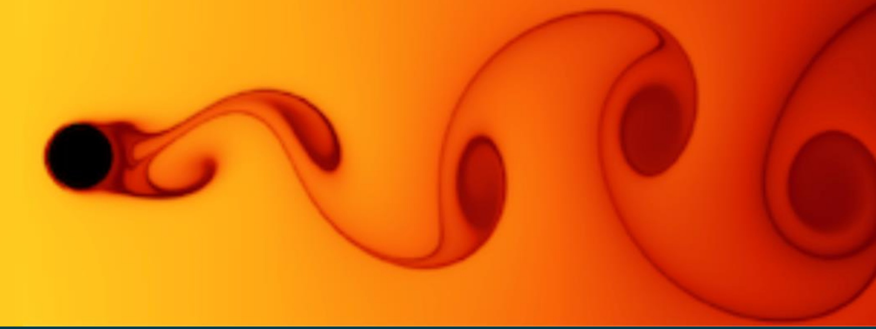
Computational and Data-Driven Fluid Dynamics



Cecil and Sally Drinkward Postdoctoral Fellowship Program

Caltech Presidential Postdoctoral Fellowship Program

National Laser Users' Facility Program

Center for High Energy Density Laboratory Astrophysics

Vortex Dynamics in Inertial Fusion and Astrophysics

Michael Wadas[1], Heath LeFevre[2], William White[2], Griffin Cearley[3], Carolyn Kuranz[2], Aaron Towne[2], Eric Johnsen[2]

[1]California Institute of Technology, Pasadena, CA
[2]University of Michigan, Ann Arbor, MI
[3]Sandia National Laboratory, Albuquerque, NM

Lawrence Livermore National Laboratory, High-Energy-Density Seminar, 9 May 2024

Introduction

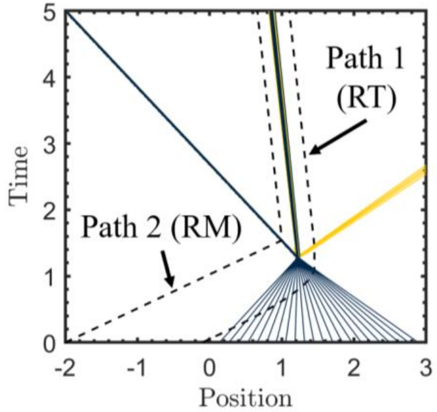
UNIVERSITY OF MICHIGAN

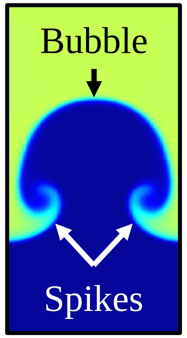
SCFP Laboratory

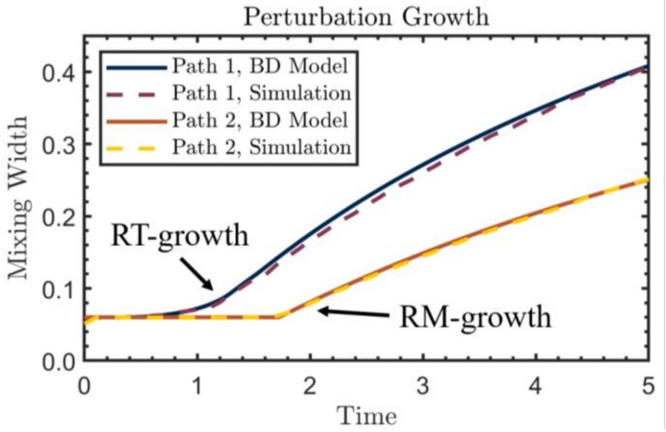
Eric Johnsen

Carolyn Kuranz

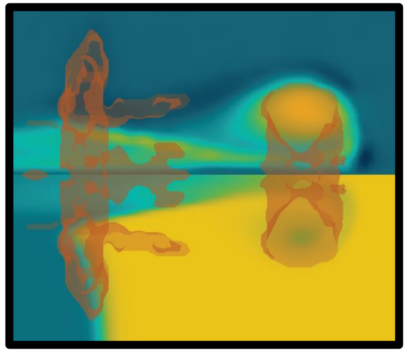
Wave Shaping and Hydrodynamic Stability

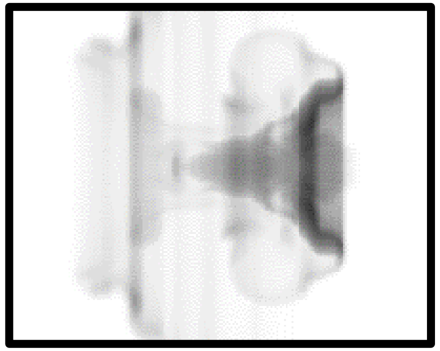


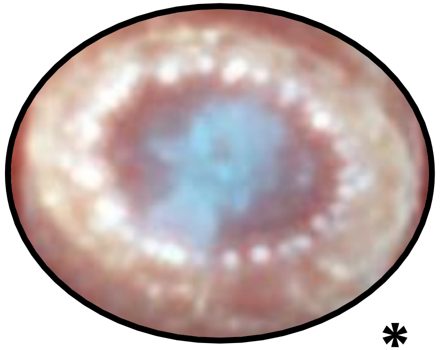


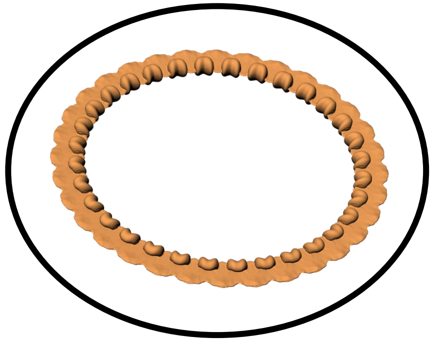


Vortex Dynamics in ICF and Astrophysics









*NASA, ESA, CSA, Matsuura et al. (2023)

Outline

Ejection: Intro

Ejection: Theory and Simulation

Ejection: Experiments

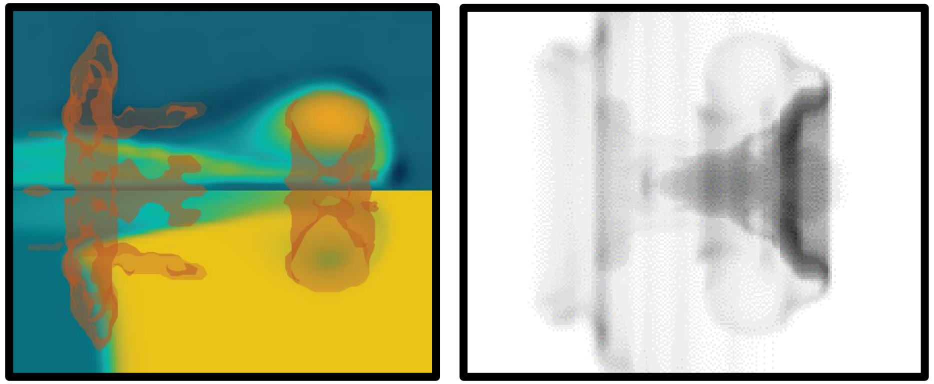
Clumping: Supernova 1987A

Clumping: Protoplanetary Disks

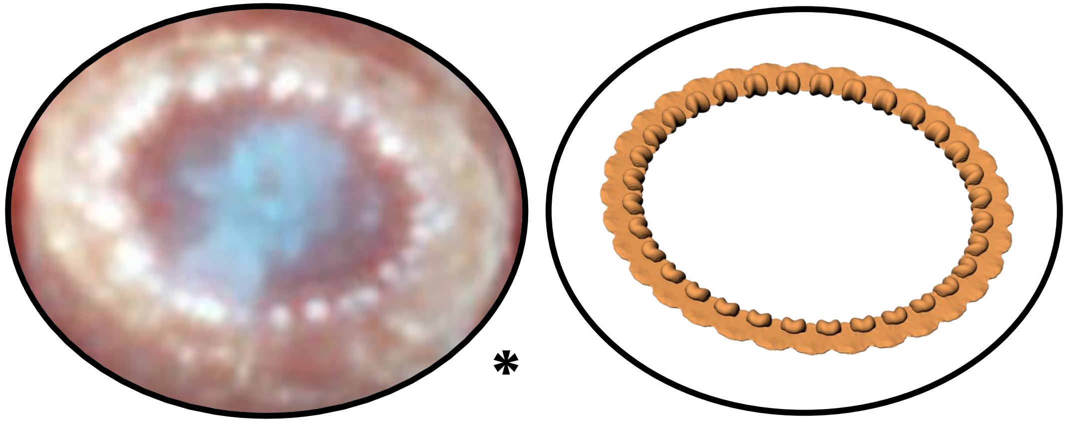
Conclusion

- Vortex Ring Ejection from Shocked Interfaces: Vortex rings abound in high-energy-density physics, including inertial fusion and supernovae, when shock waves accelerate fluid interfaces.
  - These compressible, multifluid rings may share many physics with their incompressible, single-fluid counterparts.
  - An extended theory describes the formation dynamics of such rings.
  - Ongoing experiments at the Omega EP laser facility isolate vortex ring formation.
- Vortex Instability and Circumstellar Clumping: The Crow instability may stimulate the formation of clumps along the circumstellar gas cloud around Supernova 1987A.
  - Stability analysis predicts a dominant wavelength consistent with the number of clumps, and simulations reproduce key observables.
  - A similar instability mechanism may stimulate clumping in protoplanetary disks.

Part 1

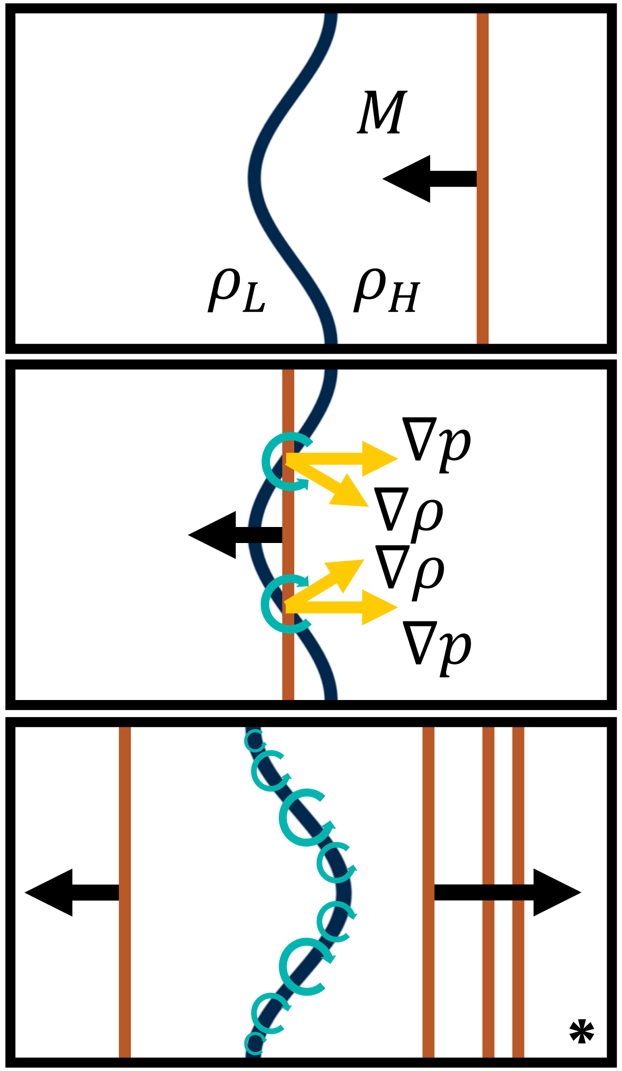


Part 2



*NASA, ESA, CSA, Matsuura et al. (2023)

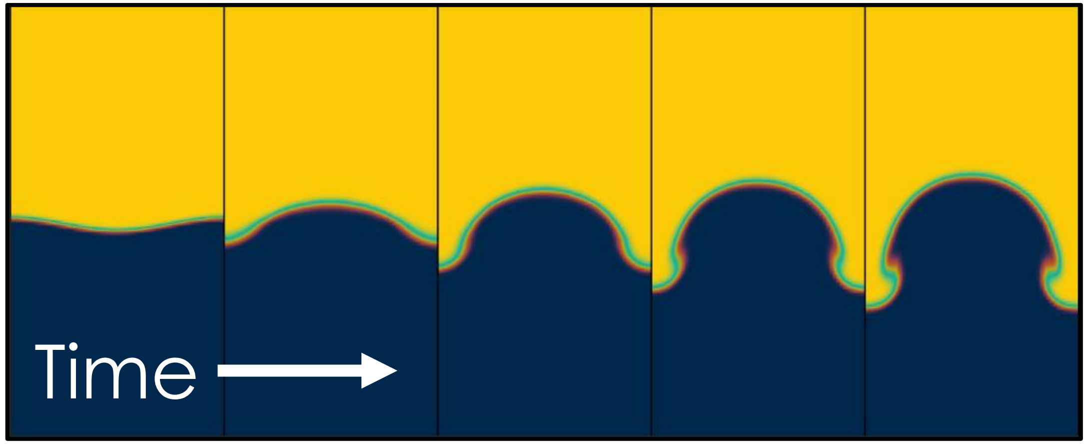
The Richtmyer-Meshkov instability describes the growth of perturbations along shocked interfaces, which can lead to the ejection of vortex rings.

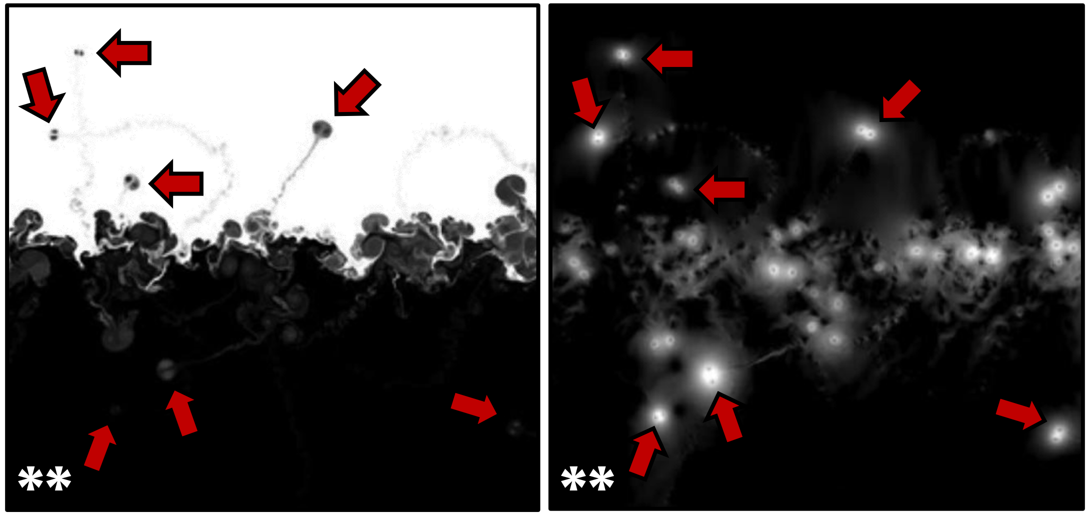


Shock impinges on heavy-to-light interface

Shock deposits baroclinic vorticity

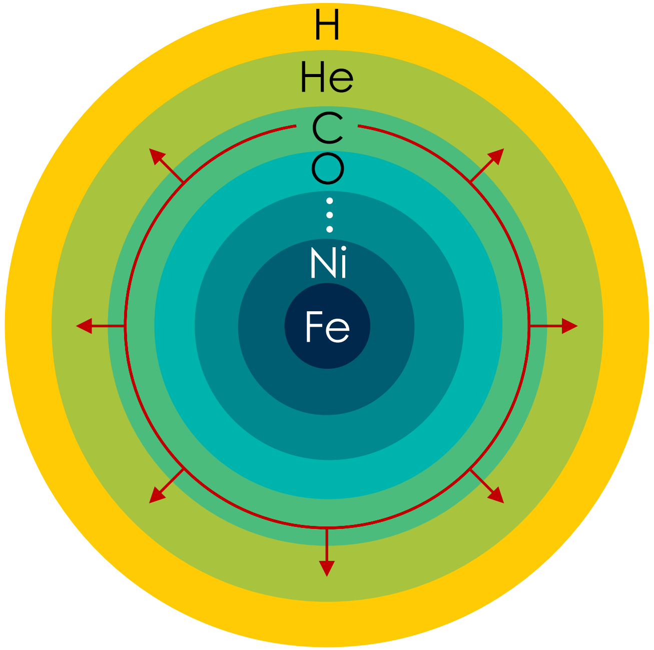
Rarefaction reflects and interface evolves

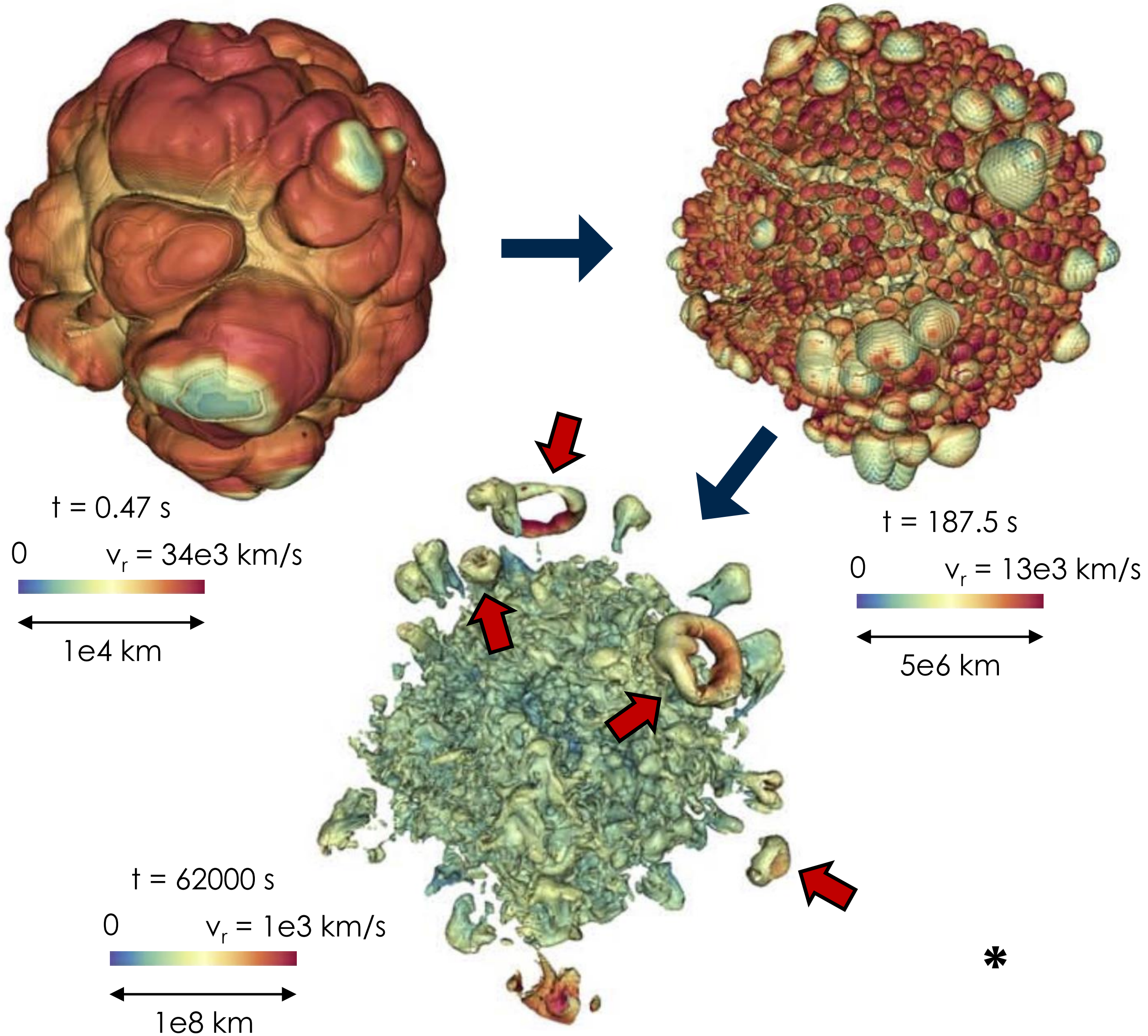




* Brouillette, Ann. Rev. Fluid Mech., 34, 2002 ** Thornber, Phys. Plasmas, 22, 2015

Shock-induced interfacial mixing also occurs in supernovae.





* Sandoval, Astrophys. J., 921, 2021

Inertial fusion uses laser-driven shocks to compress fuel, but interfaces are unstable and significant jetting can occur.

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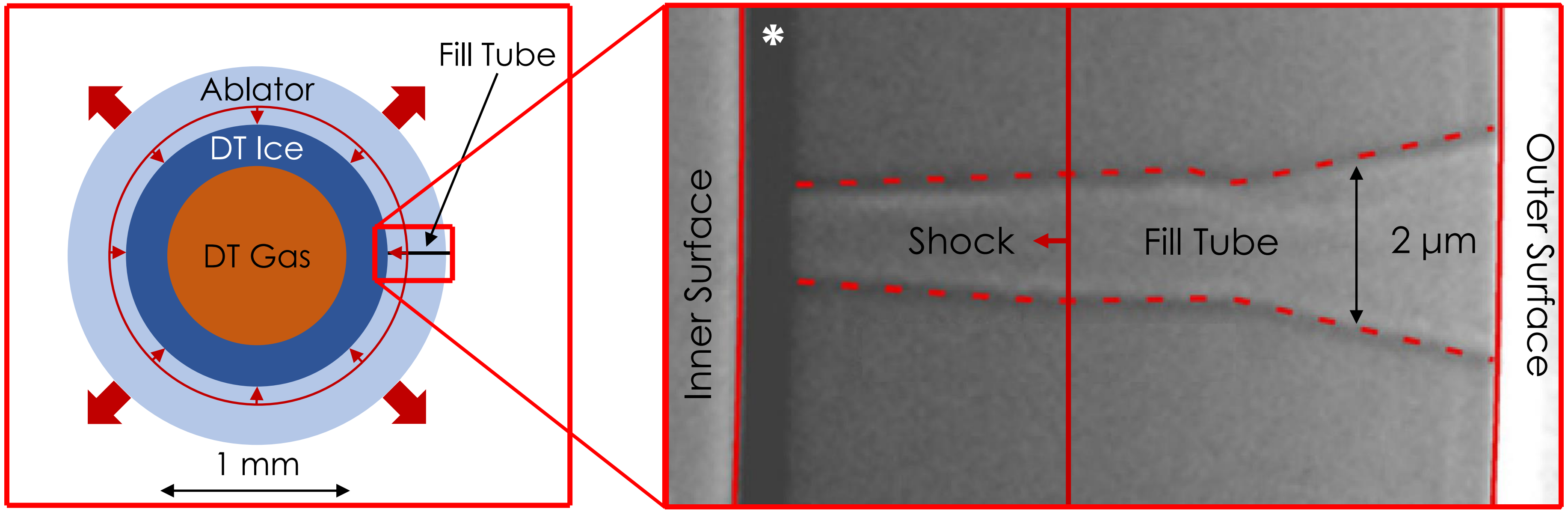
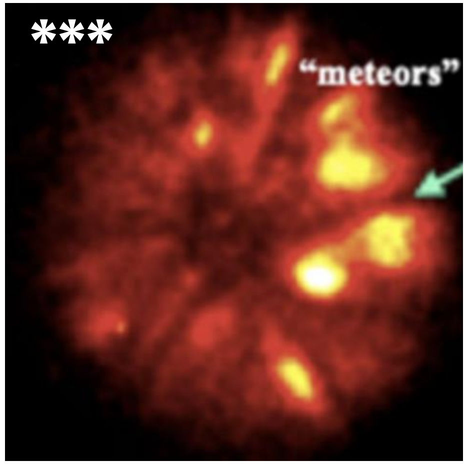
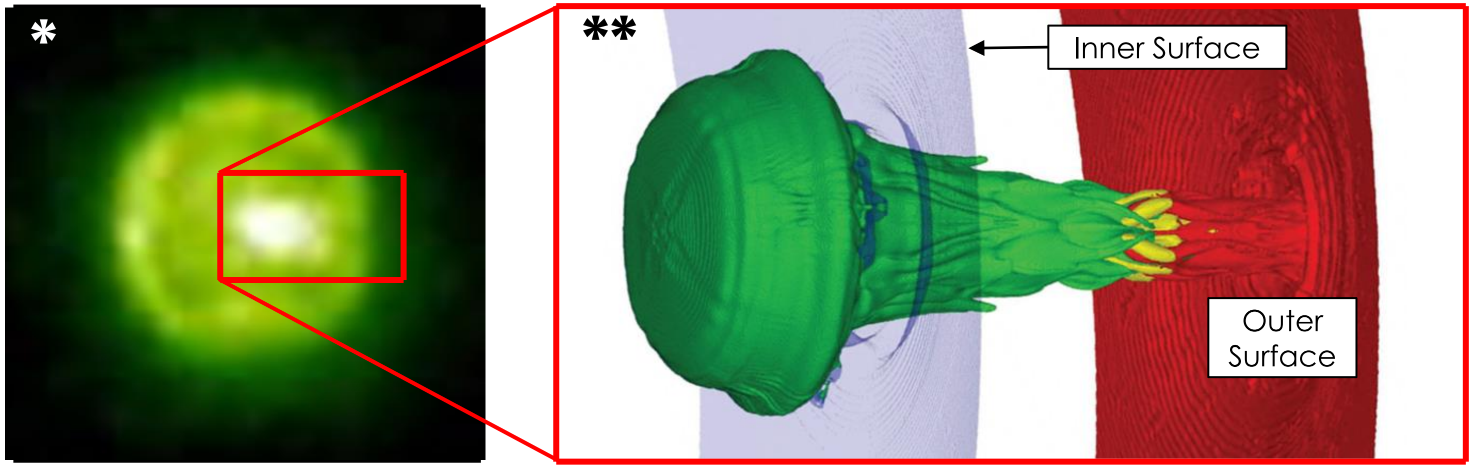


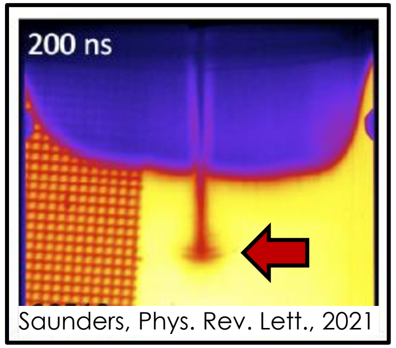




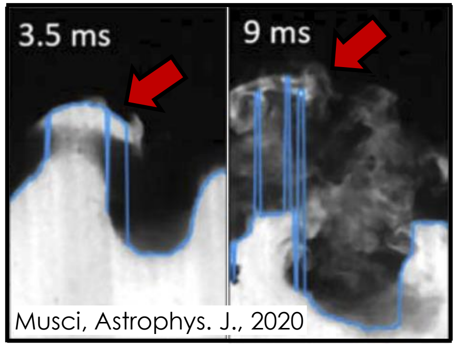
* Baker, Phys. Plasmas, 27, 2020 ** Haines, Phys. Plasmas, 26, 2019 *** Pickworth, Phys. Plasmas, 25, 2018

Vortex ring ejection from shocked interfaces is extensively observed.

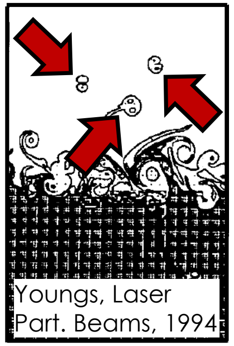

Balasubramanian, Phys. Fluids, 2012

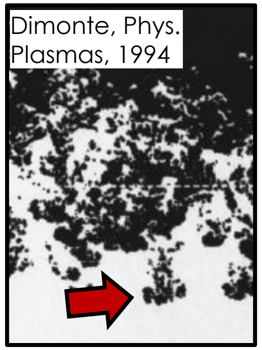


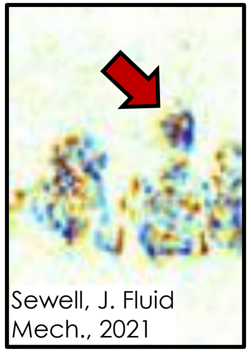
Saunders, Phys. Rev. Lett., 2021

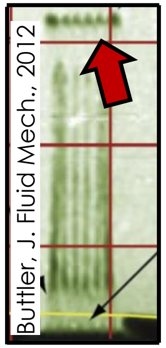


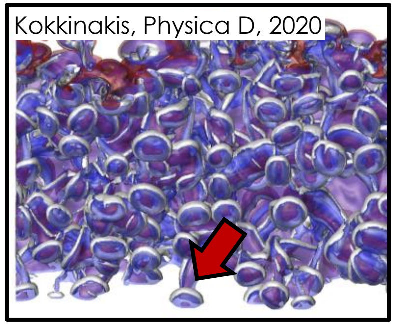
Musci, Astrophys. J., 2020

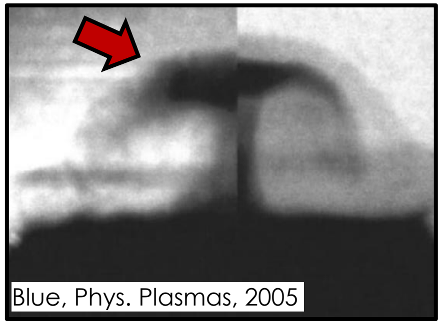

Youngs, Laser Part. Beams, 1994

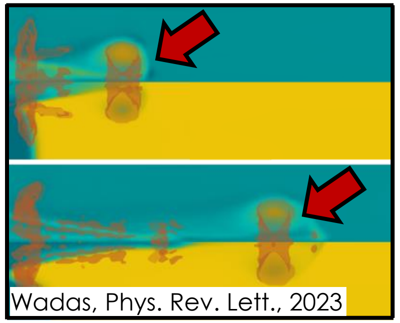

Dimonte, Phys. Plasmas, 1994

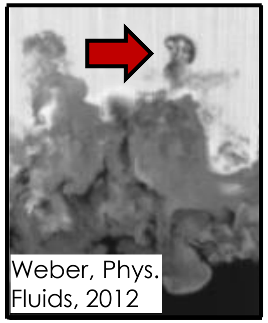

Sewell, J. Fluid Mech., 2021

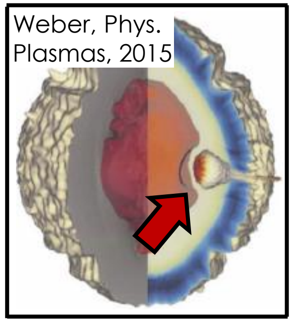

Buttler, J. Fluid Mech., 2012

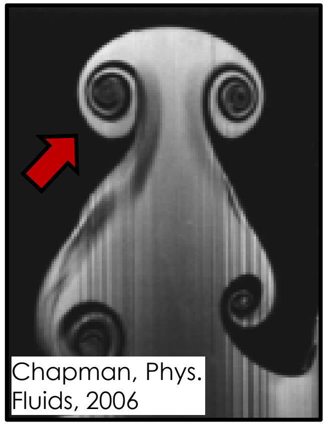

Kokkinakis, Physica D, 2020

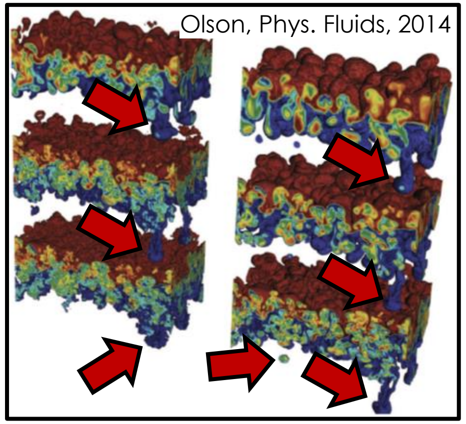

Blue, Phys. Plasmas, 2005

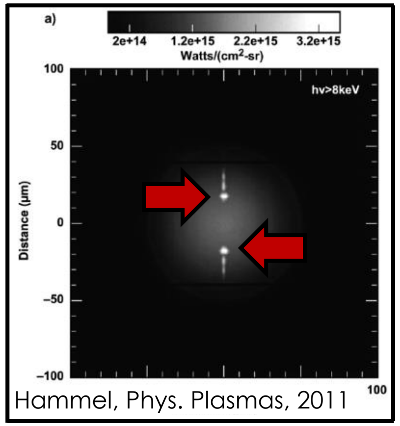

Wadas, Phys. Rev. Lett., 2023


Weber, Phys. Fluids, 2012

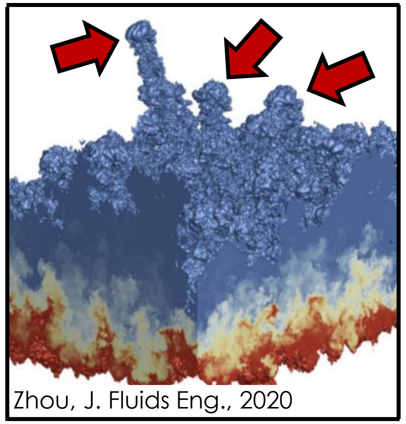

Weber, Phys. Plasmas, 2015

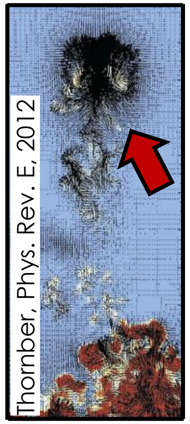

Chapman, Phys. Fluids, 2006


Olson, Phys. Fluids, 2014

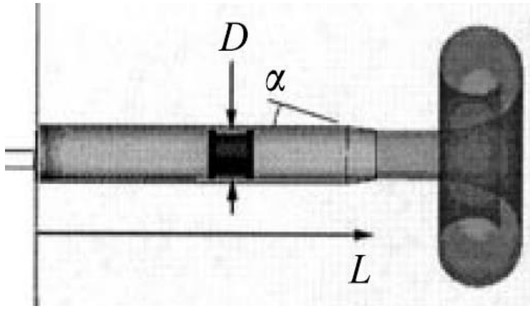


Hammel, Phys. Plasmas, 2011

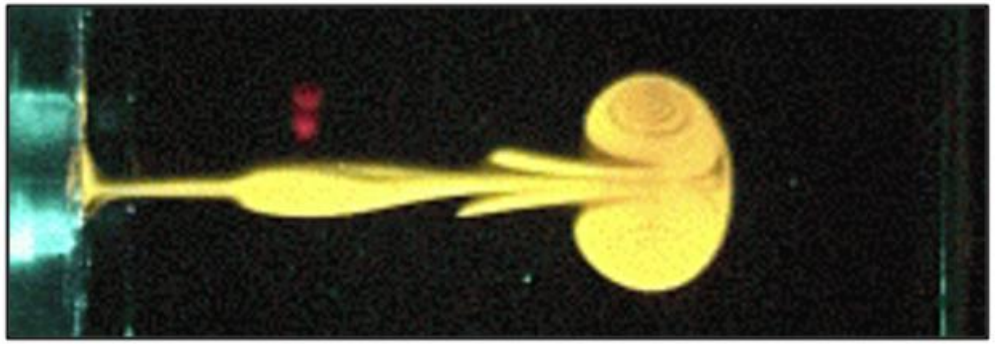

Zhou, J. Fluids Eng., 2020

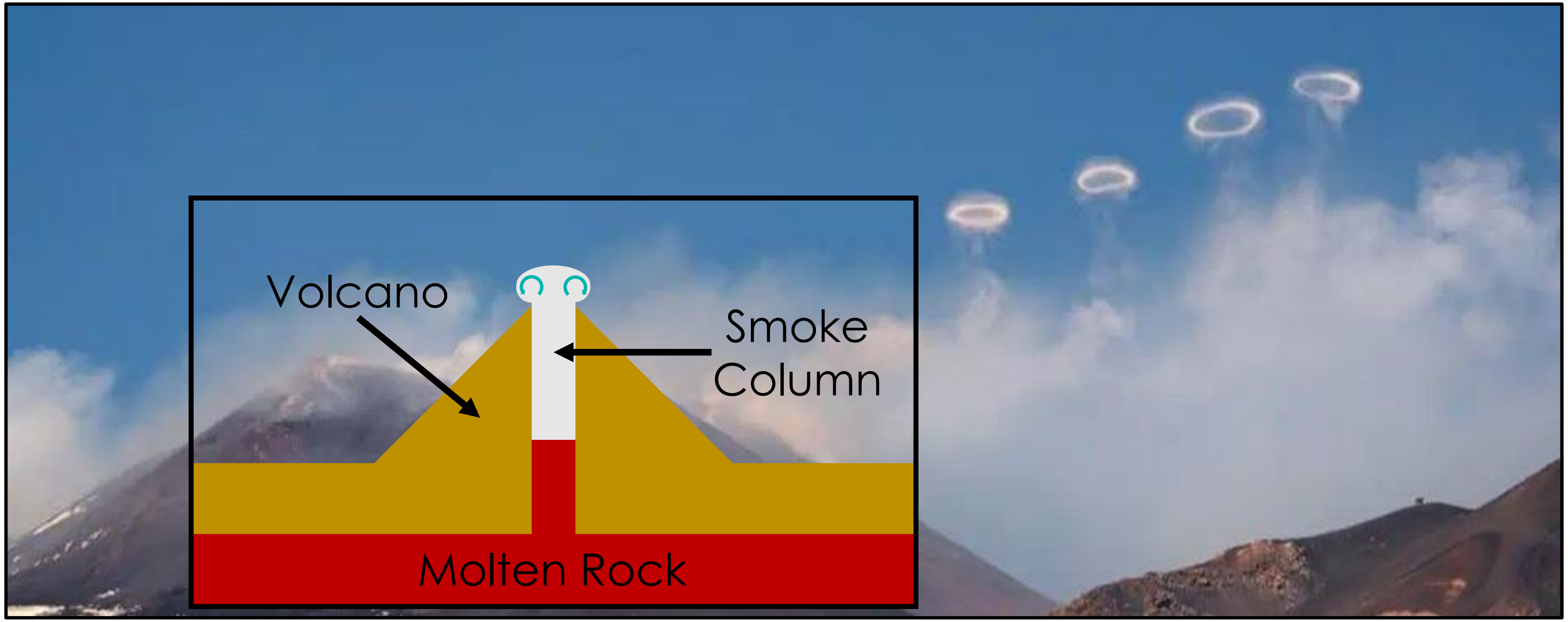

Thornber, Phys. Rev. E, 2012

Vortex ring properties scale with the stroke length of their generator.



Water Tank





Gharib, J. Fluid Mech., 360, 1998

Vortex ring properties scale with the stroke length of their generator.

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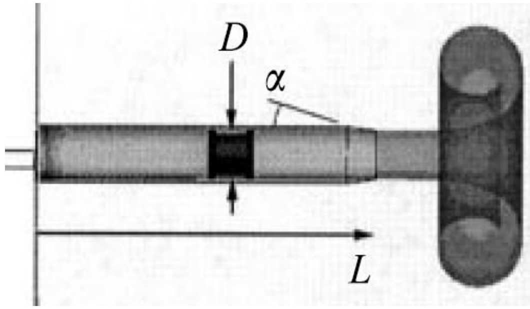
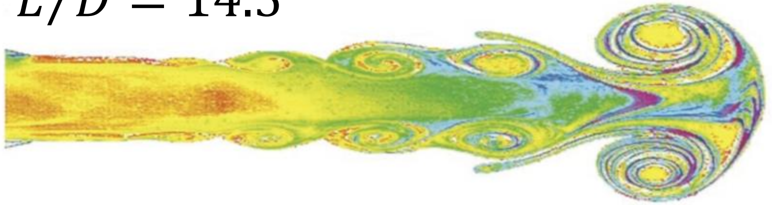


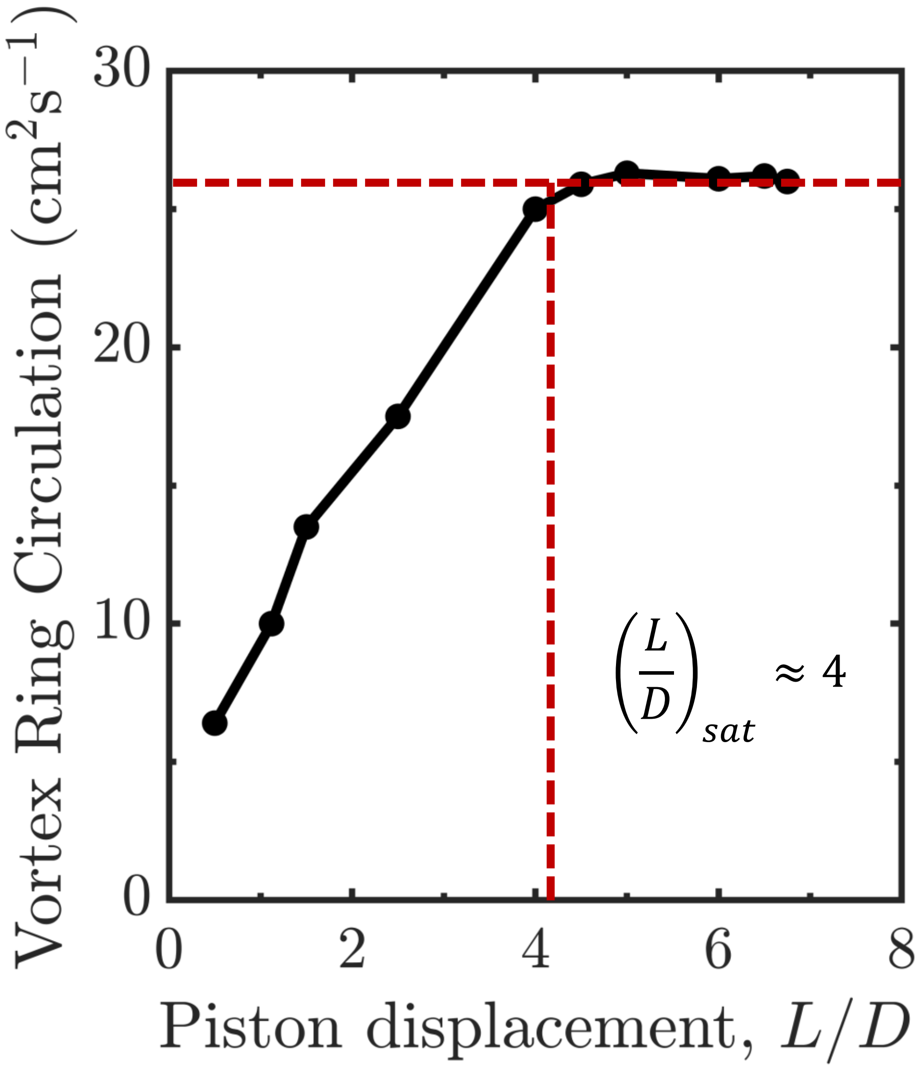
Water Tank

$L/D = 2.0$

$L/D = 3.8$

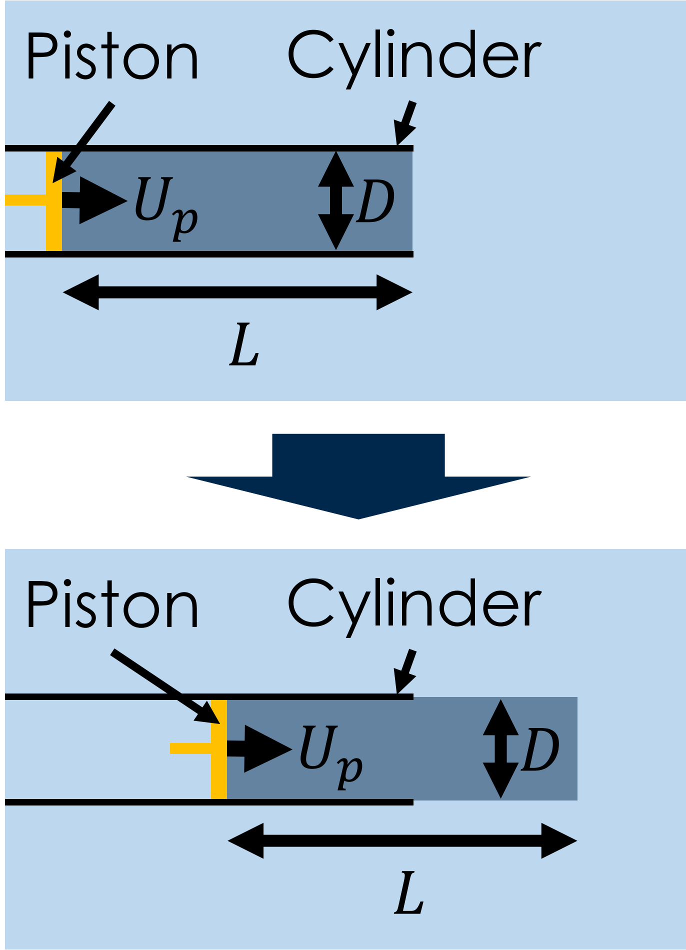
$L/D = 14.5$

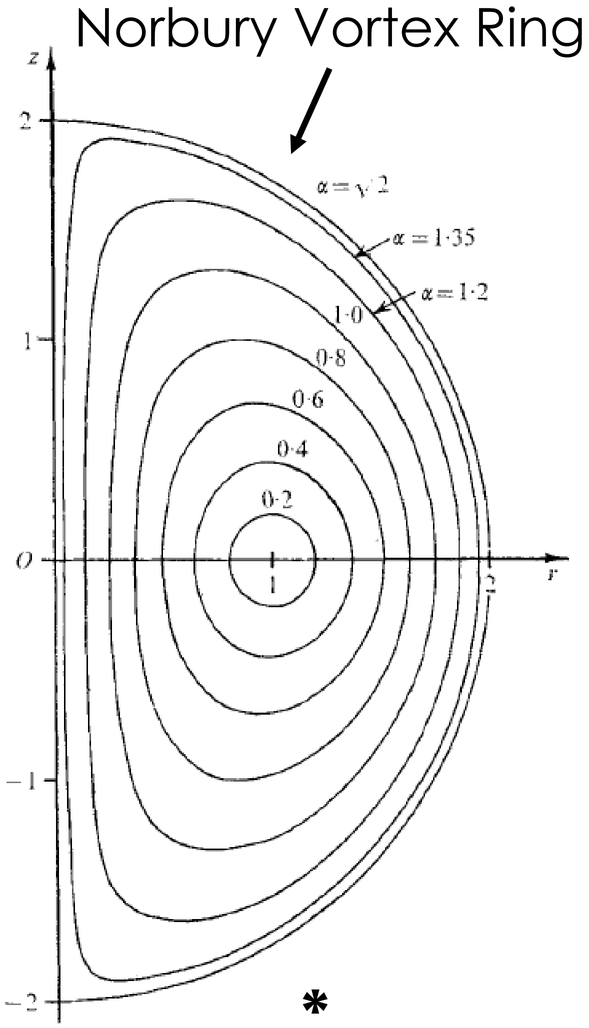




Gharib, J. Fluid Mech., 360, 1998

Analysis of energy, impulse, and circulation explains vortex rings saturation.





*

Slug Flow	**Norbury Ring**
$E = \frac{1}{8}\pi D^2 L U_p^2$	$E = (\Omega\alpha l)^2 l^3 E_N$
$\Gamma = \frac{1}{2} L U_p$	$\Gamma = (\Omega\alpha l) l \Gamma_N$
$I = \frac{1}{4}\pi D^2 L U_p$	$\mathrm{I} = (\Omega\alpha l) l^3 \mathrm{I}_N$
$U_{tr} = \frac{\partial E}{\partial I} = \frac{1}{2} U_p$	$U_{tr} = (\Omega\alpha l) U_N$

**

$$\frac{L}{D} = \sqrt{\frac{\pi}{2}}\, I_N^{\frac{1}{2}} \Gamma_N^{\frac{3}{2}} E_N^{-1}$$

$$\frac{L}{D} = \sqrt{\frac{\pi}{2}}\, I_N^{-\frac{1}{2}} \Gamma_N^{\frac{3}{2}} U_N^{-1}$$

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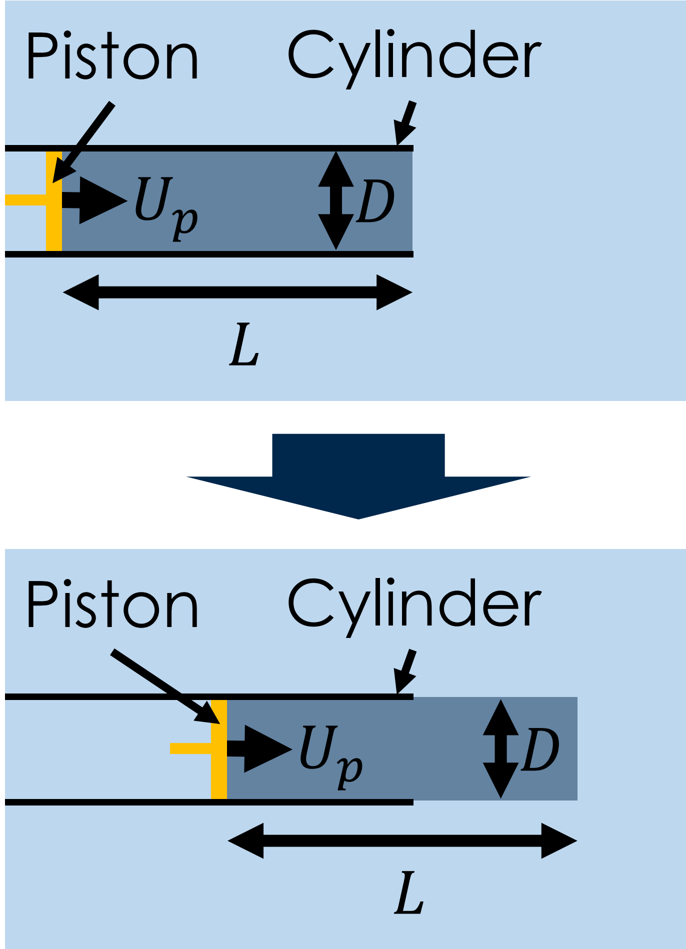
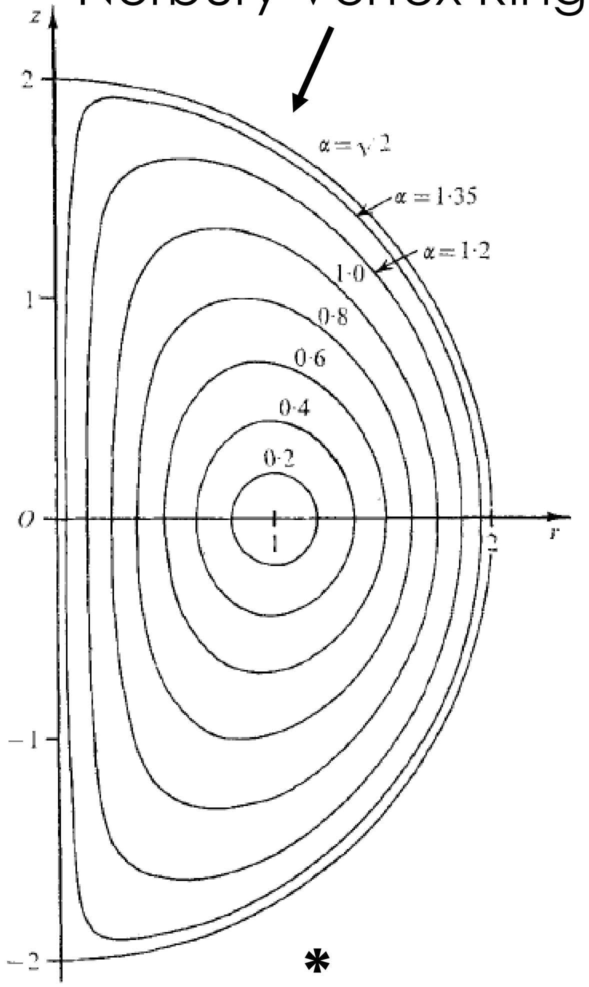
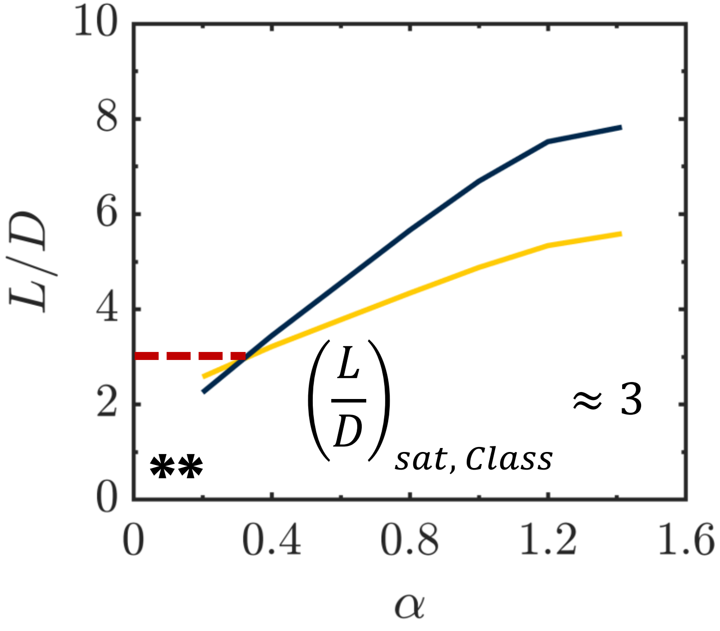
* Norbury, J Fluid Mech., 360 1973 ** Mohseni, Phys. Fluids, 10, 1998

Analysis of energy, impulse, and circulation explains vortex rings saturation.



Norbury Vortex Ring

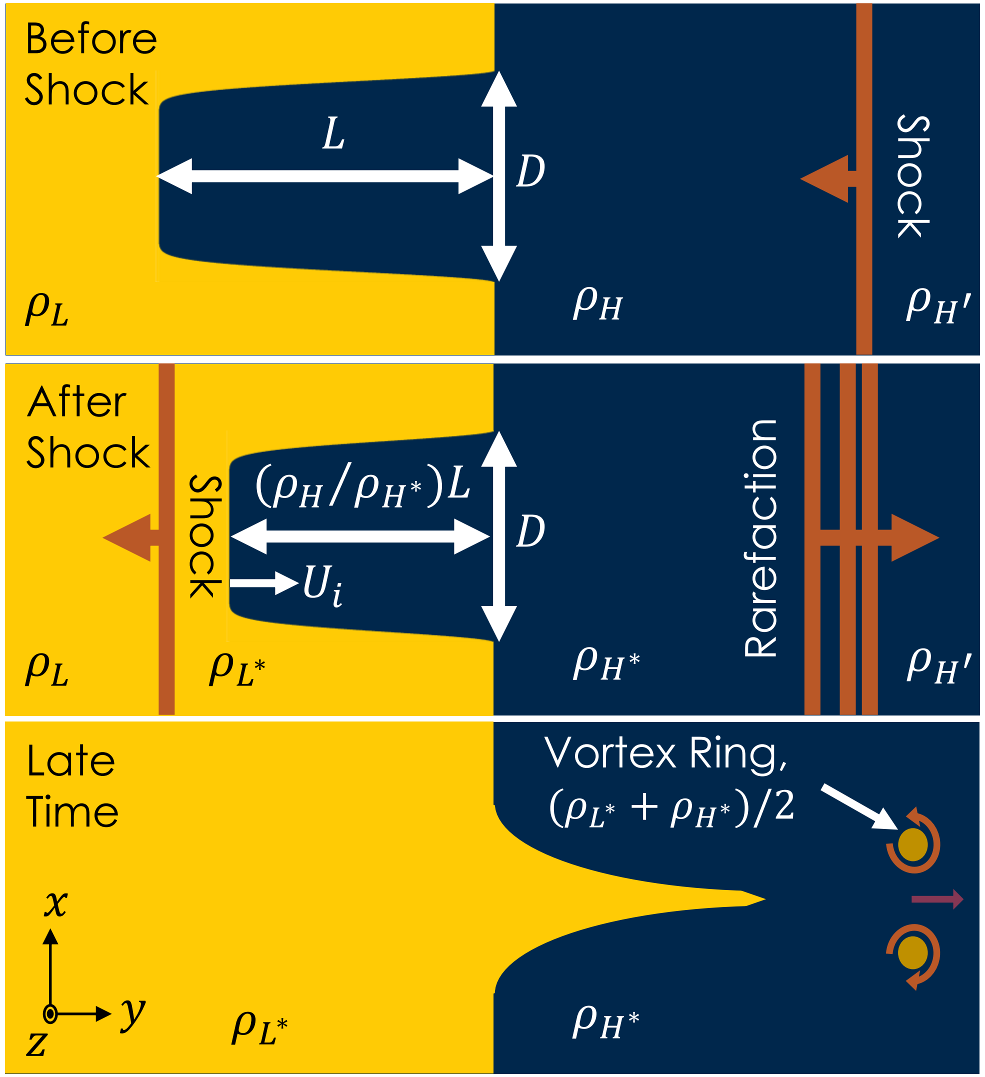




$$\boxed{3.0 \le \left(\frac{L}{D}\right)_{sat} \le 4.6}$$

* Norbury, J Fluid Mech., 360 1973 ** Mohseni, Phys. Fluids, 10, 1998

The analysis is extended to rings ejected from shocked interfaces.



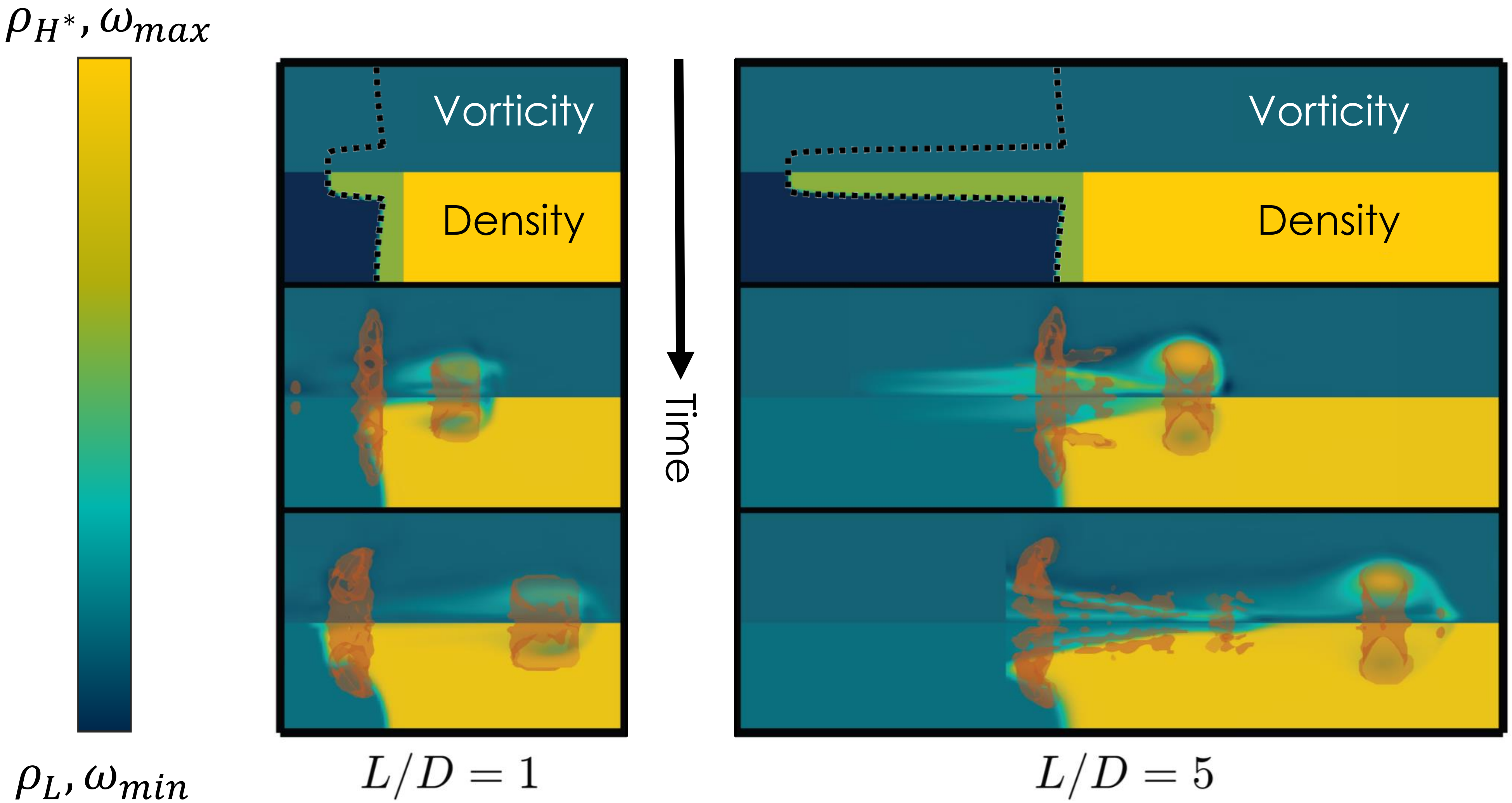
Slug Flow	**Norbury Vortex Ring**
$E = \boldsymbol{\rho_H}\frac{1}{8}\pi D^2 L U_i^2$	$E = \frac{(\boldsymbol{\rho_{L^*}}+\boldsymbol{\rho_{H^*}})}{\mathbf{2}}(\Omega a l)^2 l^3 E_N$
$\Gamma = \frac{\boldsymbol{\rho_H}}{\boldsymbol{\rho_{H^*}}}\frac{1}{2}LU_i$	$\Gamma = (\Omega a l) l \Gamma_N$
$I = \boldsymbol{\rho_H}\frac{1}{4}\pi D^2 L U_i$	$I = \frac{(\boldsymbol{\rho_{L^*}}+\boldsymbol{\rho_{H^*}})}{\mathbf{2}}(\Omega a l) l^3 I_N$
$U_{tr} = \frac{\partial E}{\partial I} = \frac{1}{2}U_i$	$U_{tr} = (\Omega a l) U_N$

$$\boxed{\left(\frac{L}{D}\right)_{sat,\,RMI} = \sigma\left(\frac{L}{D}\right)_{sat,\,Class}}$$

$$\sigma = \sqrt{\frac{2\rho_{H^*}}{\rho_{L^*}+\rho_{H^*}}\frac{\rho_{H^*}}{\rho_H}} = f(\rho_{H'}/\rho_H, \rho_H/\rho_L)$$

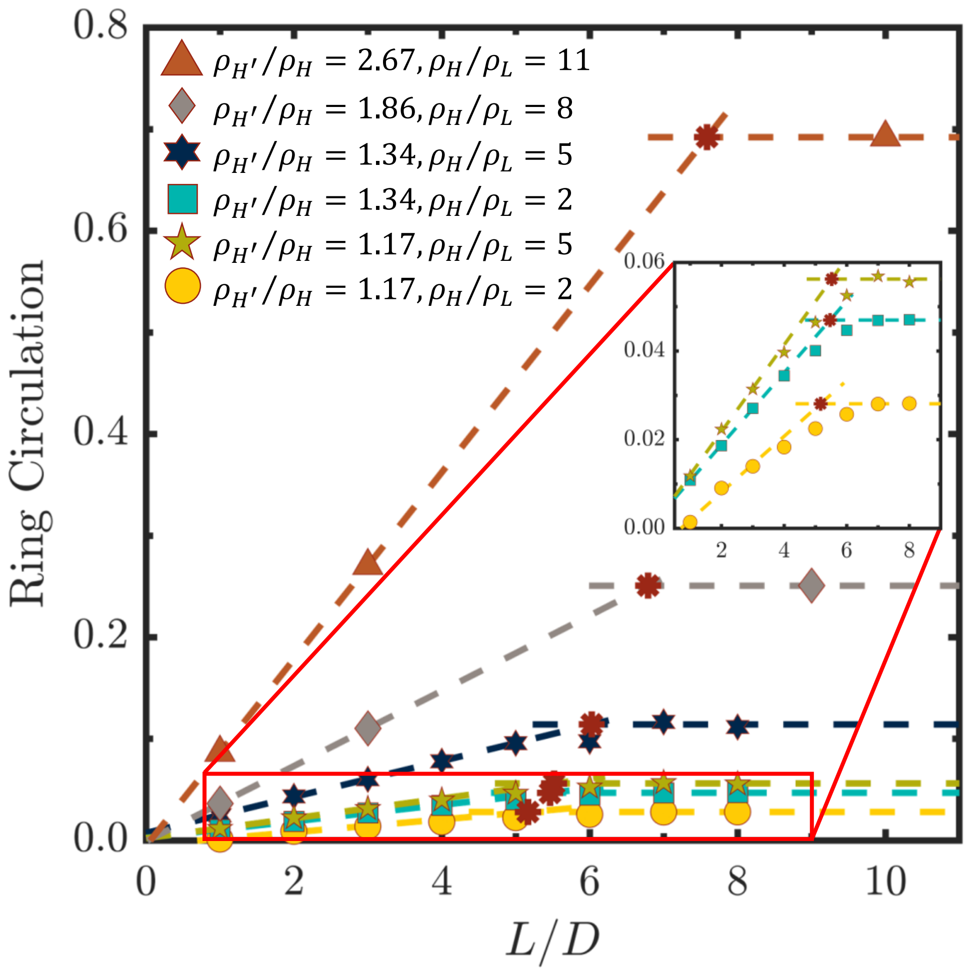
Wadas, Phys. Rev. Lett., 130, 2023

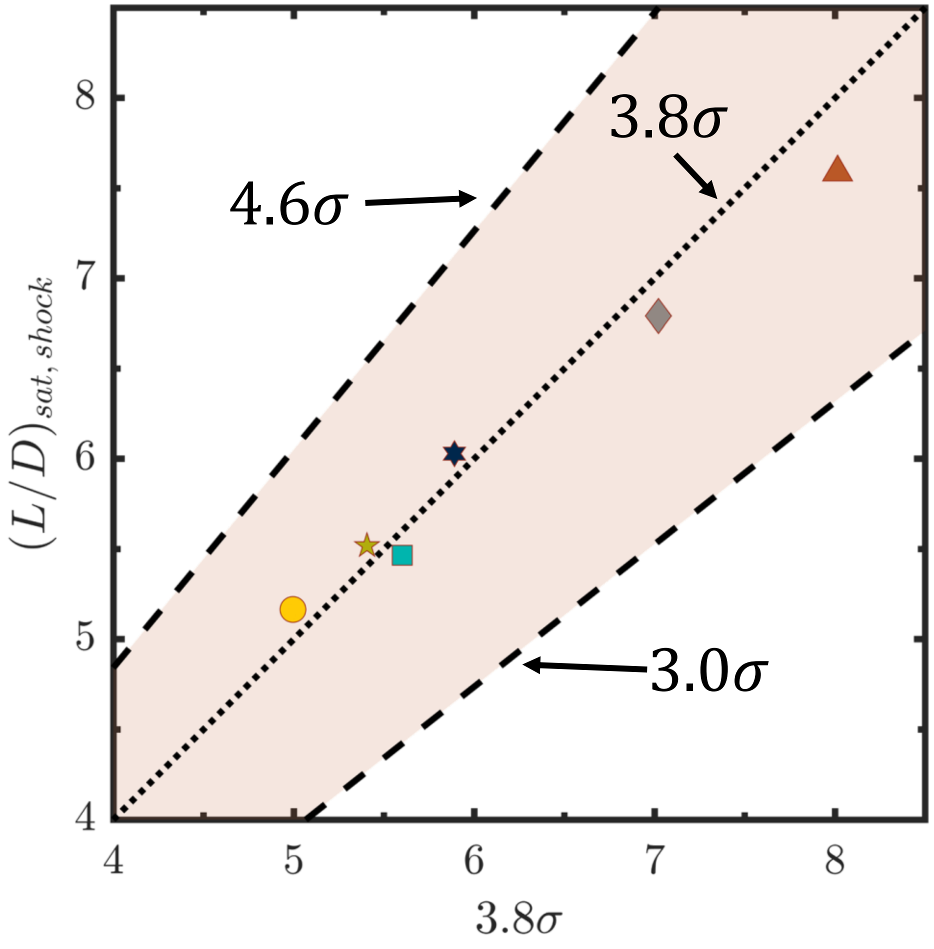
Simulations show the emergence of the trailing jet.



Wadas, Phys. Rev. Lett., 130, 2023

Simulations show good agreement with extended formation-number theory.





Wadas, Phys. Rev. Lett., 130, 2023

Laser-driven shocks can be used to examine vortex ring ejection.

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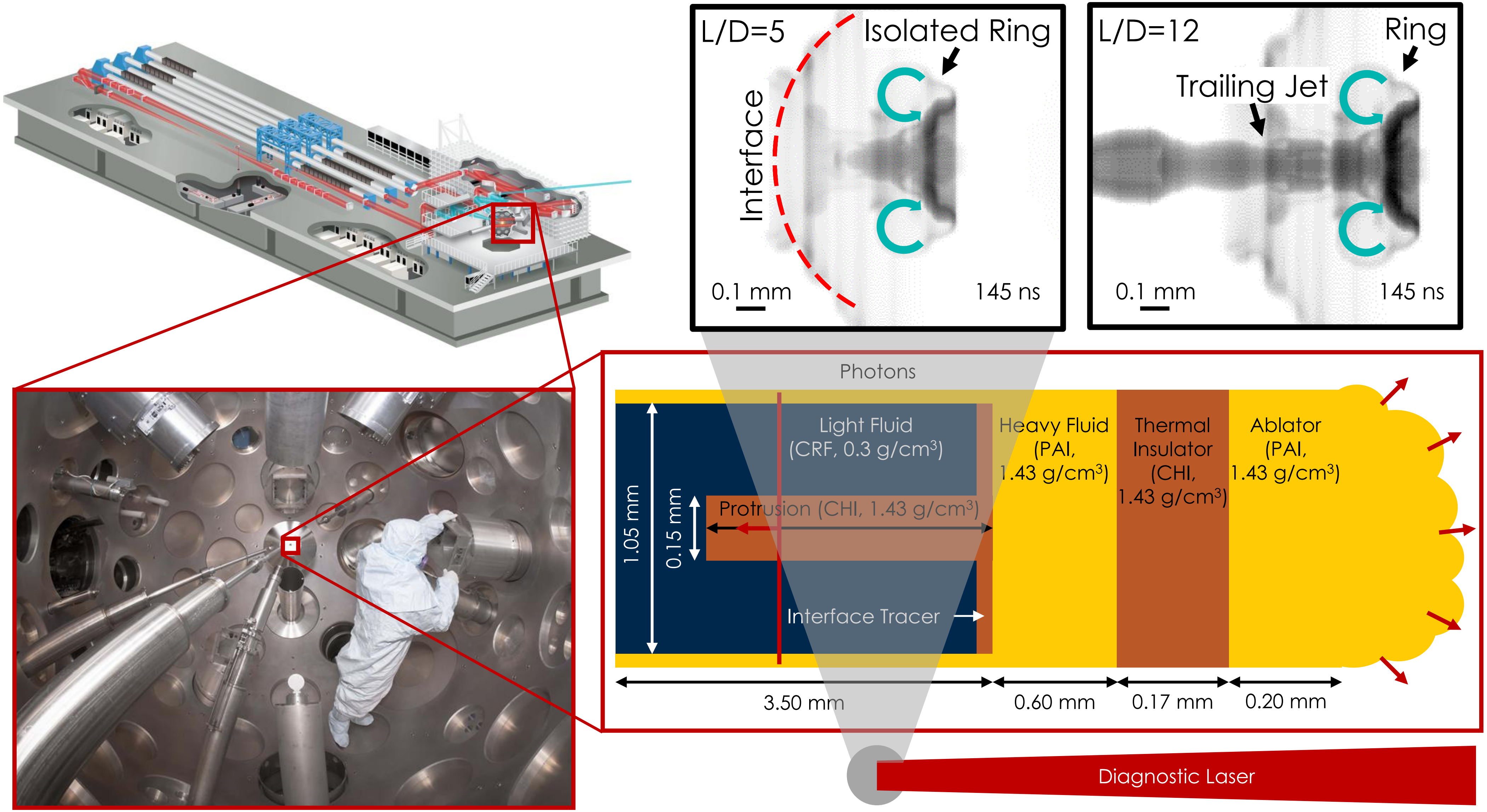


SN1987A shapes our understanding of stellar evolution.

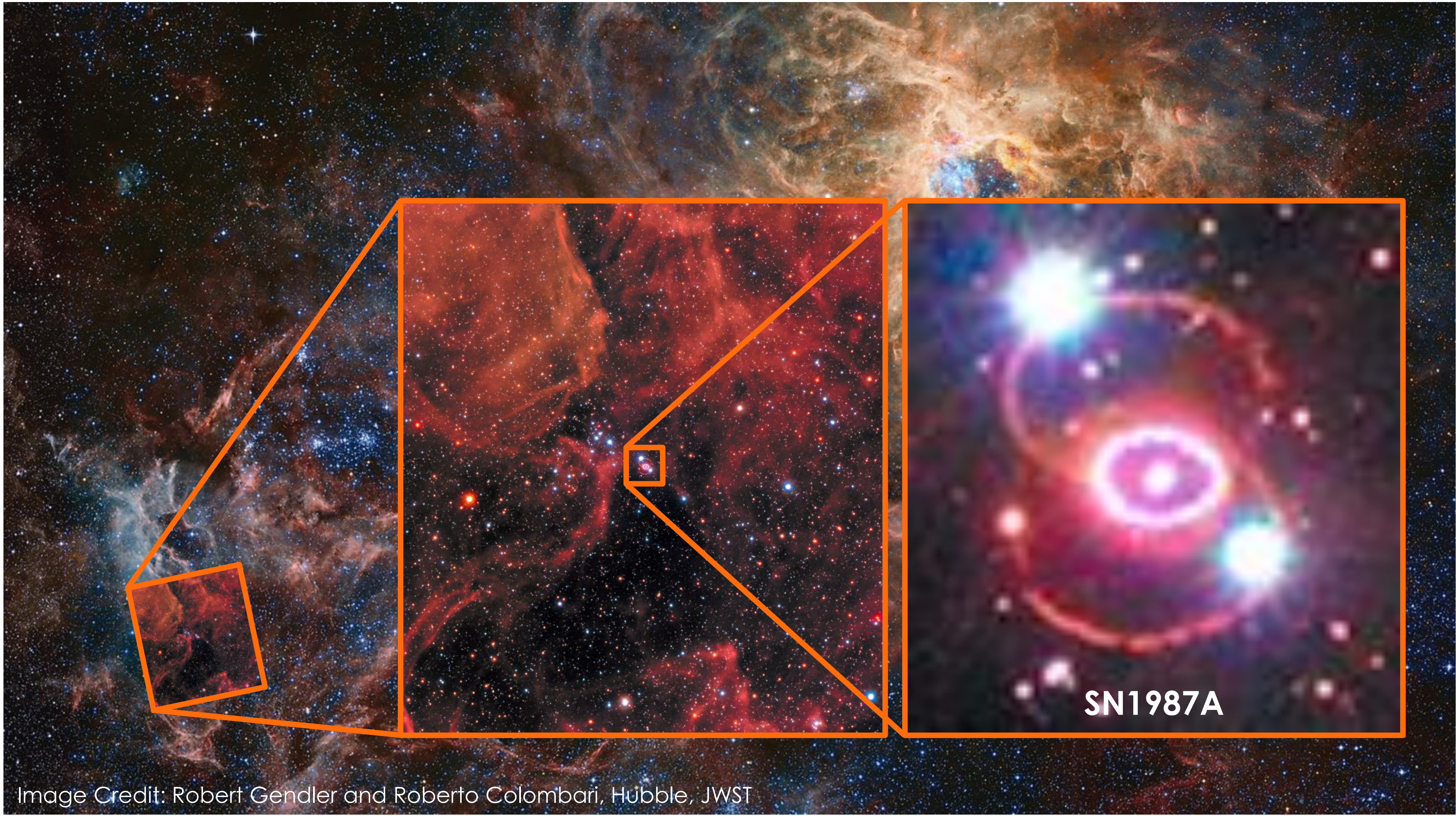
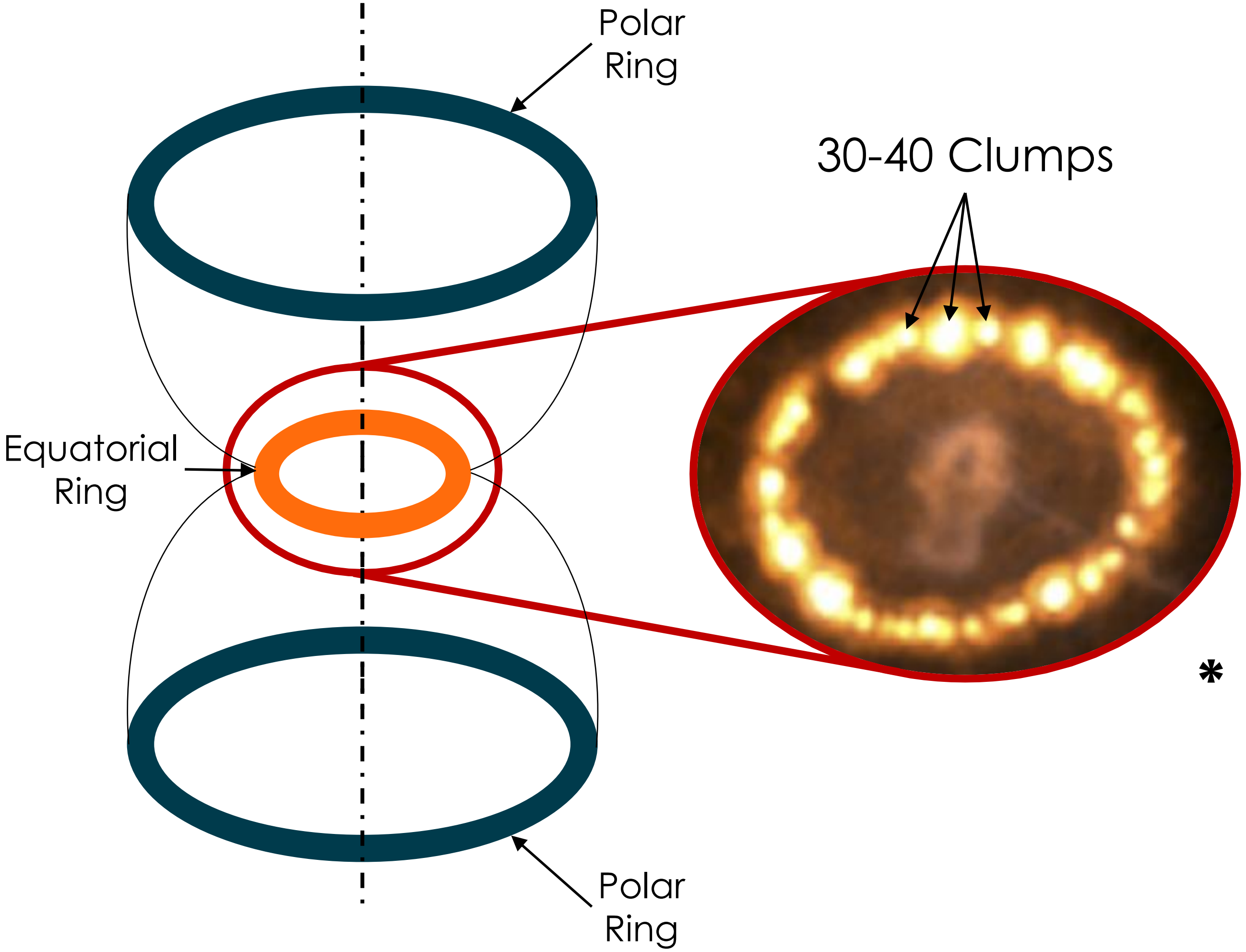


Image Credit: Robert Gendler and Roberto Colombari, Hubble, JWST

The remnant of SN1987A is dominated by a three-ring structure.



* Fransson, Astrophys. J., 806, 2015

The rings may result from a binary merger preceding the supernova.

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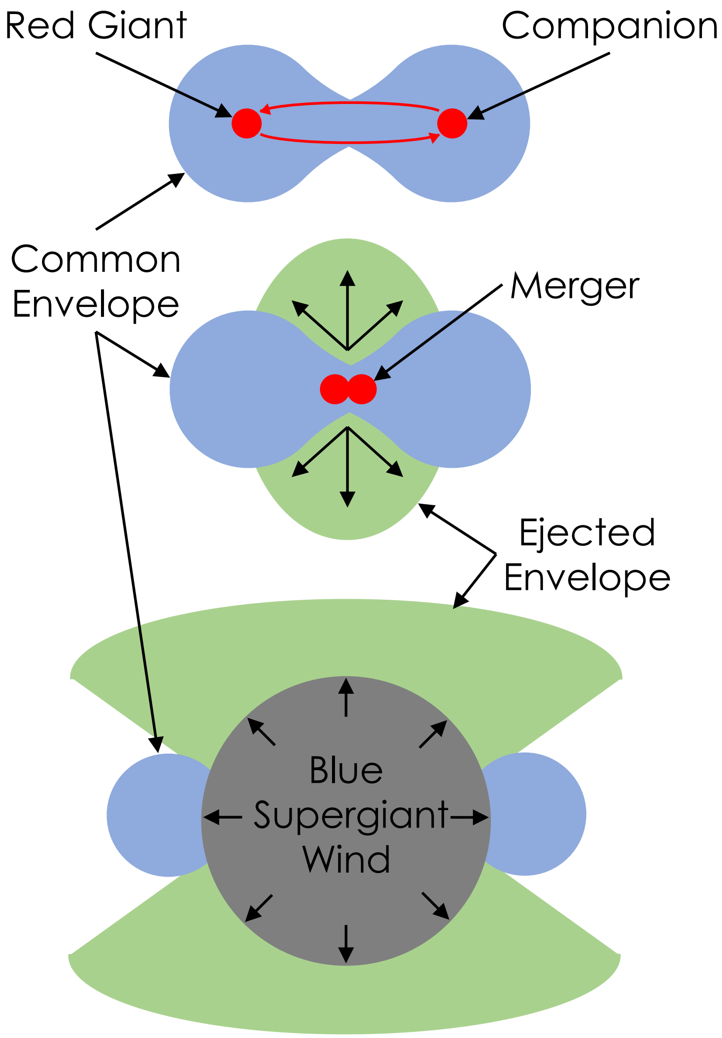


Red Giant

Companion

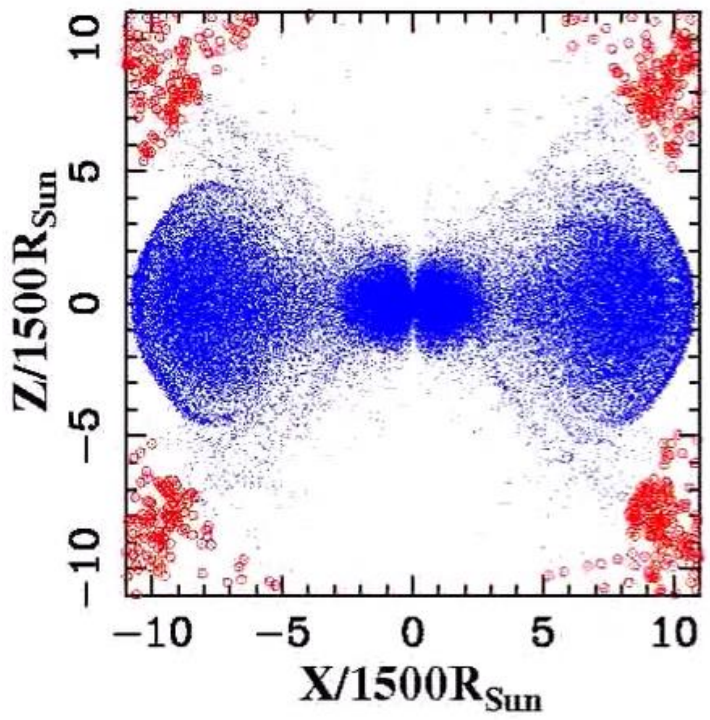
Common Envelope

Merger

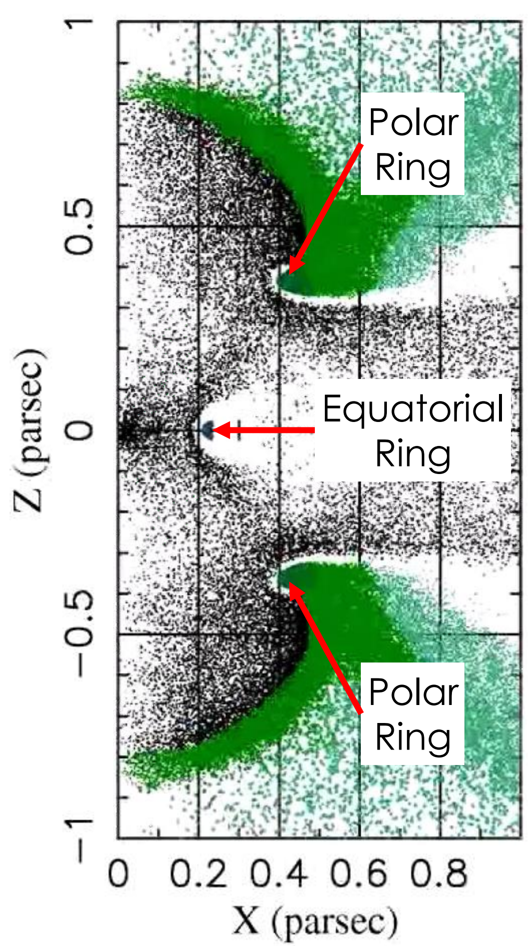
Ejected Envelope

Blue Supergiant Wind

0-13 Years

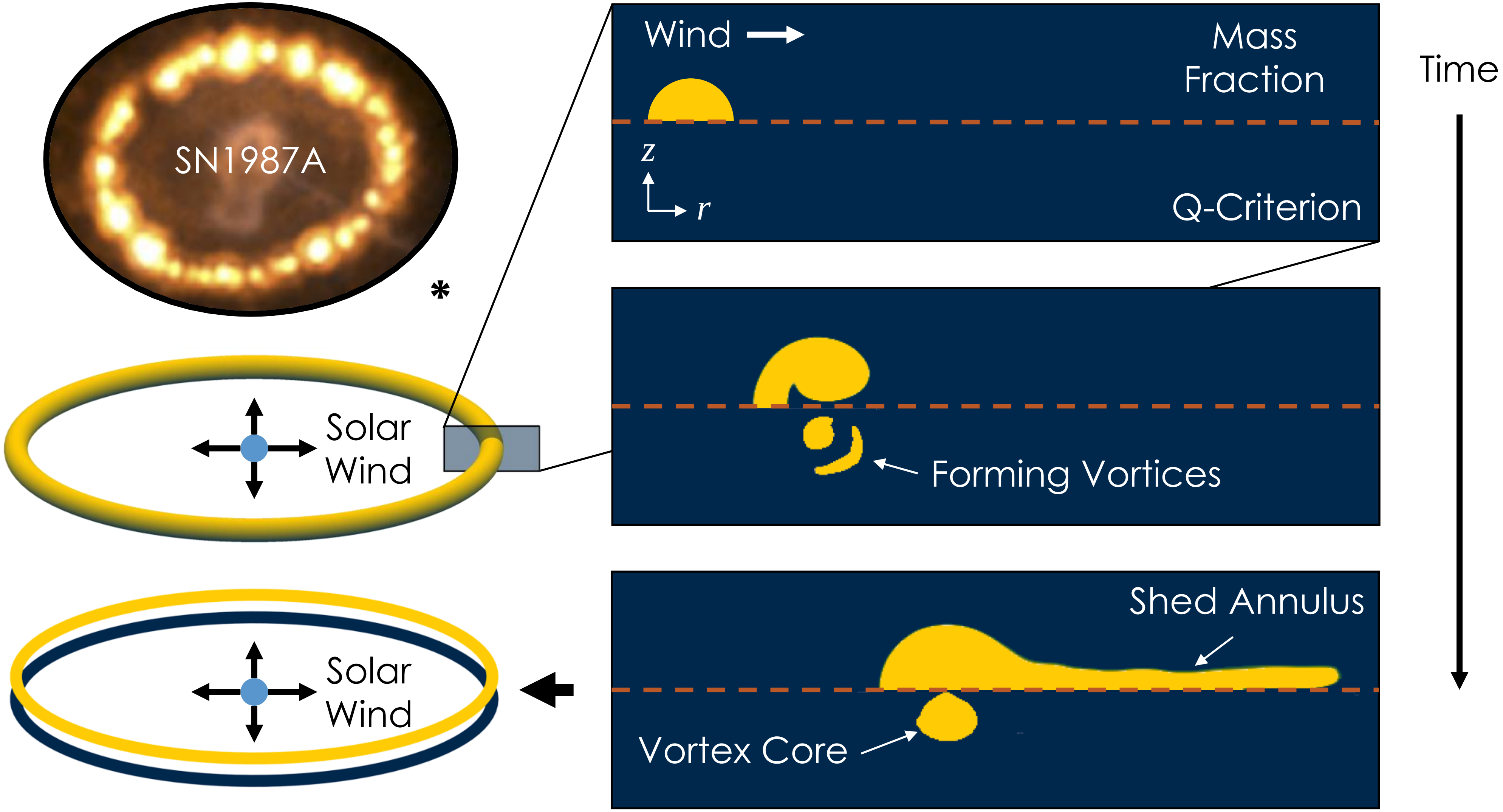


13-20000 Years



Morris, Science, 315, 2007

Solar wind can stimulate vortex dipole formation in the equatorial ring.



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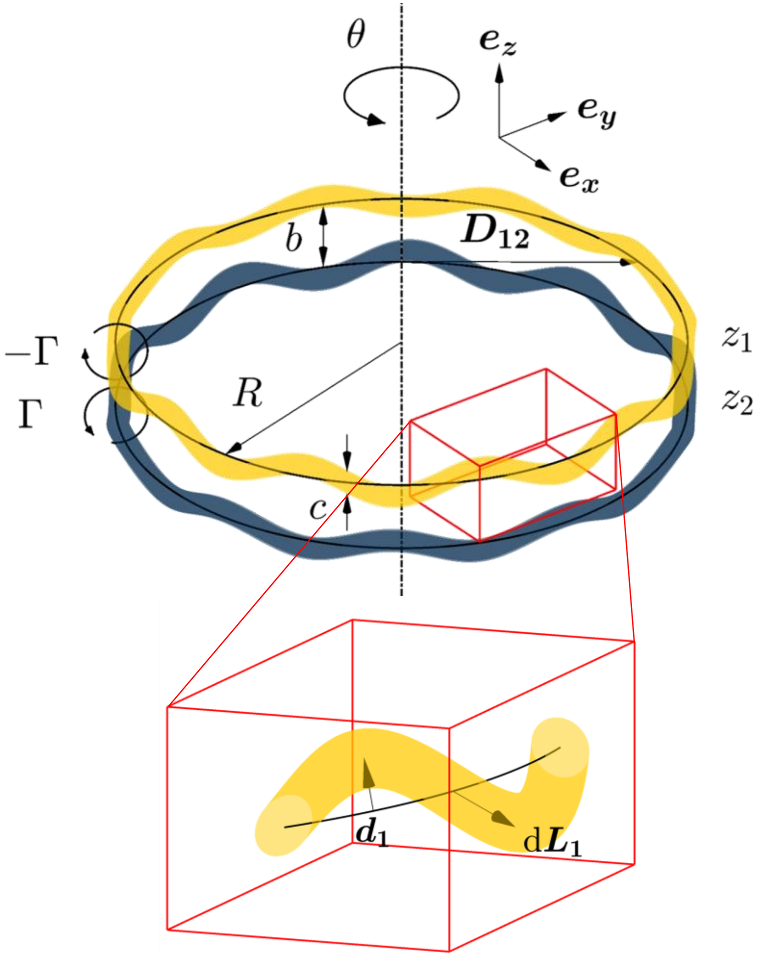
* Fransson, Astrophys. J., 806, 2015

The stability analysis considers perturbations along co-axial vortex rings.



$$\boldsymbol{U_n} = \sum_{m=1}^{2} \frac{\Gamma_m}{4\pi} \int \frac{\boldsymbol{D_{mn}} \times d\boldsymbol{L_m}}{|\boldsymbol{D_{mn}}|^3} = \boldsymbol{e_x} u_n + \boldsymbol{e_y} v_n + \boldsymbol{e_z} w_n$$

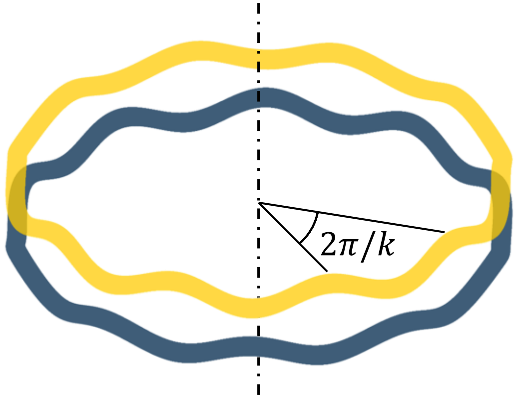
$$\boldsymbol{D_{mn}} = \boldsymbol{e_x} R(\cos\theta_{m'} - \cos\theta_n) + \boldsymbol{e_y} R(\sin\theta_{m'} - \sin\theta_n) + \boldsymbol{e_z}(z_m - z_n) + (\boldsymbol{d'_m} - \boldsymbol{d_n})$$

$$\boldsymbol{d_n} = \boldsymbol{e_x} h_n(\theta_n, t)\cos\theta_n + \boldsymbol{e_y} h_n(\theta_n, t)\sin\theta_n + \boldsymbol{e_z} s_n(\theta_n, t) \boxed{= \widetilde{\boldsymbol{d}_{\boldsymbol{n}}} e^{at+ik\theta_n}}$$

$$d\boldsymbol{L_n} = \left(-\boldsymbol{e_x} R\sin\theta_n + \boldsymbol{e_y} R\cos\theta_n + \partial\boldsymbol{d_n}/\partial\theta_n\right) d\theta_n$$

$$\partial\boldsymbol{d_n}/\partial t + u_n(\partial\boldsymbol{d_n}/\partial x_n) + v_n(\partial\boldsymbol{d_n}/\partial y_n) = \boldsymbol{e_x} u_n + \boldsymbol{e_y} v_n + \boldsymbol{e_z} w_n$$

$$a\begin{bmatrix}\hat{h}_1\\ \hat{s}_1\\ \hat{h}_2\\ \hat{s}_2\end{bmatrix} = M\begin{bmatrix}\hat{h}_1\\ \hat{s}_1\\ \hat{h}_2\\ \hat{s}_2\end{bmatrix} \longrightarrow \begin{aligned}\hat{s}_s &= \hat{s}_2 - \hat{s}_1\\ \hat{h}_s &= \hat{h}_2 + \hat{h}_1\end{aligned} \longrightarrow$$



$R \approx 1.3 \times 10^{14}$ m

$c \approx 3.2 \times 10^{12}$ m

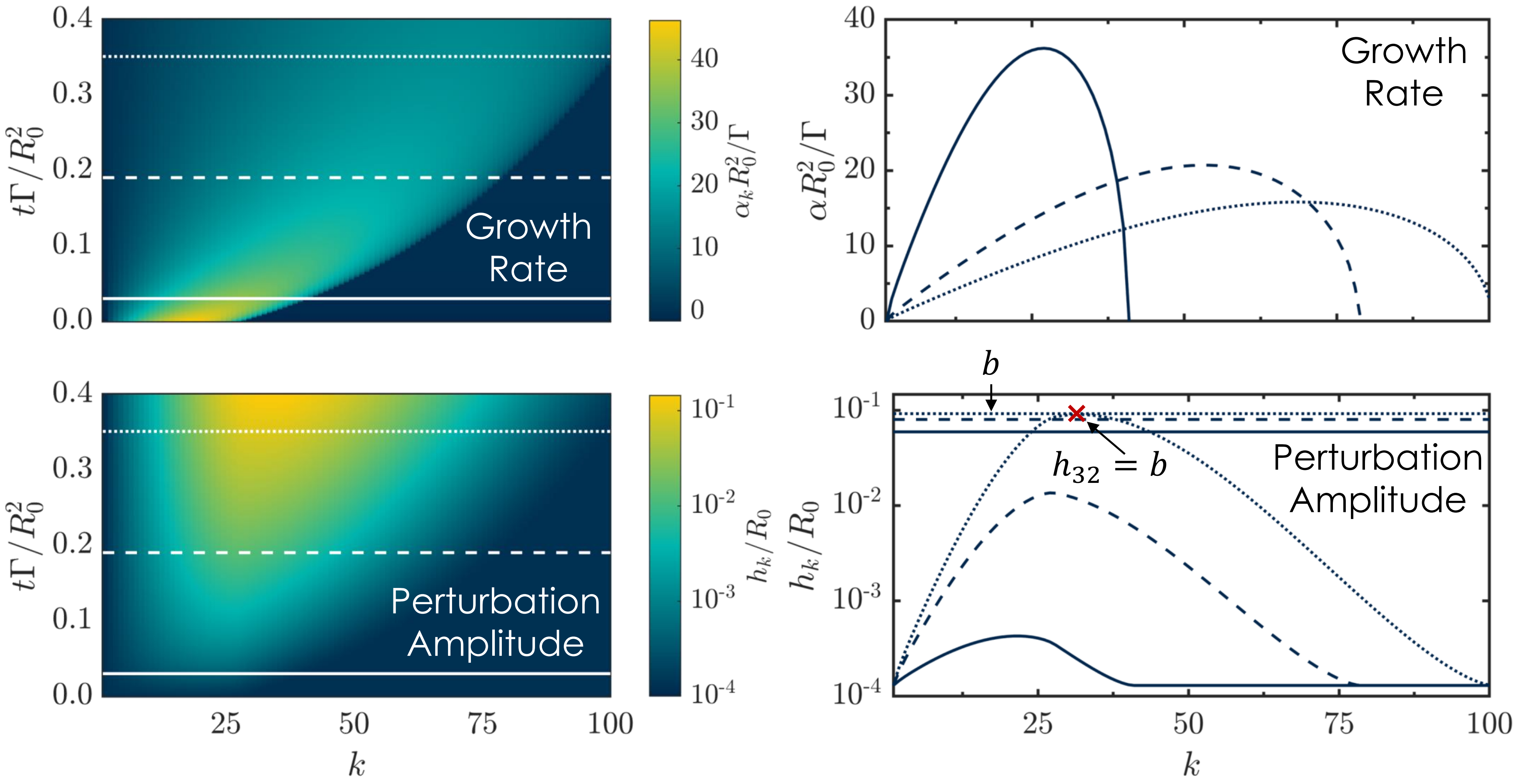
$b \approx 6.5 \times 10^{12}$ m

$\Gamma \approx 1.1 \times 10^{18}$ m^2/s

$|\boldsymbol{d}| \approx 1.6 \times 10^{10}$ m

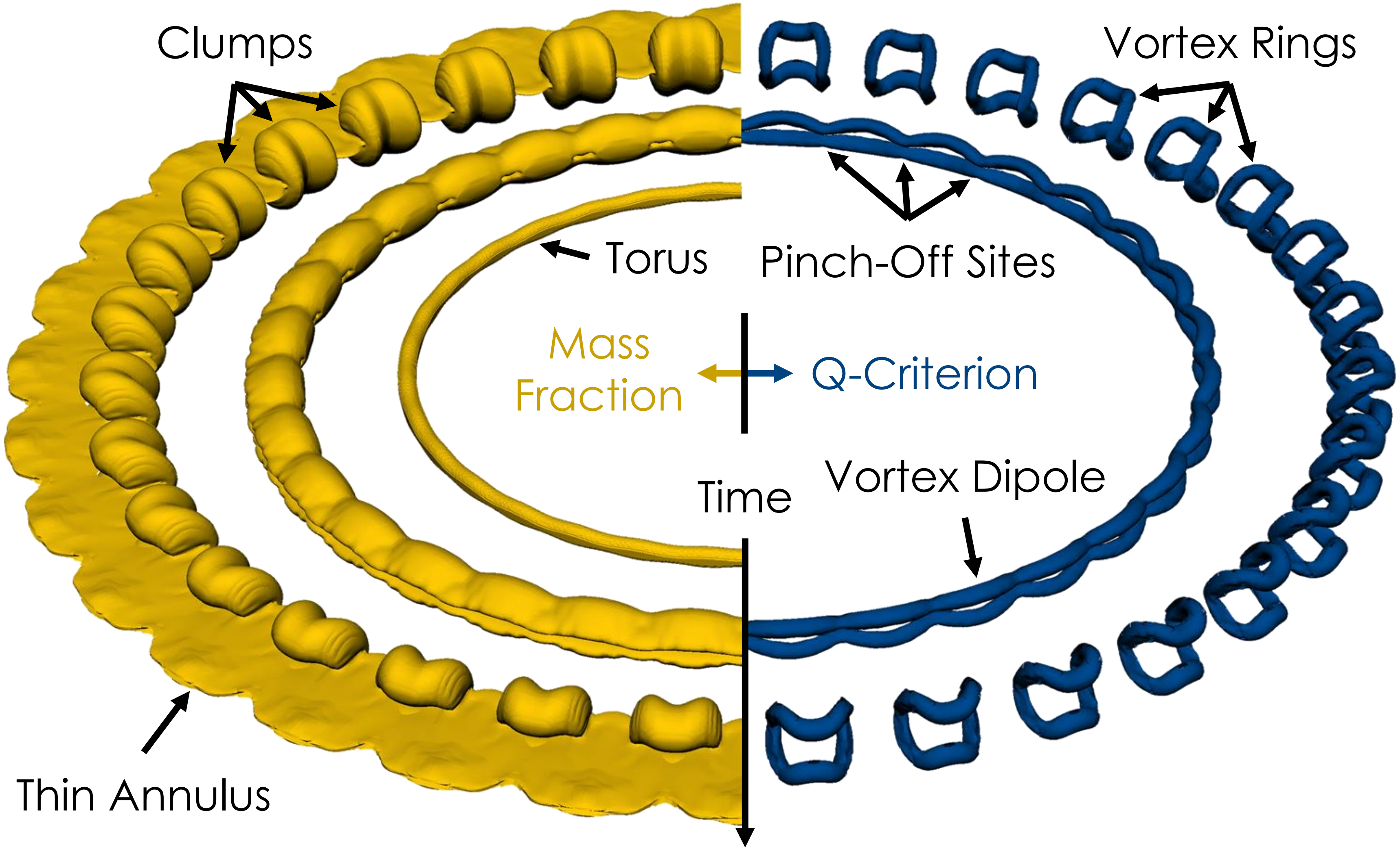
Crow, AIAA J., 8, 1970; Wadas, Phys. Rev. Lett., 132, 2024; Morris, Science, 315, 2007

For SN1987A, the dominant wavenumber matches the number of clumps.



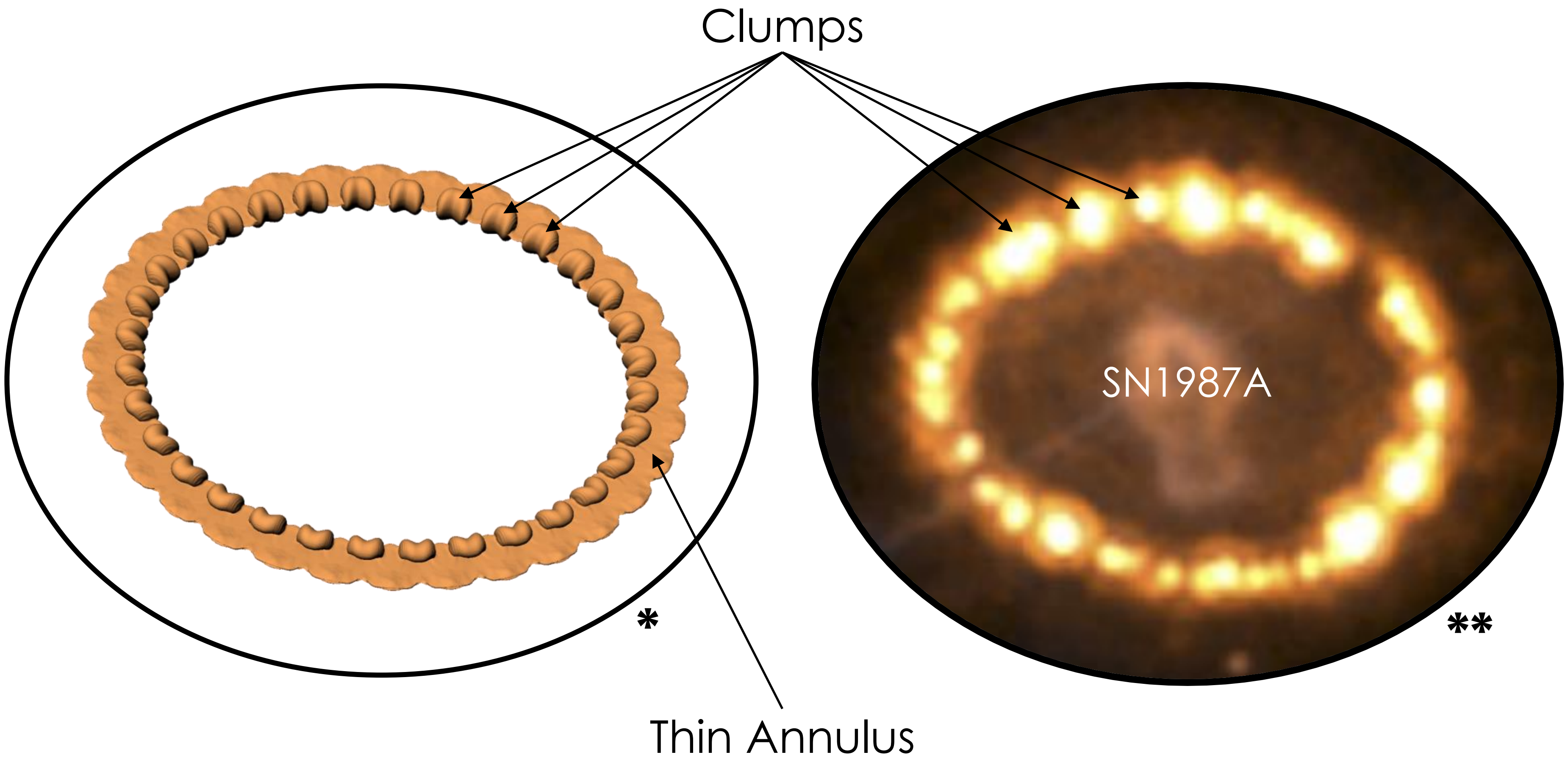
Wadas, Phys. Rev. Lett., 132, 2024

Simulations elucidate clump formation and SN1987A's inner clump annulus.



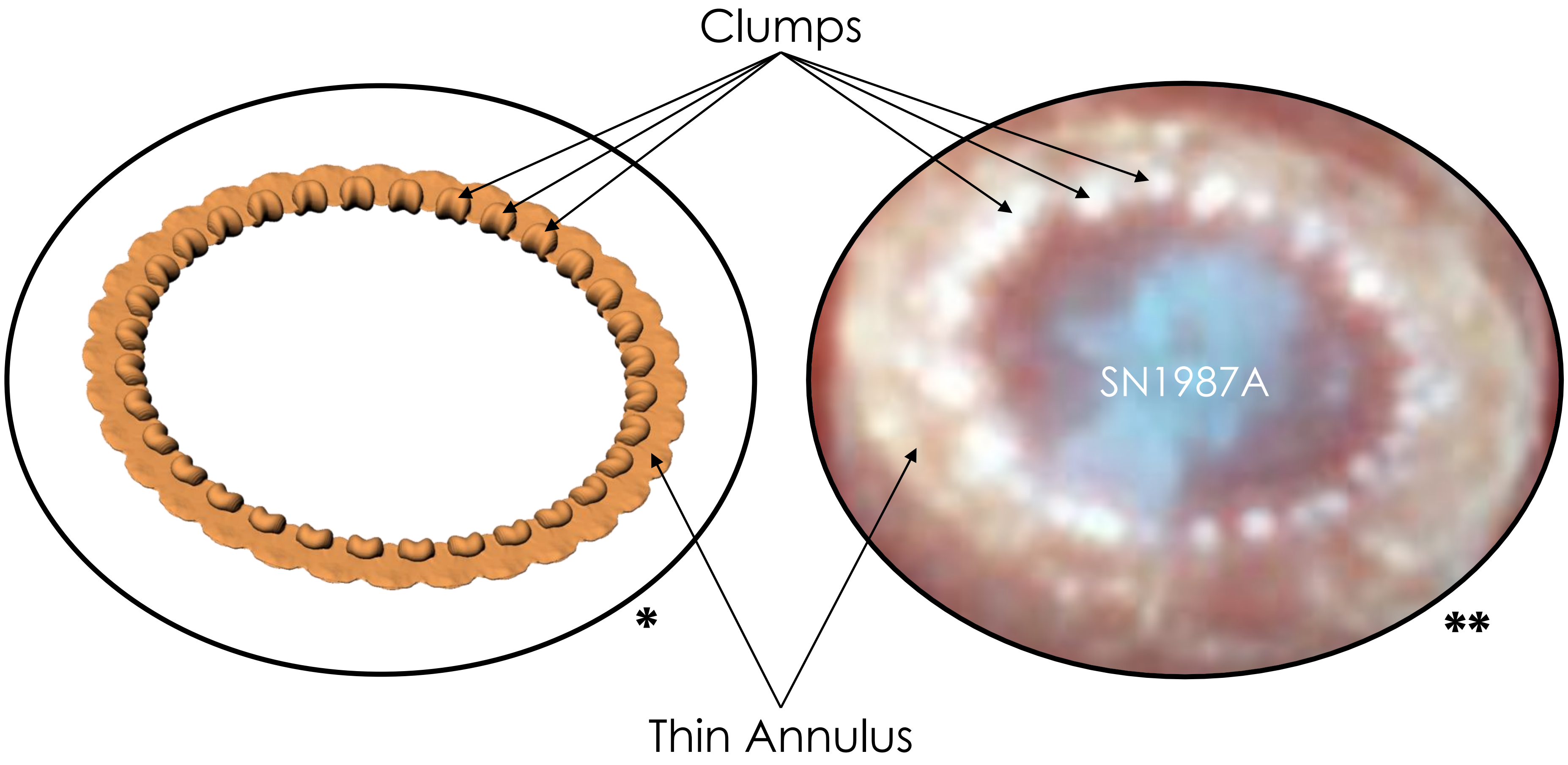
Wadas, Phys. Rev. Lett., 132, 2024

Simulations show good agreement with telescopic data.



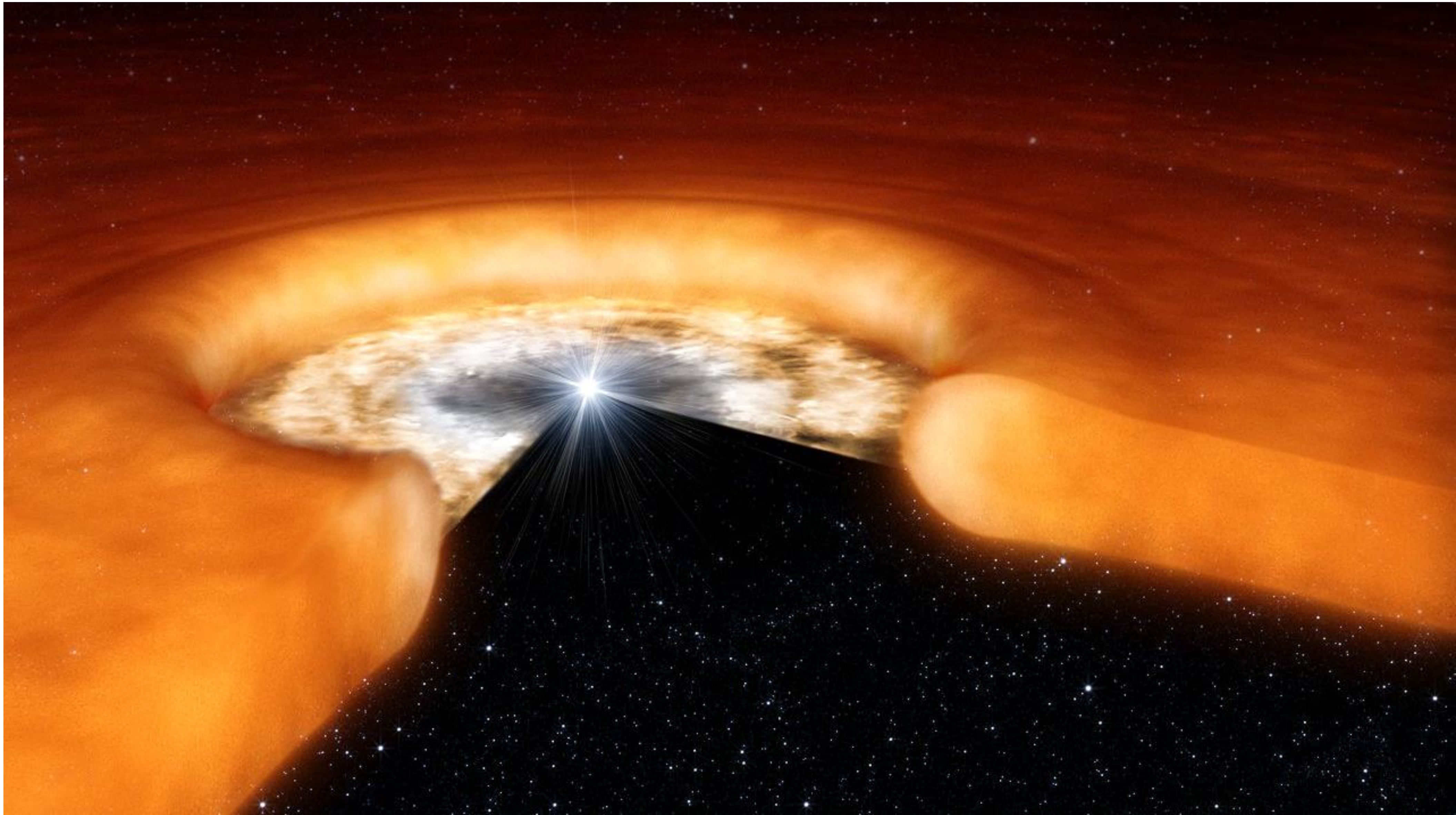
* Wadas, Phys. Rev. Lett., 132, 2024 ** Fransson, Astrophys. J., 806, 2015

Simulations show good agreement with telescopic data.



* Wadas, Phys. Rev. Lett., 132, 2024 ** NASA, ESA, CSA, Matsuura, 2023

Protoplanetary disks are the leftovers from star formation.



Solar wind can stimulate multiple vortex dipoles in protoplanetary disks.

Ejection: Intro

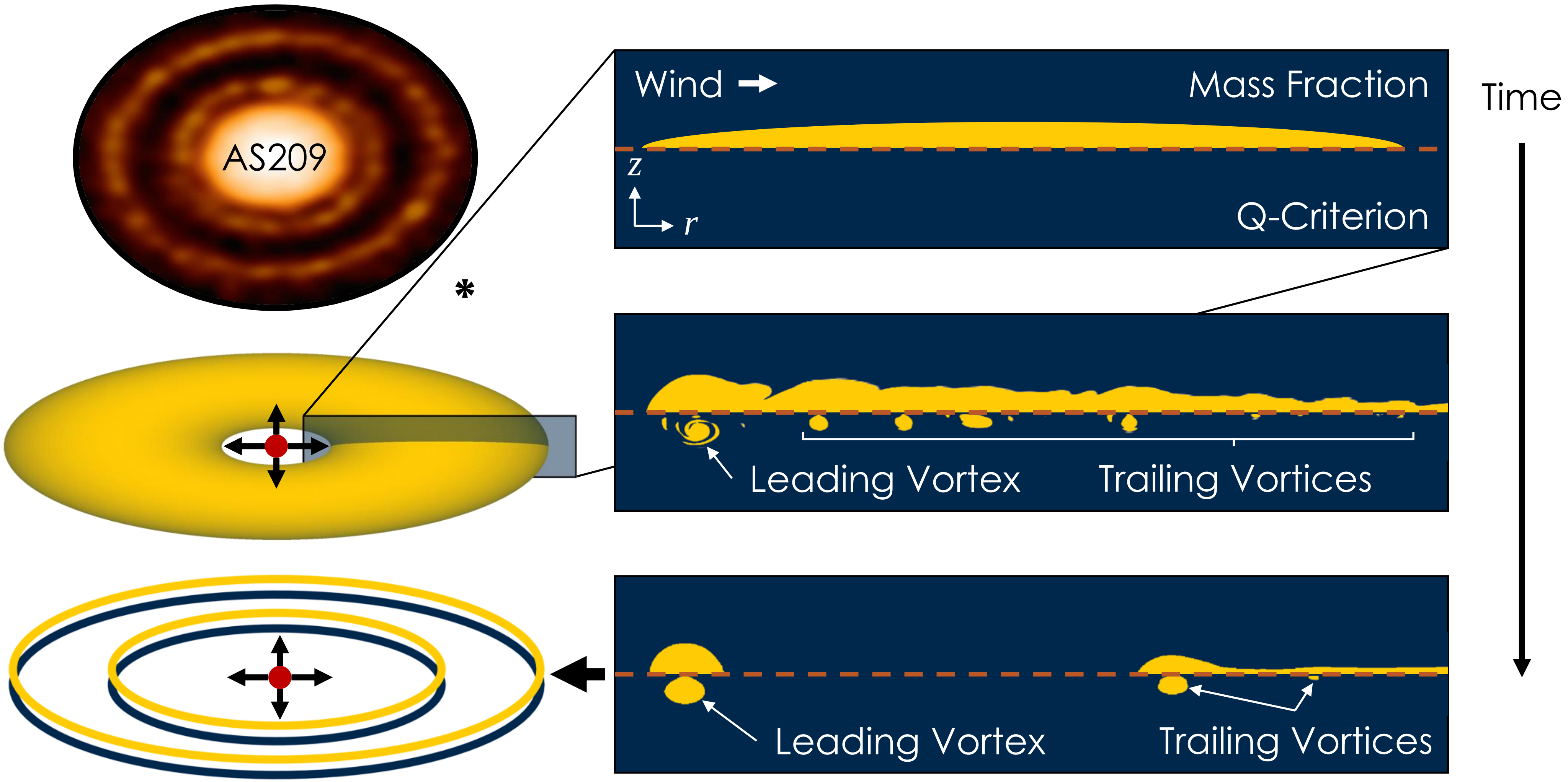
Ejection: Theory and Simulation

Ejection: Experiments

Clumping: Supernova 1987A

Clumping: Protoplanetary Disks

Conclusion



* Fedele, Astron. Astrophys. 610, 2018

Airplanes, vortex rings, and stars may share common vortex dynamics.

Ejection: Intro

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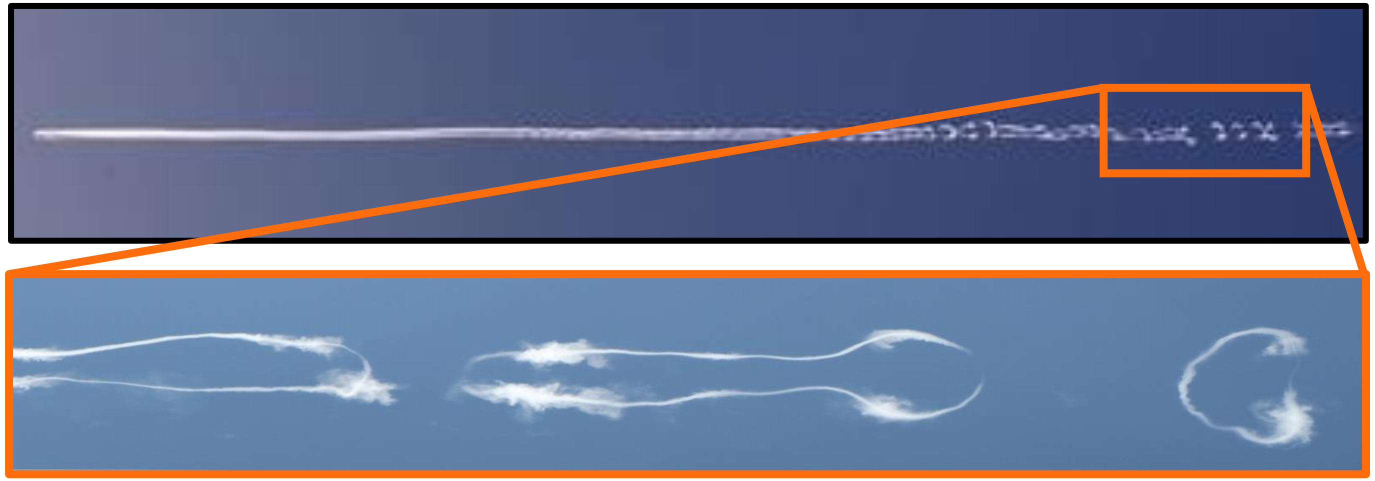

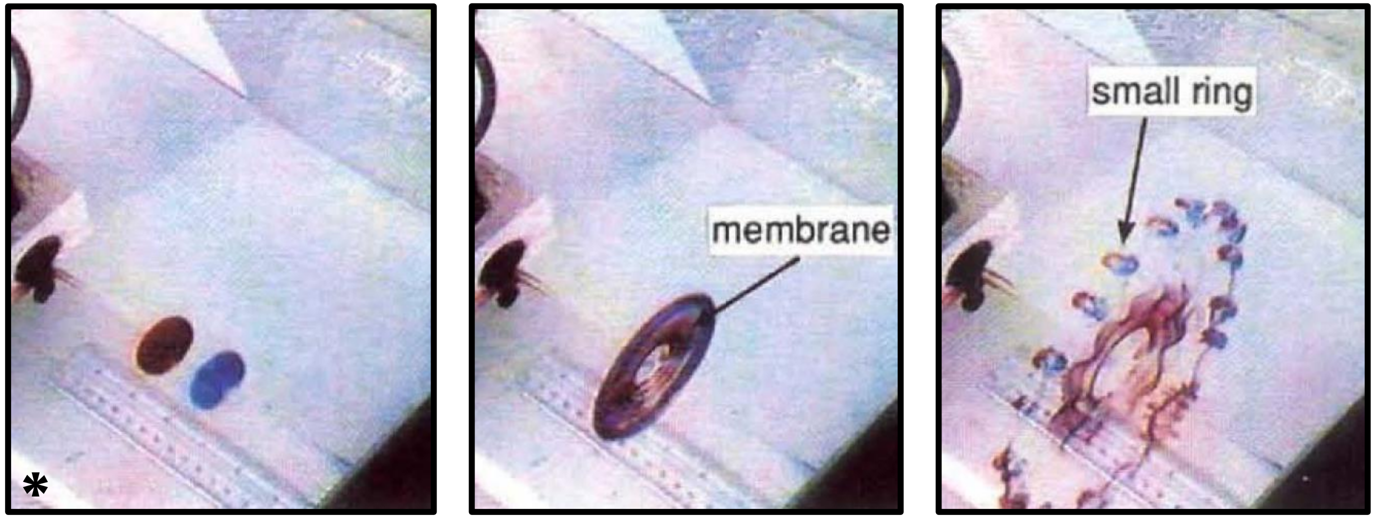

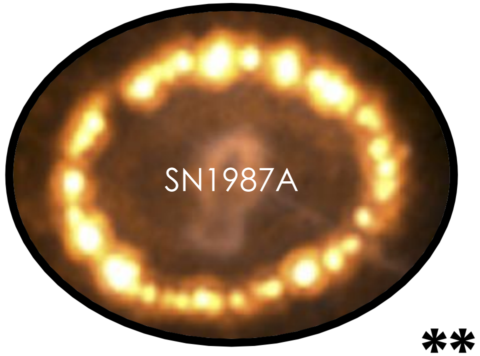

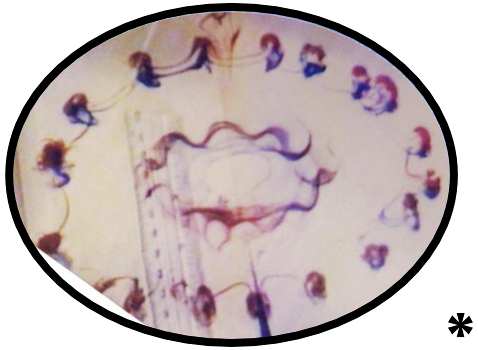

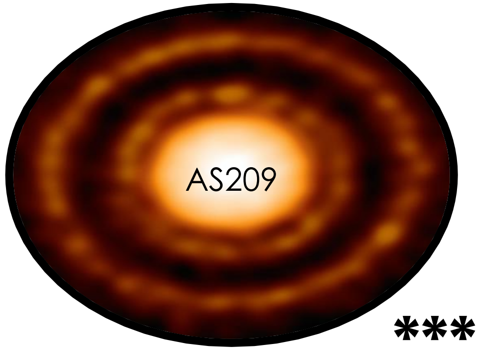

*Lim, Nat. Lett., 357, 1992 ** Fransson, Astrophys. J., 806, 2015 *** Fedele, Astron. Astrophys. 610, 2018

Ejection: Intro

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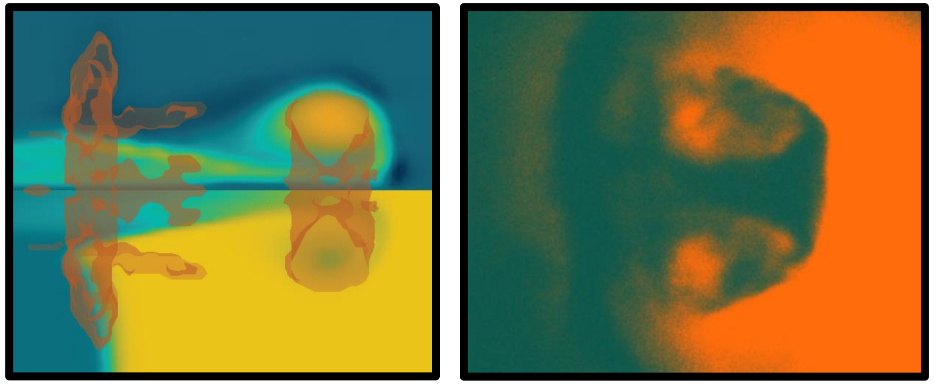
Conclusion

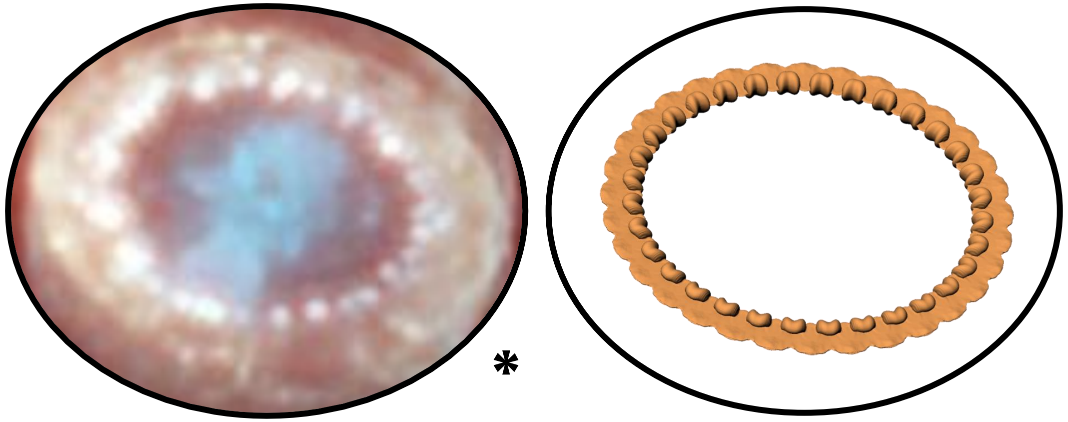
Summary

- <u>Vortex Ring Ejection from Shocked Interfaces</u>: Vortex rings abound in high-energy-density physics, including inertial fusion and supernovae, when shock waves accelerate fluid interfaces.
  - These compressible, multifluid rings may share many physics with their incompressible, single-fluid counterparts.
  - An extended theory describes the formation dynamics of such rings.
  - Ongoing experiments at the Omega EP laser facility isolate vortex ring formation.
- <u>Vortex Instability and Circumstellar Clumping</u>: The Crow instability may stimulate the formation of clumps along the circumstellar gas cloud around Supernova 1987A.
  - Stability analysis predicts a dominant wavelength consistent with the number of clumps, and simulations reproduce key observables.
  - A similar instability mechanism may stimulate clumping in protoplanetary disks.

Part 1



Part 2



*NASA, ESA, CSA, Matsuura et al. (2023)

Thank you!

Questions?