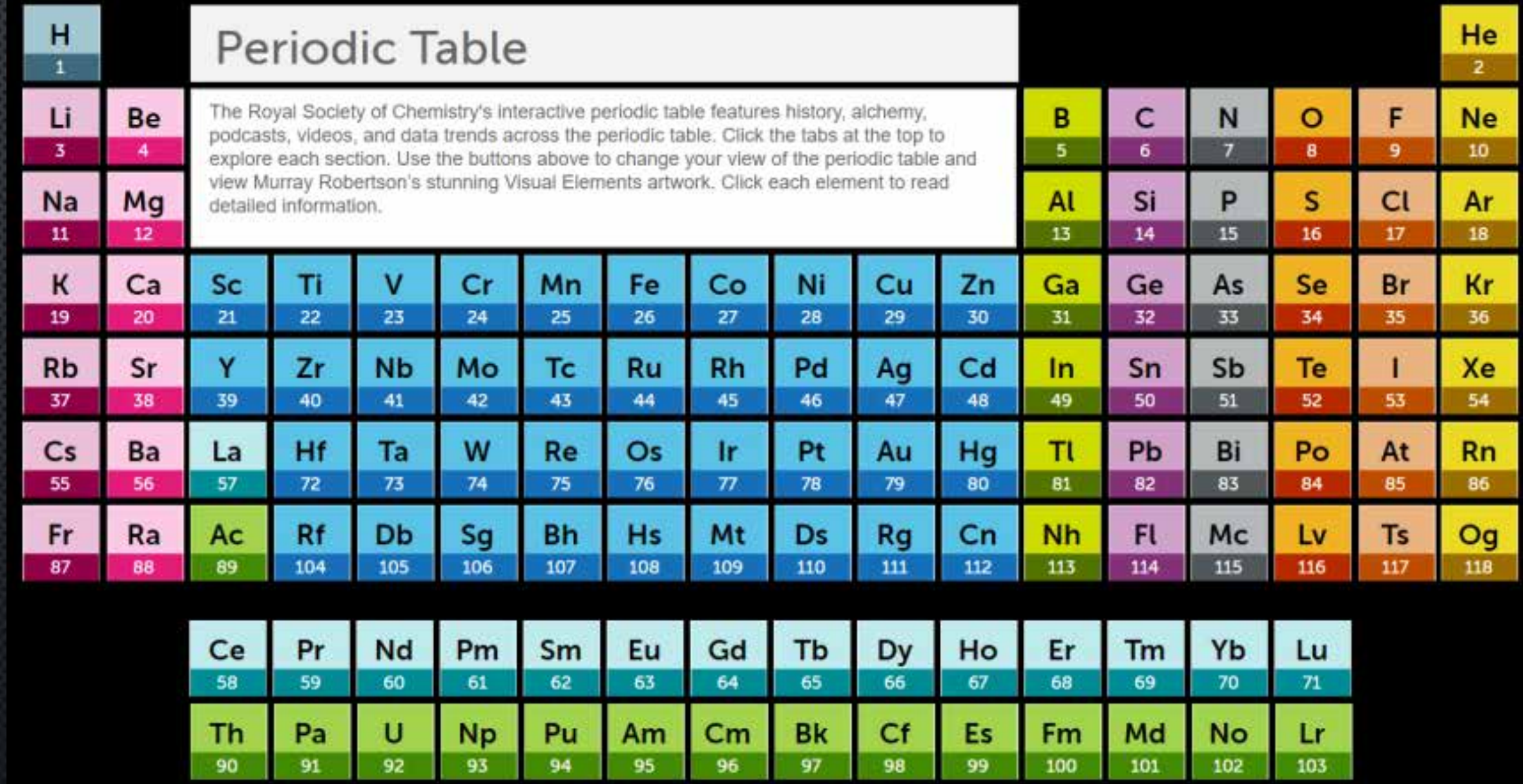
Symposium 2019 on the ITER/BA Activities
Fusion Energy Forum of Japan

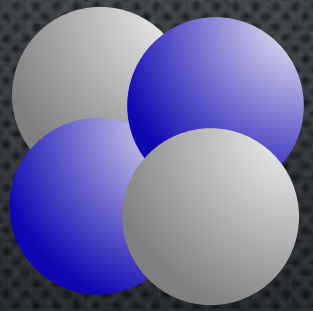
Uncharted landscapes of the universe revealed by gravitational wave observations
Status of KAGRA and future prospects

National Astronomical Observatory of Japan
Gravitational Wave Science Project
Yoichi Aso

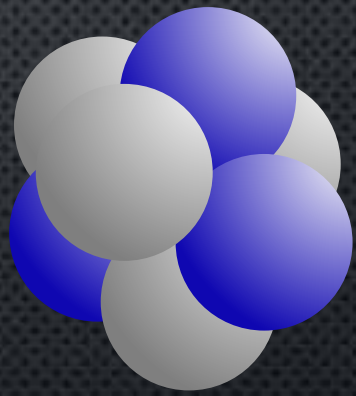

Periodic Table
The Royal Society of Chemistry's interactive periodic table features history, alchemy, podcasts, videos, and data trends across the periodic table. Click the tabs at the top to explore each section. Use the buttons above to change your view of the periodic table and view Murray Robertson's stunning Visual Elements artwork. Click each element to read detailed information.
H 1
He 2
Li 3
Be 4
B 5
C 6
N 7
O 8
F 9
Ne 10
Na 11
Mg 12
Al 13
Si 14
P 15
S 16
Cl 17
Ar 18
K 19
Ca 20
Sc 21
Ti 22
V 23
Cr 24
Mn 25
Fe 26
Co 27
Ni 28
Cu 29
Zn 30
Ga 31
Ge 32
As 33
Se 34
Br 35
Kr 36
Rb 37
Sr 38
Y 39
Zr 40
Nb 41
Mo 42
Tc 43
Ru 44
Rh 45
Pd 46
Ag 47
Cd 48
In 49
Sn 50
Sb 51
Te 52
I 53
Xe 54
Cs 55
Ba 56
La 57
Hf 72
Ta 73
W 74
Re 75
Os 76
Ir 77
Pt 78
Au 79
Hg 80
Tl 81
Pb 82
Bi 83
Po 84
At 85
Rn 86
Fr 87
Ra 88
Ac 89
Rf 104
Db 105
Sg 106
Bh 107
Hs 108
Mt 109
Ds 110
Rg 111
Cn 112
Nh 113
Fl 114
Mc 115
Lv 116
Ts 117
Og 118
Ce 58
Pr 59
Nd 60
Pm 61
Sm 62
Eu 63
Gd 64
Tb 65
Dy 66
Ho 67
Er 68
Tm 69
Yb 70
Lu 71
Th 90
Pa 91
U 92
Np 93
Pu 94
Am 95
Cm 96
Bk 97
Cf 98
Es 99
Fm 100
Md 101
No 102
Lr 103

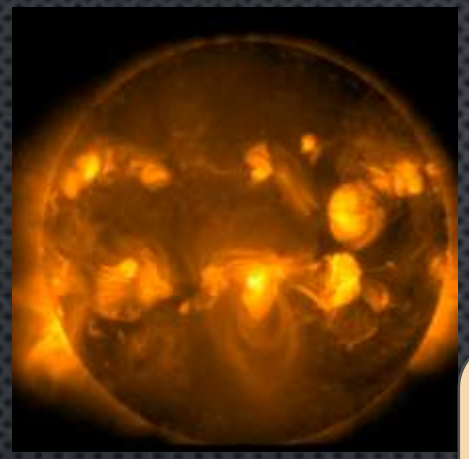
H

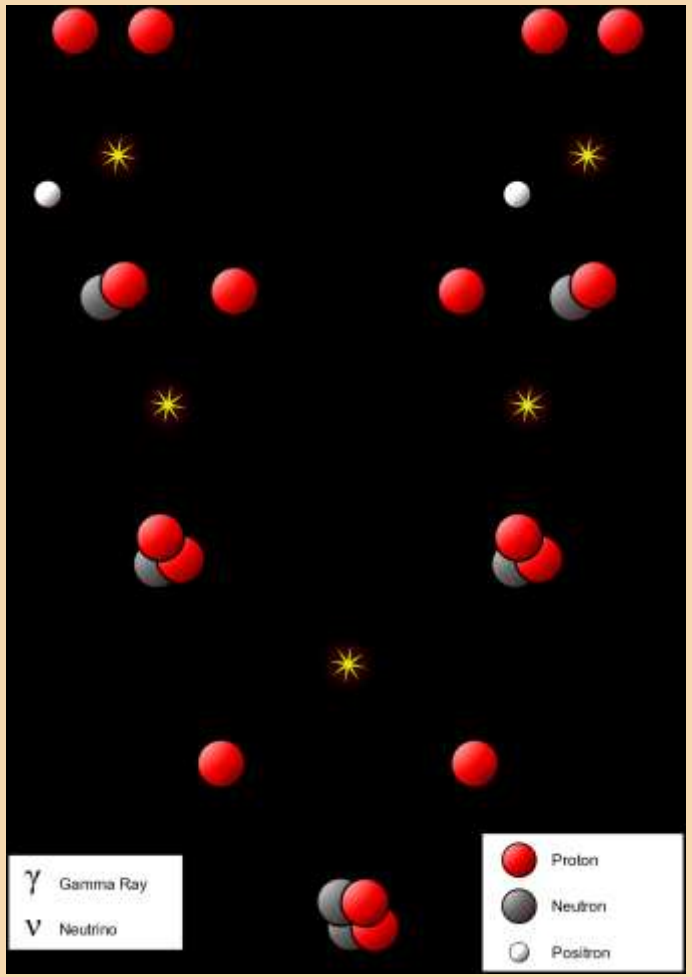
He

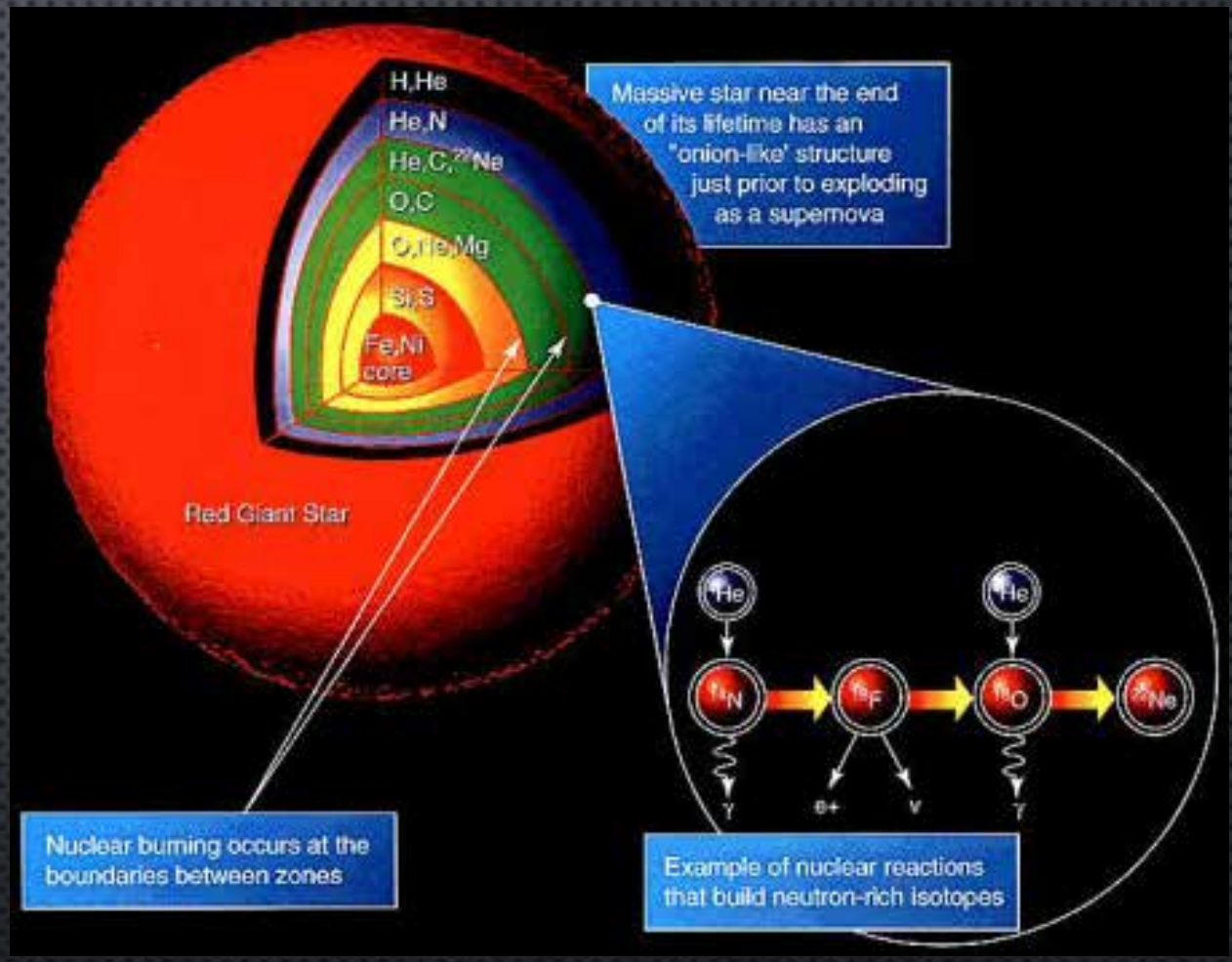


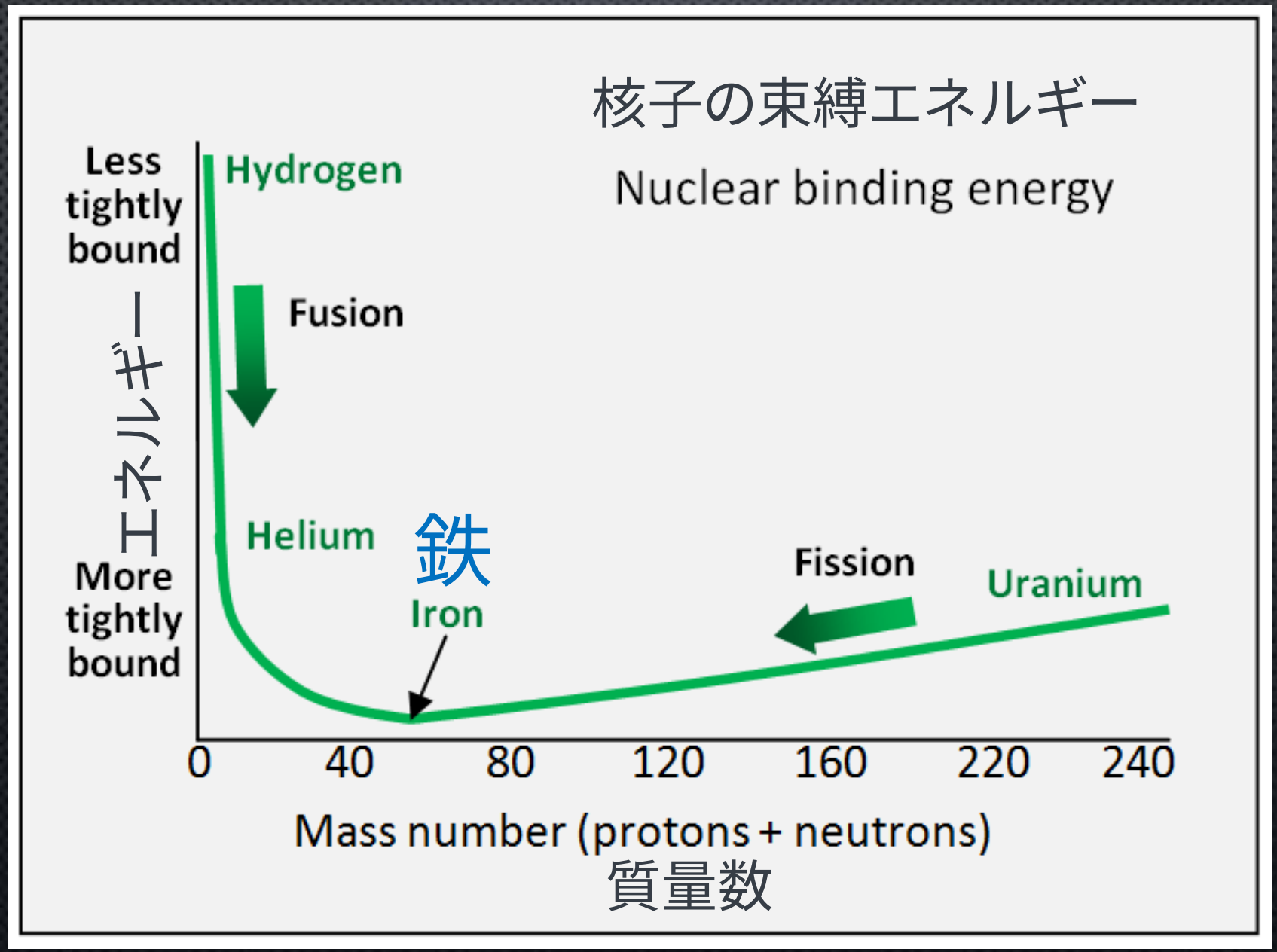
Li

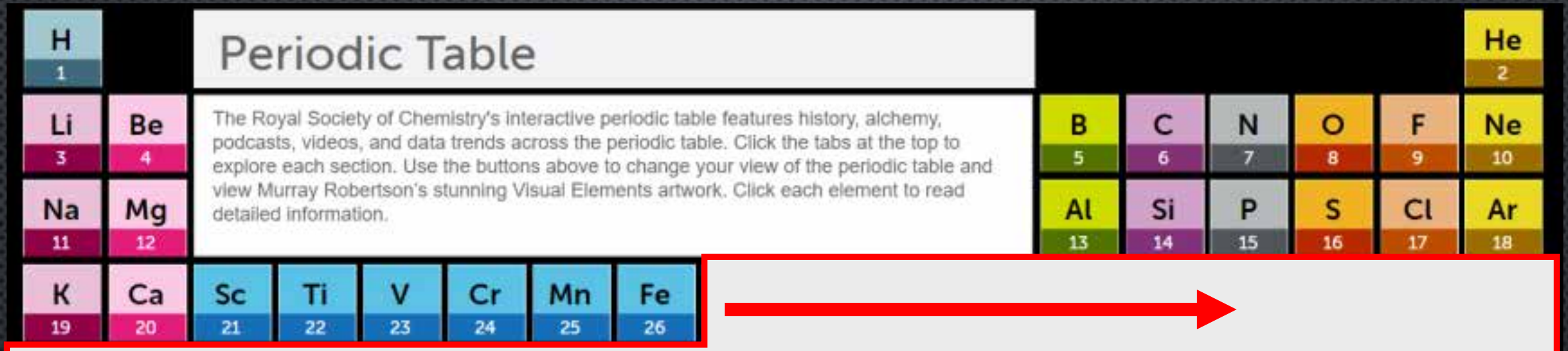





γ Gamma Ray
ν Neutrino
Proton
Neutron
Positron

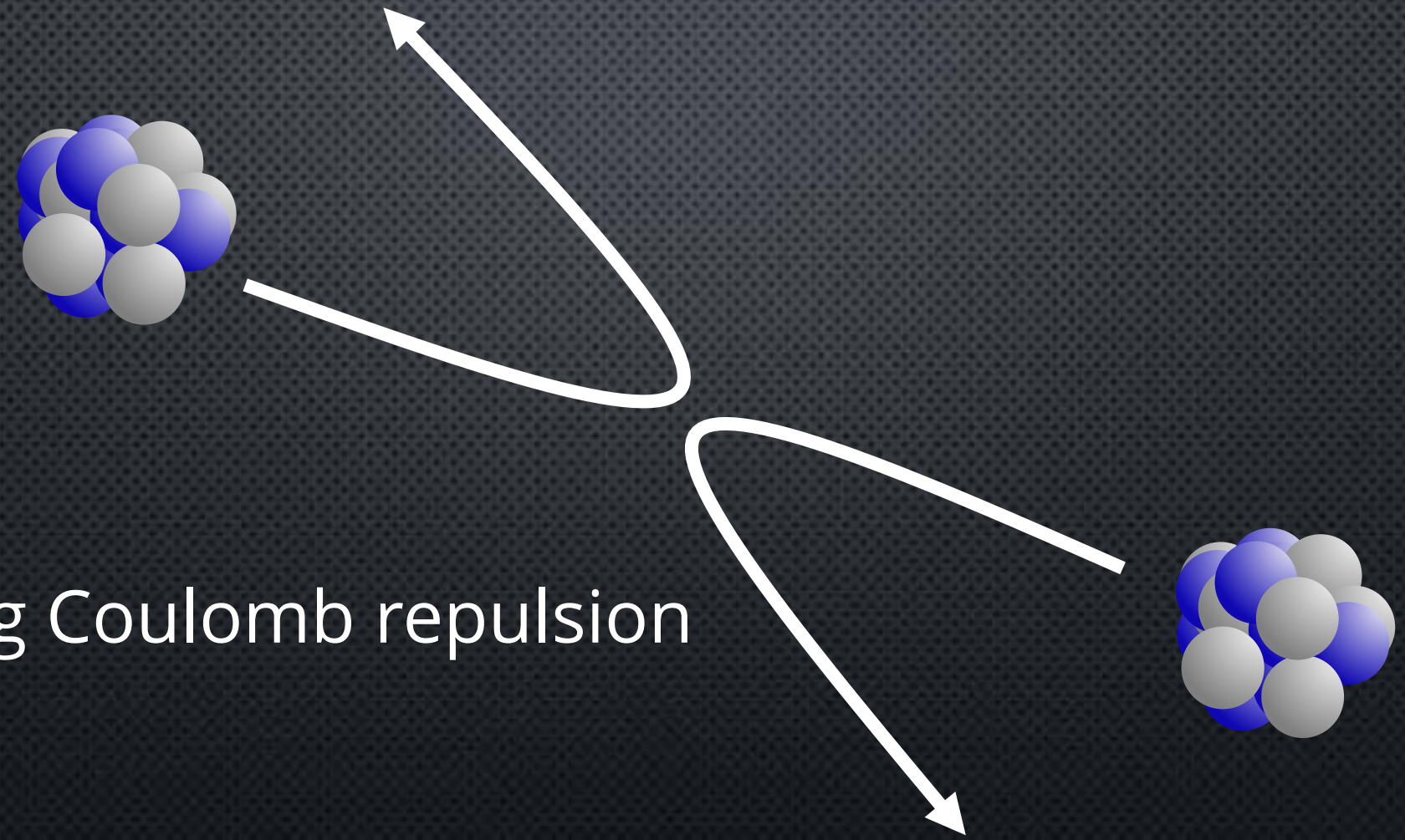

H,He
He,N
He,C,²²Ne
O,C
O,Ne,Mg
Si,S
Fe,Ni core
Red Giant Star
Massive star near the end of its lifetime has an "onion-like' structure just prior to exploding as a supernova
Nuclear burning occurs at the boundaries between zones
Example of nuclear reactions that build neutron-rich isotopes
⁴He
¹⁸N
¹⁸F
¹⁸O
²²Ne
γ
e+
ν


核子の束縛エネルギー
Nuclear binding energy
Less tightly bound
エネルギー
More tightly bound
Hydrogen
Fusion
Helium
鉄
Iron
Fission
Uranium
0
40
80
120
160
220
240
Mass number (protons + neutrons)
質量数

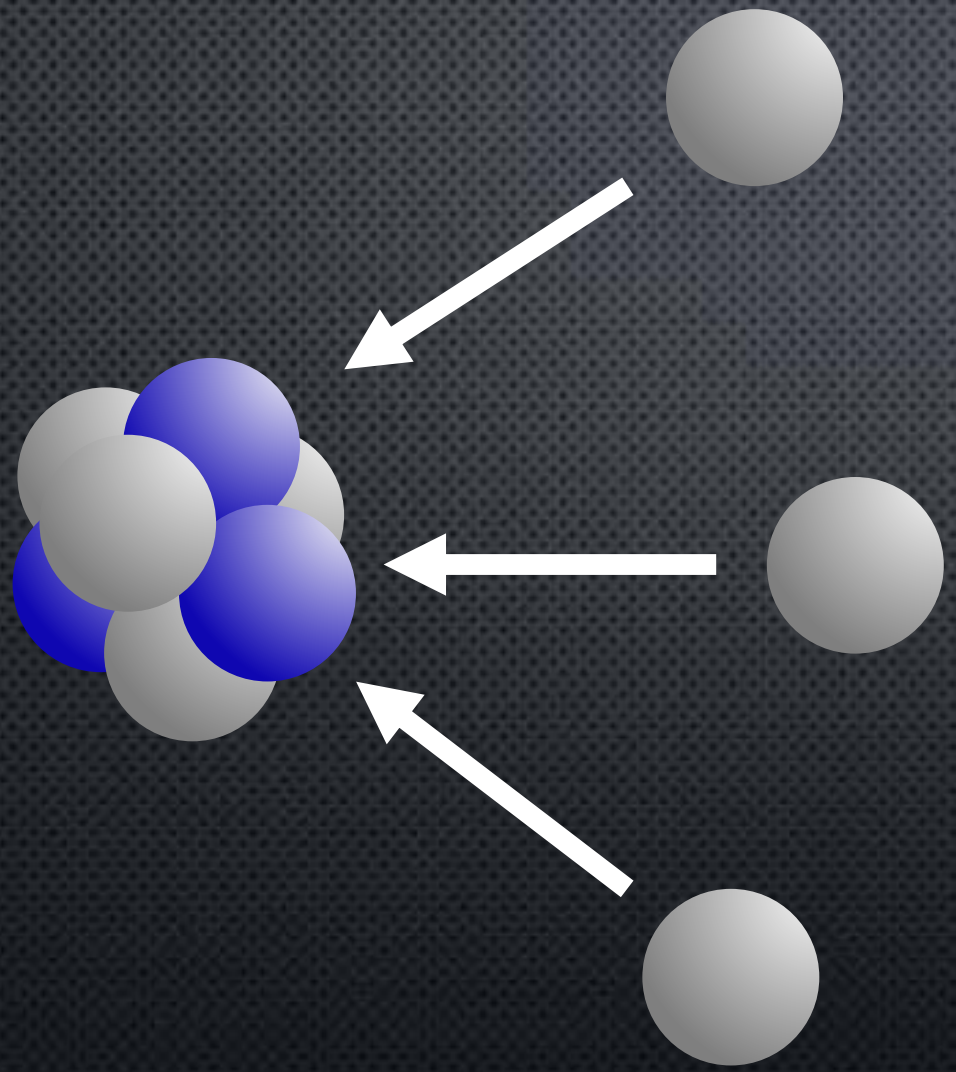


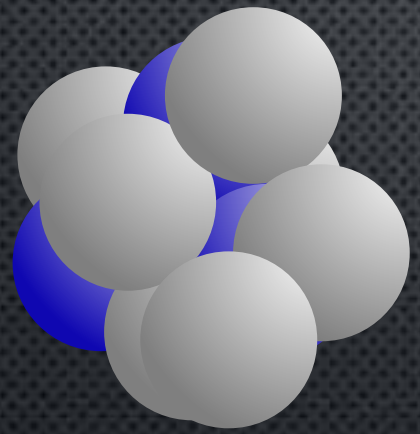
How can we make these elements ?

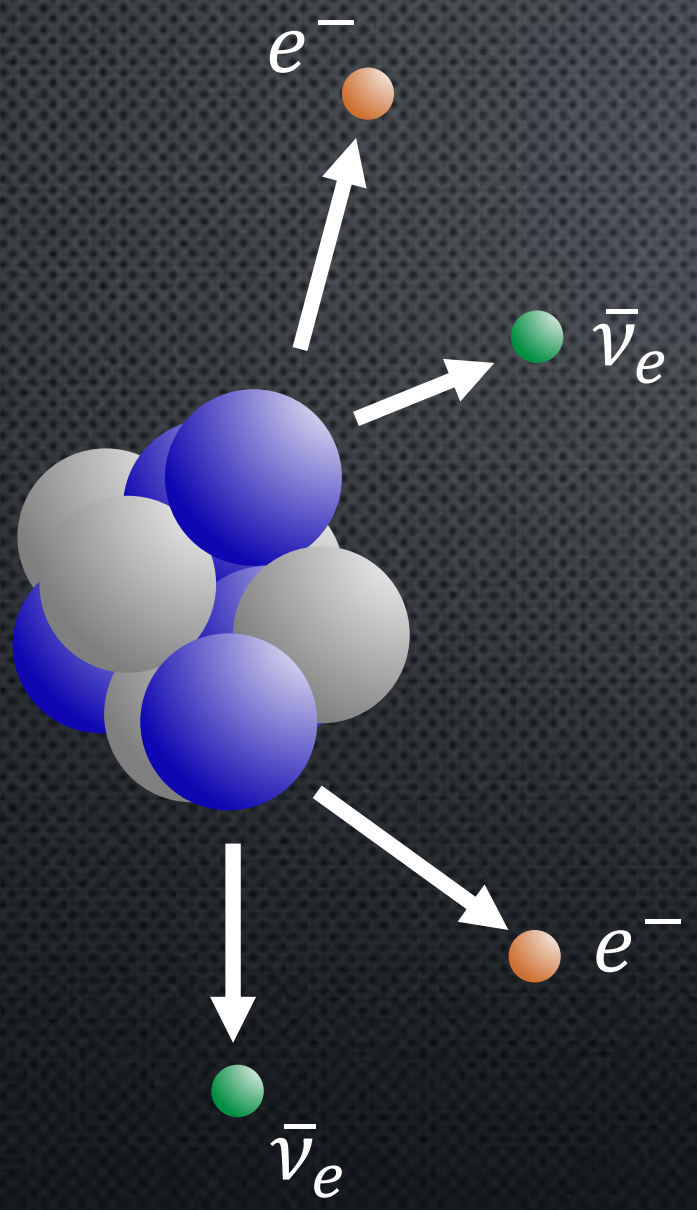
Heavy nucleus



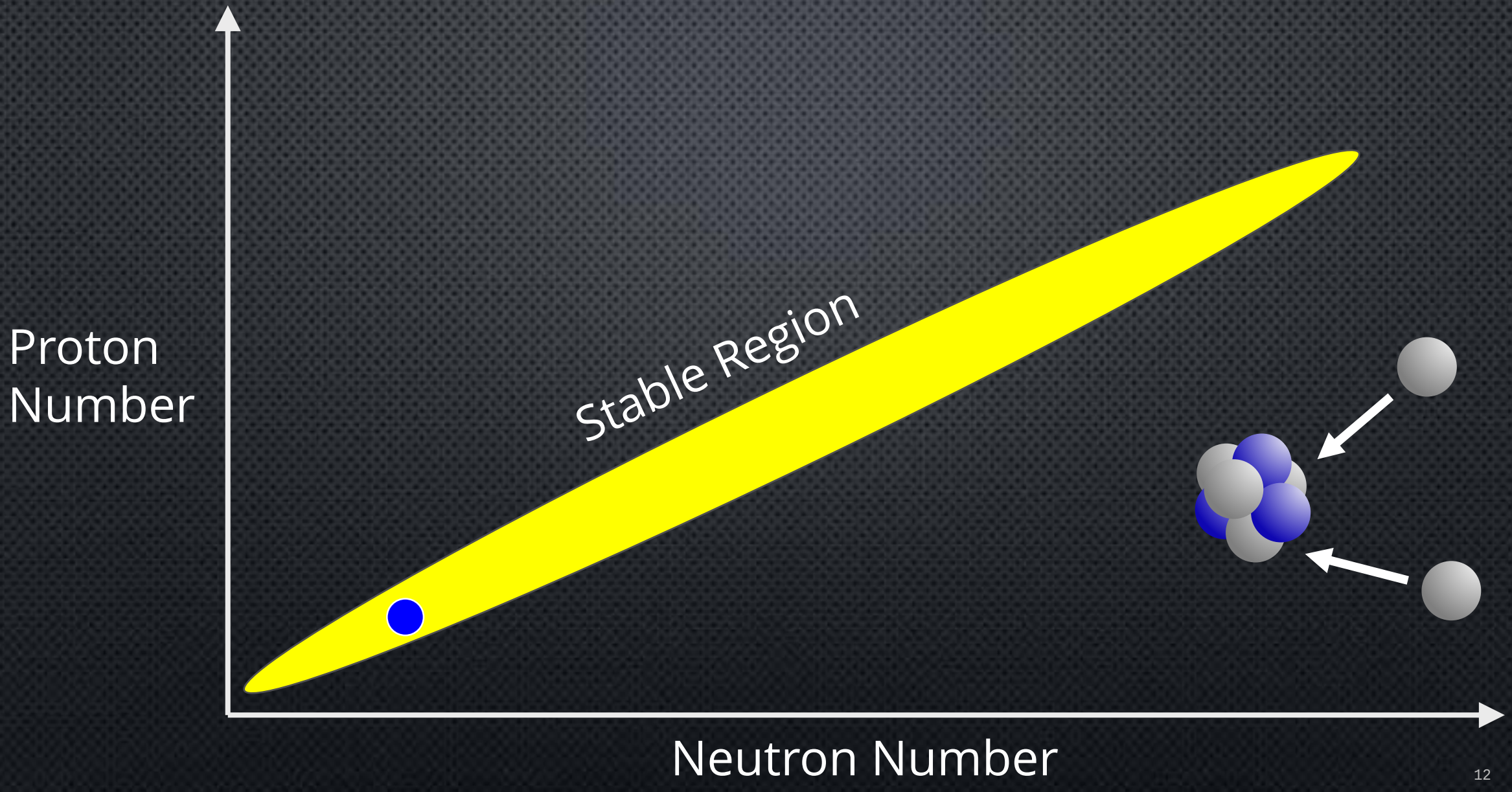
Strong Coulomb repulsion

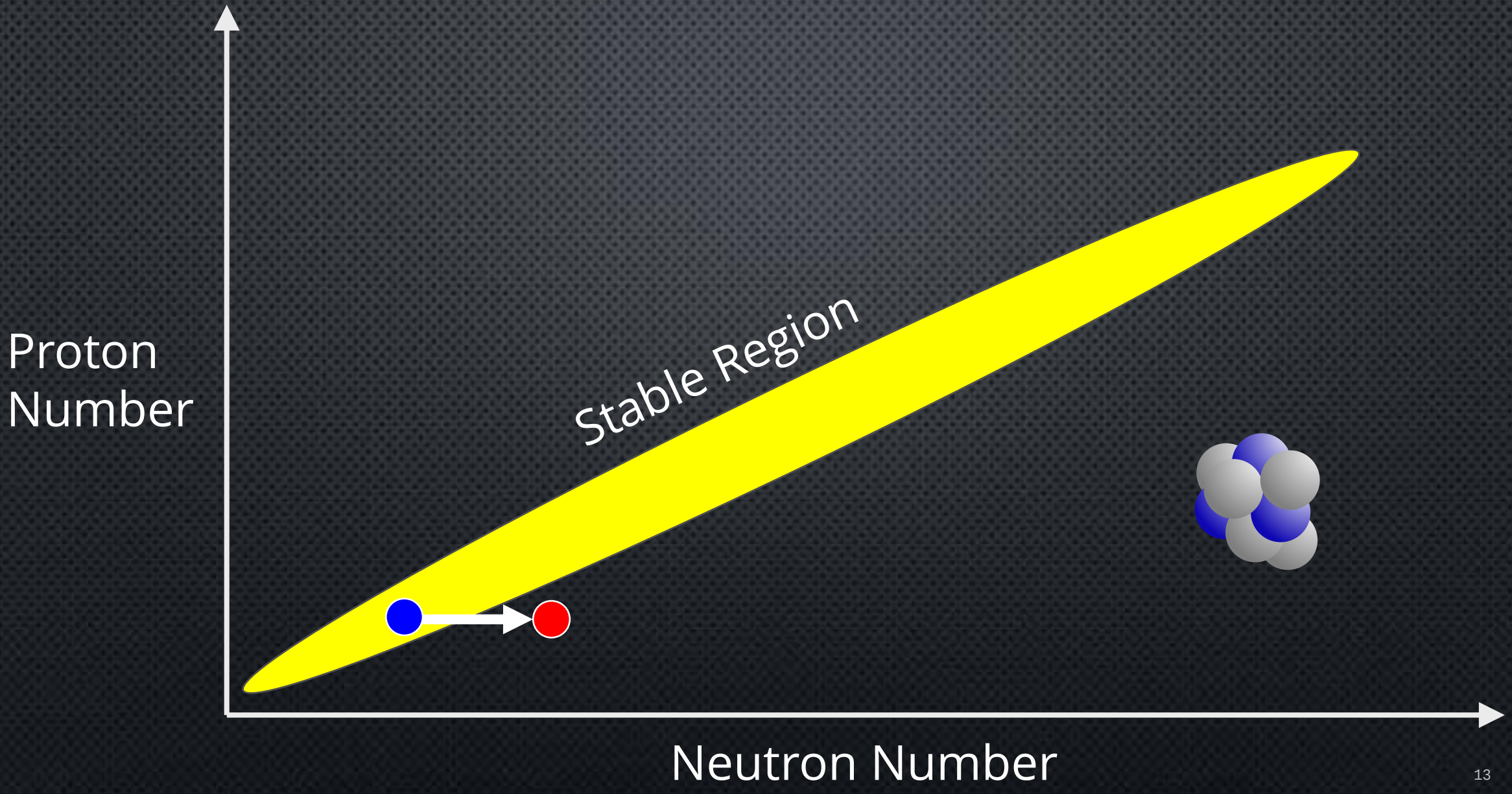


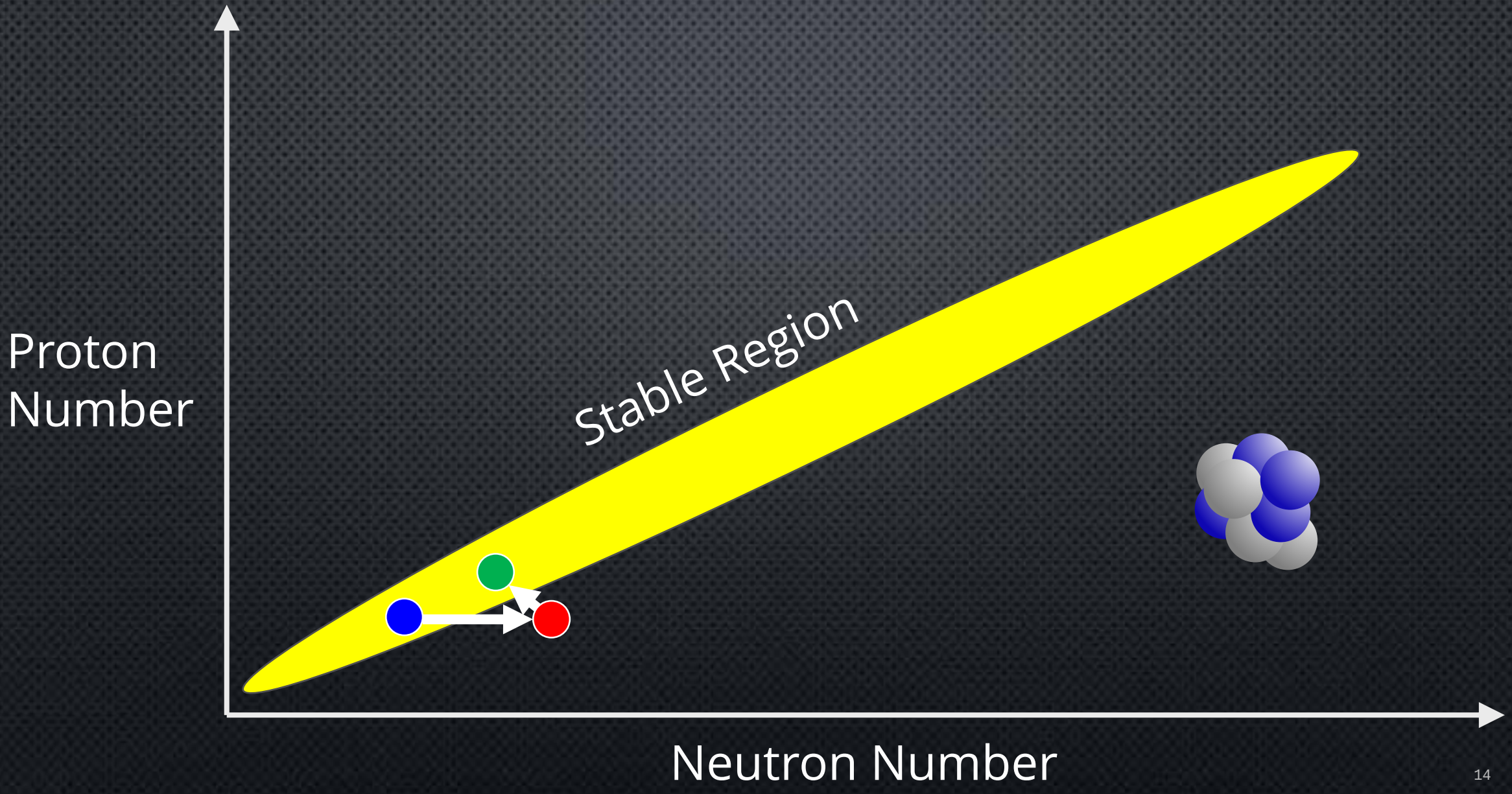


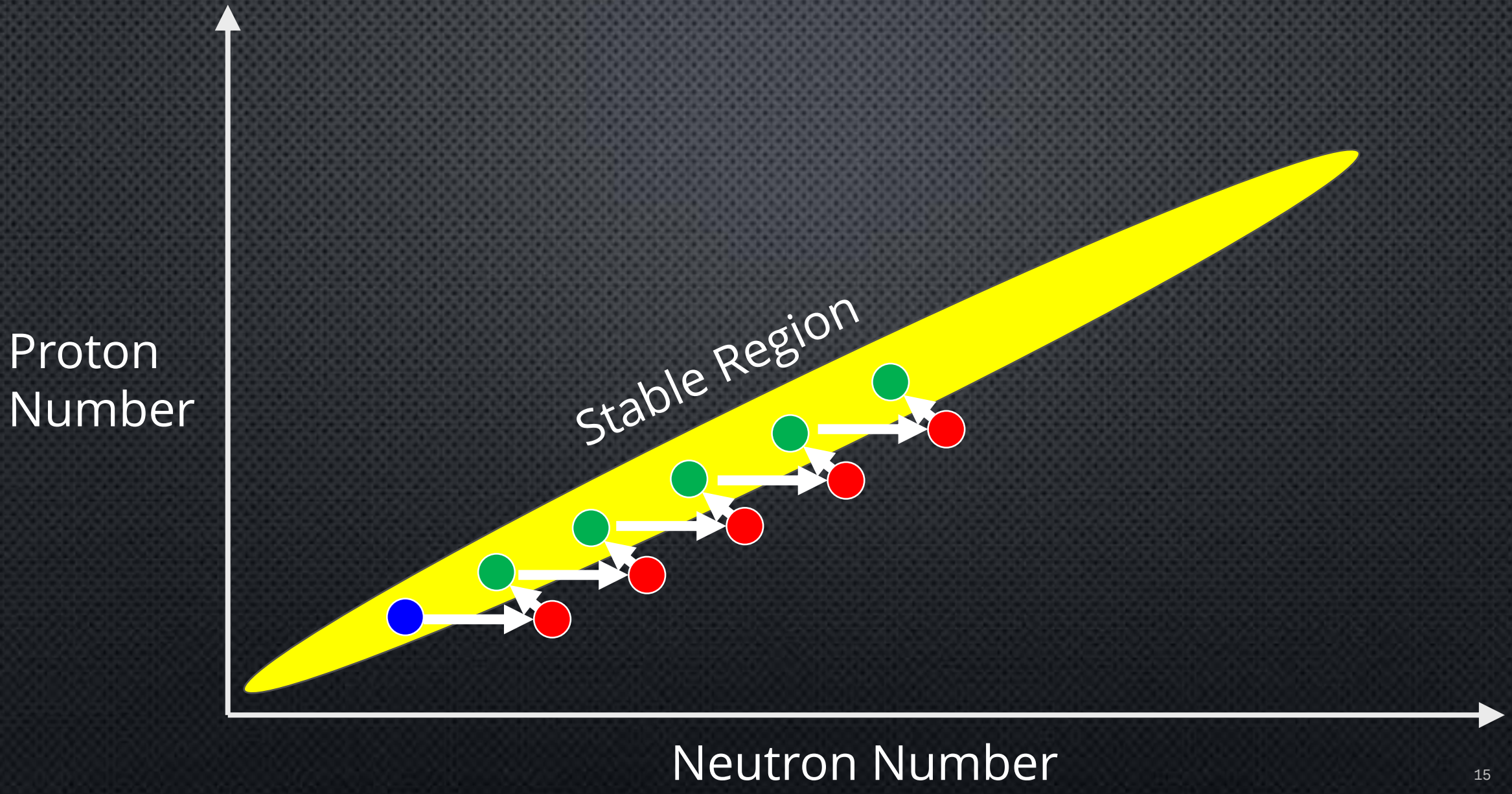


β - decay

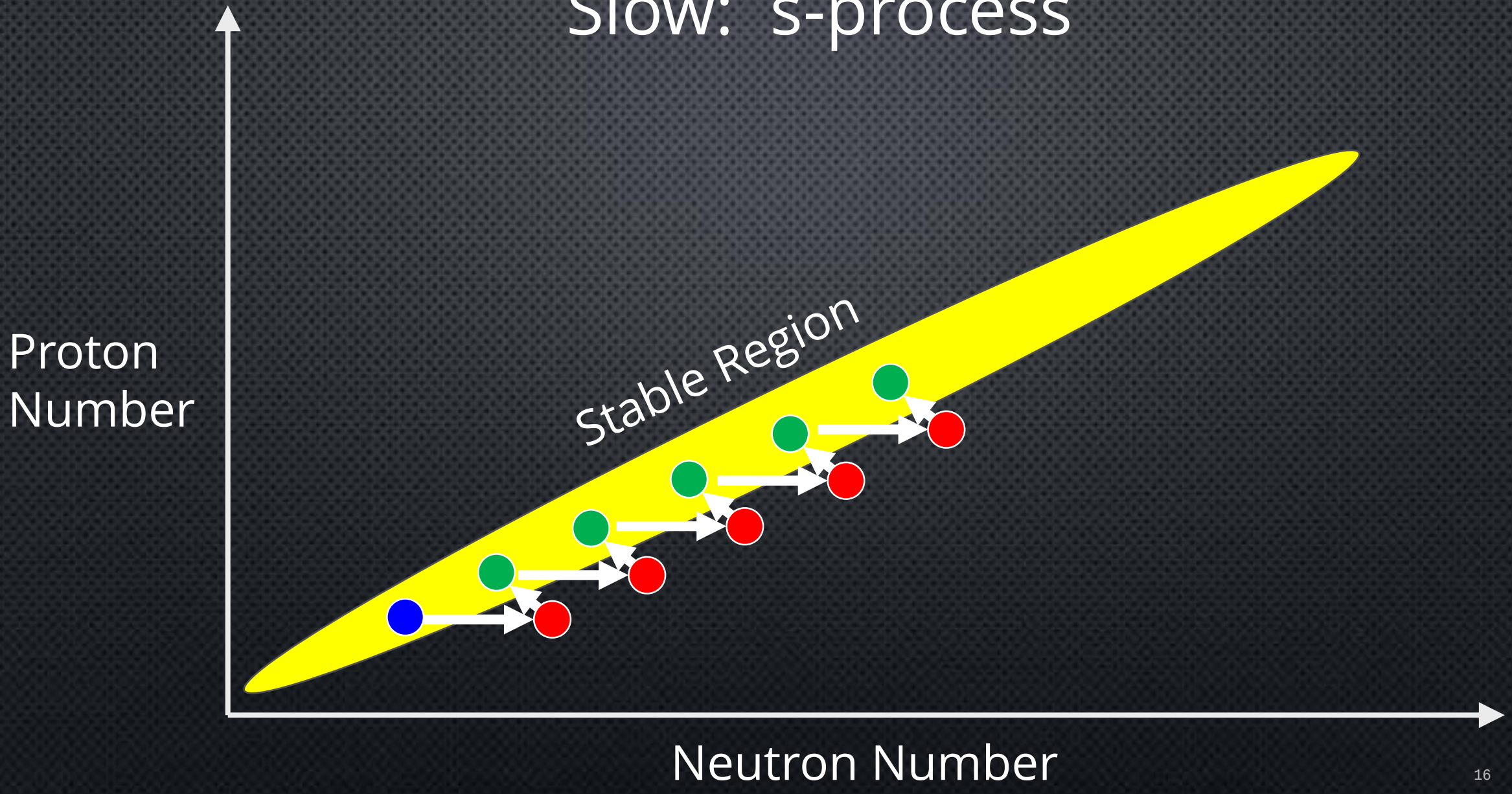

Proton Number
Stable Region
Neutron Number


Proton Number
Stable Region
Neutron Number


Proton Number
Stable Region
Neutron Number

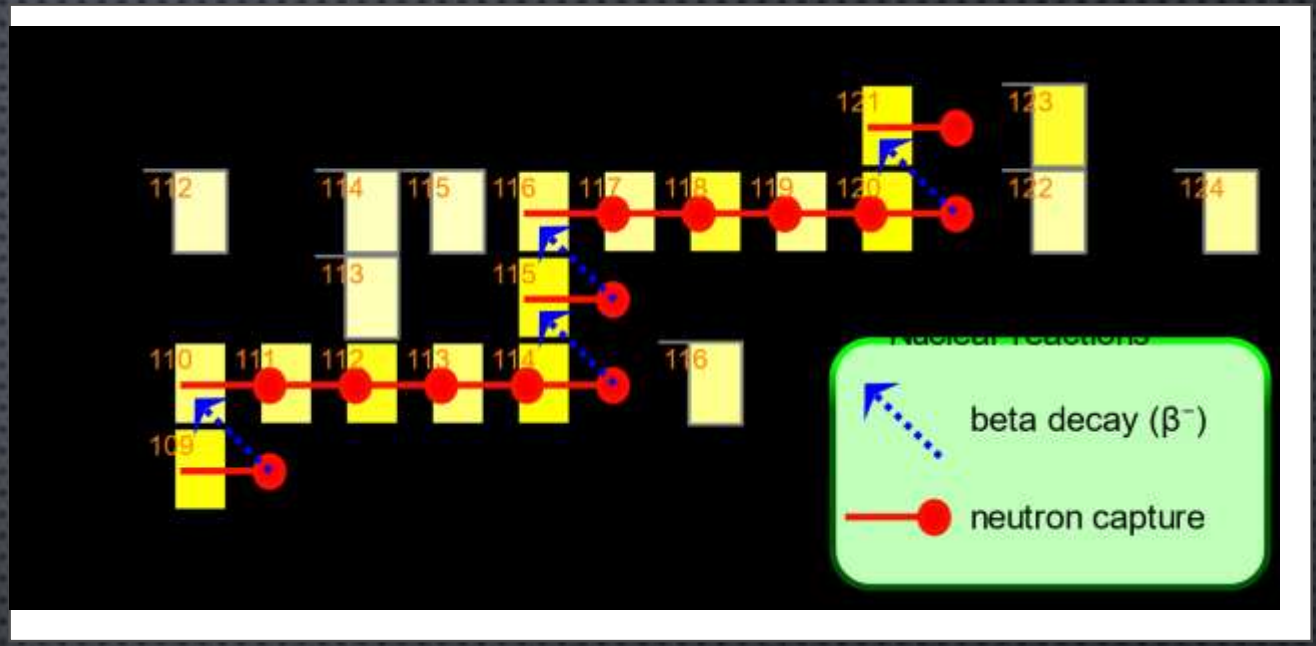

Proton Number
Stable Region
Neutron Number

Slow: s-process



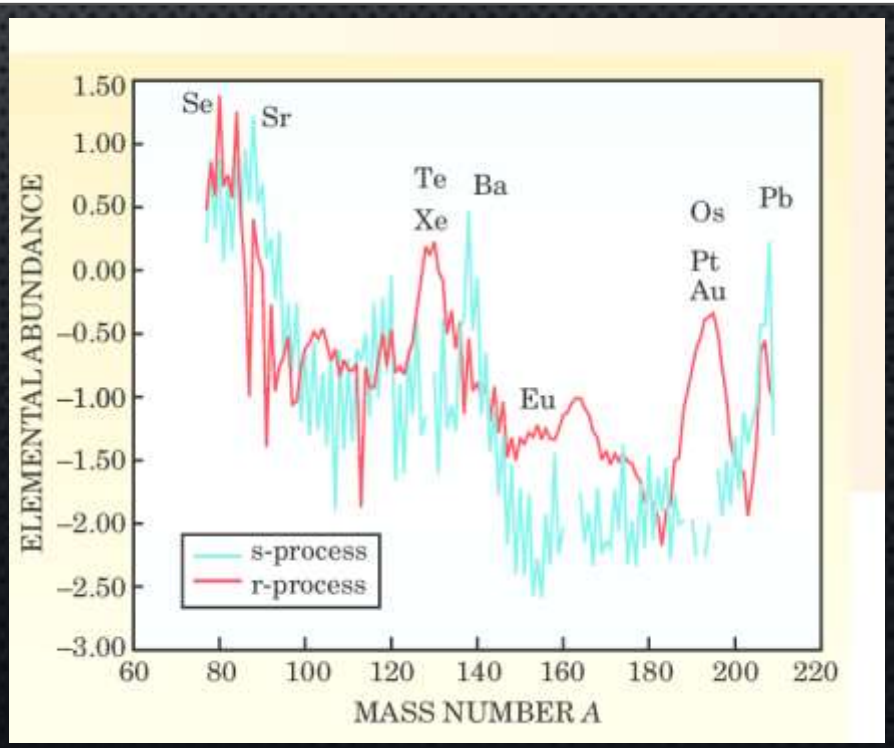
s-process

- Slow capture of neutrons
- Site: old stars



r-process

- Rapid caputure of neutrons
- Where does it happen ?



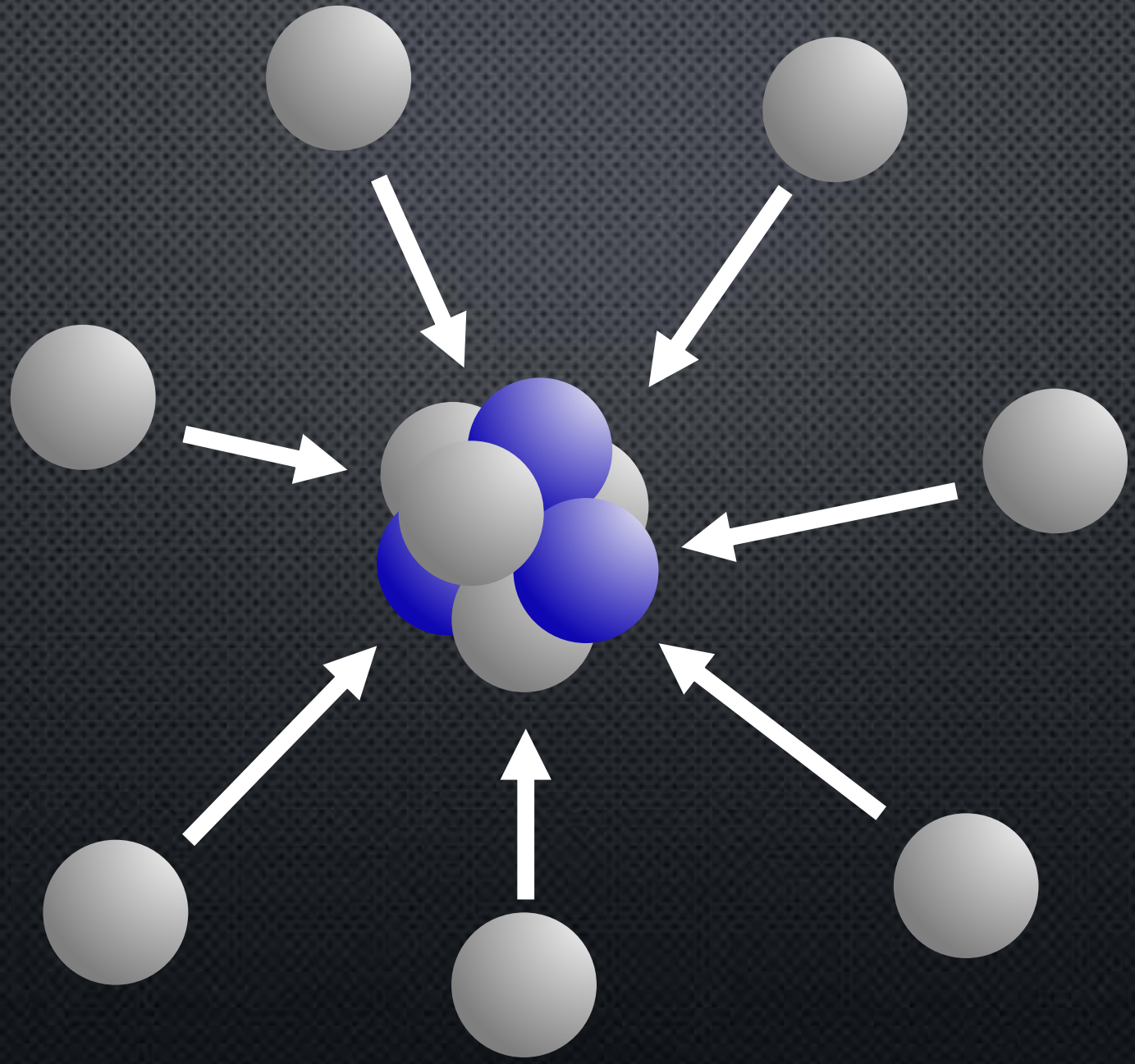
By Szaaman - https://commons.wikimedia.org/wiki/File:Gold_bullion_1.jpg, Public Domain, https://commons.wikimedia.org/w/index.php?curid=35565318

Gold

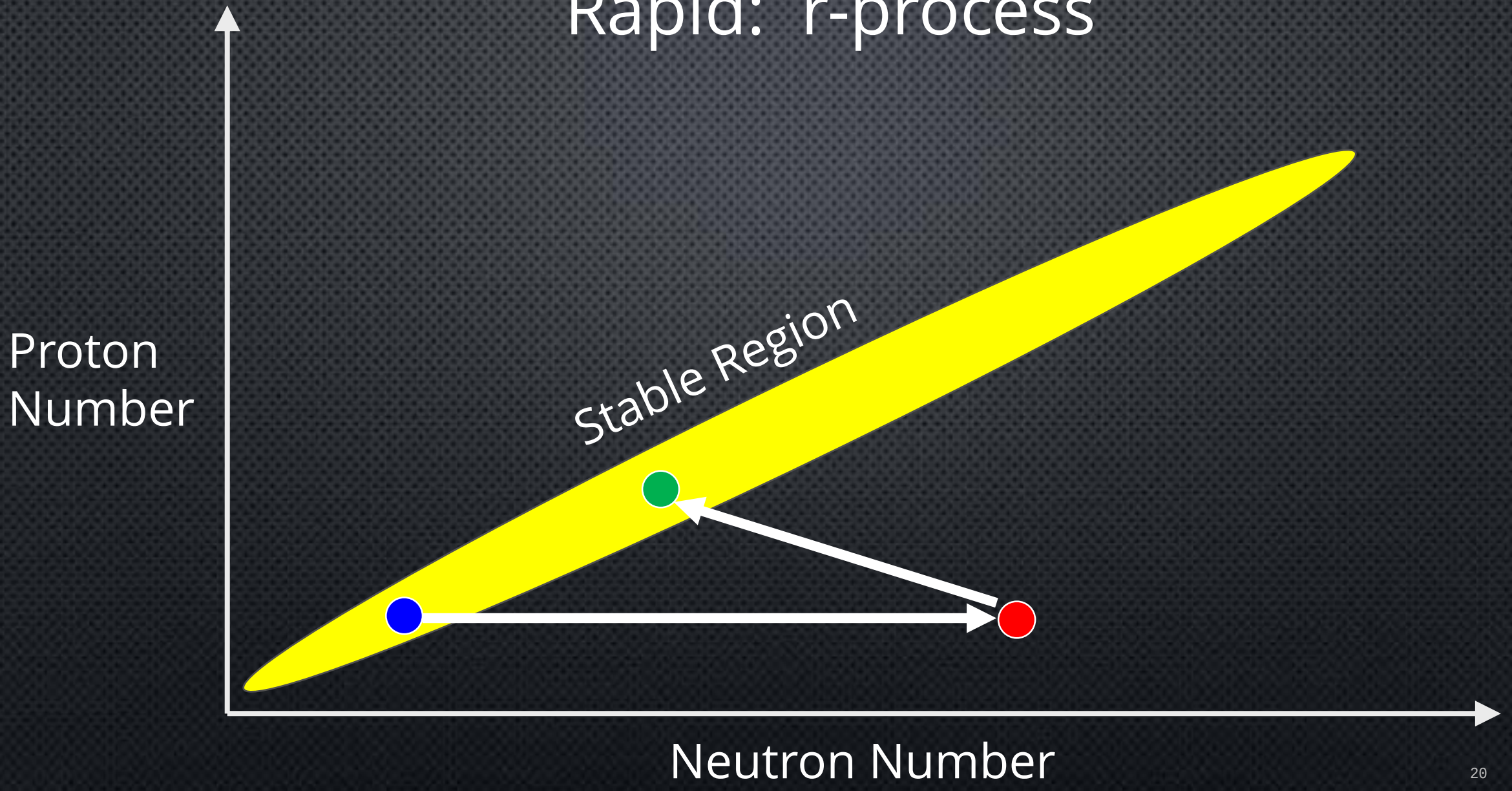
Uranium

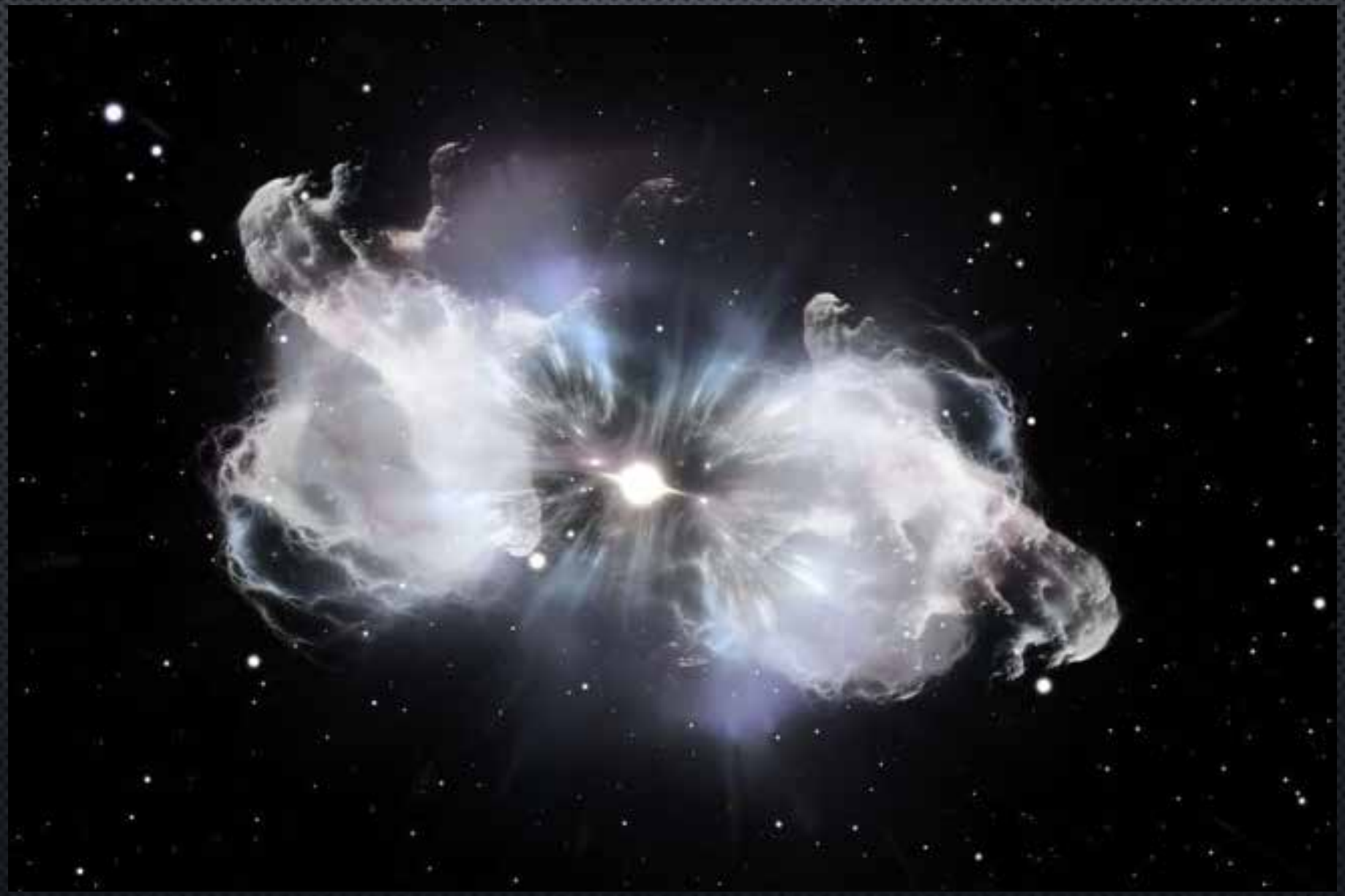
Platinum

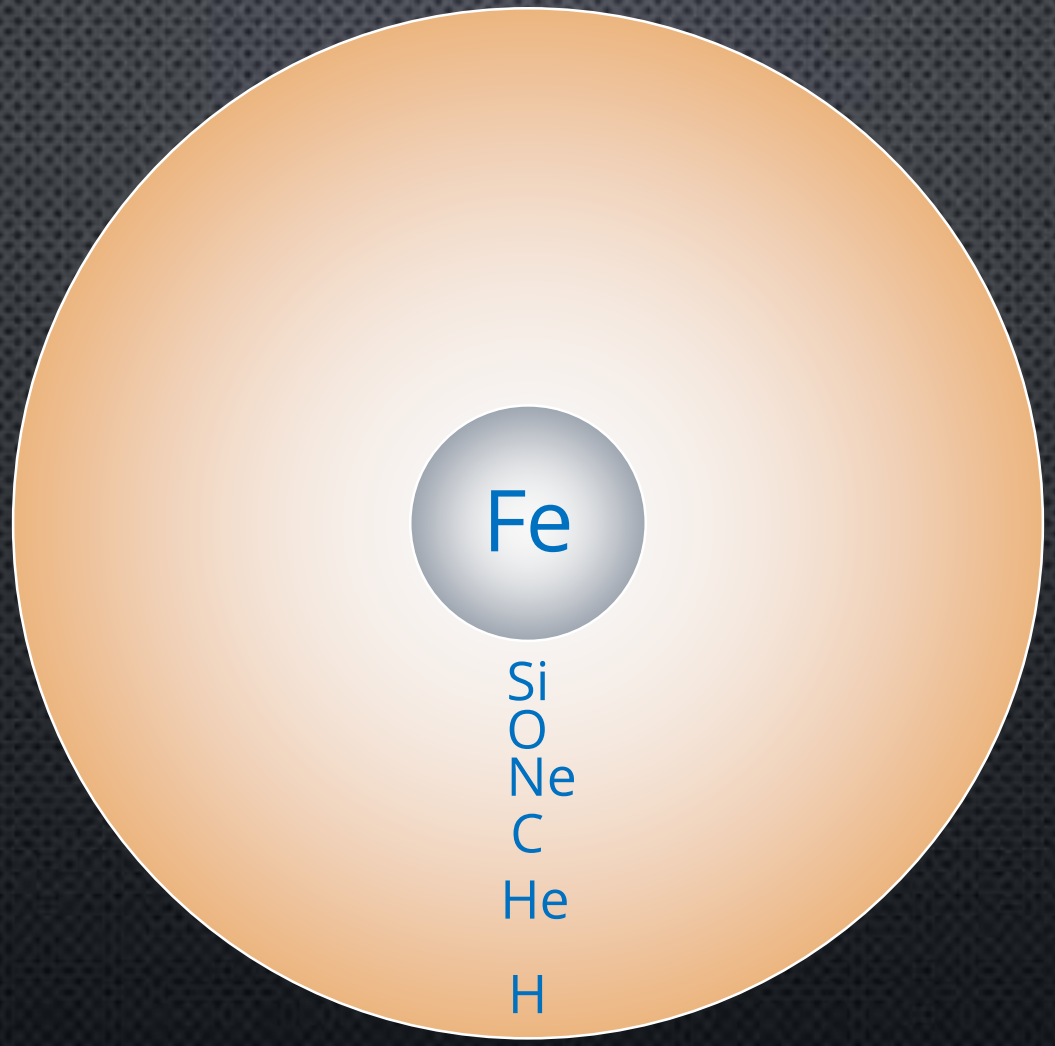
By Rob Lavinsky, iRocks.com – CC-BY-SA-3.0, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=10465065



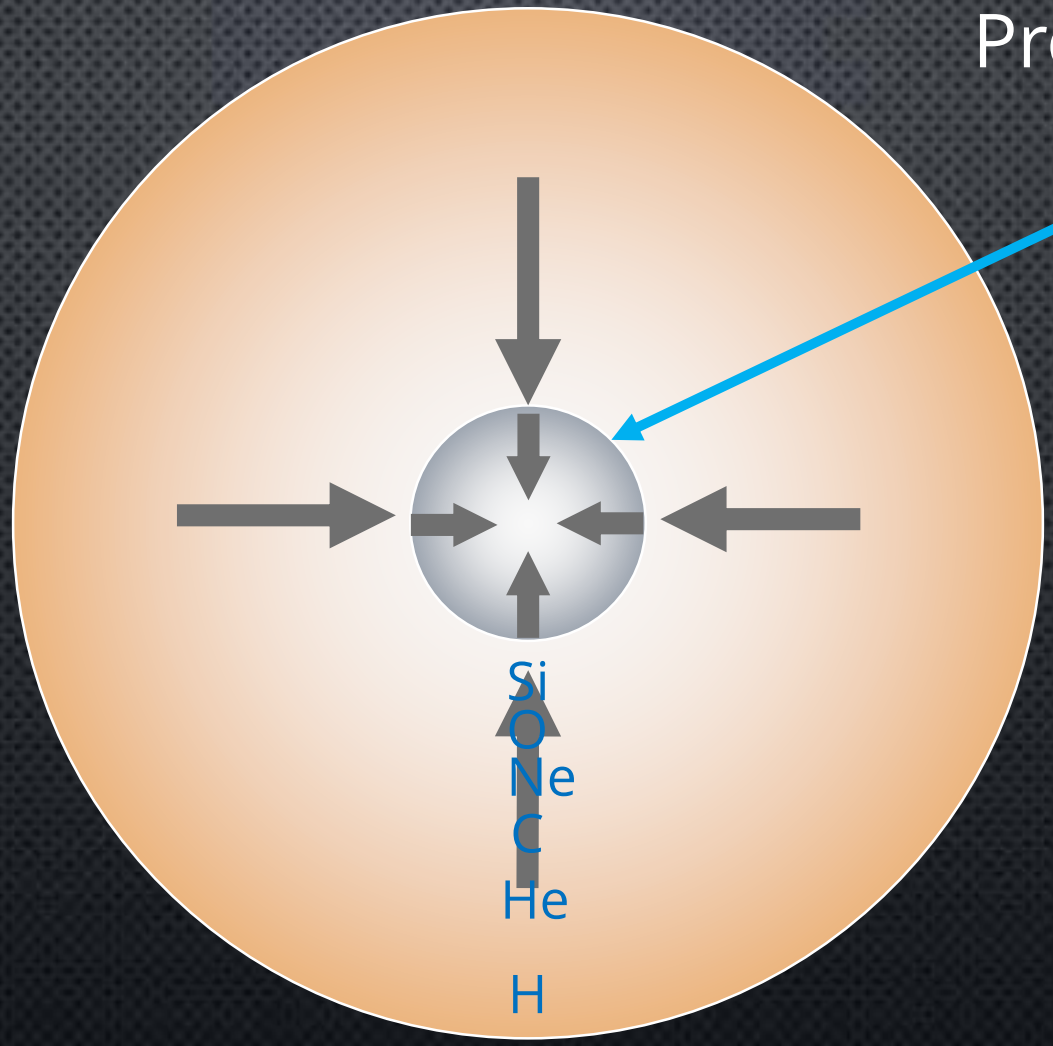
Rapid: r-process

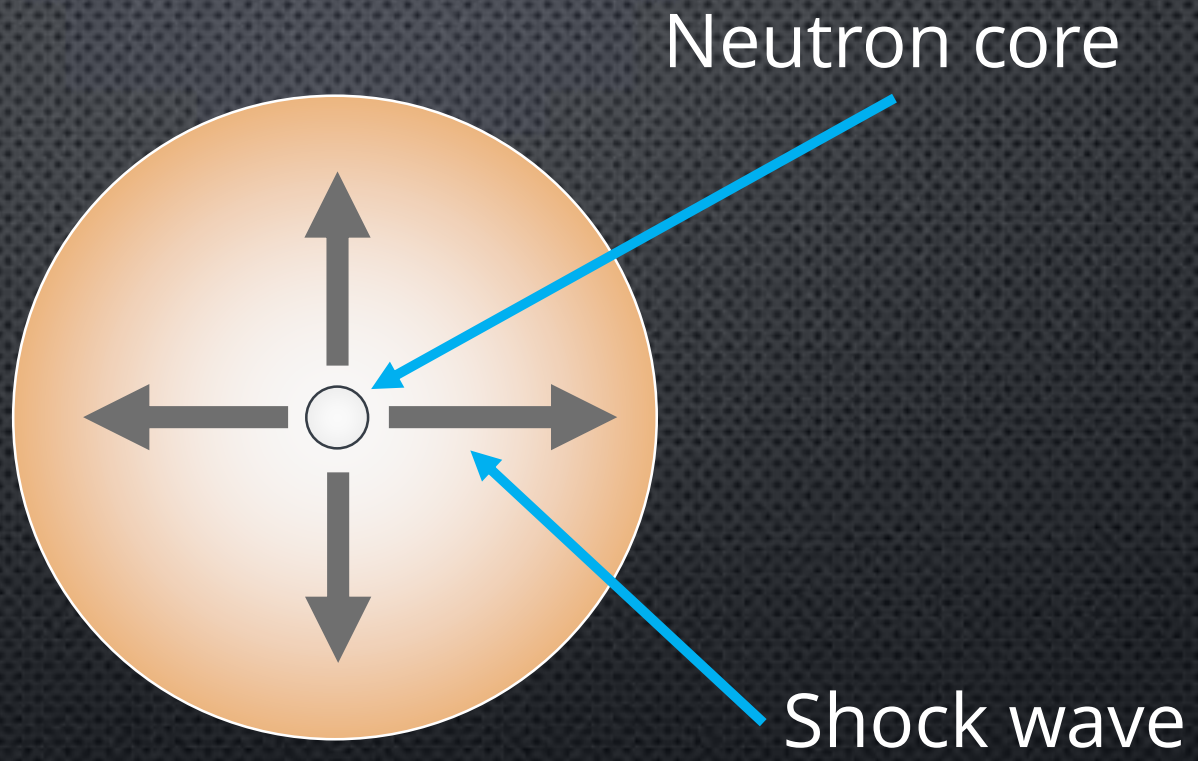




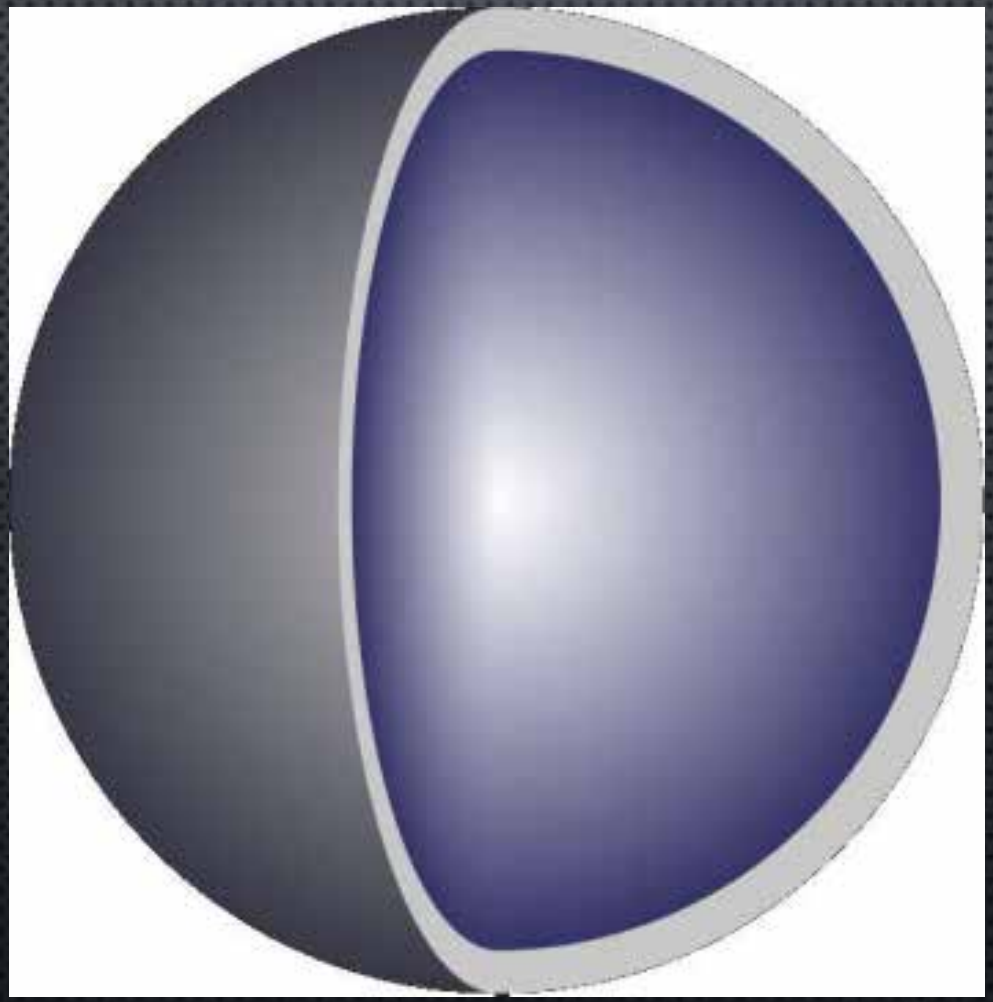

Fe
Si
O
Ne
C
He
H

Electron capture
Proton → Neutron

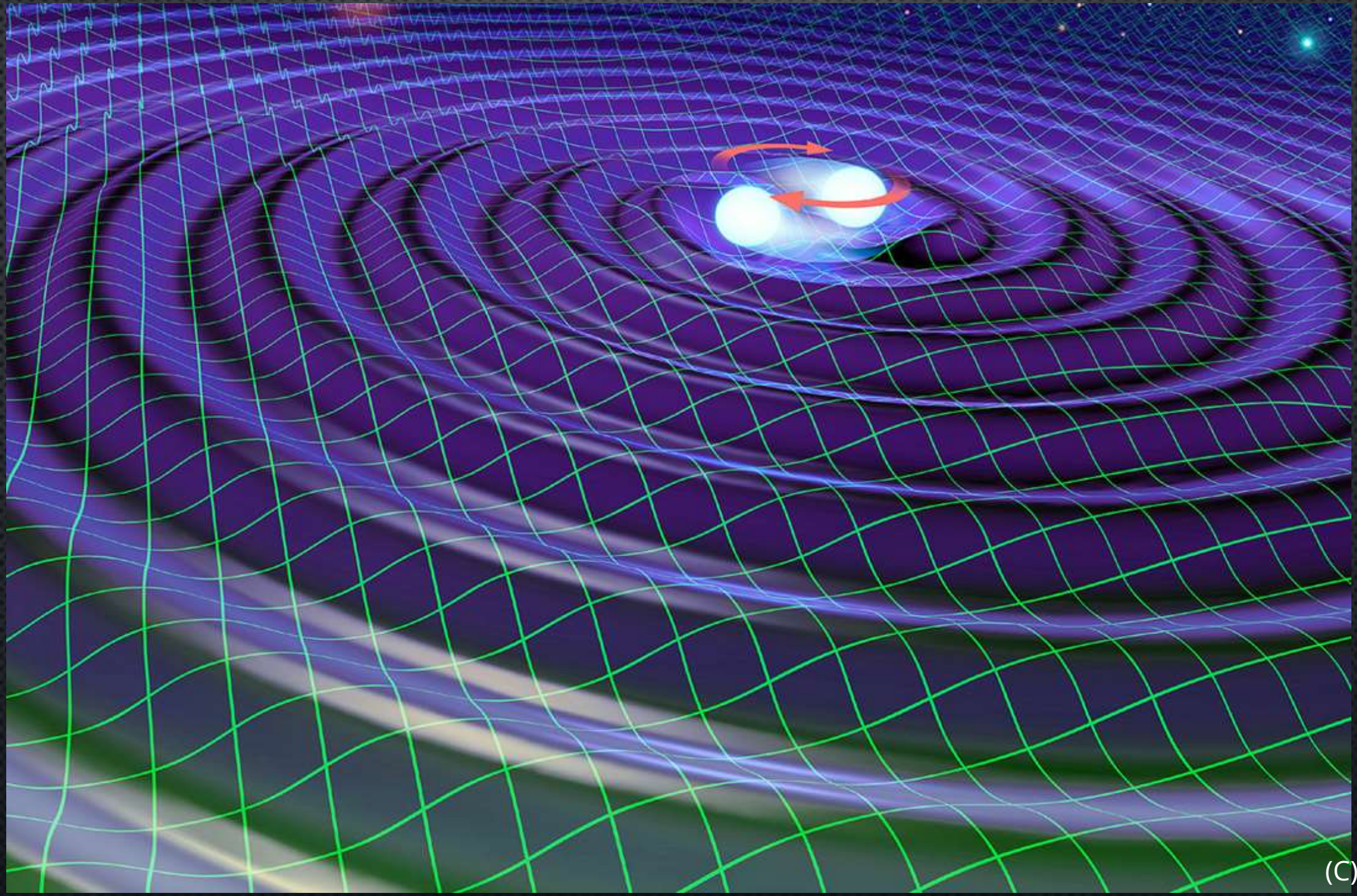


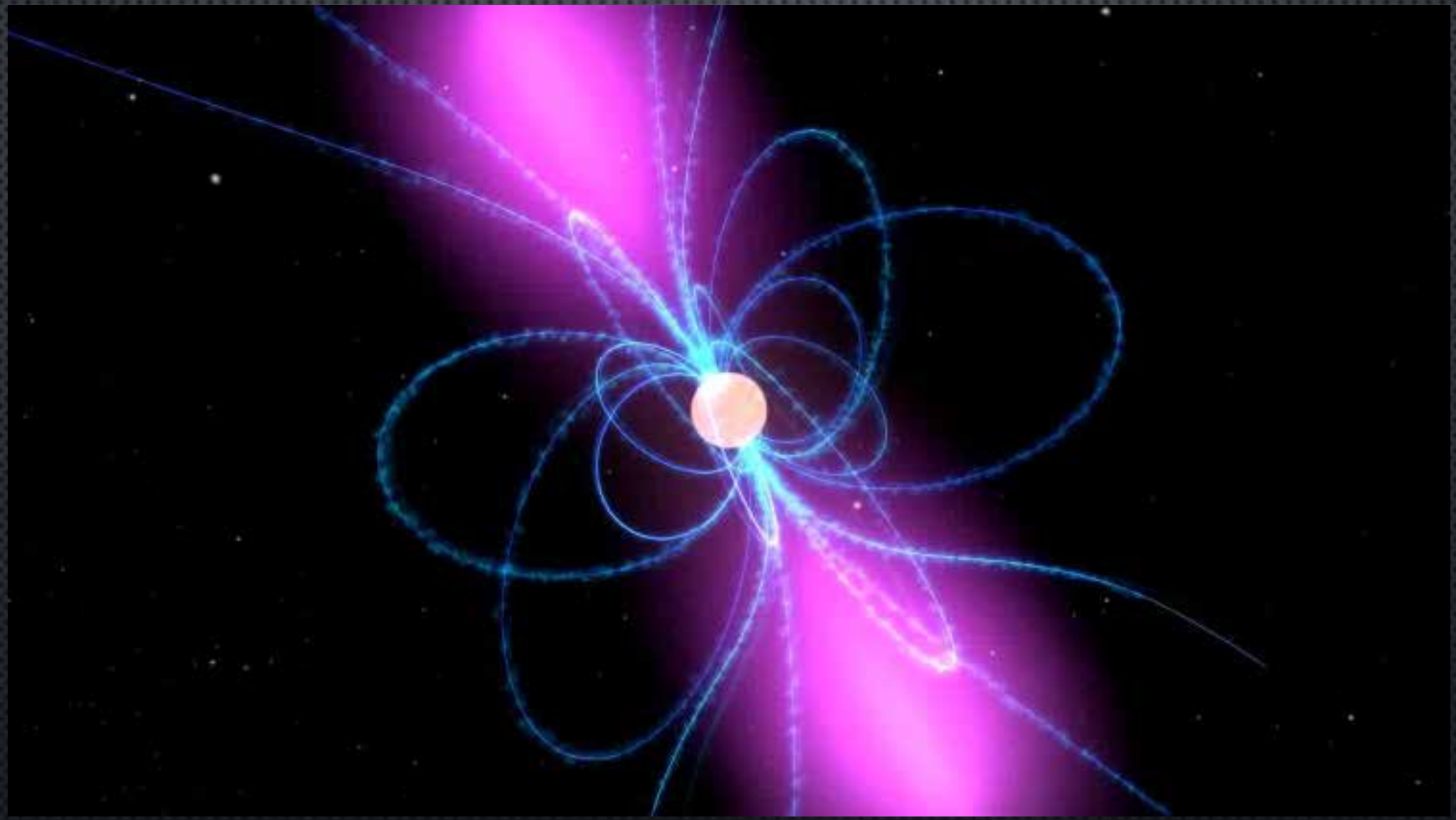

Neutron core
Shock wave

Neutron star



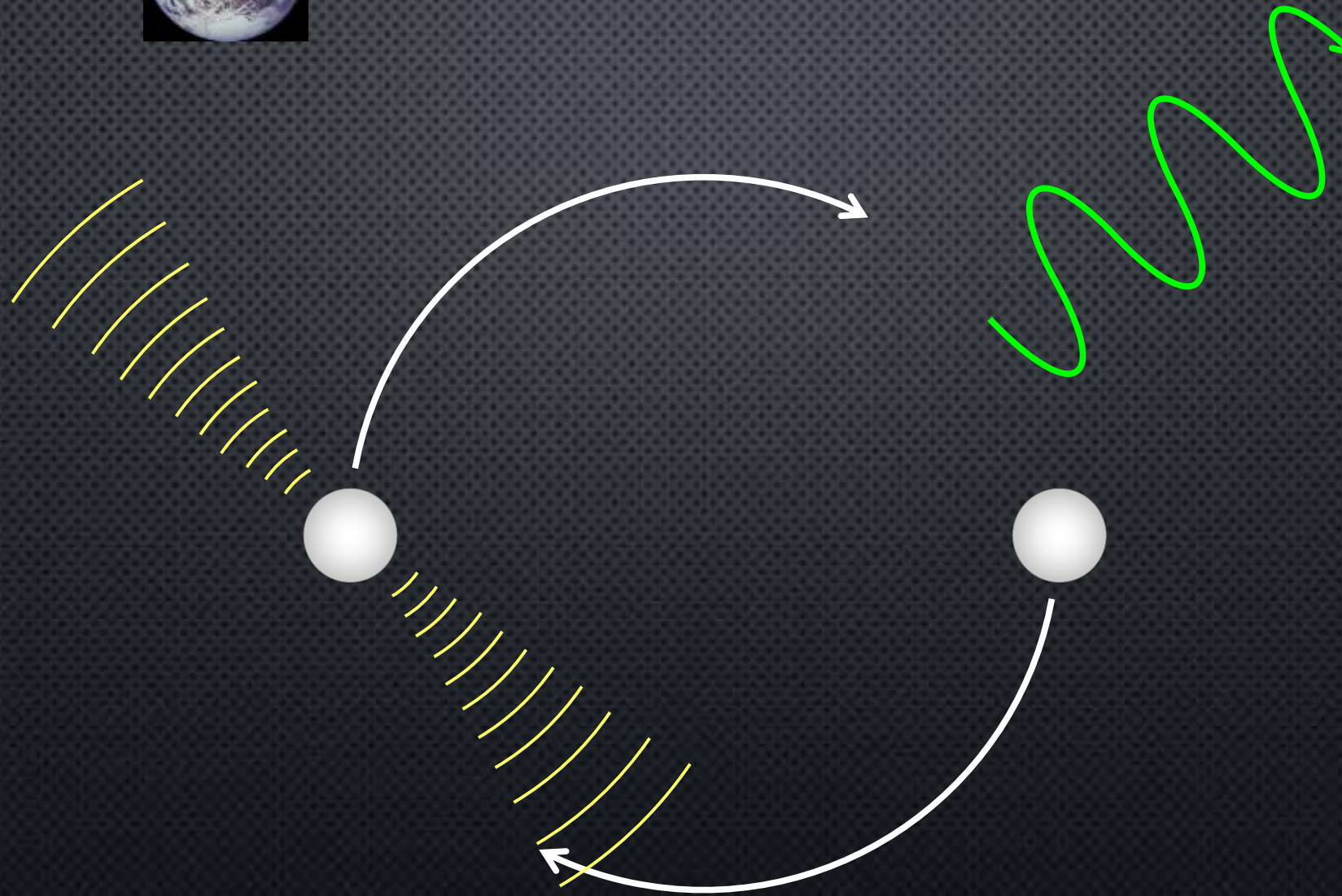
William Crochot - http://science.nasa.gov/media/medialibrary/1999/02/25/ast05mar99_1a_resources/N_sctn2.jpg, Public Domain, https://commons.wikimedia.org/w/index.php?curid=36335367

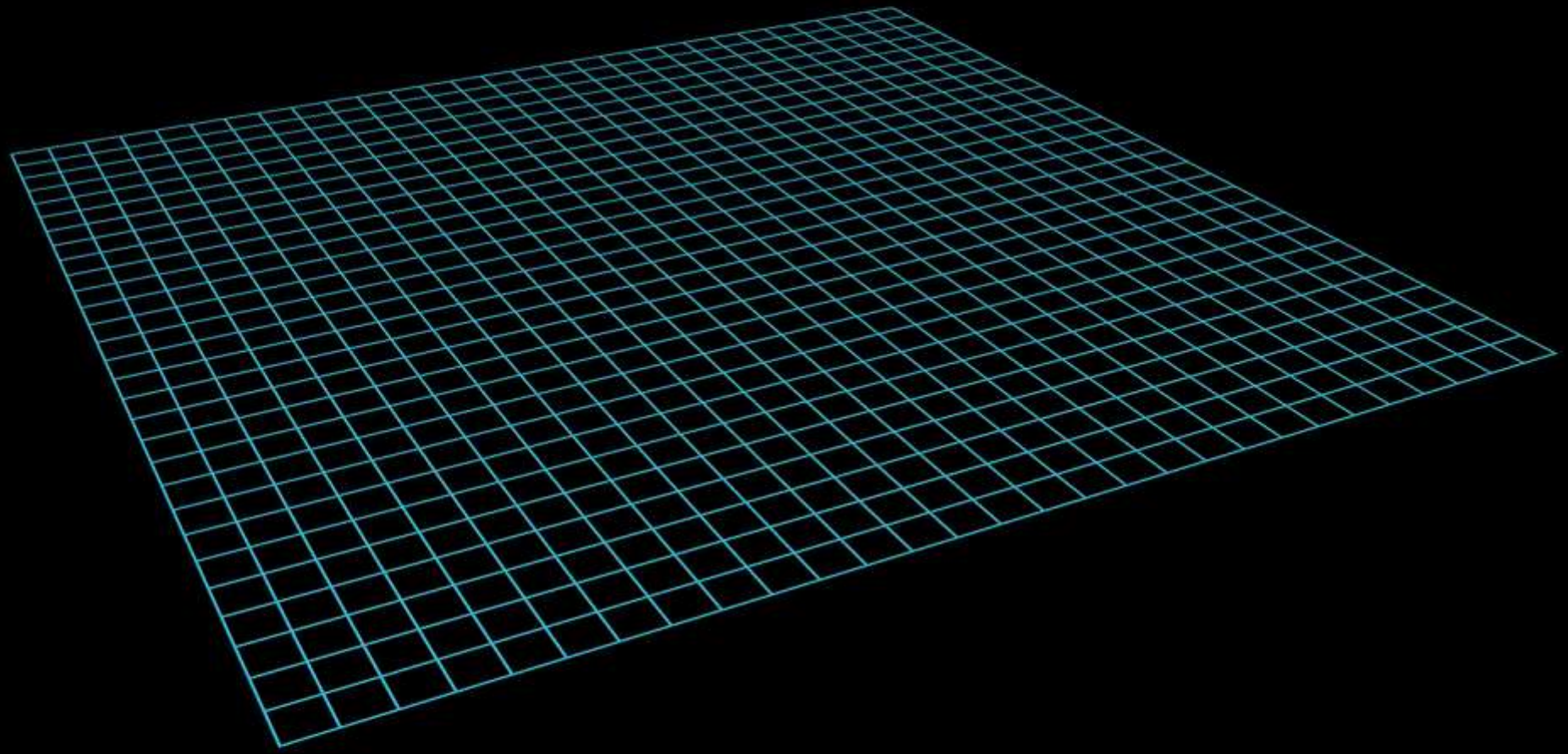

(C) KAGAYA

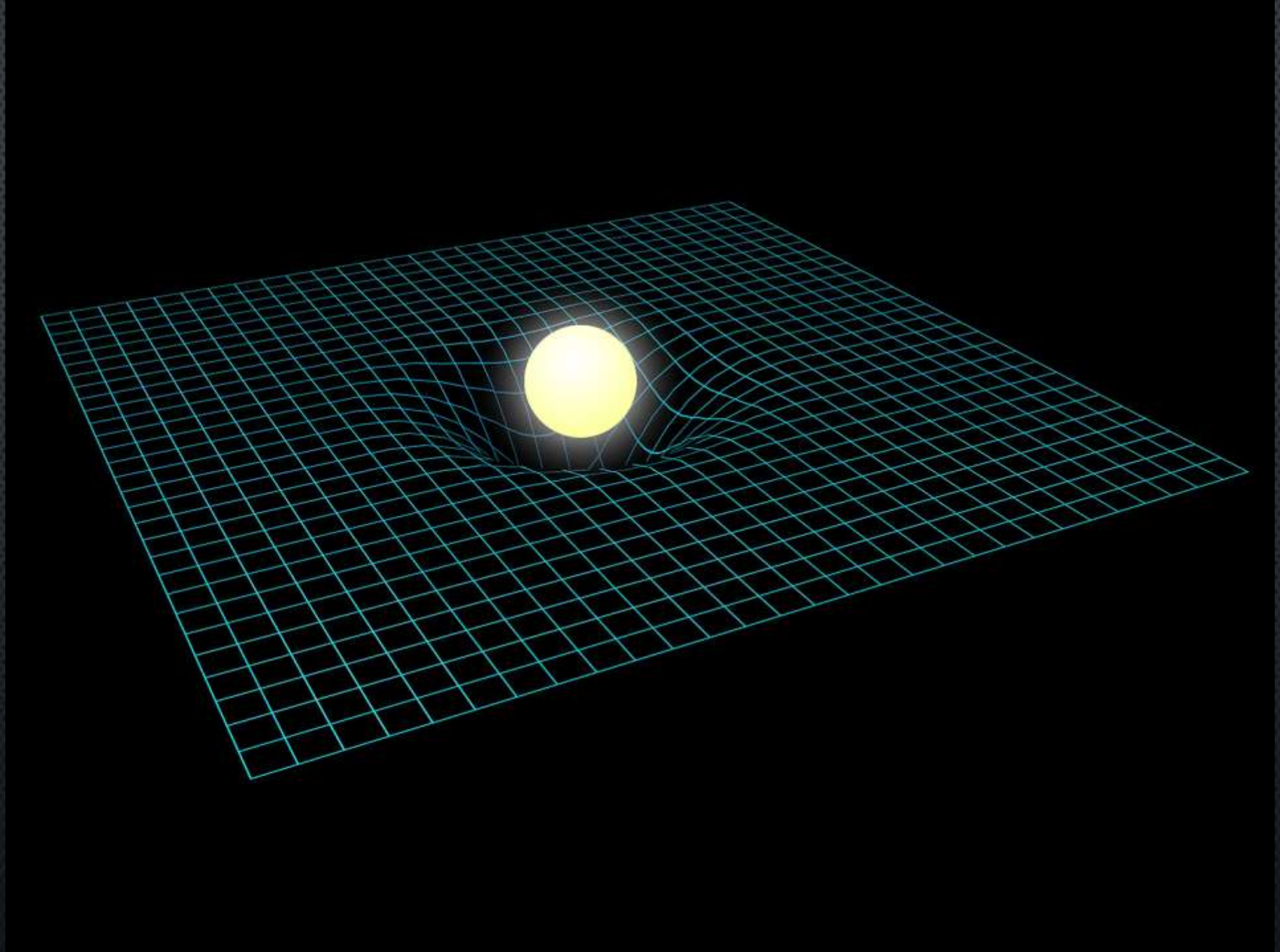


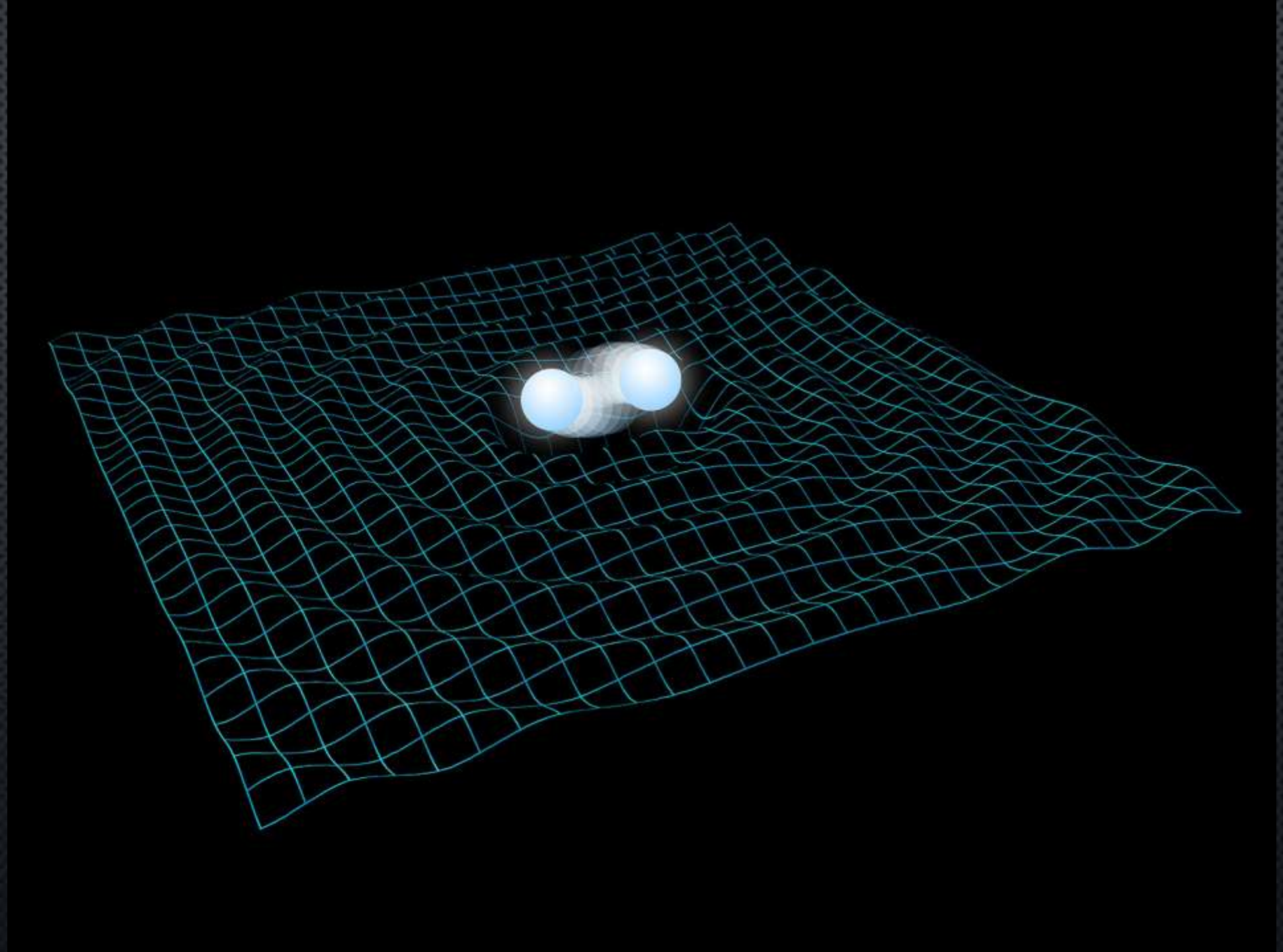
(C)NASA

Gravitational Wave









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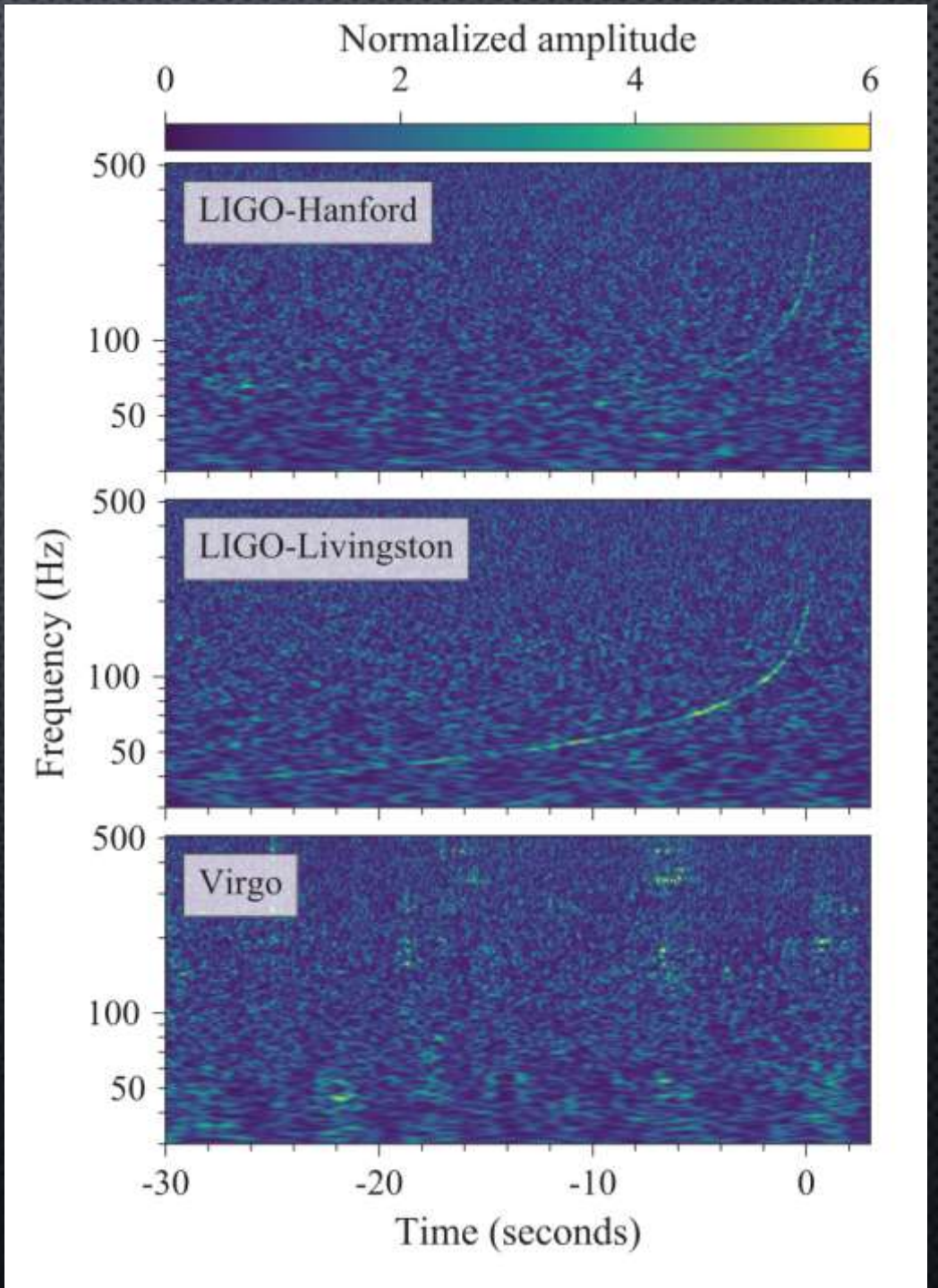
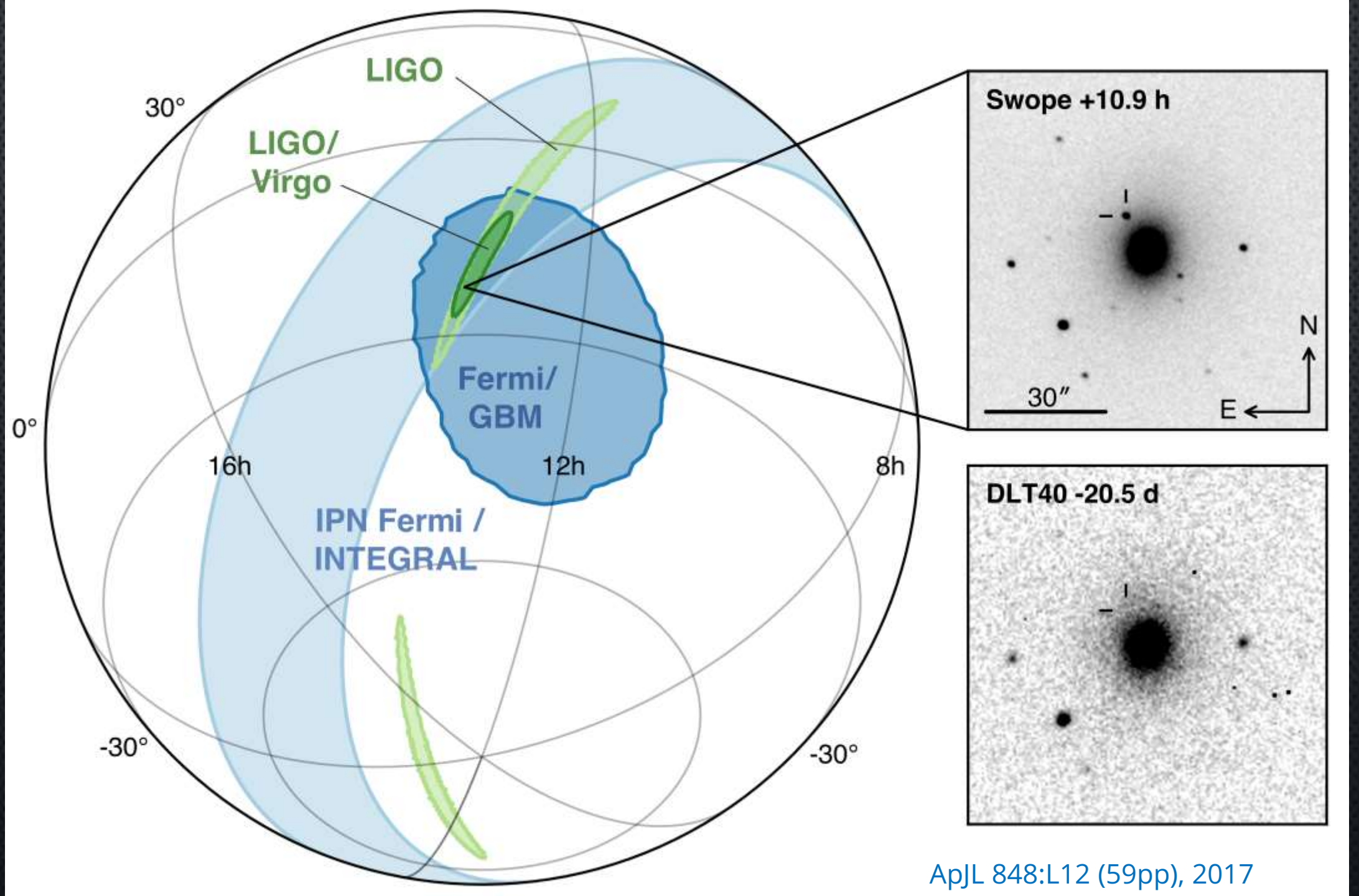
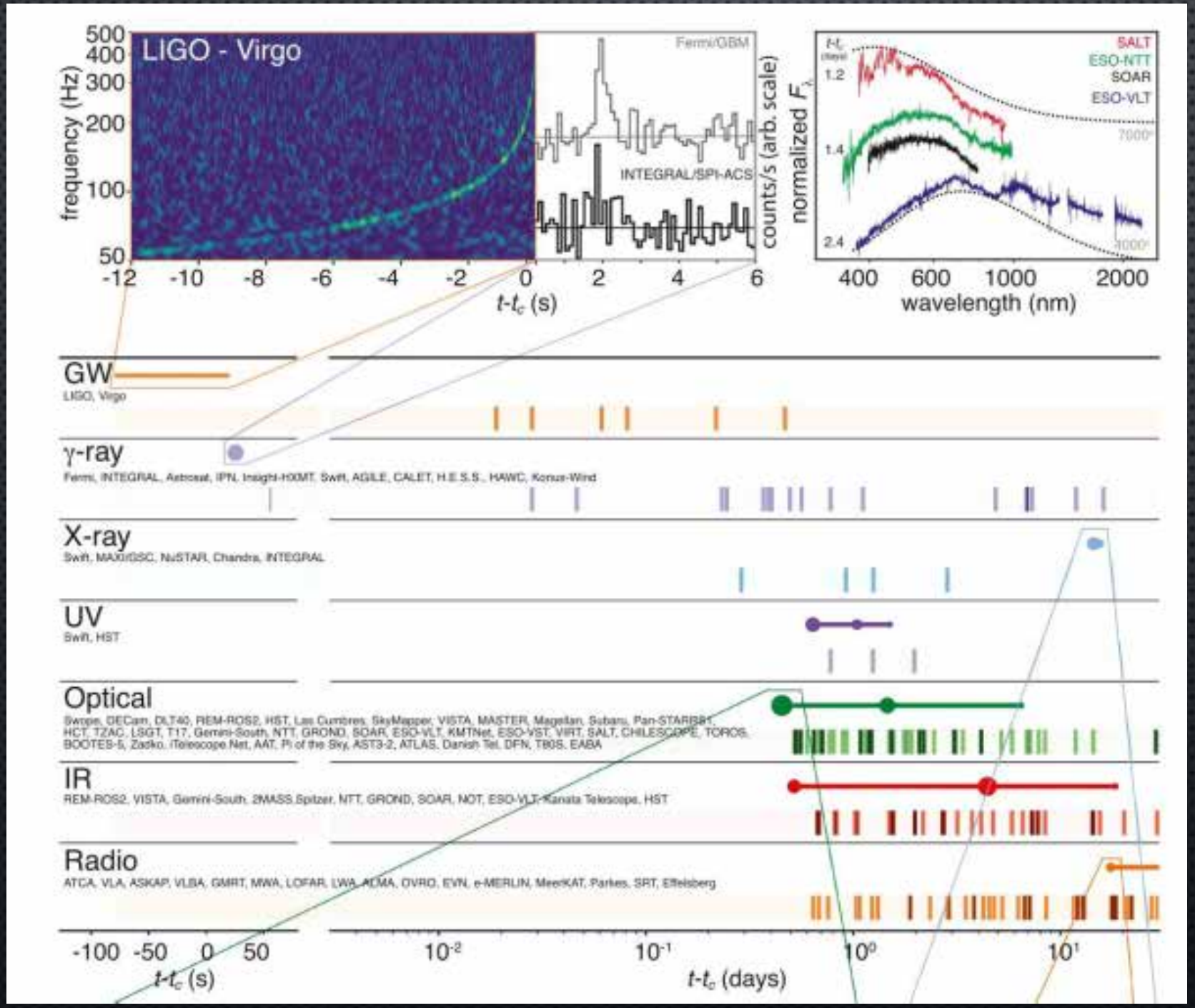


PRL 119, 161101(2017)



ApJL 848:L12 (59pp), 2017



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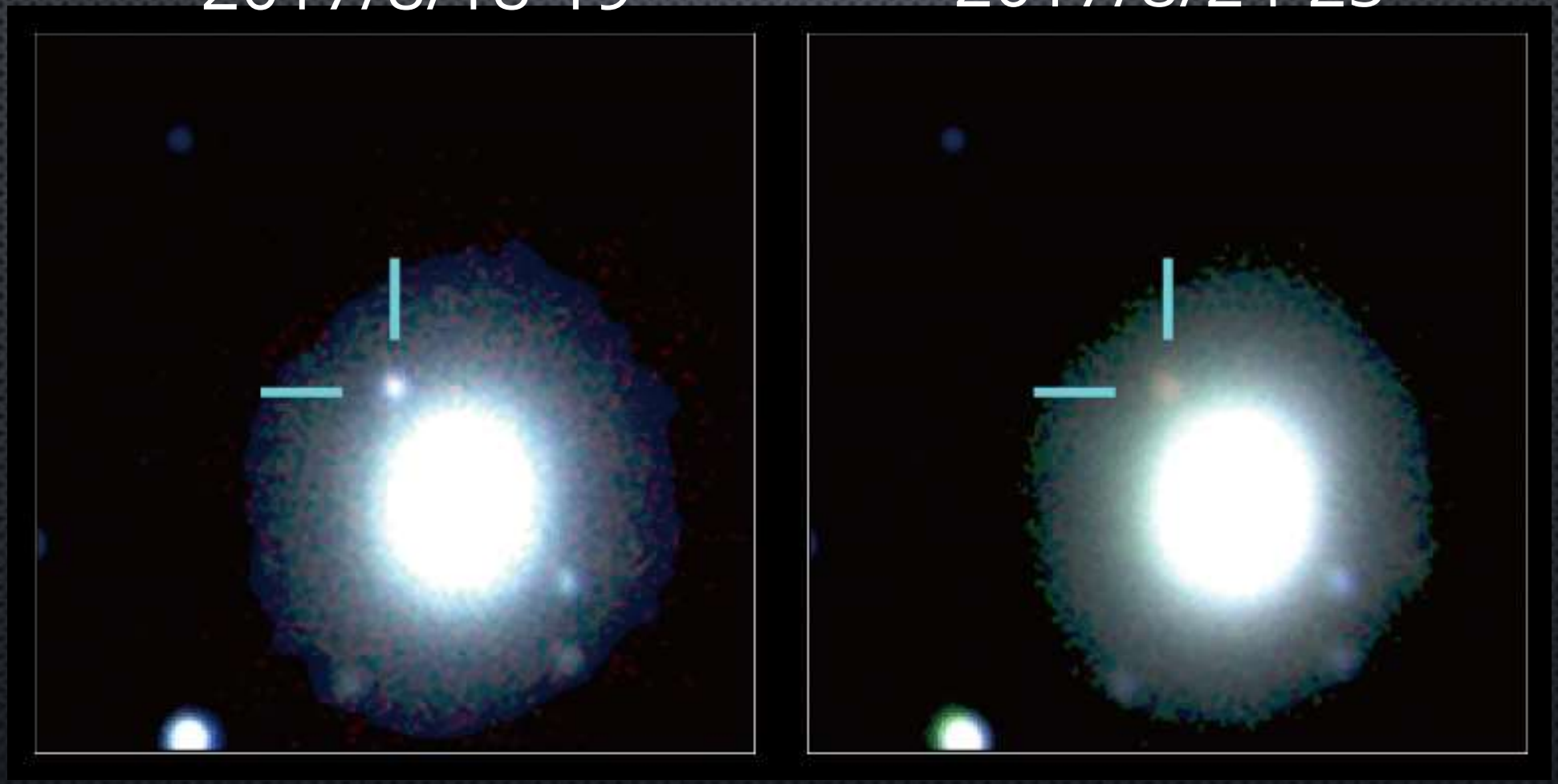
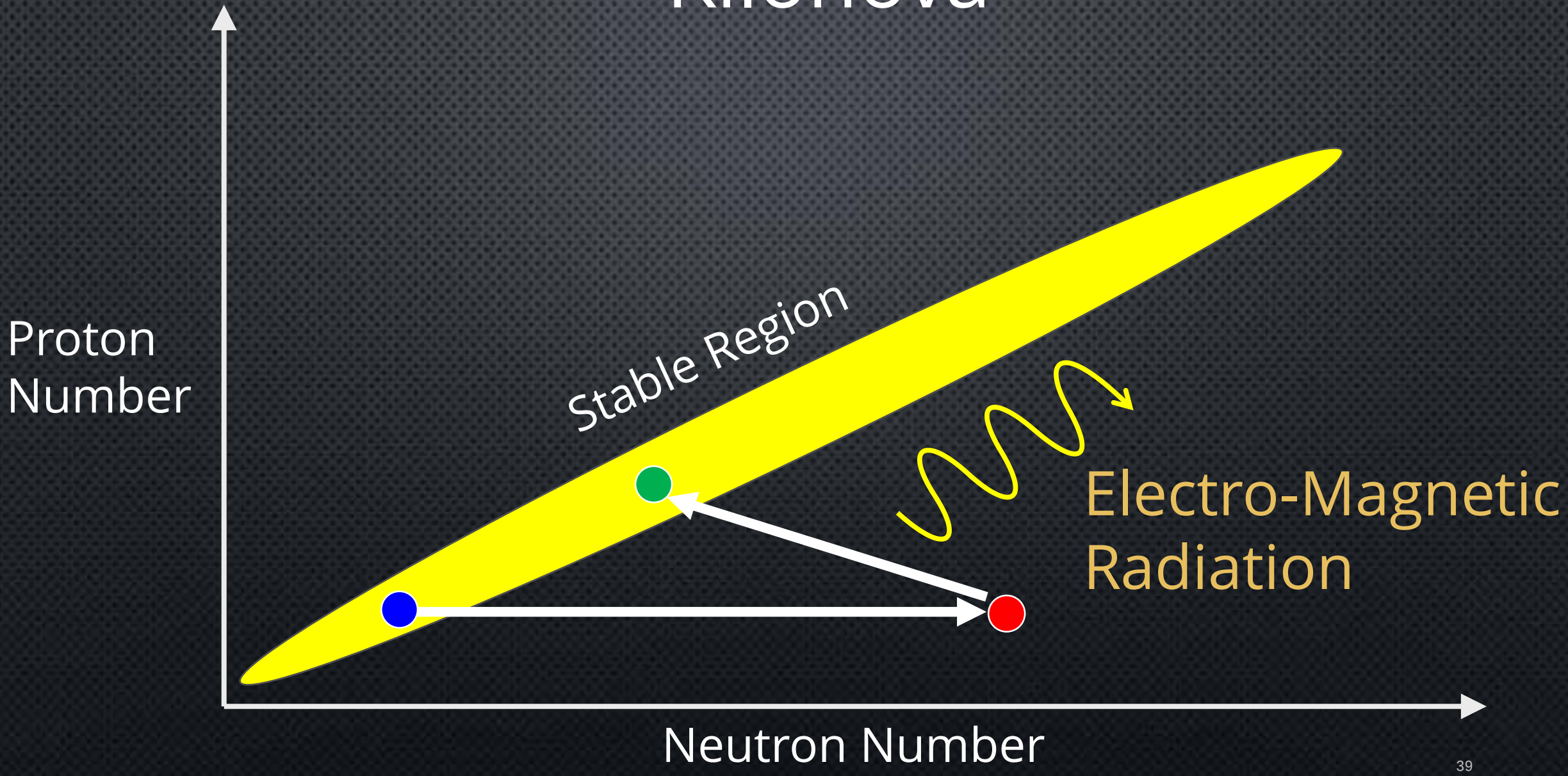
2017/8/18-19

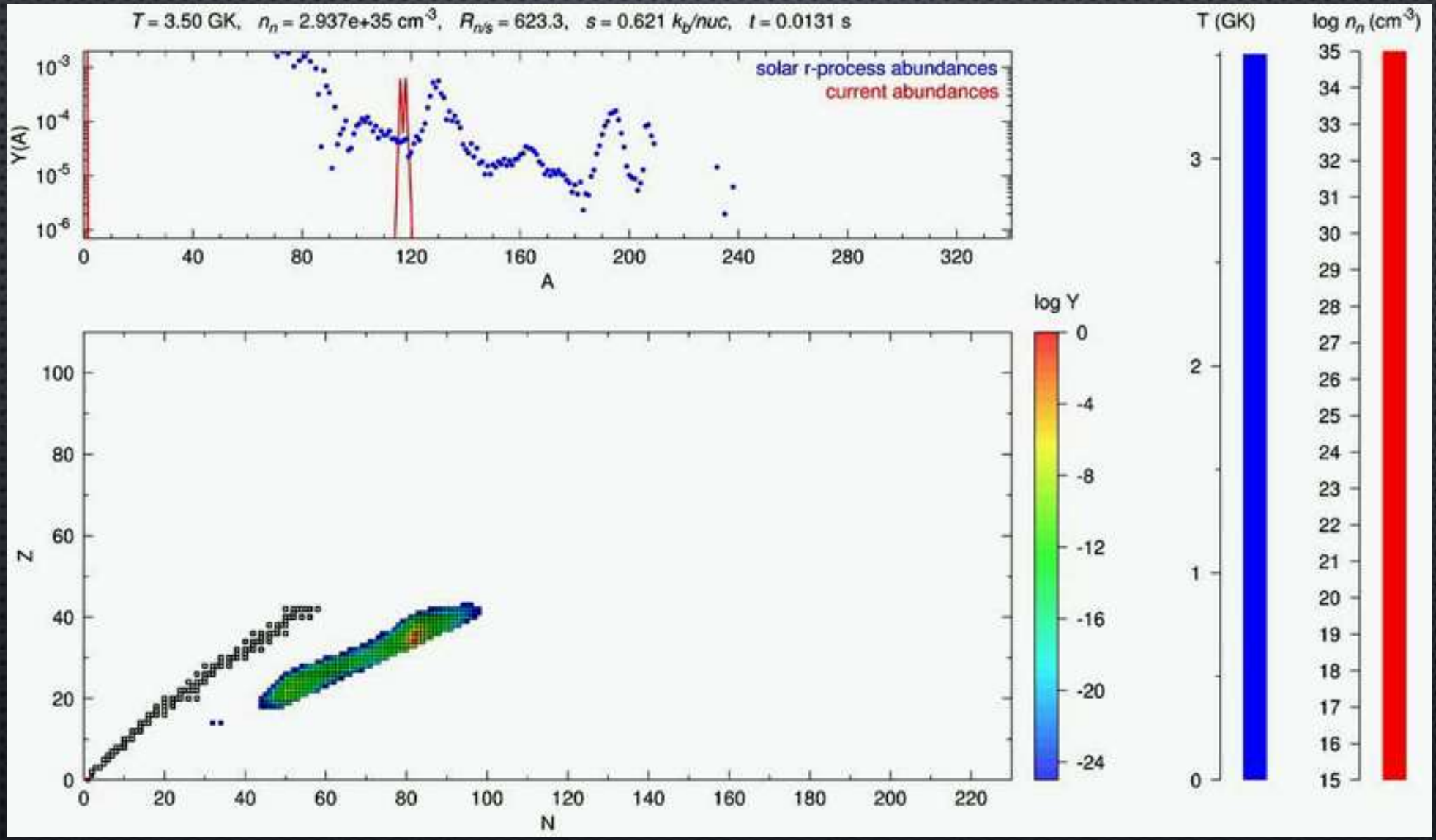
2017/8/24-25



NGC 4993

Kilonova

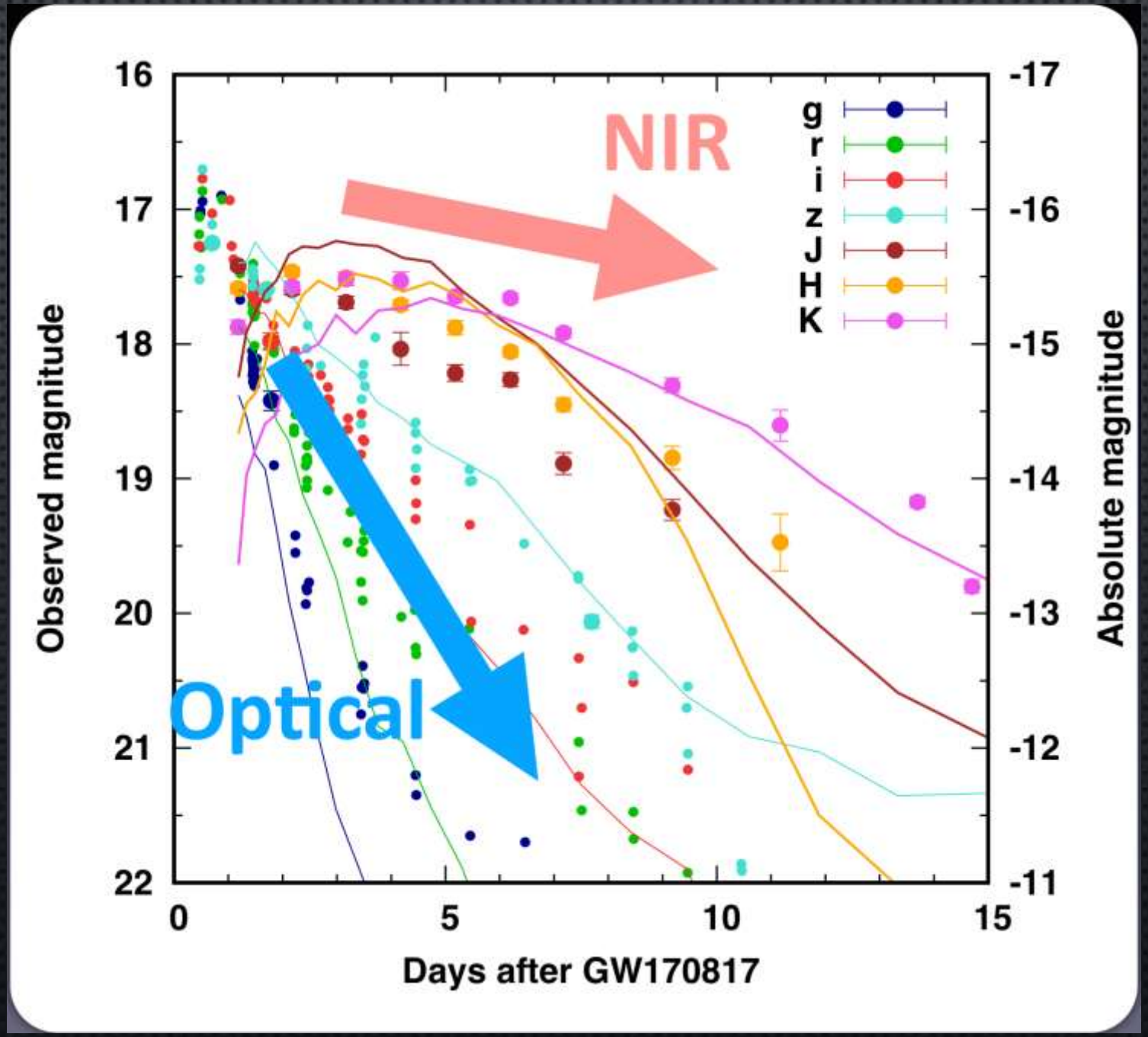

Proton Number
Stable Region
Electro-Magnetic Radiation
Neutron Number



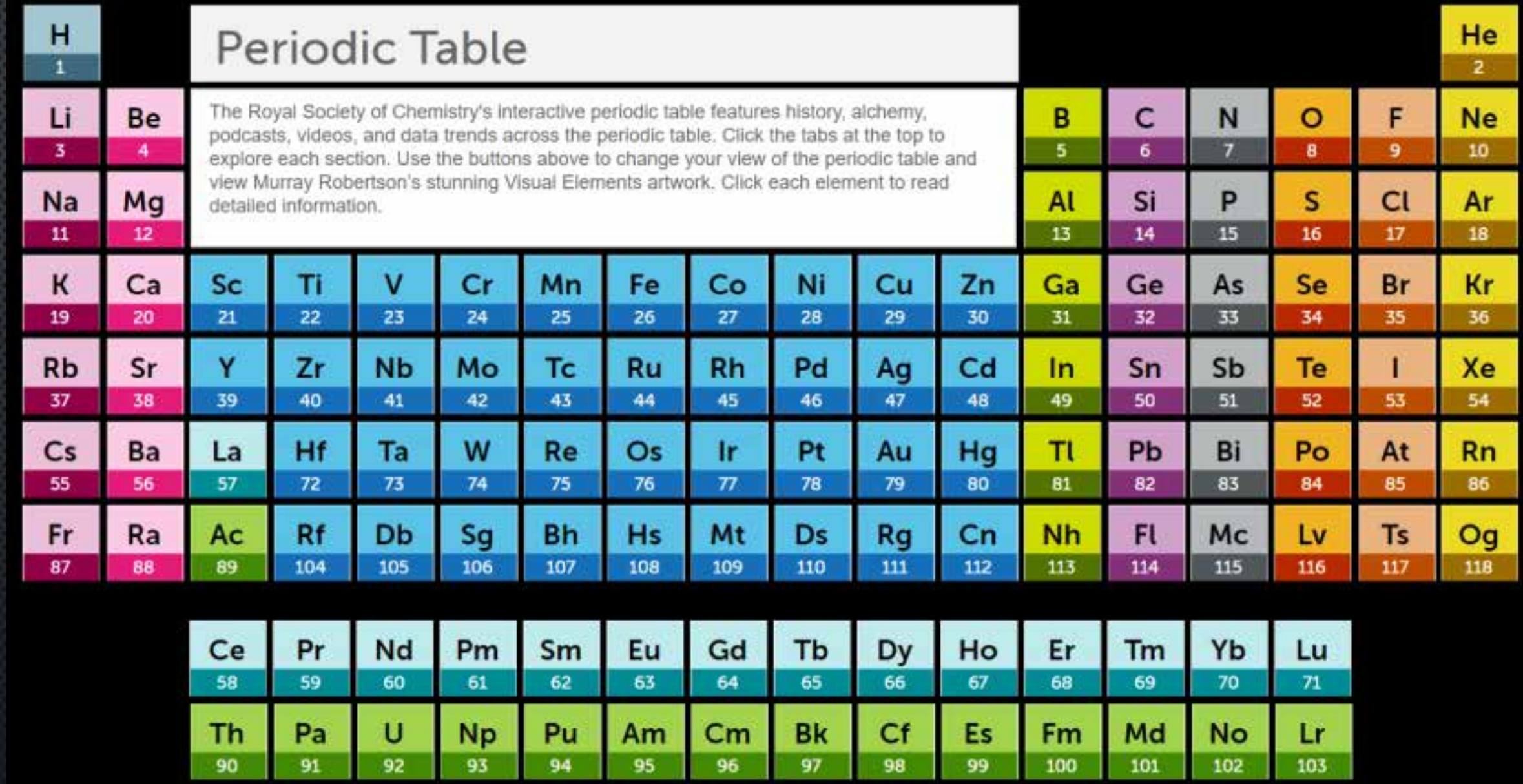
Atomic Number

Neutron number

Joel de Jesus Mendoza Temis arXiv:1409.6135


NIR
Optical
g
r
i
z
J
H
K
Observed magnitude
Absolute magnitude
Days after GW170817
16
17
18
19
20
21
22
-17
-16
-15
-14
-13
-12
-11
0
5
10
15

(C) M. Tanaka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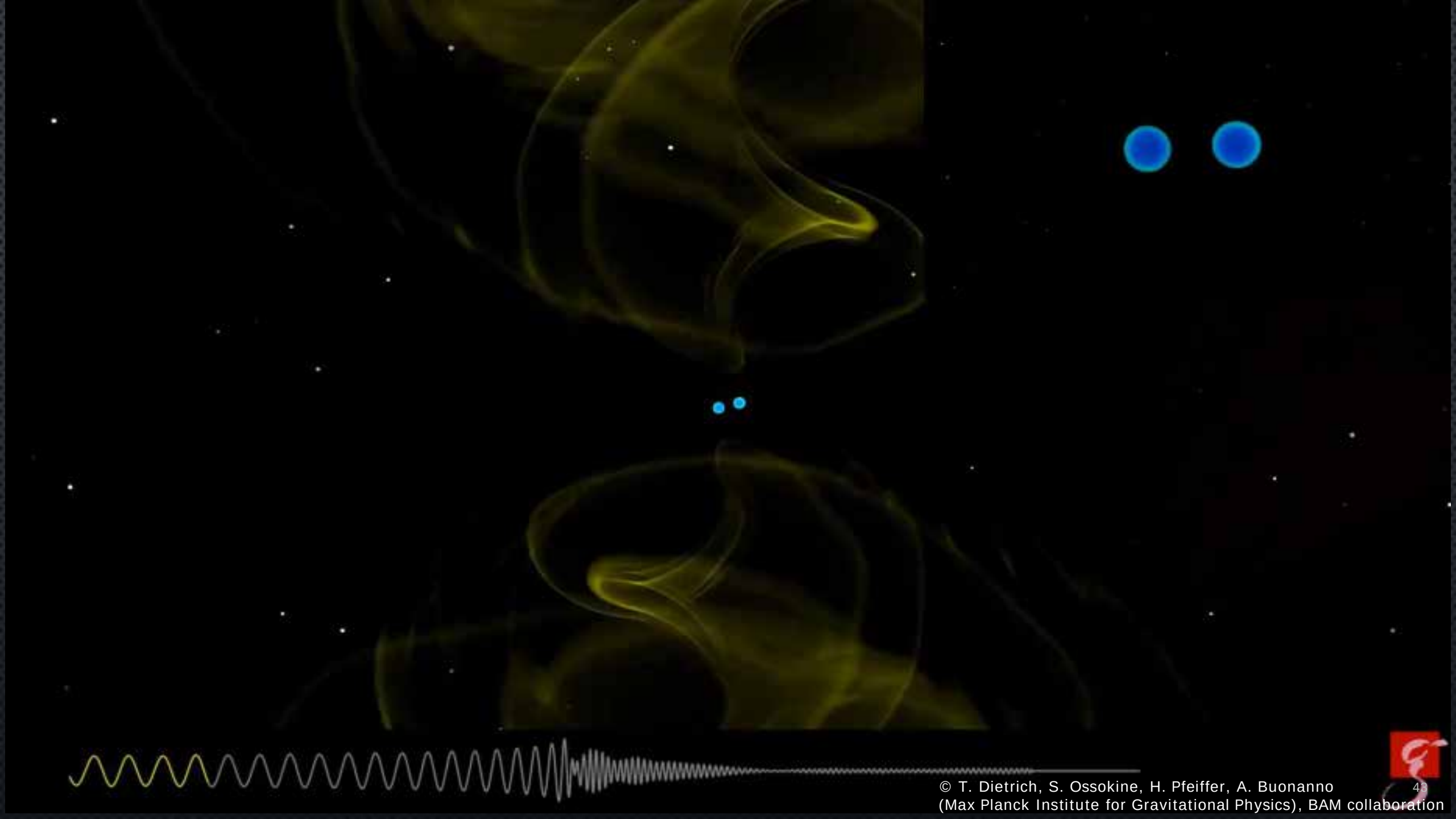
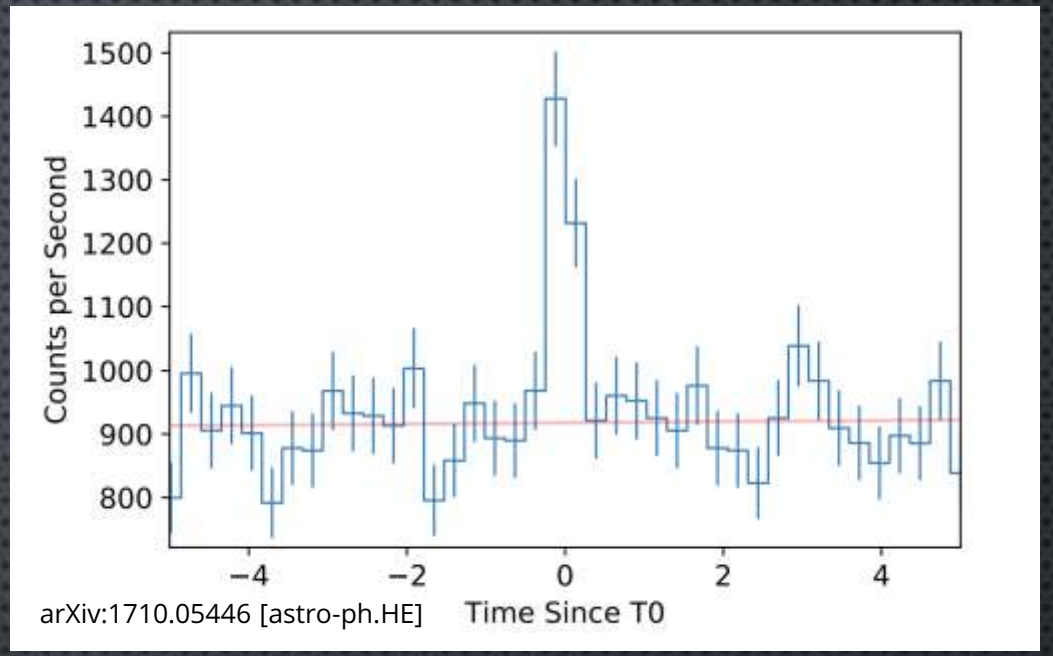
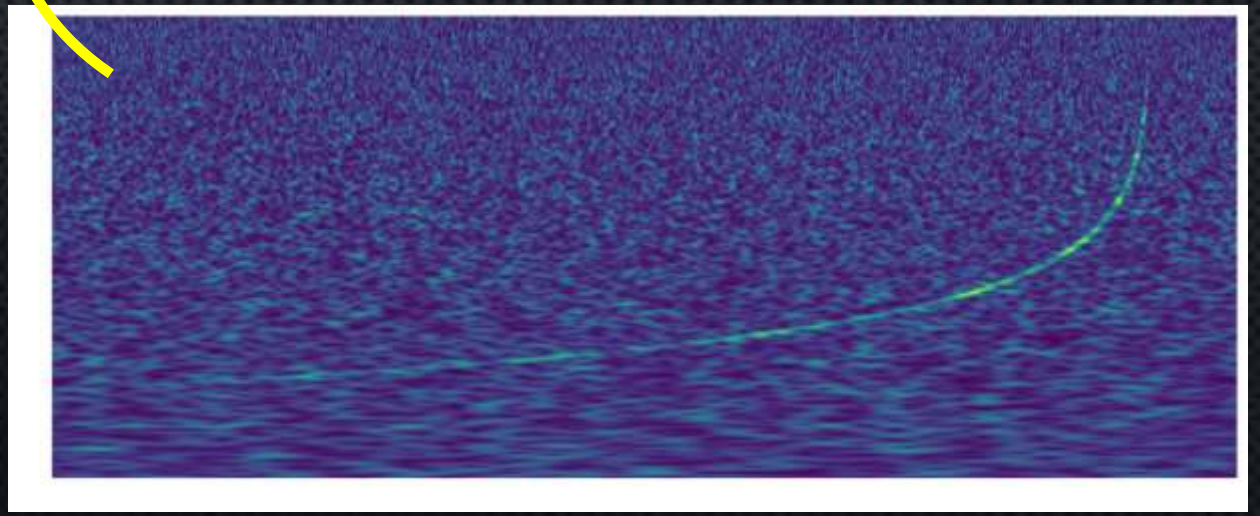
Ca 20
Sc 21
Ti 22
V 23
Cr 24
Mn 25
Fe 26
Co 27
Ni 28
Cu 29
Zn 30
Ga 31
Ge 32
As 33
Se 34
Br 35
Kr 36
Rb 37
Sr 38
Y 39
Zr 40
Nb 41
Mo 42
Tc 43
Ru 44
Rh 45
Pd 46
Ag 47
Cd 48
In 49
Sn 50
Sb 51
Te 52
I 53
Xe 54
Cs 55
Ba 56
La 57
Hf 72
Ta 73
W 74
Re 75
Os 76
Ir 77
Pt 78
Au 79
Hg 80
Tl 81
Pb 82
Bi 83
Po 84
At 85
Rn 86
Fr 87
Ra 88
Ac 89
Rf 104
Db 105
Sg 106
Bh 107
Hs 108
Mt 109
Ds 110
Rg 111
Cn 112
Nh 113
Fl 114
Mc 115
Lv 116
Ts 117
Og 118
Ce 58
Pr 59
Nd 60
Pm 61
Sm 62
Eu 63
Gd 64
Tb 65
Dy 66
Ho 67
Er 68
Tm 69
Yb 70
Lu 71
Th 90
Pa 91
U 92
Np 93
Pu 94
Am 95
Cm 96
Bk 97
Cf 98
Es 99
Fm 100
Md 101
No 102
Lr 103

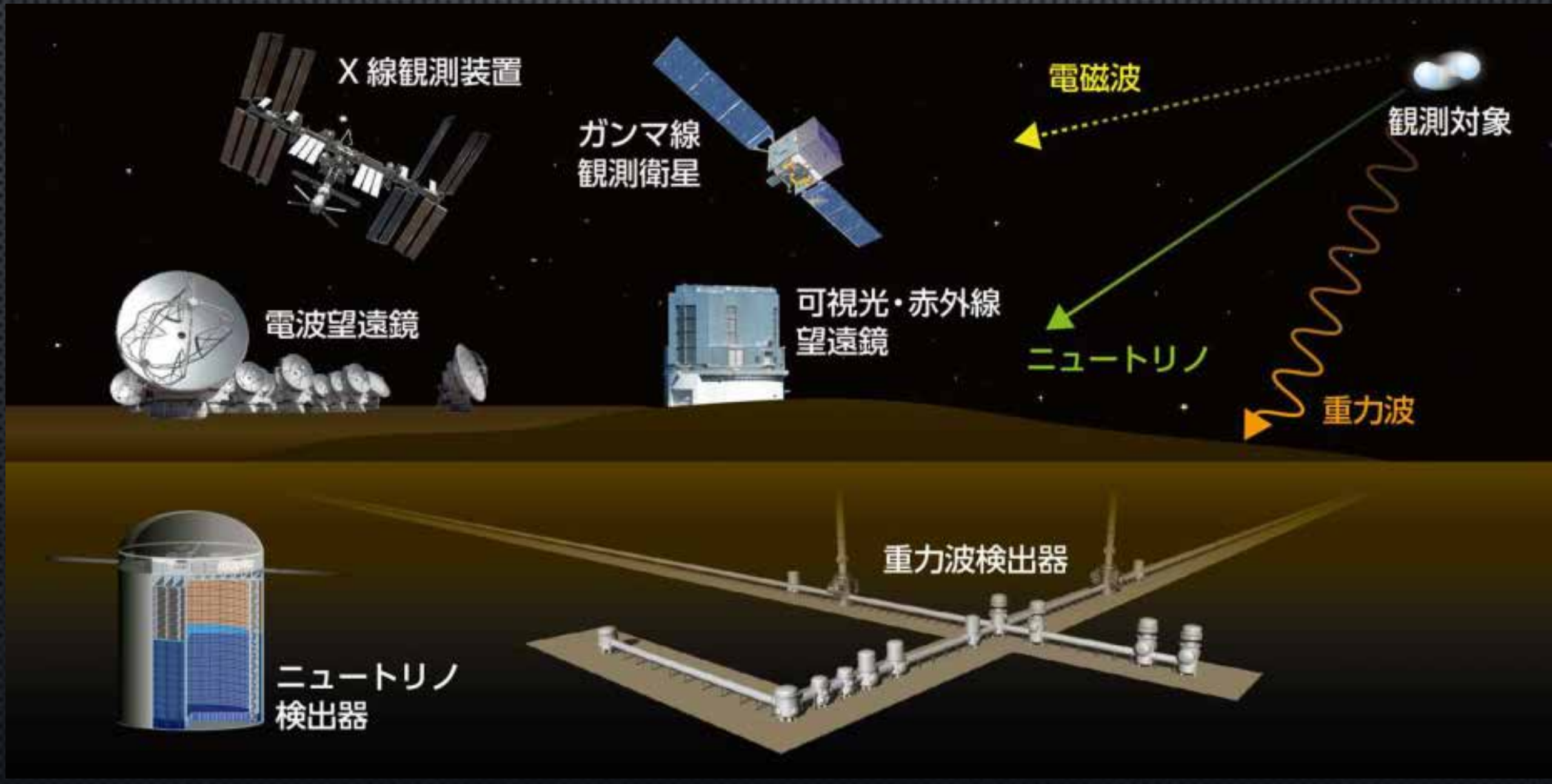


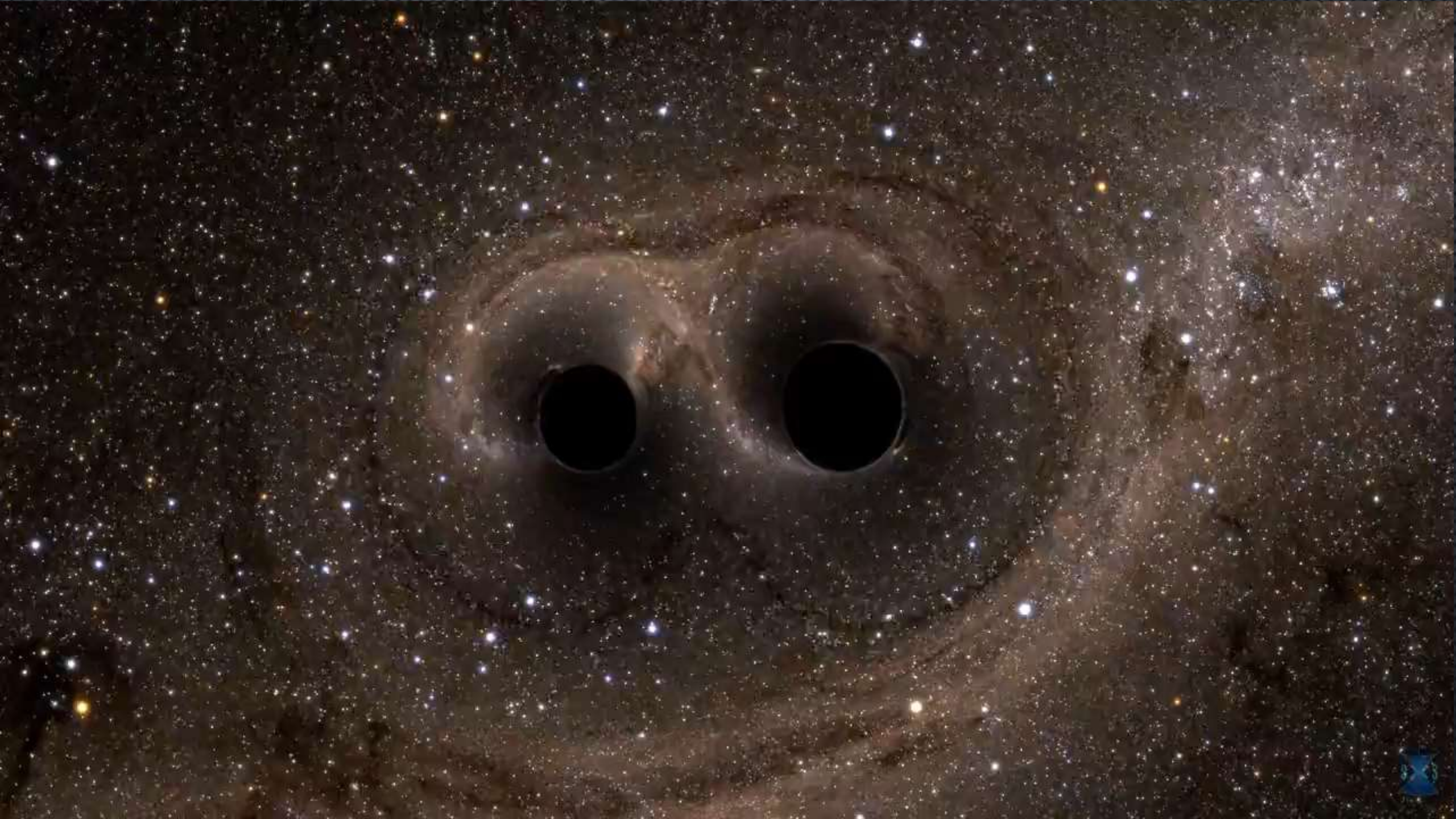


1.7sec → $|c_{GW} - 1| < 10^{-15}$

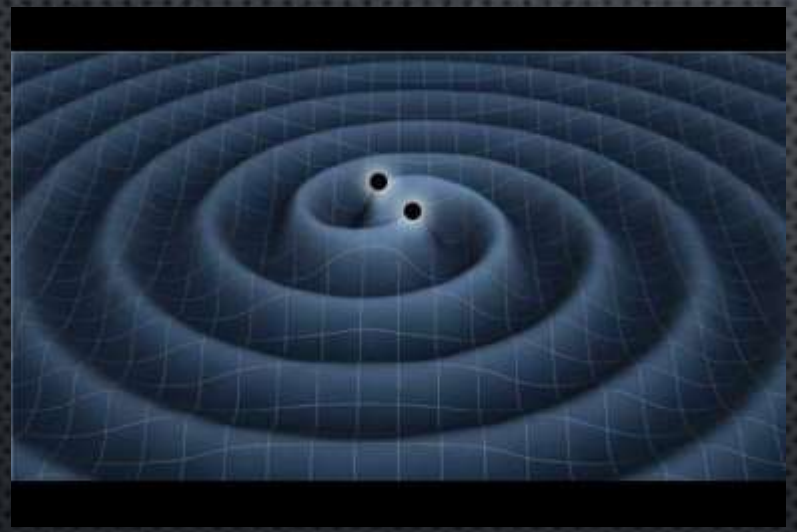


Multi-Messenger Astronomy





Gravitational Wave Luminosity



$3.6 \times 10^{49}\,\mathrm{J/s}$

$\geq$

Visible luminosity of the entire Universe

$1 \times 10^{49}\,\mathrm{J/s}$

観測運転(Observational run)

O1: 2015 Sept. 12 – 2016 Jan. 19

O2: 2016 Nov. 30 – 2017 Aug. 25
(Virgo joined on 2017 Aug. 1)

O3: 2019 Apr. 1 - on going (until 2020 Apr. 30)

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BH + BH: 23
NS + NS: 3+
BH + BS: 3+
Mass Gap: 2

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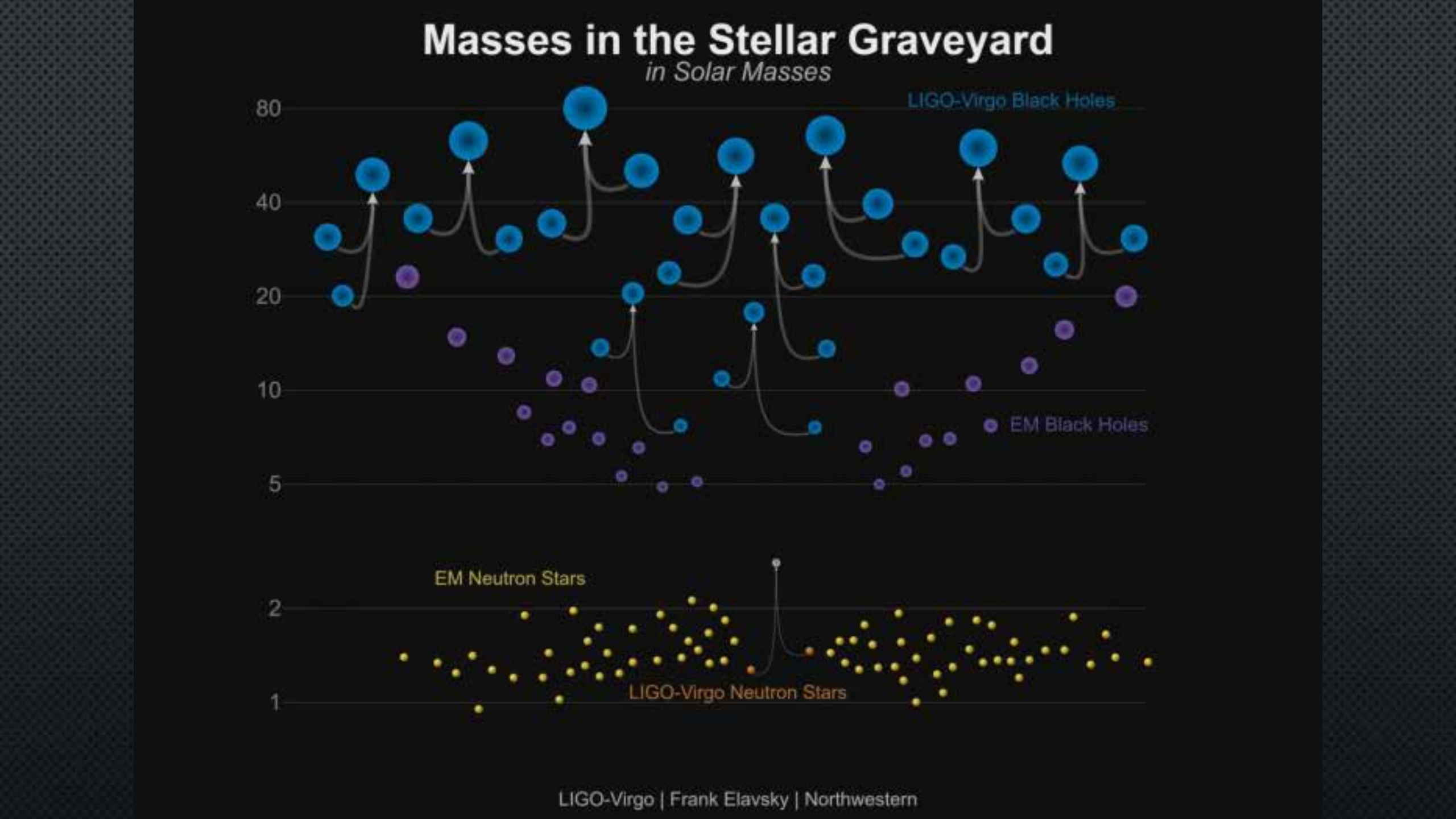
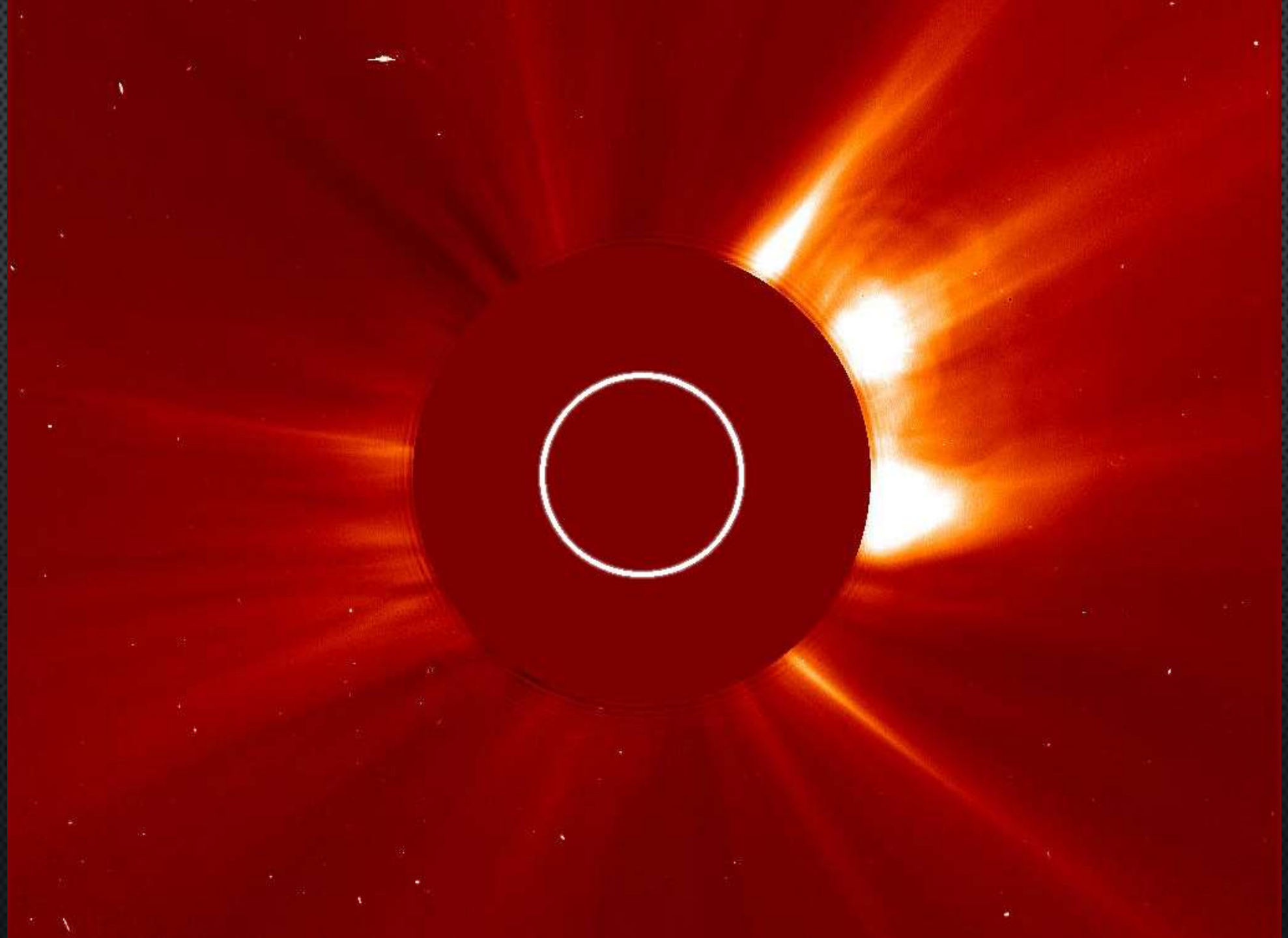
BH + BS: 3+
Mass Gap: 2

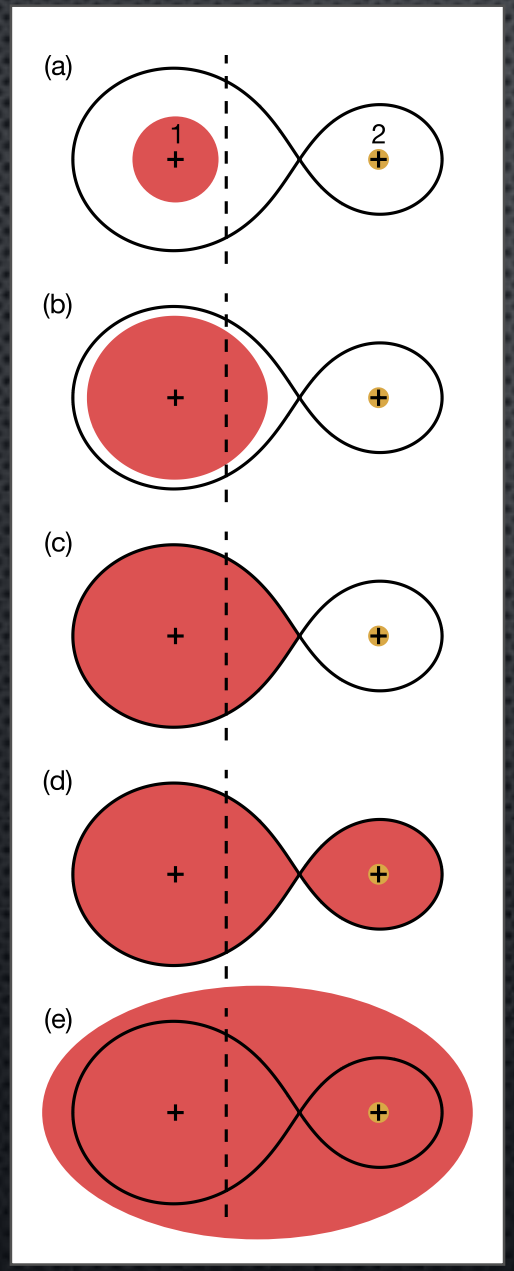
} Open Public Alert

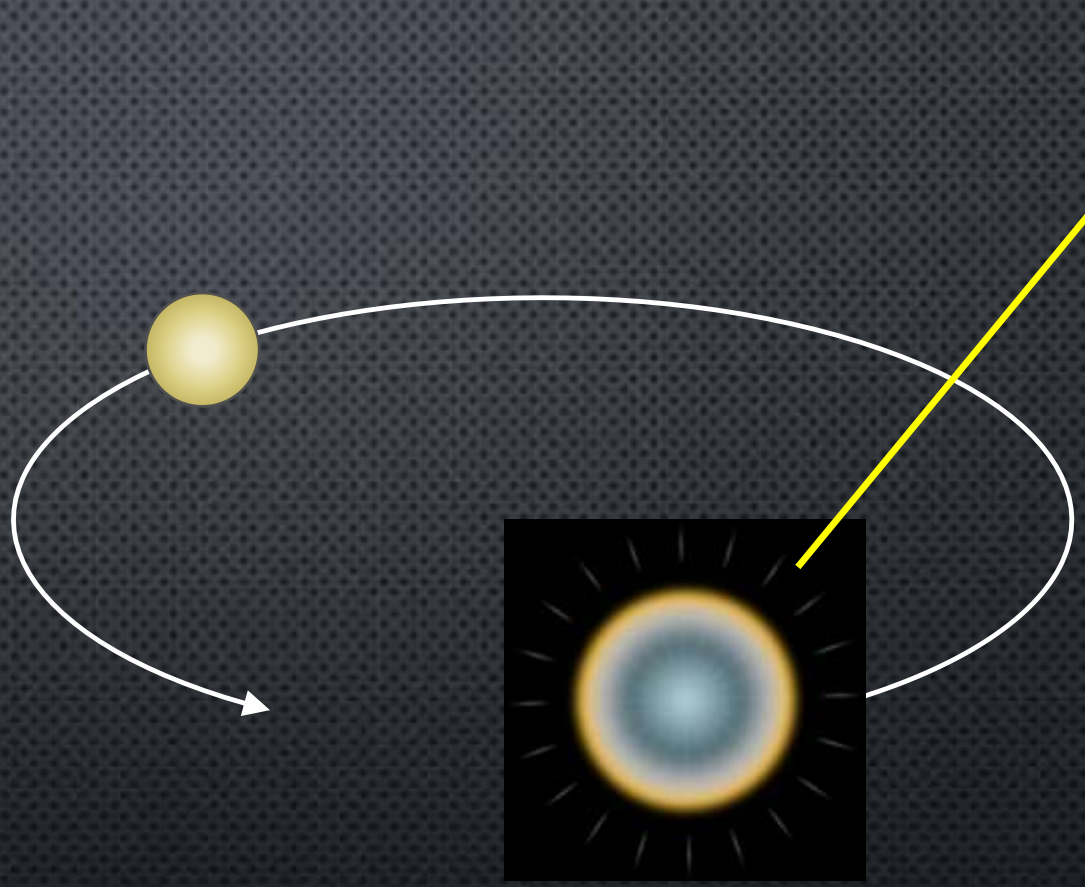

Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
LIGO-Virgo | Frank Elavsky | Northwestern



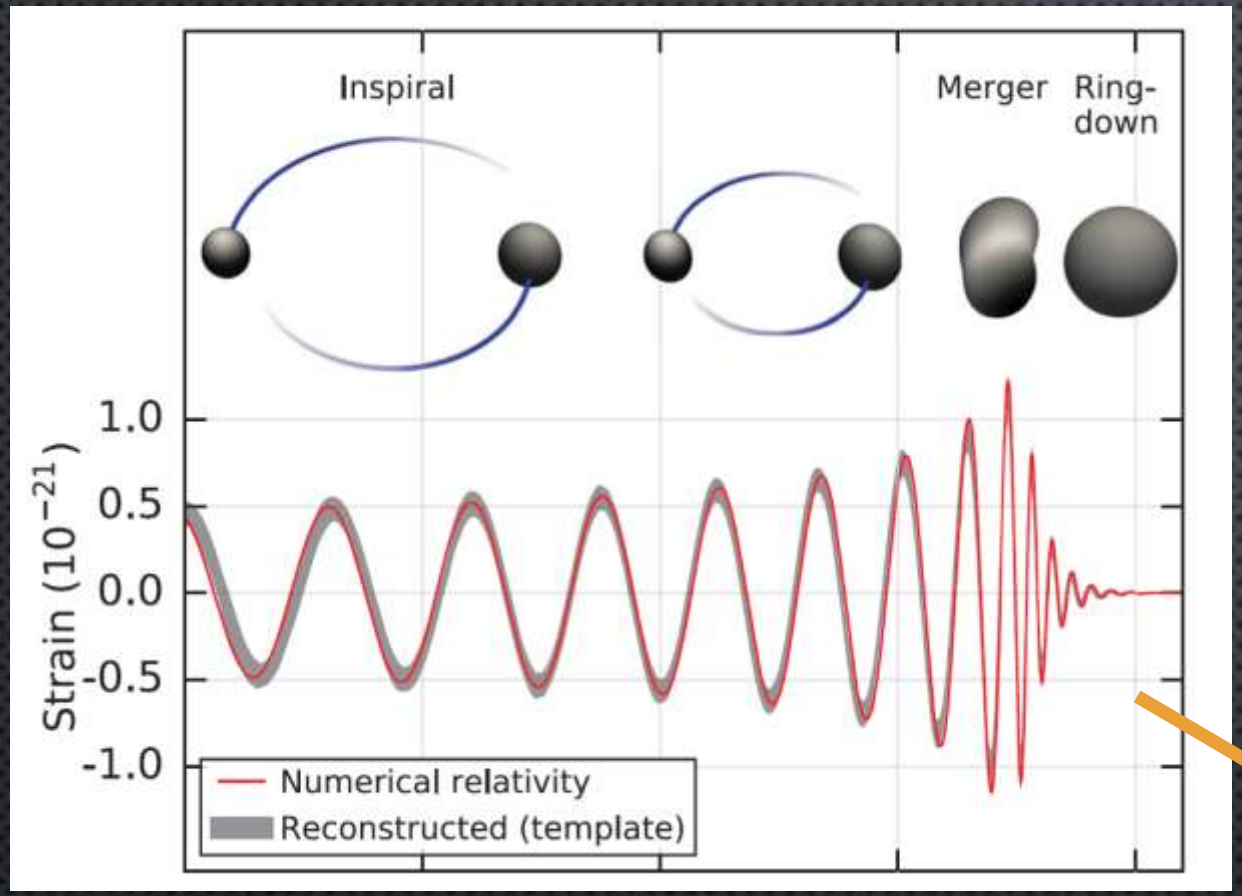
(C) NASA/SOHO


(C)NASA



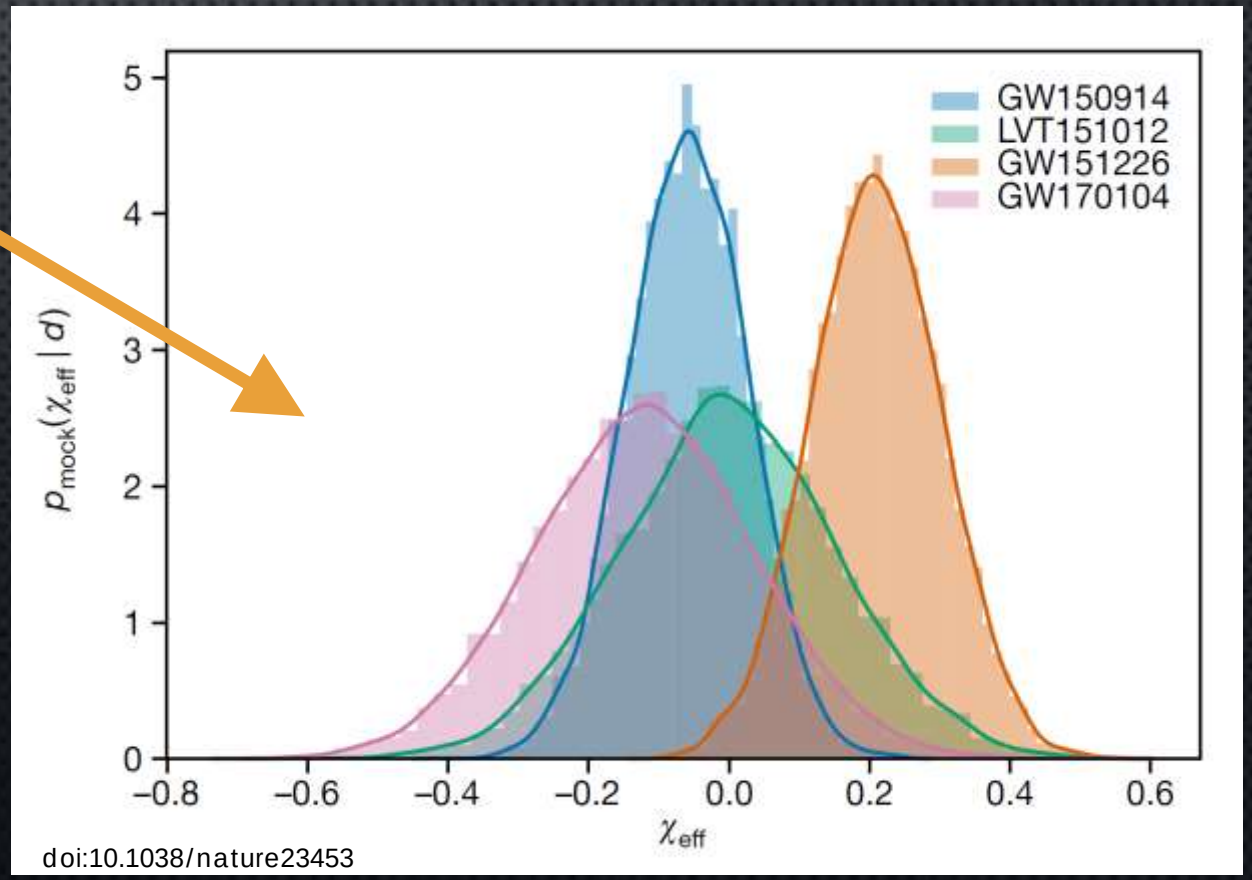


By NASA, The Hubble Heritage Team, STScI, AURA



GW waveform

Black Hole spin

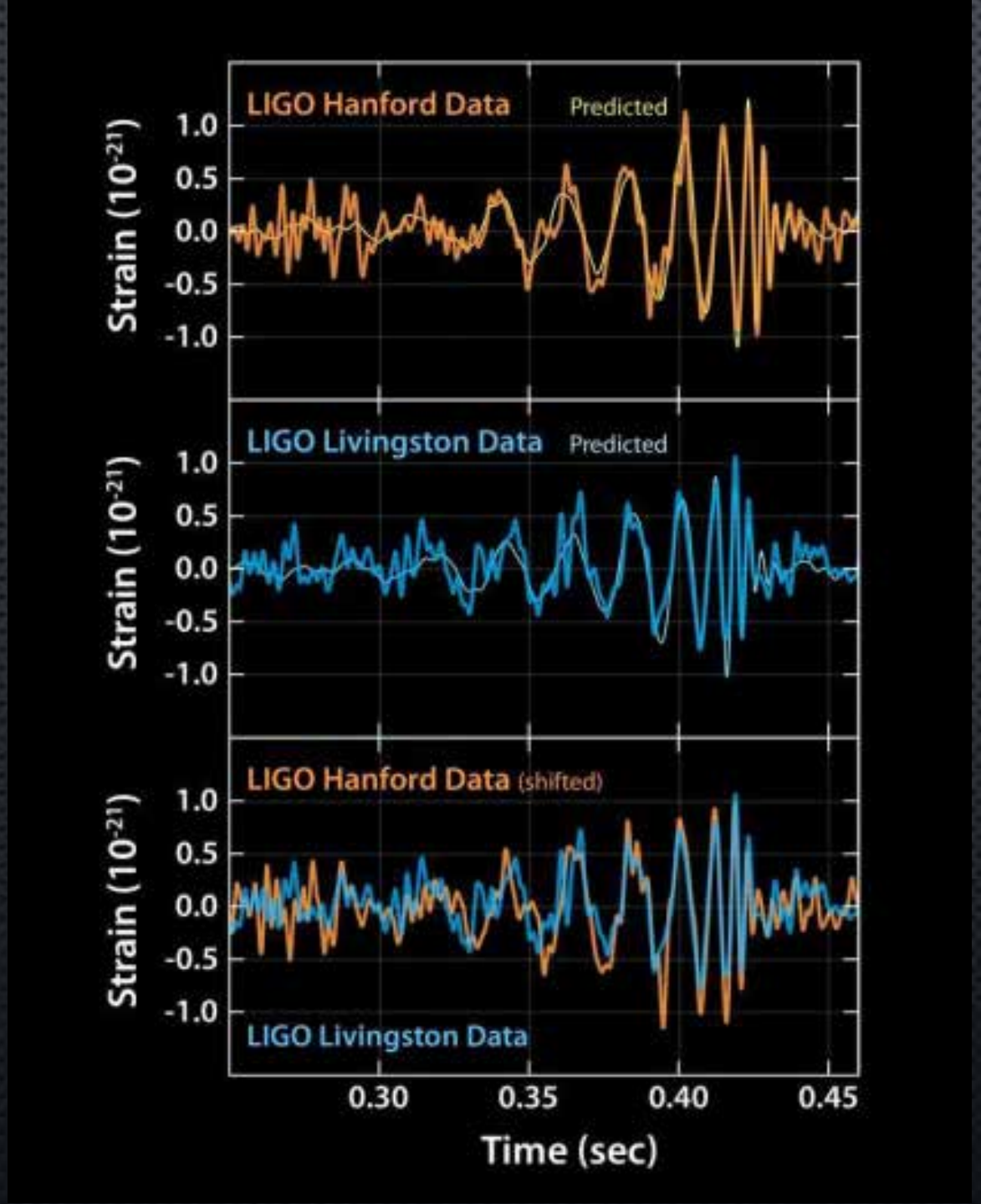


doi:10.1038/nature23453

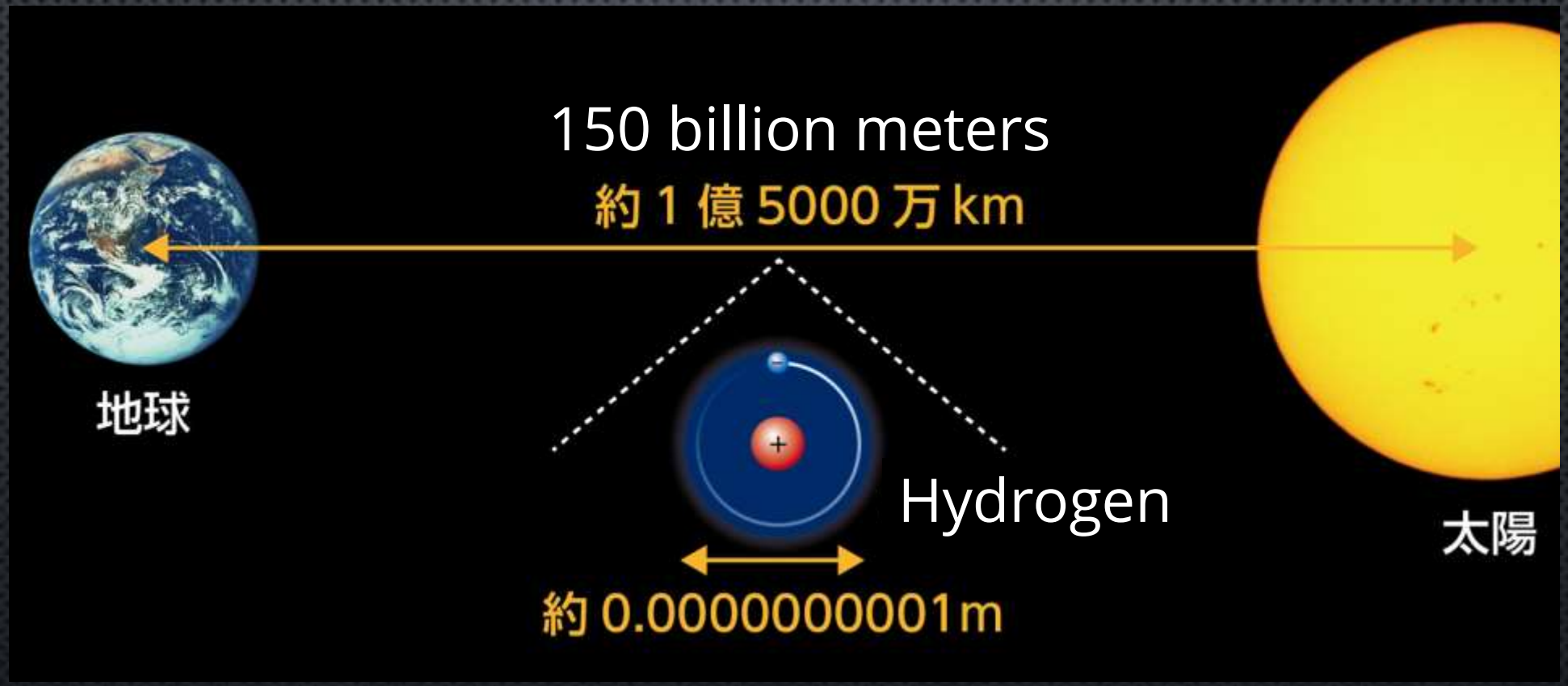
How do we detect gravitational waves ?

$$h \equiv \frac{\Delta L}{L}$$

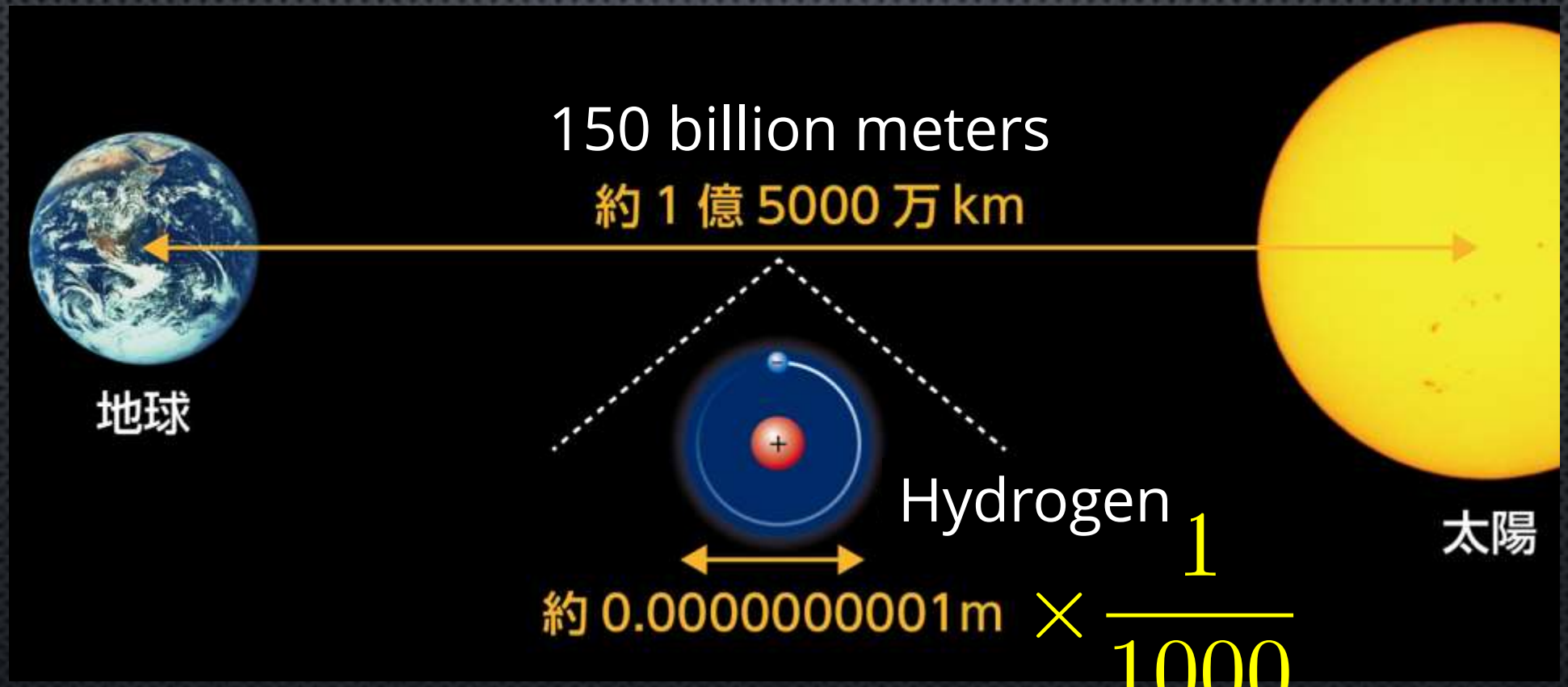
Gravitational Wave Amplitude



$$h \approx 10^{-21}$$


150 billion meters
約 1 億 5000 万 km
地球
Hydrogen
太陽
約 0.0000000001m

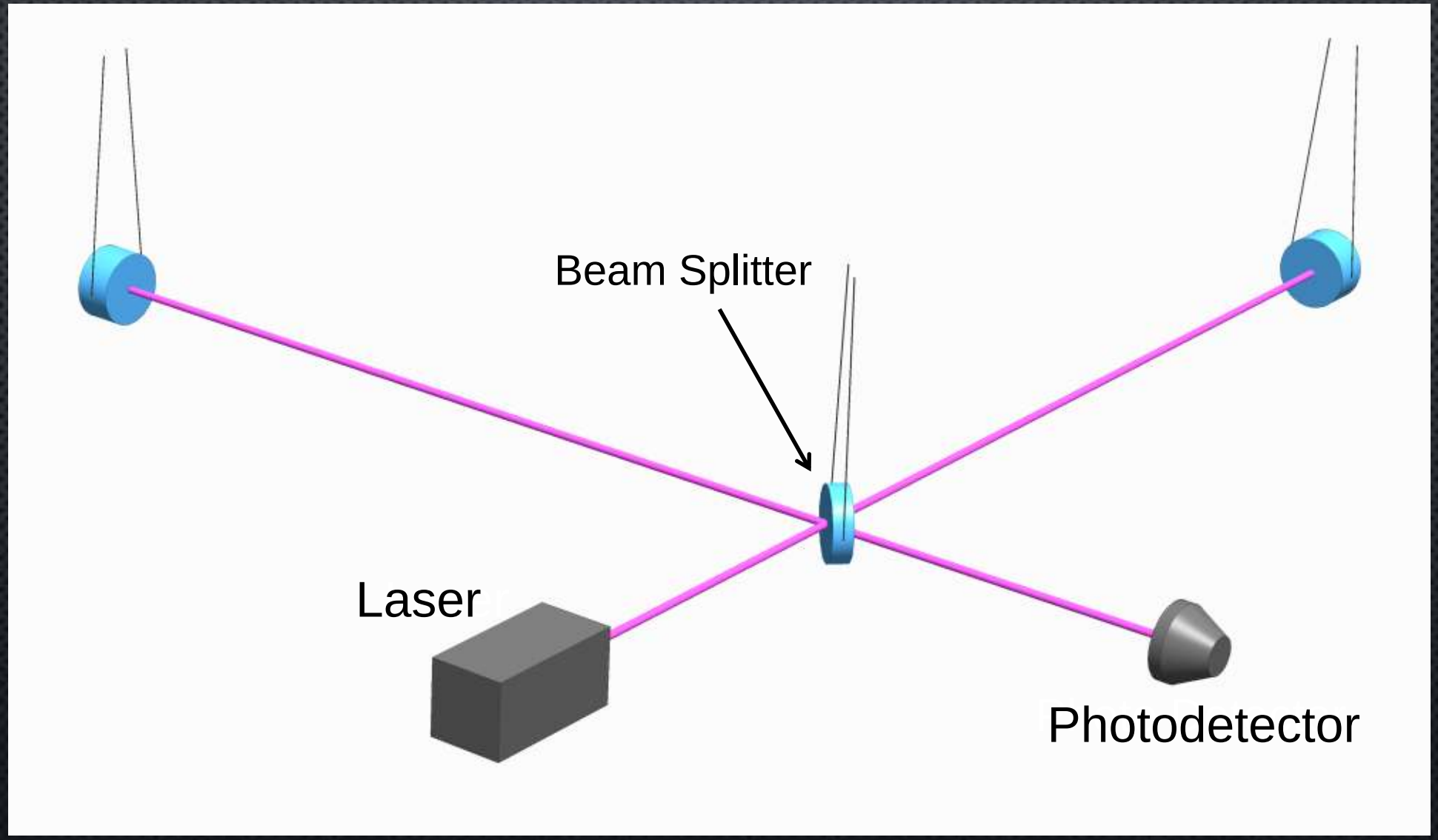
$$h = 10^{-21}$$

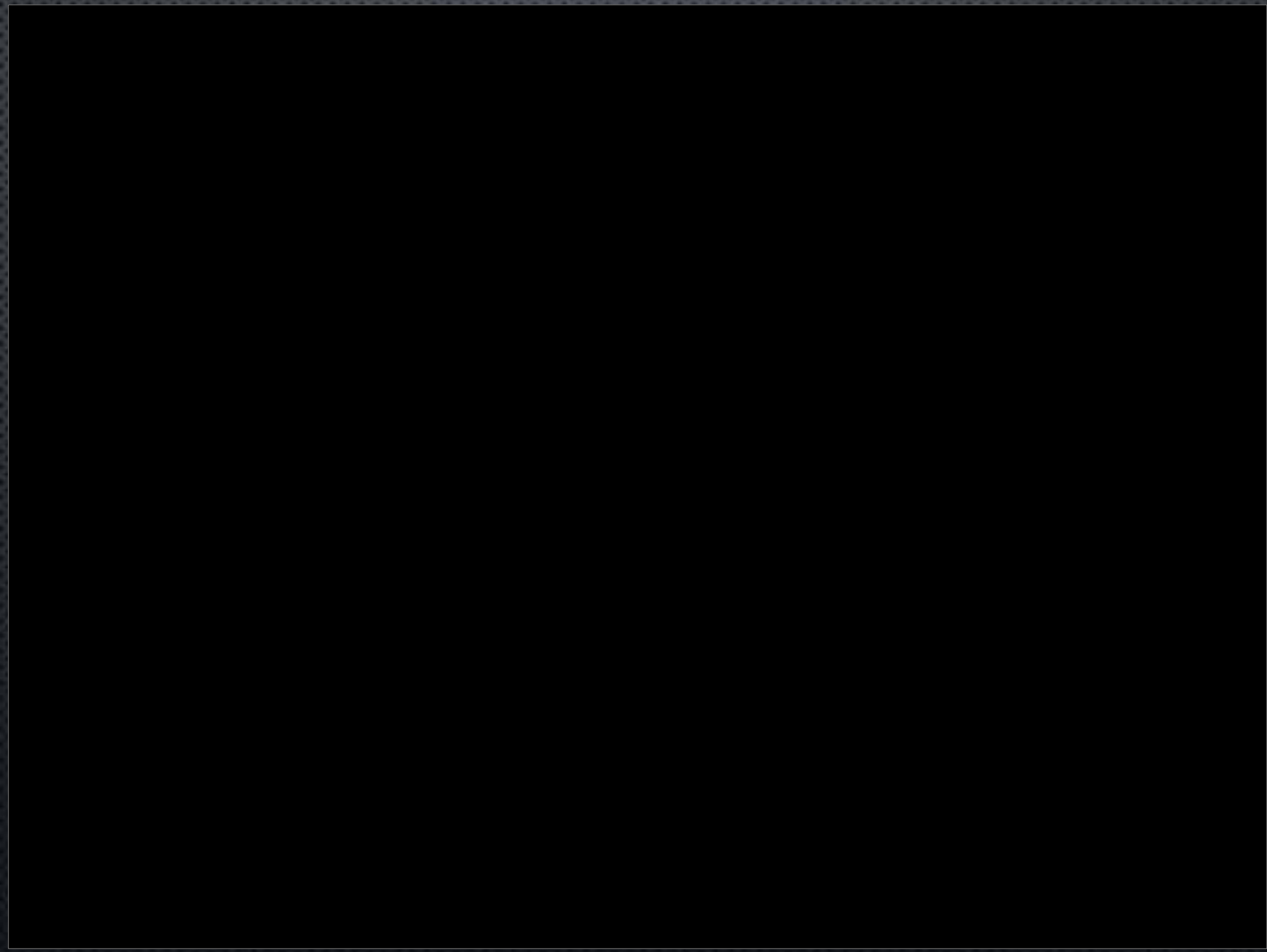


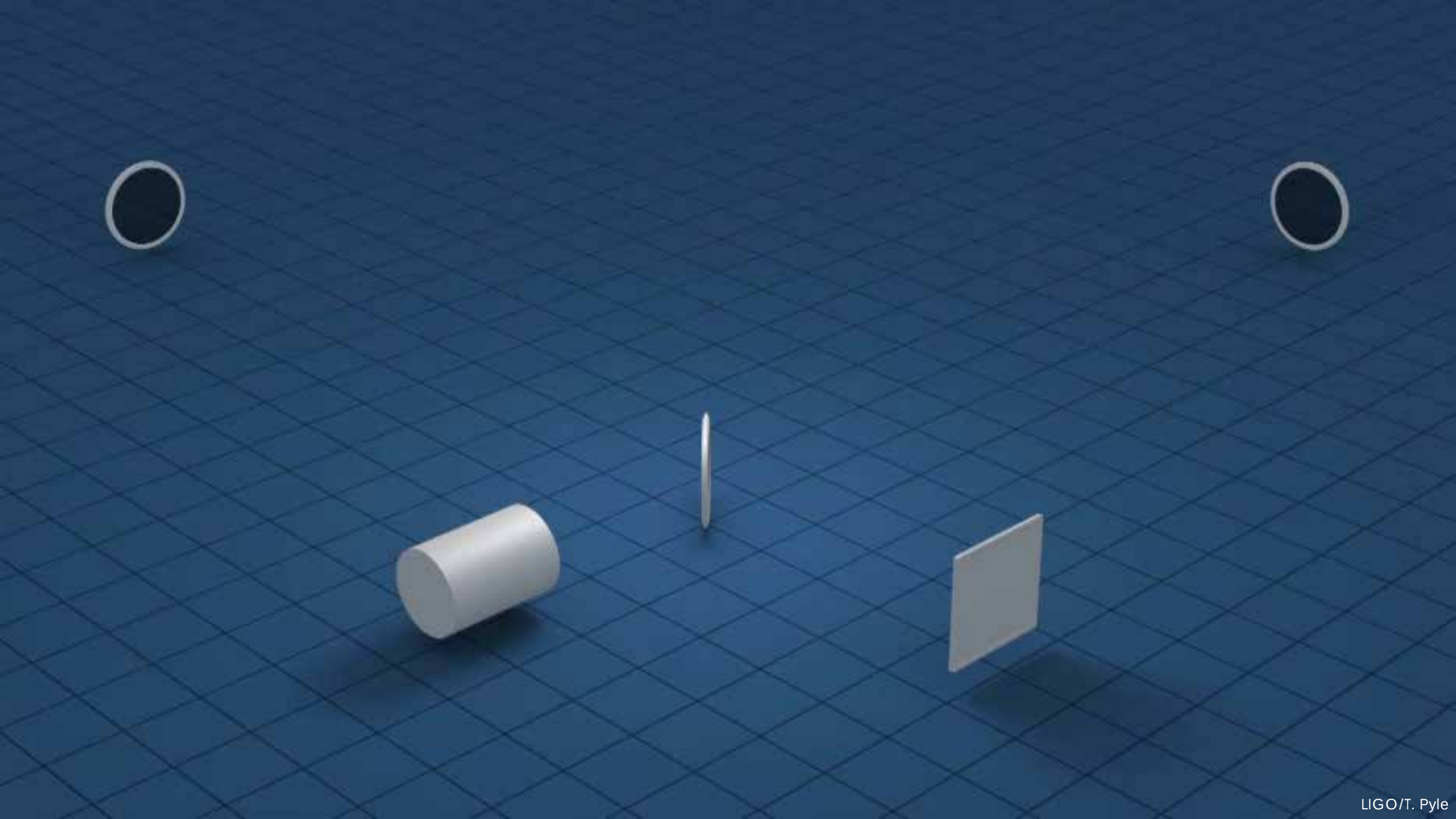
$$\times \frac{1}{1000}$$

$$h = 10^{-24}$$

Michelson Interferometer



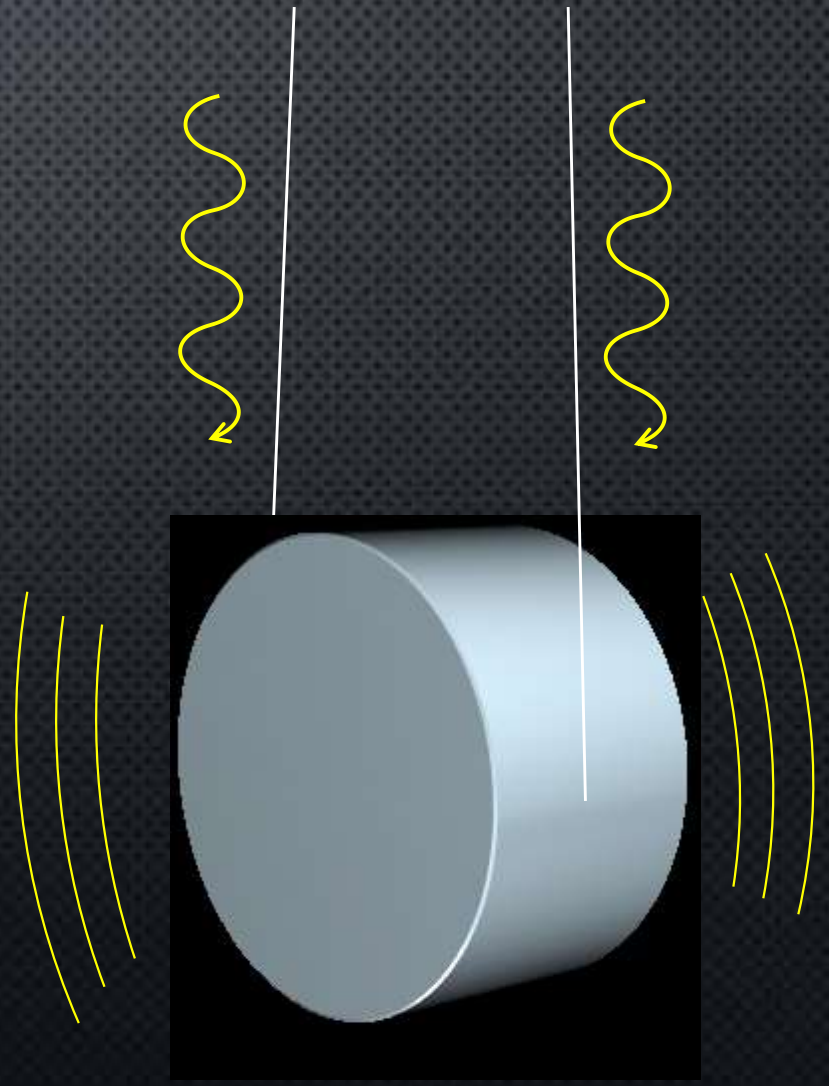



LIGO/T. Pyle

How far can we see ?

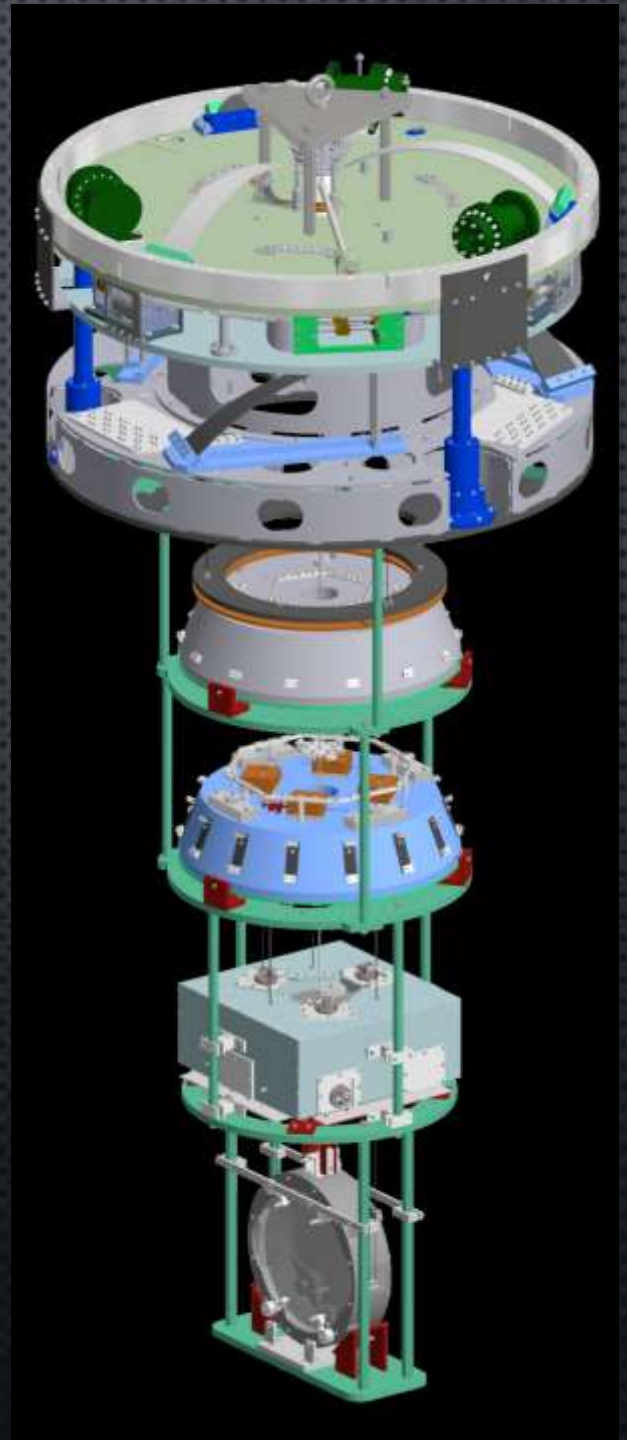
Signal Noise

Seismic Noise

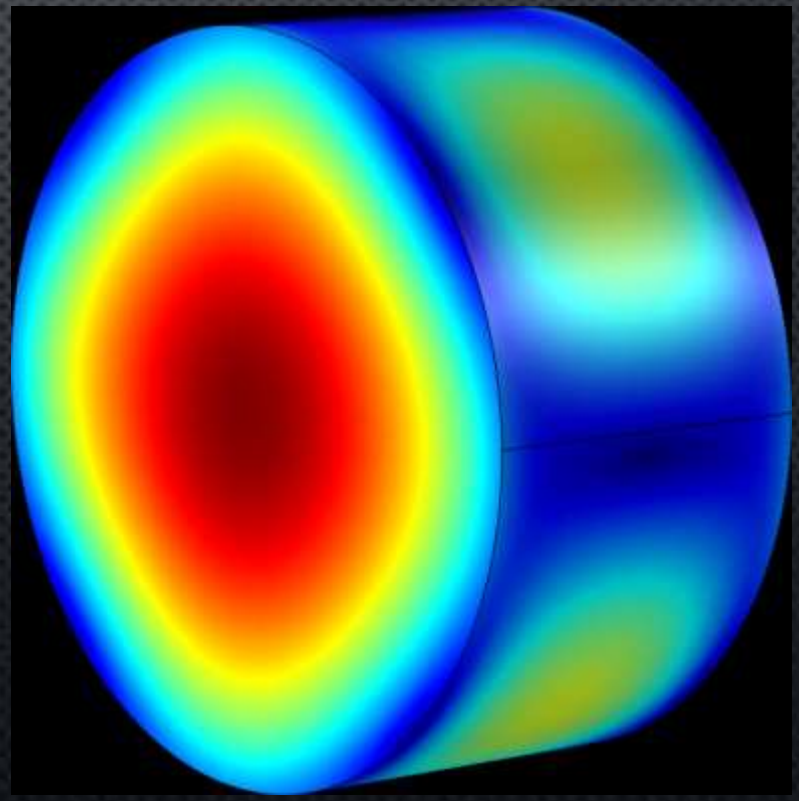


Multi-stage Vibration Isolation System

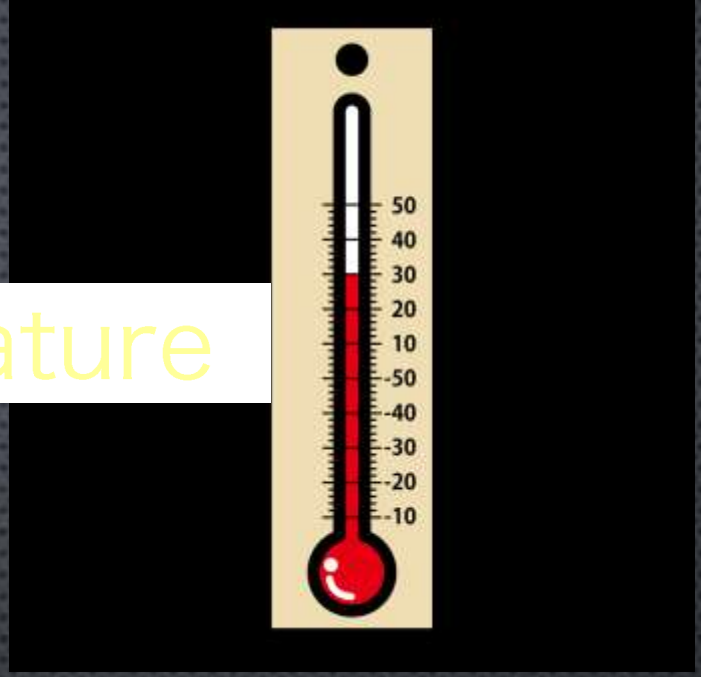
$$\frac{1}{10000000000}$$



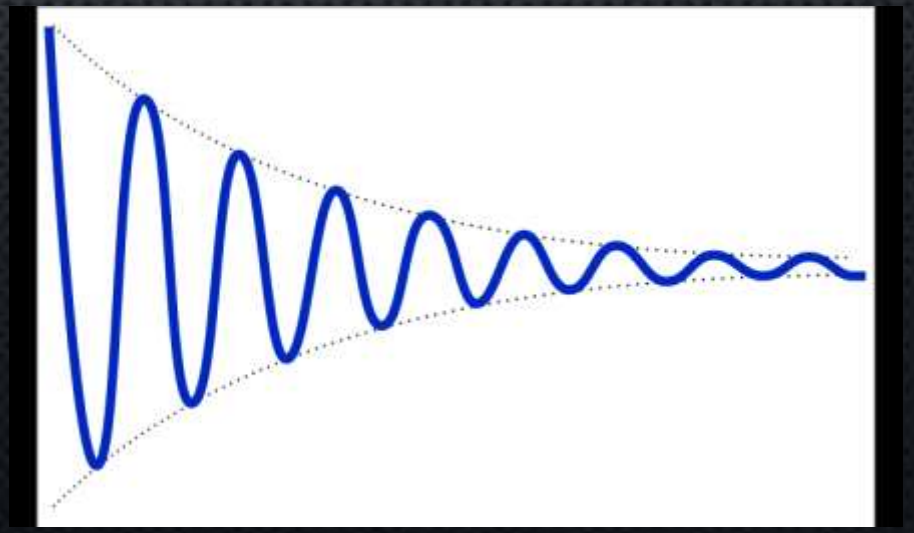
Thermal Noise



Temperature



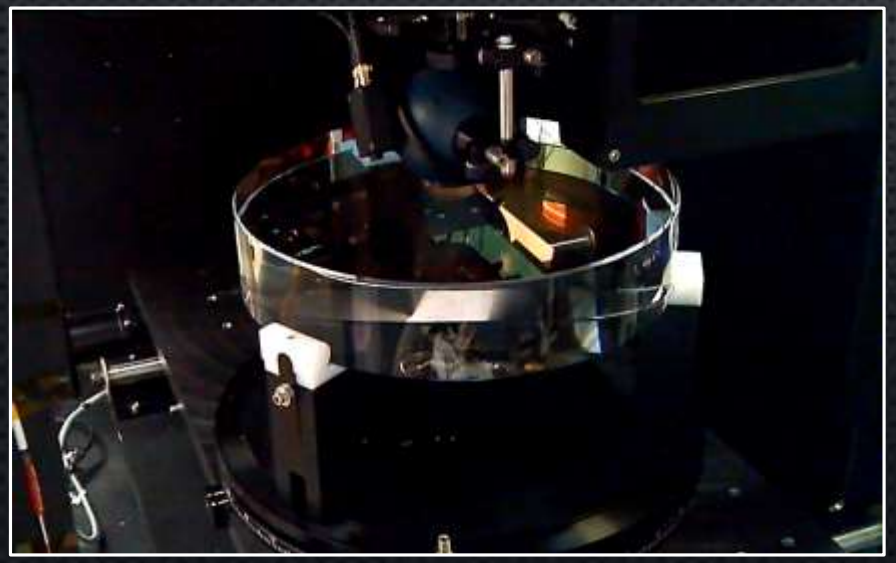
Mechanical energy loss



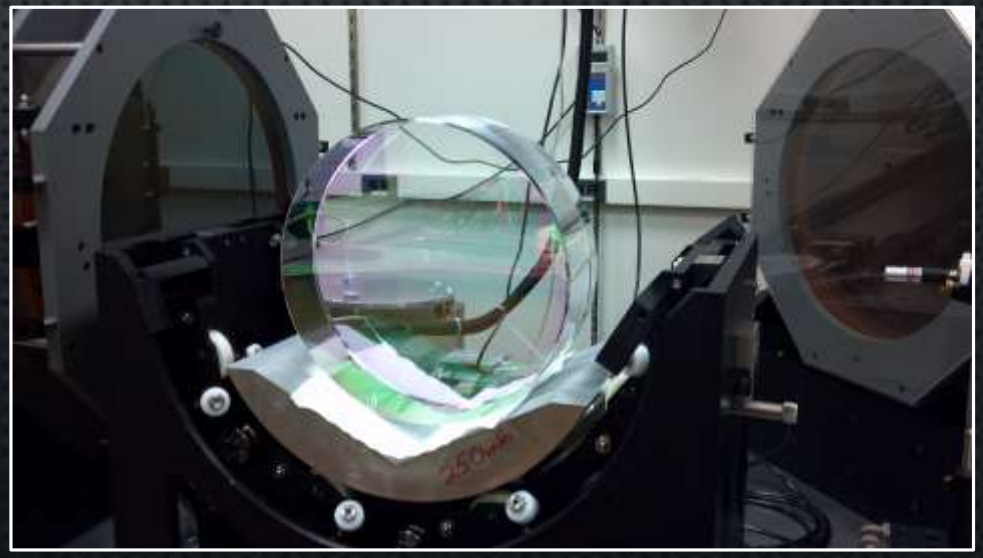
Fused Silica

Sapphire

Large low-loss mirrors

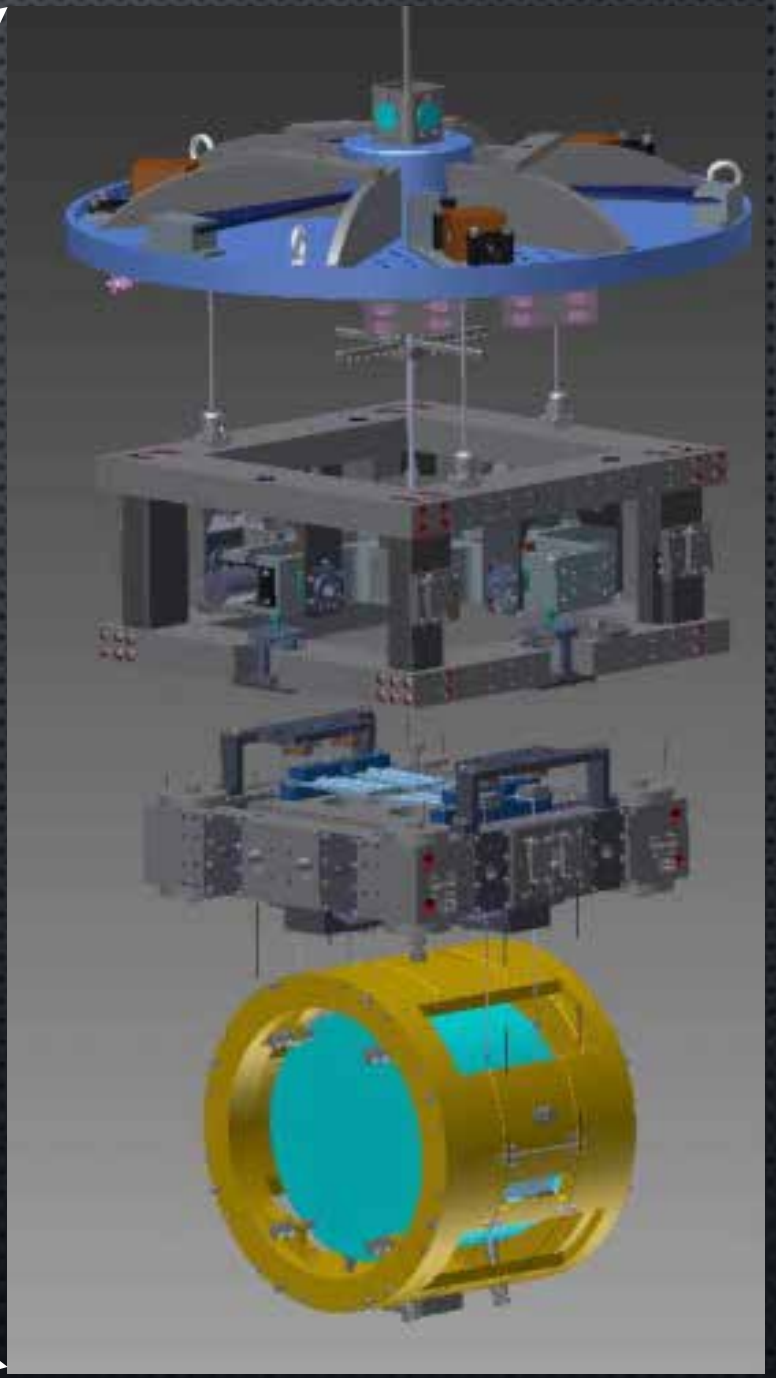


Beamsplitter(370mm dia) during coating characterization

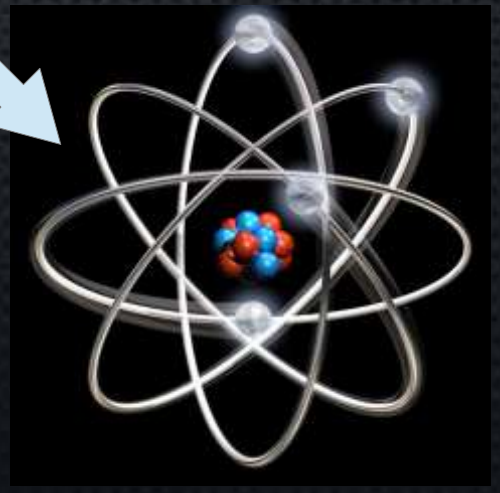


iKAGRA TM (250mm dia) during figure measurement

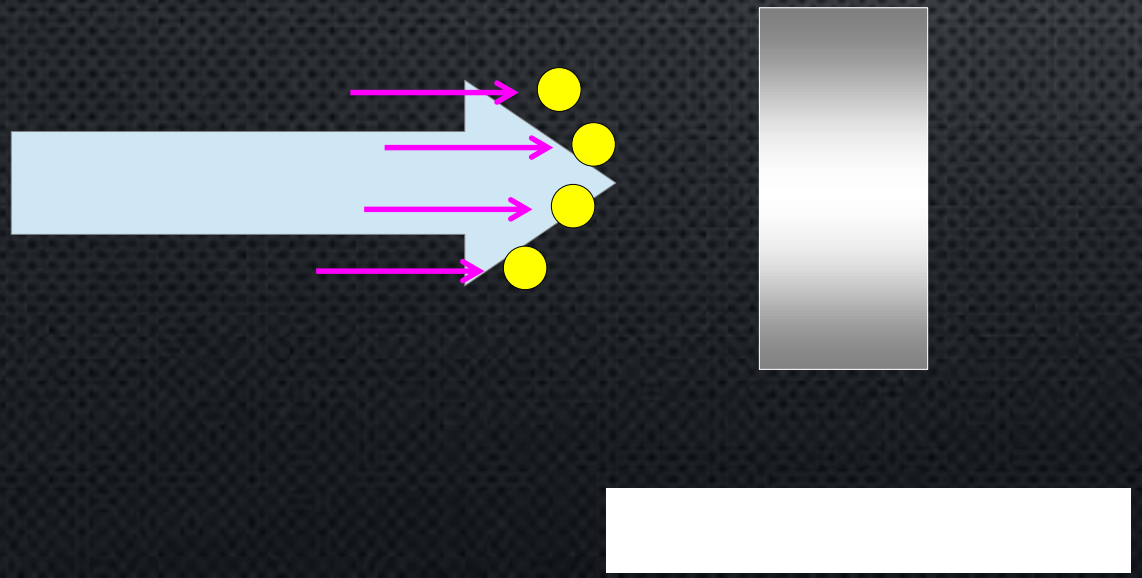
Cool down to 20K



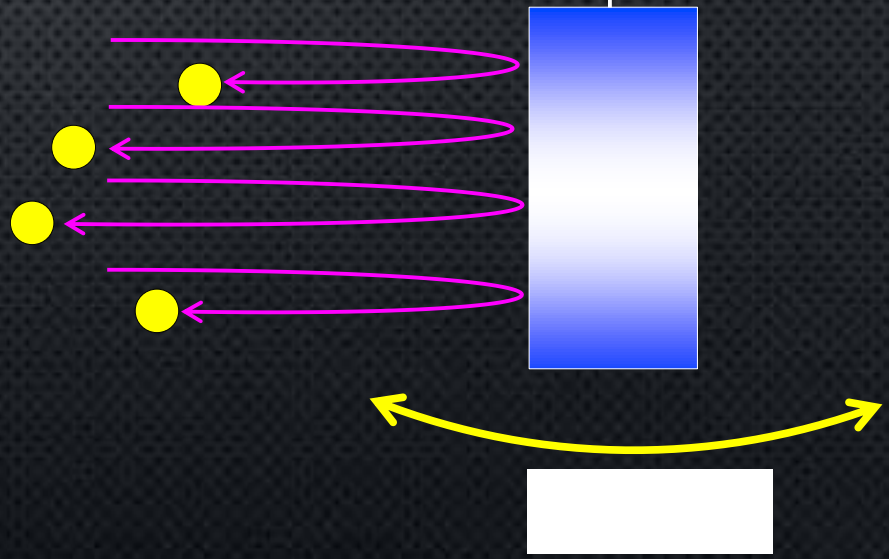
Quantum Mechanical Uncertainty Principle



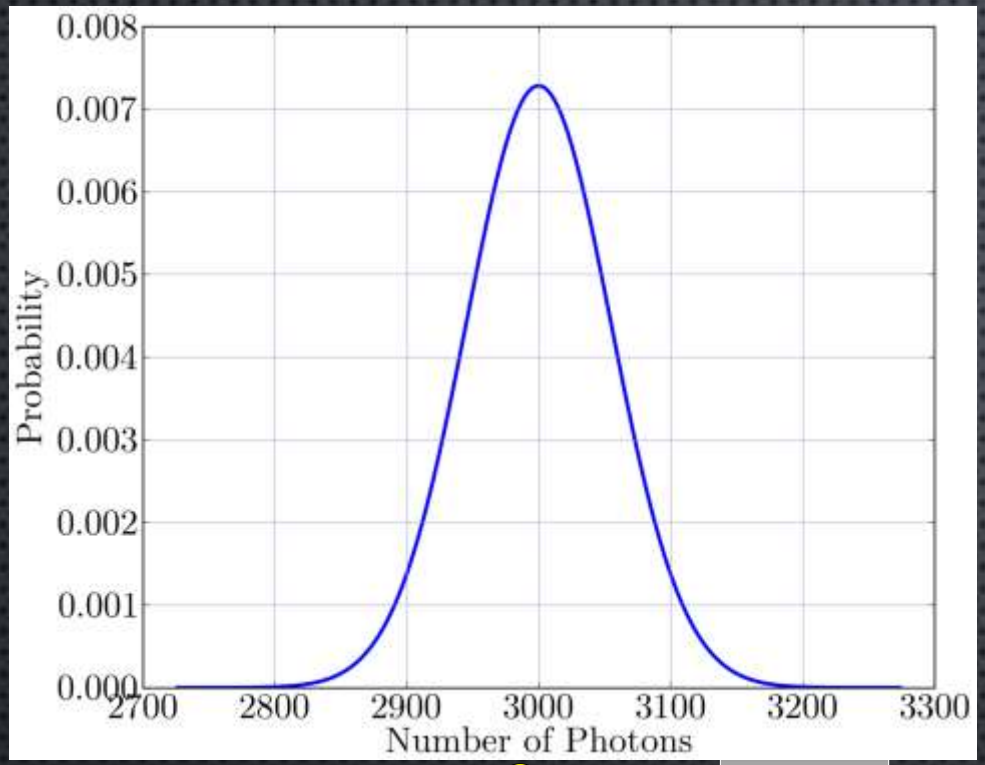
Shot Noise

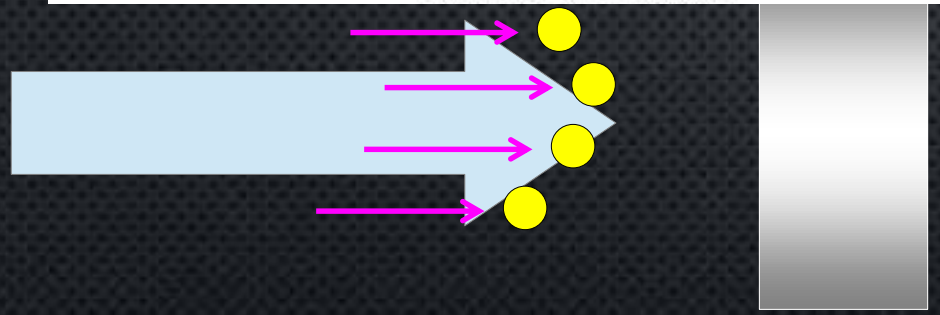


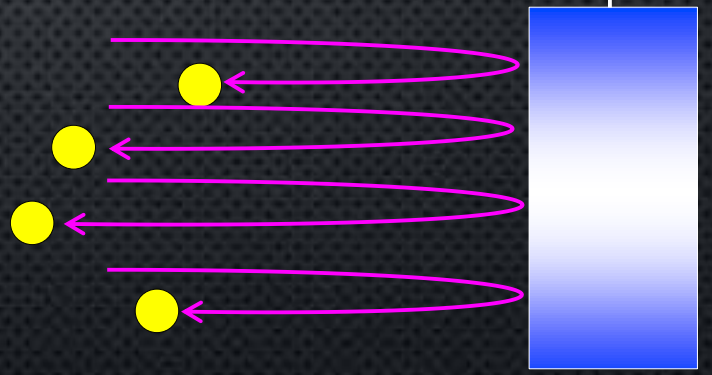
Radiation Pressure Noise



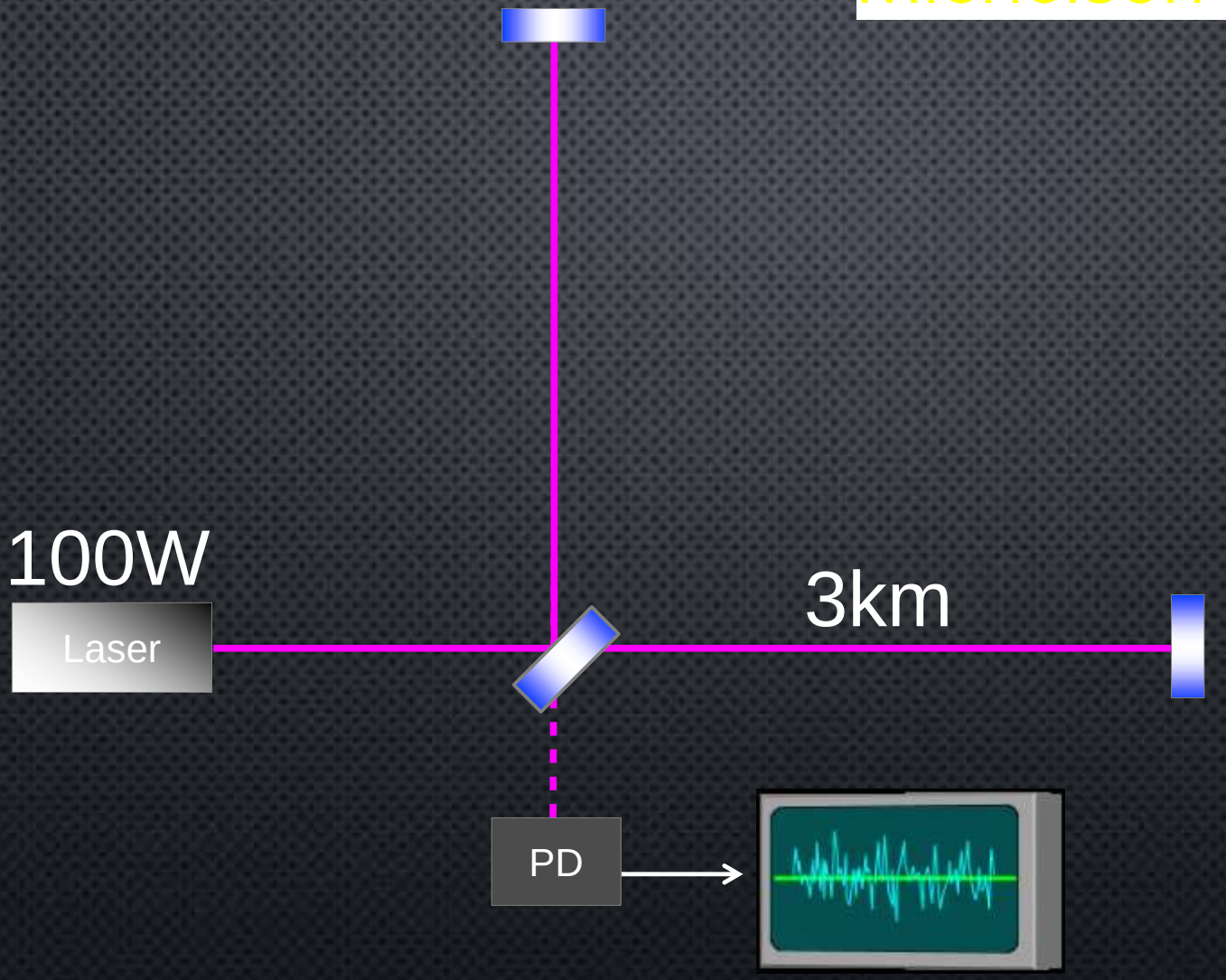
Radiation Pressure Noise





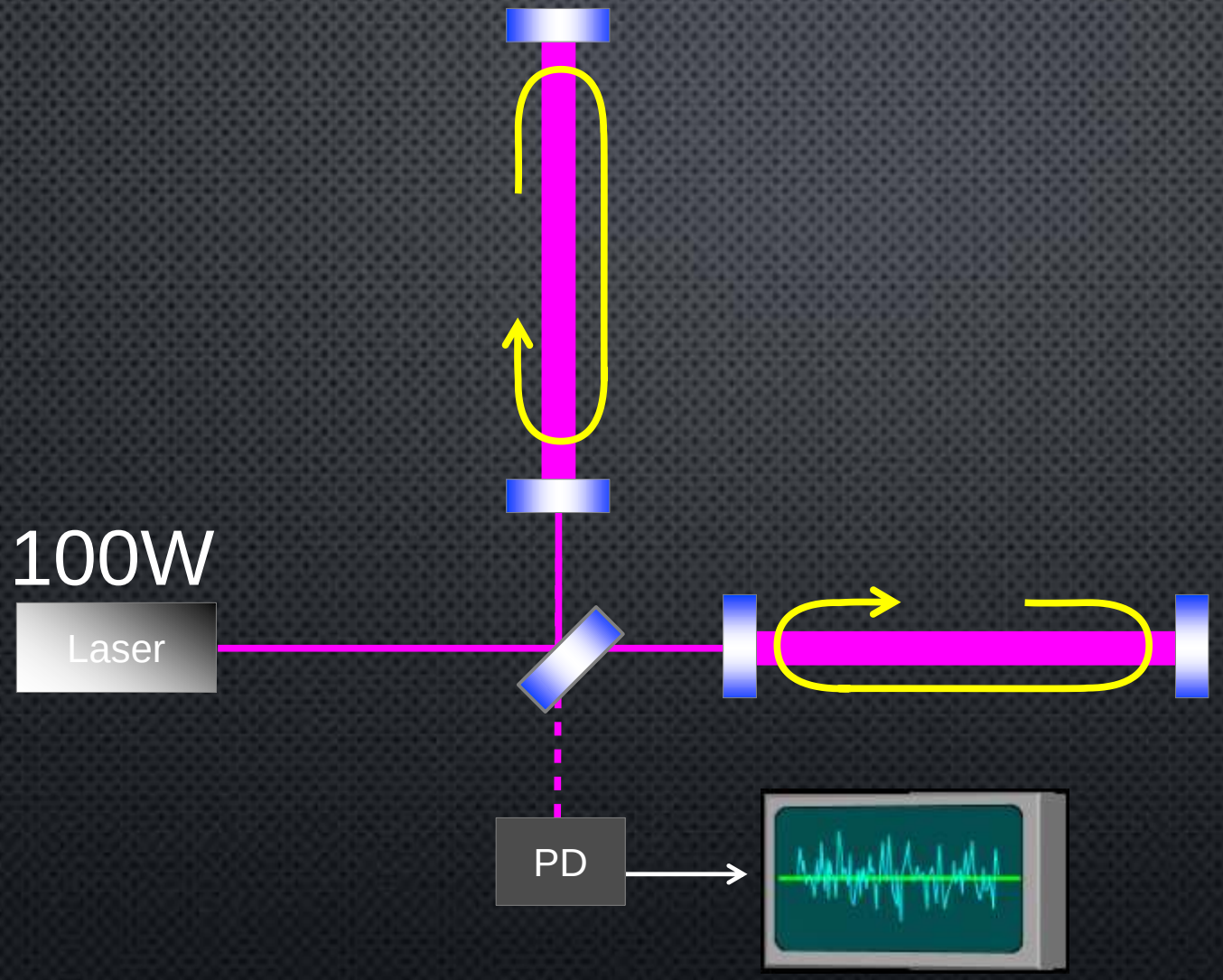


Michelson Interferometer

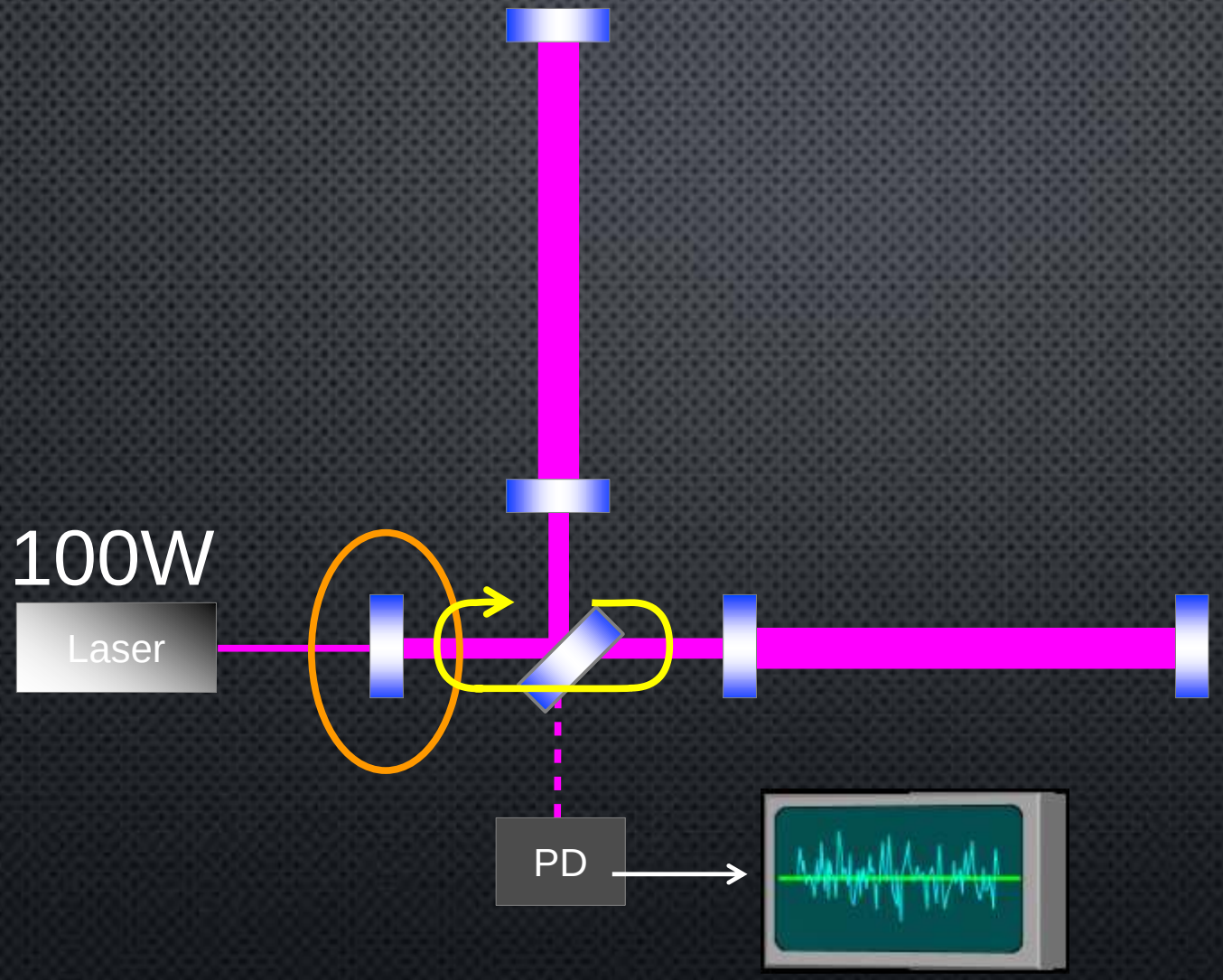


$$h = 2 \times 10^{-21}$$

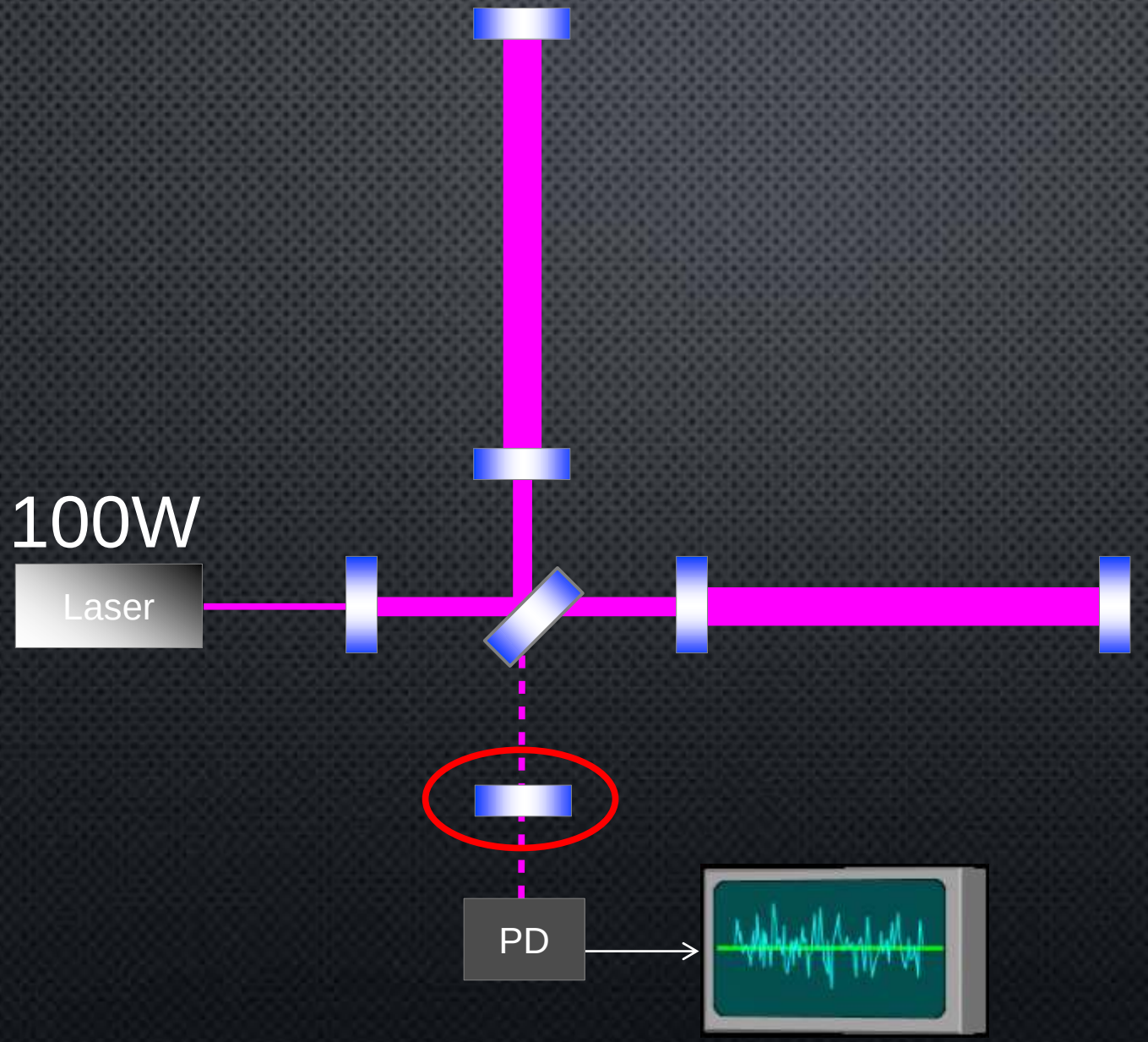
Fabry-Perot Michelson



Power Recycling

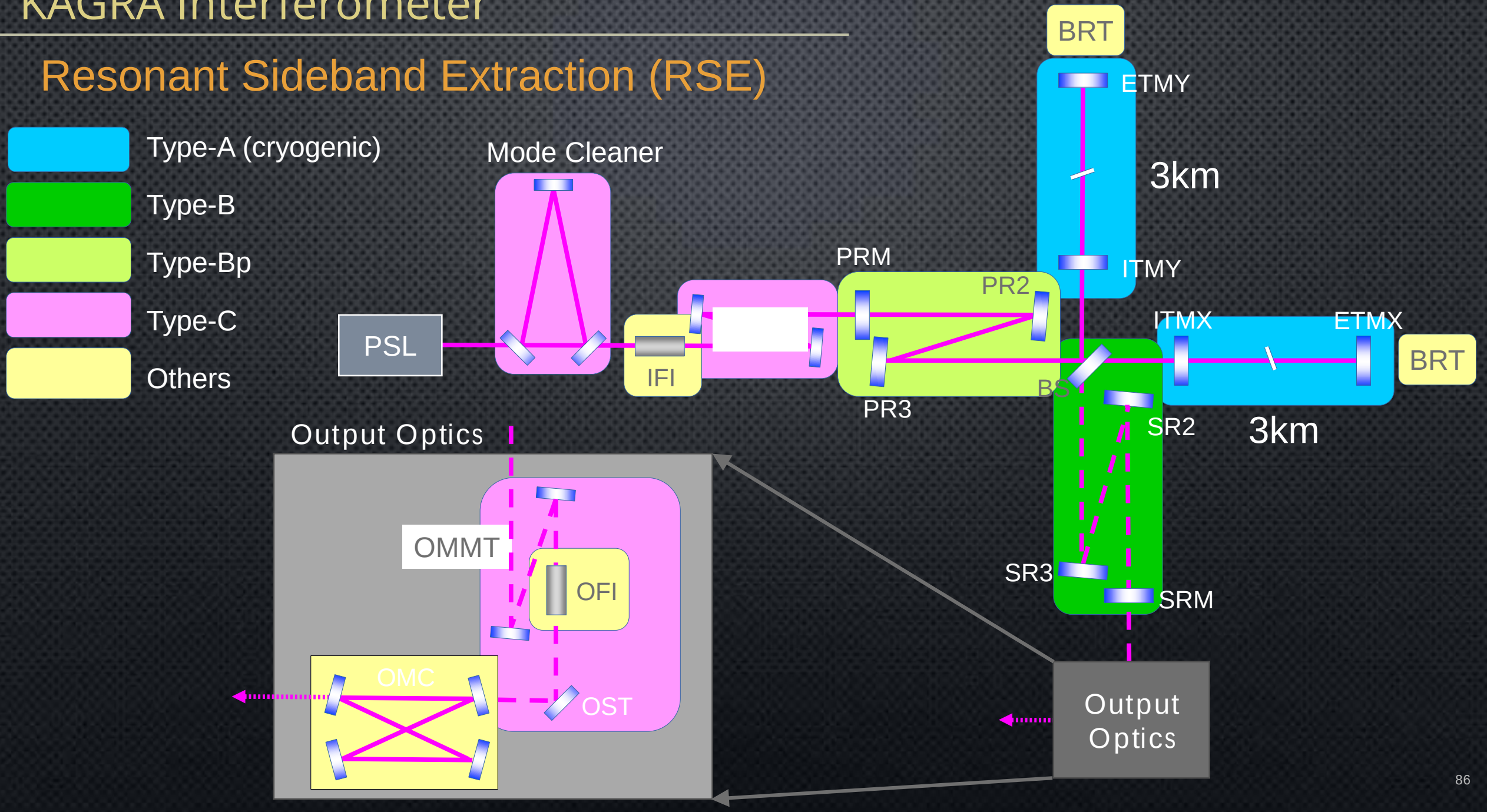


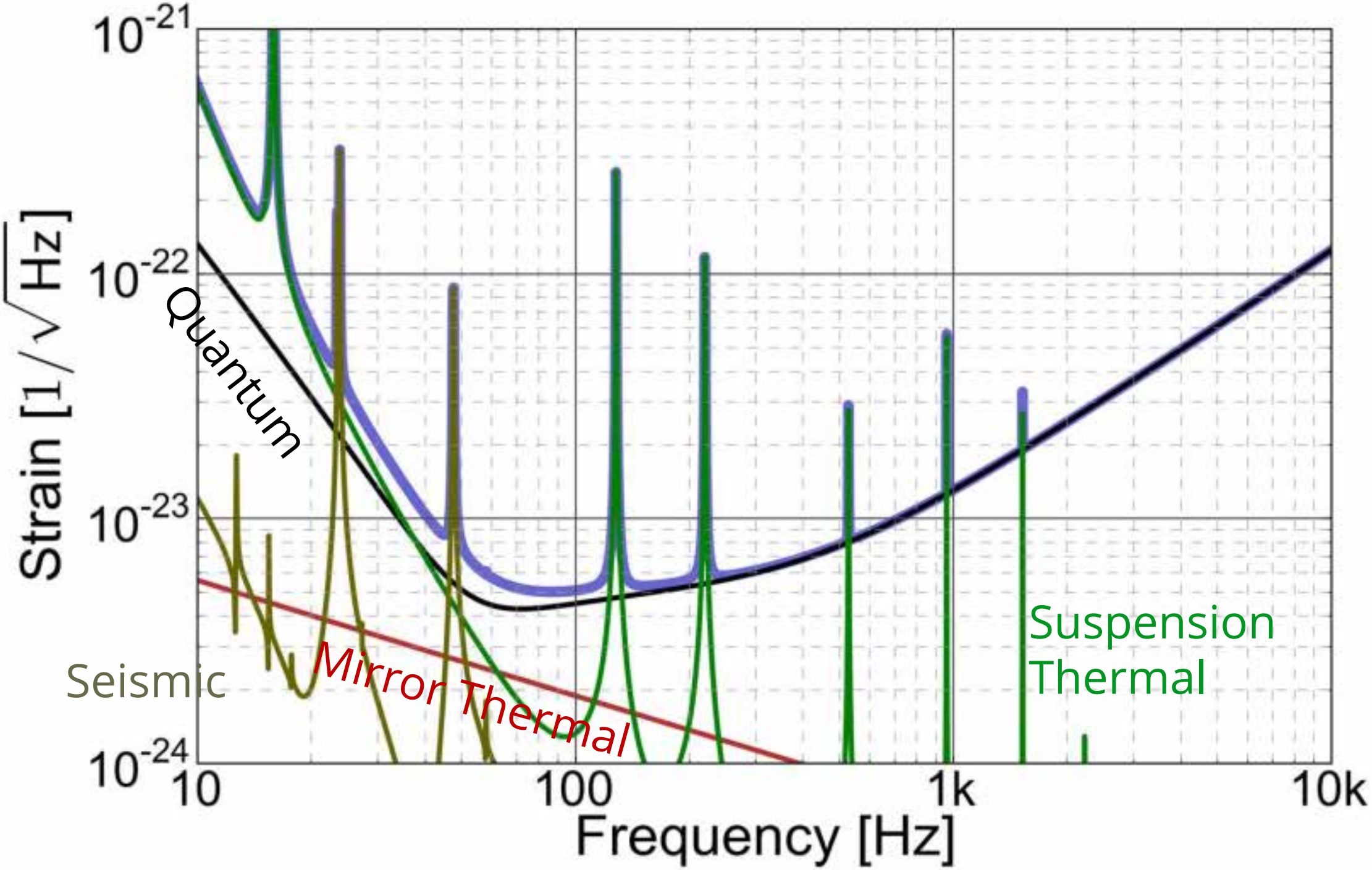
Resonant Sideband Extraction (RSE)



KAGRA Interferometer

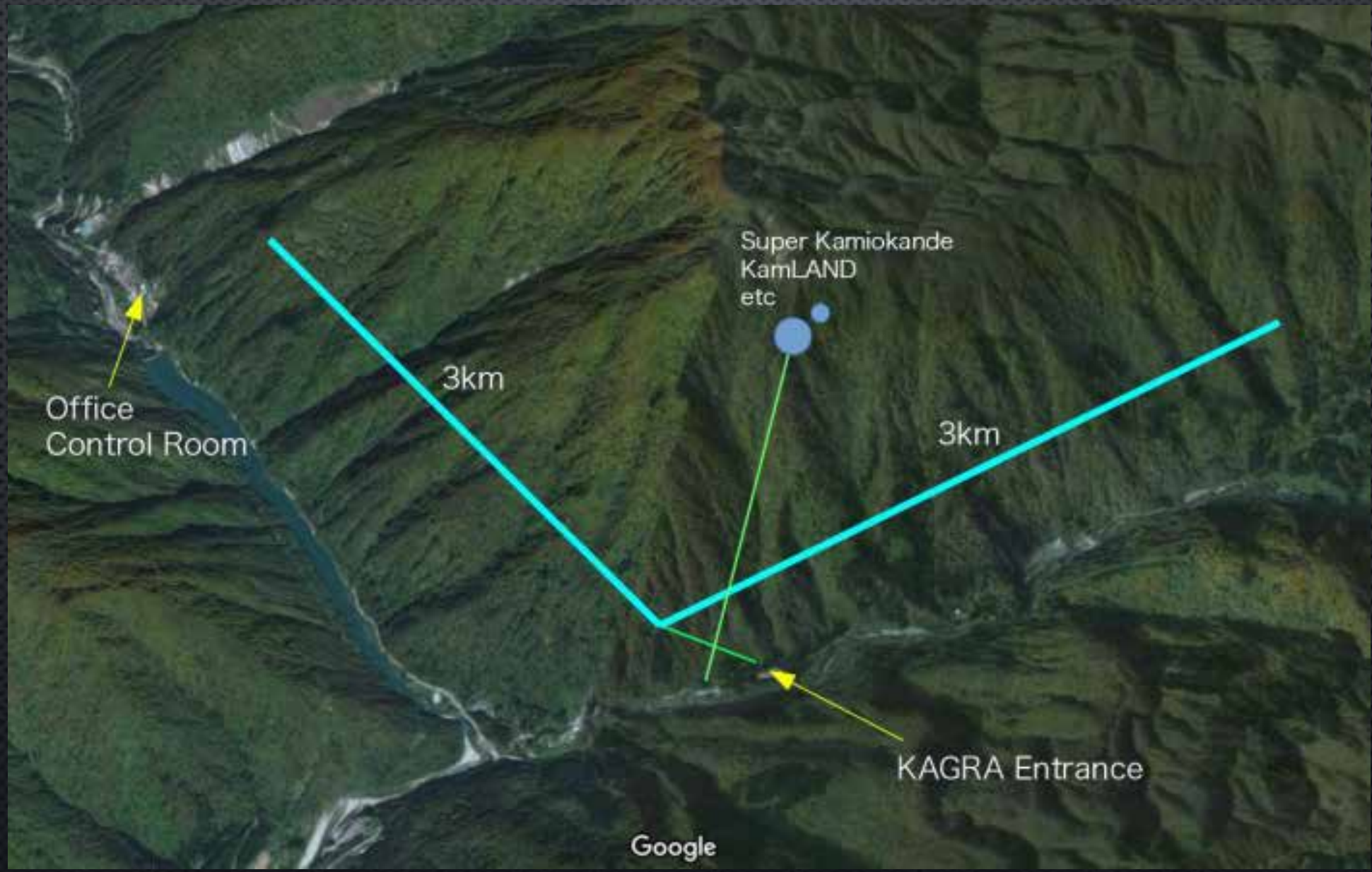
Resonant Sideband Extraction (RSE)

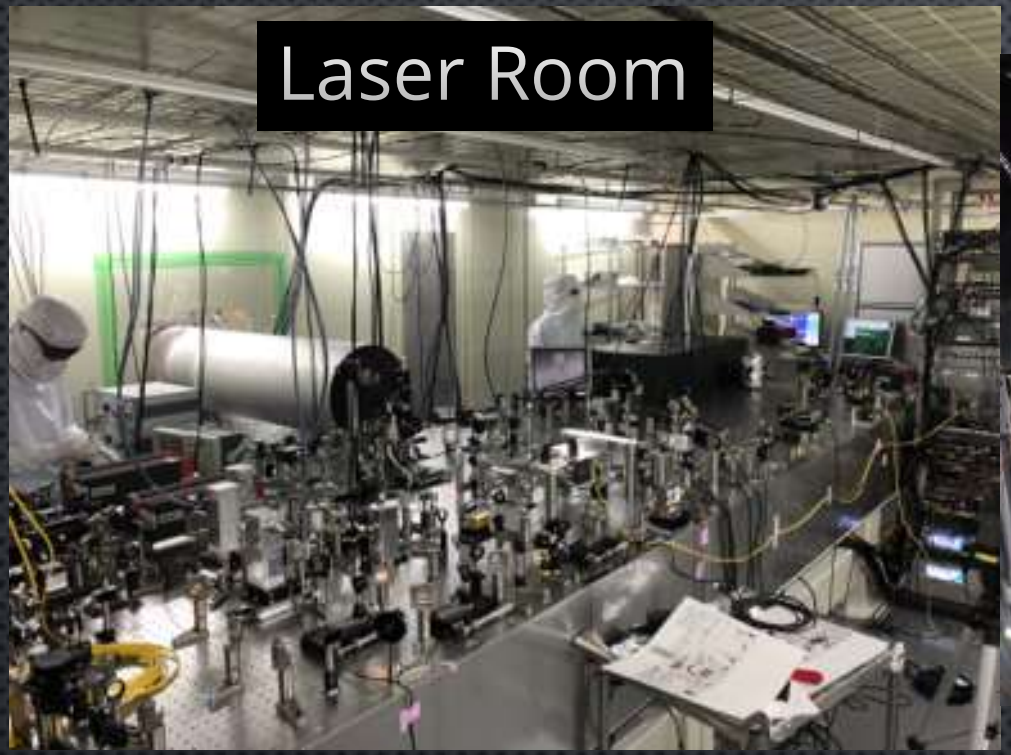



10^{-21}
10^{-22}
10^{-23}
10^{-24}
Strain [$1/\sqrt{\text{Hz}}$]
Quantum
Seismic
Mirror Thermal
Suspension
Thermal
10
100
1k
10k
Frequency [Hz]

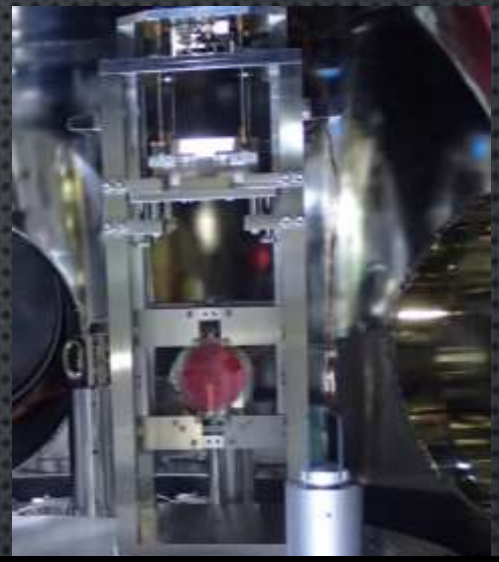
The KAGRA Project

- Over 300 collaborators
- Over 70 institutes from around the world

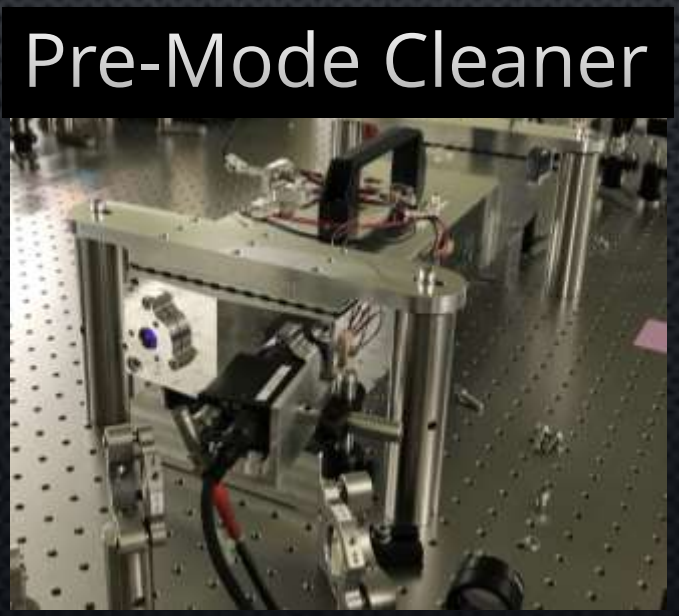

Super Kamiokande
KamLAND
etc
3km
3km
Office
Control Room
KAGRA Entrance
Google

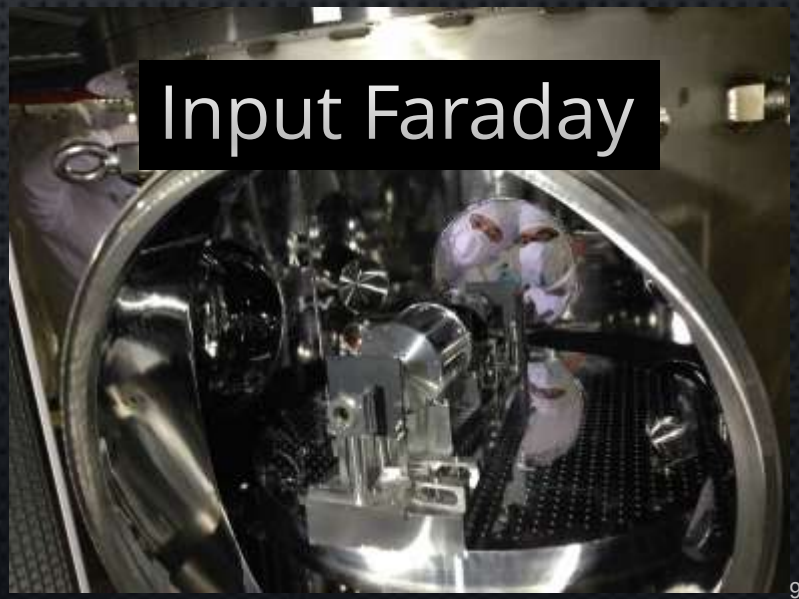

Laser Room

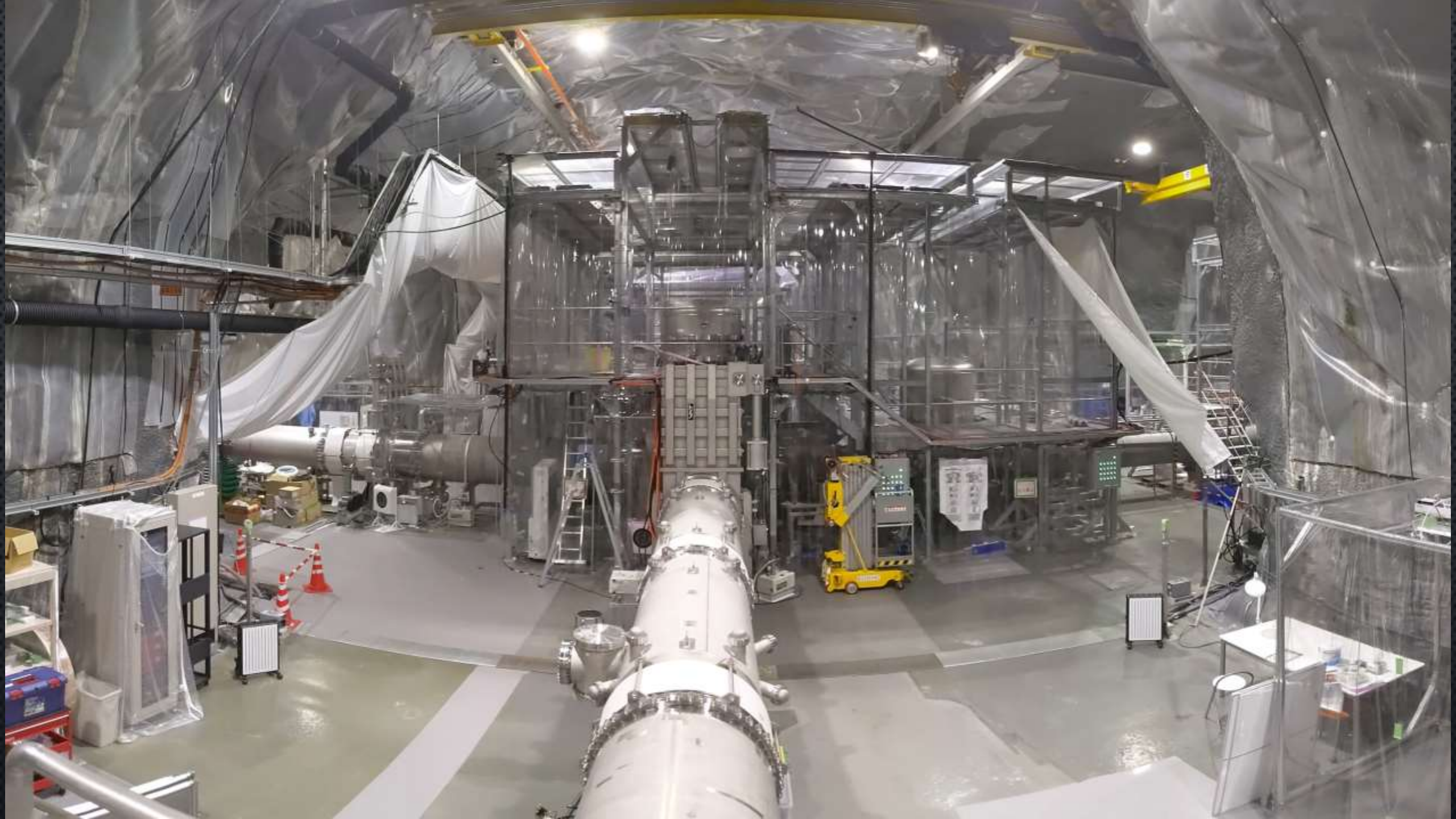

Mode Cleaner


Mode-Matching Telescope

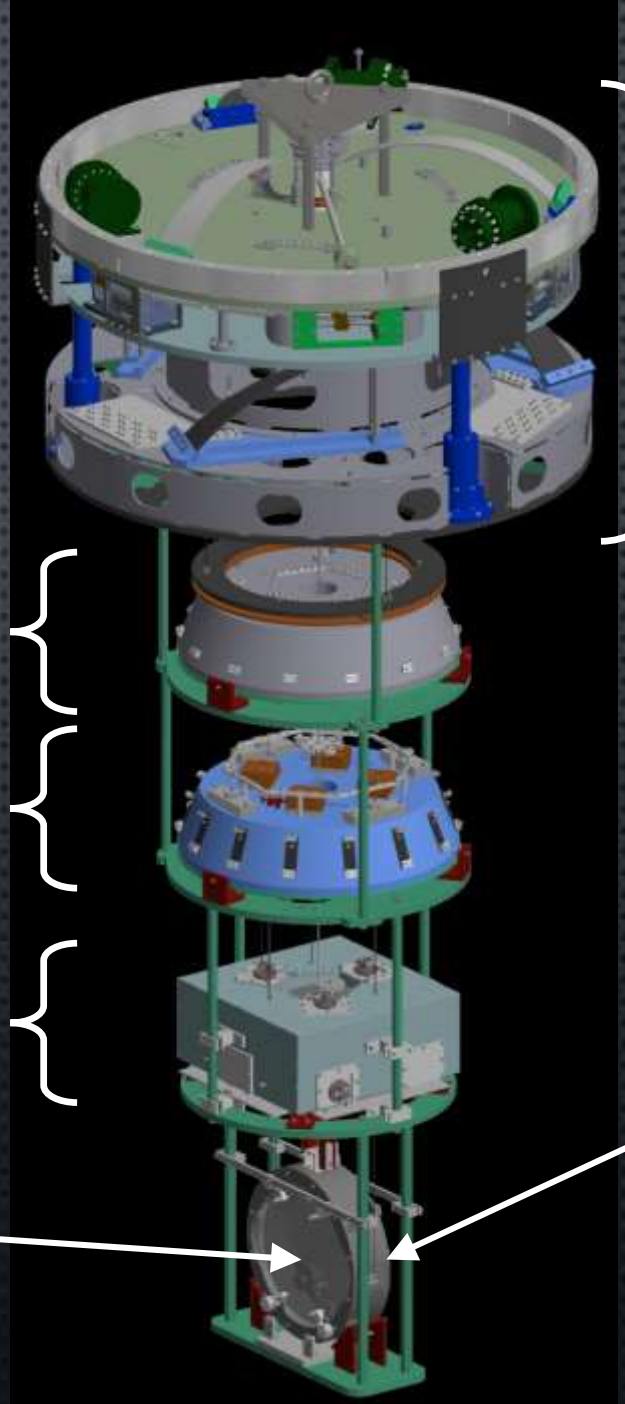

Reference Cavity

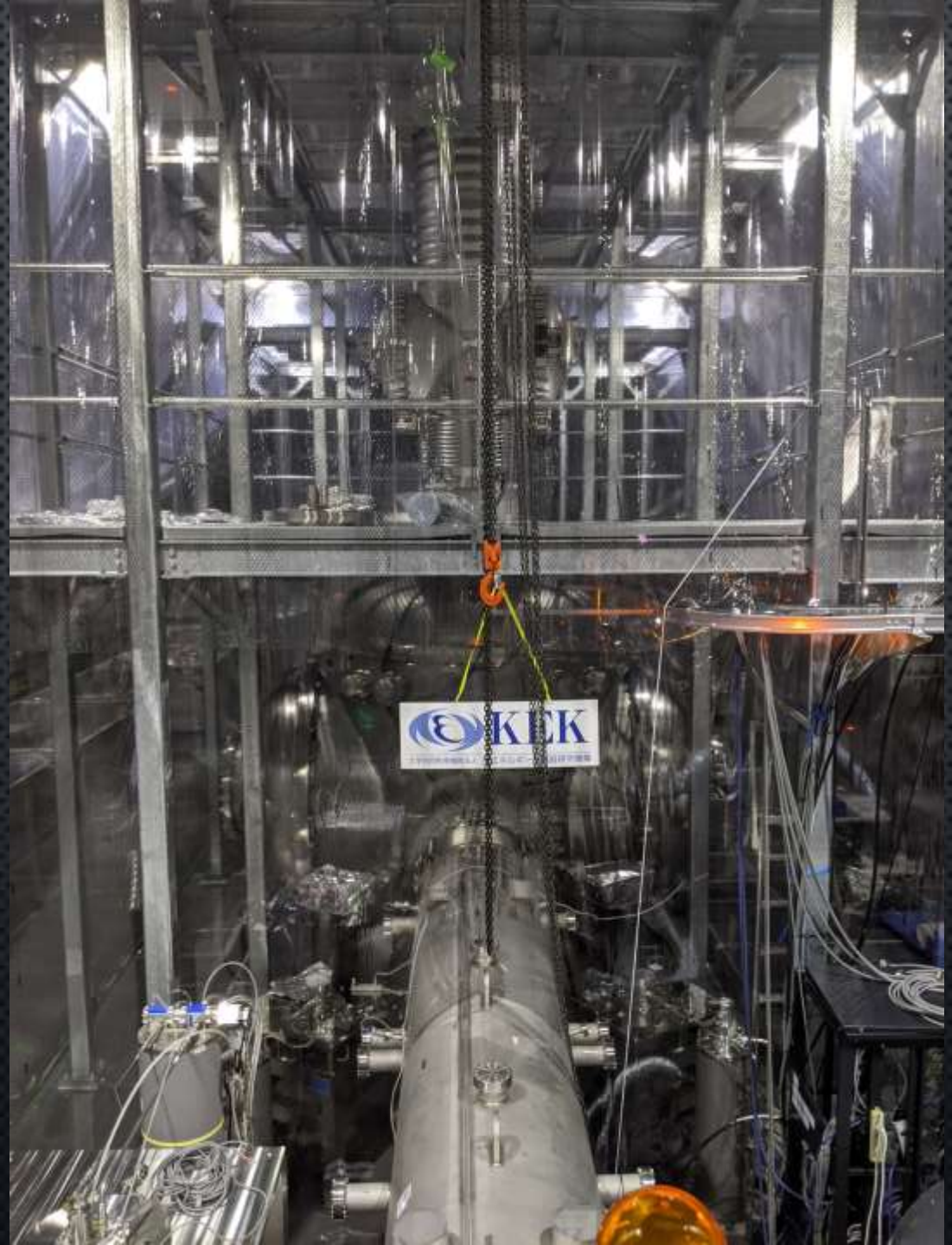

Pre-Mode Cleaner


Input Faraday



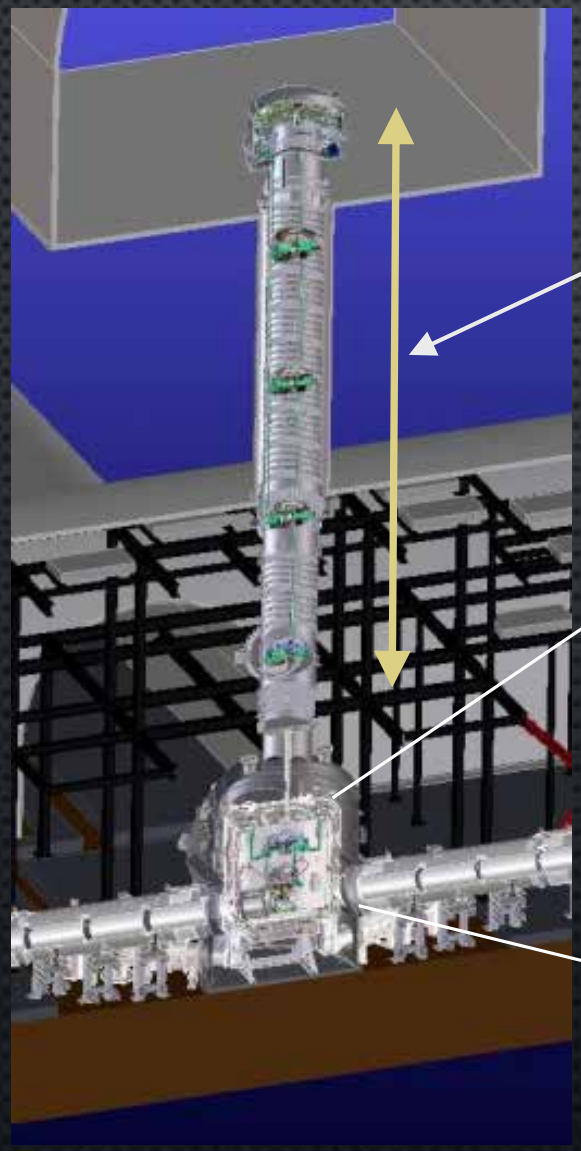
Beam Splitter Suspension




KEK

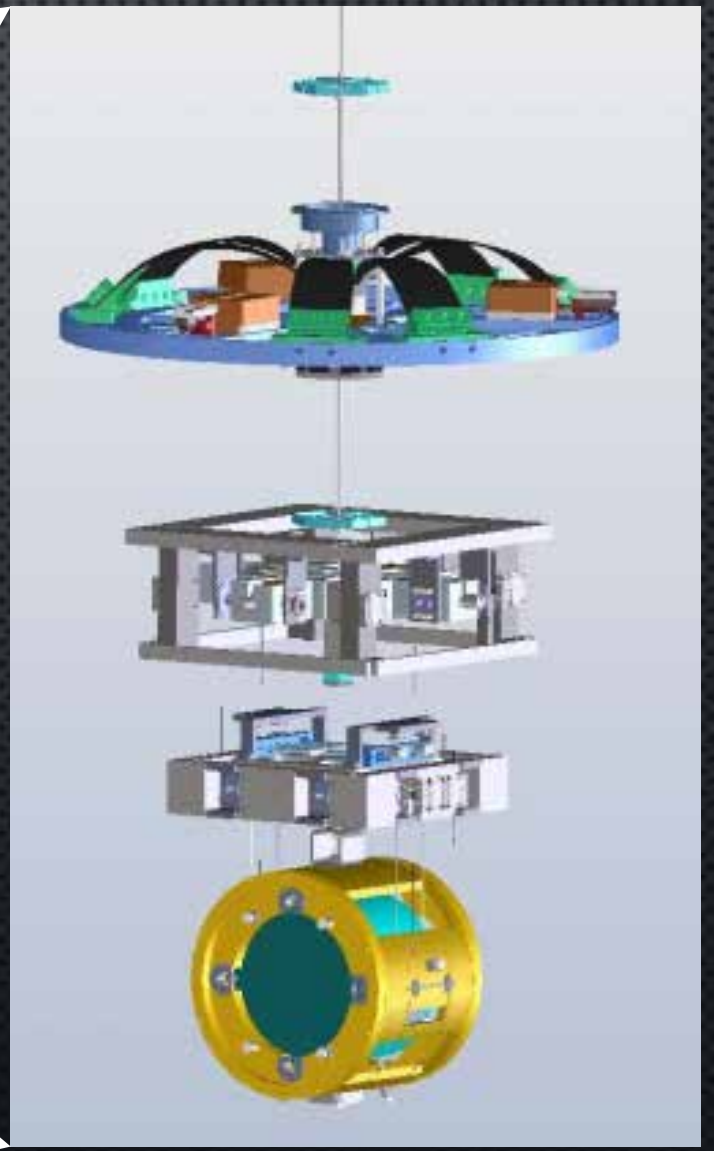
Type-A + Cryogenic Suspension

14m

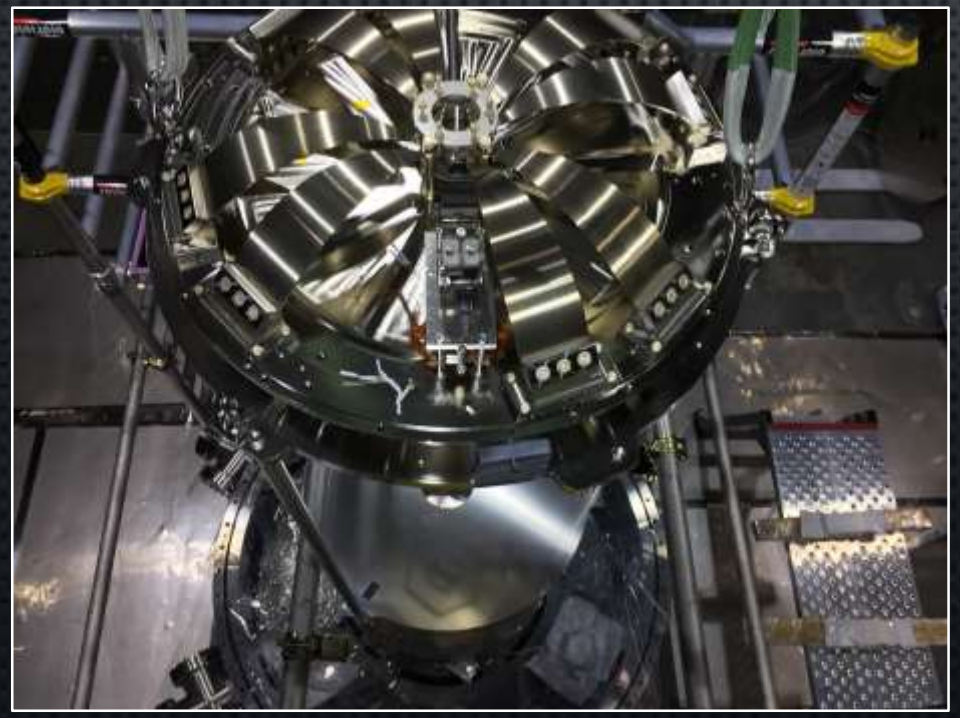


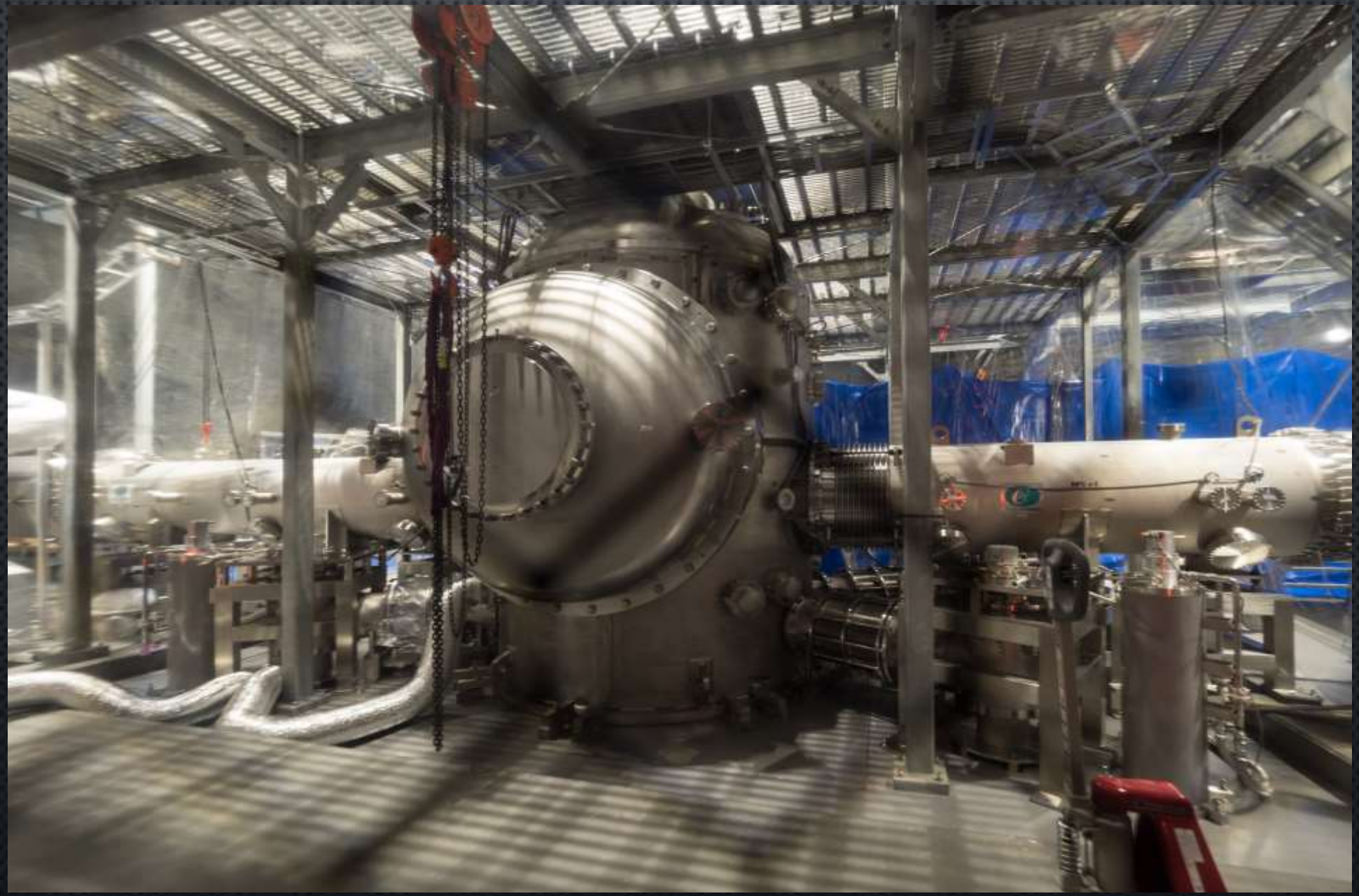
Type-A
(room temp.)

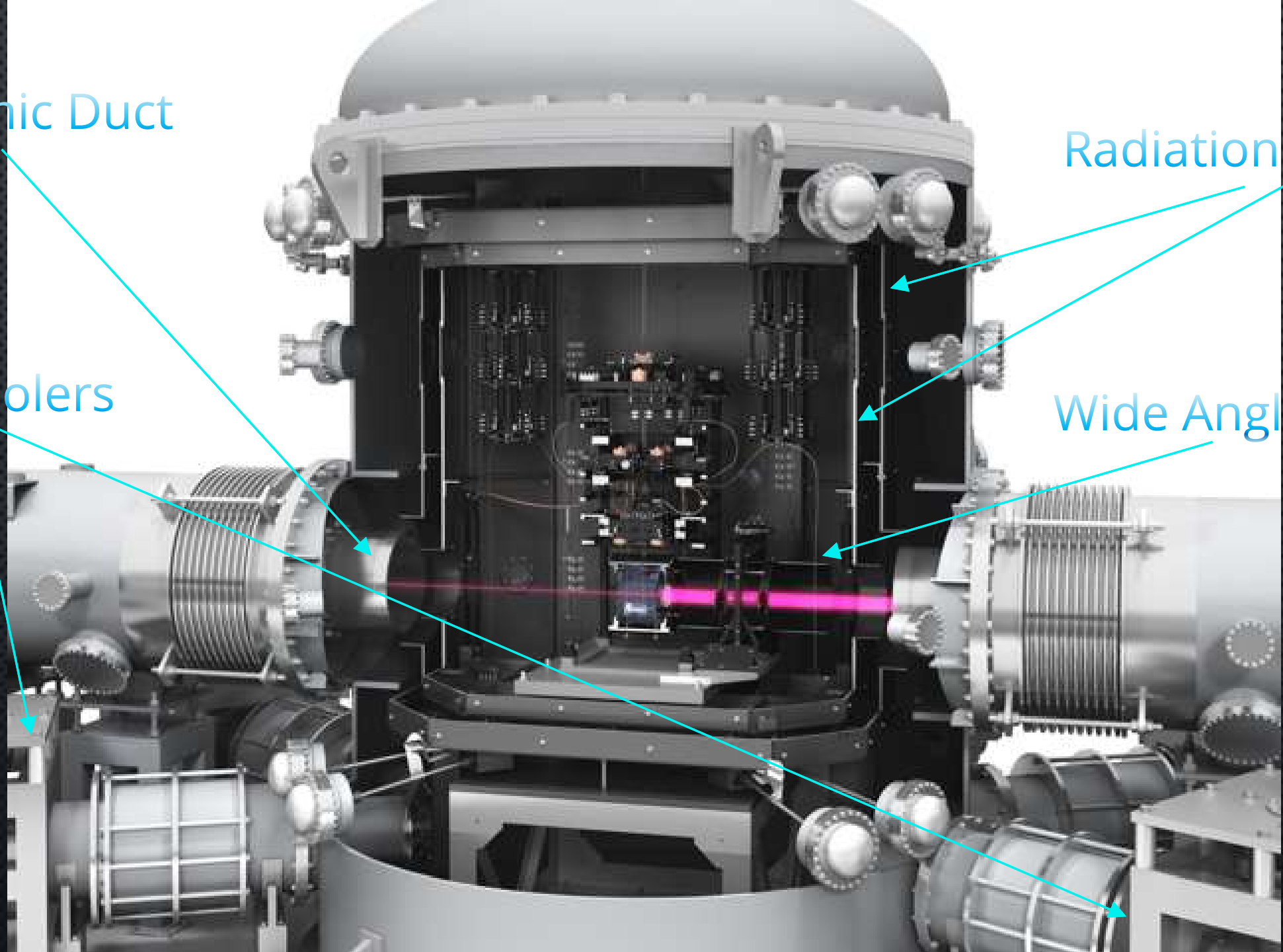
Cryo-Payload



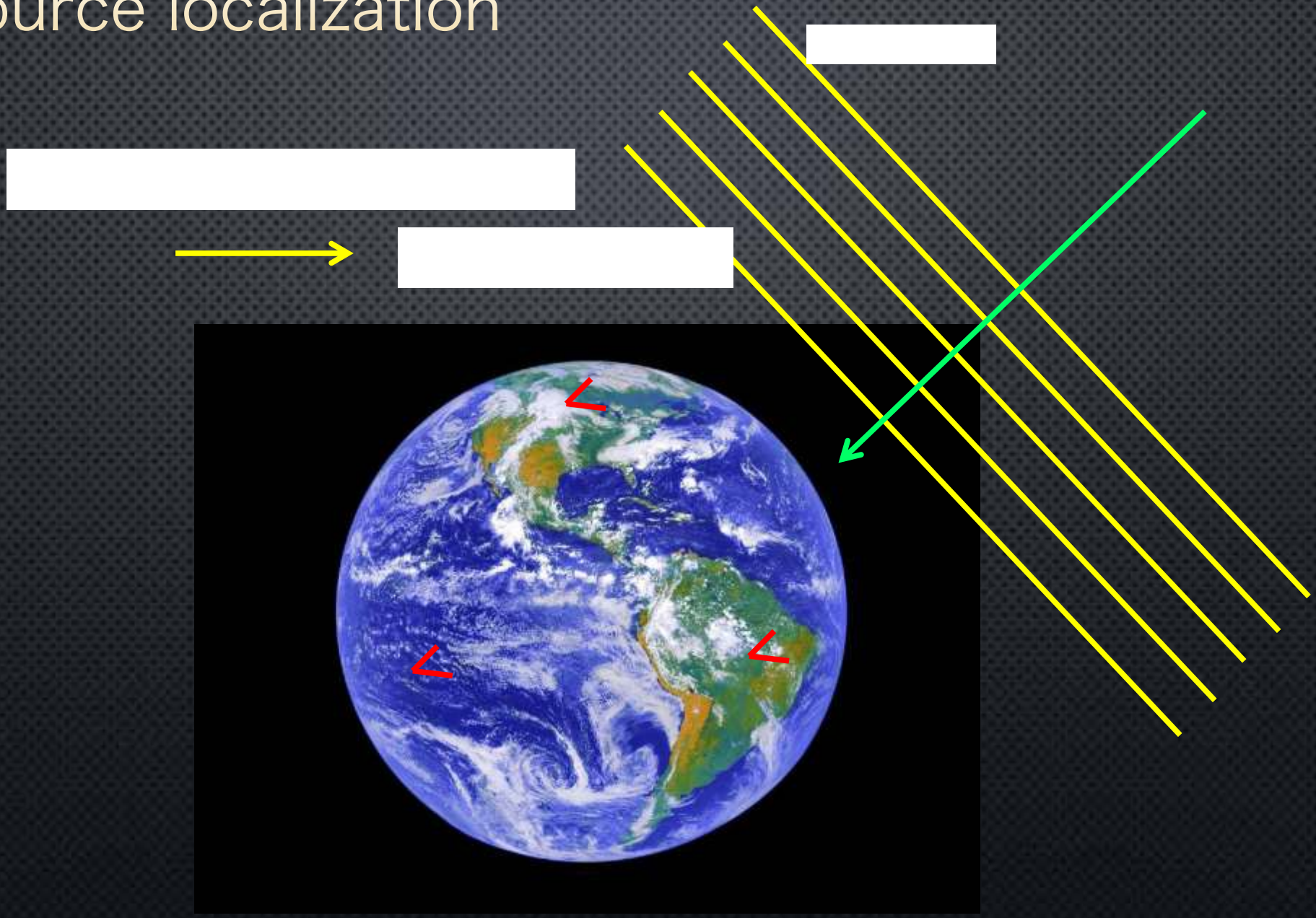
Type-A Suspension Installation

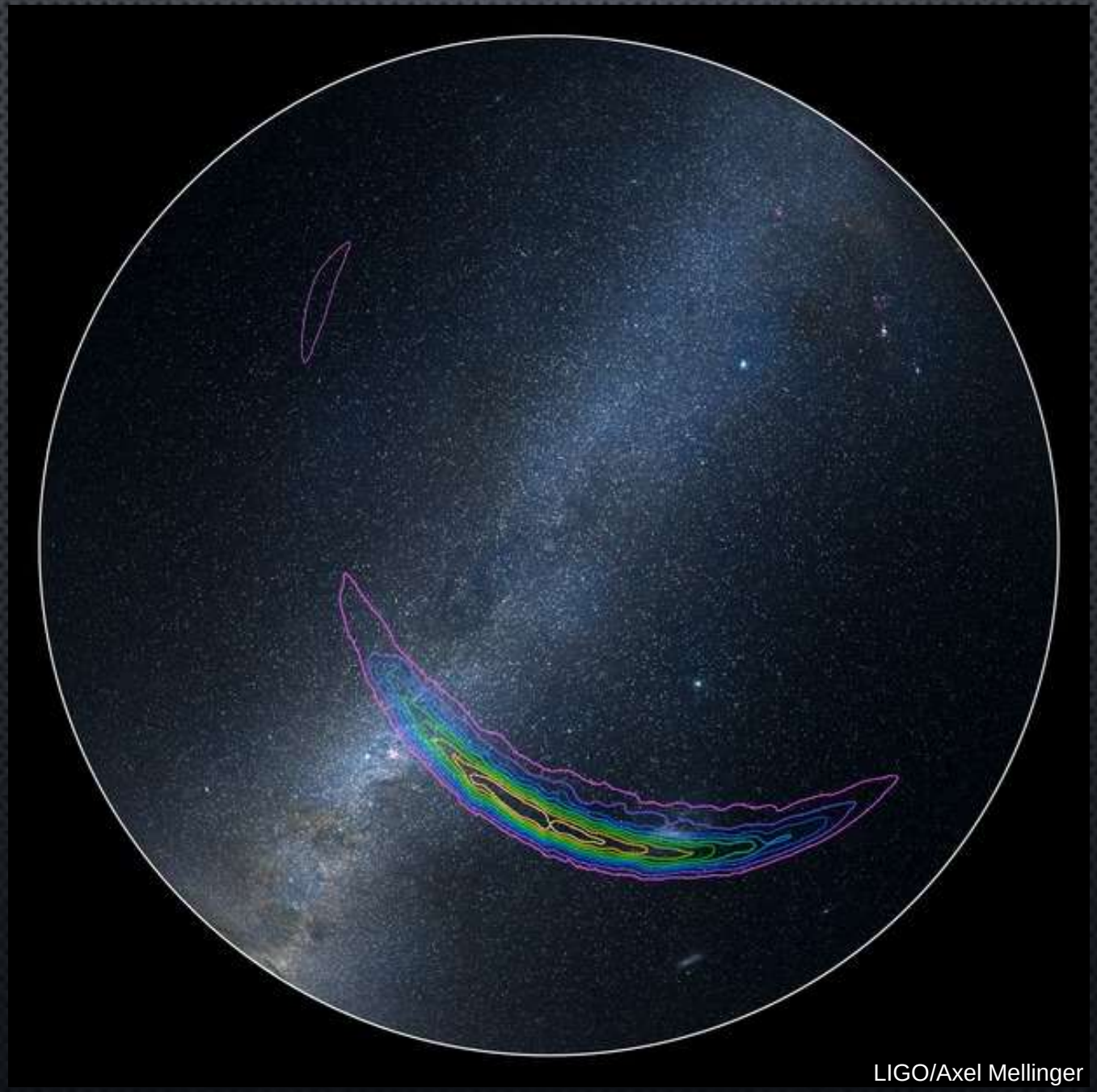




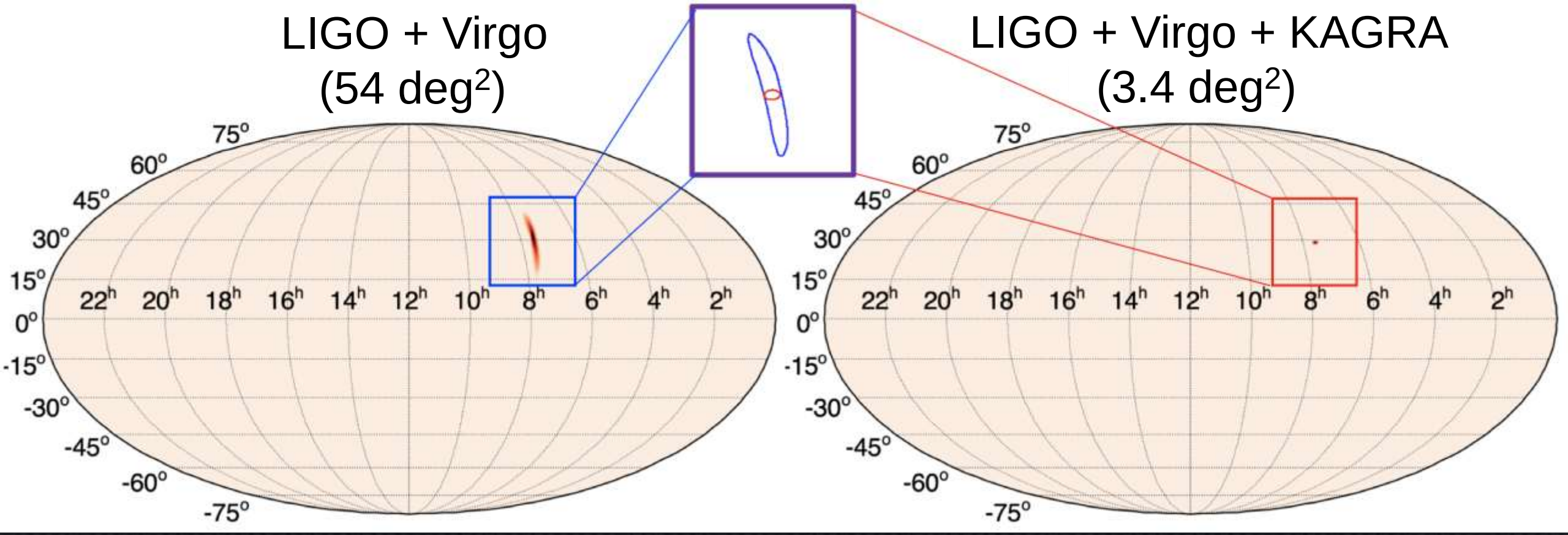

Cryogenic Duct
Radiation Shields
Cryo-Coolers
Wide Angle Baffle

GW source localization

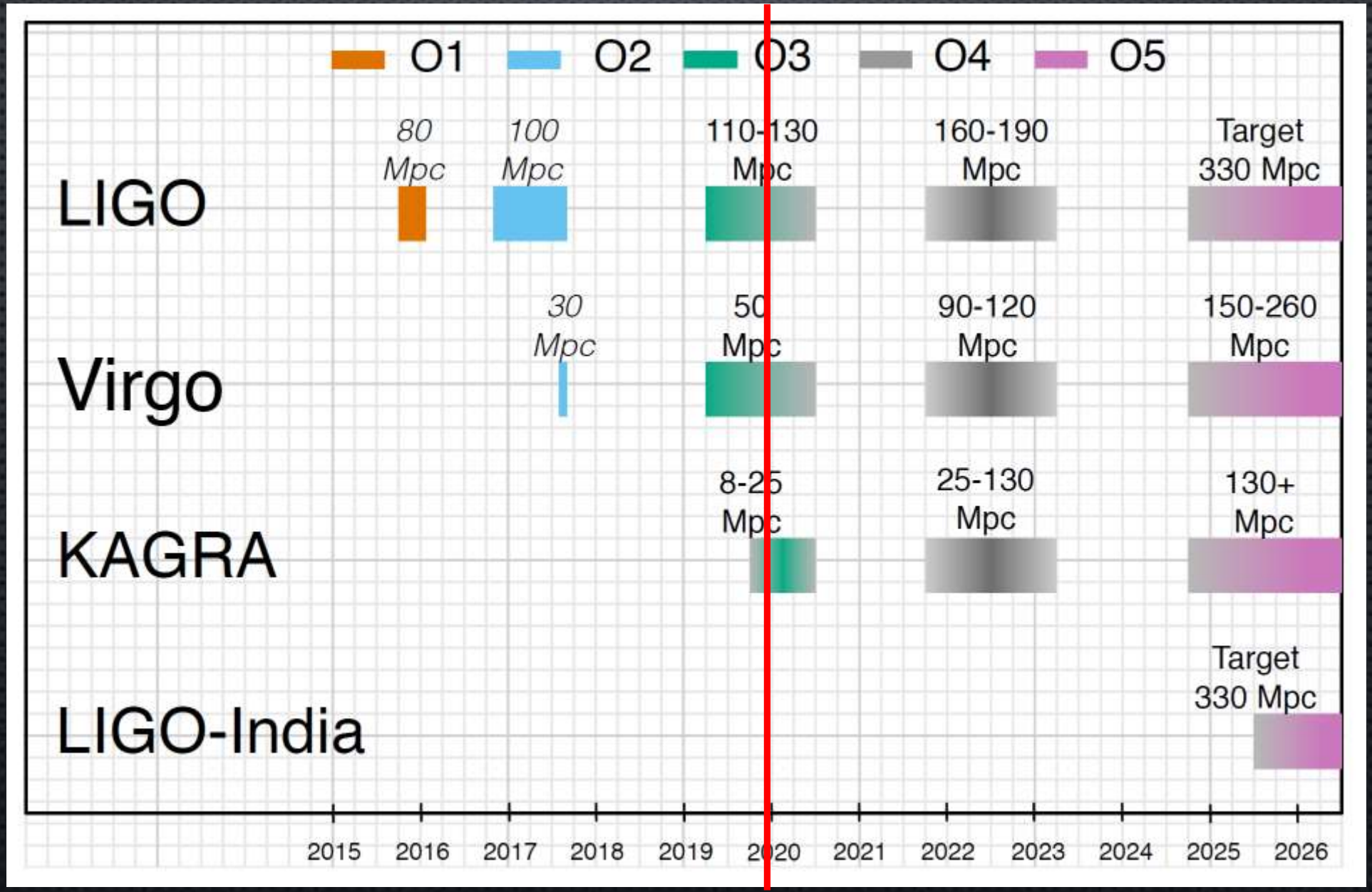



LIGO/Axel Mellinger

Improved event localization



Worldwide network of GW detectors


O1
O2
O3
O4
O5
LIGO
80 Mpc
100 Mpc
110-130 Mpc
160-190 Mpc
Target 330 Mpc
Virgo
30 Mpc
50 Mpc
90-120 Mpc
150-260 Mpc
KAGRA
8-25 Mpc
25-130 Mpc
130+ Mpc
LIGO-India
Target 330 Mpc
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026

Now