

Making Supernovae with Jets

Chelsea Harris

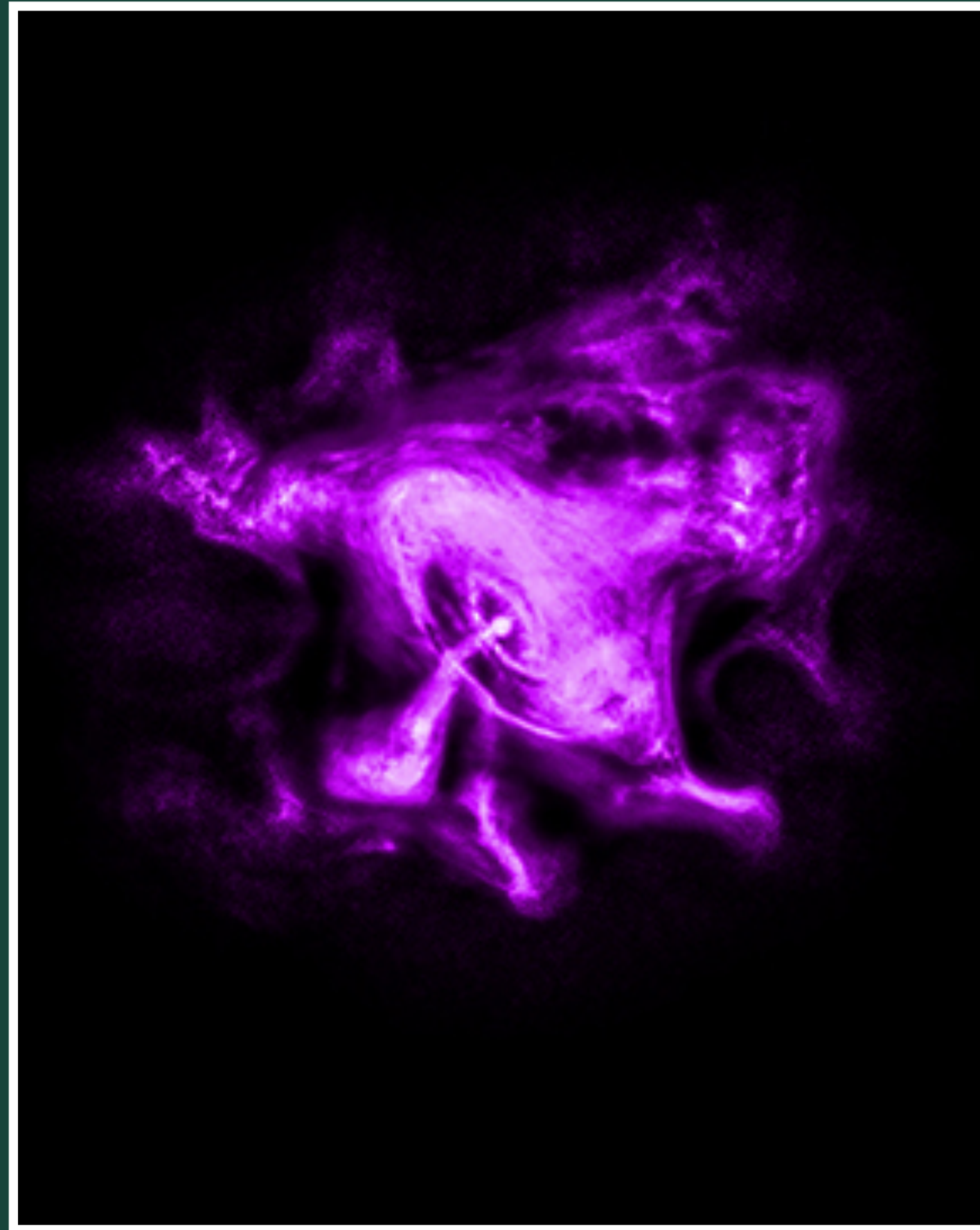
Sean Couch, Andrew Christlieb, Luke Roberts



implementing high-order magnetohydrodynamics to explore jets in stellar explosions



the cool things
I'm a part of



making jets in a
supernova



high-order magnetorotational
hydrodynamics with SparkJoy



implementing high-order magnetohydrodynamics
to explore jets in stellar explosions



the cool things
I'm a part of





MSU Department of Computational Mathematics, Science, and Engineering

**MSU
CMSE**

CMSE ... will enable application-driven computational modeling (“pull”), while also **exposing** disciplinary computational scientists to advanced tools and techniques (“push”), which will ignite new transformational **connections** in research and education.

**DOE
CSGF**

...scientists who may reside in science, mathematics, engineering or computer science departments but share an interest in research using computing and mathematical methods. ... DOE CSGF helps these computational scientists **develop a sense of community** that’s often difficult to find in a single academic department.

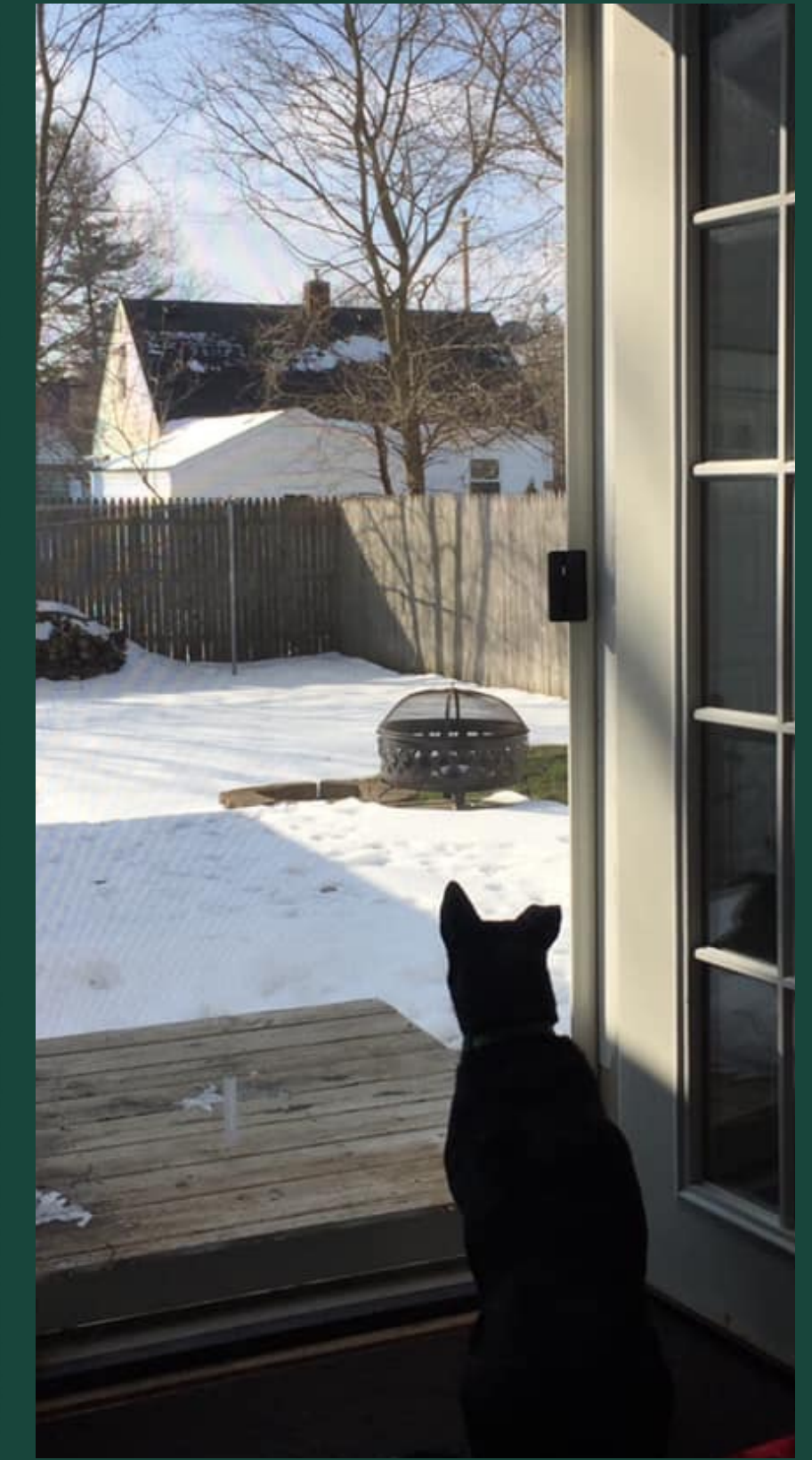




MSU Department of Computational Mathematics, Science, and Engineering



March 16



February 21





SciDAC

TEAMS

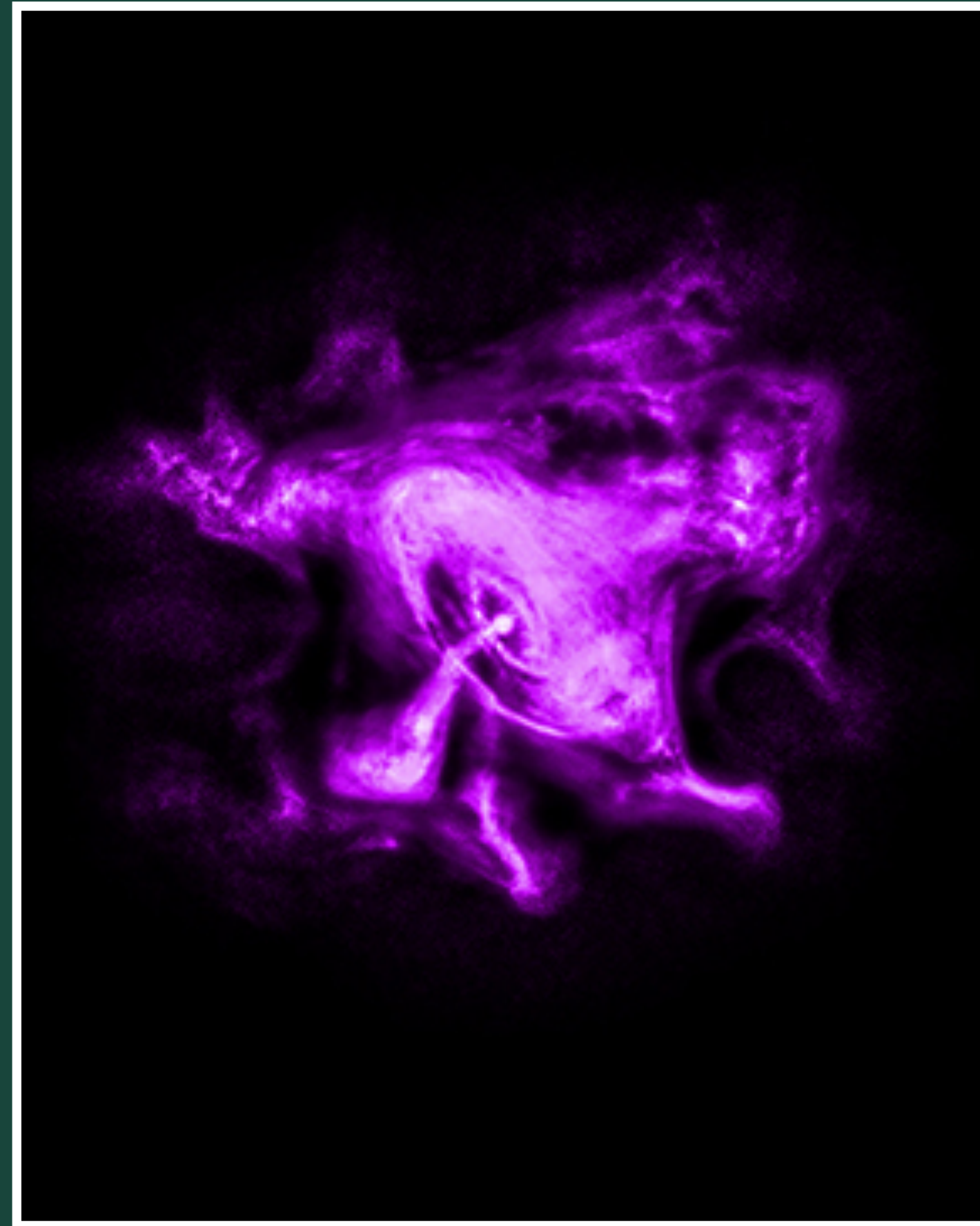
Toward Exascale Astrophysics of Mergers and Supernovae



implementing high-order magnetohydrodynamics to explore jets in stellar explosions



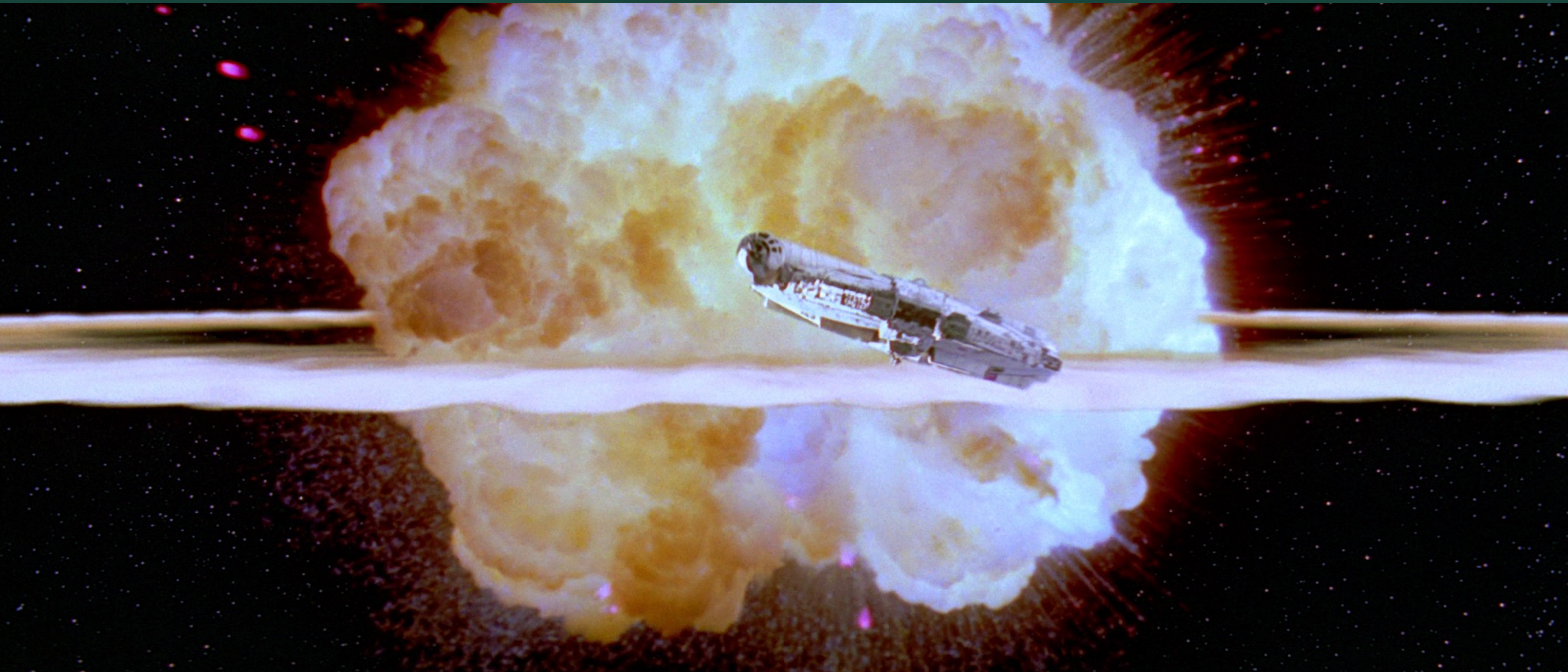
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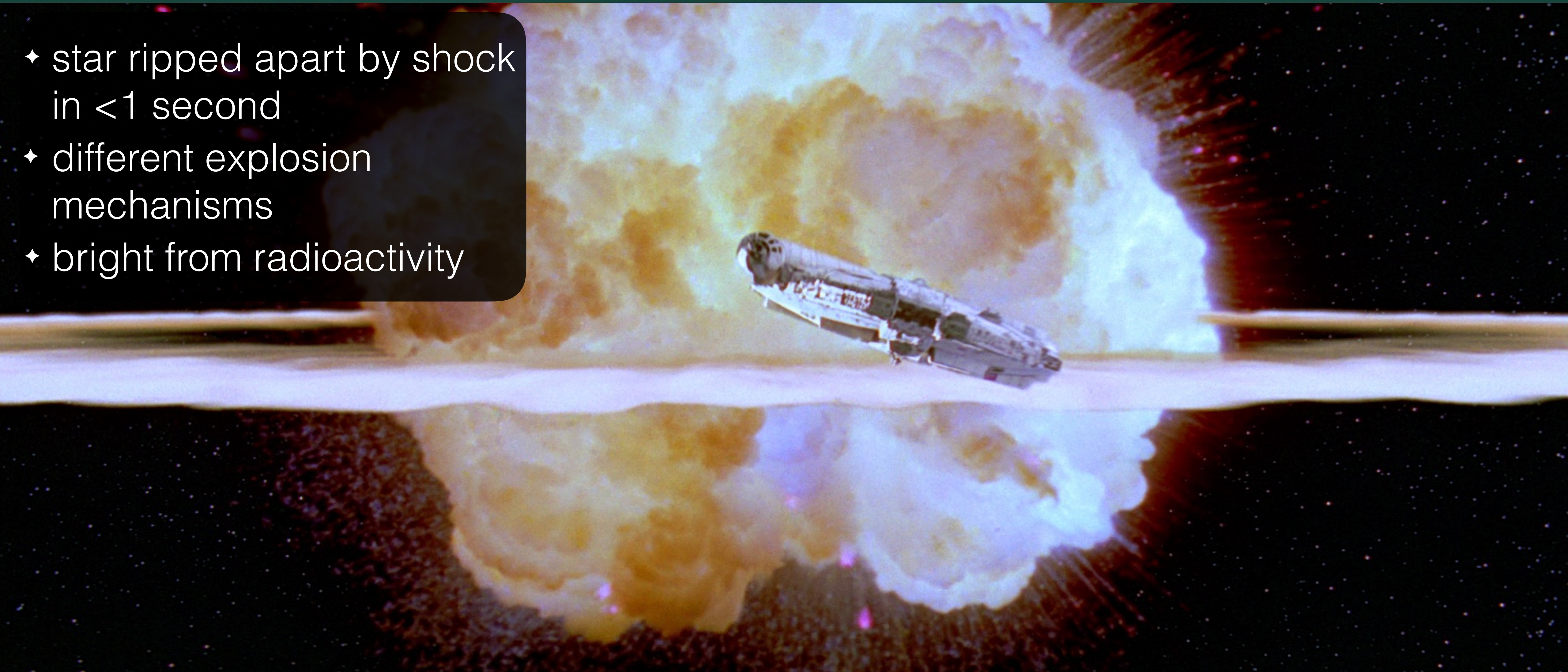


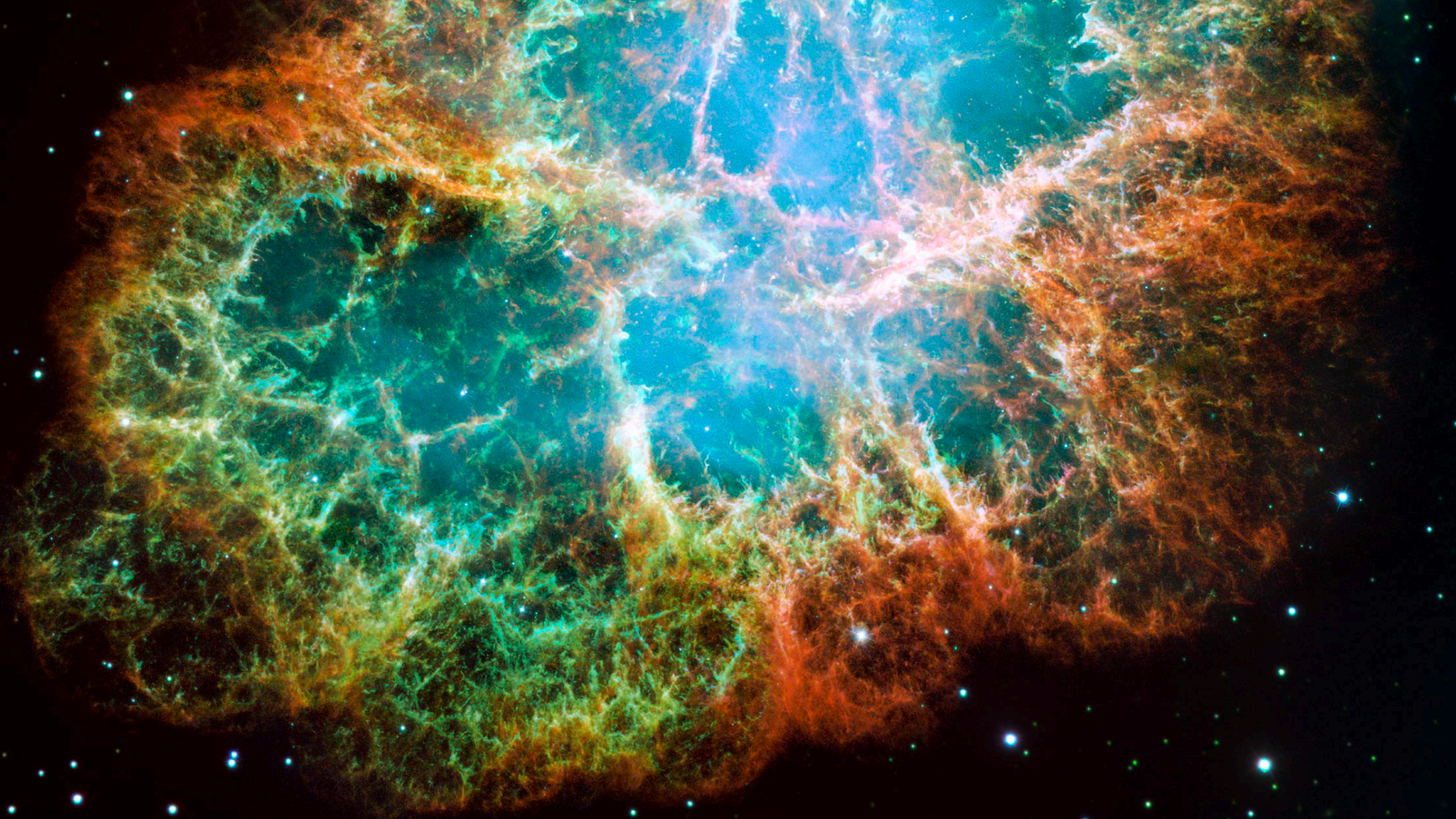
supernovae: stellar explosions

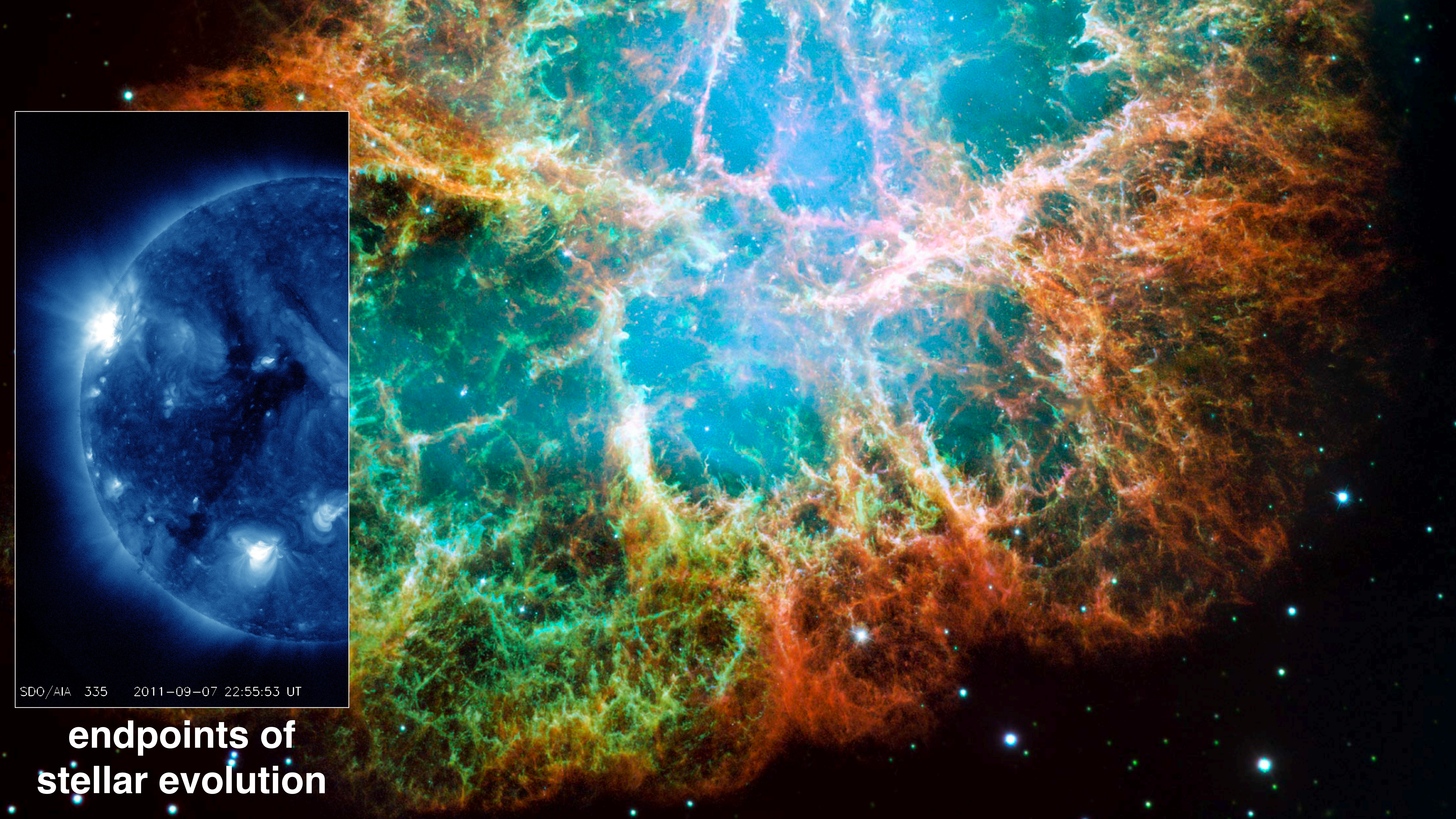


supernovae: stellar explosions

- ♦ star ripped apart by shock in <1 second
- ♦ different explosion mechanisms
- ♦ bright from radioactivity

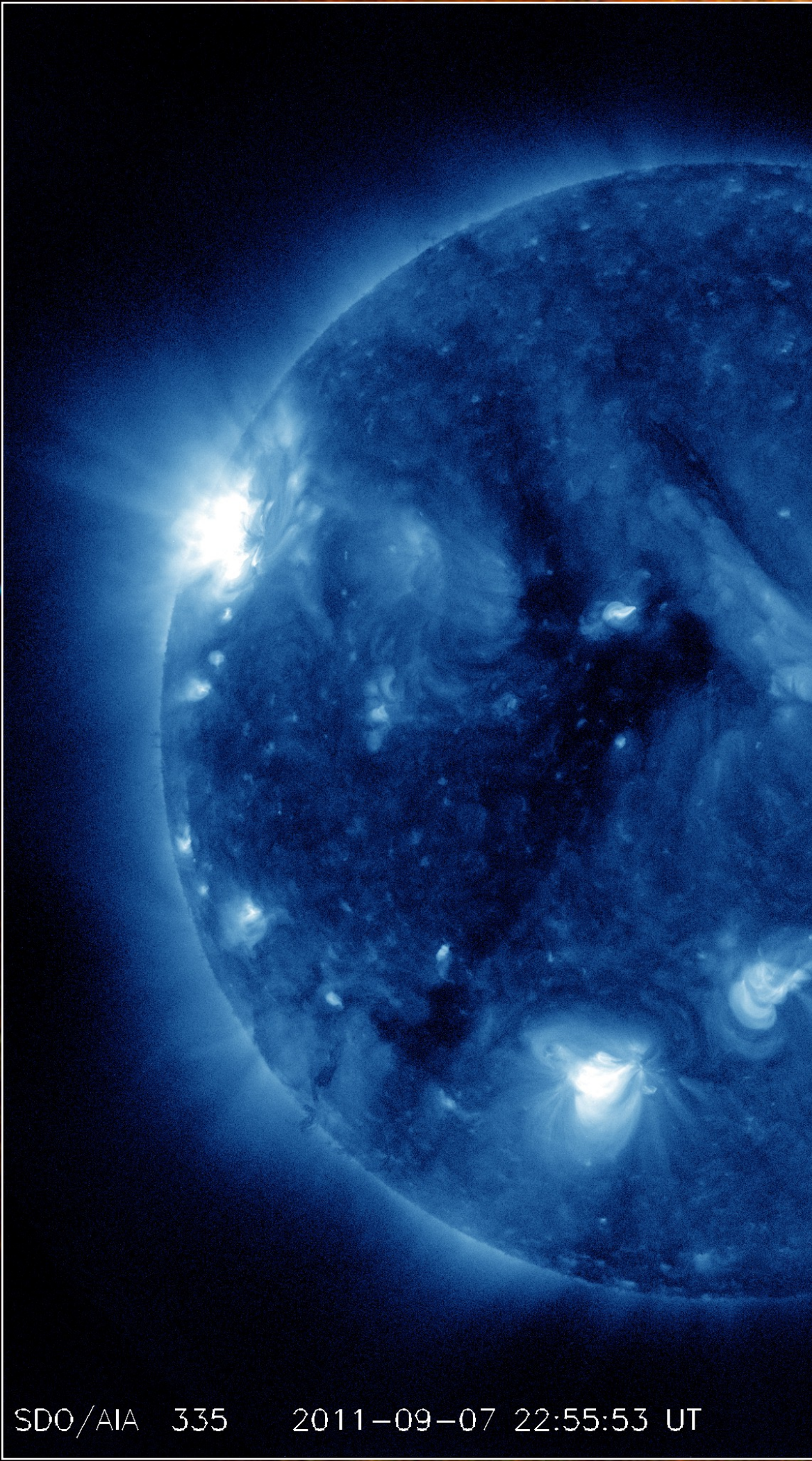






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**endpoints of
stellar evolution**

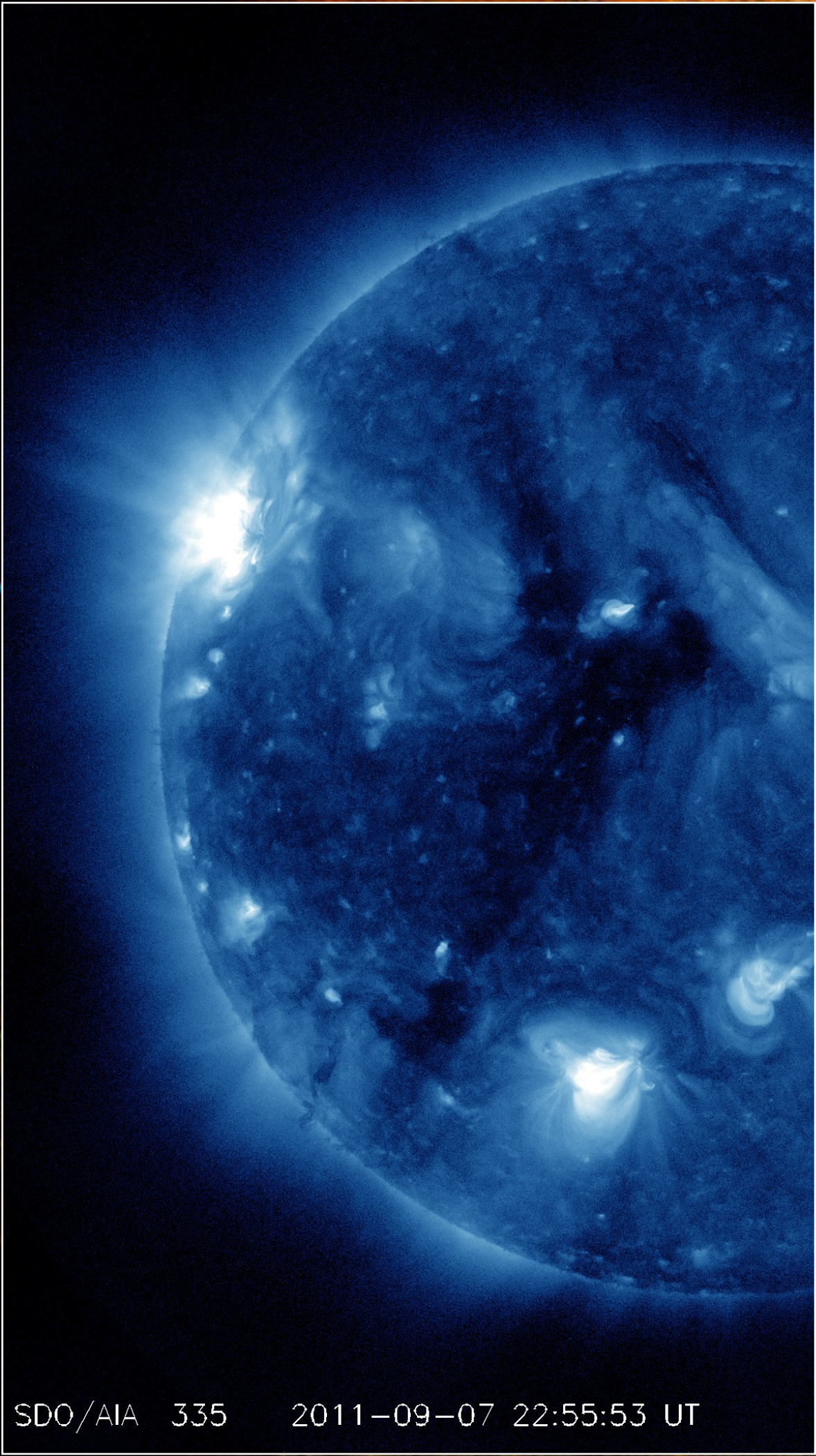


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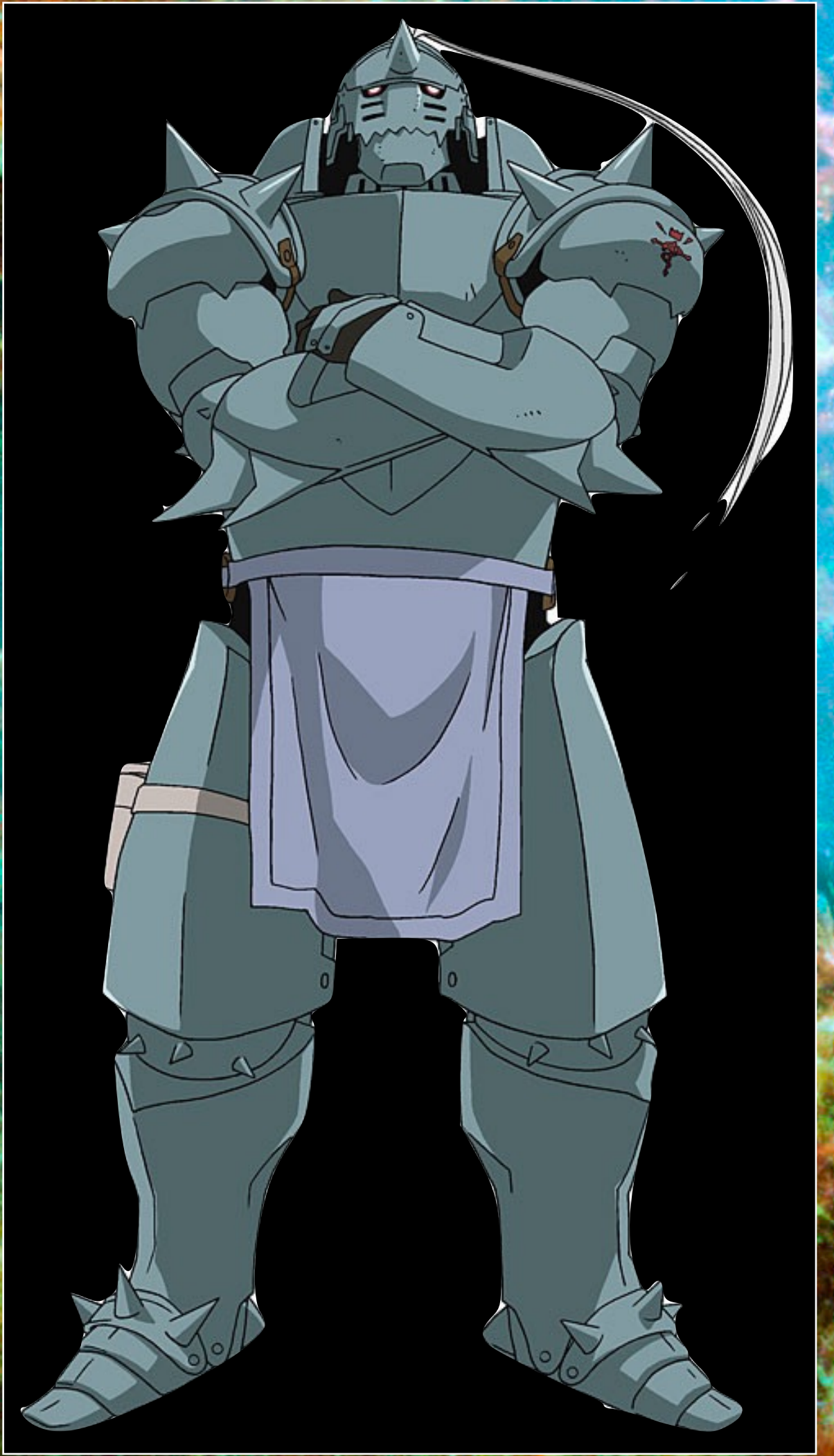


create & disperse heavy elements



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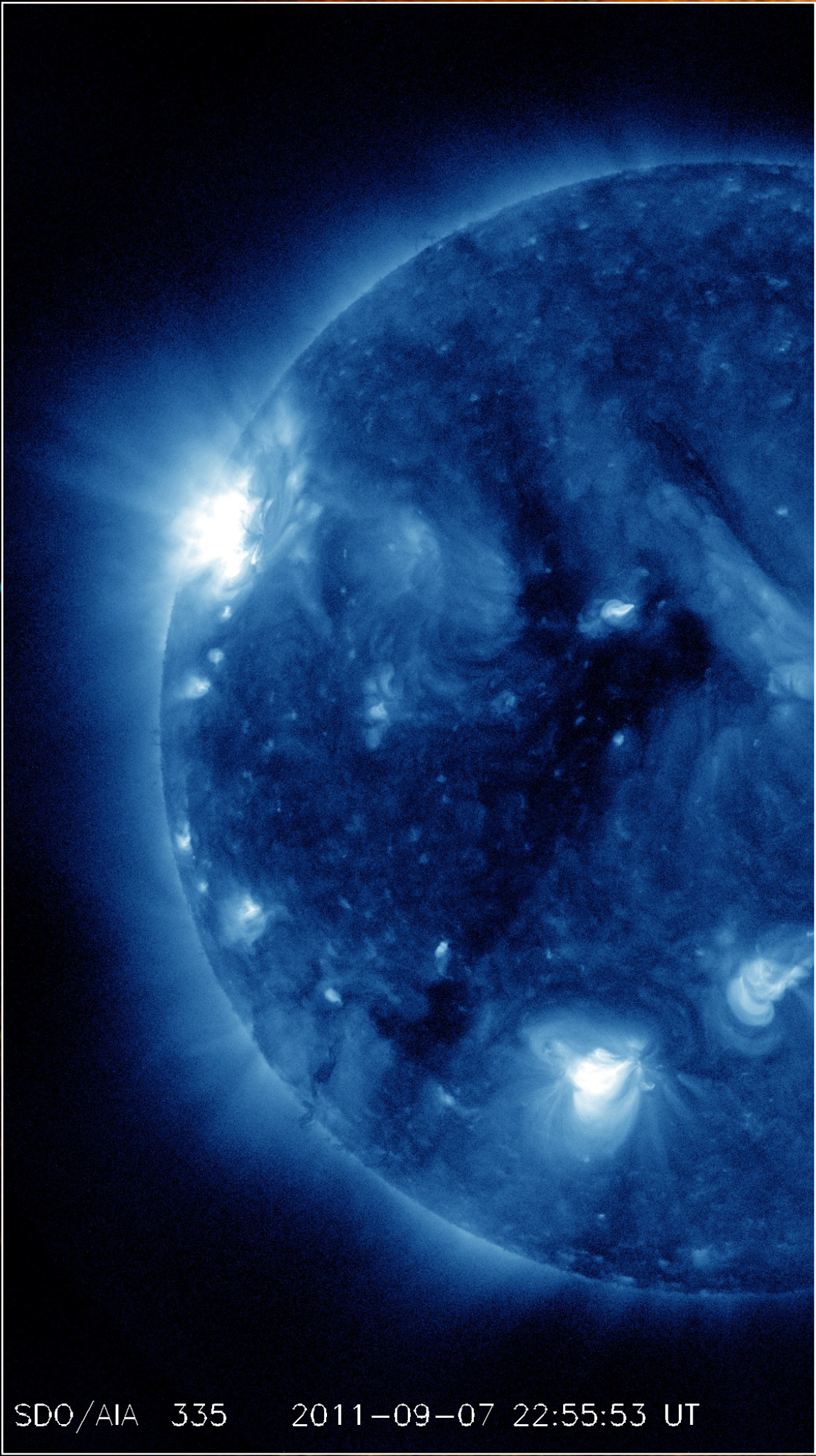
endpoints of stellar evolution



create & disperse heavy elements



energize galaxies



endpoints of stellar evolution



create & disperse heavy elements

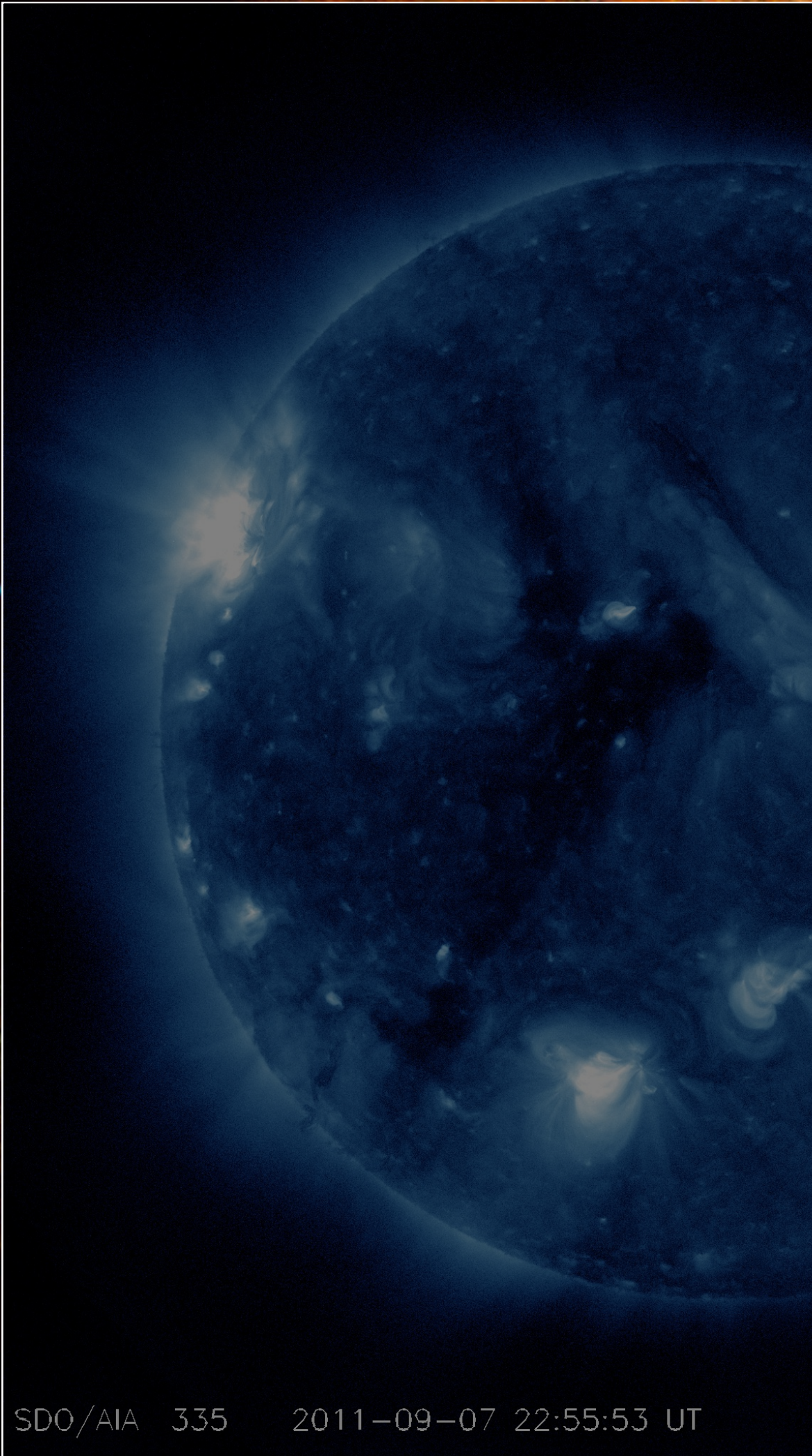


energize galaxies

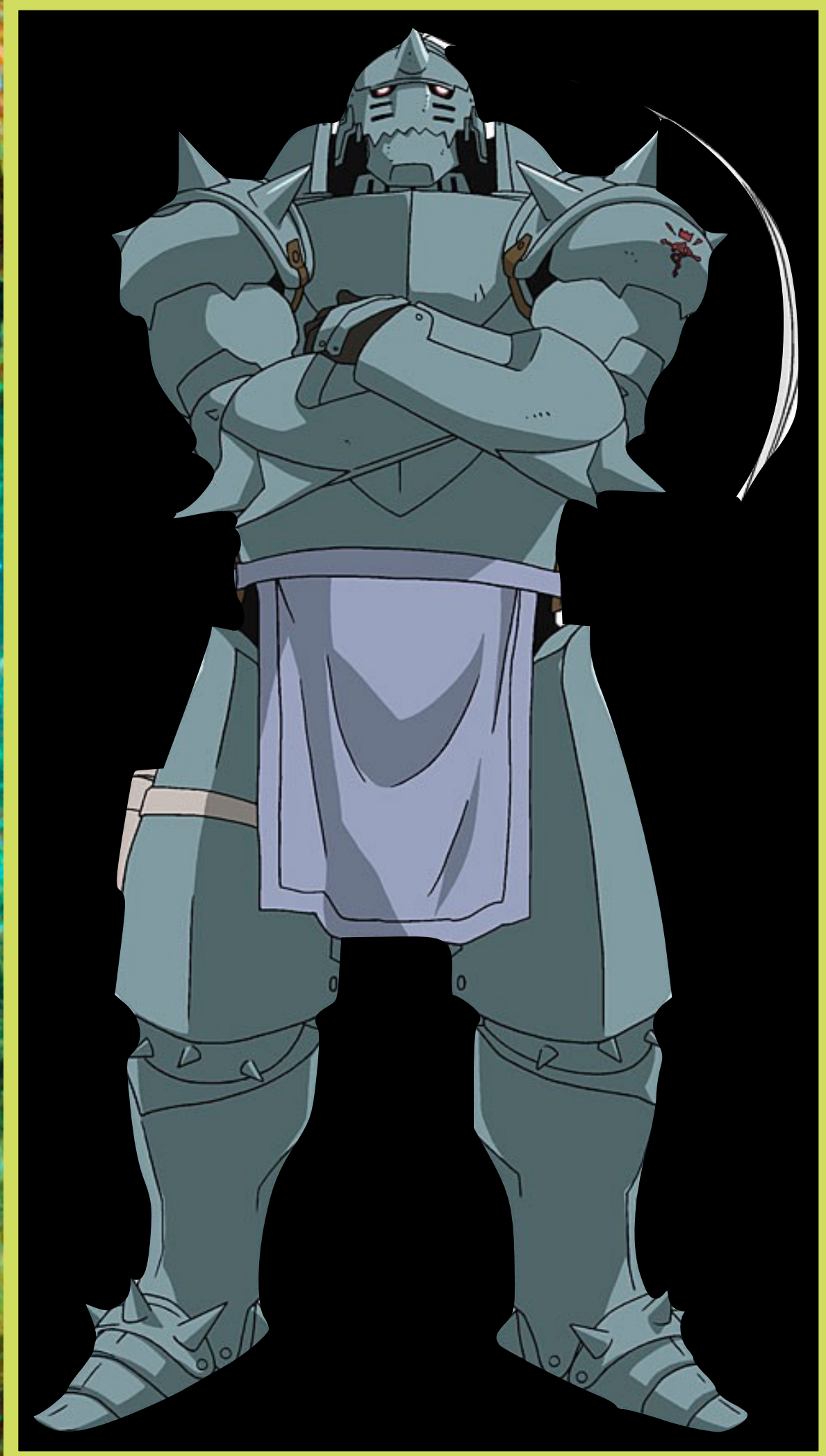


cosmological tools

site of r-process elements?



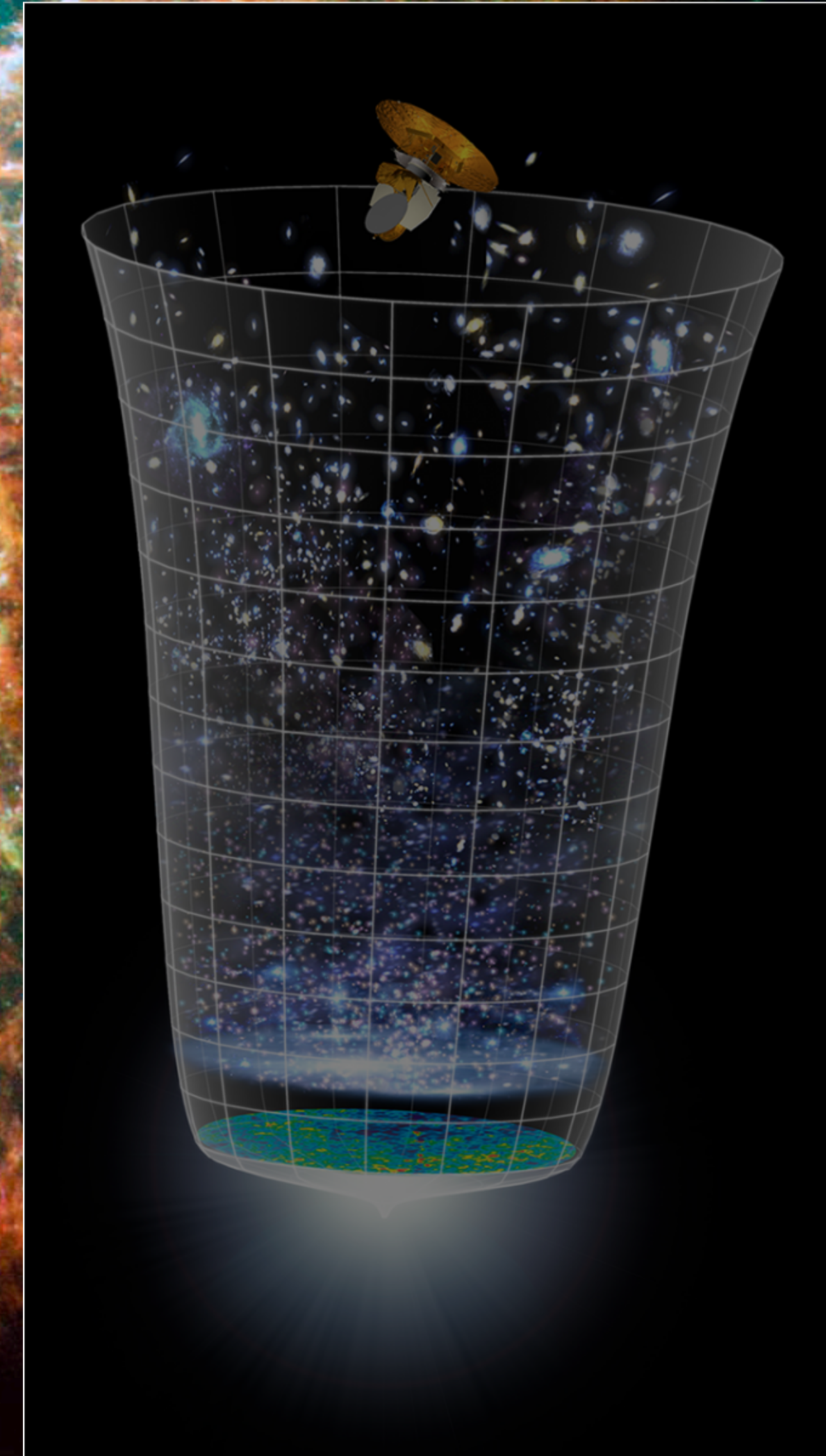
endpoints of stellar evolution



create & disperse heavy elements

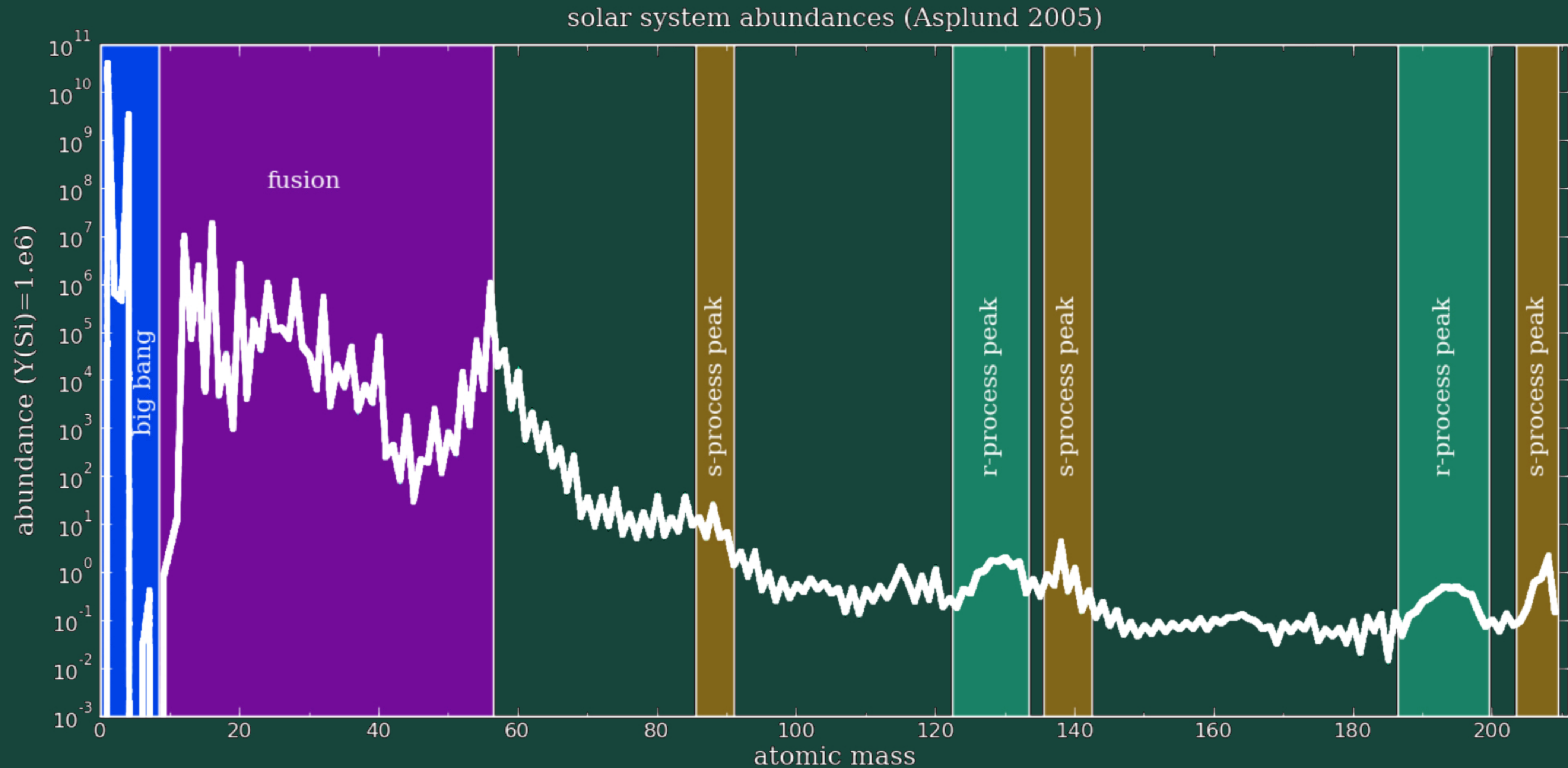


energize galaxies



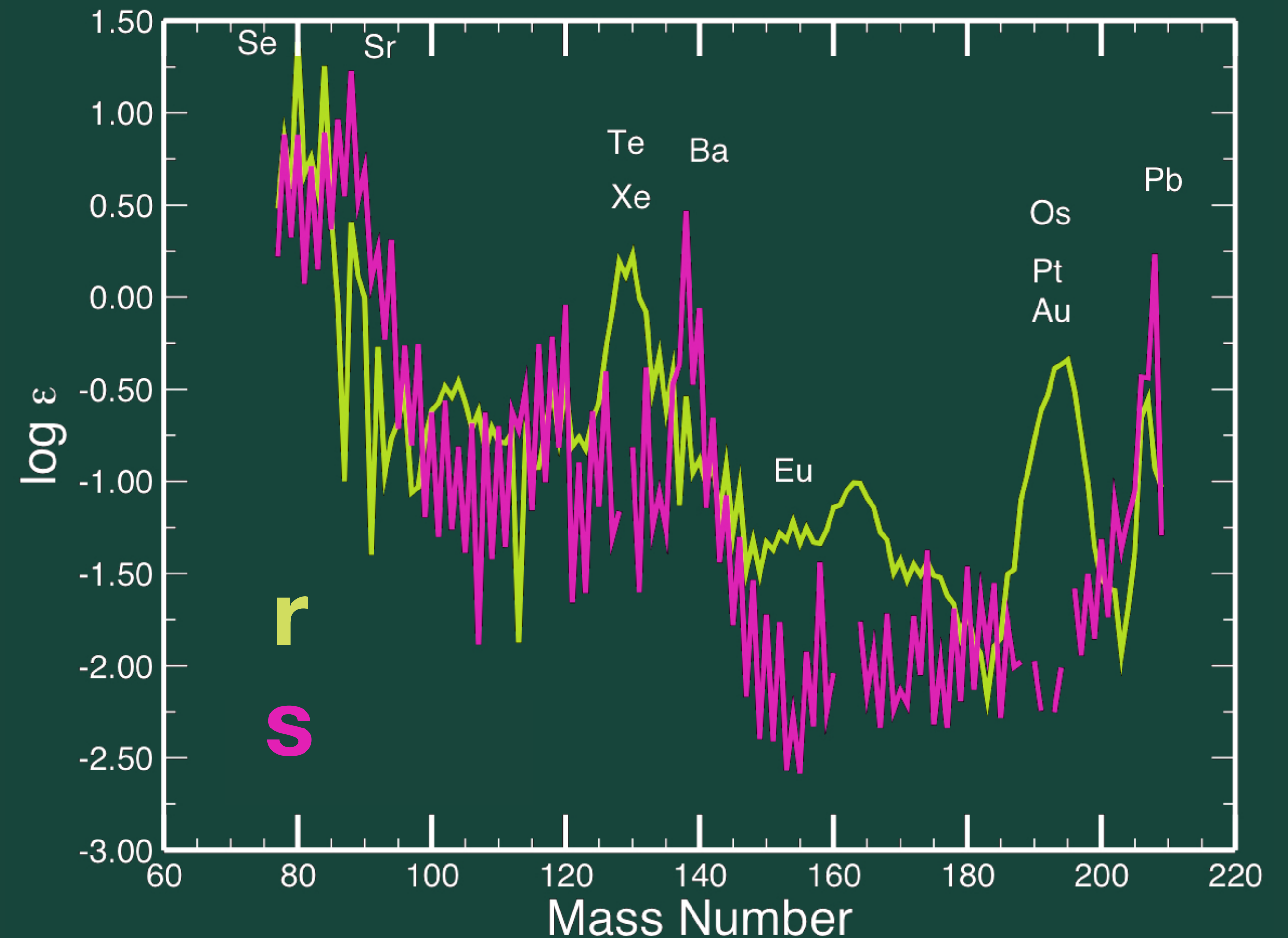
cosmological tools

elements heavier than Fe: neutron capture



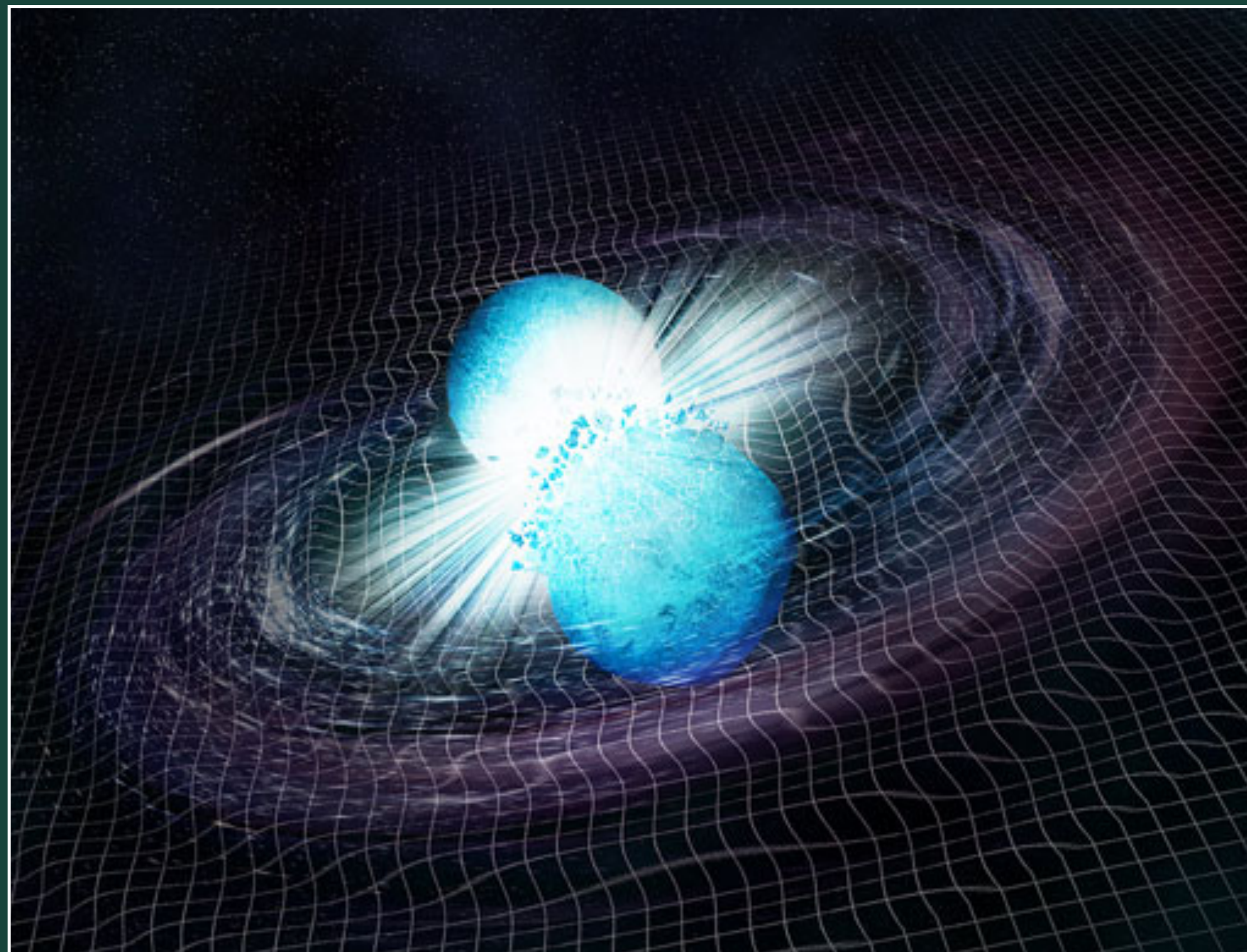
r-process: rapid neutron capture onto nuclei

- ▶ some elements/isotopes come only from r-process
 - ▶ we have tracers!
- ▶ requires neutron-rich environment



best candidates for r-process sites

neutron star mergers



supernovae





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Toward Exascale Astrophysics of Mergers and Supernovae





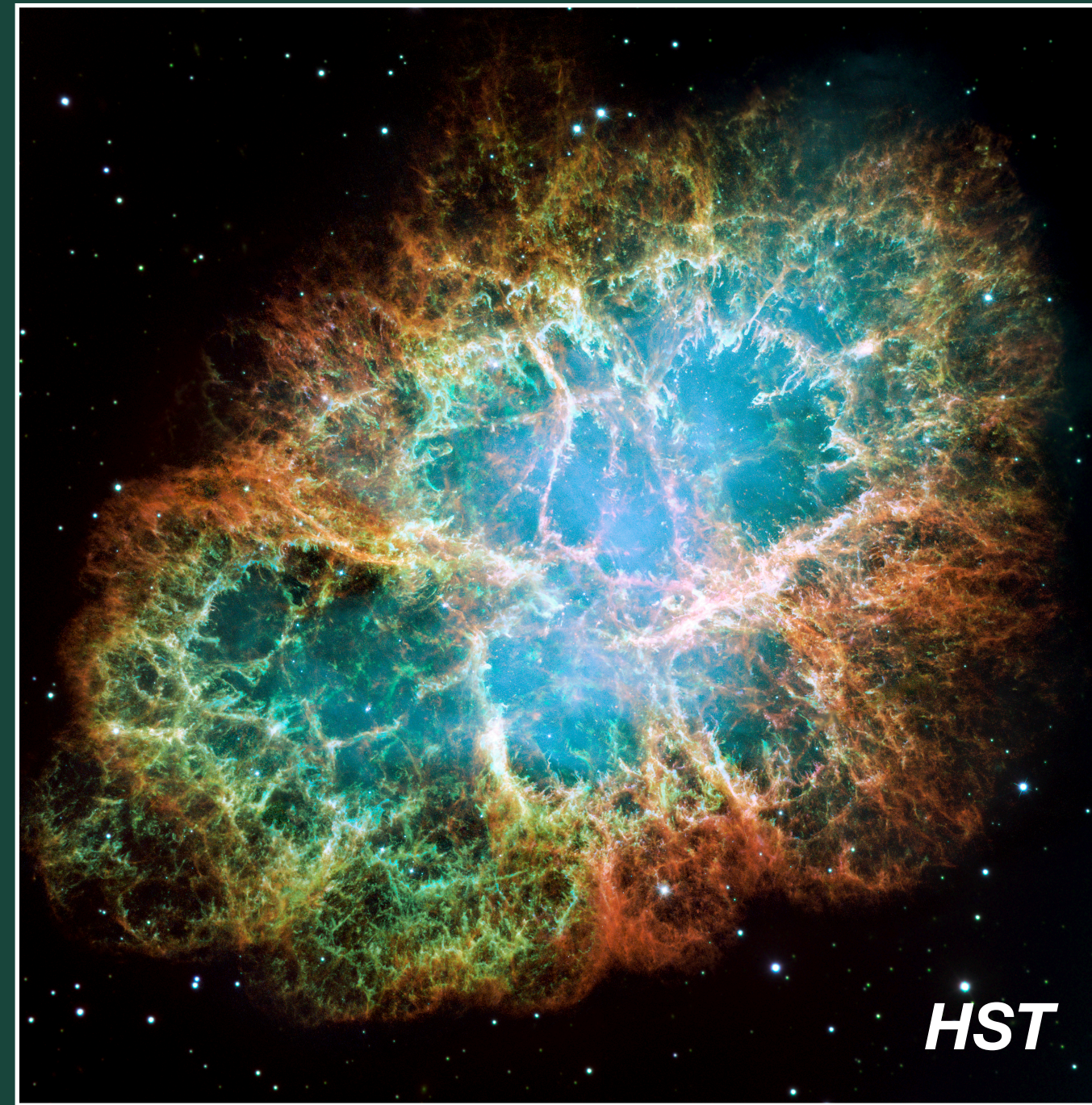
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WURP

What's Up with the R-Process?

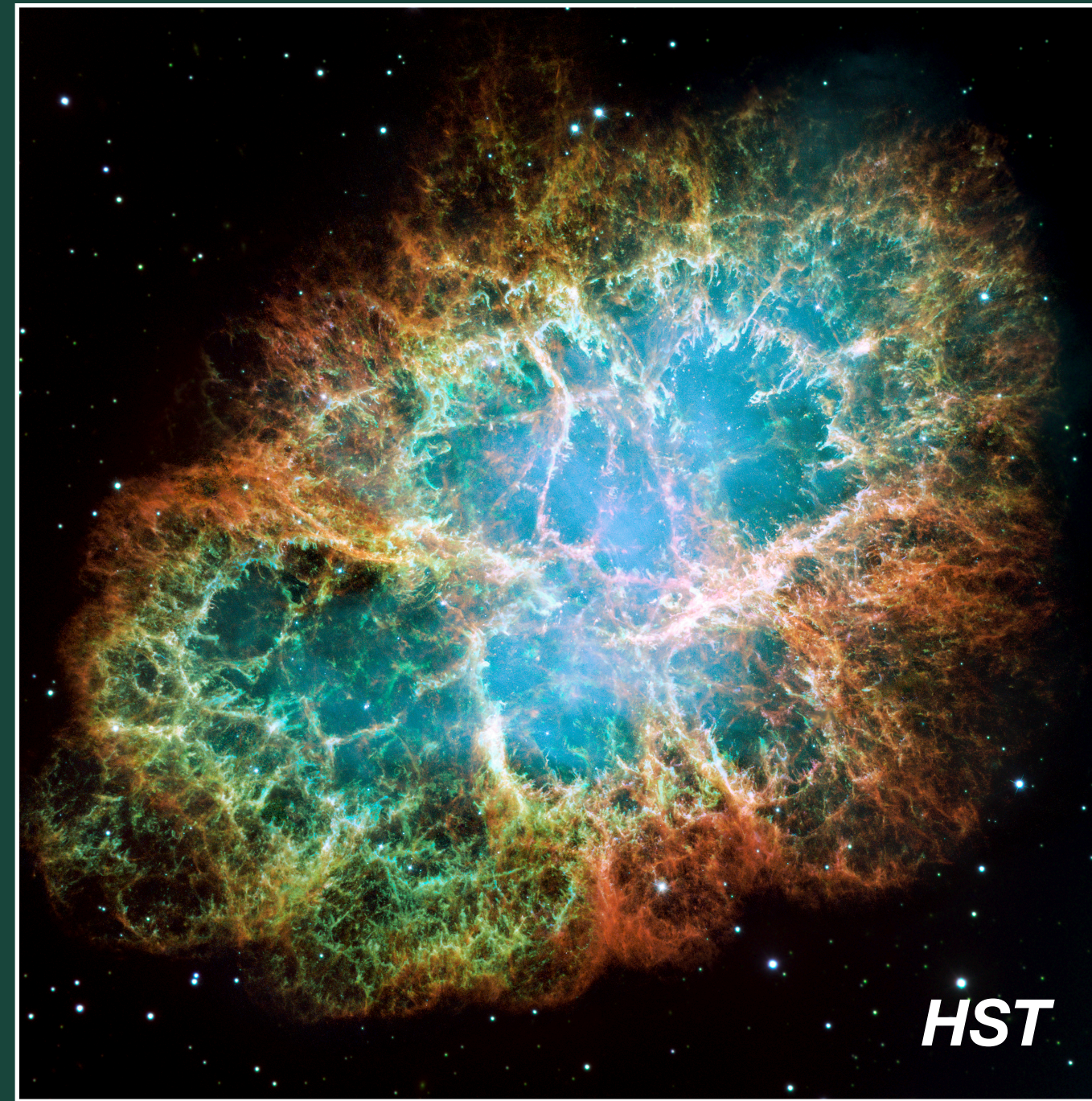


core-collapse supernovae create neutron stars



core-collapse supernovae create neutron stars

歷代名臣奏議卷之三十一
宋仁宗至和二年侍御史趙抃上言曰臣伏見自去年五月已來妖
星遂見僅及周輪至今光耀未退此谷永所謂馳騁騰虛芒熒長短
所歷奸犯其為譎變甚可畏也又去冬連今春京東西路及陝右川
蜀諸郡旱暵不雨麥苗焦死民既艱食寇掠必興此京房所謂欲
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輔之事者蓋注而仰成之若然則陰陽以和災異以消朝廷清明矣
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也小人日陽也君象也黑氣蔽日者陰侵陽小人惑君也欲雨不
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✓ Seen 1054 AD

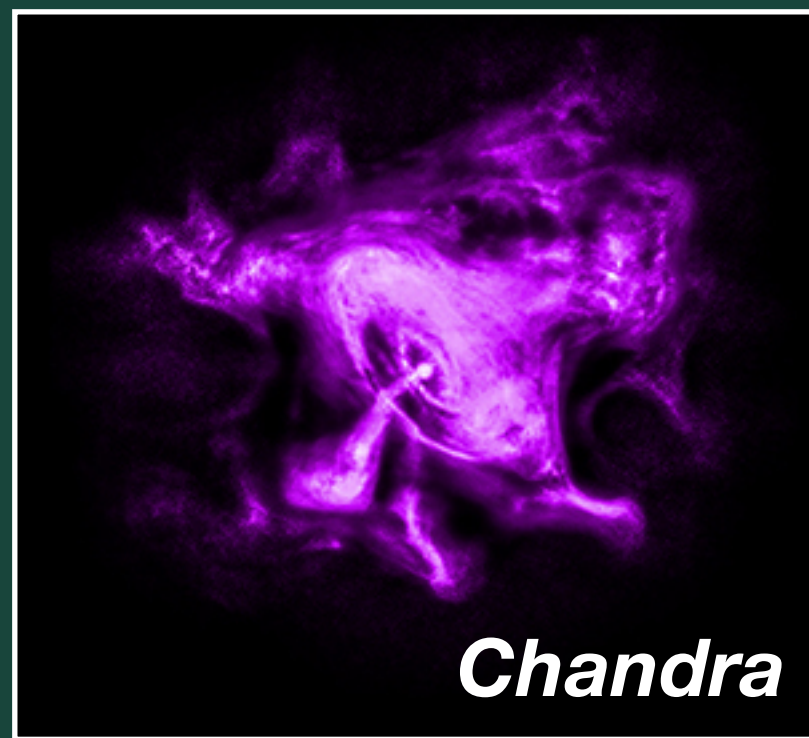
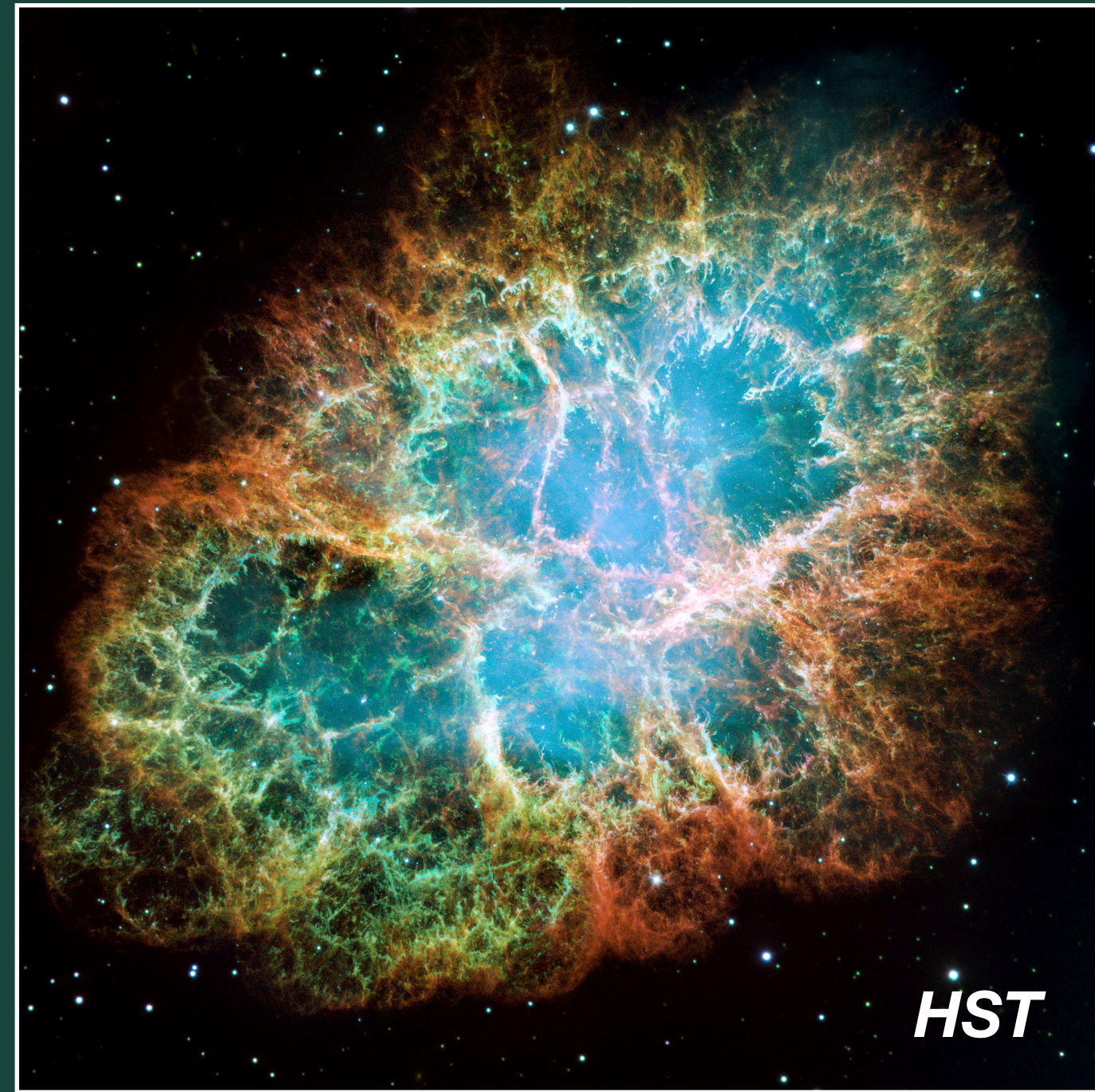


core-collapse supernovae create neutron stars

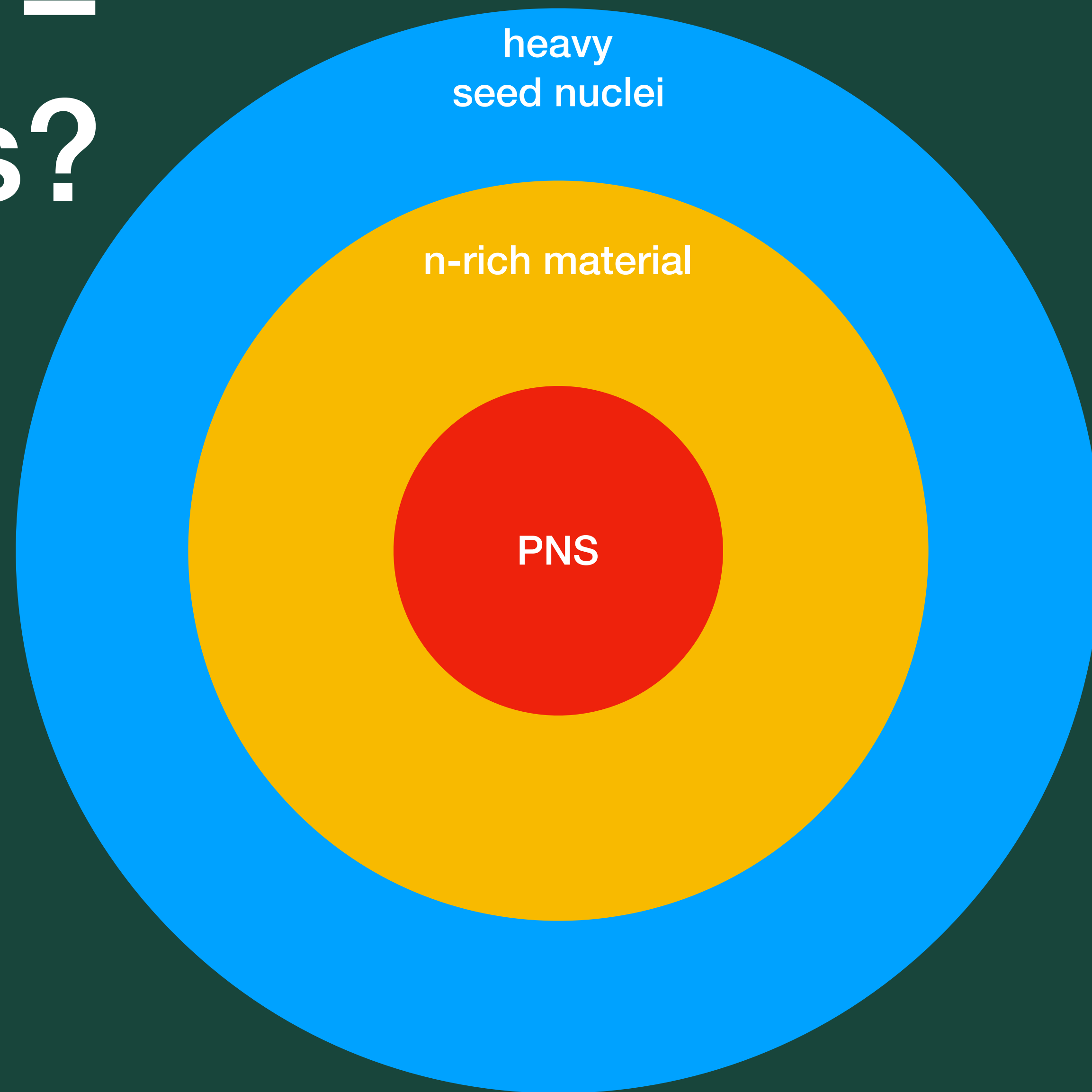
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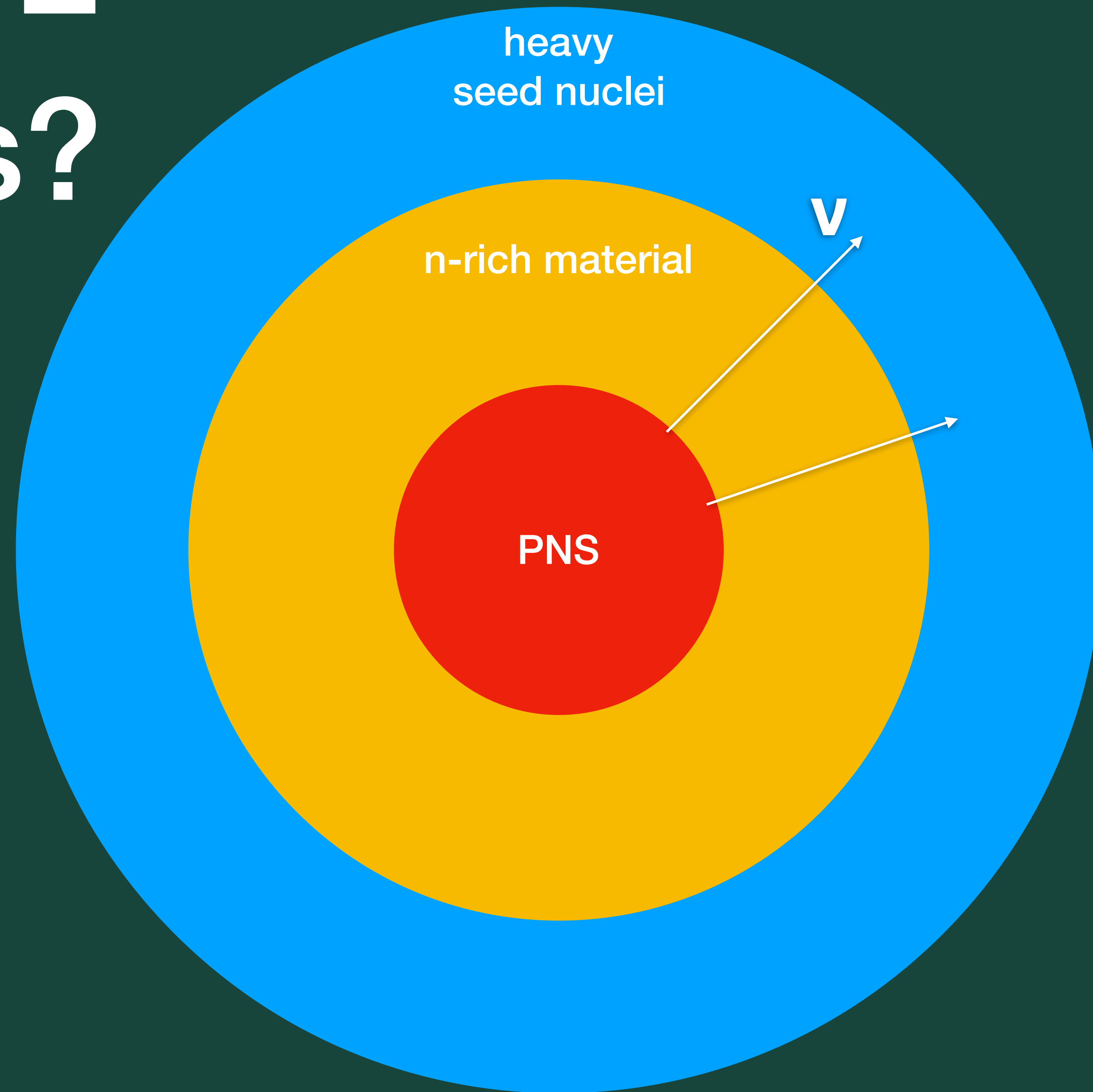
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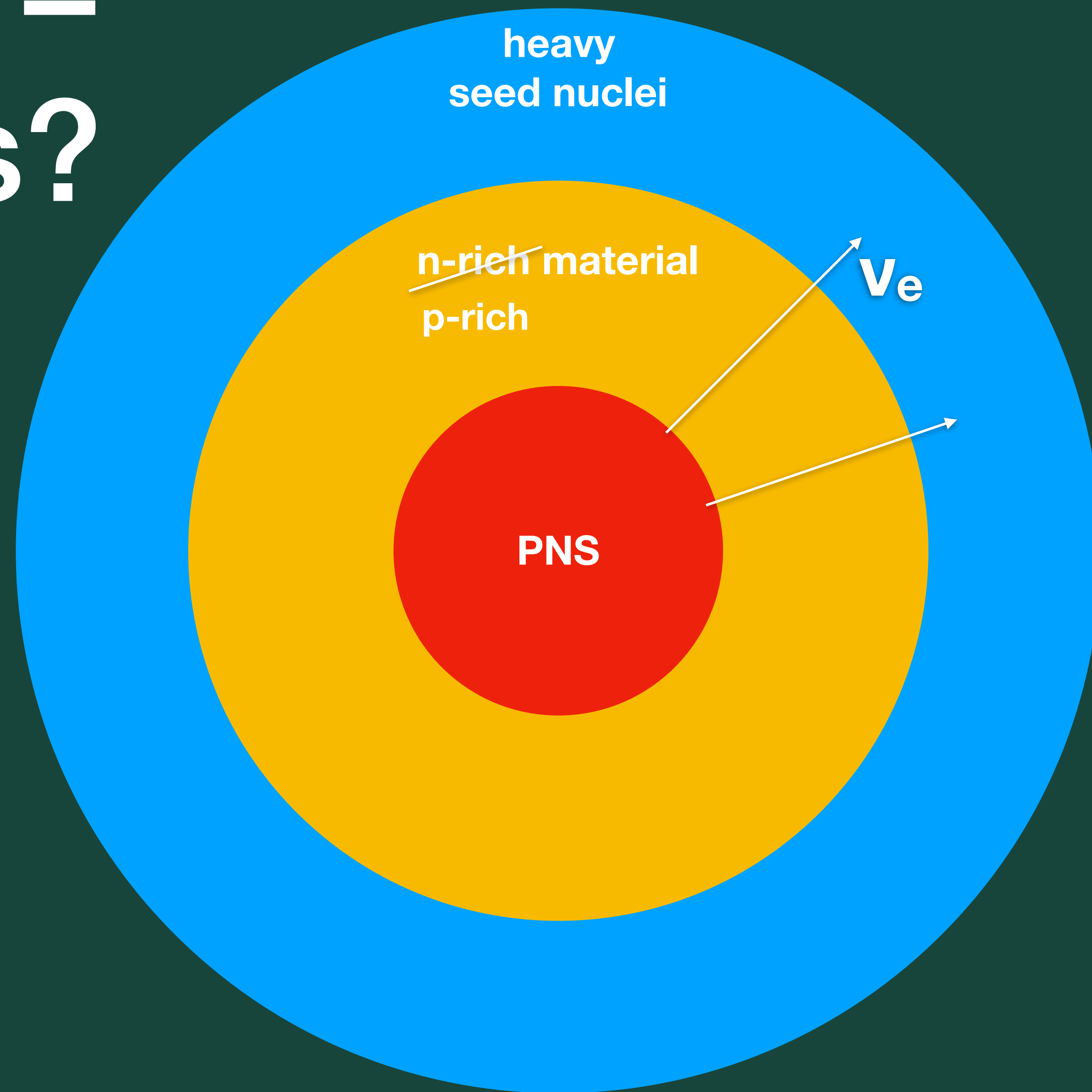
neutrons =
r-process?



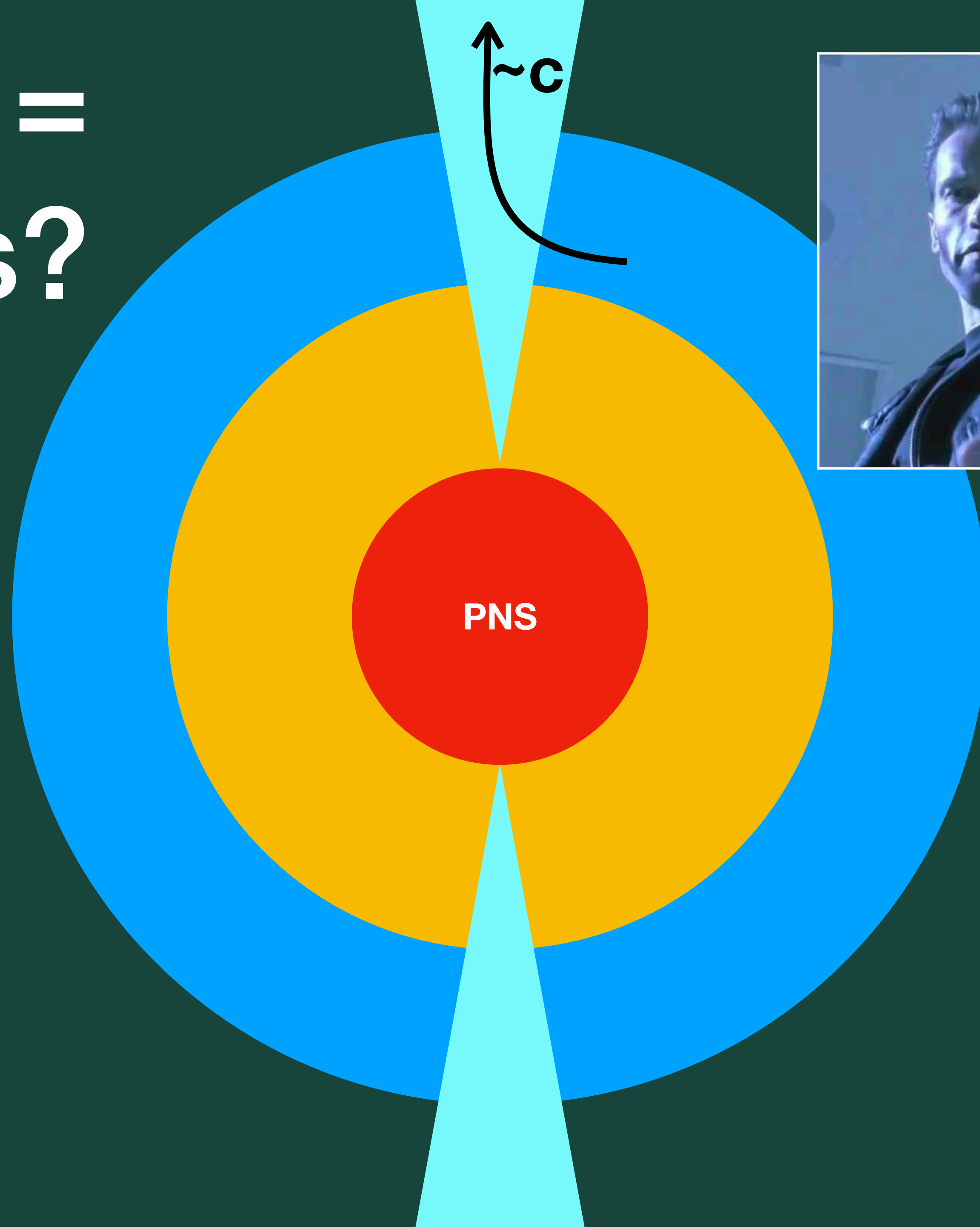
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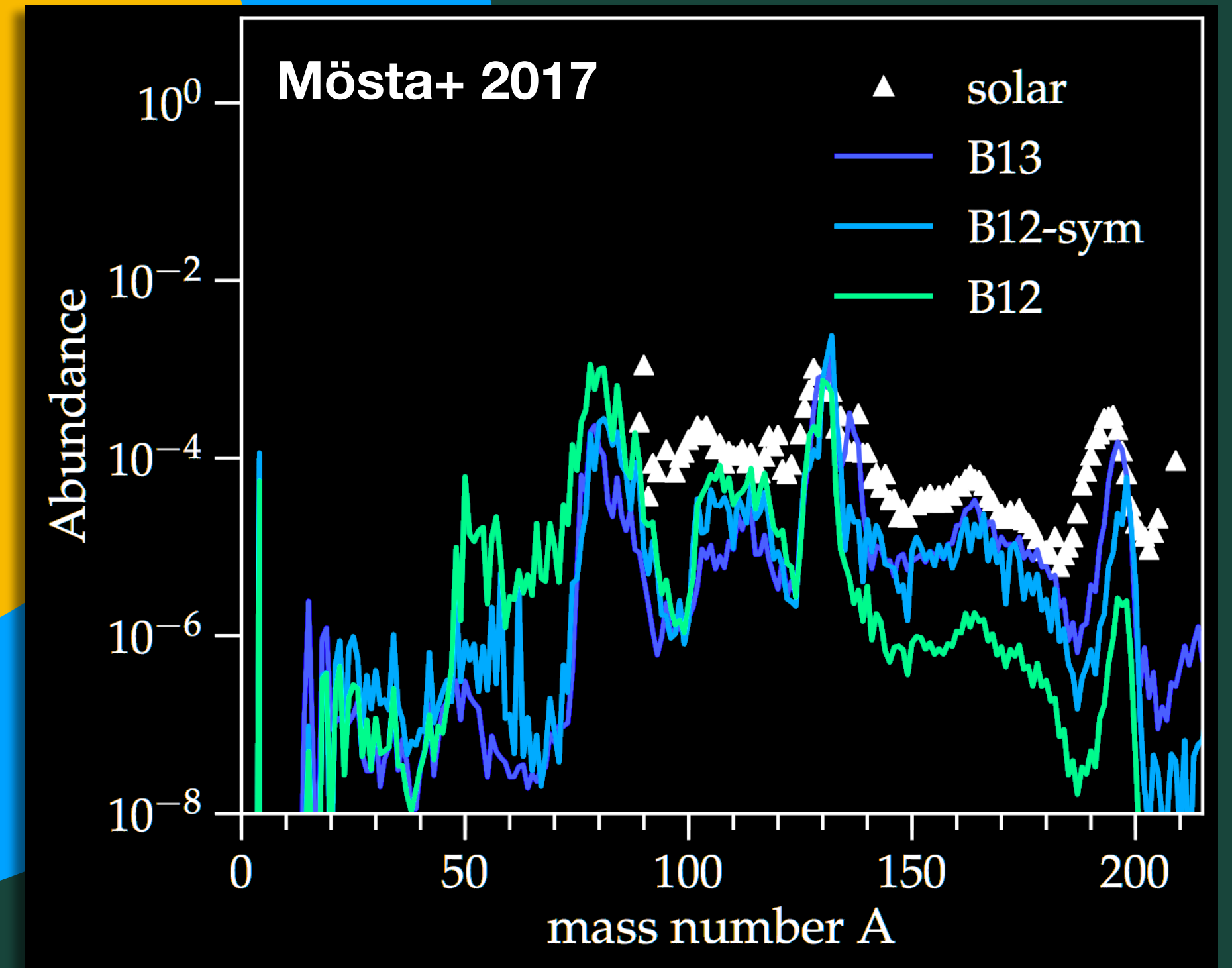
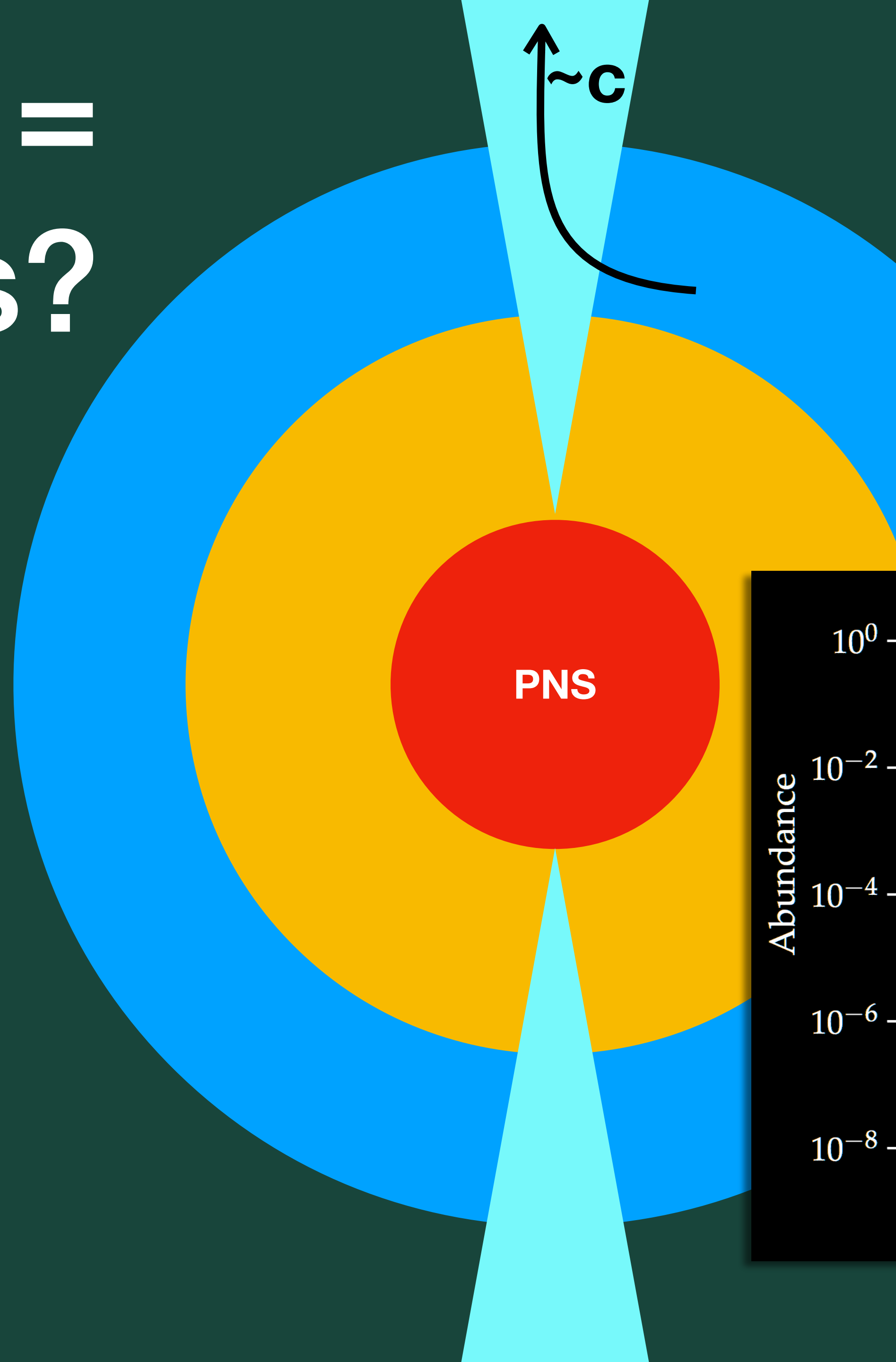
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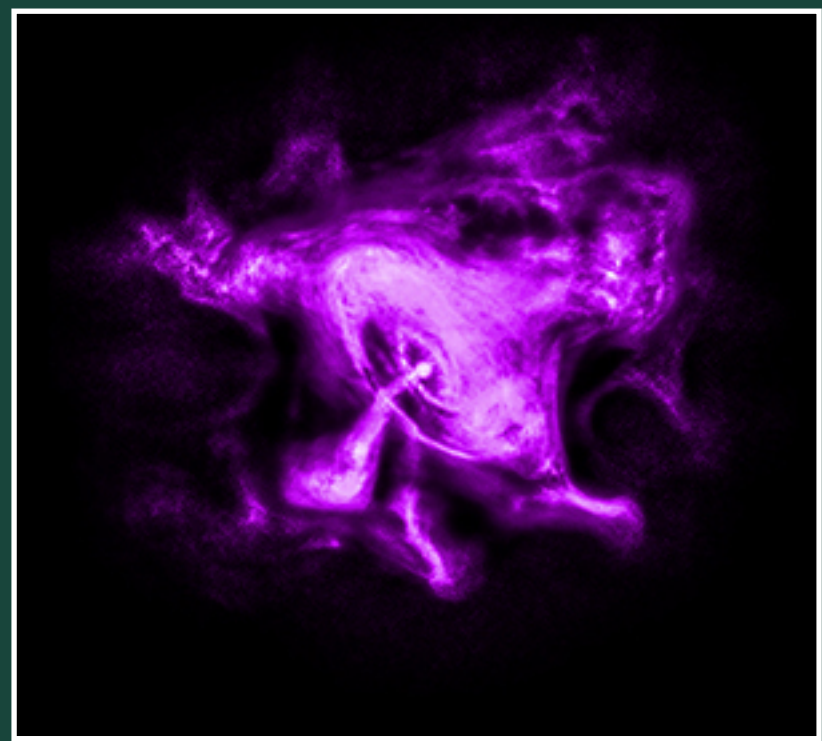


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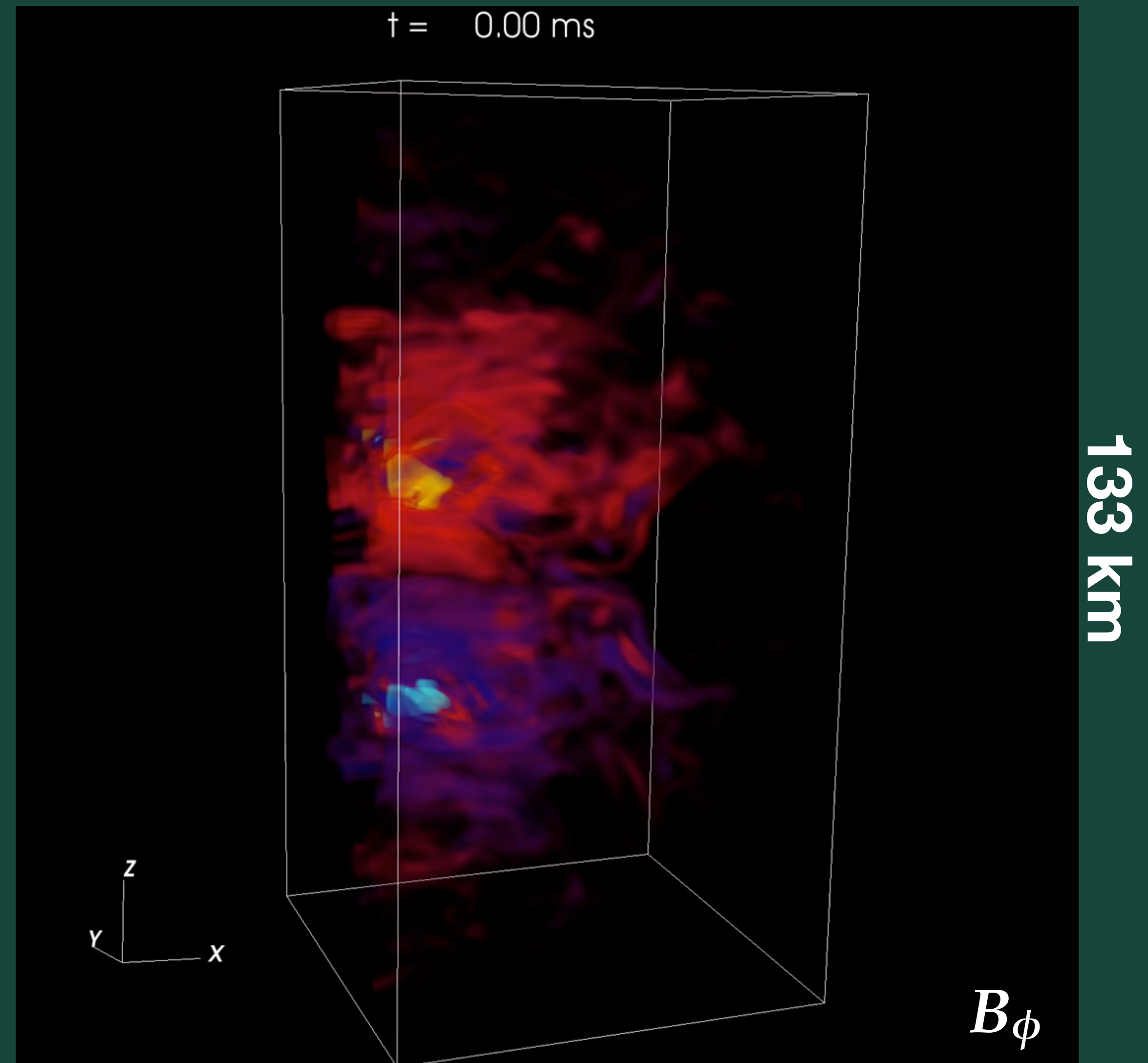
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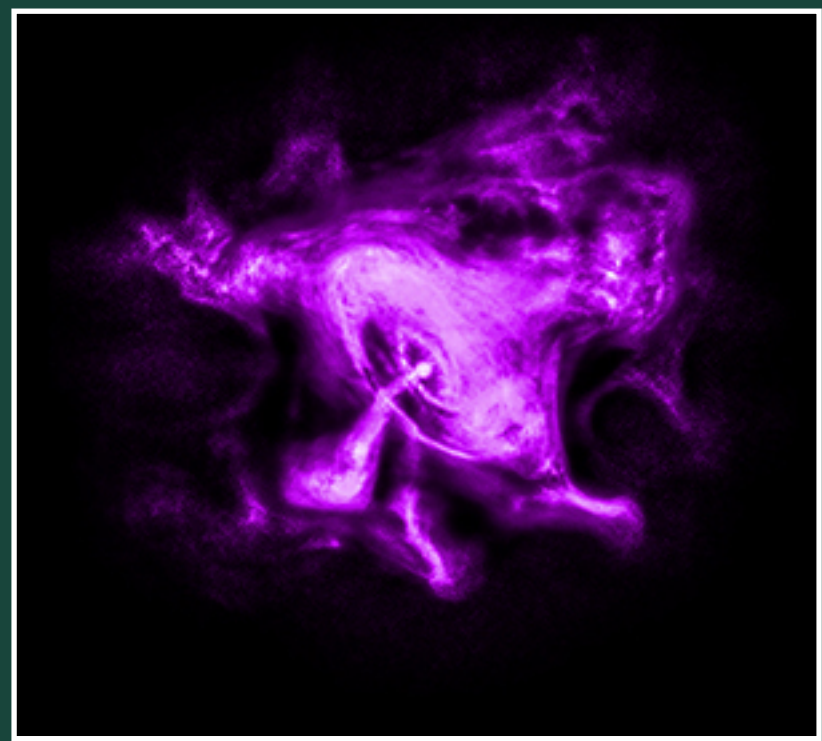




creating jets in core-collapse SNe

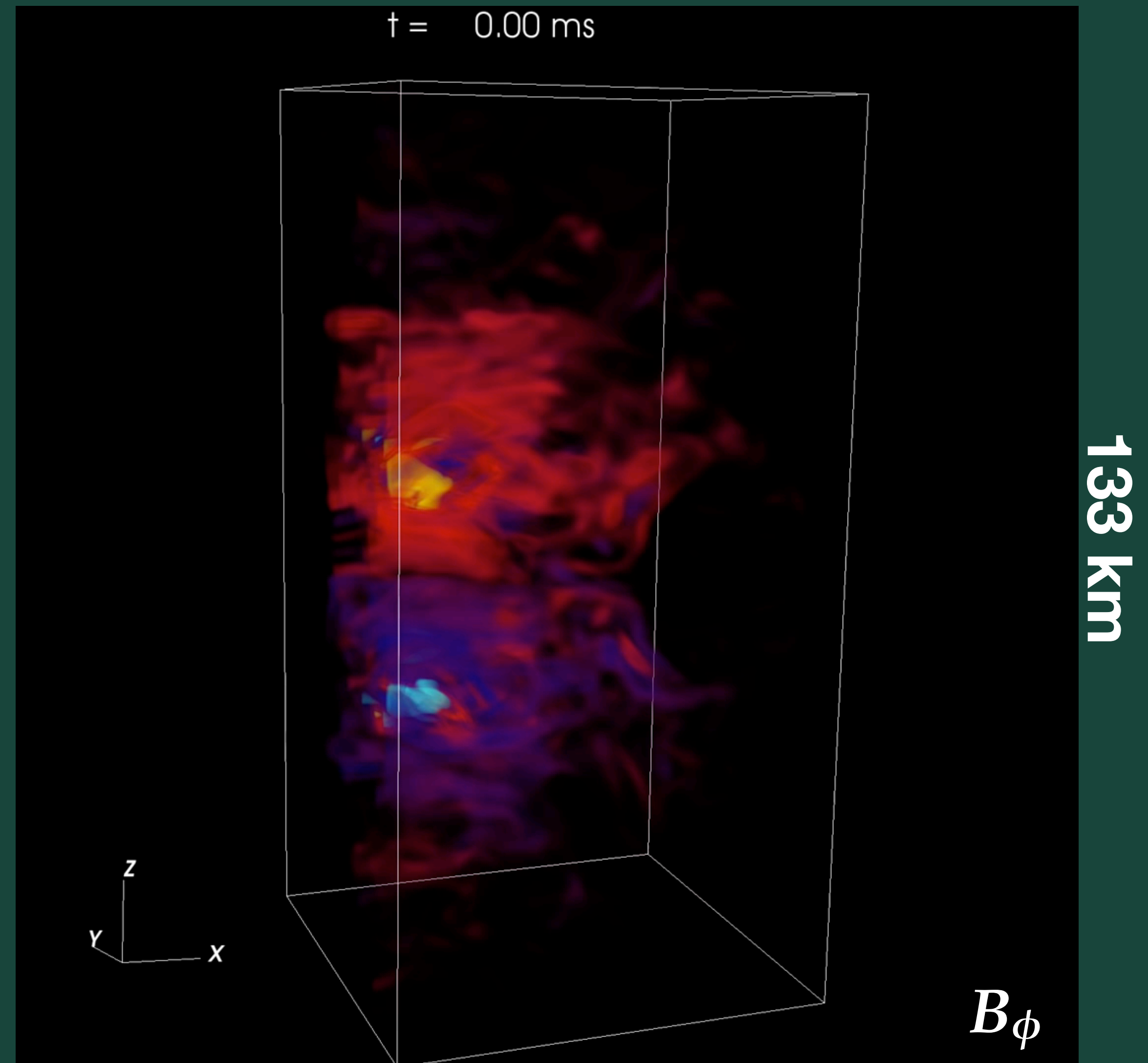
- ▶ seen in nature: long gamma-ray bursts associated with SNe
- ▶ magnetic confinement - narrow jet
- ▶ stars have magnetic fields!
- ▶ need to amplify field over one billion times ... in ~ 10 ms.





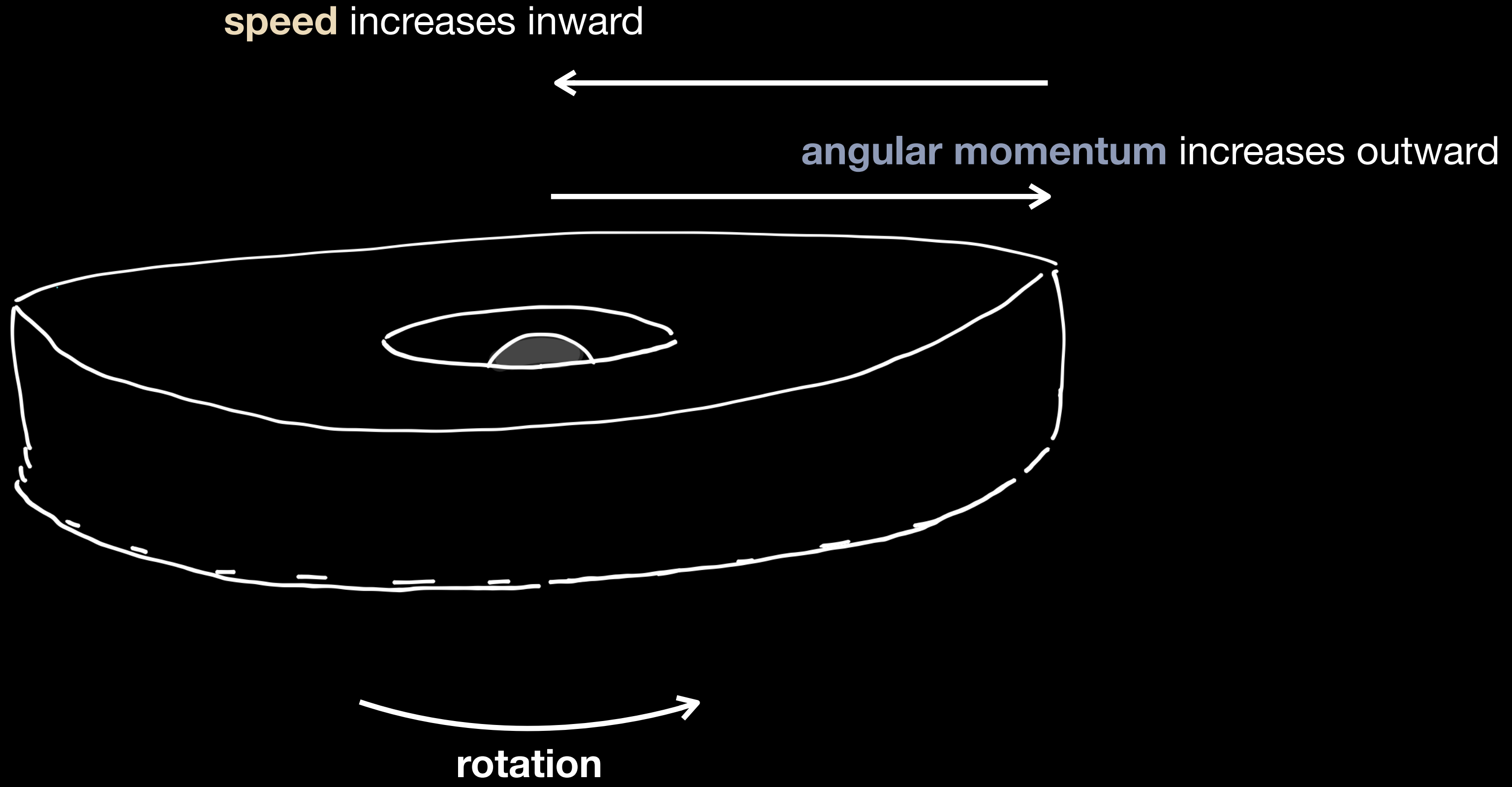
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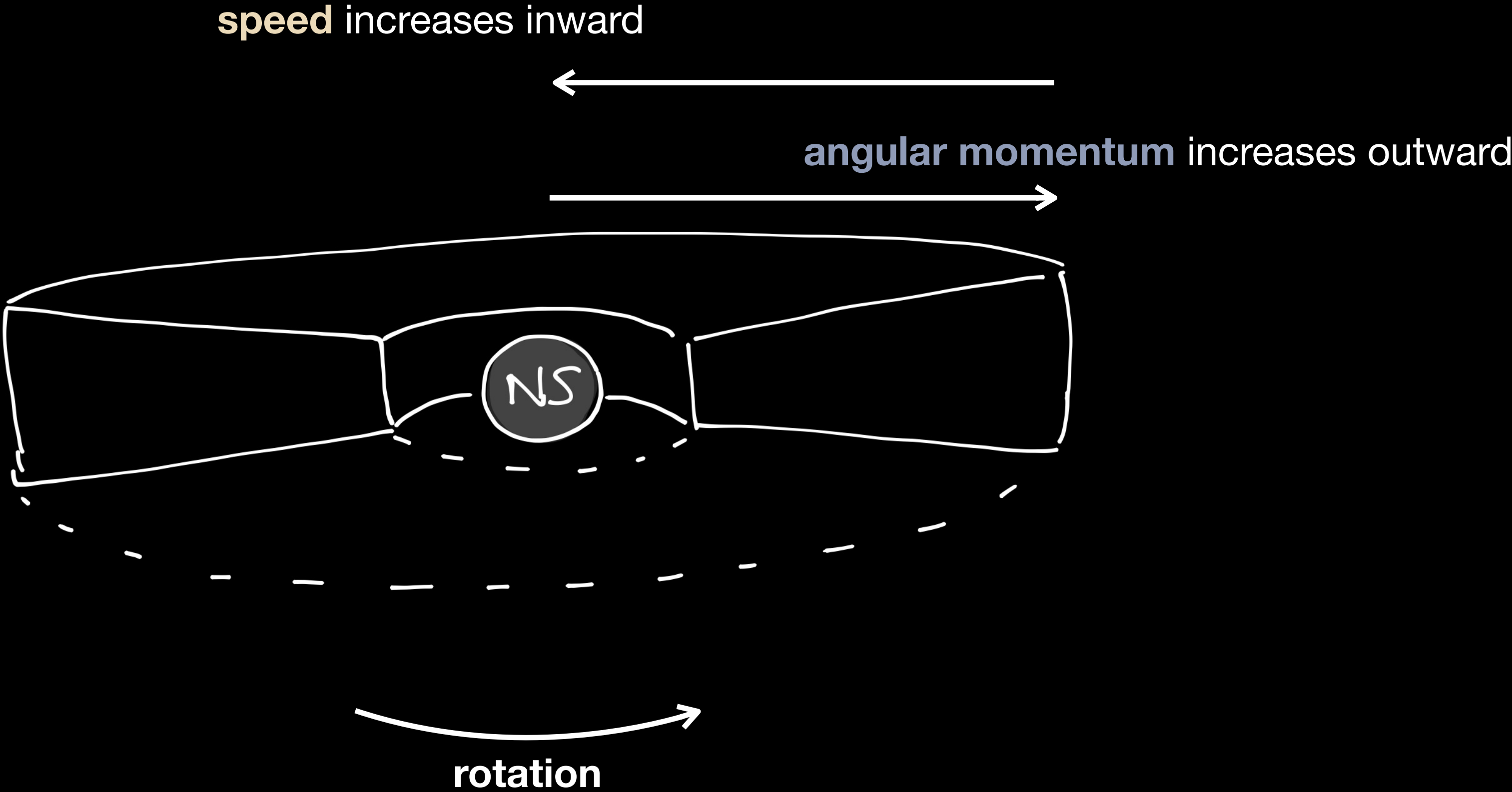


the Magneto-Rotational Instability

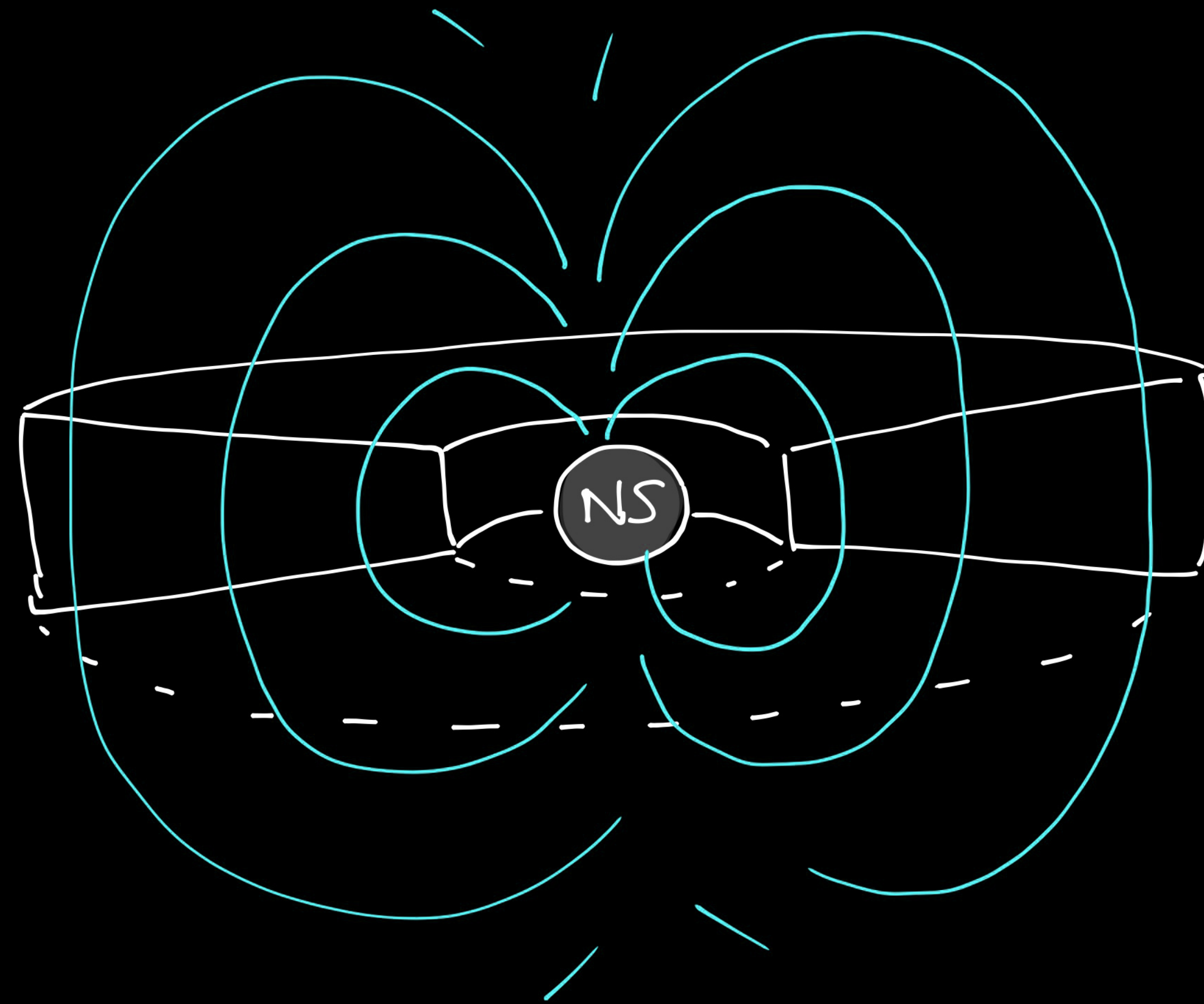
Balbus & Hawley (1991)



the Magneto-Rotational Instability



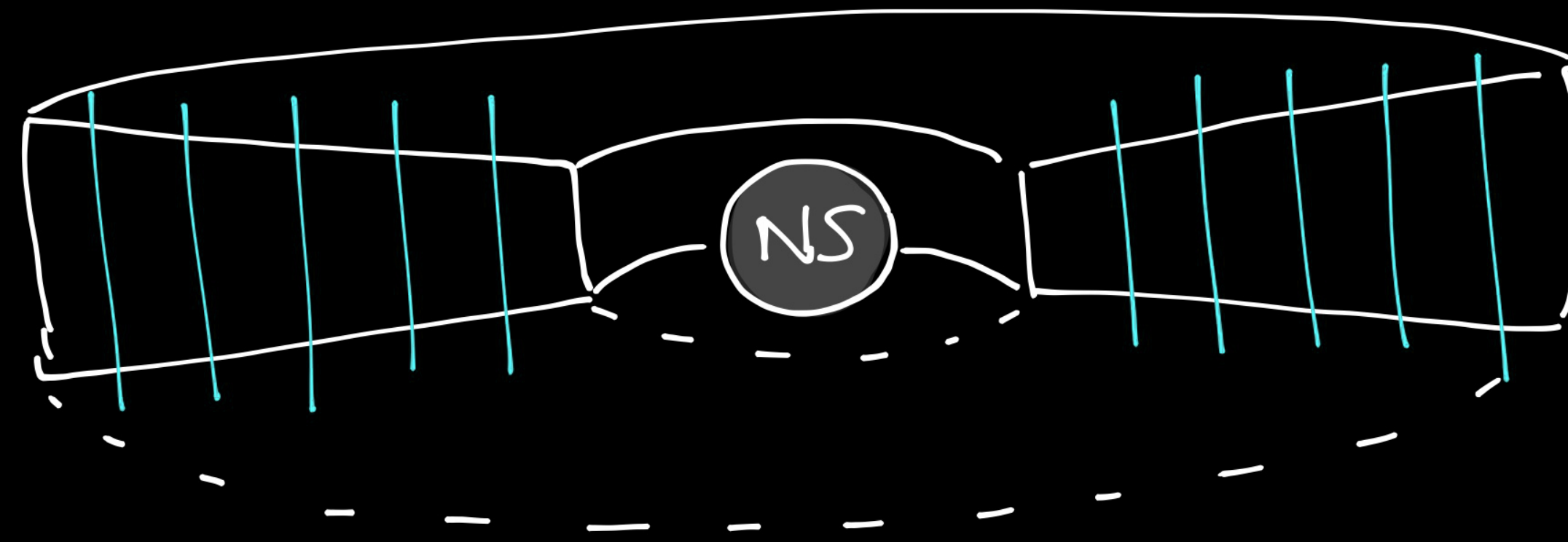
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magnetic
field, B

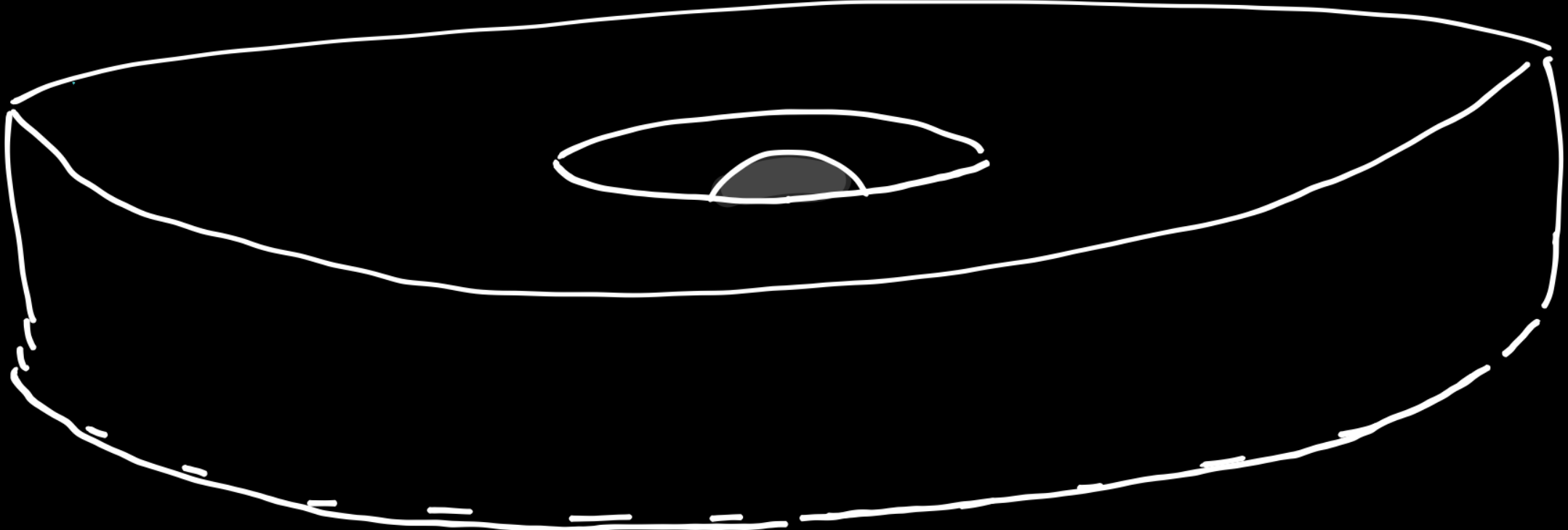
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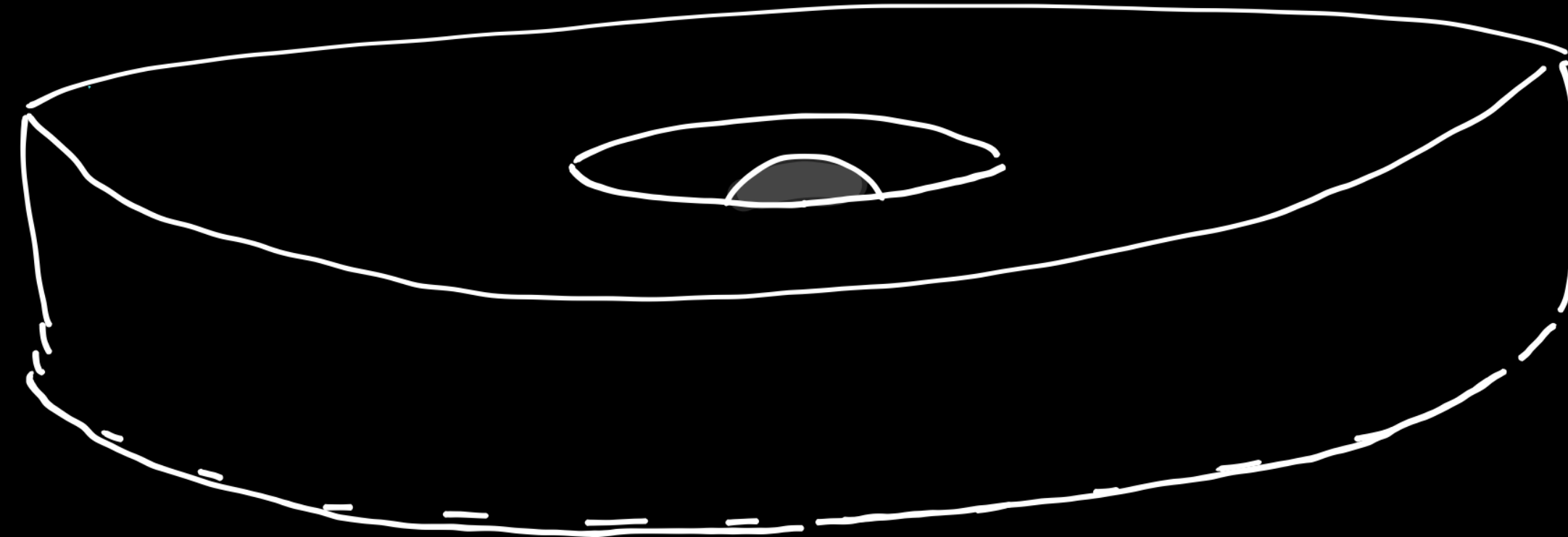
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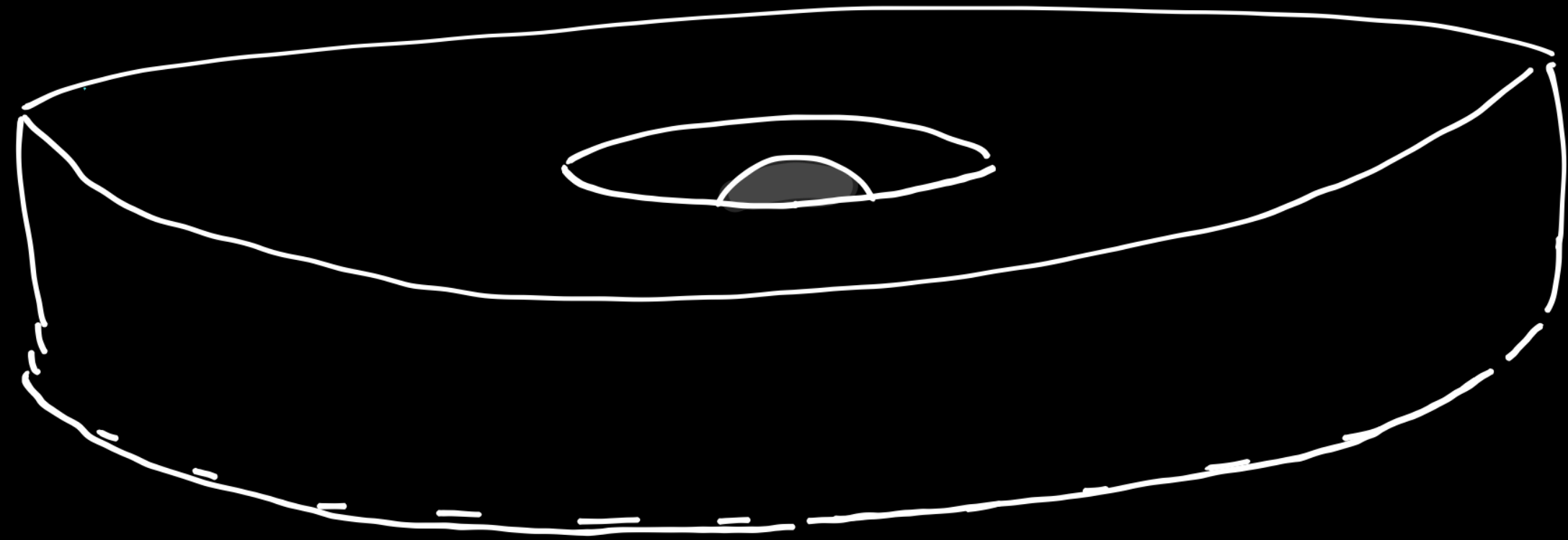
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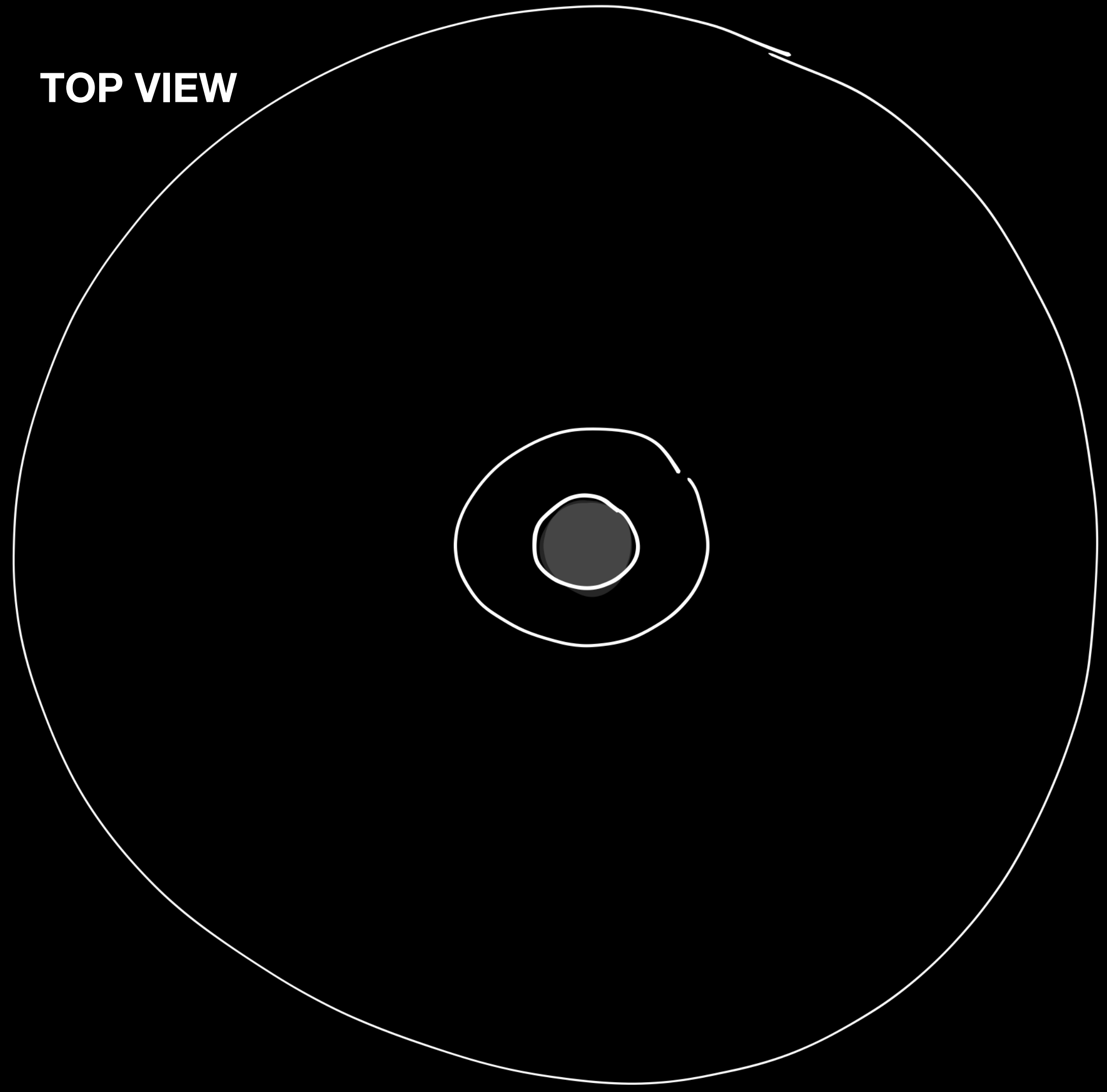
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SIDE VIEW

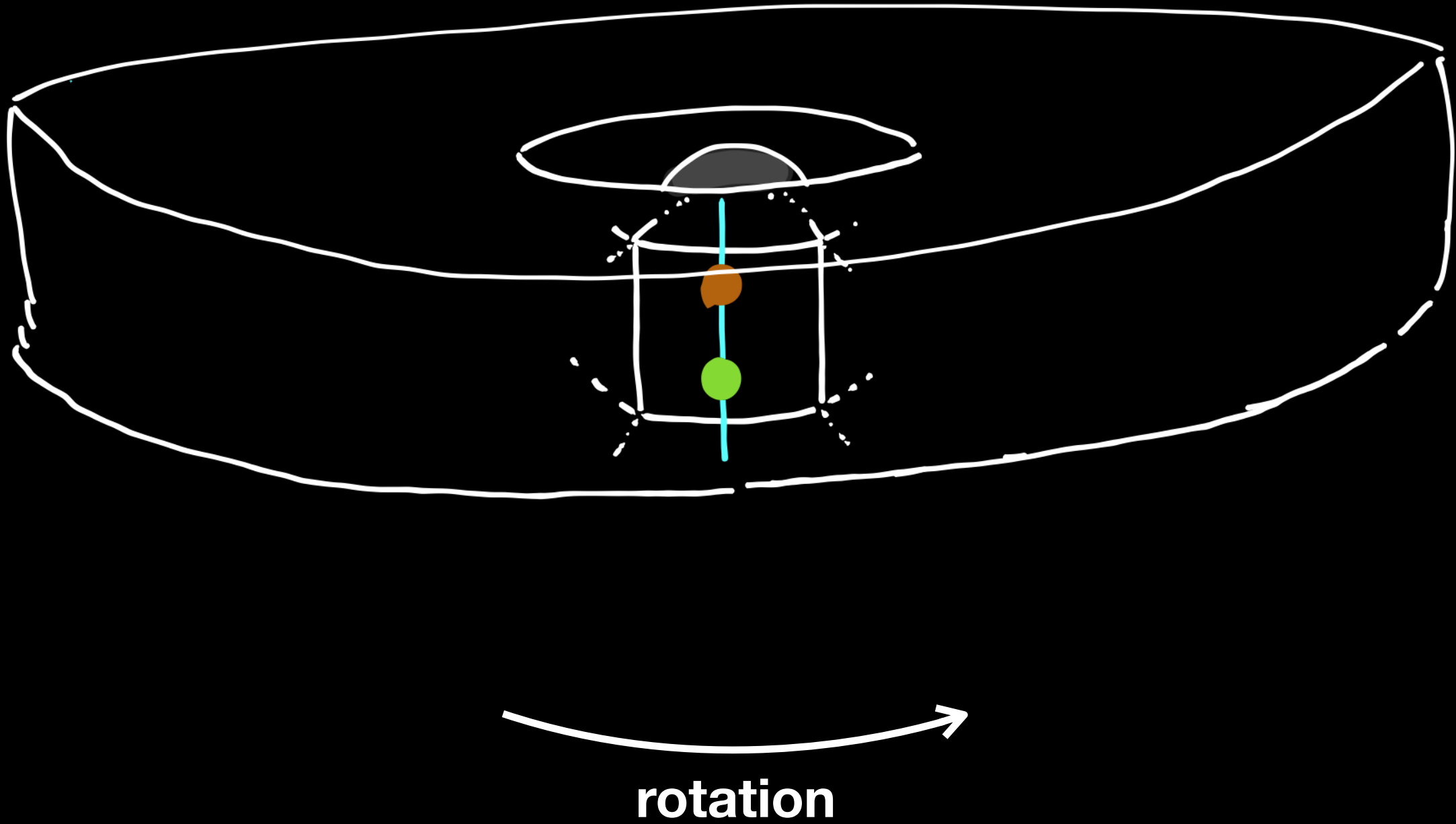


TOP VIEW

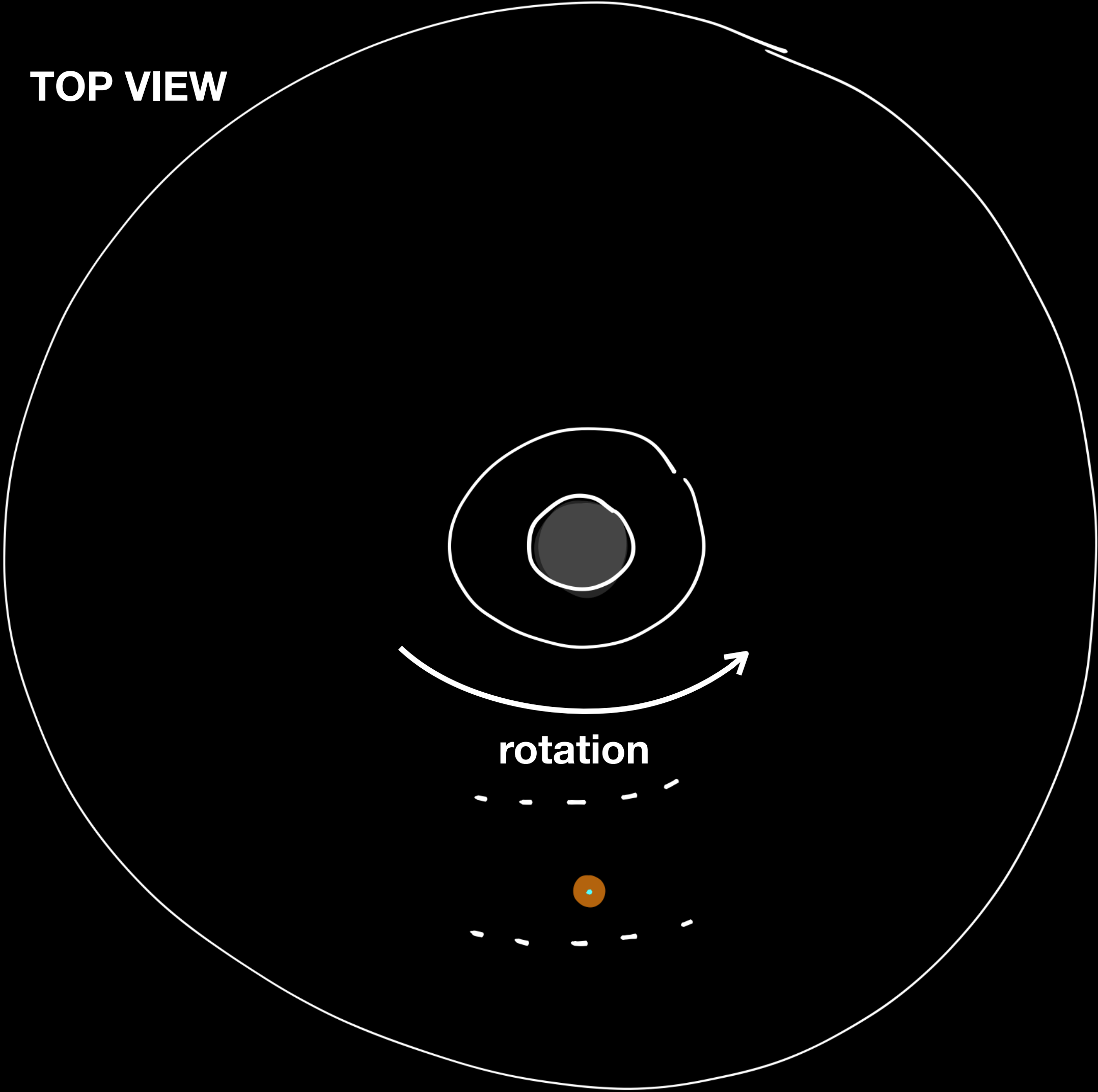


the Magneto-Rotational Instability

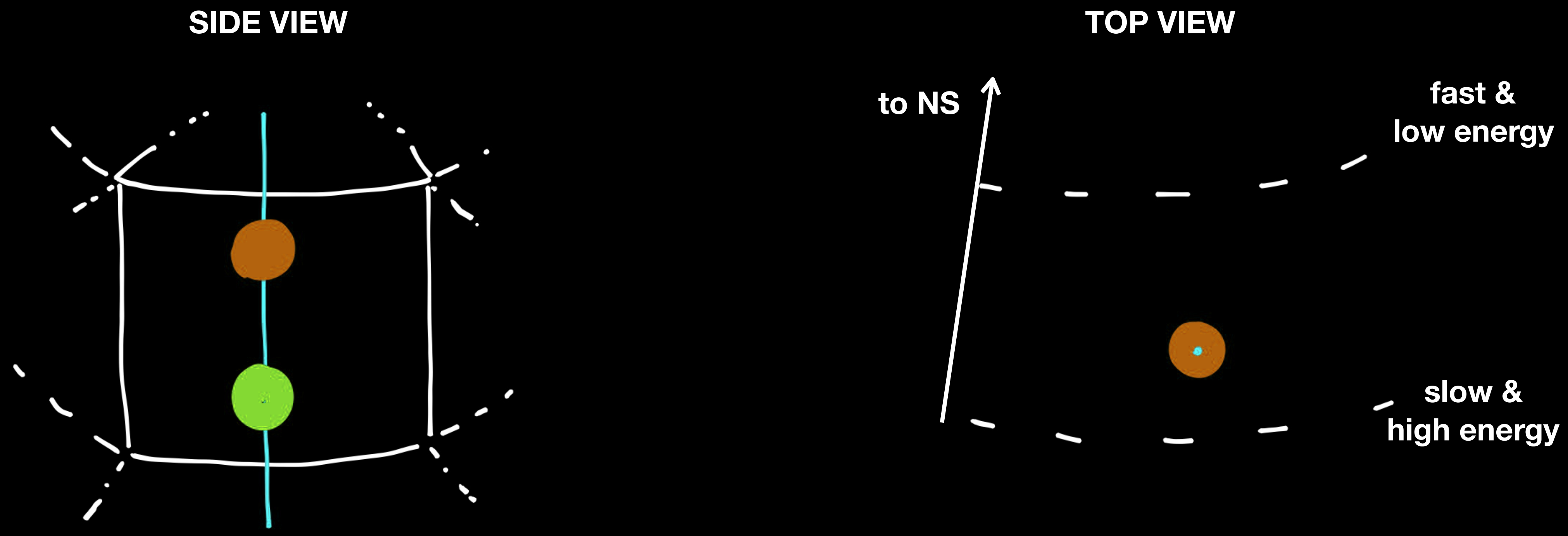
SIDE VIEW



TOP VIEW

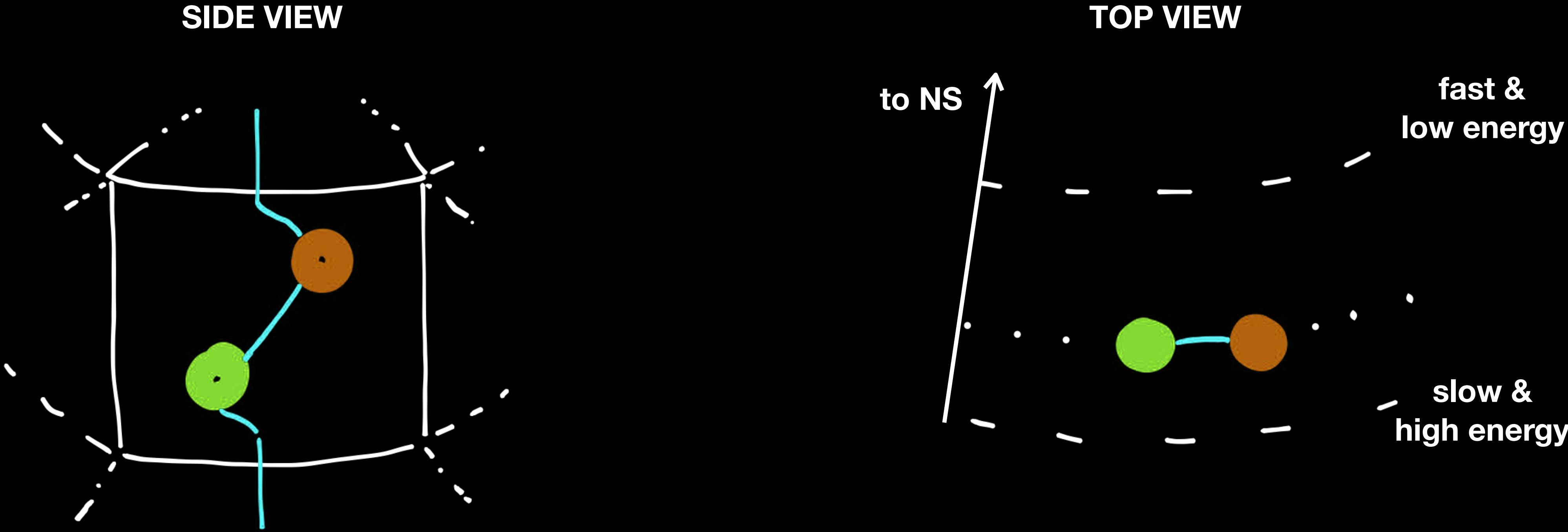


the Magneto-Rotational Instability



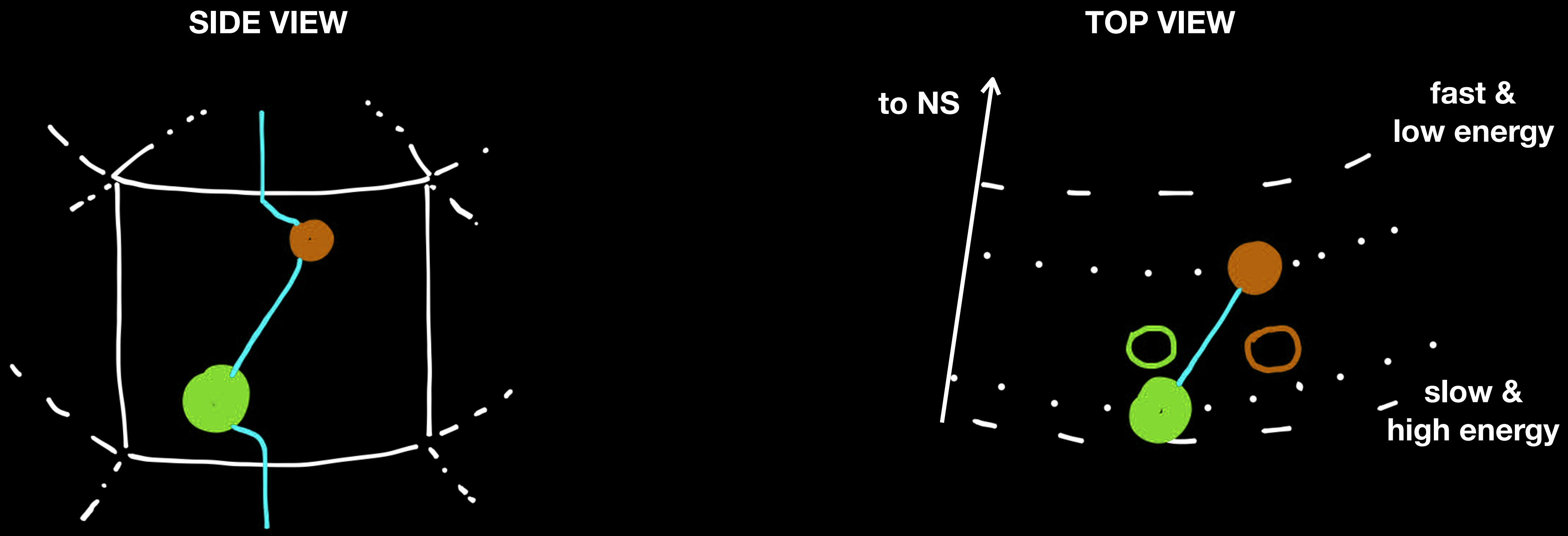
**weak
magnetic
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the Magneto-Rotational Instability



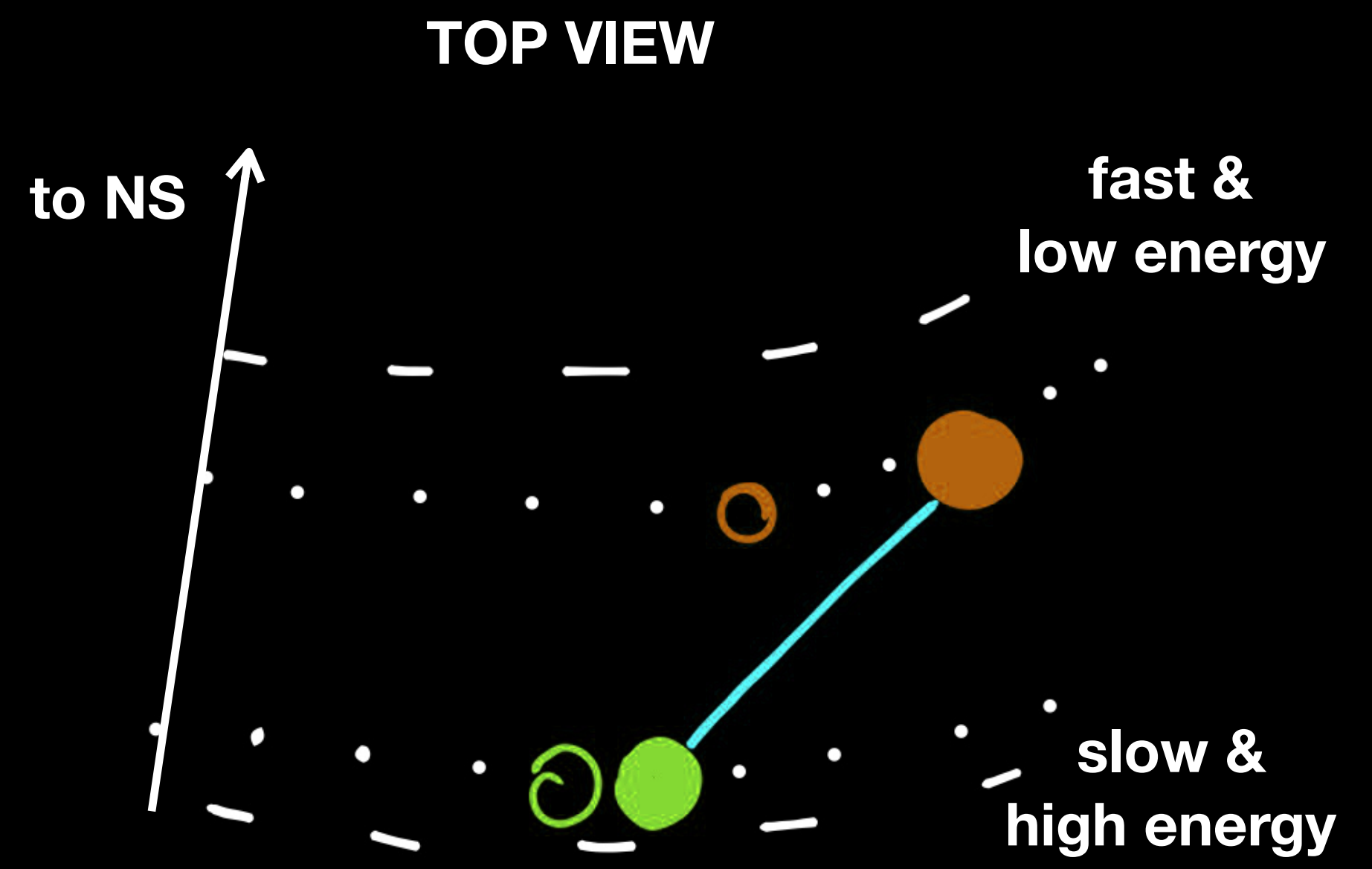
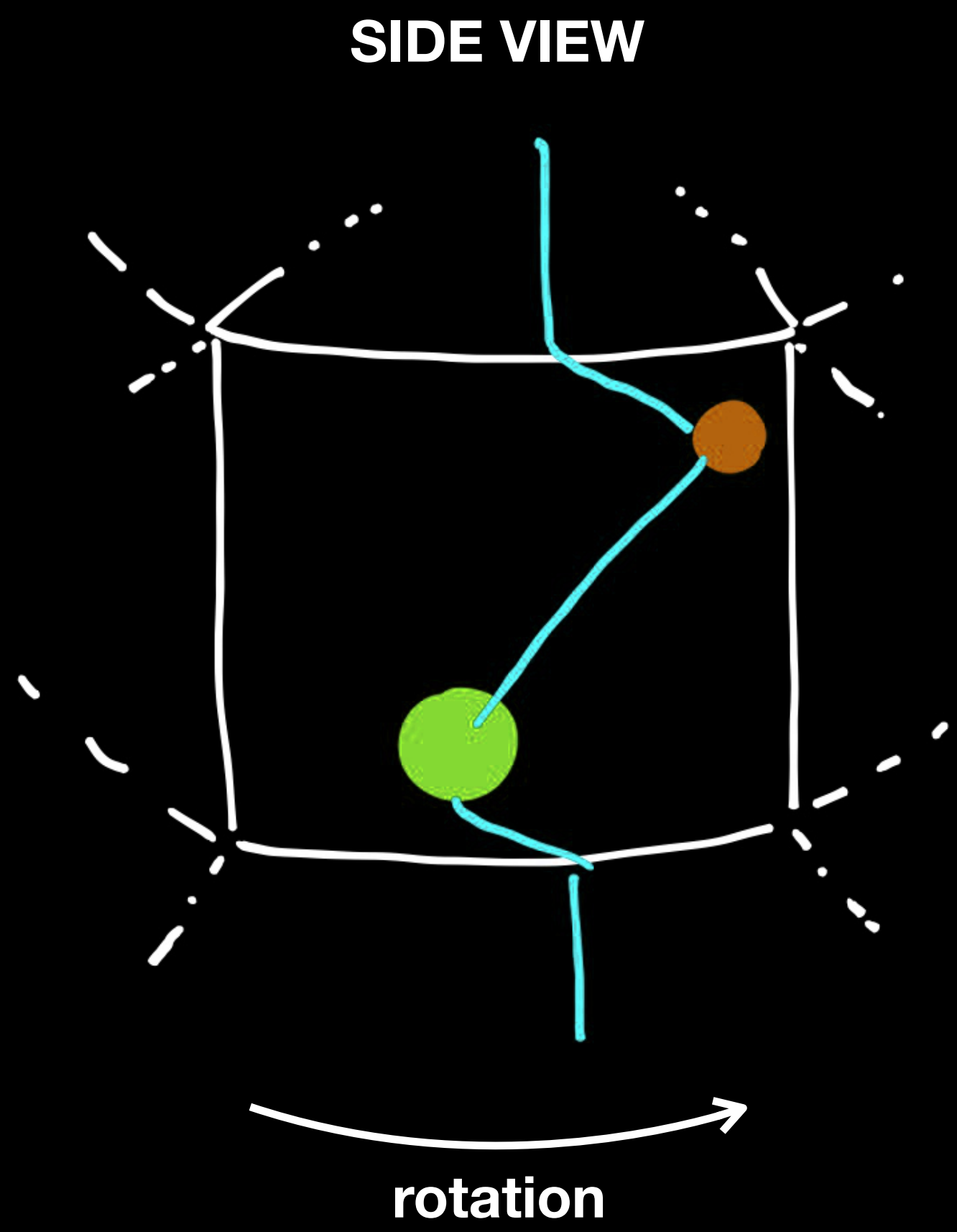
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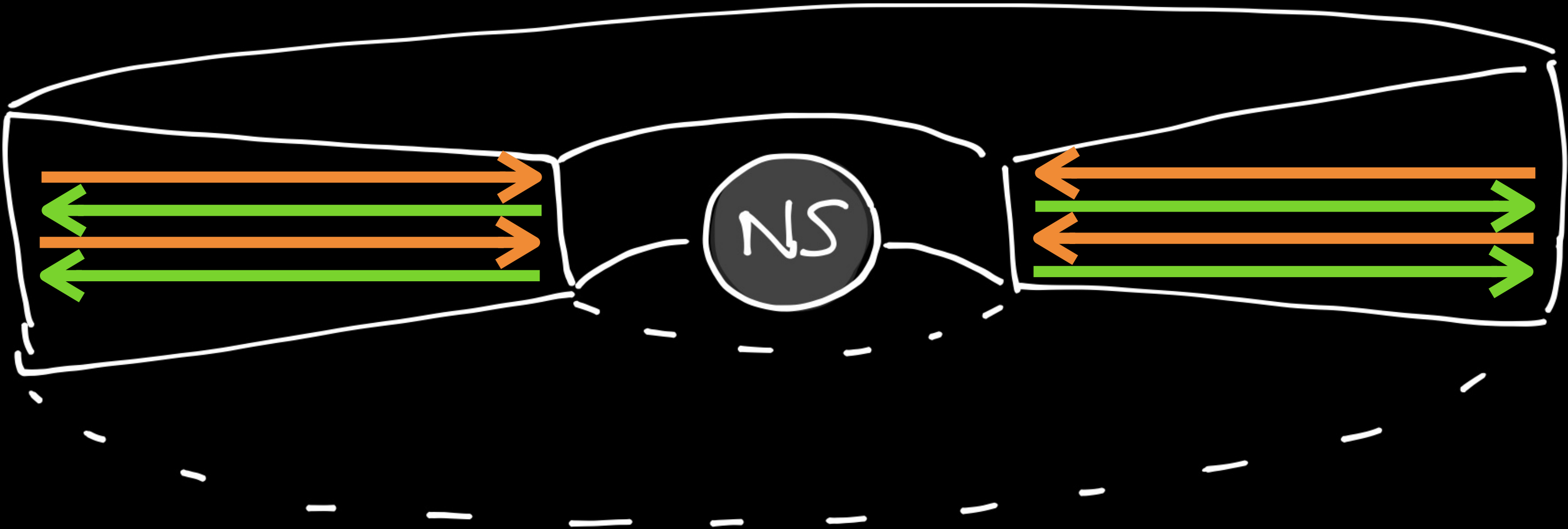
**weak
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the Magneto-Rotational Instability



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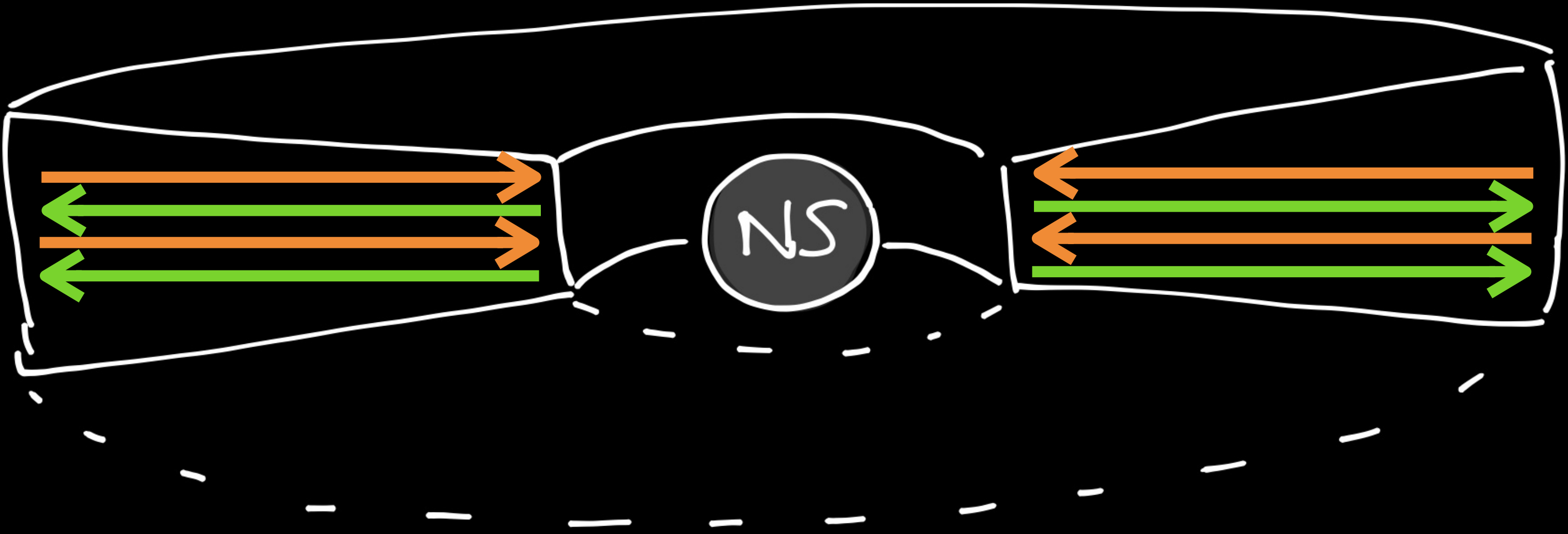


initial \vec{B} (purely poloidal)

final \vec{B} (poloidal piece)

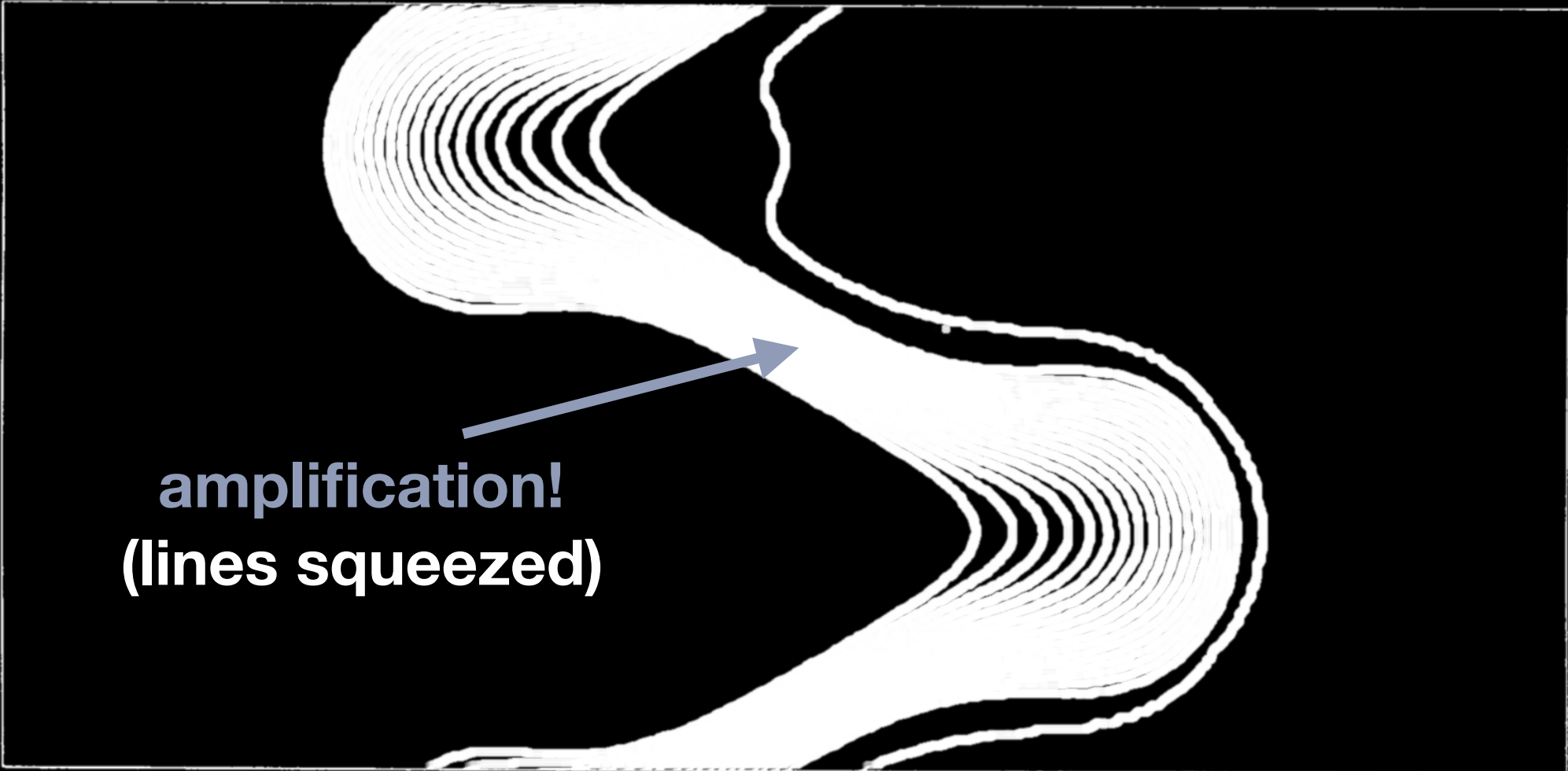
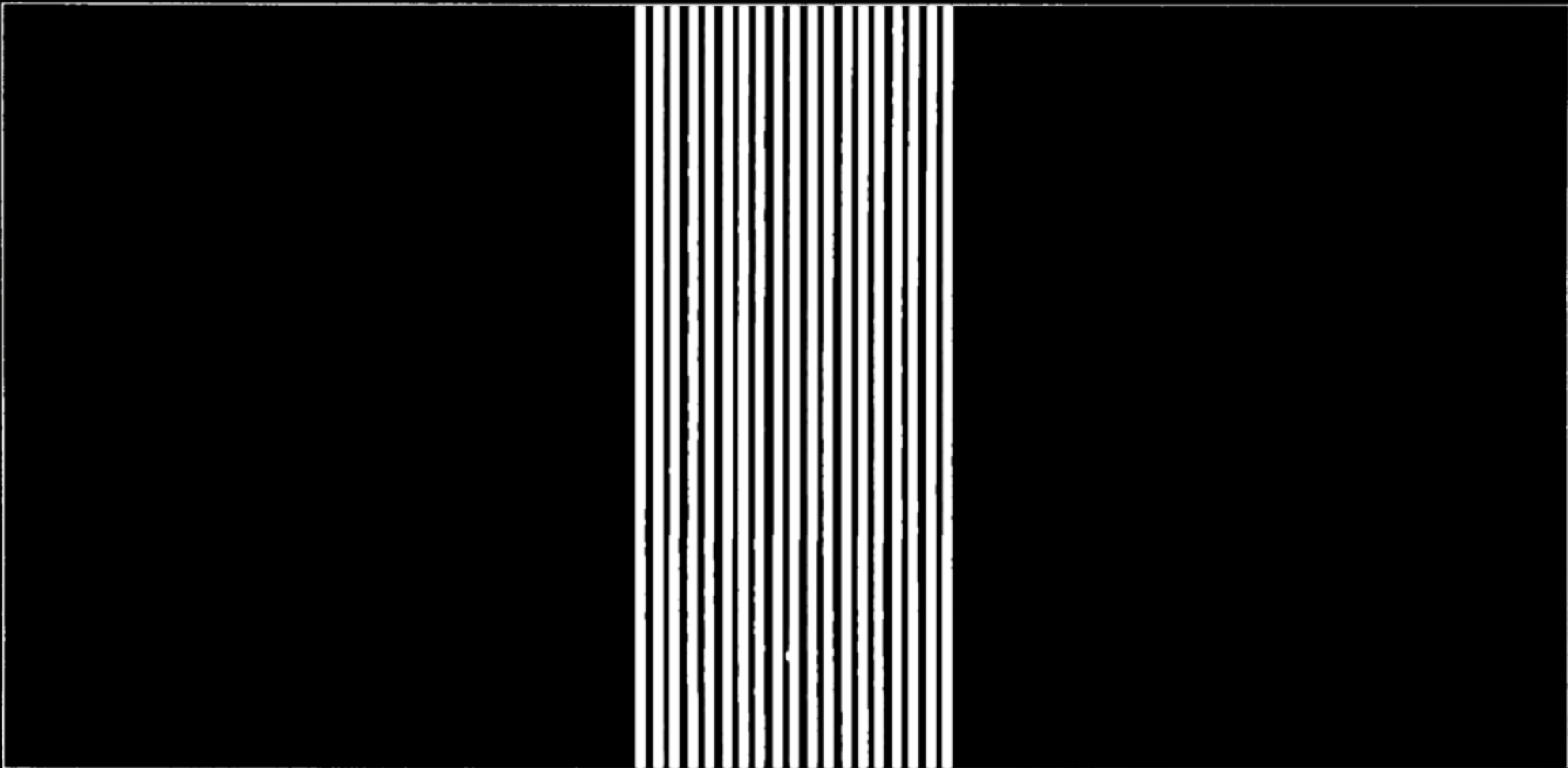
amplification!
(lines squeezed)

the Magneto-Rotational Instability



initial \vec{B} (purely poloidal)

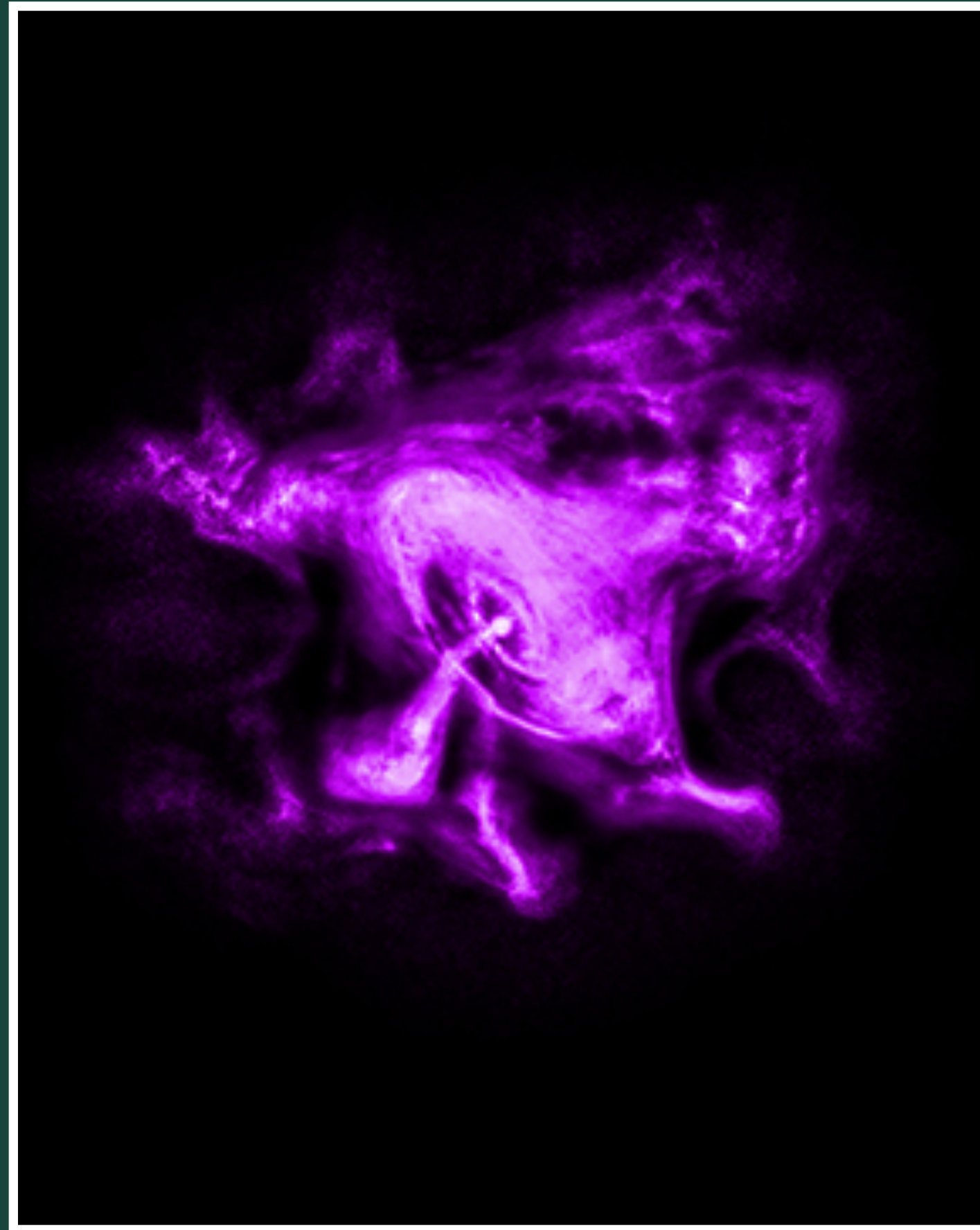
final \vec{B} (poloidal piece)



implementing high-order magnetohydrodynamics to explore jets in stellar explosions



the cool things
I'm a part of



making jets in a
supernova



high-order magnetorotational
hydrodynamics with SparkJoy



resolution issue: modes start small

$$\frac{\partial}{\partial t} \begin{bmatrix} \rho \\ \rho \mathbf{u} \\ \mathcal{E} \\ \mathbf{B} \end{bmatrix} + \nabla \cdot \begin{bmatrix} \rho \mathbf{u} \\ \rho \mathbf{u} \mathbf{u} + \left(p + \frac{1}{2} \|\mathbf{B}\|^2 \right) \mathbb{I} - \mathbf{B} \mathbf{B} \\ \mathbf{u} \left(\mathcal{E} + p + \frac{1}{2} \|\mathbf{B}\|^2 \right) - \mathbf{B} (\mathbf{u} \cdot \mathbf{B}) \\ \mathbf{u} \mathbf{B} - \mathbf{B} \mathbf{u} \end{bmatrix} = 0,$$

$$\nabla \cdot \mathbf{B} = 0,$$



$$p = (\gamma - 1) \left(\mathcal{E} - \frac{1}{2} \|\mathbf{B}\|^2 - \frac{1}{2} \rho \|\mathbf{u}\|^2 \right),$$



resolution issue: modes start small

e.g., Obergaulinger+ 2009

$$\frac{\partial}{\partial t} \begin{bmatrix} \rho \\ \rho \mathbf{u} \\ \mathcal{E} \\ \mathbf{B} \end{bmatrix} + \nabla \cdot \begin{bmatrix} \rho \mathbf{u} \\ \rho \mathbf{u} \mathbf{u} + \left(p + \frac{1}{2} \|\mathbf{B}\|^2 \right) \mathbb{I} - \mathbf{B} \mathbf{B} \\ \mathbf{u} \left(\mathcal{E} + p + \frac{1}{2} \|\mathbf{B}\|^2 \right) - \mathbf{B} (\mathbf{u} \cdot \mathbf{B}) \\ \mathbf{u} \mathbf{B} - \mathbf{B} \mathbf{u} \end{bmatrix} = \begin{bmatrix} 0 \\ \rho \nabla \Phi \\ \rho \mathbf{v} \cdot \nabla \Phi \\ 0 \end{bmatrix}$$

$$\nabla \cdot \mathbf{B} = 0,$$

Ω : rotation profile (3D)
 N : buoyancy (Brunt-Väisälä frequency)
 R : differential rotation term

equatorial:

$$\mathbf{C} = (\mathbf{N}^2 + \mathbf{R}) / \Omega^2 < 0$$
 unstable

scale of fastest growing mode:

$$\lambda_{\text{FGM}} \sim |\vec{v}_A| [-(\mathbf{N}^2 + \mathbf{R})]^{-1/2}$$

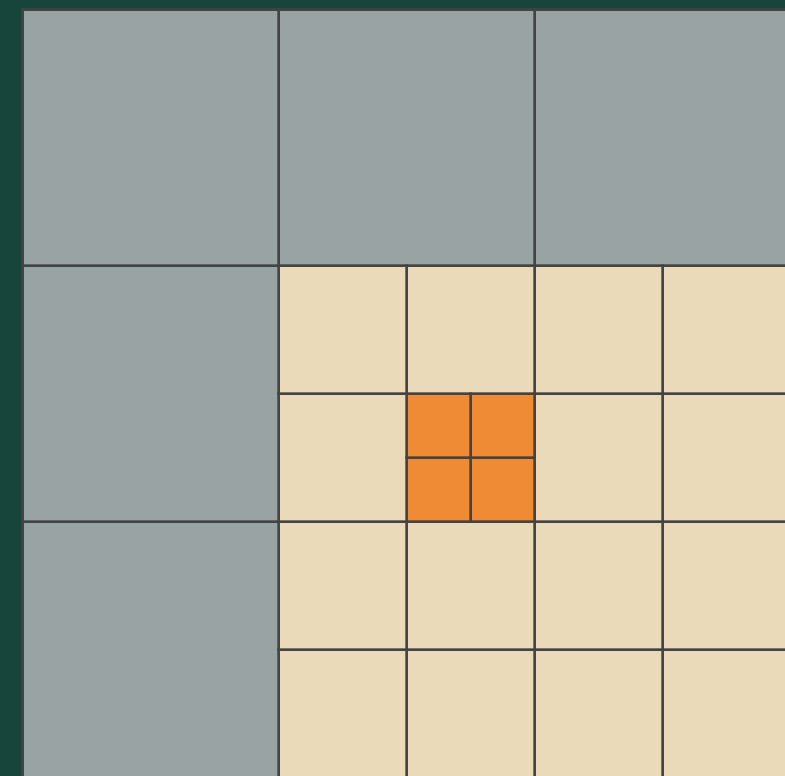
$$p = (\gamma - 1) \left(\mathcal{E} - \frac{1}{2} \|\mathbf{B}\|^2 - \frac{1}{2} \rho \|\mathbf{u}\|^2 \right),$$

$$\lambda_{\text{FGM}} \sim 6.9 \text{ km} \left(\frac{b}{10^{15} \text{ G}} \right) \left(\frac{\rho}{2.5 \cdot 10^{13} \text{ g cm}^{-3}} \right)^{-1/2} \left(\frac{\Omega}{1900 \text{ s}^{-1}} \right)^{-1}$$

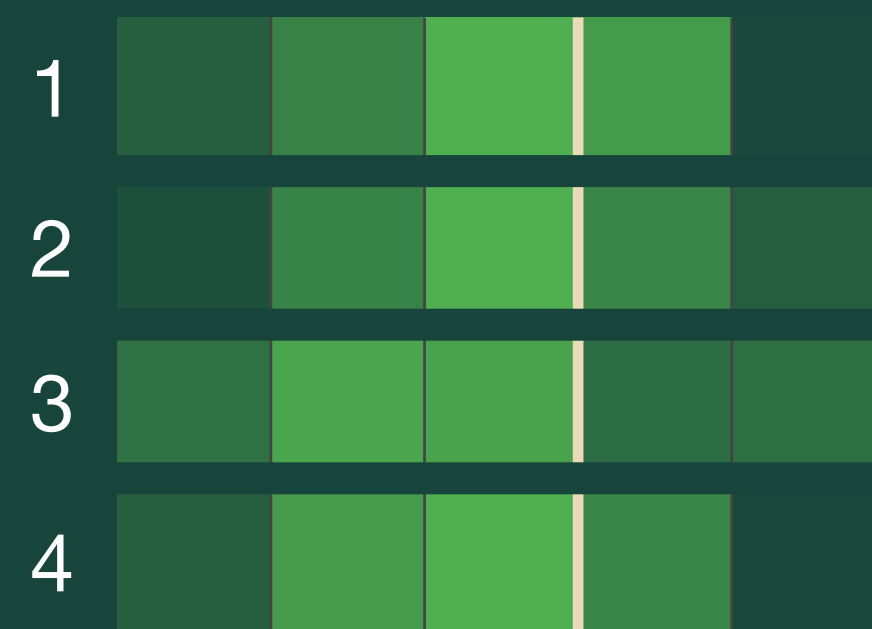
growth time ~ 10 ms



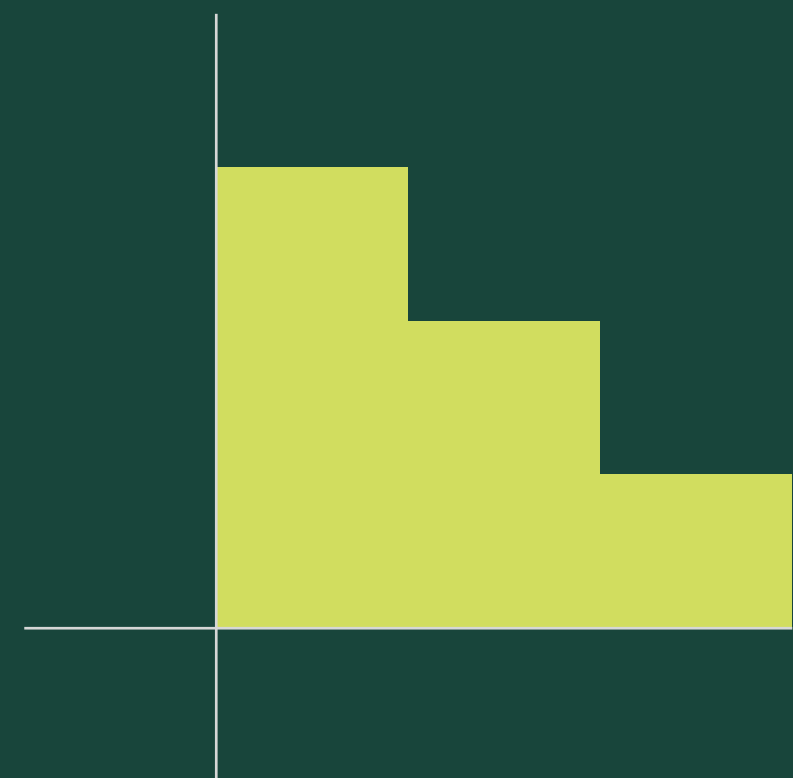
MHD in FLASH with Spark



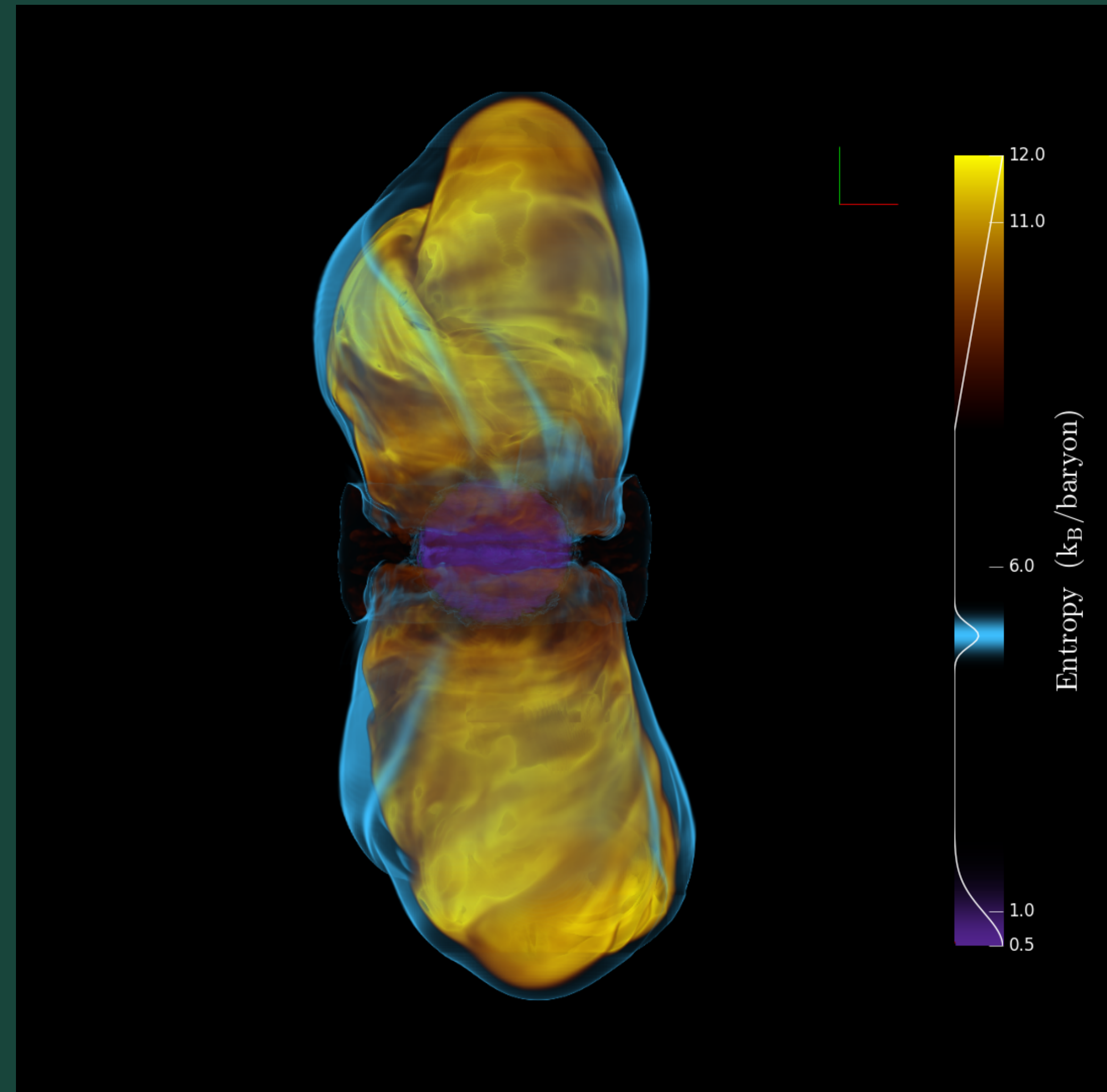
FLASH - AMReX



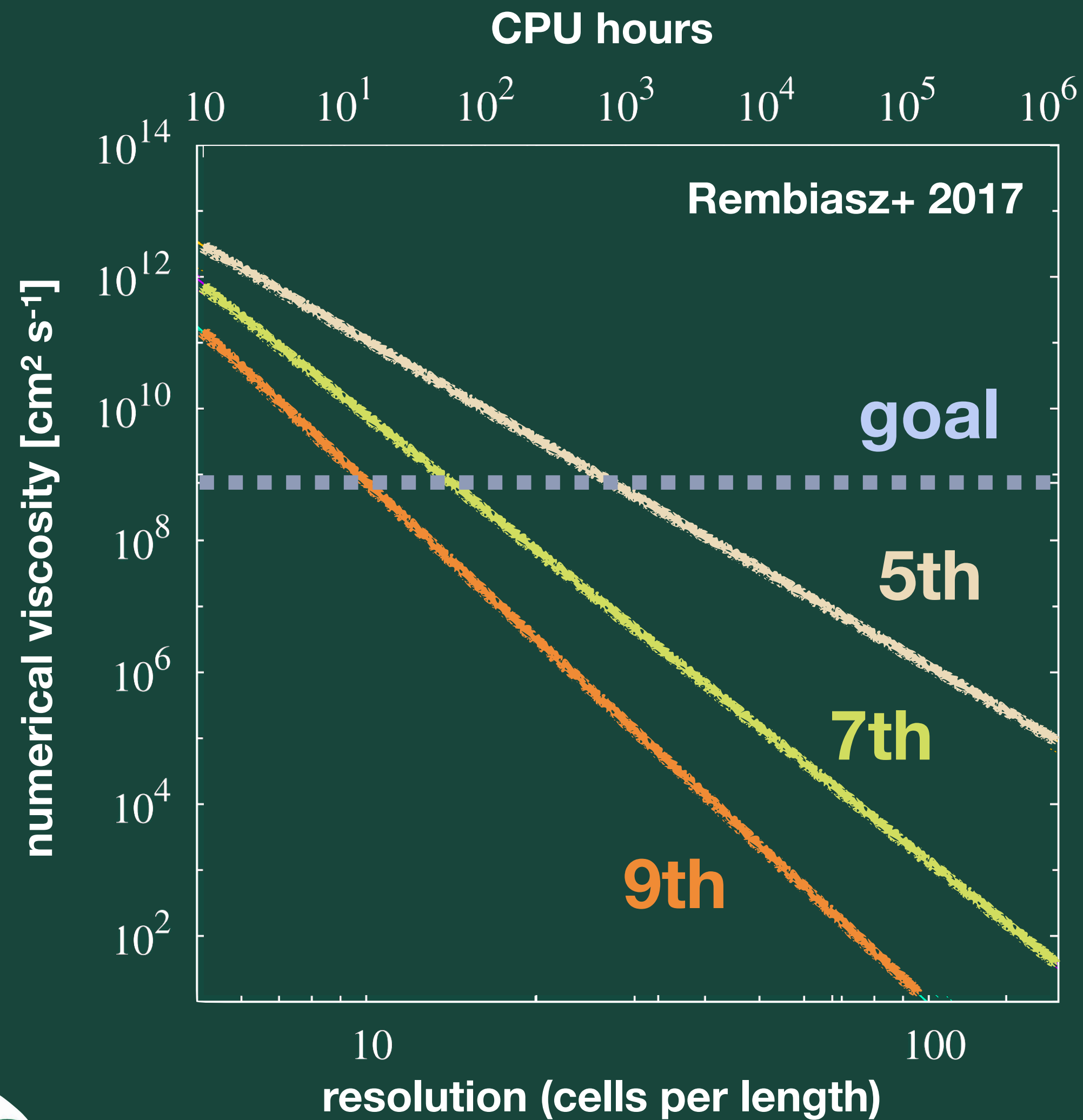
WENO reconstruction



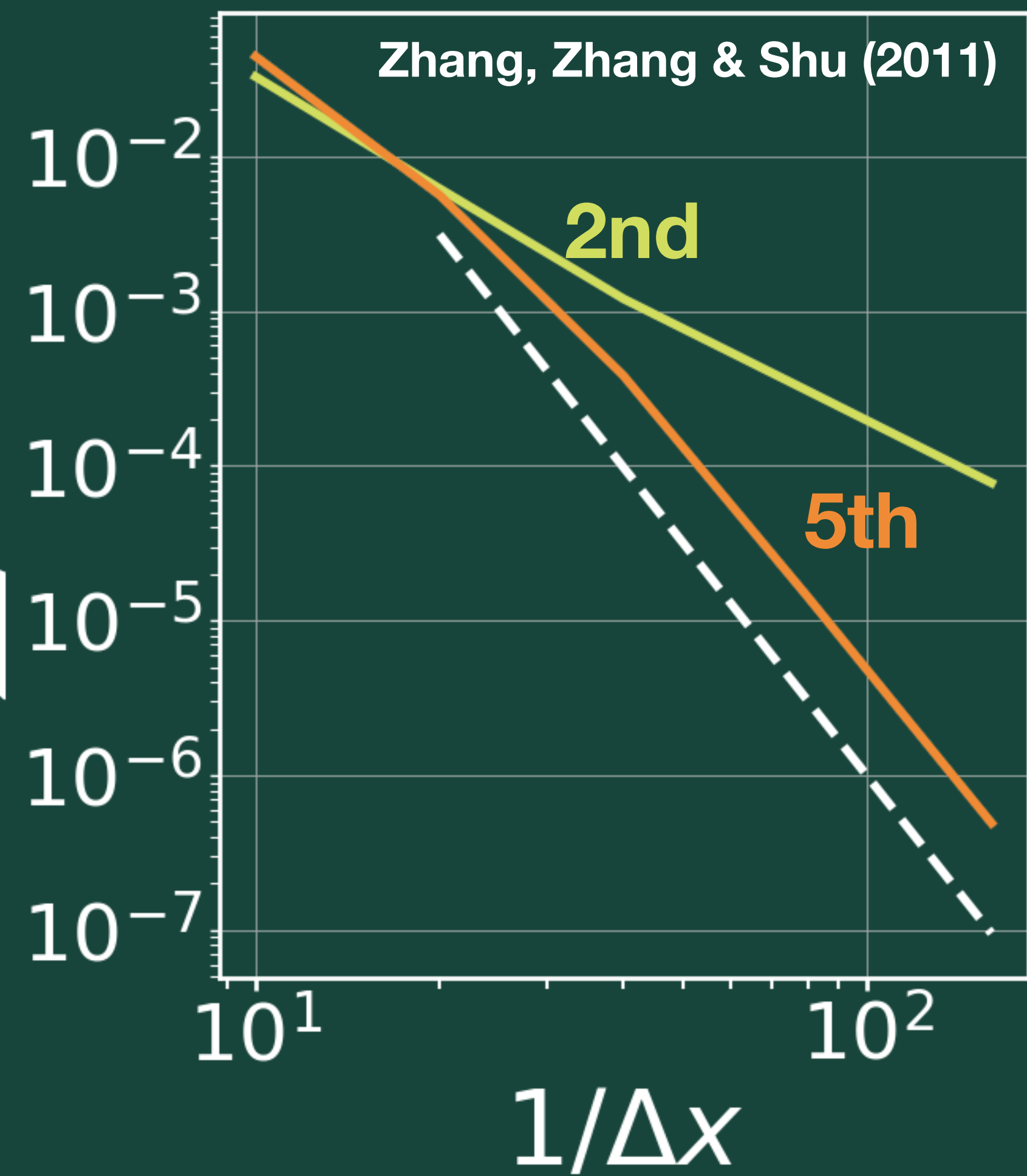
explicit Runge-Kutta



SparkJoy: high order version of Spark

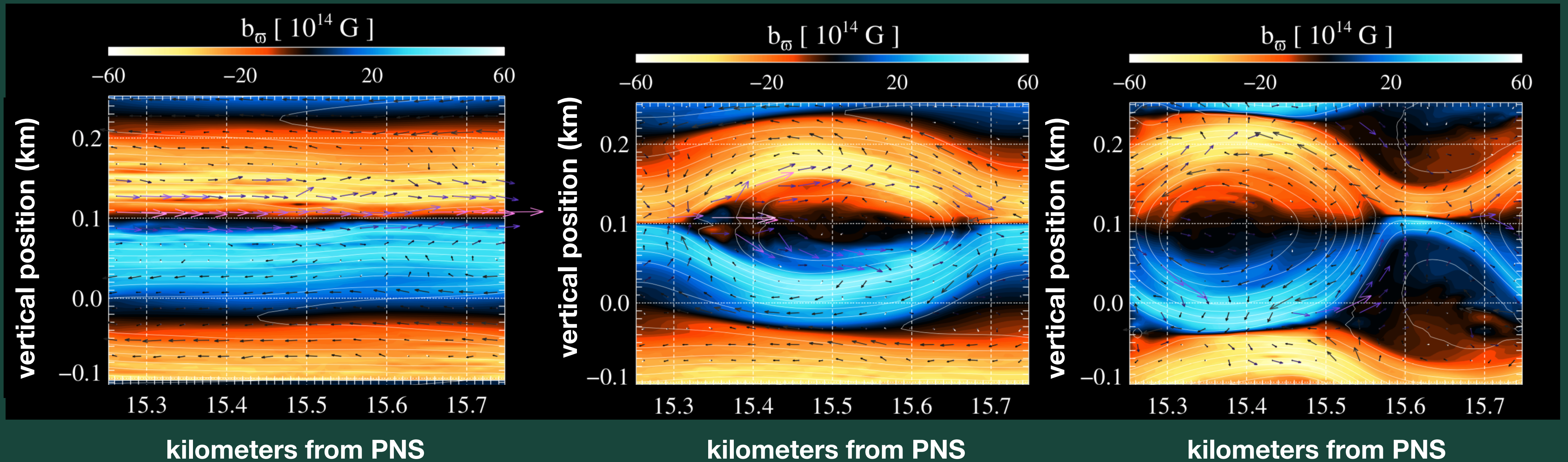


$$L_1 = \sum |y_i - y(x_i)|$$



numerical resistivity creates turbulence

Obergaulinger+ 2009

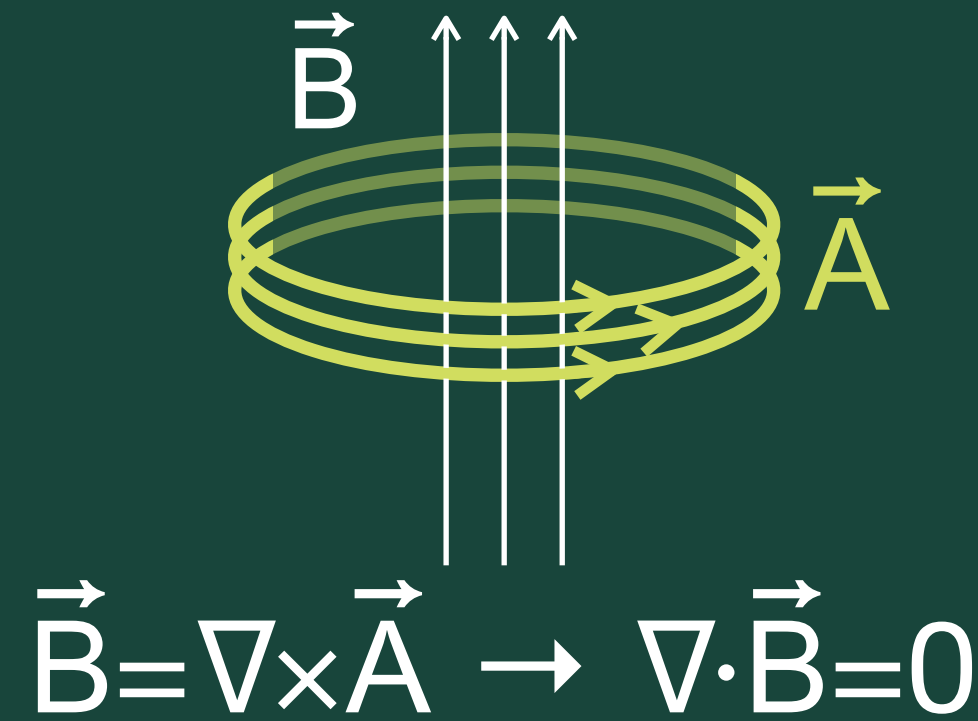


components of SparkJoy

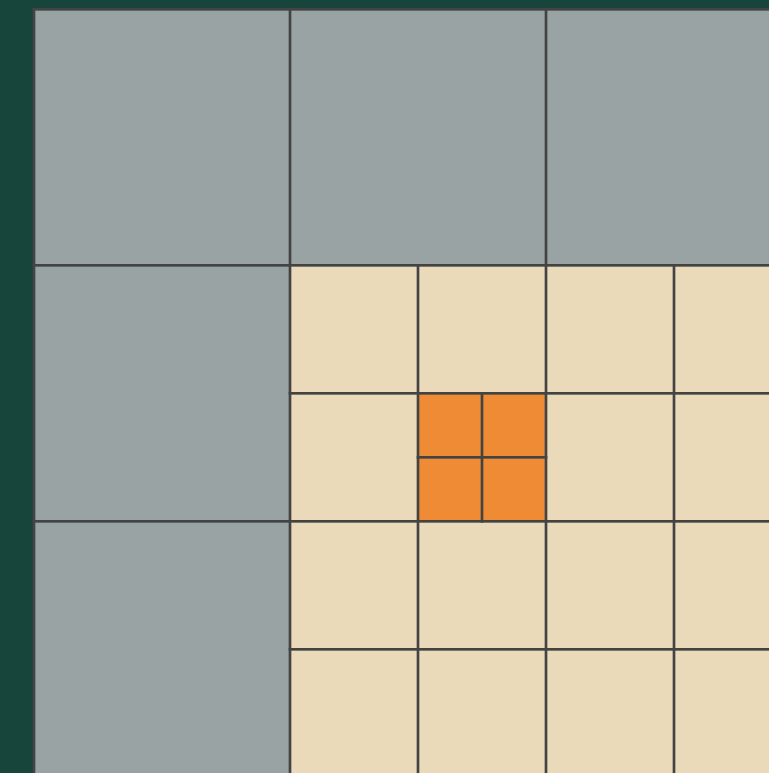
Helzel et al. (2013); Buchmuller et al. (2016)



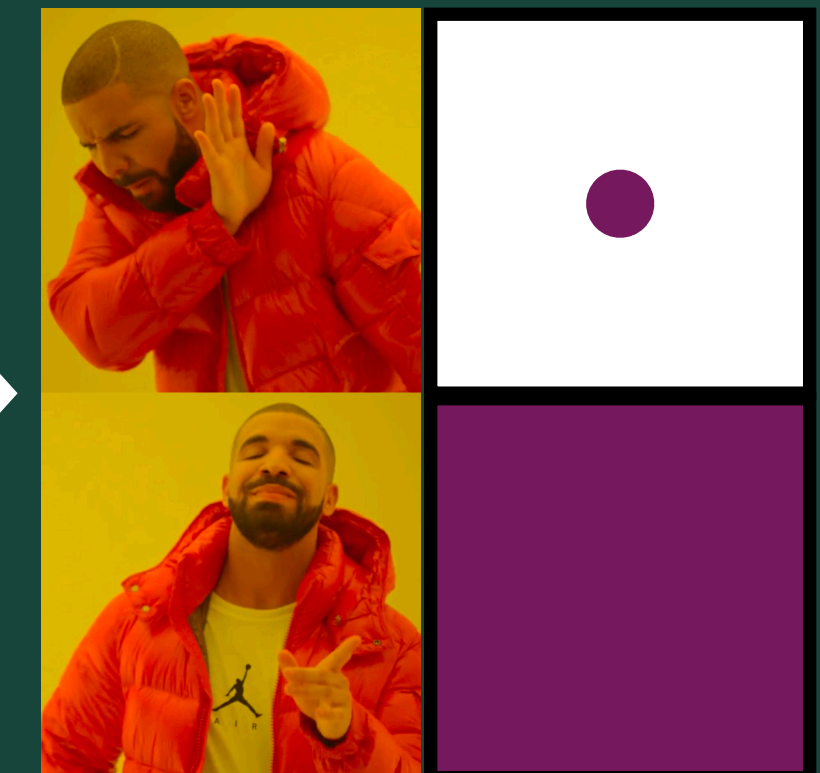
conserved variables



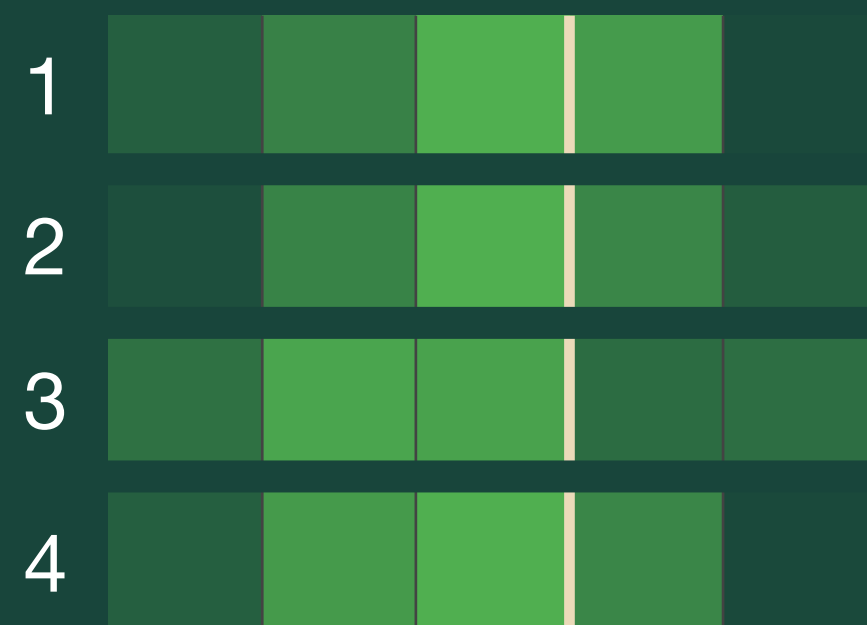
constrained transport



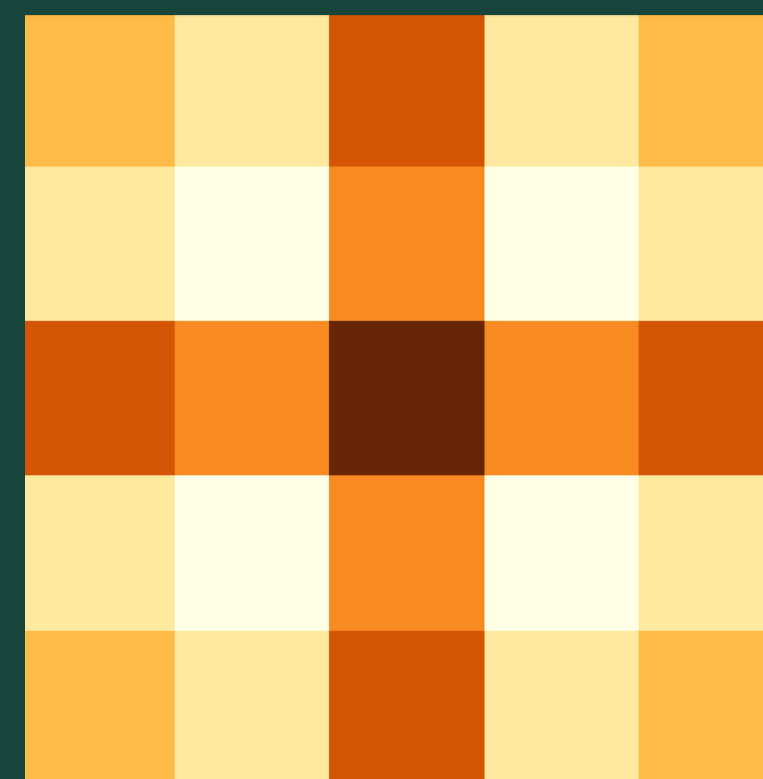
FLASH - AMReX



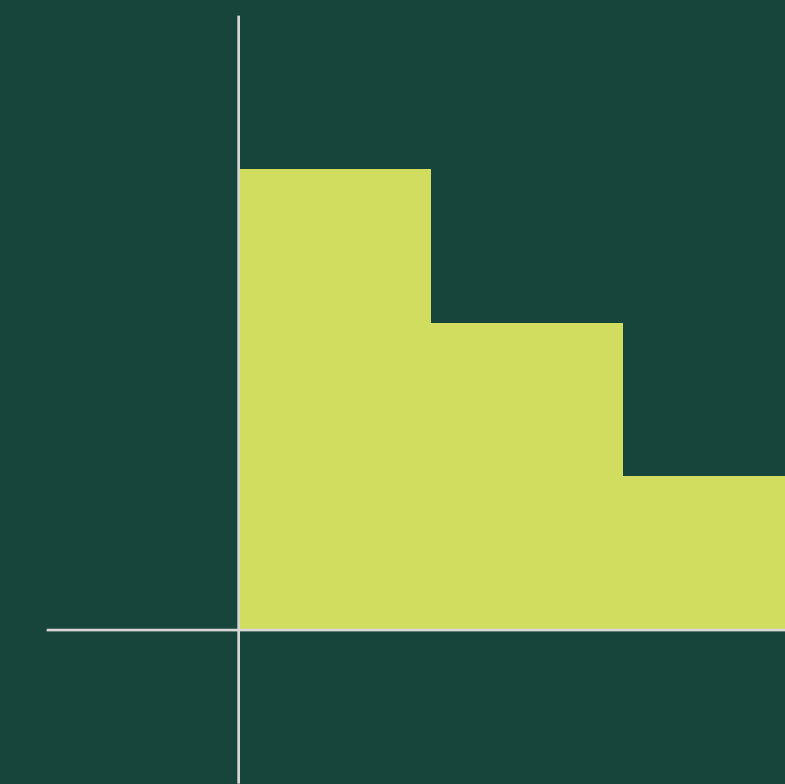
finite volume



WENO reconstruction



multi-D flux using neighbors



explicit Runge-Kutta



current status: talk-killer bug

```
Warning: Unused dummy argument 'xyz' at (1) [-Wunused-dummy-argument]
gr_xyzToBlock.F90:54:0:
    procID=proc
Warning: 'proc' is used uninitialized in this function [-Wuninitialized]
gr_xyzToBlock.F90:55:0:
    blkID=blk
Warning: 'blk' is used uninitialized in this function [-Wuninitialized]
/opt/software/OpenMPI/2.1.2-GCC-6.4.0-2.28/bin/mpif90 -gdb -c -O -fdefault-real-8 -fdefault-double-8 -pedantic -Wall -Waliasing -Wsurprising -Wconversion -
=invalid,zero,overflow -fbounds-check -fimplicit-none -fstack-protector-all -ffree-line-length-none -I /opt/software/HDF5/1.8.20-foss-2018a/include -DH5_USE_
1000 -DNXB=20 -DNYB=20 -DNZB=1 -DN_DIM=2 hy_joy_getFaceFlux.F90
hy_joy_getFaceFlux.F90:158:15:
    maxBlkSize = MAXVAL(blkPhysSize)
Warning: Possible change of value in conversion from REAL(8) to INTEGER(4) at (1) [-Wconversion]
prim2flx.F90:39:15:
    real :: E,B2,UB,Ptot
Warning: Unused variable 'b2' declared at (1) [-Wunused-variable]
prim2flx.F90:26:6:
    use Hydro_data, ONLY : hy_C_hyp
Warning: Unused module variable 'hy_c_hyp' which has been explicitly imported at (1) [-Wunused-variable]
prim2flx.F90:39:18:
    real :: E,B2,UB,Ptot
Warning: Unused variable 'ub' decla
riemann.F90:84:16:
    real :: Bn_glm, Psi_glm
Warning: Unused variable 'bn_glm' c
riemann.F90:78:37:
    real :: BxStar,ByStar,BzStar,Bn
gr_xyzToBlock.F90:55:0:
Warning: Unused variable 'bn_hll' c
riemann.F90:78:16:
    real :: BxStar,ByStar,BzStar,Bn
Warning: 'blk' is used uninitialized in this function [-Wuninitialized]
/opt/software/OpenMPI/2.1.2-GCC-6.4.0-2.28/bin/mpif90 -gdb -c -O -fdefault-real-8 -fdefault
=invalid,zero,overflow -fbounds-check -fimplicit-none -fstack-protector-all -ffree-line-lengt
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Warning: Unused variable 'b2' declared at (1) [-Wunused-variable]
prim2flx.F90:26:6:
    use Hydro_data, ONLY : hy_C_hyp
Warning: Unused module variable 'hy_c_hyp' which has been explicitly imported at (1) [-Wunuse
prim2flx.F90:39:18:
    real :: E,B2,UB,Ptot
Warning: Unused variable 'ub' declared at (1) [-Wunused-variable]
riemann.F90:84:16:
    real :: Bn_glm, Psi_glm
Warning: Unused variable 'bn_glm' declared at (1) [-Wunused-variable]
riemann.F90:78:37:
    real :: BxStar,ByStar,BzStar,Bn_hll,pStar,qStar
Warning: Unused variable 'bn_hll' declared at (1) [-Wunused-variable]
riemann.F90:78:16:
    real :: BxStar,ByStar,BzStar,Bn_hll,pStar,qStar
Warning: Unused variable 'bxstar' declared at (1) [-Wunused-variable]
riemann.F90:78:23:
    x subintervals = 1
    y subintervals = 1
Parameters computed :
ambient temperature = 1.2027221209764060E-008
ambient int. energy = 2.5000000000000000E+004
gas constant = 83144725.000000000
iteration, no. not moved = 0 0
refined: total leaf blocks = 49
refined: total blocks = 49
Finished with Grid_initDomain, no restart
Ready to call Hydro_init
Hydro initialized
Gravity initialized
Initial dt verified
*** Wrote checkpoint file to output07/isenvor_07_hdf5_chk_0000 ****
*** Wrote plotfile to output07/isenvor_07_hdf5_plt_cnt_0000 ****
Initial plotfile written
Driver init all done
*** Wrote plotfile to output07/isenvor_07_hdf5_plt_cnt_0001 ****
    n      t      dt (      x,      y,      z) | dt_hydro
    1 1.0000E-03 2.0000E-03 ( 5.036E+00, 4.607E+00, 0.000E+00) | 1.664E-02
*** Wrote checkpoint file to output07/isenvor_07_hdf5_chk_0001 ****
*** Wrote plotfile to output07/isenvor_07_hdf5_plt_cnt_0002 ****
    2 3.0000E-03 4.0000E-03 ( 5.036E+00, 4.607E+00, 0.000E+00) | 1.664E-02
*** Wrote checkpoint file to output07/isenvor_07_hdf5_chk_0002 ****
*** Wrote plotfile to output07/isenvor_07_hdf5_plt_cnt_0003 ****
    3 7.0000E-03 8.0000E-03 ( 5.321E+00, 4.821E+00, 0.000E+00) | 1.663E-02
*** Wrote checkpoint file to output07/isenvor_07_hdf5_chk_0003 ****
*** Wrote plotfile to output07/isenvor_07_hdf5_plt_cnt_0004 ****
    4 1.5000E-02 1.5248E-02 ( 4.893E+00, 4.607E+00, 0.000E+00) | 1.525E-02
*** Wrote checkpoint file to output07/isenvor_07_hdf5_chk_0004 ****
*** Wrote plotfile to output07/isenvor_07_hdf5_plt_cnt_0005 ****
    5 3.0248E-02 1.3382E-02 ( 5.536E+00, 4.893E+00, 0.000E+00) | 1.338E-02
*** Wrote checkpoint file to output07/isenvor_07_hdf5_chk_0005 ****
*** Wrote plotfile to output07/isenvor_07_hdf5_plt_cnt_0006 ****
    6 4.3630E-02 1.3250E-02 ( 4.893E+00, 4.679E+00, 0.000E+00) | 1.325E-02
*** Wrote checkpoint file to output07/isenvor_07_hdf5_chk_0006 ****
*** Wrote plotfile to output07/isenvor_07_hdf5_plt_cnt_0007 ****
    7 5.6880E-02 1.2612E-02 ( 5.393E+00, 4.679E+00, 0.000E+00) | 1.261E-02
*** Wrote checkpoint file to output07/isenvor_07_hdf5_chk_0007 ****
Program received signal SIGFPE, Arithmetic exception.
0x000000000064f7f7 in reconstruct (uplus=..., uminus=..., dataId=..., flat=1, sizeId=40, ind=31, dx=0.071428571428571425) at reconstruct.F90:88
88      Alpha5(:,1) = coeff2p(1) * (1.+(abs(betaWeno(:,1))-betaWeno(:,3))/(betaWeno(:,1)+epsilon))**2)
Missing separate debuginfos, use: debuginfo-install glibc-2.17-260.el7_6.3.x86_64 hwloc-libs-1.11.2-2.el7.x86_64 libibumad-43.1.1.MLNX20180612.87b4d9b-0.1.45101.x86_64 libibverbs
-41mlnx1-OFED.4.5.0.1.0.45101.x86_64 libmlx4-41mlnx1-OFED.4.5.0.0.3.45101.x86_64 libmlx5-41mlnx1-OFED.4.5.0.3.8.45101.x86_64 libnl3-3.2.28-4.el7.x86_64 librx-41mlnx1-OFED.4.4.2.
4.6.45101.x86_64 libtool-ltdl-2.4.2-22.el7_3.x86_64 numactl-libs-2.0.9-7.el7.x86_64 opensm-libs-5.3.0.MLNX20181108.33944a2-0.1.45101.x86_64
```



print *, SELF

```
Warning: Unused dummy argument 'xyz' at (1) [-Wunused-dummy-argument]
gr_xyzToBlock.F90:54:0:
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Warning: 'proc' is used uninitialized in this function [-Wuninitialized]
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prim2flx.F90:39:18:
  real :: E,B2,UB,Ptot
Warning: Unused variable 'ub' declared at (1) [-Wunused-variable]
riemann.F90:84:16:
  real :: Bn_glm, Psi_glm
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riemann.F90:78:37:
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Warning: Unused variable 'bn_hll' declared at (1) [-Wunused-variable]
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Warning: Unused variable 'bxstar' declared at (1) [-Wunused-variable]
riemann.F90:78:23:
```

```
x subintervals   =      1
y subintervals   =      1
Parameters computed:
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ambient int. energy = 2.500000000000000004
gas constant       = 83144725.0000000000
iteration, no. not moved =      0      0
refined: total leaf blocks =      49
refined: total blocks =      49
Finished with Grid_initDomain, no restart
Ready to call Hydro_init
Hydro initialized
Gravity initialized
Initial dt verified
*** Wrote checkpoint file to output07/isenvor_07_hdf5_chk_0000 ****
*** Wrote last file to output07/isenvor_07_hdf5_chk_0000 ****
Initia
Drive
*** W
*** W
*** W
*** W
Program
0x0000
88
Missing
-41mln
4.6.45
```

```
ibibverbs
ED.4.4.2.
```

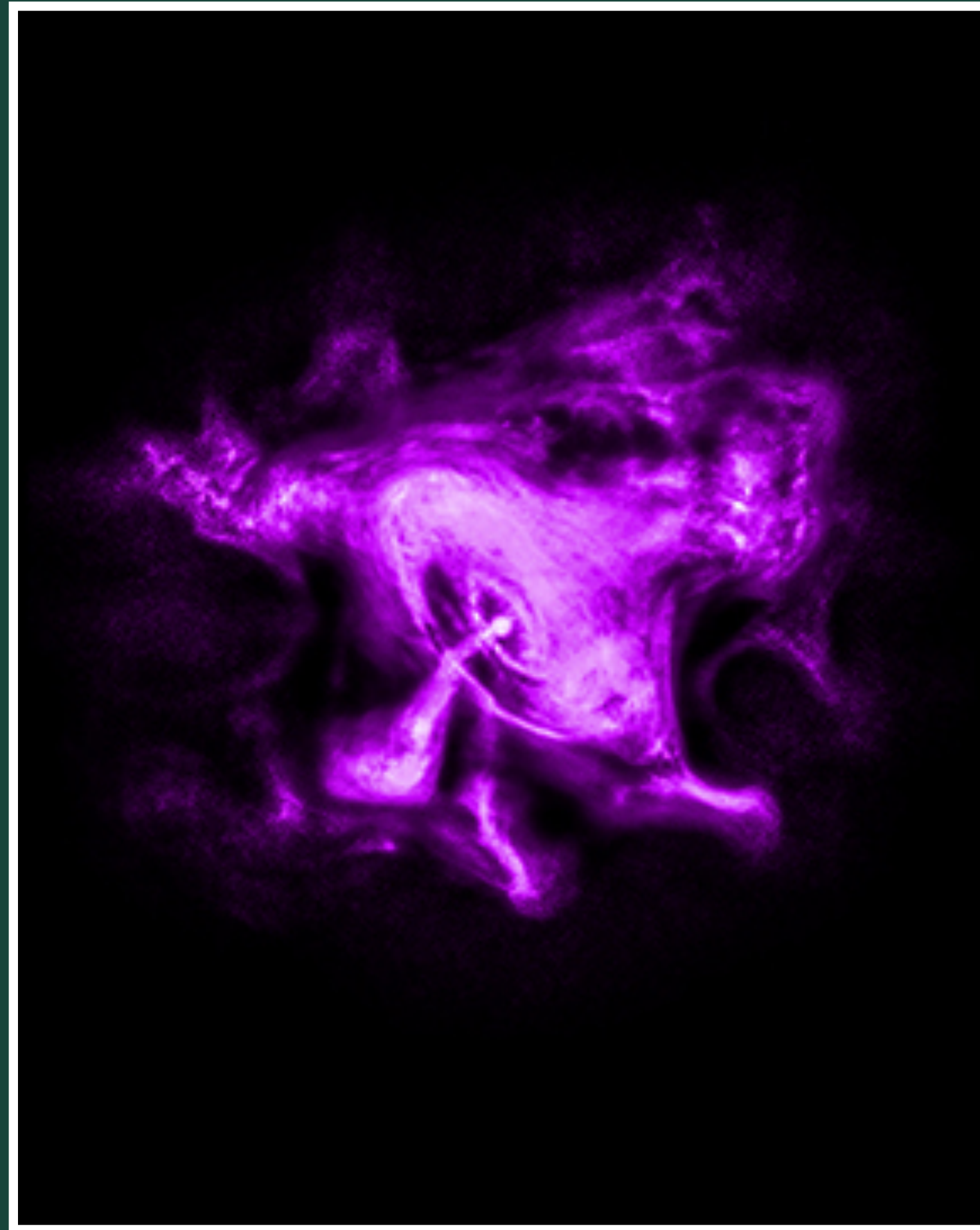
prolonged stress
+ devaluation of human interactions
+ criticism over validation
+ work/self blur (i.e. creative)
= terrible for mental health



implementing high-order magnetohydrodynamics to explore jets in stellar explosions



the cool things
I'm a part of



making jets in a
supernova



high-order magnetorotational
hydrodynamics with SparkJoy

