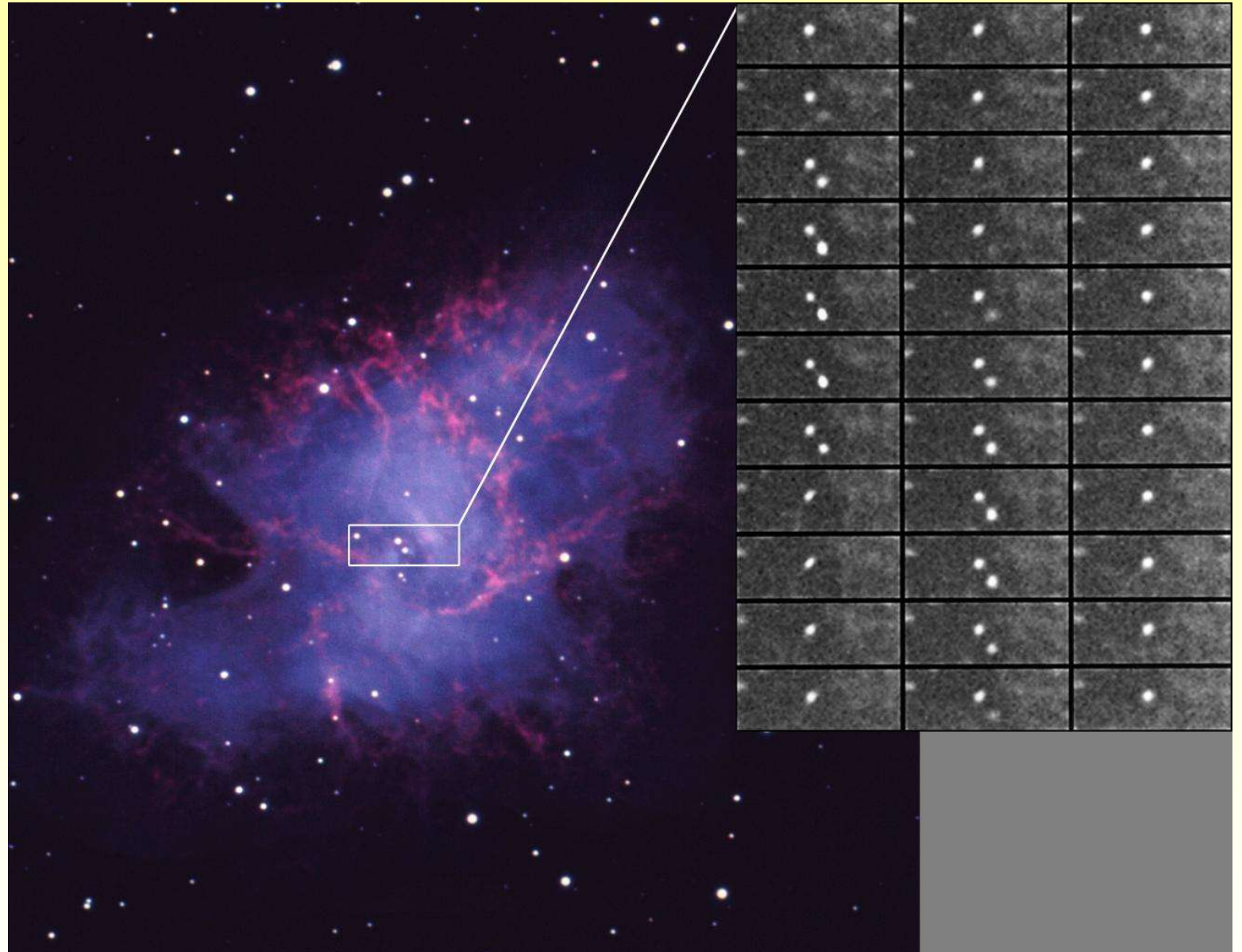
1572 Tycho

SN 1006

1680 Cas A

Crab 1054

1604 Kepler



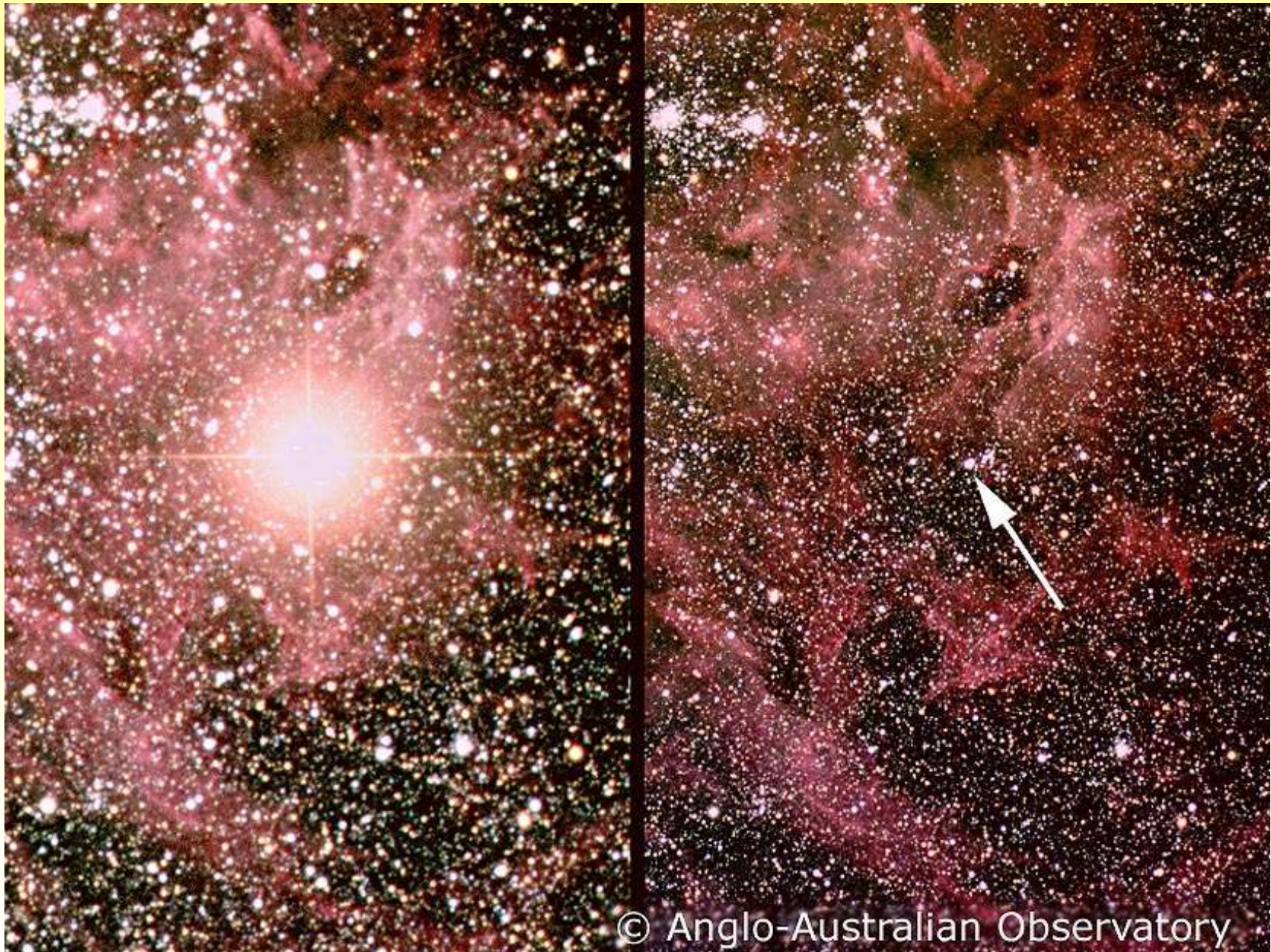


Grote Magellaanse Wolk





SN 1987 A





Restant?

Het restant van een lichte ster ($<8 M_{\text{zon}}$)

- Een Witte Dwerg

Het restant van een supernova explosie is:

- of een neutronenster (zoals de Crab pulsar)
- of een zwart gat (zoals waarschijnlijk in SN 1987A)



Fermionen en bosonen

Alle deeltjes kunnen ingedeeld worden in *fermionen* of *bosonen*

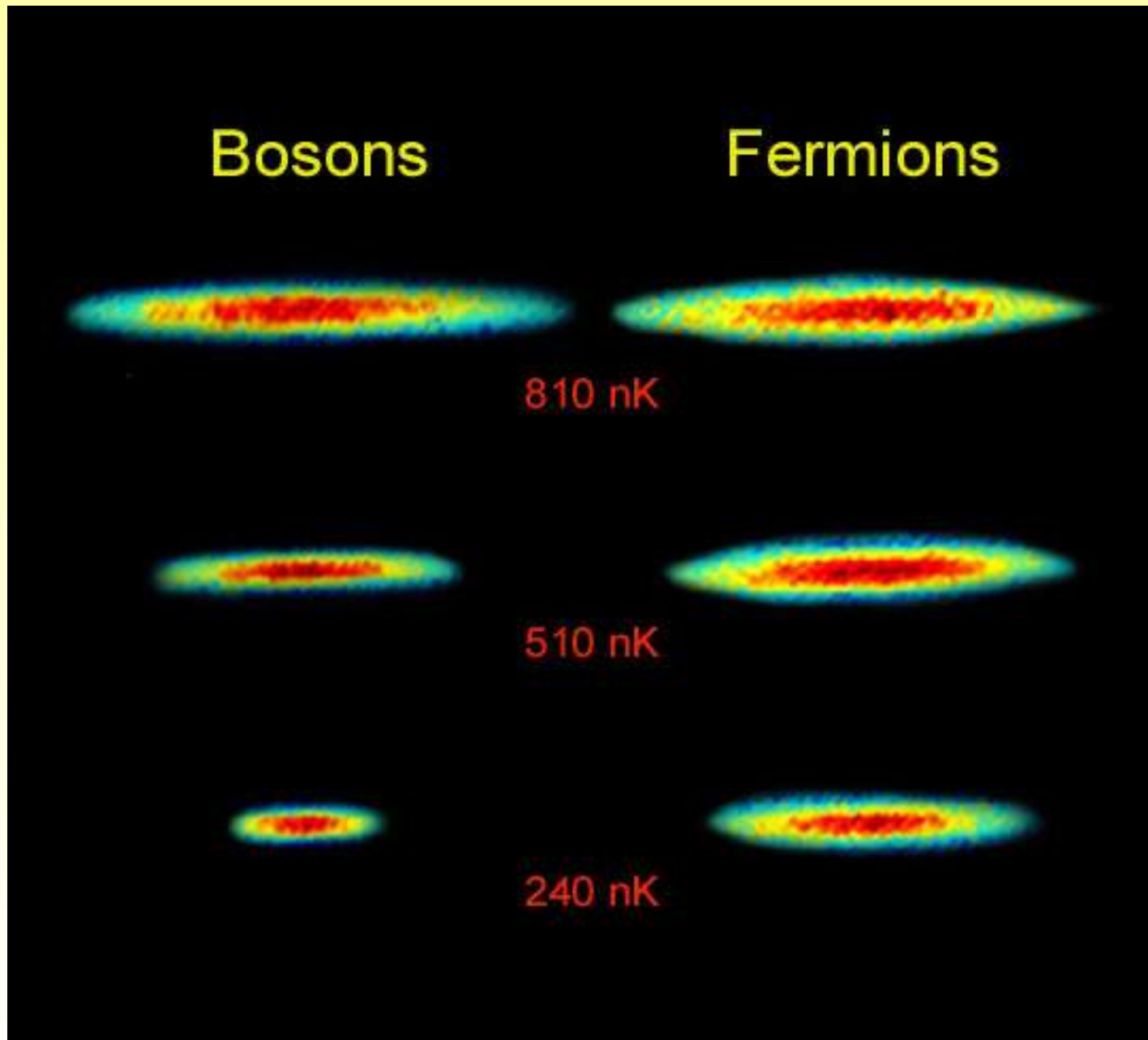
Fermions		Bosons	
Leptons Quarks	$\frac{1}{2}$	1	Carrier Bosons $\gamma W^+ W^- Z^0 g$
Baryons (qqq)	$\frac{1}{2}, \frac{3}{2}, \frac{5}{2}, \dots$	0, 1, 2, ...	Mesons (q $\bar{q}$)

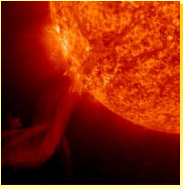
Fermionen: alle 'normale' deeltjes: electronen, protonen, neutronen

Bosonen: alle krachtendragers: fotonen, W en Z deeltjes, graviton



Fermionen en bosonen





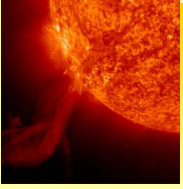
Pauli Principe



‘ Twee fermionen kunnen niet precies dezelfde quantum toestand hebben.’

Wolfgang Pauli

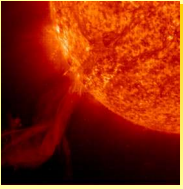
Quantum toestand: dezelfde plaats, impuls en spin.



De electronen druk

De dichtheid in een koelende kern loopt zo hoog op dat electronen als eerste last krijgen van Heisenberg en Pauli principes:

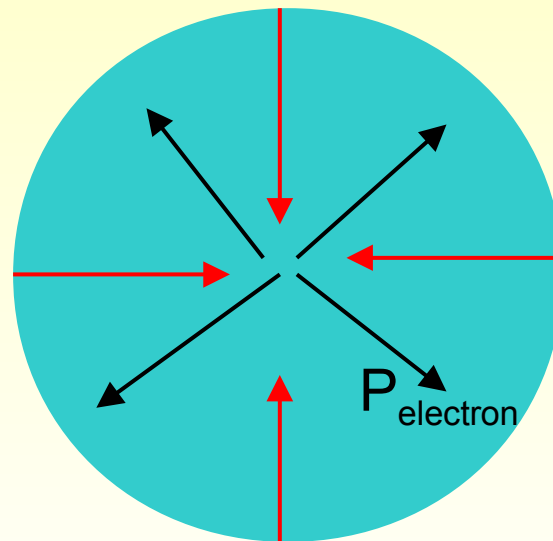
De deeltjes zitten zo dicht bij elkaar dat hun impuls omhoog moet...



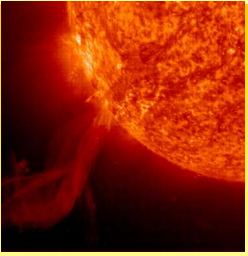
Gedegenerereerde materie

Meer impuls = meer druk.

Electronen leveren een druk op die de zwaarte kracht weerstaat.



De ster is 'gedegenerereerd'



Eigenschappen Gedegenerereerde materie

- Druk hangt niet van de temperatuur af.

$$P \propto \rho^{5/3} (non-rel.) \text{ of } P \propto \rho^{4/3} (rel.)$$

- Hoe hoger de massa (= zwaartekracht), hoe kleiner de ster

$$R \propto M^{-2}$$



In de kern

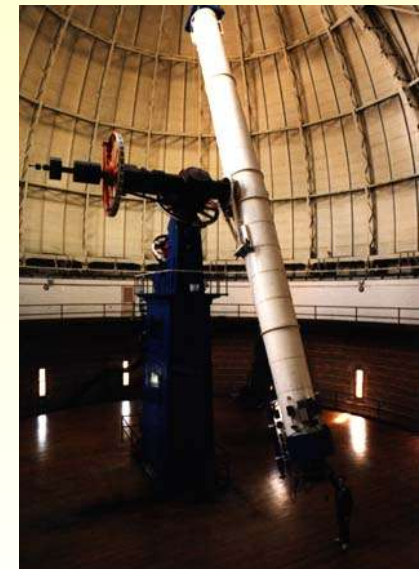
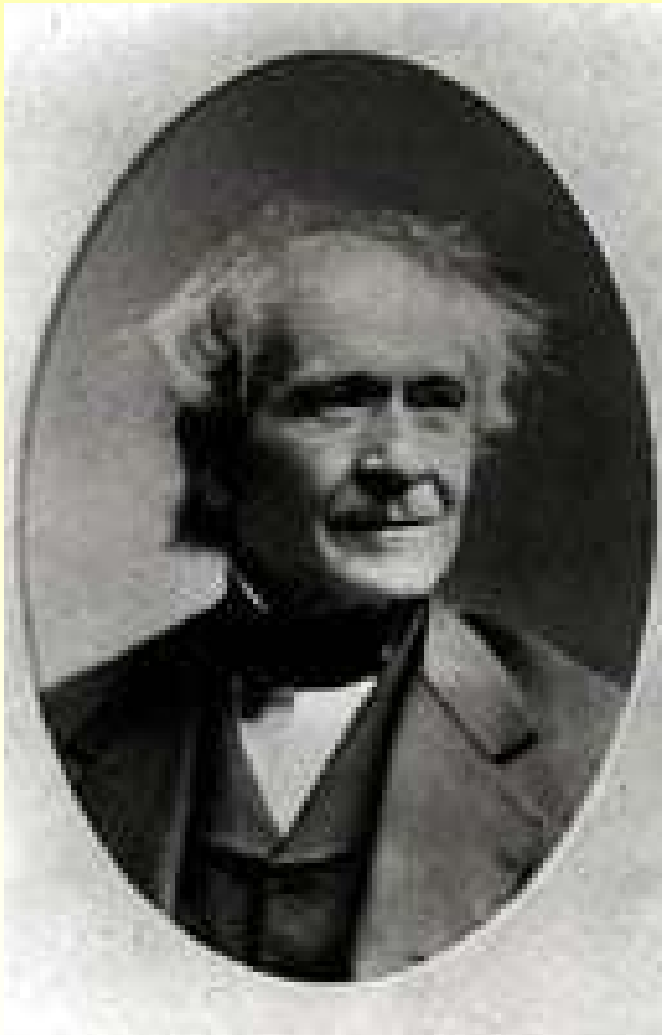
Dichtheid is zover opgelopen dat de druk door electronendruk wordt opgewekt.

De kern stopt met samentrekken en straalt aanwezige energie nog slechts uit...



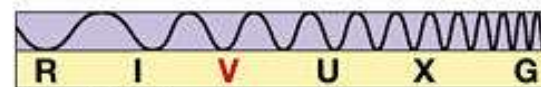
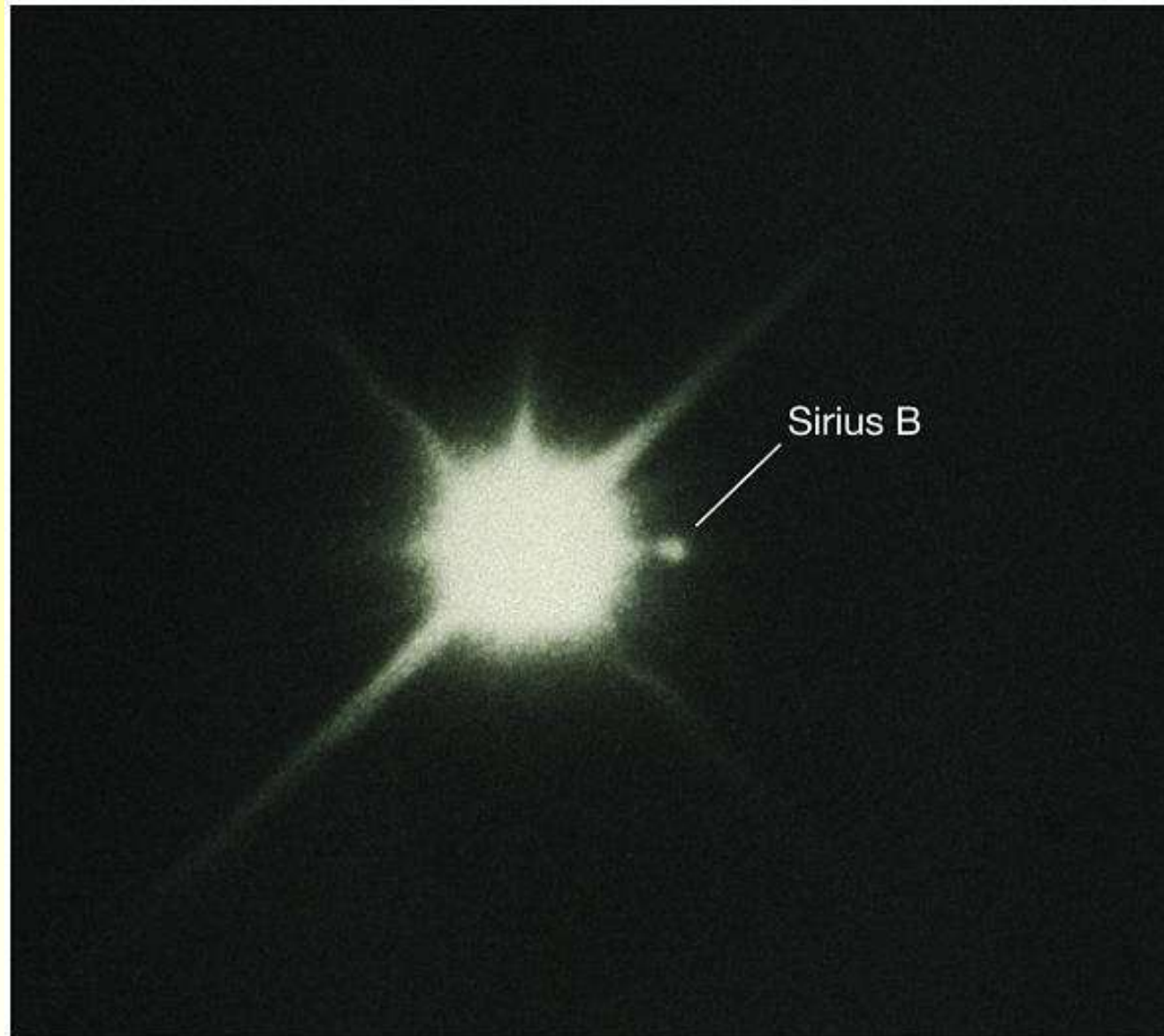
Amerikaanse lenzenslijper

Alvan Graham Clark



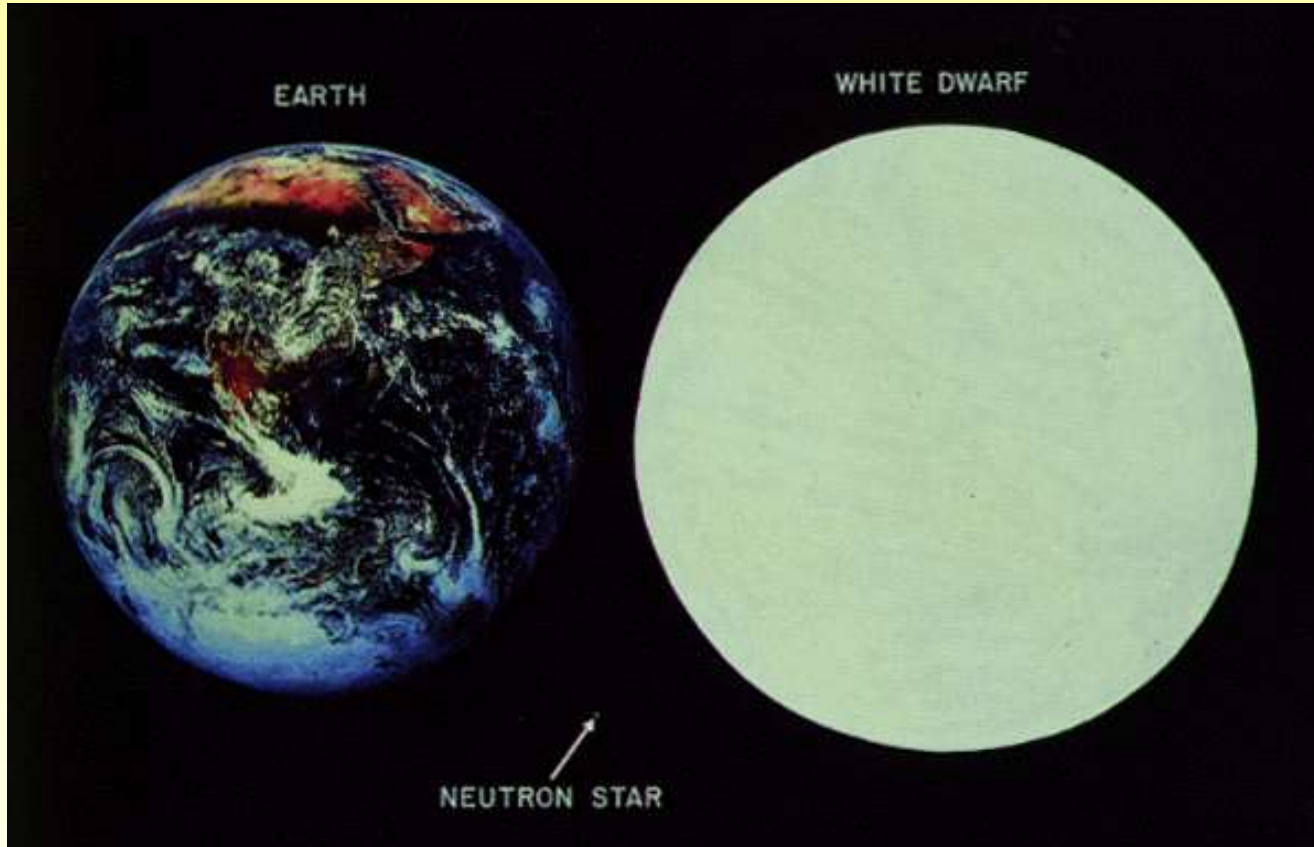


Witte dwergen





Witte dwergen



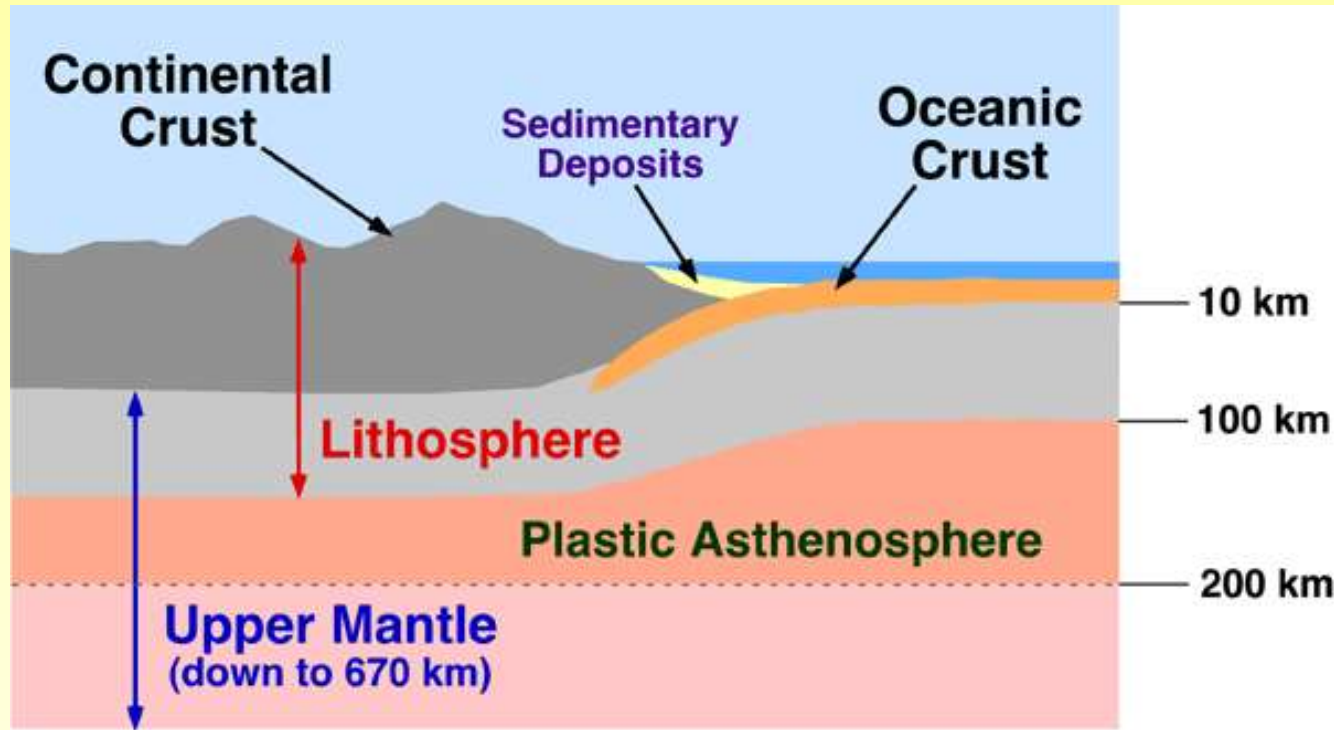
$$R_{\text{wd}} \sim R_{\text{aarde}}$$

$$M_{\text{wd}} \sim 0.6 M_{\text{zon}}$$

$$\text{Dwz: } \rho_{\text{wd}} \approx 200\,000 \rho_{\text{aarde}} !!!$$

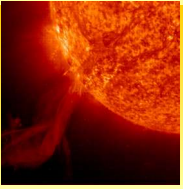


Dichtheid van rots

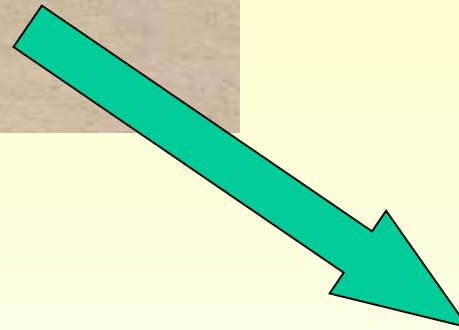


$\rho_{\text{aarde}} \sim 5 \text{ gr/cm}^3$ dwz:

$\rho_{\text{wd}} \sim 1 \text{ miljoen gr/cm}^3 \sim 1000 \text{ kg/cm}^3$



Dichtheid van witte dwerg

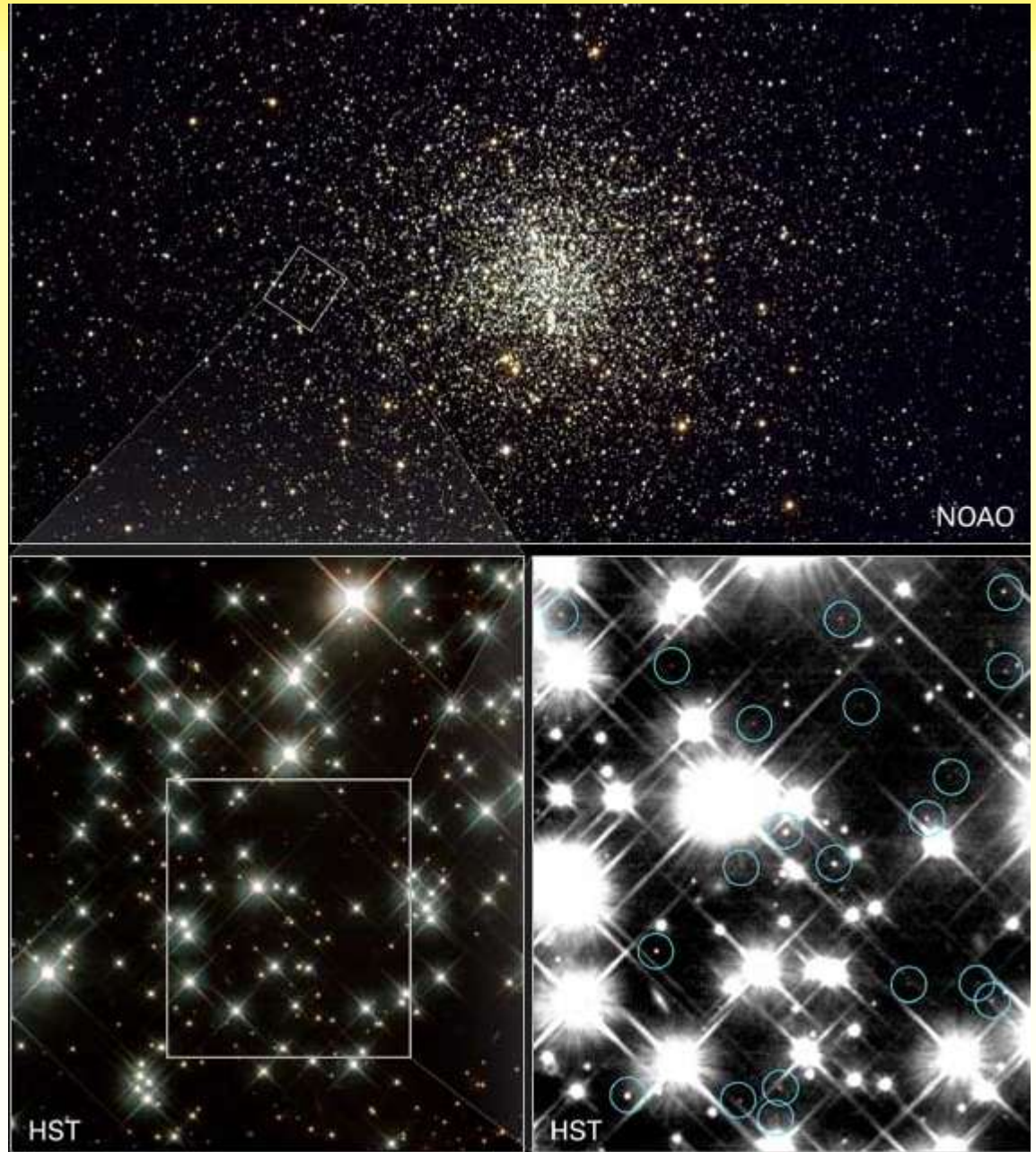


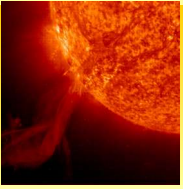


Koele dwergen

Witte dwergen
koelen slechts
heel langzaam
door thermische
energie uit te
stralen.

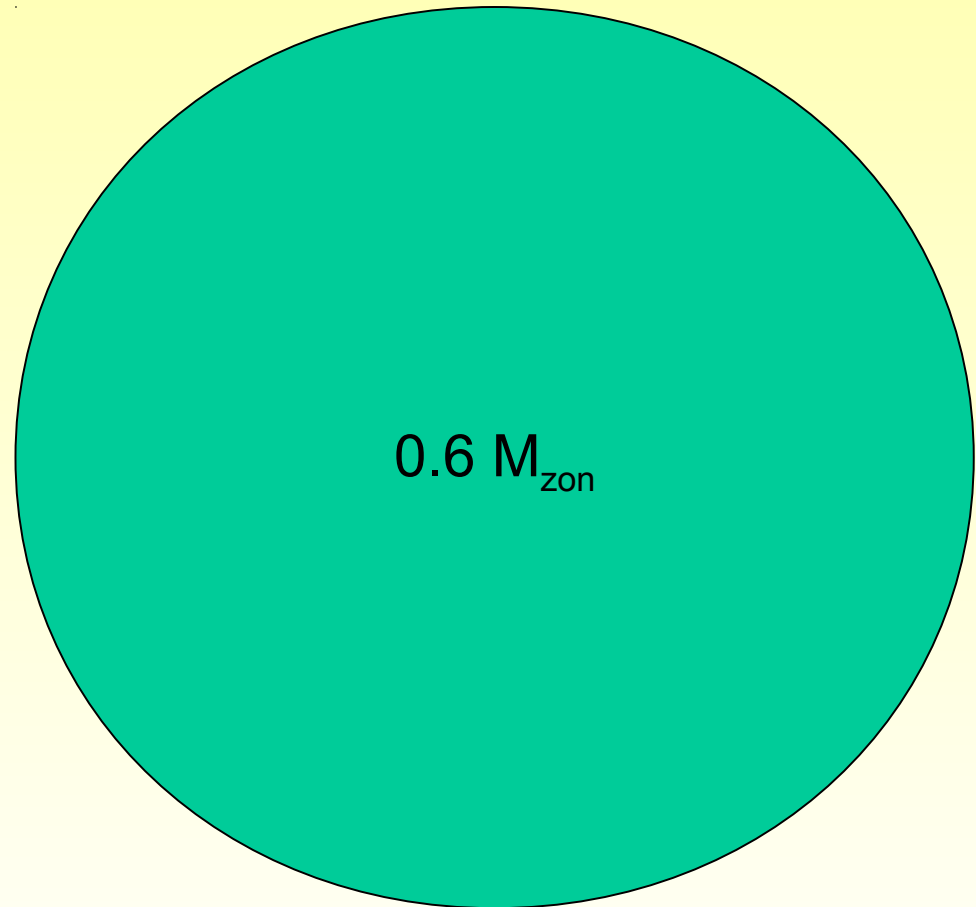
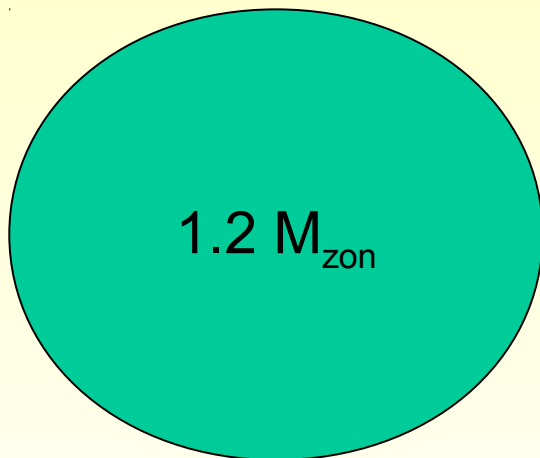
$$\tau = \frac{U}{L} = \frac{GM^2}{RL}$$





Chandrasekhar Massa

Hoe zwaarder
een witte dwerg,
hoe kleiner hij
moet zijn.

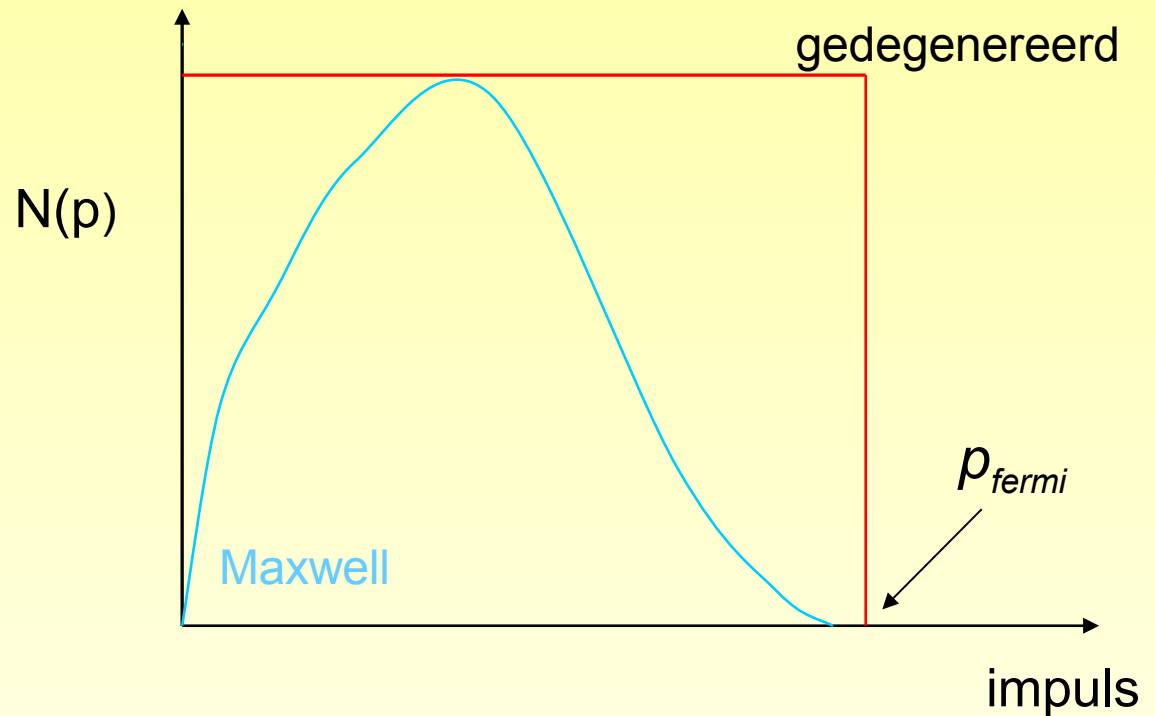


Gedegenereerde druk moet hoger worden om zwaartekracht te weerstaan



Chandrasekhar Massa

Hoe zwaarder een witte dwerg, hoe kleiner hij moet zijn, en hoe hoger de gedegenerereerde druk.

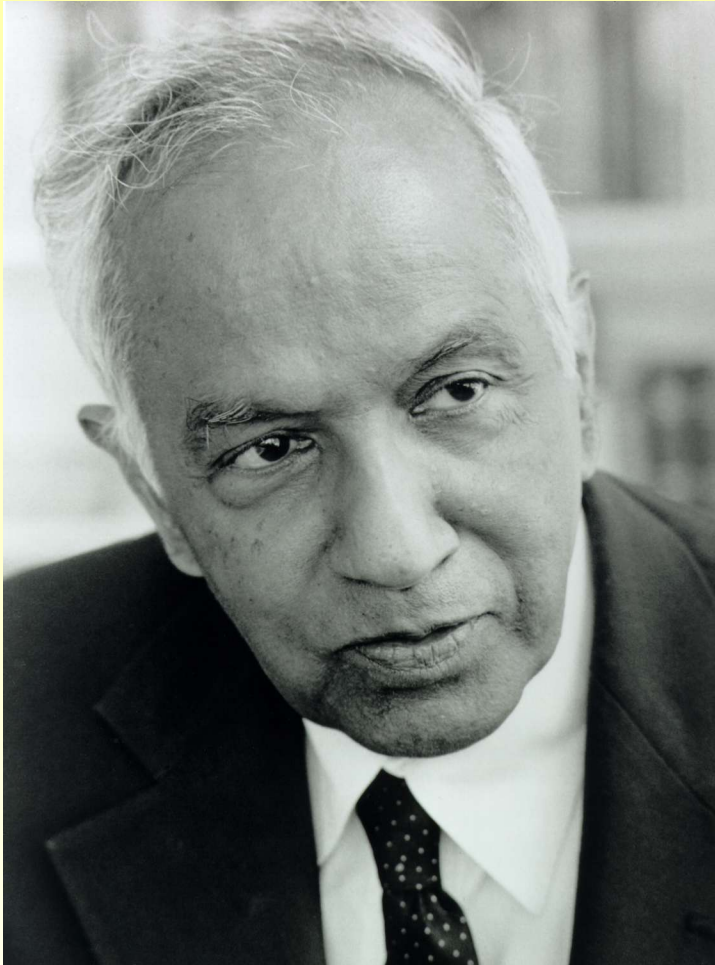


$p_{fermi} = m_e v$, maar m_e is vast. Dus als p_{fermi} omhoog moet als M omhoog gaat, moet dus v omhoog gaan.

En dat gaat fout...



Chandrasekhar Massa



Er is een maximum massa aan een witte dwerg: daar waar de snelheid $v \sim c$

Deze massa is $1.4 M_{\text{zon}}$:

De Chandrasekhar massa.

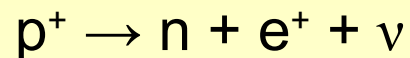
En als een witte dwerg zwaarder wordt dan dat?



Een neutronen ster

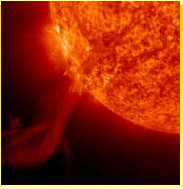
Verdere ineenstorting is een mogelijkheid (ontploffen ook...)

Tijdens verhoging van dichtheid treedt een beta-verval reactie op:



De protonen in de witte dwerg worden omgezet in neutronen.

Gelukkig zijn neutronen ook fermionen: door degeneratie kunnen ze een druk op leveren.



Een neutronen ster

$M \sim 1.4 M_{\text{zon}}$

$R \sim 10 \text{ km.}$





Een neutronen ster

Een opsomming van extremiteiten

- Dichtheid : 6 miljard mensen in een suikerklontje
: ($>$ nucleaire dichtheden)
- Magneetveld : $10^4 - 10^{10}$ Tesla
- Rotatieperiode : $1 - 10^{-3}$ seconde
- Ontsnappings snelheid: $0.5 \times c$



Radio pulsars



Jocelyn Bell

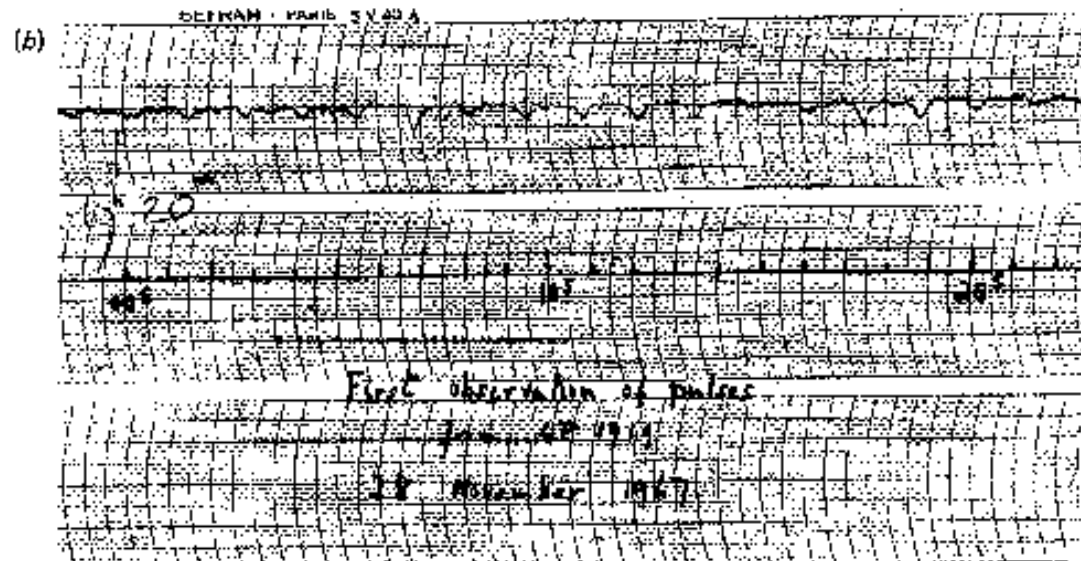
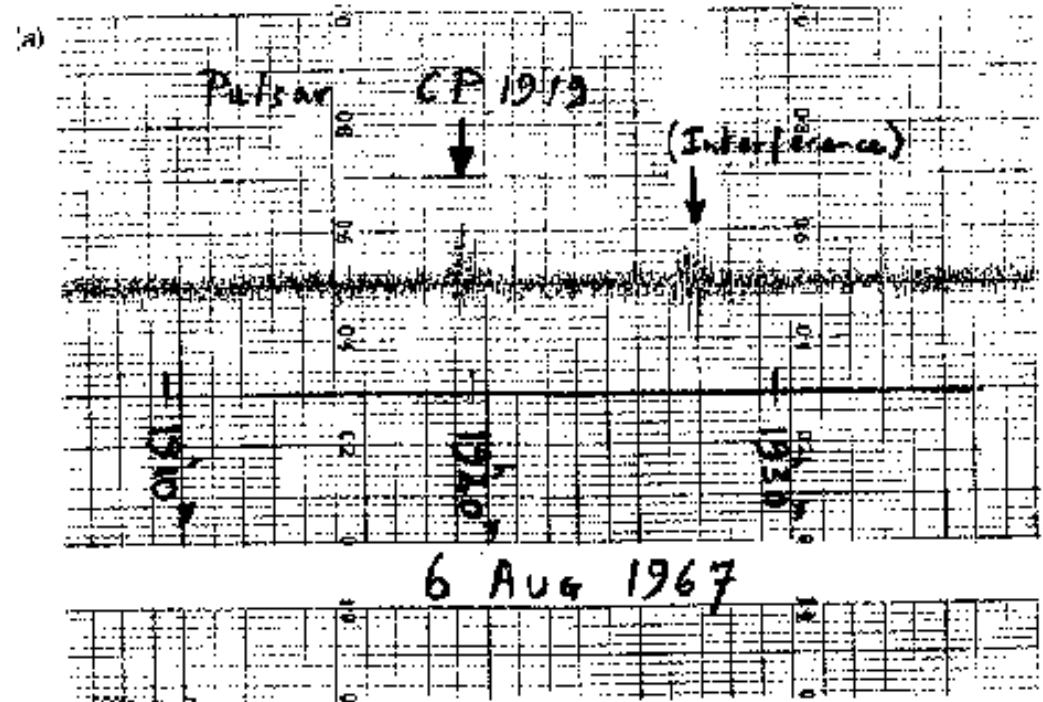


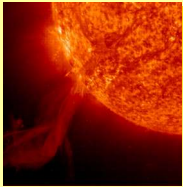
Anthony Hewish



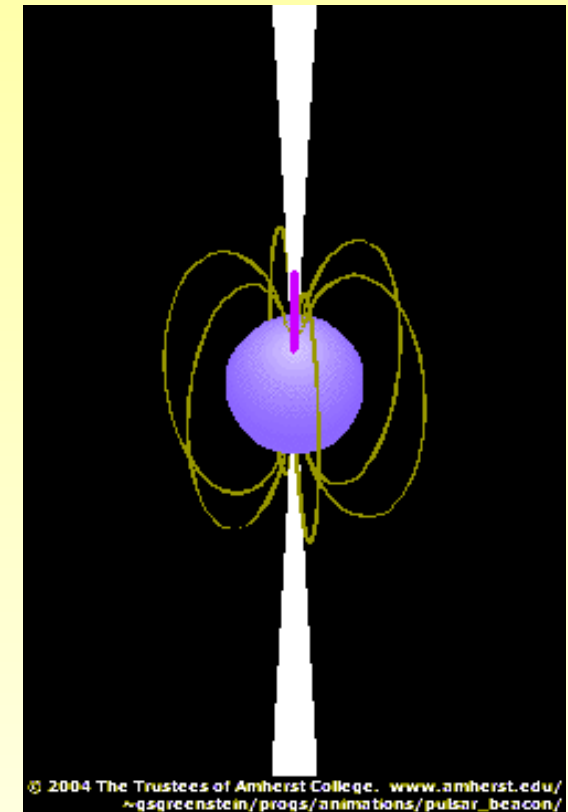
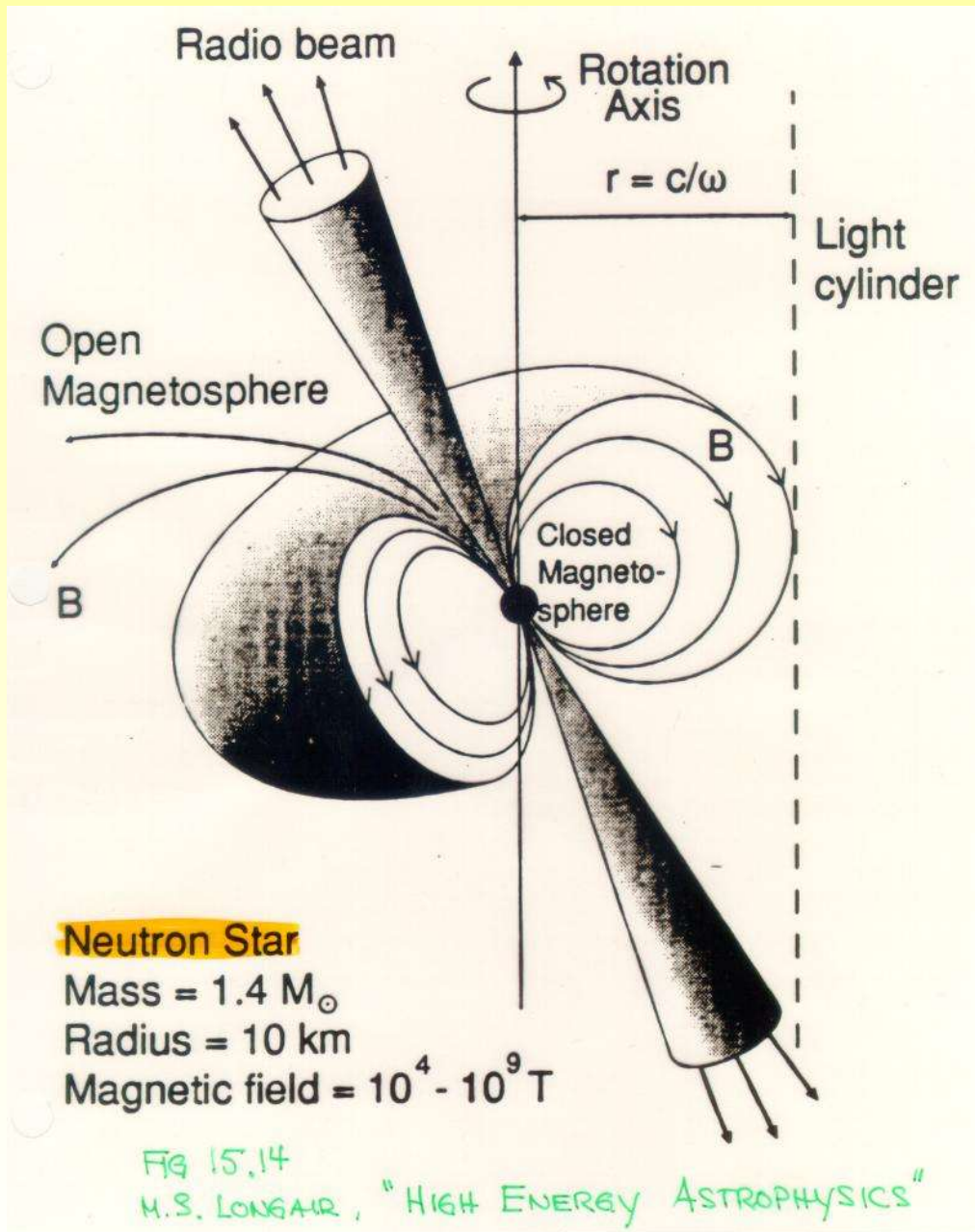
Radio pulsars

Eerste pulsar van
Bell & Hewish





Radio pulsars



Spinnende neutronen sterren



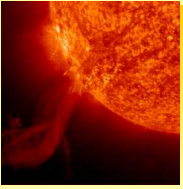
pulsar 1



pulsar 2



pulsar 3



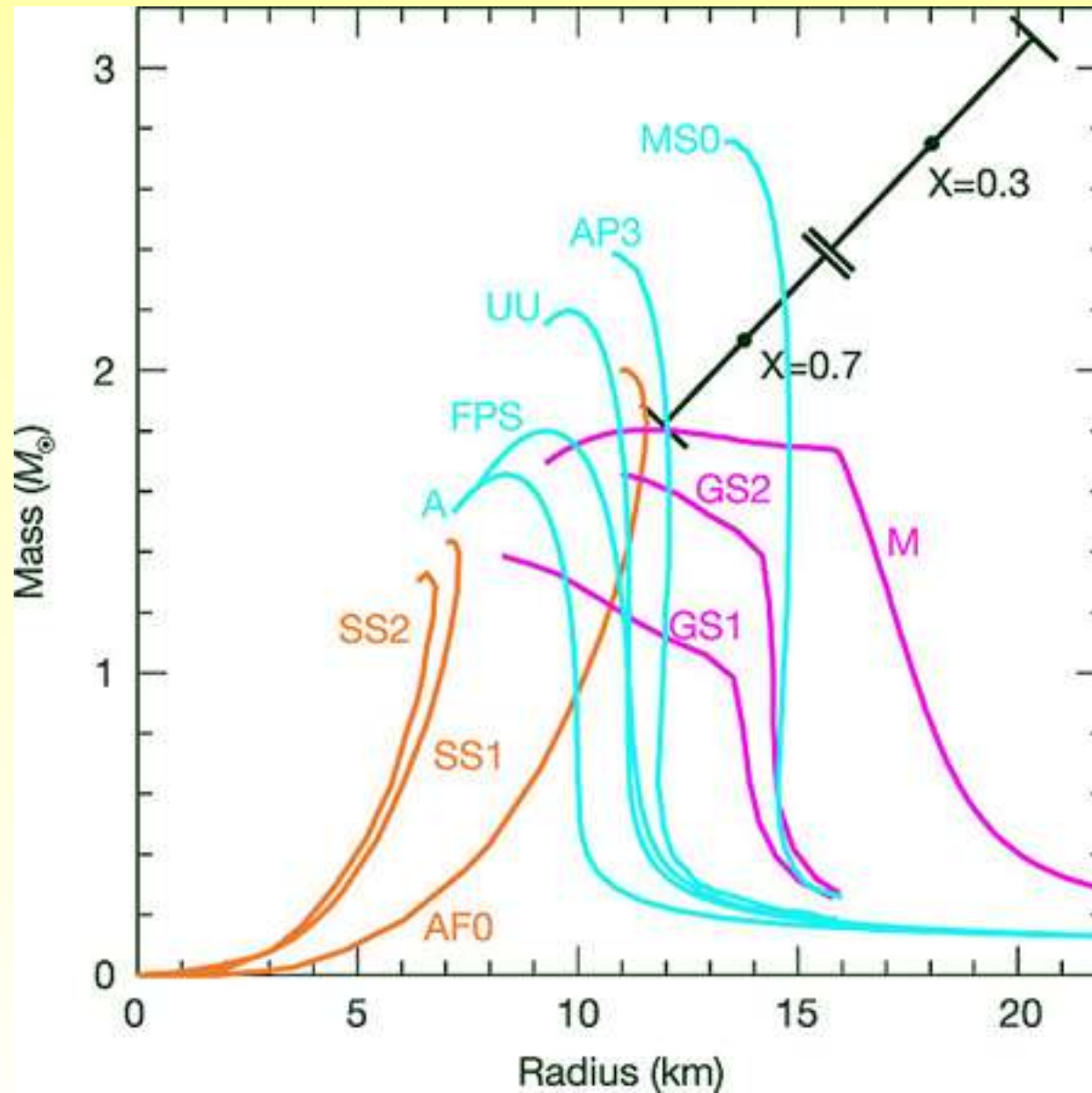
Neutronensterren

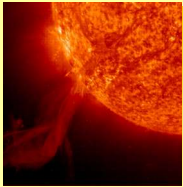


Kans voor bestuderen van extreme fysica
Simpele bepaling van straal en massa is al moeilijk

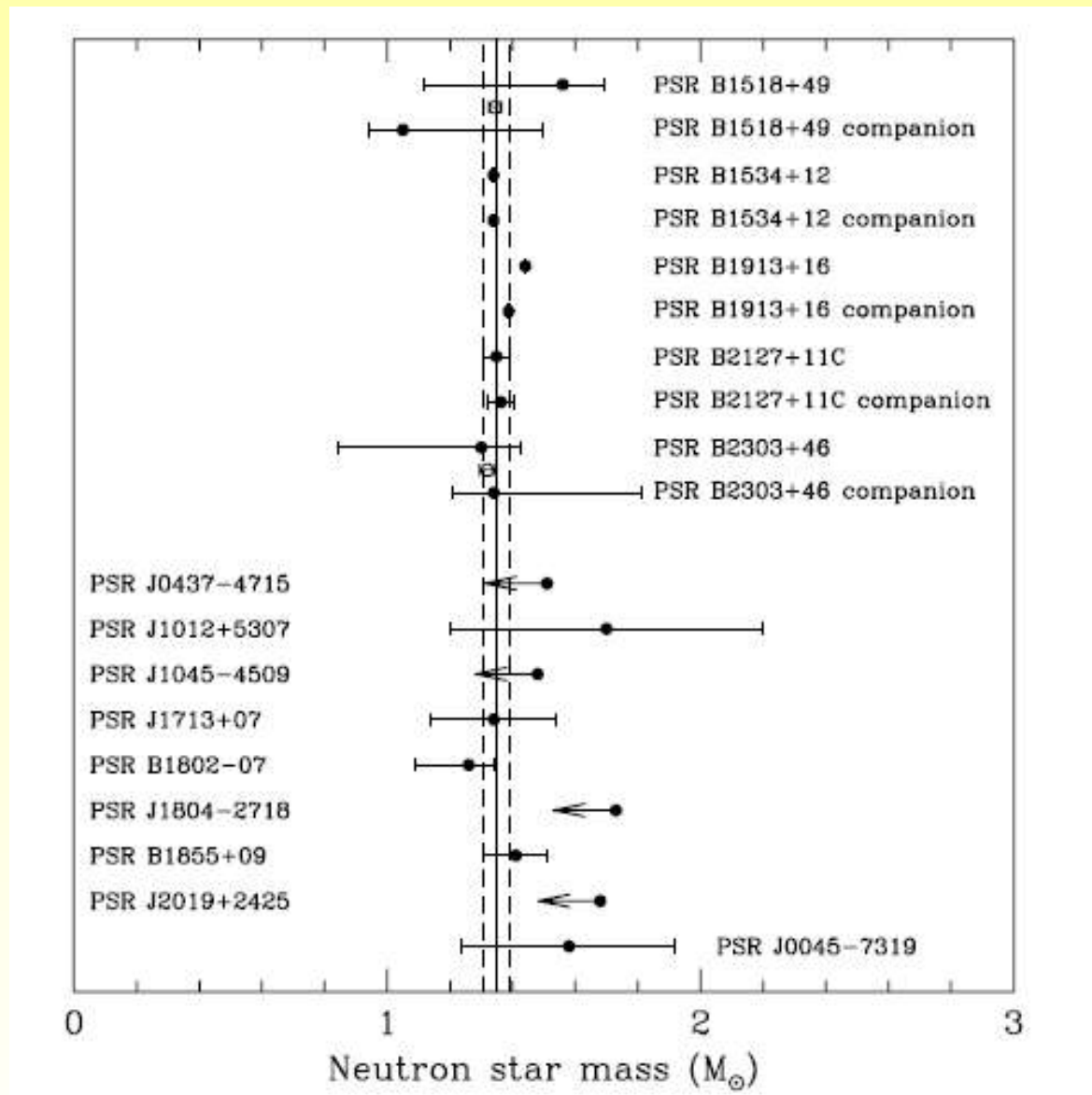


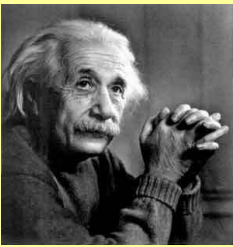
Neutronenster modellen



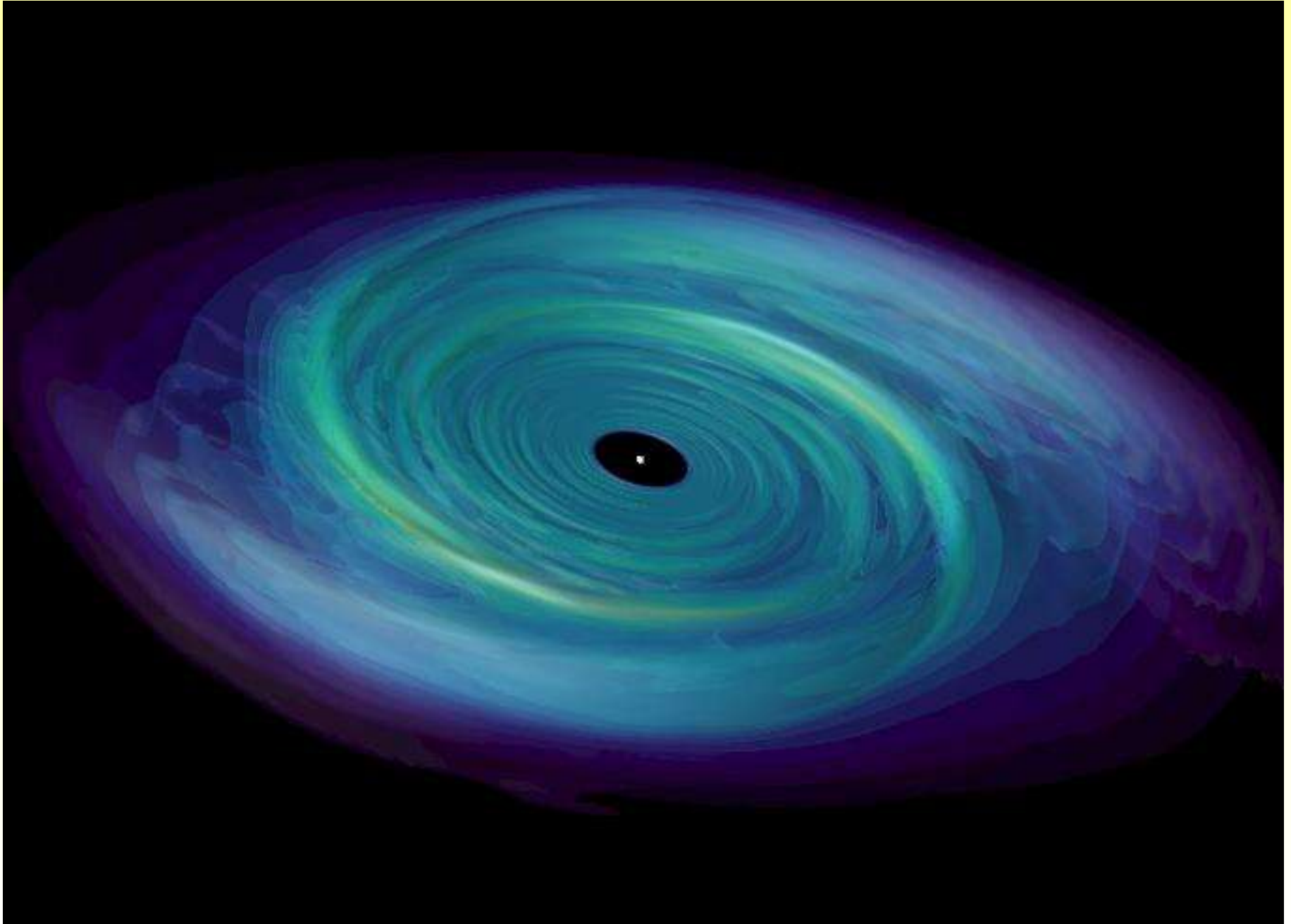


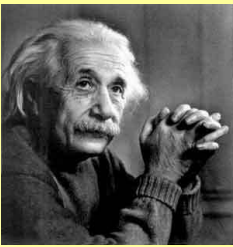
Massa bepalingen NS





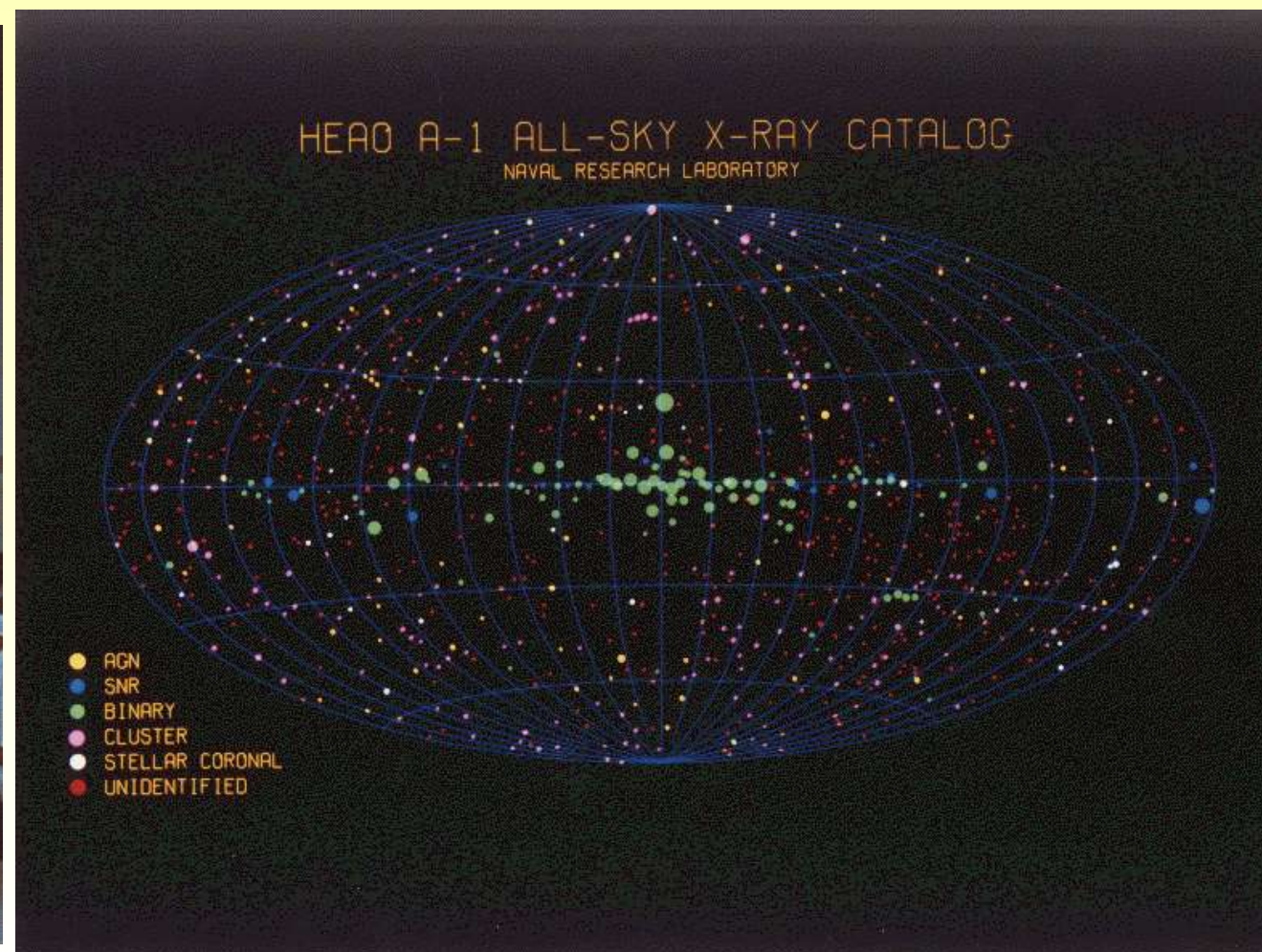
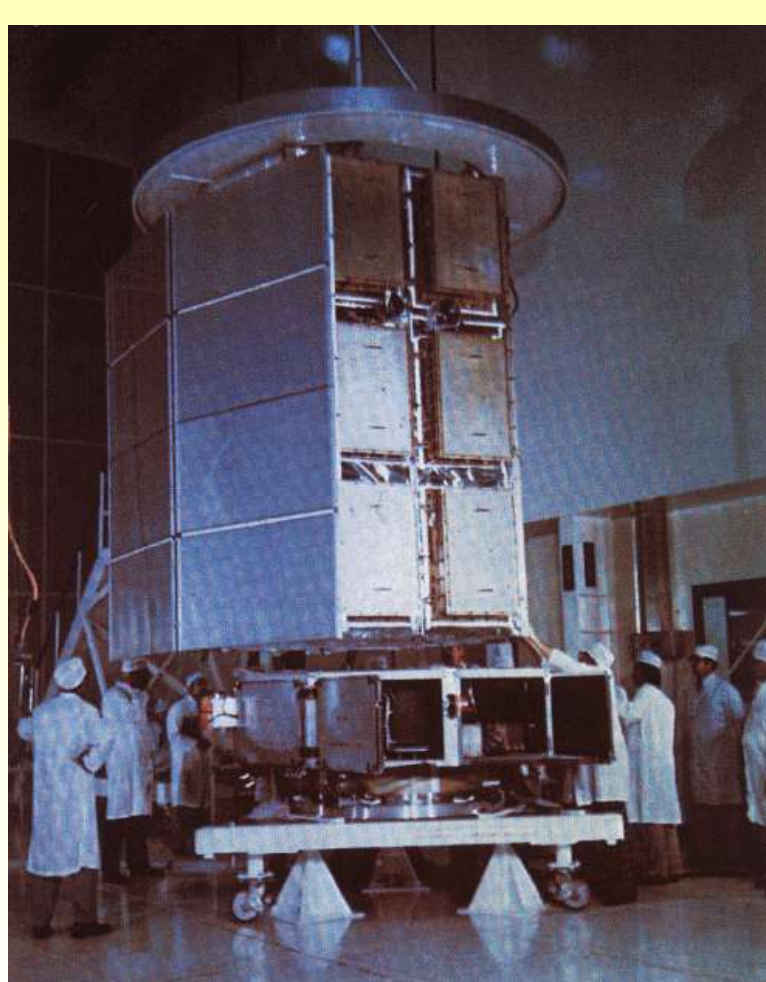
Accretie-schijven

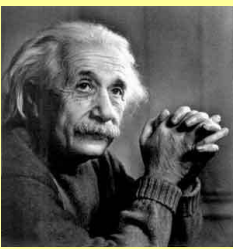




Binnenste van accretieschijf

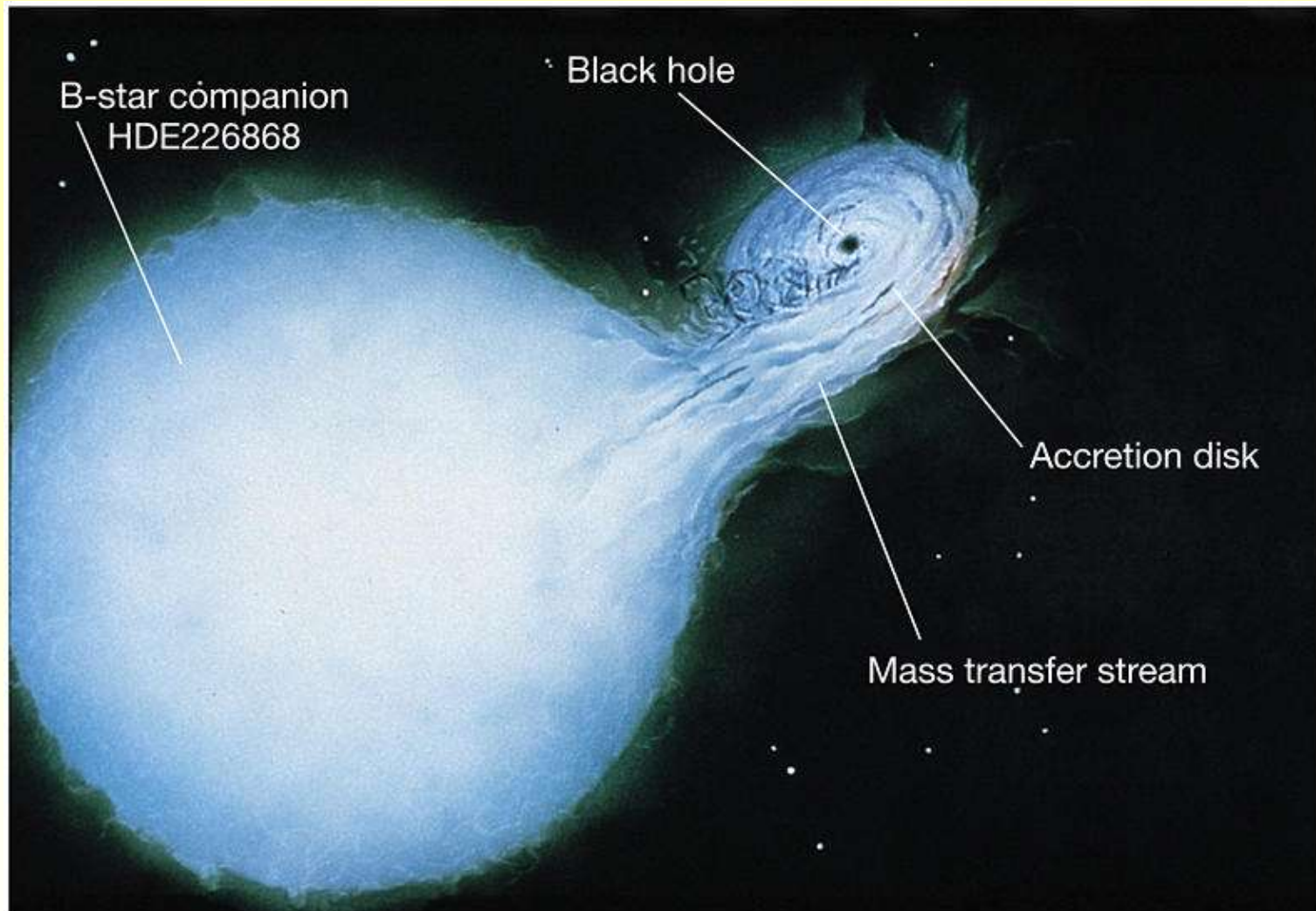
Door wrijving en vrijkomende potentiële energie:
 $T > 1 \text{ MK} \Rightarrow \text{röntgen straling!}$

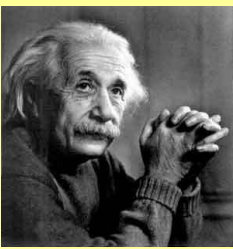




Zwart gat dubbelsterren

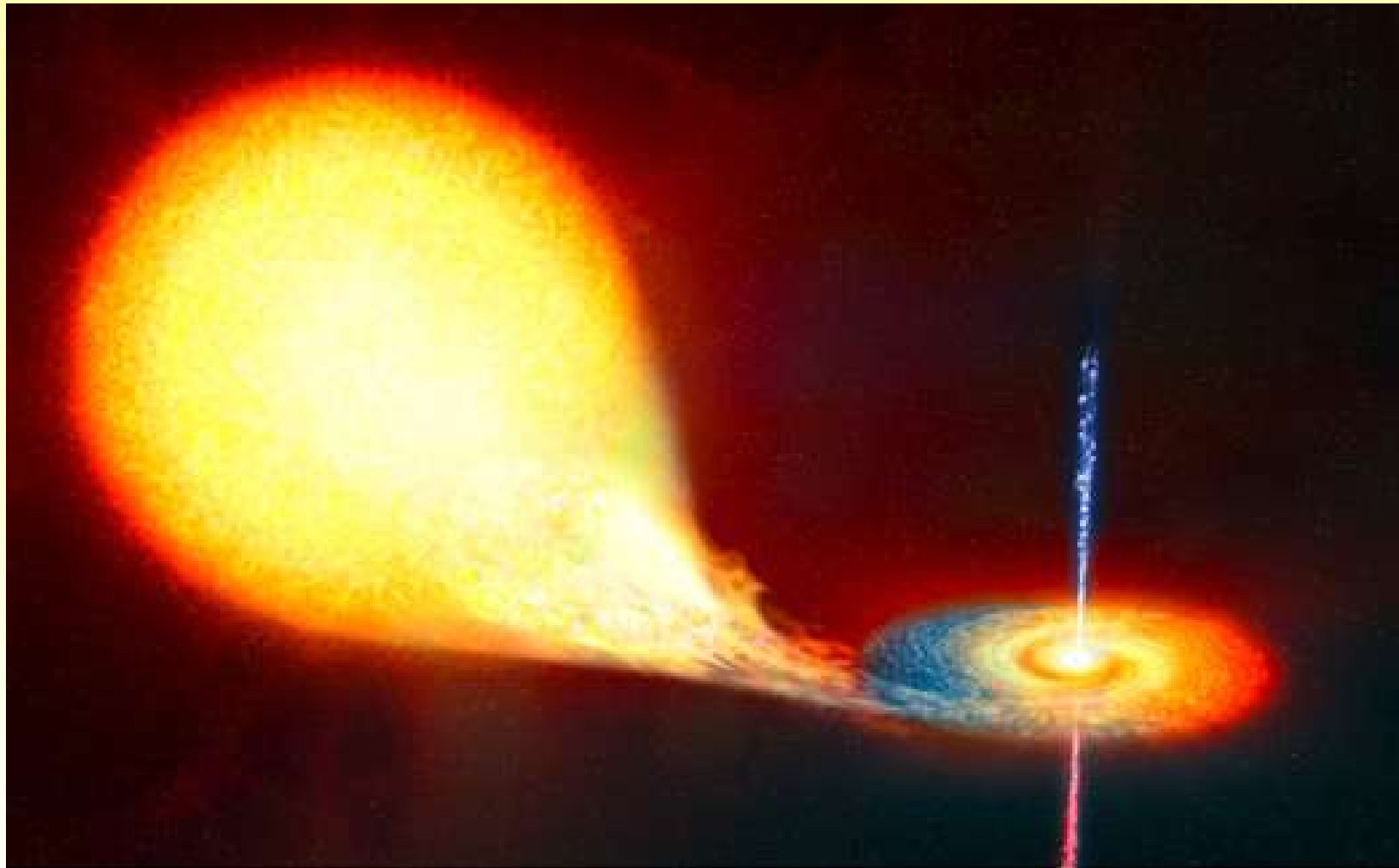
Hoge-massa Röntgen dubbelsterren.

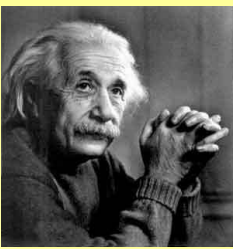




Zwart gat dubbelsterren

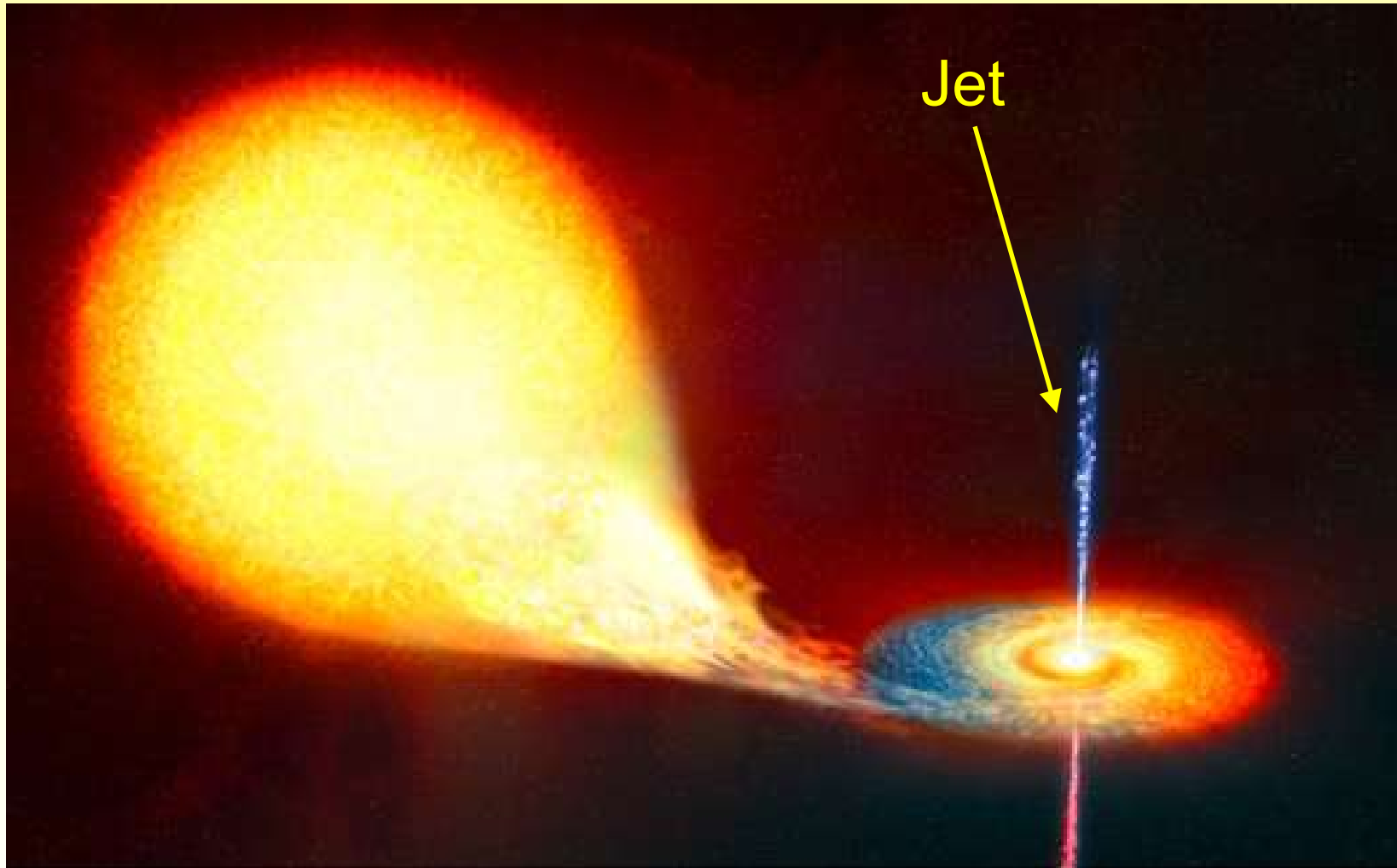
Lage-massa Röntgen dubbelsterren.

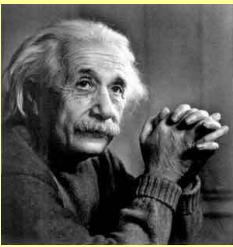




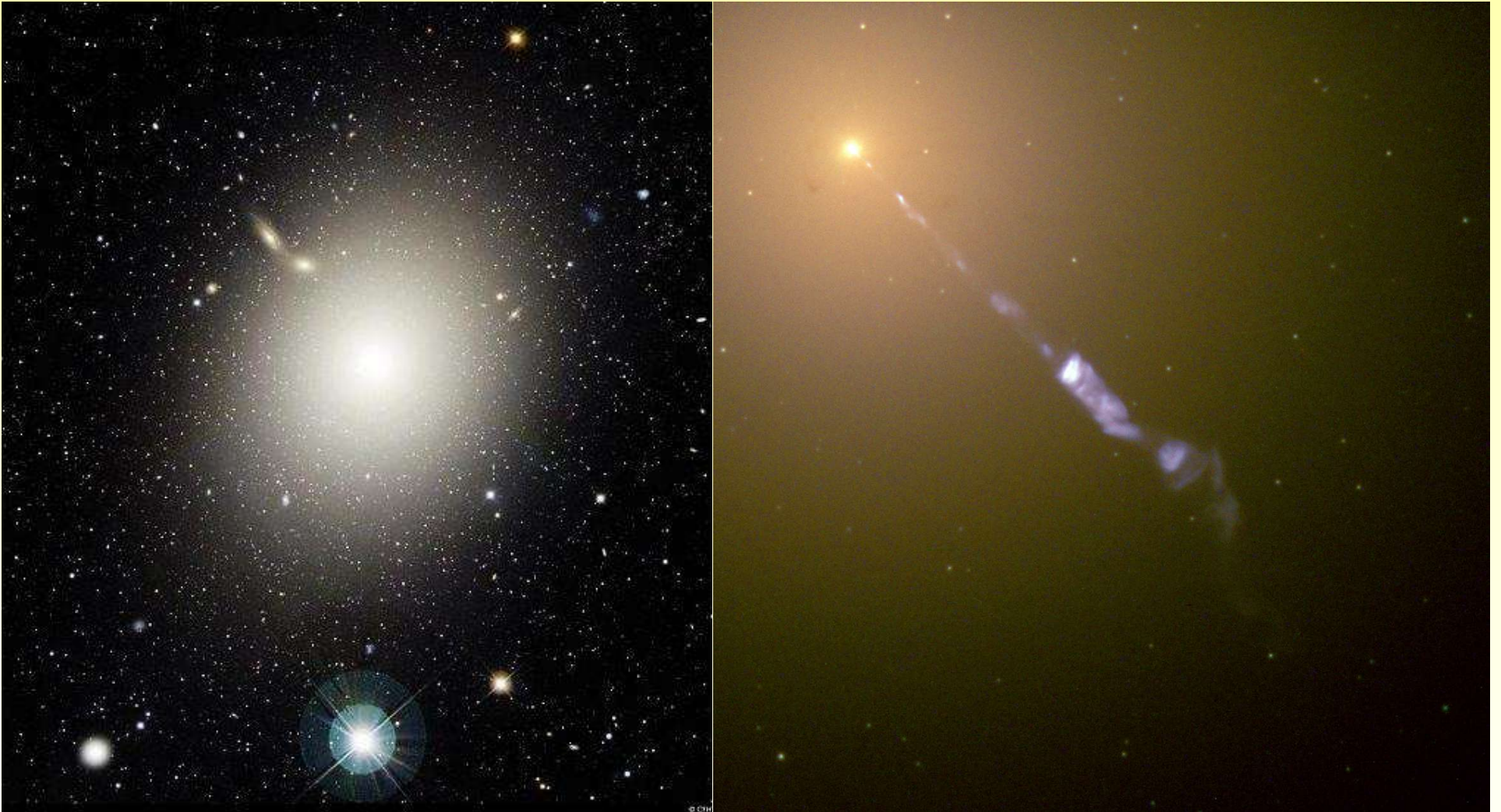
Straalstromen

Straalstromen (Jets) en zwarte gaten gaan vaak samen

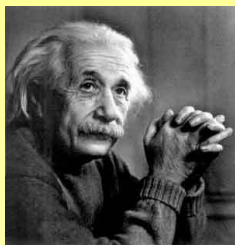




Straalstromen

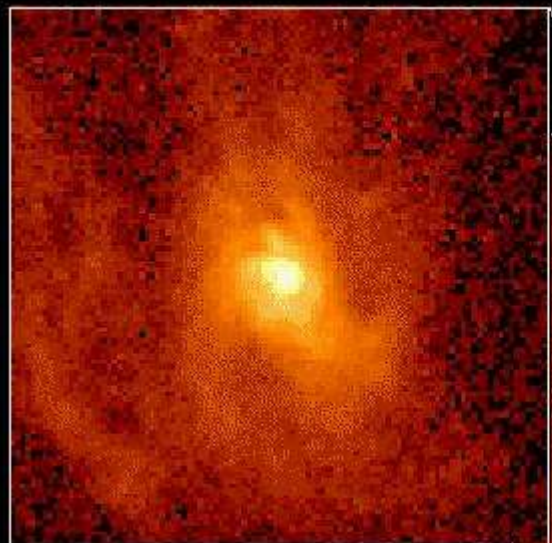


M87: Elliptisch sterrenstelsel



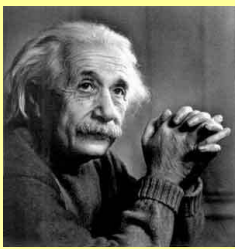
M87

Gas Disk in Nucleus of
Active Galaxy M87



Hubble Space Telescope
Wide Field Planetary Camera 2



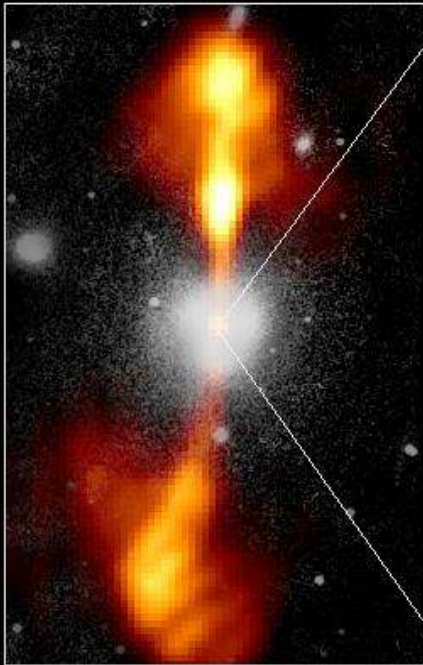


Zwart gat in NGC 4261

Core of Galaxy NGC 4261

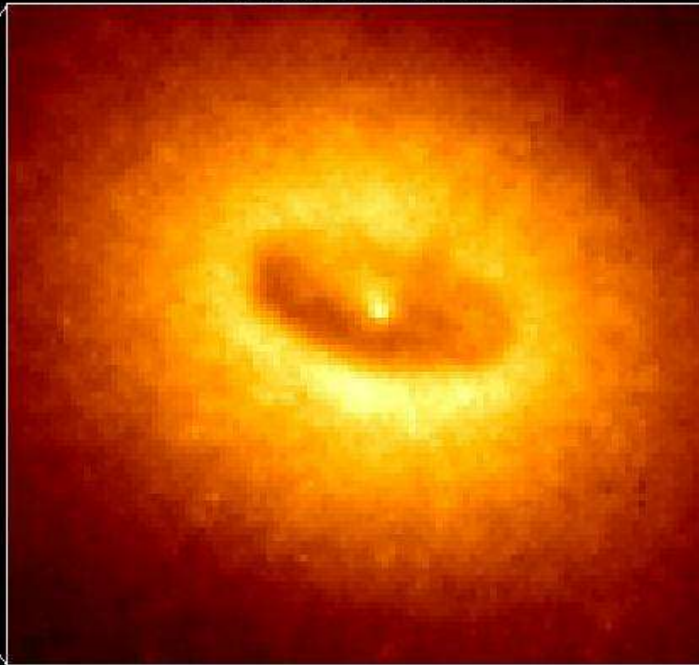
Hubble Space Telescope
Wide Field / Planetary Camera

Ground-Based Optical/Radio Image

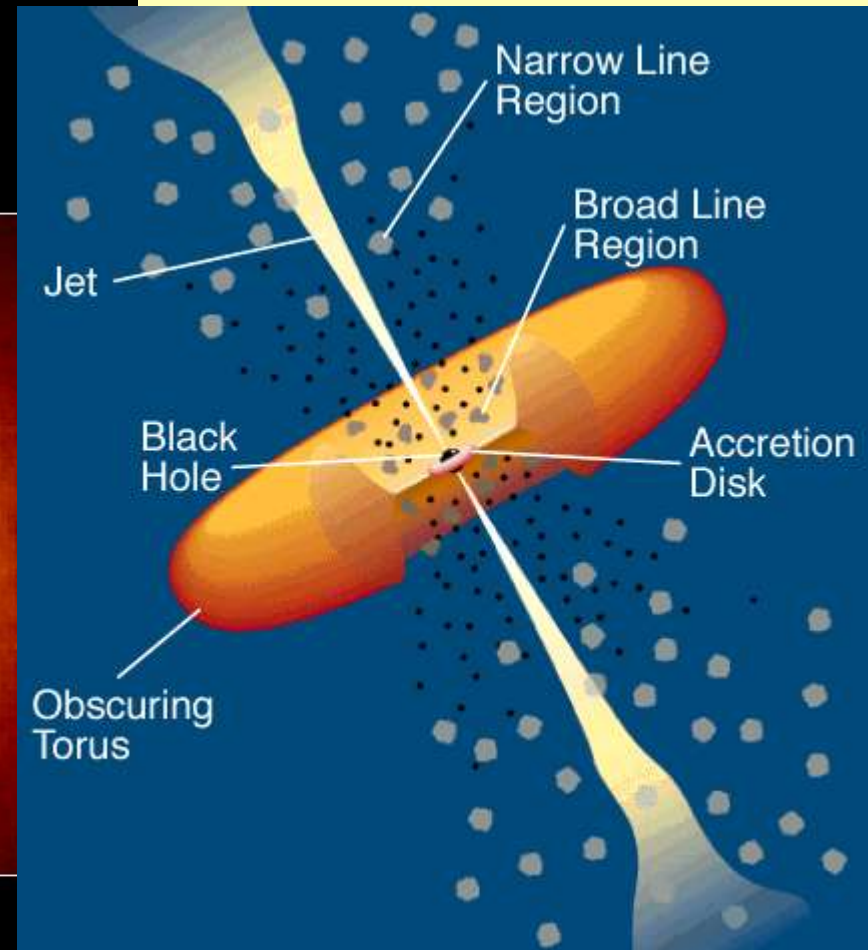


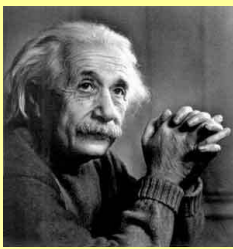
380 Arc Seconds
88,000 LIGHT-YEARS

HST Image of a Gas and Dust Disk

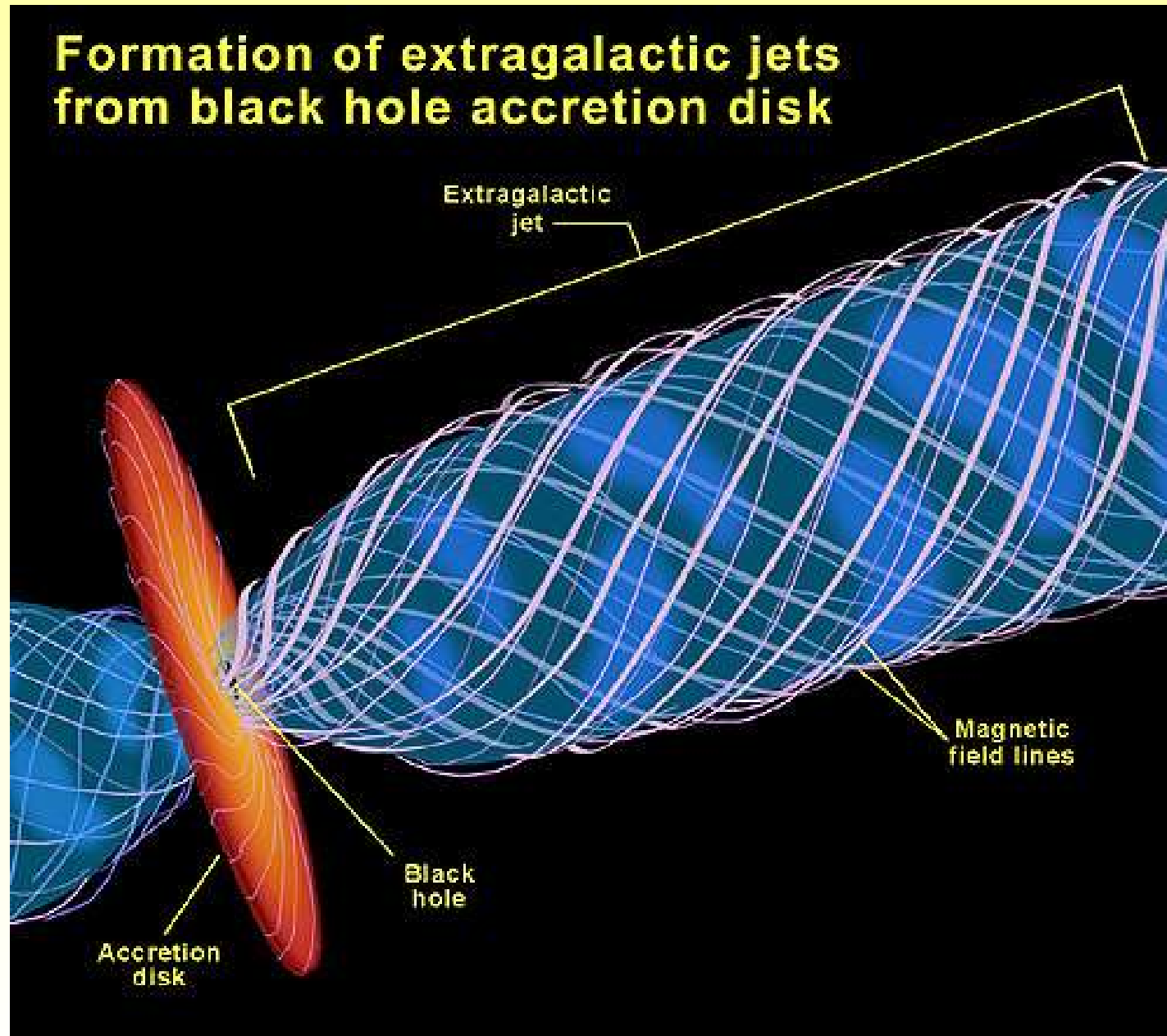


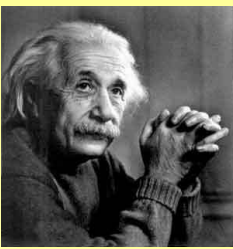
17 Arc Seconds
400 LIGHT-YEARS



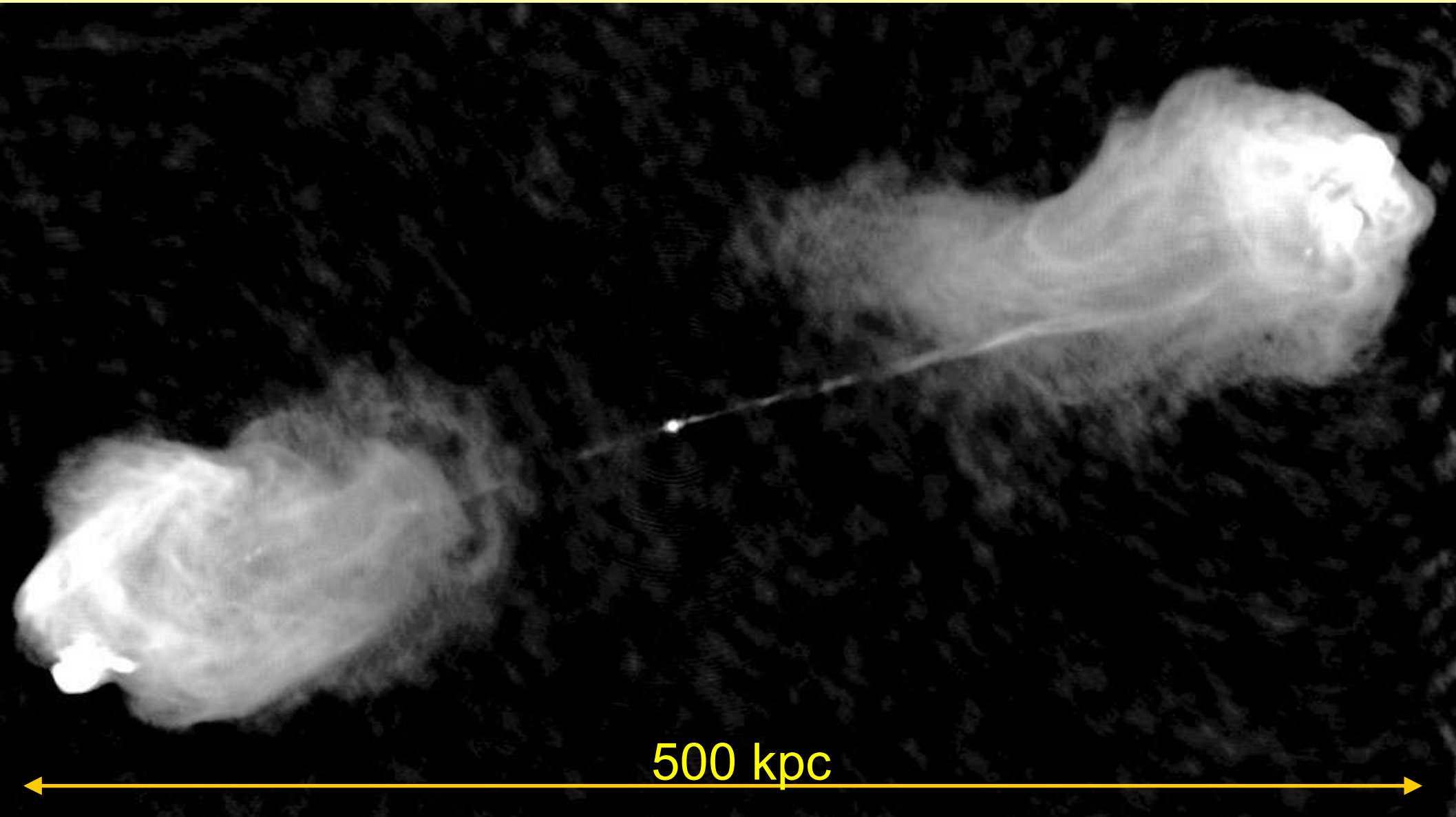


Jet lanceert nabij zwart gat

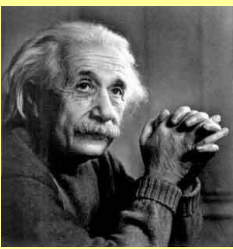




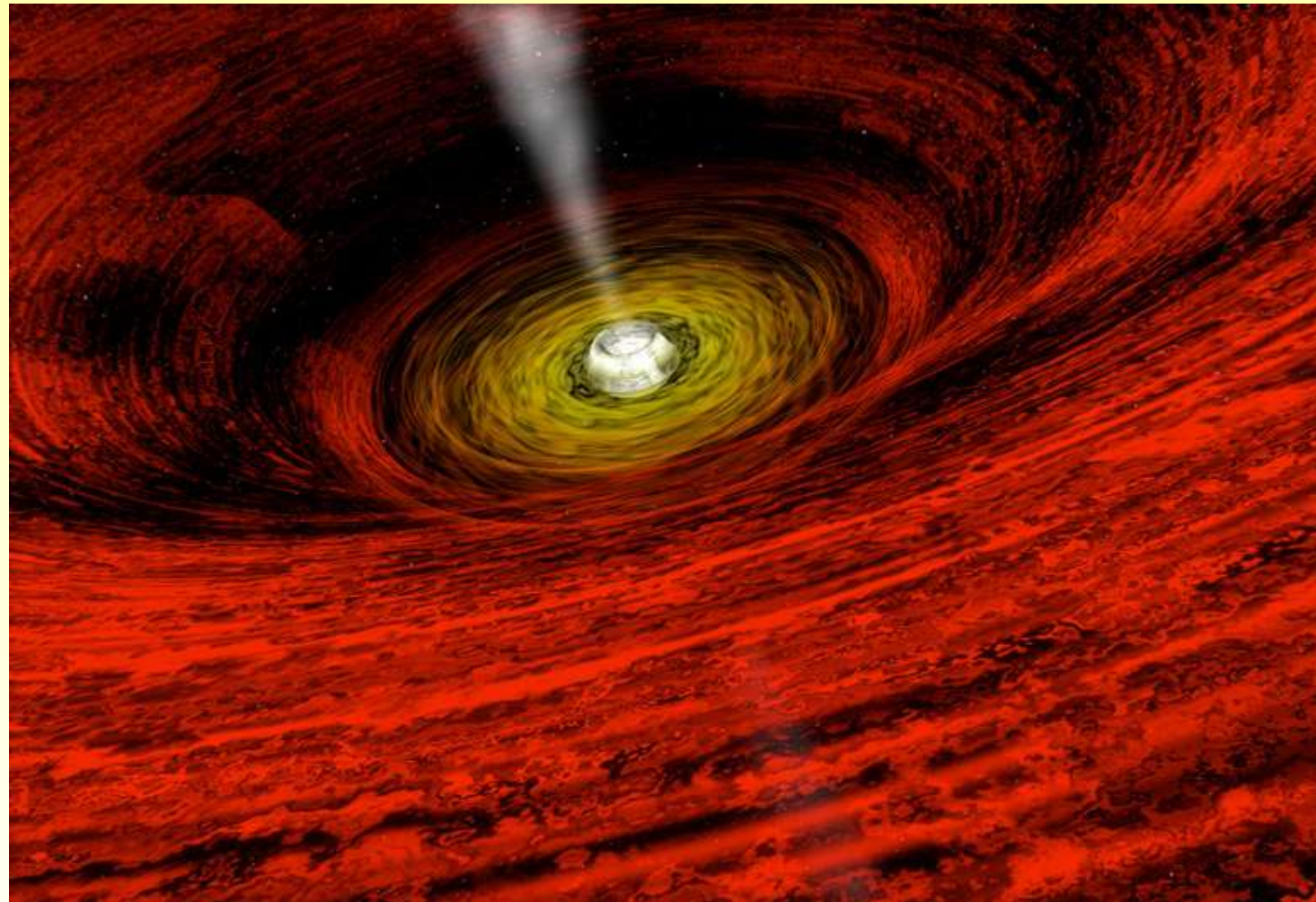
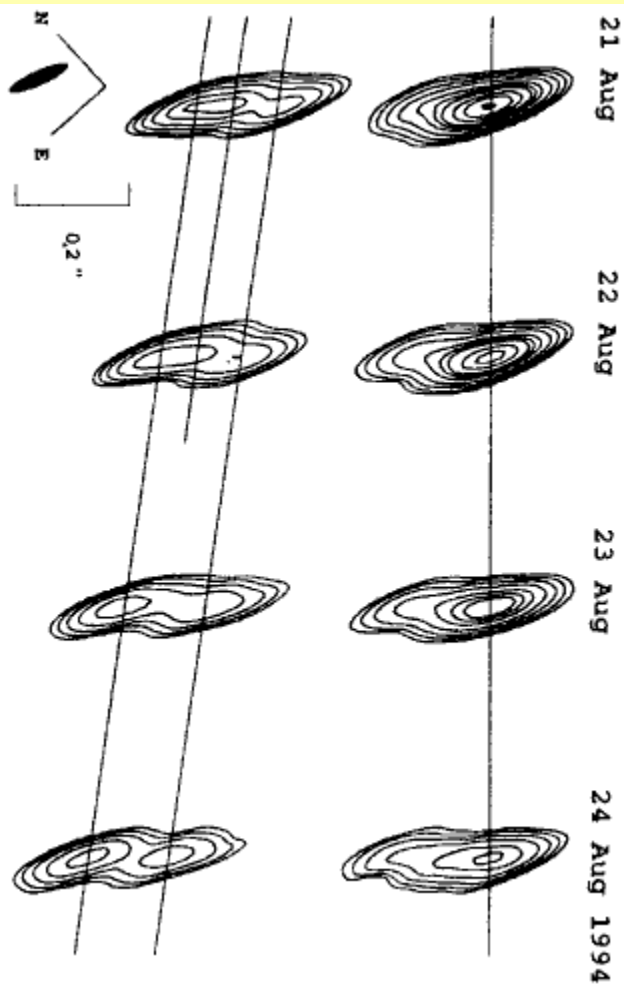
Radio-sterrenstelsels



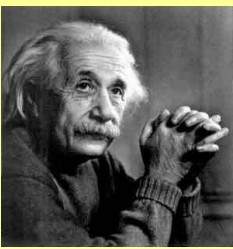
Cygnus A



En in Dubbelsterren



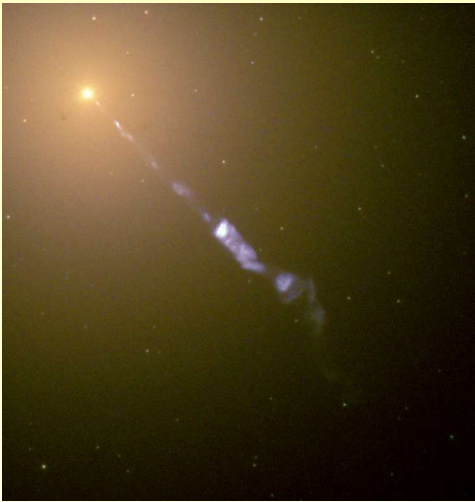
GRO J1655-40



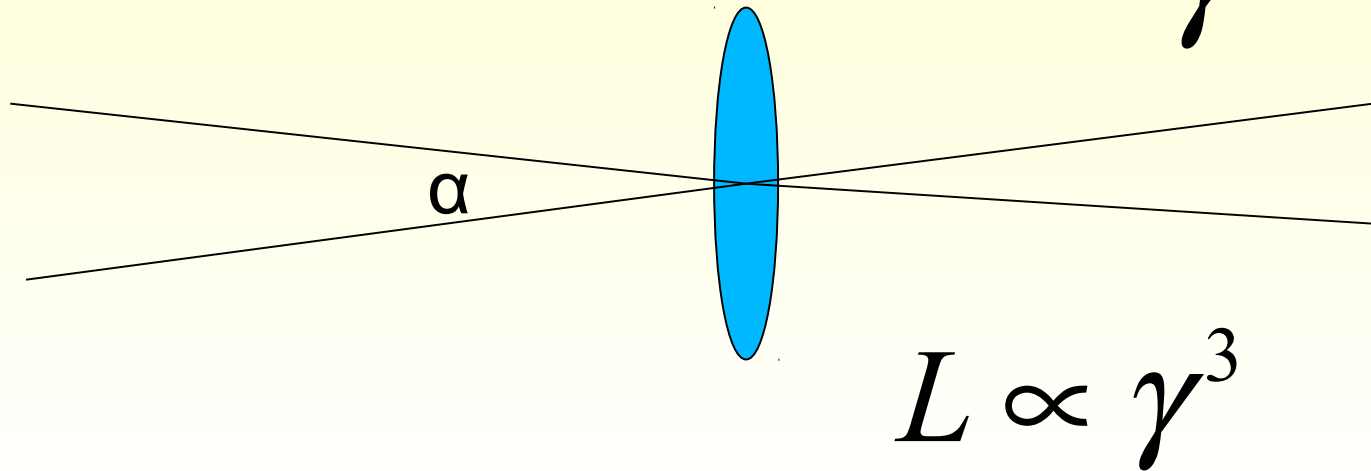
Relativistische beaming

Vaak maar 1 jet zichtbaar. Waar is tweede?

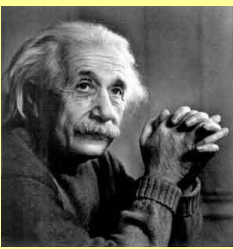
Relativistisch effect: het licht wordt voorwaarts gebundeld: beaming



Wij: ← L



$$\alpha \approx \frac{1}{\gamma}$$



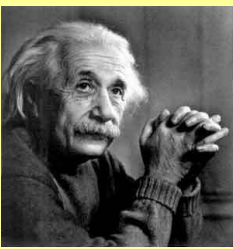
Sneller dan het licht?

Soms zien we expansie snelheid $v > c$!!

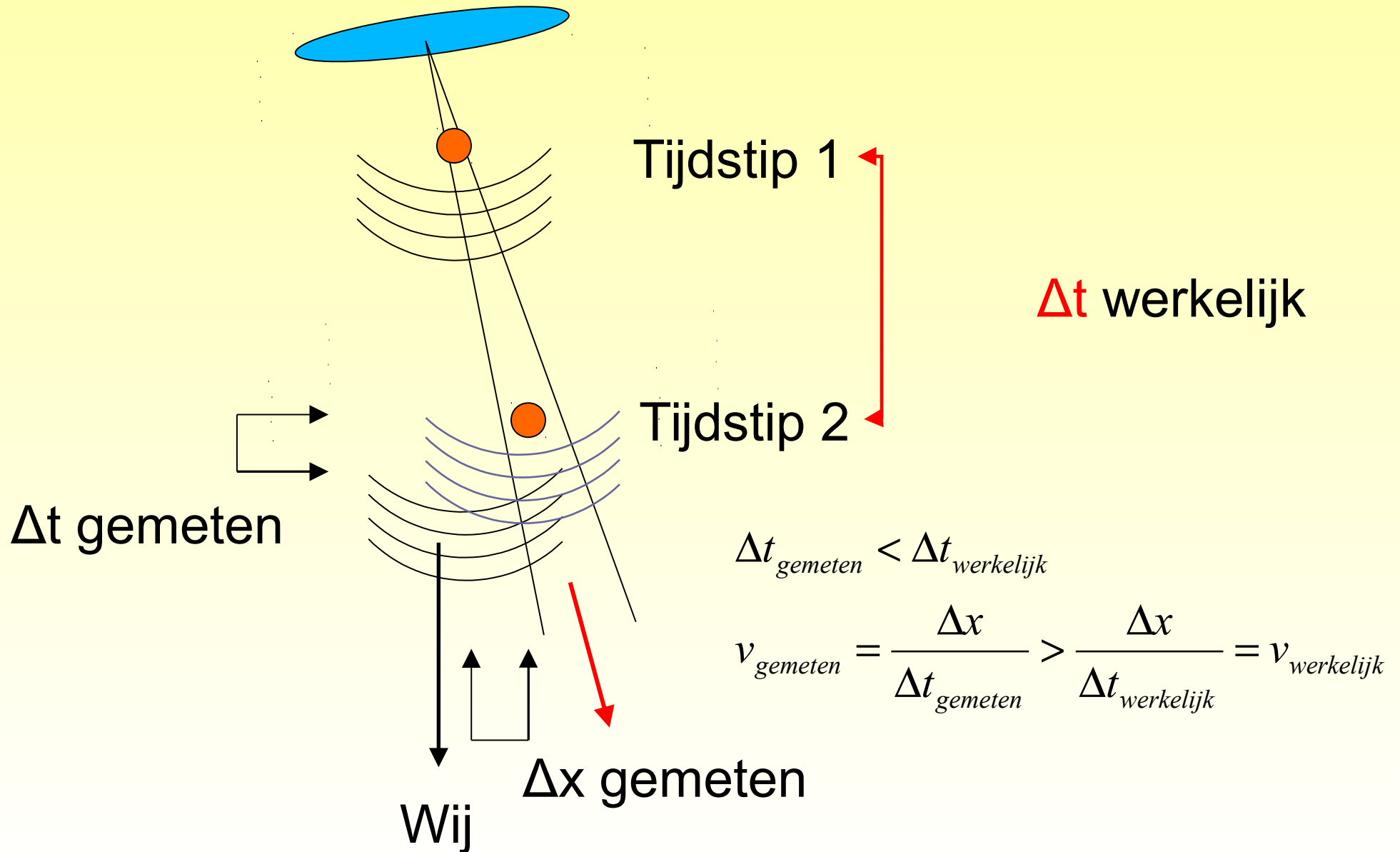


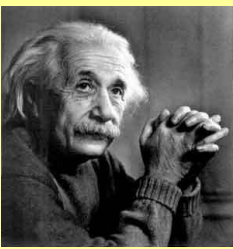
Dit is echter een schijneffect,
veroorzaakt doordat onze
gezichtslijn bijna recht de jet in is.

Materie: $v > c$?



Sneller dan het licht?

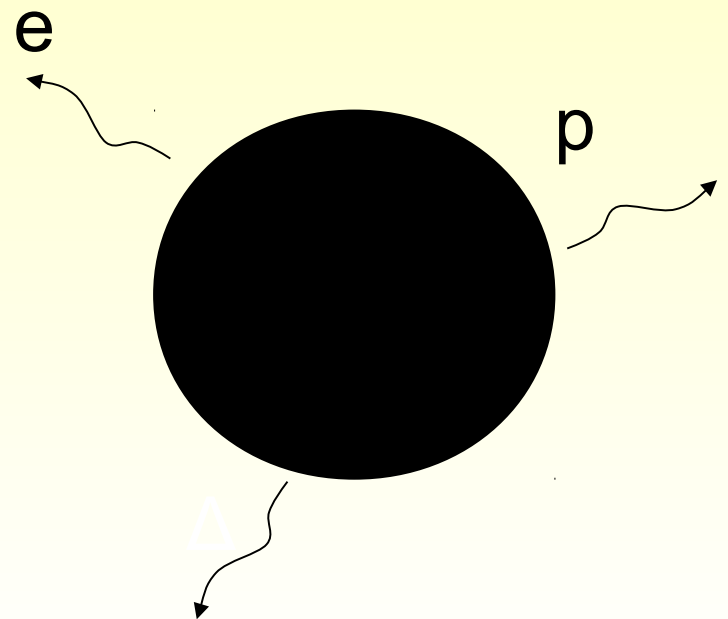


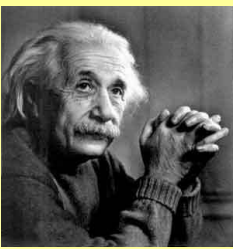


Zwart gat ook echt zwart?

Komt er werkelijk helemaal niets uit een zwart gat?

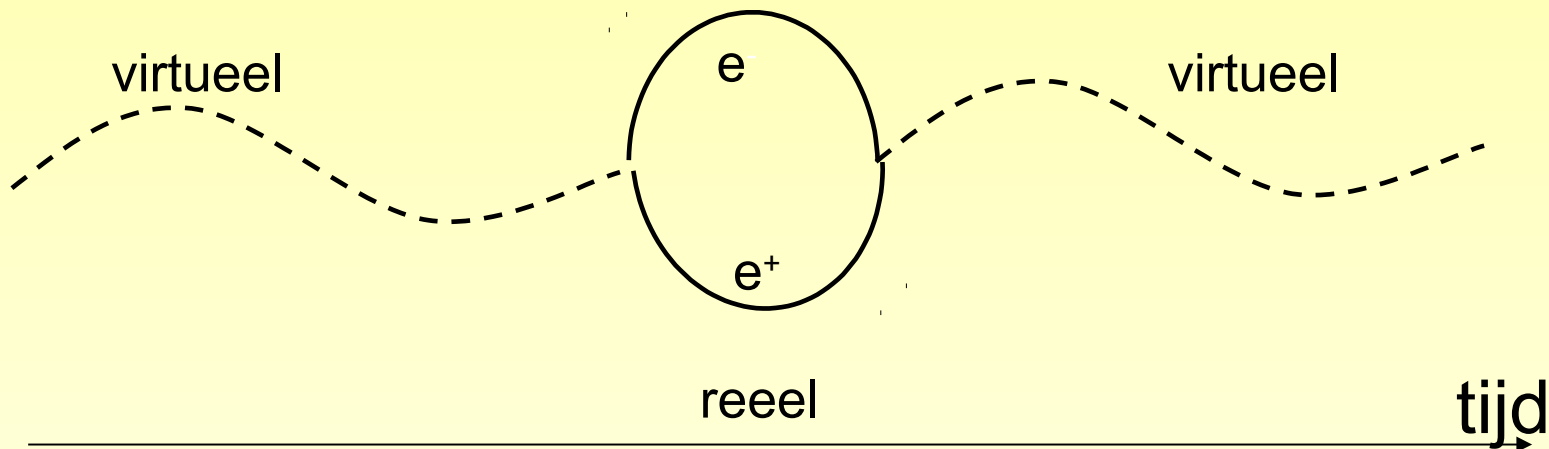
Nee, zelfs een zwart gat straalt: Hawking straling.



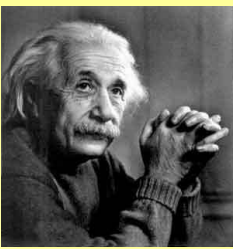


Hawking straling

In vacuum continu virtuele deeltjes:

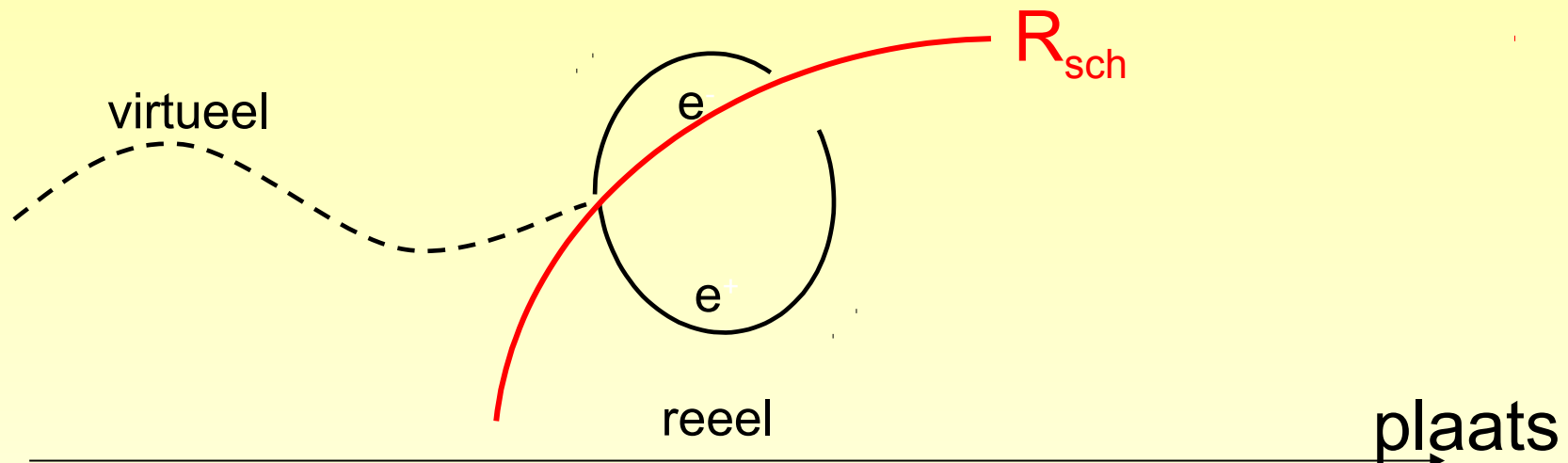


Gevolg van de quantum mechanica: ook virtuele deeltjes kunnen af en toe bestaan, en dan meteen weer annihilieren.



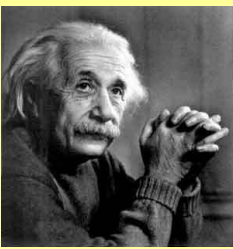
Hawking straling

Maar als dit nou op de Schwarzschild straal gebeurt?



Deeltjes kunnen niet meer recombineren en annihileren.
Ze moeten nu verder als *reeele* deeltjes.

Aangezien energie van ontsnappende deeltje positief is,
Moet energie deeltje in zwart gat negatief zijn. M.a.w:
Energie (=massa) van zwarte gat neemt af!



Hawking straling

Energie (=massa) van zwarte gat neemt af!

*Spectrum hiervan is precies dat van een zwarte straler,
Die we konden identificeren met een temperatuur T.*

$$T_{BH} = \frac{\left(\frac{h}{2\pi}\right)c^3}{8\pi kGM_{BH}} \propto \frac{1}{M_{BH}} \quad T_{BH, 1M_{zon}} = 60 \text{ nK}$$

Lichtkracht van een zwart gat van 1 M_{zon} : $L = 10^{-28} \text{ W}$

$$L \propto \frac{1}{M^2}$$

Verdampingstijd voor 1 M_{zon} : 10^{67} jaar!

$$t_{\text{verdamp}} \propto M^3$$