Towards Exascale Supernova Simulations with GenASiS

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Pedro Marronetti
Anthony Mezzacappa

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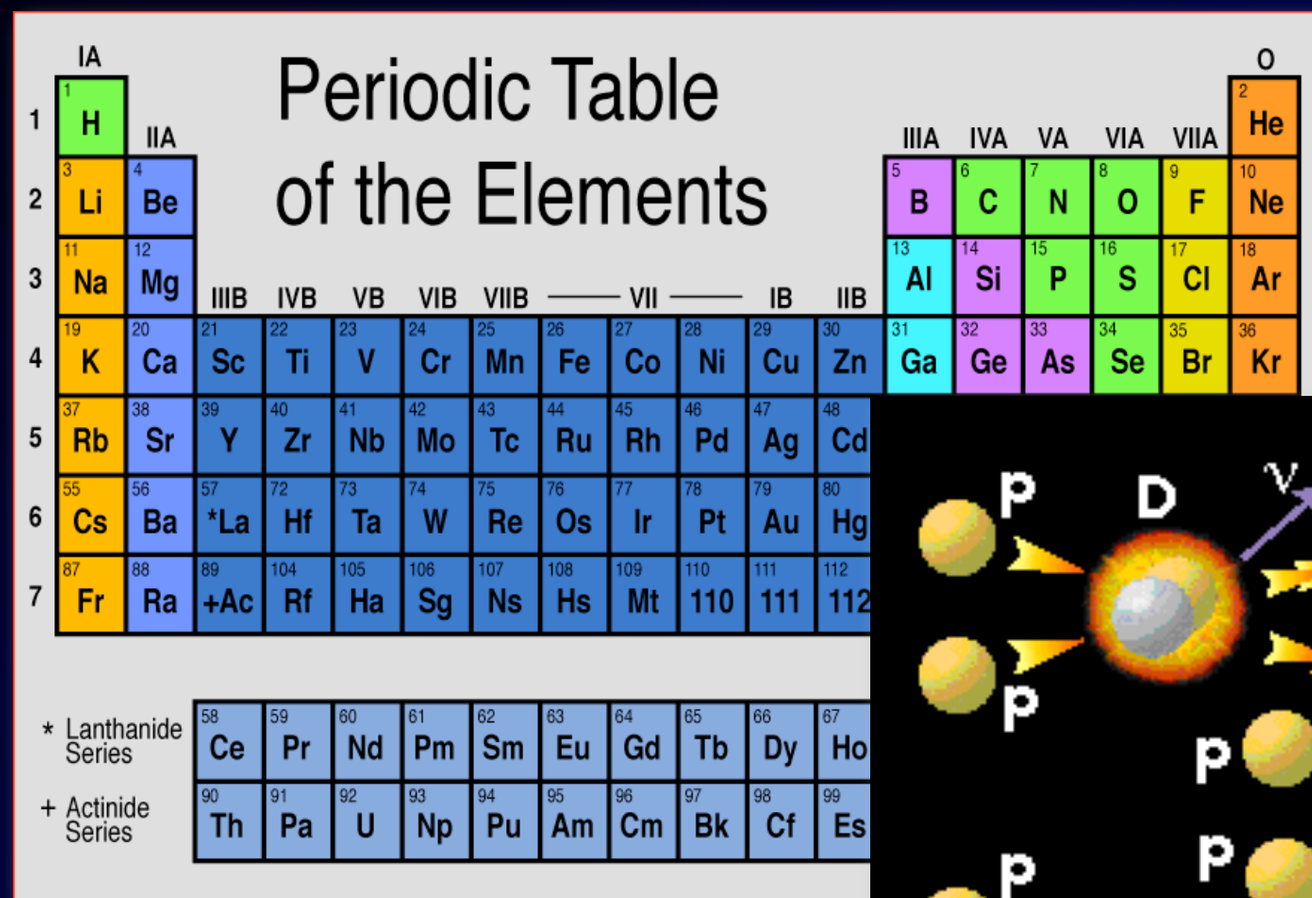
Why simulate supernovae?

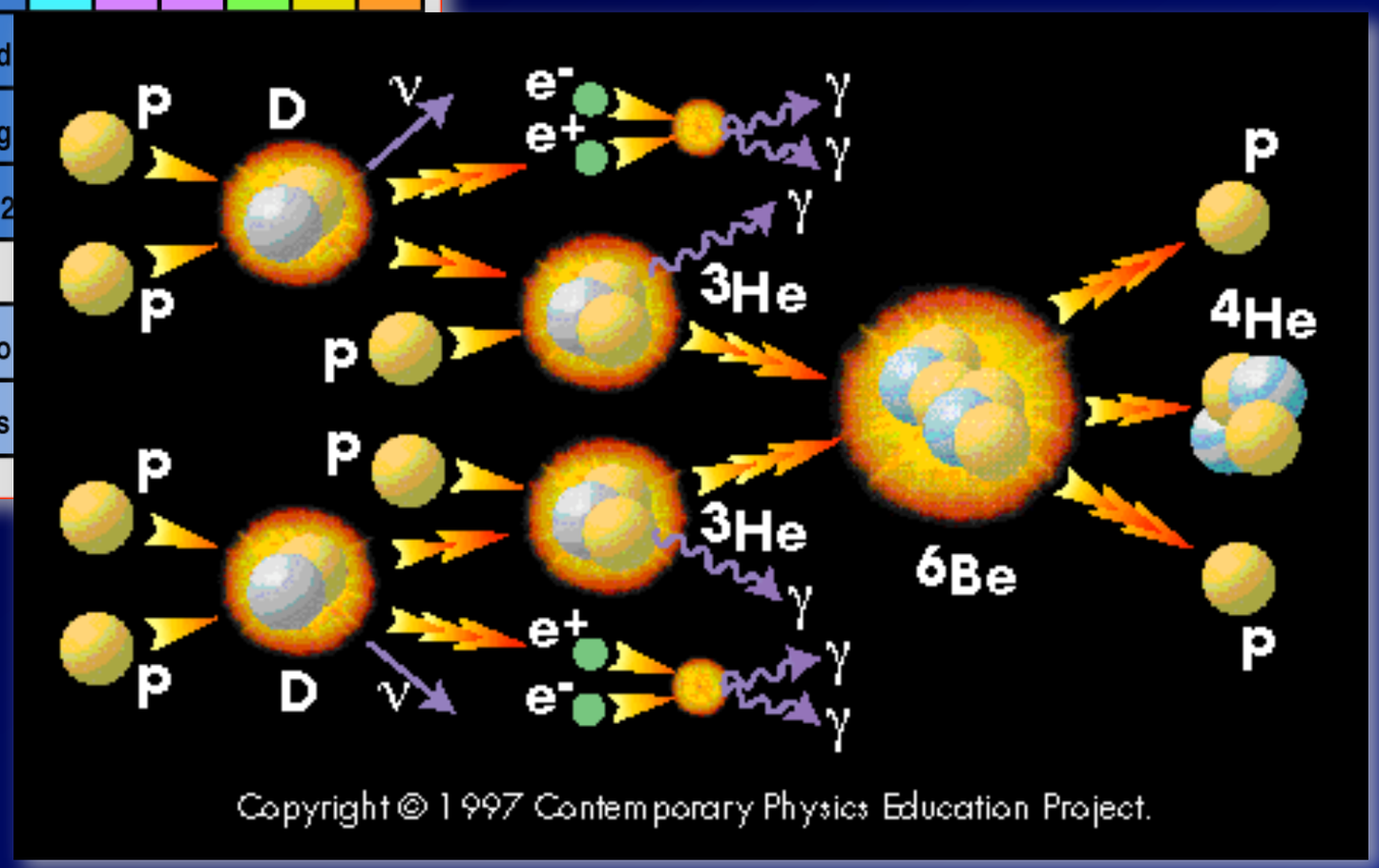
Periodic Table of the Elements

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VII		IB	IIB	IIIA	IVA	VA	VIA	VIIA	O
1	1 H																2 He
2	3 Li	4 Be										5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg										13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	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
5	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
6	55 Cs	56 Ba	57 *La	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
7	87 Fr	88 Ra	89 +Ac	104 Rf	105 Ha	106 Sg	107 Ns	108 Hs	109 Mt	110 110	111 111	112 112	113 113					

* Lanthanide Series	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
+ Actinide Series	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Many elements are formed by the nuclear fusion that powers stars.





Stars disperse elements with a whimper...

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$$0.8\,M_\odot \lesssim M \lesssim 8\,M_\odot$$

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NGC 6543

Towards the end of their lives, stars with $0.8\,M_\odot \lesssim M \lesssim 8\,M_\odot$ puff their chemically-enriched envelopes into the interstellar medium.

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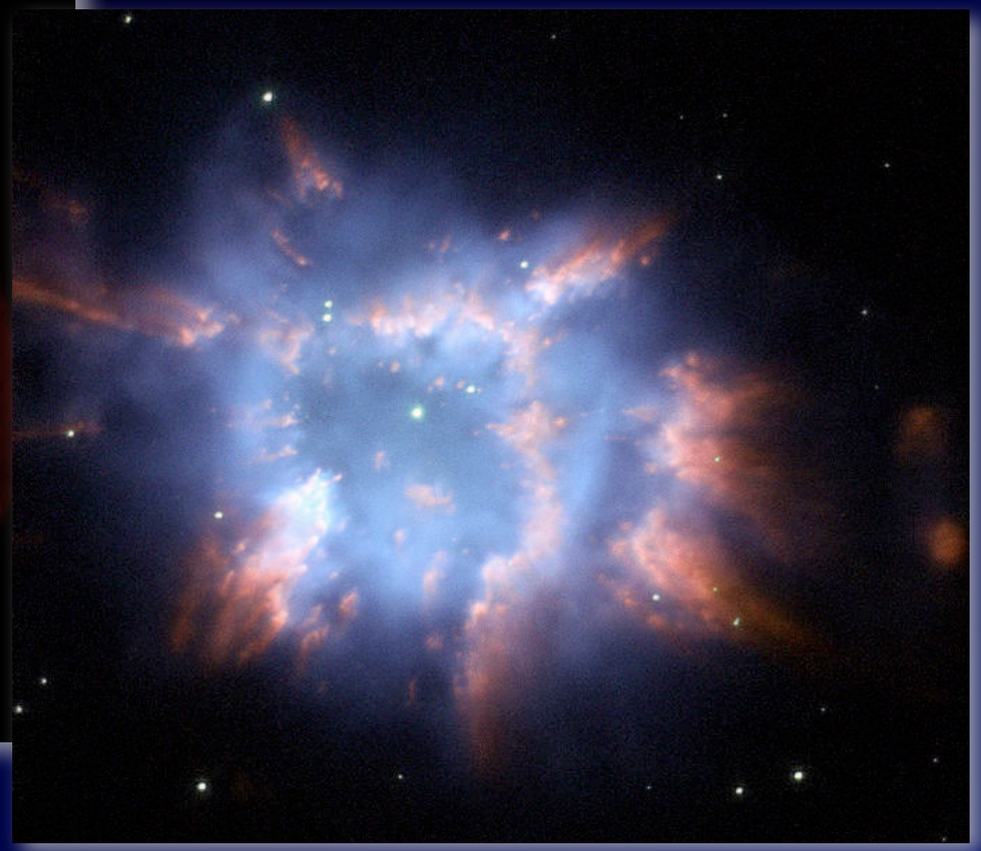

NGC 6326

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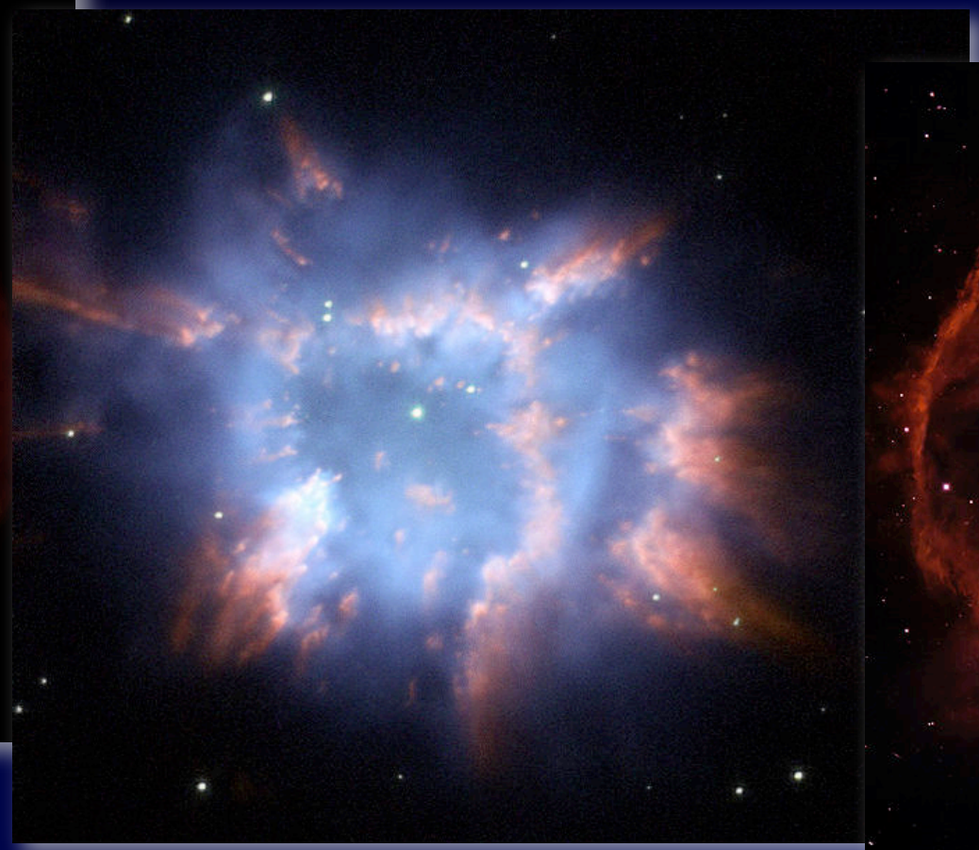

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NGC 7293

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...or a bang—one that includes further nucleosynthesis.

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SN 1994D

A ***supernova*** is an exceptionally bright new star.

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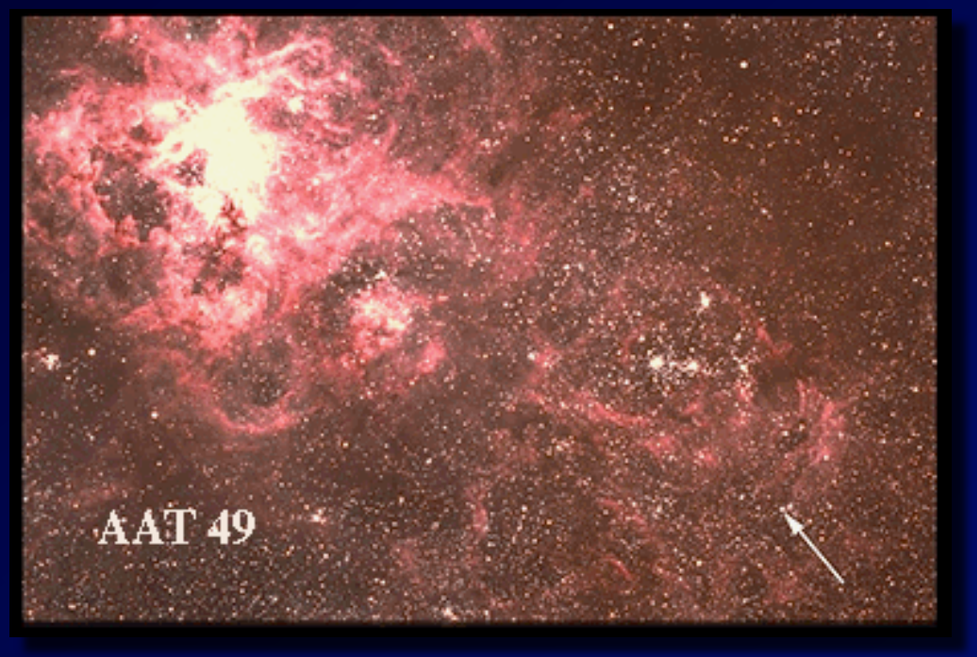

Tarantula Nebula, SN 1987A

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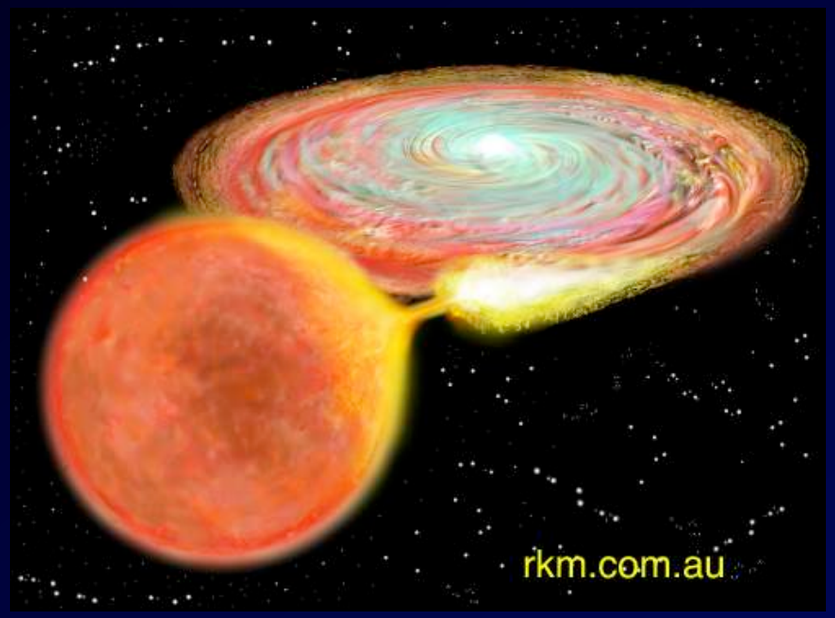

A ***thermonuclear supernova*** occurs when a white dwarf (remnant of a star with $M \lesssim 8\,M_\odot$) accretes too much mass from a binary companion.

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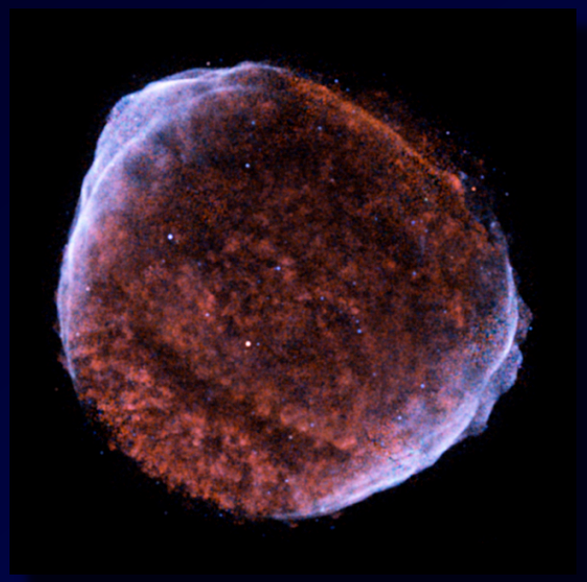
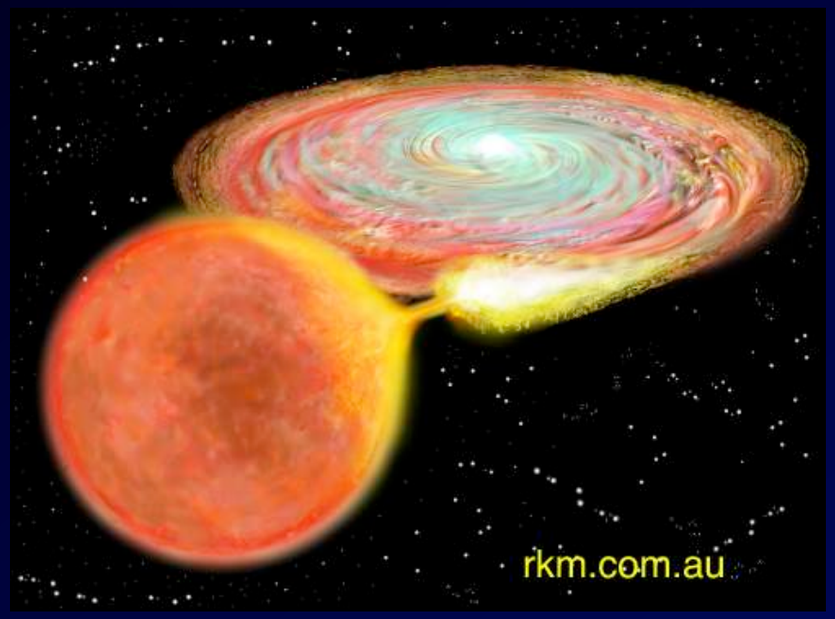


SN 1006 (X-ray)



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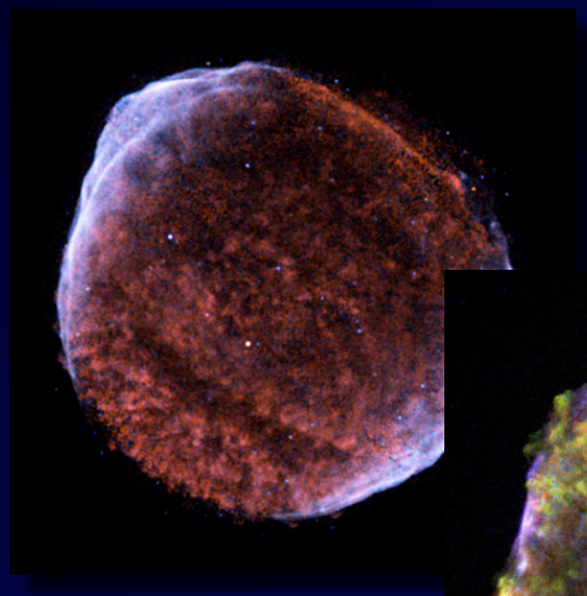

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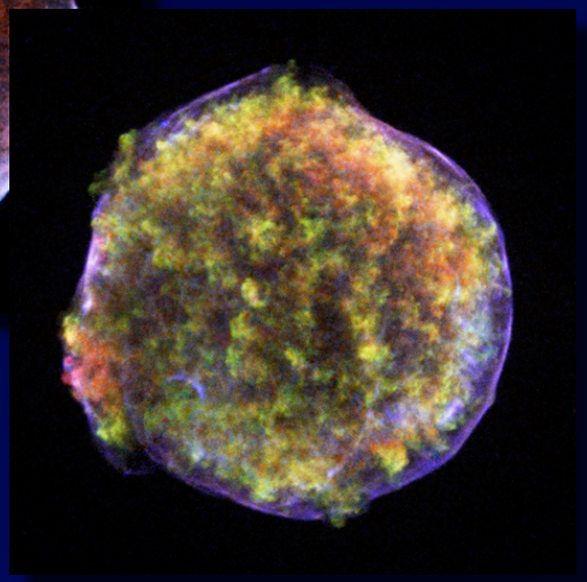
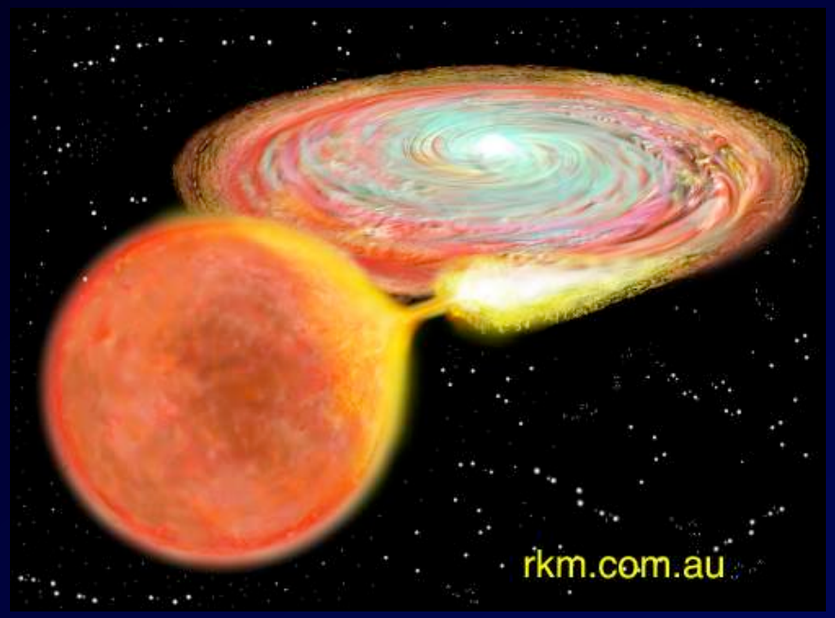


SN 1572 (X-ray)



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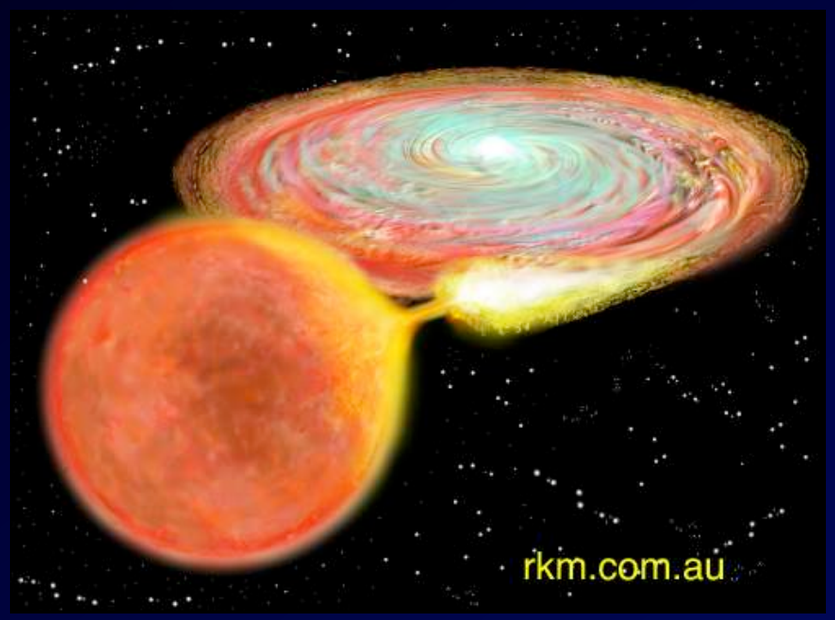

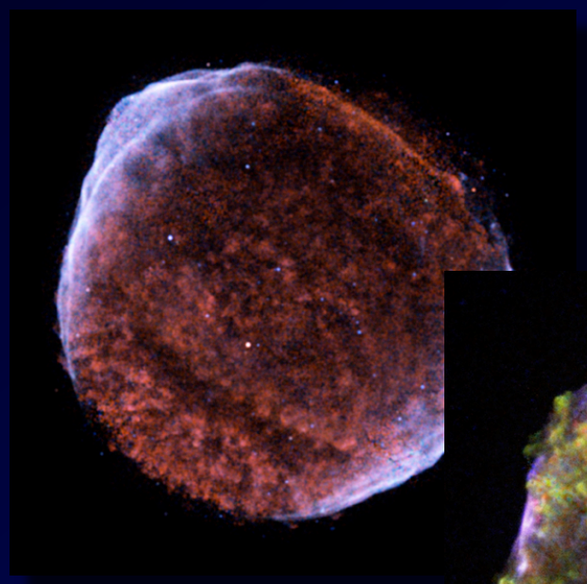

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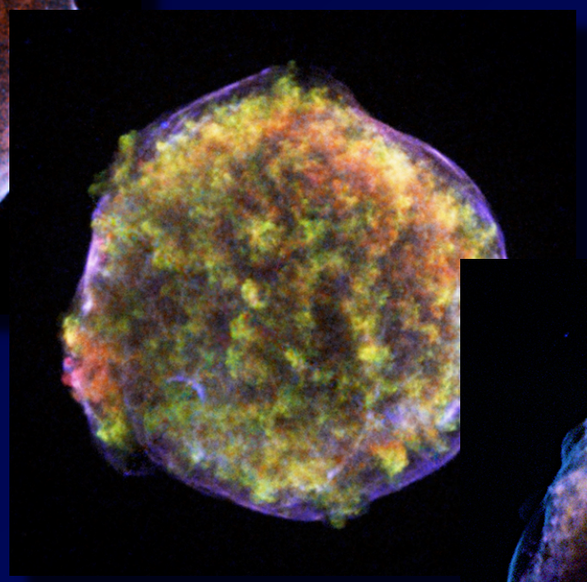

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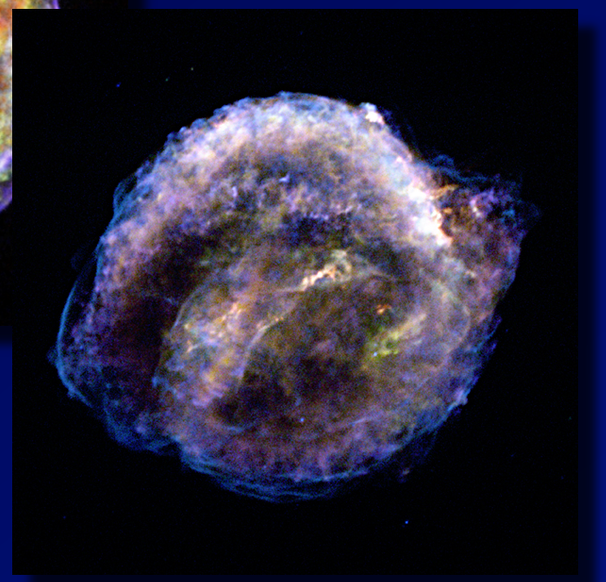

SN 1604 (X-ray)

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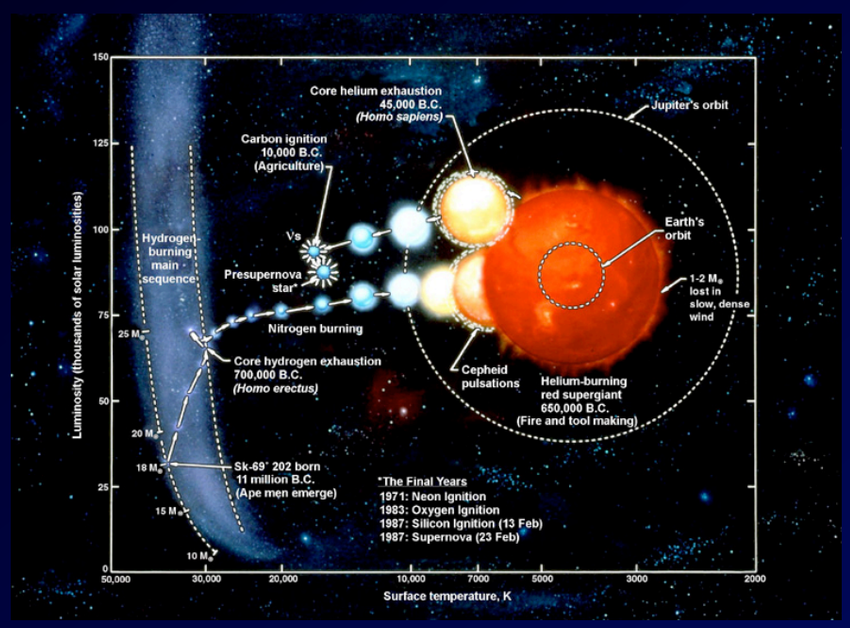

A ***core-collapse supernova*** occurs when the core of a star with $M \gtrsim 8\,M_\odot$ collapses at the end of several burning stages, releasing gravitational energy.

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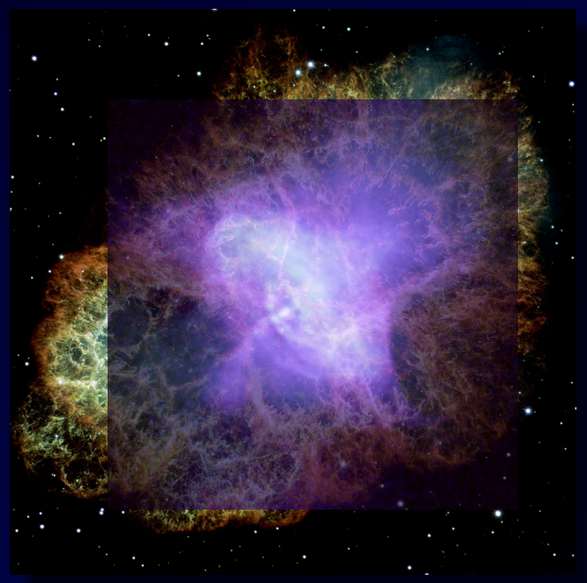
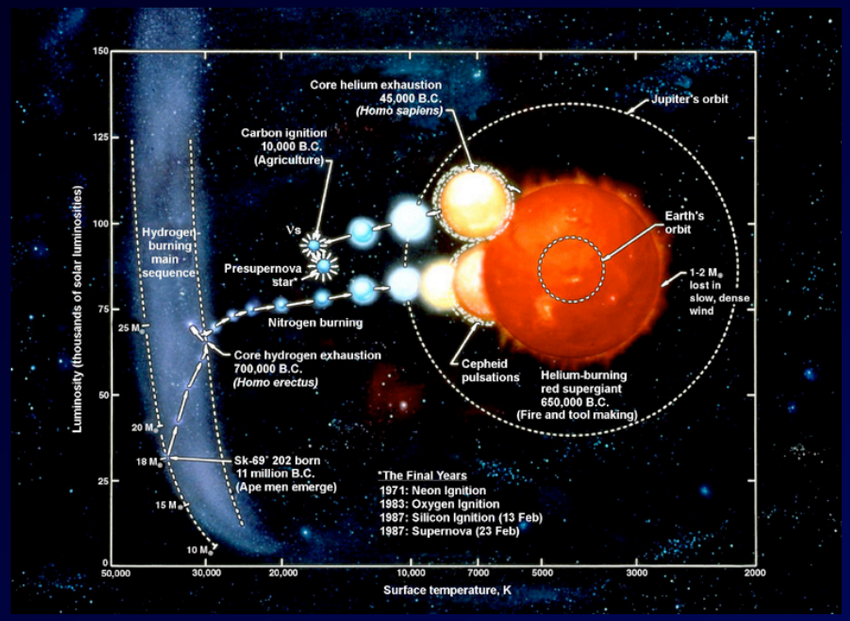


SN 1054 (Optical)



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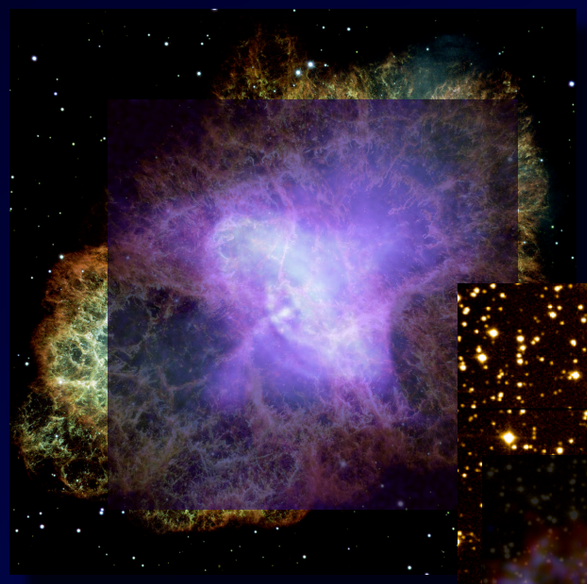
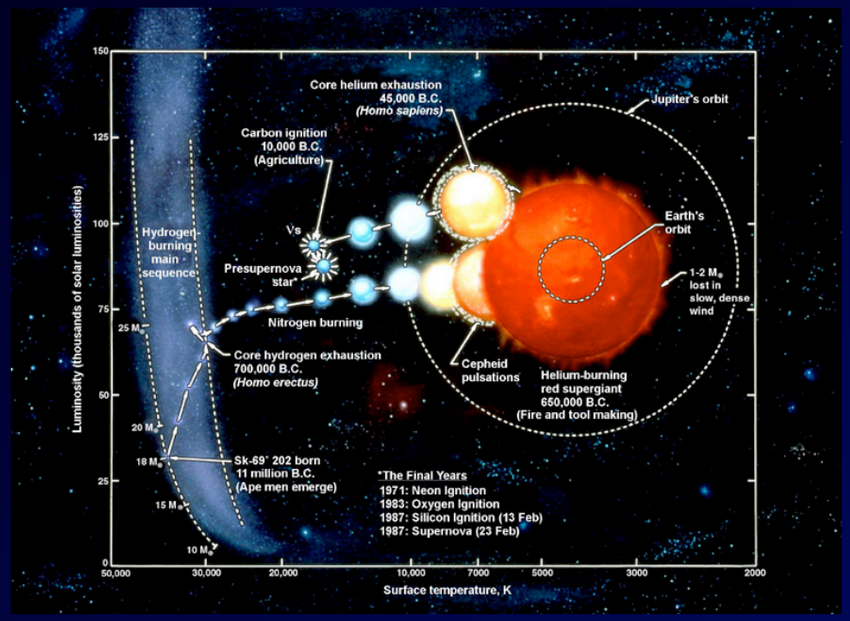


SN 1054 (Optical)

SN 1181 (Optical)



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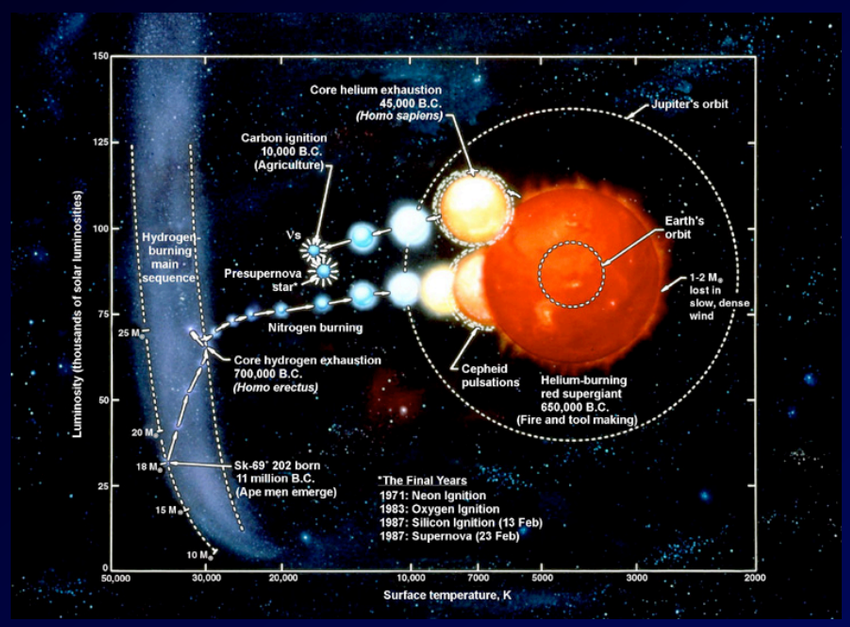

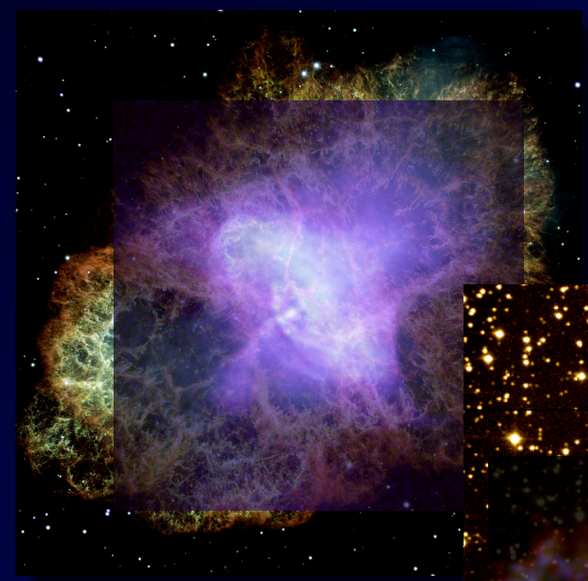

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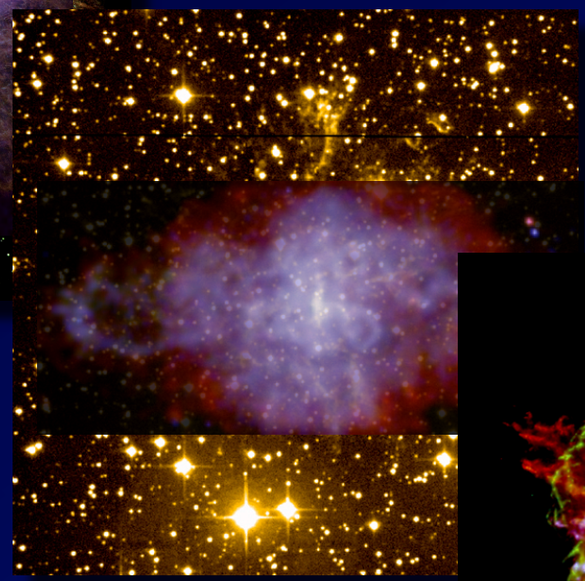

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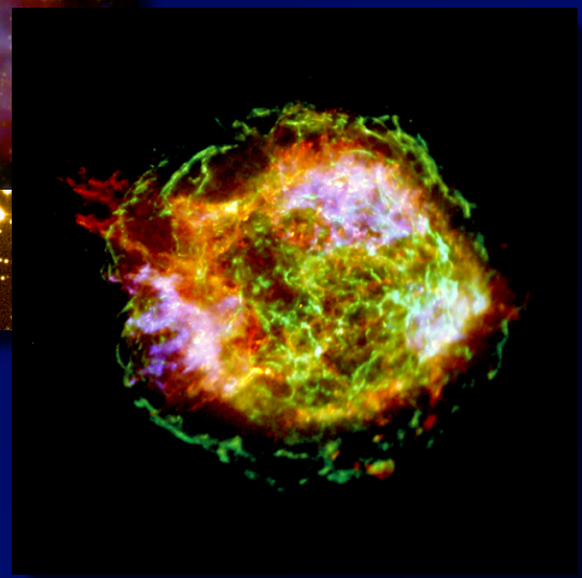
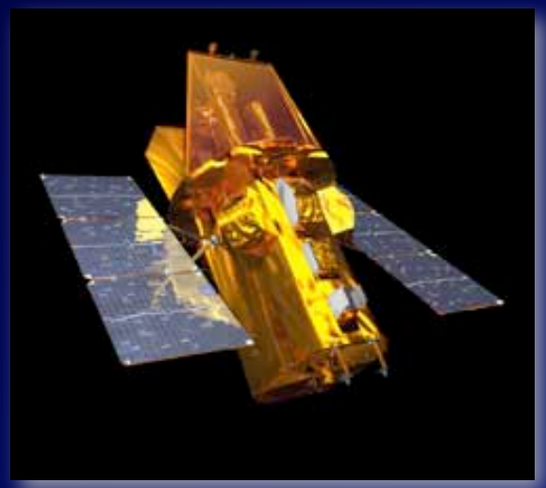


Cas A 1667? (X-ray)

A ***core-collapse supernova*** occurs when the core of a star with $M \gtrsim 8\,M_\odot$ collapses at the end of several burning stages, releasing gravitational energy.

Many core-collapse supernova observables are relevant to expensive observational programs.



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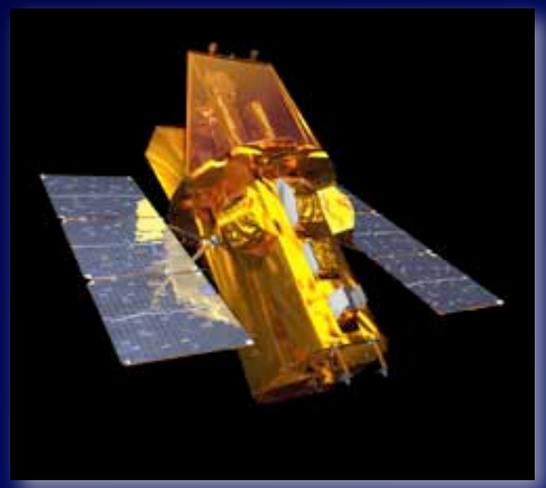
Launch of an explosion



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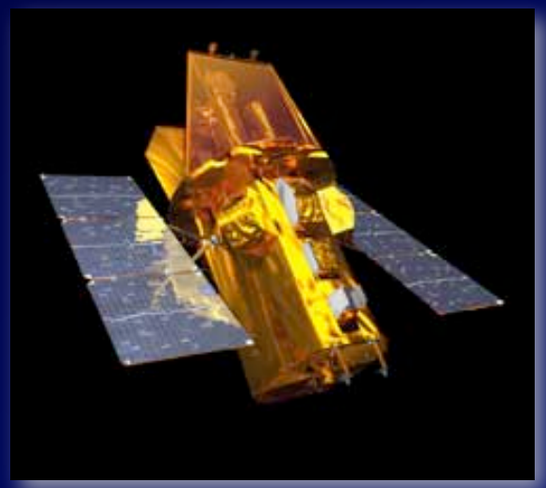
Neutron star mass, spin, magnetic field, and kick velocity



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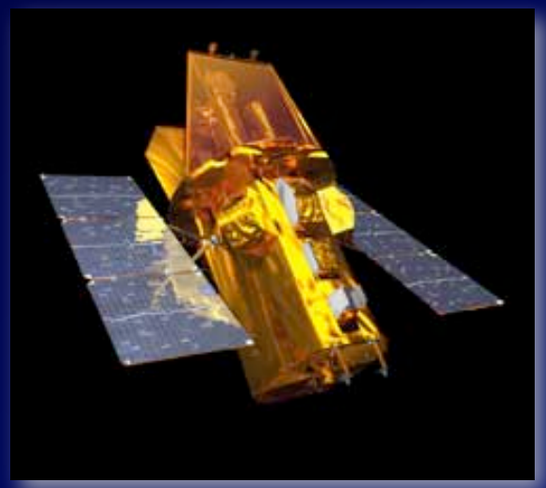
- Launch of an explosion
- Neutron star mass, spin, magnetic field, and kick velocity
- Composition of ejecta



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- Launch of an explosion
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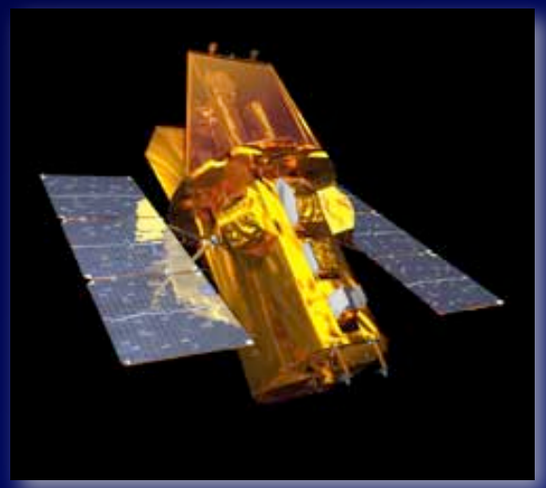
- Composition of ejecta
- Explosion morphology



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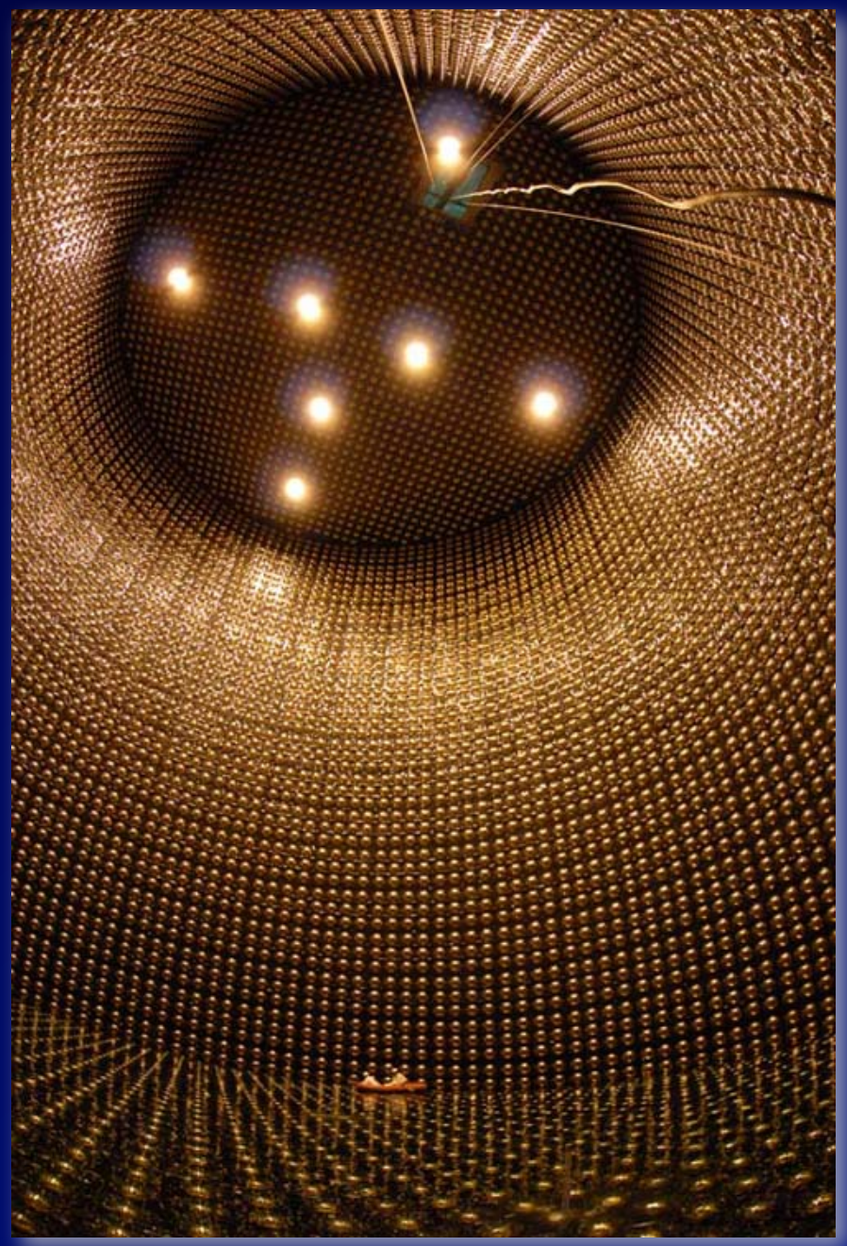
Neutrino signals



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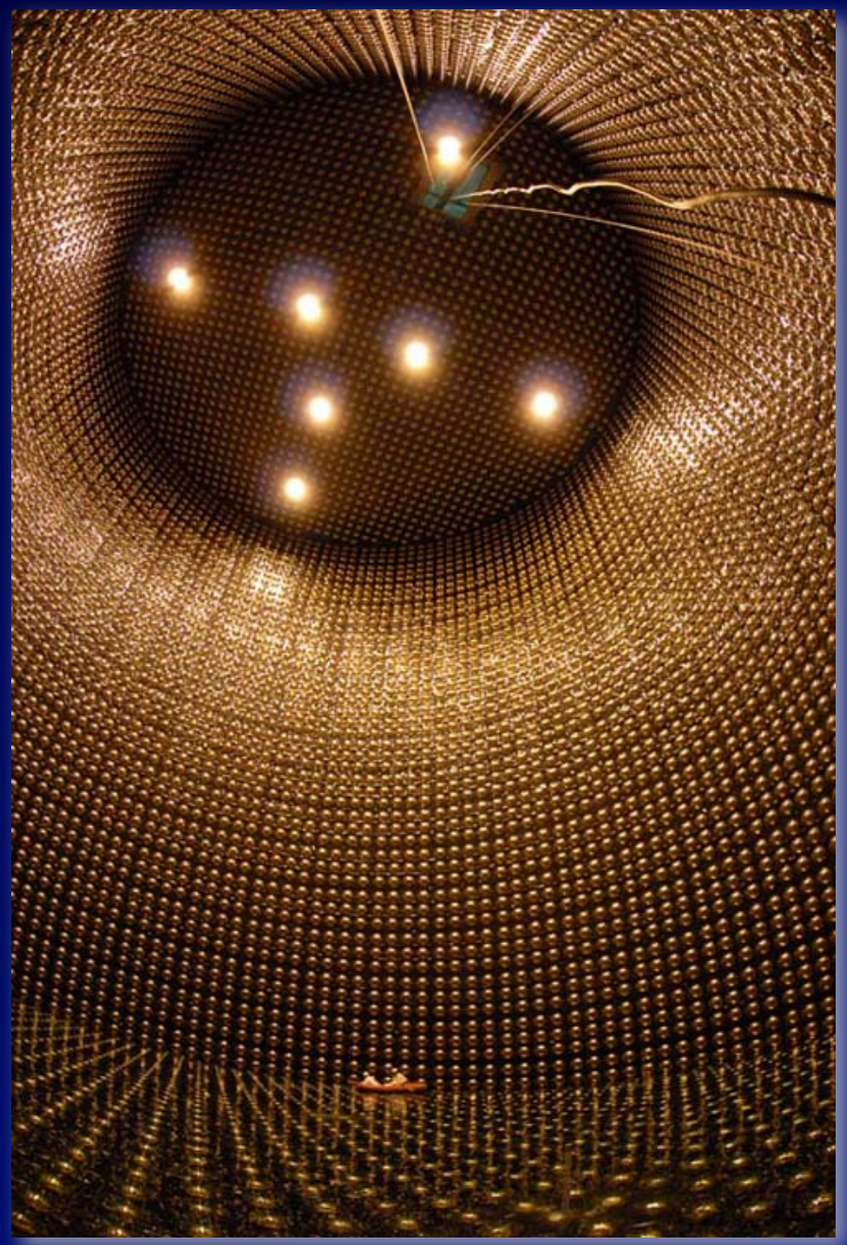

Gravitational wave signals

Core-collapse supernova simulations yield computational experience of practical value.

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(Magneto)hydrodynamics

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Reaction kinetics

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Particle transport

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- (Magneto)hydrodynamics
- Reaction kinetics
- Particle transport
- Multidimensional, multiscale, multiphysics system

Why is the core-collapse supernova mechanism an exascale problem?

A massive star develops a degenerate core, which can only get so big…

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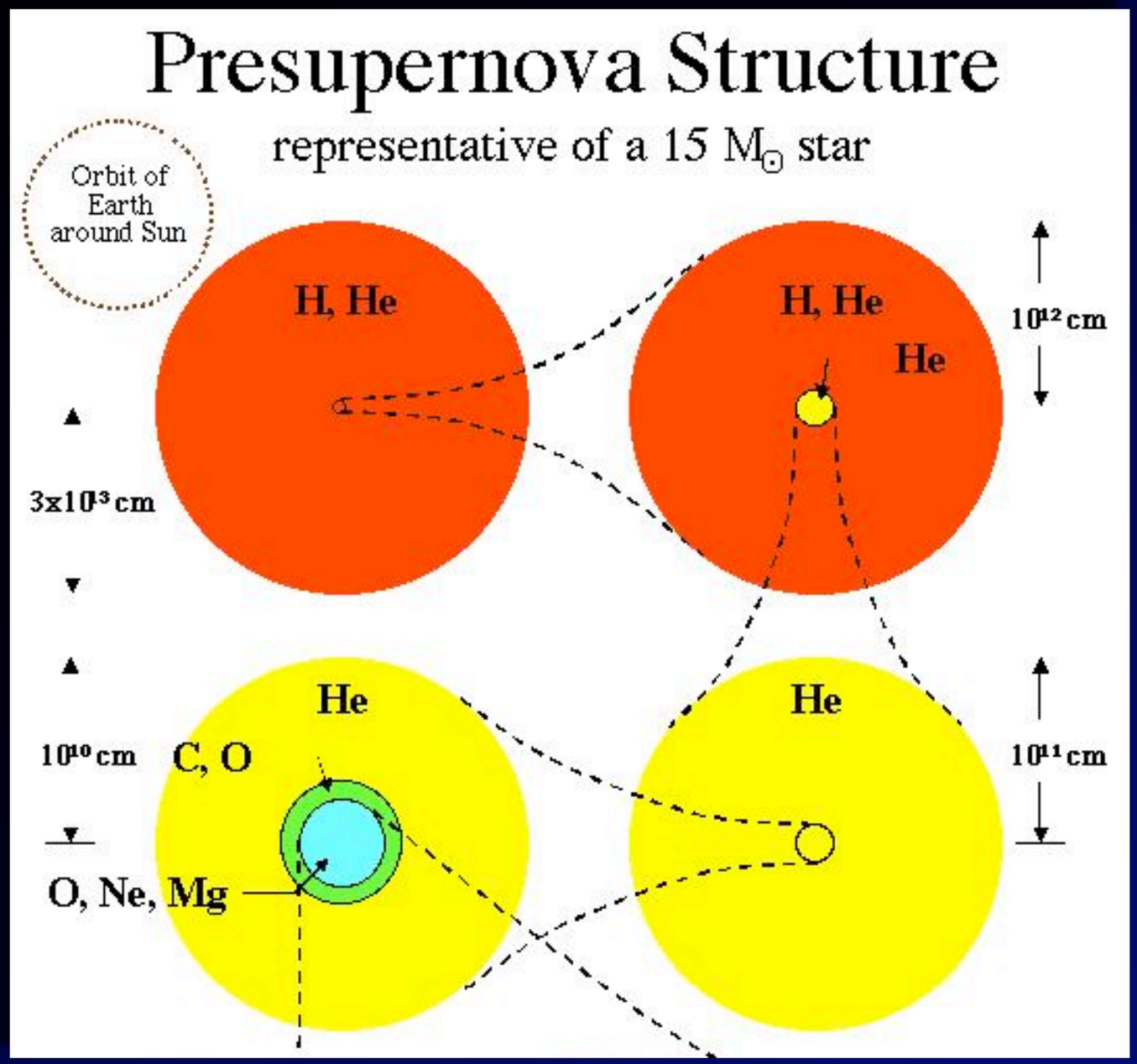

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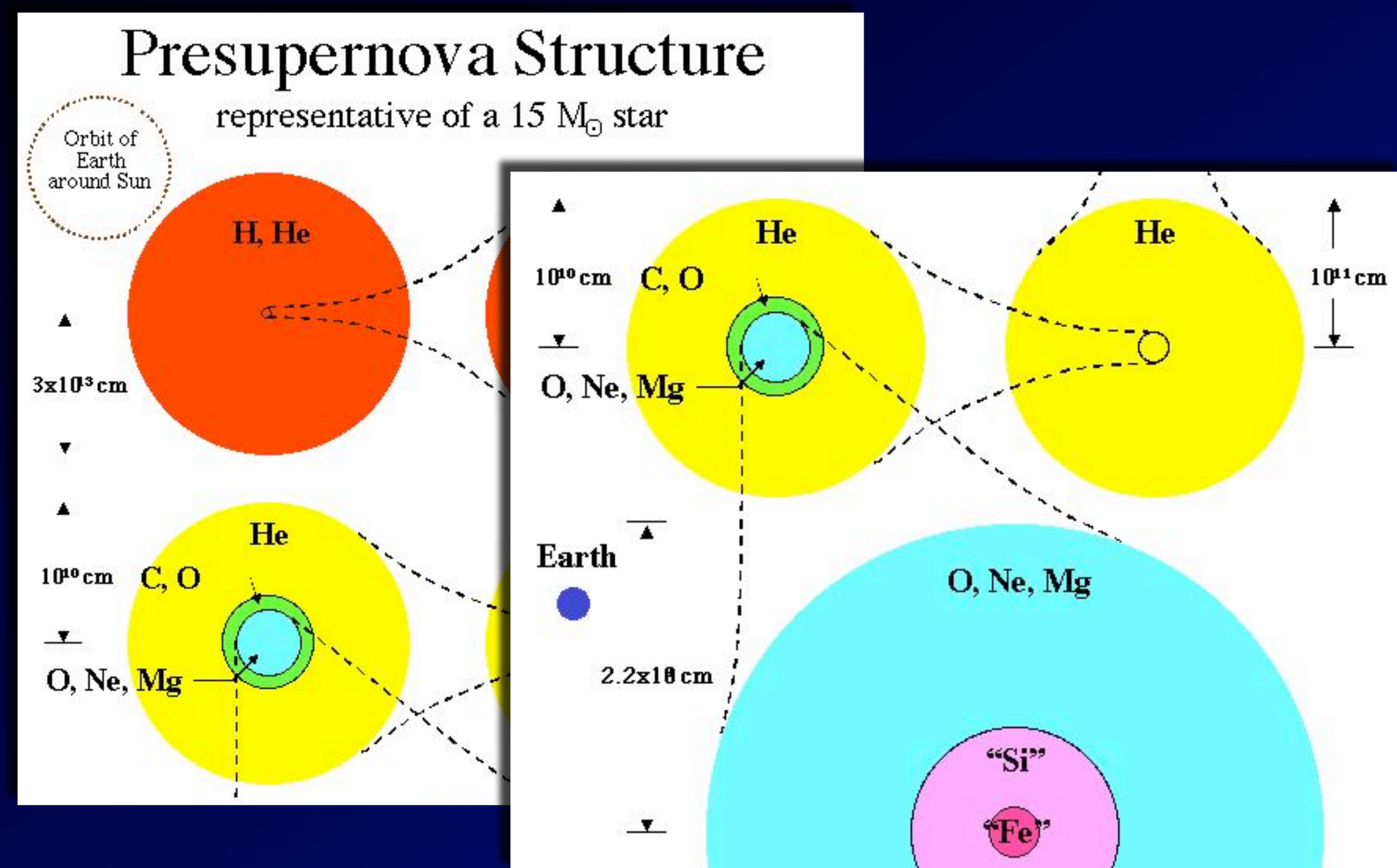

...before undergoing catastrophic collapse, which halts when the nuclear equation of state stiffens.

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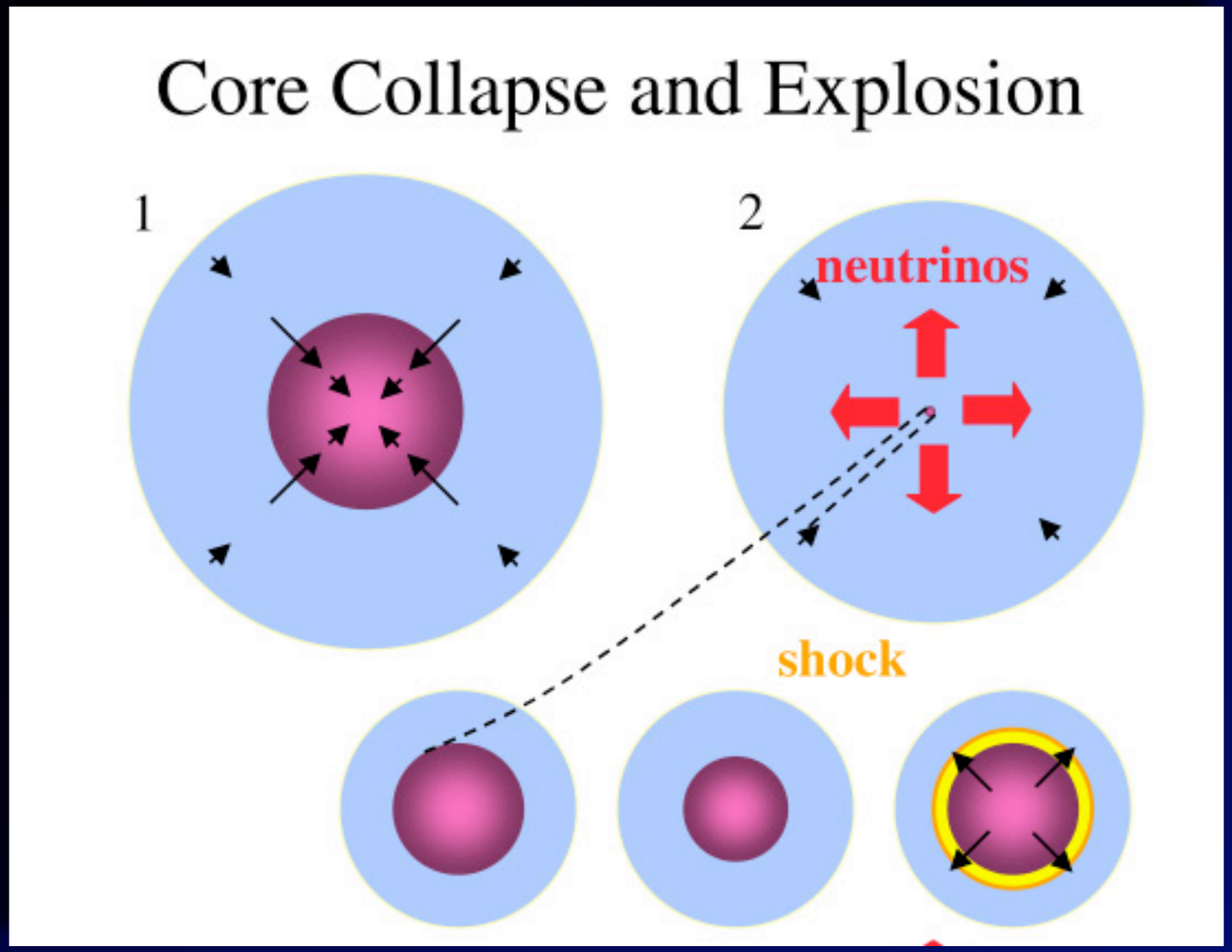
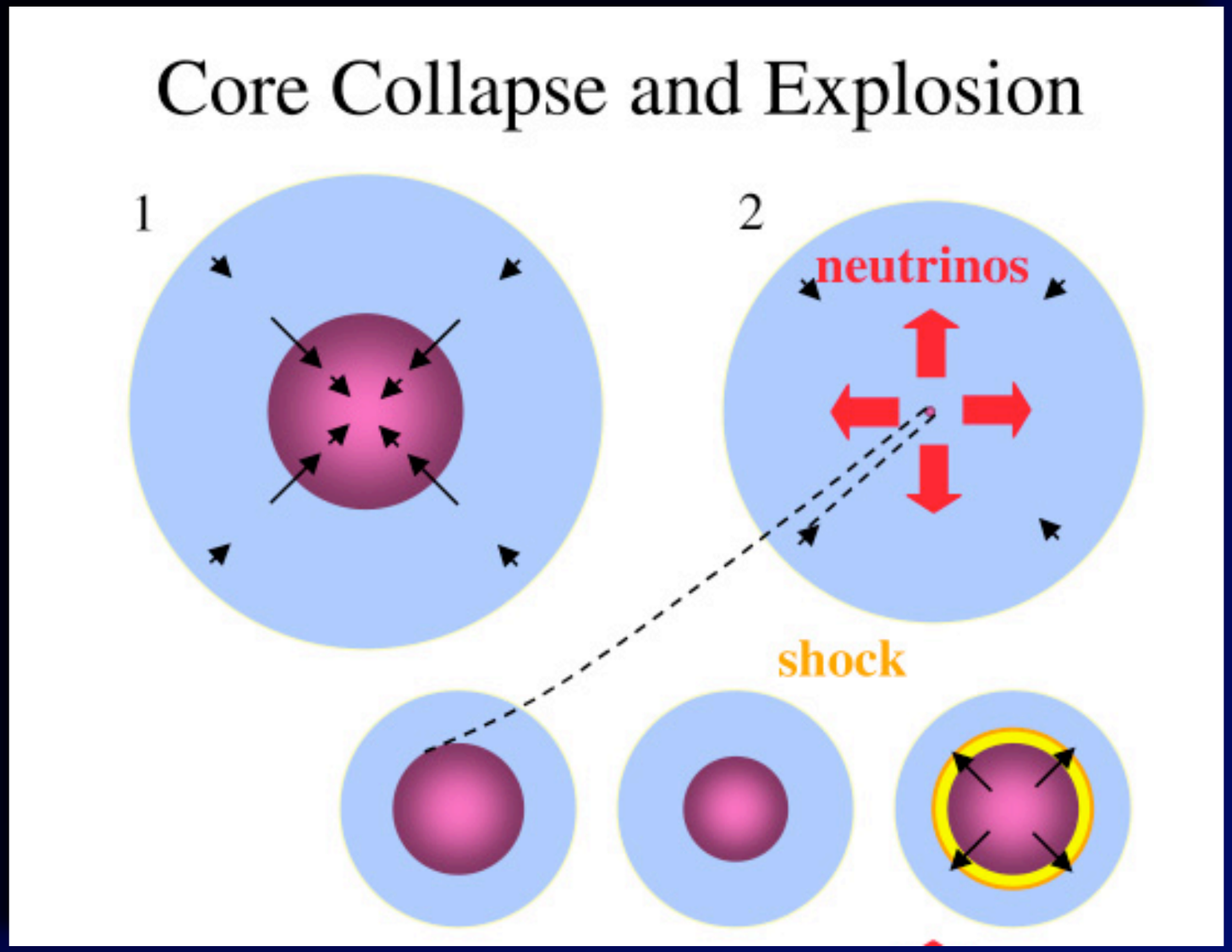


A shock forms and stalls. Neutrino heating and cooling and changes in nuclear composition affect its fate.



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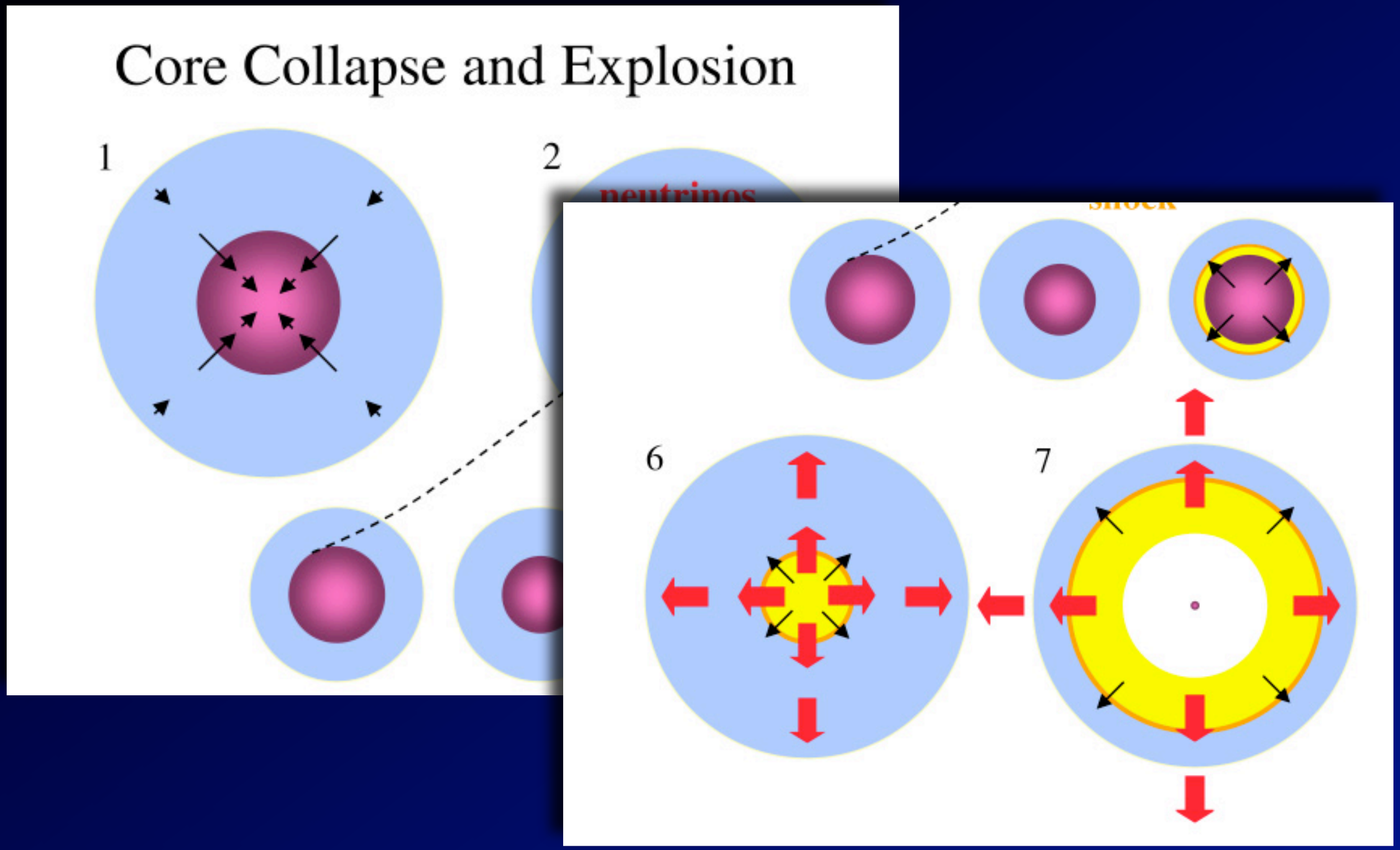
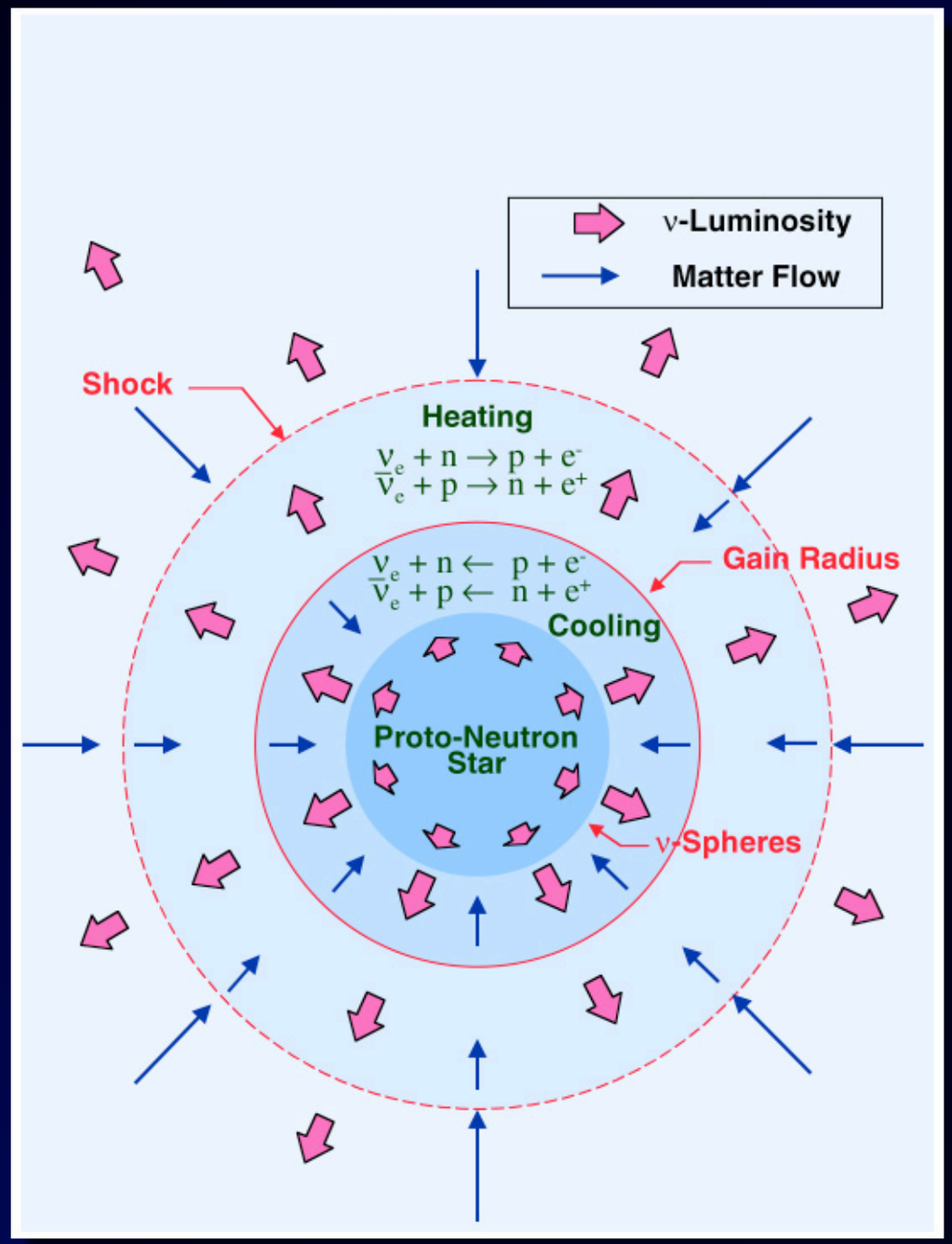


Heating/cooling rates depend on accurate evolution of neutrino distributions.



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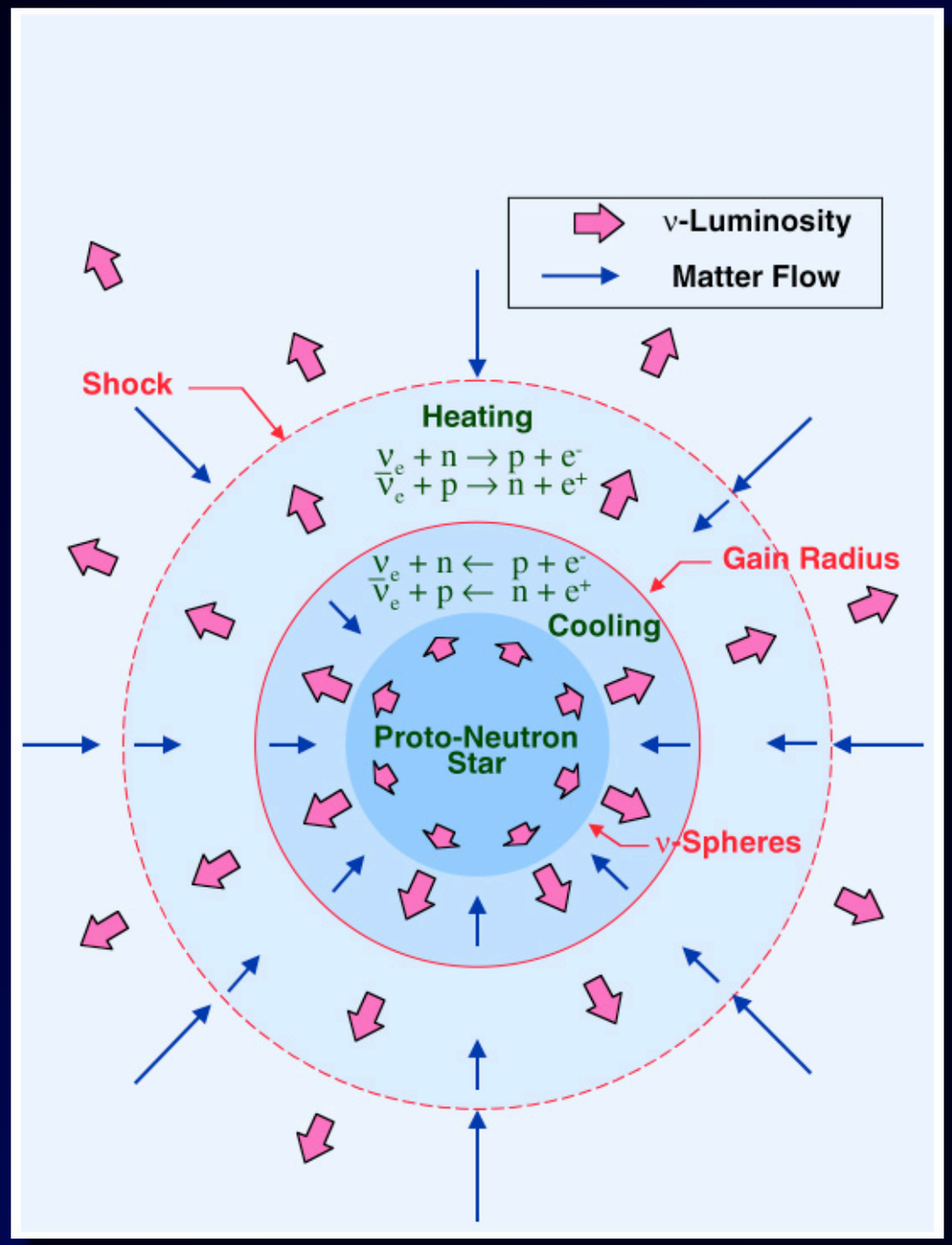

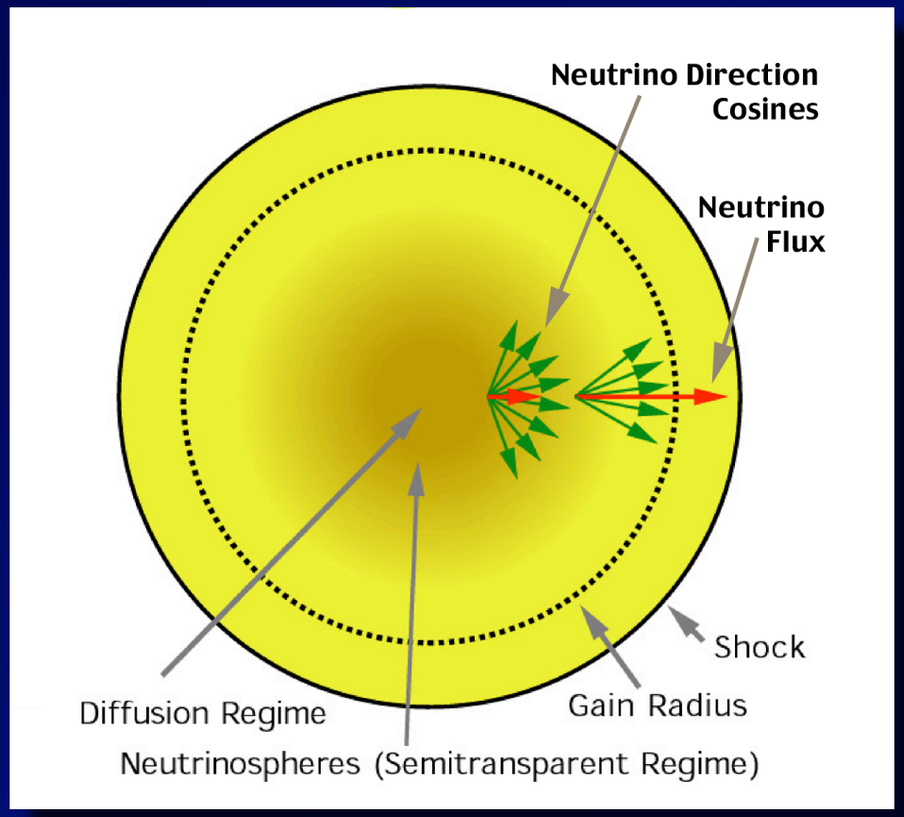

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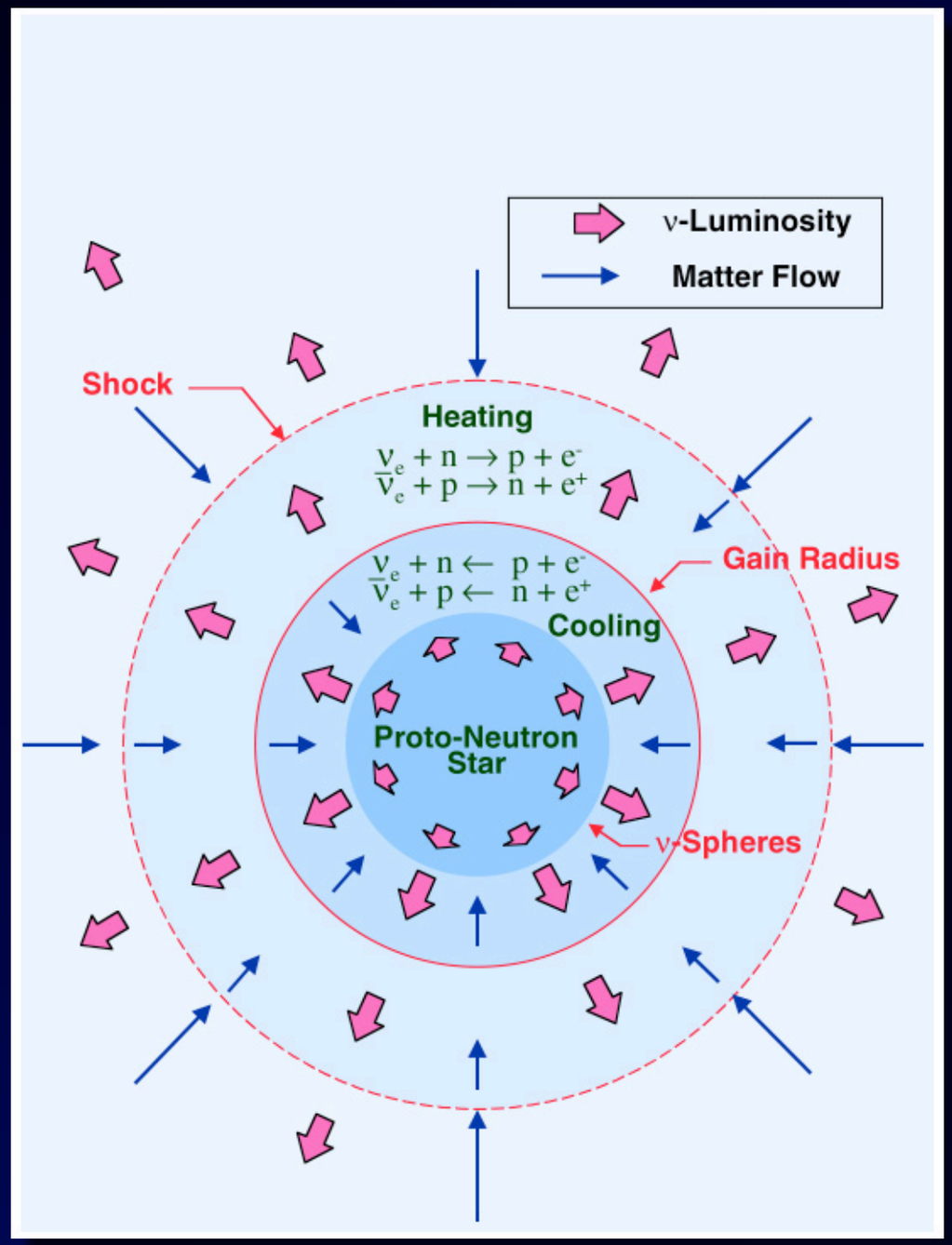
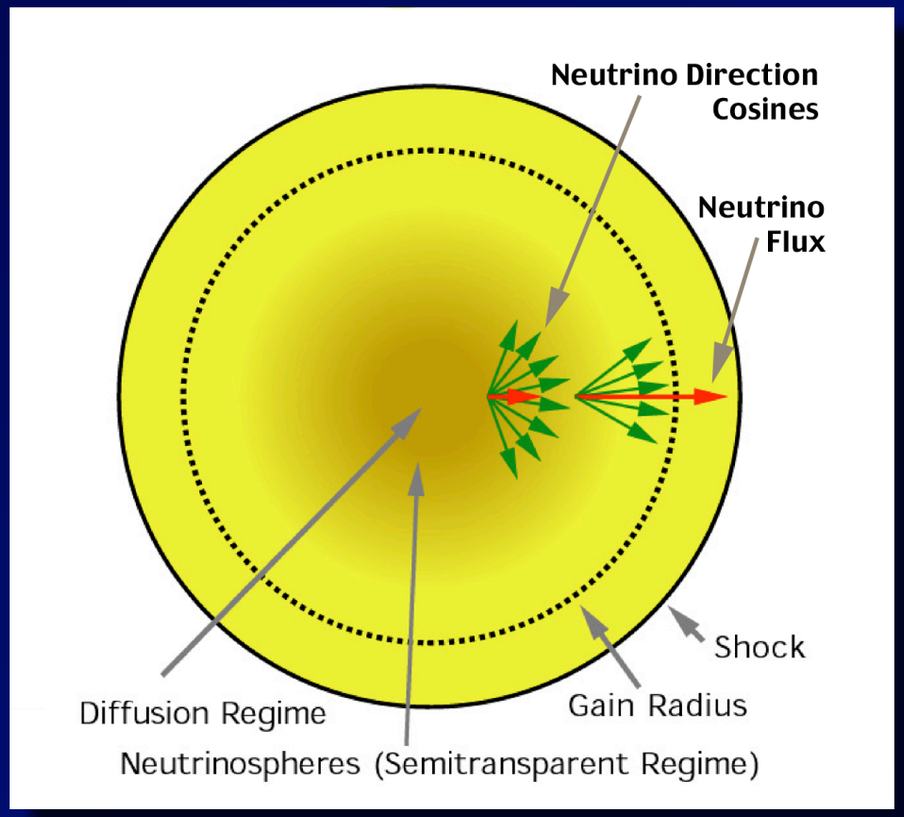


$$f(t, \mathbf{x}, \mathbf{p})$$



Convection, rotation, and magnetic fields all come into play.

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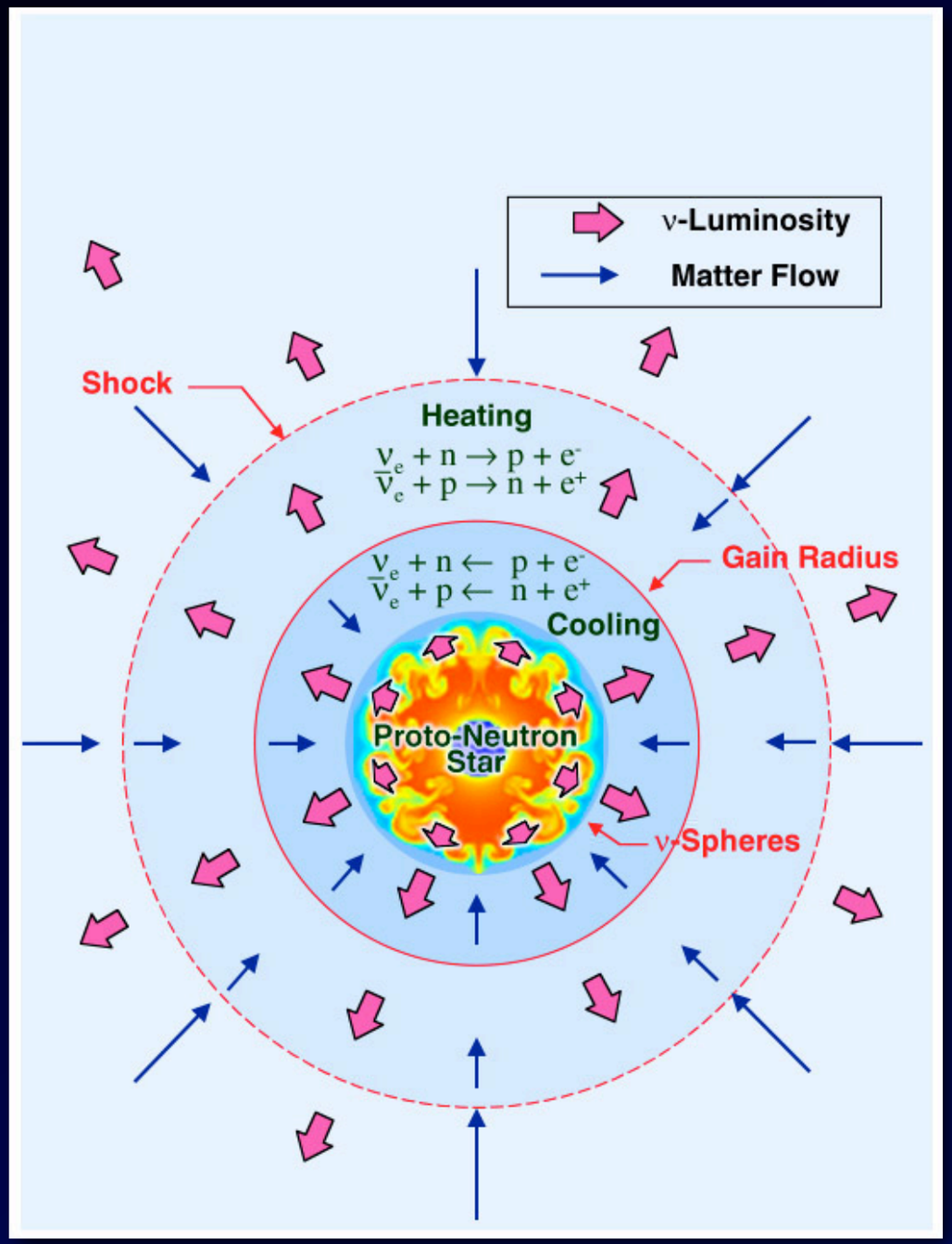

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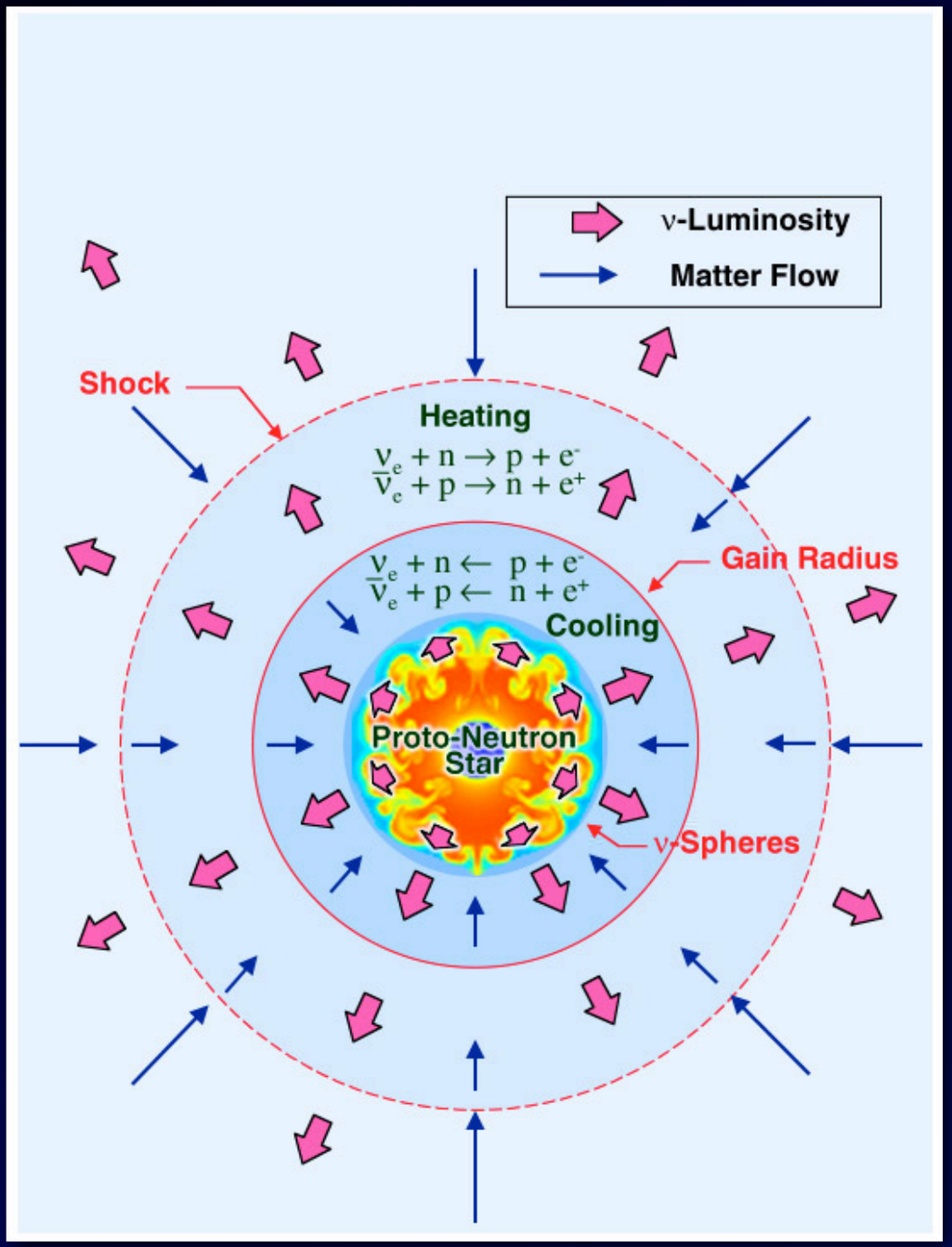

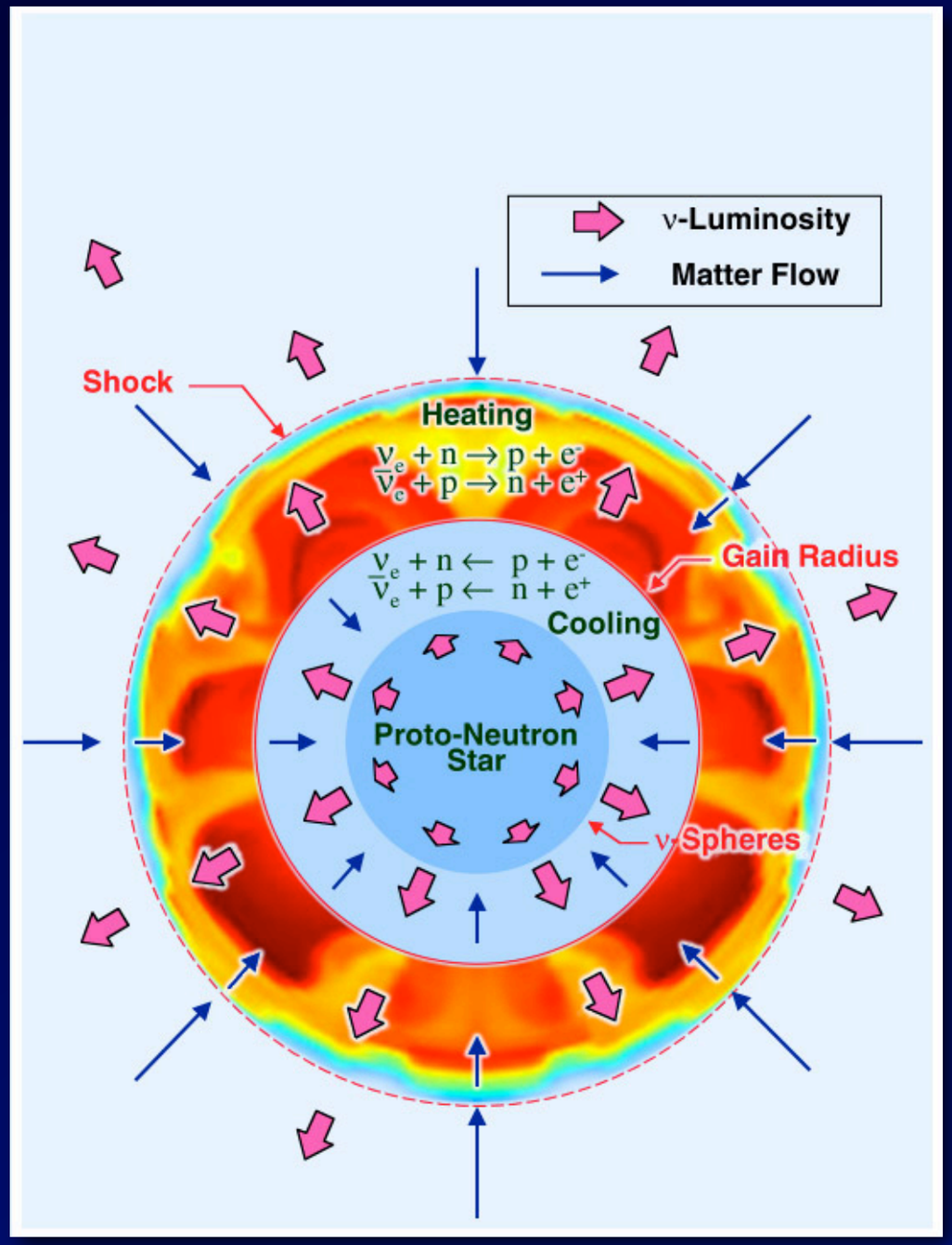

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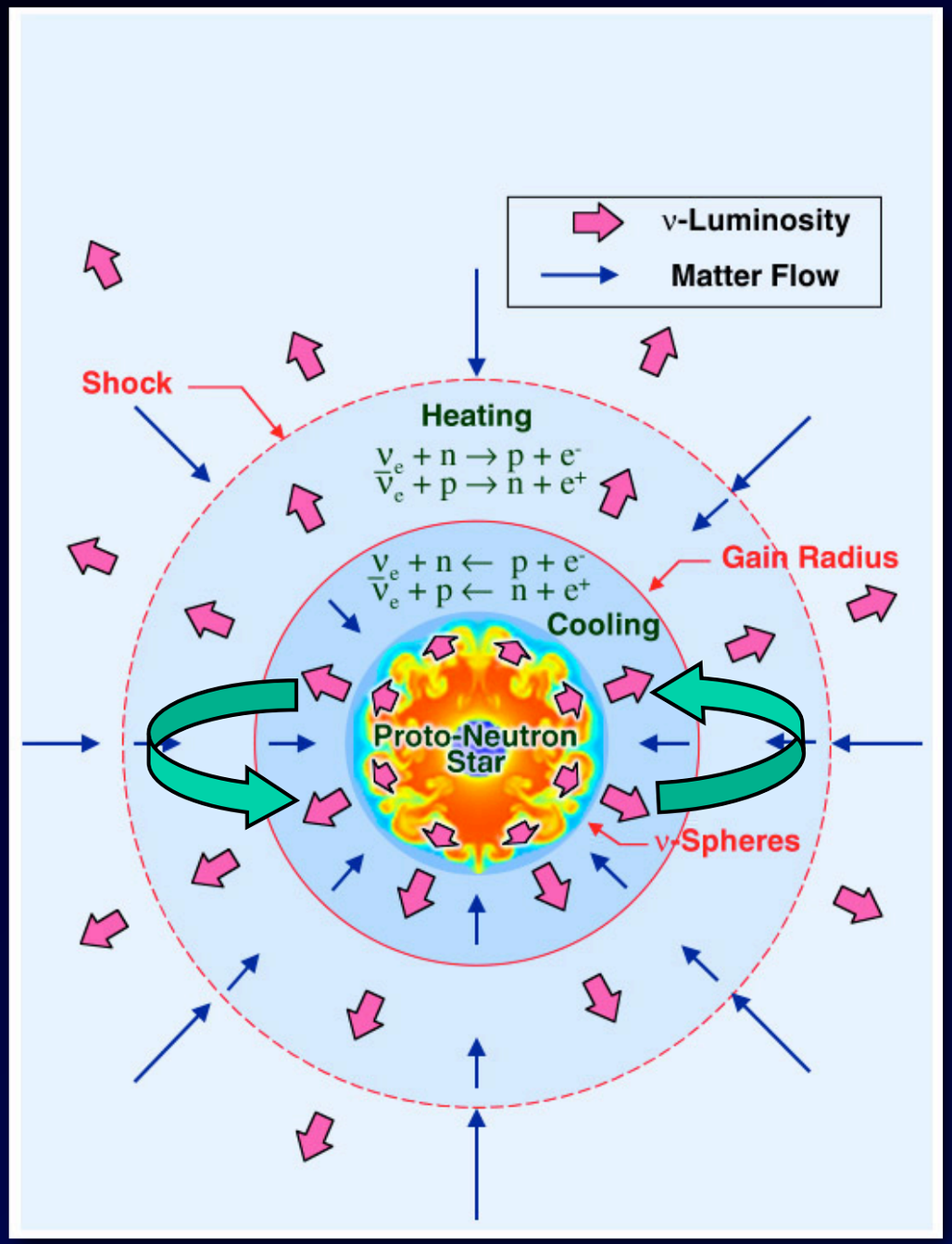

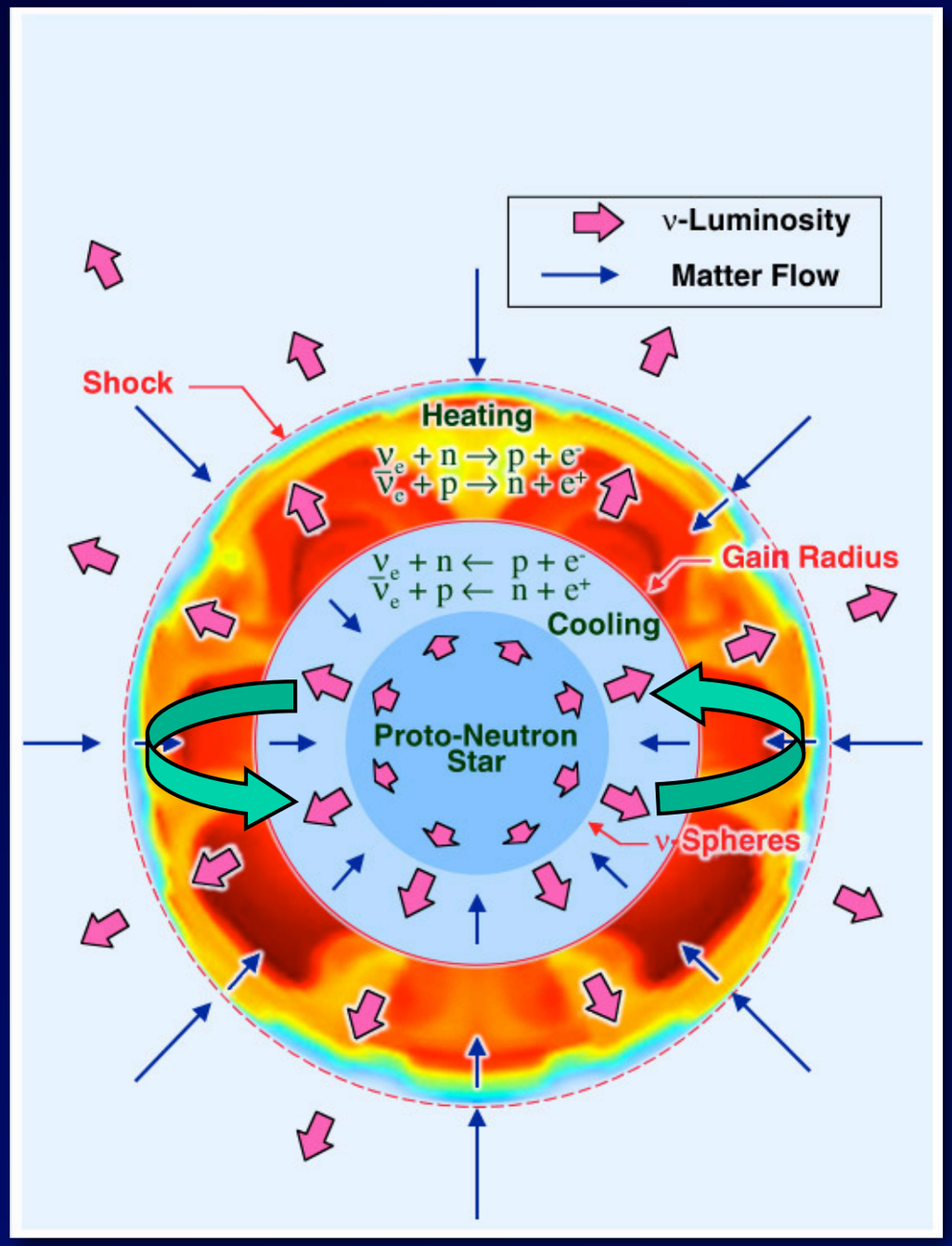

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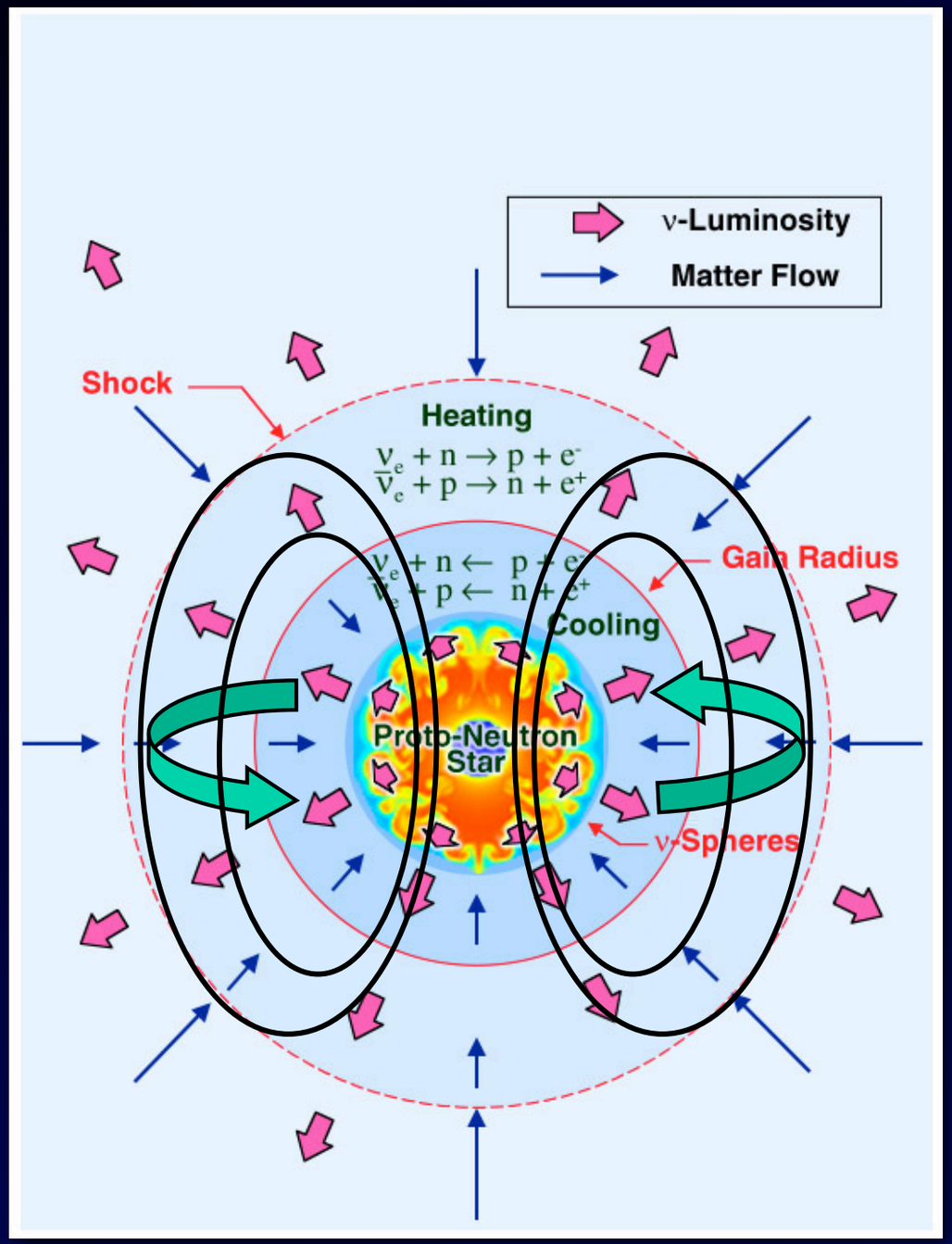

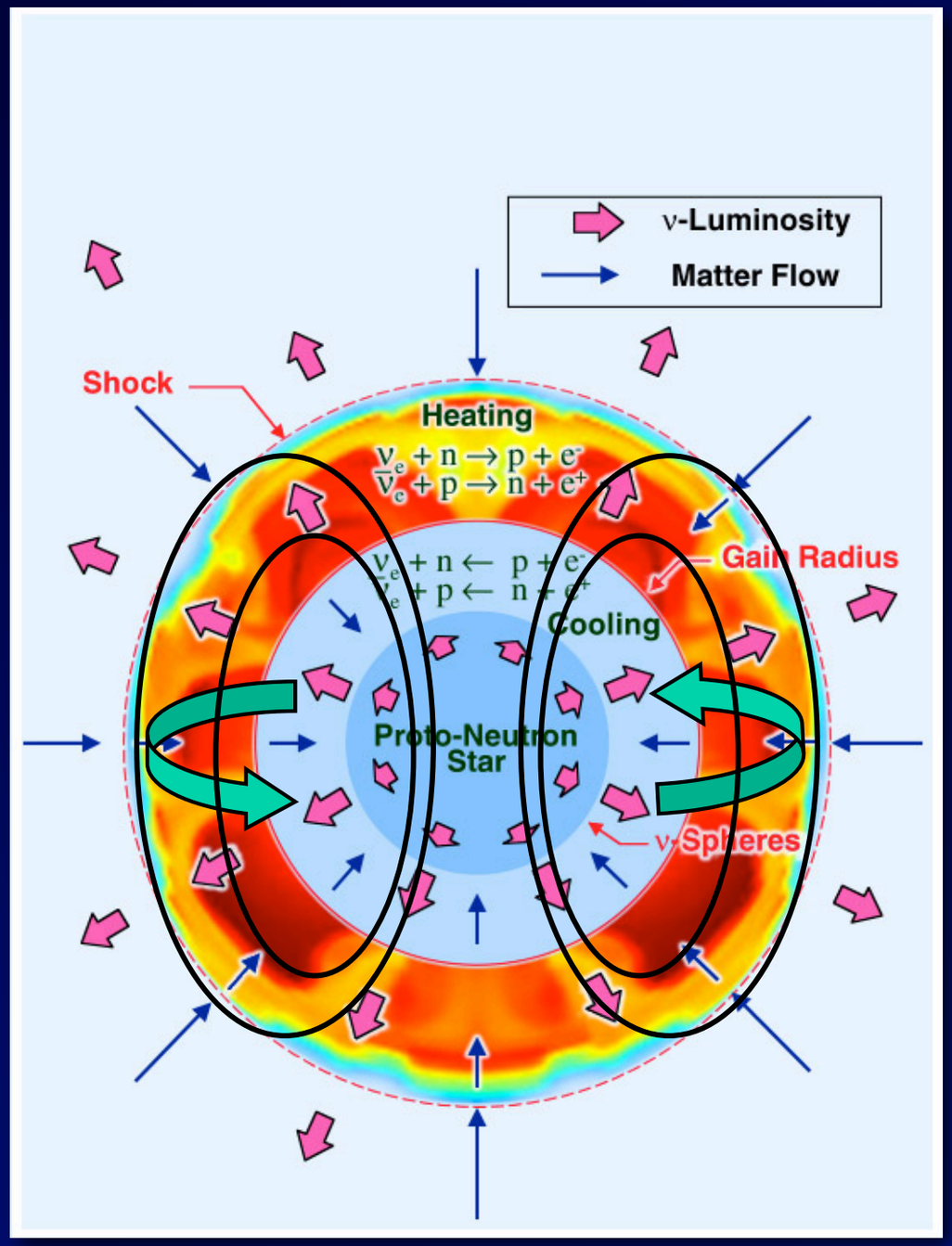

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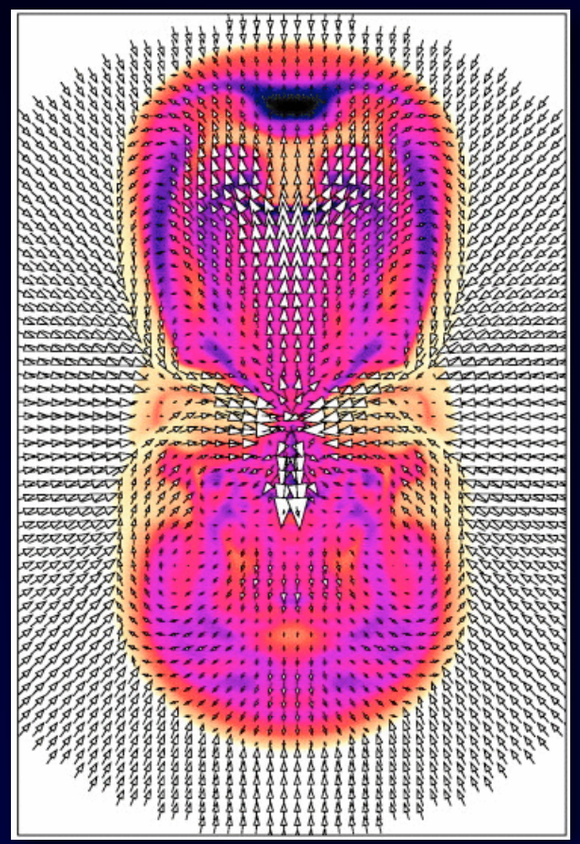

Blondin, Mezzacappa, and DeMarino (2003)

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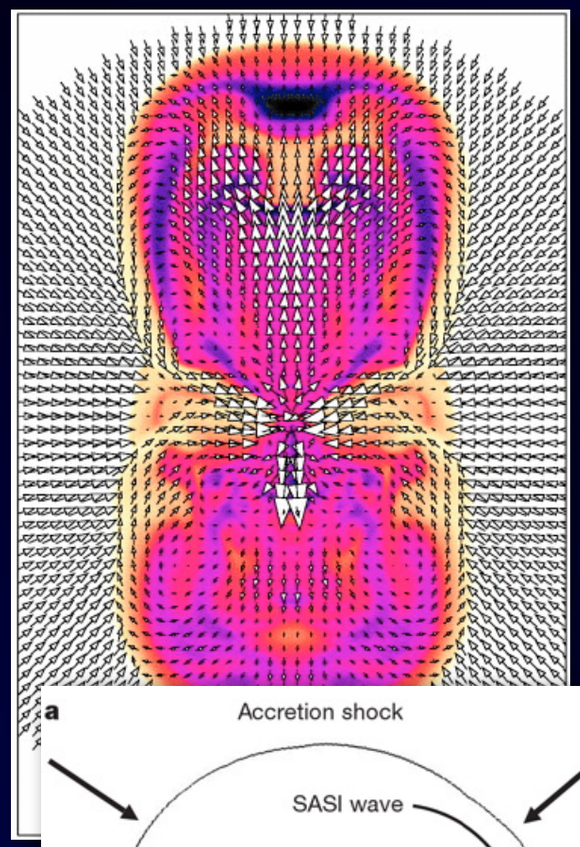

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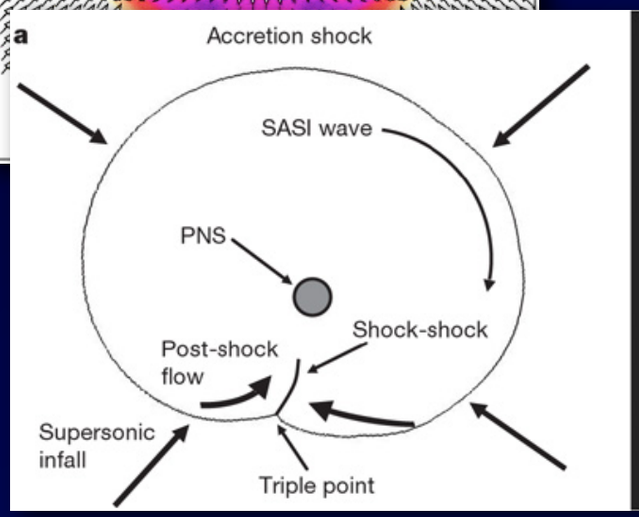

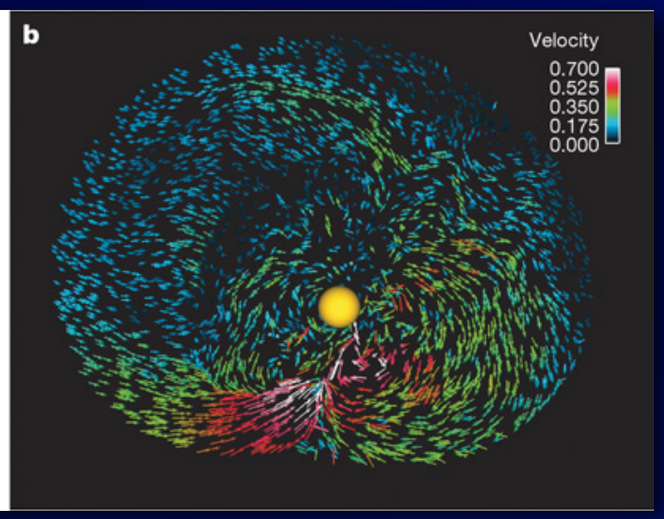

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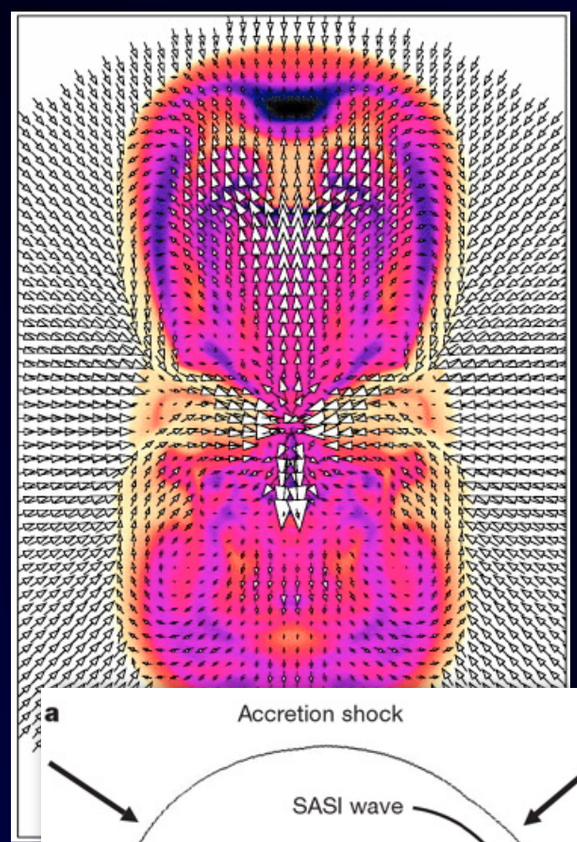

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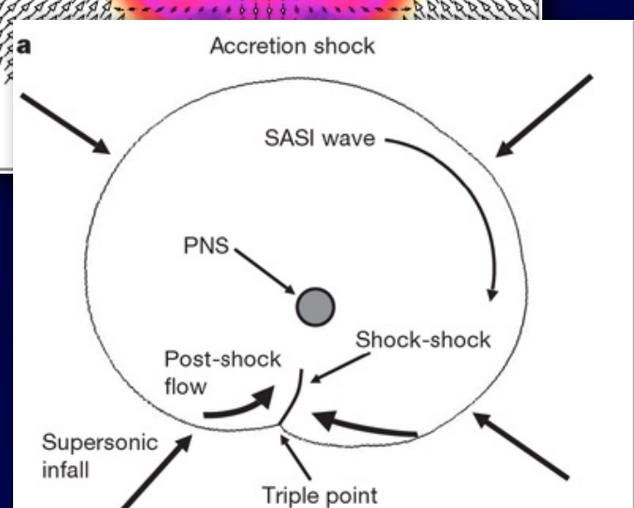

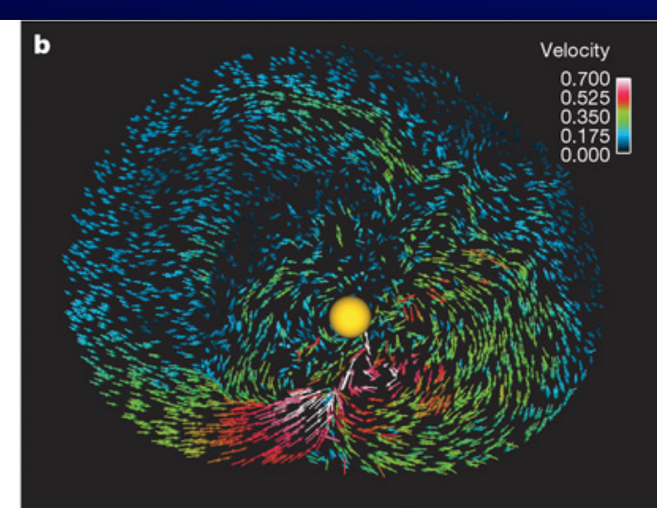

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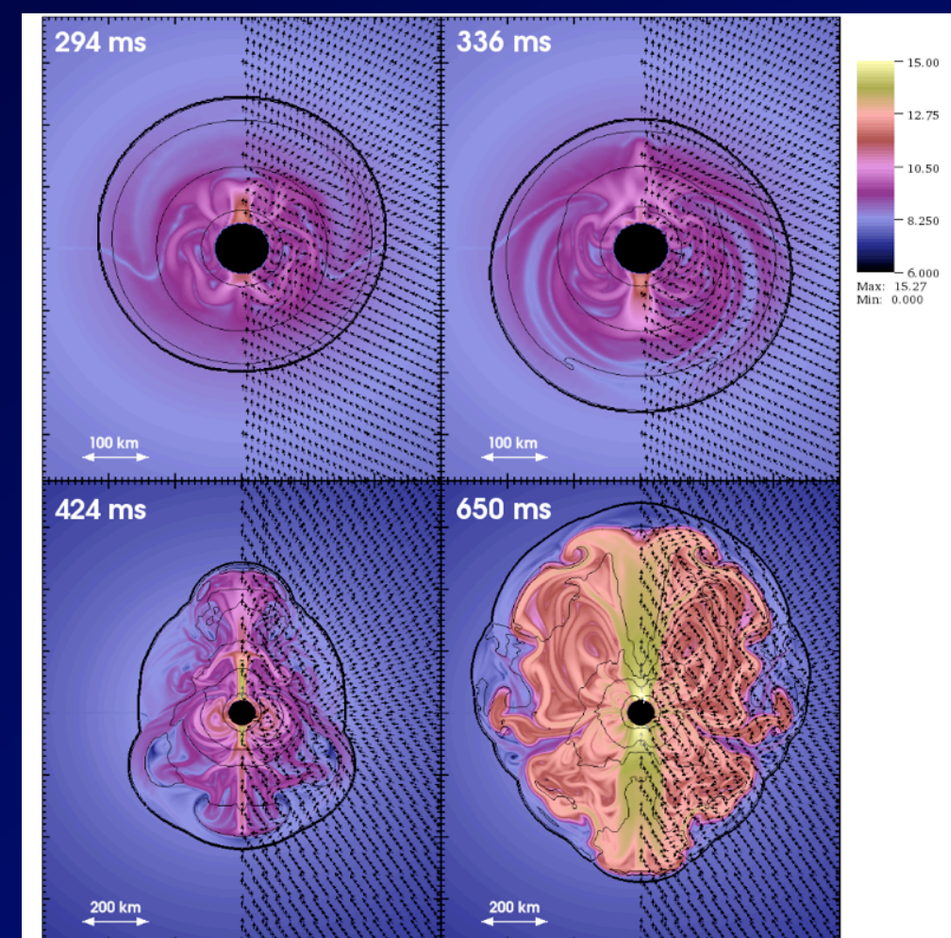

Magnetic field generation

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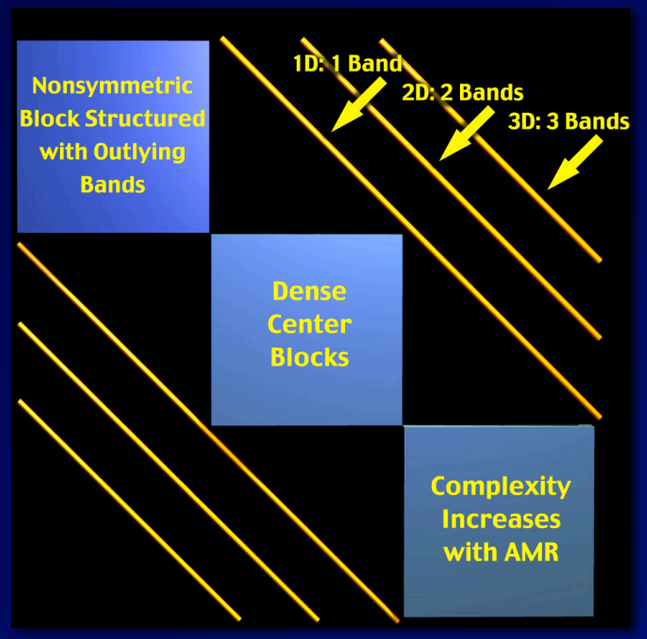

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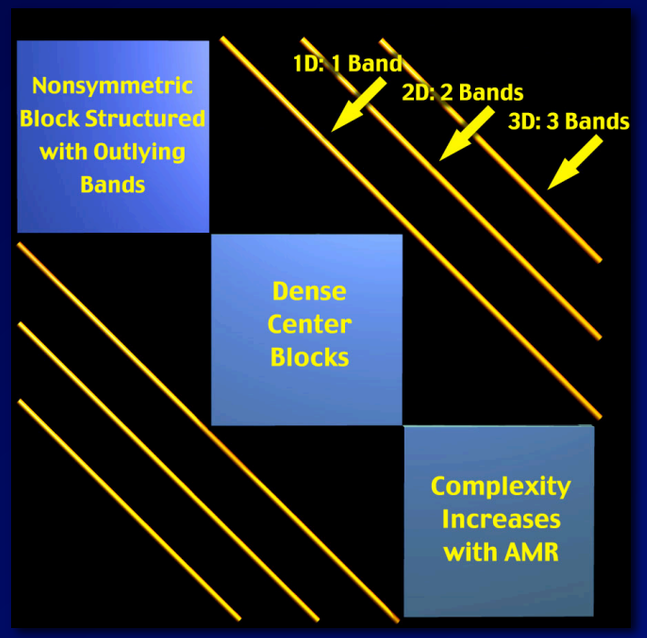

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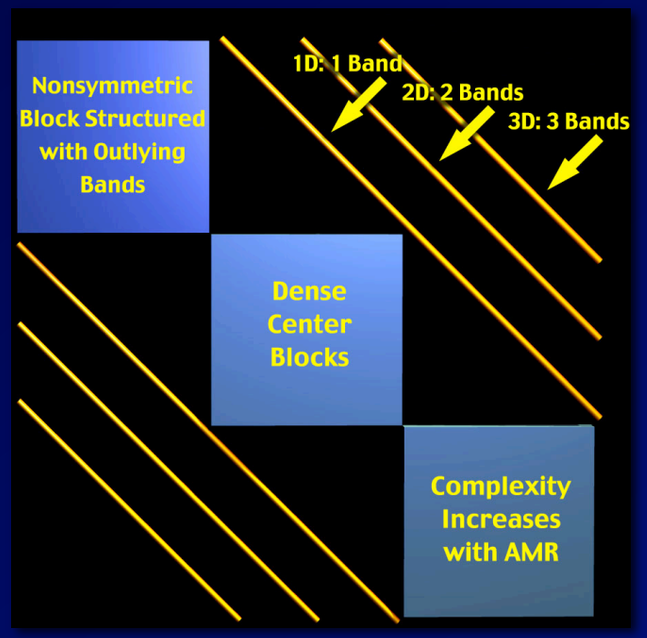

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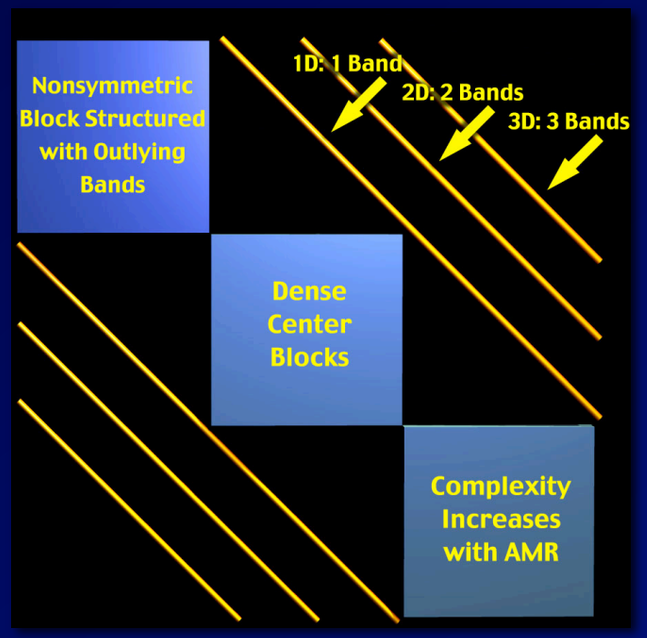

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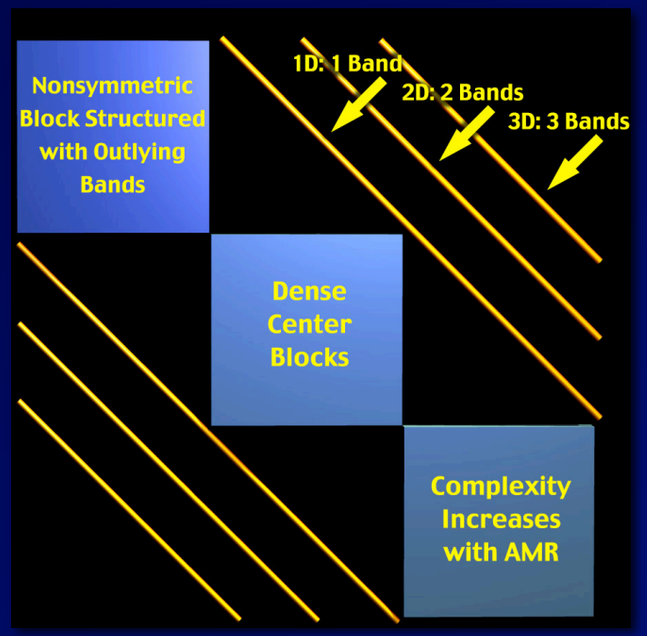

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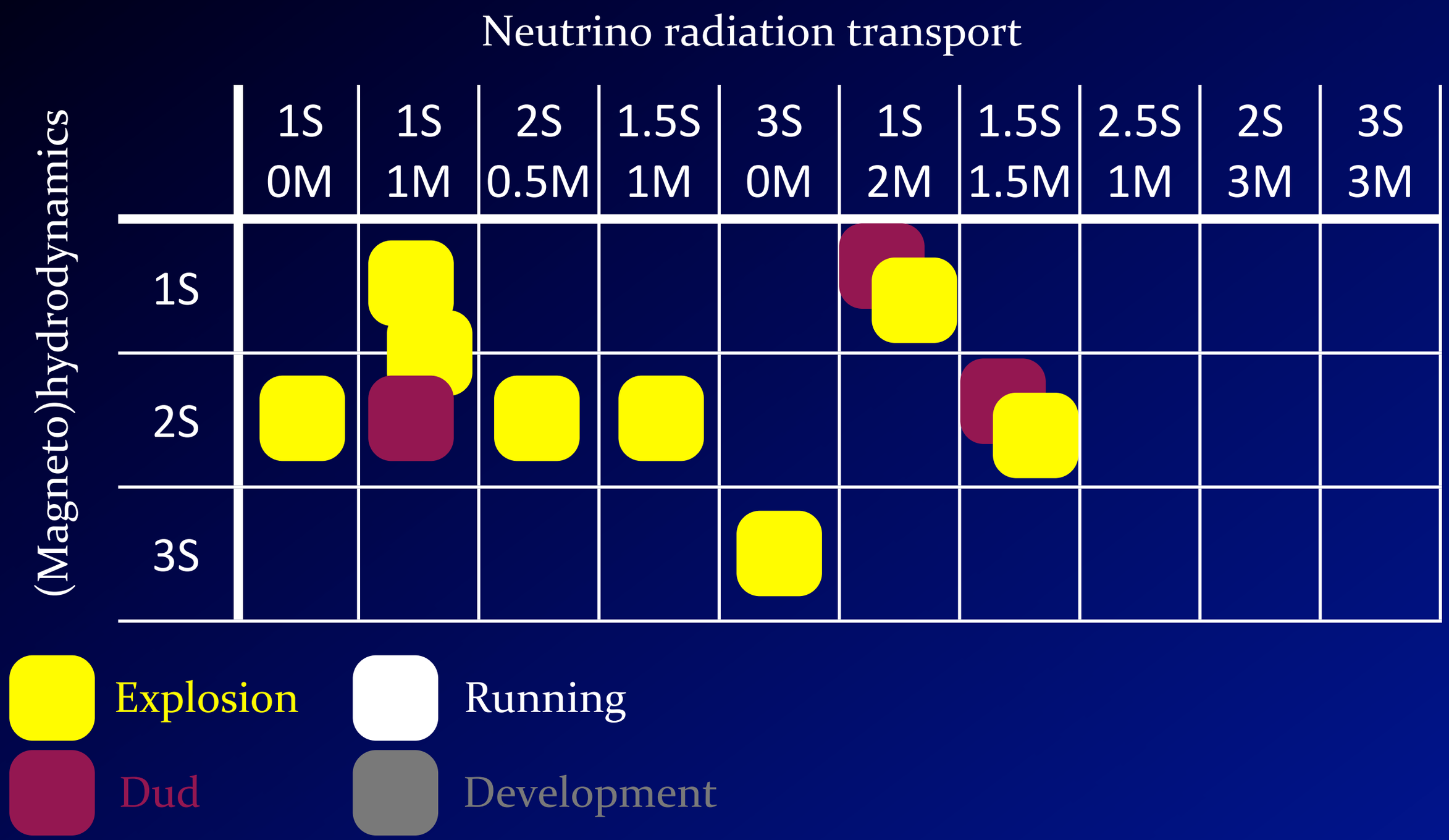

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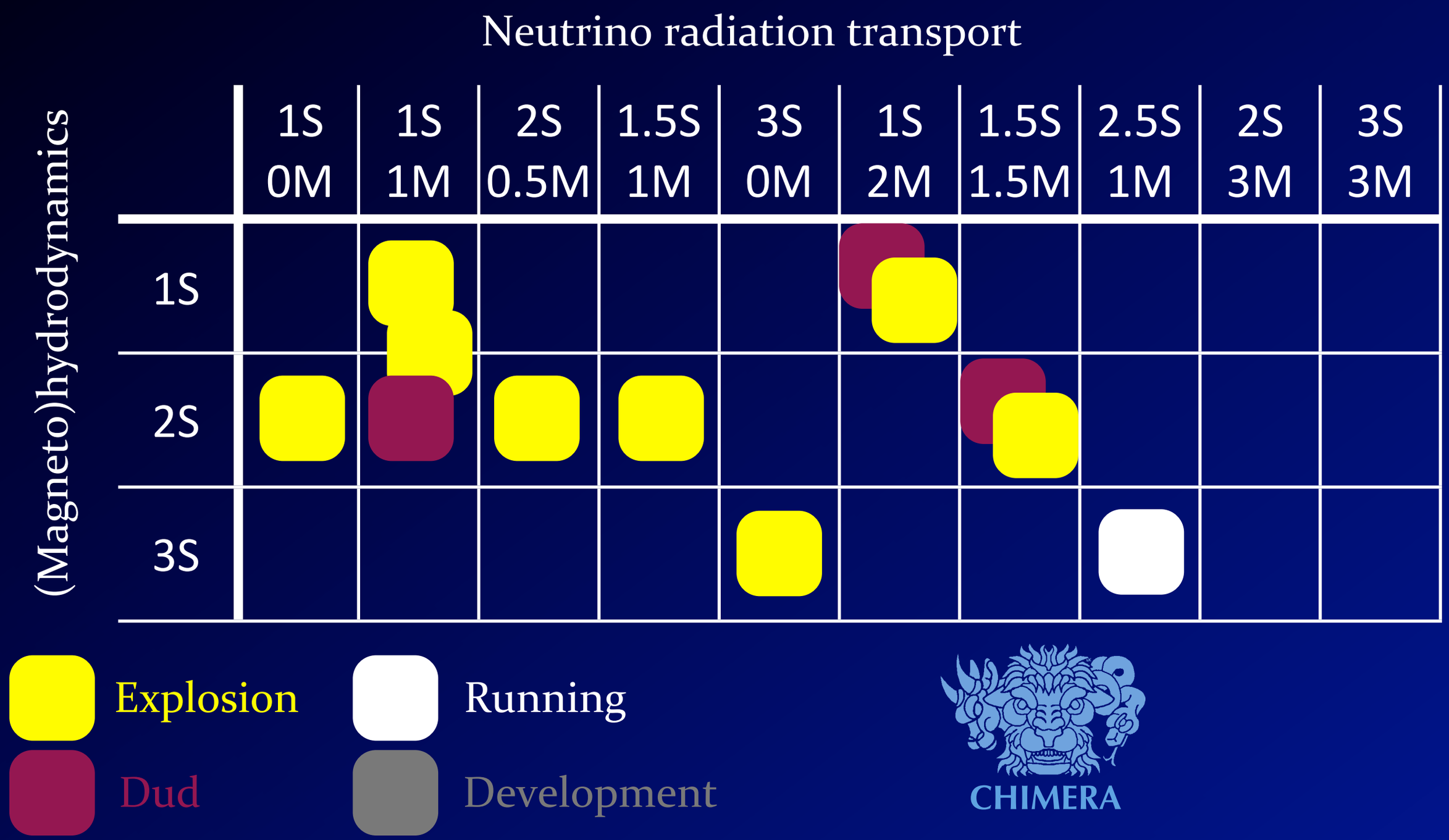

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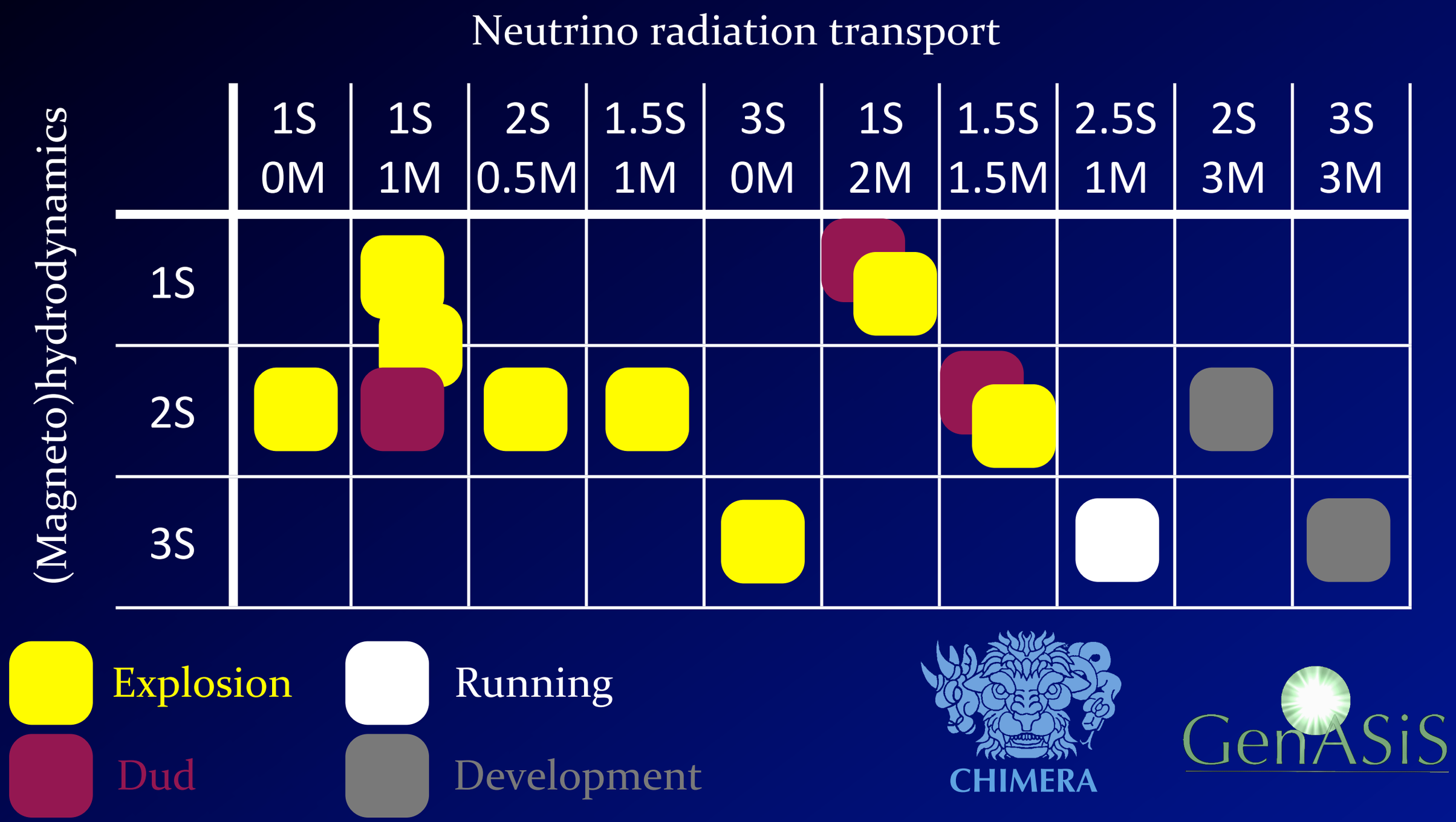

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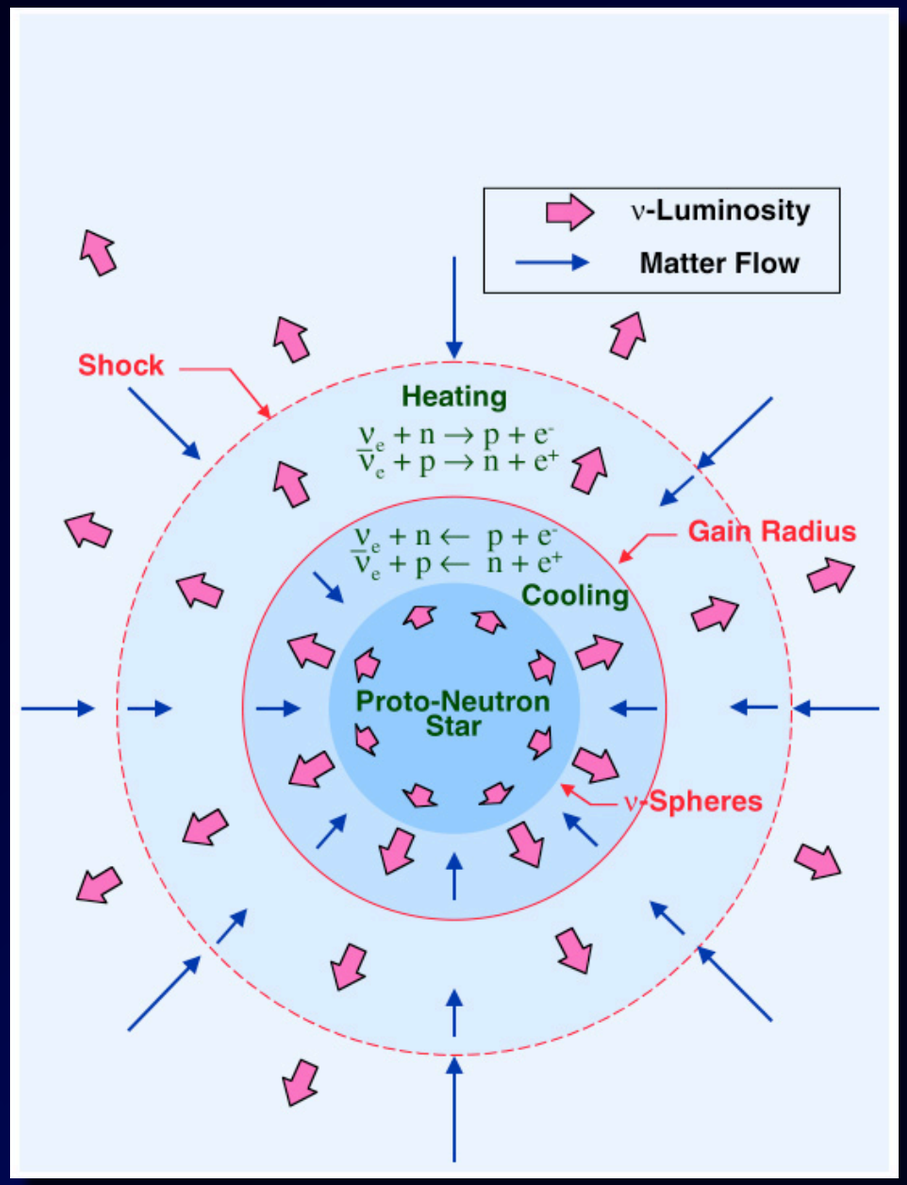

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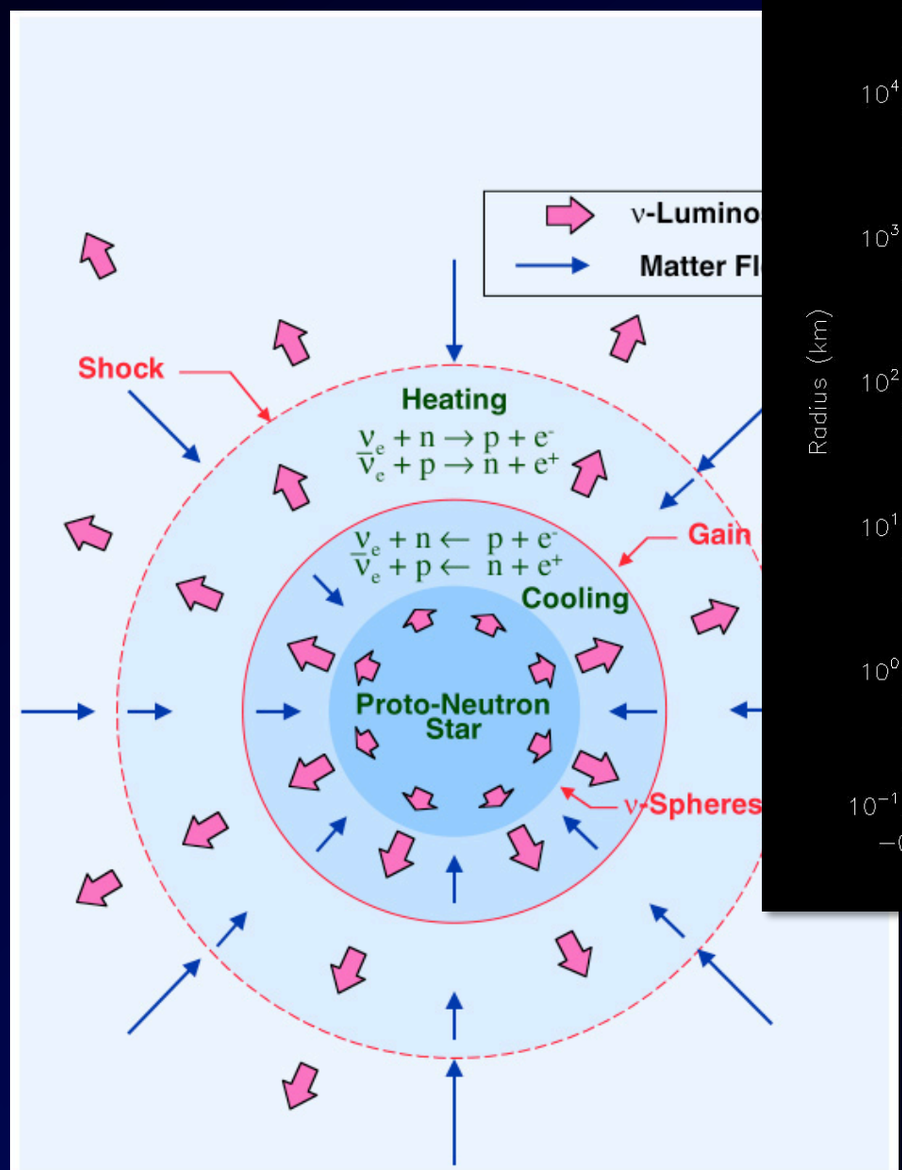

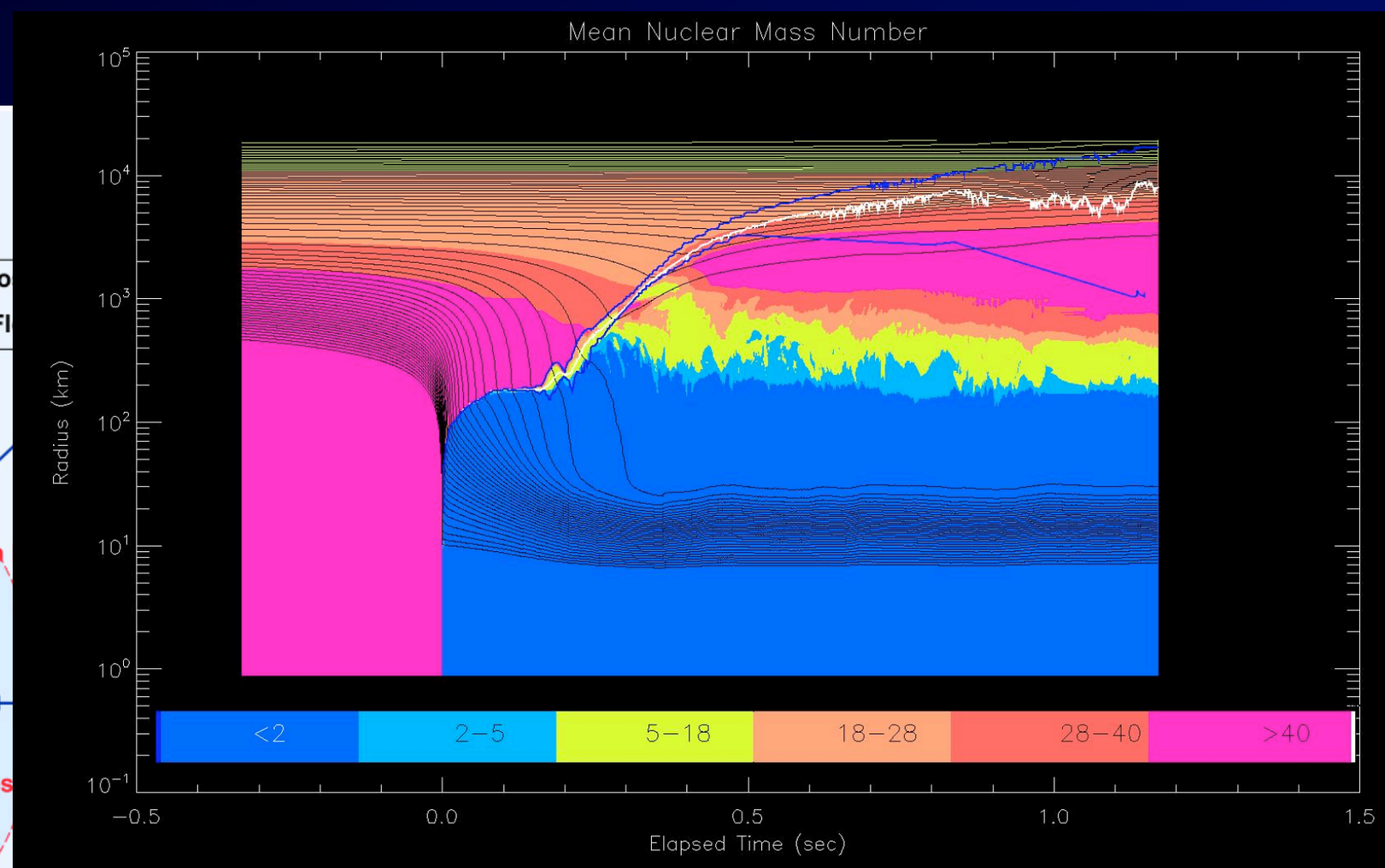

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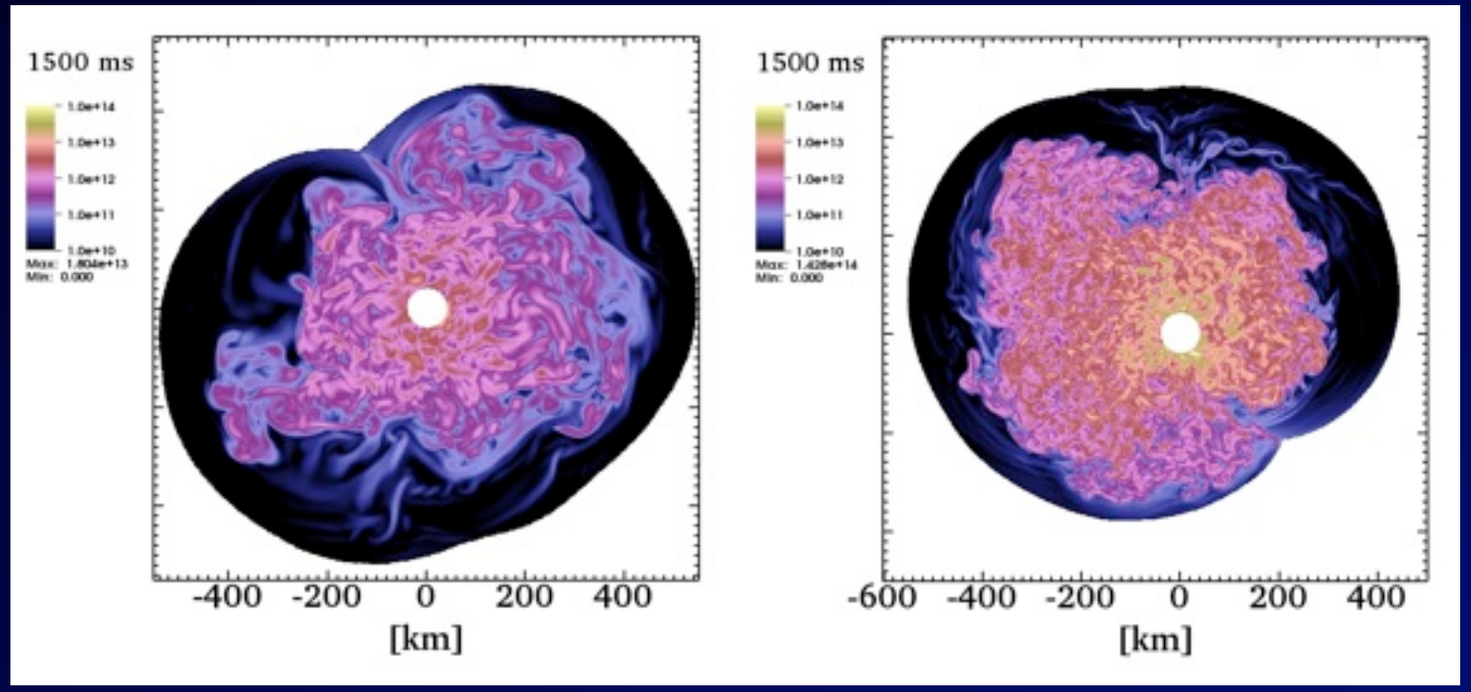

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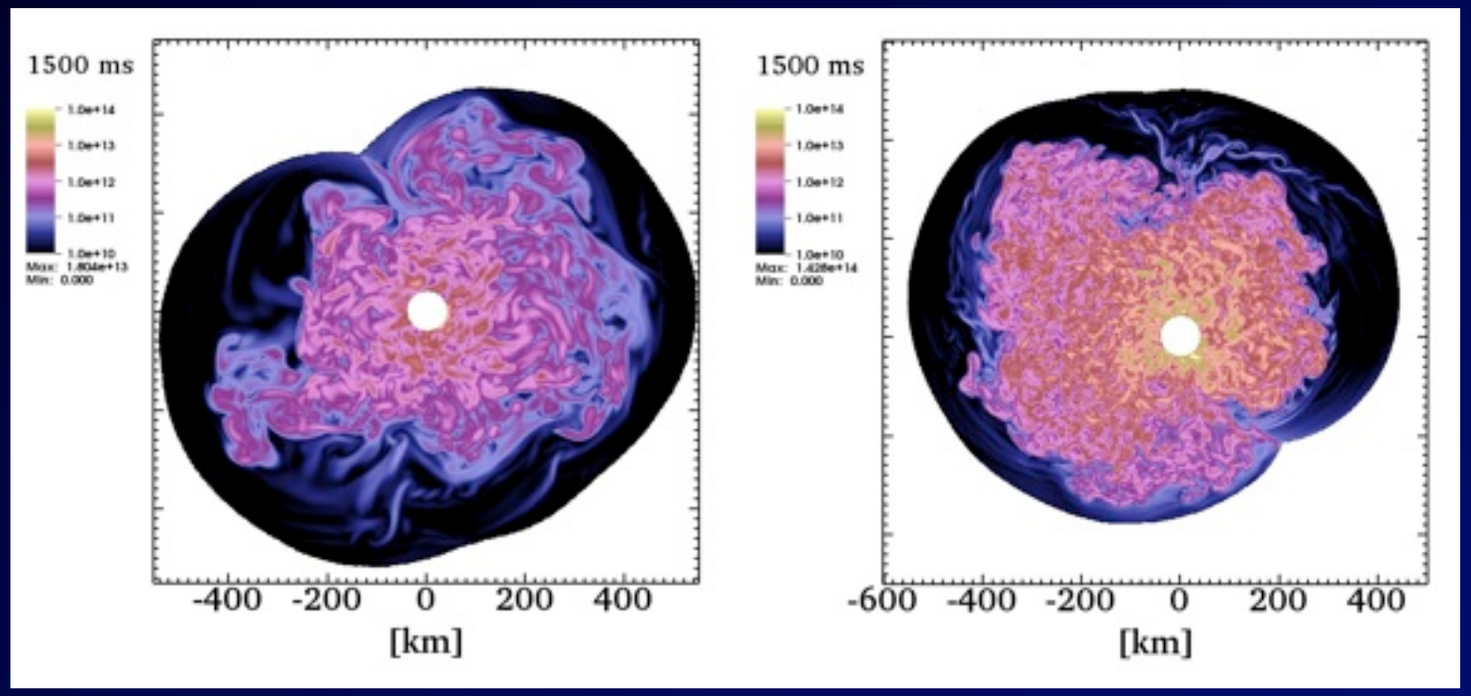
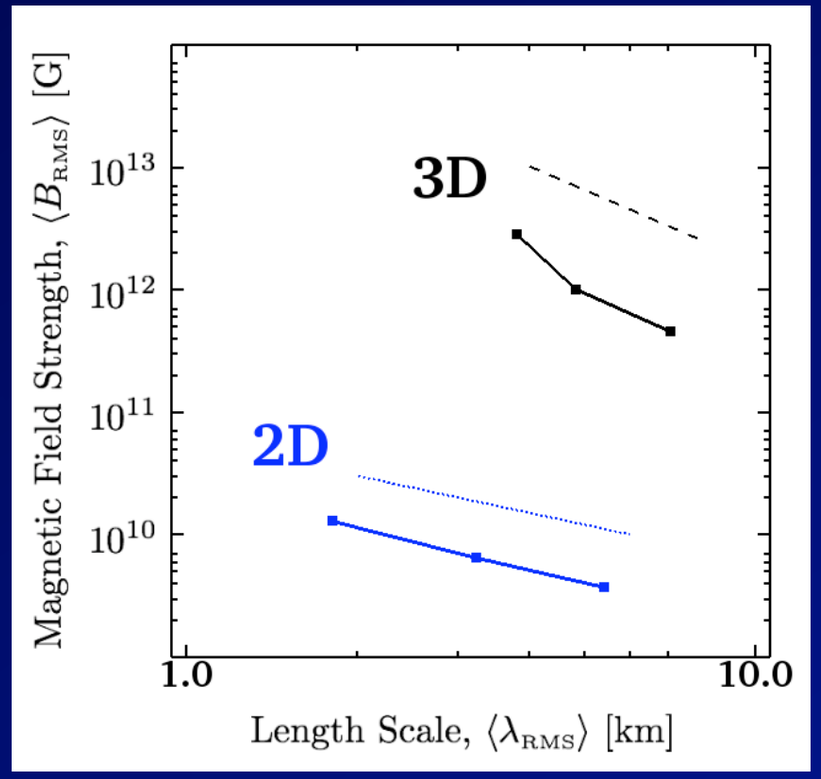
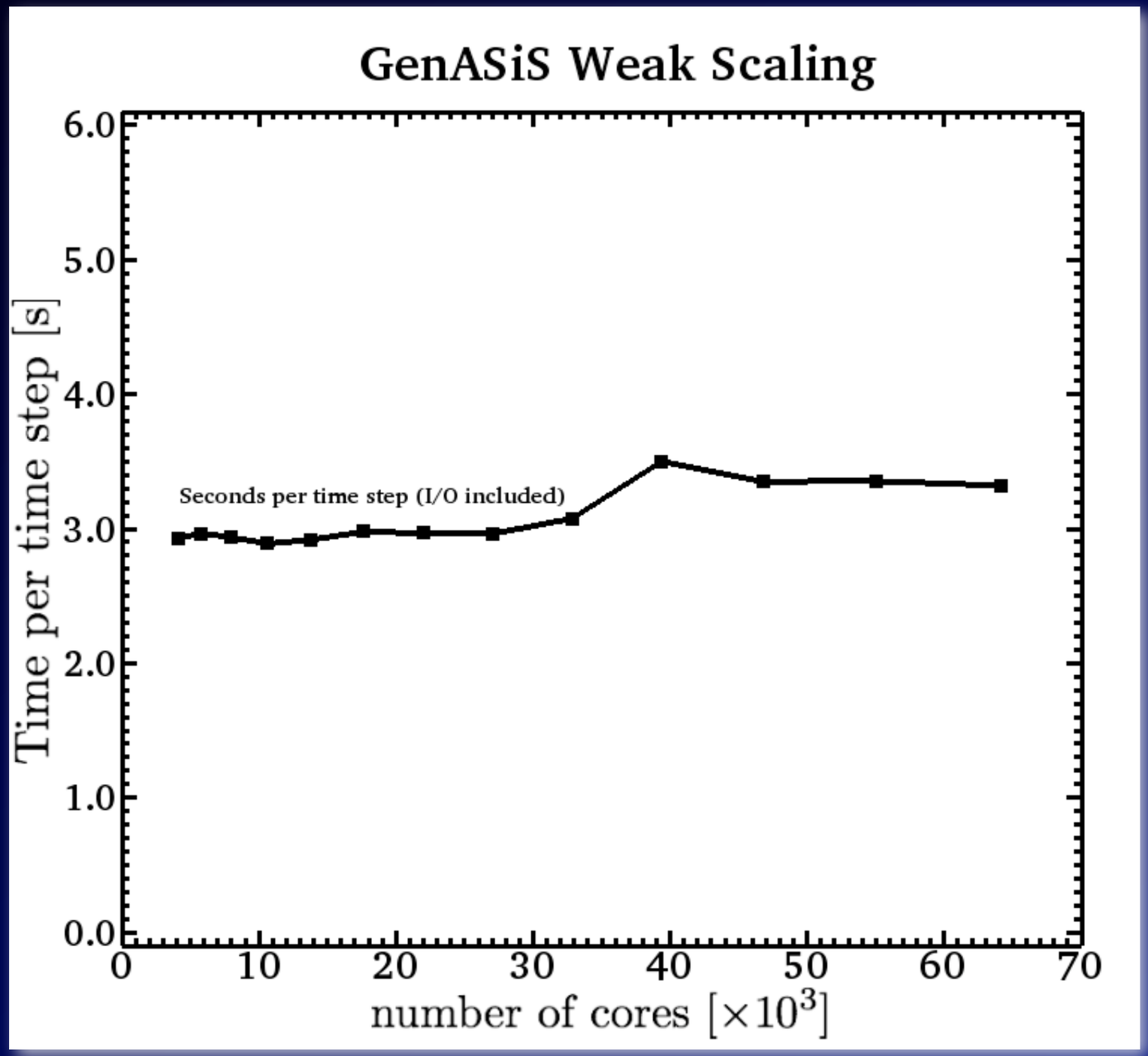




GenASiS simulations still unresolved at 1024^3 on 32k cores, Endeve et al. (2010)

(GenASiS MHD has been pushed further, to 1280^3 on 64,000 cores.)



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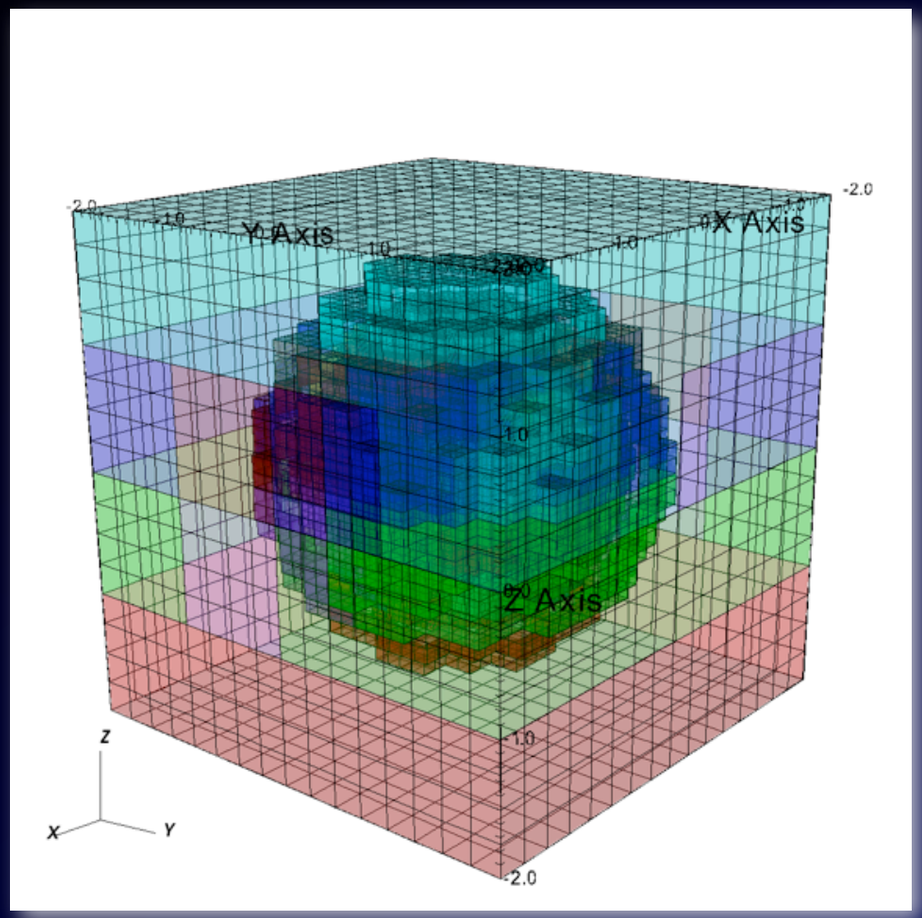
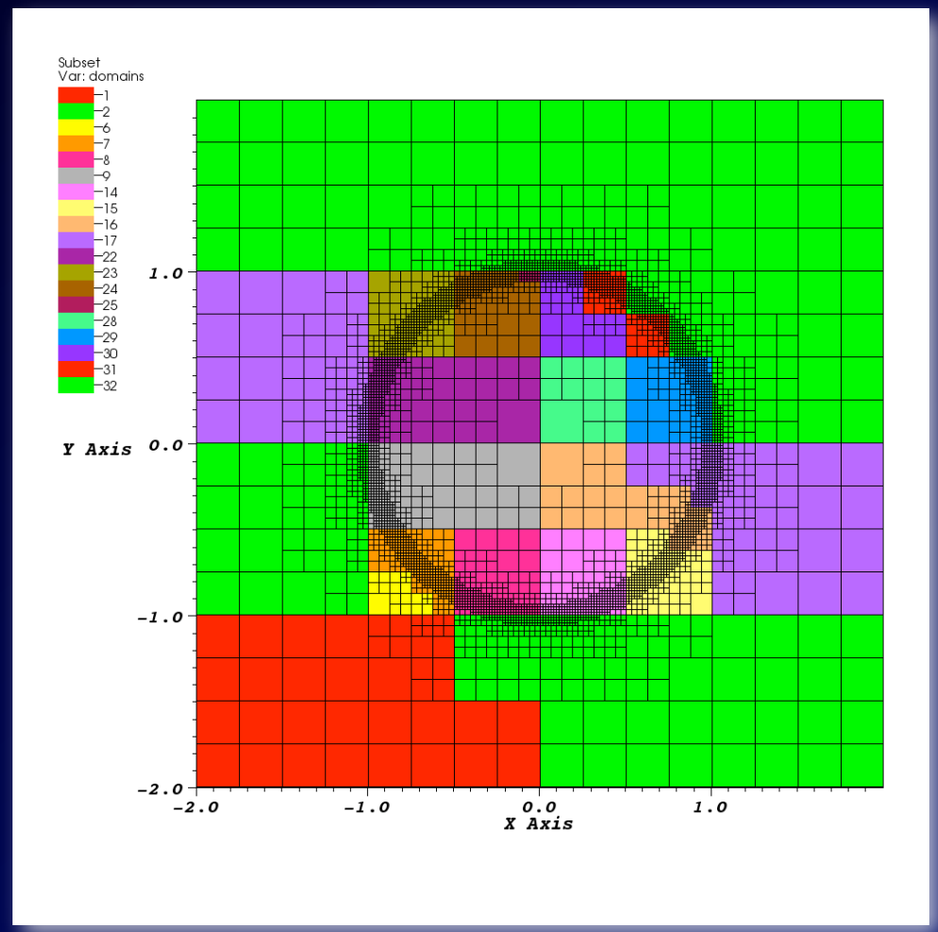
Bridging a wide range of time scales requires implicit evolution for some of the physics.

Multigrid Poisson solve with cell-by-cell AMR





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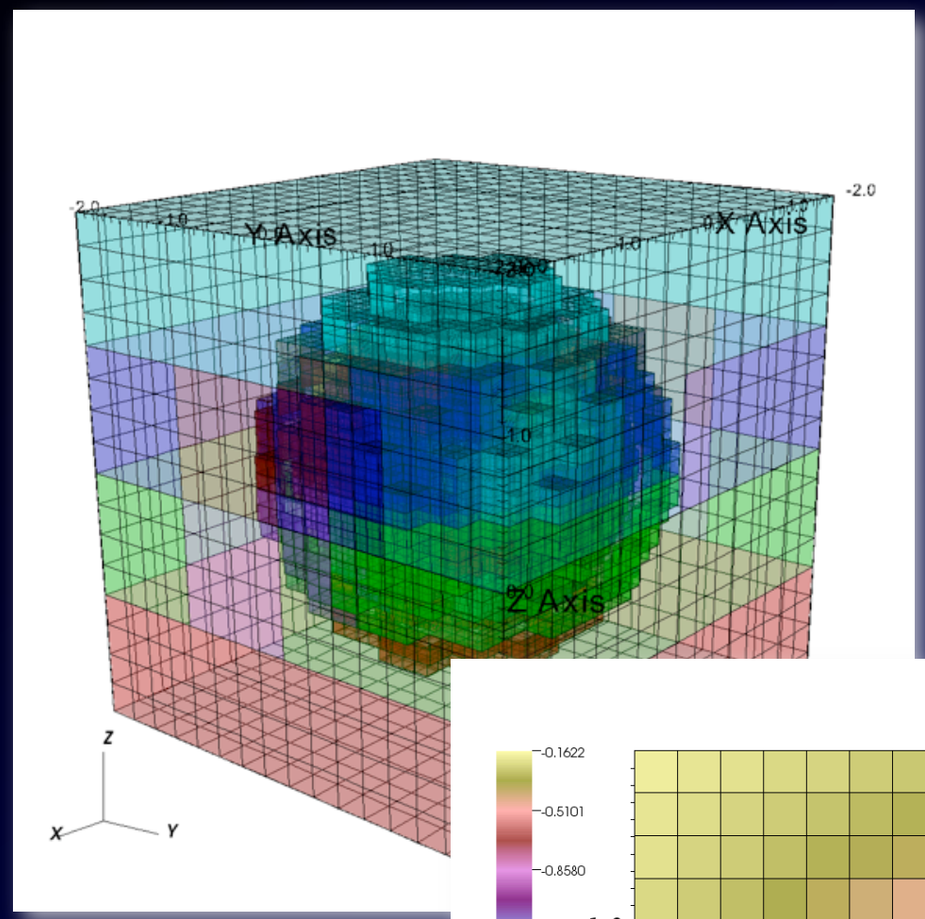

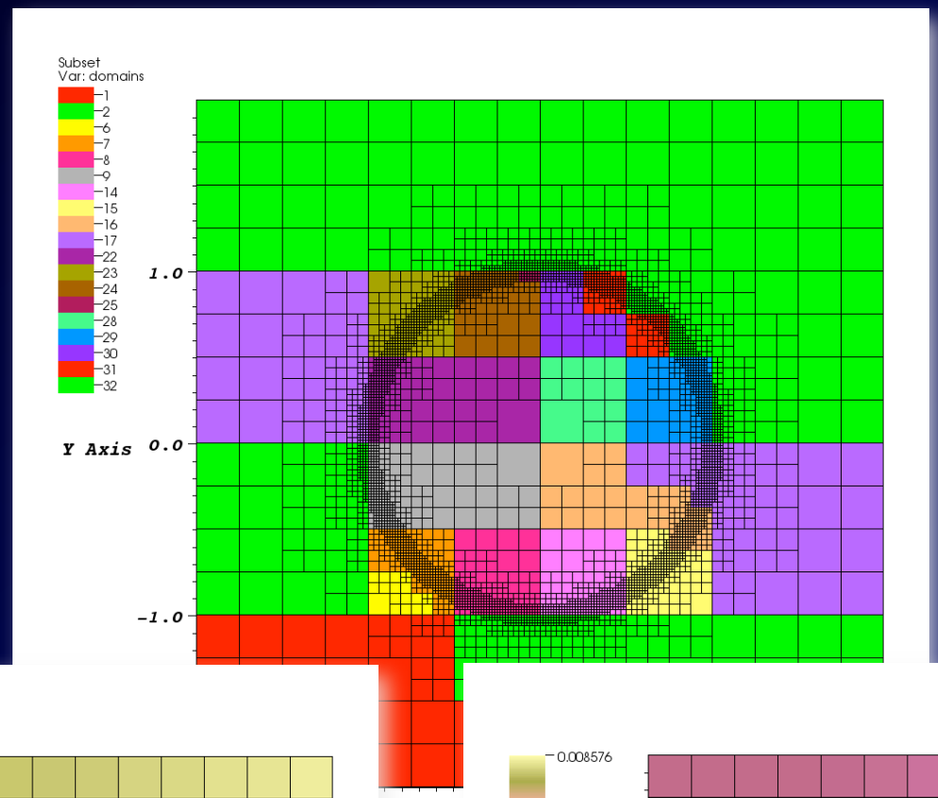

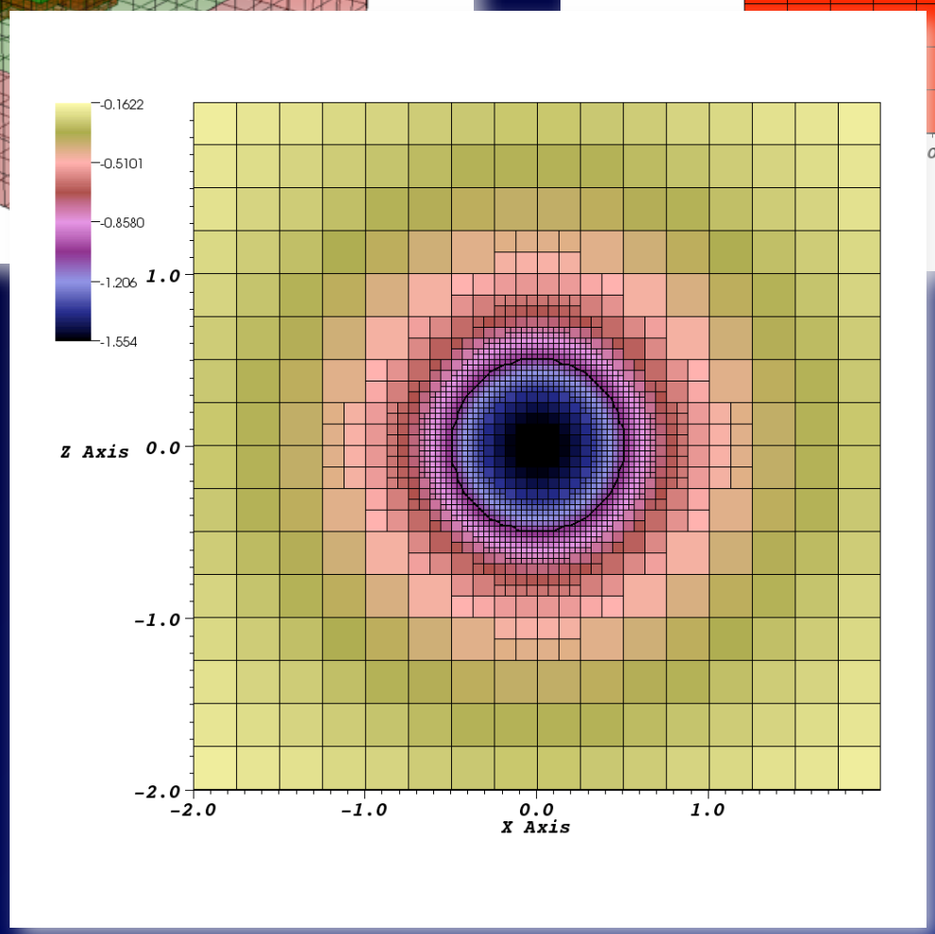

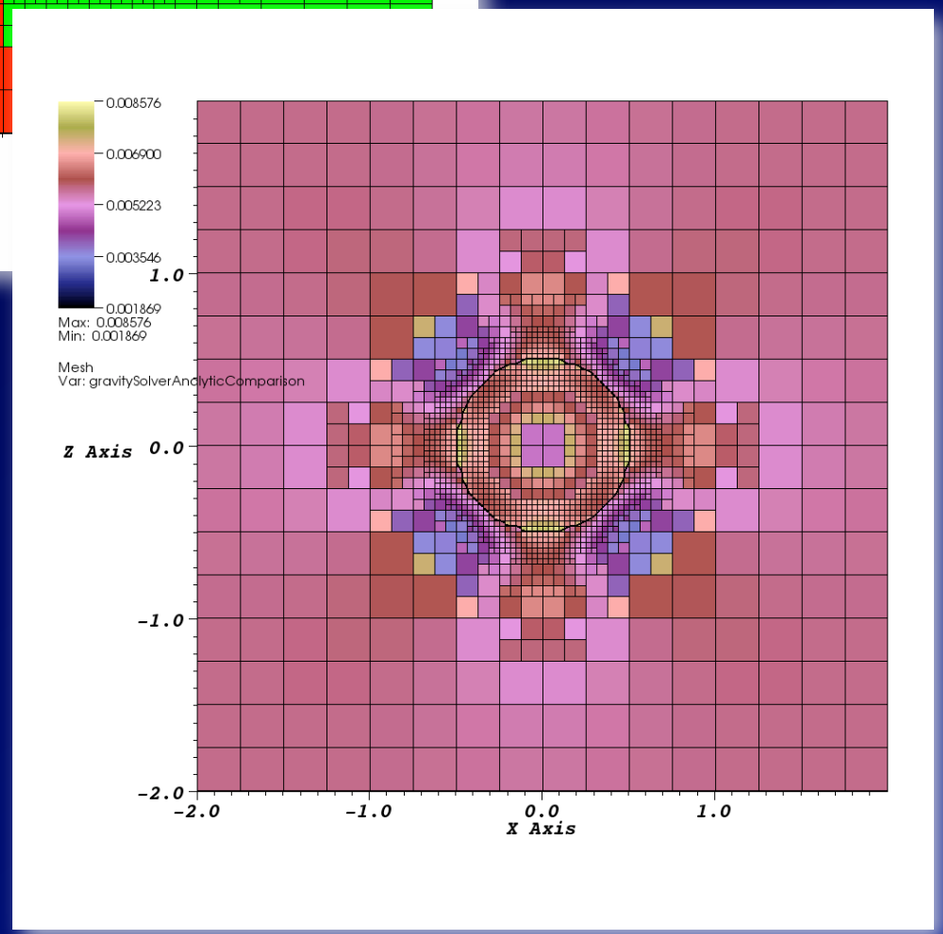

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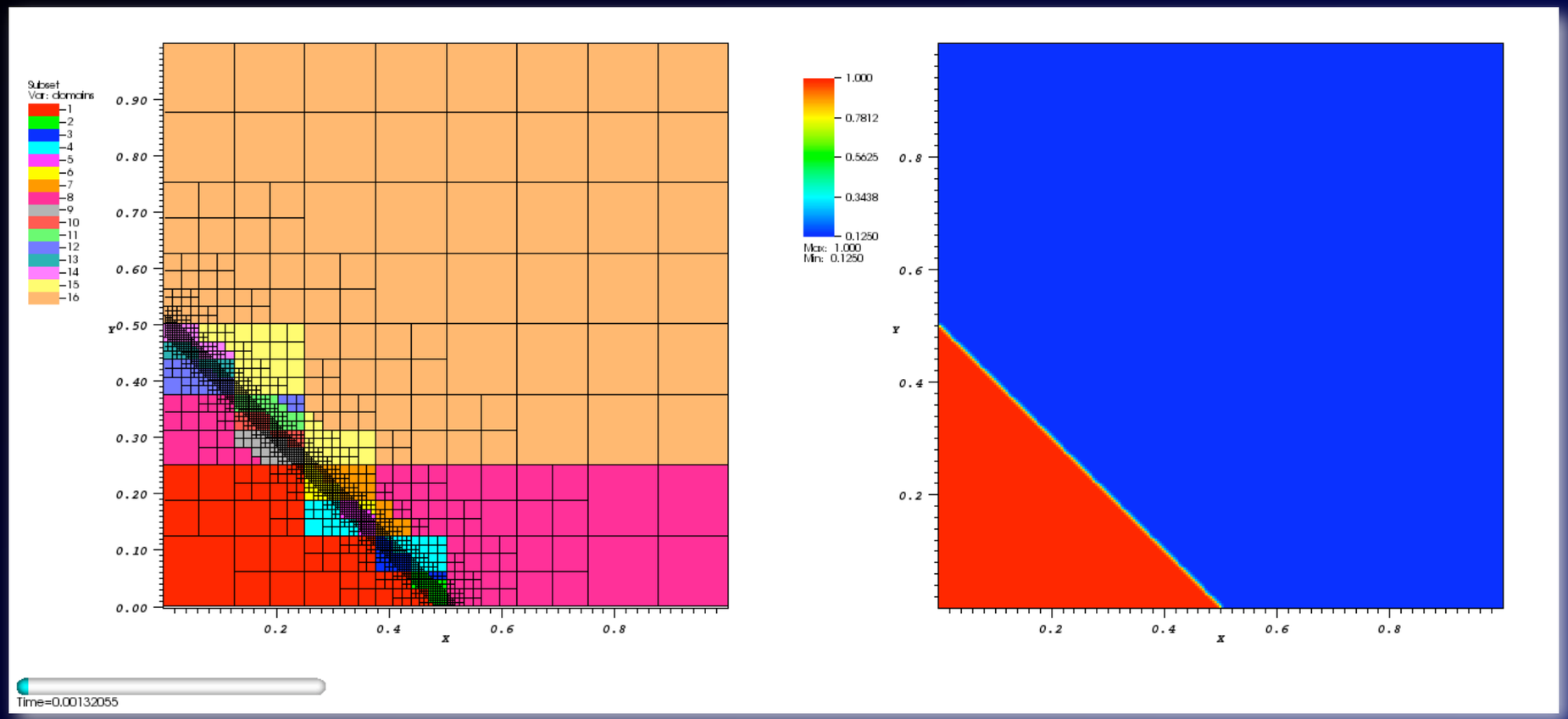

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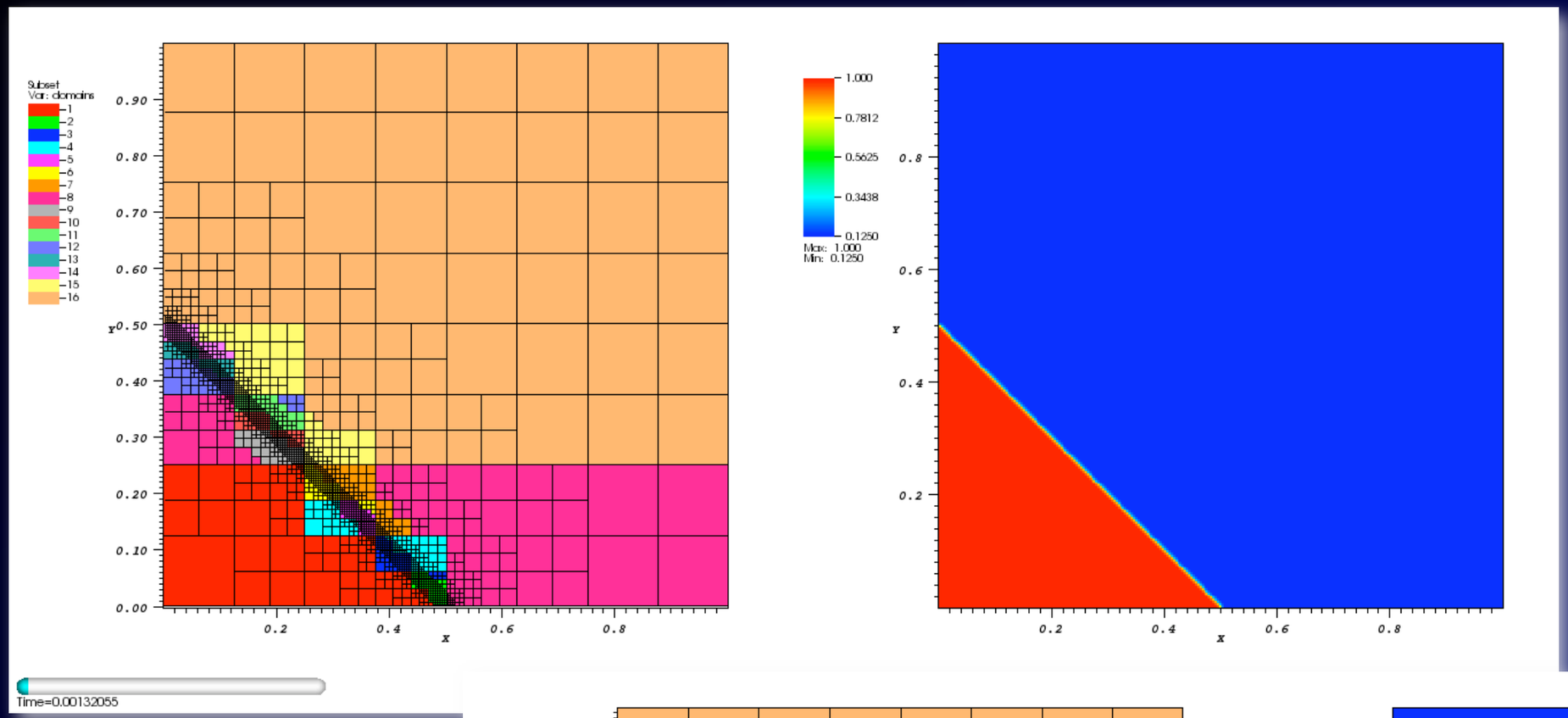

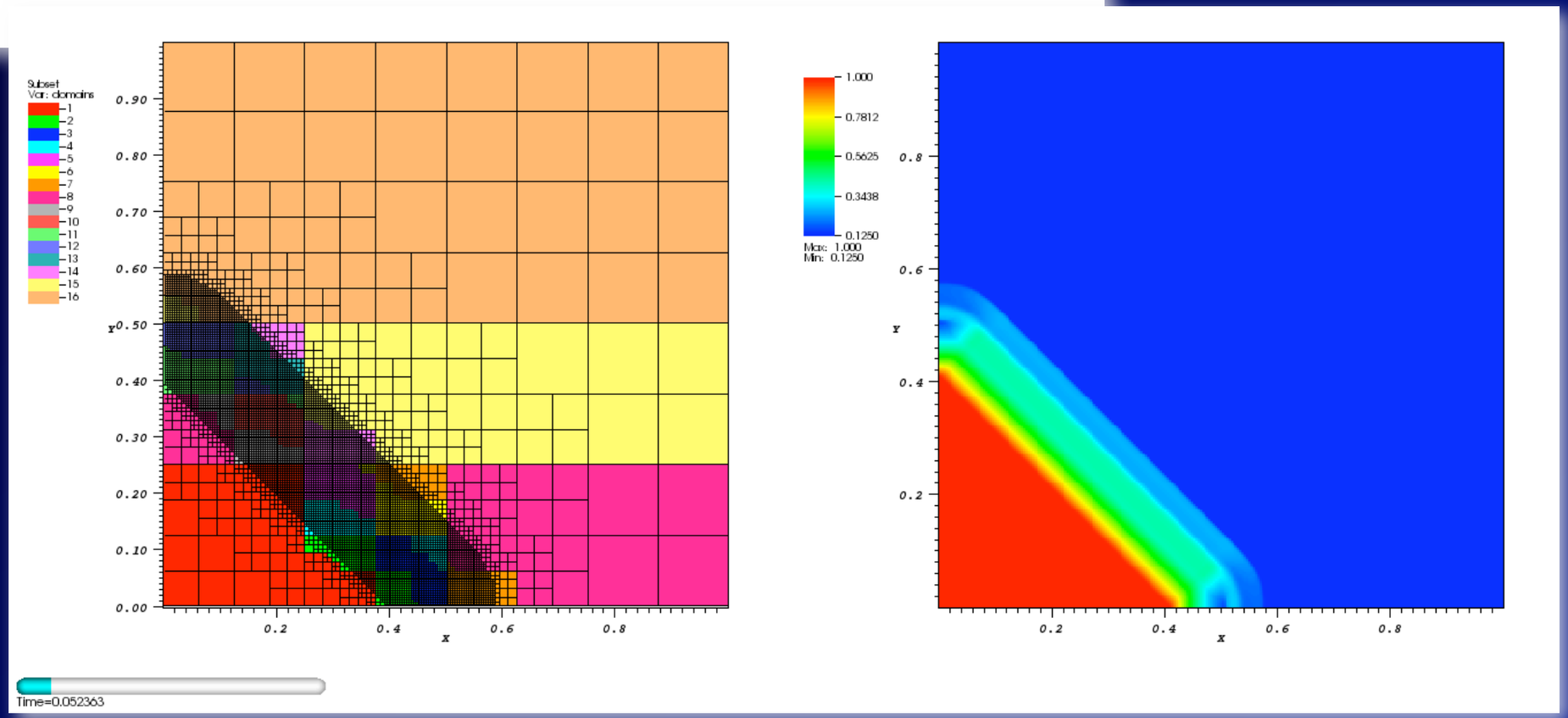

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Linear solve: dense blocks from momentum space couplings, one for each spatial cell; sparse matrices from nearest-neighbor couplings, one for each momentum space bin; invert separately and iterate with fixed-point convergence (d'Azevedo et al.)

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Distributed sparse solves over spatial domain *(parallel solver libraries)*

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Example 1: Lagged time step determination

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Synchronized evolution of the entire domain in time

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Example 1: Lagged time step determination

Example 2: Momentum space dense block solves performed while transpose needed for spatial sparse solves goes on in the background

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With adaptive mesh refinement and implicit evolution.

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We look to applied mathematicians and computer scientists to provide libraries that deploy capabilities needed by our solvers in heterogeneous and communication-unfriendly environments.