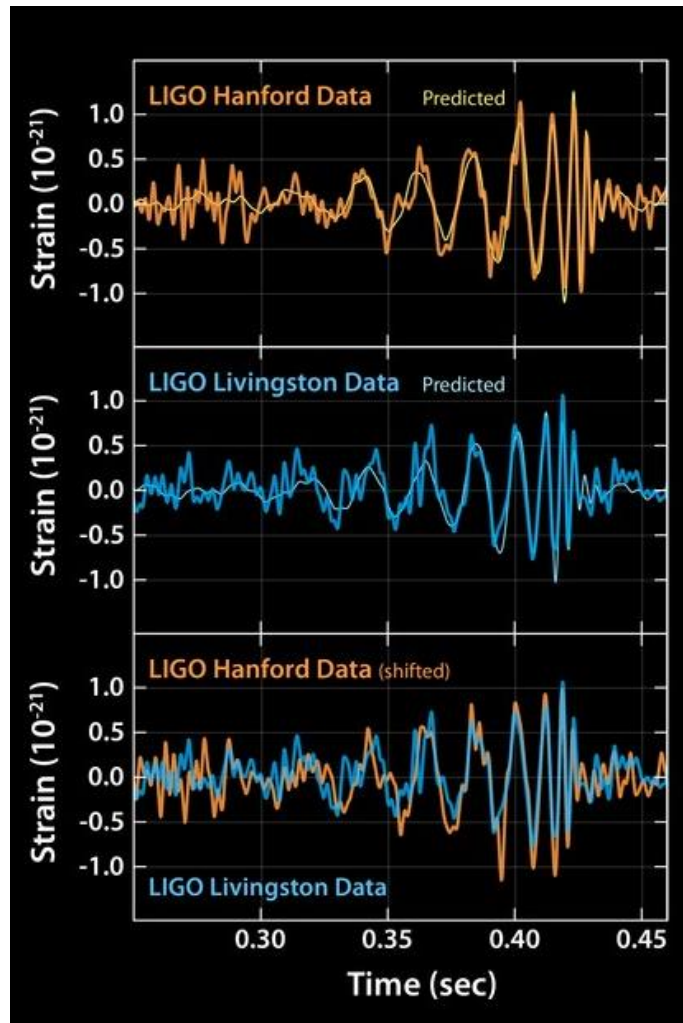# Astrophysics of gravitational wave sources
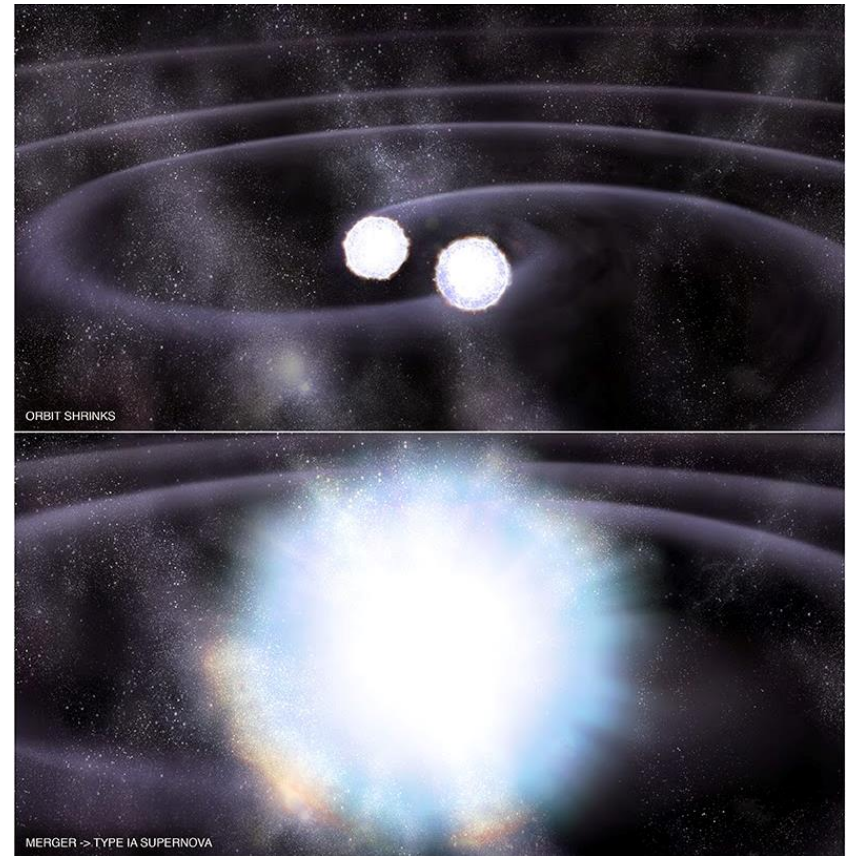## Lecture 1: Topics covered and implications

Ondřej Pejcha

ÚTF MFF UK
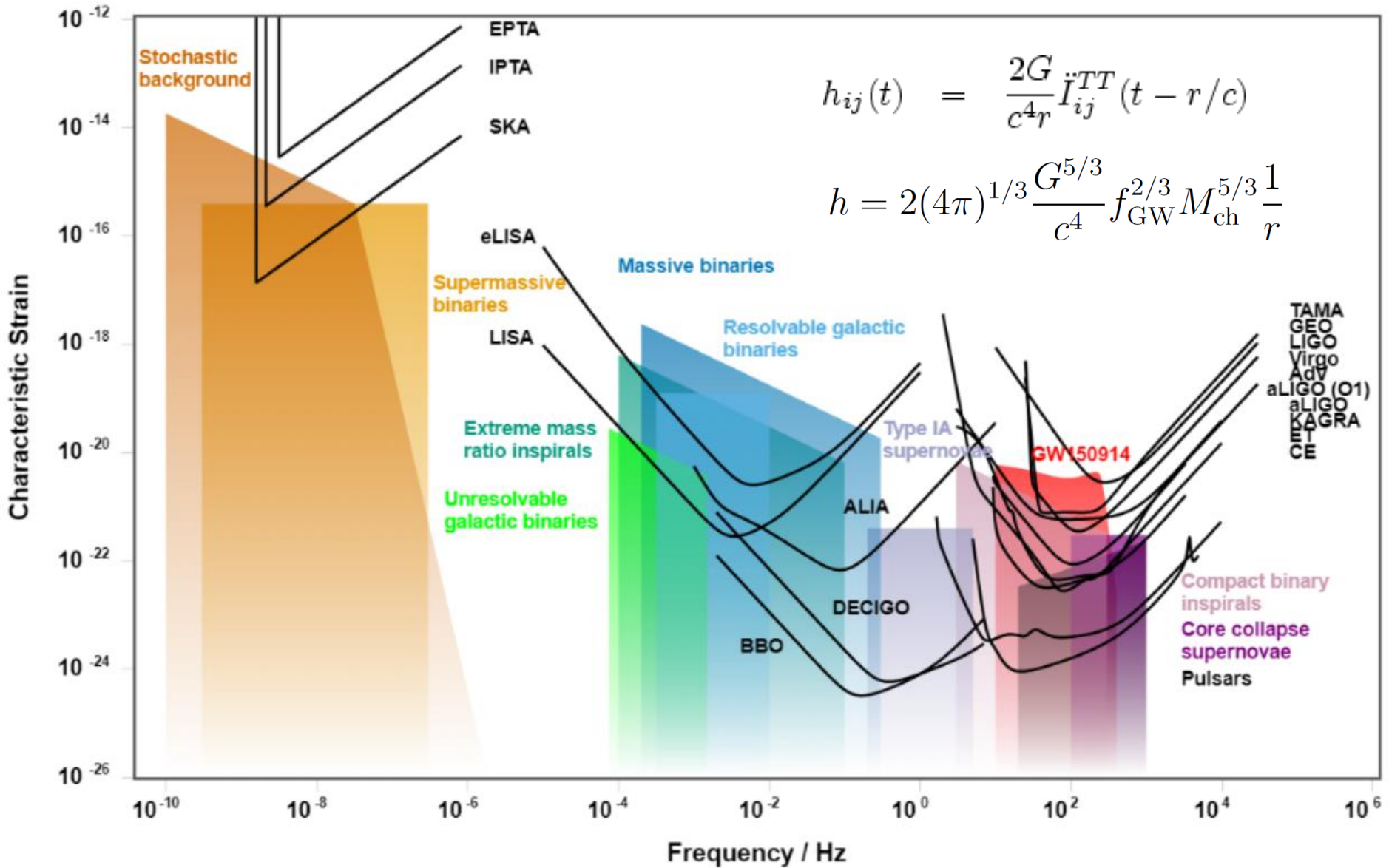
Mergers due to gravitational wave emission

Caltech/MIT/LIGO Lab

NASA/CXC/M.Weiss

Gravitational Wave Detectors and Sources

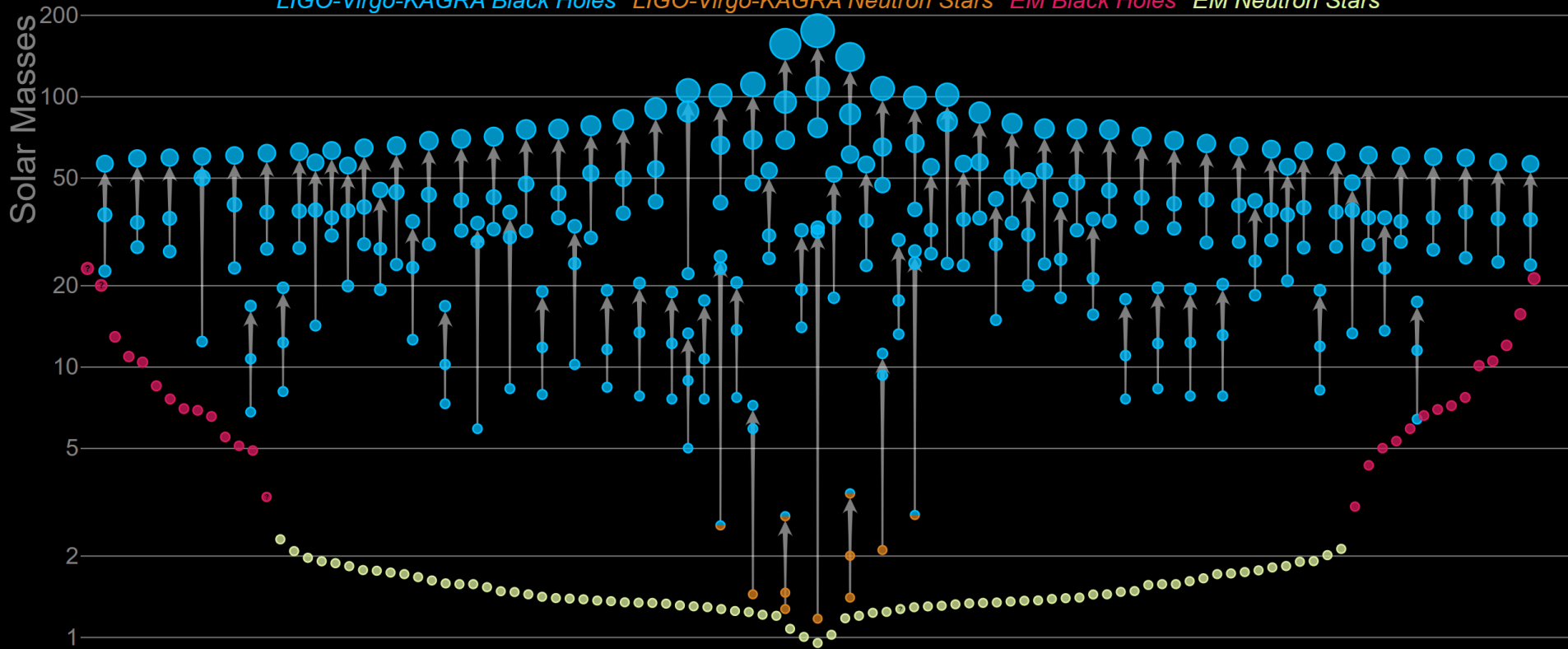

$$h_{ij}(t) = \frac{2G}{c^4 r}\ddot{I}_{ij}^{TT}(t - r/c)$$

$$h = 2(4\pi)^{1/3}\frac{G^{5/3}}{c^4}f_{\mathrm{GW}}^{2/3}M_{\mathrm{ch}}^{5/3}\frac{1}{r}$$

gwplotter.com

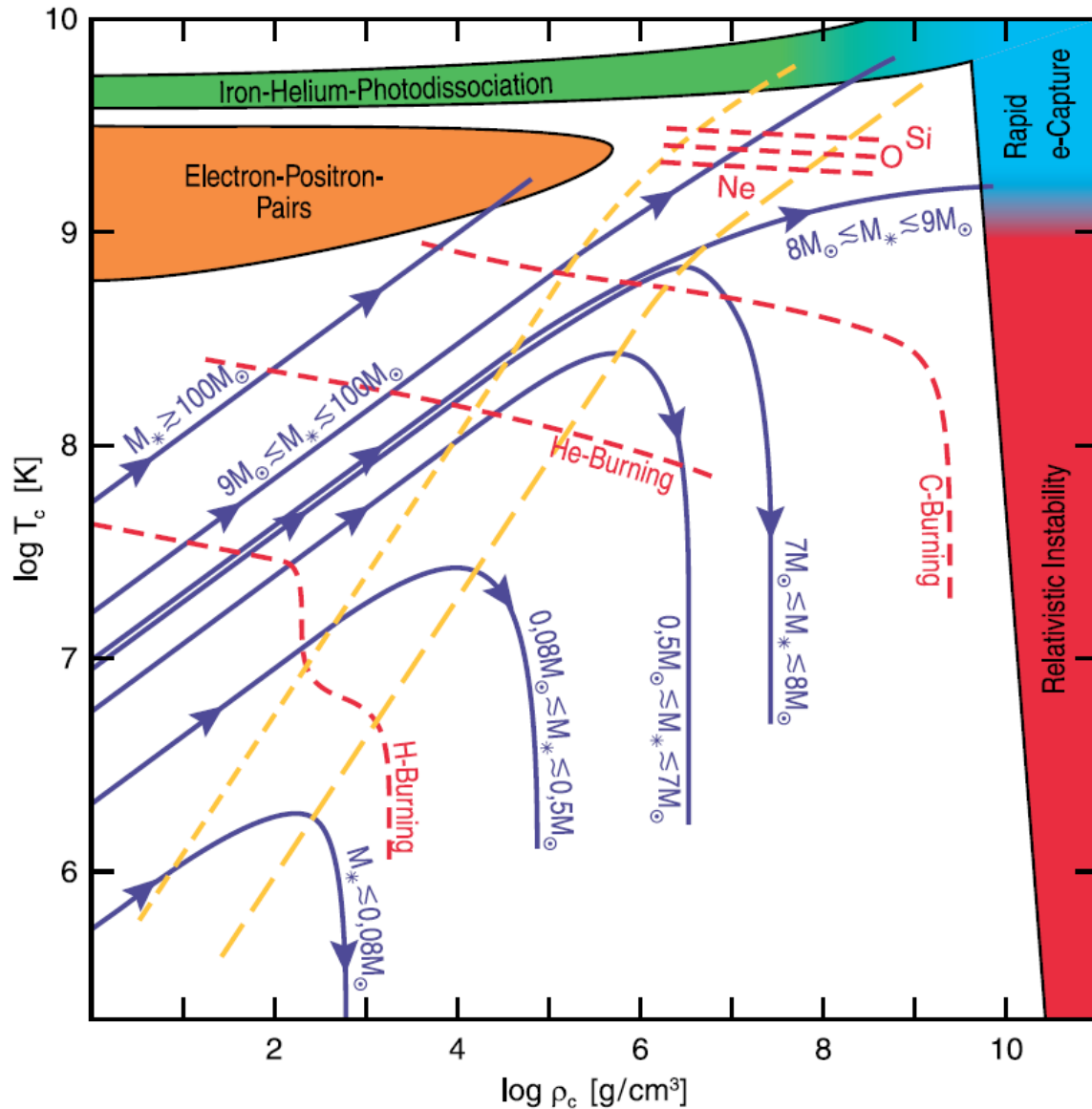# Masses in the Stellar Graveyard

LIGO-Virgo-KAGRA Black Holes   LIGO-Virgo-KAGRA Neutron Stars   EM Black Holes   EM Neutron Stars

Solar Masses
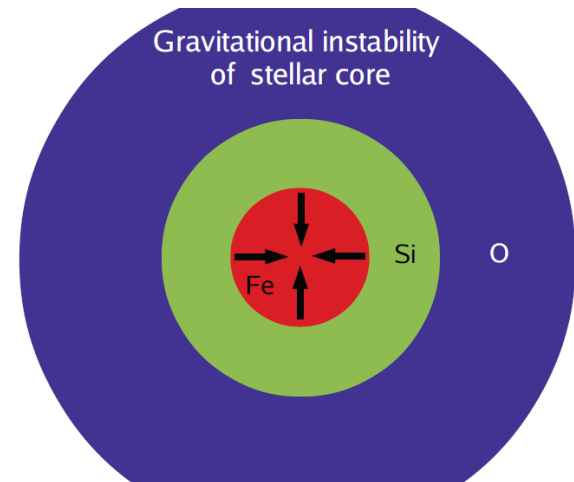
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

The Origin of the Solar System Elements

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	93 Np	94 Pu									

Legend:
- big bang fusion
- cosmic ray fission
- merging neutron stars?
- exploding massive stars
- dying low mass stars
- exploding white dwarfs

Very radioactive isotopes; nothing left from stars

Single star evolution

Central temperature and pressure

Janka (2012)

A. Heger website 2sn.org

Massive star death

1 erg = 10^{-7} J

1 $L_\odot$ = 3.9×10^{33} ergs/s

Gravitational instability of stellar core

Fe
Si
O

$M_{initial}$ > 8 $M_\odot$
Collapse from WD size ~0.3s

Core bounce at nuclear density

Accretion
Fe
Si
Shock wave
Proto-neutron star

Proto-neutron star ~60 km
Binding energy ~ 3×10^{53} ergs

$\underrightarrow{\text{<10m}}$
s

Shock stagnation
Accretion
Si
Fe
n, p
Shock wave
Proto-neutron star

Stalled shock at 100-200 km
Neutrino cooling ~ 10^{52} ergs/s
Duration up to ~1 s

Reason not fully understood

Shock revival
Accretion
O
Si
ν
n, p
ν
Shock wave
Proto-neutron star
Si

All NS binding energy released before 10-100s

Explosion
O
Ni
ν
n, p
ν
n, p, α
Shock wave
Proto-neutron star

Explosion energy ~10^{51} ergs
$10^{-3} - 10^{-1}$ $M_\odot$ of Nickel-56
Shock at surface in ~hours

Explosion and nucleosynthesis
O
Ni
ν
n, p
n, p, α
(Z_k, N_k)
ν
ν
Shock wave
Neutrino-driven "wind"
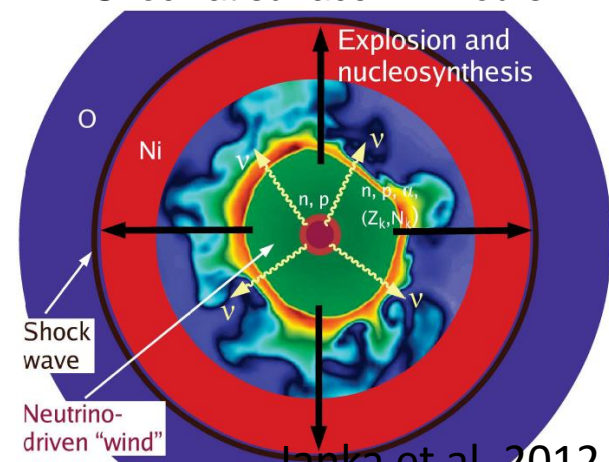
Janka et al. 2012

Binary star evolution

Zero Age Main Sequence (MS) binary → Roche Lobe overflow (RLO) → MS star - He star binary → First Type Ib/c SN

He star - NS binary ← Common envelope spiral in ← High mass X-ray binary phase ← MS star - neutron star (NS) binary

He star (stable/unstable) RLO. Most He is ejected from the system → Stripped He star + NS Intense mass loss leads to expanding envelope. → iPTF 14gqr: Ultra-stripped SN inside He-rich envelope → Double NS system
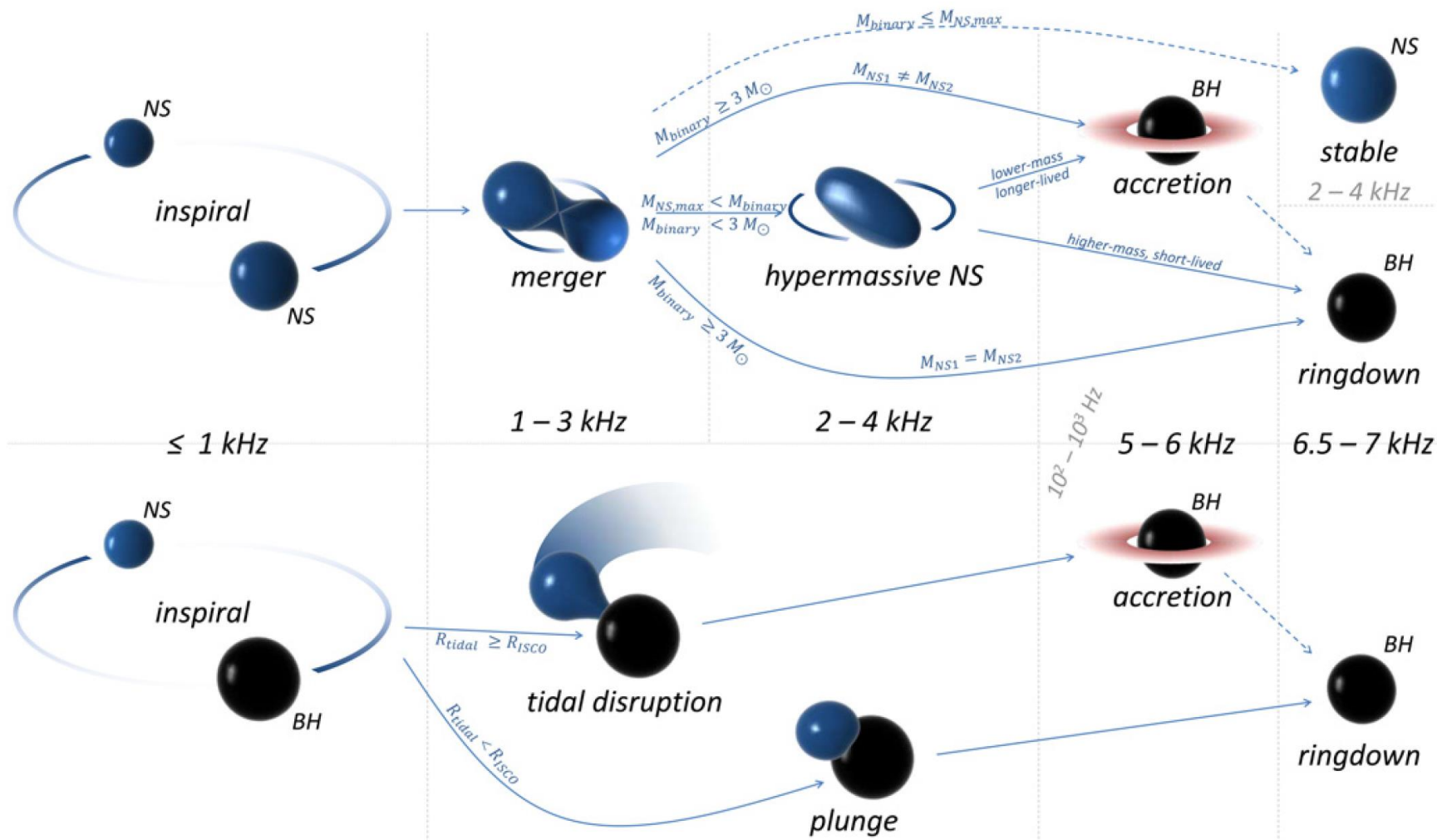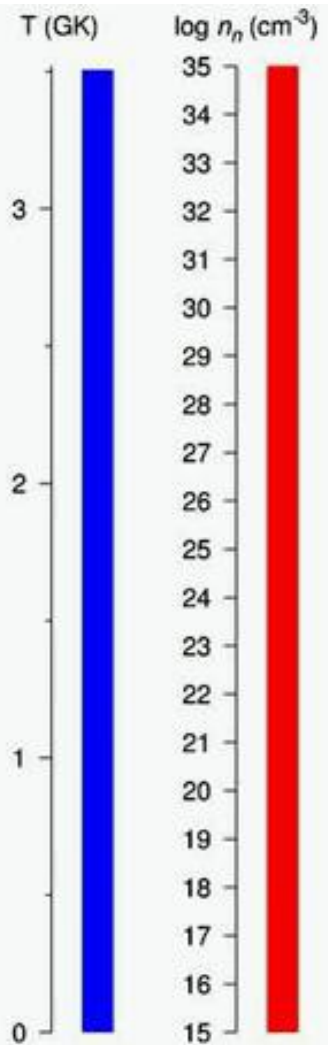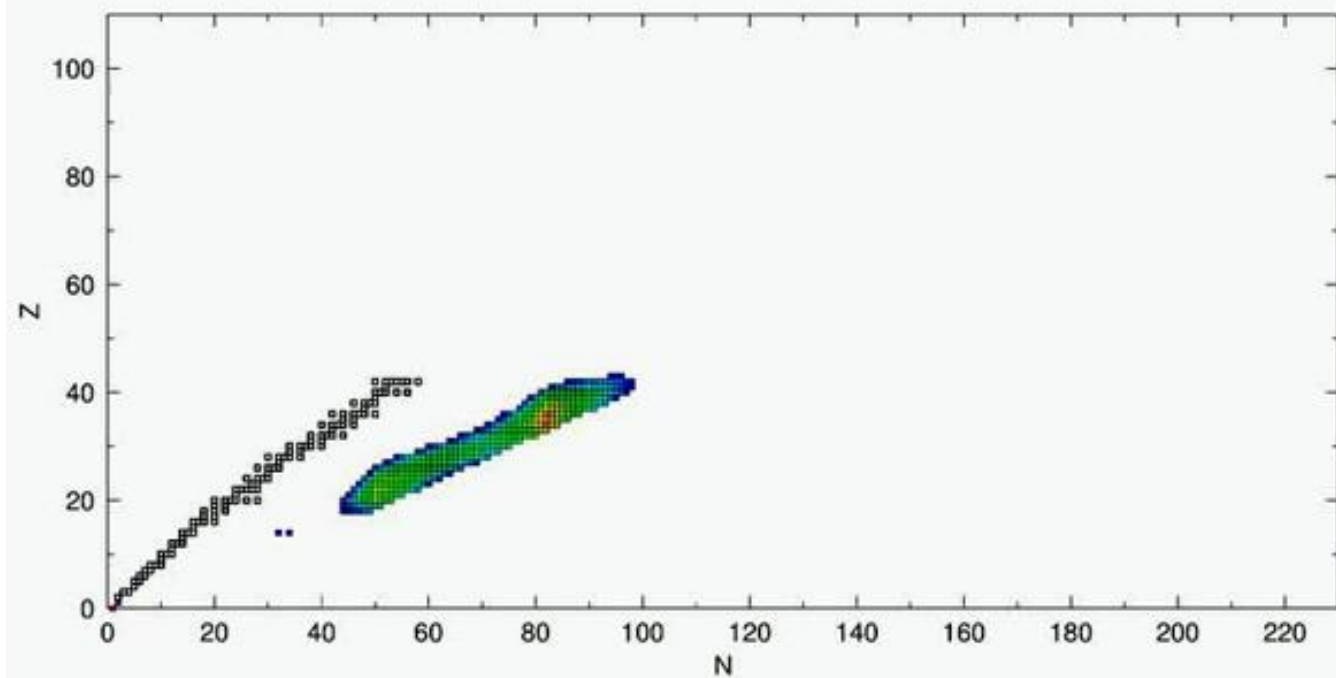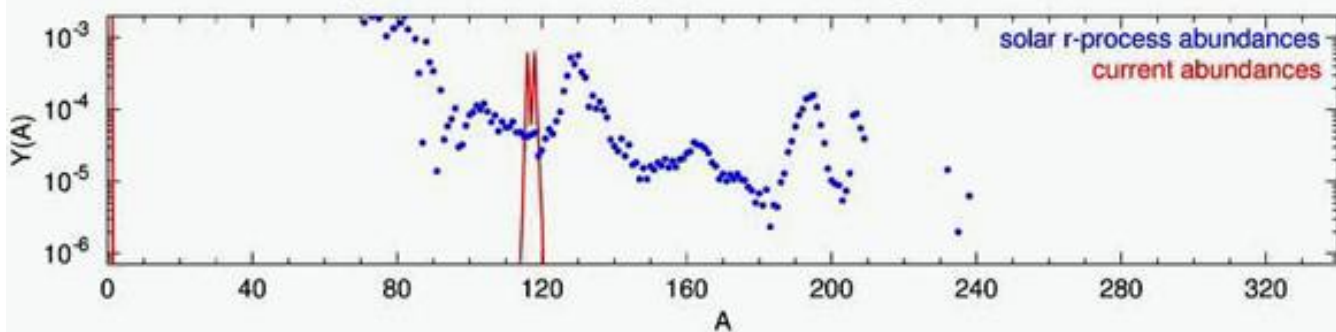
Figure 6: **Stellar evolutionary sequence leading from a binary system of massive stars (starting from the top left) to a NS-NS system, adapted from (9).** NS-BH systems are expected to arise from binaries where the first formed compact object is a BH. NS-WD systems follow a similar evolutionary sequence starting from the HMXB stage (where the NS is replaced by the WD), but require additional mass transfer in the earlier stages (52). The material composition of the stars is indicated by their colors – red indicates H-rich material, cyan / blue indicate He-rich material, grey indicates CO-rich material and green indicates degenerate matter (in NS). The specific phase of the evolution is indicated by the text next to the systems, with black text indicating phases that have been observed previously, while red text indicates phases that have not been previously observed, and bold red text phases we observed in this work.
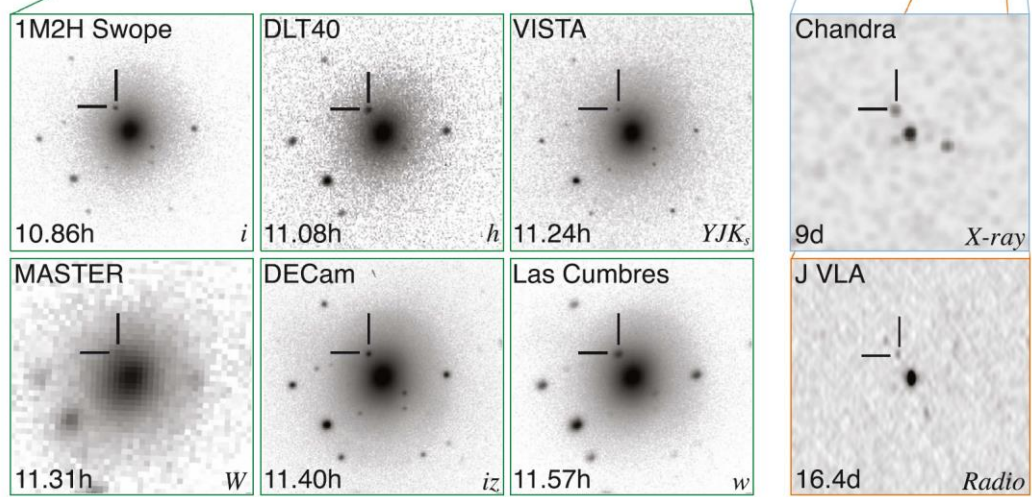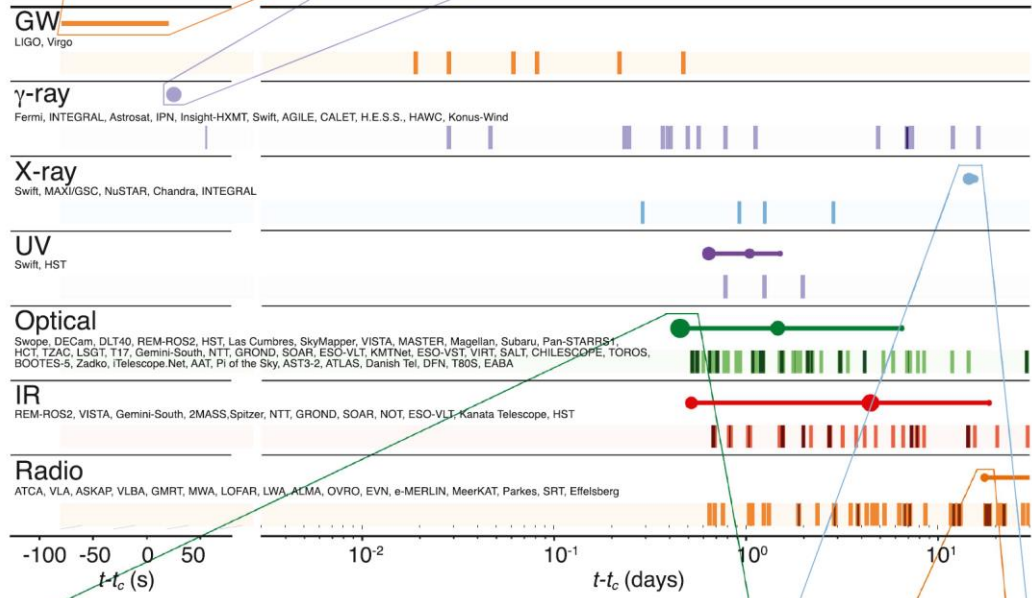
De et al. (2018)

$M_{binary} \lesssim M_{NS,max}$

$M_{binary} \gtrsim 3\,M_\odot$ $M_{NS1} \neq M_{NS2}$

NS

inspiral

NS

$M_{NS,max} < M_{binary}$
$M_{binary} < 3\,M_\odot$

merger

lower-mass
longer-lived

BH

accretion

NS

stable

$2-4$ kHz

hypermassive NS

higher-mass, short-lived

$M_{binary} \gtrsim 3\,M_\odot$ $M_{NS1} = M_{NS2}$

BH

ringdown

≤ 1 kHz $1-3$ kHz $2-4$ kHz $5-6$ kHz $6.5-7$ kHz

$10^2 - 10^3$ Hz

NS

inspiral

BH

$R_{tidal} \geq R_{ISCO}$

tidal disruption

$R_{tidal} < R_{ISCO}$
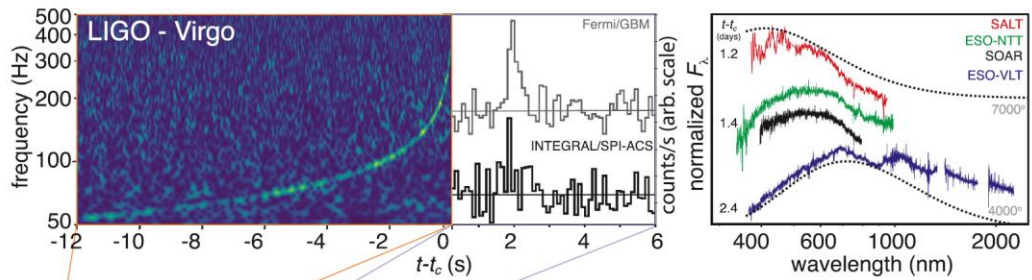
plunge

BH

accretion

BH

ringdown

Bartos et al. (2013)

Binary neutron star mergers

$T = 3.50$ GK, $n_n = 2.937e+35$ cm^{-3}, $R_{n/s} = 623.3$, $s = 0.621$ k_b/nuc, $t = 0.0131$ s

GW
LIGO, Virgo

γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind

X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL

UV
Swift, HST

Optical
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1,
HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS,
BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN, T80S, EABA

IR
REM-ROS2, VISTA, Gemini-South, 2MASS, Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata Telescope, HST

Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg

Students Think Lectures Are Best, But Research Suggests They're Wrong

A study reveals students prefer low-effort learning strategies—like listening to lectures—despite doing better with active learning.

By Youki Terada

October 16, 2019

John Hersey / The iSpot

Students are often "poor judges" of their own learning, according to researchers in a study recently published in the **Proceedings of the National Academy of Sciences** . Strategies that require low cognitive effort—such as passively listening to a lecture—are often perceived by students to be more effective than active strategies such as hands-on experimentation and group problem-solving. The group dynamic can make students feel frustrated and "painfully aware of their lack of understanding," but the study concluded that the more effort and struggle involved—hallmarks of a student-centered, active approach—the more students learned.
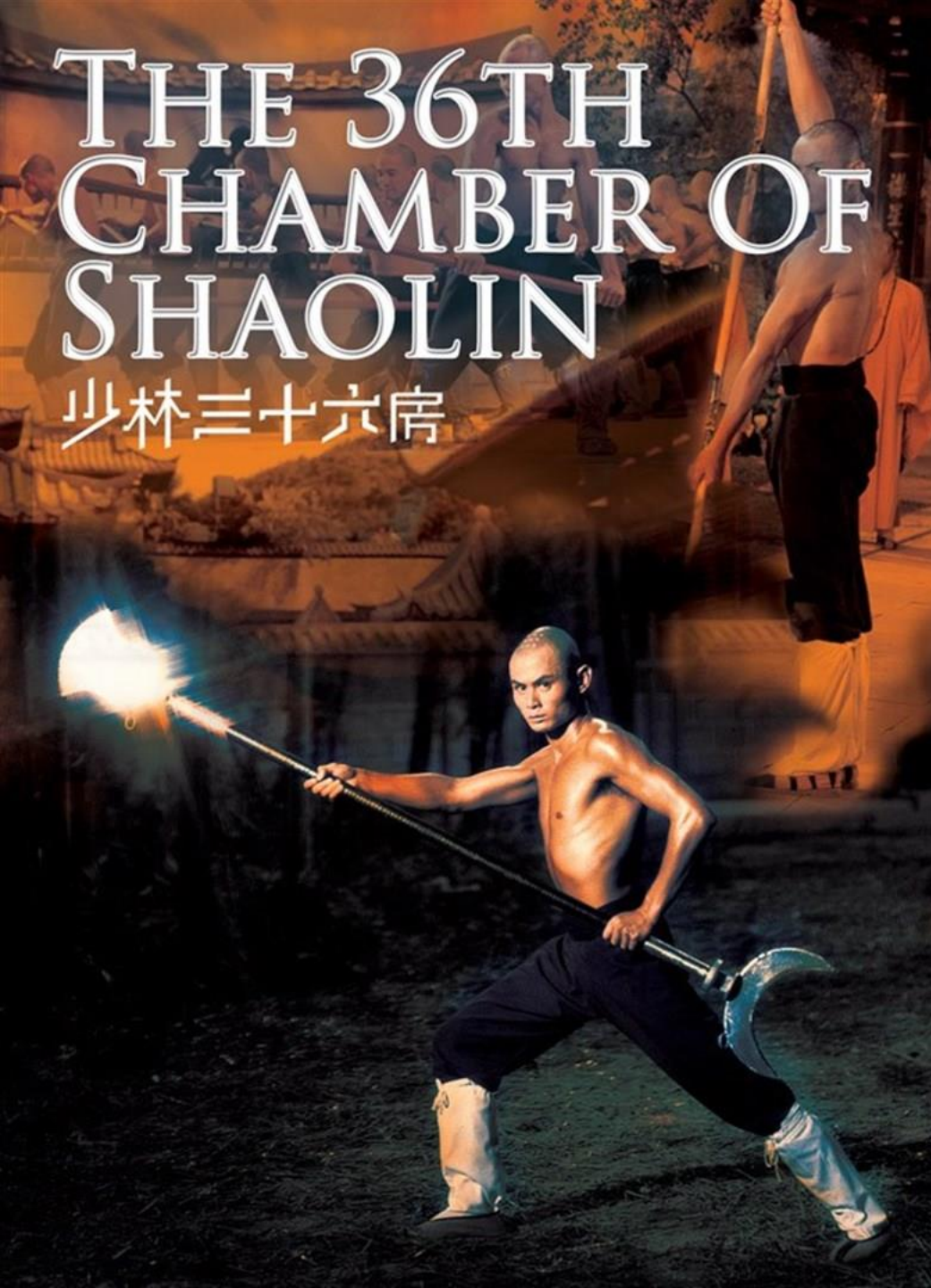
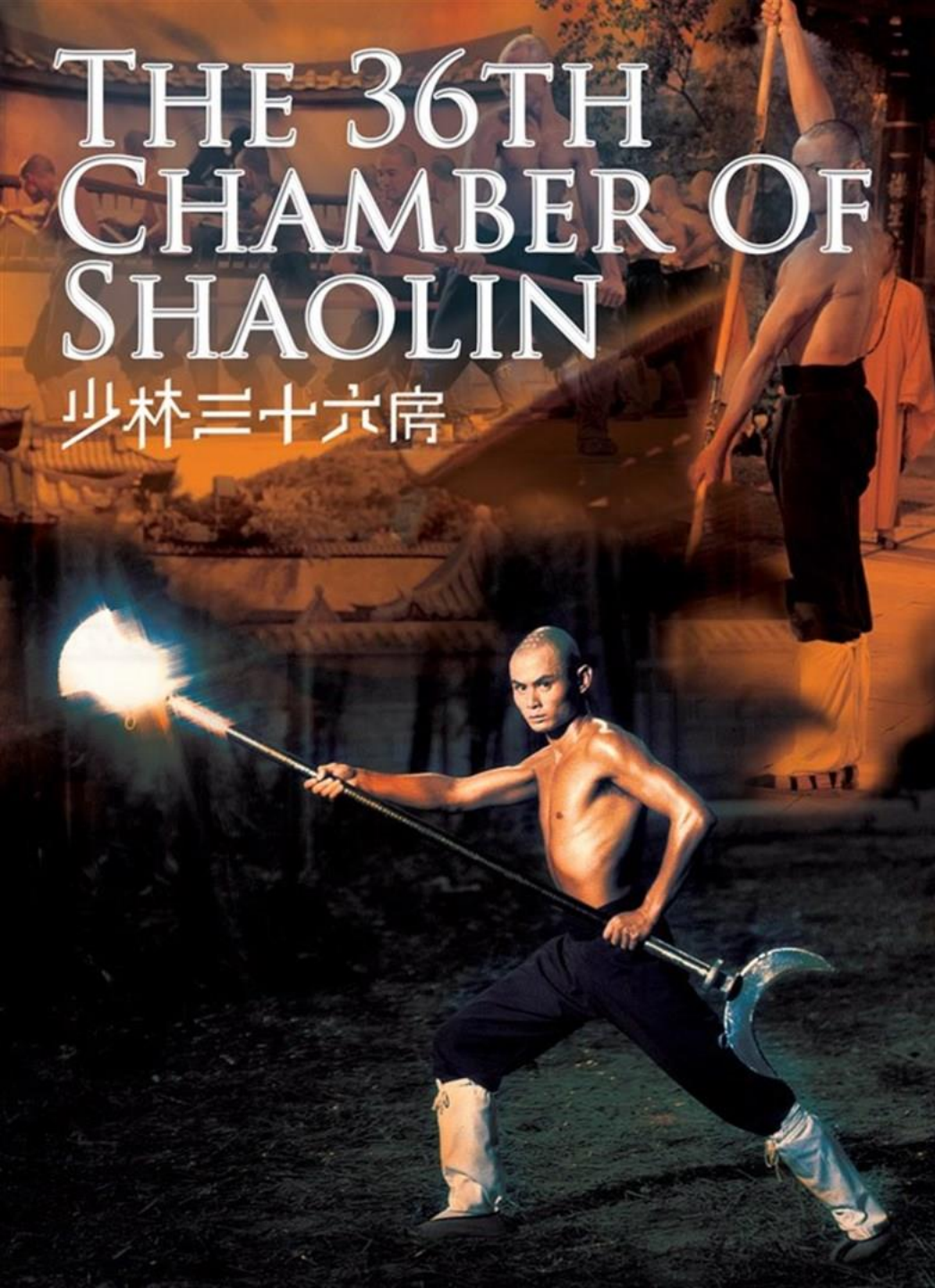Teach kung fu to lay people

Philosophical training

Weapons

Leg, head strikes

Dexterity

Strength, balance

Teach physics at MFF

Nobel prize

Overthrowing paradigms

Finding your own topics

Presentation of results

Writing papers

Reading papers

Experimental techniques

Integration

Derivative/Taylor expansion

Algebra

Question:

How fast does grass grow?