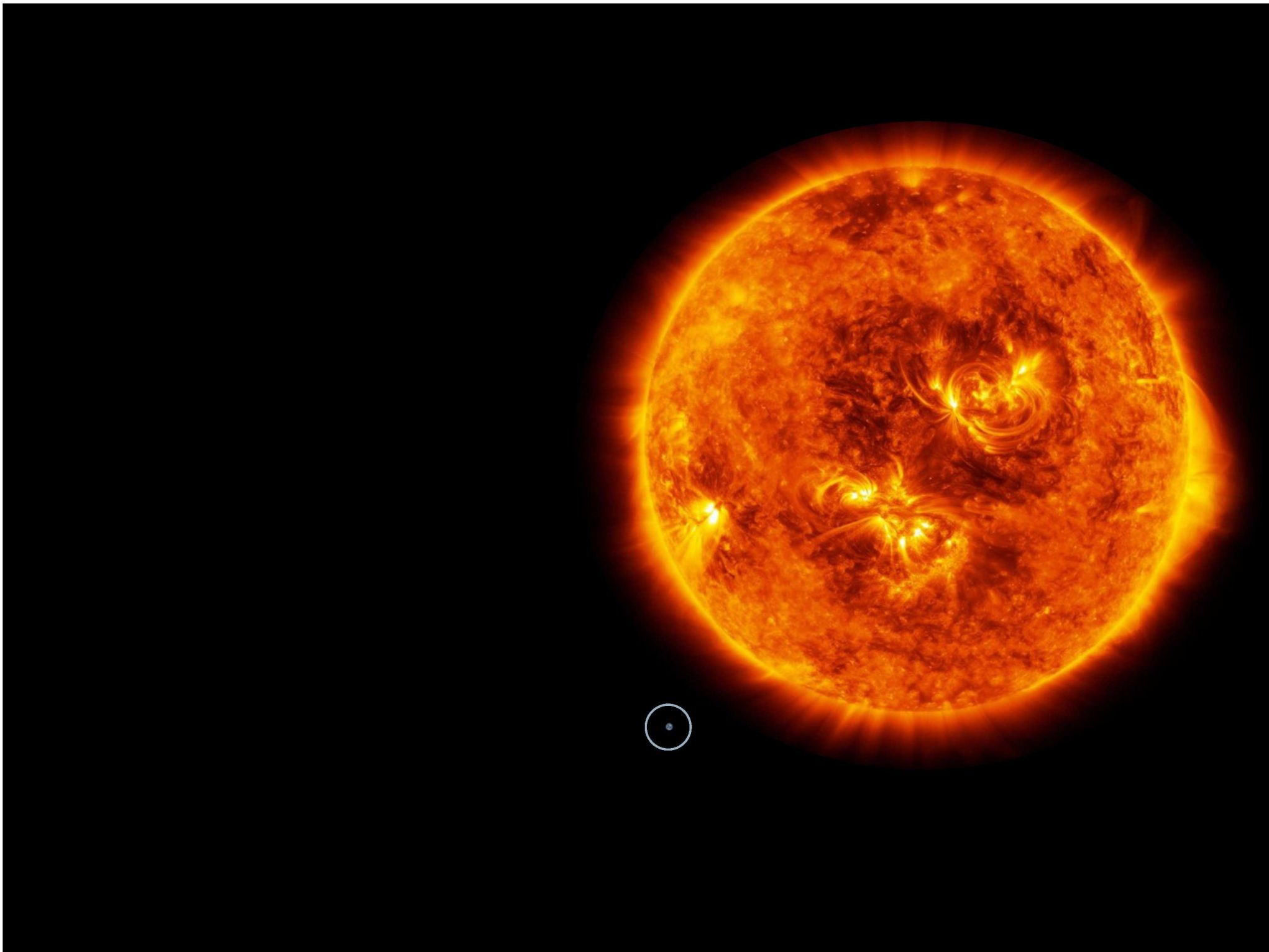
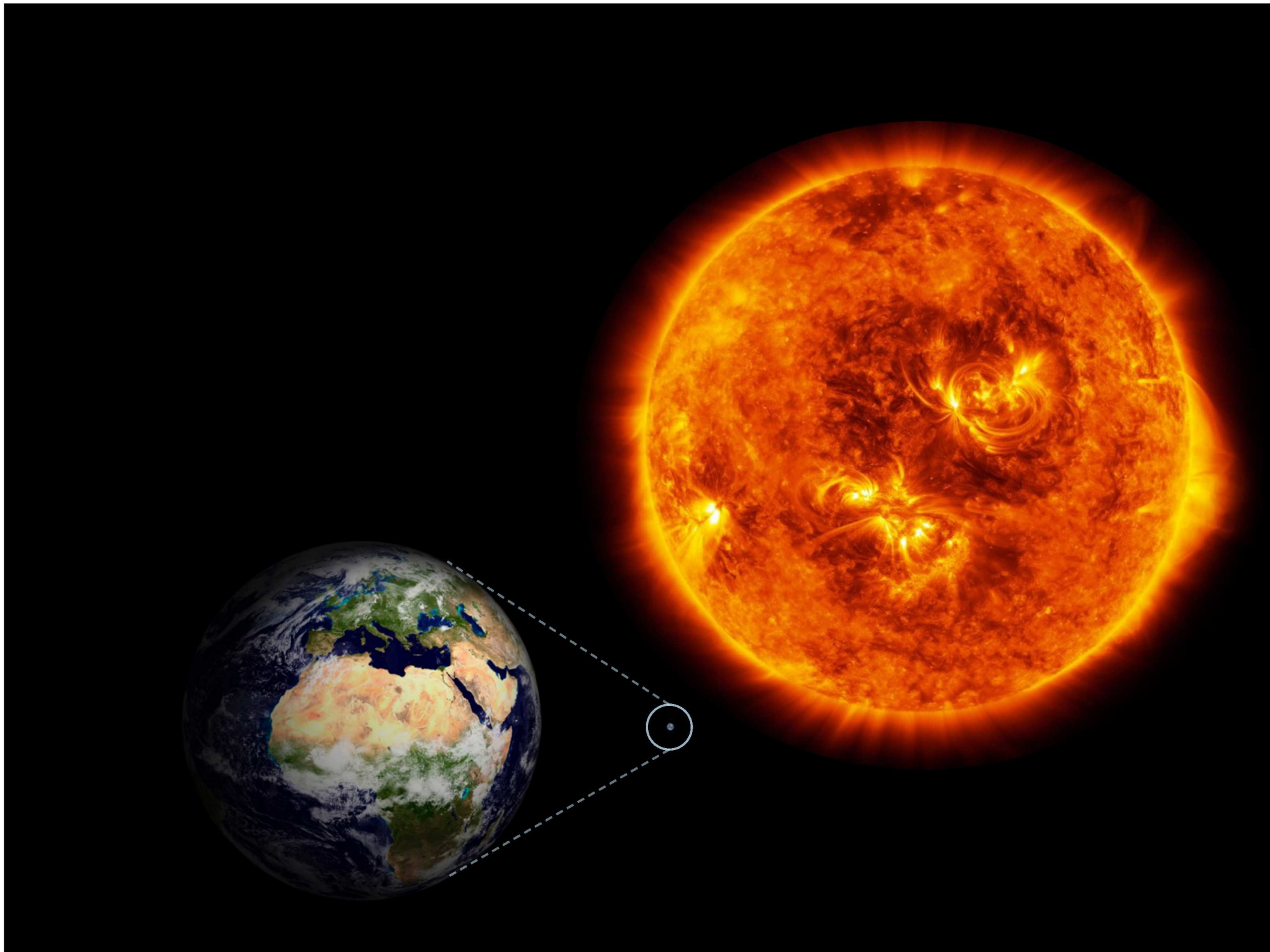


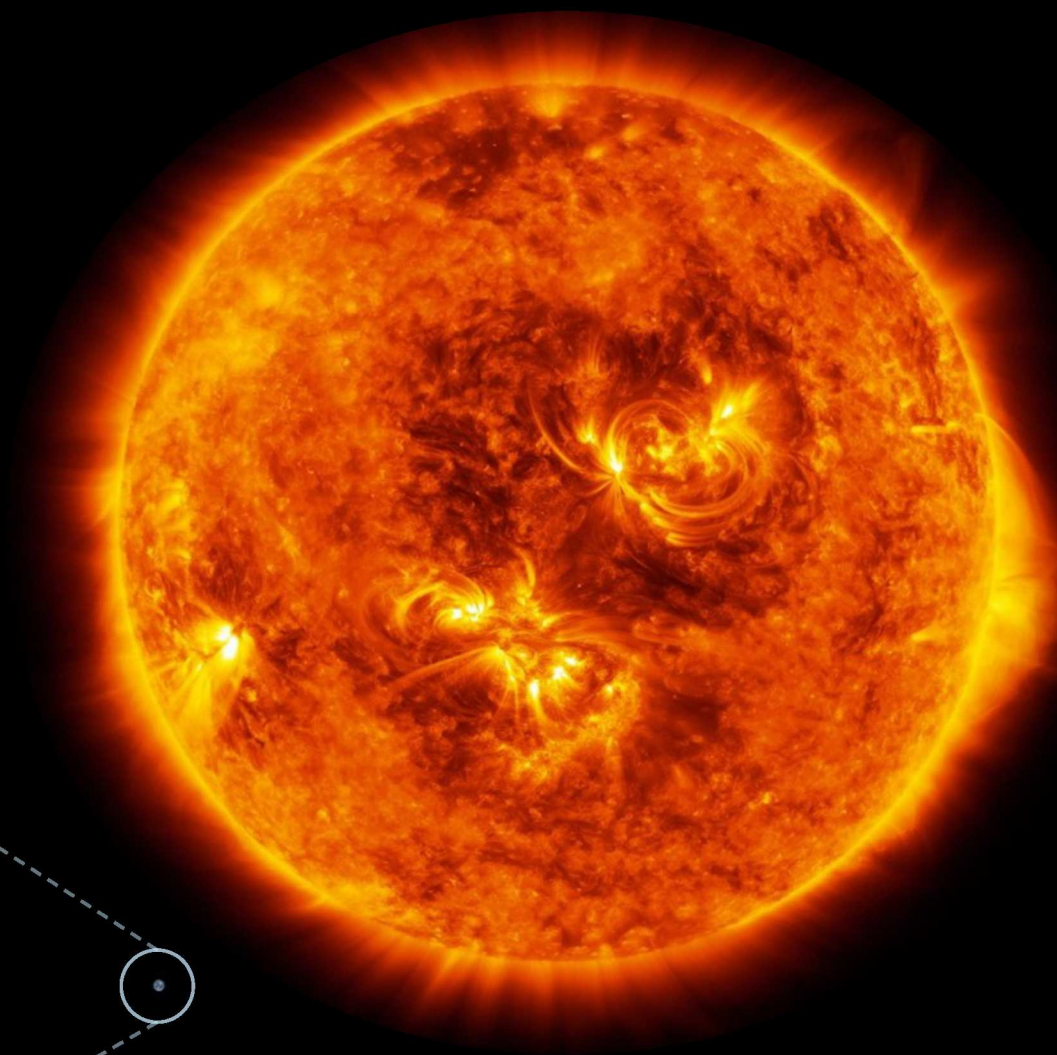
Extreme natuurkunde in- en rond neutronensterren



Rudy Wijnands
Anton Pannekoek Instituut
Universiteit van Amsterdam







*500.000 Aardes in een bol ter grootte
van Amsterdam*

Neutronensterren

- Zeer compacte sterren
 - Veel massa
 - Klein volume
- Zeer hoge
dichtheden

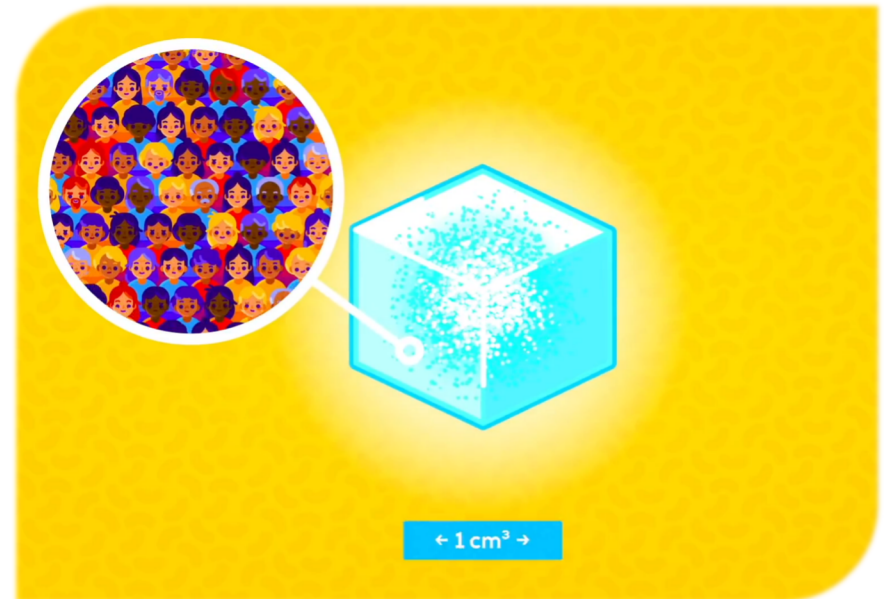


Waarom zijn ze interessant?

- Extreme natuurkunde
 - Extreme dichtheden
 - Extreme spin
 - Extreme zwaartekracht
 - Extreme magneetvelden
 - Niet op Aarde na te bootsen
- Eindstadium sterevolutie
 - Ontstaan van de elementen

Extreme dichtheden

- De dichtheden in neutronensterren zijn groter dan de dichtheden in een atoomkern!
 - $> 1.000.000.000.000 \text{ kg cm}^{-3}$
 - Biljoen kg cm^{-3}
 - Water: $0,001 \text{ kg cm}^{-3}$
 - Alle lege ruimte is opgevuld
 - Alle mensen op Aarde in een suikerklontje
- Hoe gedraagt materie zich onder zulke omstandigheden?
 - Niet bekend
 - Exotisch gedrag

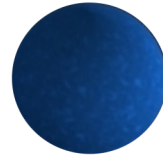


Normale materie

Neutron



Proton

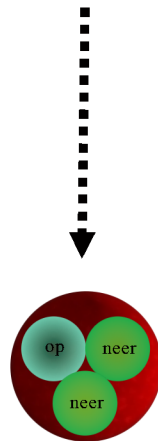


Elektron

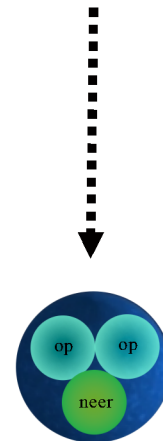
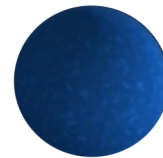


Normale materie

Neutron



Proton

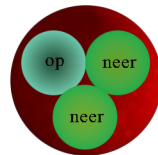


Elektron

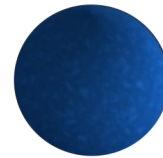


Normale materie

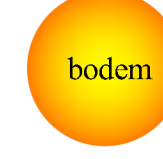
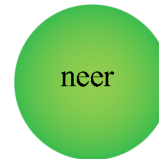
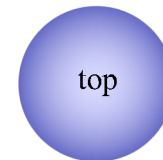
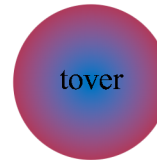
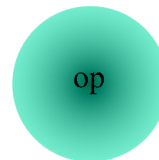
Neutron



Proton



Elektron



Komen niet
los voor in
het heelal

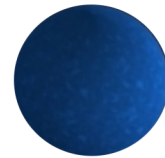
Zes “smaken” quarks

Normale materie

Neutron

Proton

Elektron



+



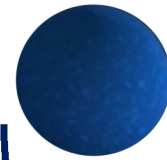
Vervalt in ~15 minuten

Normale materie

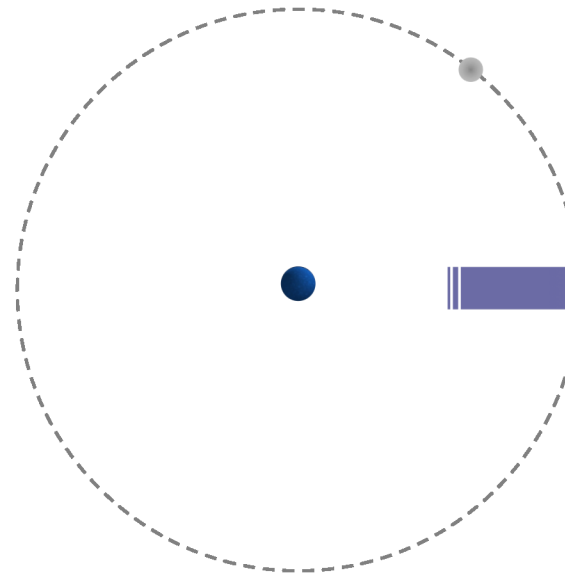
Neutron



Proton



Elektron



99,9999999 %
lege ruimte!

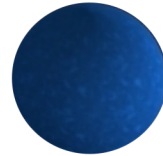
Waterstofatoom

Normale materie

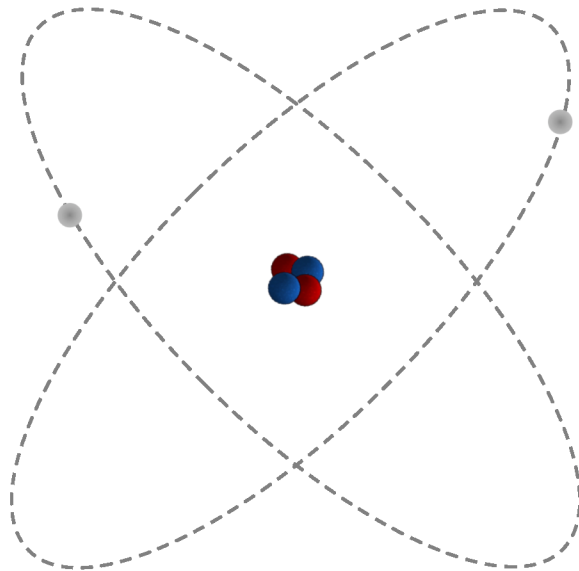
Neutron



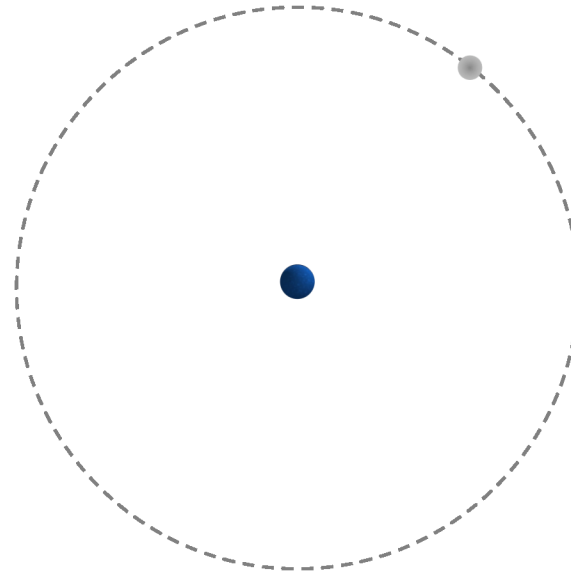
Proton



Elektron



Heliumatoom



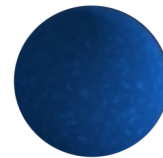
Waterstofatoom

Geïoniseerde materie

Neutron



Proton



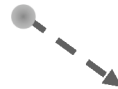
Elektron



Ionen



← - - - Vrije elektronen



• Vrije protonen

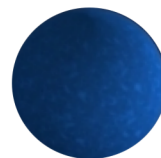


Materie onder hoge druk

Neutron



Proton

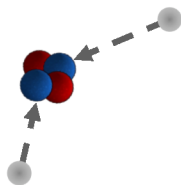


Elektron

+



Ionen



Vrije elektronen



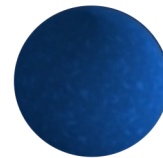
Vrije protonen

Neutronenstermaterie

Neutron



Proton



Elektron

+



Neutronenstermaterie

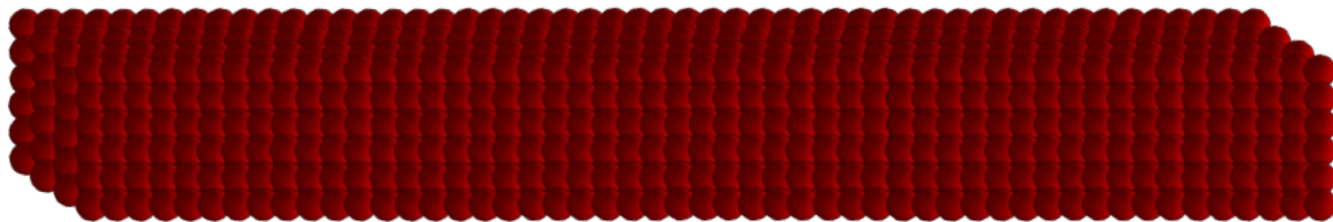
Neutron

Proton

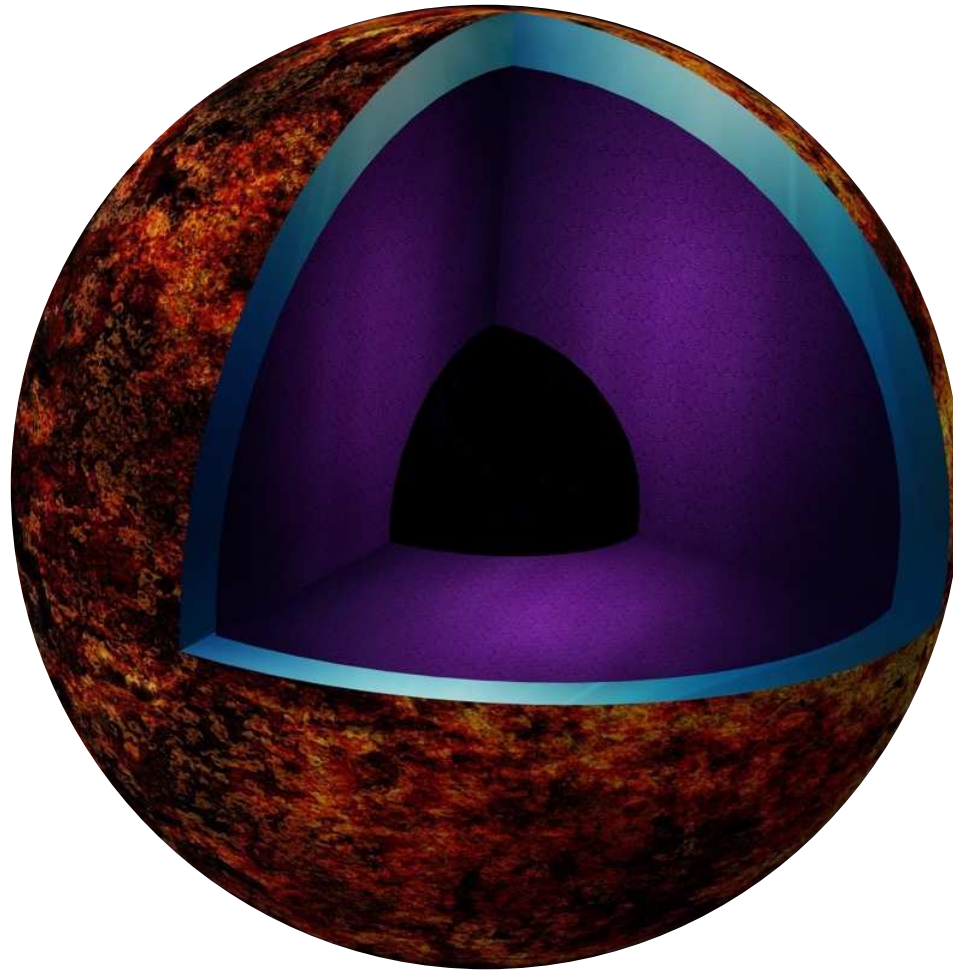
Elektron

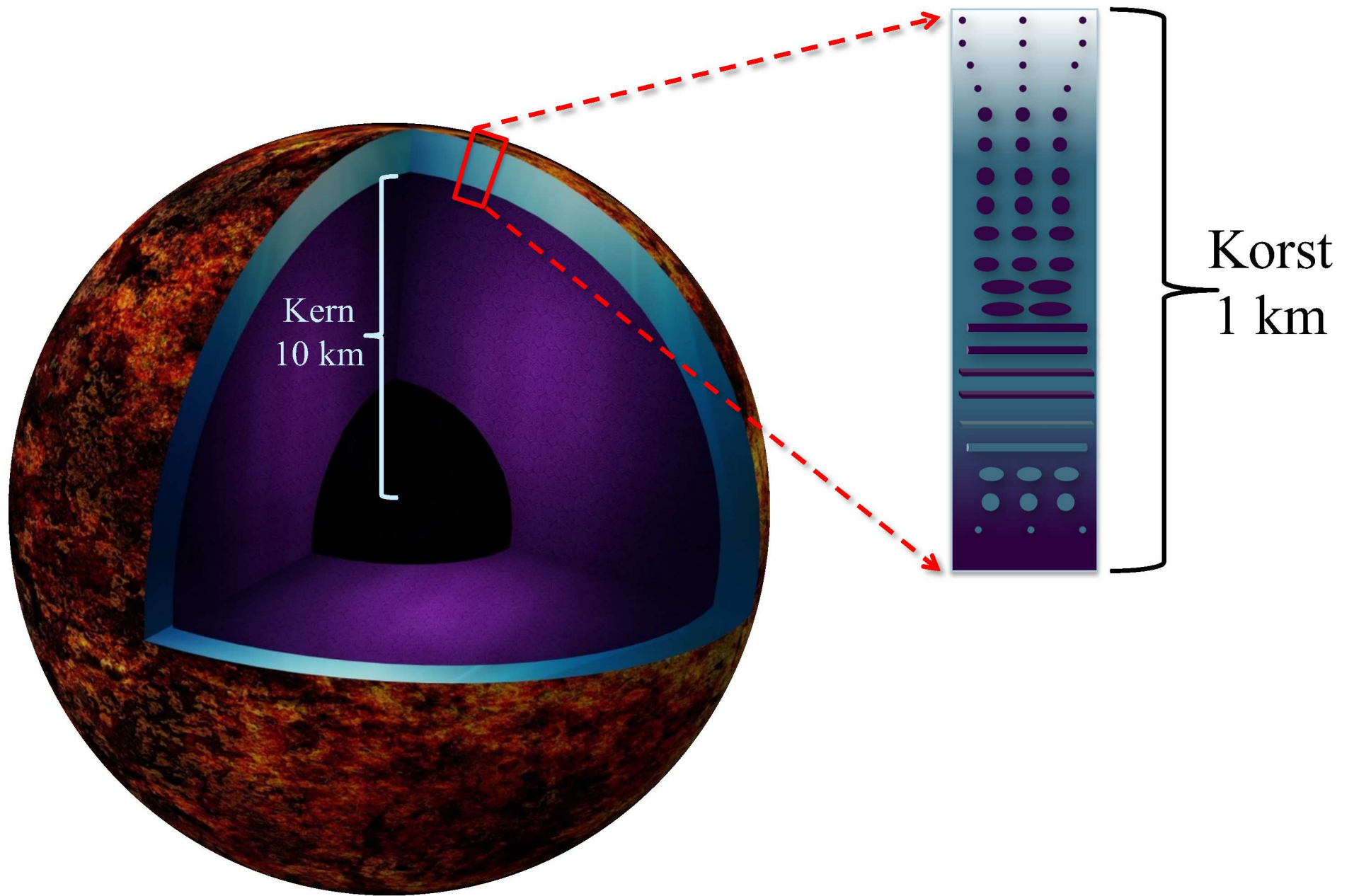


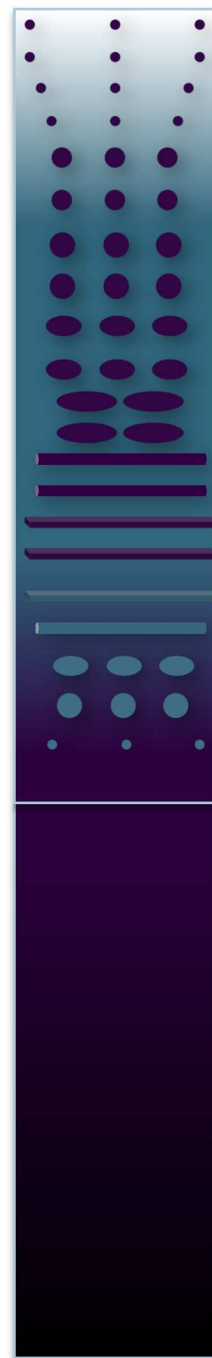
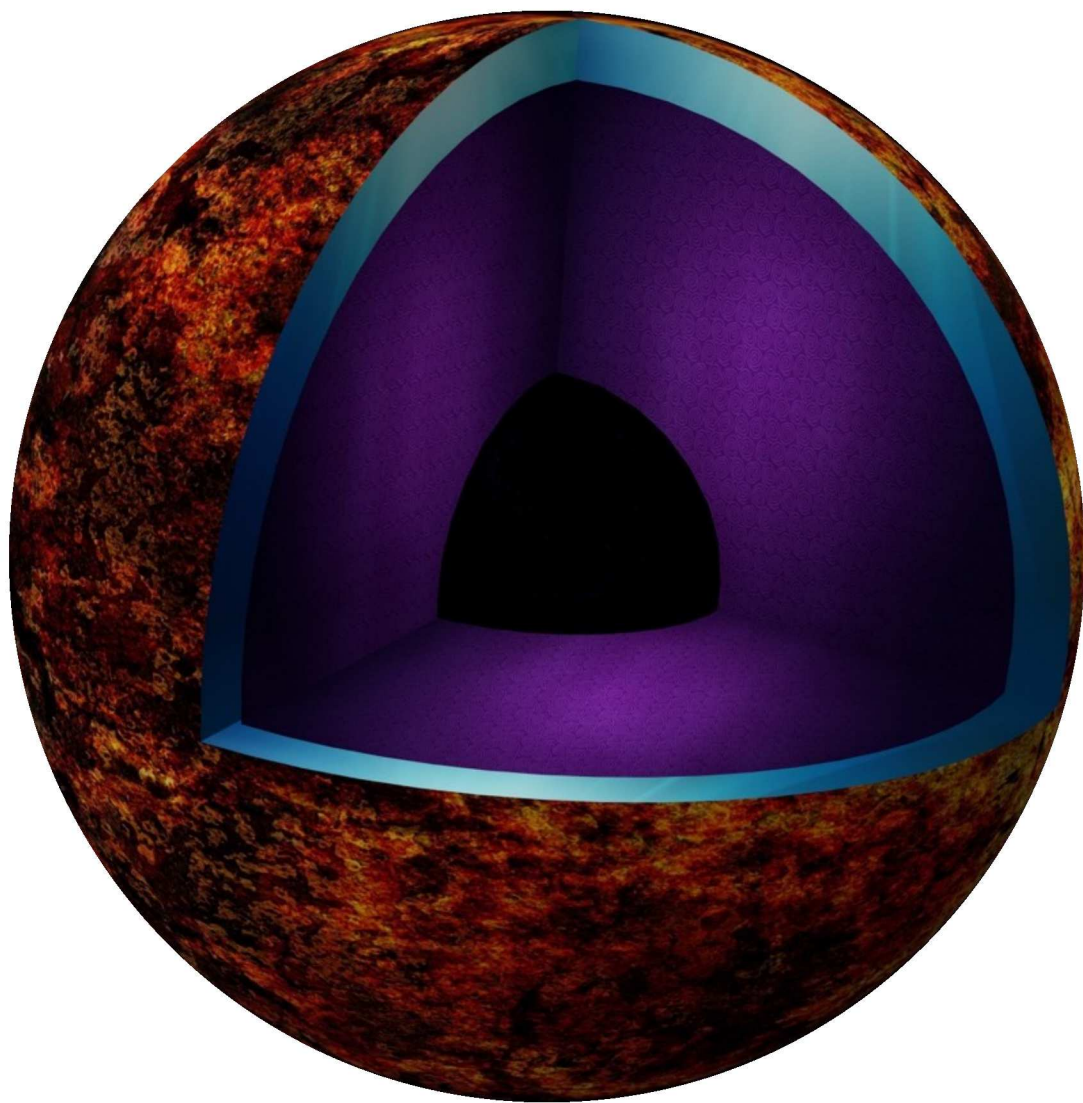
Soep van vrije neutronen



Binnen in een neutronenster







Druk



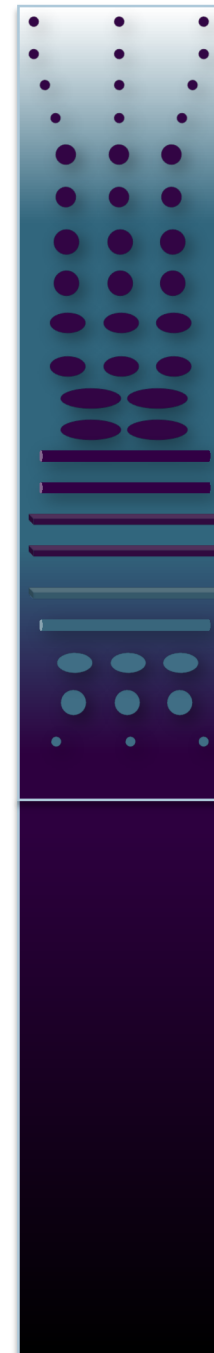
Druk



Neutron



Proton



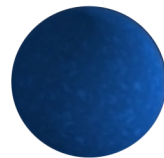
Druk



Neutron

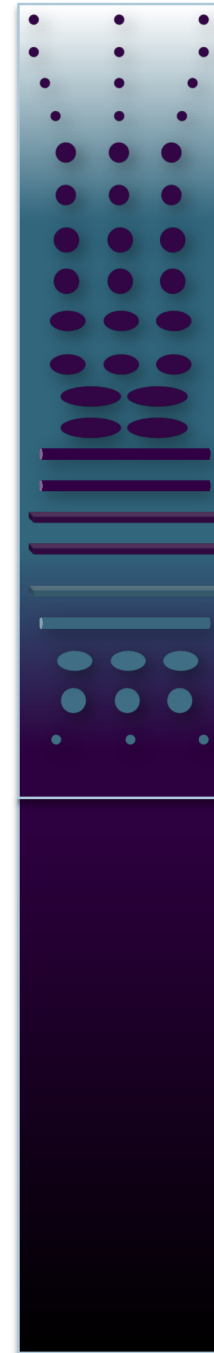


Proton



+

Elektron



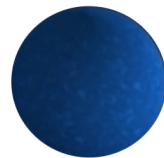
Druk



Neutron



Proton

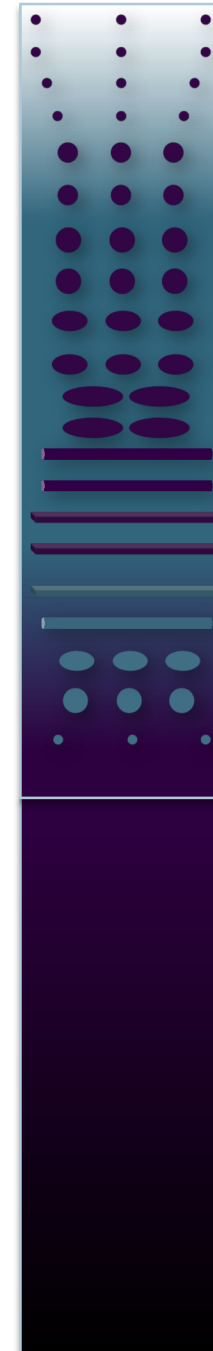


+

Elektron

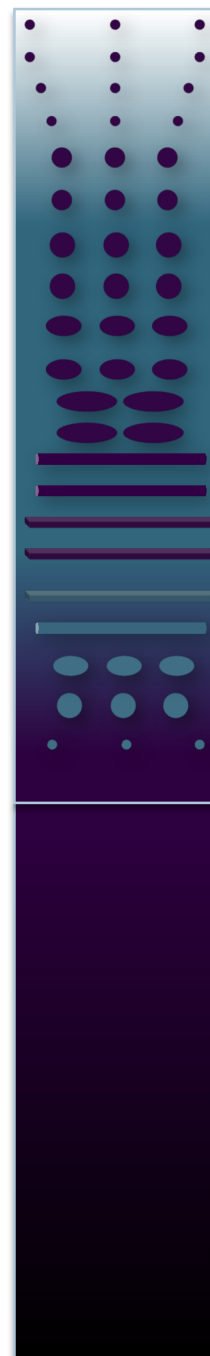


Zeer hoge druk



Druk



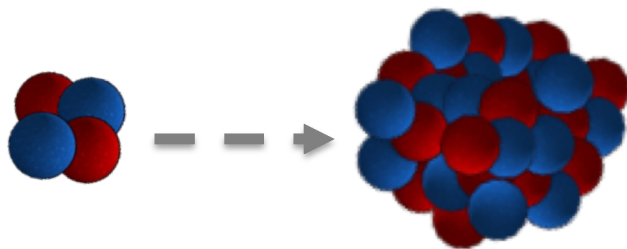


Druk



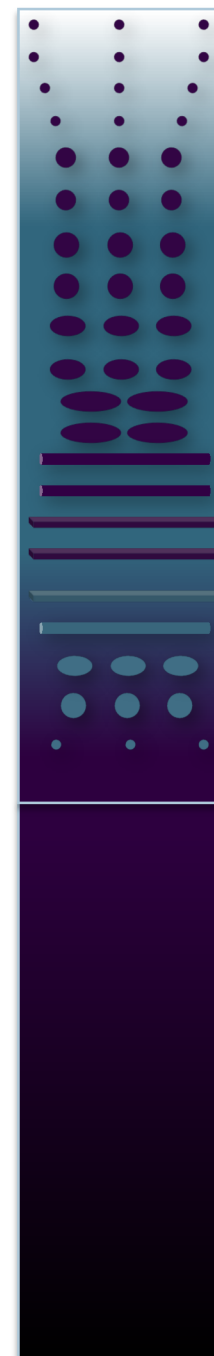
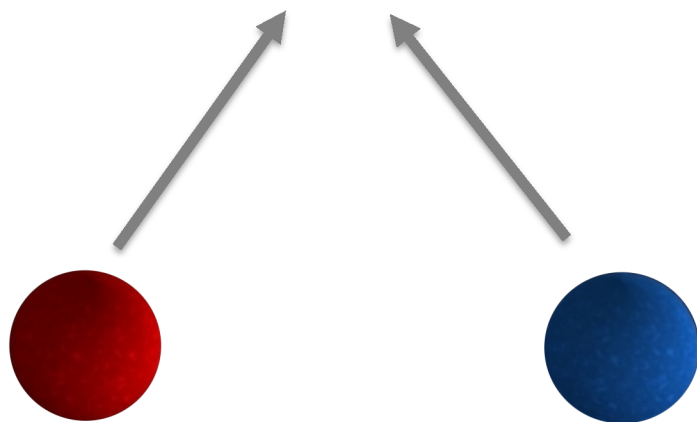
Helium
atoom

(2● 2●)



IJzer
atoom

(26● 30●)



Druk



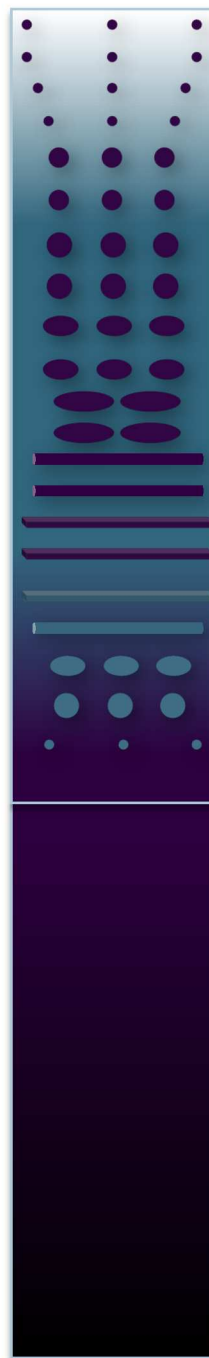
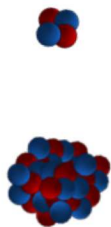
Druk





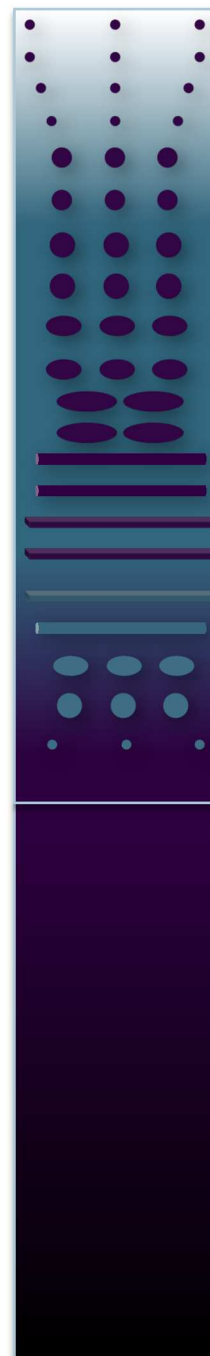
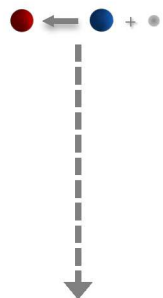
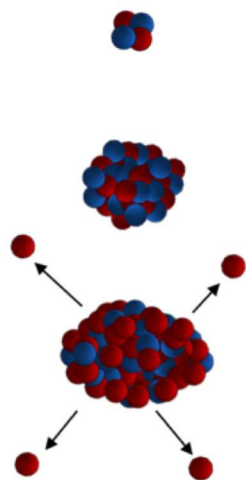
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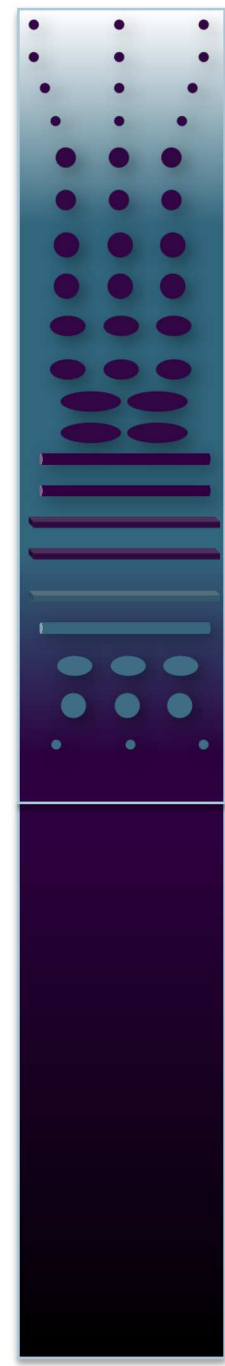
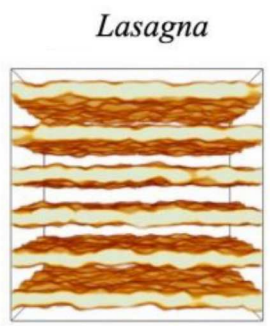
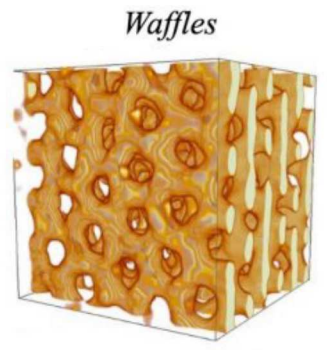
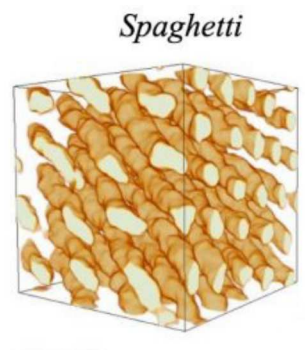
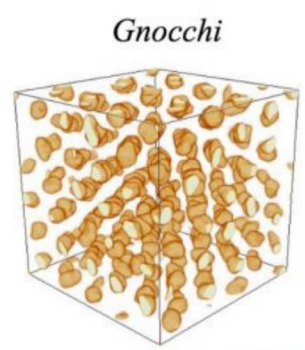
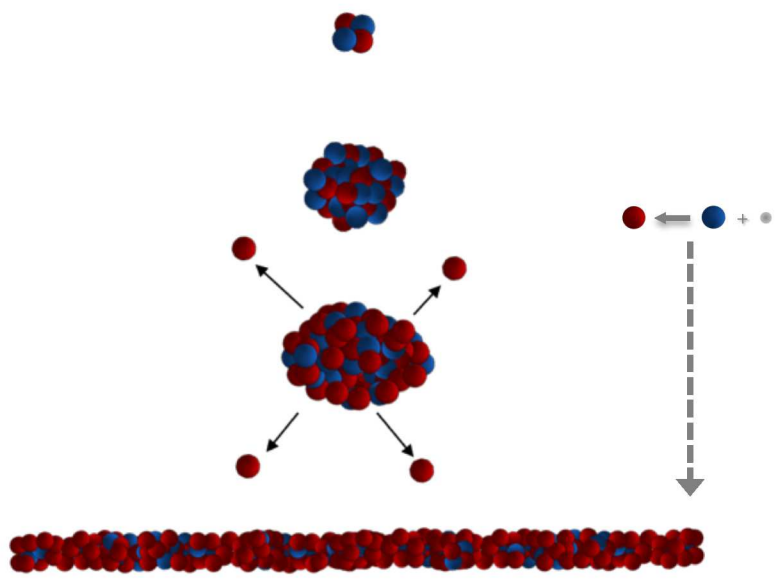
Druk





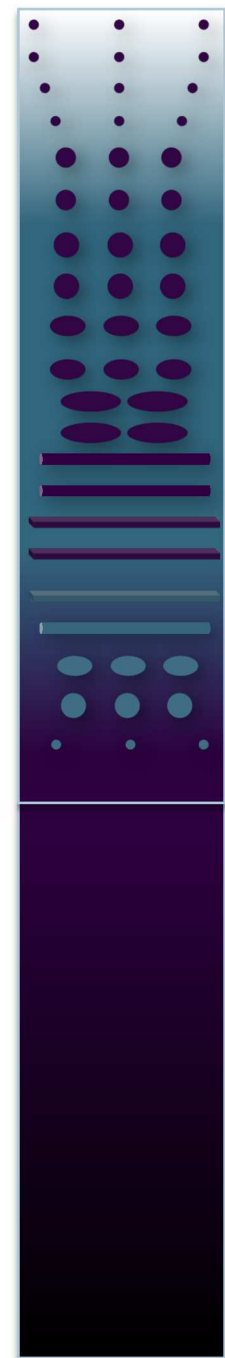
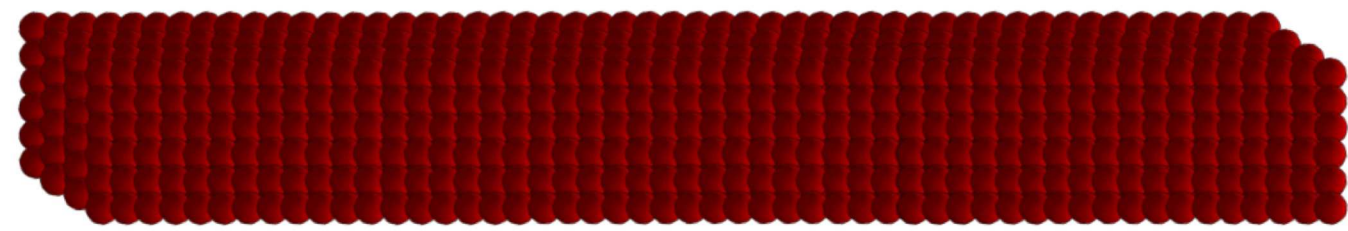
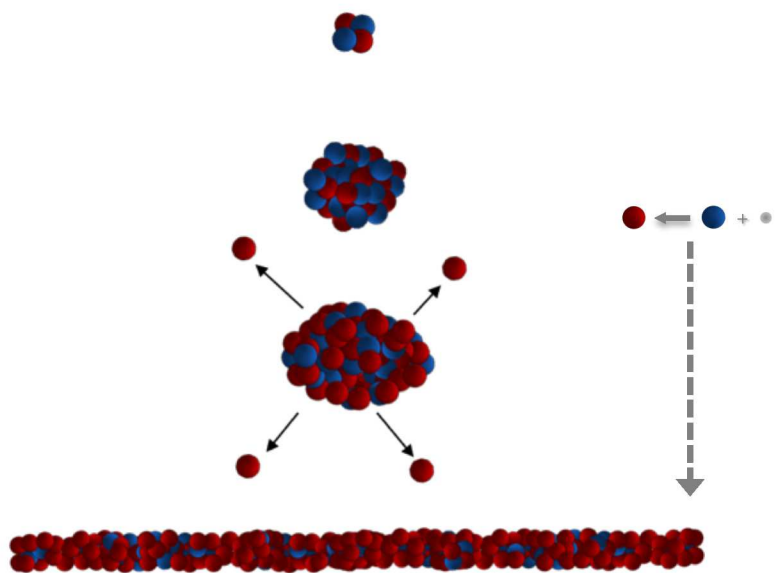
Druk



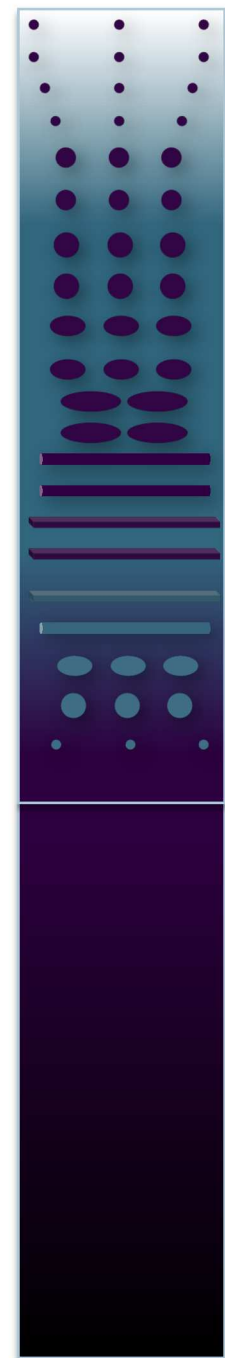
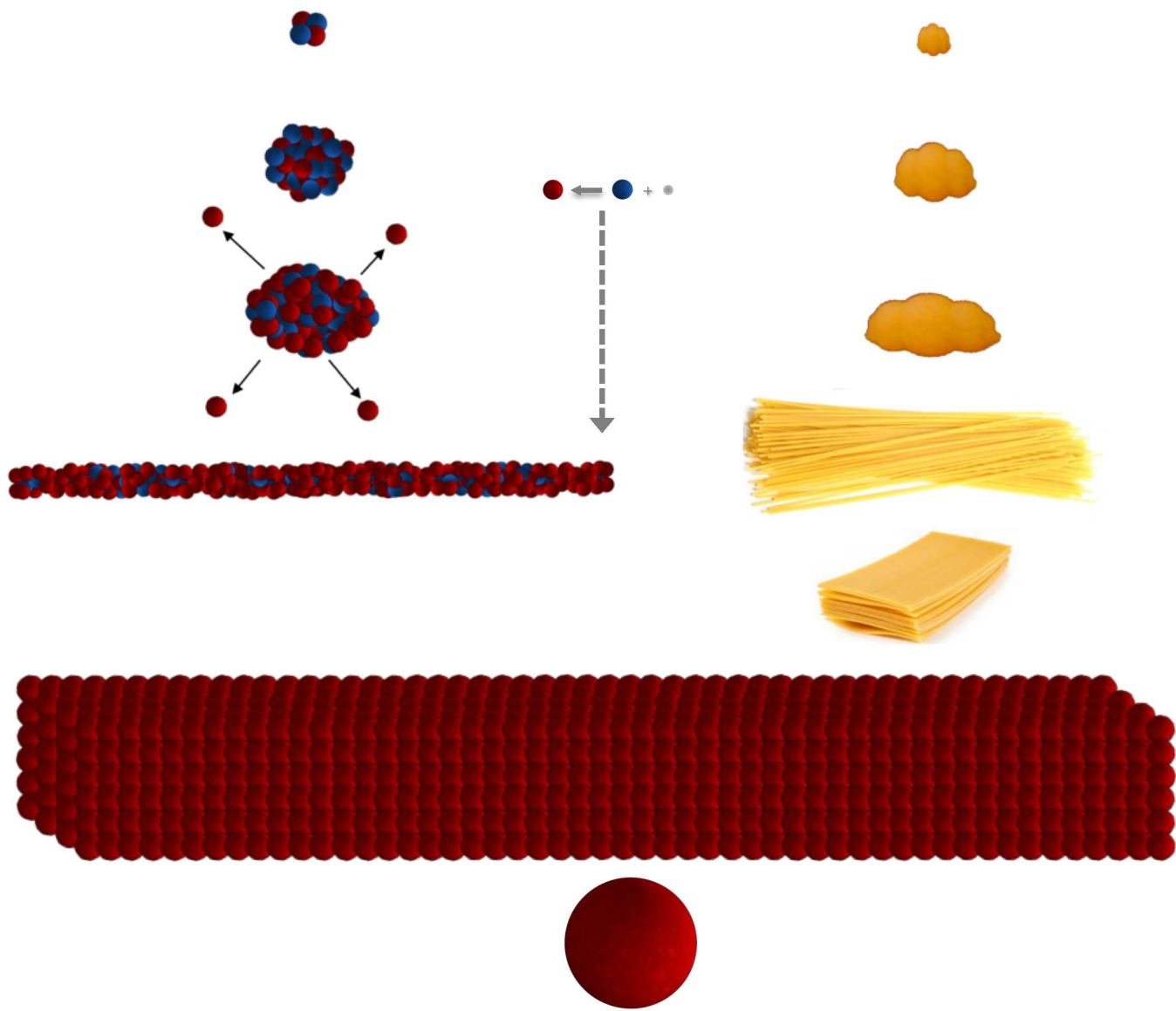


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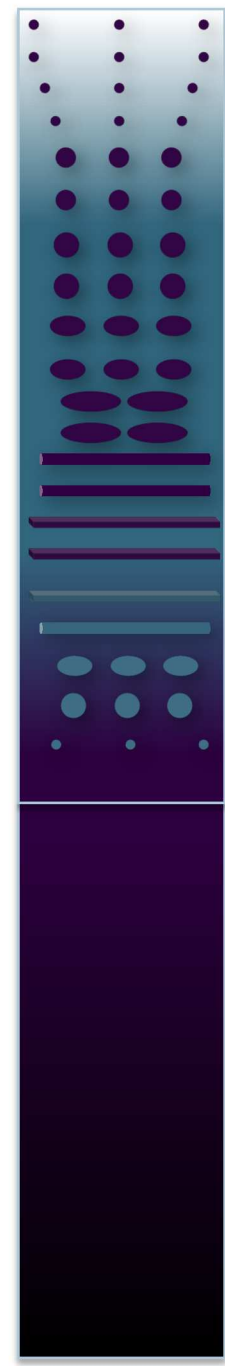
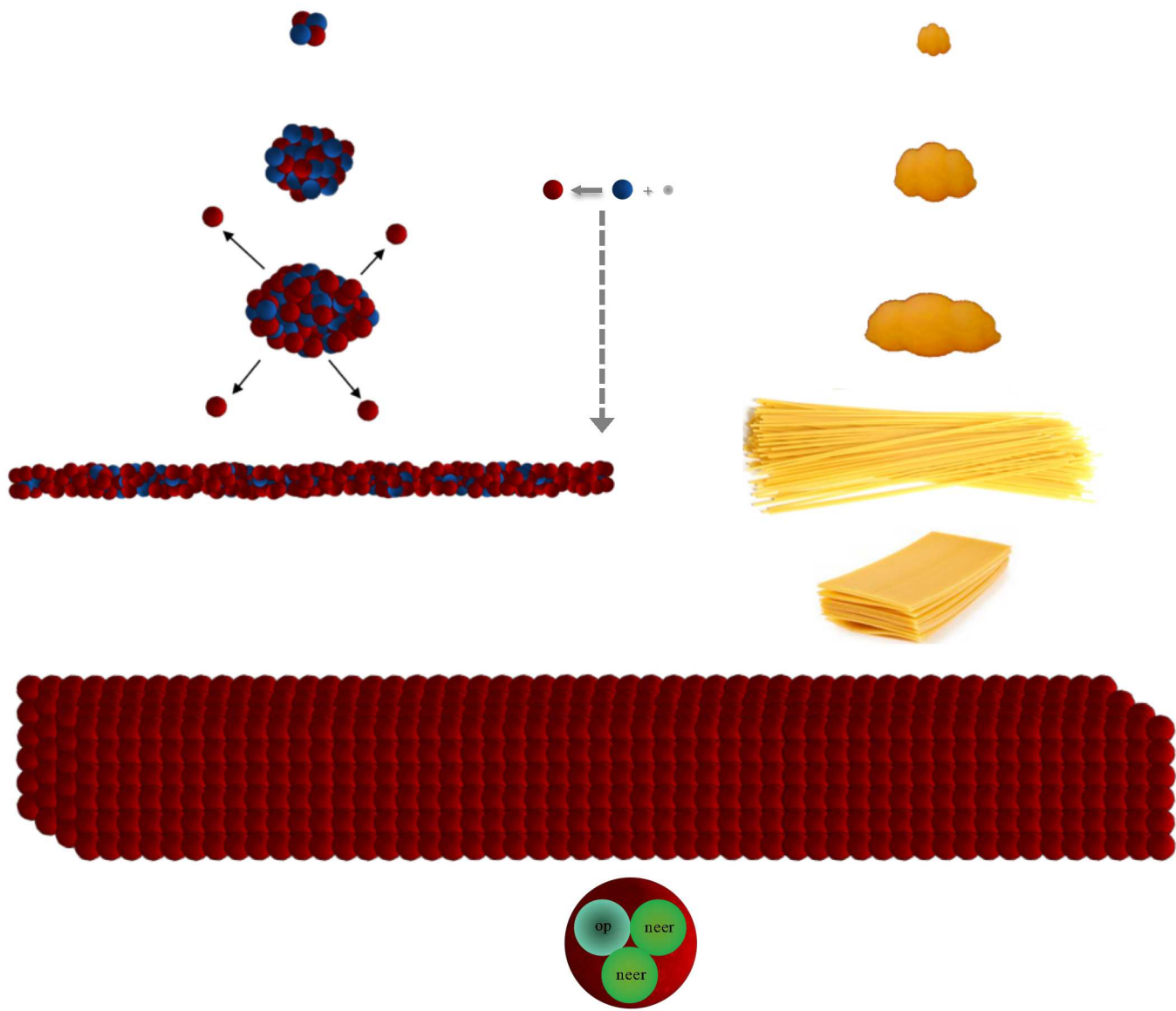


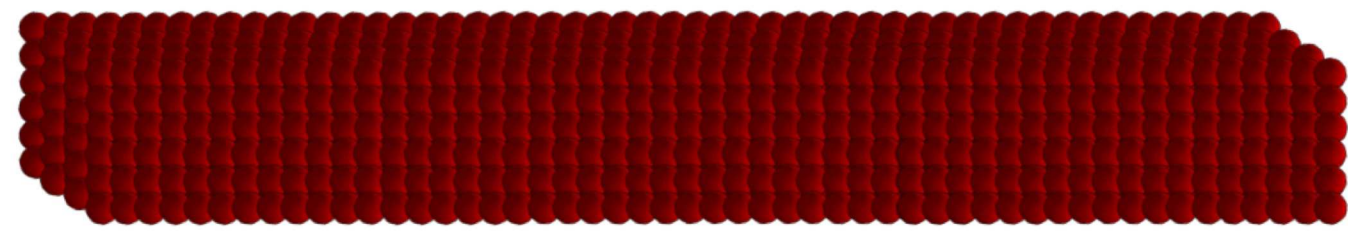
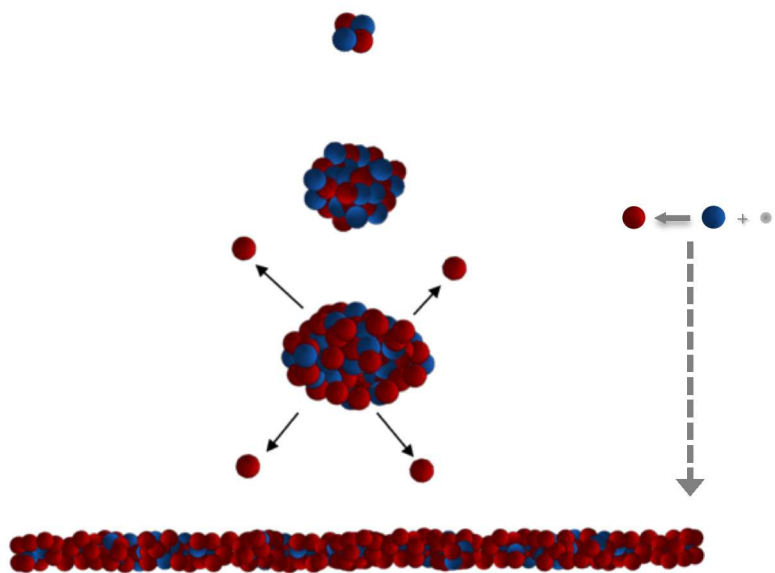
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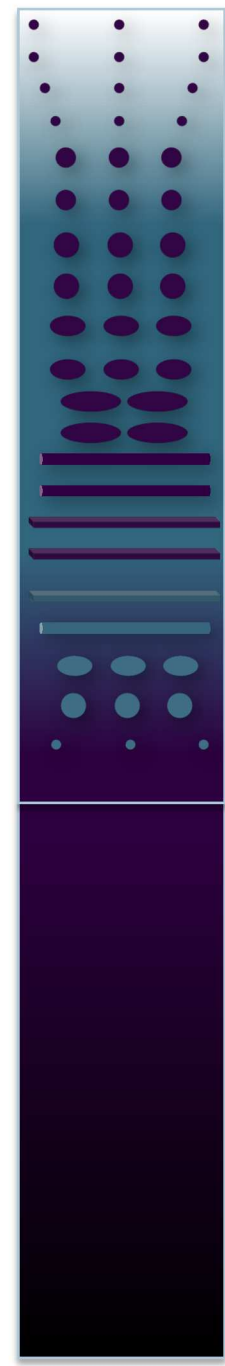
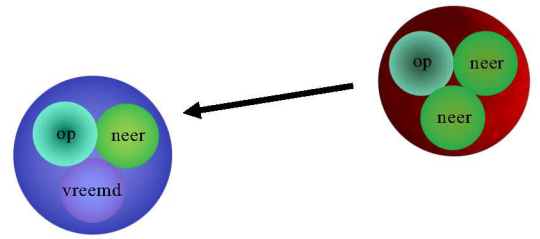
Druk





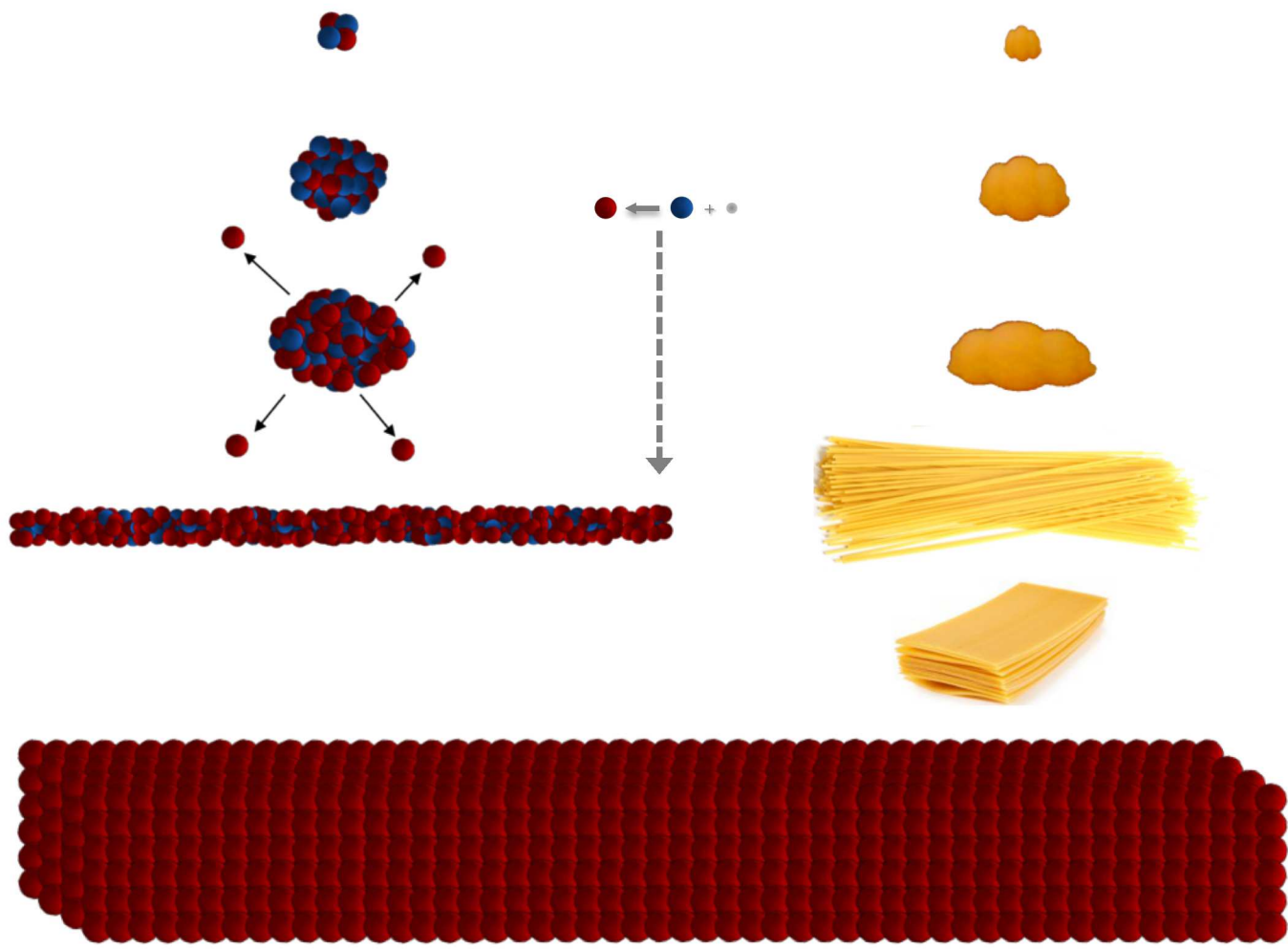


Hyperonen



Druk

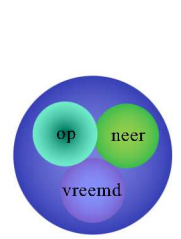




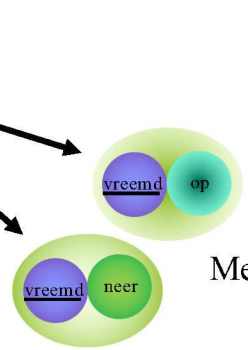
Druk

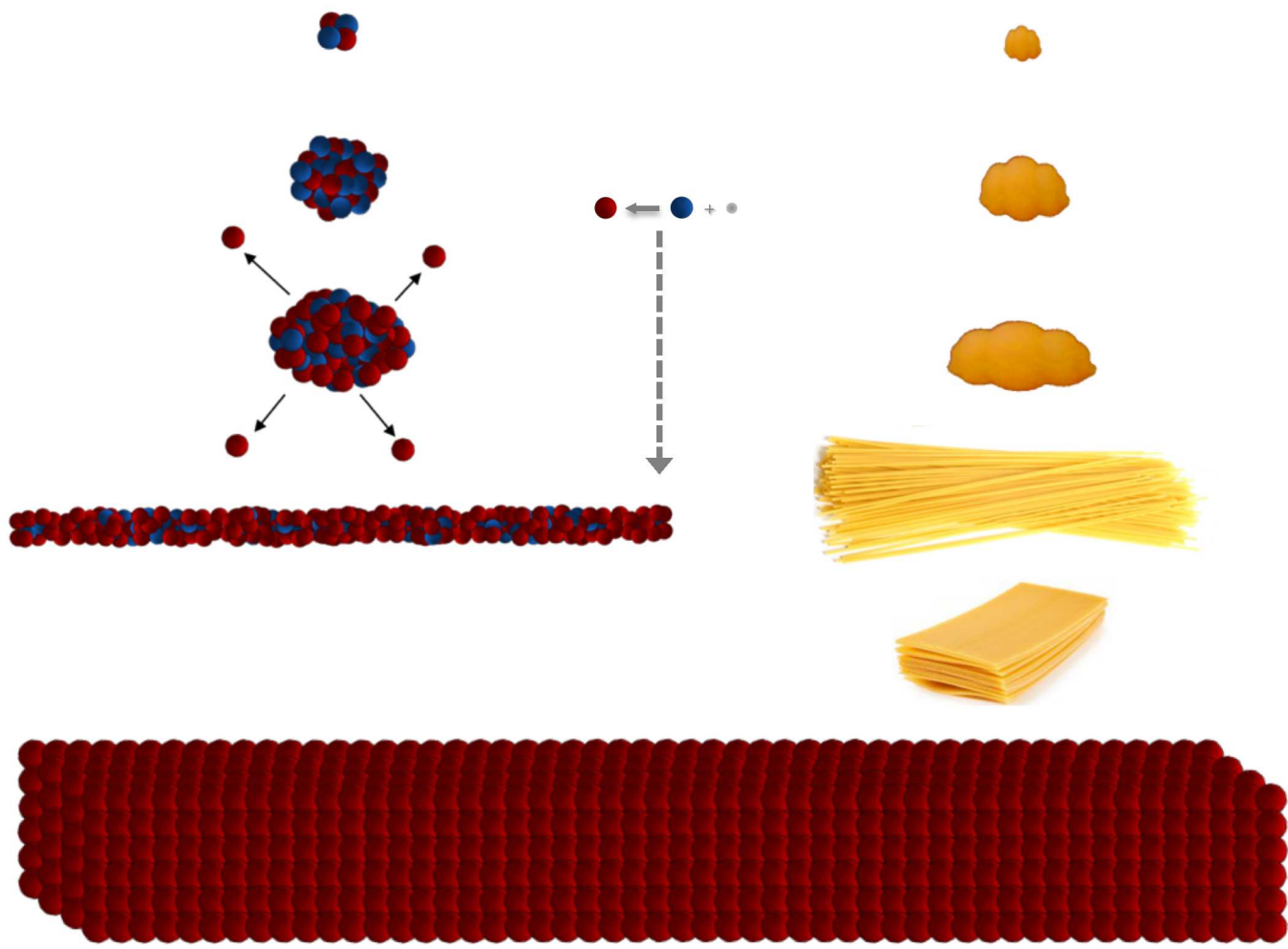


Hyperonen



Mesonen

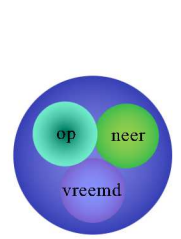




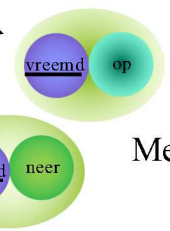
Druk



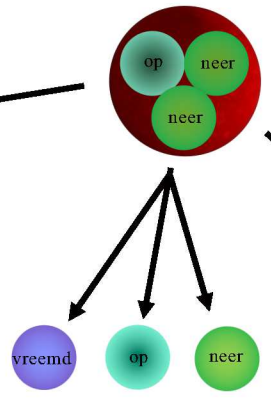
Hyperonen

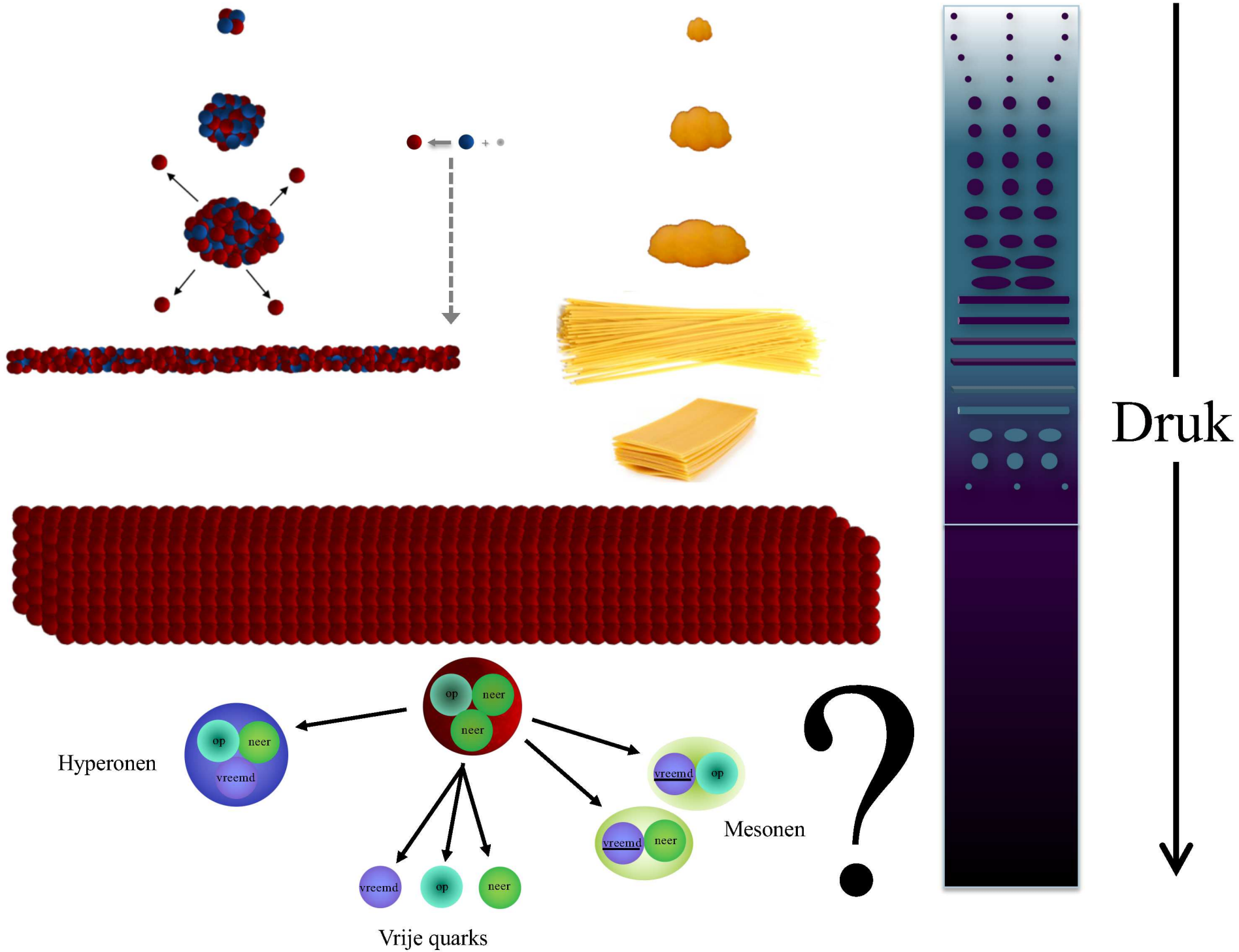


Mesonen



Vrije quarks





Extreme spin

- Draaien tot 700 keer per seconde rond



Wasmachine

- 1200 r/m
- 20 r/s

Neutronenster:

- 700 r/s

Extreme spin

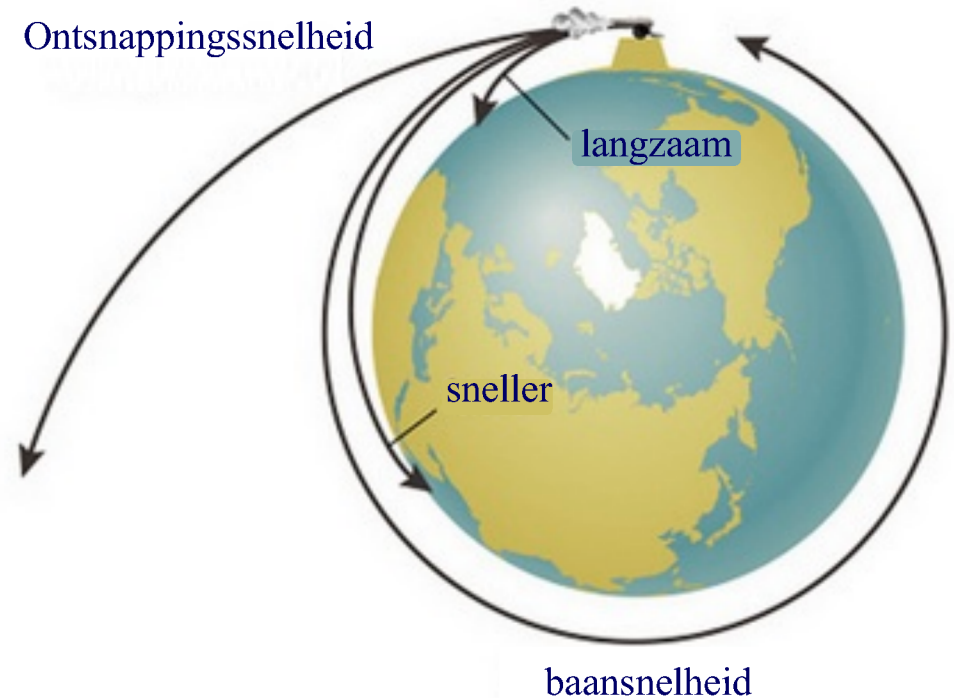
- Draaien tot 700 keer per seconde rond
- Bijverschijnsel ontstaan neutronenster



Extreme zwaartekracht

Snelheid nodig om aan zwaartekrachtsveld te ontsnappen

Aarde: $\sim 11 \text{ km/s}$

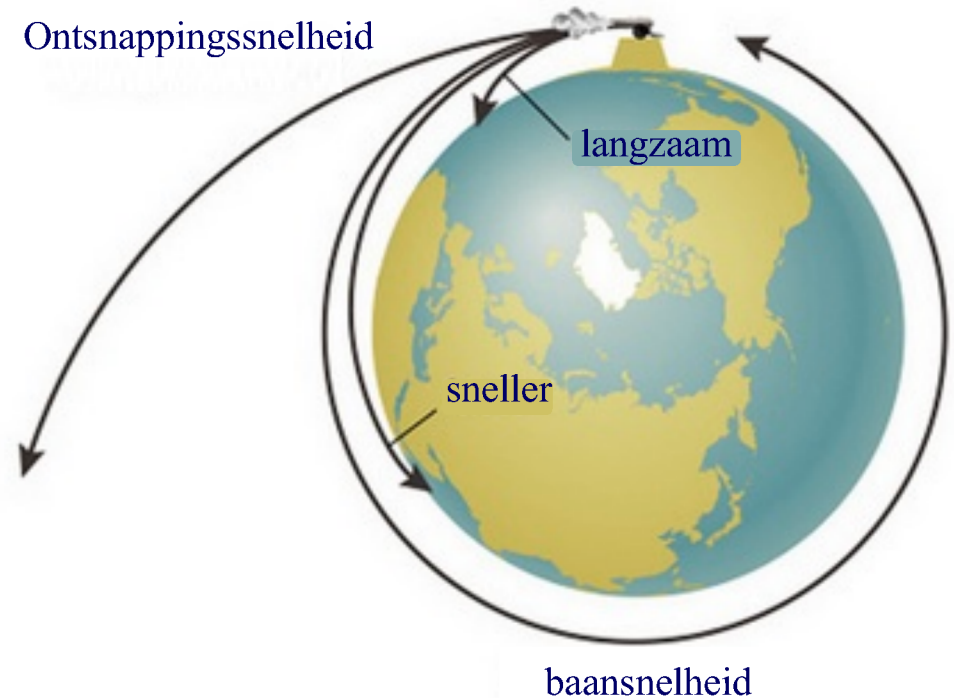


Extreme zwaartekracht

Snelheid nodig om aan zwaartekrachtsveld te ontsnappen

Aarde: $\sim 11 \text{ km/s}$

Zon: $\sim 620 \text{ km/s}$



Extreme zwaartekracht

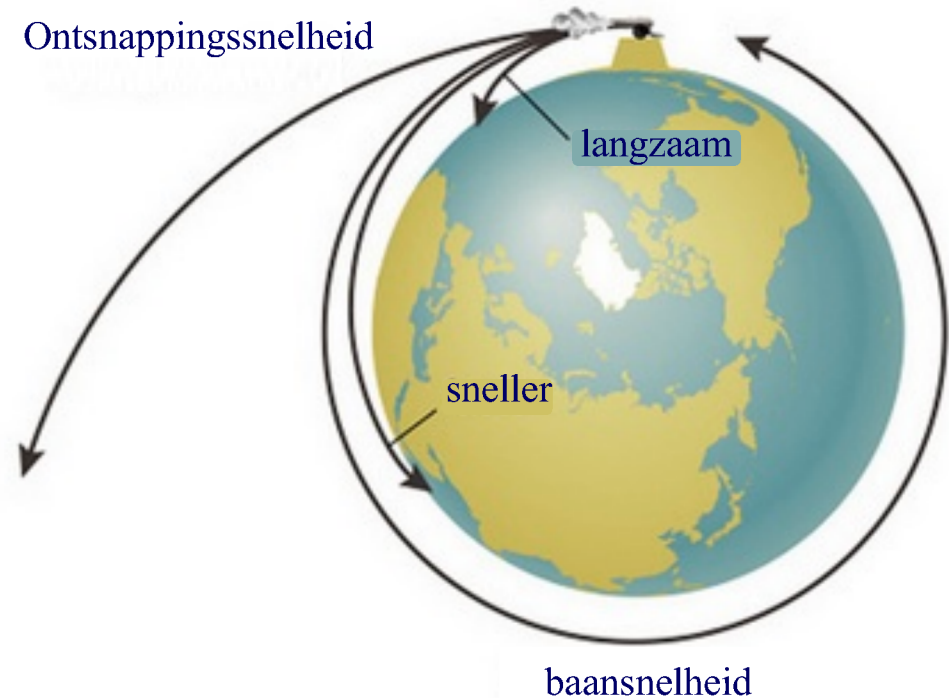
Snelheid nodig om aan zwaartekrachtsveld te ontsnappen

Aarde: $\sim 11 \text{ km/s}$

Zon: $\sim 620 \text{ km/s}$

Neutronenster: $\sim 150.000 \text{ km/s}$

$\sim 0,5 \times$ lichtsnelheid



Extreme zwaartekracht

Snelheid nodig om aan zwaartekrachtsveld te ontsnappen

Aarde: ~ 11 km/s

Zon: ~ 620 km/s

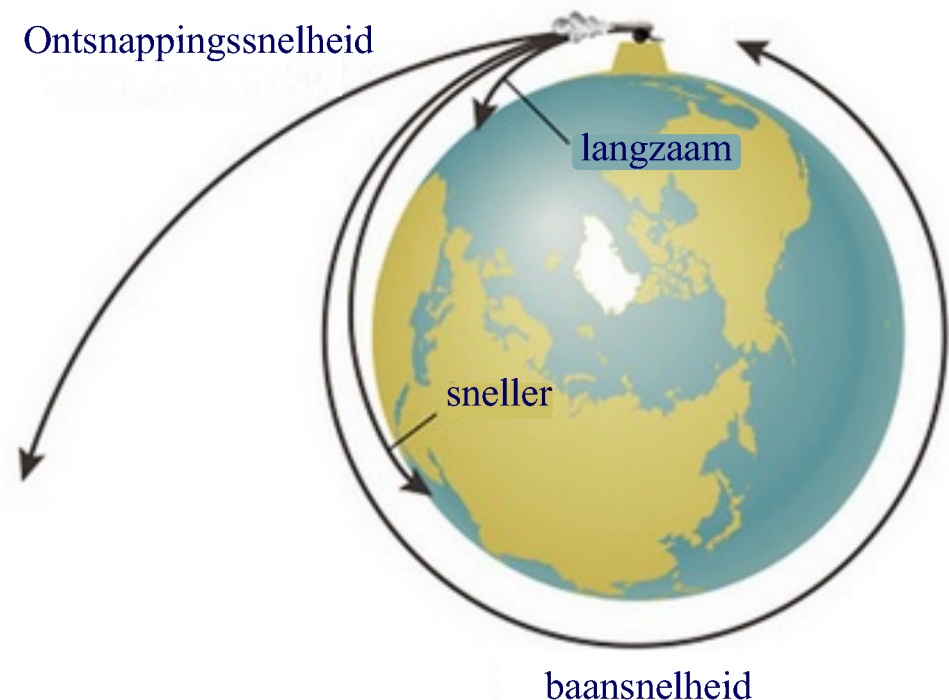
Neutronenster: ~ 150.000 km/s

$\sim 0,5$ x lichtsnelheid

Zwart gat: > 300.000 km/s

groter dan lichtsnelheid!

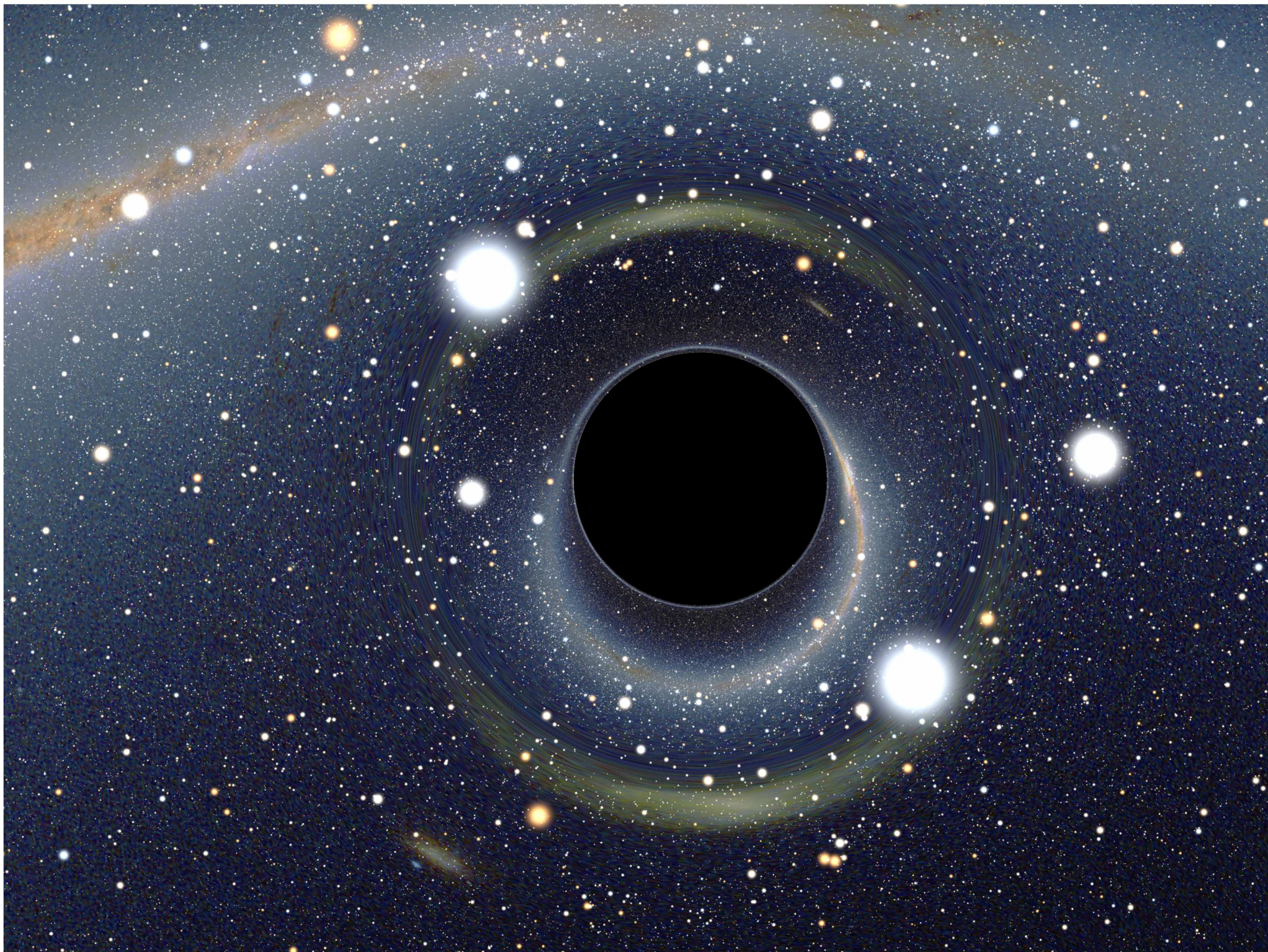
(in Newtoniaanse termen)



Buiging van licht

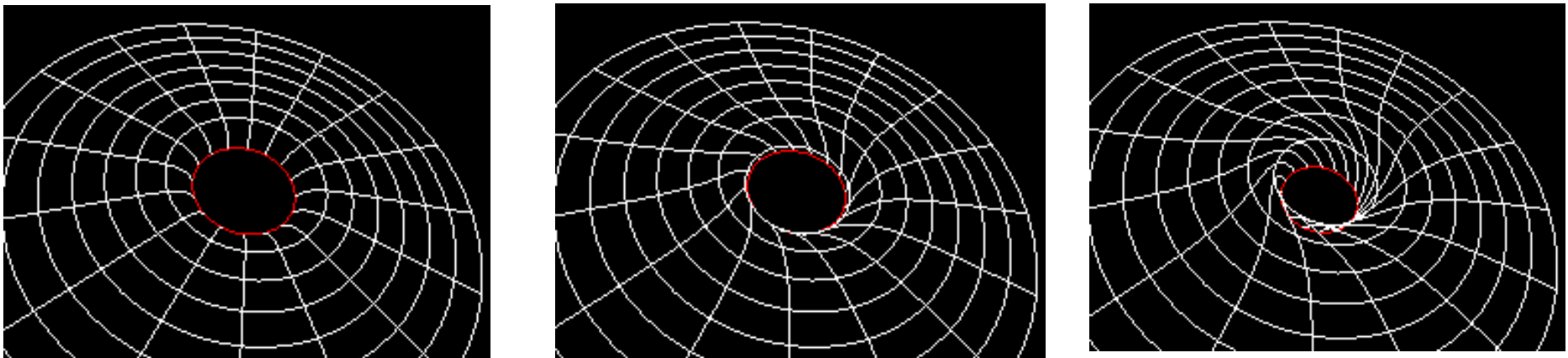
- Licht wordt afgebogen
- Men kan de achterkant van de sterren zien!





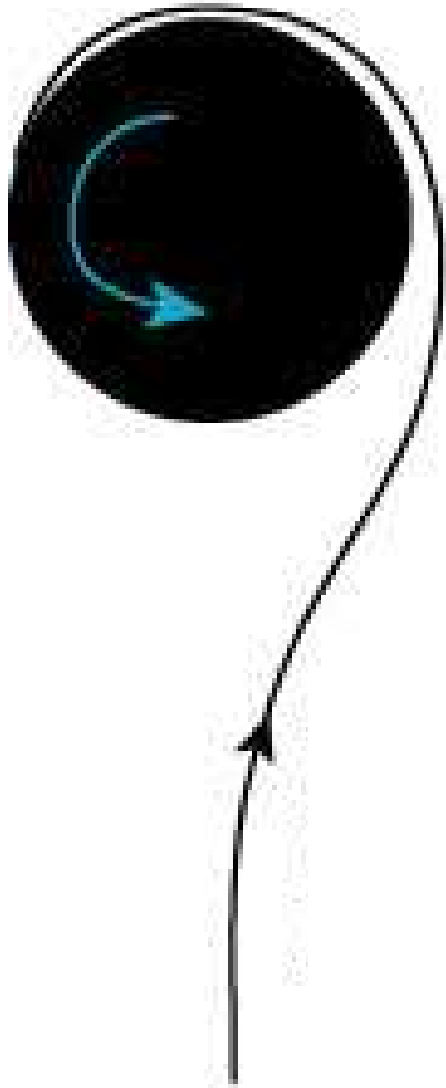
Extreme zwaartekracht en spin

- Spin van 500 tot 1000 keer per seconde
- Extra relativistische effecten
 - “Frame dragging”
 - Je moet meebewegen in de draairichting!
 - Zeer sterk bij roterend zwart gat

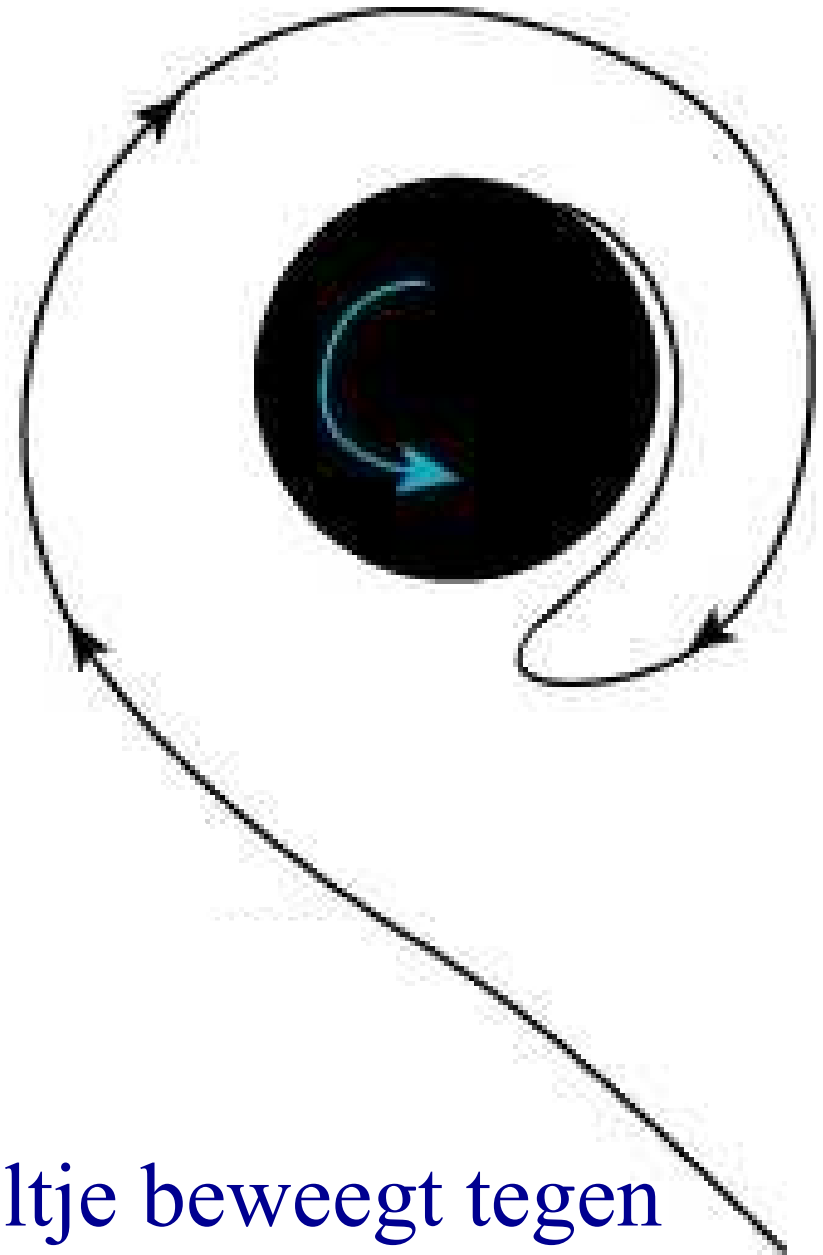


Toename van de spin →

Deeltje beweegt met
het zwarte gat mee

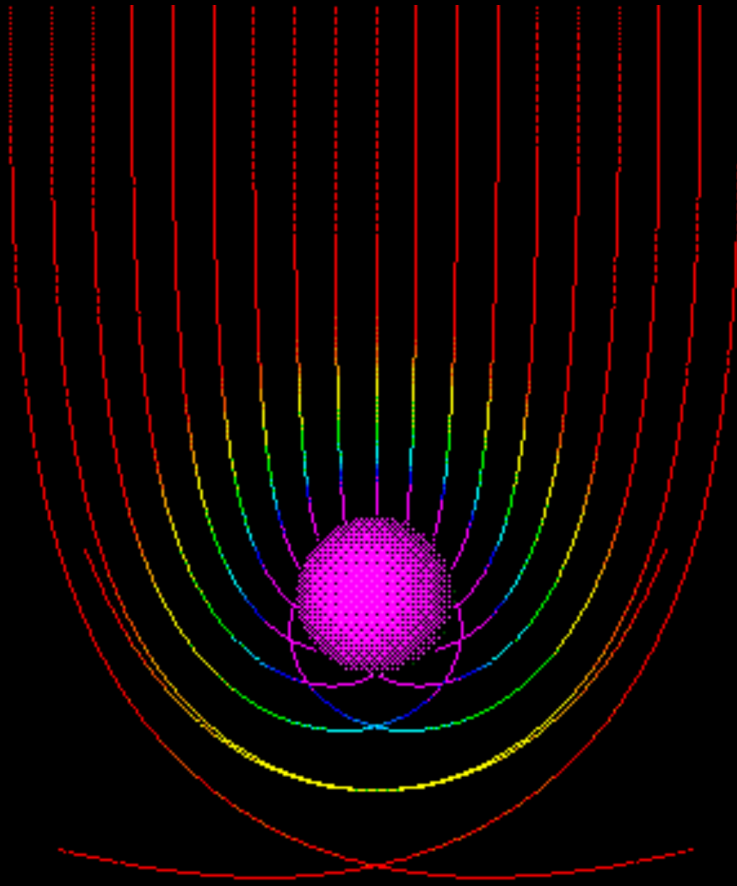


Deeltje beweegt tegen
het zwarte gat in

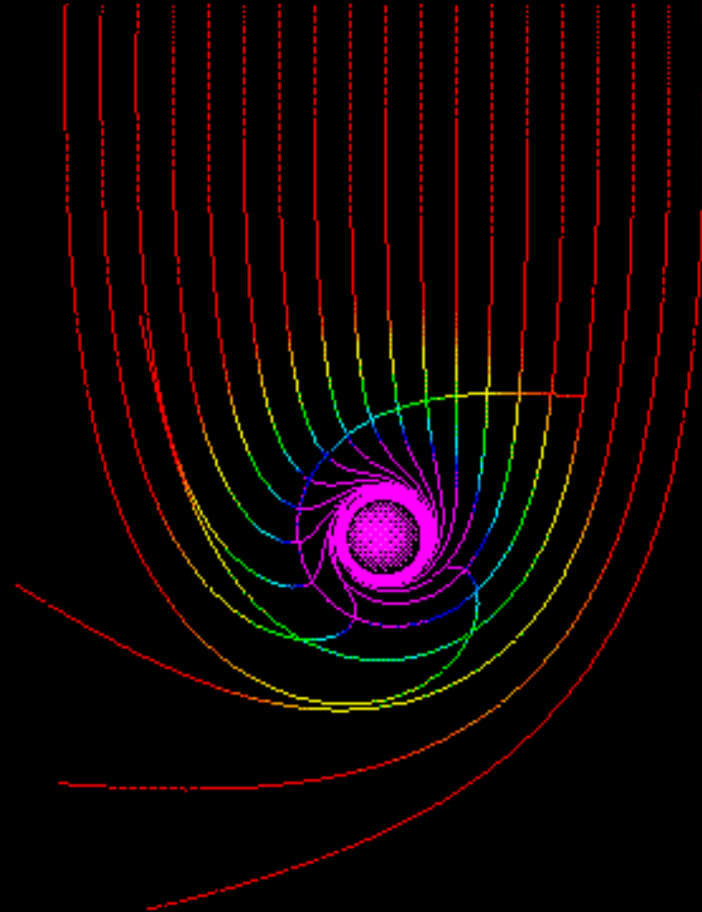


Zelfs licht!

Niet roterend zwart gat



Roterend zwart gat



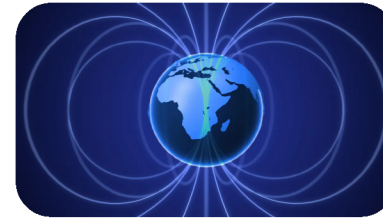
Extreme magneetvelden

- Op Aarde
 - Aarde: $\sim 0,6 \text{ G}$ ($\sim 0,00006 \text{ Tesla}$)
 - Koelkastmagneet: $\sim 100 \text{ G}$



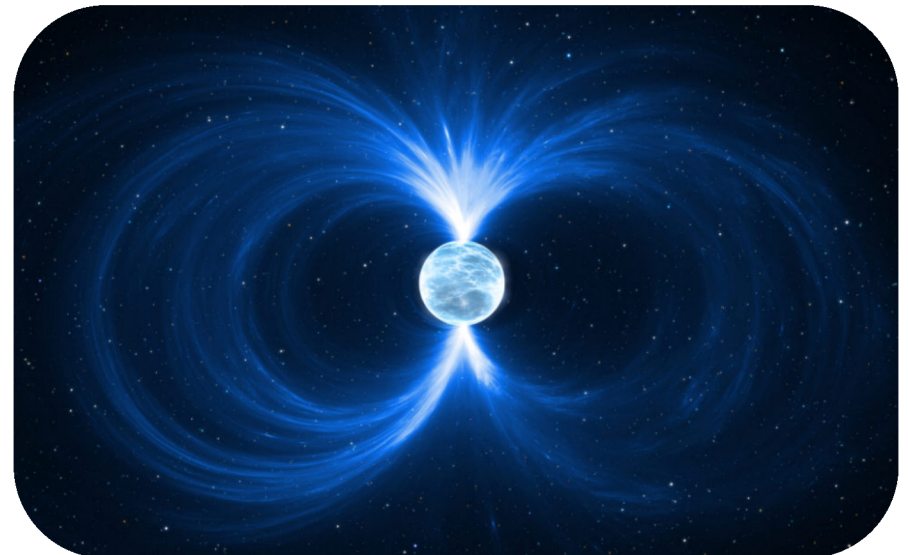
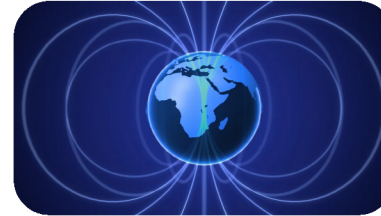
Extreme magnetevelden

- Op Aarde
 - Aarde: $\sim 0,6 \text{ G}$ ($\sim 0,00006 \text{ Tesla}$)
 - Koelkastmagneet: $\sim 100 \text{ G}$
 - MRI scan: $\sim 10.000 \text{ G}$
 - Speciale labs: $\sim 450.000 \text{ G}$



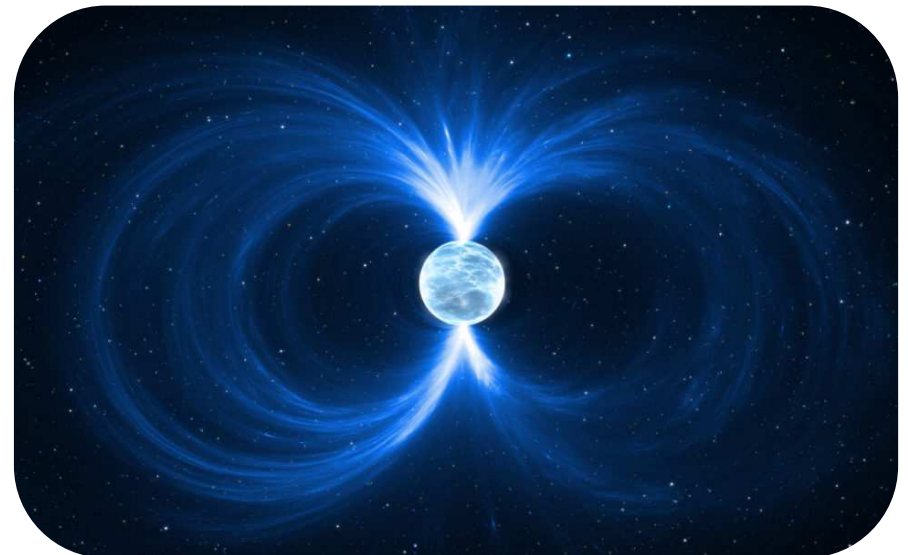
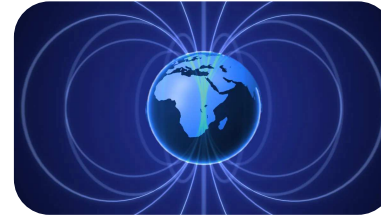
Extreme magneetvelden

- Op Aarde
 - Aarde: $\sim 0,6$ G ($\sim 0,00006$ Tesla)
 - Koelkastmagneet: ~ 100 G
 - MRI scan: ~ 10.000 G
 - Speciale labs: ~ 450.000 G
- Neutronensterren
 - $1.000.000.000.000.000$ G
 - 1 biljard keer die van de Aarde
 - Fossiel magneetveld



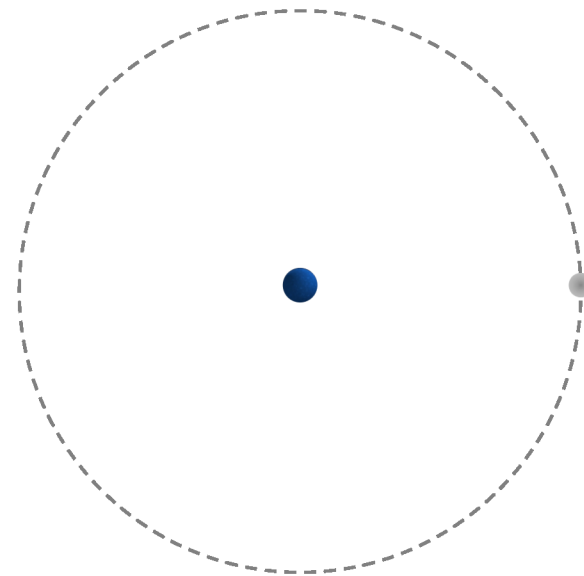
Extreme magneetvelden

- Op Aarde
 - Aarde: $\sim 0,6$ G ($\sim 0,00006$ Tesla)
 - Koelkastmagneet: ~ 100 G
 - MRI scan: ~ 10.000 G
 - Speciale labs: ~ 450.000 G
- Neutronensterren
 - $1.000.000.000.000.000$ G
 - 1 biljard keer die van de Aarde
 - Fossiel magneetveld
- Rare effecten op materie
 - Atomen worden uitgerekt
 - 200 keer zo lang als breed



Extreme magnetevelden

- Op Aarde
 - Aarde: $\sim 0,6$ G ($\sim 0,00006$ Tesla)
 - Koelkastmagneet: ~ 100 G
 - MRI scan: ~ 10.000 G
 - Speciale labs: ~ 450.000 G
- Neutronensterren
 - $1.000.000.000.000.000$ G
 - 1 biljard keer die van de Aarde
 - Fossiel magnetveld
- Rare effecten op materie
 - Atomen worden uitgerekt
 - 200 keer zo lang als breed



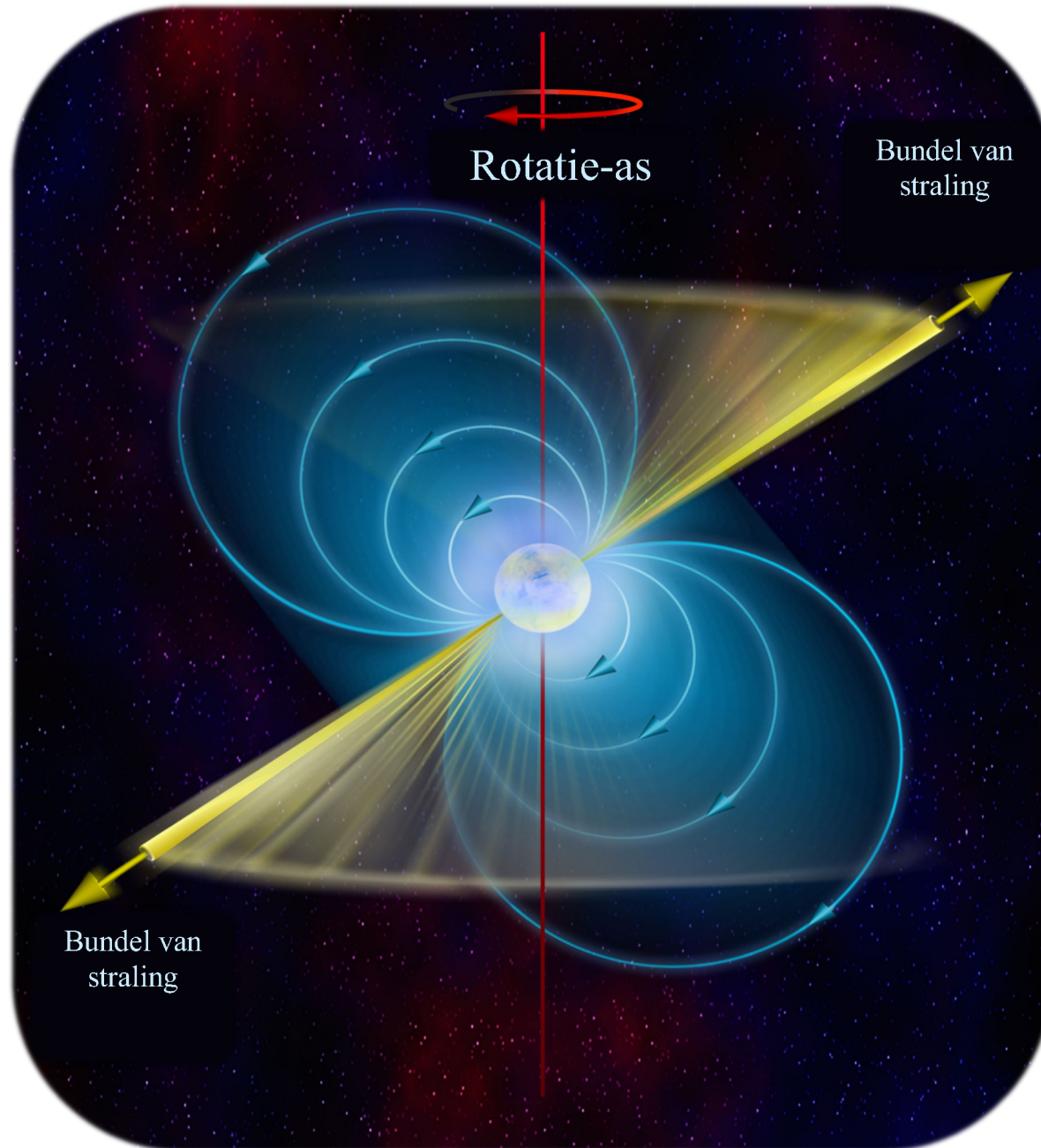
Waterstofatoom

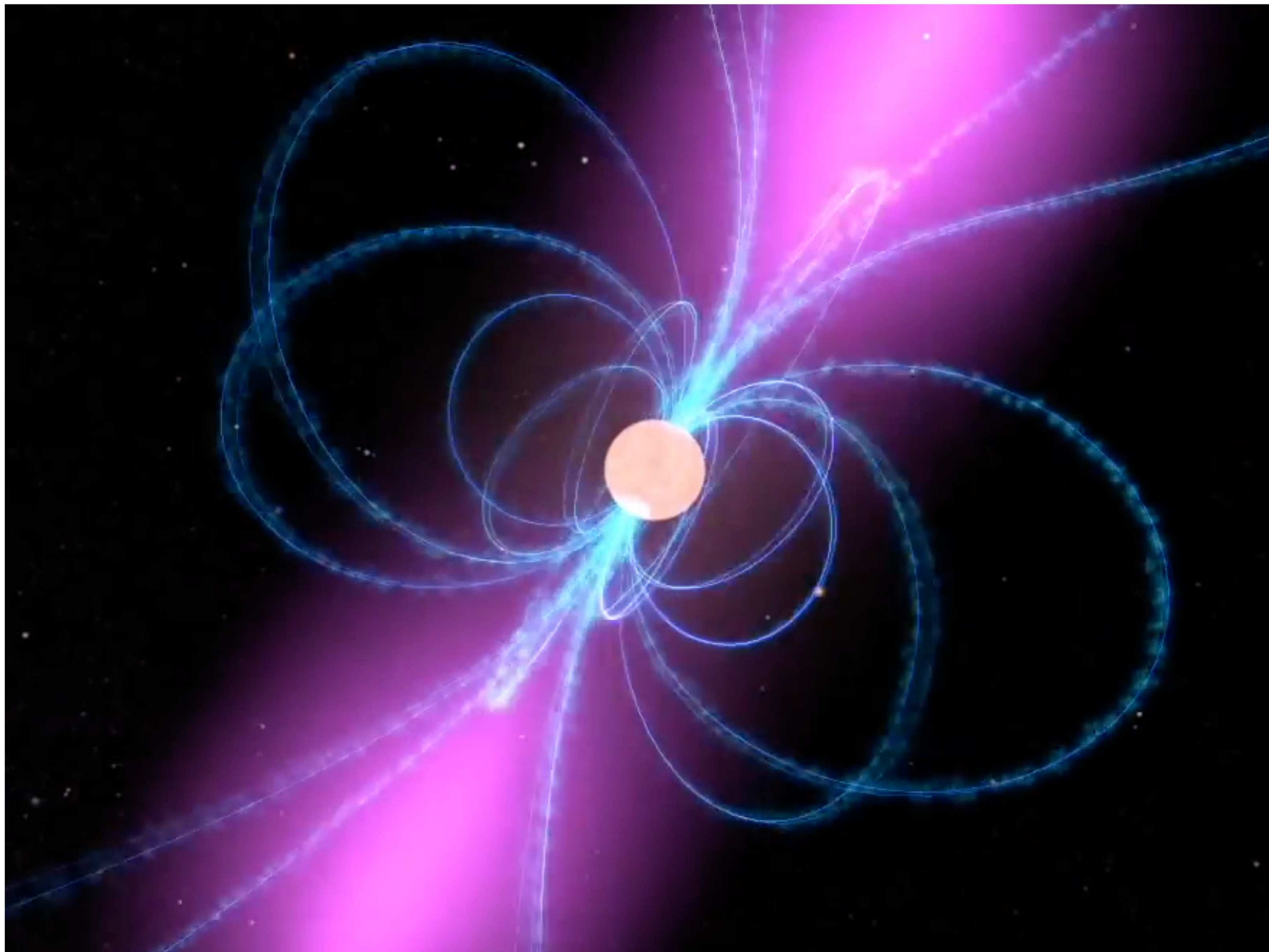
Extreme magnetvelden

- Op Aarde
 - Aarde: $\sim 0,6$ G ($\sim 0,00006$ Tesla)
 - Koelkastmagneet: ~ 100 G
 - MRI scan: ~ 10.000 G
 - Speciale labs: ~ 450.000 G
- Neutronensterren
 - $1.000.000.000.000.000$ G
 - 1 biljard keer die van de Aarde
 - Fossiel magnetveld
- Rare effecten op materie
 - Atomen worden uitgerekt
 - 200 keer zo lang als breed



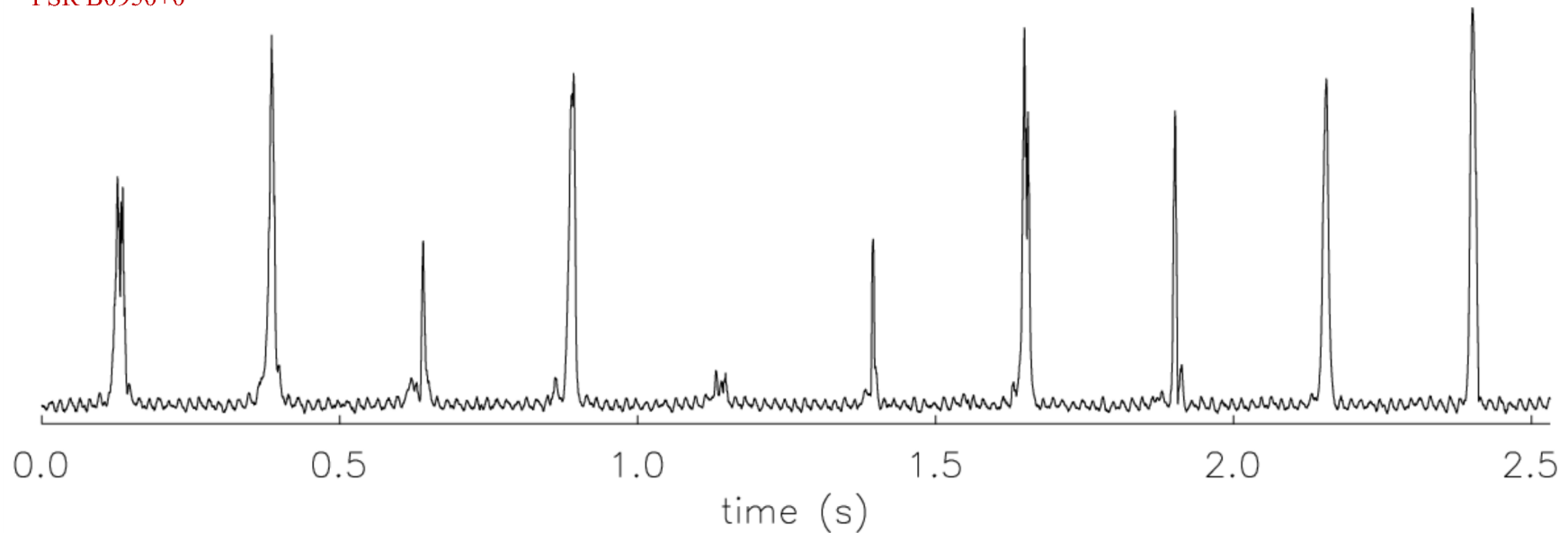
Extreme spin + magneetveld





Radiopulsars waarnemen

PSR B0950+0



PSR 0329+54: 0.715 s



1,4 keer per seconde

PSR 0833-45: 89.3 ms



11 keer per seconde

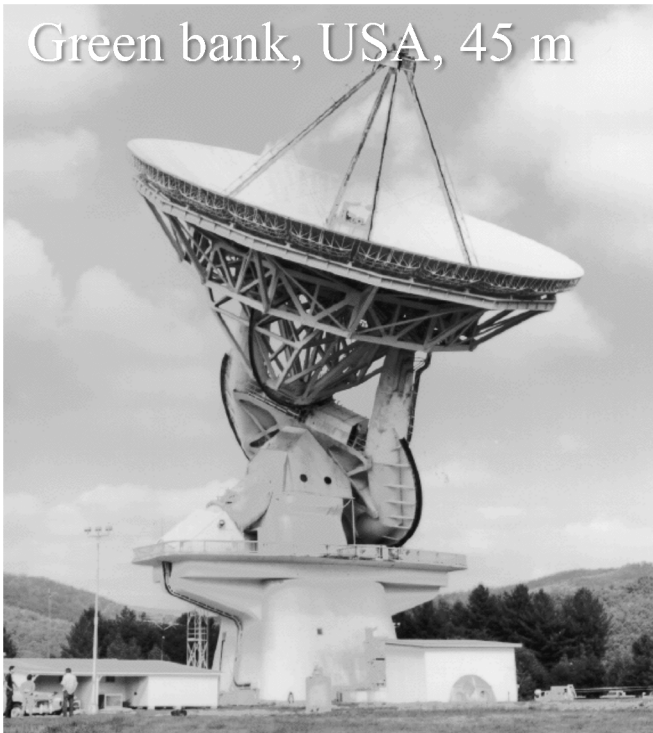
PSR 1937+21: 1.56 ms



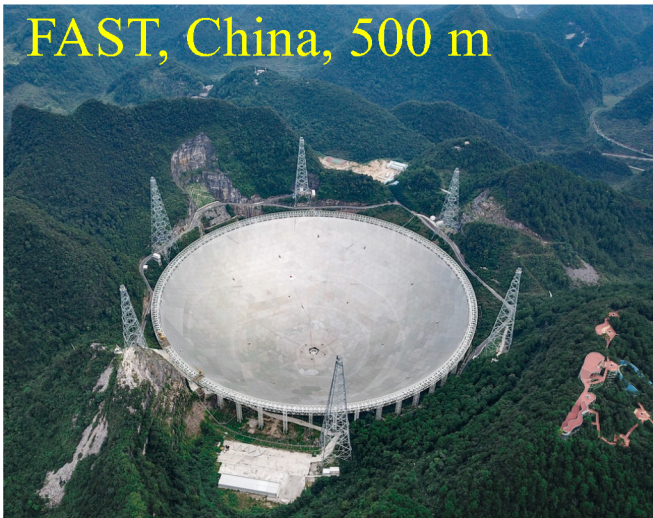
641 keer per seconde

Radiopulsars waarnemen

Green bank, USA, 45 m



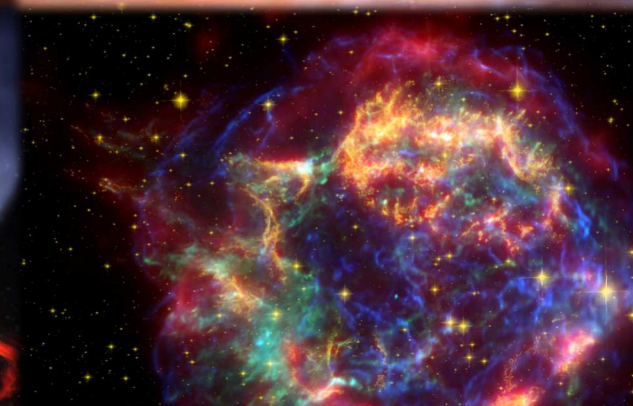
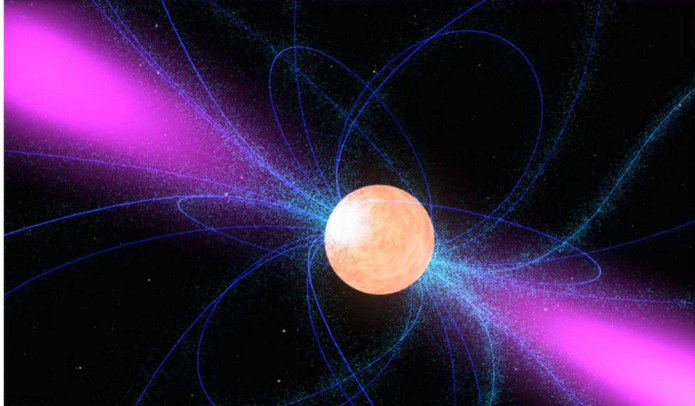
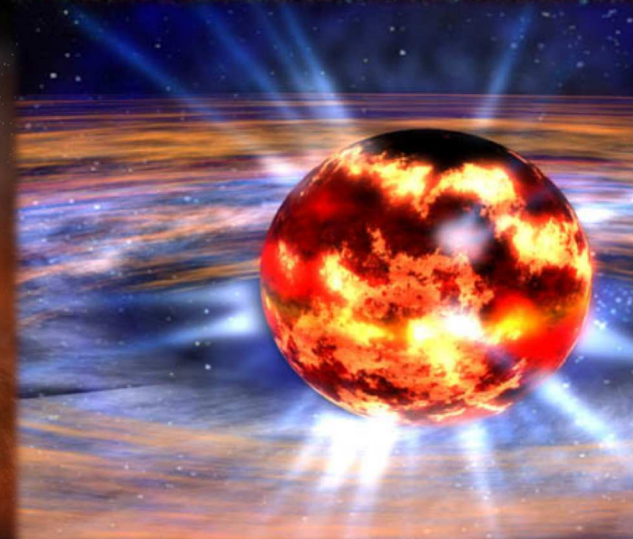
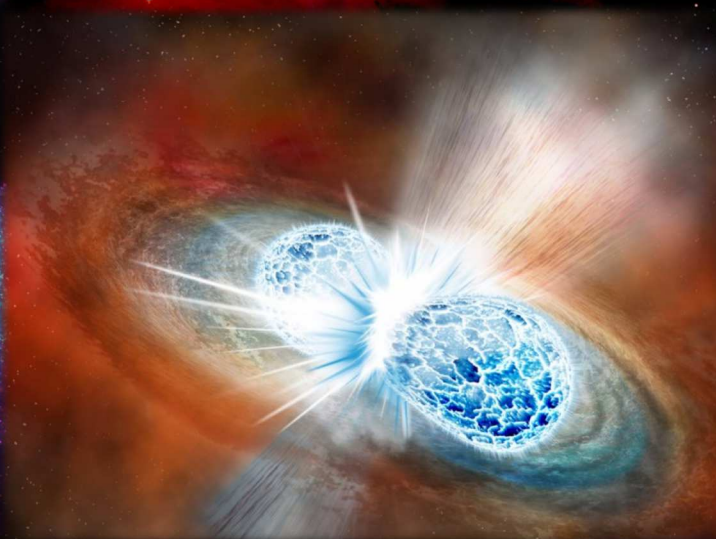
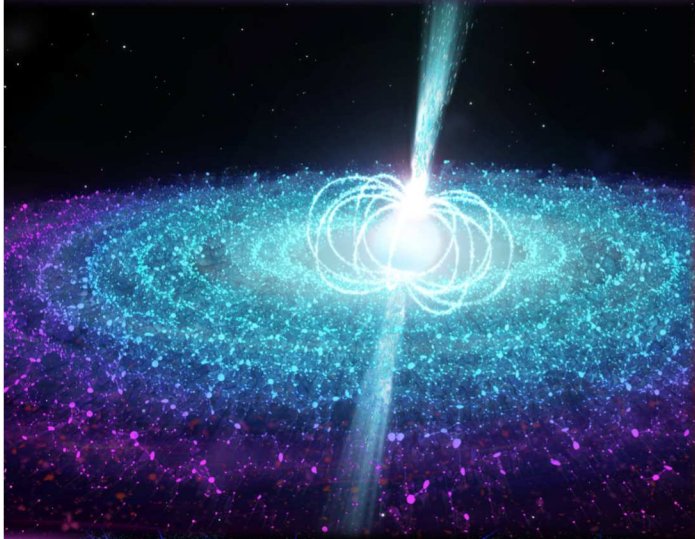
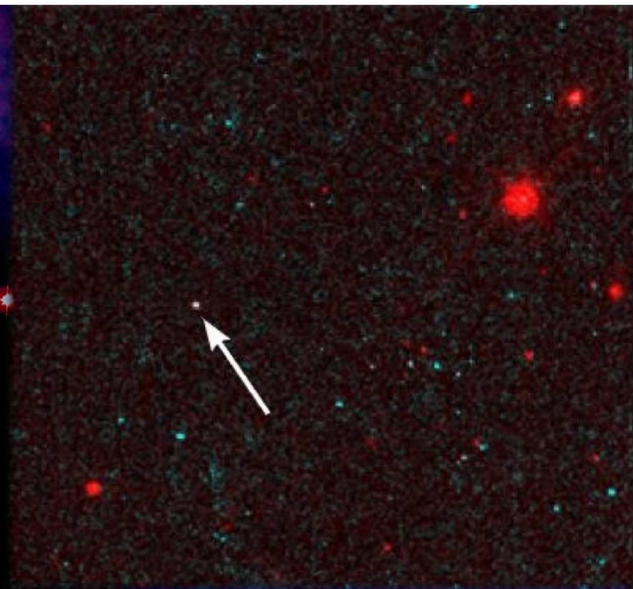
FAST, China, 500 m



Effelsberg, Bonn, 100 m

Westerbork telescoop





Waarom zijn ze interessant?

- Extreme natuurkunde
 - Extreme dichtheden
 - Extreme spin
 - Extreme zwaartekracht
 - Extreme magneetvelden
 - Niet op Aarde na te bootsen
- Eindstadium sterevolutie
 - Ontstaan van de elementen

Periodiek systeem van de elementen

1 H																	2 He	
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne	
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar	
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	
55 Cs	56 Ba			72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra																	
			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
			89 Ac	90 Th	91 Pa	92 U												

Herkomst van de elementen

1 H	Oerknal kernfusie						Kosmische straling kernsplijting												2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne		
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar		
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr		
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe		
55 Cs	56 Ba			72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn	
87 Fr	88 Ra																		
		57 La		58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu		
		89 Ac		90 Th	91 Pa	92 U													

Evolutie van een ster



Evolutie van een ster

Ster condenseert uit gaswolk



Evolutie van een ster

Kernfusie stopt
zwaartekracht
de ster gaat stralen



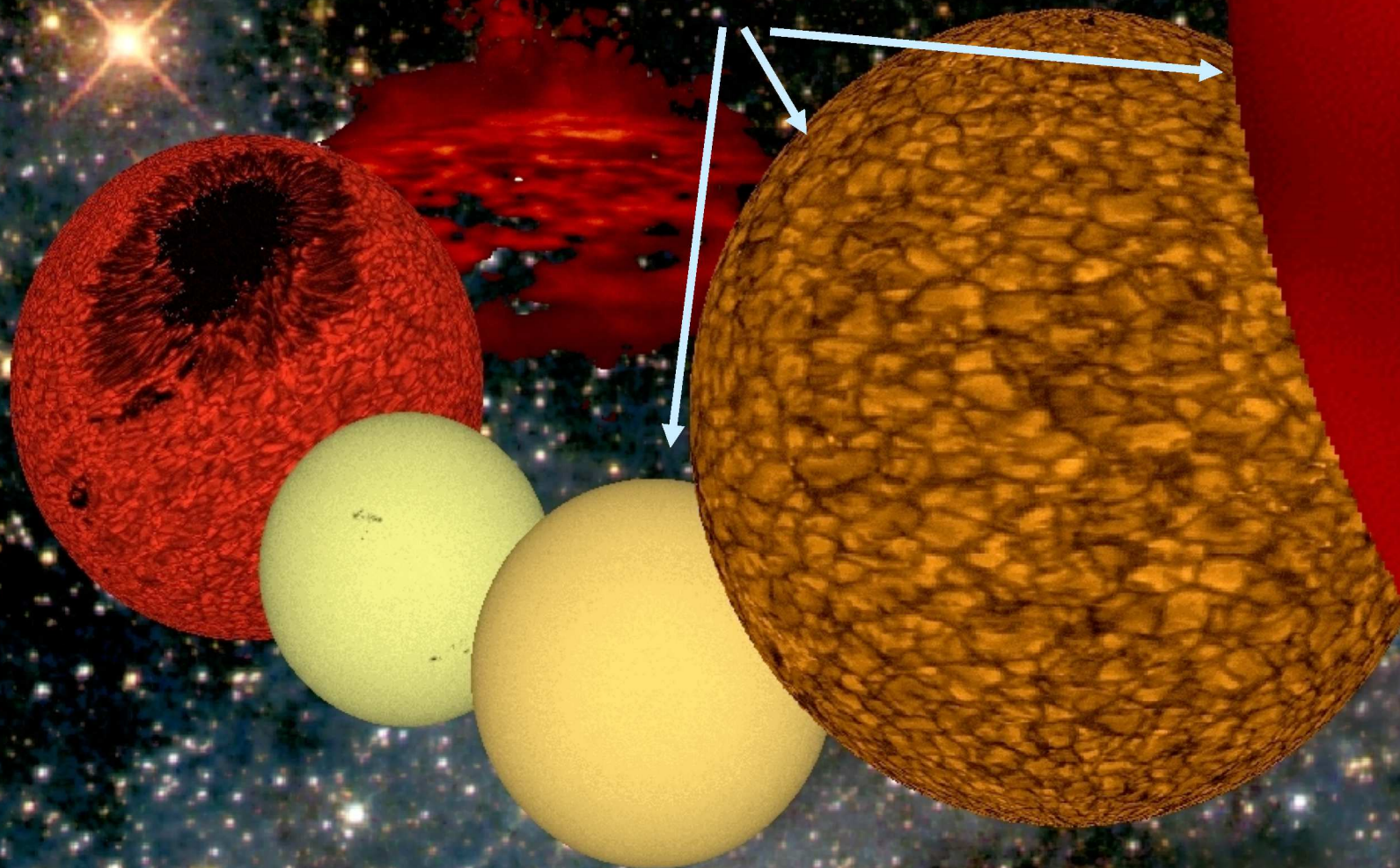
Evolutie van een ster

Kernfusie stopt
zwaartekracht
de ster gaat stralen



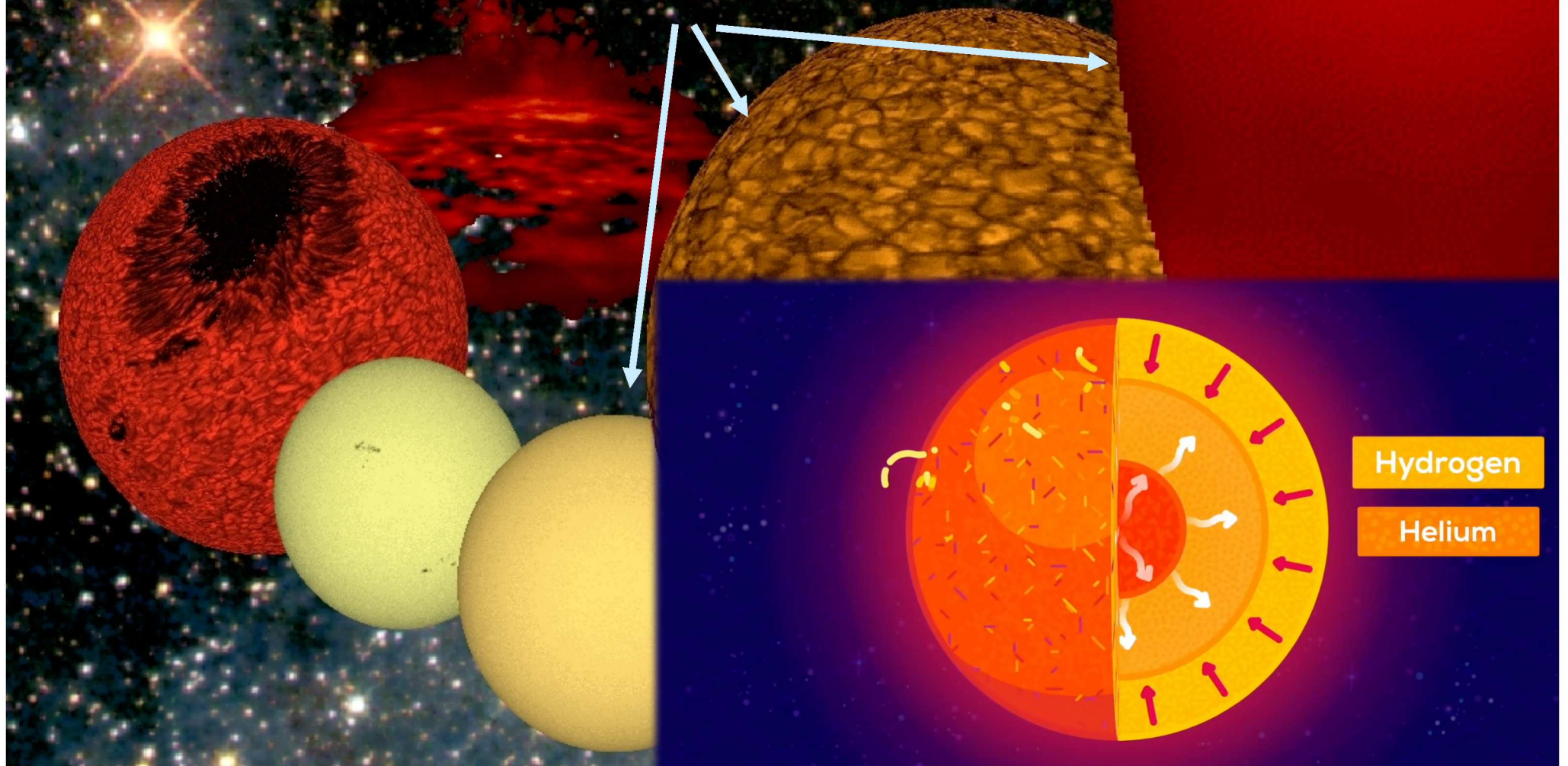
Evolutie van een ster

Fusie van zwaardere elementen
ster zwelt op



Evolutie van een ster

Fusie van zwaarder elementen
ster zwelt op



Het einde van een lichte ster

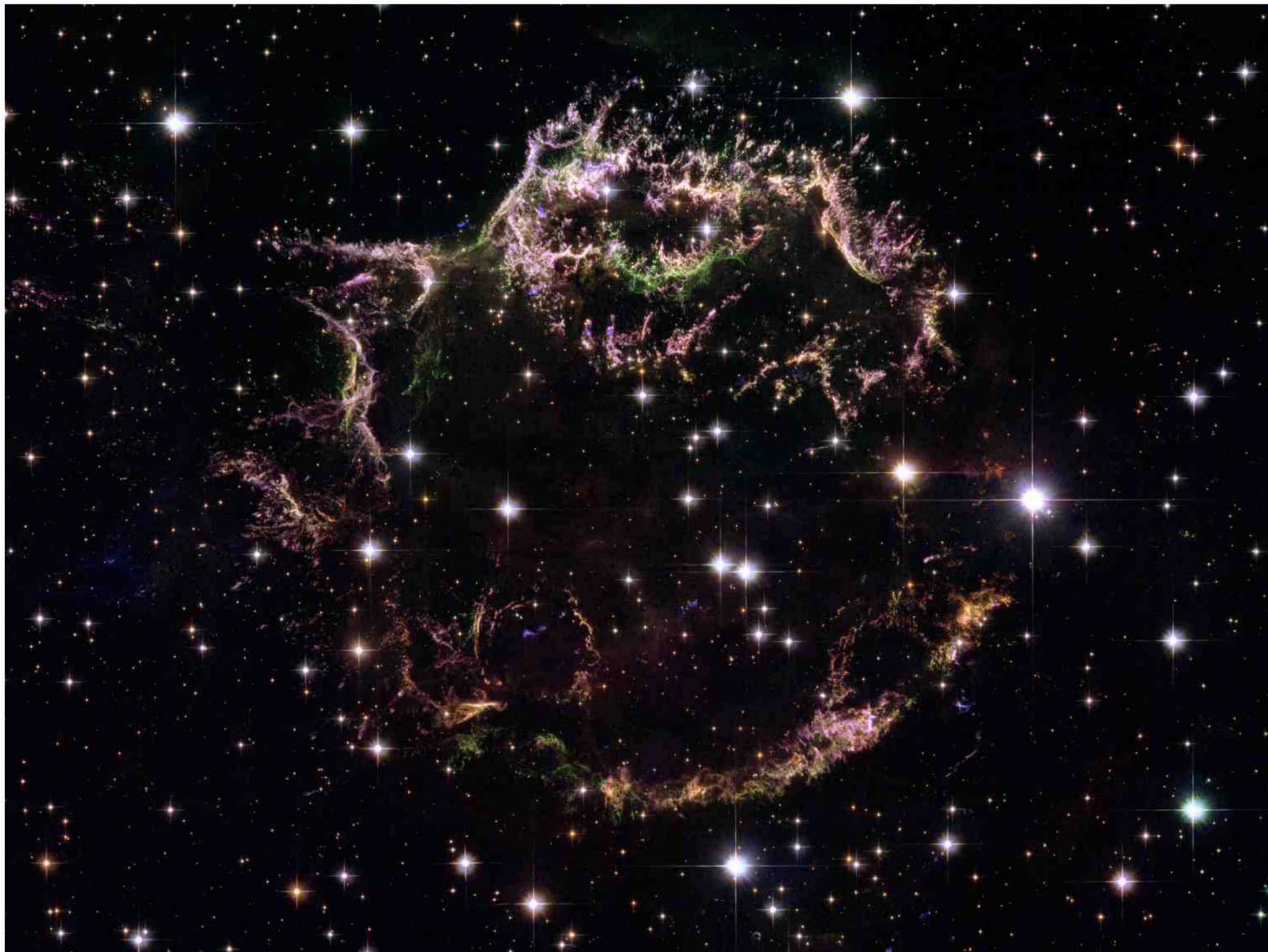
- Na koolstof geen kernfusie meer
- Kern stort in tot een witte dwerg
- Buitenmantel wordt uitgestoten en vormt een planetaire nevel
- Niet verder besproken vandaag

Herkomst van de elementen

[illegible]

Het einde van een massieve ster

- Na ijzer geen kernfusie
 - Kost energie om zwaardere elementen te maken
- Kern stort in
 - Neutronenster
 - Zwart gat
- Mantel wordt weggeblazen
 - Supernova explosie
 - Supernova restant



Herkomst van de elementen

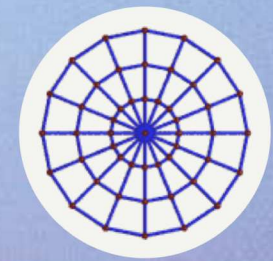
1 H	Oerknal kernfusie						Kosmische straling kernsplijting						2 He						
3 Li	4 Be	Stervende lichte sterren						Exploderende massieve sterren						5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg	Exploderende witte dwergen												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr		
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe		
55 Cs	56 Ba			72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn	
87 Fr	88 Ra																		
		57 La		58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu		
		89 Ac		90 Th	91 Pa	92 U													

Dubbele neutronensterren

- Twee neutronensterren om elkaar
- Zenden zwaartekrachtstraling uit
- Uiteindelijk smelten ze samen



Detecteren van zwaartekrachtstraling

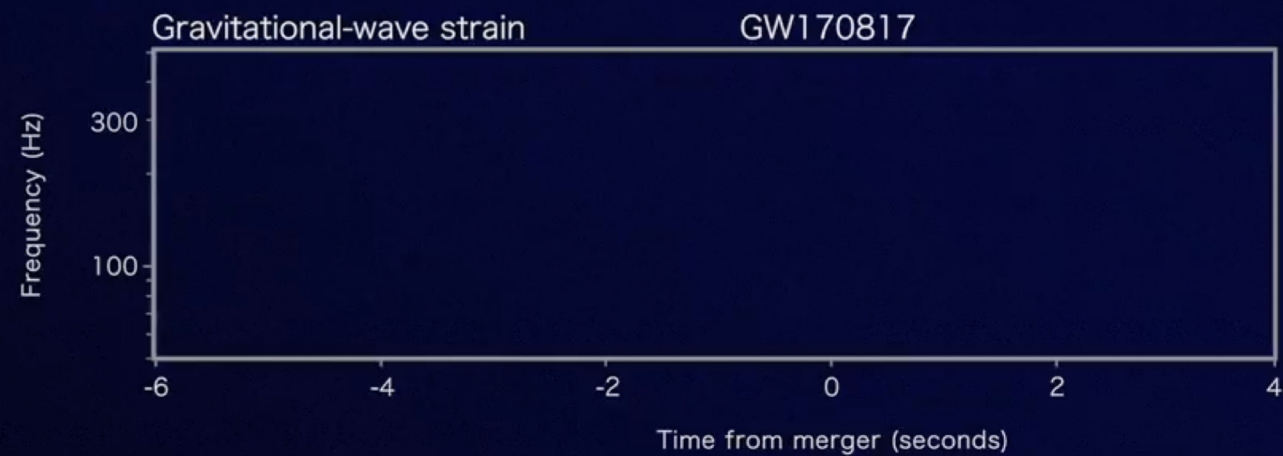


GW 170817

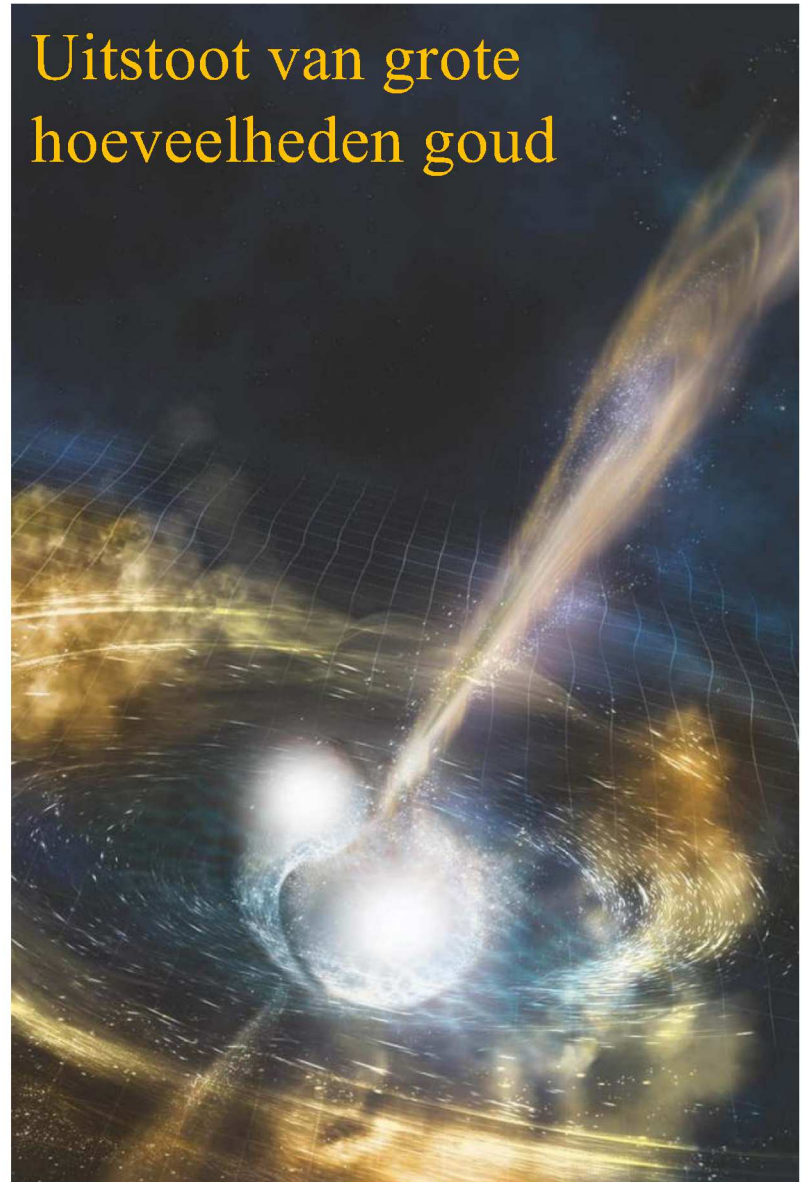
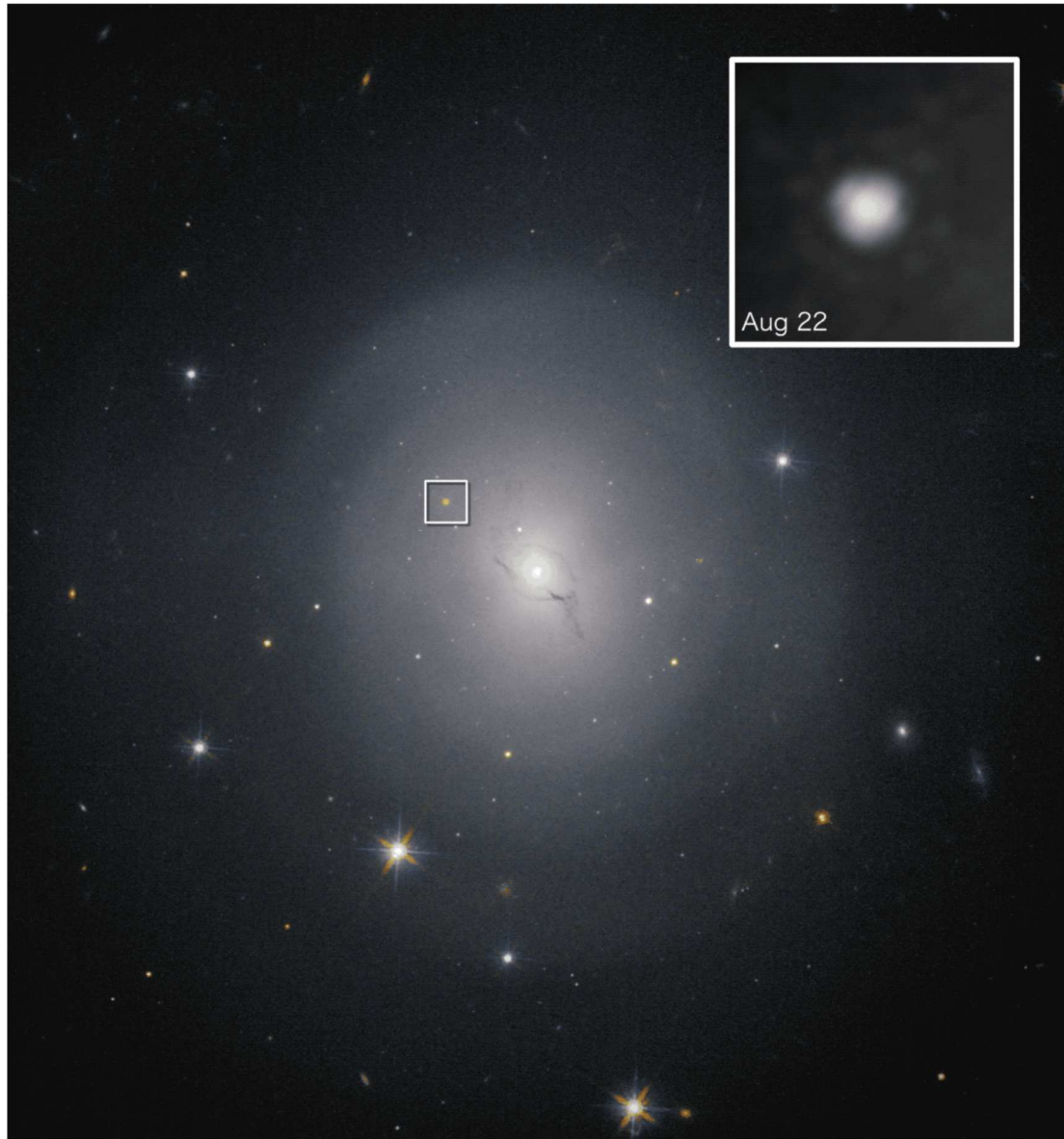
Fermi



LIGO



GW 170817



Herkomst van de elementen

1 H	Oerknal kernfusie						Kosmische straling kernsplijting												2 He
3 Li	4 Be	Stervende lichte sterren					Exploderende massieve sterren					5 B	6 C	7 N	8 O	9 F	10 Ne		
11 Na	12 Mg	Exploderende witte dwergen					Samensmeltende neutronensterren					13 Al	14 Si	15 P	16 S	17 Cl	18 Ar		
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr		
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe		
55 Cs	56 Ba			72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn	
87 Fr	88 Ra																		
		57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu			
		89 Ac	90 Th	91 Pa	92 U														

Radioactief verval

Conclusies

- Neutronensterren zijn extreme sterren
 - Extreme dichtheden
 - Extreme spin
 - Extreme zwaartekrachtsvelden
 - Extreme magneetvelden
 - Uitstekende objecten om fundamentele natuurkunde te bestuderen
- Erg belangrijk in stervolutie en voor het creëren van de zwaarste elementen
- Super interessante sterren!

Interessante YouTube filmpjes

- In het Engels
- Leuke filmpjes van *Kurzgesagt – In a Nutshell*
 - Neutronen sterren
 - <https://www.youtube.com/watch?v=udFxKZRyQt4>
 - ”Strange stars”
 - https://www.youtube.com/watch?v=p_8yK2kxmoo
- Pulsars (*NASA*)
 - https://www.youtube.com/watch?v=gjLk_72V9Bw
- Zwaartekrachtstraling (*PHD Comics*)
 - <https://www.youtube.com/watch?v=4GbWfNHtHRg>