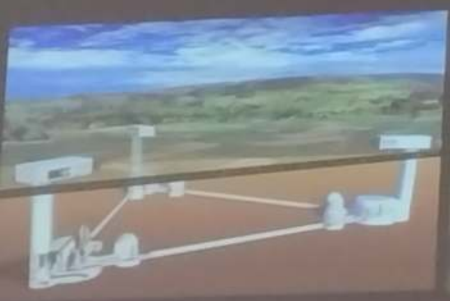
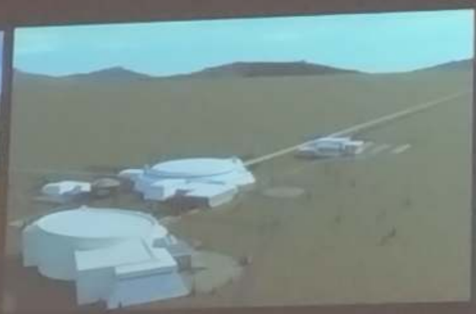
Next-generation detectors

Einstein Telescope
(<2035)



- Triangle with 10 km arms
- 2L with 15 km arms

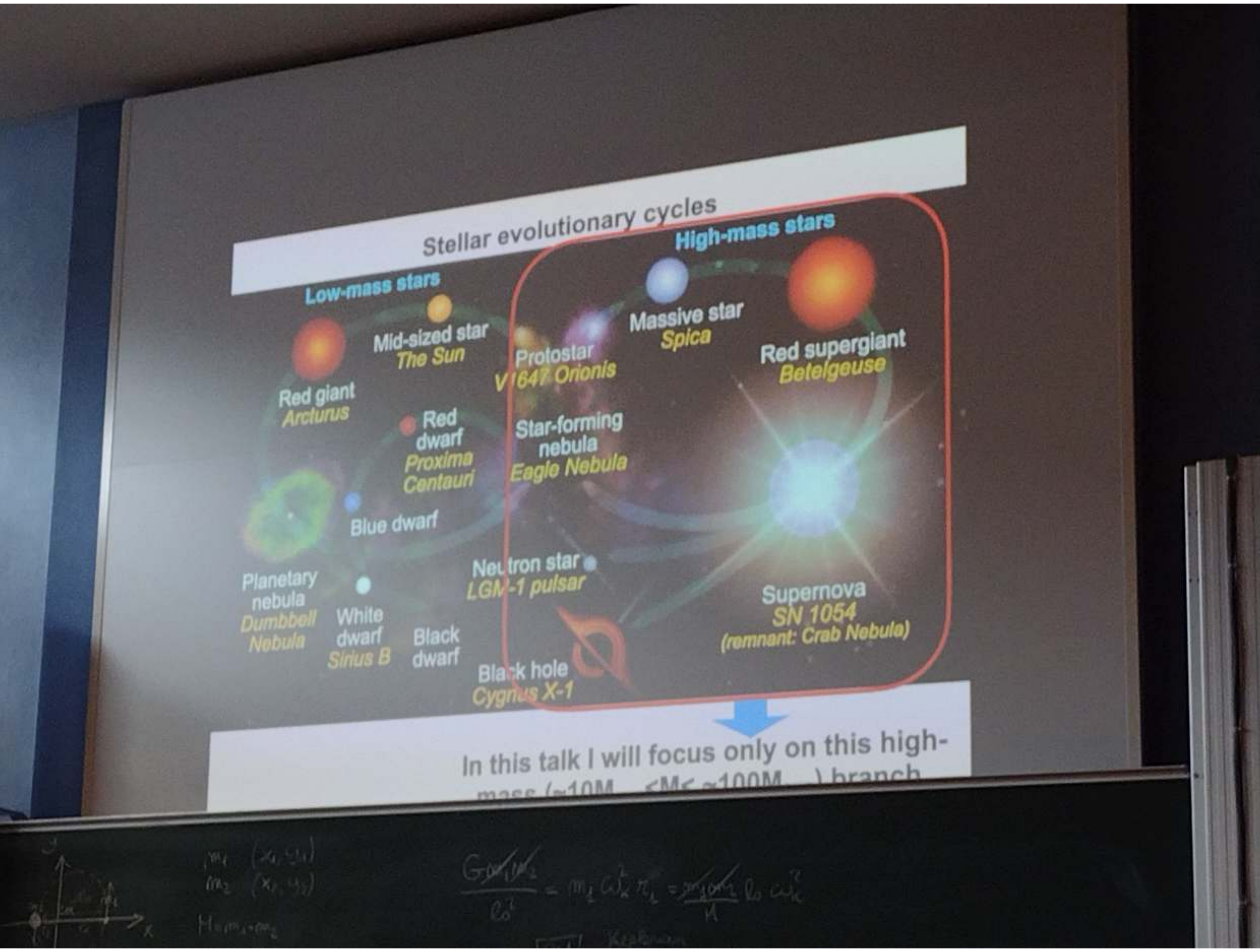
Cosmic Explorer
(<2035)



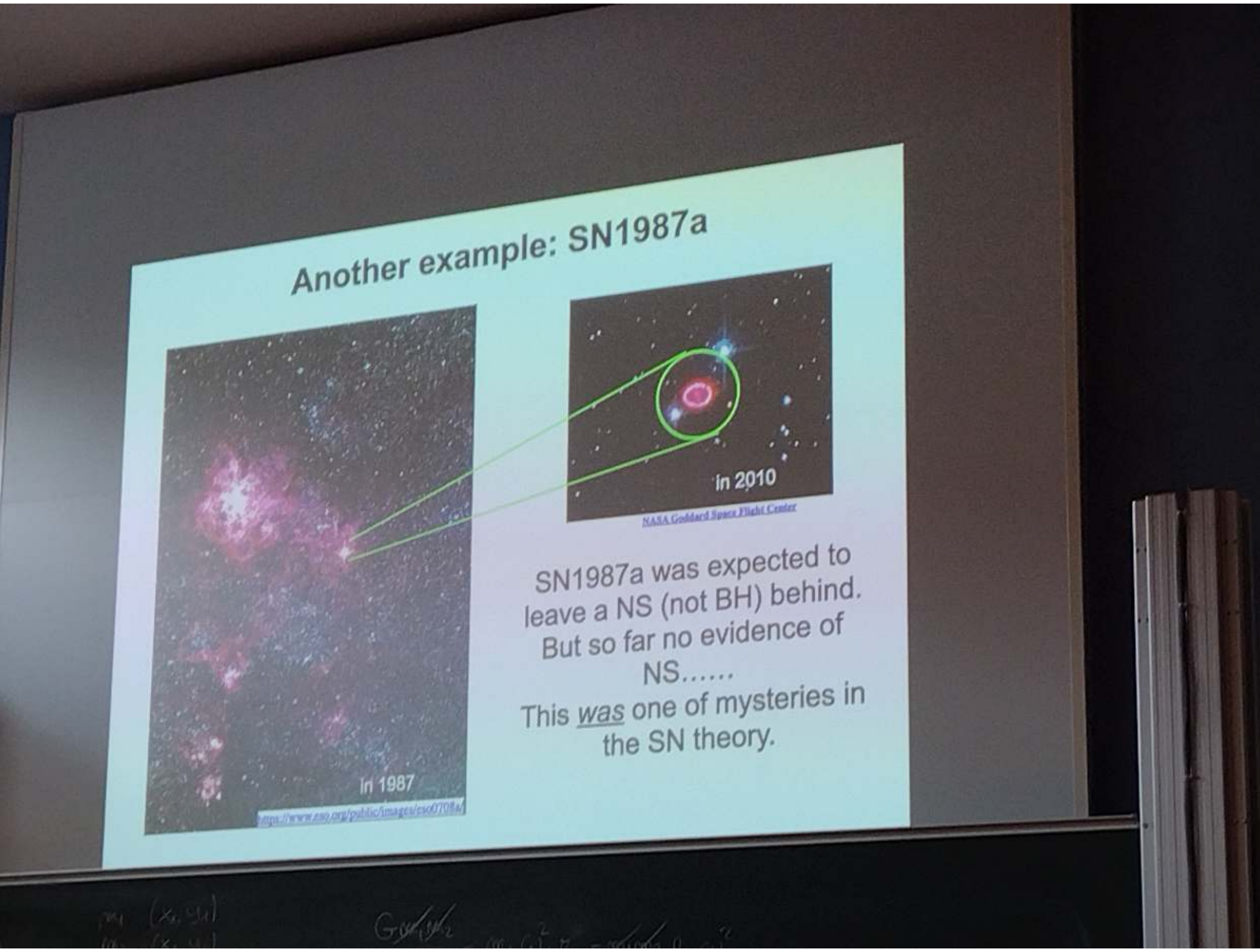
2L, one 40 km and one 20 km arms.

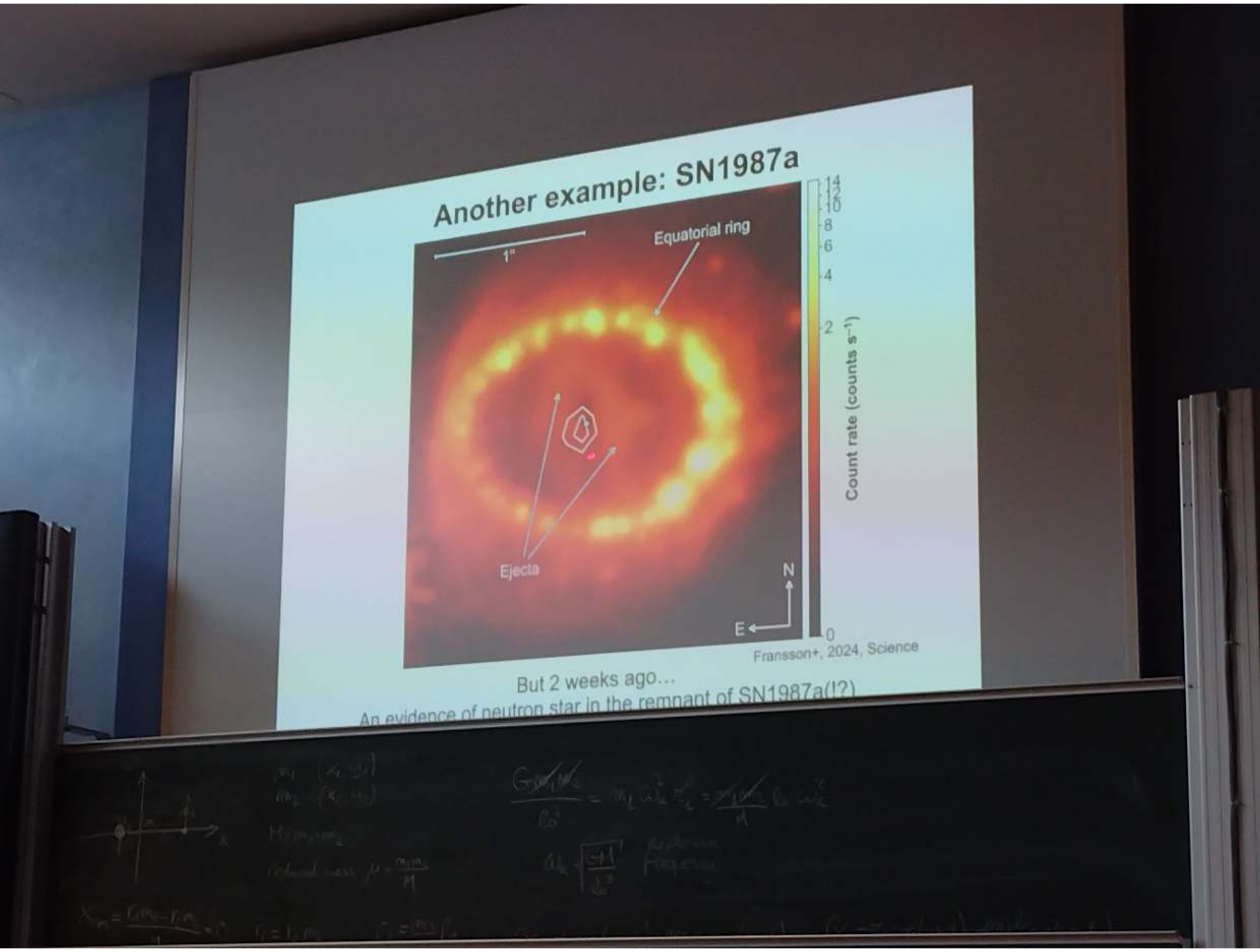
LISA
(2035)

3 spacecrafts in a triangular configuration following Earth in its orbit around the Sun.

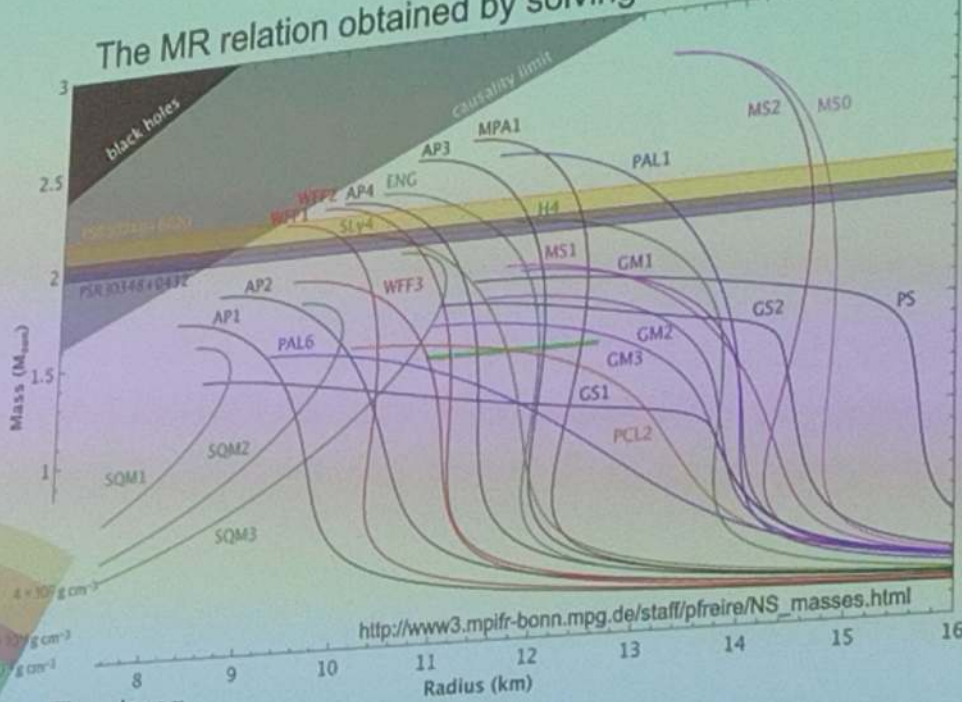


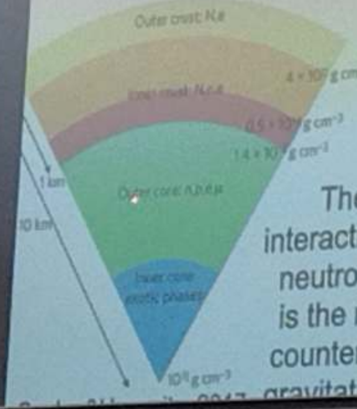
Stellar evolutionary cycles
Low-mass stars
High-mass stars
Mid-sized star
The Sun
Red giant
Arcturus
Red
dwarf
Proxima
Centauri
Blue dwarf
Planetary
nebula
Dumbbell
Nebula
White
dwarf
Sirius B
Black
dwarf
Protostar
V1647 Orionis
Star-forming
nebula
Eagle Nebula
Massive star
Spica
Red supergiant
Betelgeuse
Neutron star
LGM-1 pulsar
Black hole
Cygnus X-1
Supernova
SN 1054
(remnant: Crab Nebula)
In this talk I will focus only on this high-


Another example: SN1987a
in 2010
NASA Goddard Space Flight Center
SN1987a was expected to leave a NS (not BH) behind. But so far no evidence of NS……
This *was* one of mysteries in the SN theory.
in 1987
https://www.eso.org/public/images/eso0708a/


Another example: SN1987a
1"
Equatorial ring
Ejecta
N
E
14
12
10
8
6
4
2
0
Count rate (counts s⁻¹)
Fransson+, 2024, Science
But 2 weeks ago…
An evidence of neutron star in the remnant of SN1987a(!?)

The MR relation obtained by solving the TOV equation

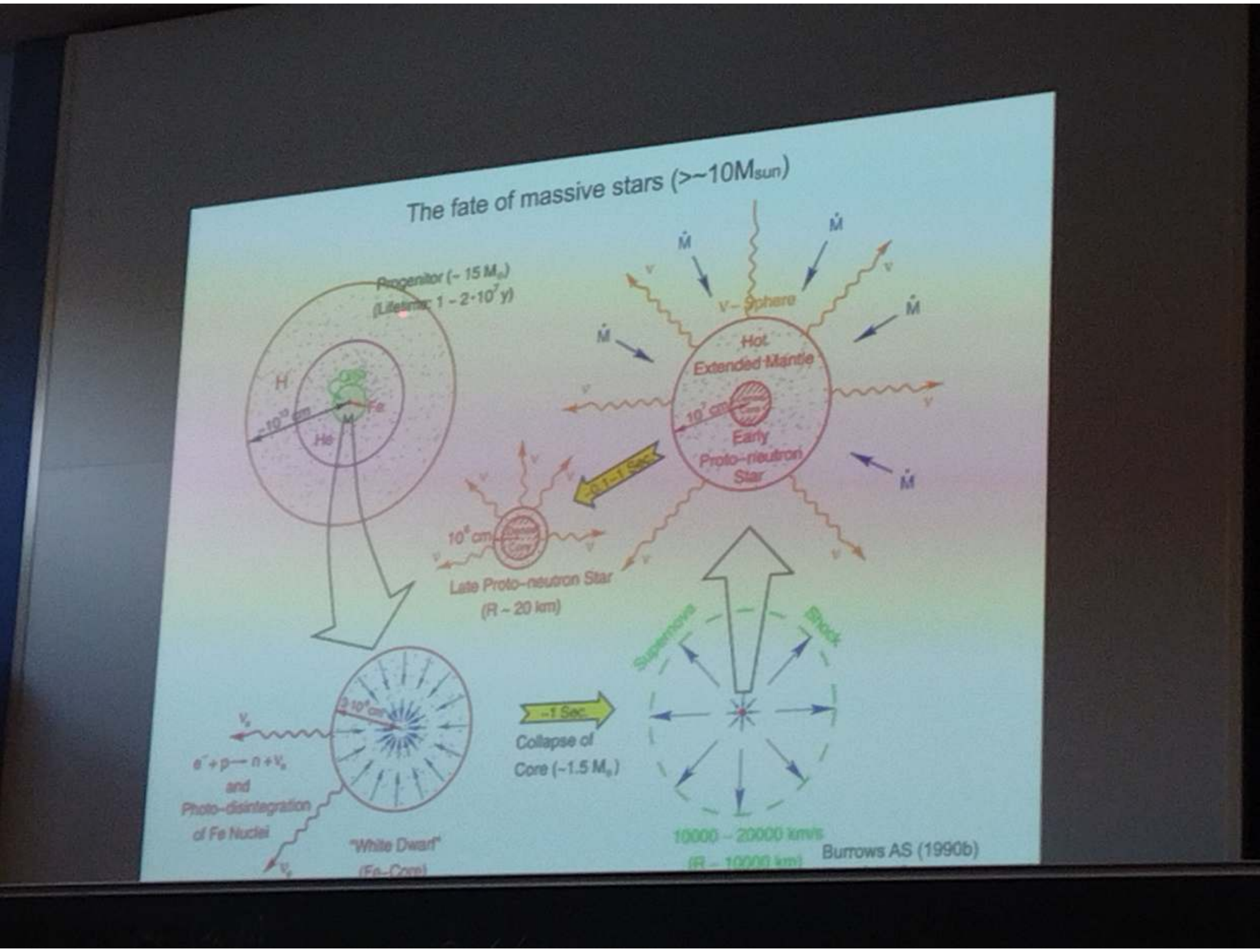




The strong interaction between neutron & proton is the main force countervailing the gravitational force

The maximum NS mass is likely to be ~3M_{sun}.

I.e. if the remnant mass exceeds that threshold, the remnant becomes BH.


The fate of massive stars (>~10Msun)
Progenitor (~ 15 M☉)
H
He
Fe
Hot
Extended Mantle
Early
Proto-neutron
Star
~0.1-1 Sec
Late Proto-neutron Star
(R ~ 20 km)
Supernova
Shock
~1 Sec
Collapse of
Core (~1.5 M☉)
e⁻ + p → n + νe
and
Photo-disintegration
of Fe Nuclei
"White Dwarf"
10000 - 20000 km/s
Burrows AS (1990b)

The breakdown of energies in the proto-neutron star

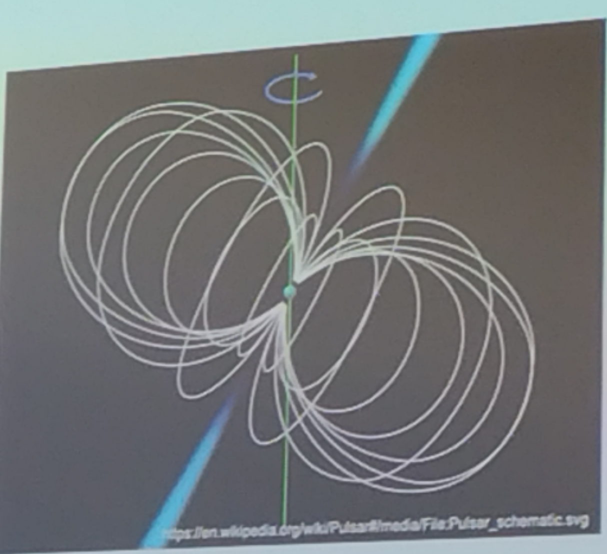
$$\left(-\frac{GM^2}{R_{\rm iron}}\right) - \left(-\frac{GM^2}{R_{\rm NS}}\right) \approx \text{a few} \times 10^{53}\ \text{ergs}$$

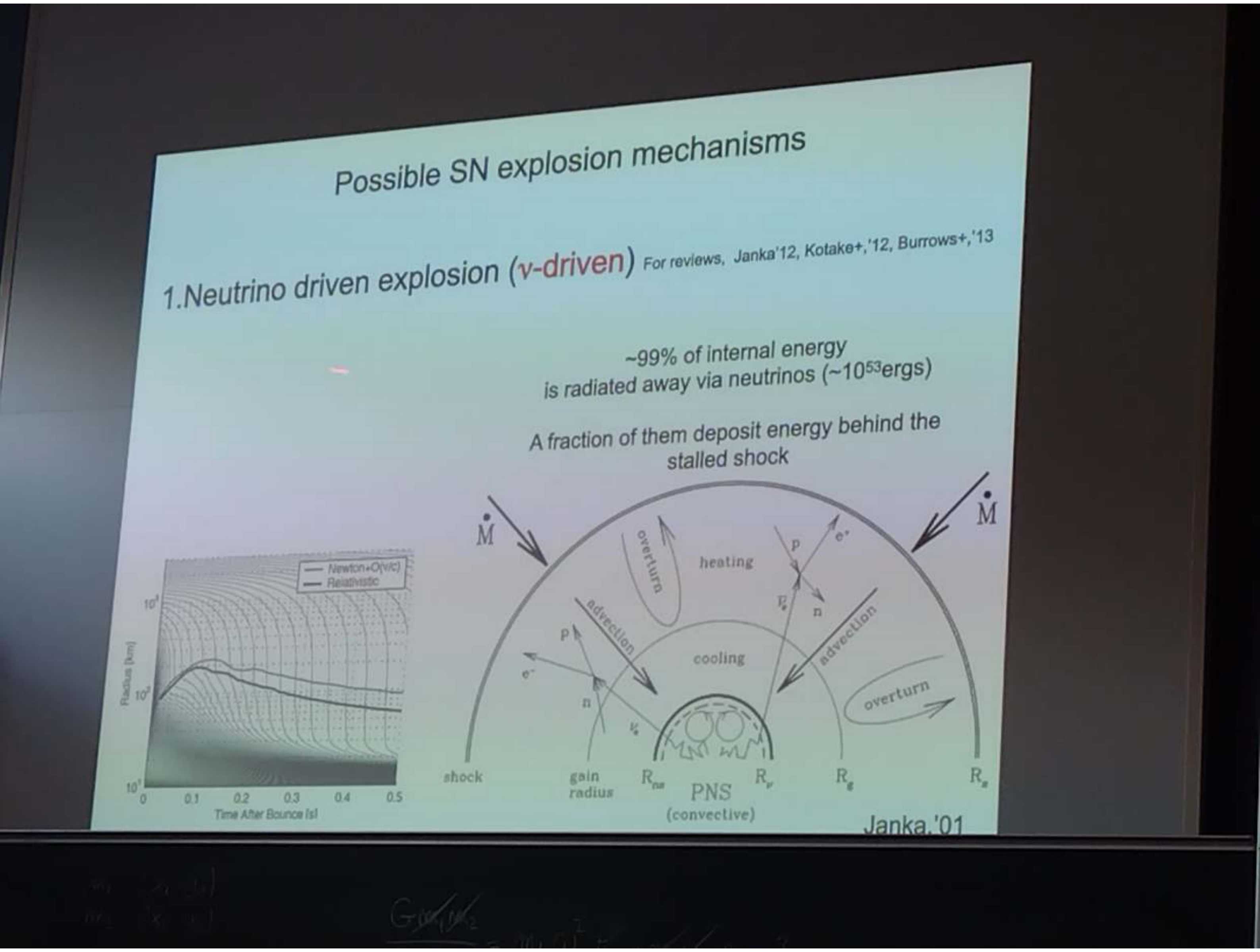
$$M \approx M_\odot$$
$$R_{\rm iron} \approx 10^8\ \text{cm}$$
$$R_{\rm NS} \approx 10^6\ \text{cm}$$

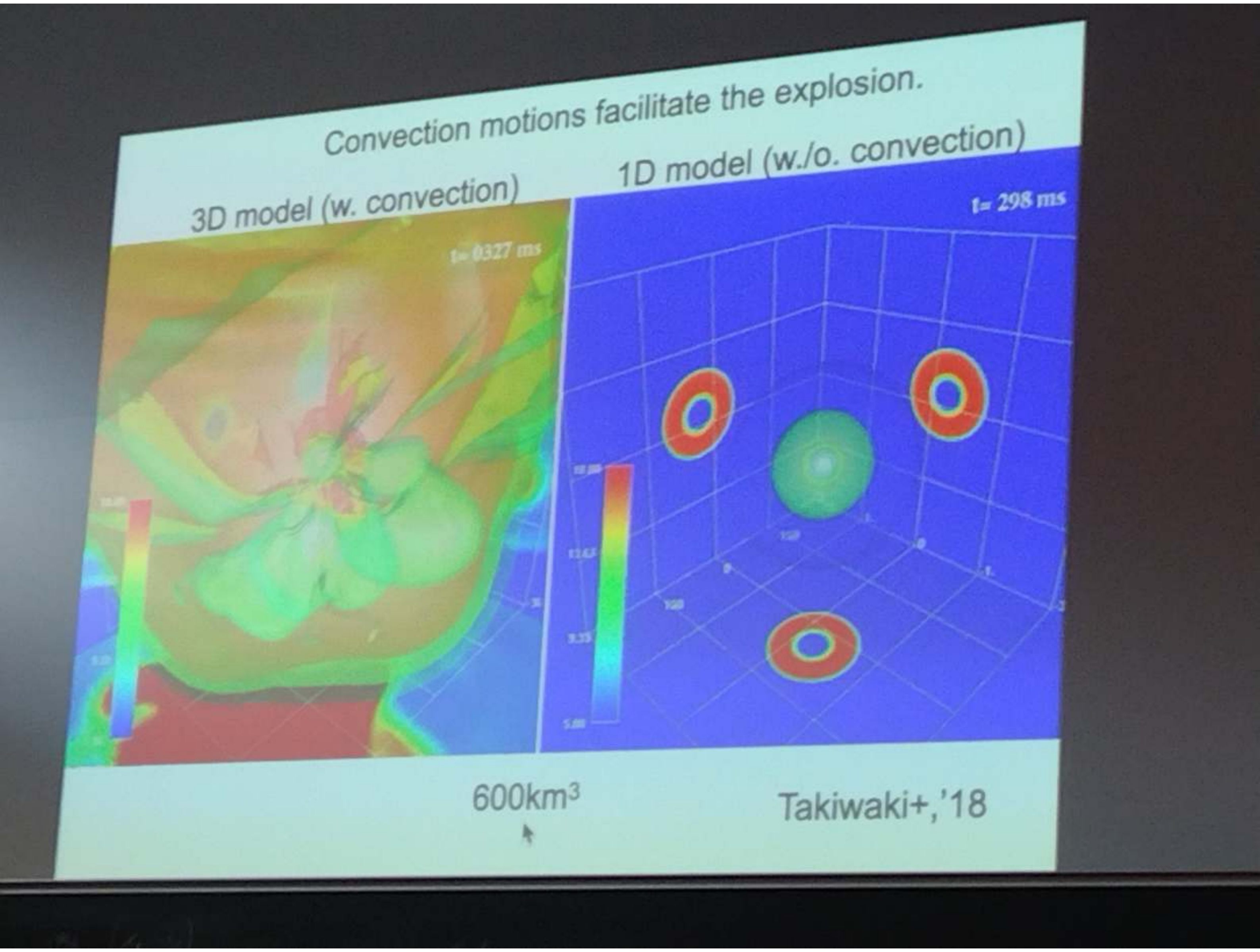
Liberation of gravitational binding energy of ~10^{53} erg

- E_{int}~10^{53}ergs
- $E_{rot} < 10^{52}$ergs
- $E_{mag} < 10^{51}$ergs

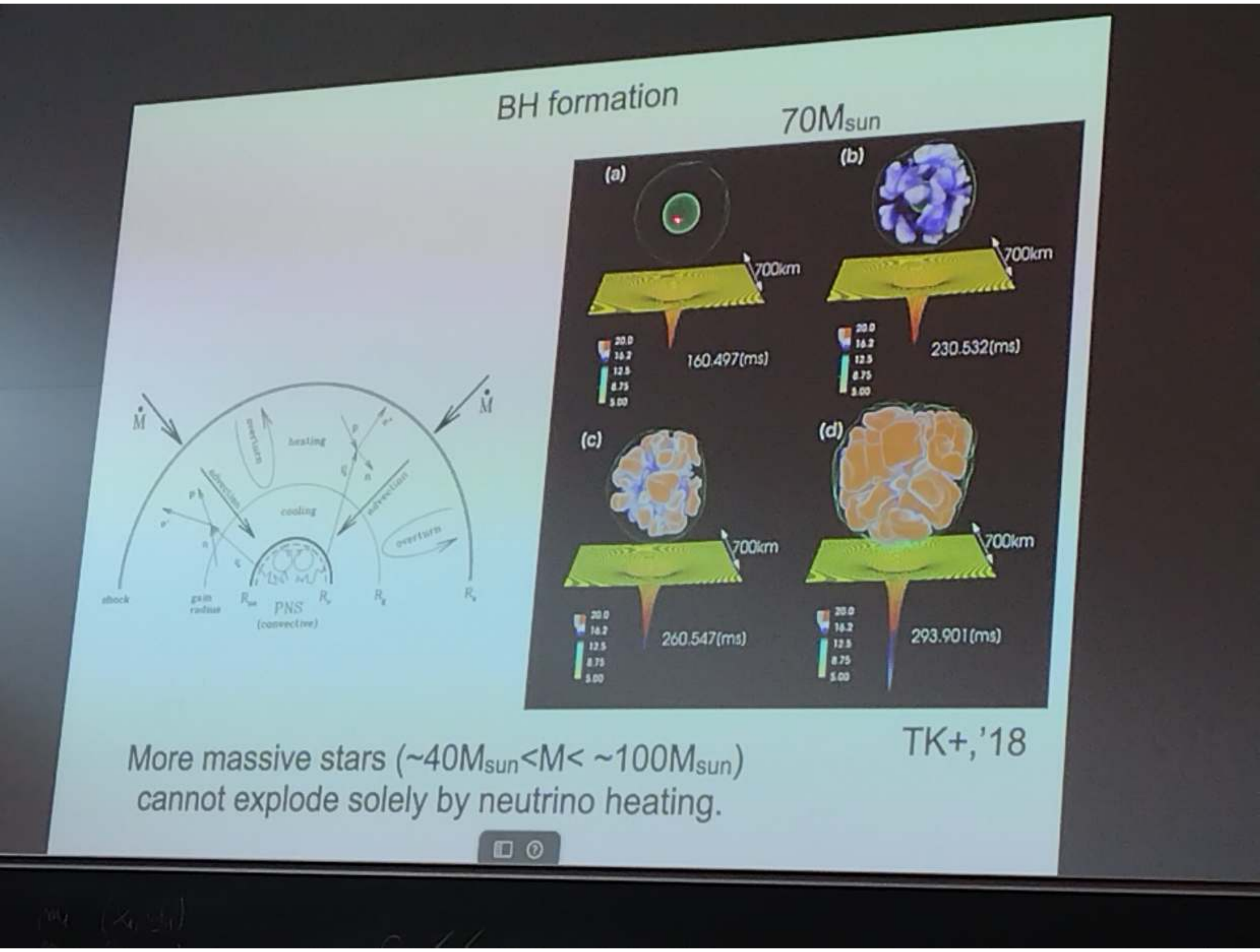
What we can use to explode the star are these three energy sources.

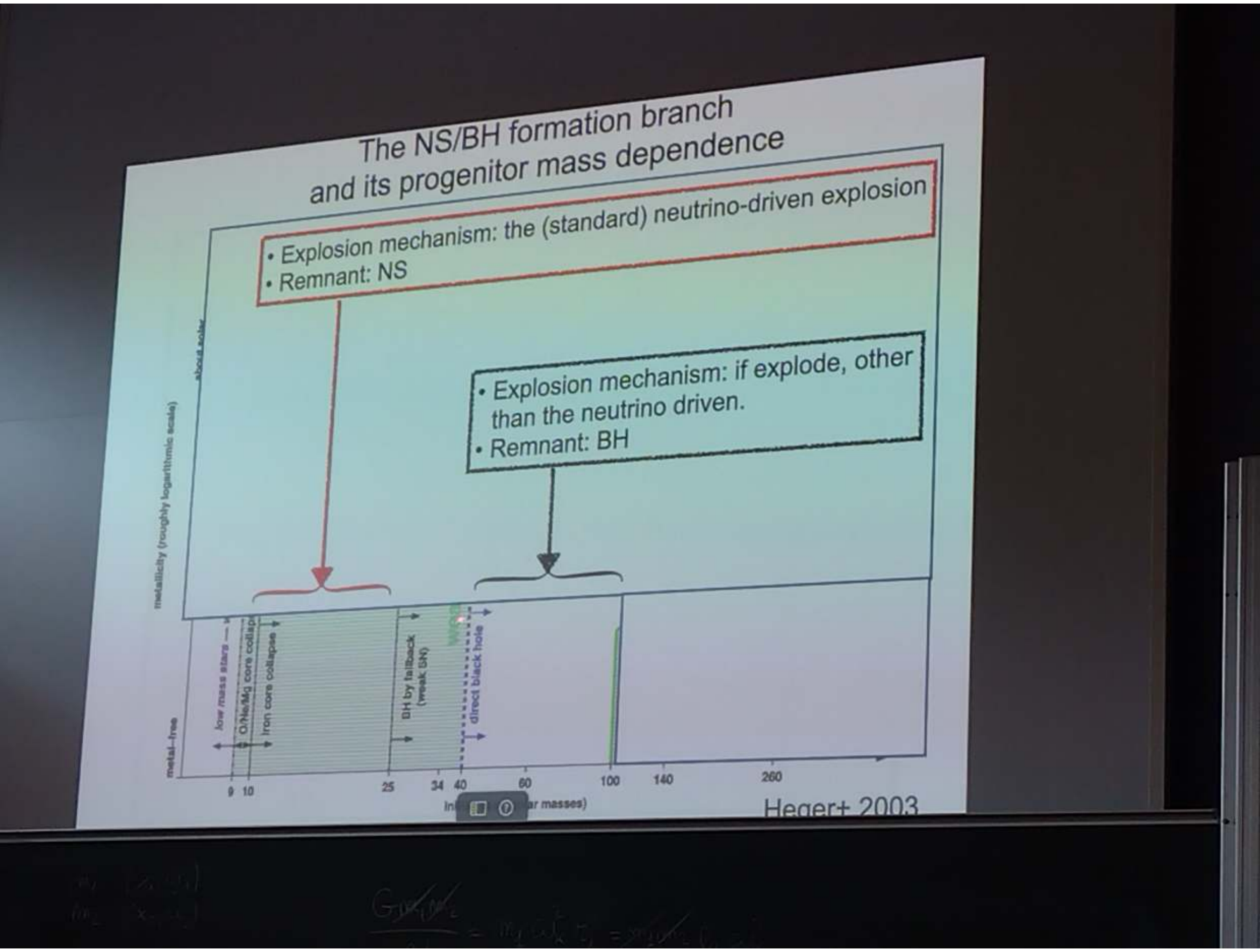



Possible SN explosion mechanisms
1.Neutrino driven explosion (ν-driven) For reviews, Janka'12, Kotake+,'12, Burrows+,'13
~99% of internal energy
is radiated away via neutrinos (~10^53 ergs)
A fraction of them deposit energy behind the
stalled shock
Newton+O(v/c)
Relativistic
Radius [km]
Time After Bounce [s]
Ṁ
overturn
heating
advection
cooling
shock
gain
radius
PNS
(convective)
Janka,'01



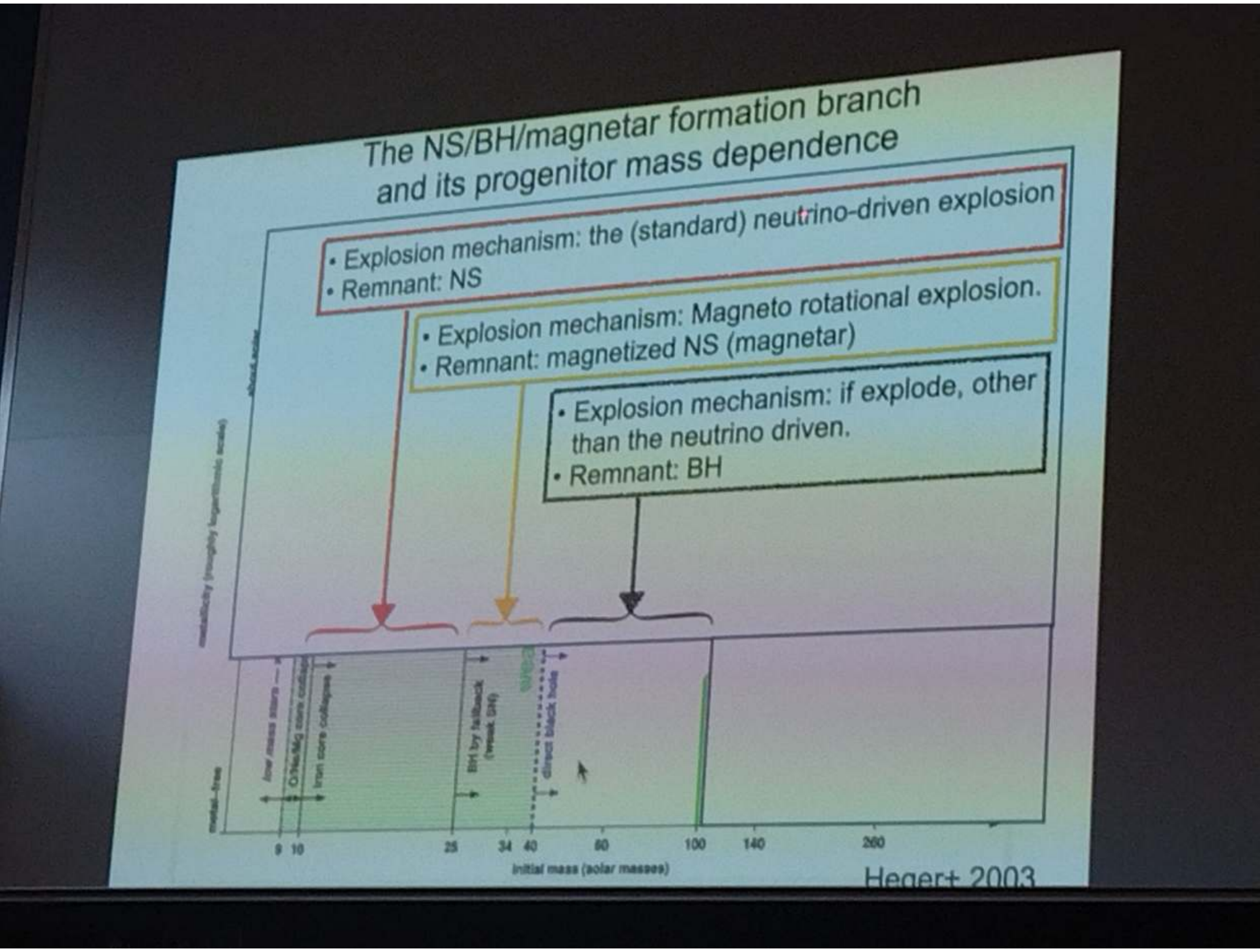
Convection motions facilitate the explosion.
3D model (w. convection)
1D model (w./o. convection)
t= 0327 ms
t= 298 ms
600km3
Takiwaki+,'18


BH formation
70Msun
(a)
(b)
(c)
(d)
700km
160.497(ms)
230.532(ms)
260.547(ms)
293.901(ms)
20.0
16.2
12.5
8.75
5.00
overturn
heating
advection
cooling
shock
gain radius
PNS
(convective)
TK+,'18
More massive stars (~40Msun<M< ~100Msun)
cannot explode solely by neutrino heating.

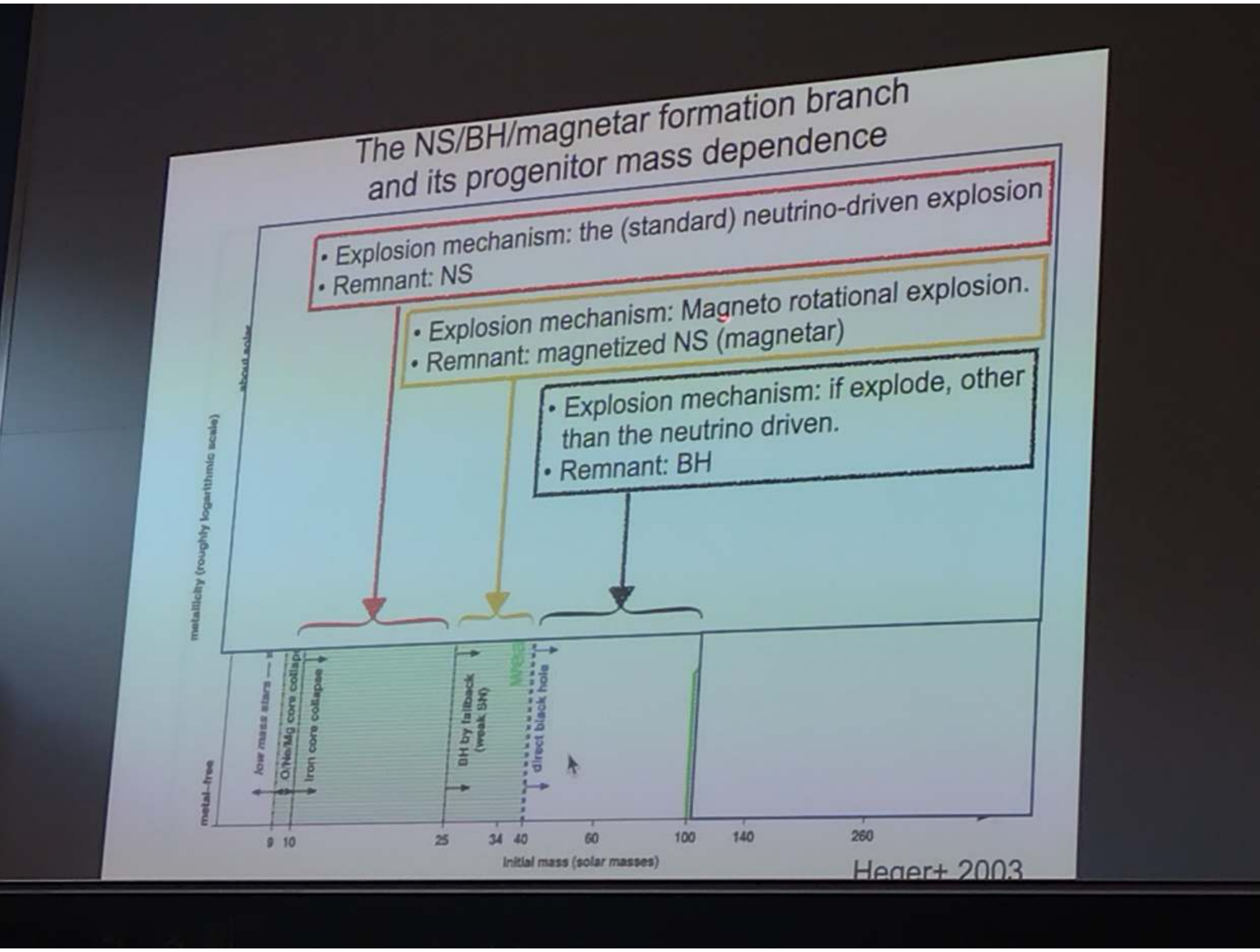


The NS/BH formation branch
and its progenitor mass dependence
• Explosion mechanism: the (standard) neutrino-driven explosion
• Remnant: NS
• Explosion mechanism: if explode, other than the neutrino driven.
• Remnant: BH
metallicity (roughly logarithmic scale)
metal-free
low mass stars
O/Ne/Mg core collapse
iron core collapse
BH by fallback (weak SN)
direct black hole
9
10
25
34
40
60
100
140
260
Heger+ 2003


(1)The standard explosion mechanism
Neutrino driven explosion,
Colgate&White'66, Bethe&Wilson'85
For reviews, Janka'12, Kotake+,'12, Burrows+,'13
(2)If the magnetic field is strong enough
Magneto-rotational explosion (MRE) takes place,
Takiwaki+,'09,
2D: Ardeljan+,'00, Kotake+,'04, Obergaulinger+,'06,'17, Burrows+,'07,
3D: Mikami+, '08;
Mösta+,'14;
Obergaulinger+,'19,'20;
Kuroda+,'20a(b);
Newtonian, no neutrino, Polytropic EOS
full GR but very simplified neutrino transport
SR with M1 neutrino transport
full GR with M1 neutrino transport
Entropy
1600 km
Mösta+,'14
(a)
Obergaulinger+,'20
500km
TK+,'20



The NS/BH/magnetar formation branch
and its progenitor mass dependence
• Explosion mechanism: the (standard) neutrino-driven explosion
• Remnant: NS
• Explosion mechanism: Magneto rotational explosion.
• Remnant: magnetized NS (magnetar)
• Explosion mechanism: if explode, other than the neutrino driven.
• Remnant: BH
low mass stars
iron core collapse
BH by fallback
(weak SN)
direct black hole
metal-free
9
10
25
34
40
60
100
140
260
initial mass (solar masses)
Heger+ 2003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• Remnant: magnetized NS (magnetar)
• Explosion mechanism: if explode, other than the neutrino driven.
• Remnant: BH
metallicity (roughly logarithmic scale)
about solar
metal-free
low mass stars
iron core collapse
BH by fallback
(weak SN)
direct black hole
9
10
25
34
40
60
100
140
260
Initial mass (solar masses)
Heger+ 2003

Summary

Our understanding of the SN explosion physics
and of the formation process of various compact stars
has been remaining patchy in these several decades.

In SN physics, all the *four fundamental forces* play substantial roles.

- General relativity (GR) governs the overall dynamics.
- The nuclear force (i.e. strong force) determines structure of compact stars.
- SN explosion is driven by the neutrino heating (weak force) or sometimes by magnetic (B-)fields (electromagnetic force).

The current status of SN theory

progenitor mass	explosion mechanism	remnant type
~10-20M_{sun}	Neutrino driven explosion (ν-driven)	neutron star (NS)
~30-40M_{sun}	Magneto rotational explosion (MRE)	magnetar, black hole (BH)
~50M_{sun}	Explosion by the hadron-quark phase transition (PT)	quark star (QS)
>~70M_{sun}	Failed explosion	BH

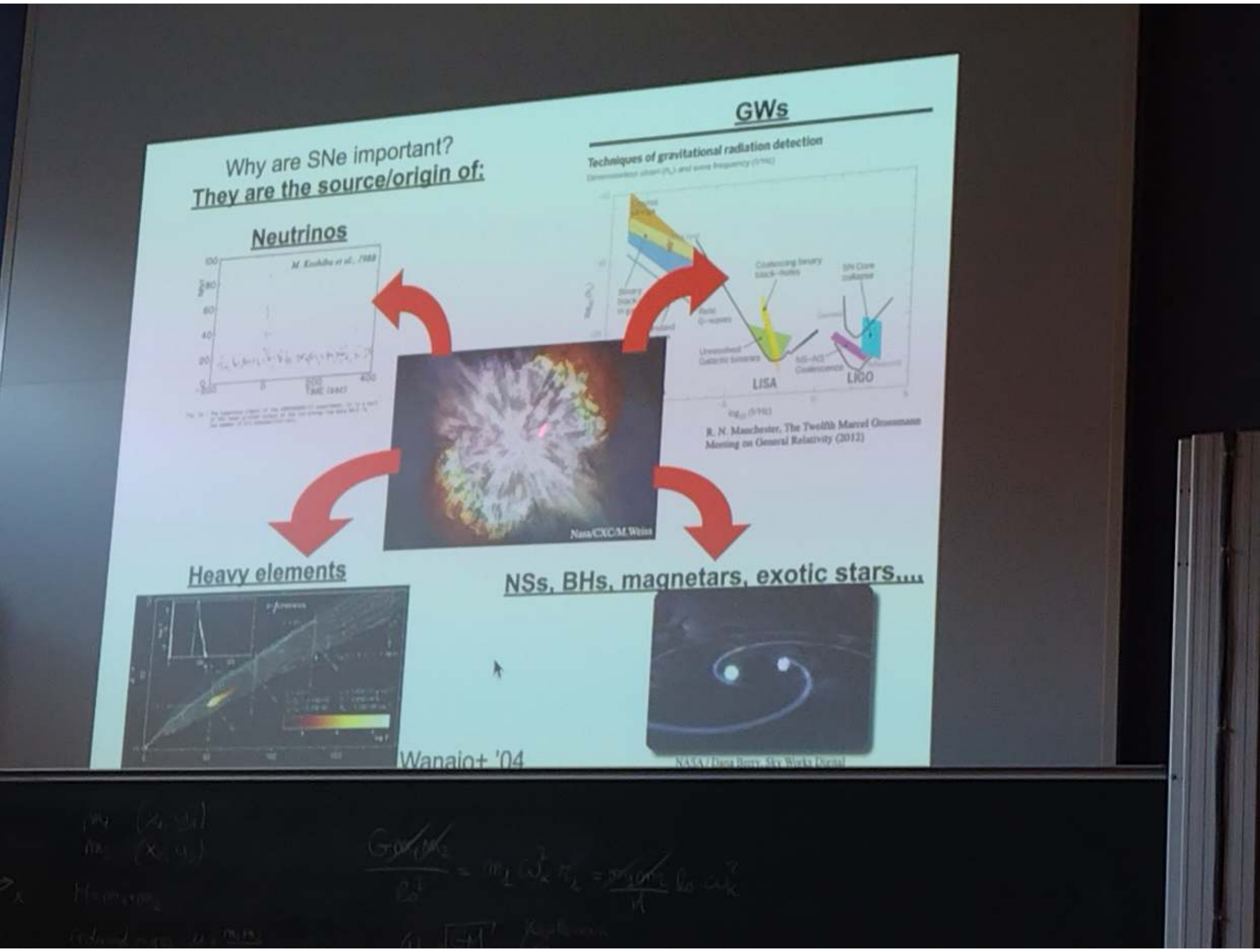
Various properties of progenitor stars: mass, spin, magnetic fields, etc.

→

Various explosion mechanisms:
- ν-driven
- MRE
- PT
- ???

→

Various remnants:
- NSs
- BHs
- magnetars
- QSs


Why are SNe important?
They are the source/origin of:
Neutrinos
GWs
Techniques of gravitational radiation detection
LISA
LIGO
R. N. Manchester, The Twelfth Marcel Grossmann Meeting on General Relativity (2012)
Nasa/CXC/M.Weiss
Heavy elements
NSs, BHs, magnetars, exotic stars,...
Wanajo+ '04