New results on the VISHNIAC and RYU-VISHNIAC instabilities in astrophysics and laboratory astrophysics

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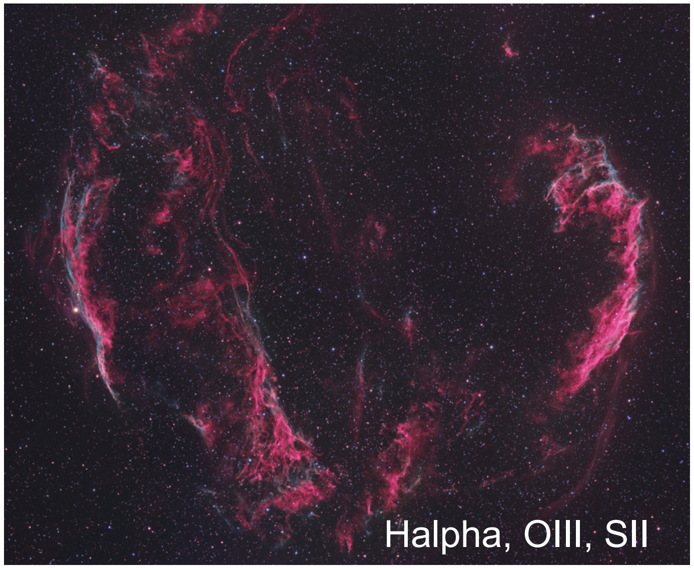
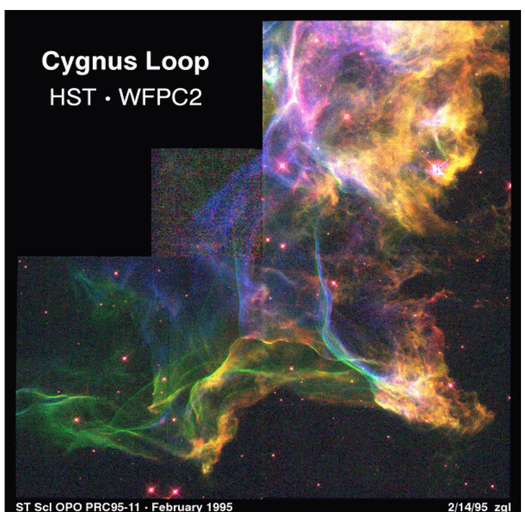
Contributions

- **Antoine GINTRAND, Marco MANCINI, Claire MICHAUT and Julien MINIERE**
- **Javier SANZ**
- **John L. PORTER and Nathan J. RILEY**

Fine and intricated filaments attributed to a thin shock wave …

Cygnus loop (dentelle du Cygne) ~ 8000 y.o, distance ~ 2000 l.y, size ~ 100 l.y



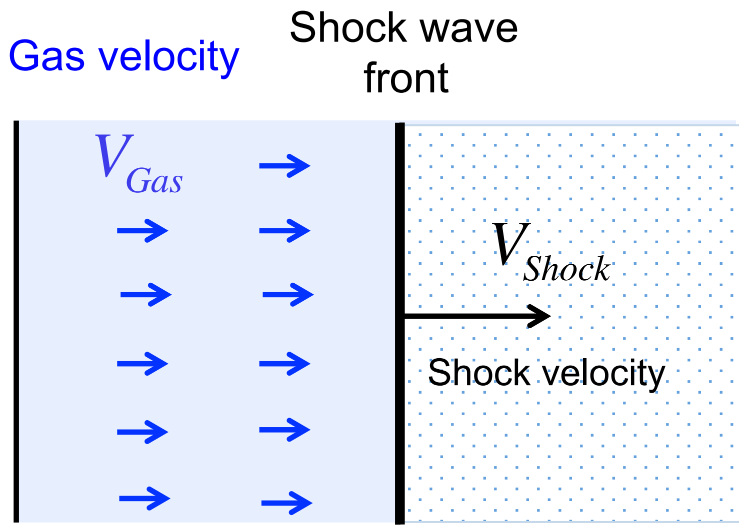


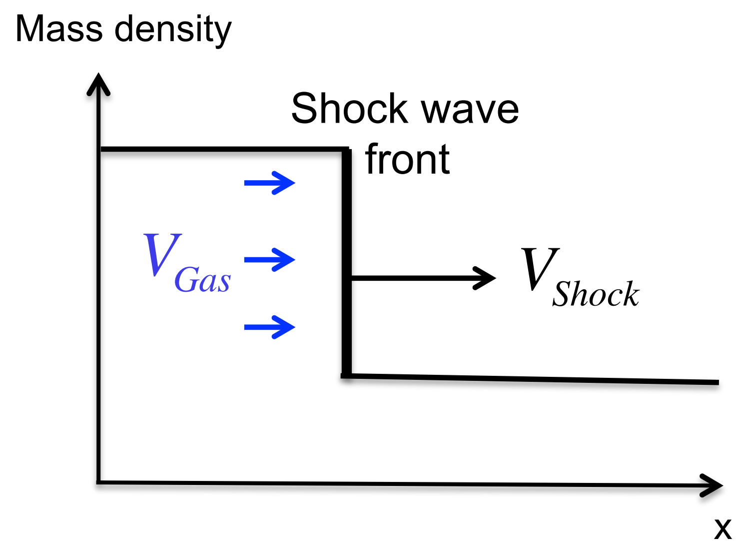
understand the physics of radiative blast waves such as these supernova remnants, and specifically the Vishniac overstability (instability) thought to produce the structures seen in these remnants

Outline

1. Shock waves and blast waves
2. Vishniac instability in supernova remnants
3. New theoretical and numerical developments
4. Latest blast wave experiments
5. Conclusion

Shock waves (SW) vs. Blast waves (BW)





$$V_{Gas} = \frac{2}{\gamma + 1} V_{Shock} \quad \text{(strong shock)}$$

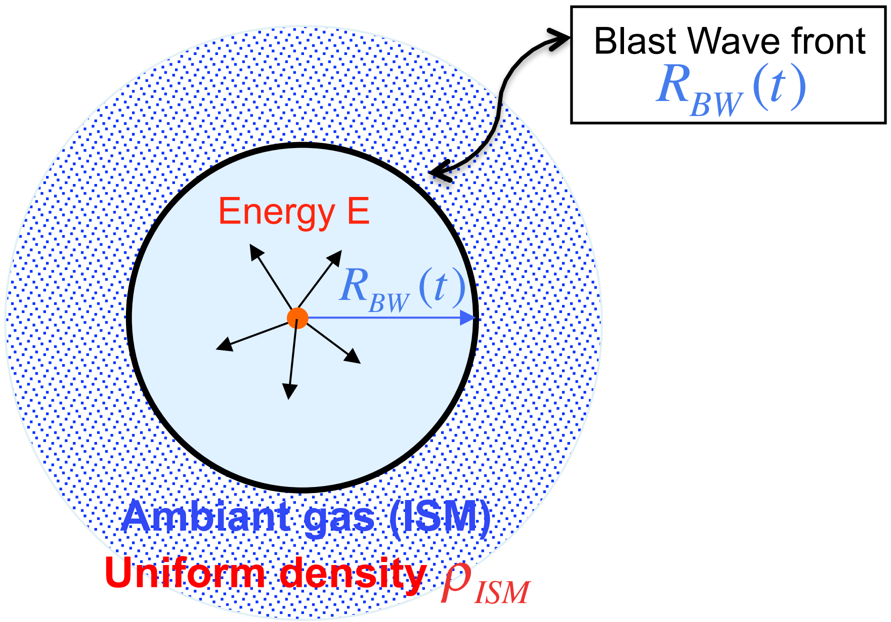
✓ The mass of the shocked material increases

✓ The dowstream flow might be steady (constant velocity V_{gas}) if the Shock Wave (SW) is sustained

✓ For a Blast Wave (BW) [un-sustained SW, the energy is released briefly], the velocity of the dowstream flow decays

Spherical blast wave (Sedov-Taylor blast wave: STBW)

Supernova remnant (SNR)



✓ $R_{BW}(t) \approx \left(\frac{E}{\rho_{ISM}}\right)^{1/5} \times t^{2/5}$

E, ρ_{ISM} : physical ingredients

[E] = M.L^2.T^{-2} ; [ρ_{ISM}] = M.L^{-3}

[E / ρ_{ISM}] = L^5.T^{-2}

SEDOV – TAYLOR blast wave (STBW)

Self-Similar Solution (SSS)

✓ **Velocity of the BW front:** $V_{BW}(t) = \frac{d}{dt} R_{BW}(t) \propto \frac{R_{BW}(t)}{t} \propto t^{-3/5}$

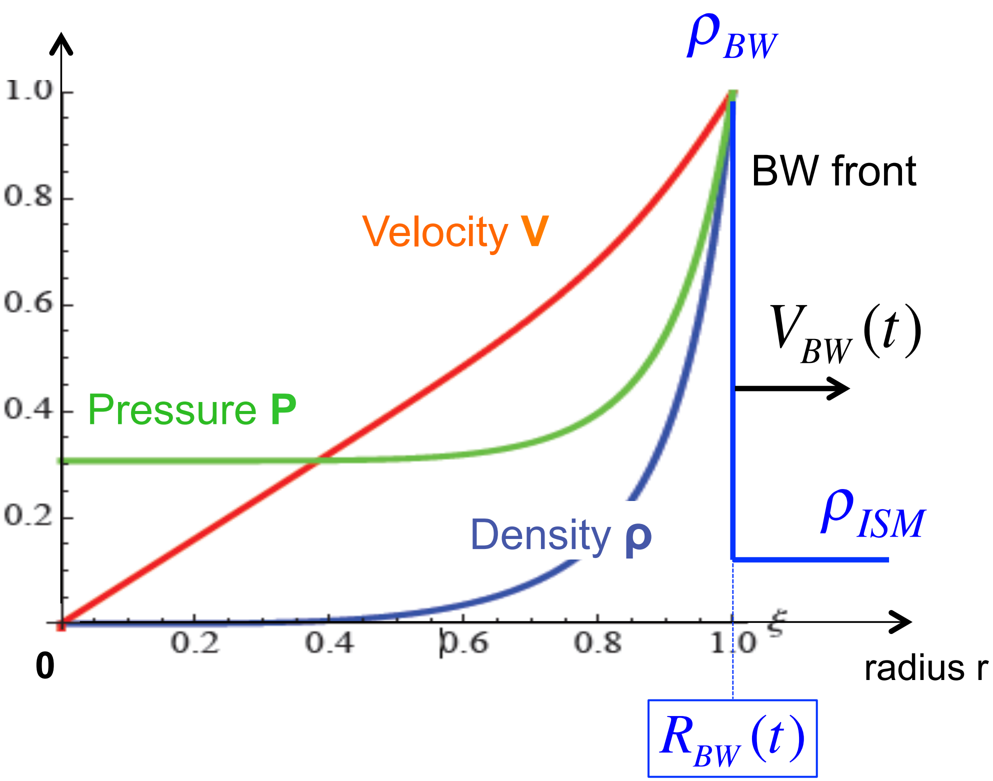
✓ **Pressure at the BW front:** $P_{BW}(t) = \left(2/(\gamma+1)\right) \rho_{ISM} (V_{BW})^2 \propto t^{-6/5} \propto R_{BW}^{-3}$

$P_{BW} \times (R_{BW})^3 \sim$ **thermal energy** $E_{thermal} \sim constant$

✓ **Kinetic energy is constant:** $E_{kinetic} \sim M(t) \times (V_{BW})^2 \sim (R_{BW})^3 \times t^{-6/5} \sim constant$

No energy transfer between $E_{thermal}$ and $E_{kinetic}$

Self-Similar Solution (SSS) for the STBW



- $\rho_{BW} = \left(\dfrac{\gamma+1}{\gamma-1}\right)\rho_{ISM}$
- $P_{BW} = \left(\dfrac{2}{\gamma+1}\right)\rho_{ISM}(V_{BW})^2$

✓ **Velocity:** V(r) almost ~ r

but not strictly (**NOT** homologous)

✓ **Pressure:** P almost uniform

except close to the shock front

✓ **Density:** ρ

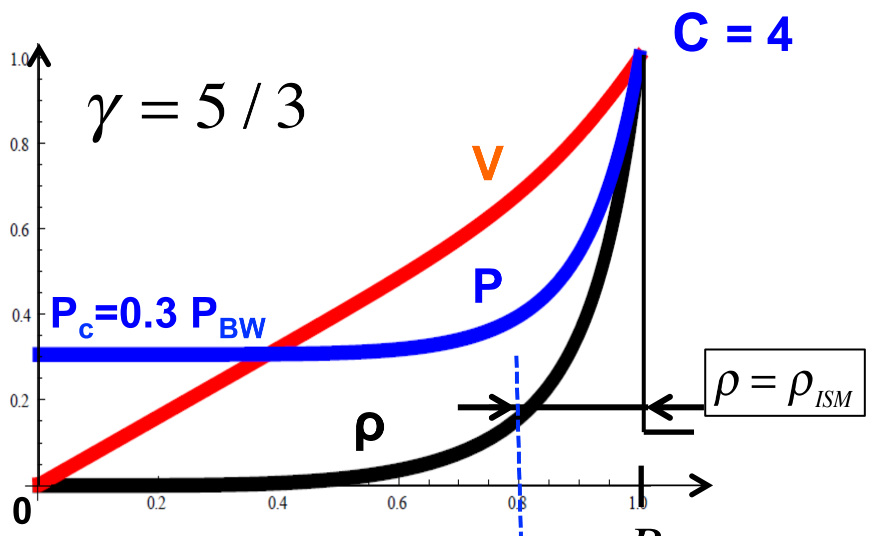
1. Almost **empty bubble** ($\rho_{bubble} \approx 0$)
2. Density **peak** ρ_{BW} at the BW front
3. Compression *C* (strong BW):

$$C \equiv \frac{\rho_{BW}}{\rho_{ISM}} = \frac{\gamma+1}{\gamma-1}$$ γ: adiab. constant

γ **decreases (** $\gamma \to 1$**), C increases**

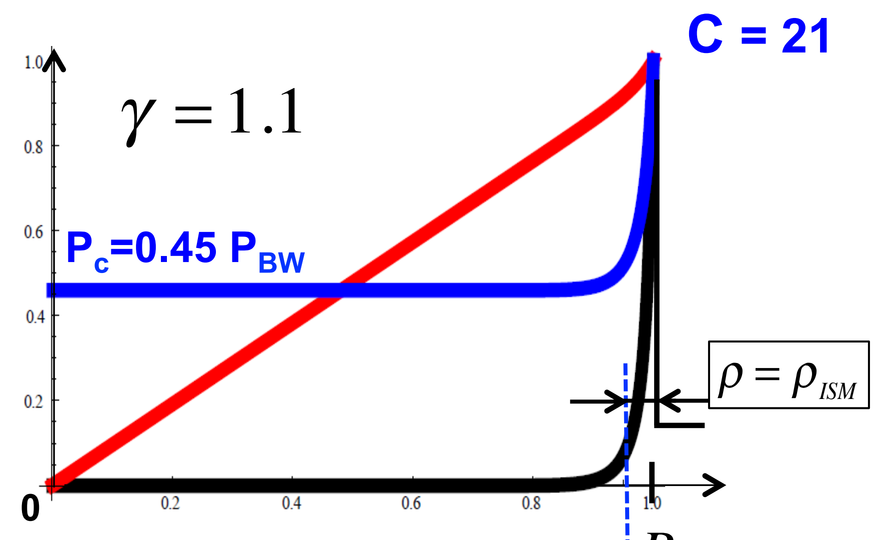
Thickness of the STBW front varies with γ

- **Thickness** x C **~ constant (mass conservation)**
- $C \equiv (\gamma+1)/(\gamma-1)$ **(compression)**



Large thickness

$\text{thickness} \sim 20\% \times R_{BW}$



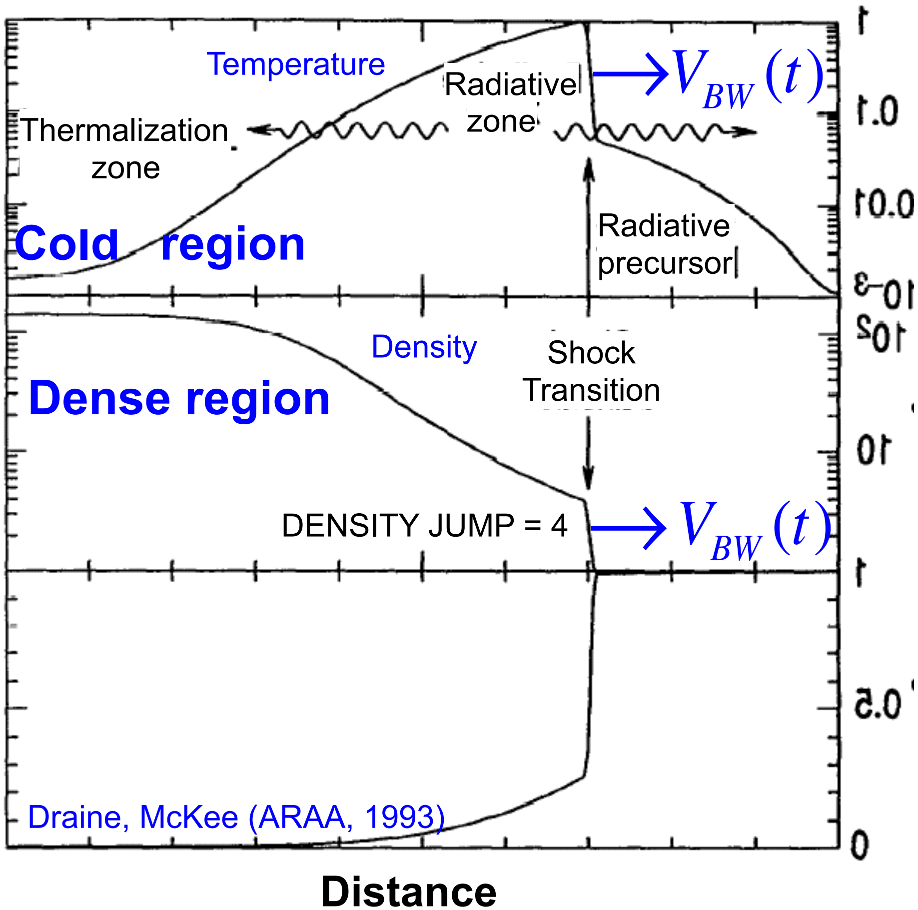
Small thickness

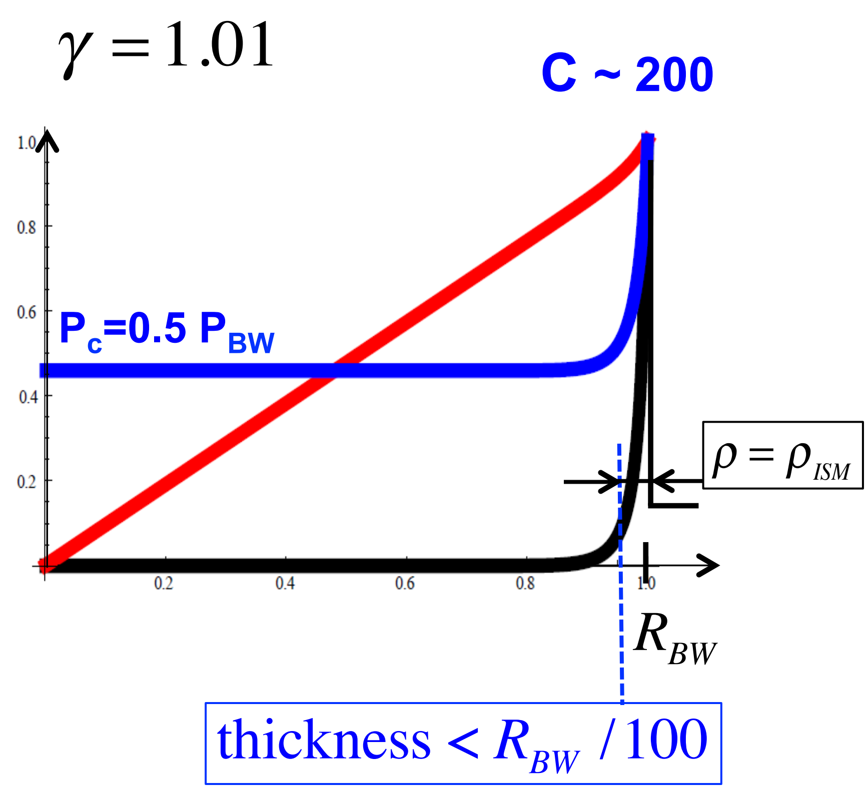
$\text{thickness} \sim 5\% \times R_{BW}$

- **P(center)** $\nearrow$ **when** $\gamma \searrow$: $\gamma = 1 \quad P(\text{center}) = \left(\frac{1}{2}\right) P_{BW} \propto t^{-6/5}$
- $V(\text{center}) = \left(\frac{2}{5\gamma}\right)\frac{r}{t}$ **Lagrangian particle:** $r(t) \propto t^{2/(5\gamma)}$

$P(\text{center}) \sim r^{-3\gamma}$ **adiabatic**

Small γ's $(\gamma \to 1)$ imitate radiative cooling

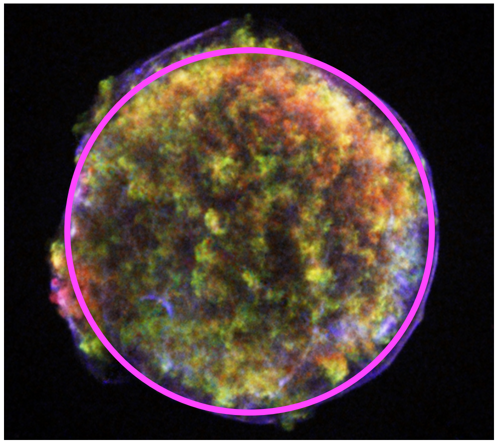




$C \equiv \dfrac{\rho_{BW}}{\rho_{ISM}} \approx 150$ **Non adiabatic (cooling)** $C \equiv \dfrac{\gamma_{eff}+1}{\gamma_{eff}-1}$ $\boxed{\gamma_{eff} = \dfrac{C+1}{C-1} \approx 1.013}$

BW in supernova remnants (SNR)

Tycho (1572, Cass. B, 3 kpc)



Simeis 147 (~30 000 y.o.,Taurus, 1 kpc)

Nébuleuse du Spaghetti

Diameter of SNR's: from a few to several pc (1 parsec $\approx 3\times10^{18}$ cm)

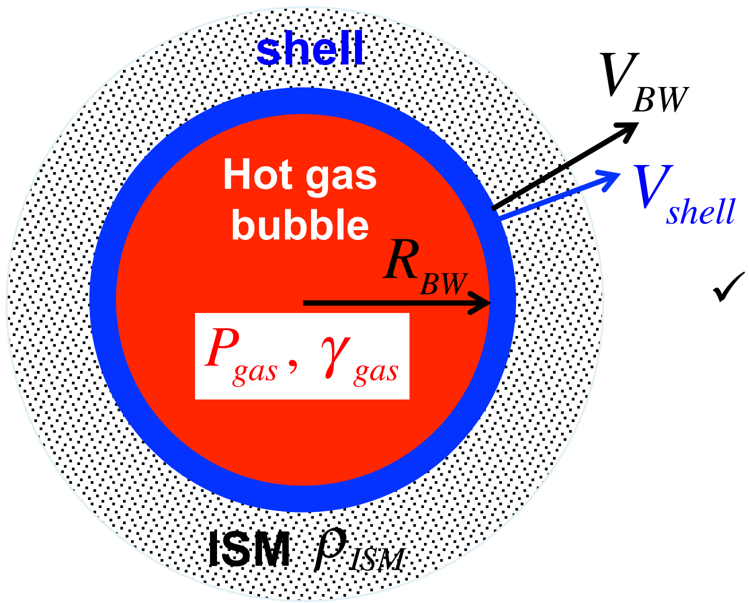
Radius of the SNR: $R_{BW}(t)$, 3 self-similar solutions (SSS's)

- ✓ **Ballistic (ejecta dominated) stage:** $R_{BW}(t) \propto t$ (t ~ < 1 000 yrs)
- ✓ **Sedov-Taylor stage:** $R_{BW}(t) \propto t^{2/5}$ (t ~ < 10 000 yrs)
- ✓ **Isothermal** (or radiative) **stage:** $R_{BW}(t) \propto t^{1/4}$ (t > 10 000 yrs)

1/4 ? **(2/7 ?)**

Late evolution of a SNR : 1/4 or 2/7?

Cooling ⇨ Formation of a thin shell



$$V_{shell} = \left(\frac{2}{\gamma_{shell}+1}\right) V_{BW}$$

Thin → dense

$$\gamma_{shell} \approx 1$$

✓ **Equation of motion of the shell:**

$$\frac{d}{dt}\big(M_{shell}(t) \times V_{shell}(t)\big) = 4\pi (R_{BW})^2 P_{gas}(t)$$

$$\frac{\rho_{ISM} R_{BW}}{3} \frac{d}{dt} V_{BW} = \left(\frac{\gamma_{shell}+1}{2}\right) P_{gas} - \rho_{ISM} (V_{BW})^2$$

$$P_{gas} \sim (R_{BW})^{-3\gamma_{gas}}$$ **and** $$R_{BW}(t) \propto t^{2/(3\gamma_{gas}+2)}$$

$$\gamma_{gas} = 5/3 \quad R_{BW}(t) \propto t^{2/7}$$ McKee & Ostriker (ApJ, 1977)

✓ **Momentum conservation:**

$$M_{shell}(t) \times V_{shell}(t) \sim (R_{BW})^3 \times (dR_{BW}/dt) \sim constant$$

$$R_{BW}(t) \propto t^{1/4}$$ Spitzer

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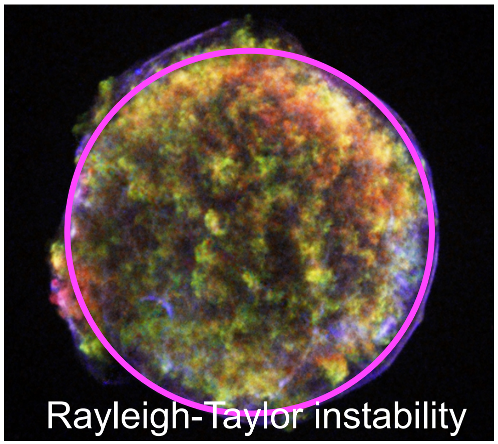
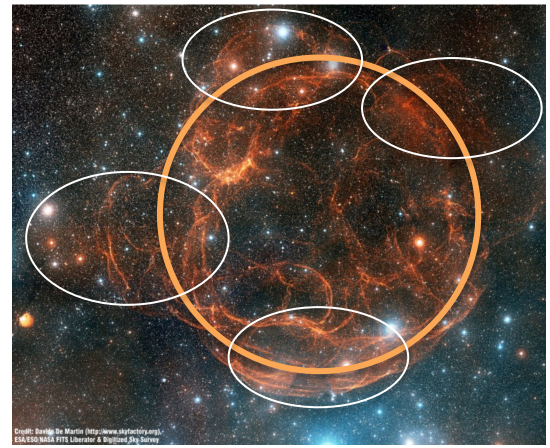
Complex structure of old SNR

Tycho (1572, Cass. B, 3 kpc)



Simeis 147 (~30 000 y.o.,Taurus, 1 kpc)



Nébuleuse du Spaghetti

Diameter of SNR's: from a few to several pc (1 parsec $\approx 3\times10^{18}\,\mathrm{cm}$)

- ✓ **Strong deformations, filaments, messy structures are observed**
- ✓ **Stability of BW is a key issue: so-called Vishniac instability (ApJ, 1983)**

Overstability (V83) :

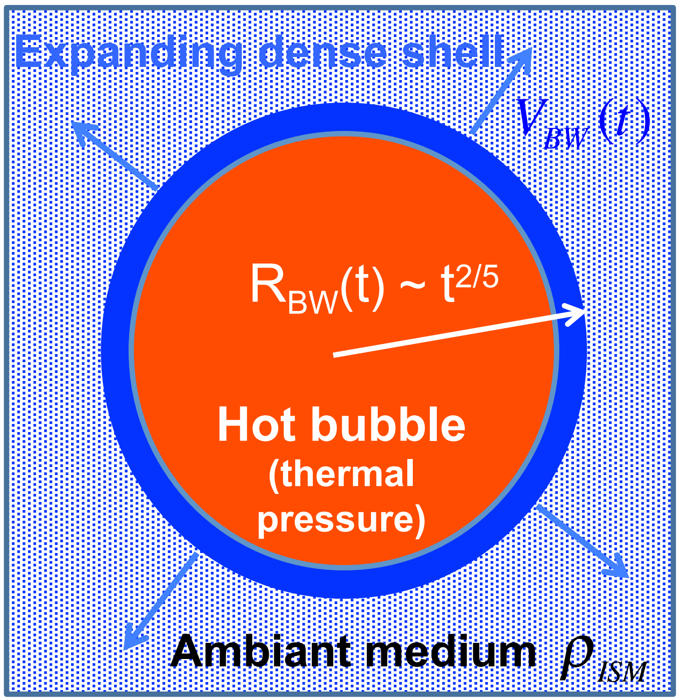
Oscillation with growing amplitude

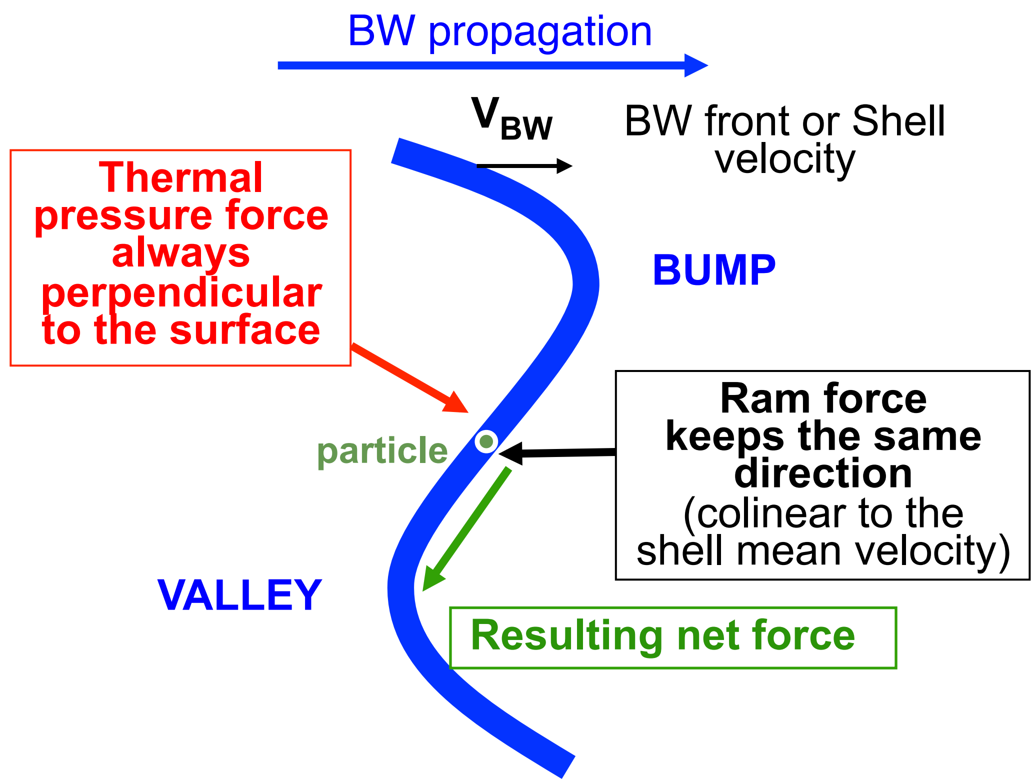
A simple mechanical model by E.T. Vishniac

Ethan T. Vishniac (ApJ, 1983)

The shell is distorted (overdensities $\Delta\rho_{ISM}$)

- ✓ **Infinitely dense and thin shell**
- ✓ **Corresponds to $\gamma = 1$**

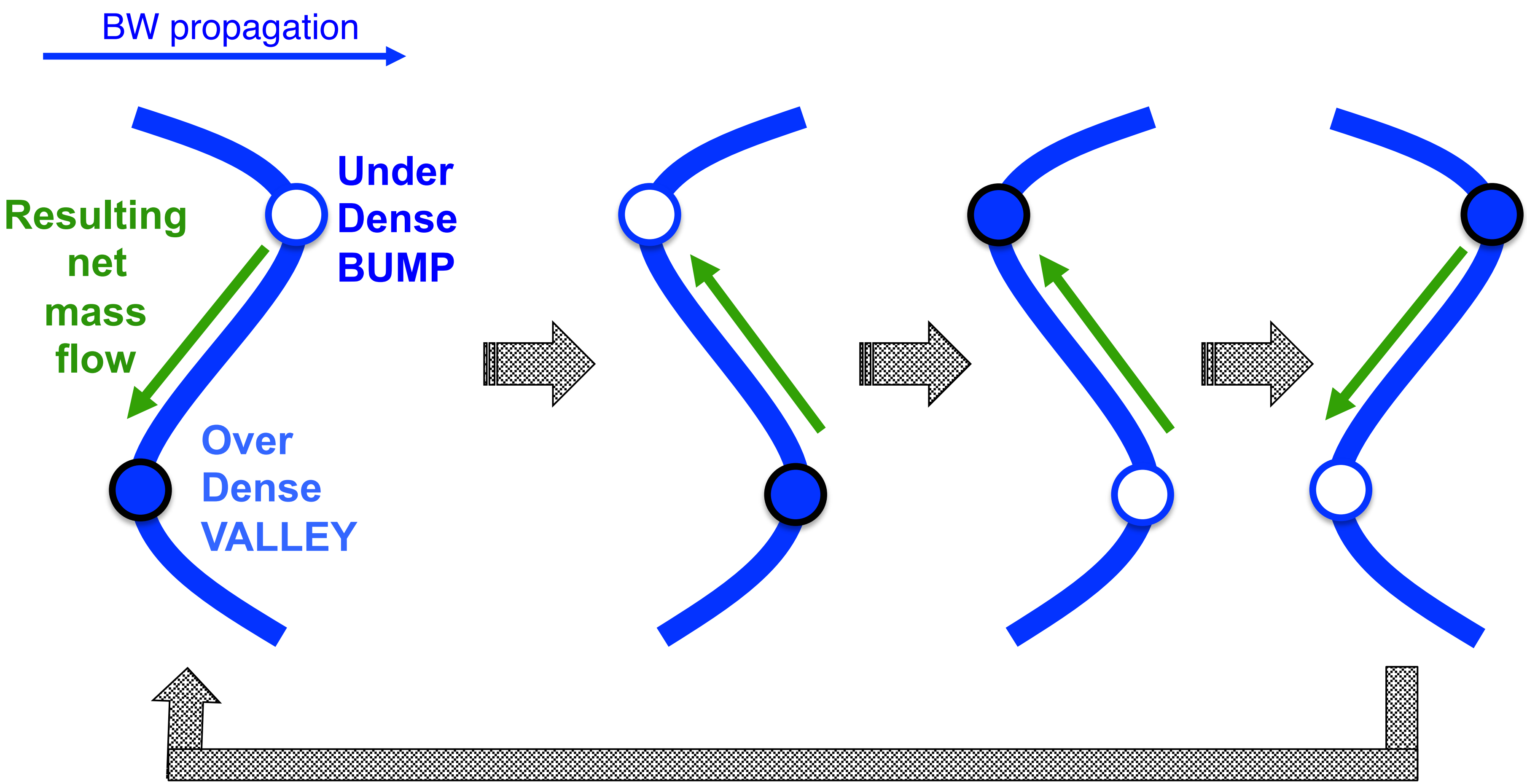




Material flows along the shell from a « BUMP » to a « VALLEY »

Disruption of the shell

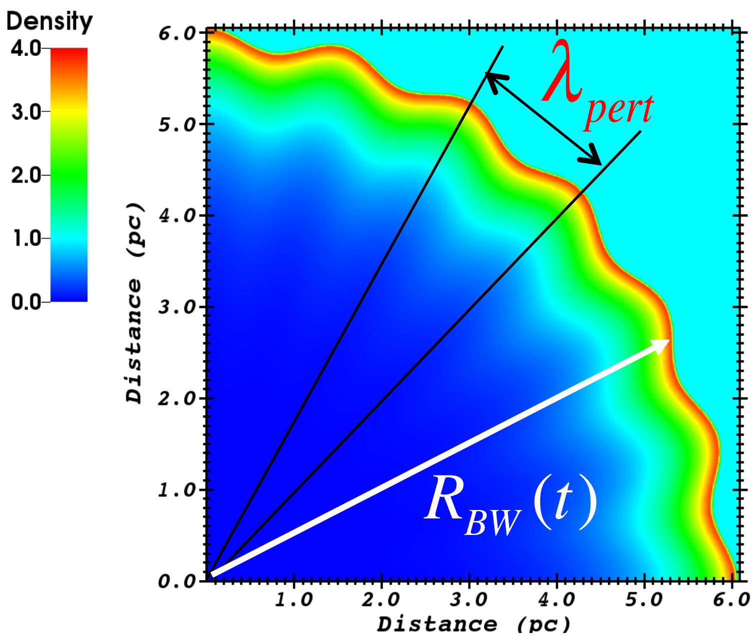
Overstability



Oscillations with growing amplitude: Overstability

Dispersion relation for Vishniac instability (V83)

Ethan T. Vishniac (ApJ, 1983)



Single mode perturbation: λ_{pert}

Amplitude: $\Delta R_{BW} \propto Y_{l,m}(\theta,\varphi) \times t^{s}$

s: complex « **growth rate** »

$s = s_r + i \times s_i$

- **$s_r > 0$: perturbation grows: UNSTABLE**
  → shell disruption
- **s_i** : oscillations

$t^{i.s_i} \sim \cos[s_i \times \ln(t/t_0)]$

Dispersion relation:

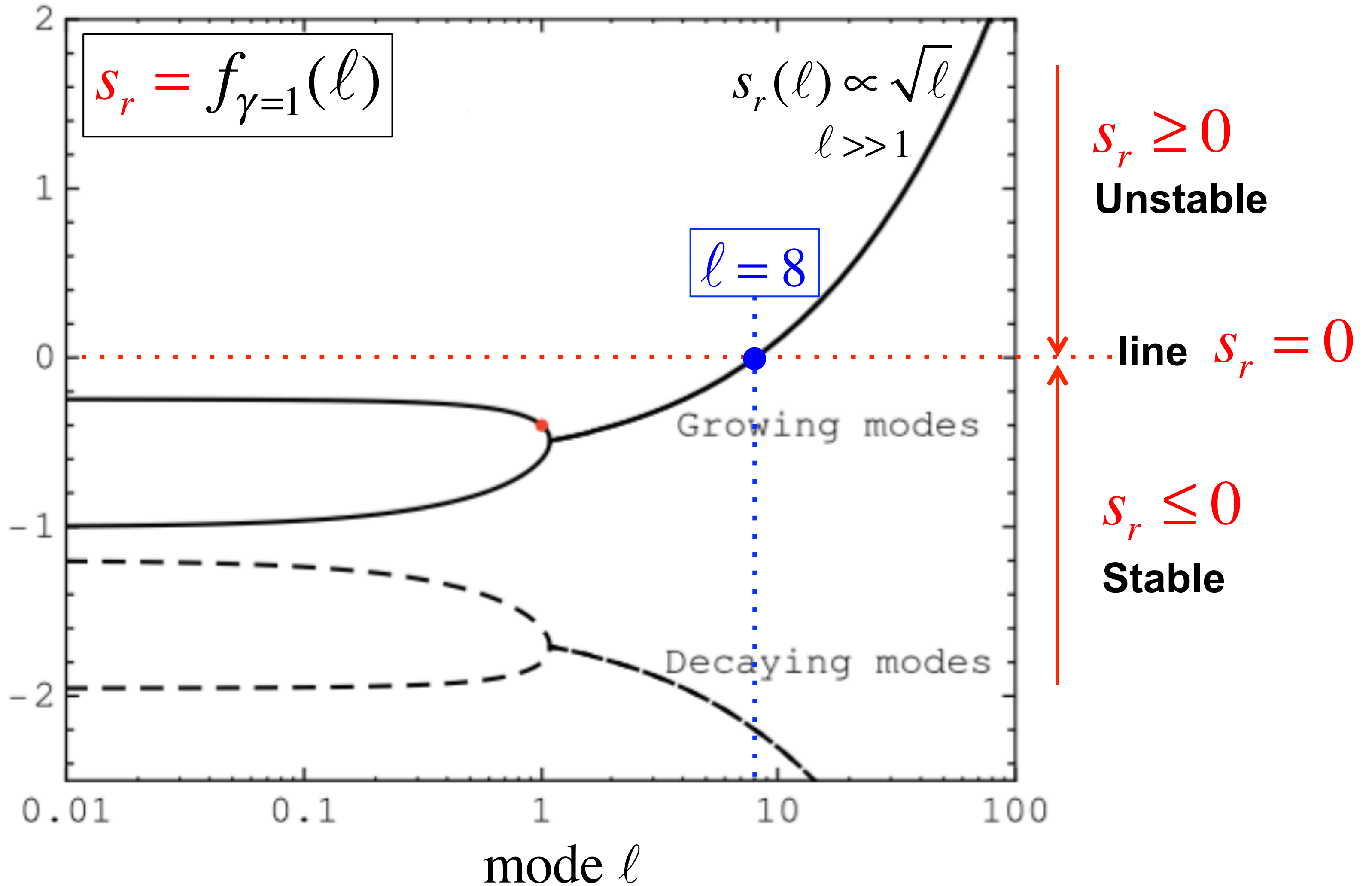
$$D(s,\ell,\ldots) = (s+1)(5s+6)(25s^2+55s+12)+36\ell(\ell+1)/5=0$$

$$\boxed{s(\ell) \propto \sqrt{\ell}}$$

$\ell = 2\pi R_{BW} / \lambda_{pert} = \text{mode number}$

Rayleigh-Taylor

$$D(s,\ell,...) = (s+1)(5s+6)(25s^2+55s+12)+36\ell(\ell+1)/5=0$$

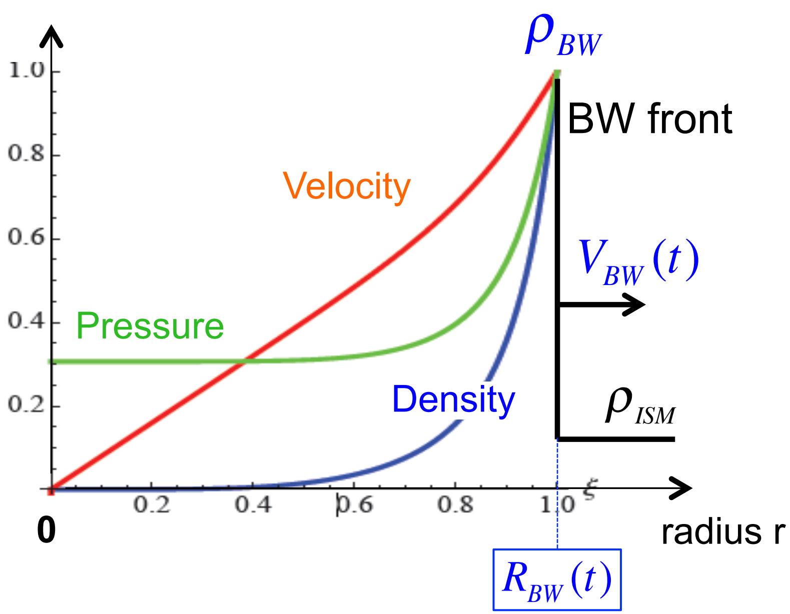


But … Ryu-Vishniac (1987) !

Stability of the STBW for arbitrary $\gamma \geq 1$ (RV87)

Ryu & Vishniac (ApJ, 1987)

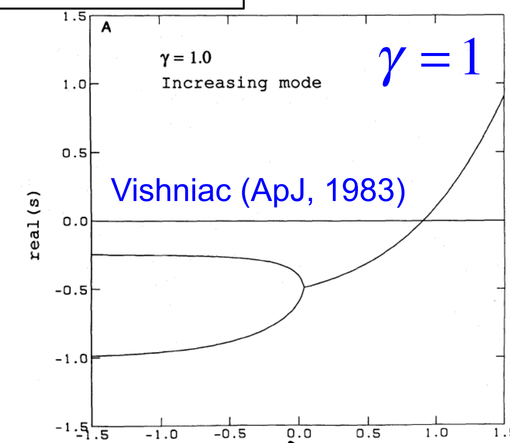
Profiles are accounted

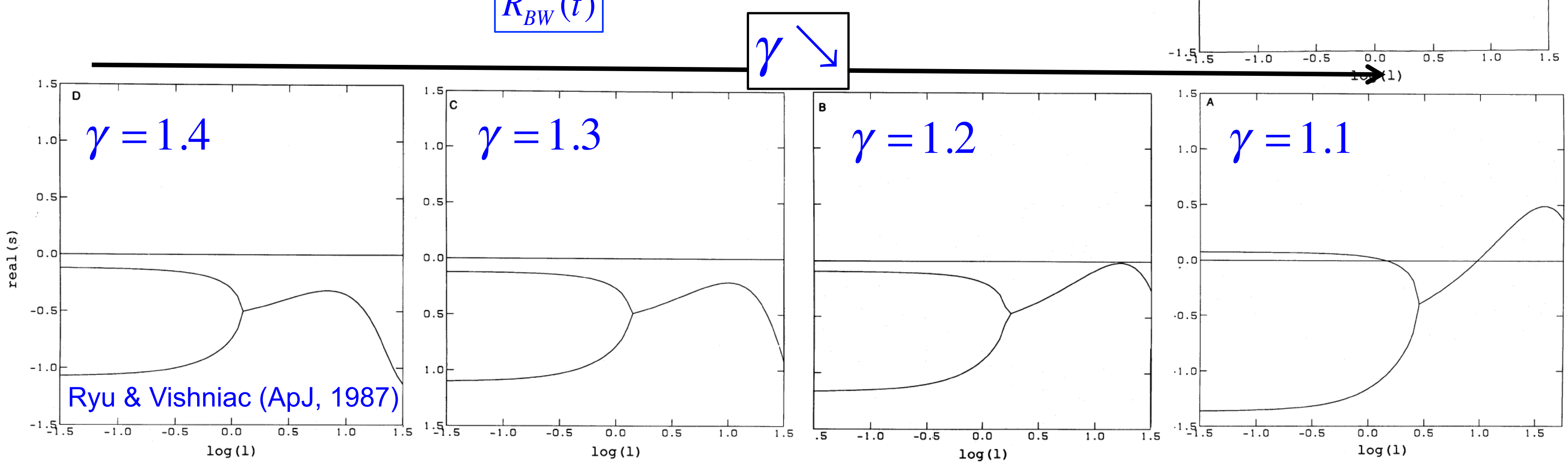


Growth rate *s*

$D(s,\ell)=0$ **becomes** $D_\gamma(s,\ell,\gamma\geq 1)=0$

$$D_\gamma(s,\ell,\gamma\to 1)\neq D(s,\ell)$$





1. **Shock waves and blast waves in astrophysics**

2. **Vishniac instability in supernova remnants**

3. **New theoretical and numerical developments**

4. **Latest blast wave experiments**

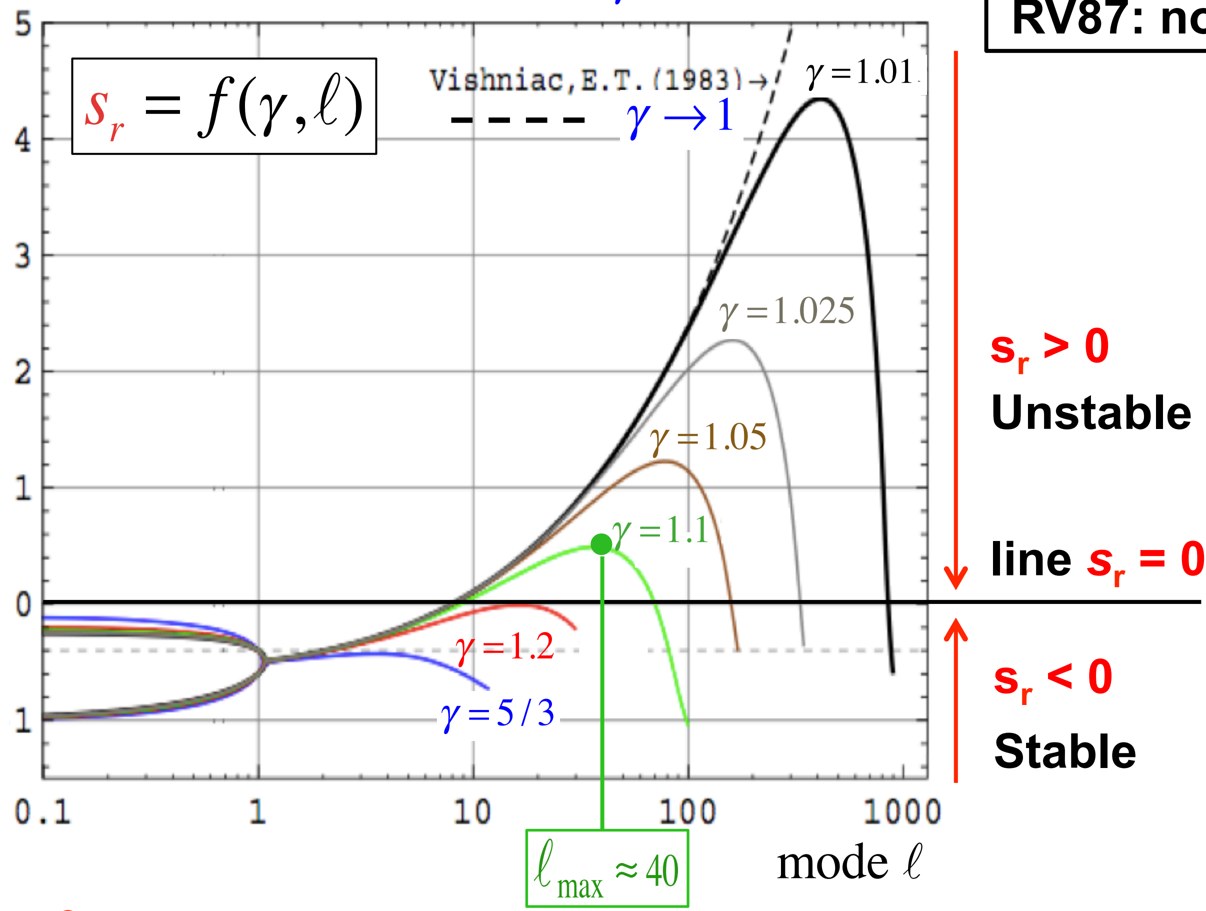
5. **Conclusion**

New dispersion relation for $\gamma \geq 1$

Sanz, Bouquet, Michaut & Minière (Phys. of Plasmas, 2016)

Unification for the first time: $D'_\gamma(s,\ell,\gamma)=0$

V83: recovered
RV87: not correct



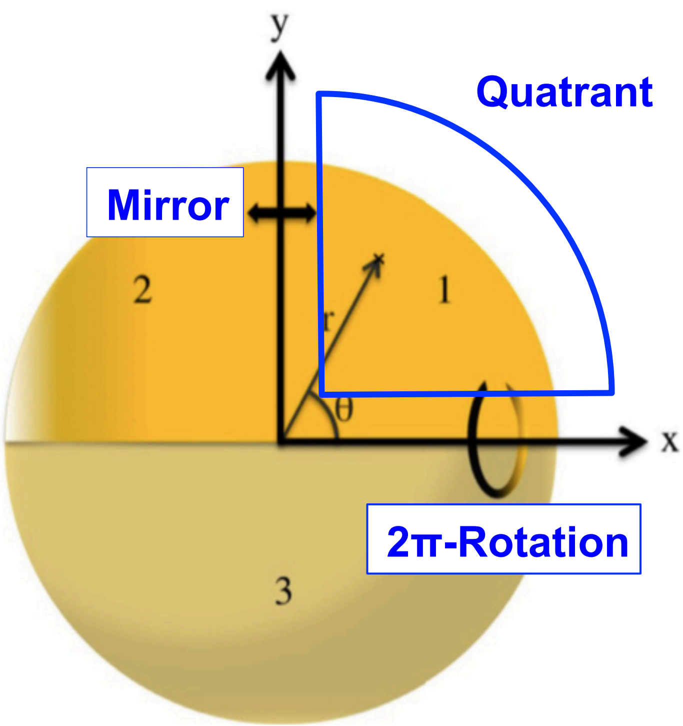
- $\gamma \geq 1.2$, $s_r \leq 0$ **no instability**
- **« Weak » instability:** $\gamma \geq 1.05 \quad s_r \leq 1$ | t^{s_r} **grows slowly** | $\frac{\Delta R_{BW}}{R_{BW}} \propto t^{s_r - 0.4}$

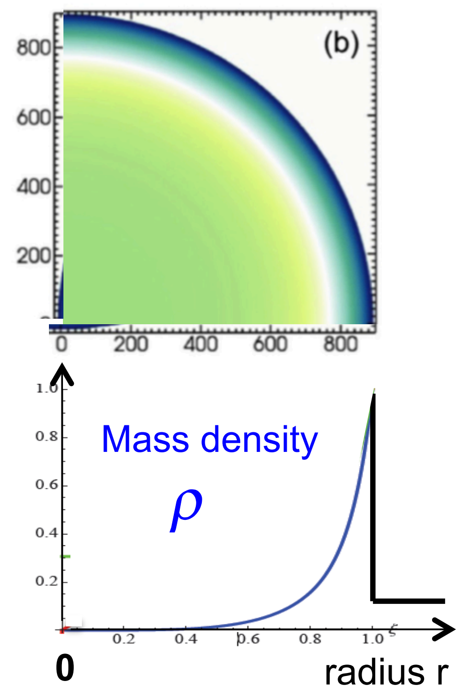
HADES: Code for 2D radiation hydrodynamics

- **Until now, no numerical proof of the V.I.**

  Mac Low & Norman (ApJ, 1993) **: ZEUS-2D, growth stops**
  Strickland & Blondin (ApJ, 1995) **: 2D perturbed steady state ≠ BW**
  Blondin & Marks (New Astron. 1996) **: 2 shock bounded slab**
  Blondin, Wright, Borkowski, Reynolds (ApJ, 1998) **: 2D + cooling**

- **Code HADES-2D:** LUTH, C. Michaut Michaut, Di-Menza, Nguyen, Bouquet, Mancini (HEDP, 2017)
  Radiation hydrodynamics
  HPC (144 cores on MesoPSL, 1472 max), high resolution (30x10^6 meshes)





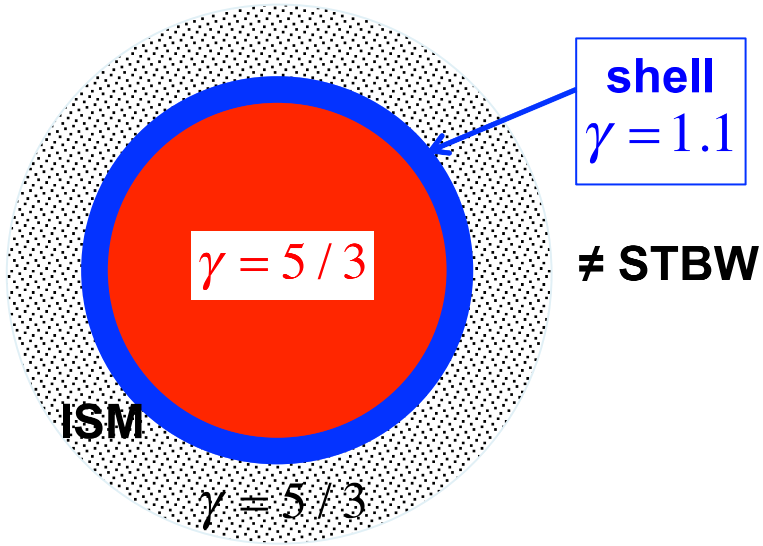
- **PhD thesis:**

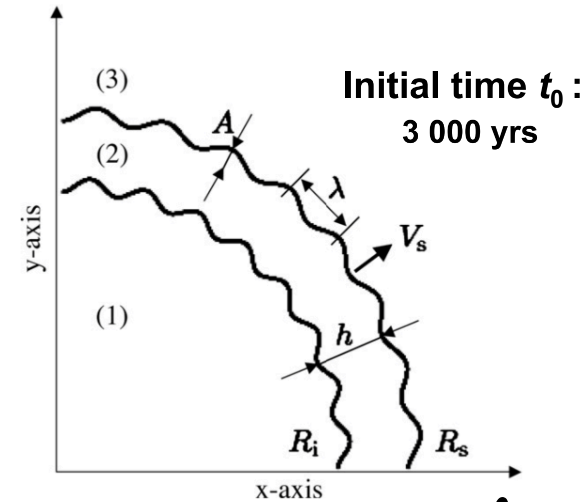
  C. Cavet (2010)
  C. Nguyen (2011)
  J. Minière (2014)
  O. Saincir (en cours)
  A. Gintrand (en cours)

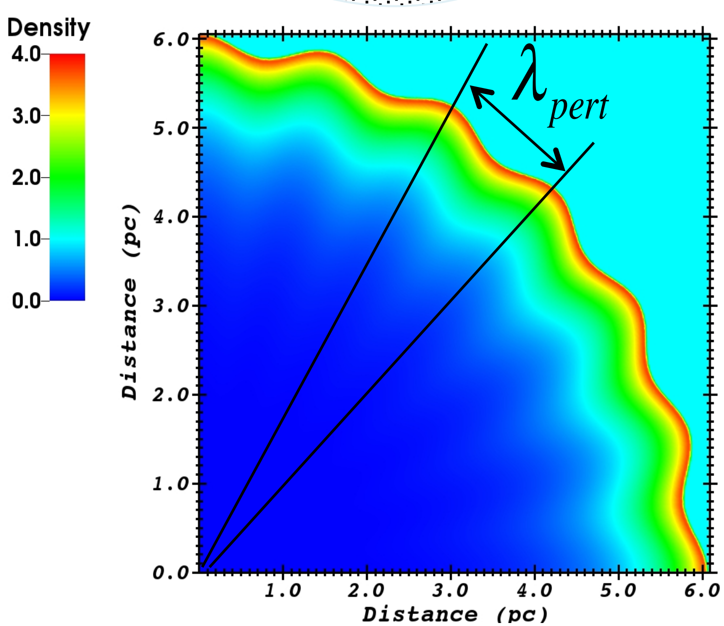
Initial conditions for the numerical simulations

Thèse C. Cavet

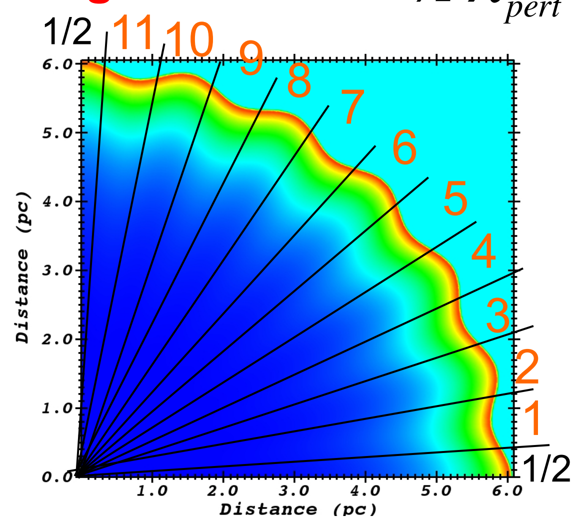
Michaut, Cavet, Bouquet, Roy & Nguyen (ApJ, 2012)







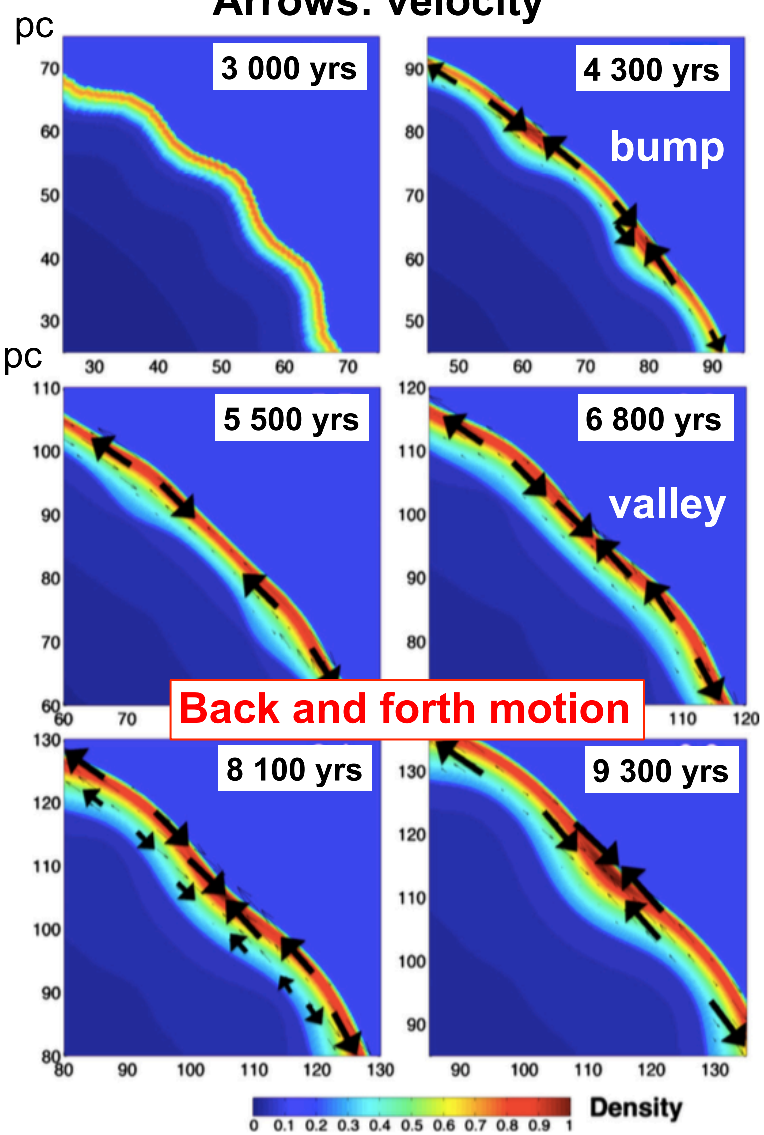
Angular sectors ½ λ_{pert}



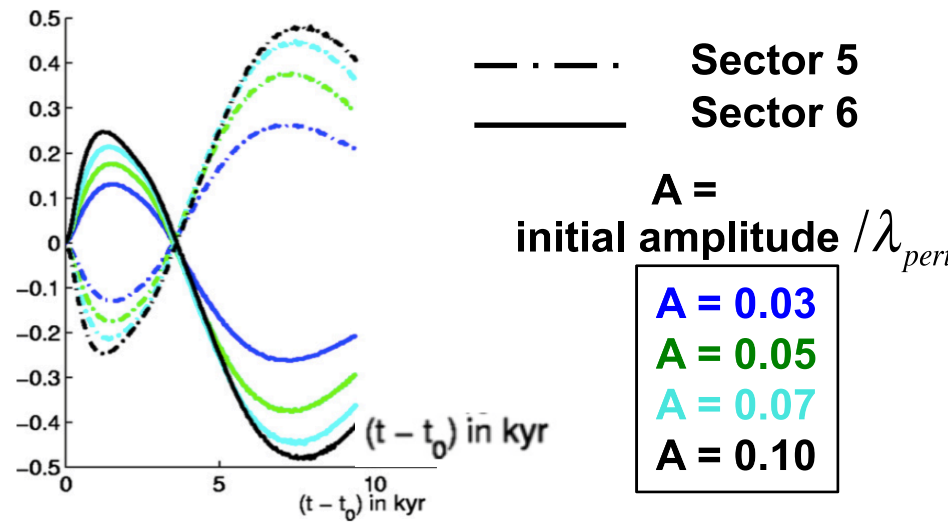
Study of linear and nonlinear stages

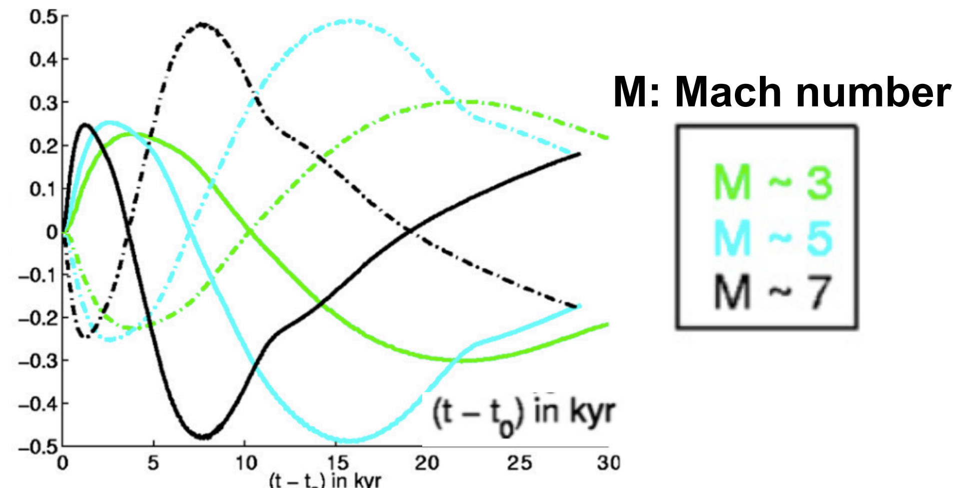
Linear and nonlinear evolution of the shell

Arrows: velocity



Mass variation: $\Delta M(\text{sector}) / M(\text{sector})$

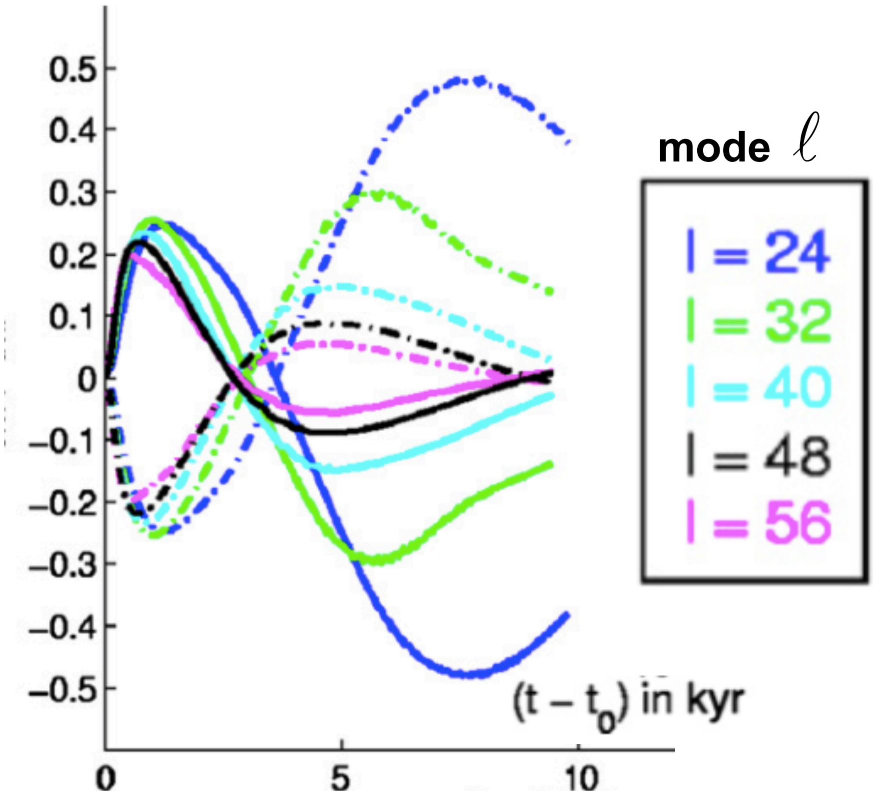


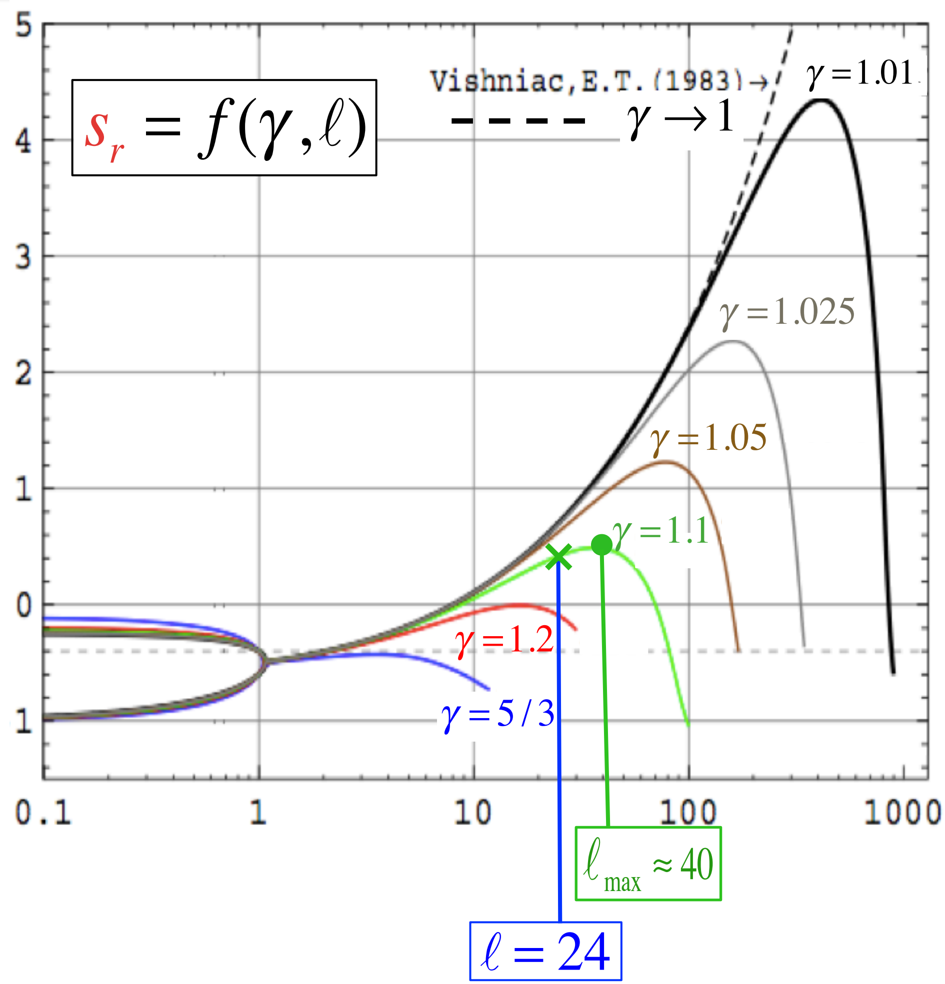


Oscillation period grows: $t^{i.s_i} \sim \cos[s_i \times \ln(t / t_0)]$

Variation with the mode number ℓ

$\gamma = 1.1, \ A = 0.10, \ M = 7$

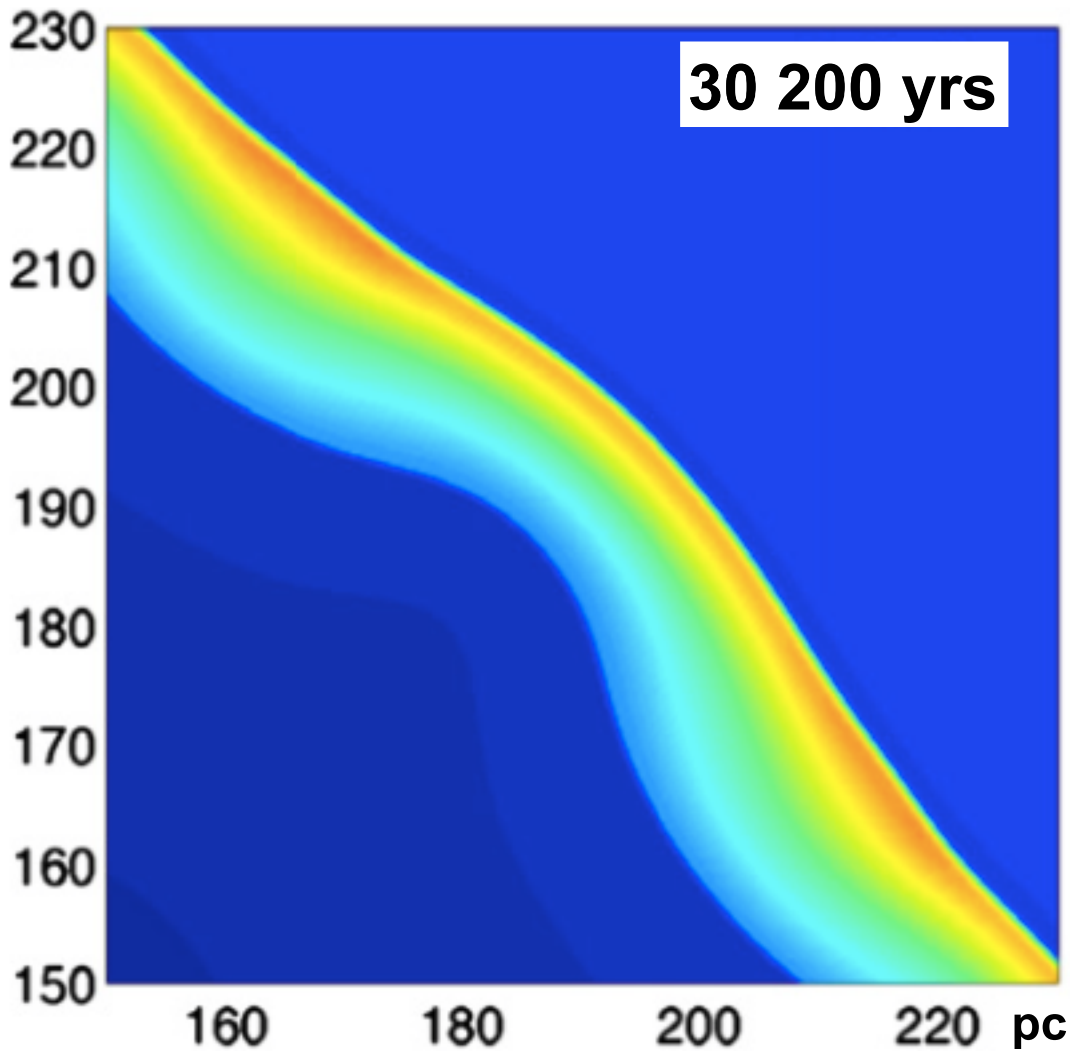




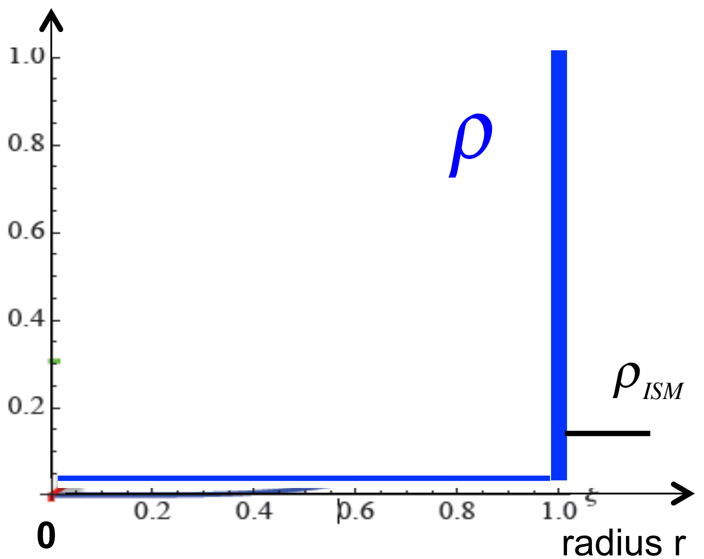
Numerics: ✓ $s_r(\ell = 24) \approx 0.4$ **: Not bad** ✓ $\ell = 24$ **has the max** s_r **: Bad …**

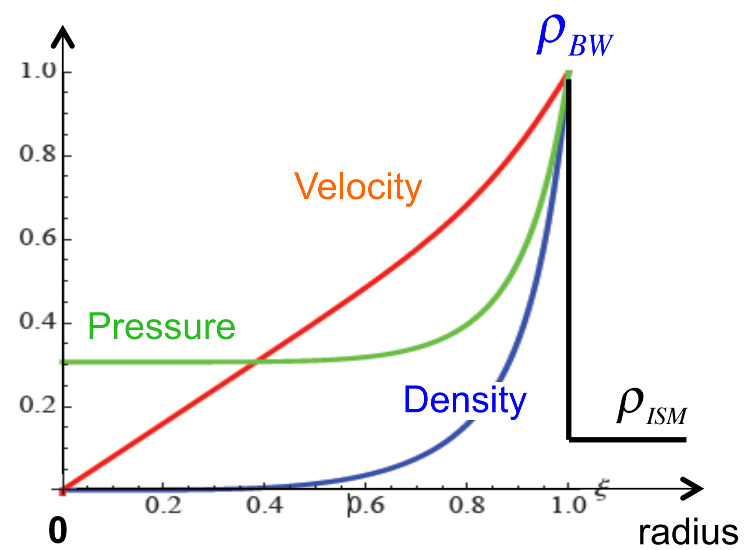
The shell does not break. The perturbation is smoothed out …

Expansion smoothes out the ripples



Simulations of the STBW





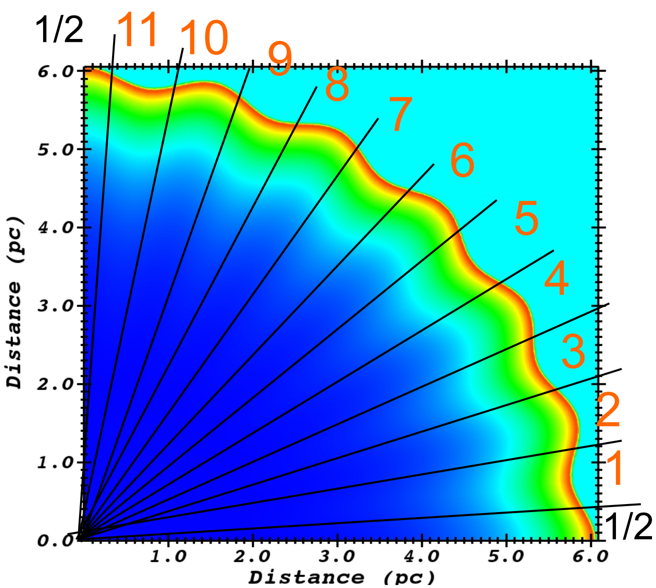
And longer runs: up to 200 000 years

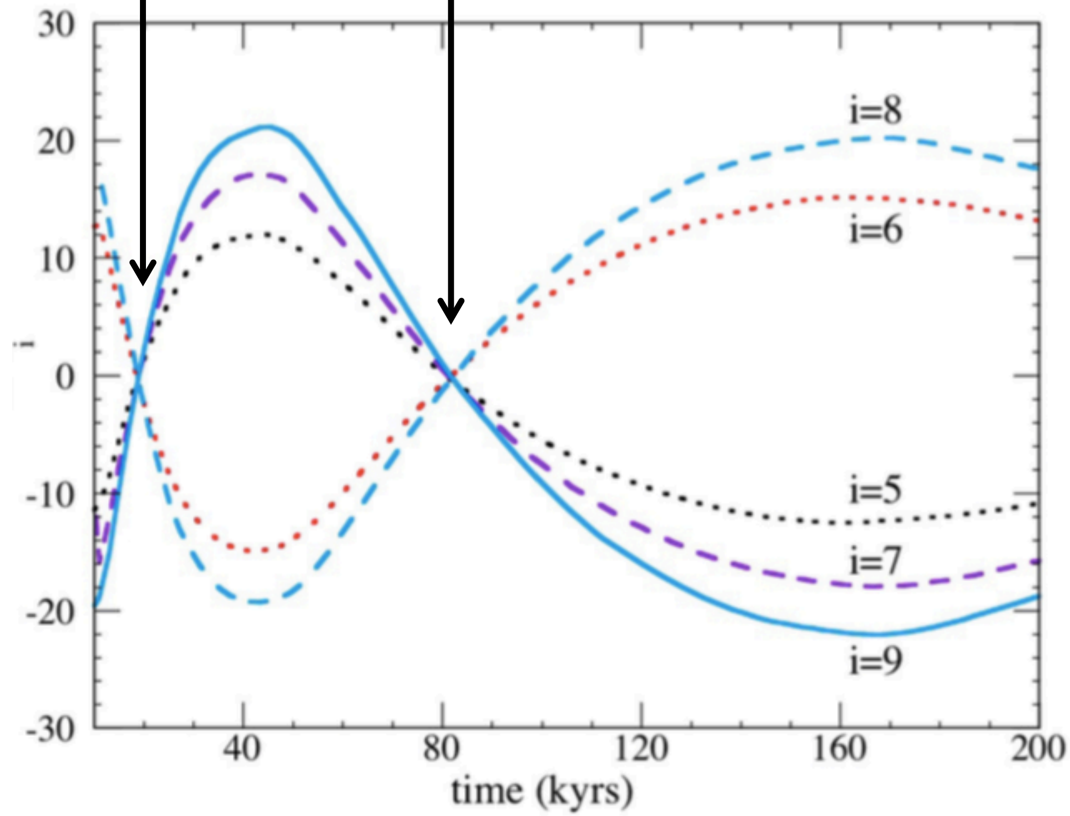
Simulation for $\gamma = 1.1$ and $\ell = 24$

First inversion $t \approx 18\,\mathrm{kyrs}$

Second inversion $t \approx 80\,\mathrm{kyrs}$

$\ell = 24 \quad \gamma = 1.1$



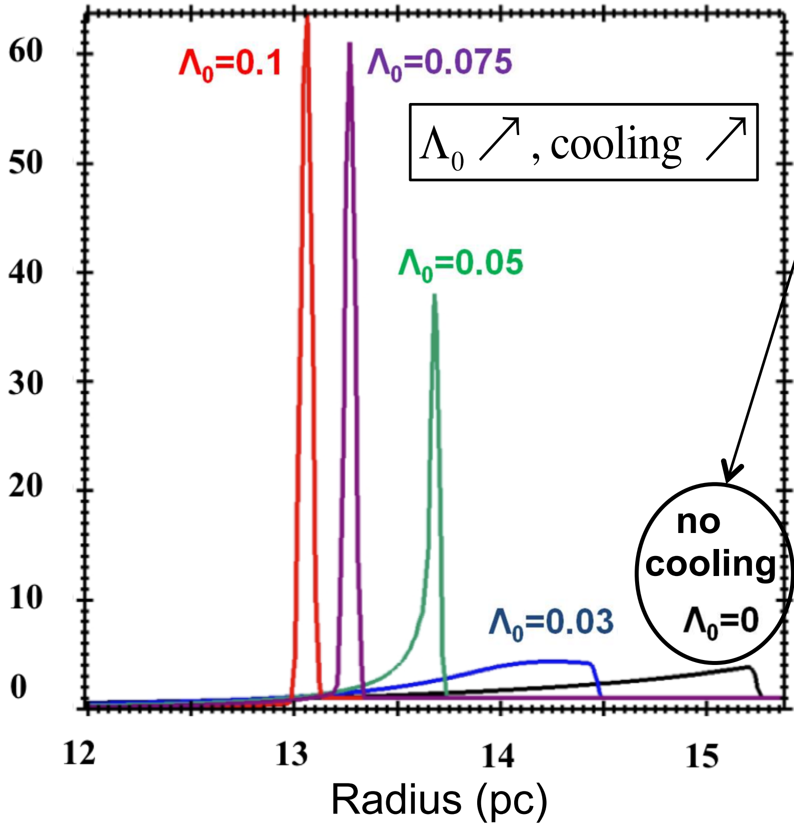


- **Oscillations are clearly evidenced, but no growth is observed!**
  - **Increase *C*** $(C \equiv \rho_{BW} / \rho_{ISM})$? **Additional physics**
    - **Cooling**

Compression with cooling (shown for $\gamma = 5/3$)

$\gamma = 5/3$ is stable against V.I

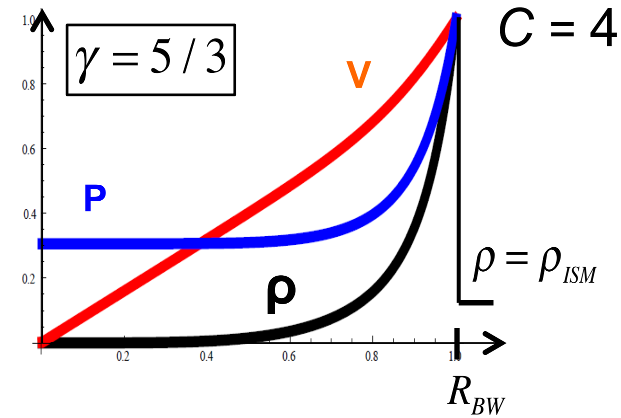
Mass density $t \approx 30\,\mathrm{kyrs}$



Cooling parameter: Λ_0 in W/kg

STBW:

$(\Lambda_0 = 0)$



$$C = \rho_{BW} / \rho_{ISM} = (\gamma+1)/(\gamma-1) = 4$$

✓ $\Lambda_0 \neq 0$ Define $\gamma_{eff} \neq \gamma$

$$C \equiv \frac{\rho_{BW}}{\rho_a} = \frac{\gamma_{eff}+1}{\gamma_{eff}-1} \qquad \gamma_{eff} = \frac{C+1}{C-1} \neq \gamma$$

✓ $\Lambda_0 = 0.1$

$C \approx 60 \quad \gamma_{eff} \approx 1.03 \quad (\gamma = 5/3)$

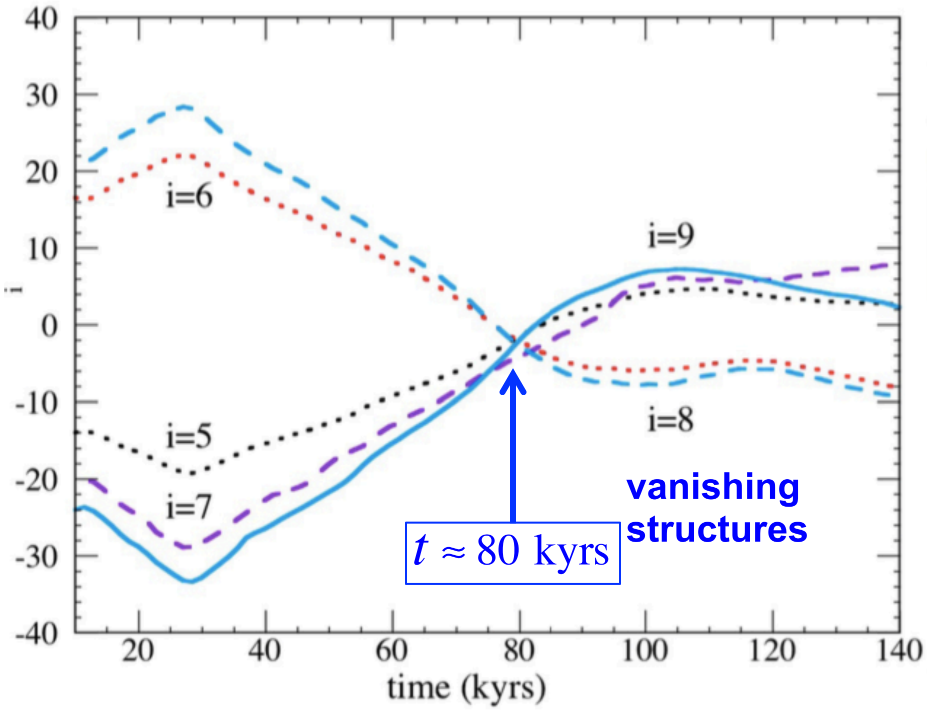
Effective gamma very close to 1

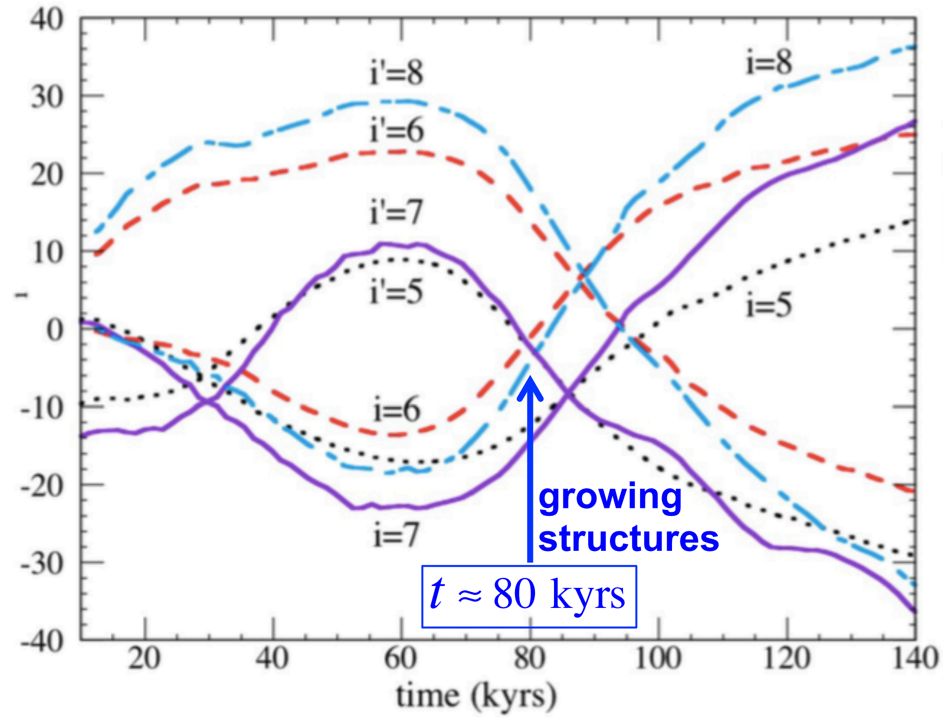
Unstable?

The V.I. appears for twice smaller angular sectors

Simulation for $\gamma = 5/3, \ell = 24$ and $\Lambda_0 = 0.1$

Minière, Bouquet, Michaut, Sanz (A&A, en cours)





✓ Vanishing structures $t \geq 80$ kyrs

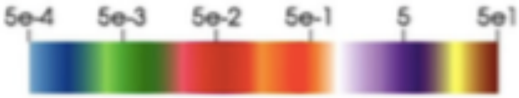
✓ Not in agreement with density maps (twice smaller structures appear)

✓ Subdivision of the angular sectors by 2 (twice more sectors)

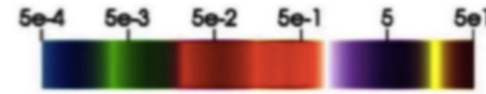
✓ The new mode is $\ell' = 2\ell = 48$

For $\gamma = 1.1$, $\ell_{max} \approx 40$, $s_r \approx 0.5$

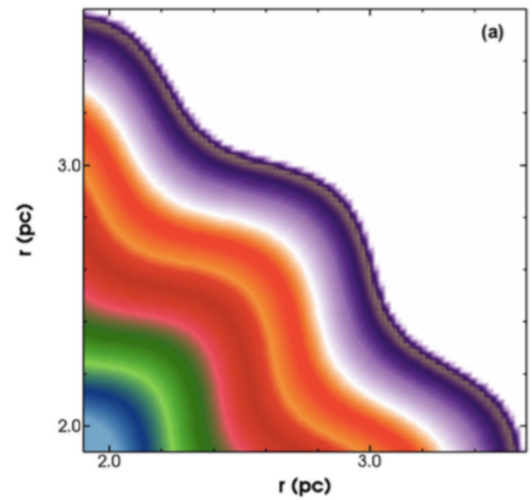
✓ Growth rate: $s_r \approx 0.3$



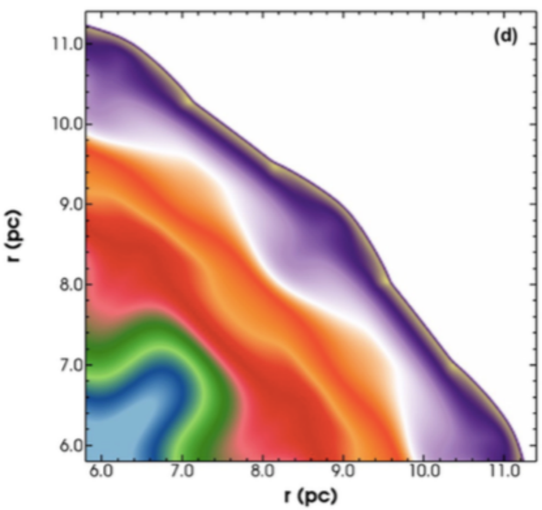
$$C = \rho_{BW} / \rho_{ISM}$$



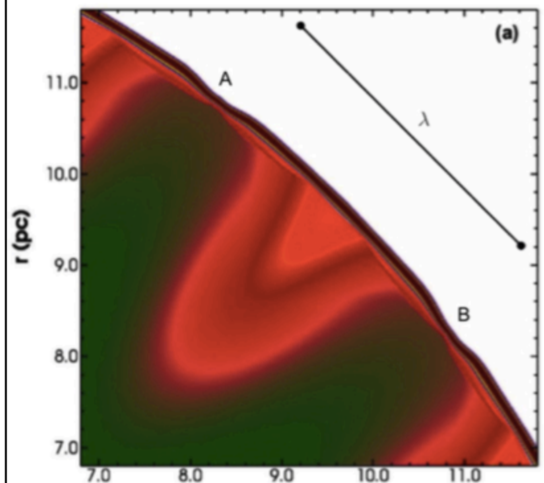
$t \approx 18$ kyrs



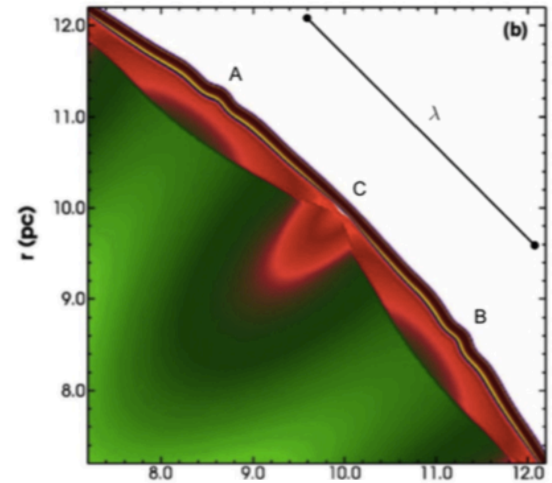
$t \approx 53$ kyrs



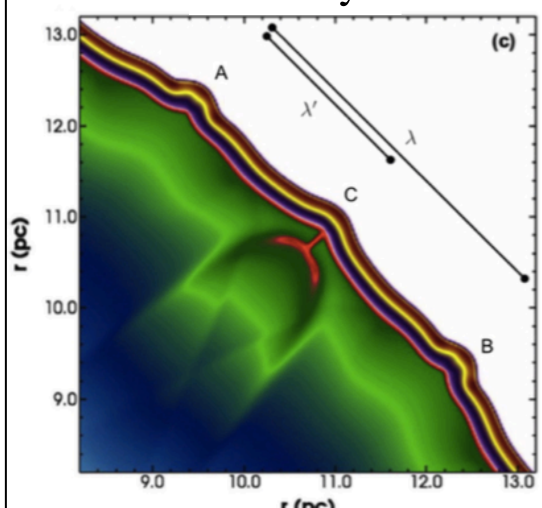
$t \approx 38$ kyrs



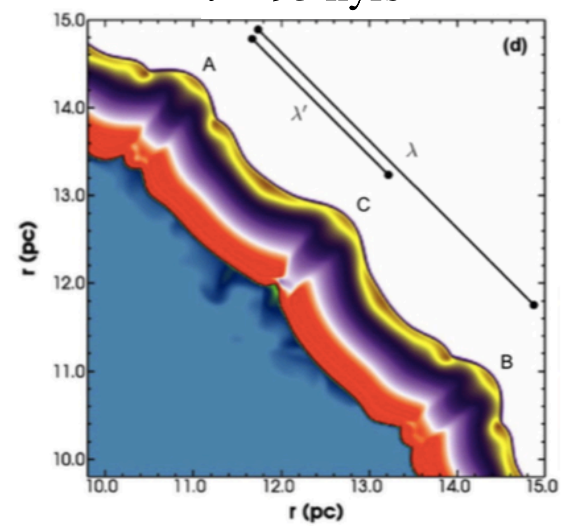
$t \approx 43$ kyrs



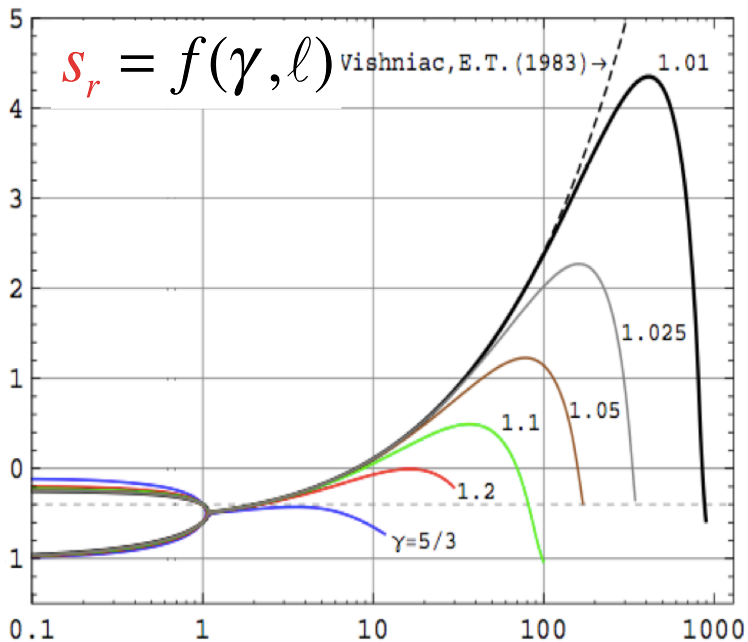
$t \approx 58$ kyrs



$t \approx 93$ kyrs



Deceleration rate for $\gamma = 5/3,\ \Lambda_0 = 0.1\,\mathrm{W/kg}$

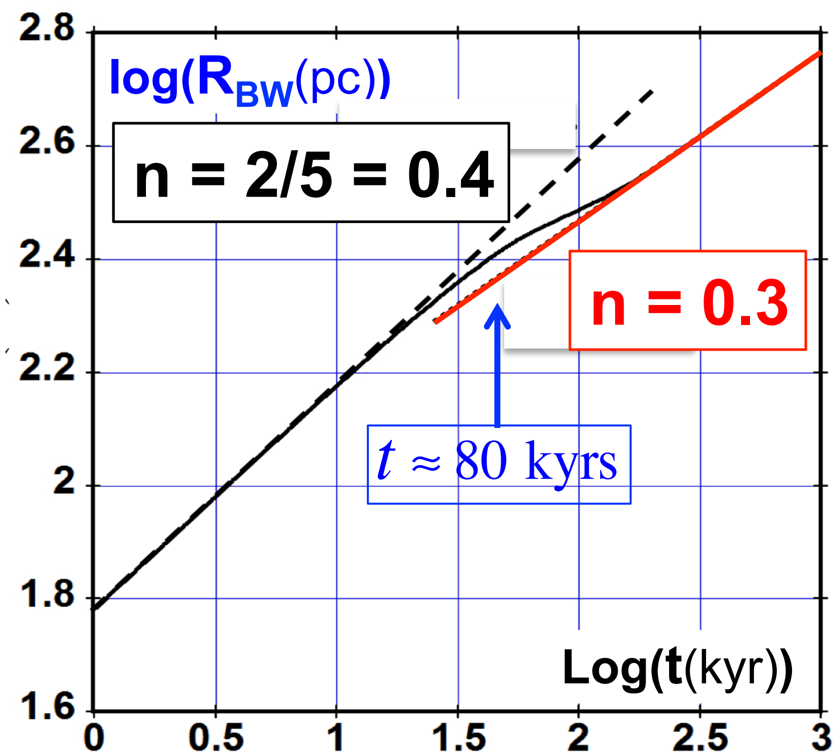


- ✓ simulations: $s_r \approx 0.3$
- ✓ theory:

$C \sim 60,\ \gamma_{eff} \approx 1.03,\ \ell' = 48$

For $\gamma = 1.025 \simeq 1.03$

$s_r \approx 1.5 \text{ for } \ell \approx 50$



Deceleration is amplified

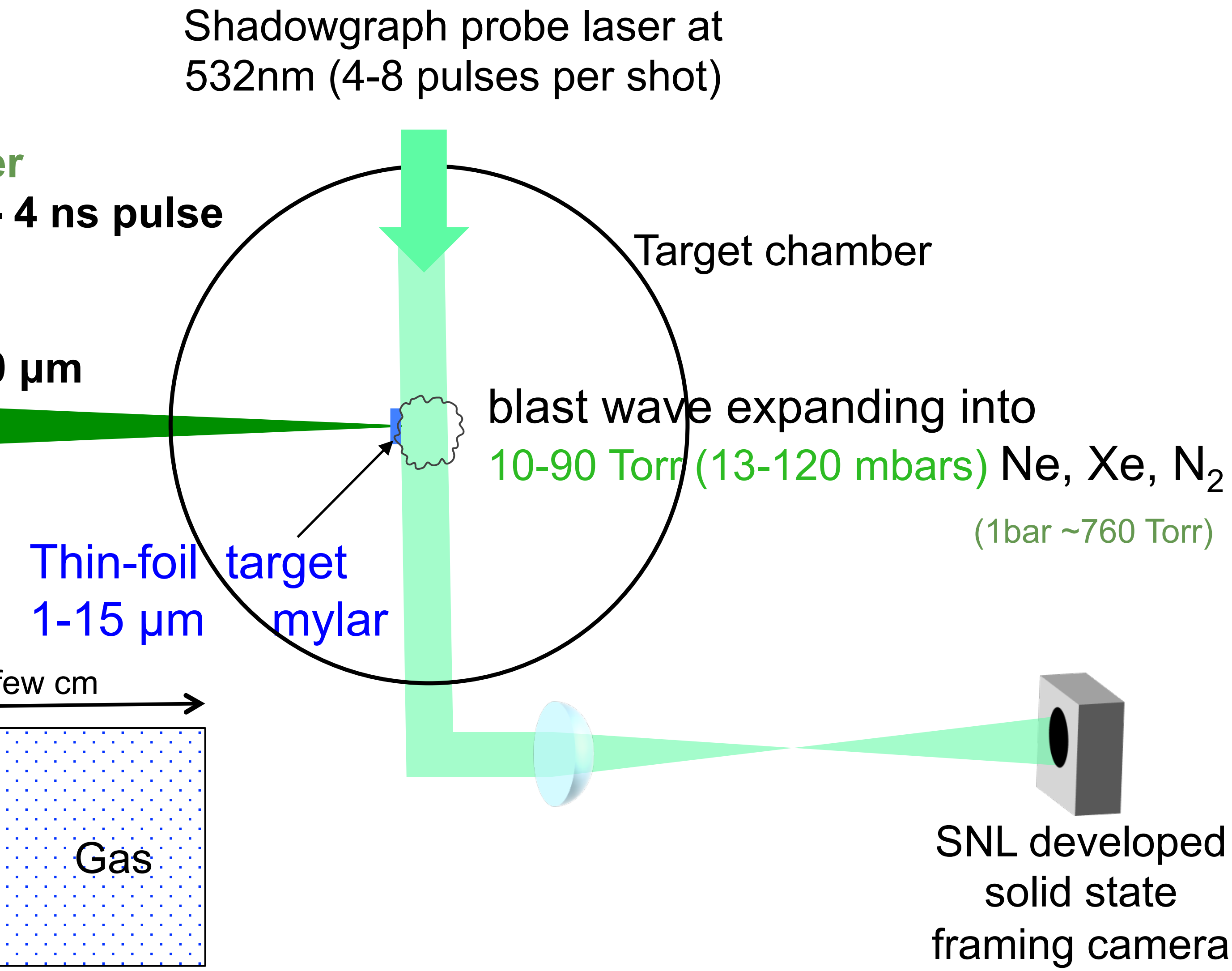
$$R_{BW}(t) \propto t^n$$
$$n:\ 2/5 \rightarrow 0.3$$

Chevalier, ApJ 1974 (simus 1D)
Mac Kee & Ostriker, ApJ 1977
Cioffi, McKee & Bertschinger, ApJ 1988

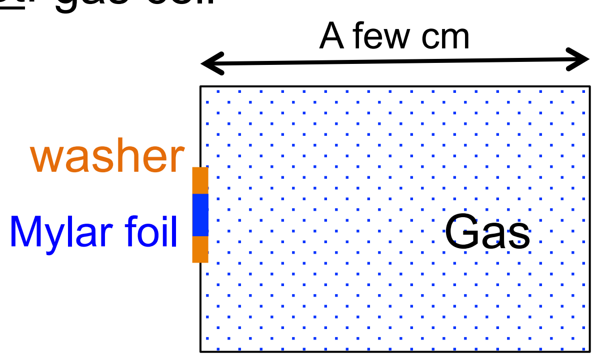
1. **Shock waves and blast waves in astrophysics**
2. **Vishniac instability in supernova remnants**
3. **New theoretical and numerical developments**
4. **Latest blast wave experiments**
5. **Conclusion**

Experimental Set-up on the Z-Beamlet laser (ZBL) @ Sandia

Z-Beamlet laser driver
1- 4 kJ on target in 1- 4 ns pulse
527 nm
I = 10^{15} J/cm^3
Focal spot : 250-2500 µm



Target: gas cell



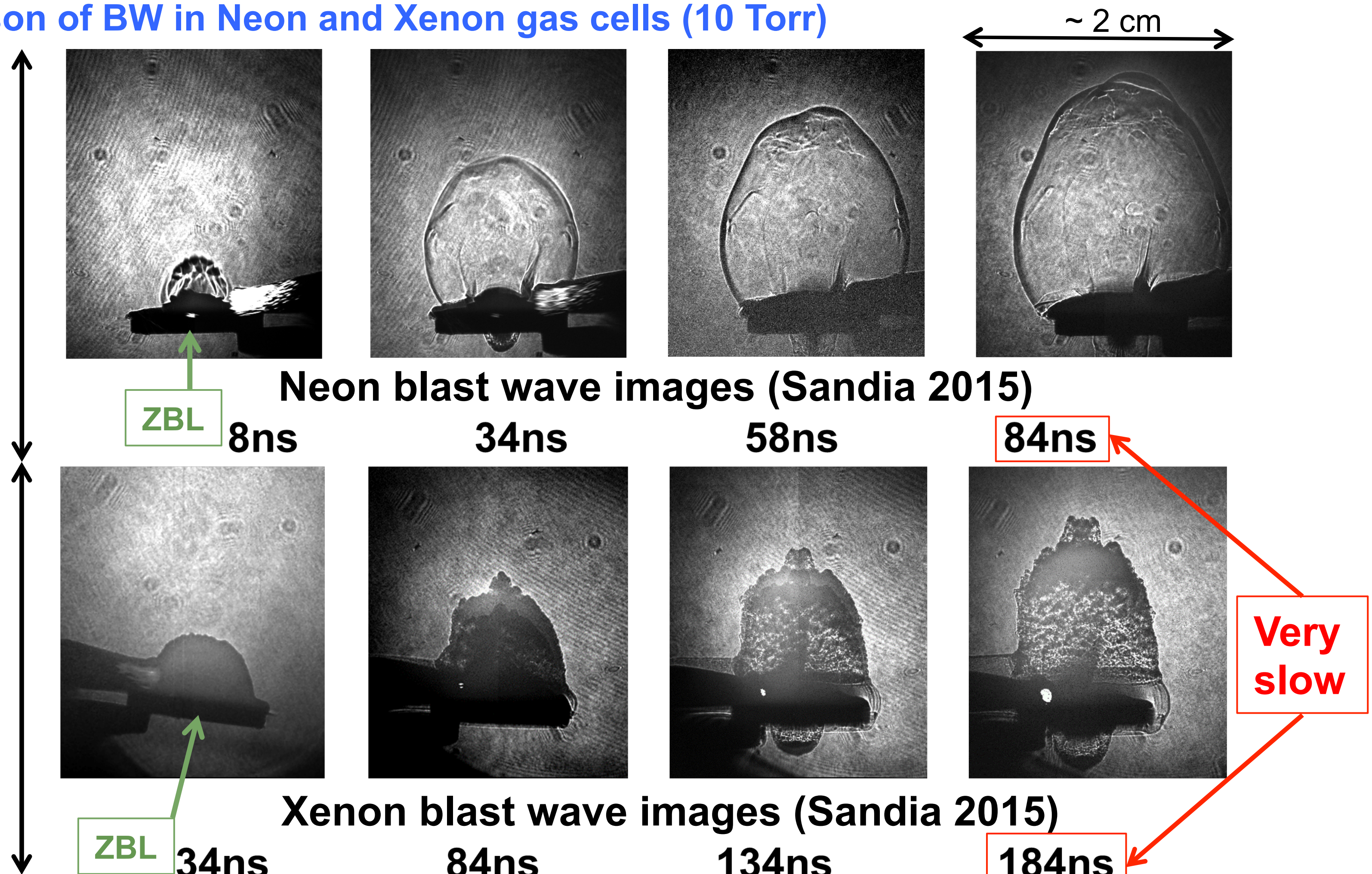
Preliminary experimental results @1kJ, 1ns

Nathan Riley & John Porter (Sandia, 2015)

Comparison of BW in Neon and Xenon gas cells (10 Torr)

Neon
smooth
BW front

Xenon
disrupted
BW front

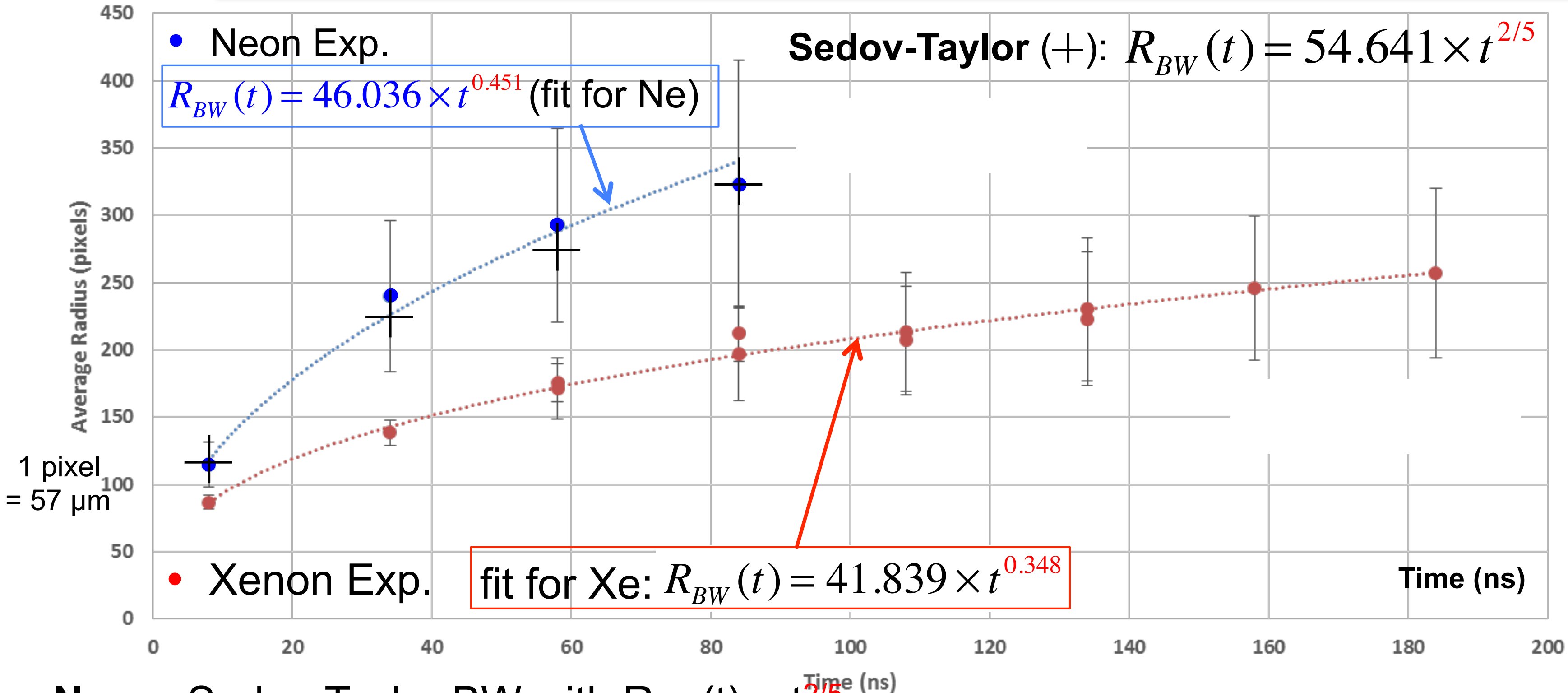


Slow → loss by radiative cooling → T decays → ρ increases $[\rho_{BW} / \rho_a = (\gamma + 1)/(\gamma - 1)]$

→ dense shell with $\gamma_{eff} \rightarrow 1$ → relevant condition for Vishniac instability → disruption

Trajectory (radius) of the BW's

Nathan Riley & John Porter (Sandia, 2015)

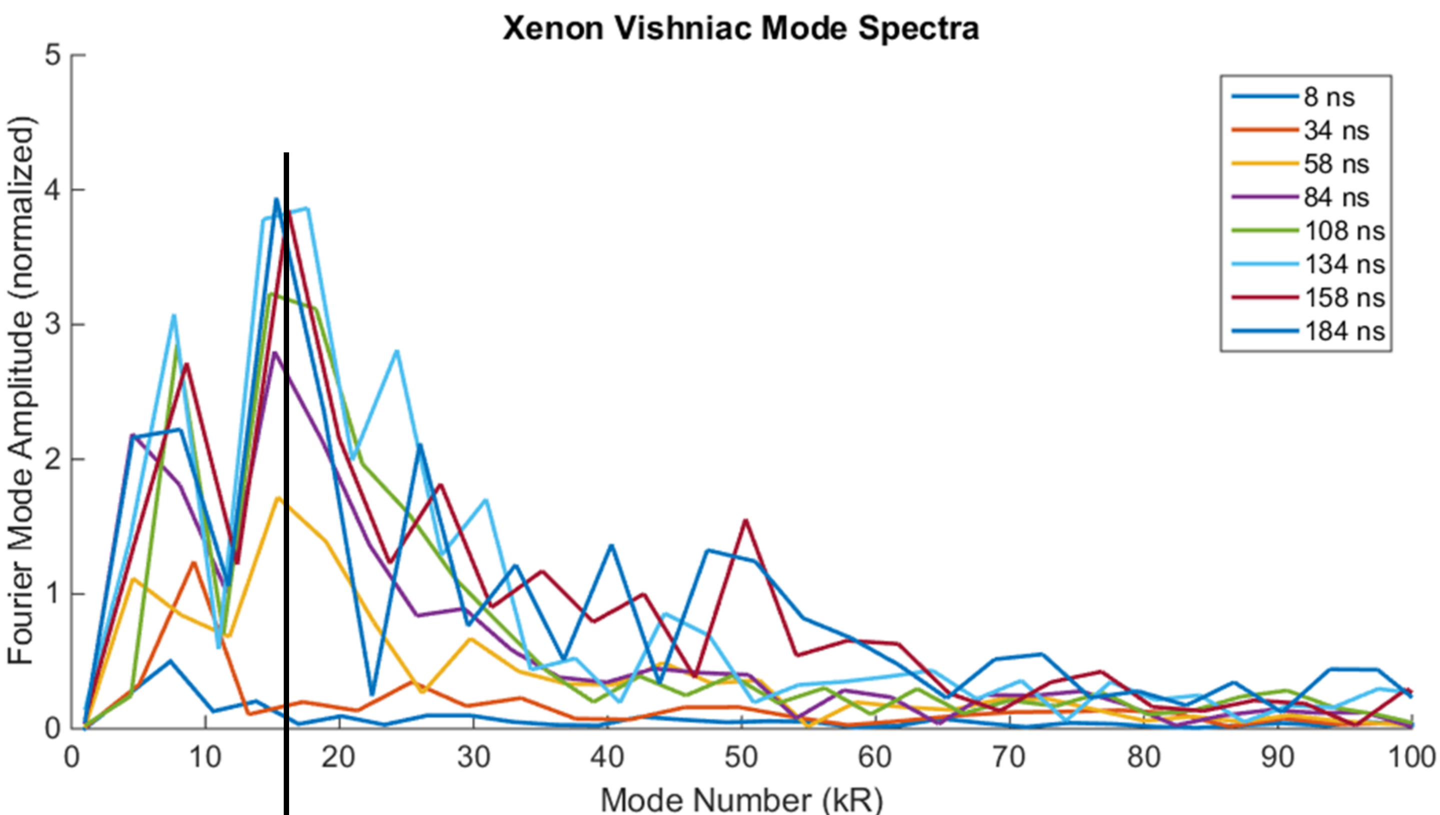


- **Neon:** Sedov-Taylor BW with $R_{BW}(t) \sim t^{2/5}$
- **Xenon:** Decelerated Sedov-Taylor BW with $R_{BW}(t) \sim t^{n}$ (n≈0.348) due to cooling
  - Numerical simulations with HADES by J. Minière (**Minière, PhD thesis, Nov. 2014**): Radiative cooling $\Lambda \propto \rho^2$, $R_{BW}(t) \propto t^{0.3}$
  - Theory for late regime (Momentum Conservation Snowplow regime): $R_{BW}(t) \propto t^{1/4}$

Mode decomposition for Xenon experiments

Nathan Riley (Sandia, 2015)

Spatial modes show maximum growth in region predicted by Vishniac



$\ell_{max} \approx 15$

Conclusion

- ✓ **Theory of the Vishniac instability (V.I.) revisited**
- ✓ **Role of cooling:** $\gamma_{eff} \to 1$
- ✓ **Simulations with HADES over 200 kyrs : mode doubling**

- ✓ **2D:** $Y_{\ell,m}(\theta,\varphi)$ versus $\cos\theta$
- ✓ **Rayleigh-Taylor instability: Contact discontinuity ≠ Surface disc.**
- ✓ **Analytical stability analysis with cooling** **Antoine Gintrand**
- ✓ **Ionisation:** $\gamma_{eff} \to 1$ **AG**
- ✓ **Simulations in the comoving frame** **AG**
- ✓ **Experiments**
- ✓ **Comparisons Theory/Simulations/Experiments**