

Title: Understanding the SASI with simple microphysics

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URL: <http://pirsa.org/11060026>

Abstract: A stalled core-collapse supernova shock is unstable to non-spherical perturbations, in what is known as the Standing Accretion Shock Instability (SASI). This instability is global and oscillatory, affecting the region between the protoneutron star surface and the shock. I'll discuss several insights into this instability obtained by combining linear stability analysis and time-dependent simulations, using simple prescriptions for the microphysics that capture the essential physics of the problem.

Understanding the SASI with simple Microphysics

Rodrigo Fernández
Einstein Fellow - Institute for Advanced Study

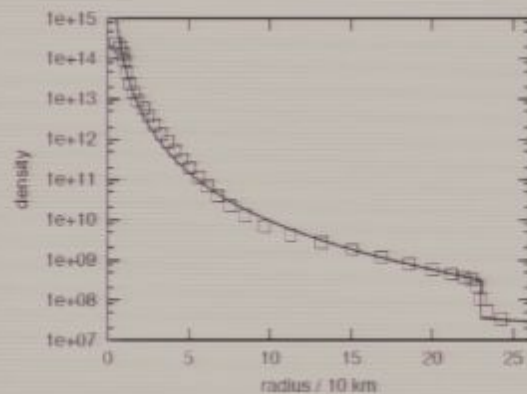
Outline

1. What is the SASI?
2. Some General Properties
3. Angular Momentum Redistribution in 3D

Brief History

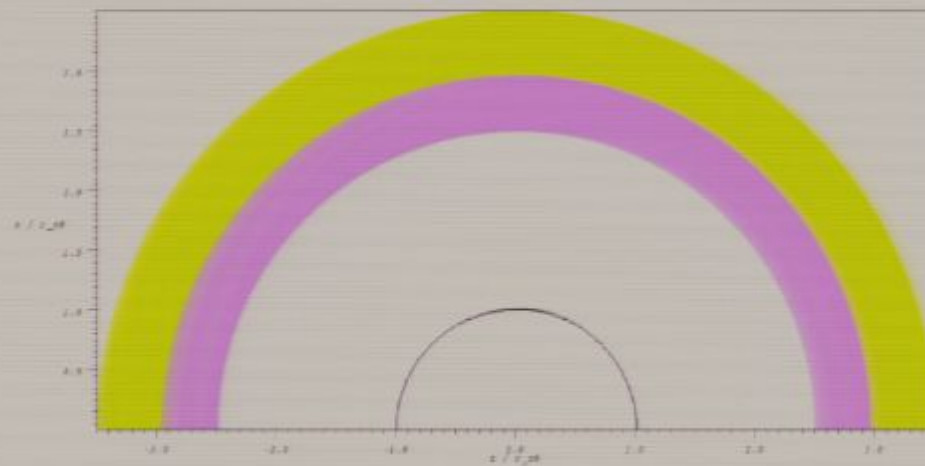
SASI = Standing/Spherical/Stationary Accretion Shock Instability

- First seen in **2D** core-collapse simulations with Riemann solvers (Burrows et al. 1995, Janka & Müller 1996, Mezzacappa et al. 1998)
- **SASI** isolated in simplified setup by Blondin et. al (2003):



Non-radial modes unstable for CCSNe parameters (2D)

SASI (no heating/convection)



Mass shells colored by
passive scalar,
shock is black circle
(FLASH2.5 Simulations)

$$r_{s0} = \text{unperturbed shock radius} = 1$$

$$v_{ff0} = \sqrt{\frac{2GM}{r_{s0}}} = 1$$

$$\rho_1 = \text{upstream density} = 1$$

$$\dot{M} = \text{constant}$$

$$\gamma = 4/3 \quad \text{ideal gas EOS}$$

Point Mass Gravity

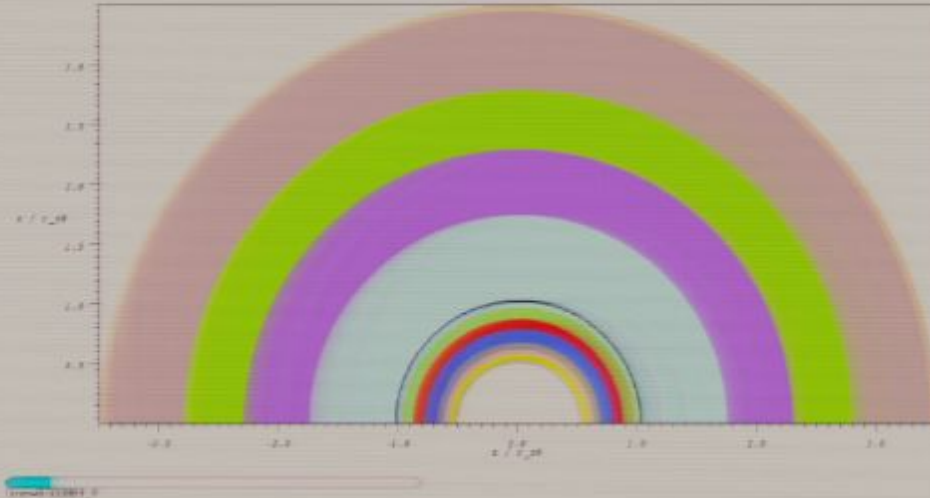
$$r_*/r_{s0} = 0.4$$

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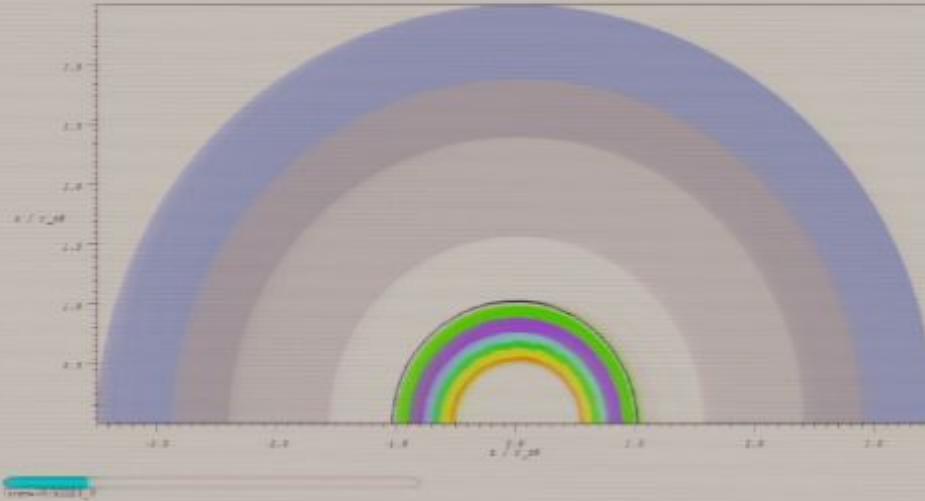
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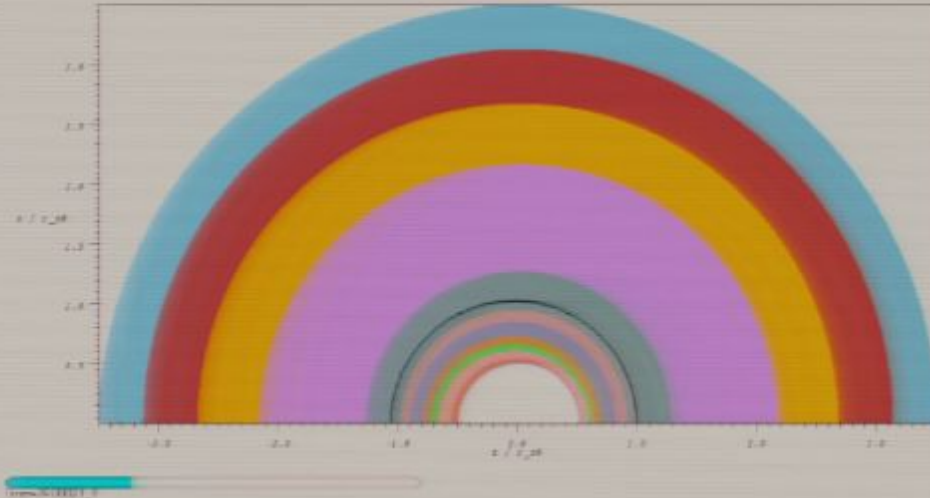
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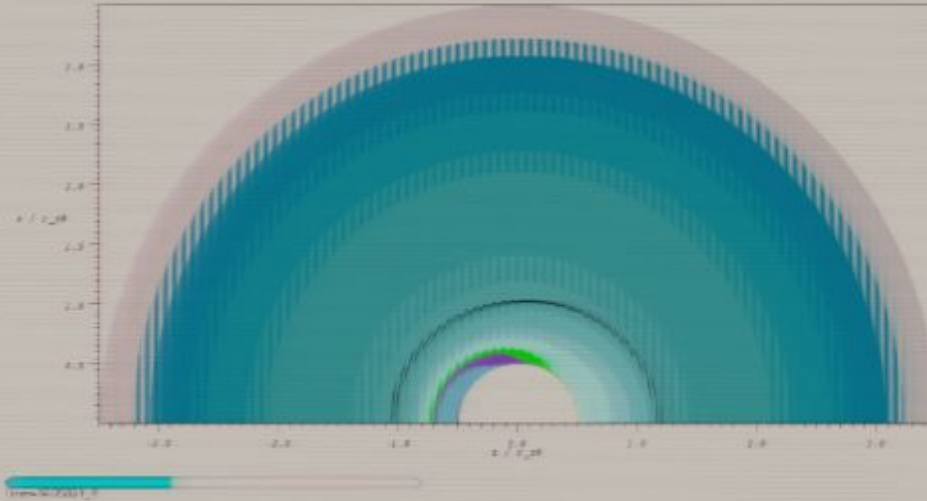
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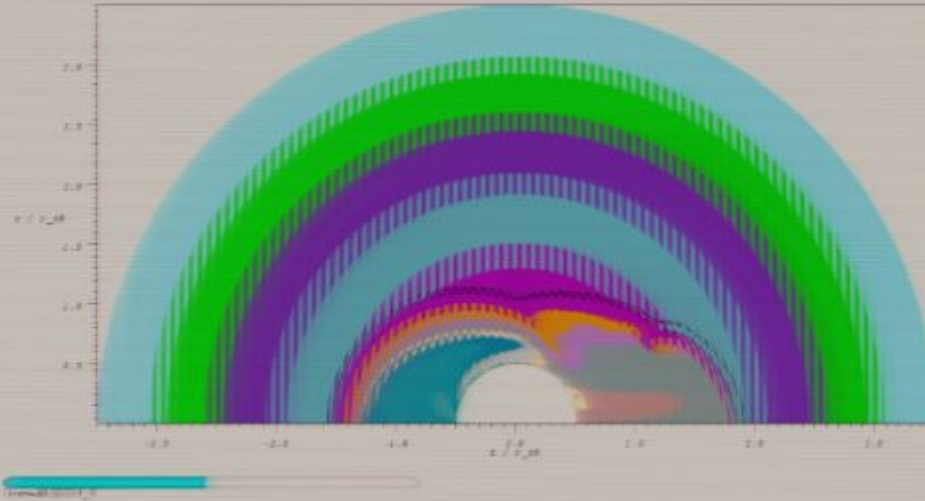
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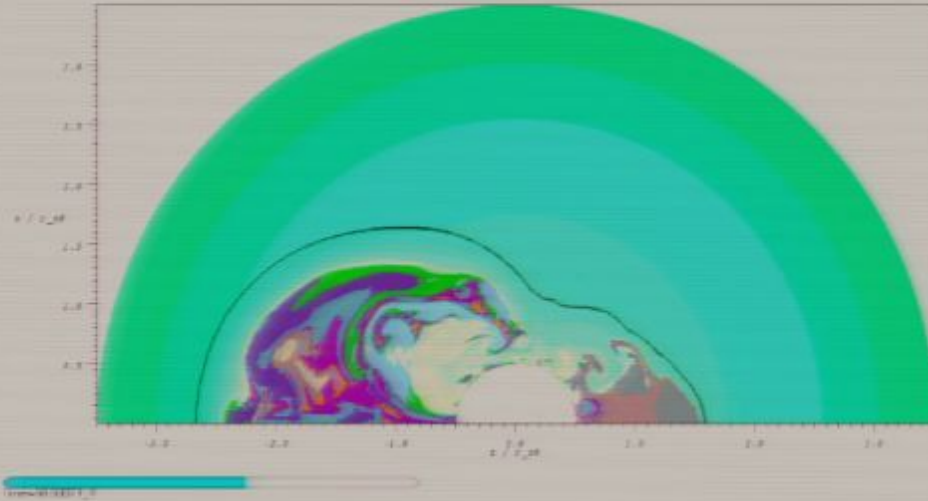
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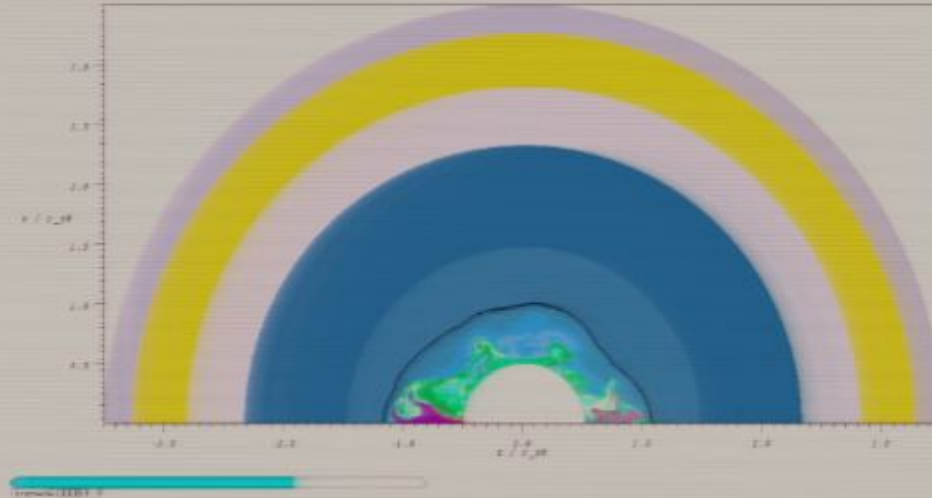
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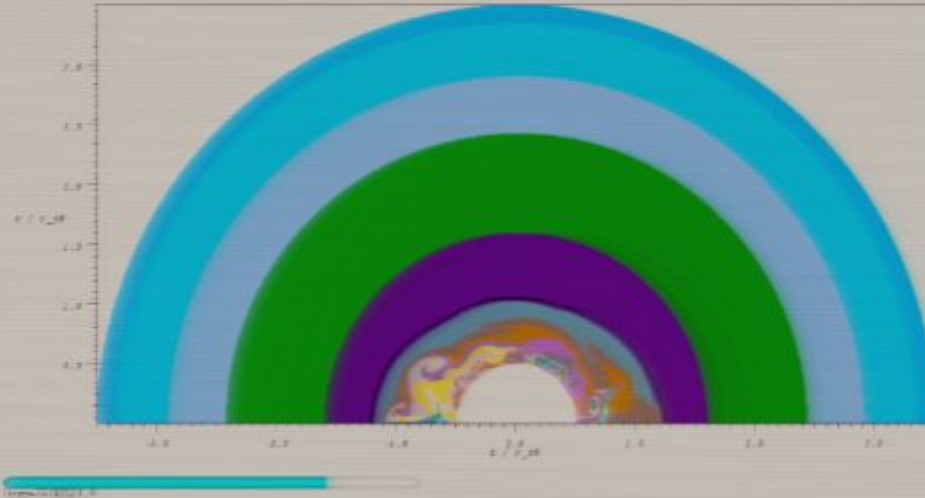
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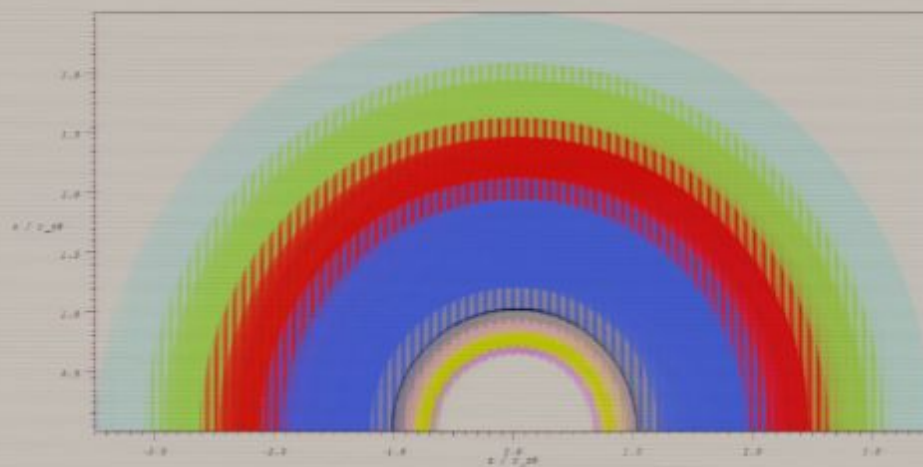
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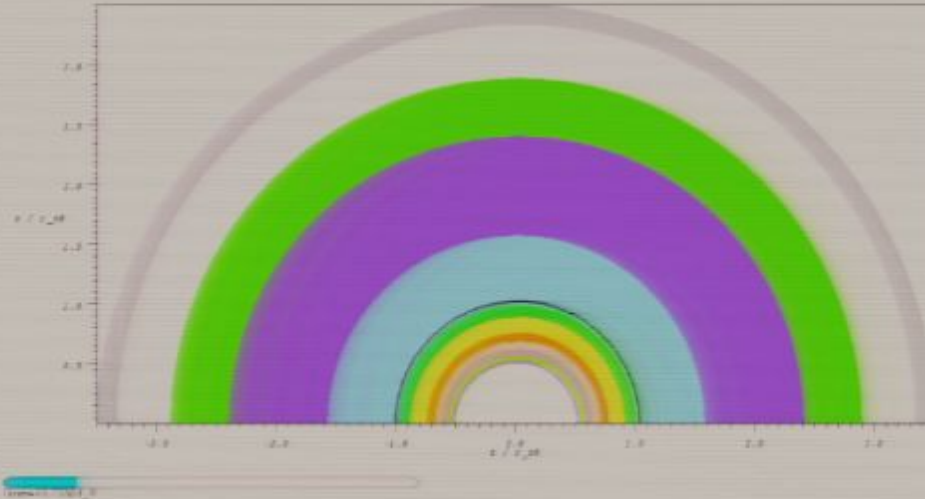
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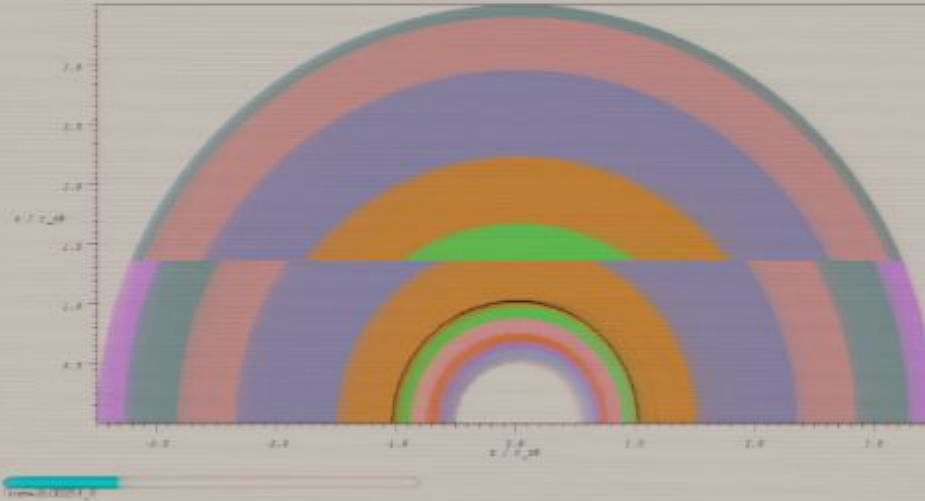
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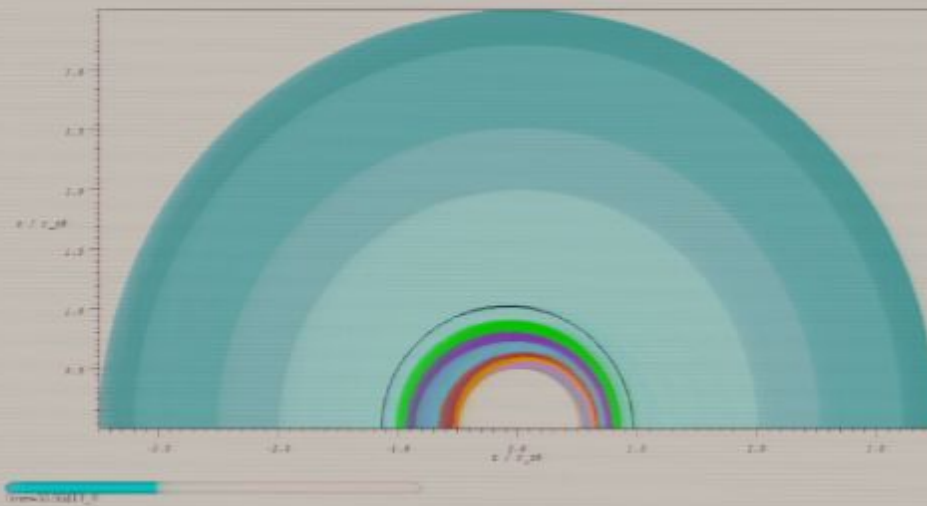
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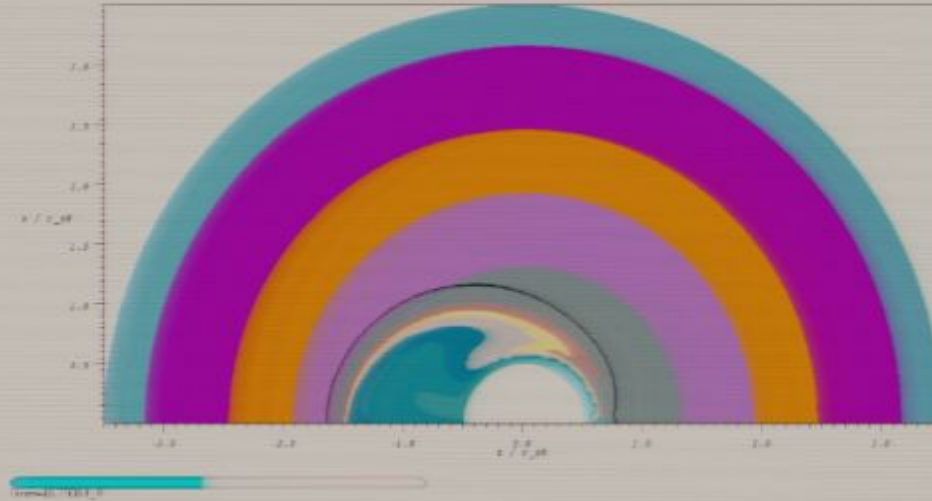
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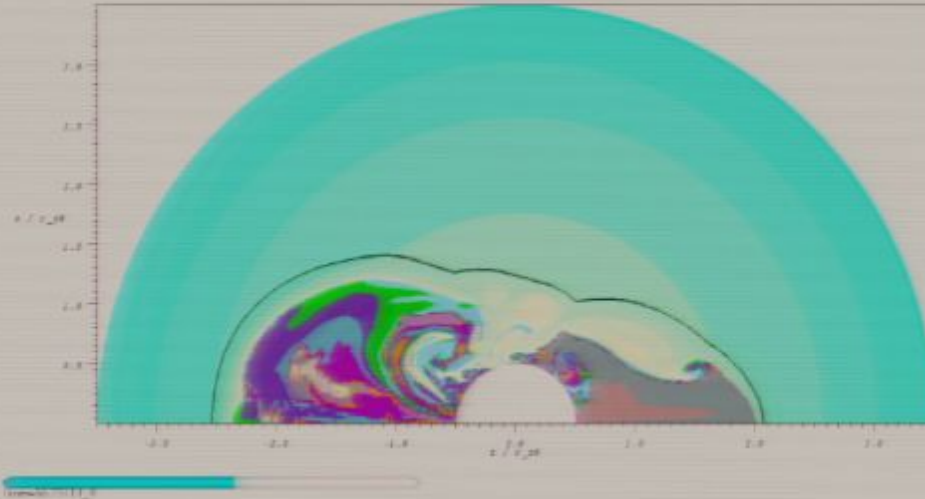
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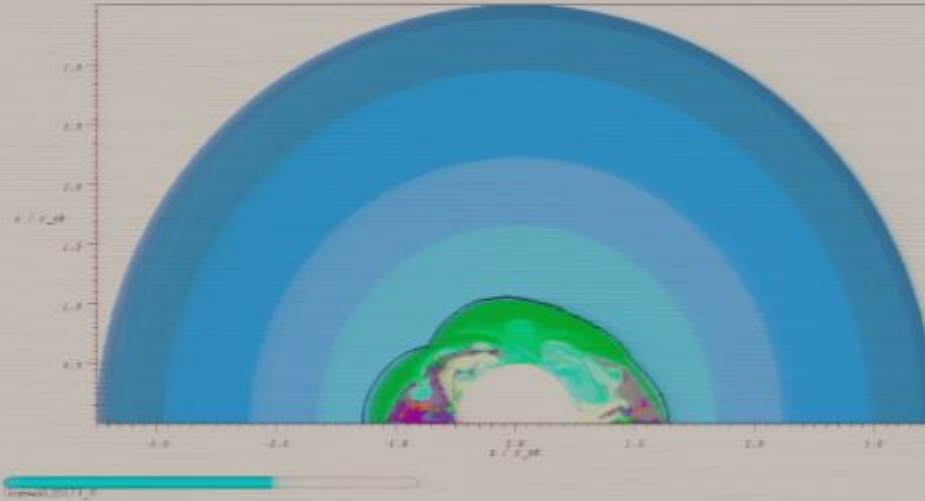
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Instability Mechanism

Lateral Sound Waves

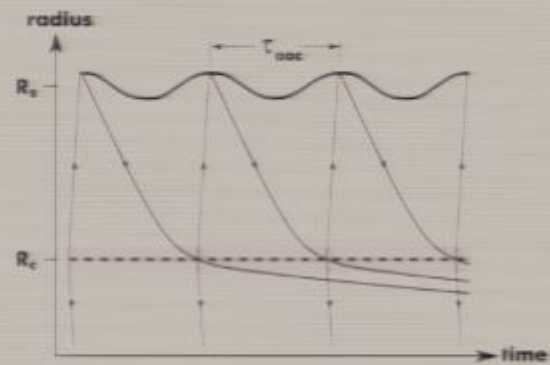
Blondin & Mezzacappa (2006)



Blondin & Mezzacappa (2006)

Advective-Acoustic Cycle

Fogliizzo et al. (2007)



Scheck et al. (2008)

Good in WKB limit

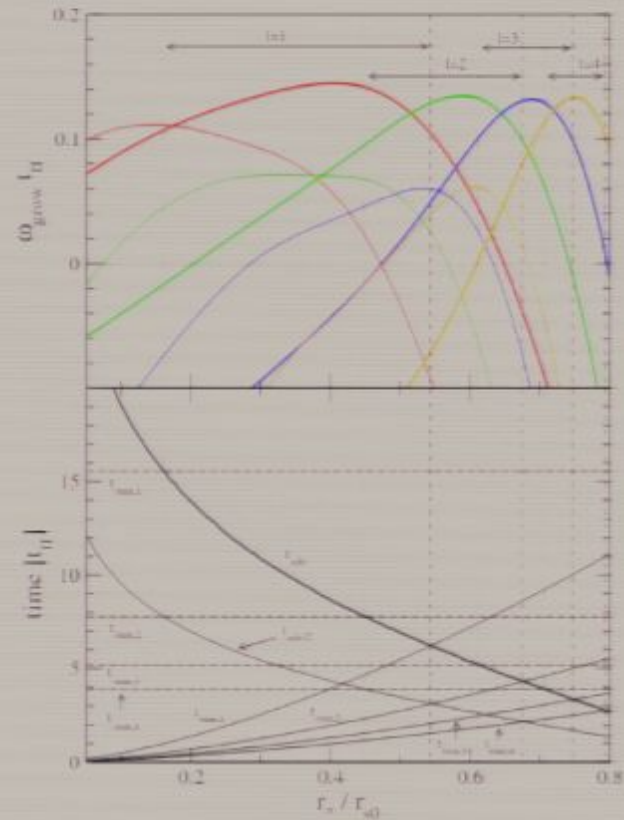
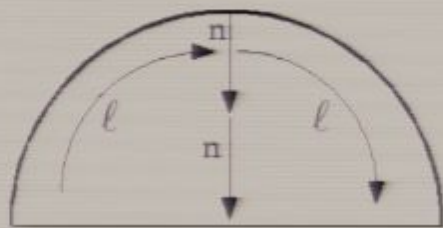
Relevant Timescales

Most unstable mode:

$$t_{\min,\ell} < \frac{t_{\text{adv}}}{(n+1)} < t_{\max,\ell}$$

$$t_{\max,\ell} = \frac{2\pi r_{s0}}{\ell c_{s,2}} \leftarrow \text{postshock} \quad \text{Legendre index}$$

$$t_{\min,\ell} = \frac{2\pi r_*}{\ell c_{s,\text{max}}} \simeq t_{\max,\ell} \left(\frac{r_*}{r_{s0}} \right)^{3/2}$$

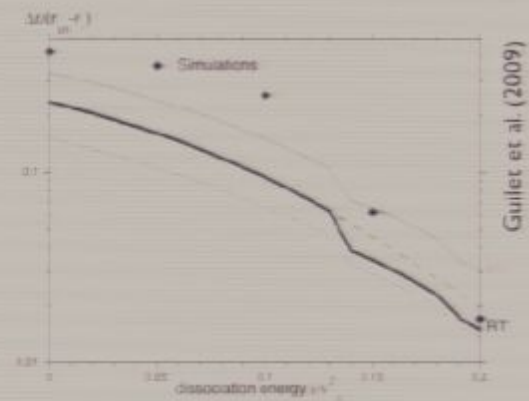
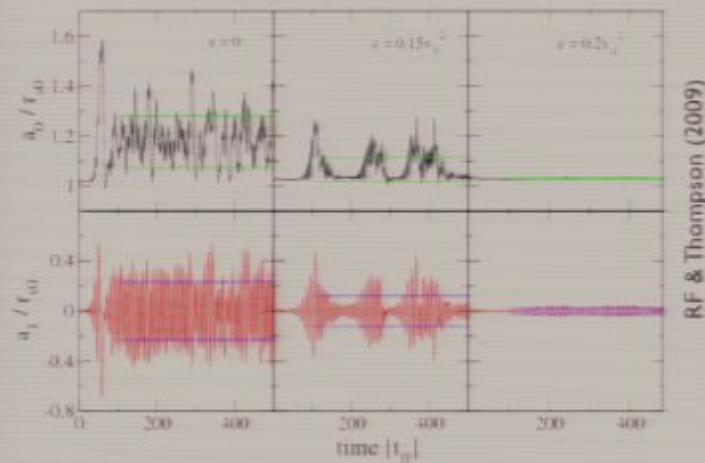


RF & Thompson (2009)

Saturation Amplitude (2D)

Nuclear Dissociation at Shock Reduces Amplitudes:

$\varepsilon =$ nuclear dissociation energy per unit mass $a_0(t), a_1(t) =$ shock Legendre coefficients

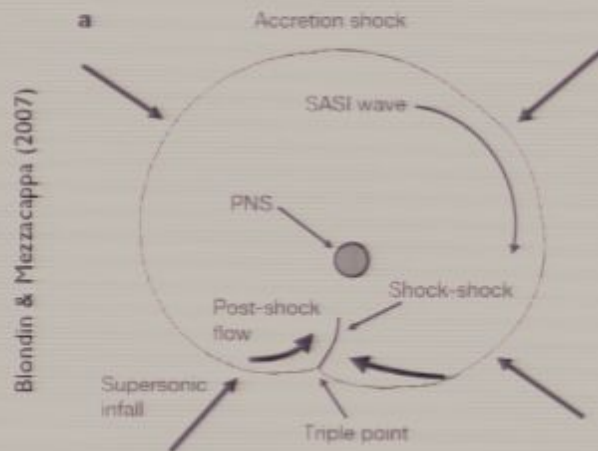


Linear Modes are subject to **Parasitic Instabilities**

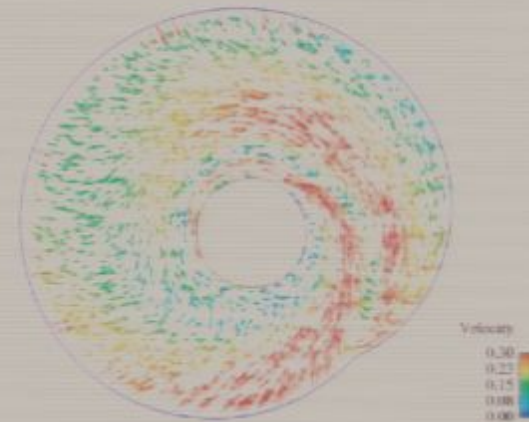
- Rayleigh Taylor (RT)
- Kelvin Helmholtz (KH)



Spiral Modes (3D)



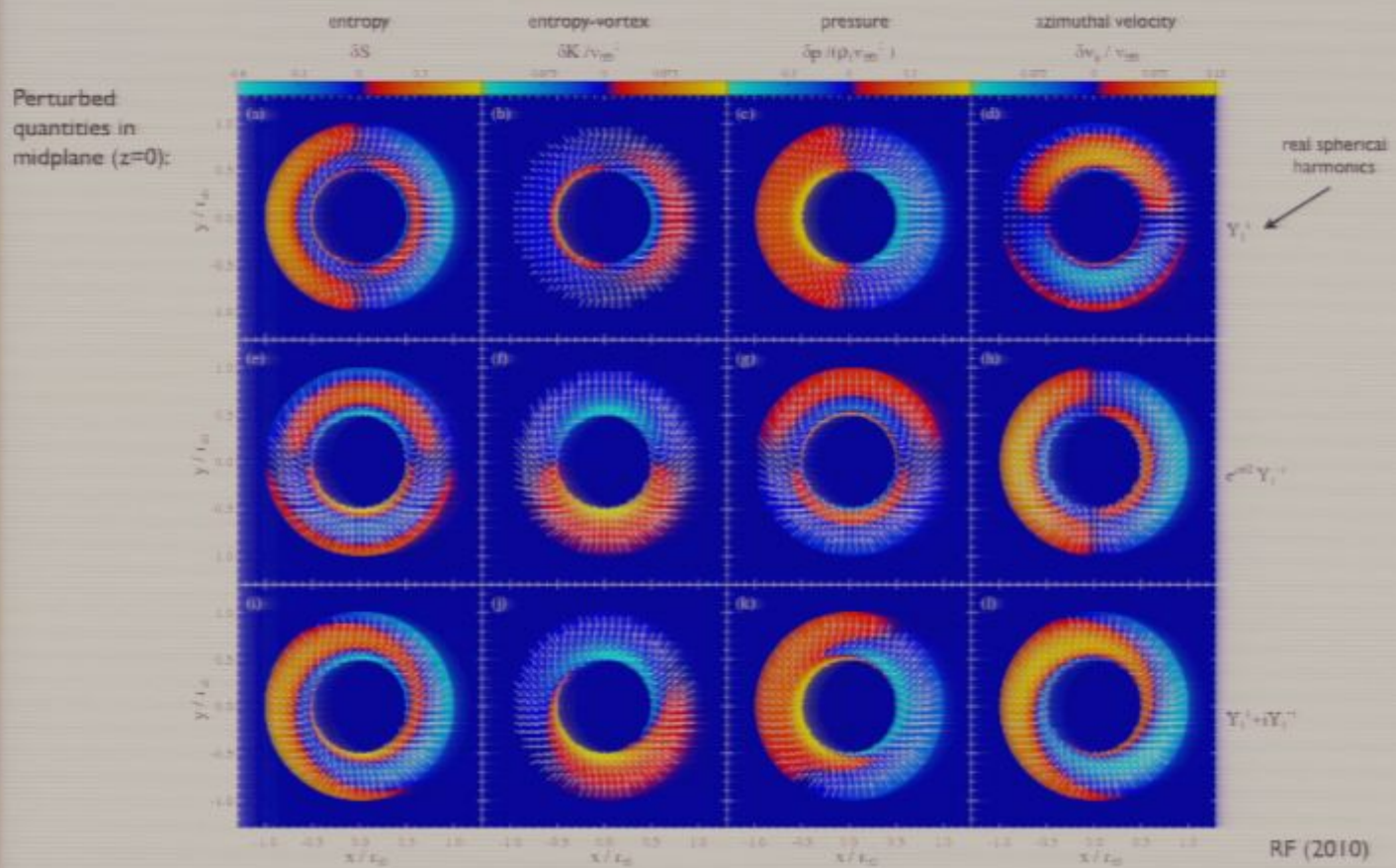
Blondin & Shaw (2007)



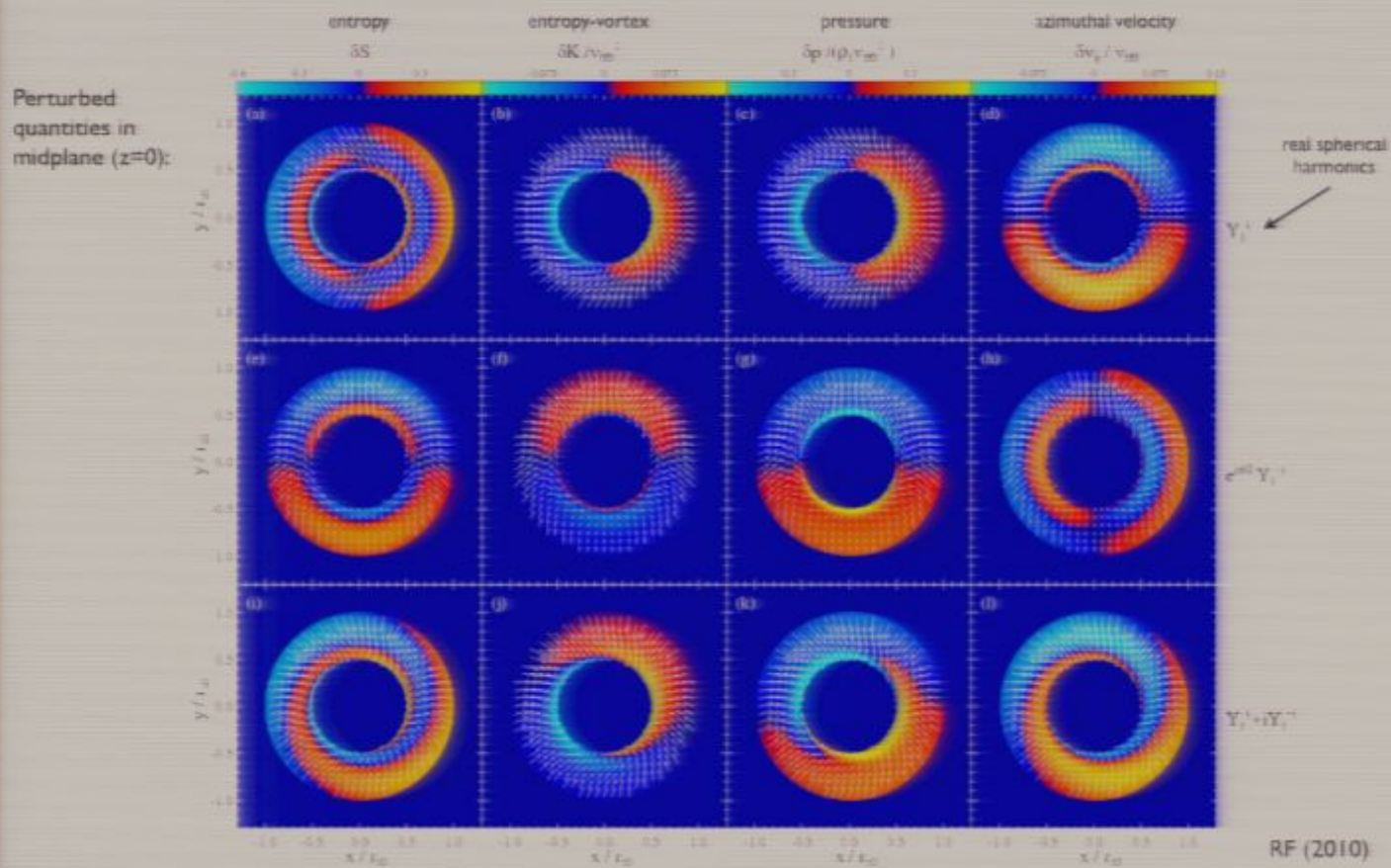
Accreted Angular Momentum: $\Delta L \sim 2.5 \times 10^{47} \left(\frac{\Delta M}{0.1 M_{\odot}} \right) \text{ g cm}^2 \text{ s}^{-1}$

Pulsar Spin: $P = \frac{2\pi I}{\Delta L} \sim 50 \left(\frac{I}{2 \times 10^{45} \text{ g cm}^2} \right) \text{ ms}$

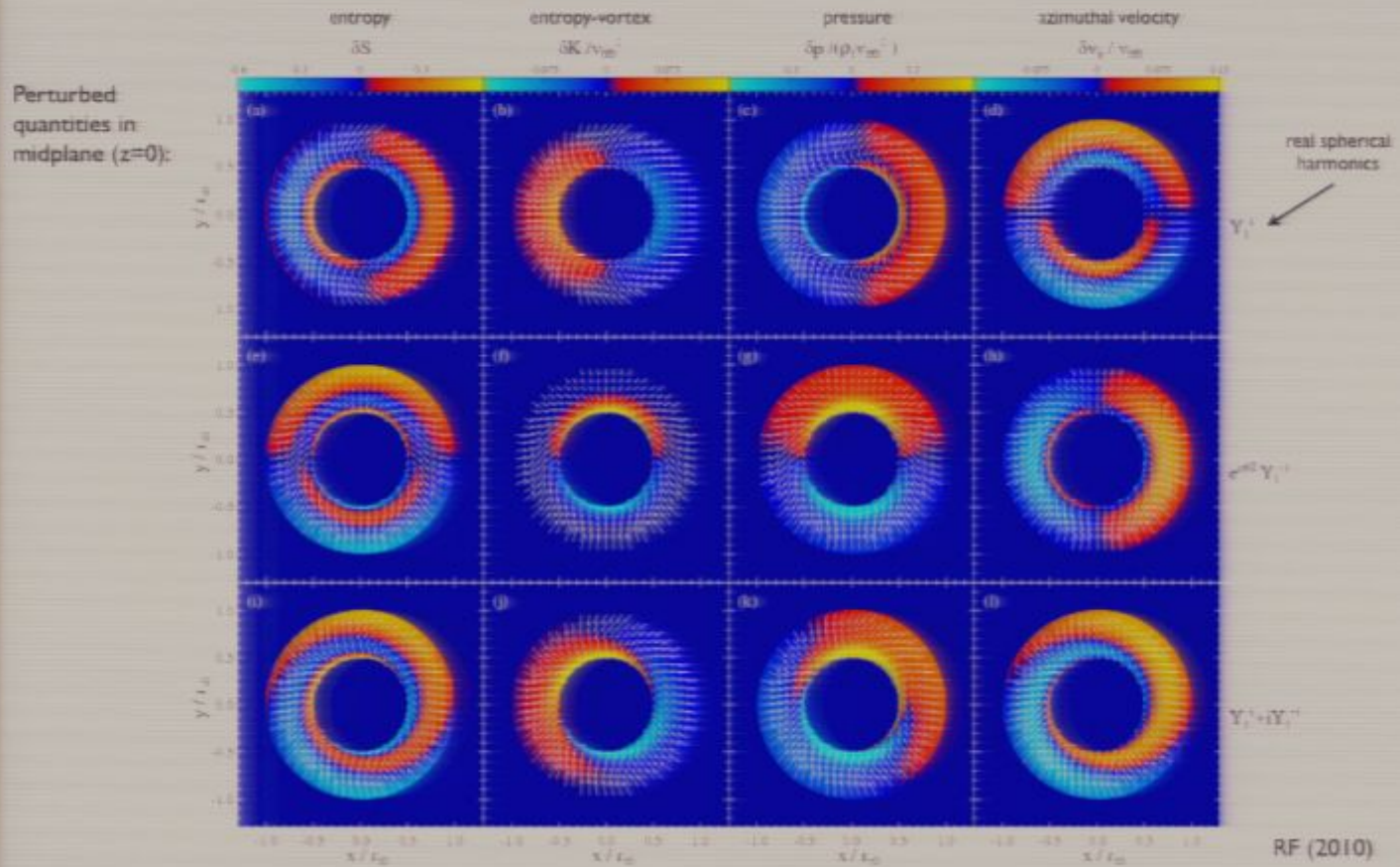
Spiral Modes = 2+ Axisymmetric Modes out of Phase



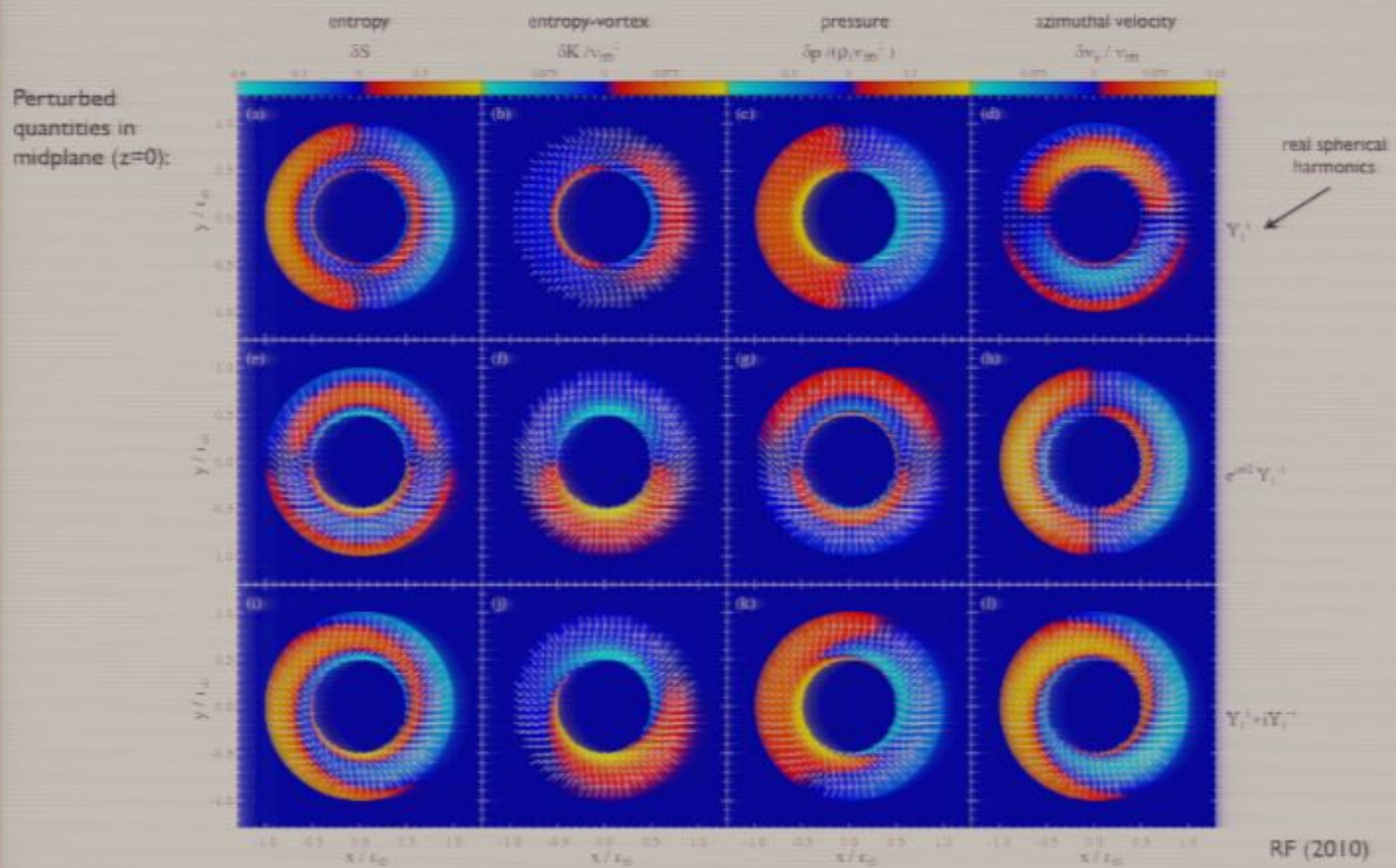
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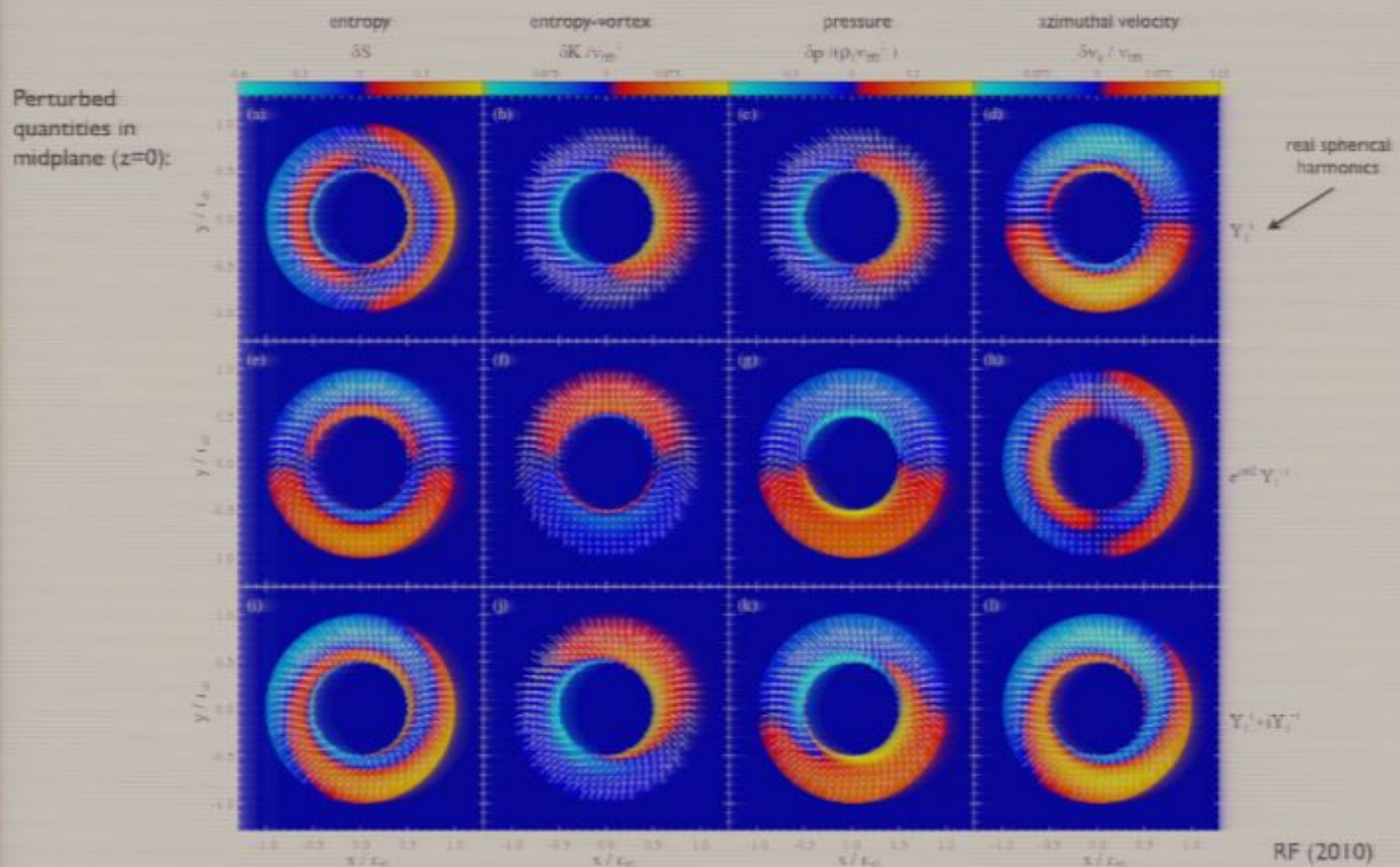
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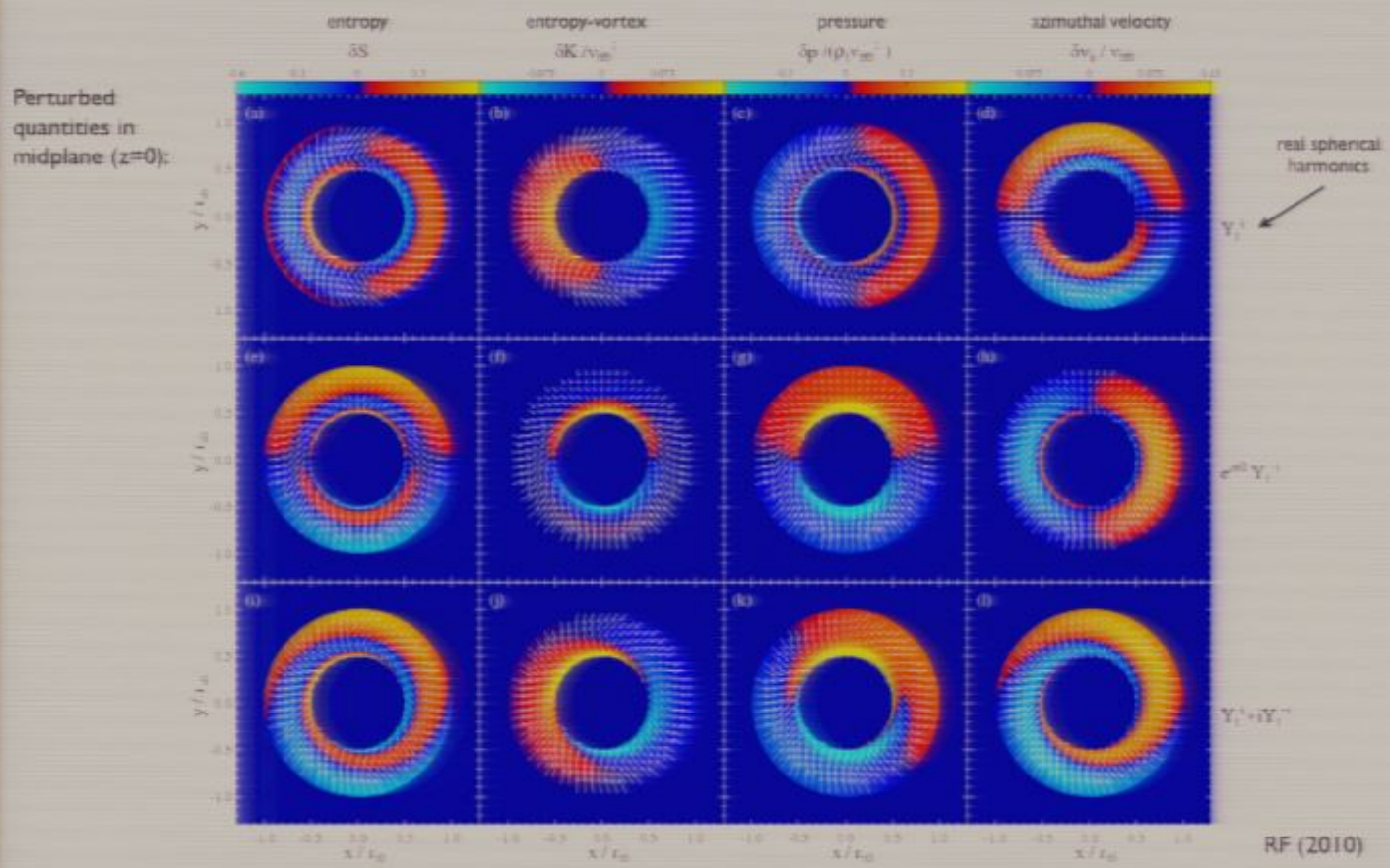
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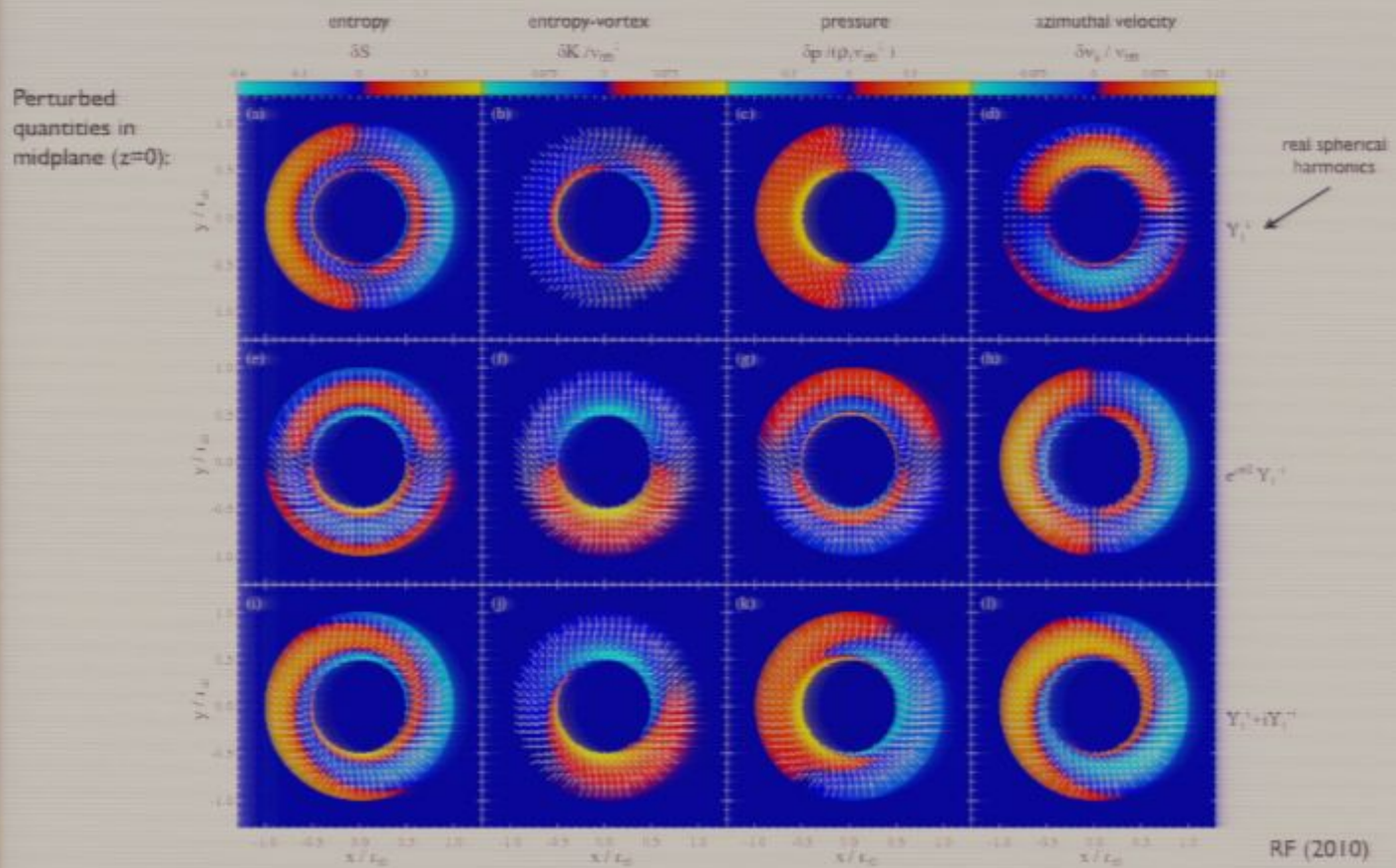
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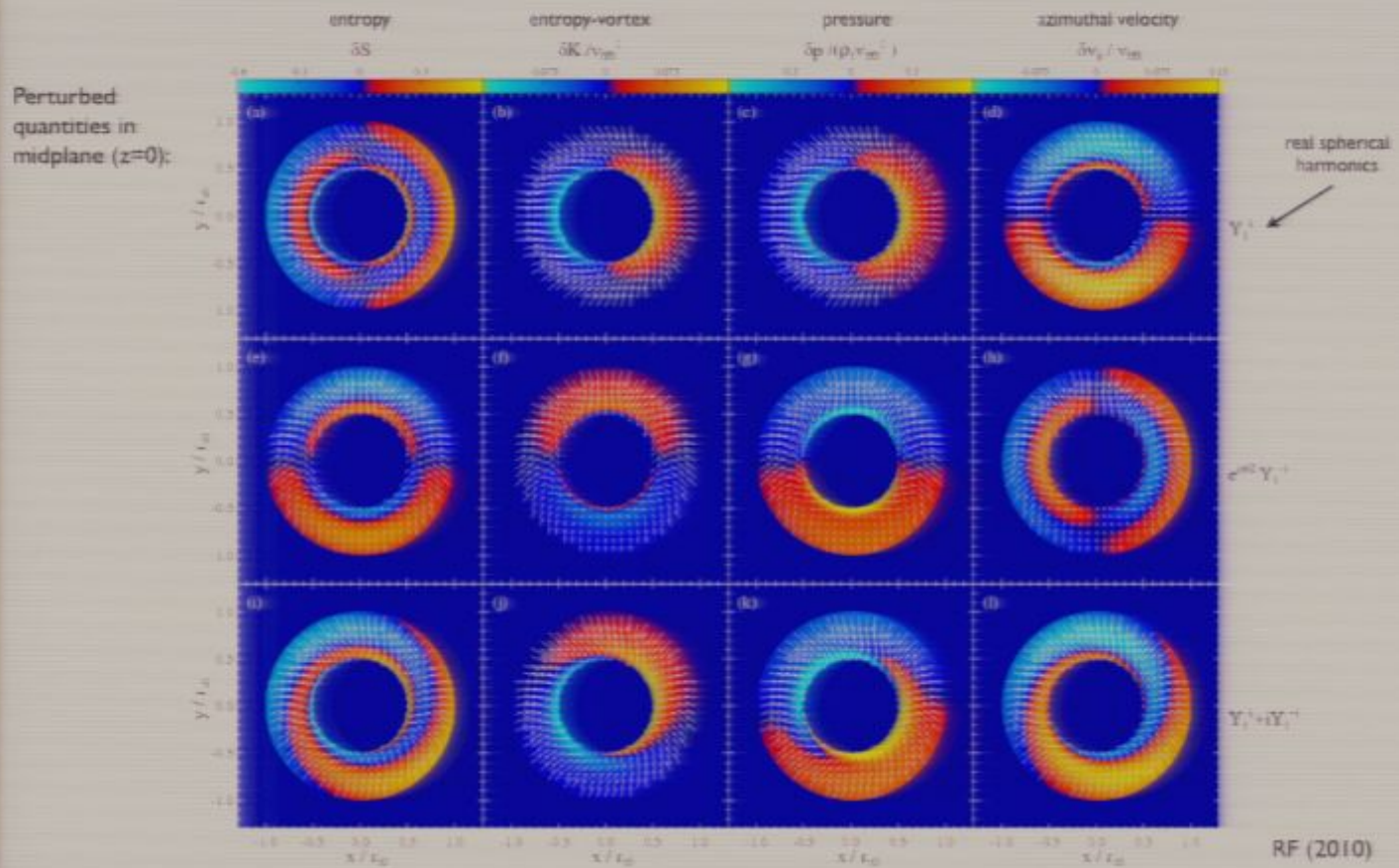
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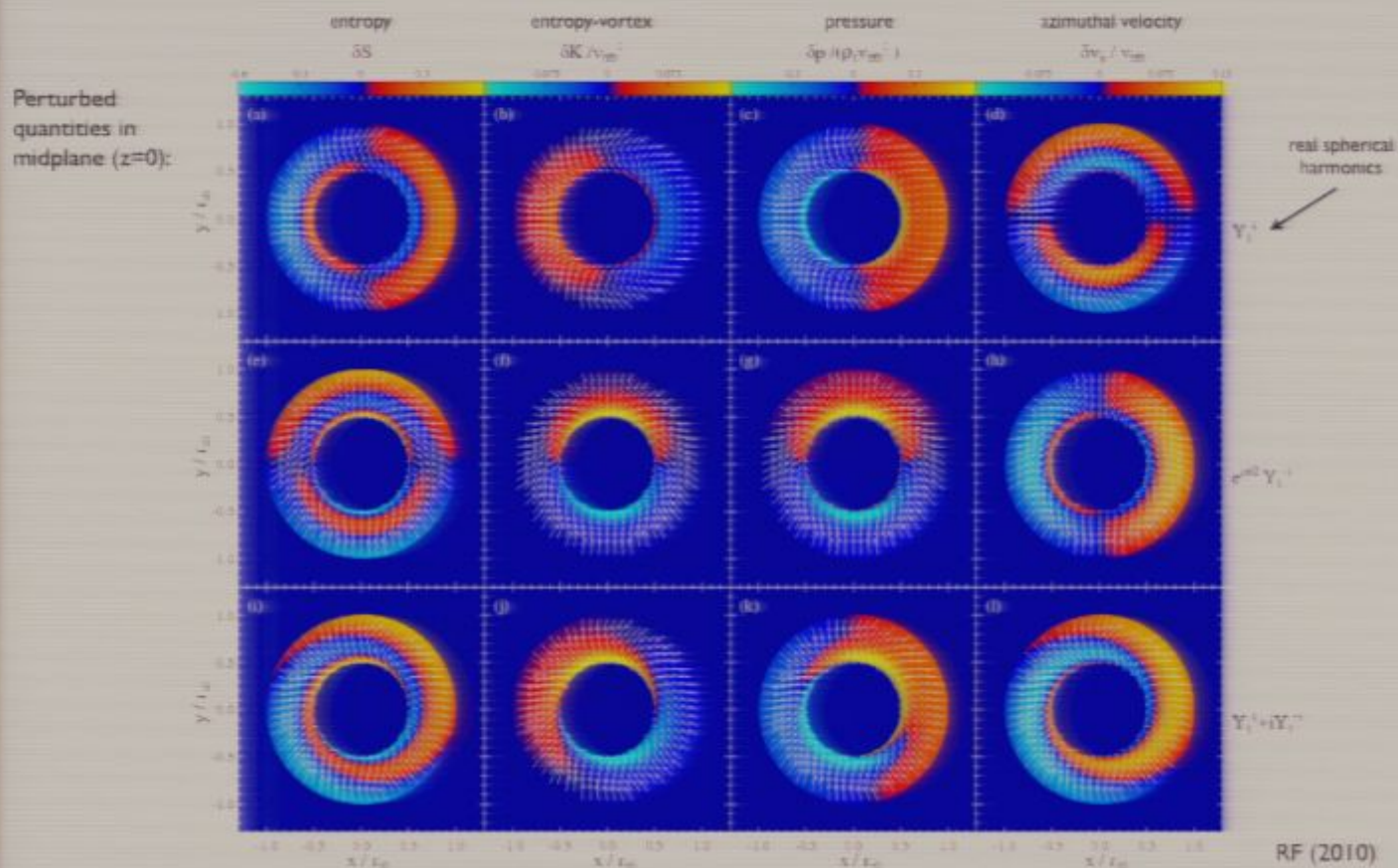
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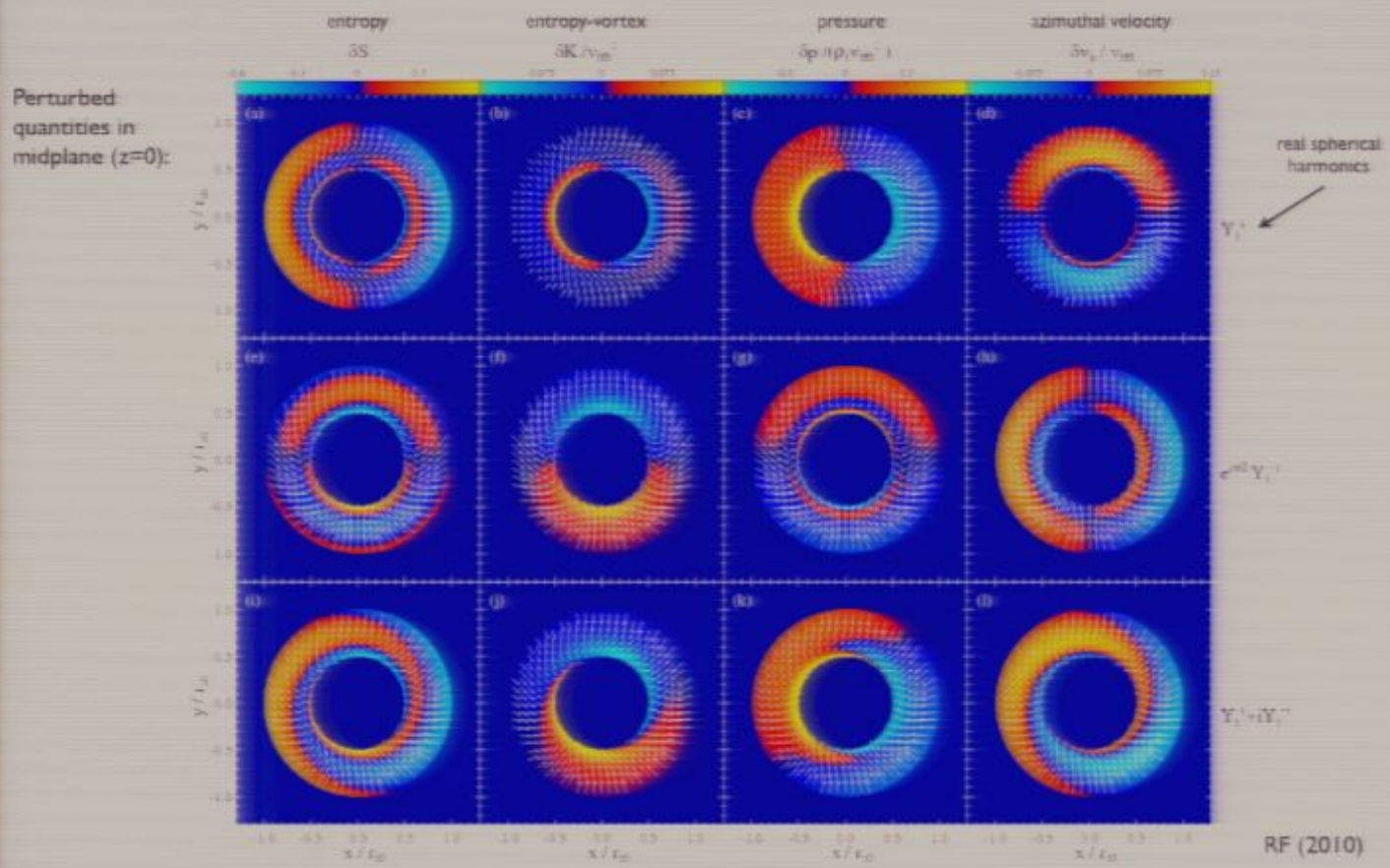
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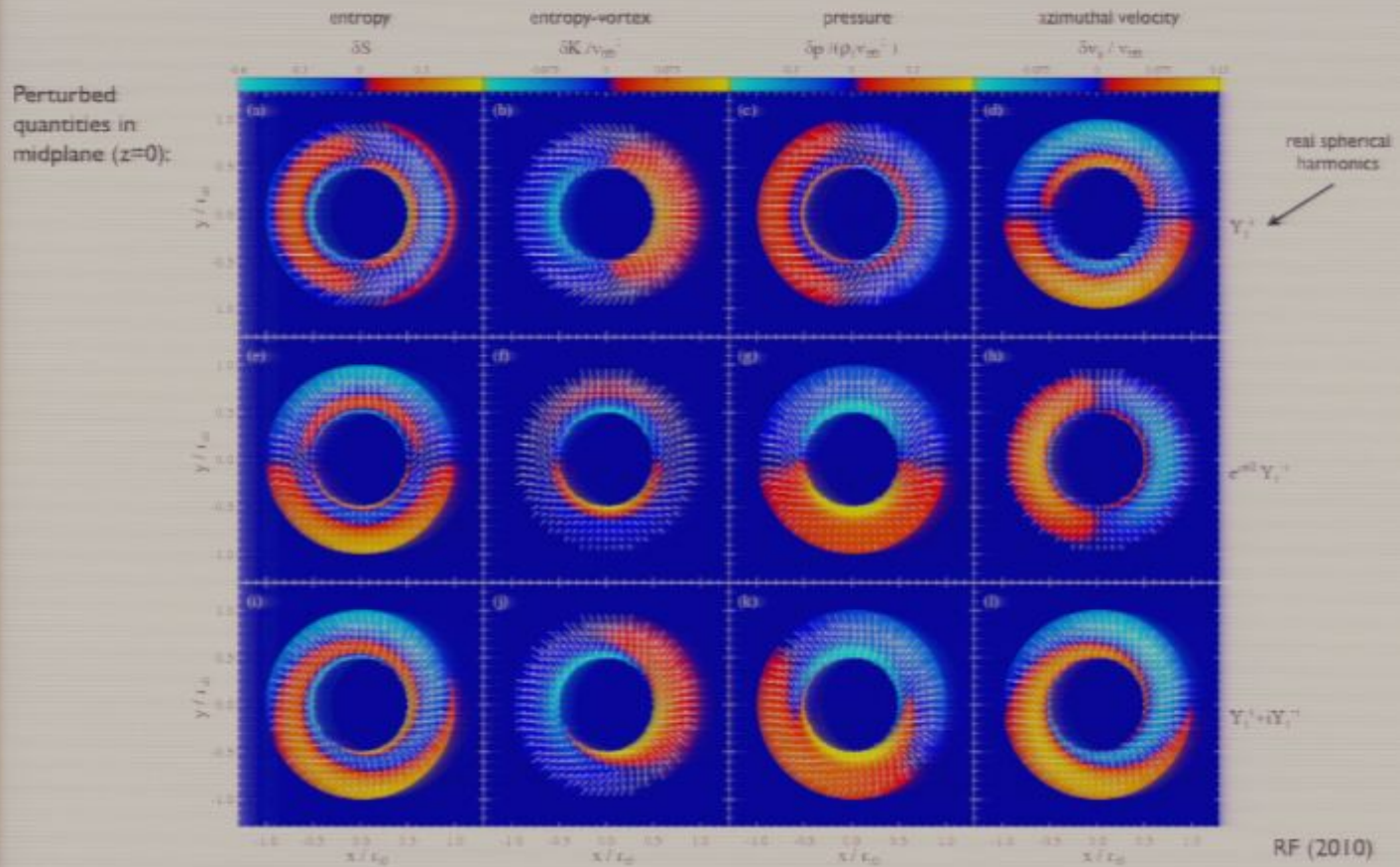
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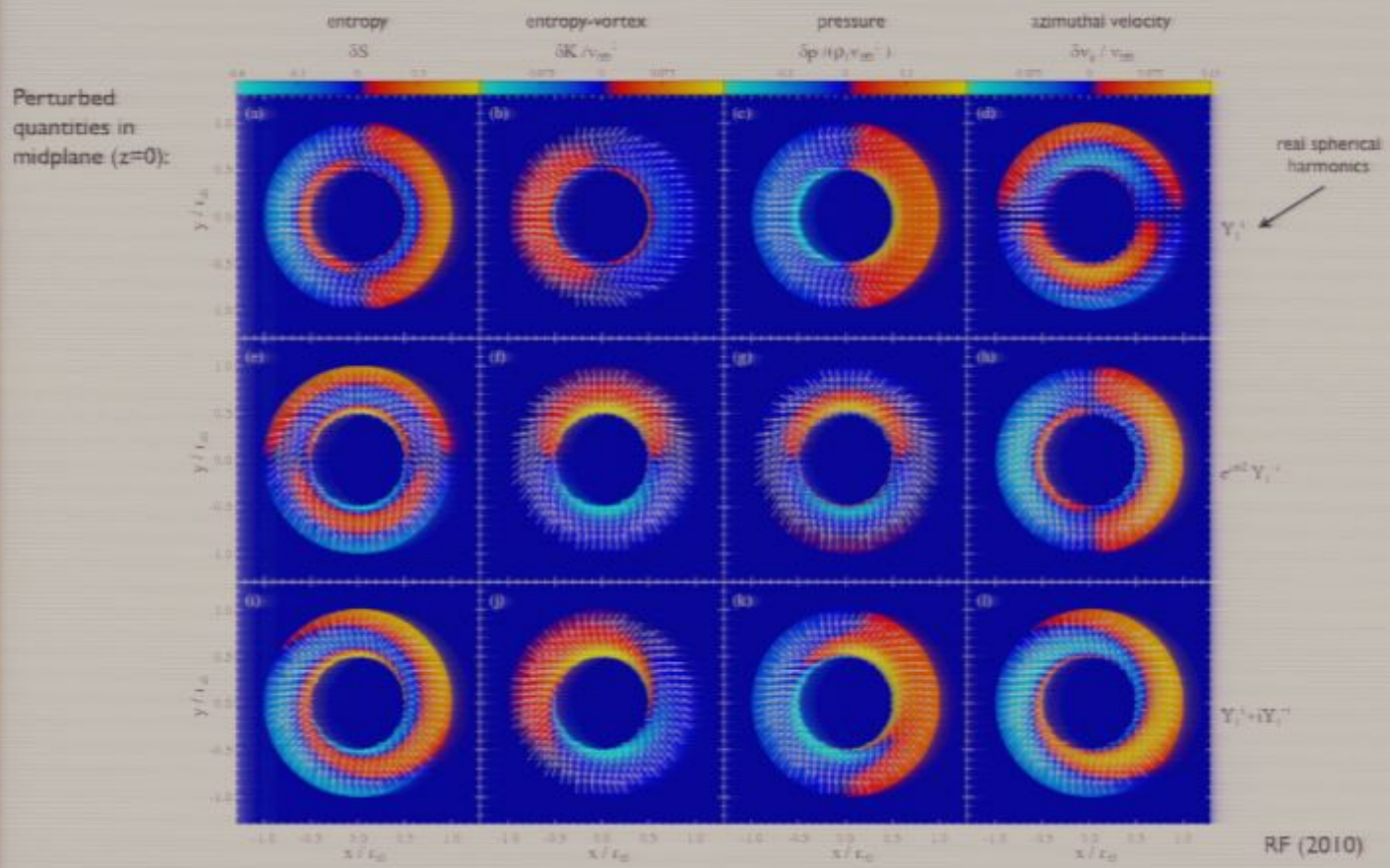
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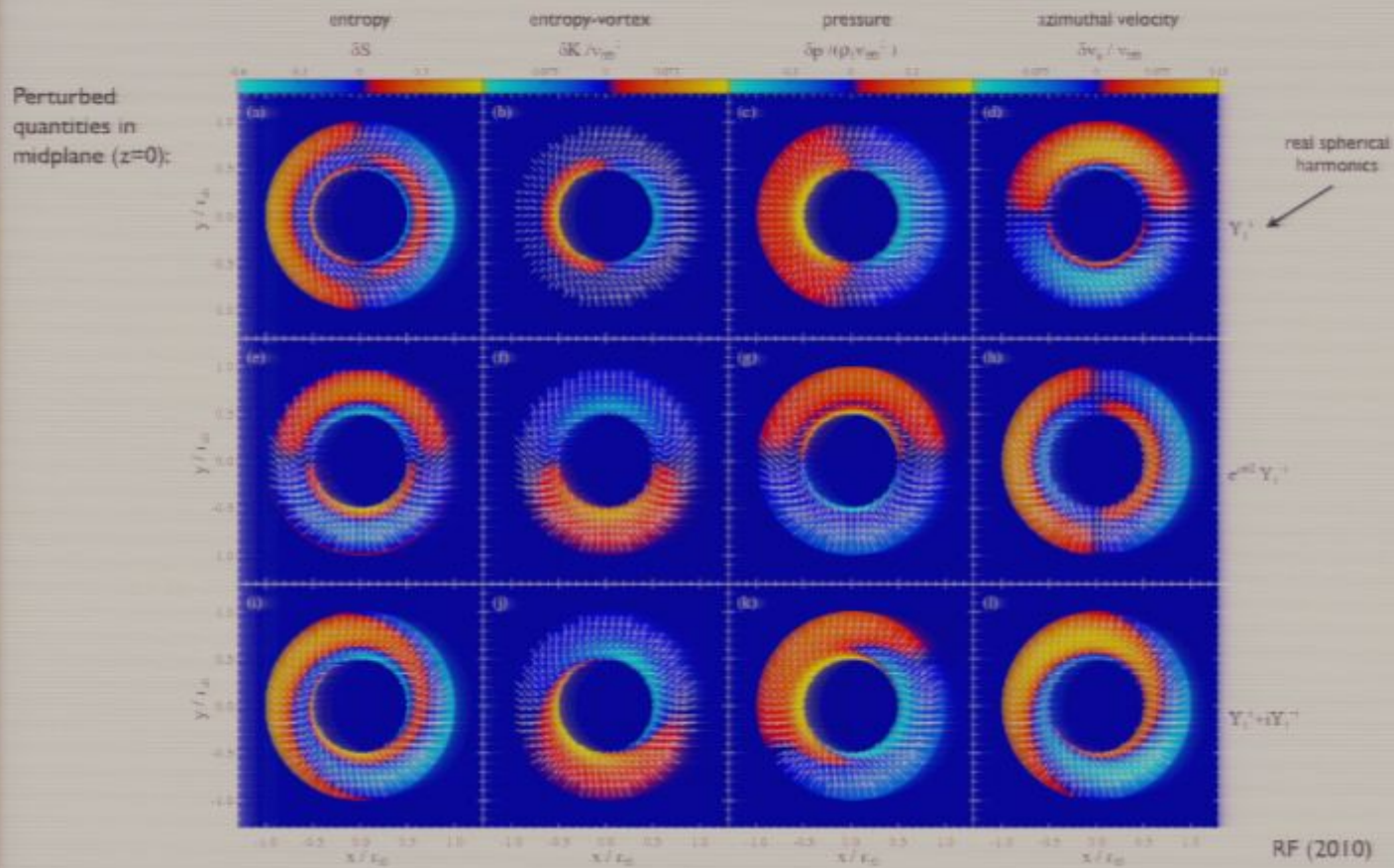
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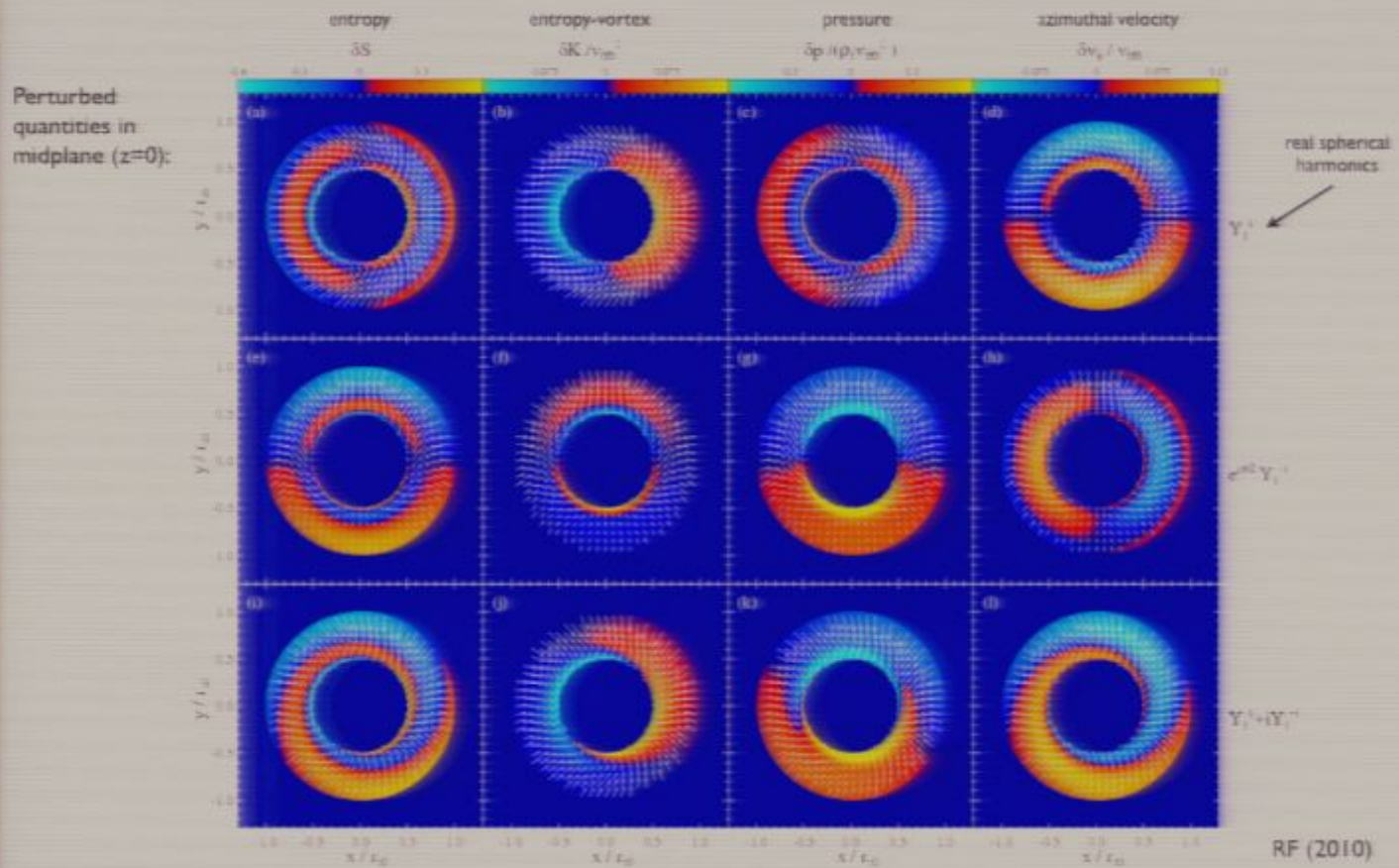
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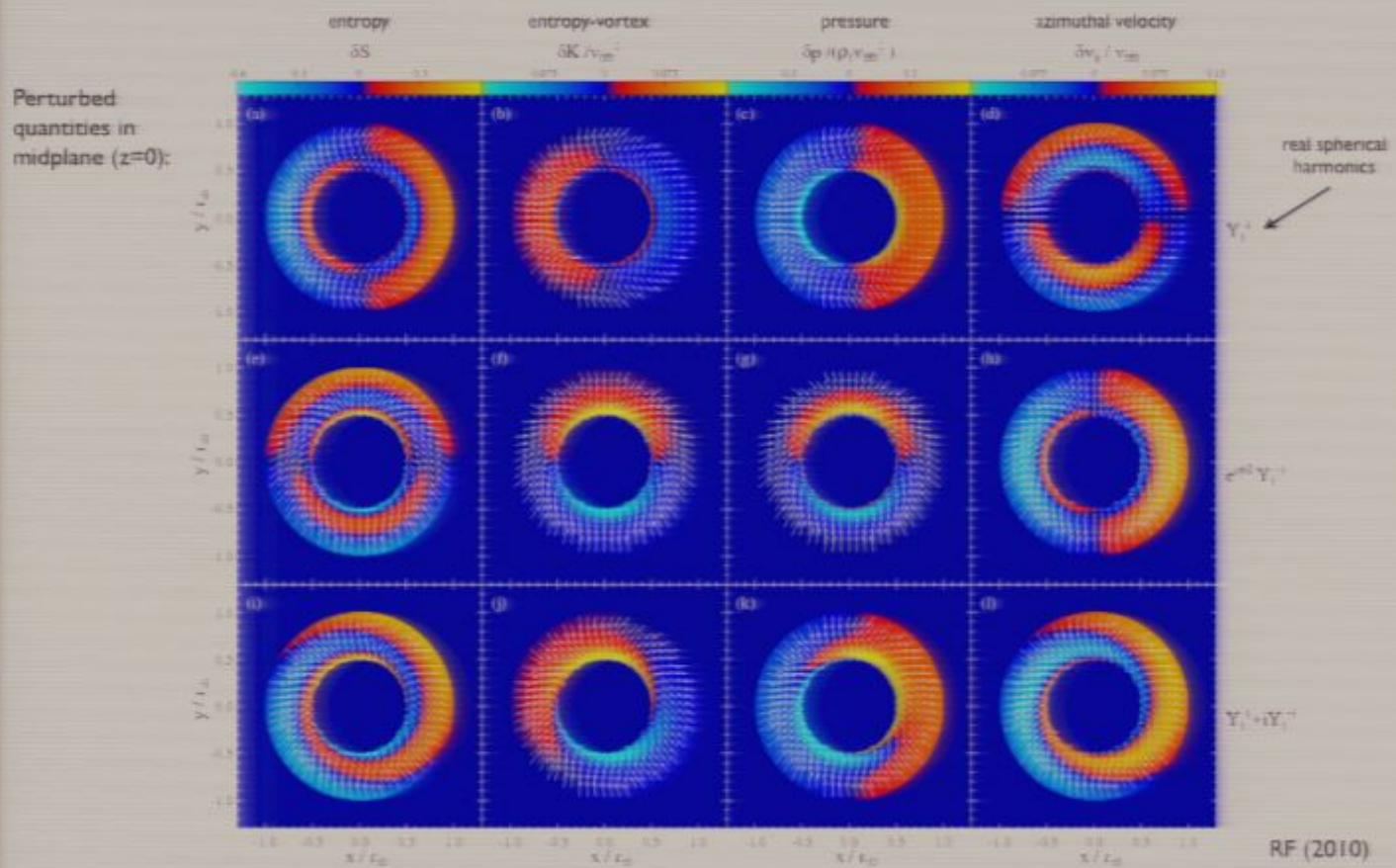
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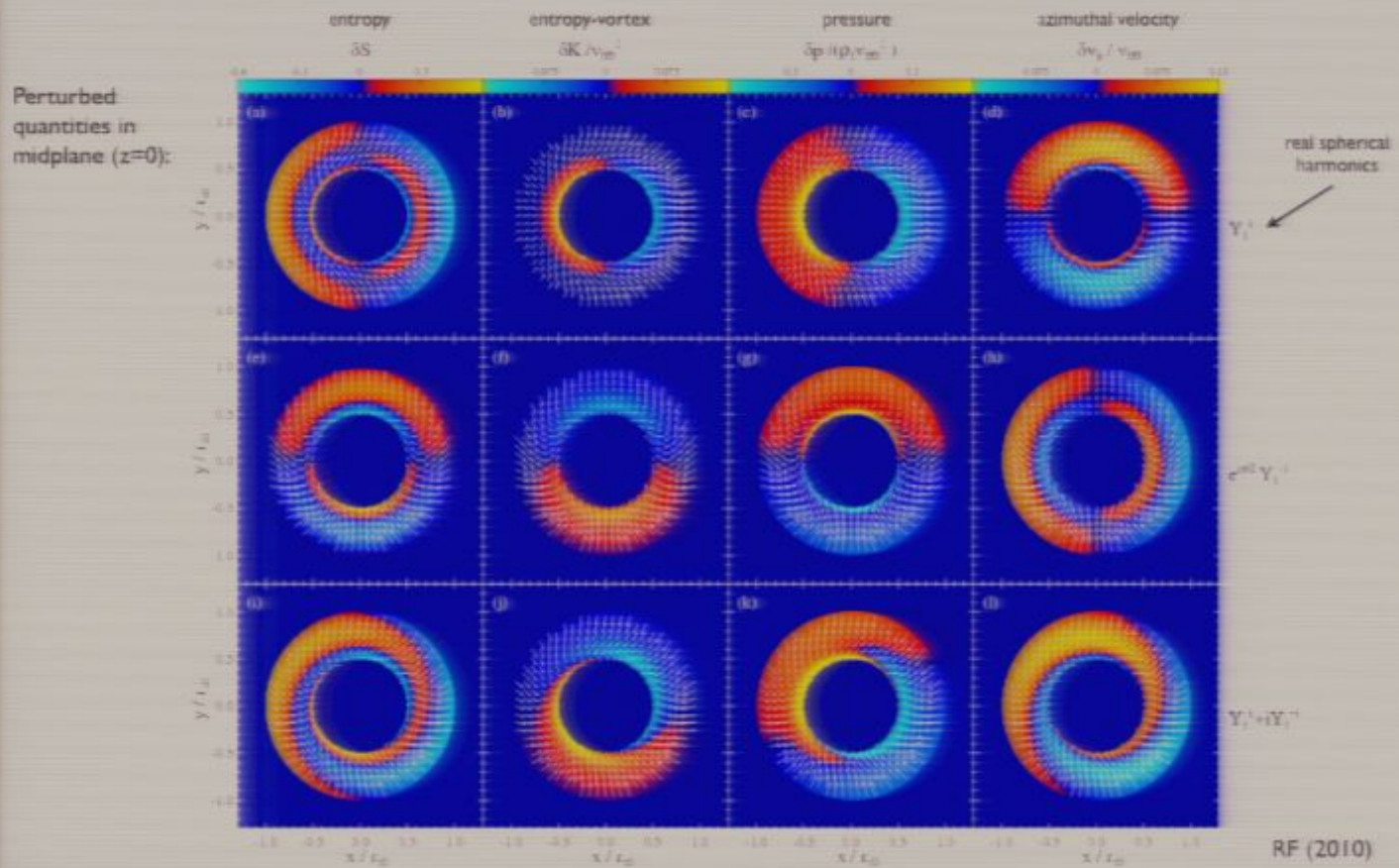
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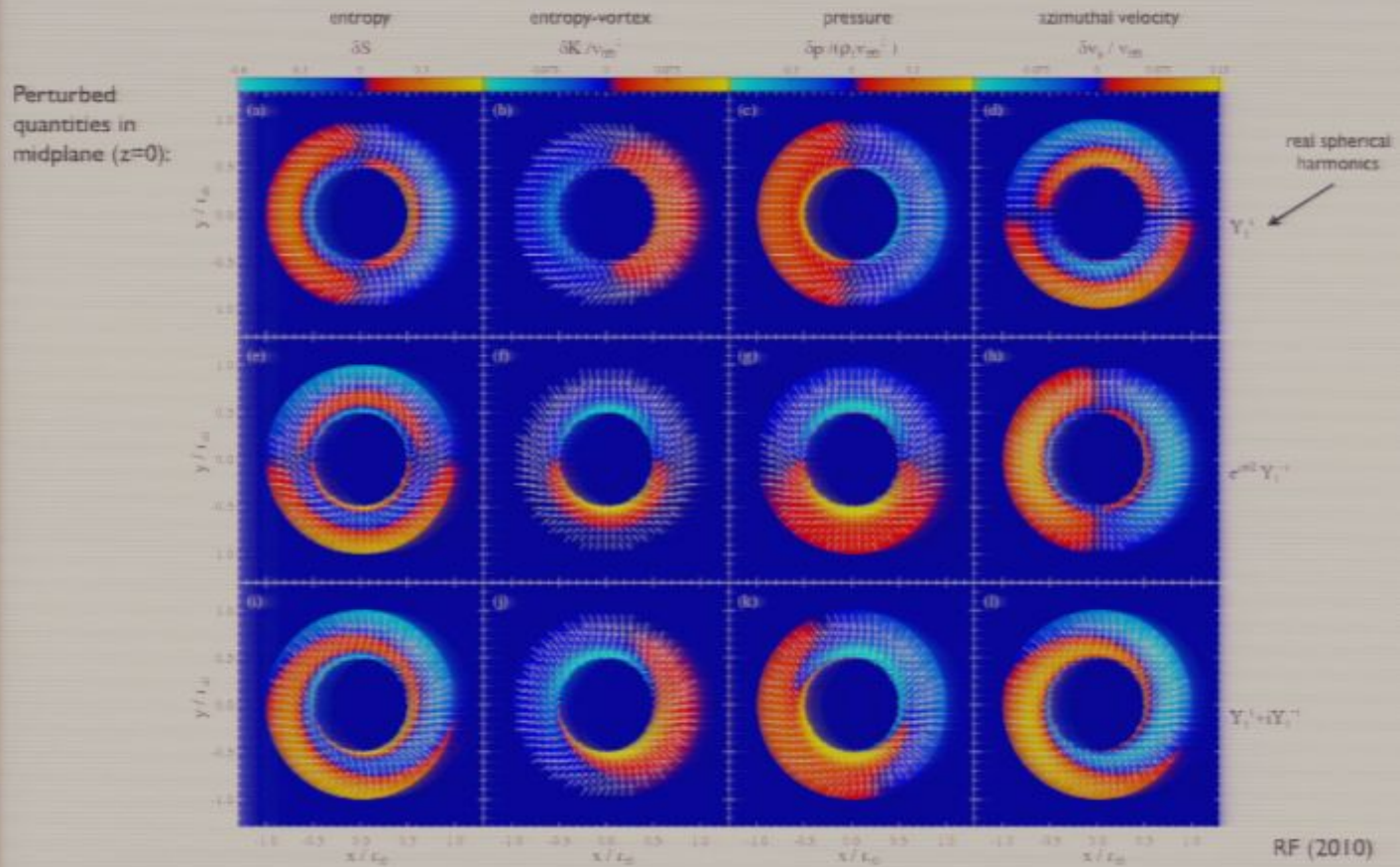
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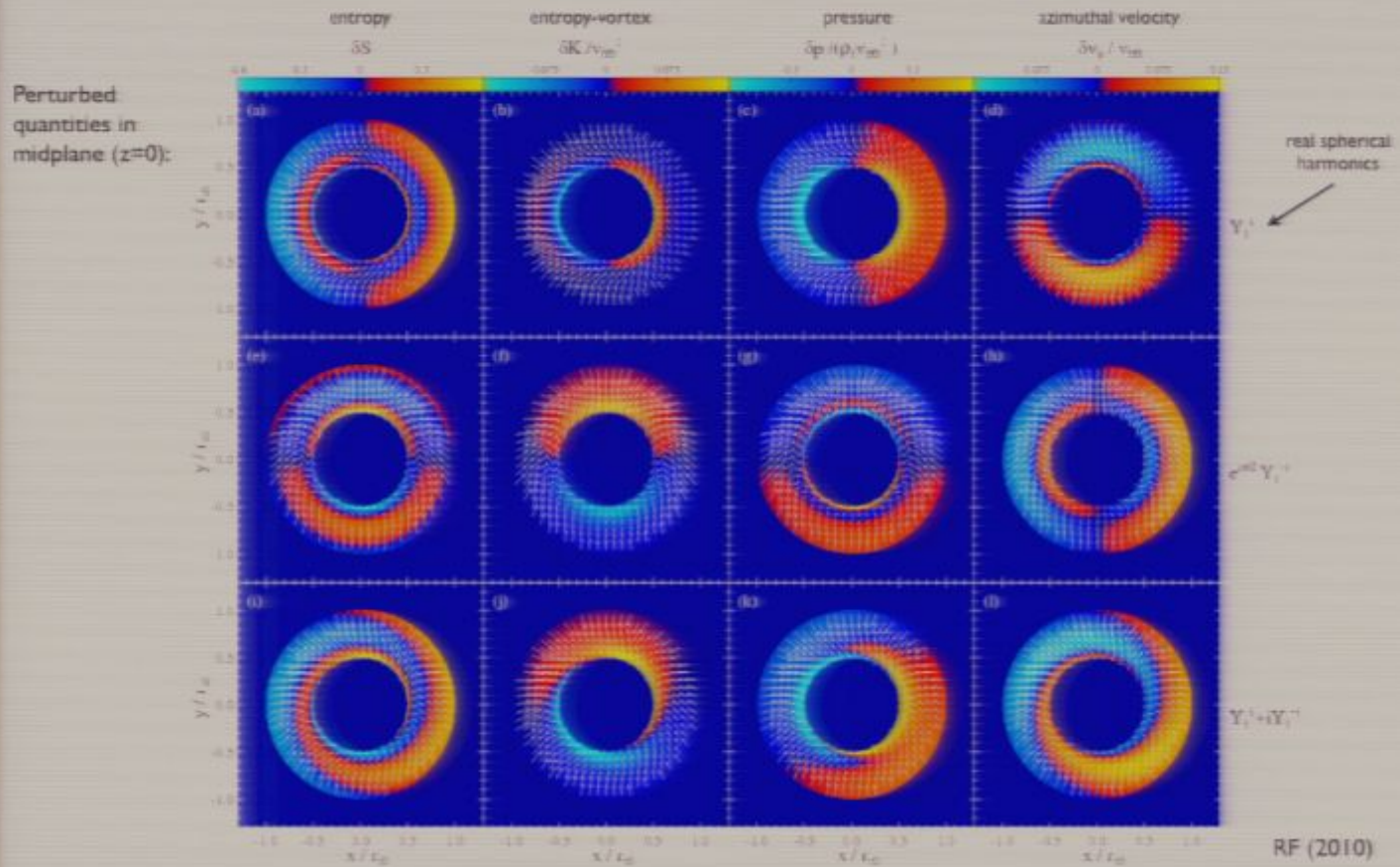
Spiral Modes = 2+ Axisymmetric Modes out of Phase



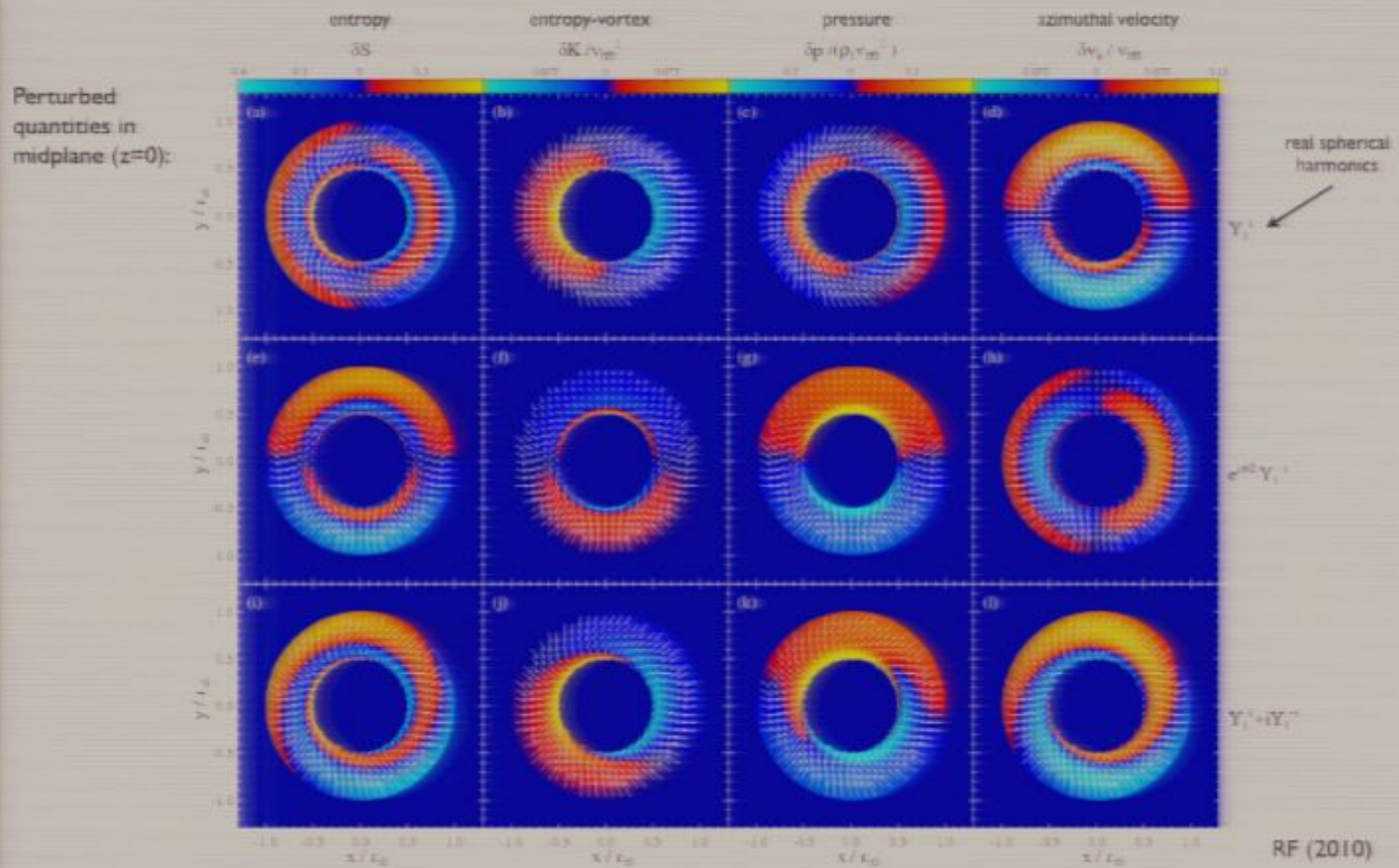
Spiral Modes = 2+ Axisymmetric Modes out of Phase



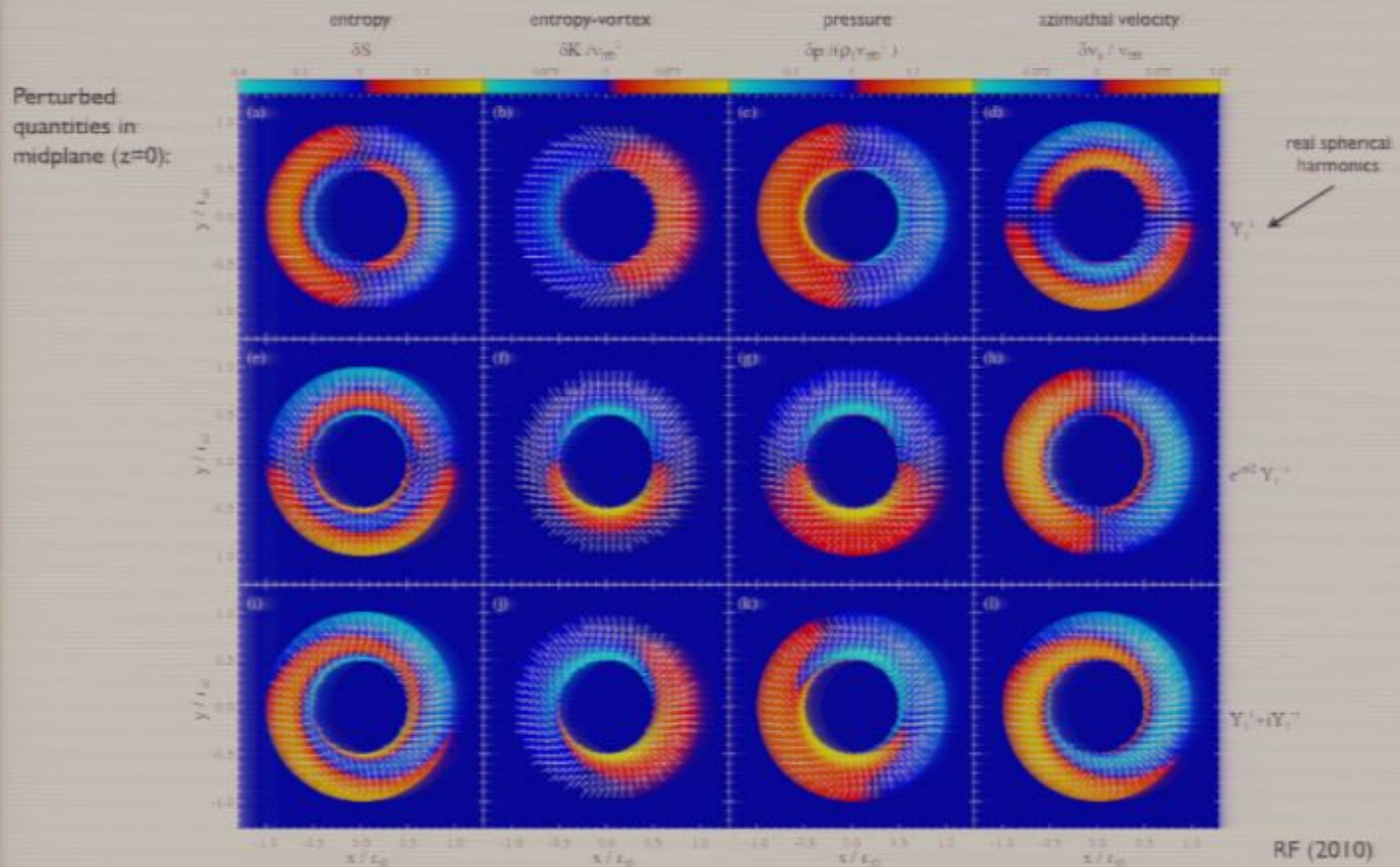
Spiral Modes = 2+ Axisymmetric Modes out of Phase



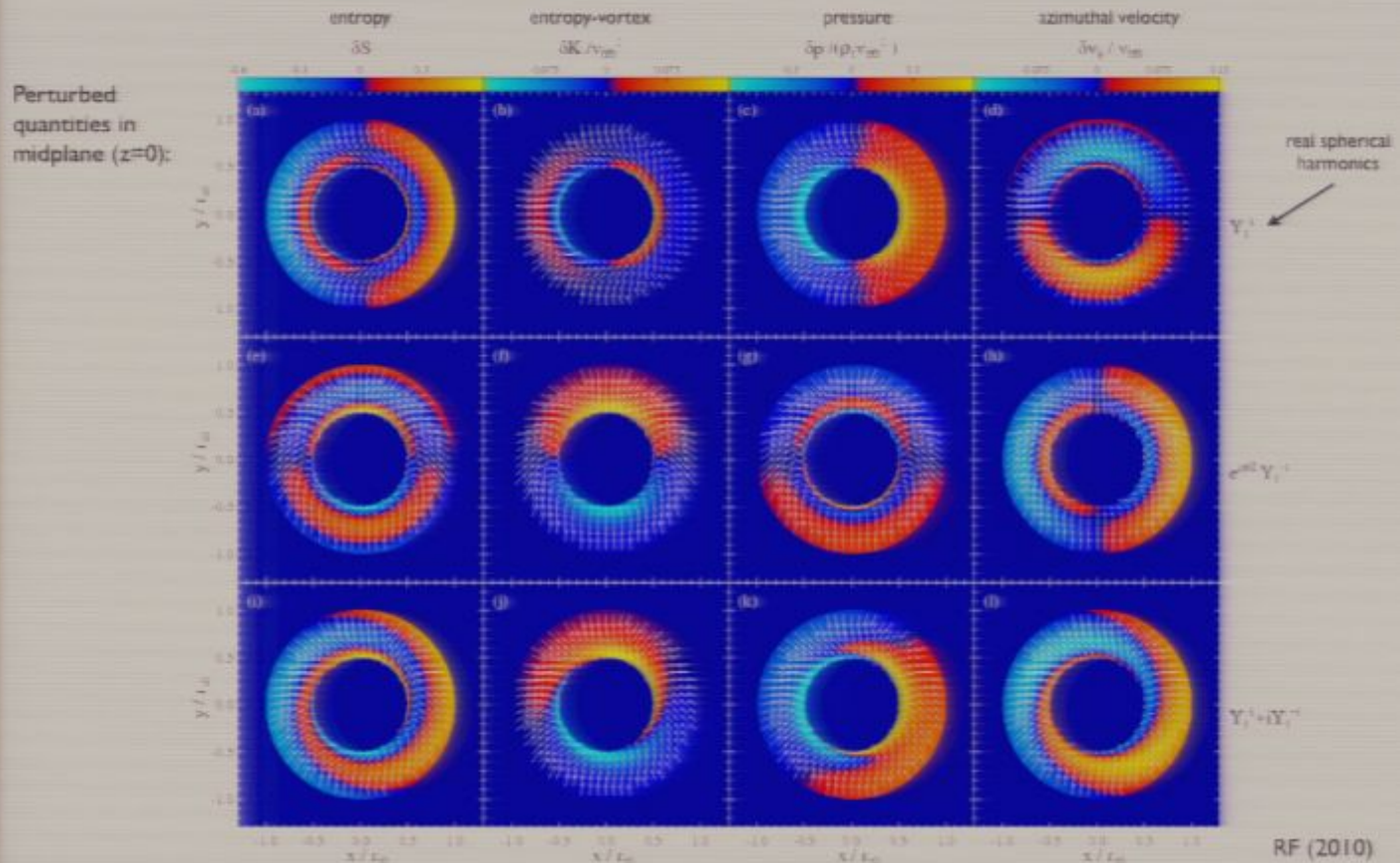
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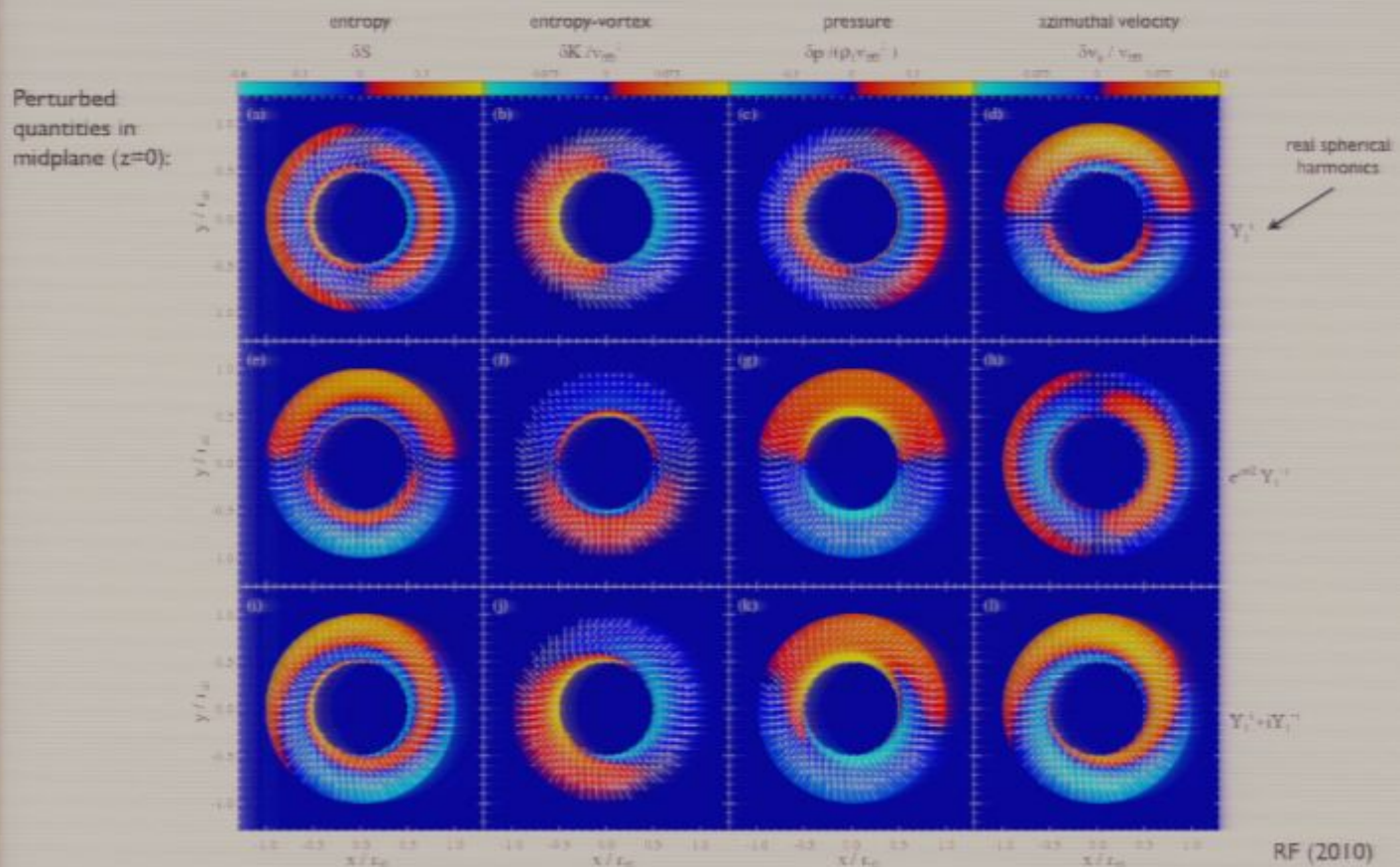
Spiral Modes = 2+ Axisymmetric Modes out of Phase



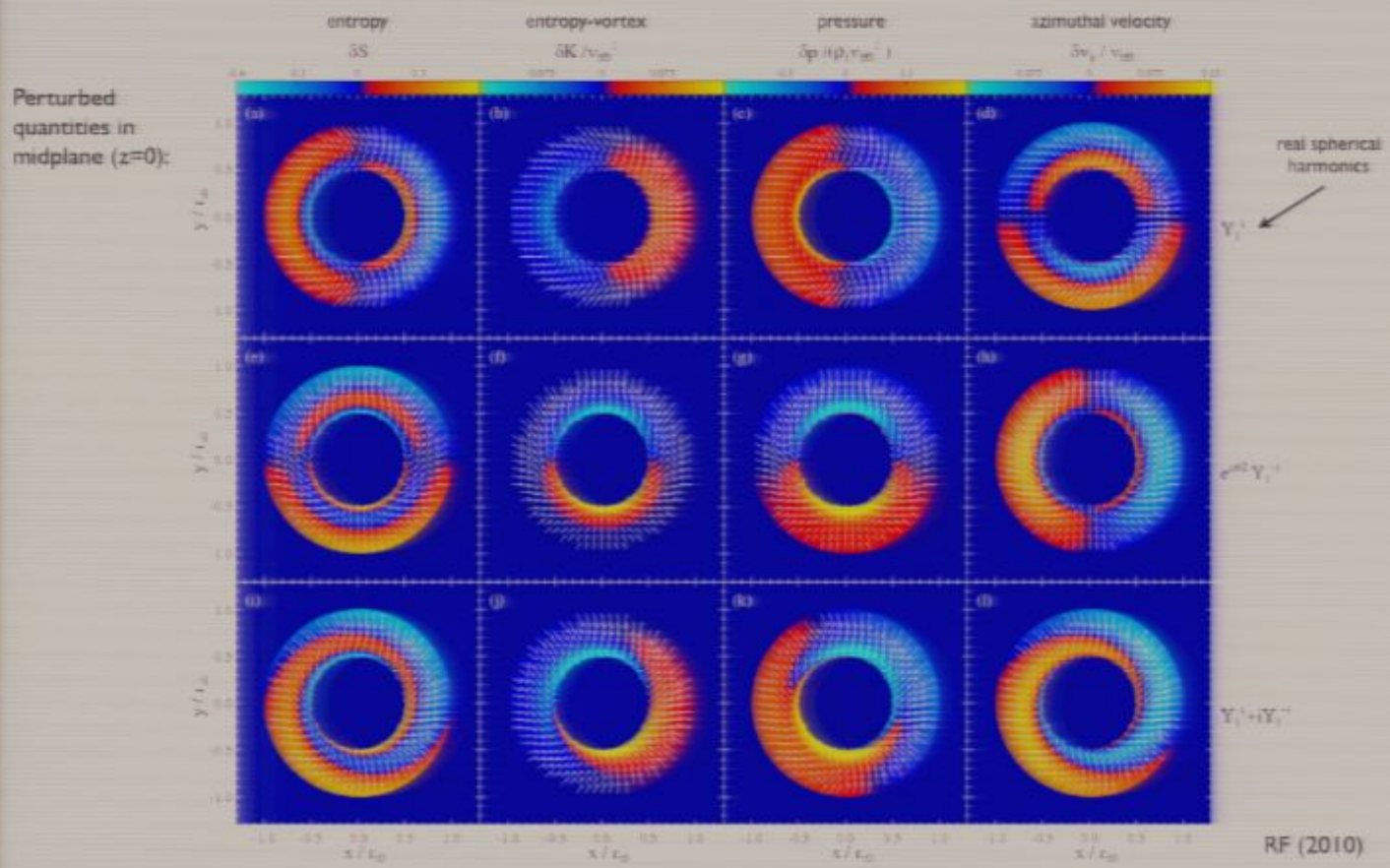
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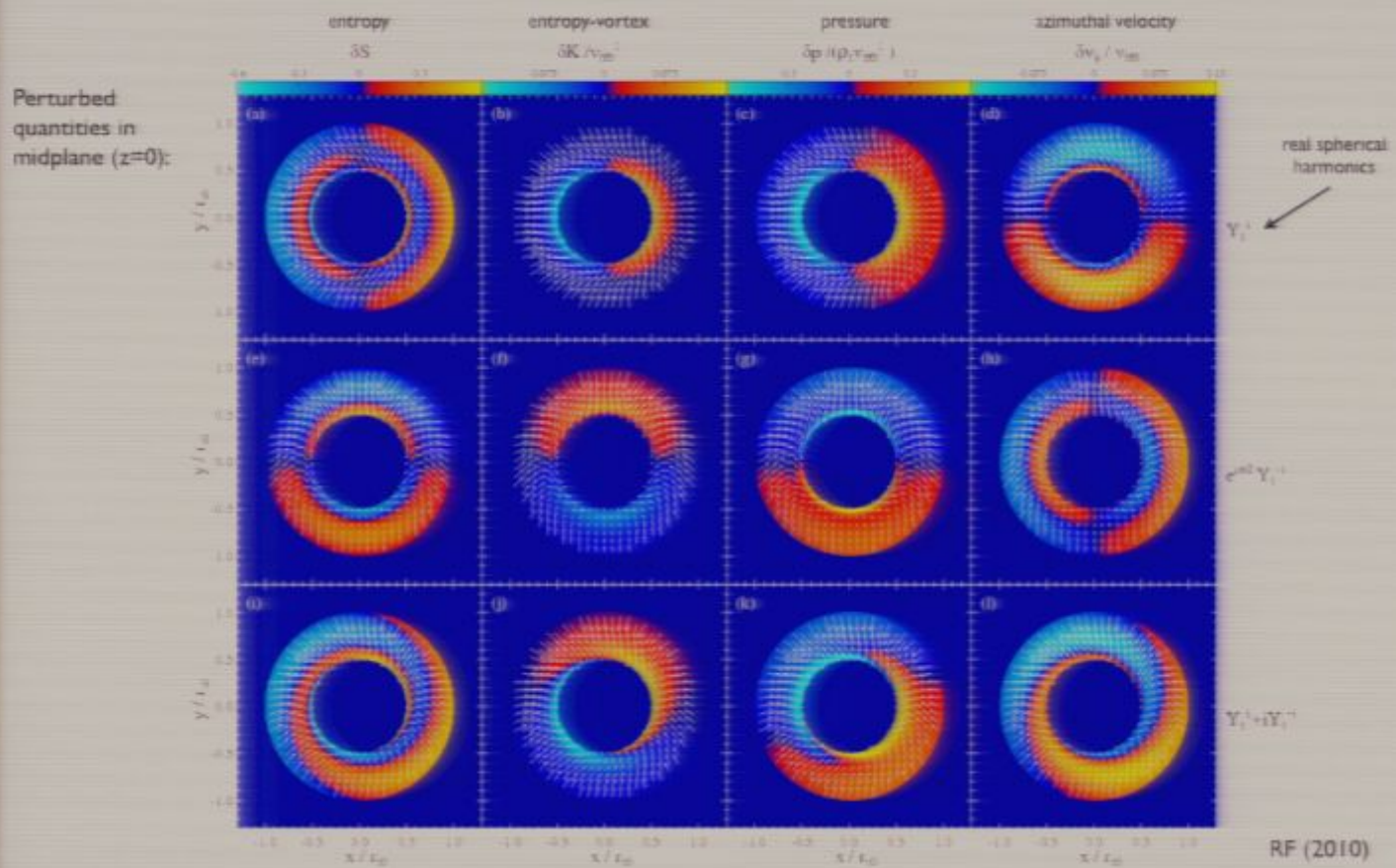
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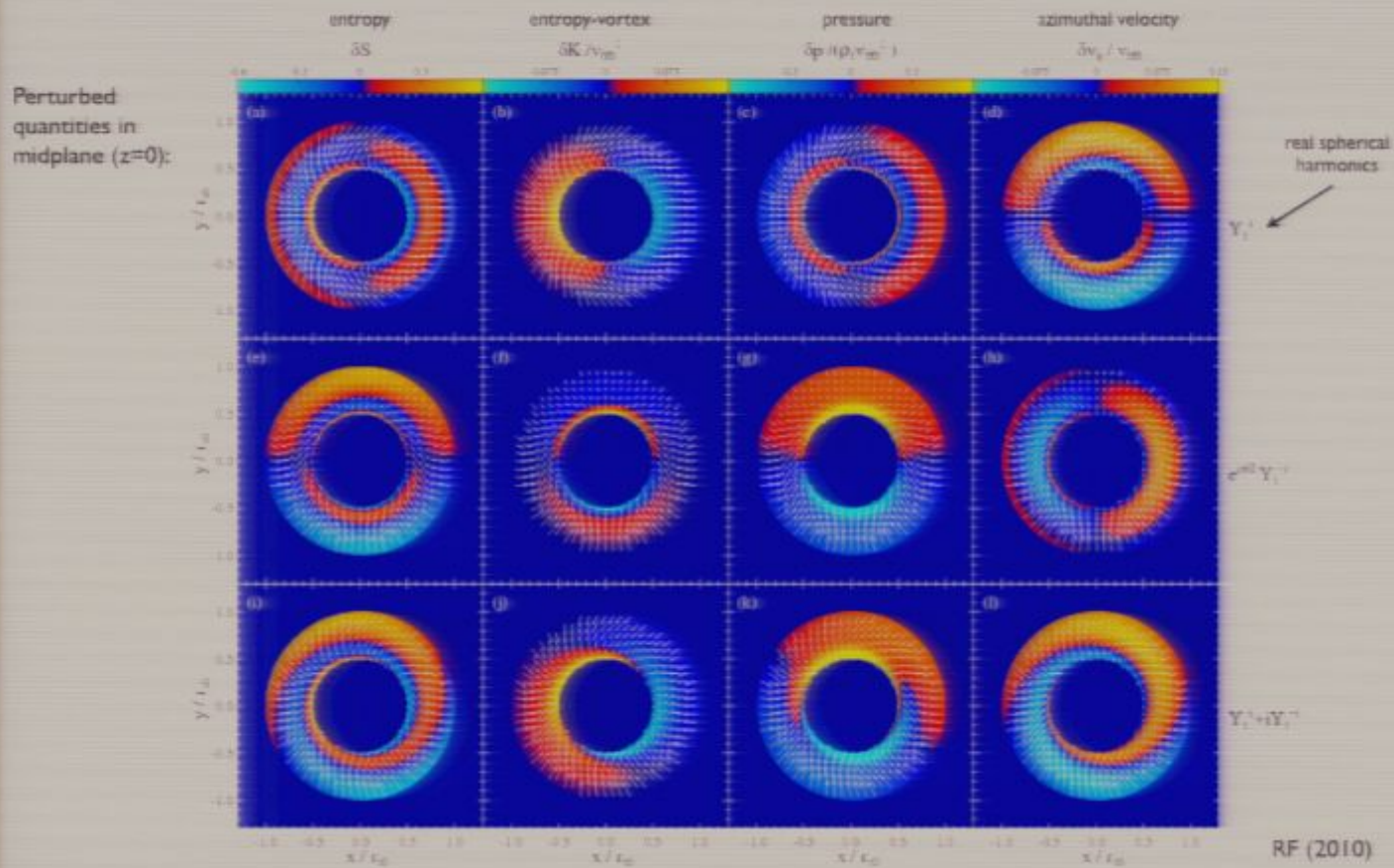
Spiral Modes = 2+ Axisymmetric Modes out of Phase



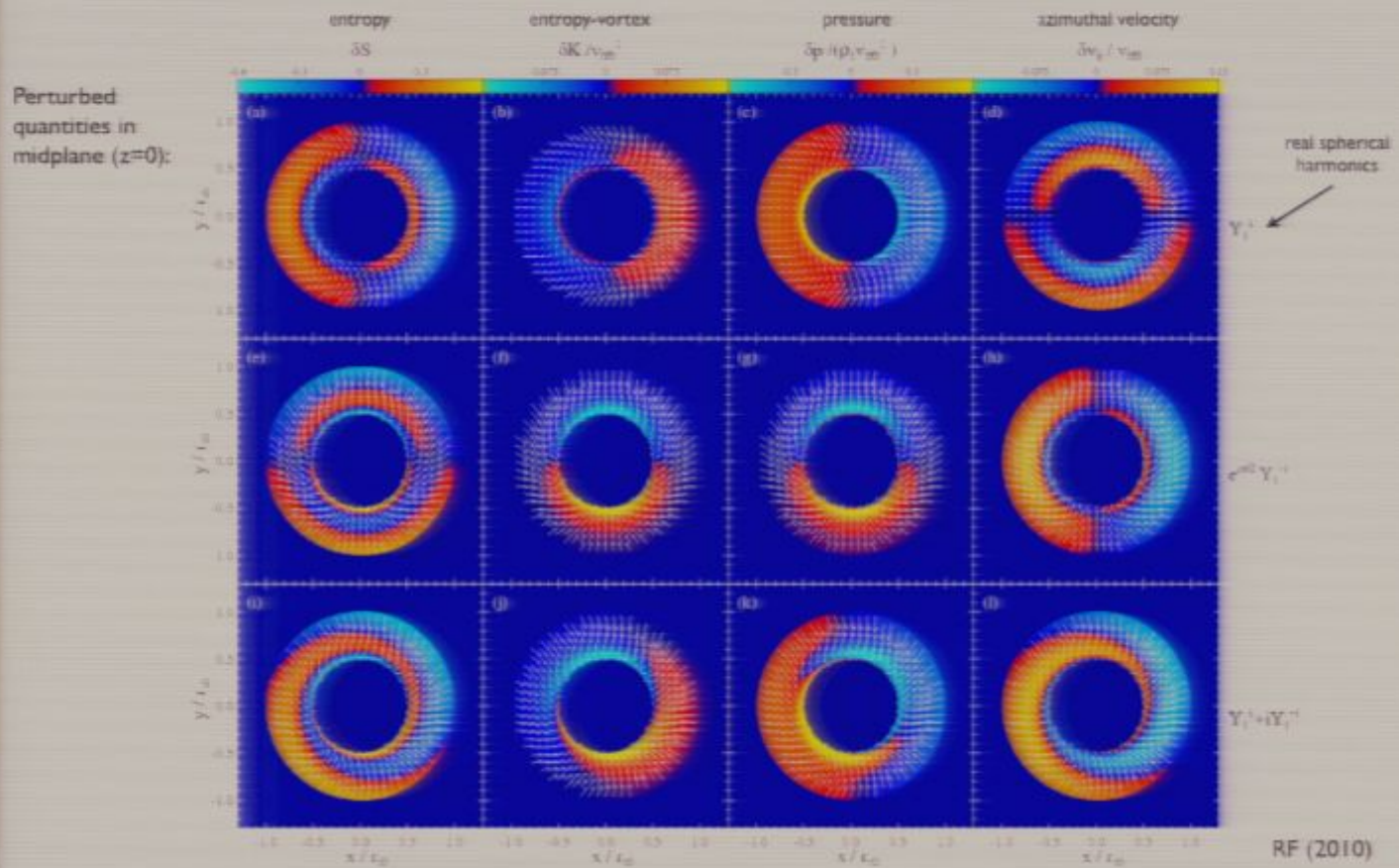
Spiral Modes = 2+ Axisymmetric Modes out of Phase



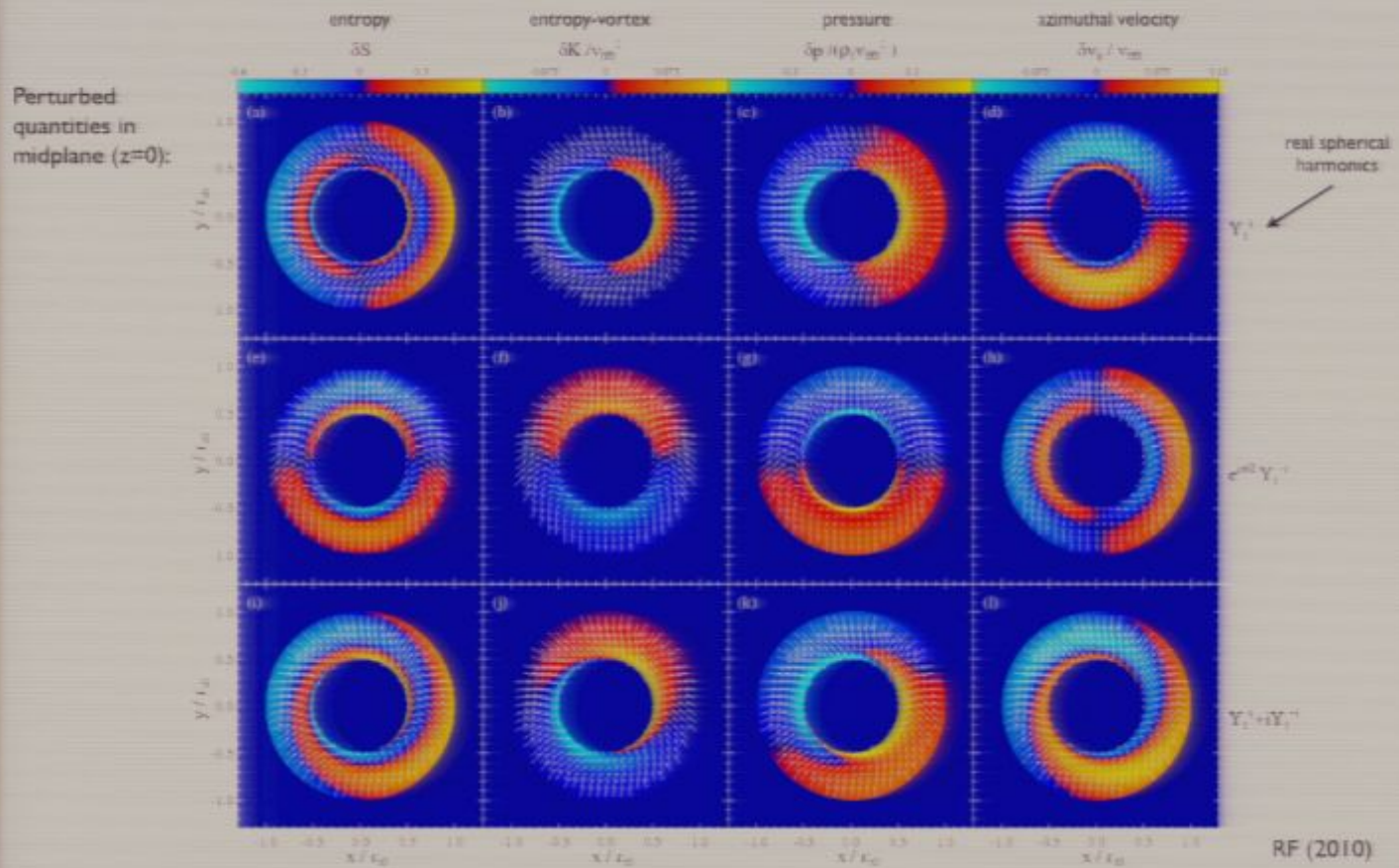
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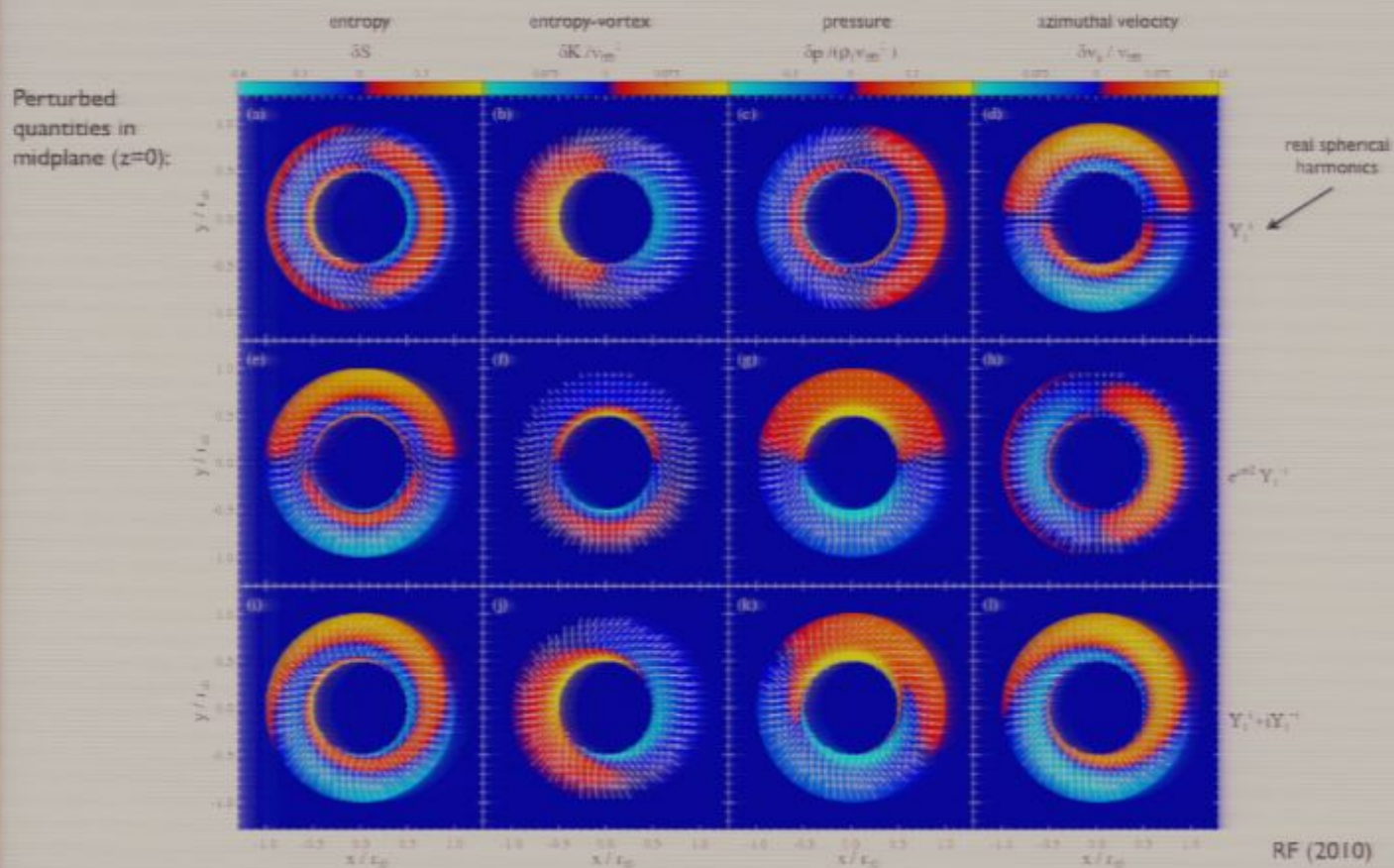
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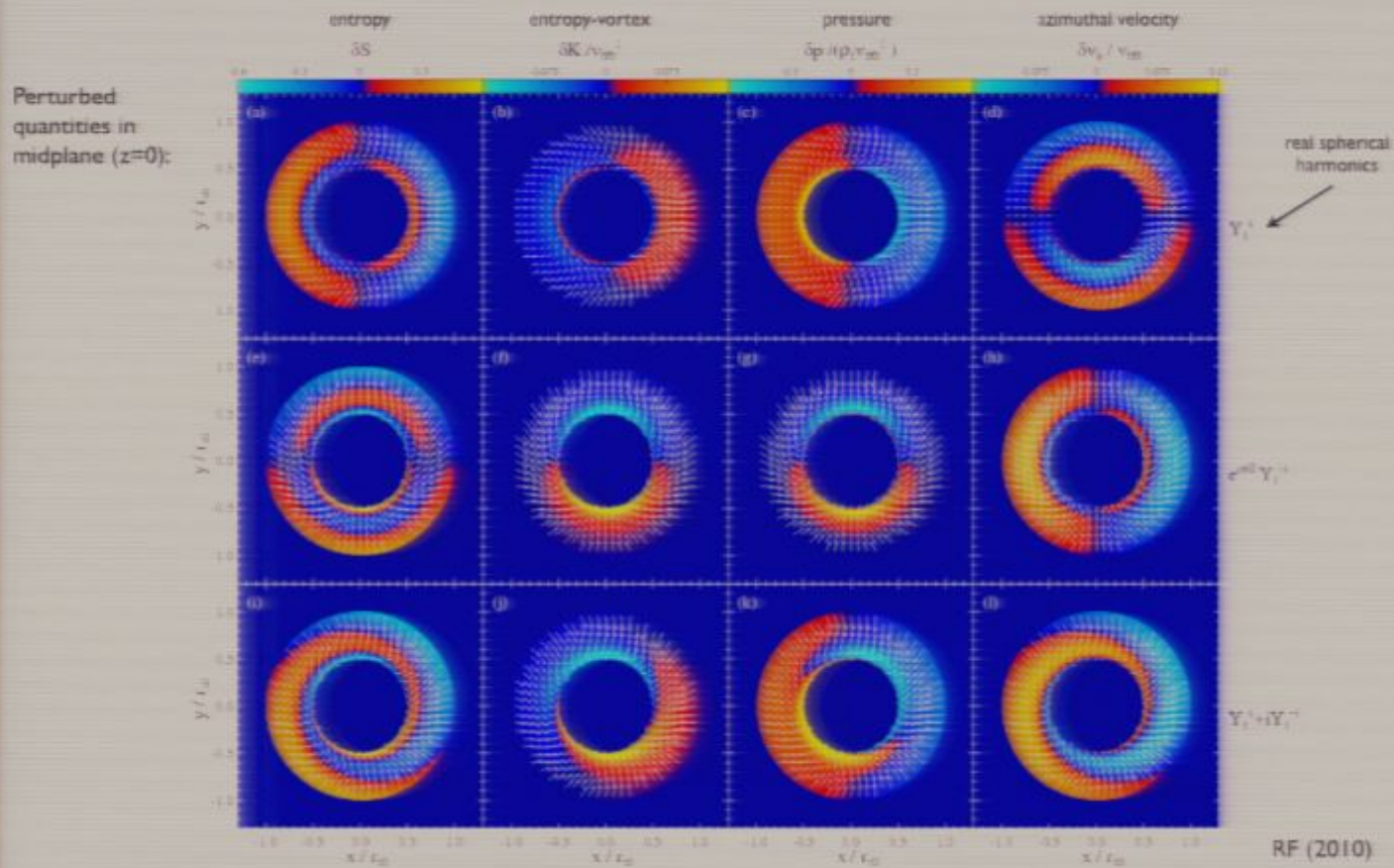
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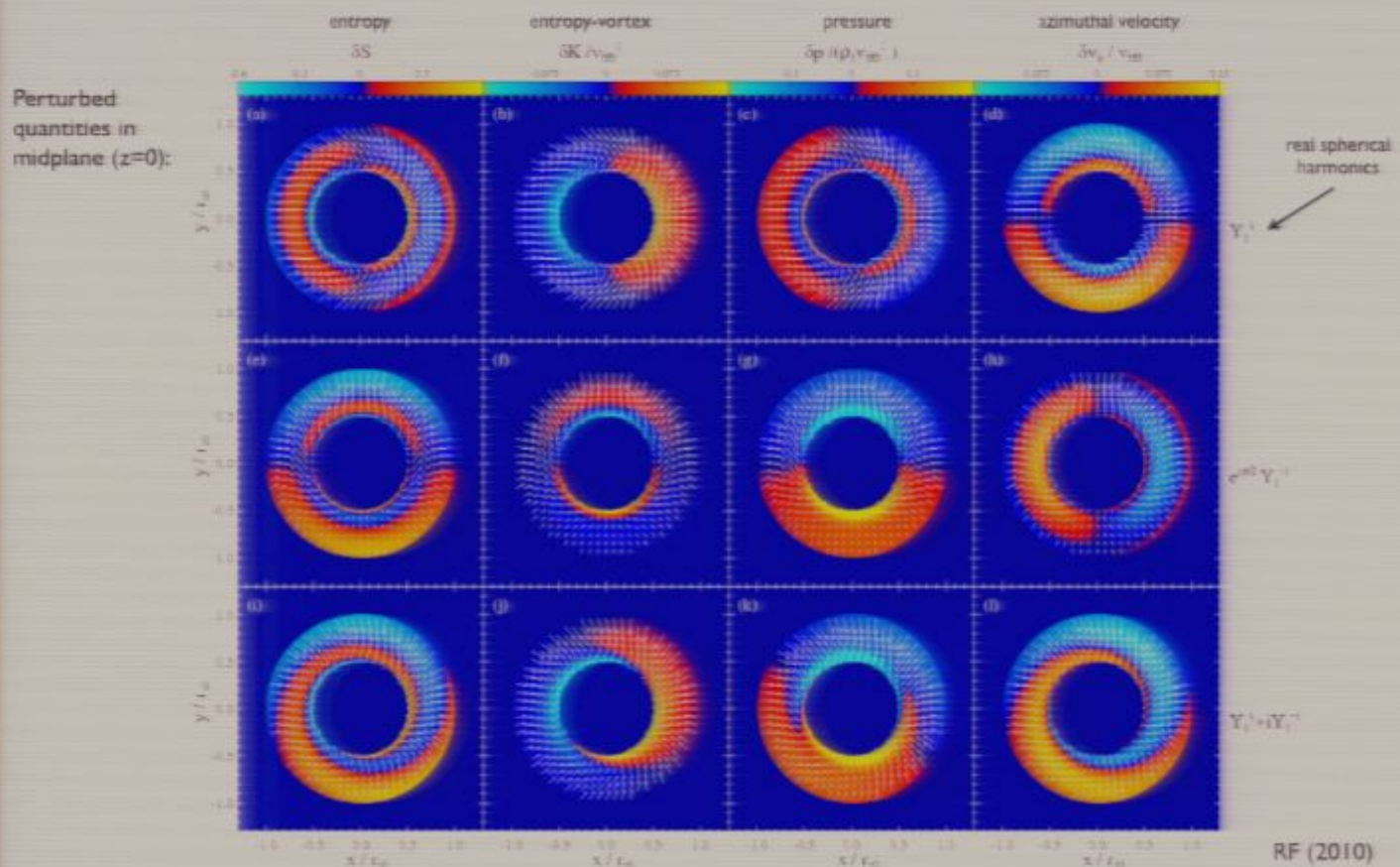
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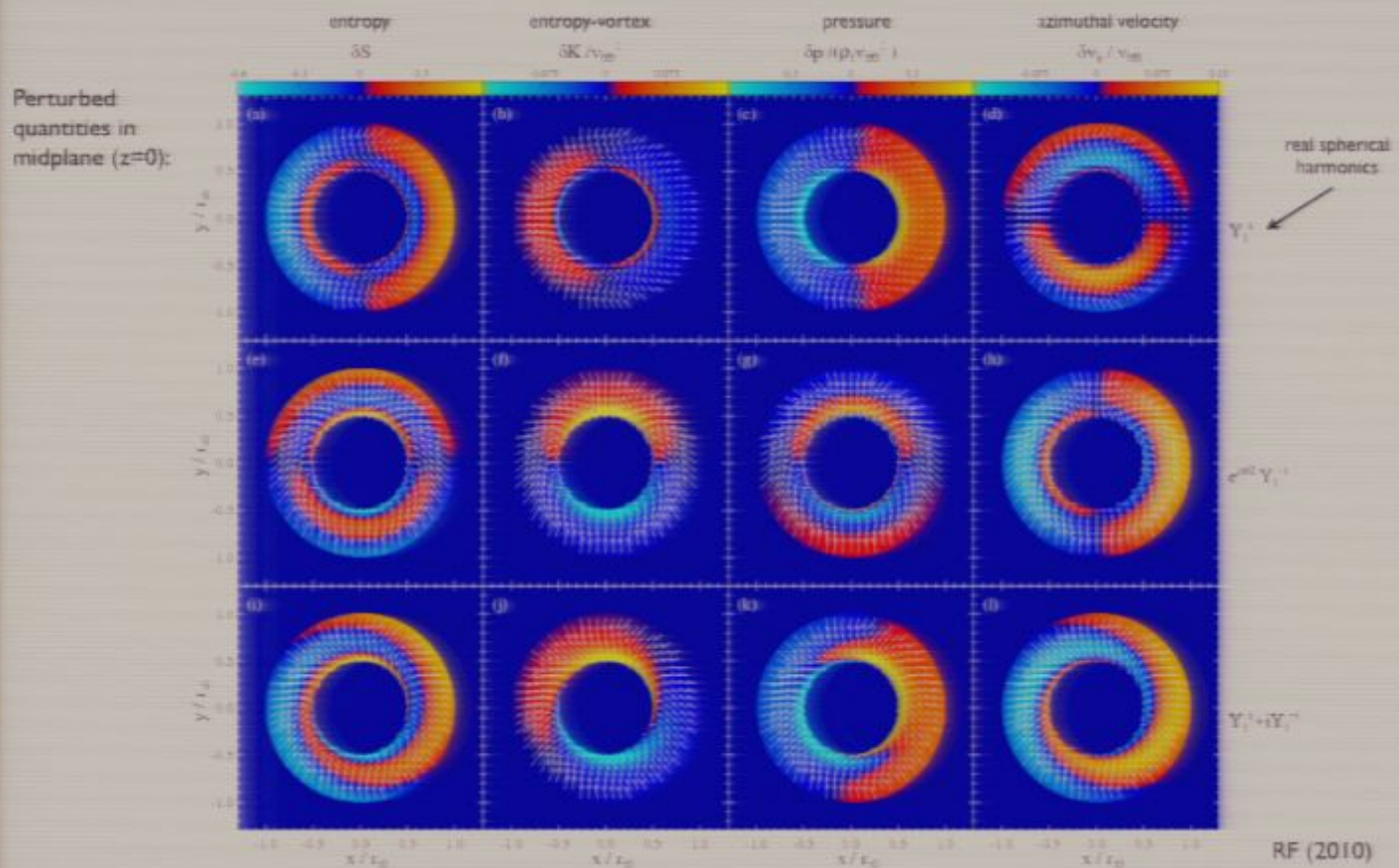
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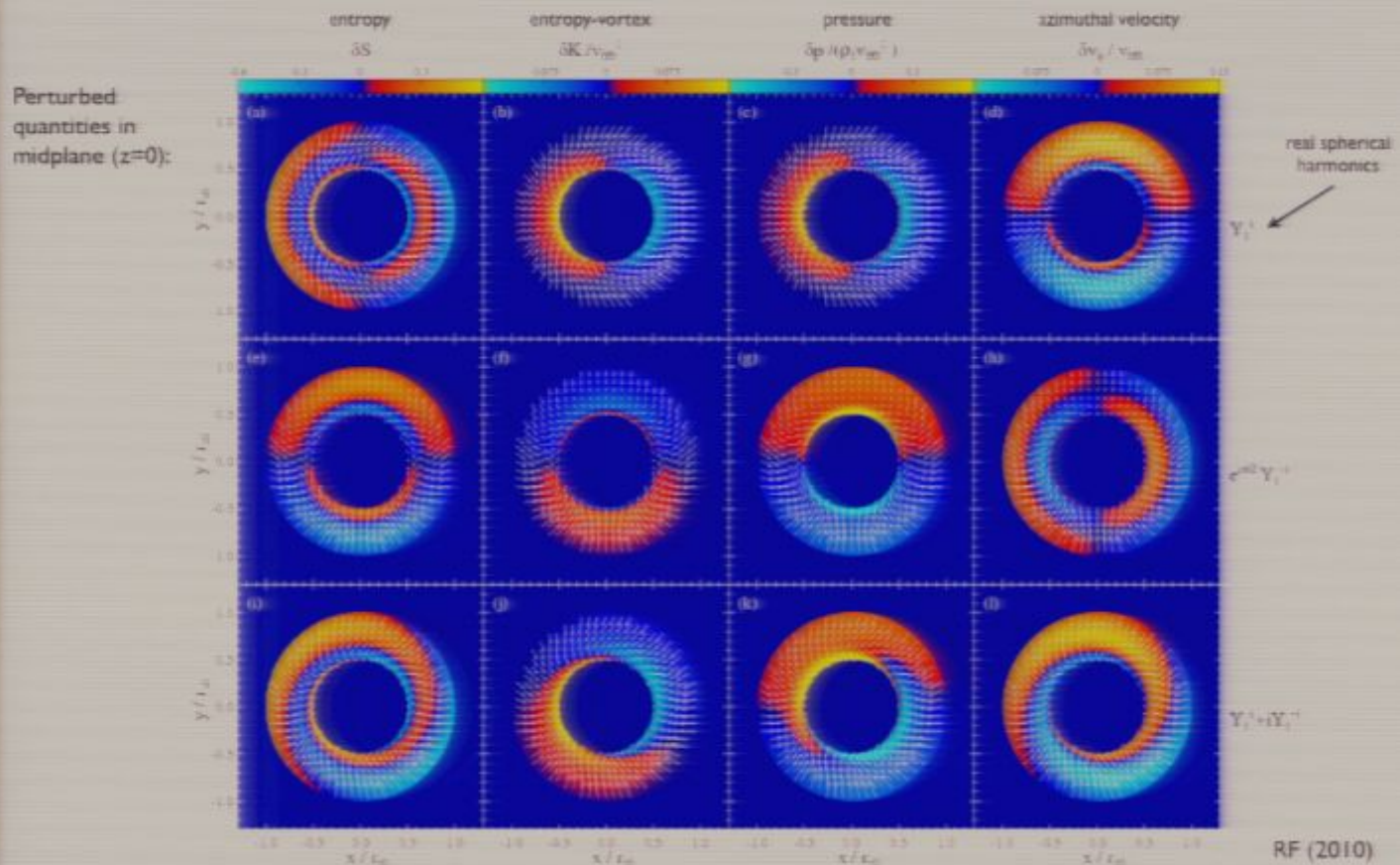
Spiral Modes = 2+ Axisymmetric Modes out of Phase



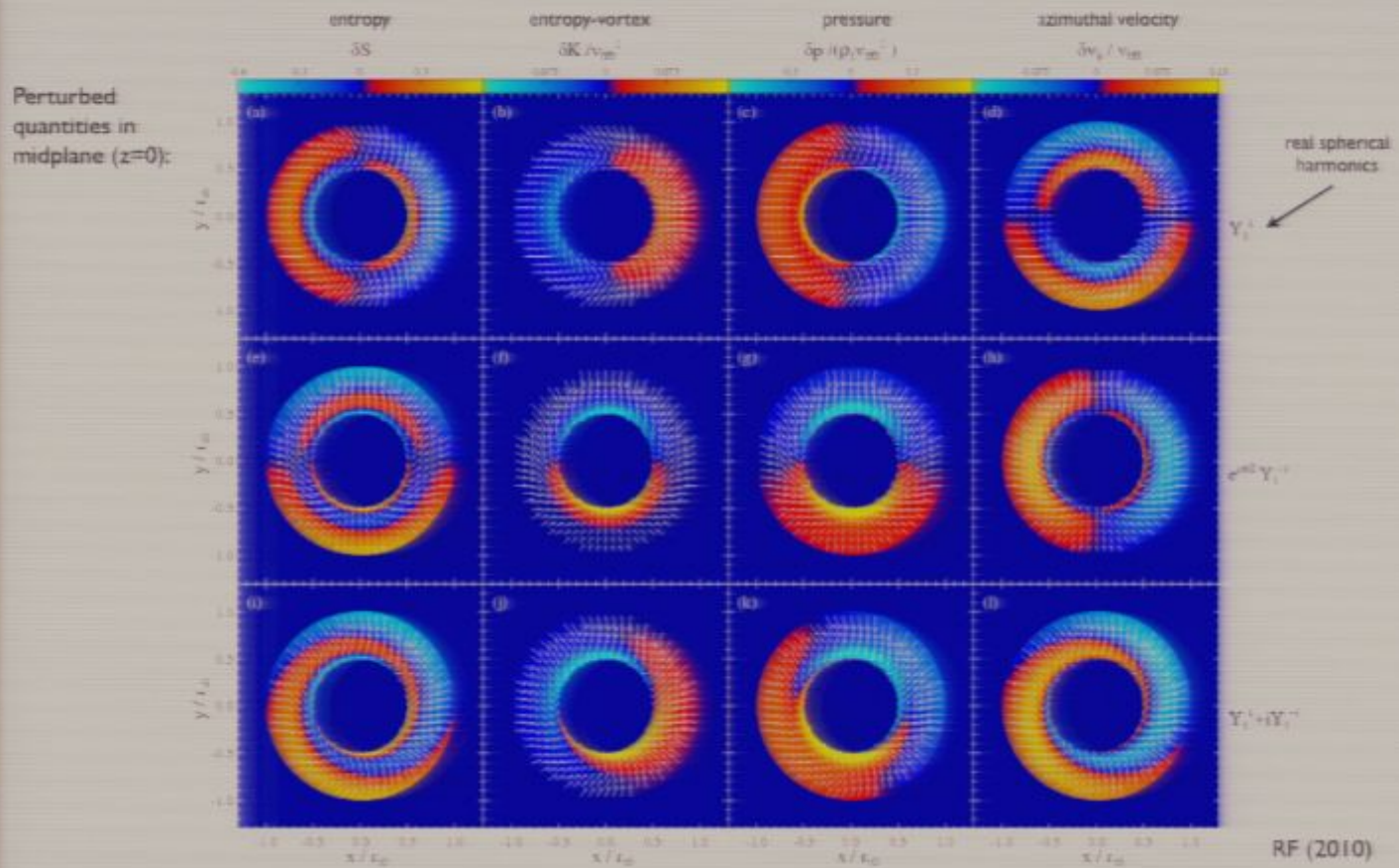
Spiral Modes = 2+ Axisymmetric Modes out of Phase



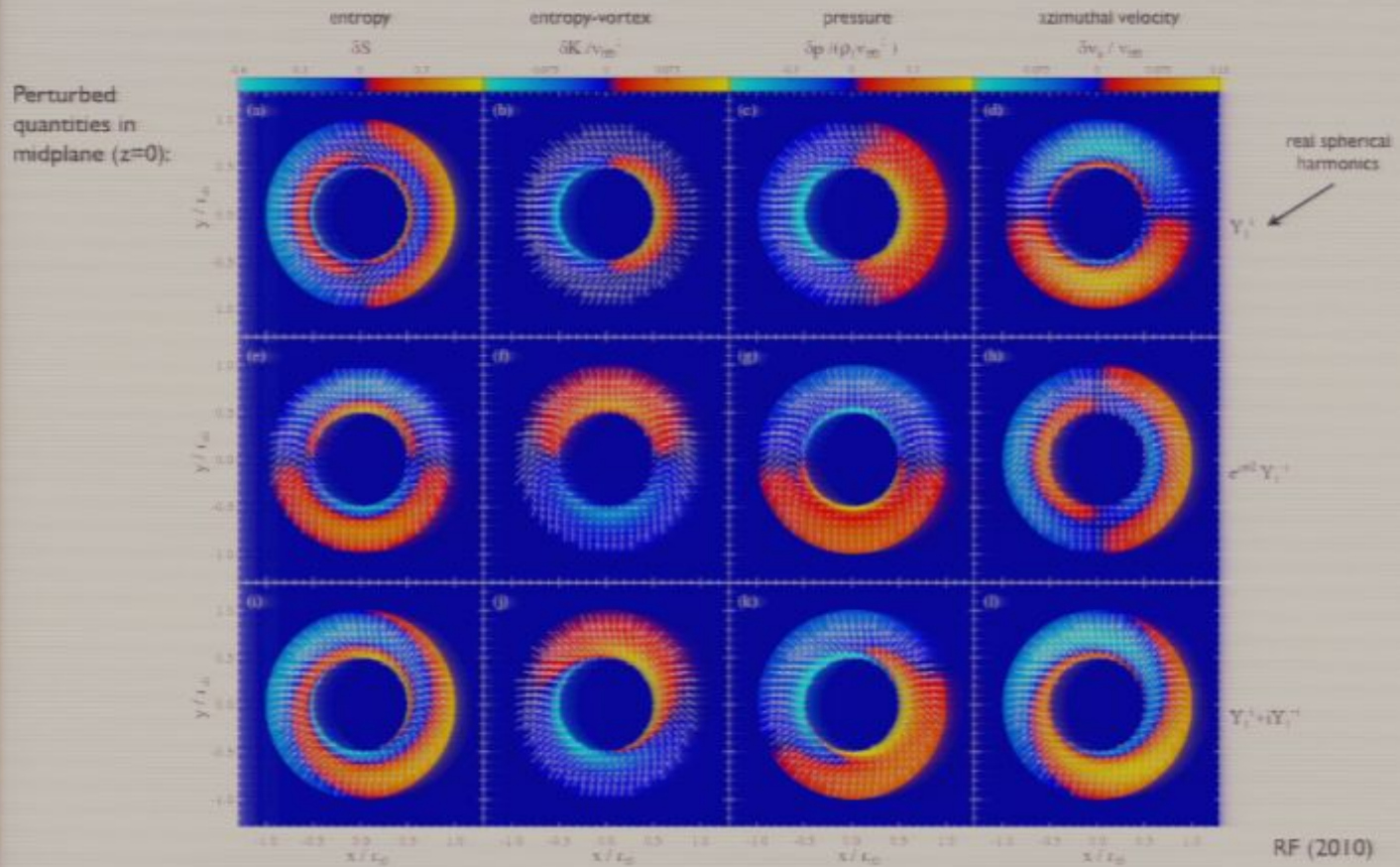
Spiral Modes = 2+ Axisymmetric Modes out of Phase



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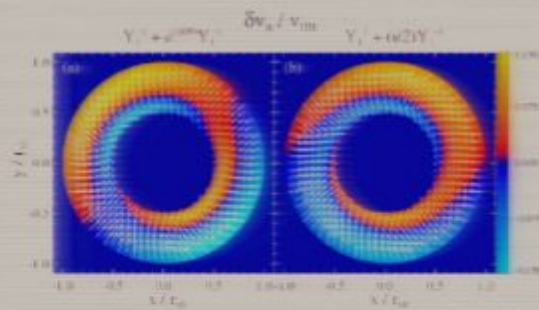


Spiral Modes: Excitability

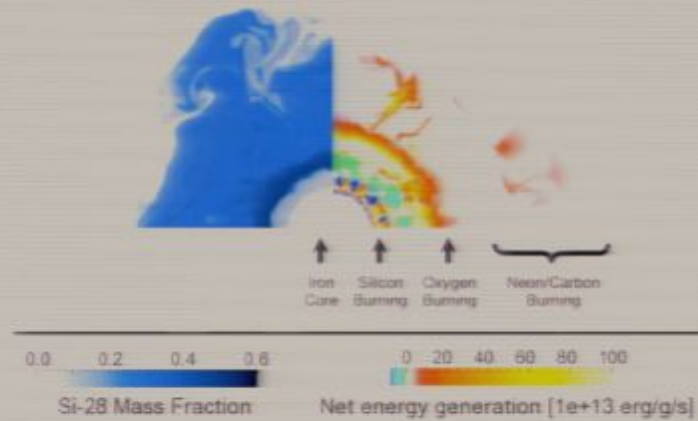
- With rotation: **prograde** modes grow faster (Yamasaki & Foglizzo 2008)

Density perturbations: 2D stellar convection simulations

- **Relative phase** doesn't need to be 90 deg:



RF (2010)

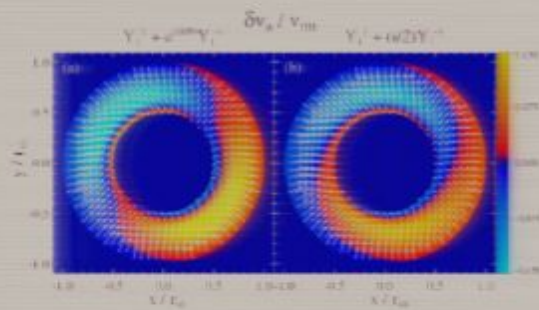


Arnett & Meakin (2011)

Spiral Modes: Excitability

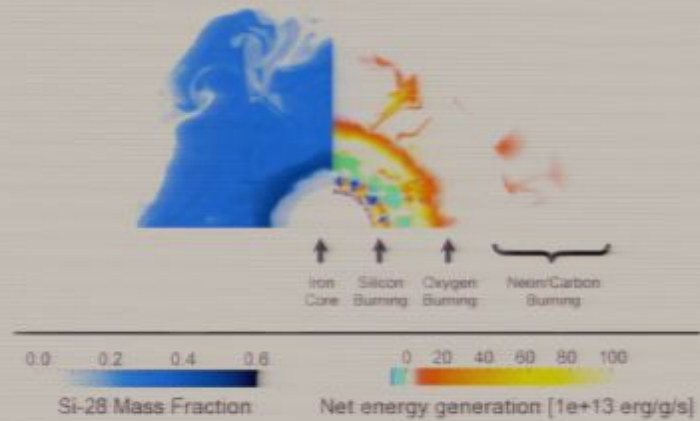
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Density perturbations: 2D stellar convection simulations

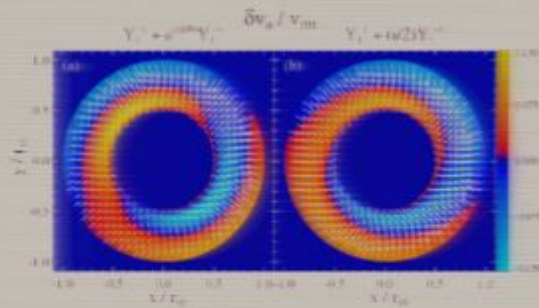


Arnett & Meakin (2011)

Spiral Modes: Excitability

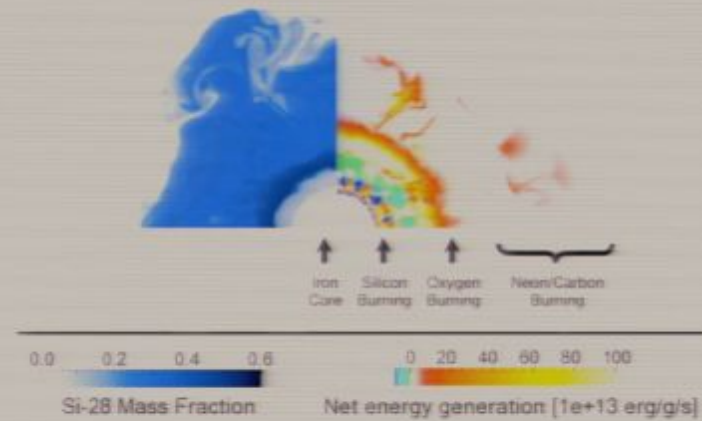
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Density perturbations: 2D stellar convection simulations

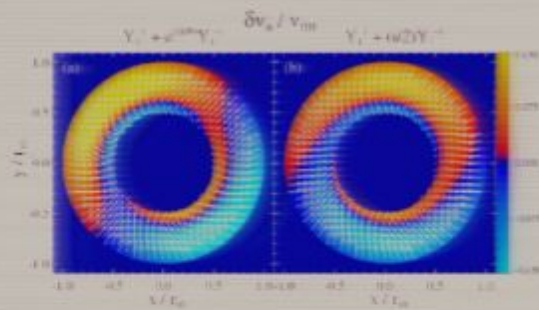


Arnett & Meakin (2011)

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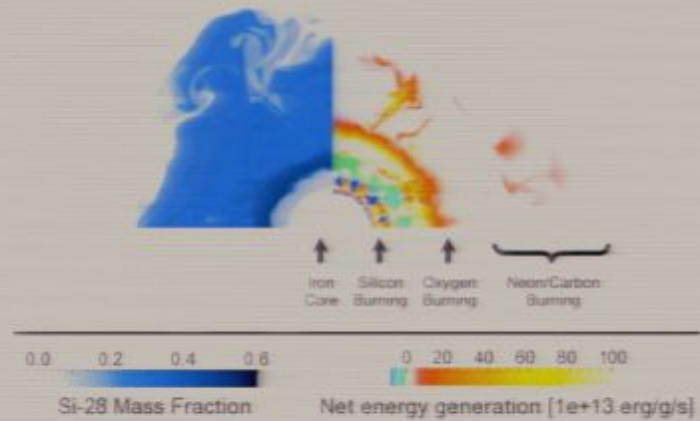
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Density perturbations: 2D stellar convection simulations

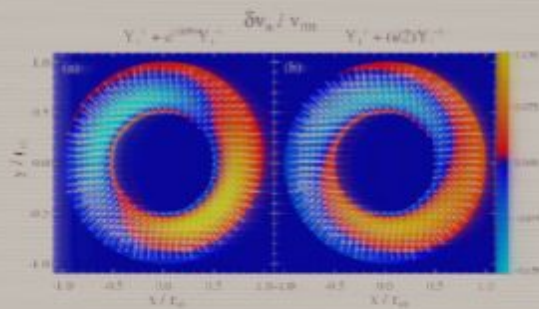


Arnett & Meakin (2011)

Spiral Modes: Excitability

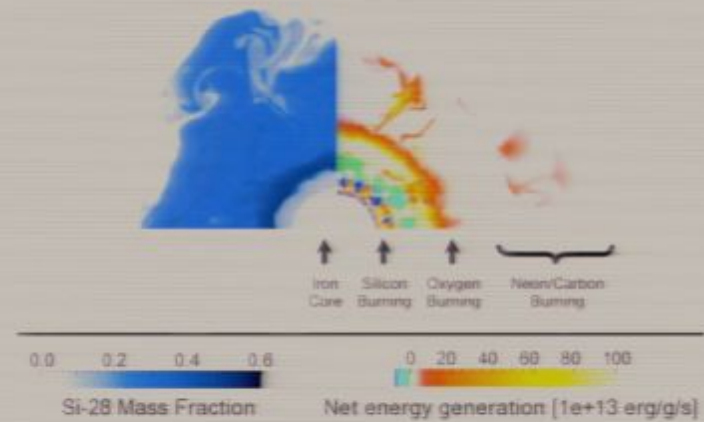
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RF (2010)

Density perturbations: 2D stellar convection simulations



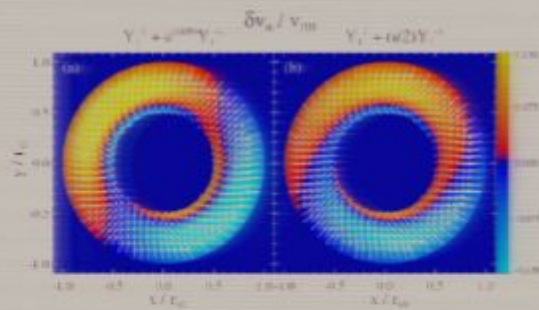
Arnett & Meakin (2011)

Spiral Modes: Excitability

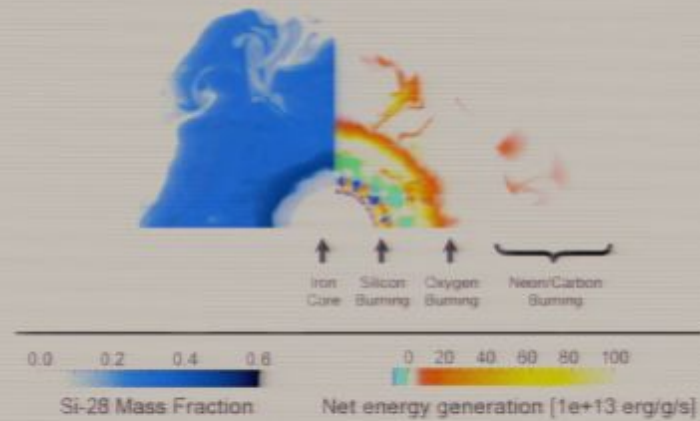
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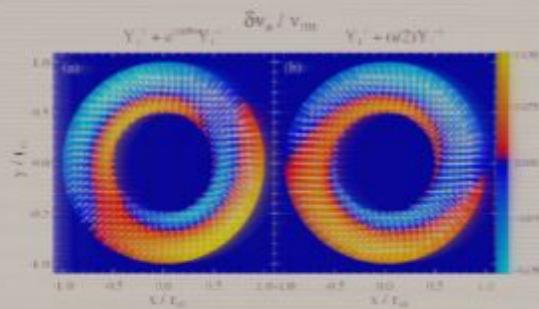
Arnett & Meakin (2011)

Spiral Modes: Excitability

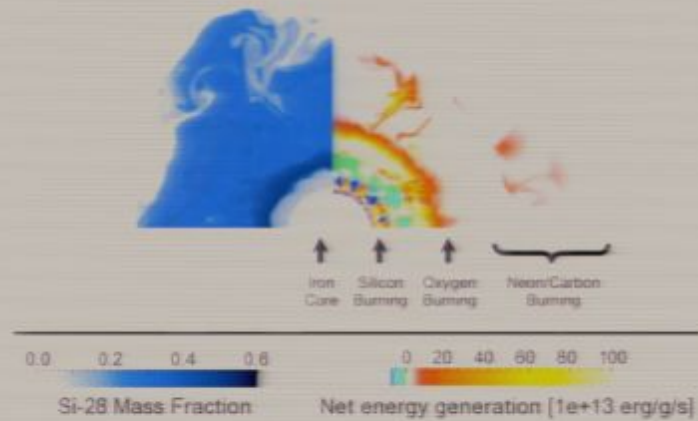
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Density perturbations: 2D stellar convection simulations

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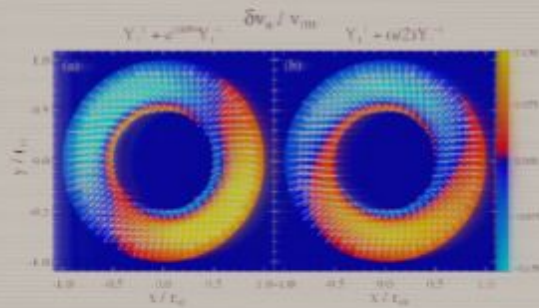
Arnett & Meakin (2011)

Spiral Modes: Excitability

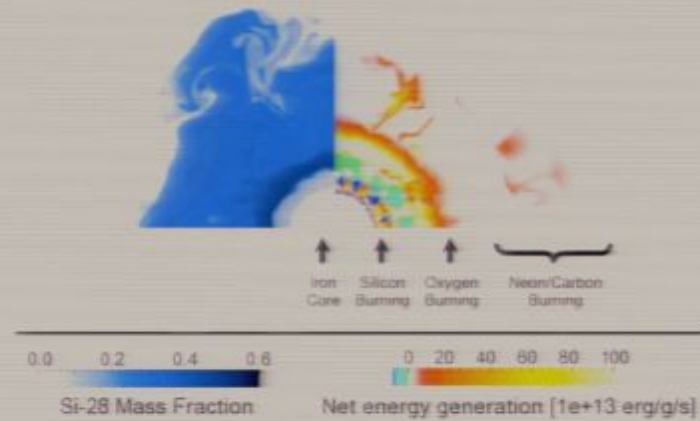
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RF (2010)

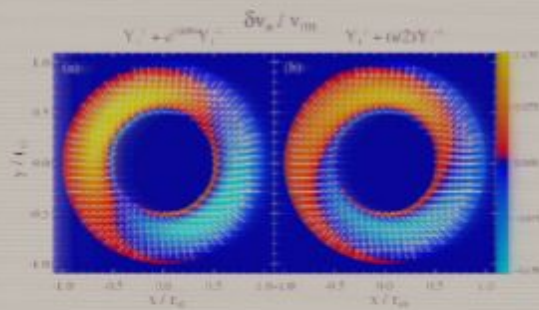


Arnett & Meakin (2011)

Spiral Modes: Excitability

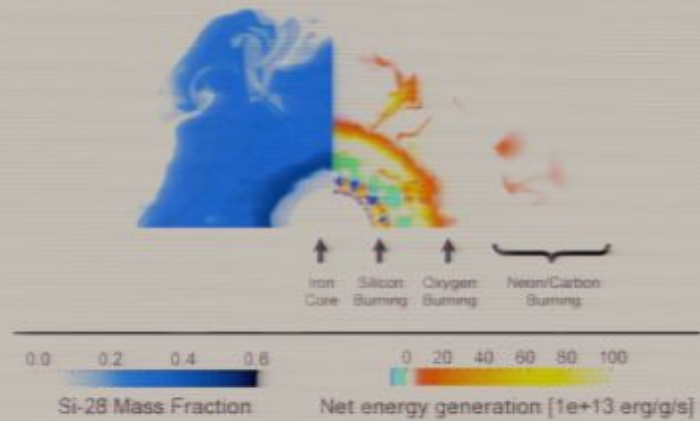
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Density perturbations: 2D stellar convection simulations

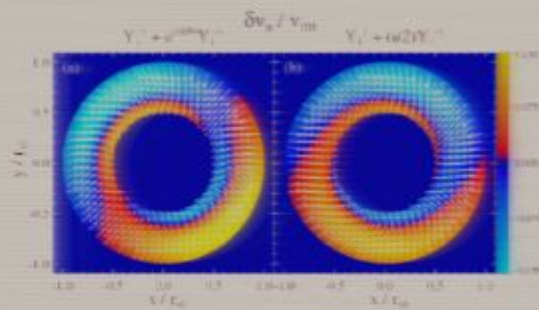


Arnett & Meakin (2011)

Spiral Modes: Excitability

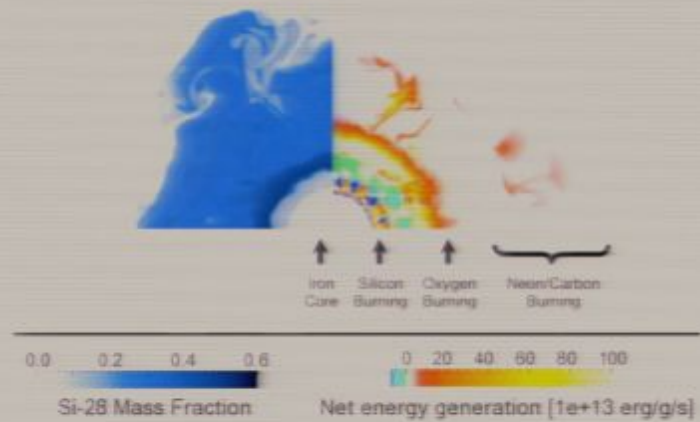
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Density perturbations: 2D stellar convection simulations

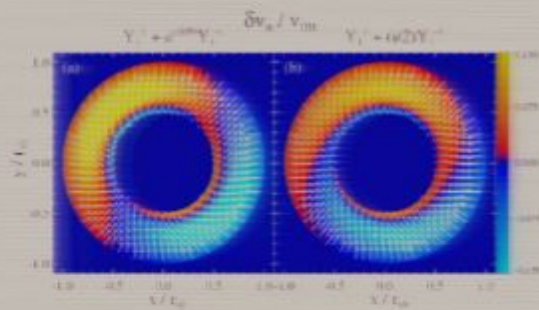


Arnett & Meakin (2011)

Spiral Modes: Excitability

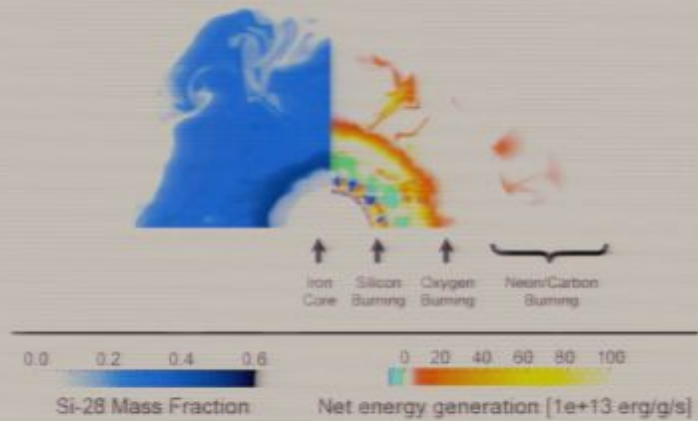
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Density perturbations: 2D stellar convection simulations



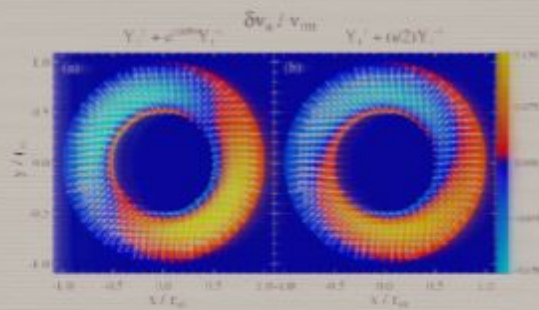
Arnett & Meakin (2011)

Spiral Modes: Excitability

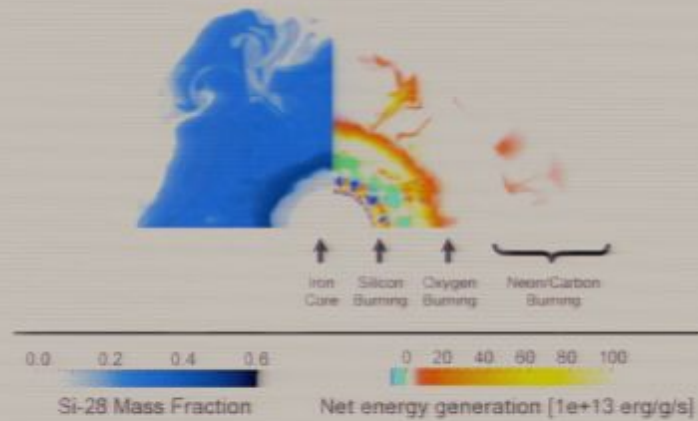
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Density perturbations: 2D stellar convection simulations

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RF (2010)



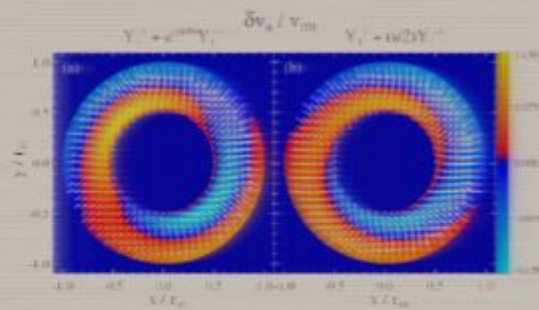
Arnett & Meakin (2011)

Spiral Modes: Excitability

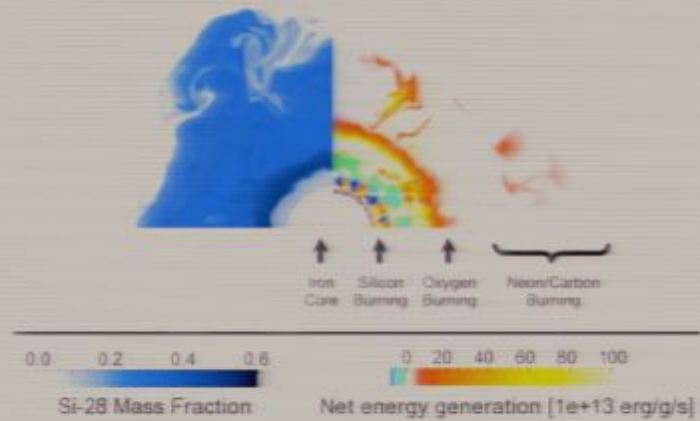
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Density perturbations: 2D stellar convection simulations

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RF (2010)

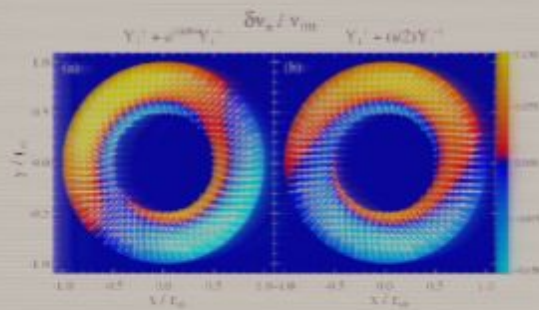


Arnett & Meakin (2011)

Spiral Modes: Excitability

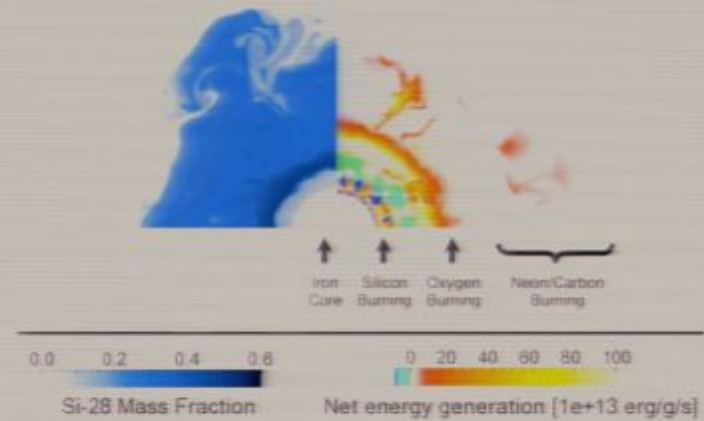
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Density perturbations: 2D stellar convection simulations

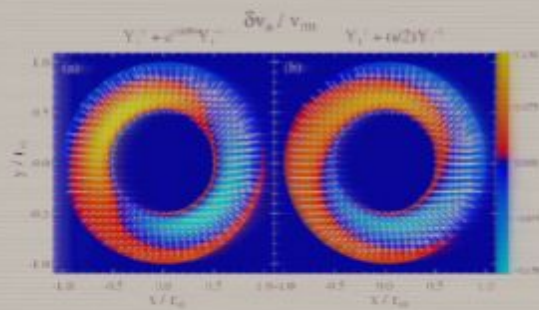


Arnett & Meakin (2011)

Spiral Modes: Excitability

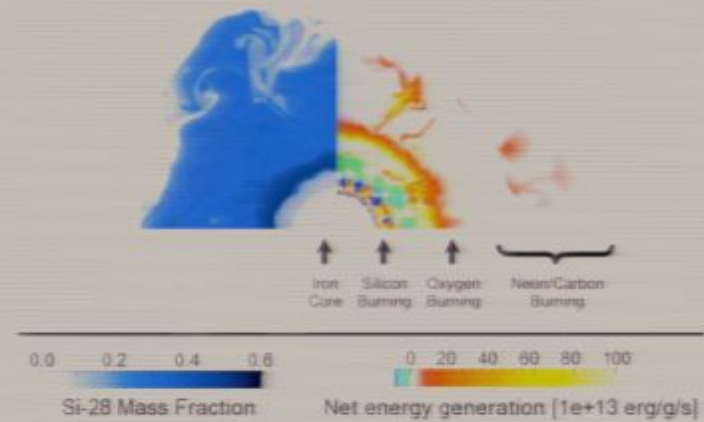
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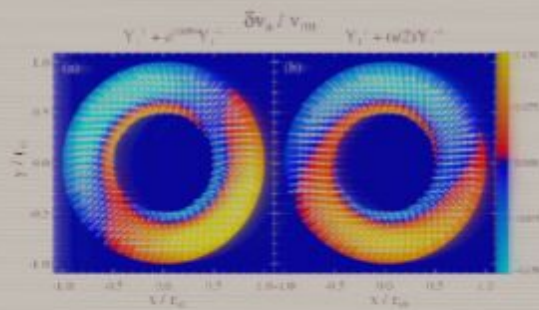
Arnett & Meakin (2011)

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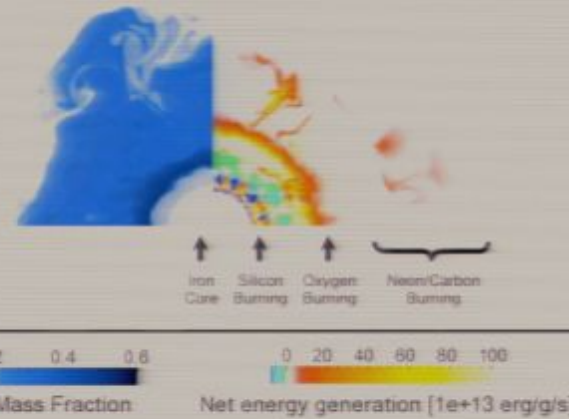
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RF (2010)

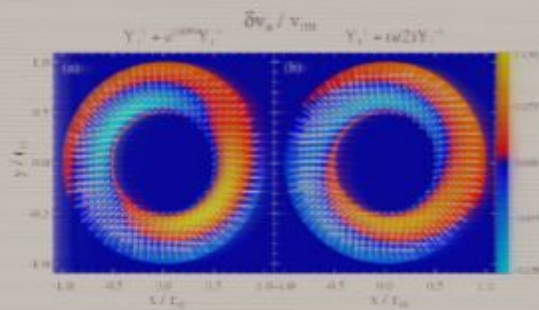


Arnett & Meakin (2011)

Spiral Modes: Excitability

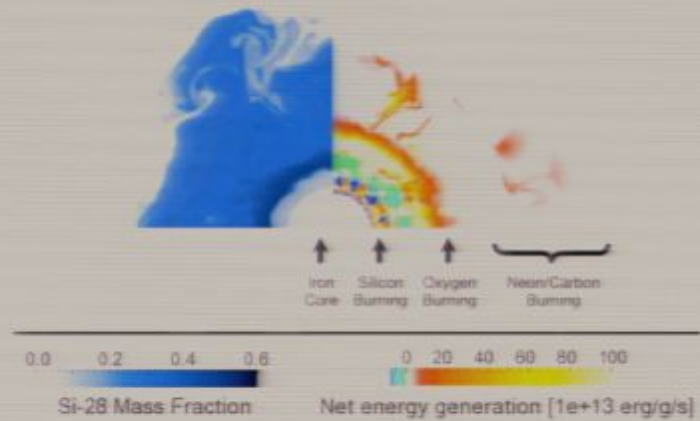
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Density perturbations: 2D stellar convection simulations

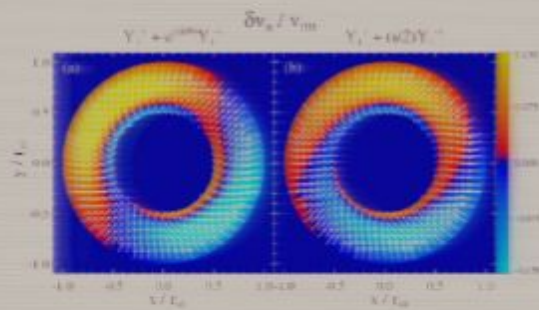


Arnett & Meakin (2011)

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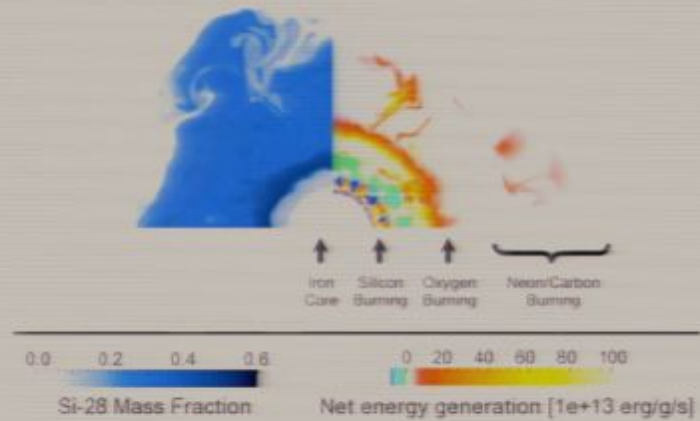
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Density perturbations: 2D stellar convection simulations

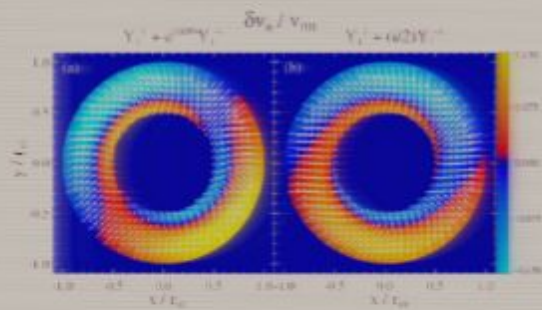


Arnett & Meakin (2011)

Spiral Modes: Excitability

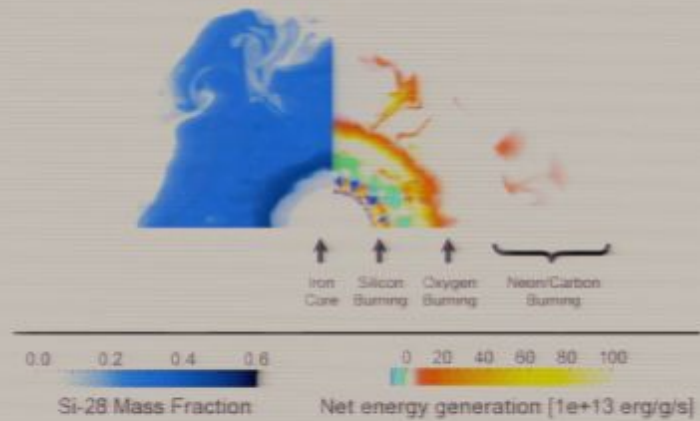
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Density perturbations: 2D stellar convection simulations

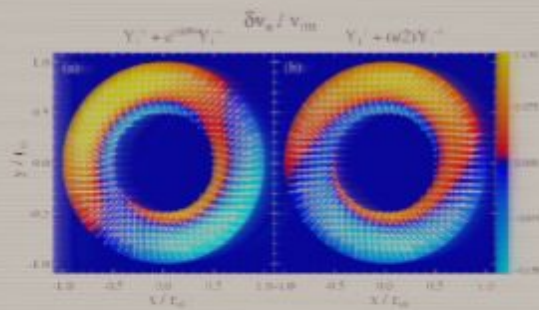


Arnett & Meakin (2011)

Spiral Modes: Excitability

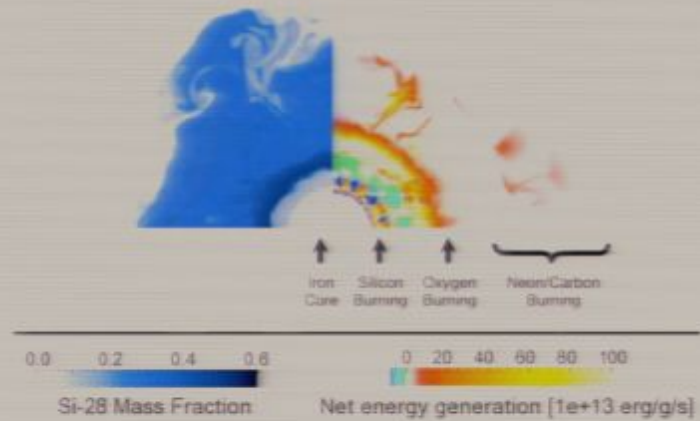
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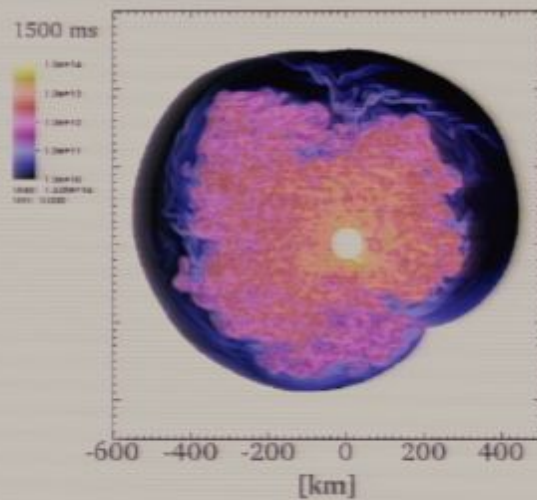
Density perturbations: 2D stellar convection simulations



Arnett & Meakin (2011)

Spiral Modes: Other Applications

Magnetic Field Amplification



Endeve et al. (2010)

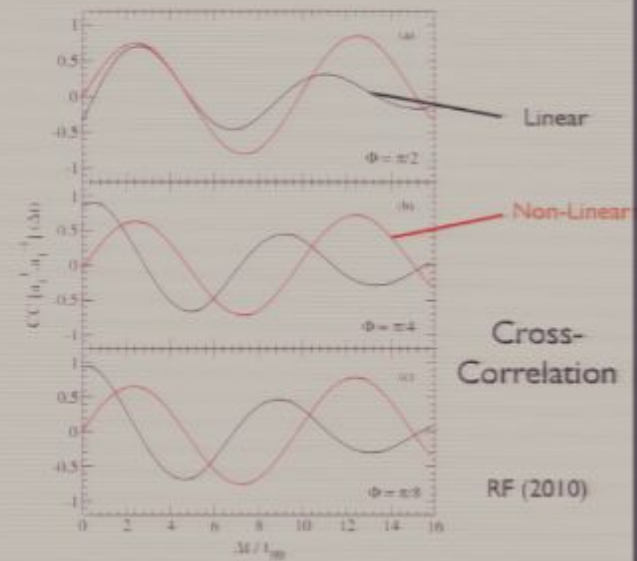
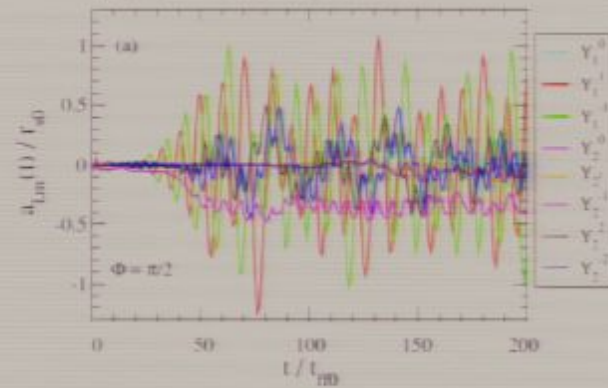
Gravitational Waves

Work by Kei Kotake
and collaborators
(arXiv/1106.0544)

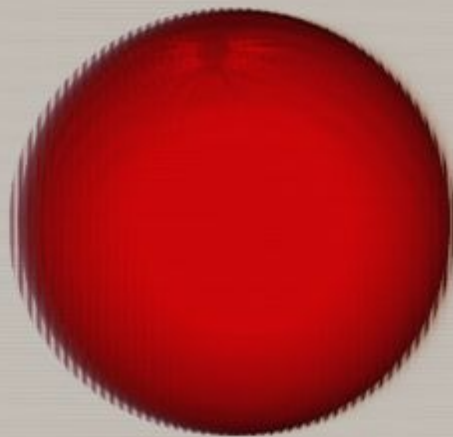
Spiral Modes: 3D Simulations (Zeus-MP)



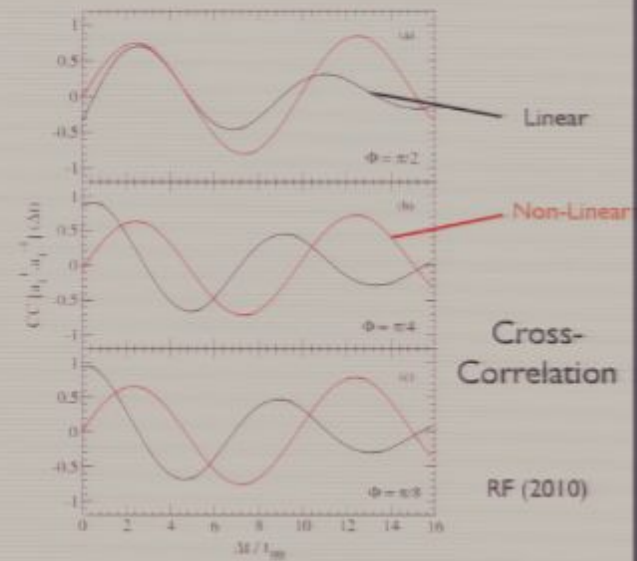
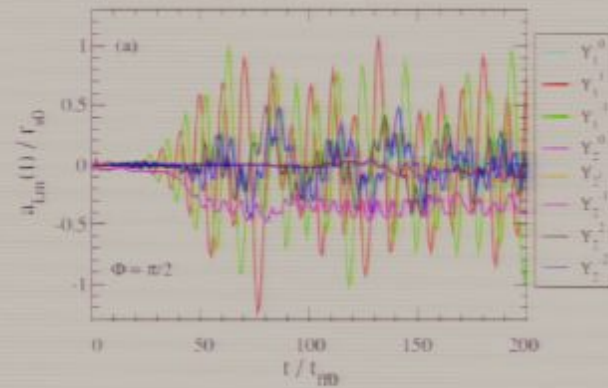
Spherical Harmonic Coefficients



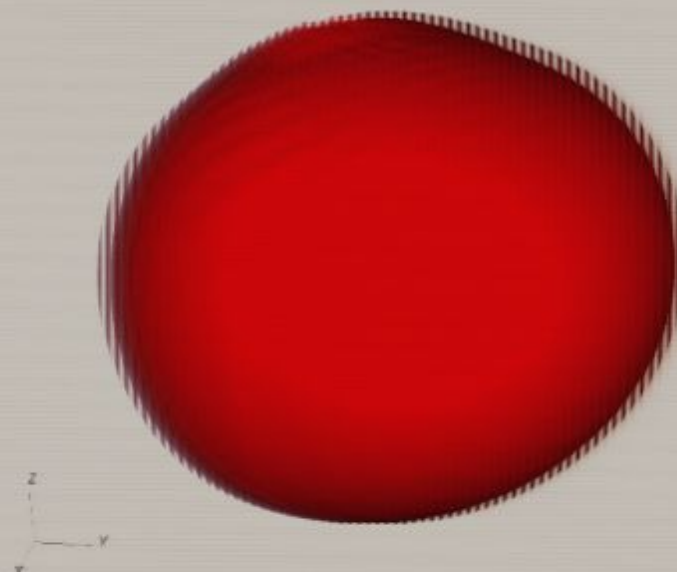
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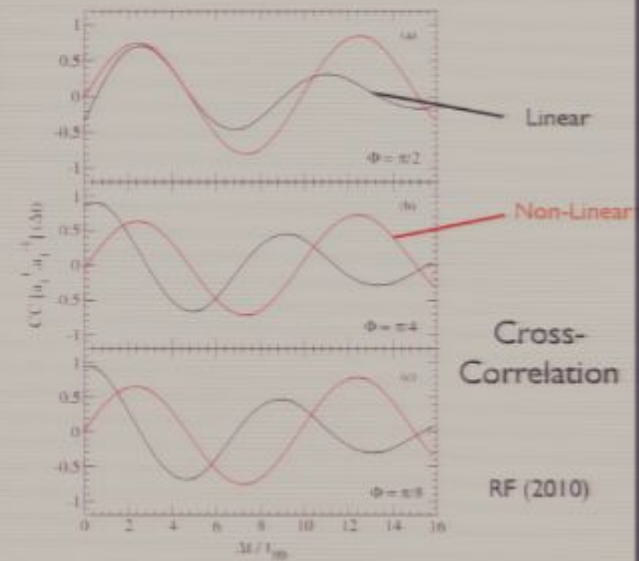
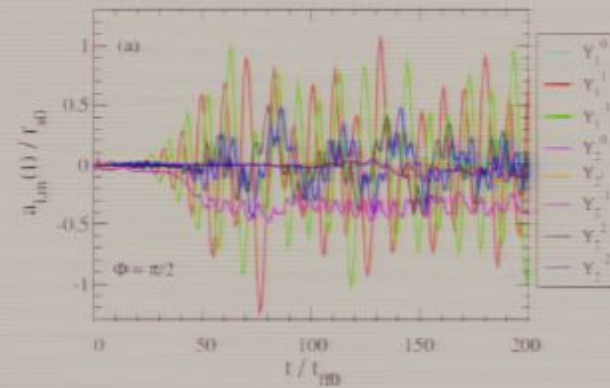
Spherical Harmonic Coefficients



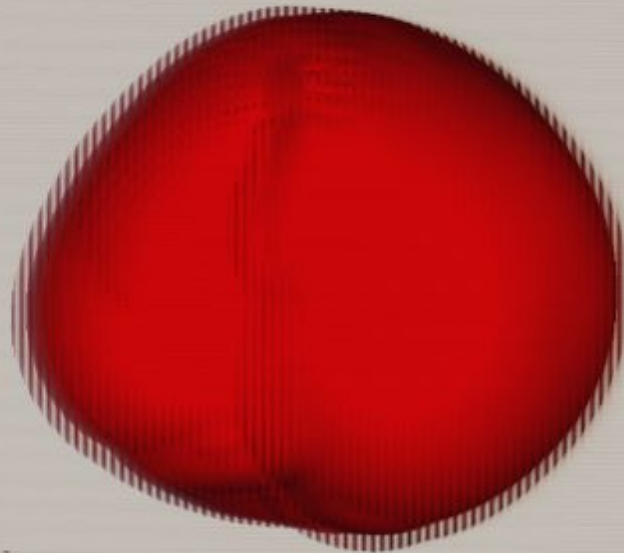
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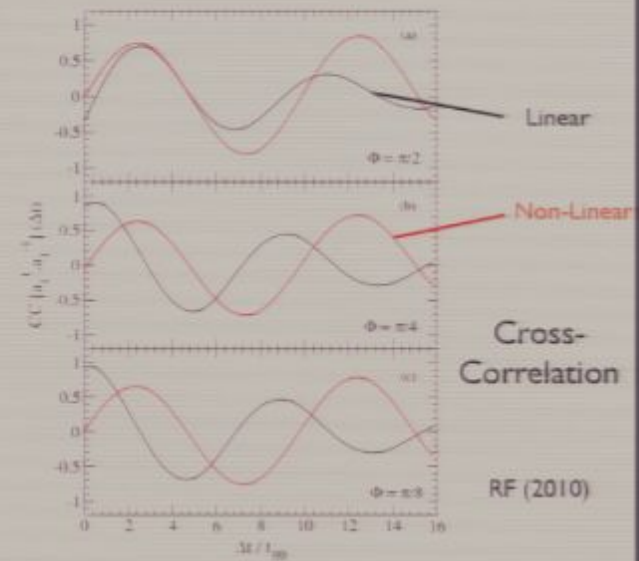
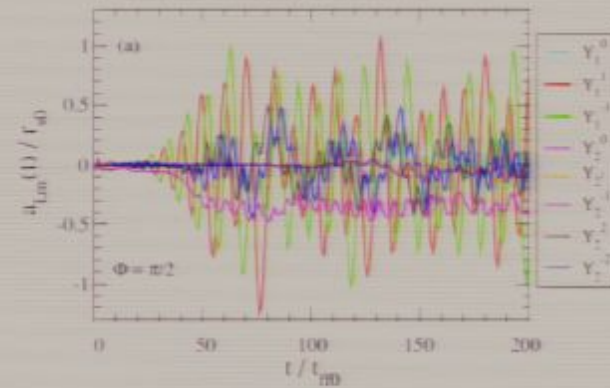
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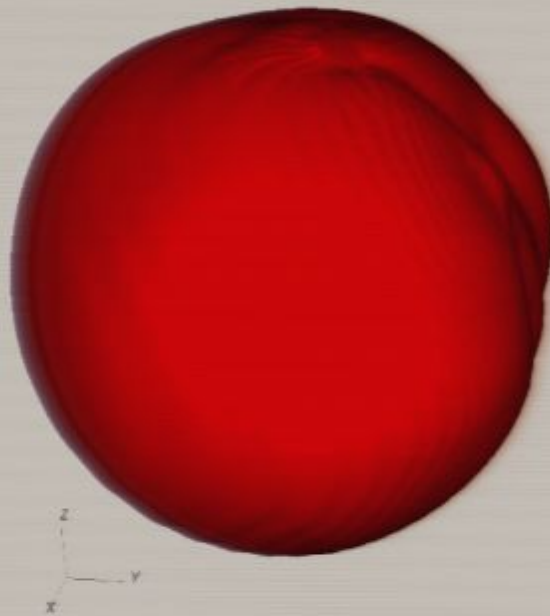
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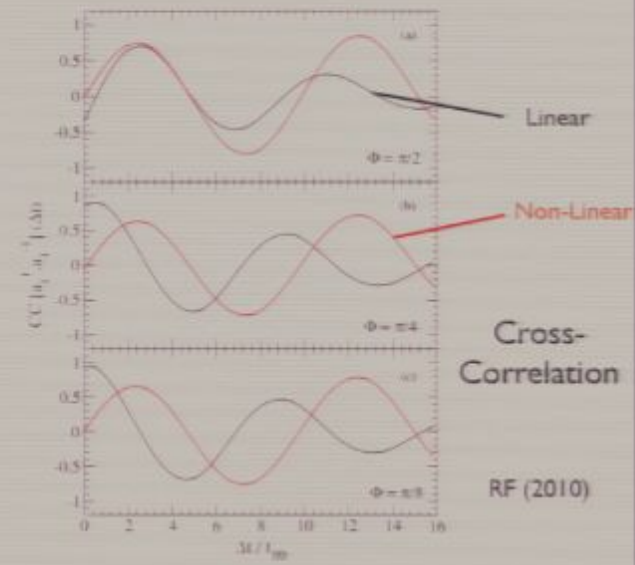
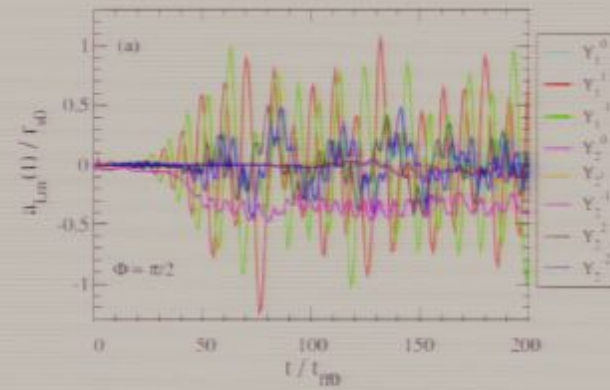
Spherical Harmonic Coefficients



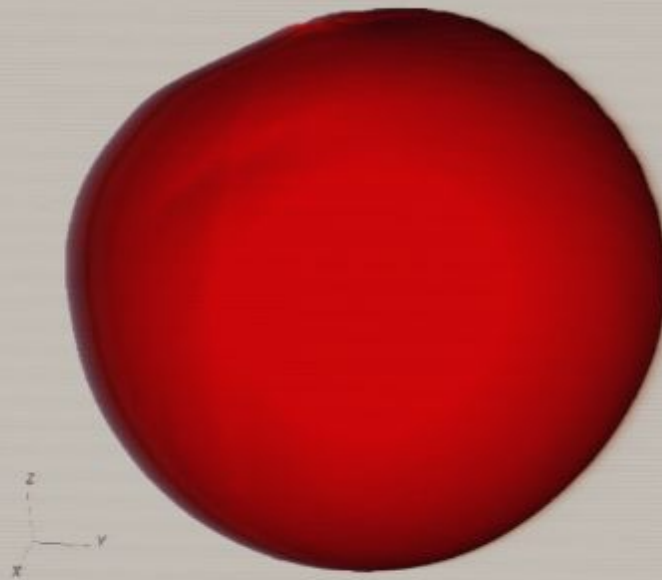
Spiral Modes: 3D Simulations (Zeus-MP)



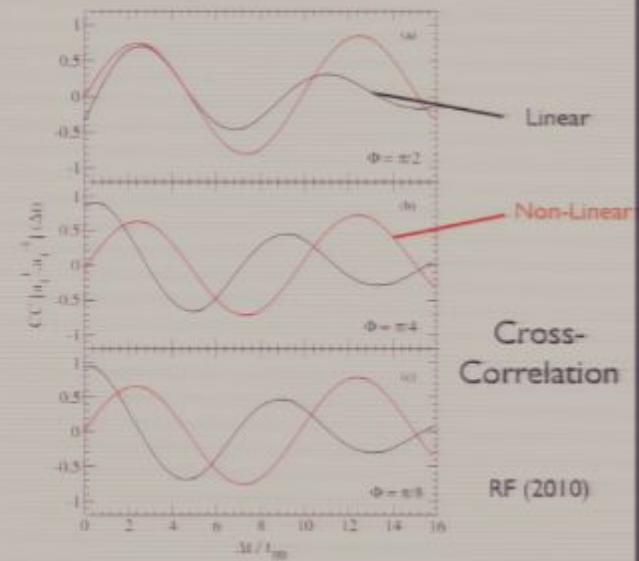
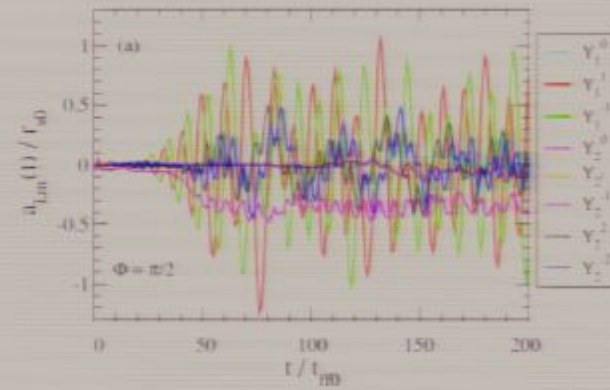
Spherical Harmonic Coefficients



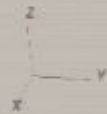
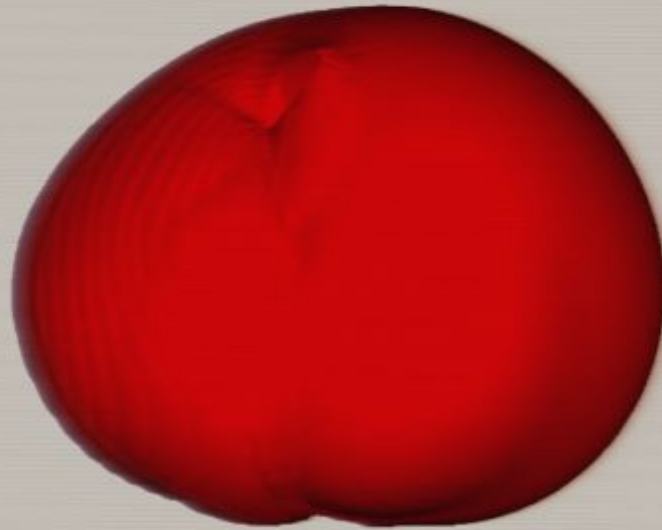
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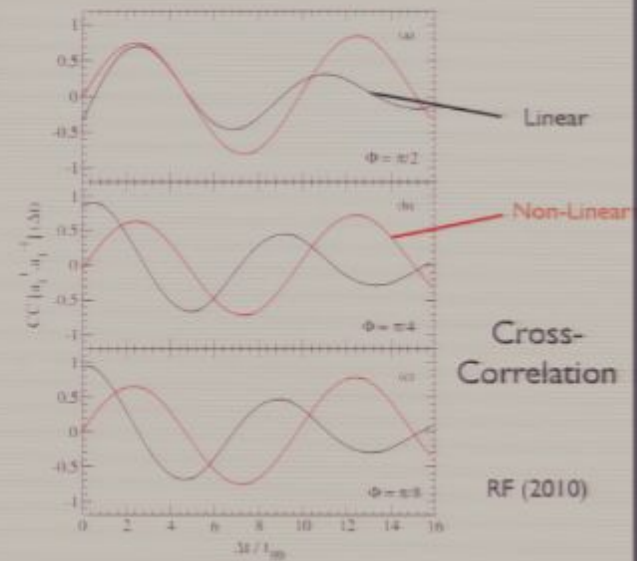
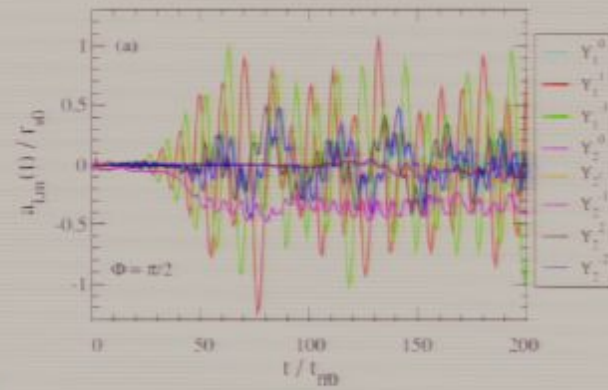
Spherical Harmonic Coefficients



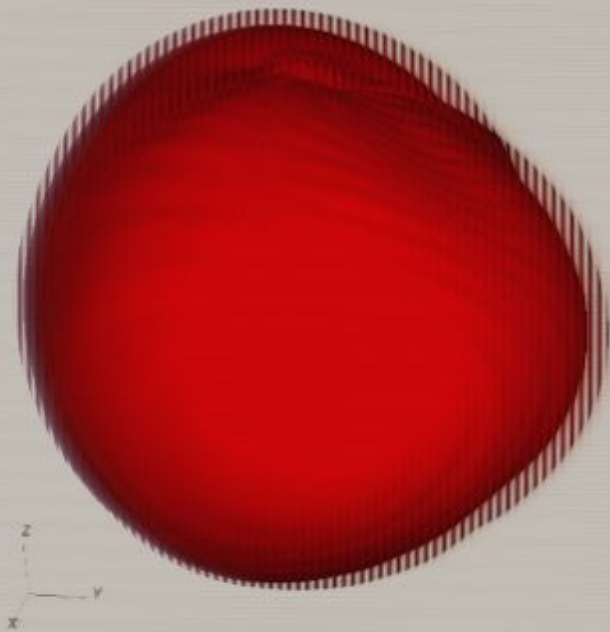
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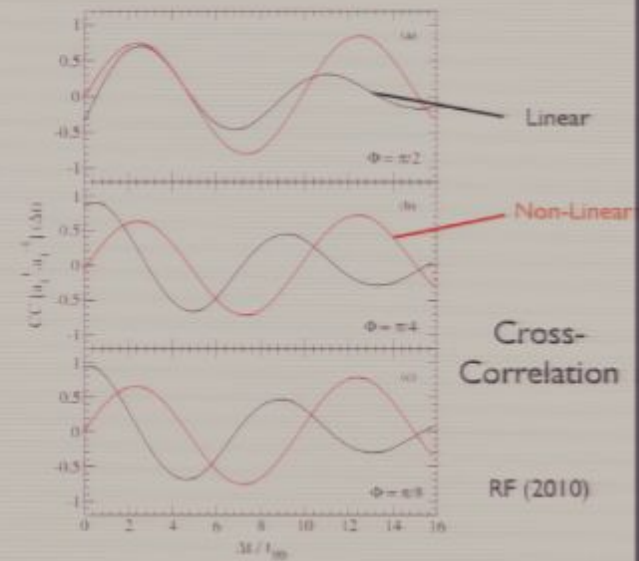
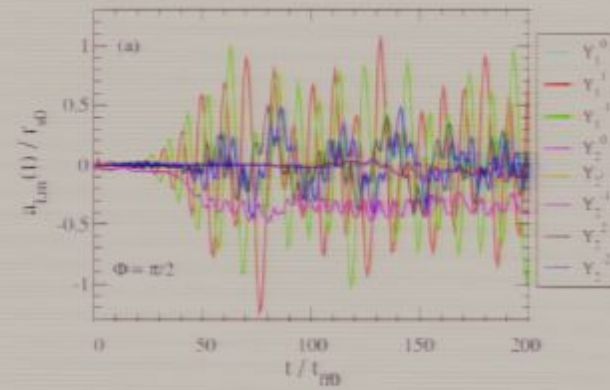
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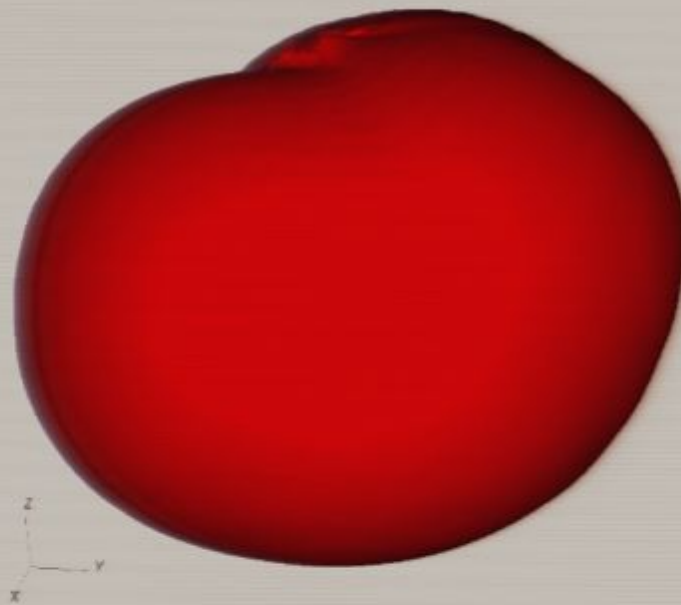
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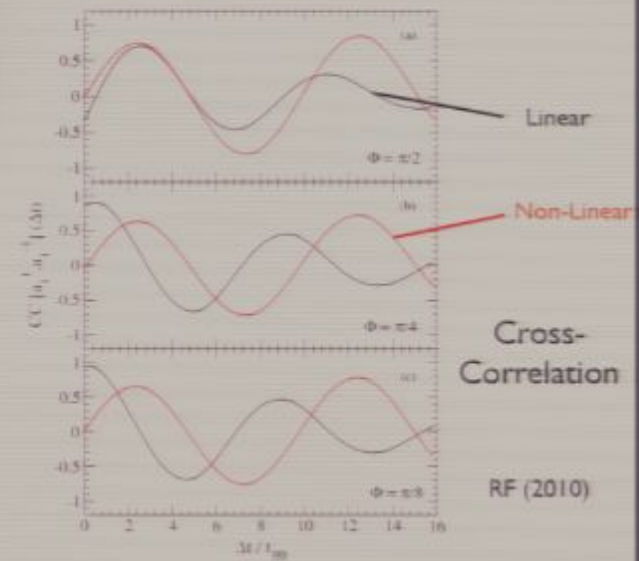
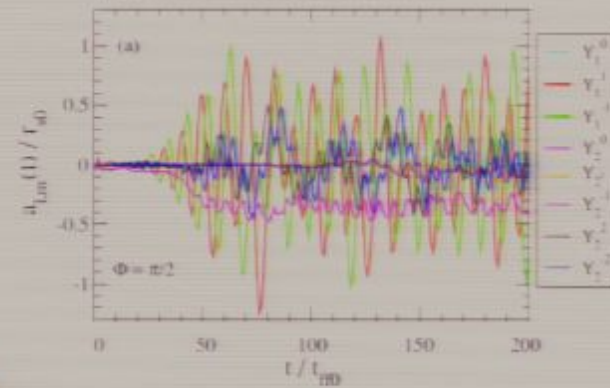
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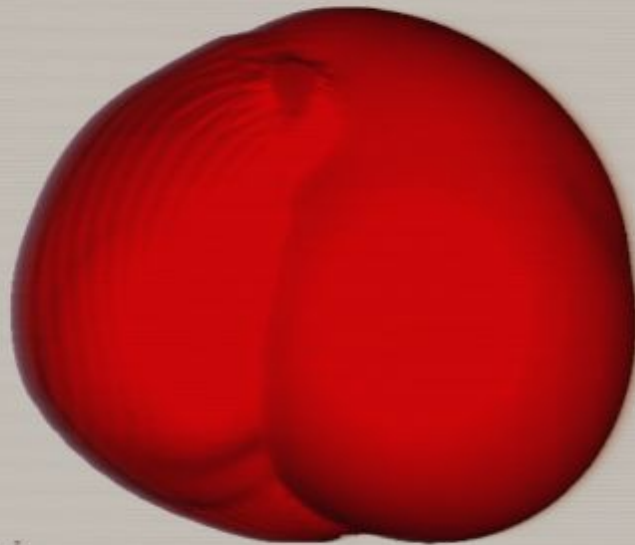
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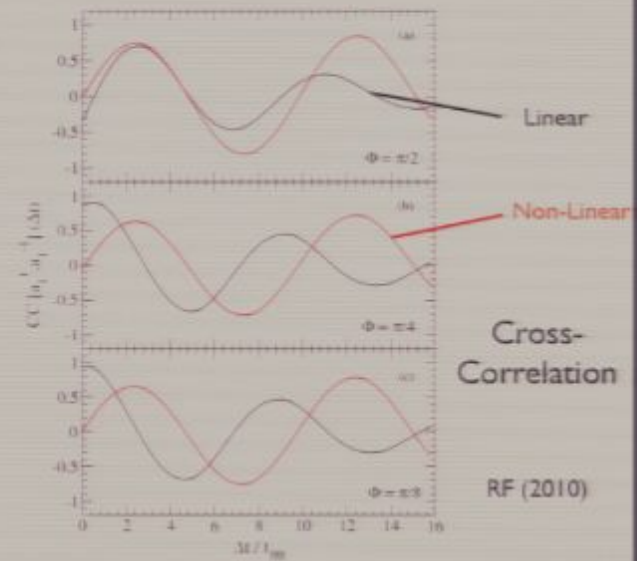
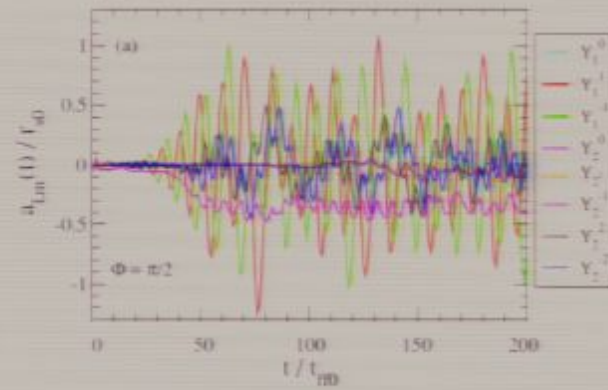
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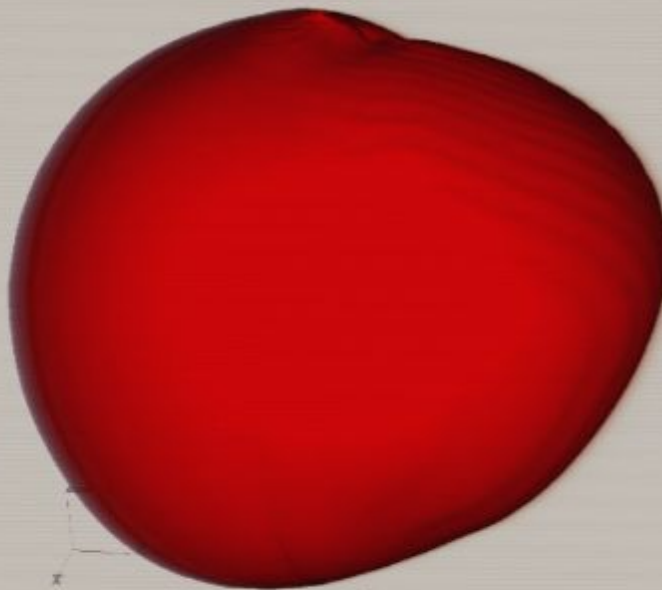
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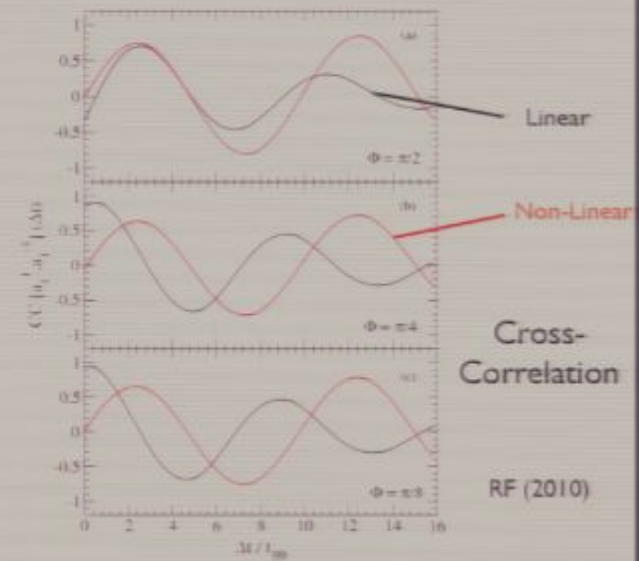
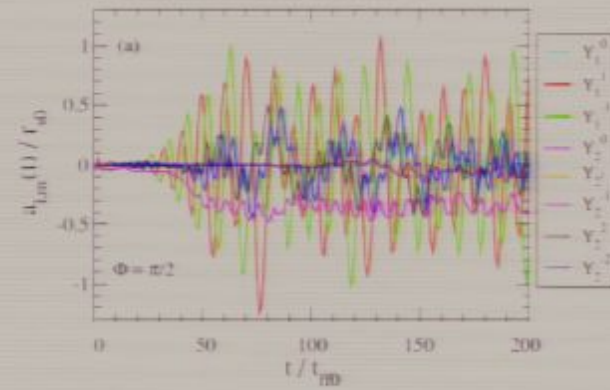
Spherical Harmonic Coefficients



Spiral Modes: 3D Simulations (Zeus-MP)



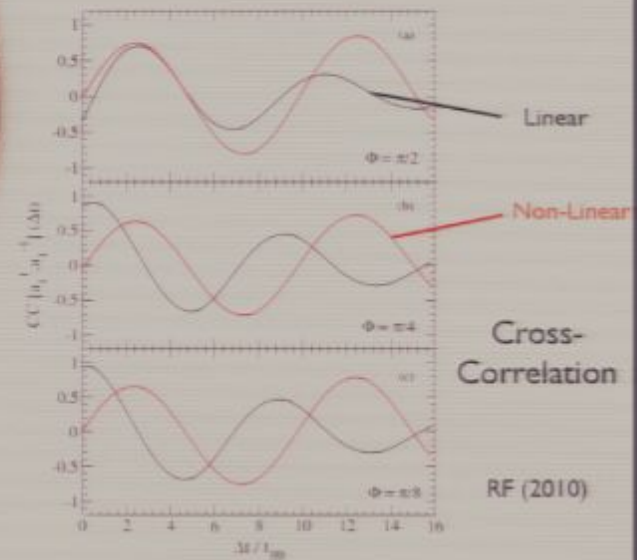
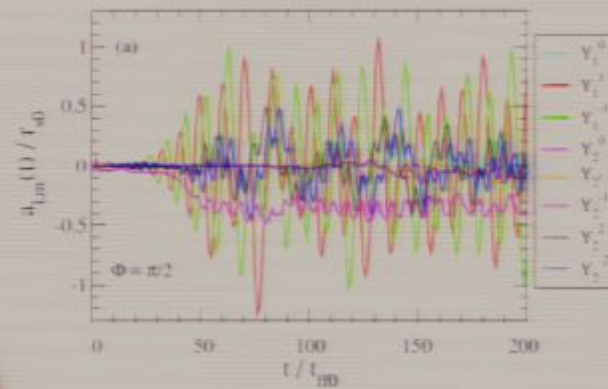
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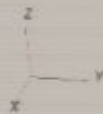
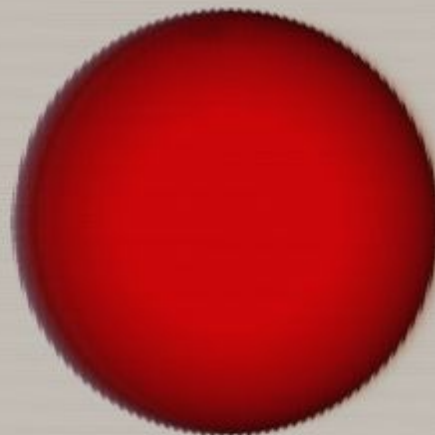
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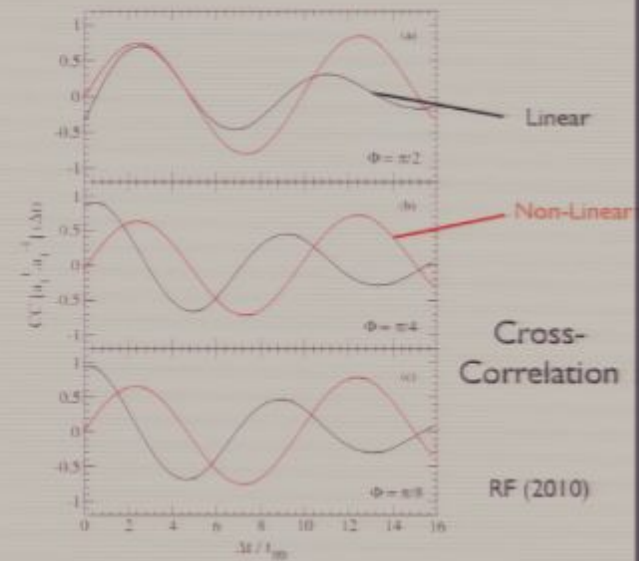
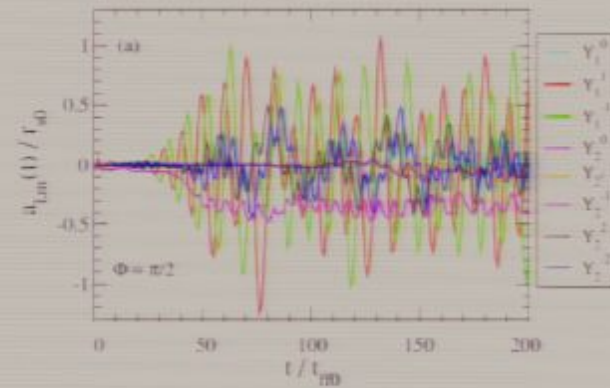
Spherical Harmonic Coefficients



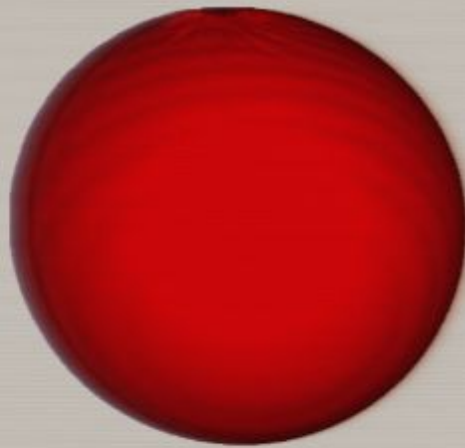
Spiral Modes: 3D Simulations (Zeus-MP)



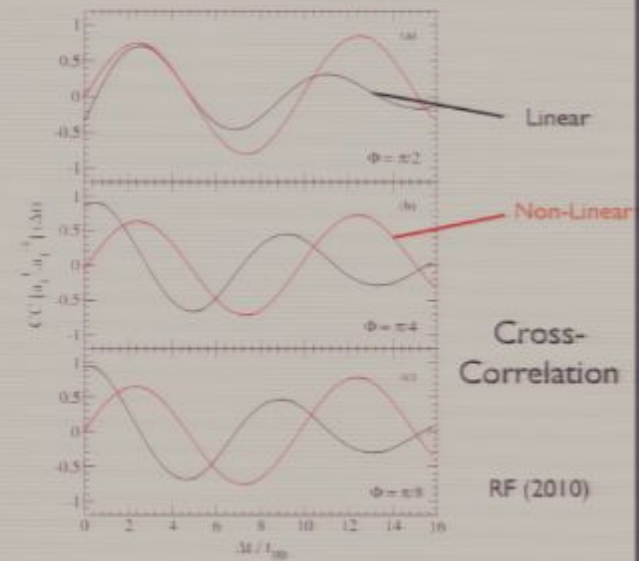
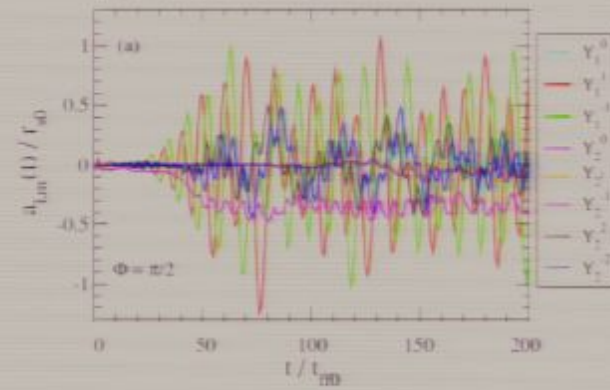
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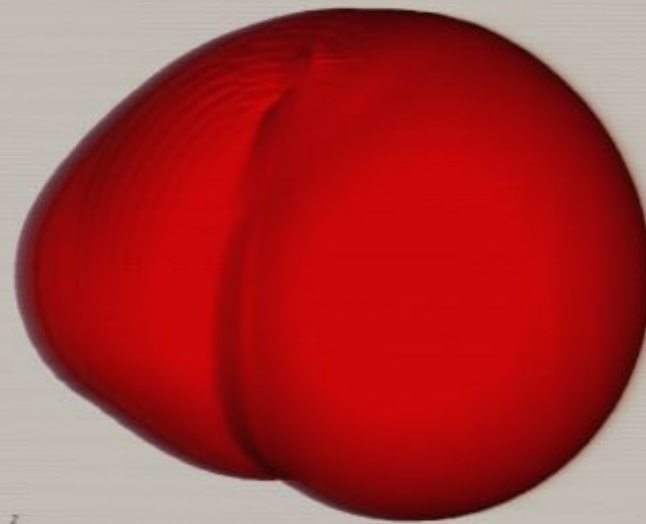
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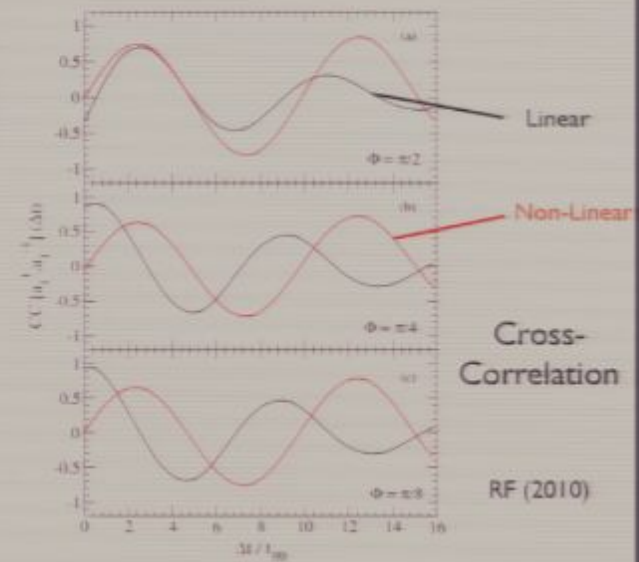
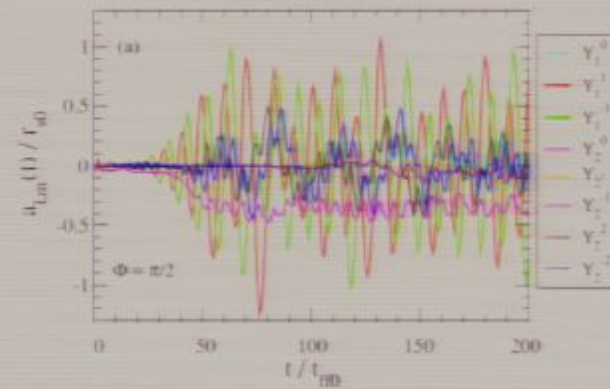
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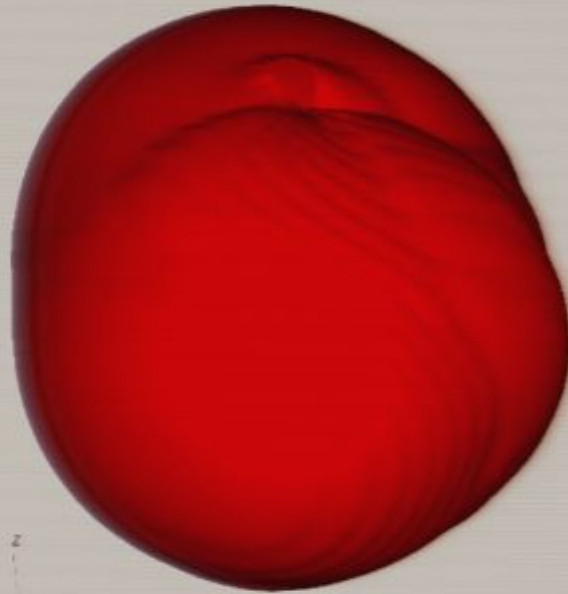
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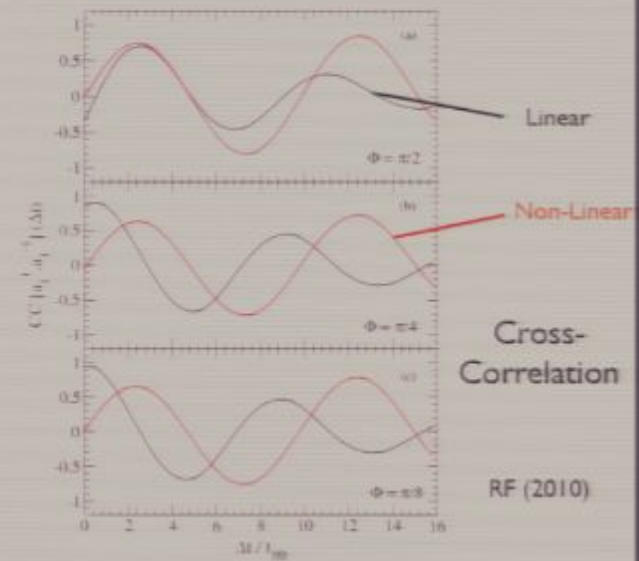
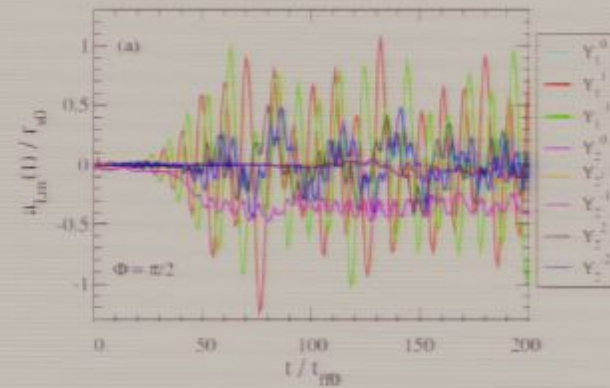
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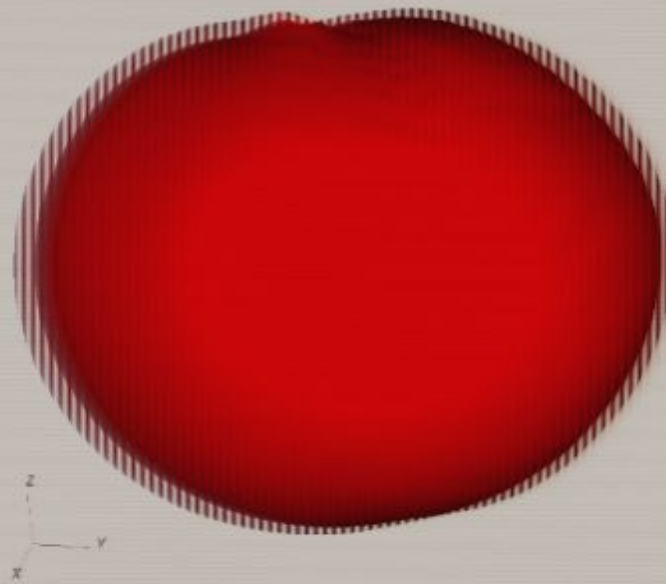
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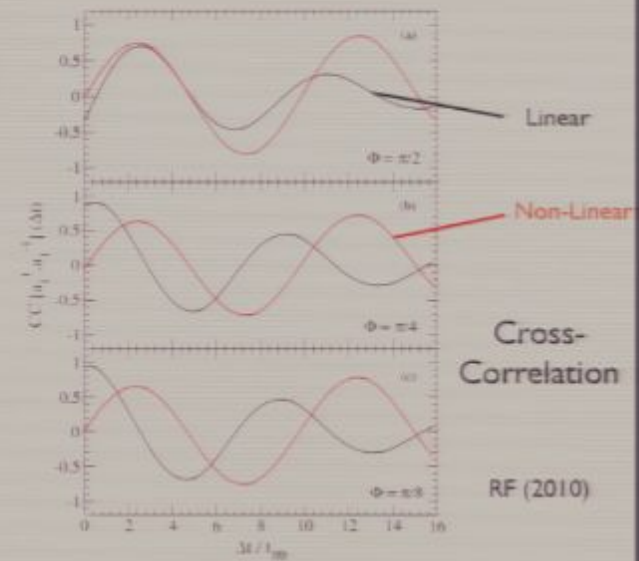
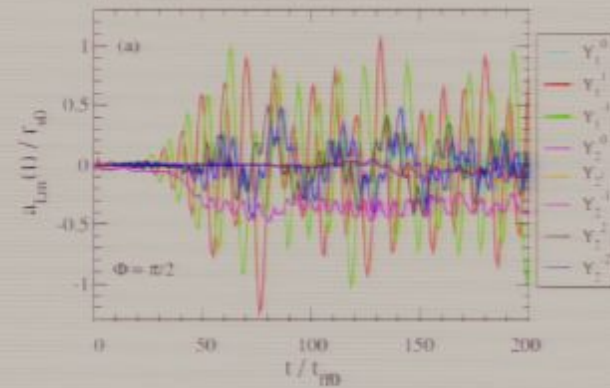
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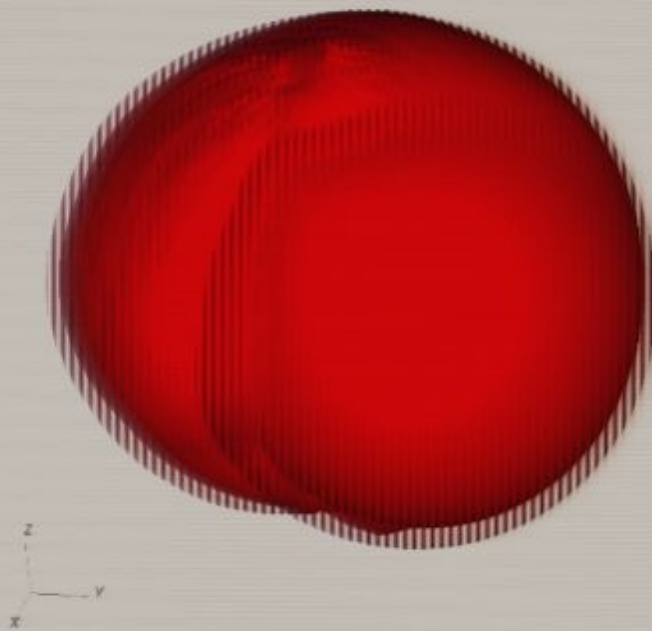
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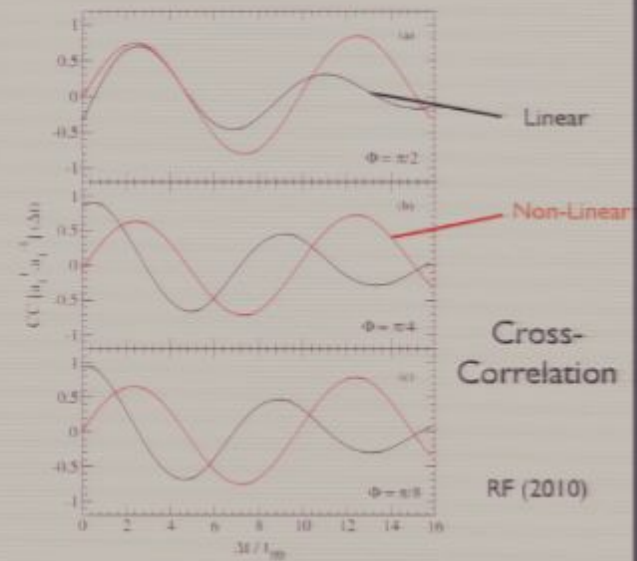
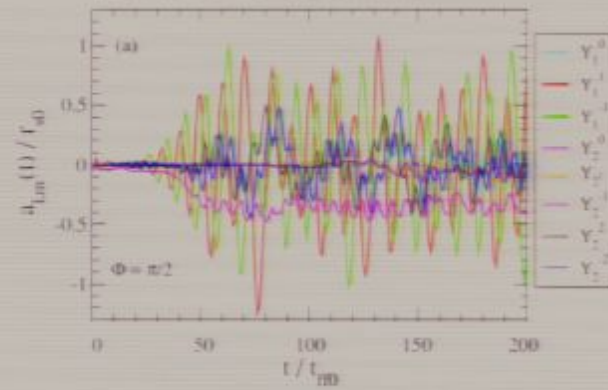
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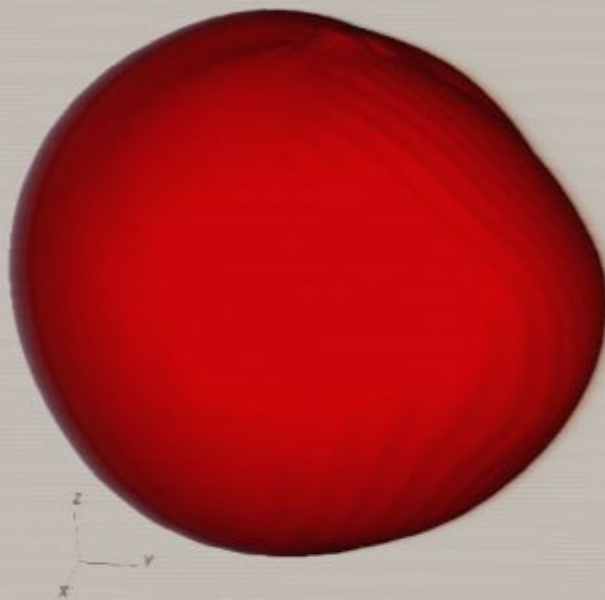
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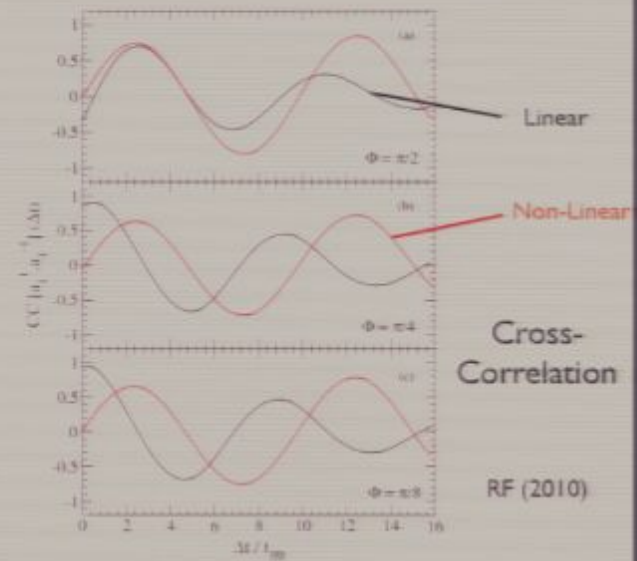
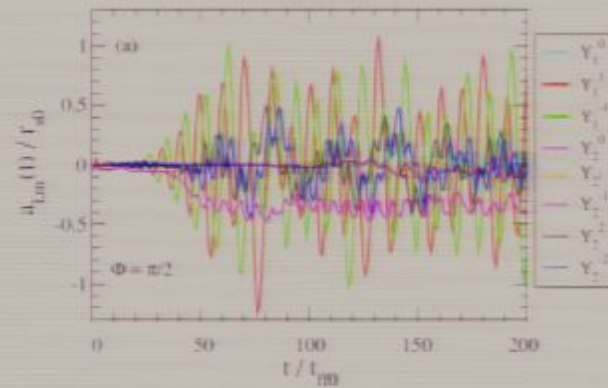
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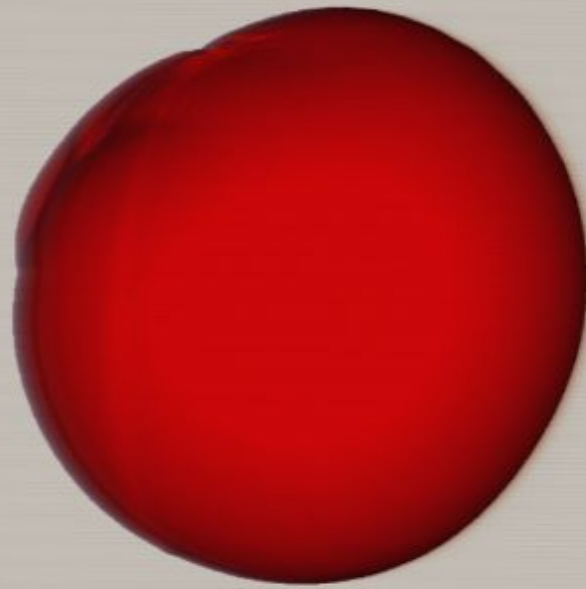
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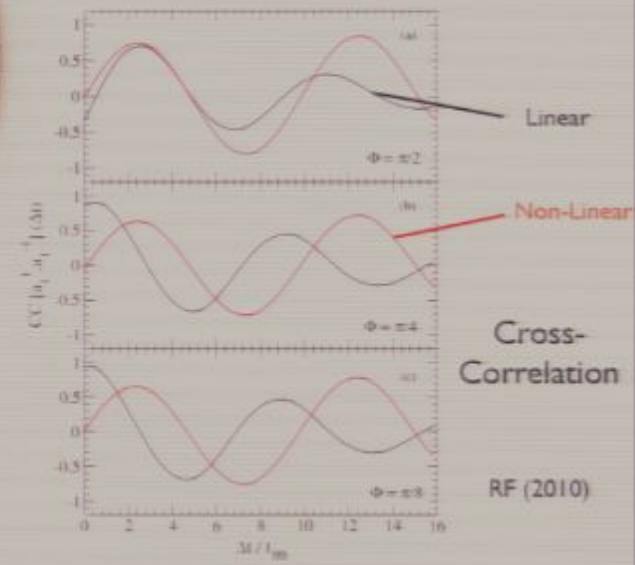
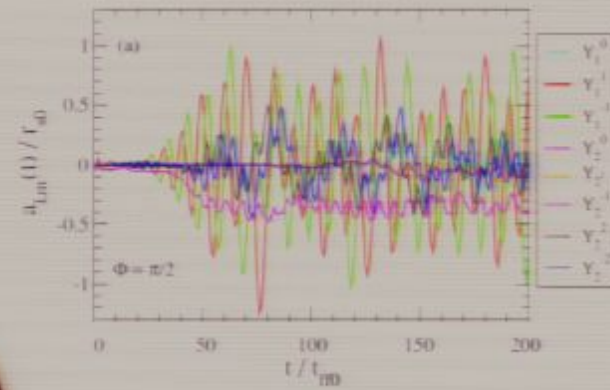
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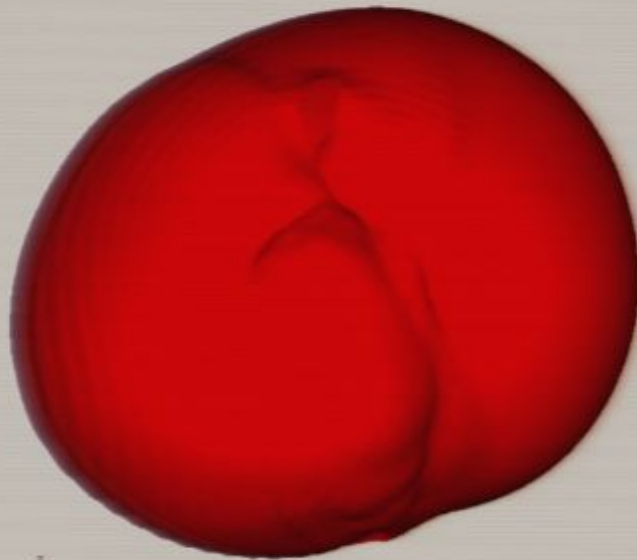
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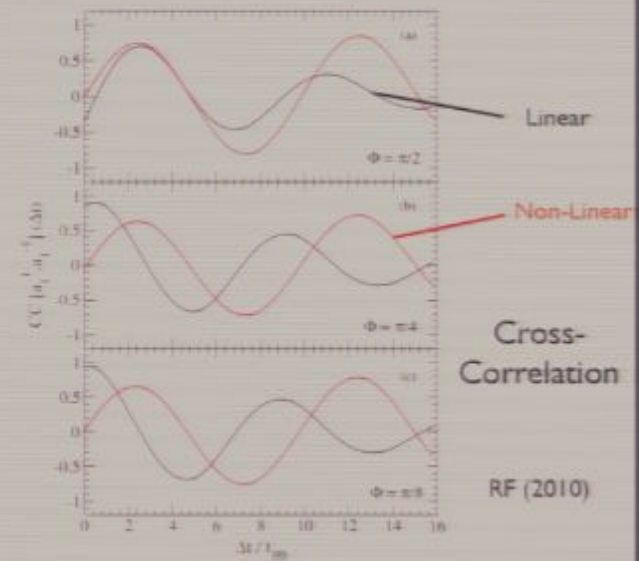
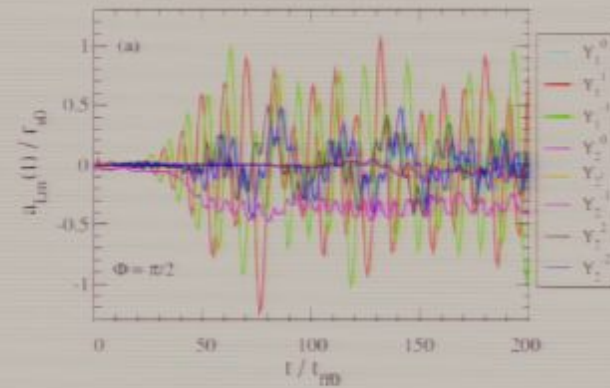
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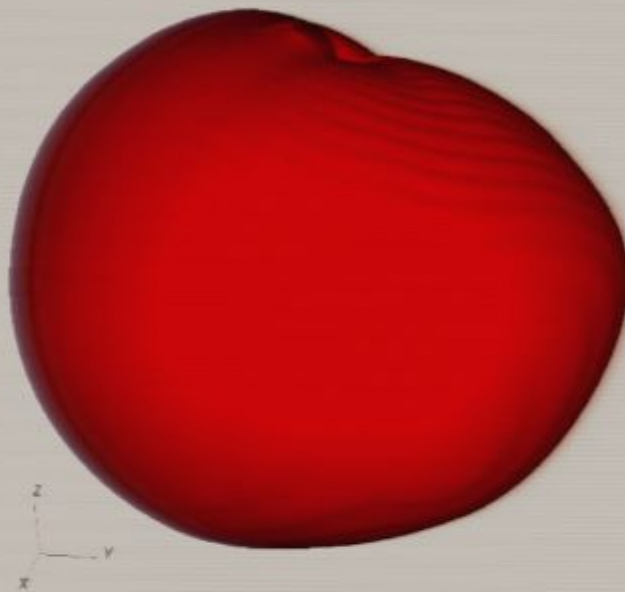
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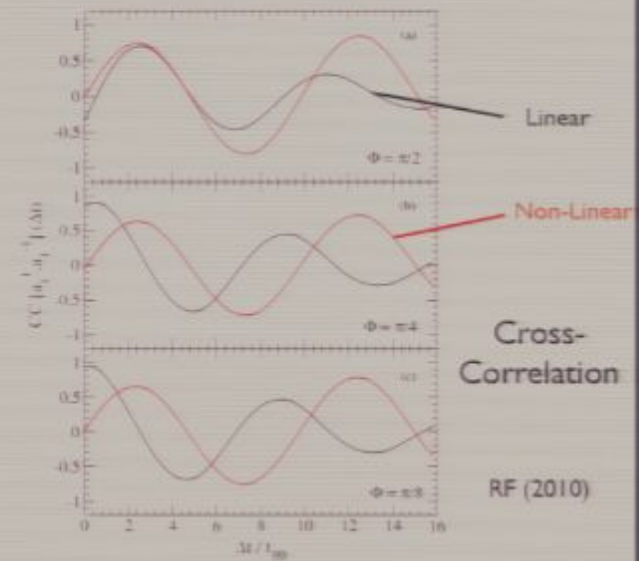
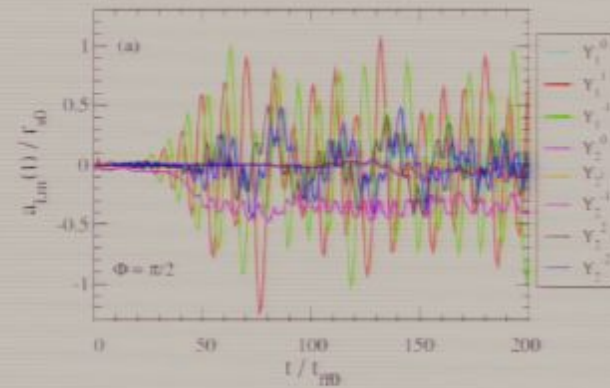
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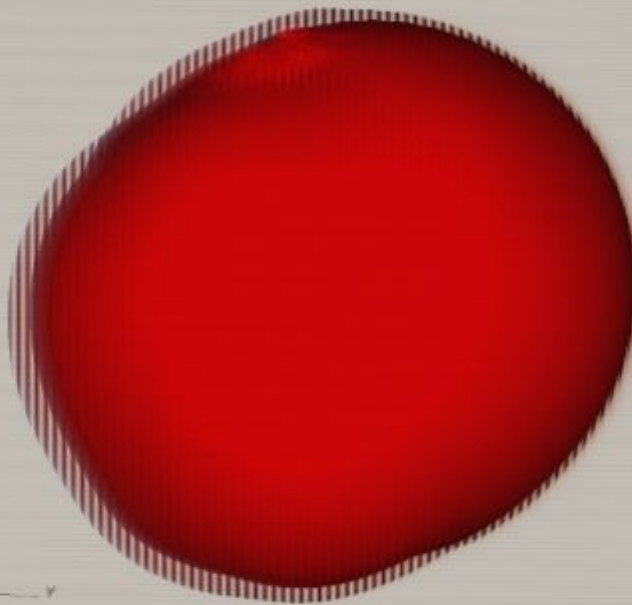
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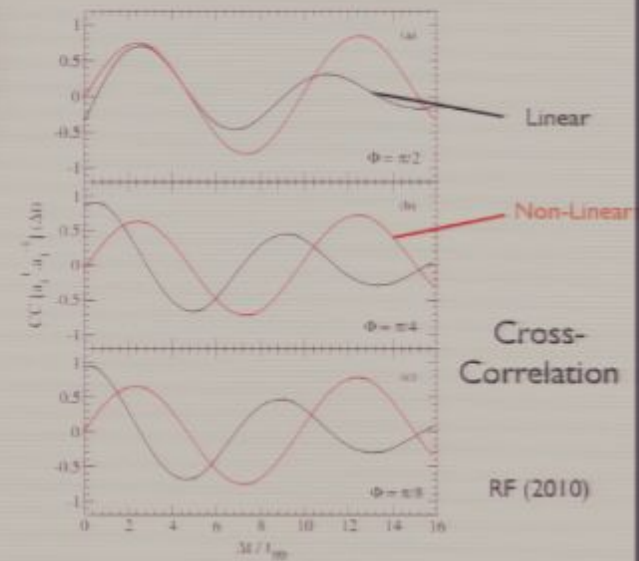
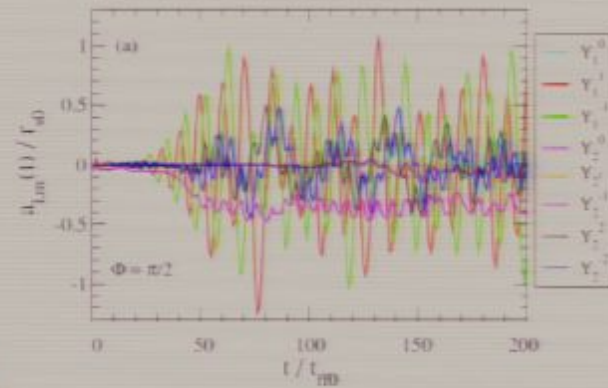
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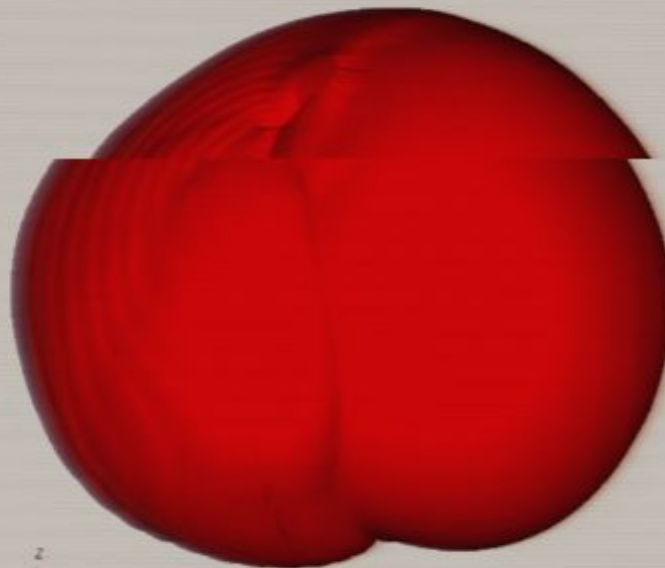
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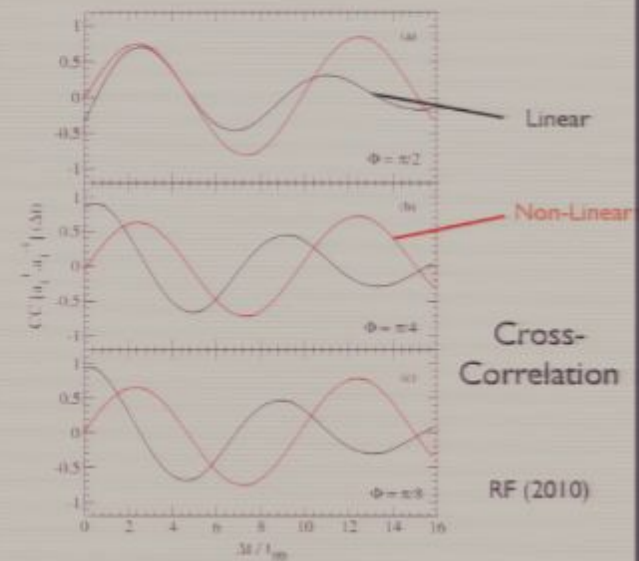
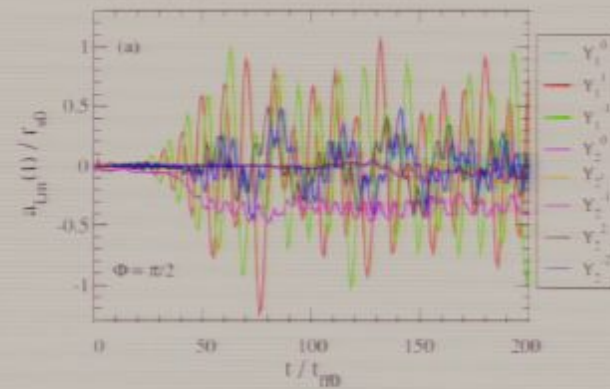
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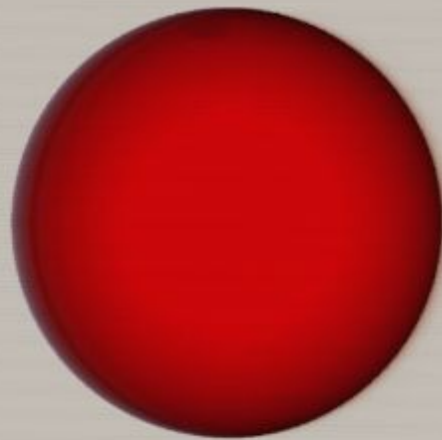
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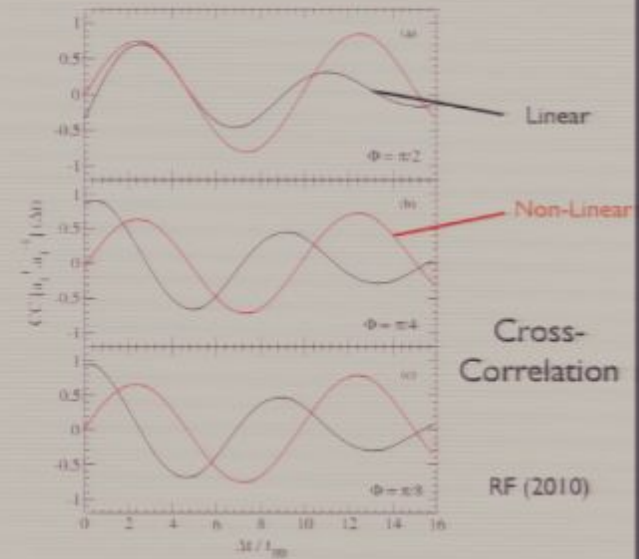
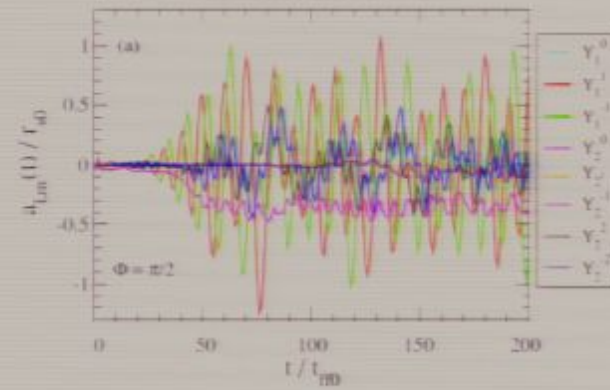
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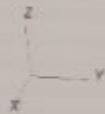
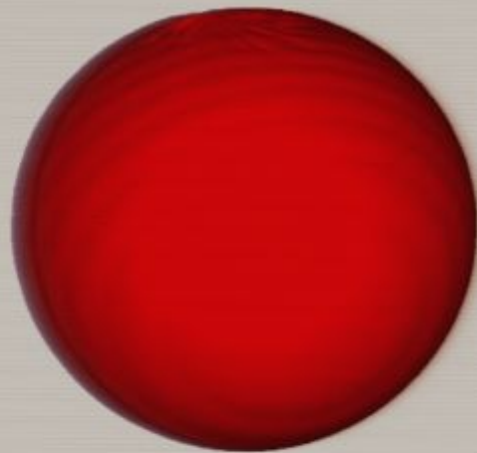
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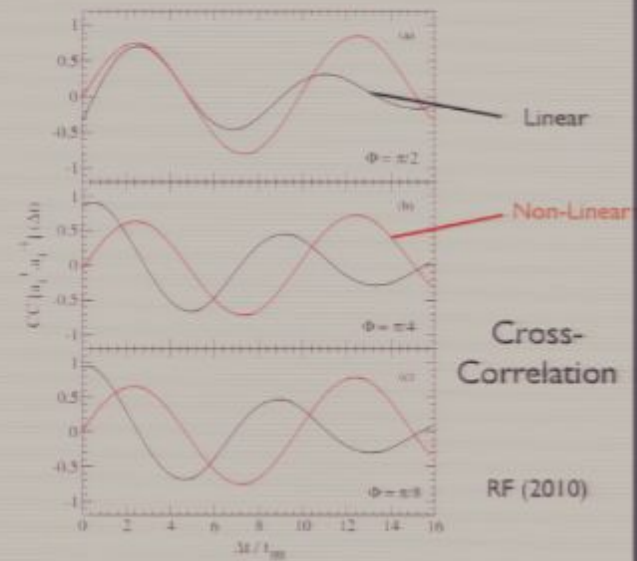
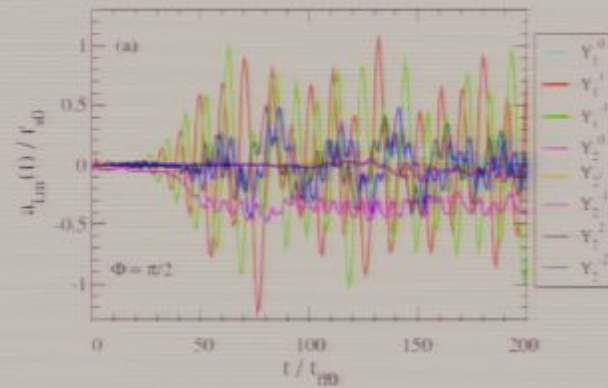
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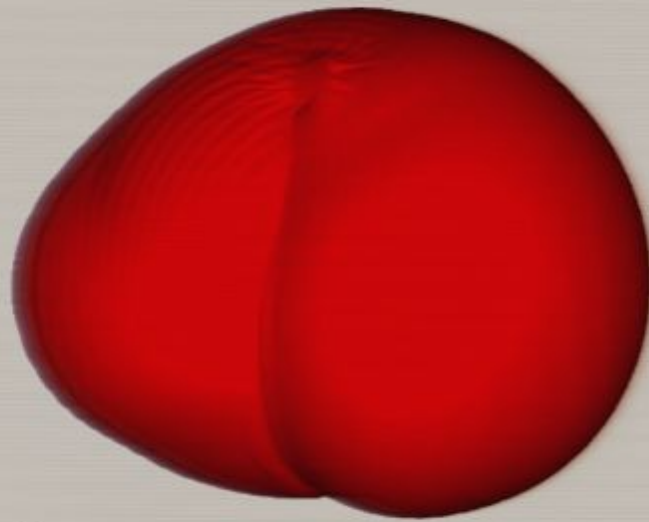
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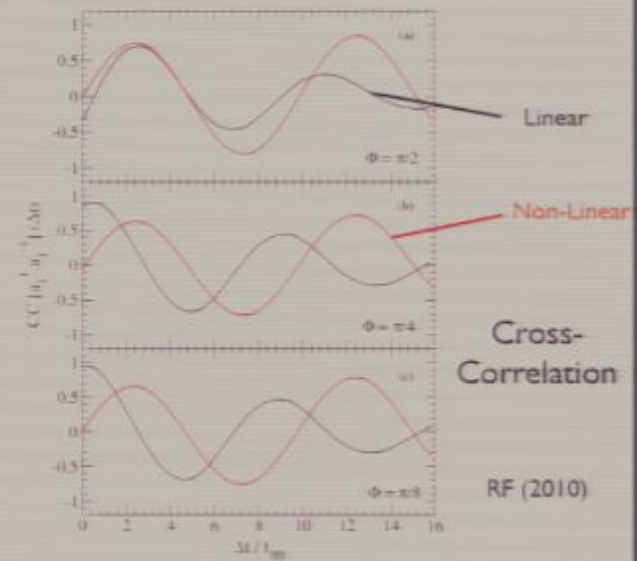
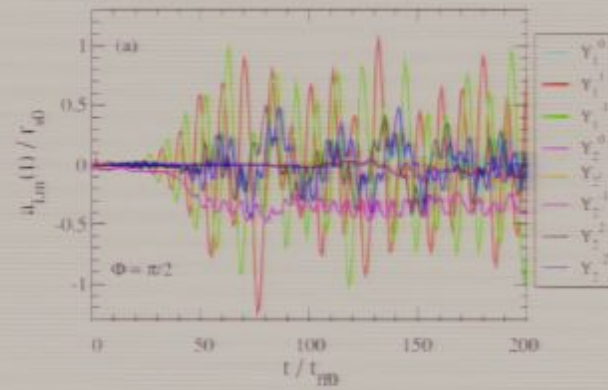
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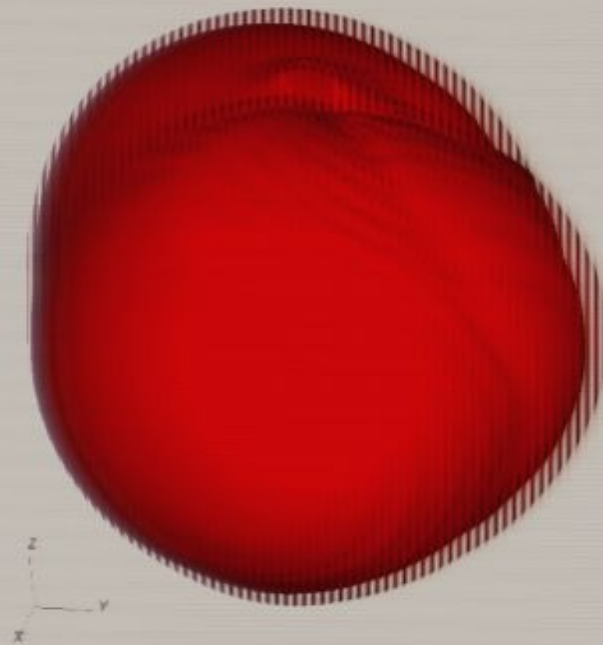
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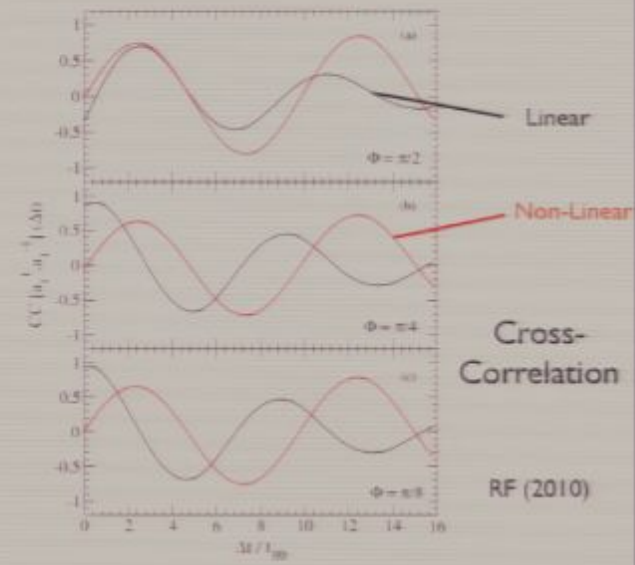
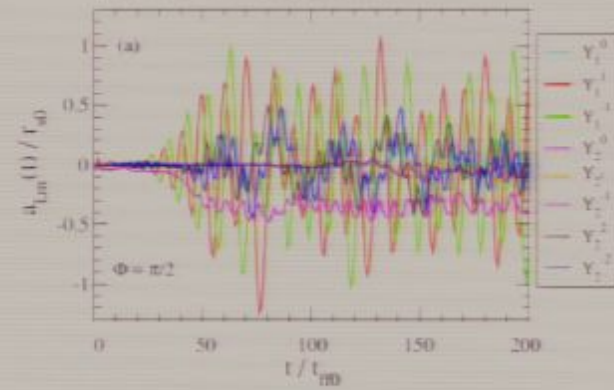
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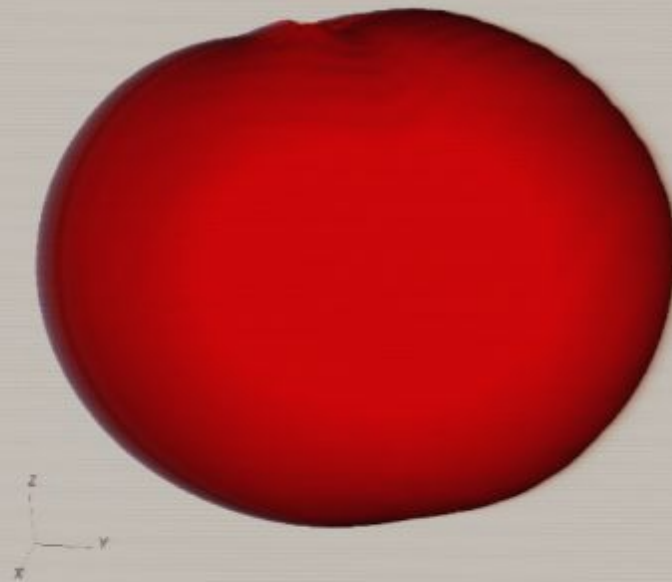
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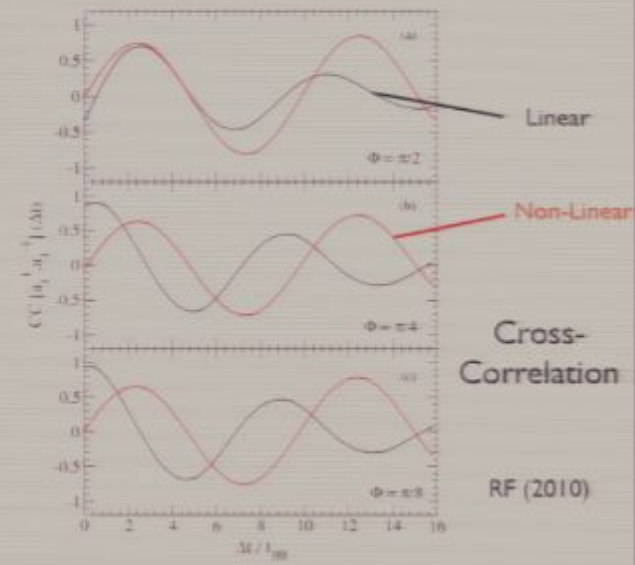
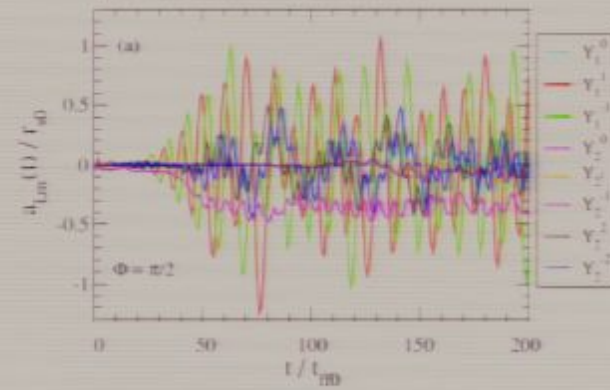
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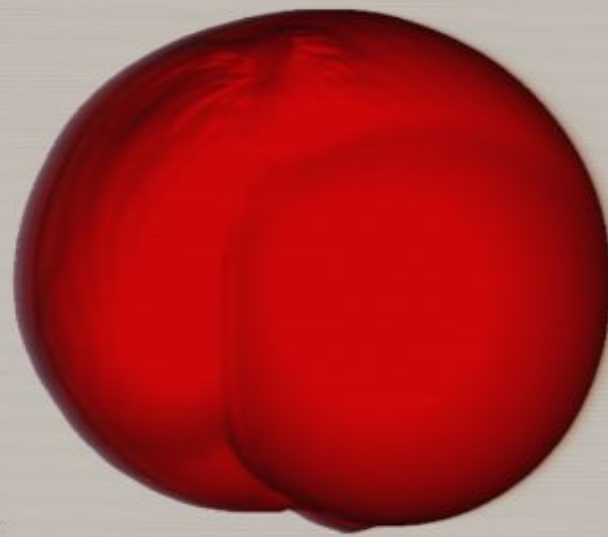
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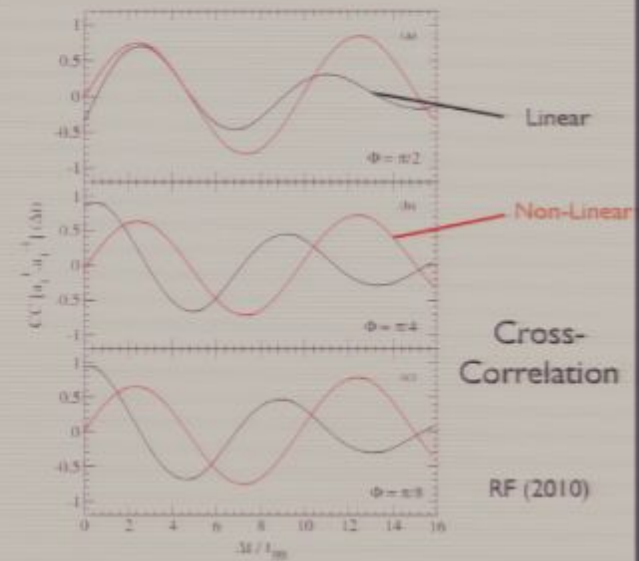
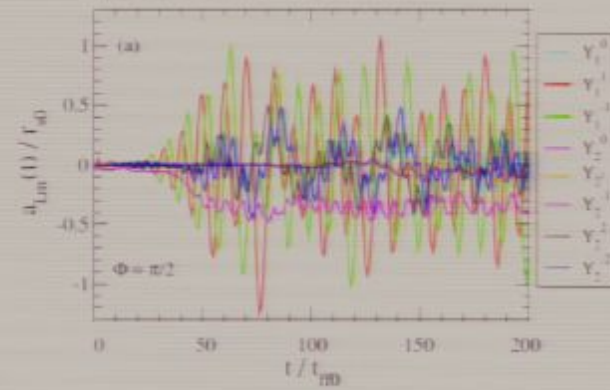
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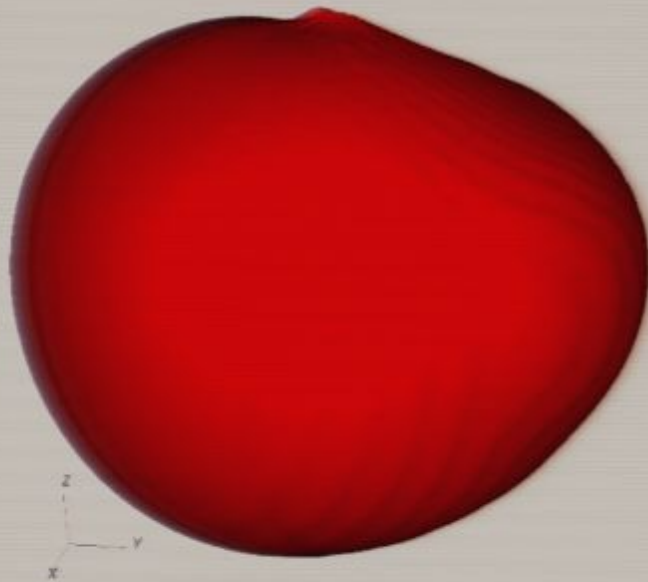
Spiral Modes: 3D Simulations (Zeus-MP)



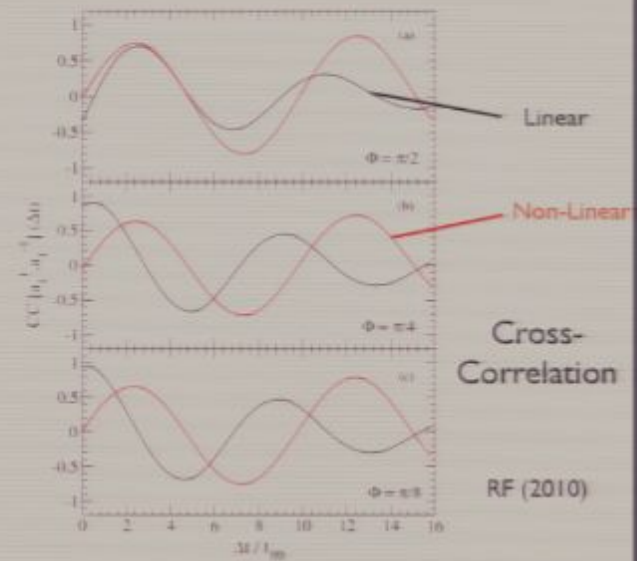
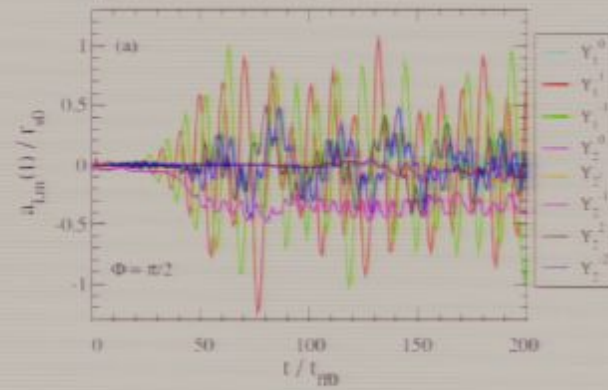
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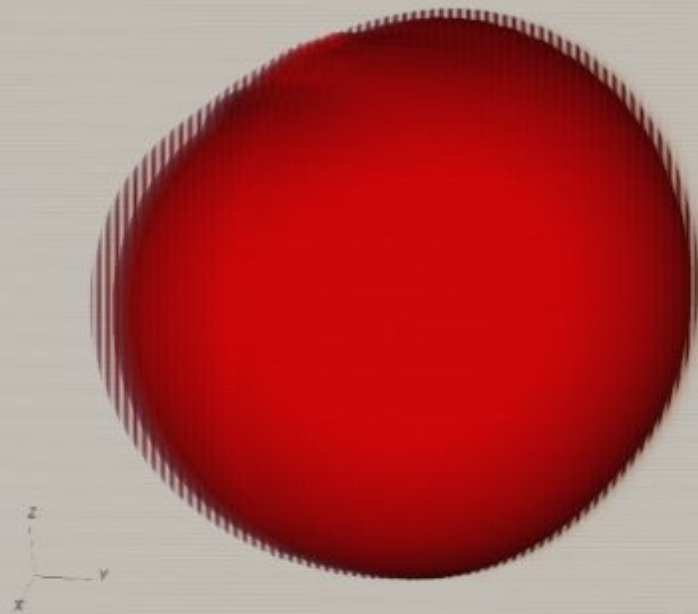
Spiral Modes: 3D Simulations (Zeus-MP)



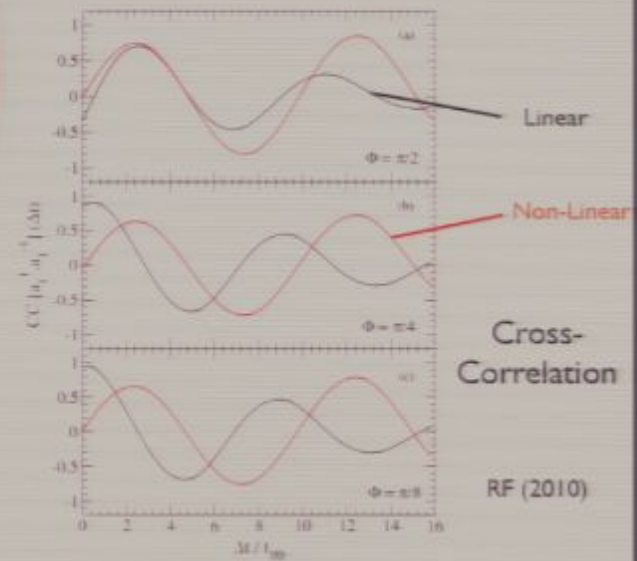
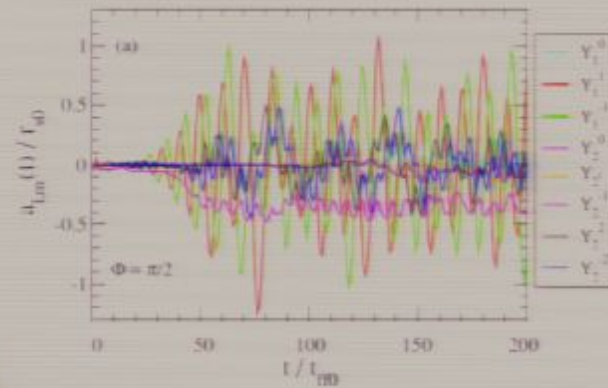
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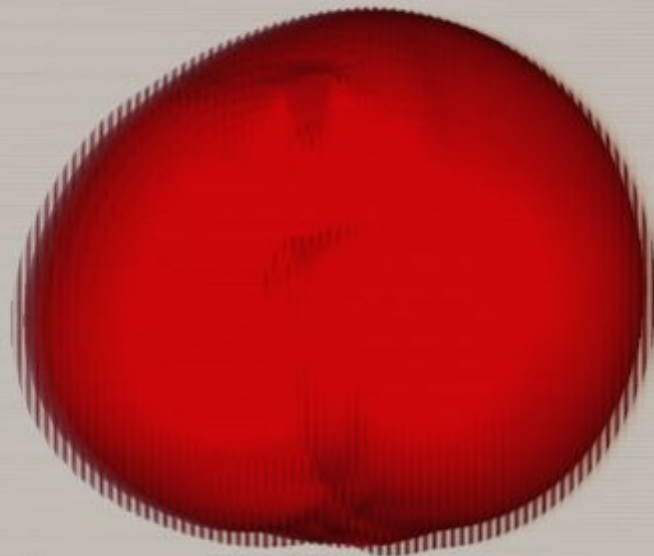
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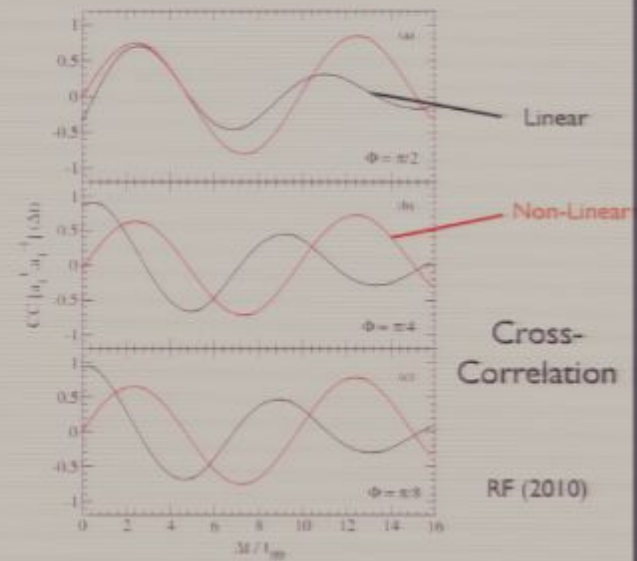
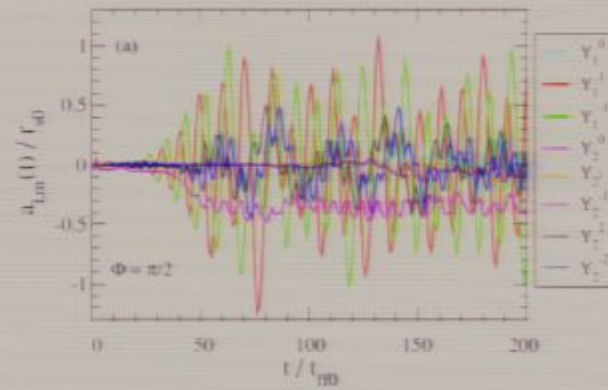
Spherical Harmonic Coefficients



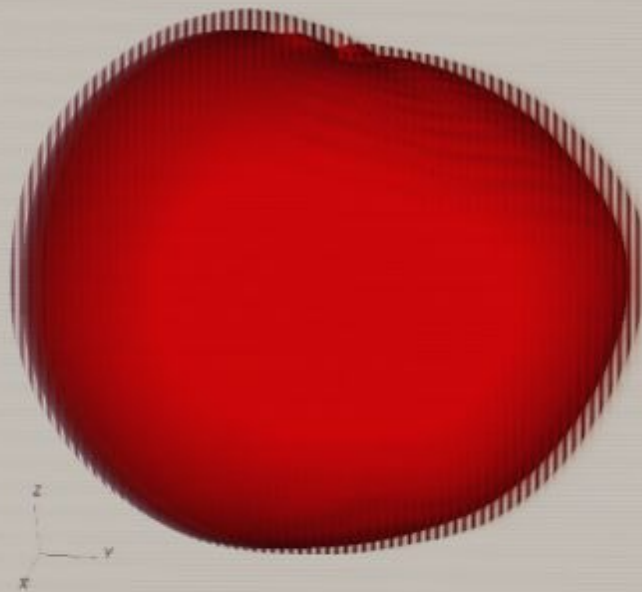
Spiral Modes: 3D Simulations (Zeus-MP)



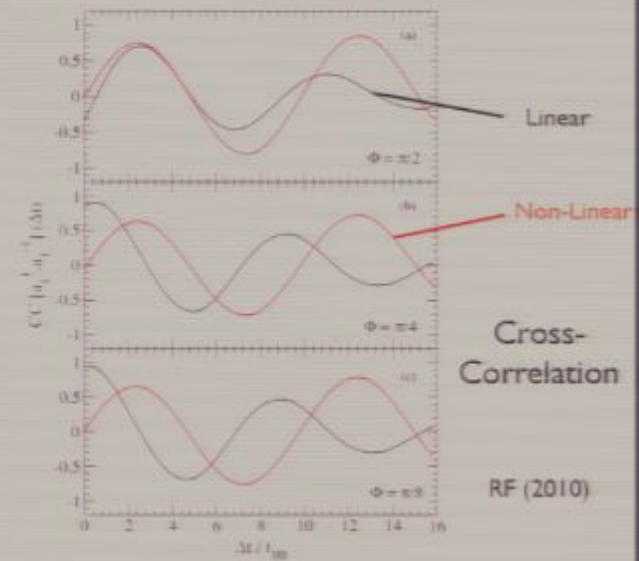
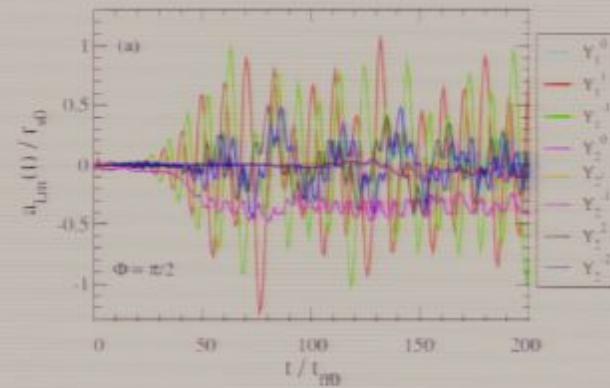
Spherical Harmonic Coefficients



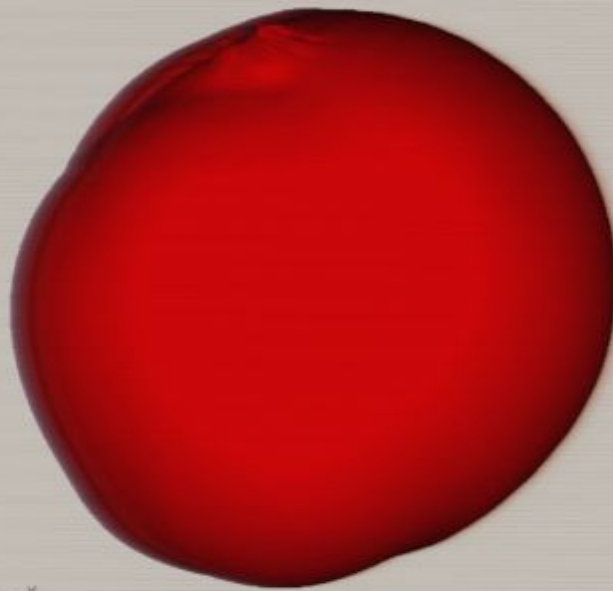
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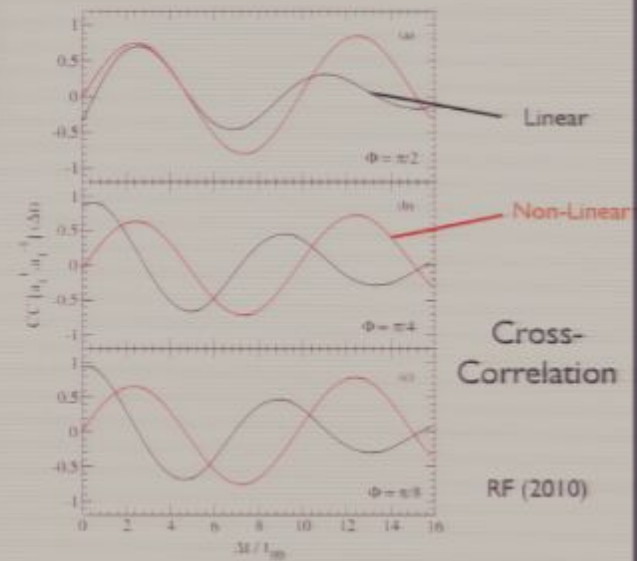
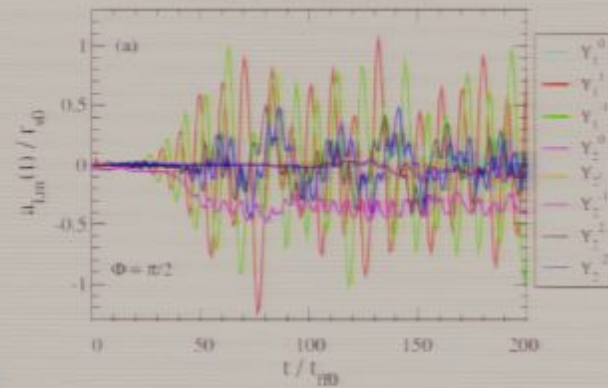
Spherical Harmonic Coefficients



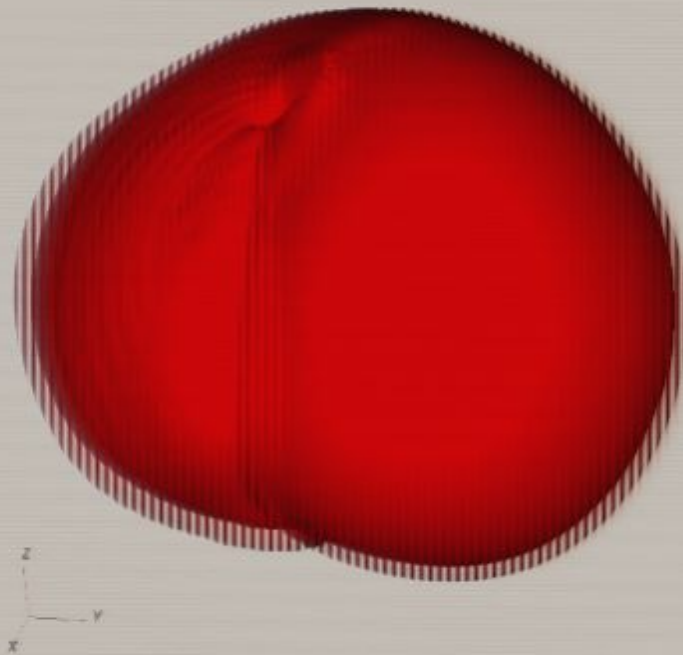
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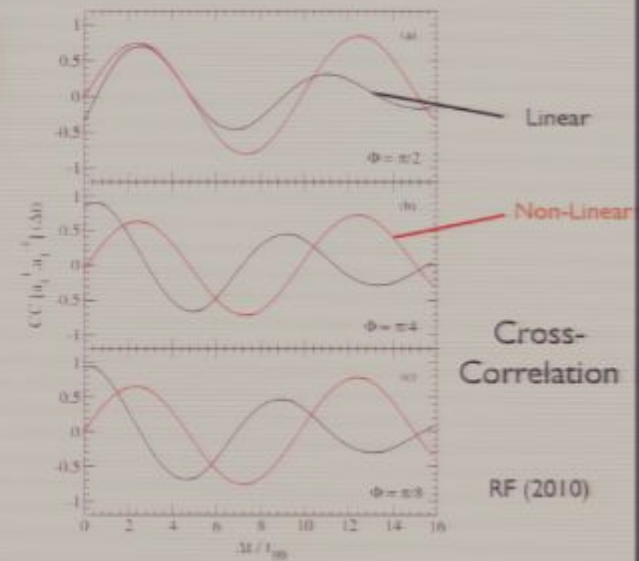
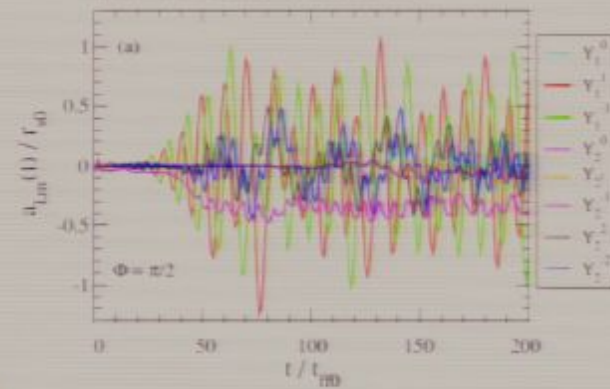
Spherical Harmonic Coefficients



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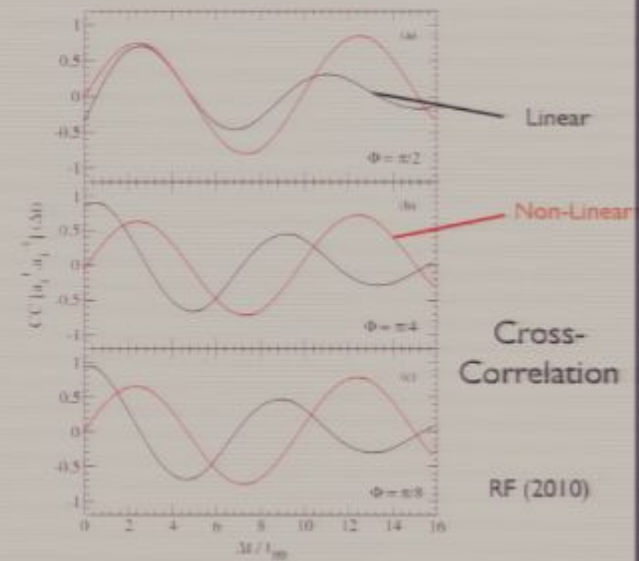
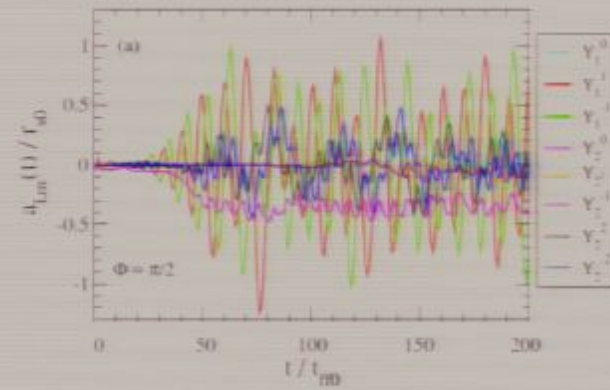
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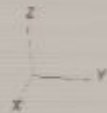
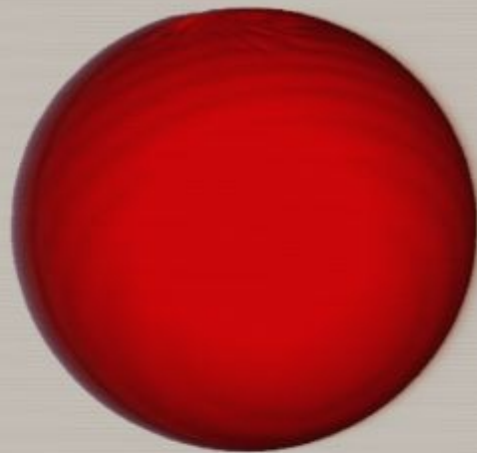
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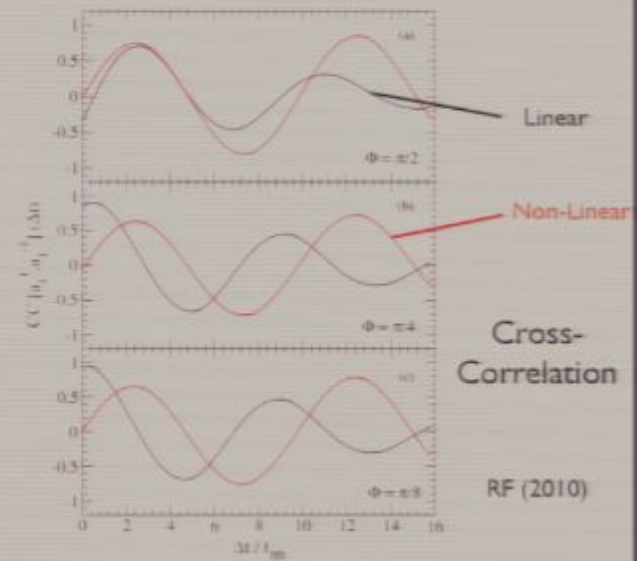
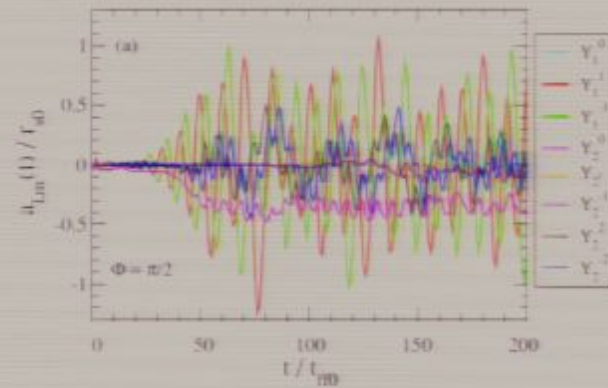
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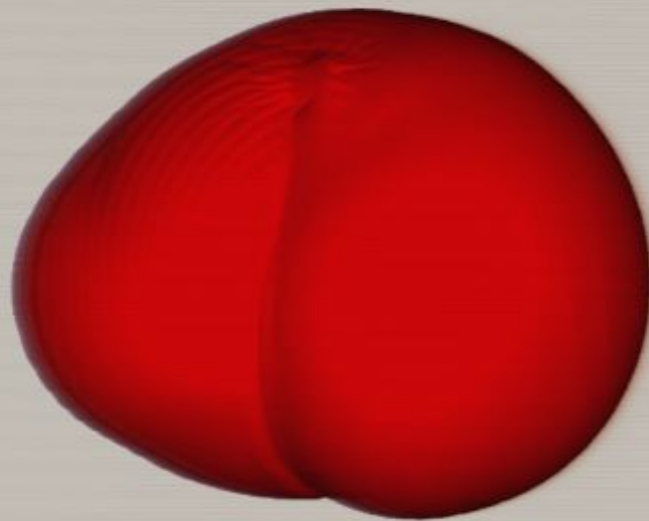
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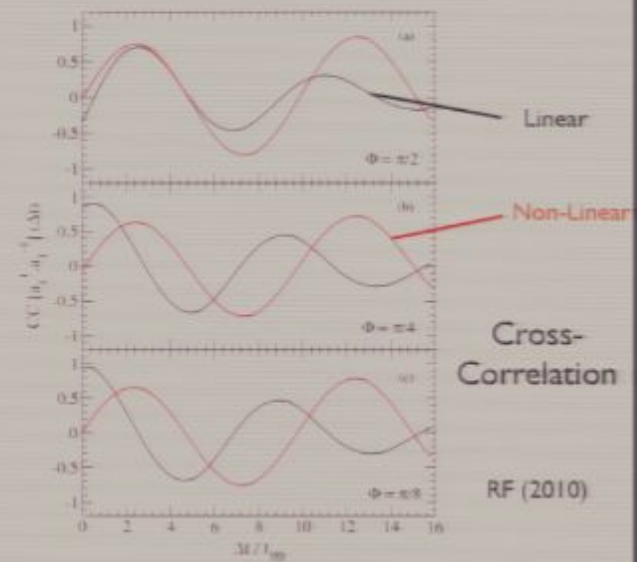
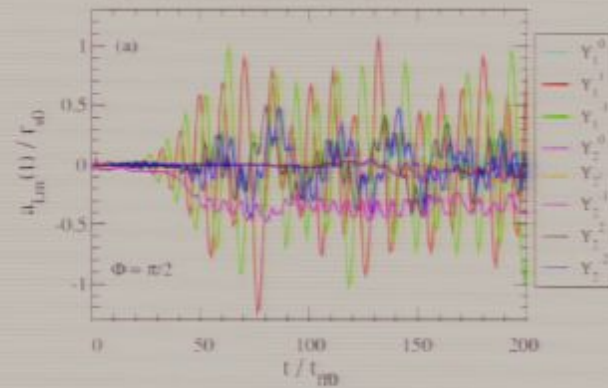
Spherical Harmonic Coefficients



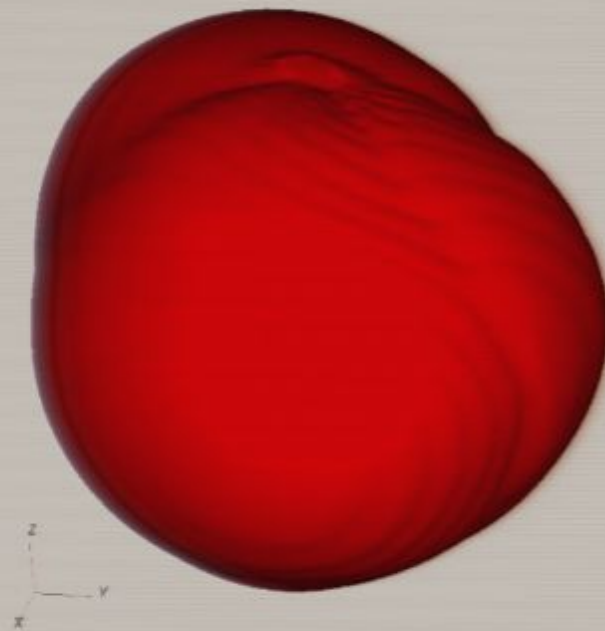
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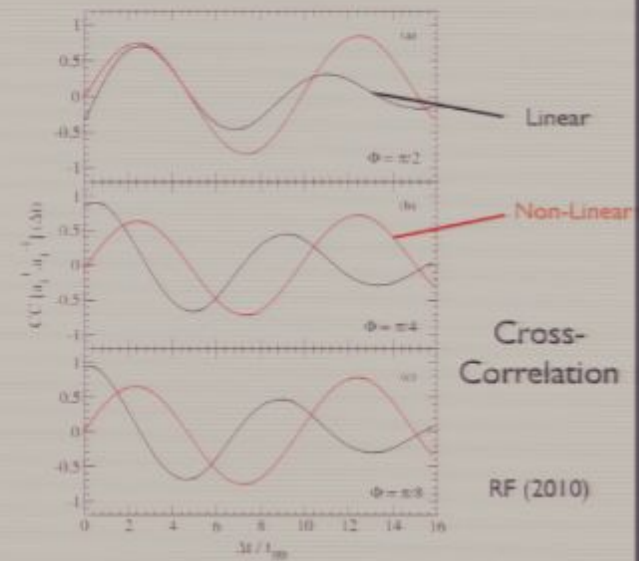
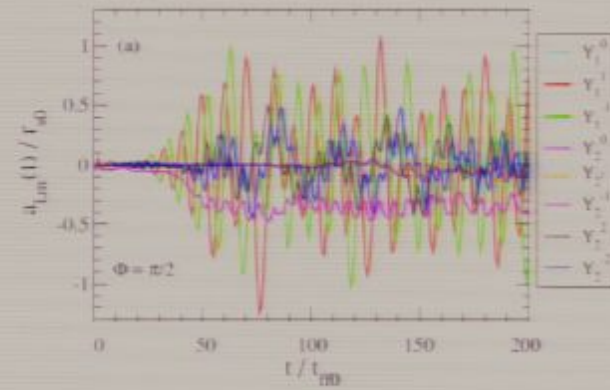
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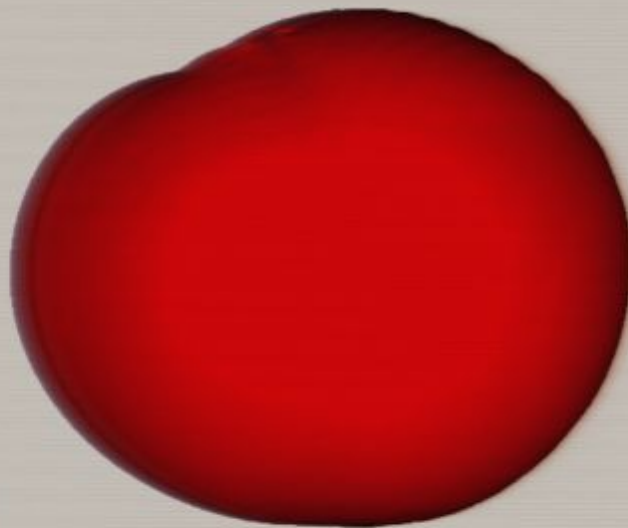
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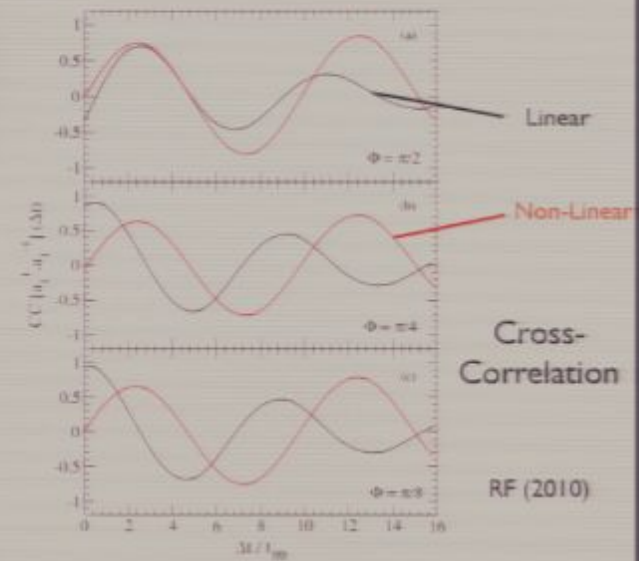
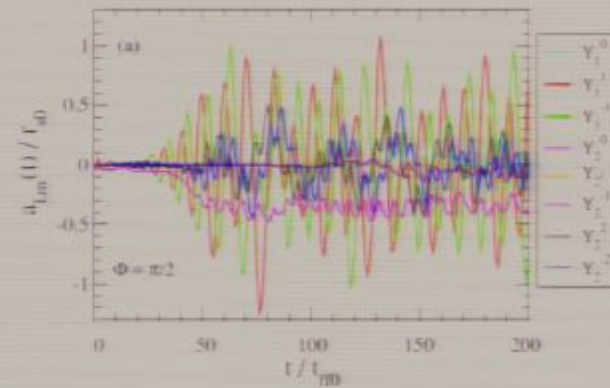
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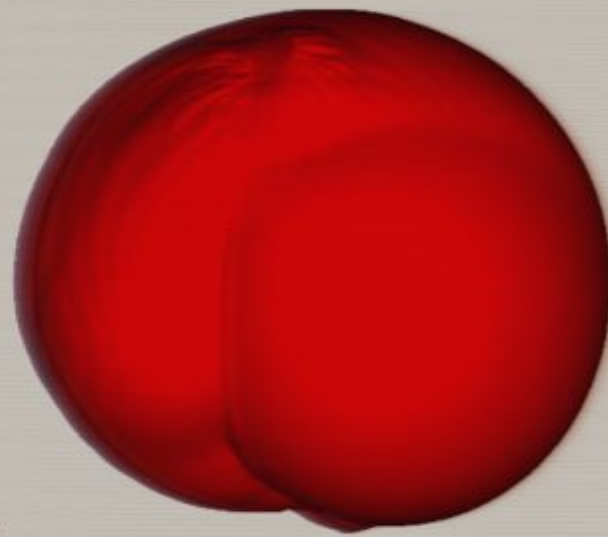
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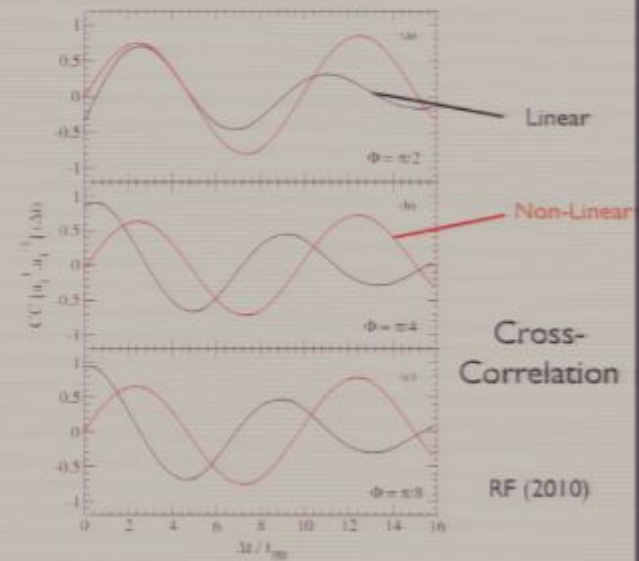
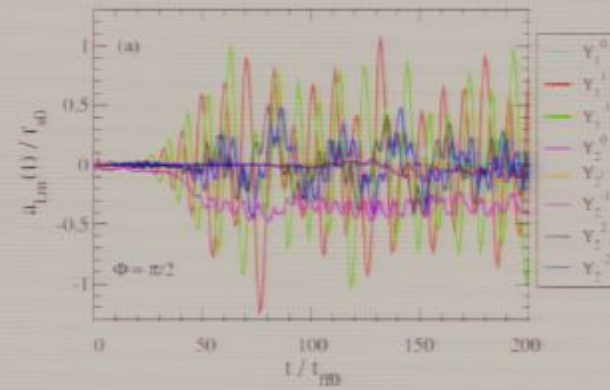
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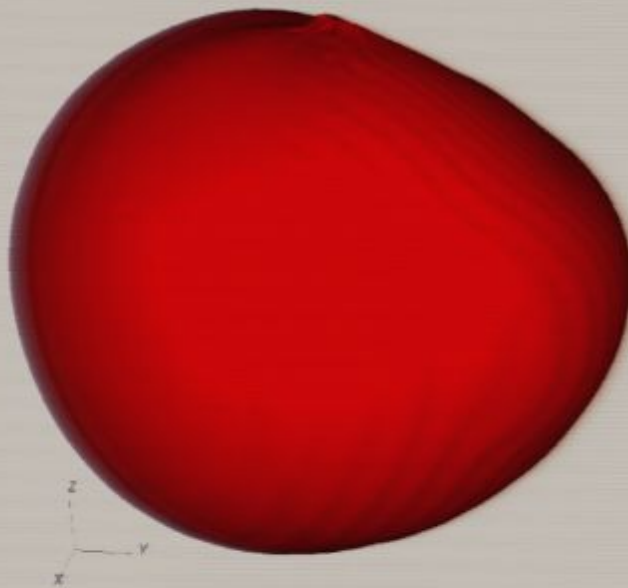
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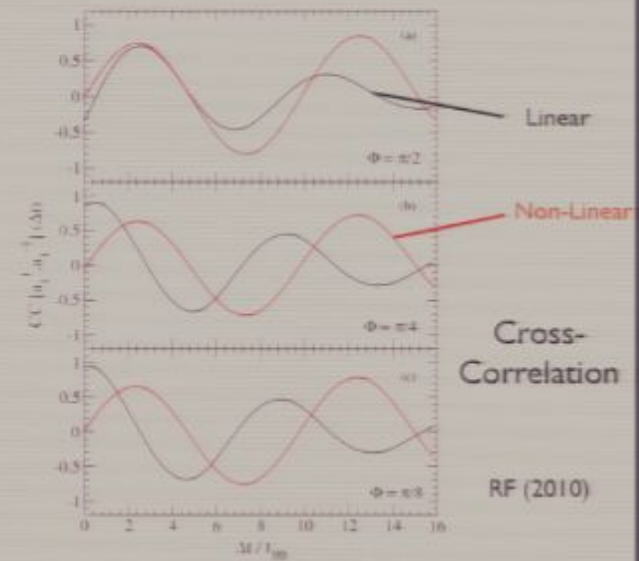
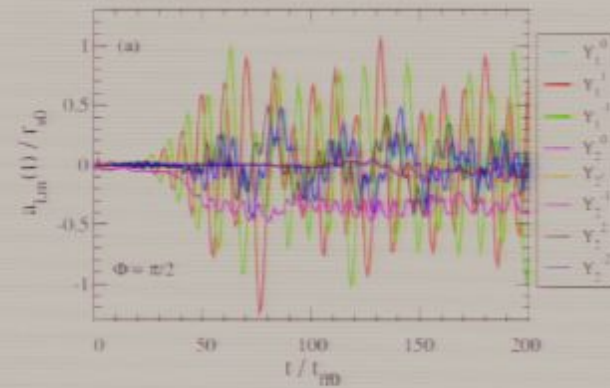
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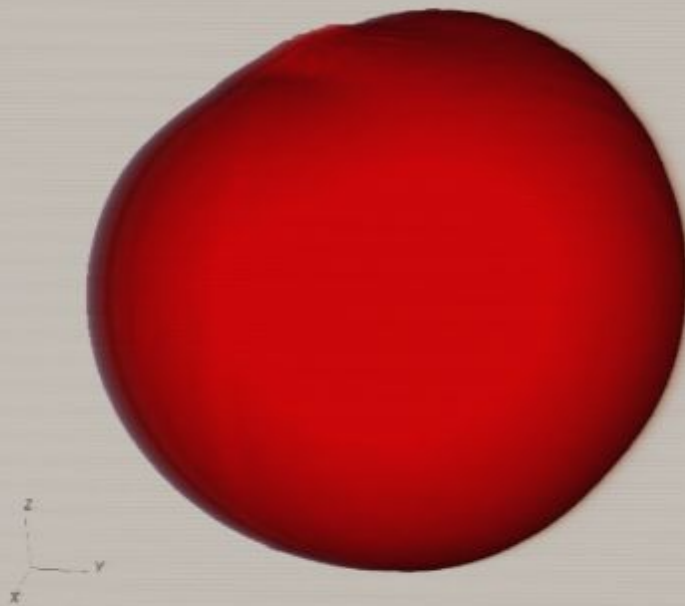
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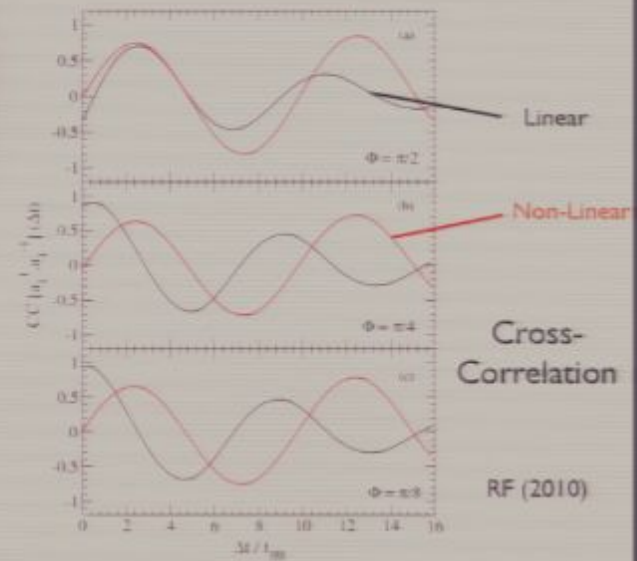
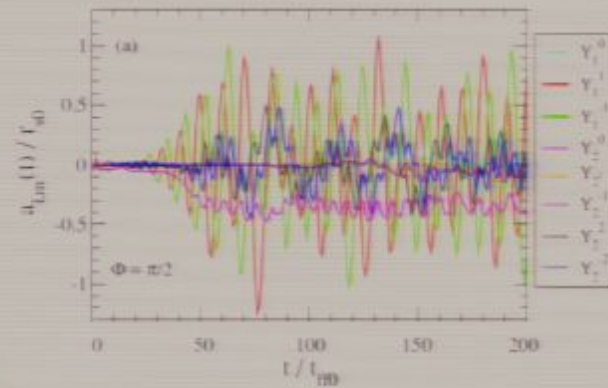
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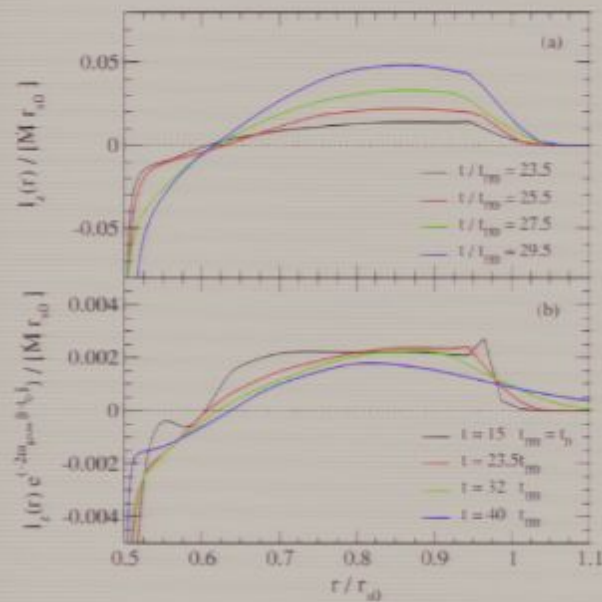
Spherical Harmonic Coefficients



Angular Momentum Redistribution

Angle integrated specific angular mom.:

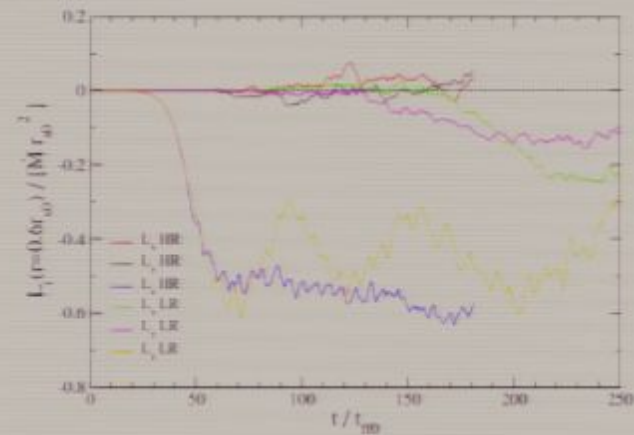
$$l_z(r) = r^2 \int d\Omega \rho r \sin\theta v_\phi$$



Perturbation to angular momentum is **second order** and **non-oscillatory**.

Bulk of spin-up imparted during phase of **exponential growth** (not the triple point)

$$L_i(r) = \int_{r_c}^r l_i(s) ds \quad (i = x, y, z)$$



RF (2010)

Contribution from Individual Mode

Upper limit for non-exploding:

$$\frac{\Delta r_{\text{shock}}}{r_{\text{shock}}} \sim 1 \rightarrow v_{\phi} \sim v_r$$

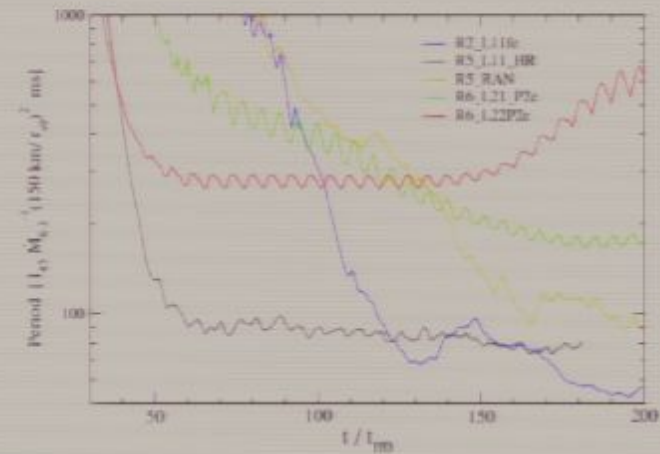
$$L_z \sim (r^3 \rho) r v_{\phi} \sim (r^2 \rho_2 v_1) \times r^2$$

$$\sim \dot{M} r_{\text{shock}}^2 \sim 10^{47} (\text{cgs}) \dot{M}_{0.3} r_{150}^2$$

$$P \simeq 80 l_{45} \dot{M}_{0.3}^{-1} \left(\frac{150 \text{ km}}{r_{50}} \right)^2 \left(\frac{0.6}{f_{\text{amp}}} \right) \text{ms}$$

If **individual mode** is allowed to grow to saturation, substantial fraction of maximum value is reached. Otherwise about 1/10th

Minimum spin period:



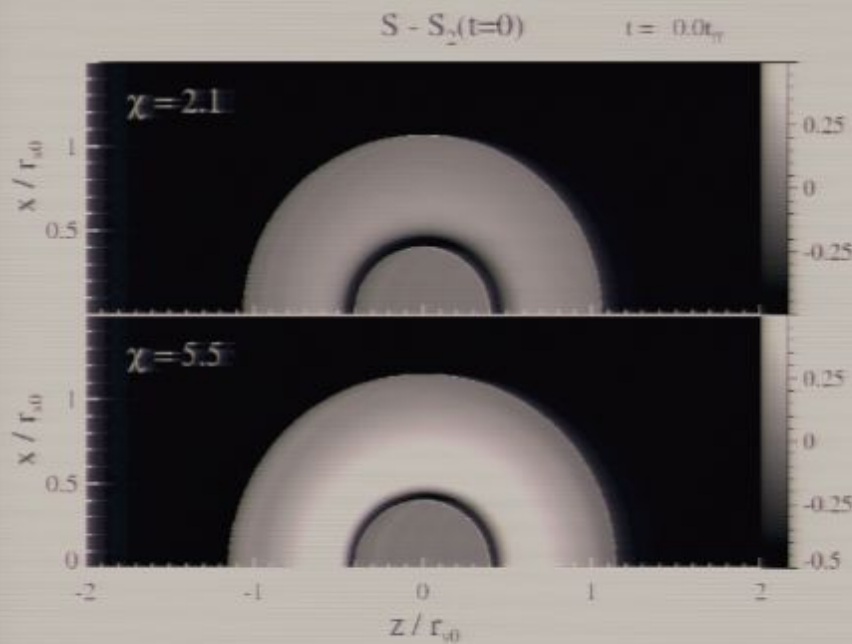
RF (2010)

Open Questions

1. Mass-cut in exploding situations
2. Effect of convective stresses

Preliminary evidence that they suppress coherent growth:
Wongwathanarat et al. (2010), Rantsiou et al. (2010)

Effect of Convective Stresses



Buoyancy vs. Advection:

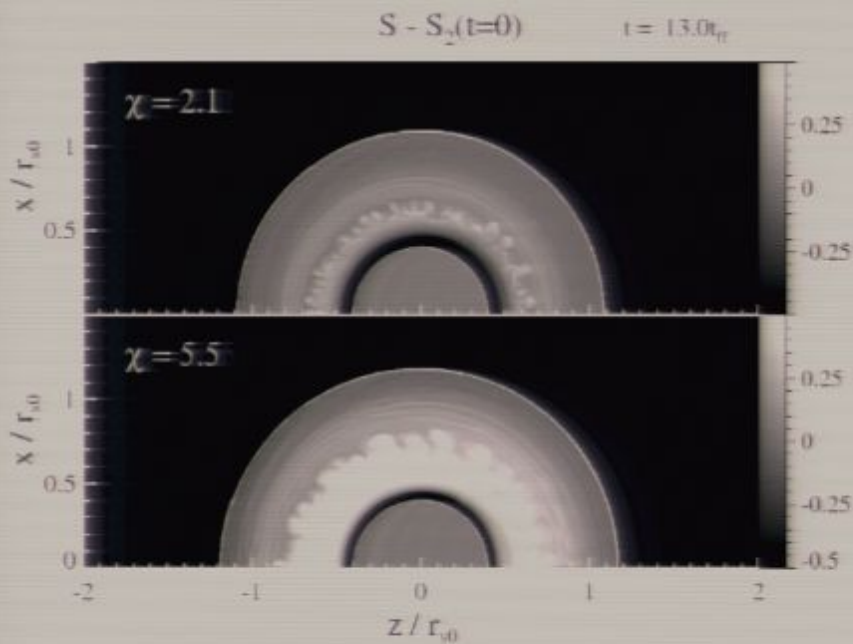
(Foglizzo et al. 2006)

$$\chi = \int_{\text{gain}} |\omega_{\text{BV}}| \frac{dr}{|v_r|}$$

$$\chi_{\text{crit}} = 3$$

RF & Thompson (2009)

Effect of Convective Stresses



Buoyancy vs. Advection:

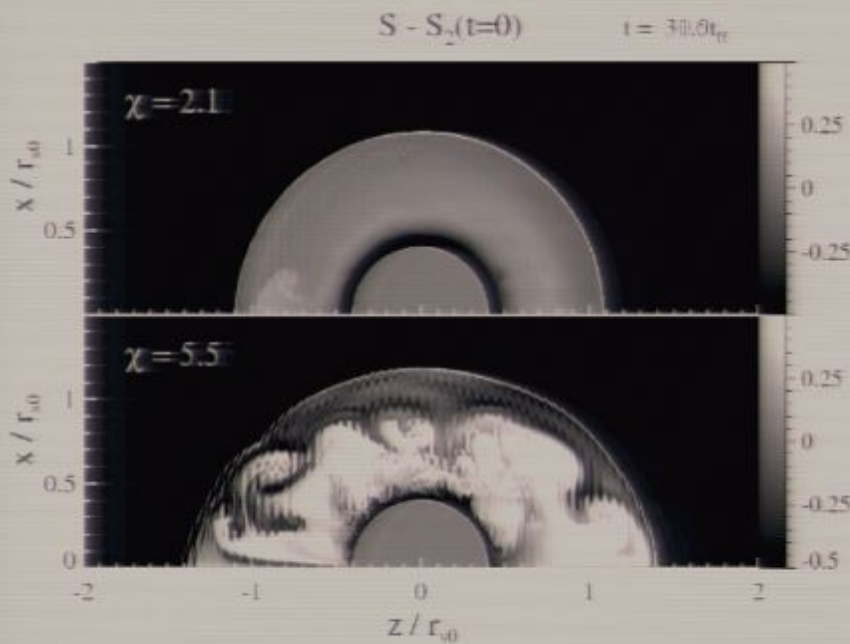
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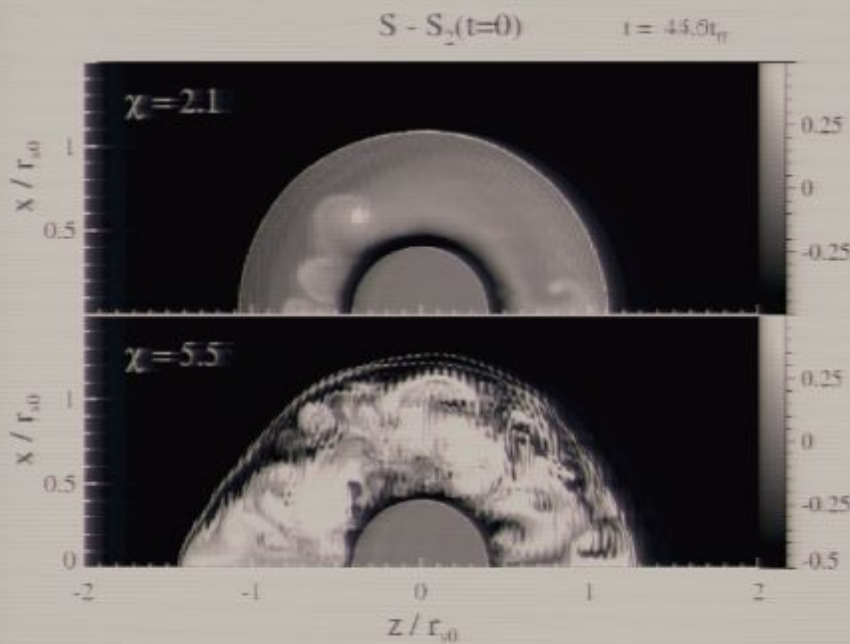
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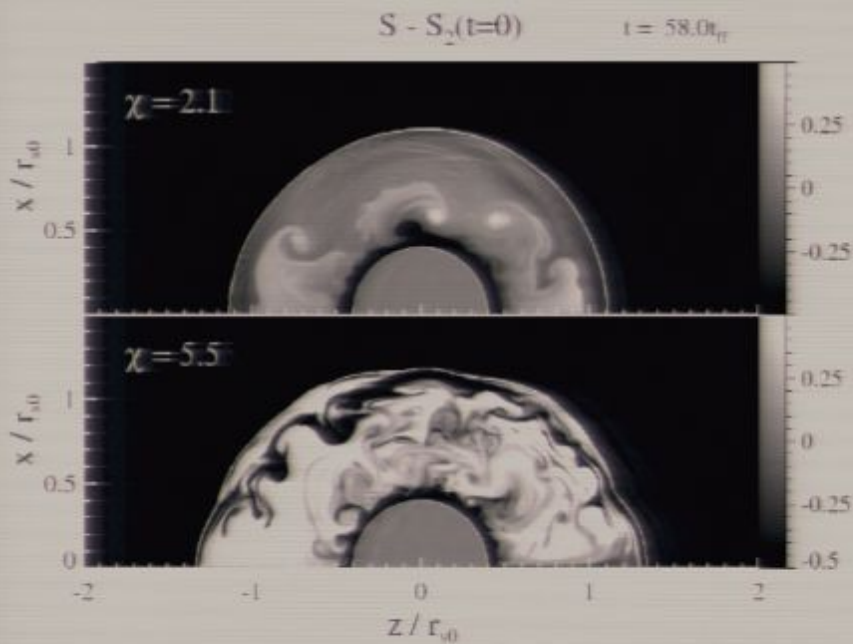
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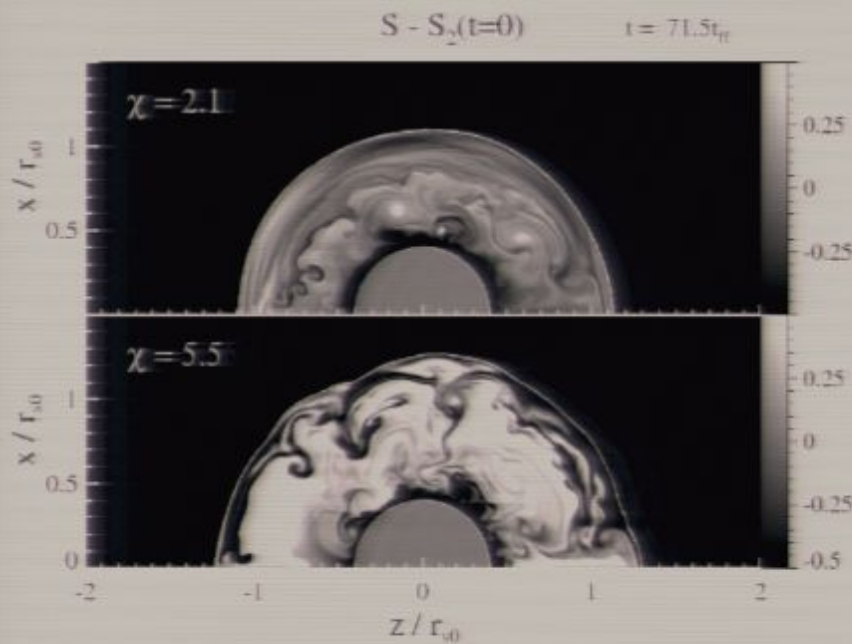
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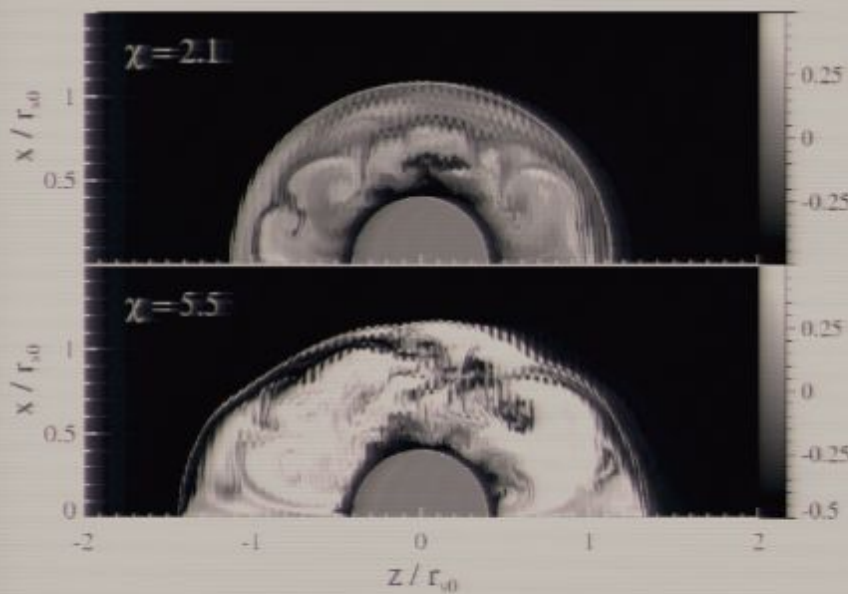
$$\chi = \int_{\text{gain}} |\omega_{\text{BV}}| \frac{dr}{|v_r|}$$

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RF & Thompson (2009)

Effect of Convective Stresses

$S - S_2(t=0)$ $t = 84.0t_T$



Buoyancy vs. Advection:

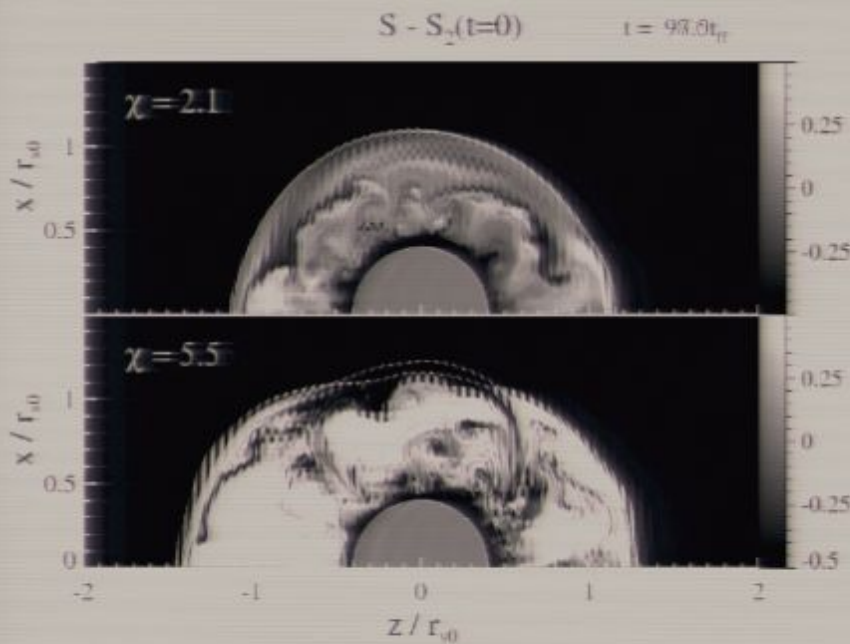
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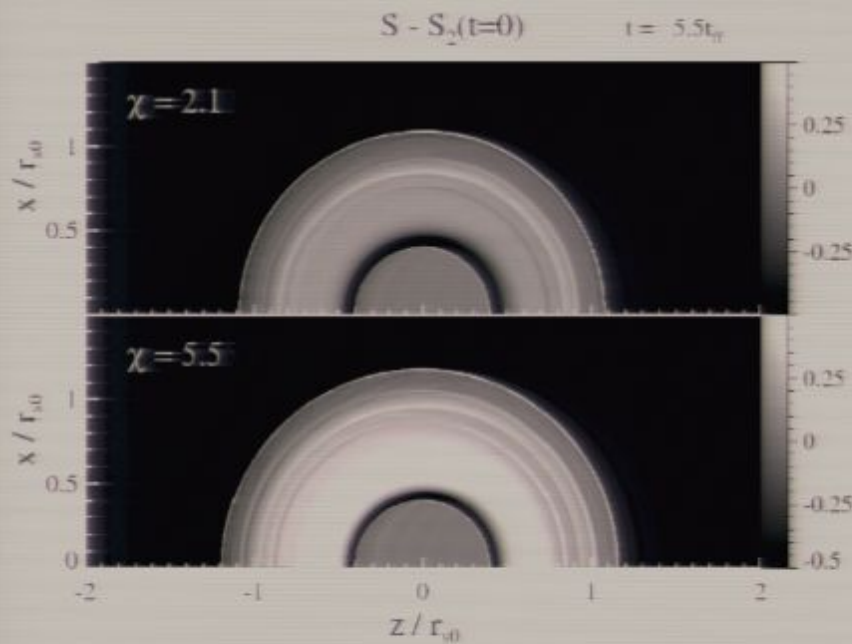
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RF & Thompson (2009)

Summary

1. Intrinsic SASI properties are most easily studied in isolation with simple microphysics
2. Large amplitude Spiral Modes easy to excite in 3D if Convection weak
3. Coherent modes can impart $|\mathbf{L}| \sim \dot{M} r_{\text{shock}}^2 \sim 10^{47} \text{ g cm}^2/\text{s}$ ($P \sim 50 \text{ ms}$), about ten times less if non-coherent