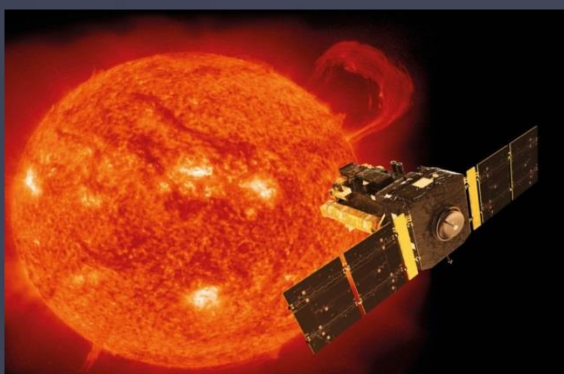
Miniaturiser l'Univers en laboratoire

É. Falize
Astrophysicien au CEA



Festival d'astronomie de Fleurance
Ferme des étoiles

Les lois de la nature sont faites de telles sorte que l'on puisse construire des univers miniatures
R. Tolman (1914)

Univers miniature ?

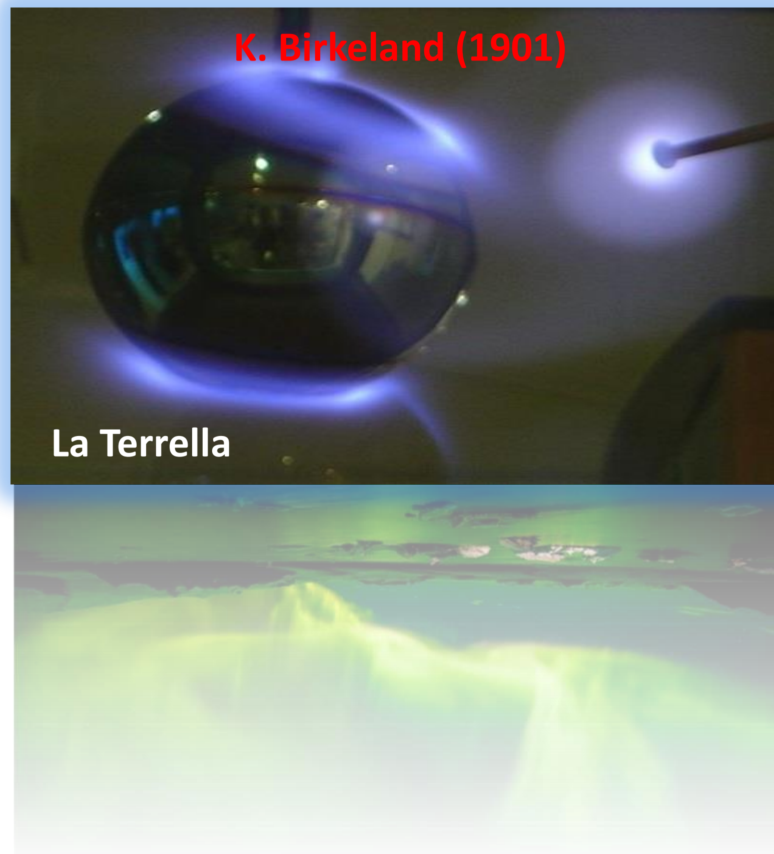
Existence d'une Invariance d'échelle

Pas d'invariance d'échelle

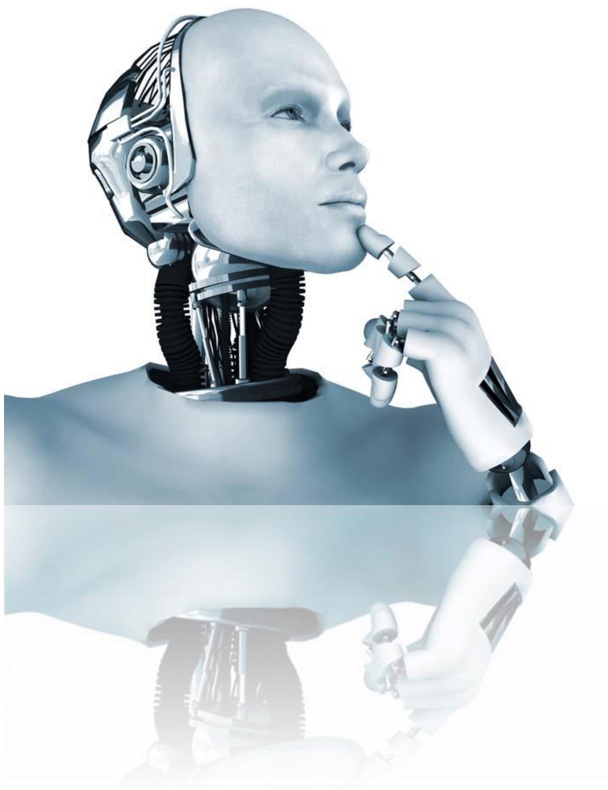
Les expériences dynamiques d'astrophysique

L'âge de la Terre

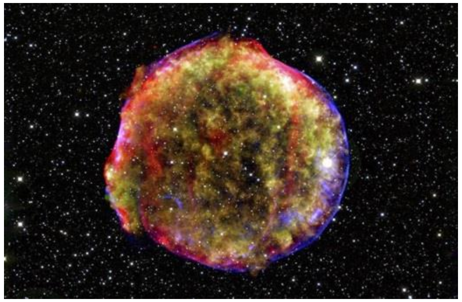
L'origine des aurores boréales



Pourquoi une astrophysique expérimentale ?



- **Mieux comprendre la physique extrême et valider nos théories par l'expérience**



- **Obtenir des quantités physiques complémentaires, voire inaccessibles, avec les télescopes**

- **Valider et compléter les simulations numériques**

L’astrophysique expérimentale : un cabinet de curiosités

D. Remps (1690)

La classification de l'astrophysique de laboratoire

Expériences statiques

Expériences dynamiques

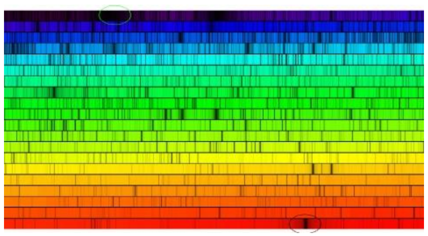
Classification d'Aristote

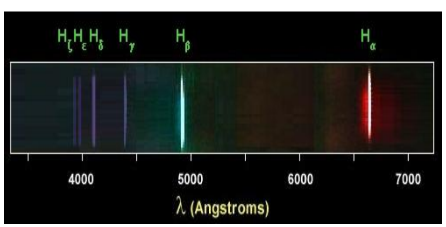
Identité

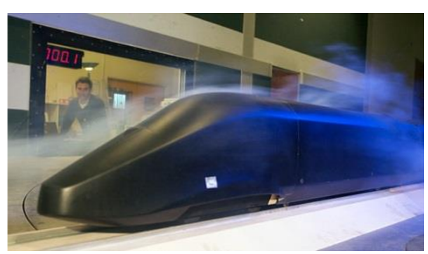
Similitude

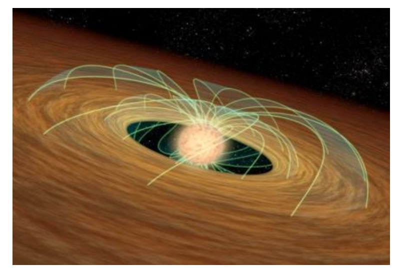
Ressemblance

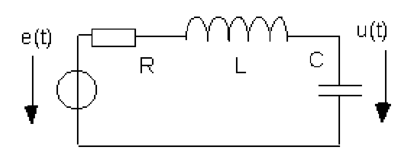
Analogie



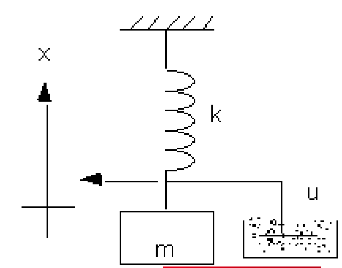






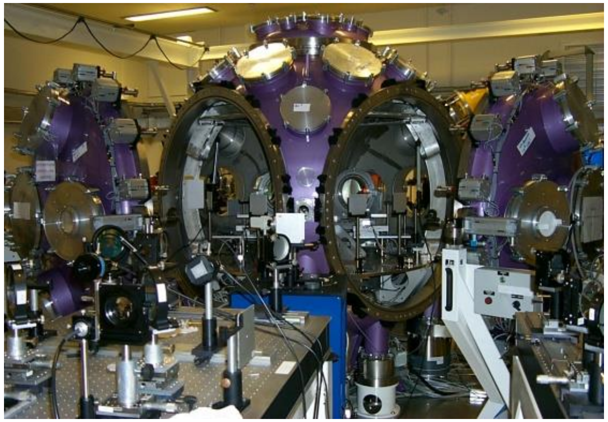


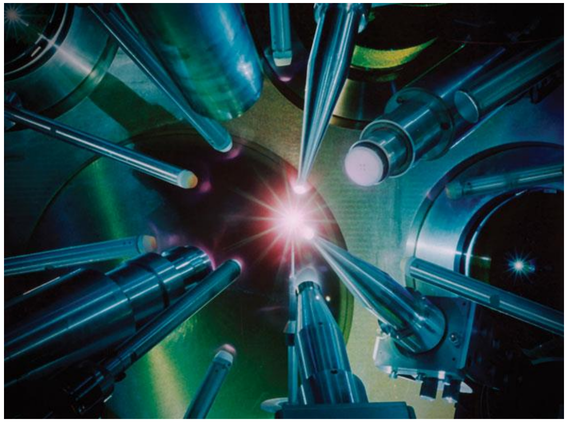
Descriptions mécaniques:

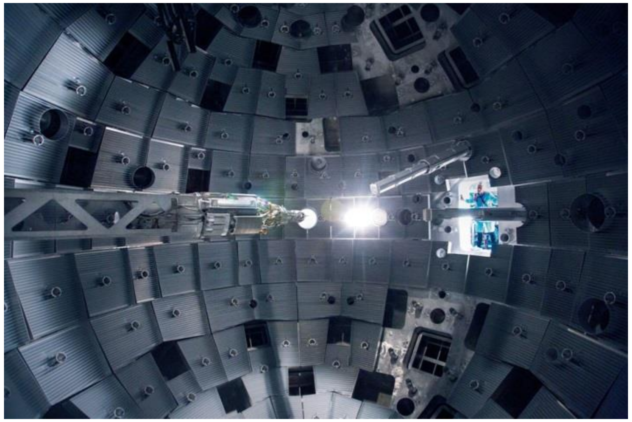


Trois grandes classes de lasers de puissance

Les lasers kJ	Les lasers multi-kJ	Les lasers Mégajoule







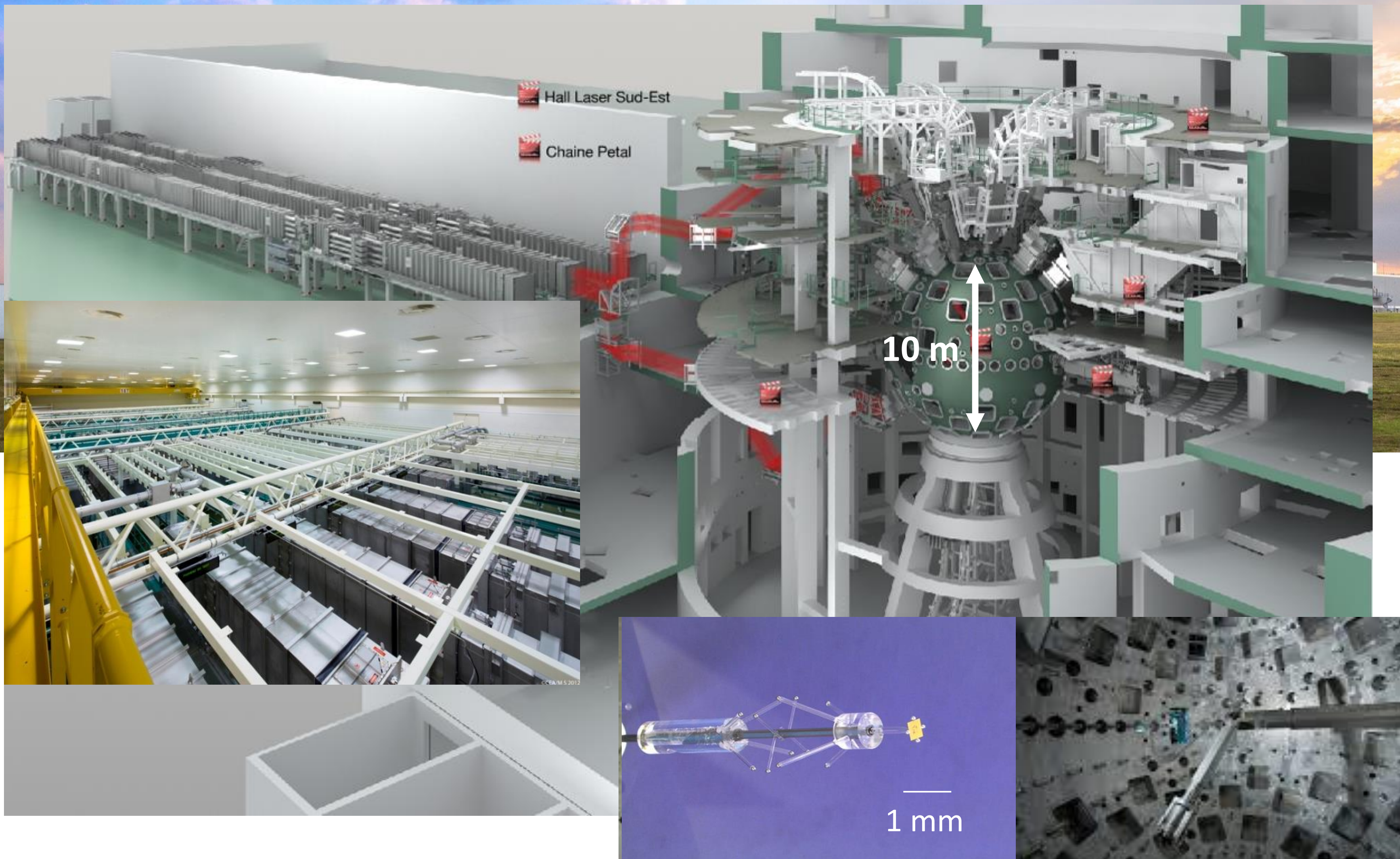
Capacité à concentrer de l'énergie dans
des **volumes millimétriques** pendant **des laps de temps très courts (~ 1ns)**

$$I_L = \frac{P_L}{\Sigma} = \frac{E_L}{\tau}\frac{1}{\Sigma} \qquad p_a = 12\left[\frac{I_L}{10^{14} W.cm^{-2}}\right]^{2/3}\left[\frac{\lambda_L}{1\mu m}\right]^{-2/3} \text{Mbars}$$

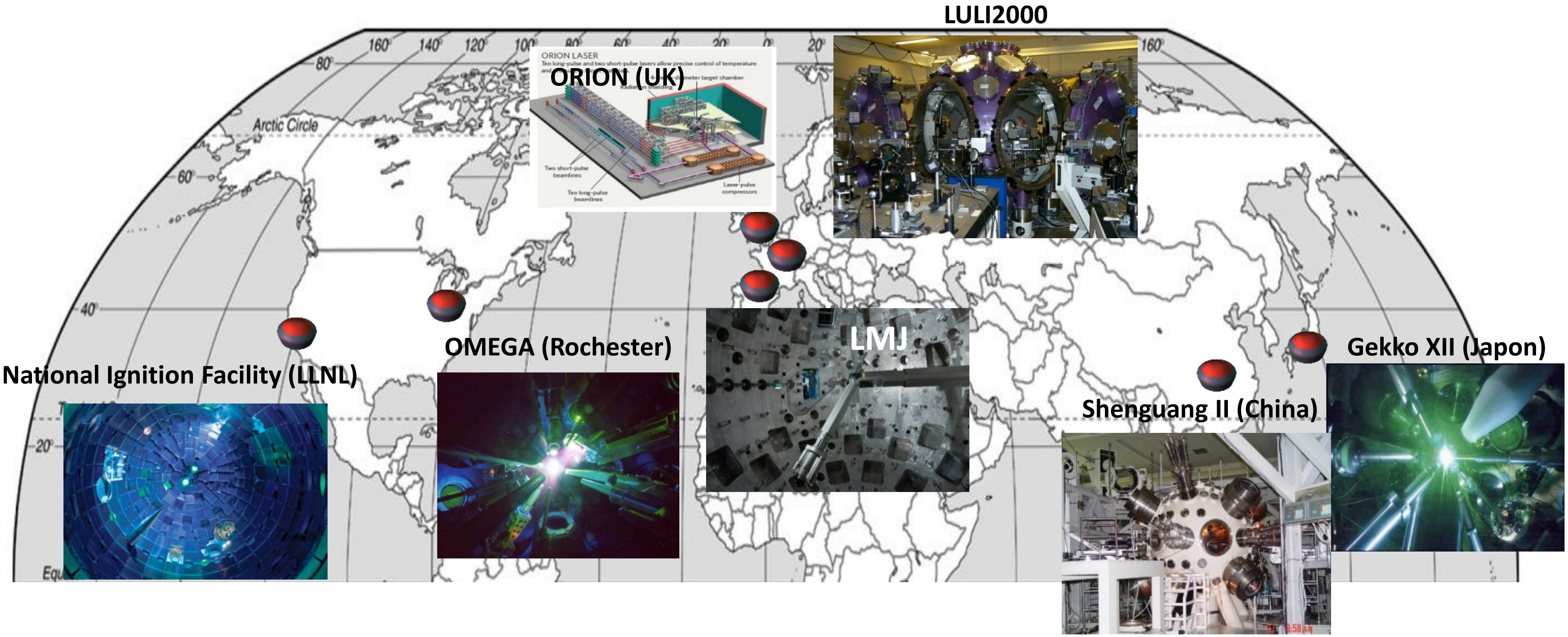
Possibilité de soumettre la matière à des conditions extrêmes
[Remington et al. (2006)]

- de pression (plusieurs GBars)
- de température (de quelques eV à plusieurs keV)
- de vitesse (de quelques km/s à plus de 1000 km/s)

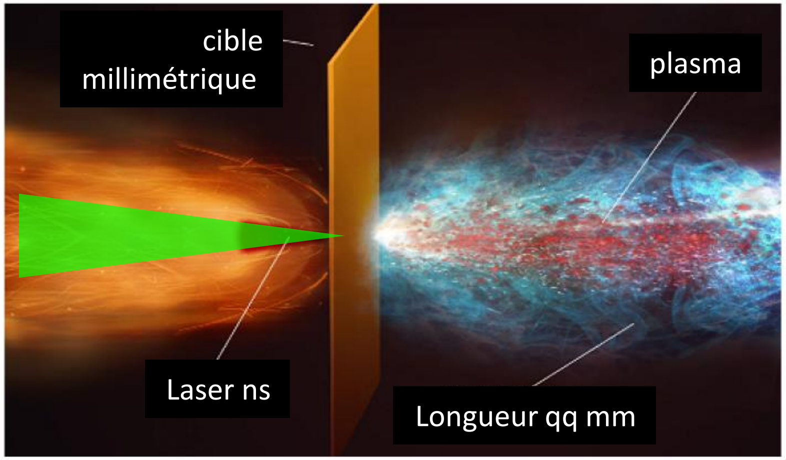
Le laser MégaJoule

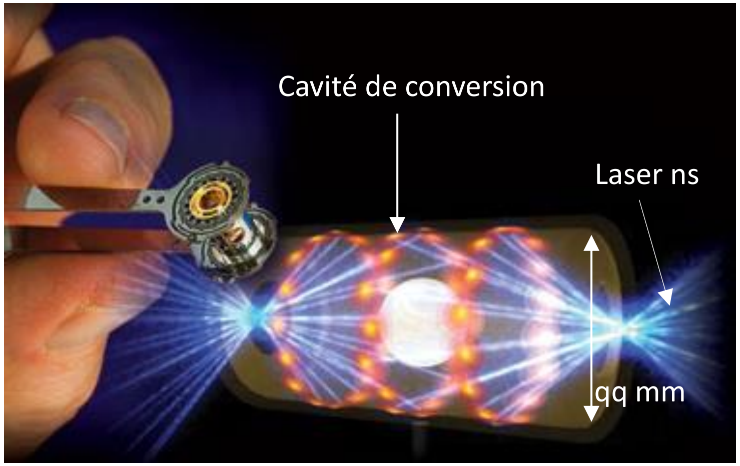


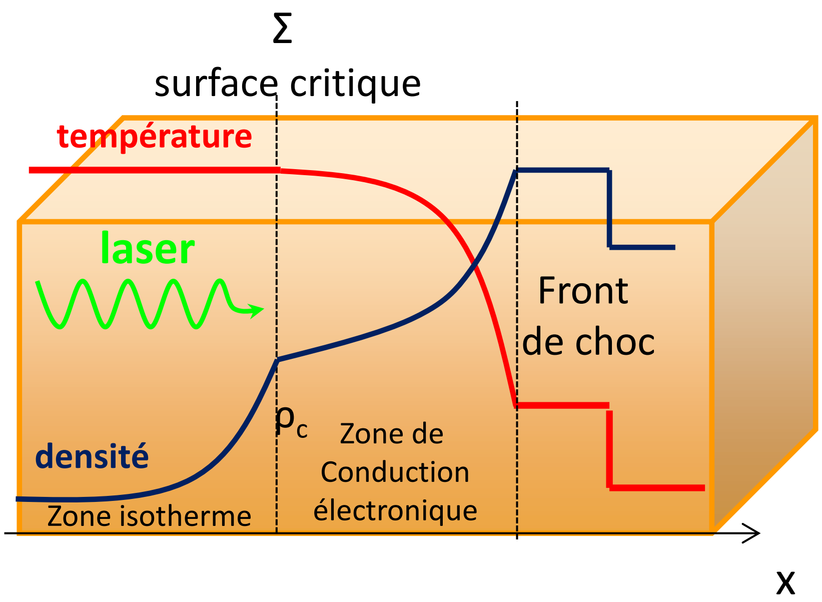
Les lasers de puissance nanoseconde dans le monde

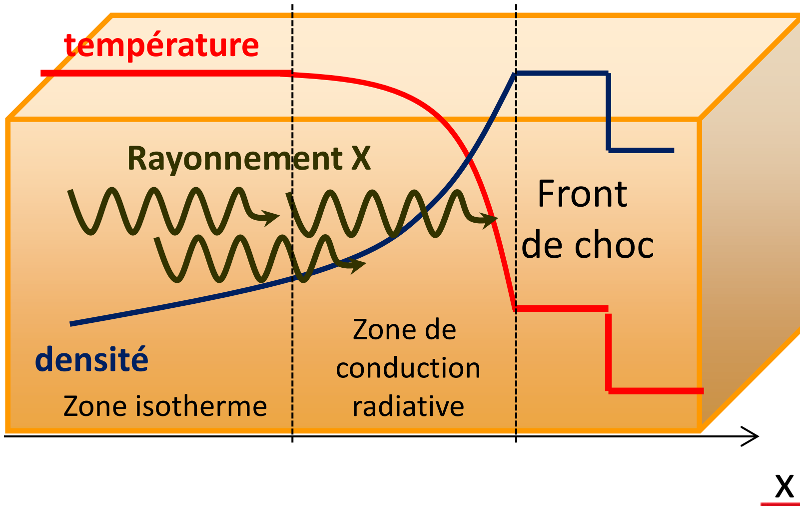


Créer des conditions extrêmes avec les lasers de puissance



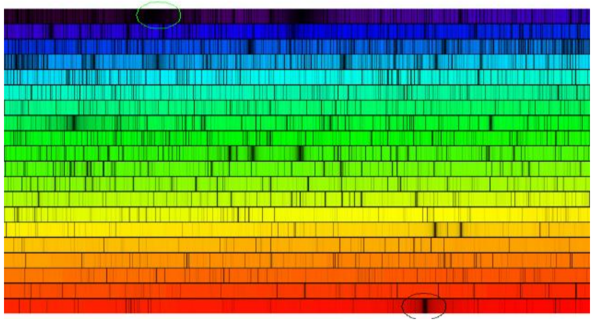




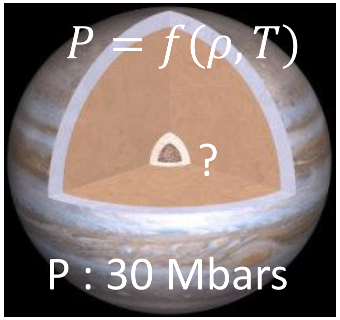


L’astrophysique et les expériences : quelques exemples

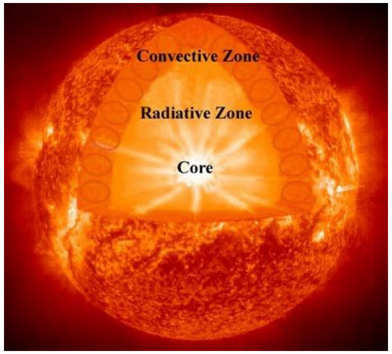
Les données spectroscopiques



Les équations d’état

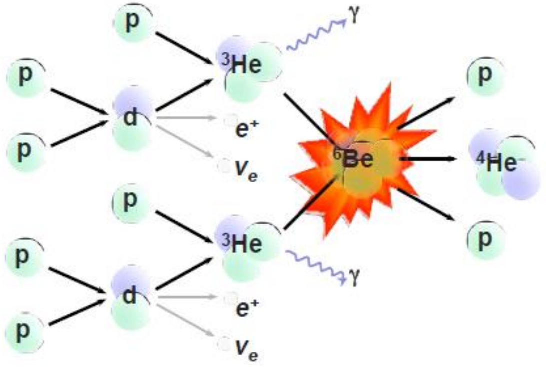


Les opacités

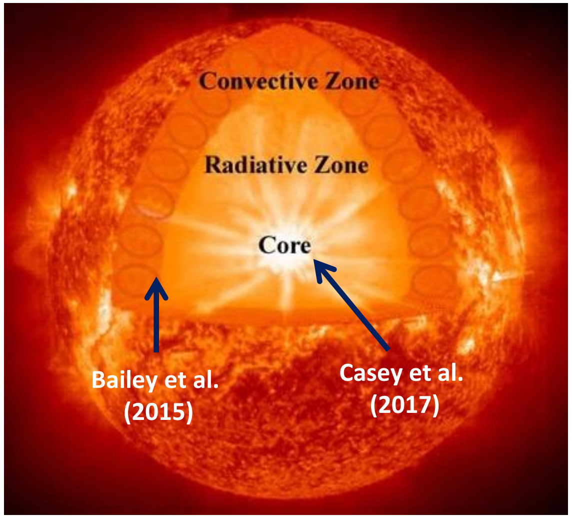


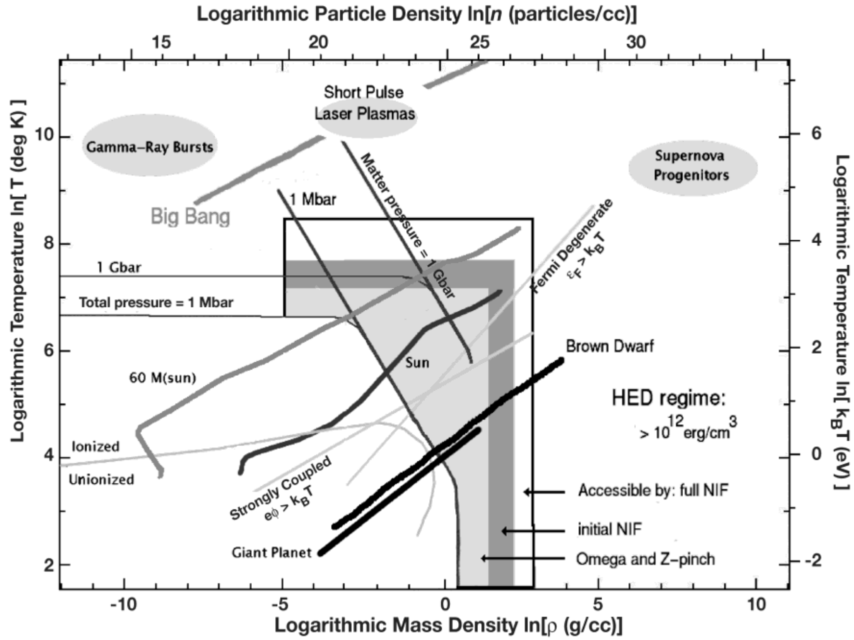
Conditions de la base
de la zone convective

Les sections efficaces nucléaires

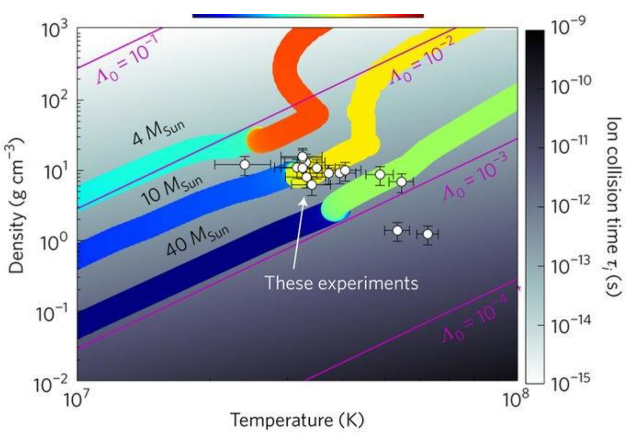


Reproduire l'intérieur des étoiles

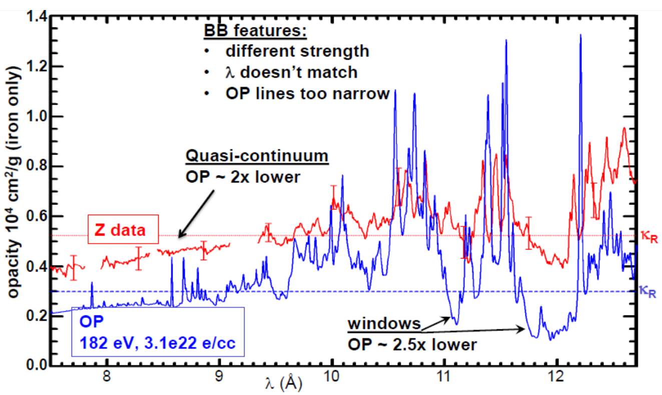




[Casey et al. Nature Phys. (2017)]



[Bailey et al. Nature (2015)]



Le principe de similitude où comment passer des environnements astrophysiques aux plasmas de laboratoire

Le théorème de Vaschy-Buckingham-Carvallo (1914)

$$F(x,t,V,rho,P,\gamma)=0 \longleftrightarrow F(St,M,rho)=0$$

Le nombre de Mach $M = \dfrac{V}{c_s}$

$$St = \frac{V\,t}{L}$$

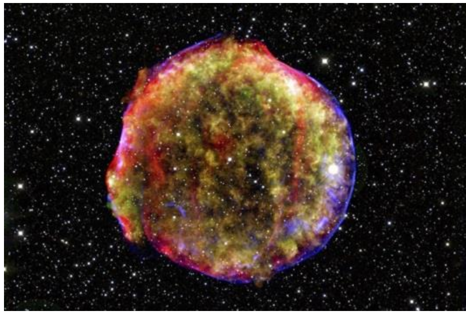
V =5000 km/s	$\longleftrightarrow$	V = 100 km/s
t = 3.15x 10^7 s		t = 10 x 10^{-9} s
L= 1.57 10^{11} km		L= 1 mm

Le principe de similitude de Tolman (1914)

Les lois de la nature sont faites de telles sorte que l'on puisse construire des univers miniatures

R. Tolman (1914)

Le principe de similitude où comment passer des environnements astrophysiques aux plasmas de laboratoire

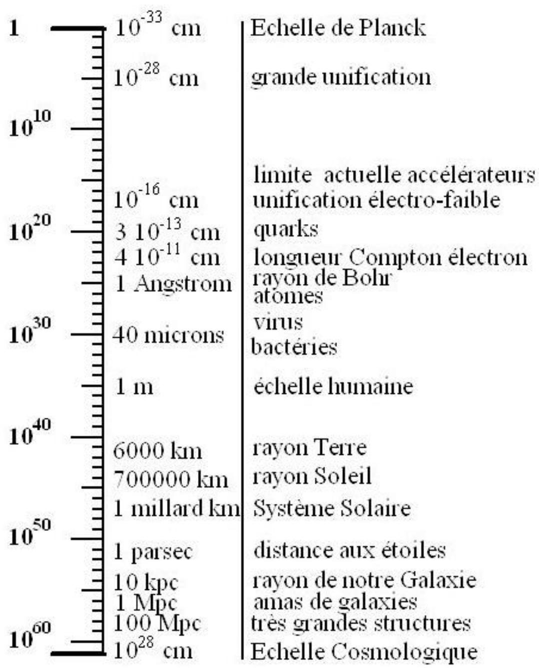


?

Existence d'une Invariance d'échelle

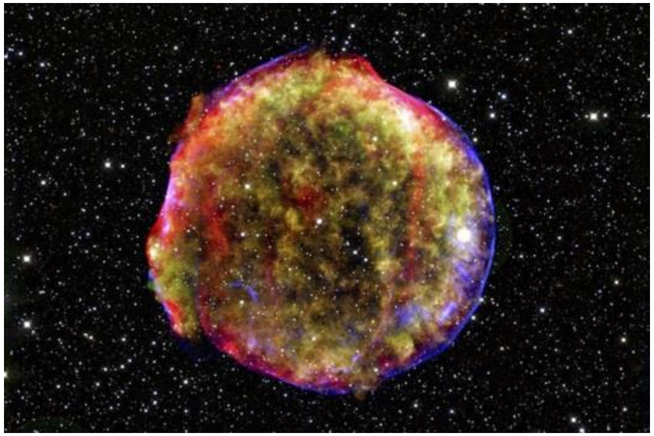
aux défauts d'échelle près …

Limite naturelle des lois de similitude



Pas d'invariance d'échelle

Les nombres sans dimension et les lois d'échelle



$$\frac{\partial \rho}{\partial t} + \boldsymbol{\nabla}.[\rho \boldsymbol{V}] = 0 \qquad \rho\left[\frac{\partial}{\partial t} + (\boldsymbol{V}.\boldsymbol{\nabla})\right]\boldsymbol{V} = -\boldsymbol{\nabla} p$$

$$\frac{\partial}{\partial t}\left[\frac{1}{2}\rho V^2 + \frac{p}{\gamma - 1}\right] + \boldsymbol{\nabla}.\left[\boldsymbol{V}\left(\frac{1}{2}\rho V^2 + \frac{\gamma p}{\gamma - 1}\right)\right] = 0$$

$$\begin{aligned} L_{astro} &= \boldsymbol{a} \times L_{labo} \\ t_{astro} &= \boldsymbol{b} \times t_{labo} \\ V_{astro} &= \boldsymbol{c} \times V_{labo} \\ \rho_{astro} &= \boldsymbol{d} \times \rho_{labo} \\ p_{astro} &= \boldsymbol{e} \times p_{labo} \\ \gamma_{astro} &= \boldsymbol{f} \times \gamma_{labo} \end{aligned}$$

$$\frac{\partial \rho}{\partial t} + \frac{\boldsymbol{cb}}{\boldsymbol{a}}\boldsymbol{\nabla}.[\rho \boldsymbol{V}] = 0 \qquad \boldsymbol{\rho}\left[\frac{\boldsymbol{a}}{\boldsymbol{bc}}\frac{\partial}{\partial t} + (\boldsymbol{V}.\boldsymbol{\nabla})\right]\boldsymbol{V} = -\frac{\boldsymbol{e}}{\boldsymbol{dc^2}}\boldsymbol{\nabla} p$$

$$\frac{\partial}{\partial t}\left[\frac{1}{2}\rho V^2 + \frac{\boldsymbol{e}}{\boldsymbol{dc^2}}\frac{p}{\boldsymbol{f}\gamma - 1}\right] + \frac{\boldsymbol{cb}}{\boldsymbol{a}}\boldsymbol{\nabla}.\left[\boldsymbol{V}\left(\frac{1}{2}\rho V^2 + \frac{\boldsymbol{e}}{\boldsymbol{dc^2}}\frac{\boldsymbol{f}\gamma p}{\boldsymbol{f}\gamma - 1}\right)\right] = 0$$

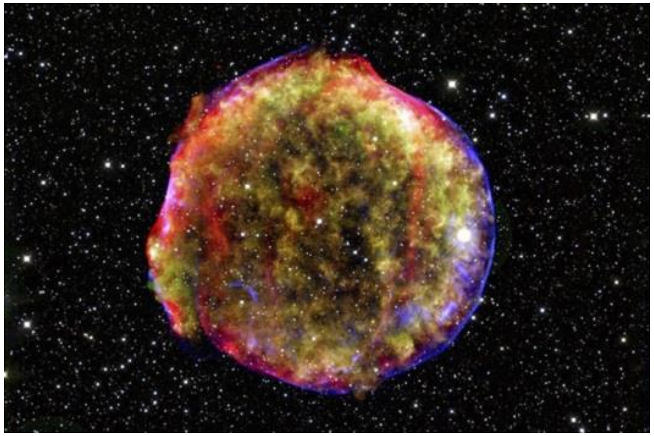
$$\frac{\boldsymbol{cb}}{\boldsymbol{a}} = 1 \qquad \frac{\boldsymbol{e}}{\boldsymbol{dc^2}} = 1 \qquad \boldsymbol{f} = 1$$

a, $\boldsymbol{d}$, $\boldsymbol{e}$ libres

$$\boldsymbol{c} = \sqrt{\frac{\boldsymbol{e}}{\boldsymbol{d}}} \qquad V_{astro} = \sqrt{\frac{\boldsymbol{e}}{\boldsymbol{d}}} \times V_{labo}$$

$$\boldsymbol{b} = \boldsymbol{a}\sqrt{\frac{\boldsymbol{d}}{\boldsymbol{e}}} \qquad t_{astro} = \boldsymbol{a}\sqrt{\frac{\boldsymbol{d}}{\boldsymbol{e}}} \times t_{labo}$$

Les nombres sans dimension et les lois d'échelle



$$L_{astro} = \boldsymbol{a} \times L_{labo}$$
$$t_{astro} = \boldsymbol{b} \times t_{labo}$$
$$V_{astro} = \boldsymbol{c} \times V_{labo}$$
$$\rho_{astro} = \boldsymbol{d} \times \rho_{labo}$$
$$p_{astro} = \boldsymbol{e} \times p_{labo}$$
$$\gamma_{astro} = \boldsymbol{f} \times \gamma_{labo}$$

$\mathbf{a}, \boldsymbol{d}, \boldsymbol{e}$ libres

$$\boldsymbol{c} = \sqrt{\frac{\boldsymbol{e}}{\boldsymbol{d}}}$$
$$\boldsymbol{b} = \boldsymbol{a}\sqrt{\frac{\boldsymbol{d}}{\boldsymbol{e}}}$$

$$\frac{\boldsymbol{cb}}{\boldsymbol{a}} = 1 \longrightarrow \frac{V_{astro}}{V_{labo}}\frac{t_{astro}}{t_{labo}}\frac{L_{labo}}{L_{astro}} = 1 \qquad \frac{t_{astro}V_{astro}}{L_{astro}} = \frac{t_{labo}V_{labo}}{L_{labo}}$$

Le nombre de Strouhal

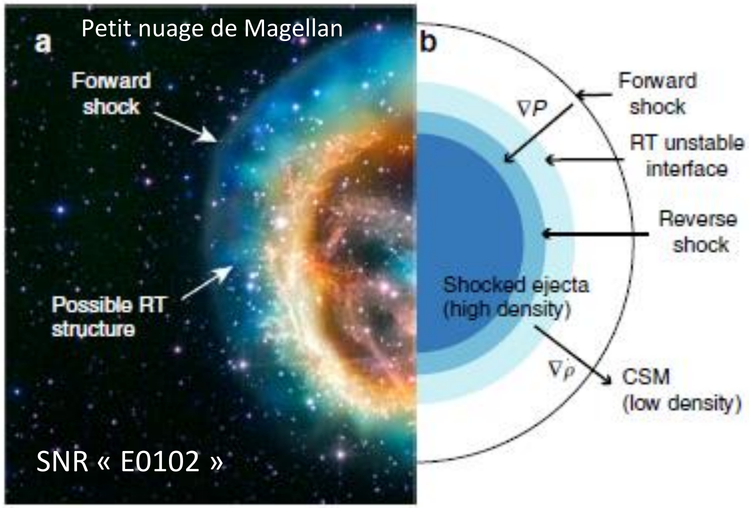
$$\frac{\boldsymbol{e}}{\boldsymbol{dc^2}} = 1 \longrightarrow \frac{p_{astro}}{\rho_{astro}\,[V_{astro}]^2} = \frac{p_{labo}}{\rho_{labo}\,[V_{labo}]^2}$$

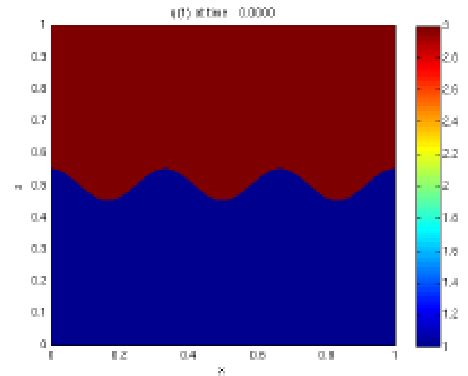
Le nombre d'Euler

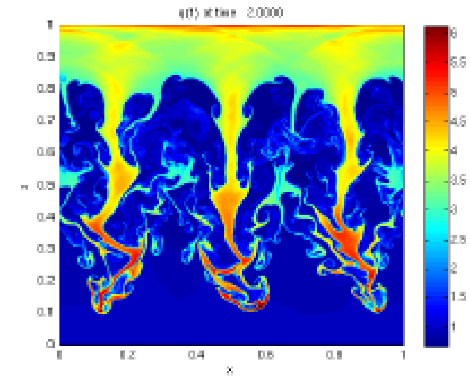
$$\boldsymbol{f} = 1 \longrightarrow \frac{\gamma_{astro}}{\gamma_{labo}} = 1 \qquad \gamma_{astro} = \gamma_{labo}$$

Conservation Indice adiabatique

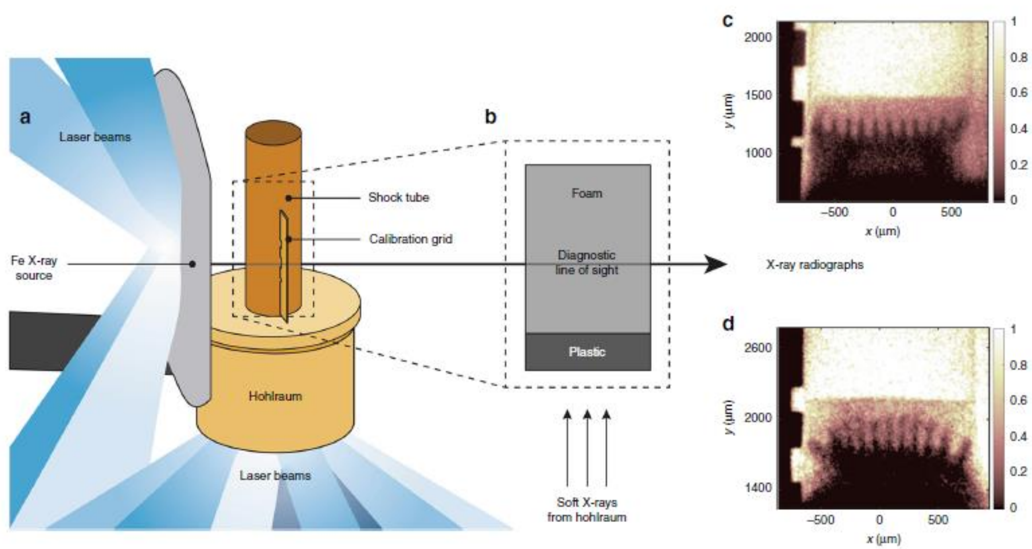
Les instabilités dans les restes de supernovae



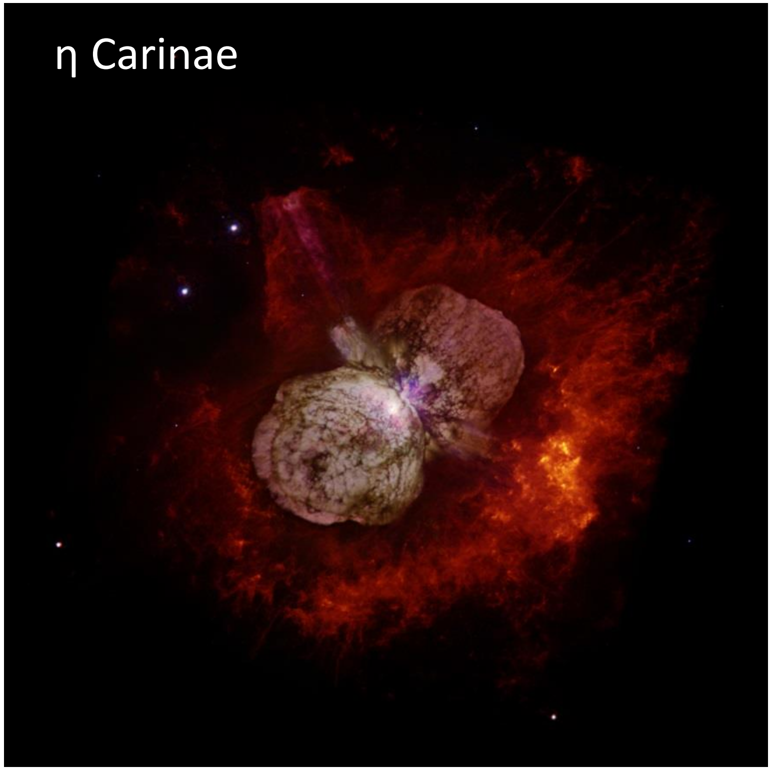


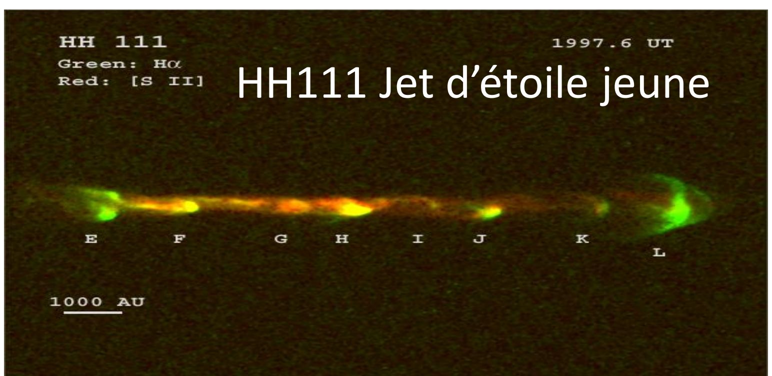


[Kuranz et al. Nature Comm. (2018)]



Les phénomènes couplant rayonnement et matière


η Carinae



HH111 Jet d'étoile jeune

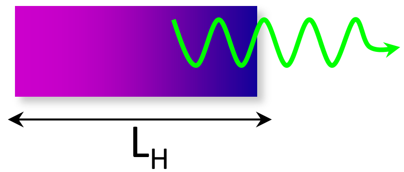

Les piliers de la création

Le rayonnement responsable de la masse limite des étoiles

- **Le Knudsen radiatif :** $Kn_{rad} = \frac{\lambda_P}{\mathrm{L_H}}$ **Couplage rayonnement-matière**

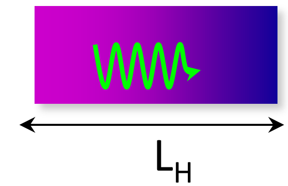
Cas optiquement mince :

$$Kn_{rad} = \frac{\lambda_P}{\mathrm{L_H}} >> 1$$



Cas optiquement épais :

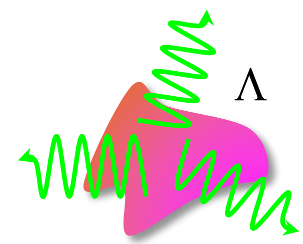
$$Kn_{rad} = \frac{\lambda_P}{\mathrm{L_H}} << 1$$



- **Le Boltzmann :** $Bo = \frac{\rho h \nu}{\mathrm{F_{rad}}} = \frac{\rho h \nu}{\sigma T^4}$ **Efficacité du rayonnement à transporter l'énergie**

- **Le Mihalas :** $R = \frac{\rho e}{\mathrm{E_{rad}}} = \frac{\rho e}{a_R T^4}$ **Contenu énergétique**

- **Le paramètre de refroidissement :** $\chi = \frac{\mathrm{t_R}}{\mathrm{t_H}} = \frac{1}{\mathrm{t_H}} \frac{P}{(\gamma - 1)\Lambda}$

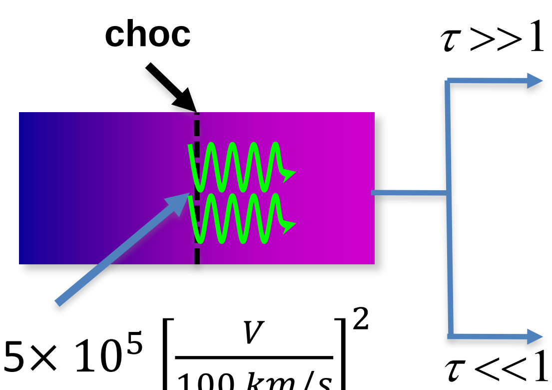


Effet des pertes radiatives sur la dynamique du plasma

Chaque régime est reproductible (théoriquement) en laboratoire !

Les lasers de puissance permettent de faire de l'hydrodynamique radiative une science expérimentale

Hydrodynamique violente → émission et absorption de rayonnement

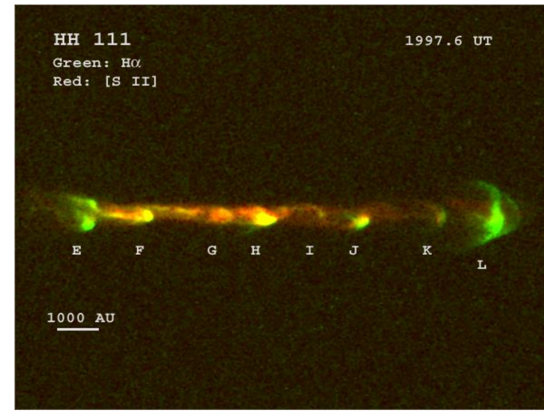


$$T_S[\mathrm{K}] = 1.5\times 10^5 \left[\frac{V}{100\ km/s}\right]^2$$

Structure complexe devant le choc formation d'un précurseur radiatif

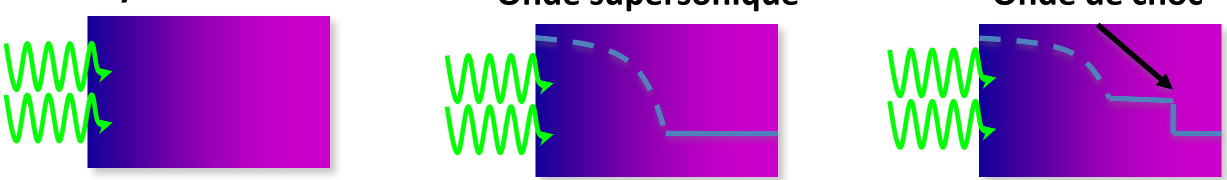
épaisseur optique $d\tau = \kappa . ds$

Émission de rayonnement = perte d'énergie

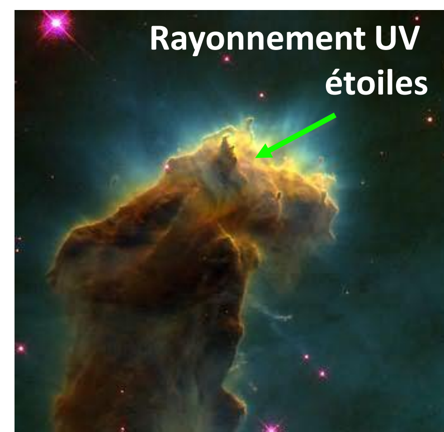


Absorption et émission de rayonnement → hydrodynamique

Rayonnement **Onde supersonique** **Onde de choc**



$$c_V \frac{\partial [T]}{\partial t} = \frac{\partial}{\partial x}\left[\kappa \frac{\partial T}{\partial x}\right] \rightarrow h_s \approx h_{s,0} t^{1/2}$$



Les chocs d’accrétion radiatifs

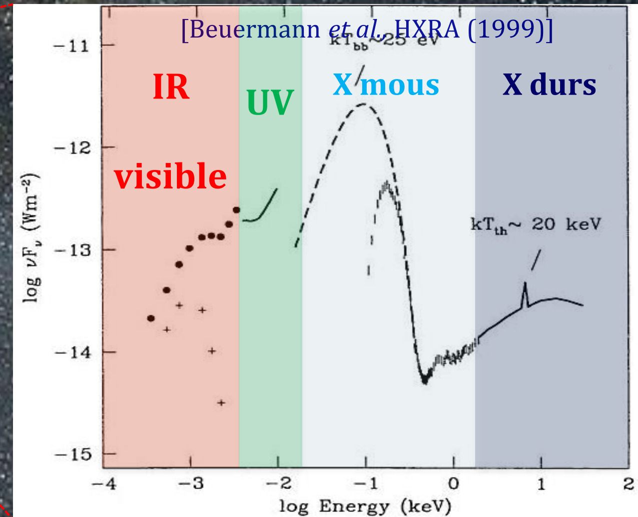
Si Dumbledore avait un laser de puissance dans sa baguette, c’est un laser de puissance avec une énergie de 1 GJ

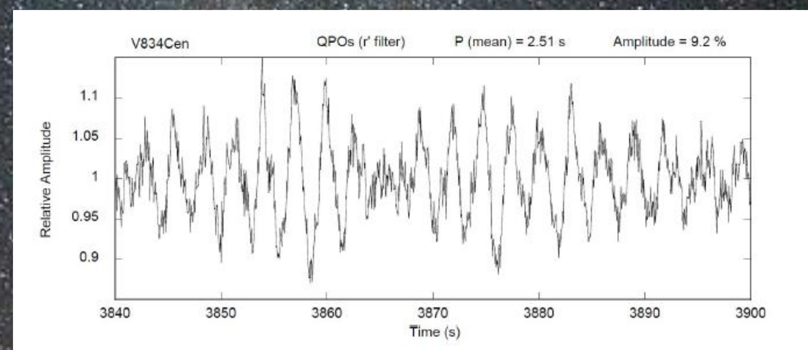
Dumbledore

Choc radiatif

On ne prononce pas son nom …

Harry Potter





[Mouchet et al. Astron. Astrophys. (2017)]

We visited the Helix Nebula!

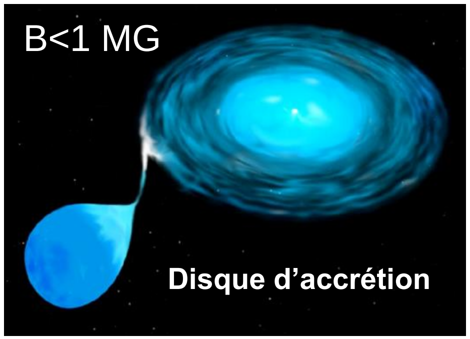
NRF National Research Foundation | SAAO South African Astronomical Observatory

Le groupe STARAcc

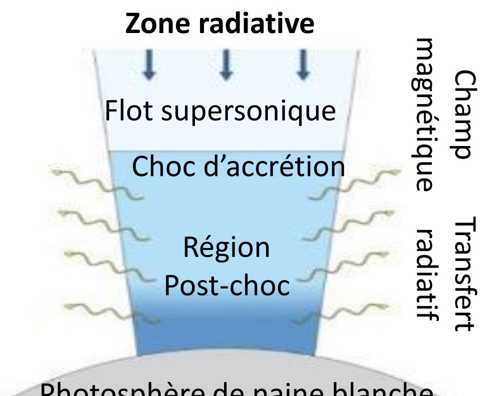
cea

Les variables cataclysmiques magnétiques : des sondes parfaites des processus d’accrétion dans un régime de hautes énergies

Les VCs non magnétiques

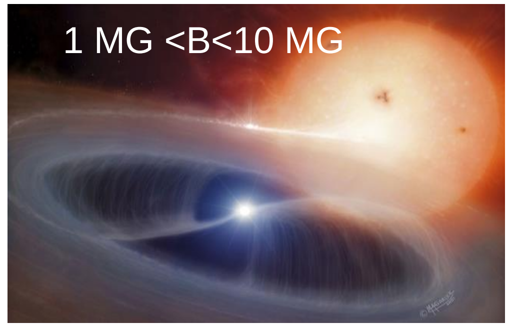


Processus d’accrétion dans un régime de hautes énergies

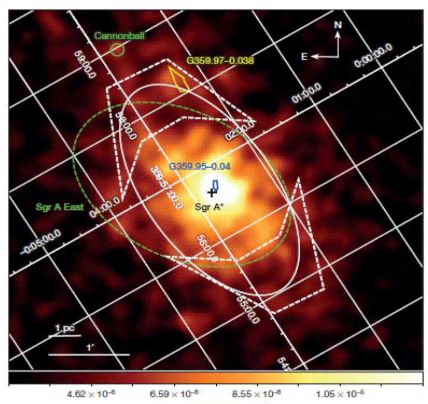


[Cropper et al. MNRAS (1990)], [Wu et al. APJ (1995)]

Les polars intermédiaires

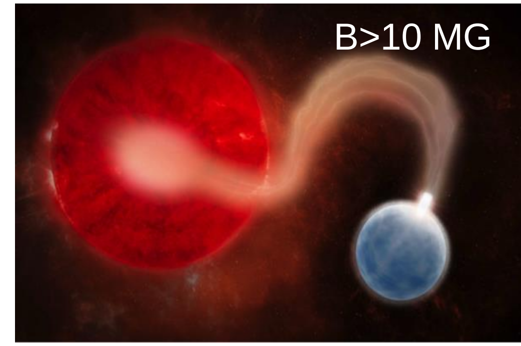


Population importante de sources X galactiques

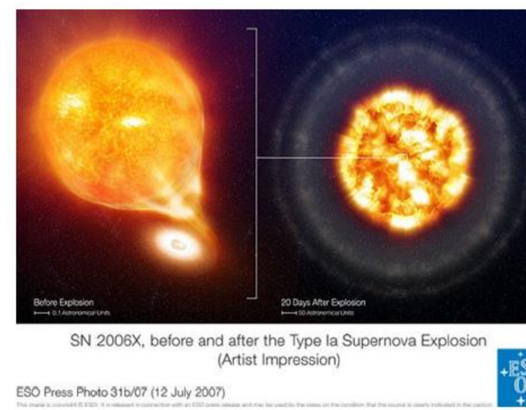


[Perez et al. Nature (2015)], [Revnivtsev et al. Nature (2009)]

Les polars

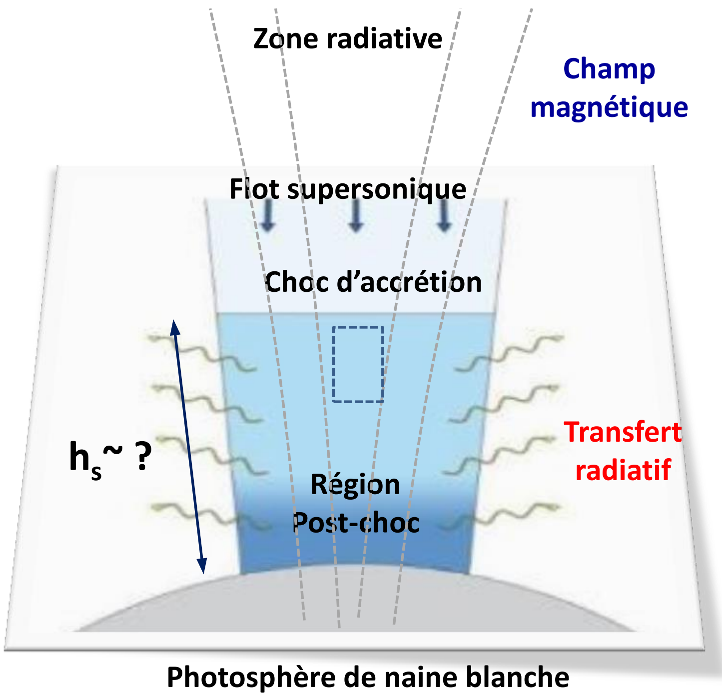


potentiels progéniteurs des supernovae de type Ia



[Wheeler ApJ (2012)], [Maoz et al. ARAA (2014)]

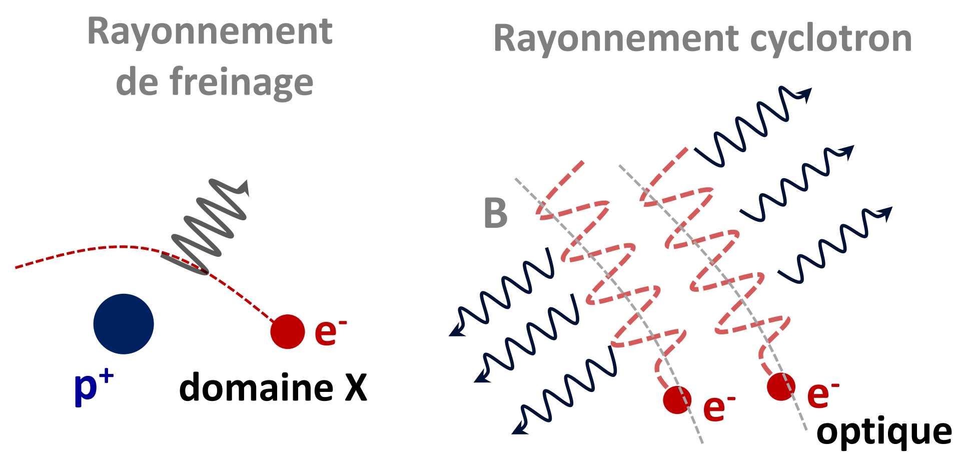
Reproduire l'accrétion dans les variables cataclysmiques magnétiques



Formation d'une onde de choc

$$T_s \approx 10 \left[\frac{V_f}{1000\ \mathrm{km/s}}\right]^2 \mathrm{MK}$$

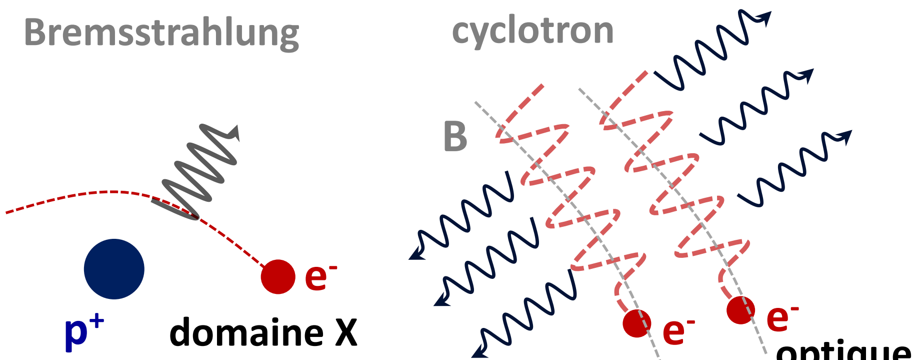
Les processus de rayonnement



t_{brem} ~ 0.1 s -1 s

t_{cycl} ~ 0.1 s -1 min

Reproduire l'accrétion dans les variables cataclysmiques magnétiques



t_{brem} ~ 0.1 s -1 s

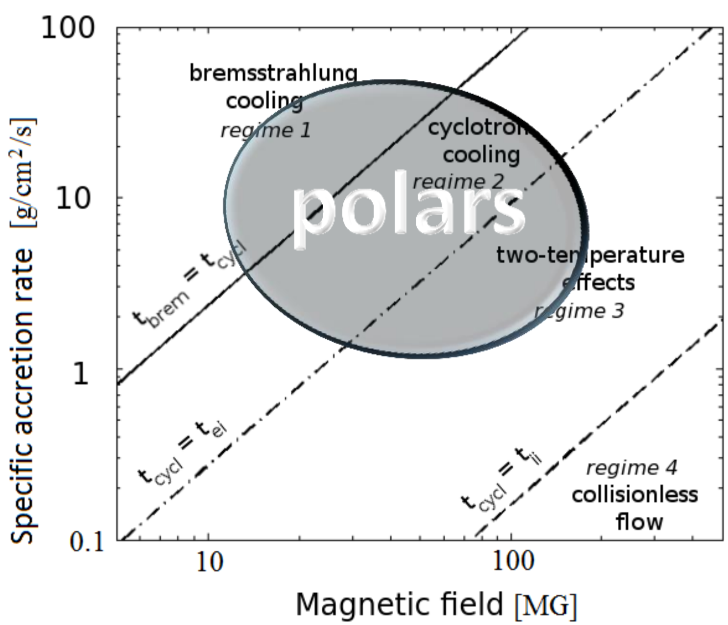
t_{cycl} ~ 0.1 s -1 min

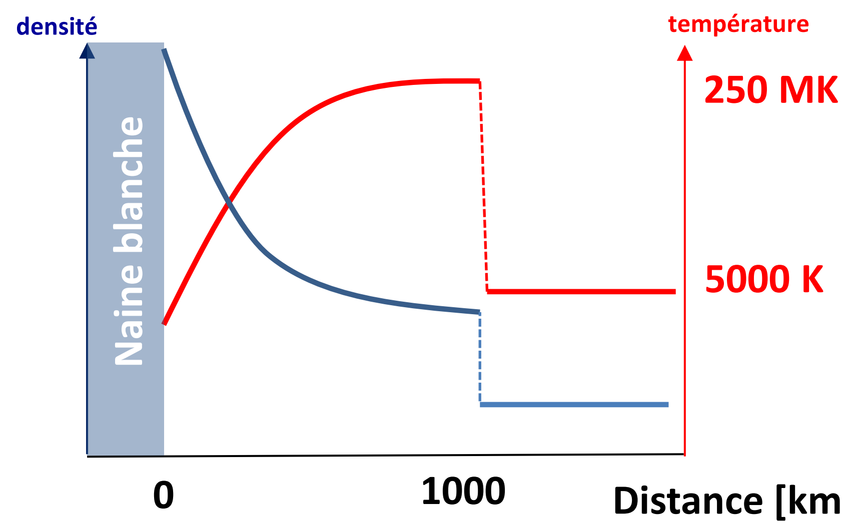
Altitude du choc

$$h_s \approx \frac{1}{4} V_f \times t_{ref}$$

$$h_s \approx 100 - 1000 \text{ km}$$

Inaccessible aux télescopes actuels



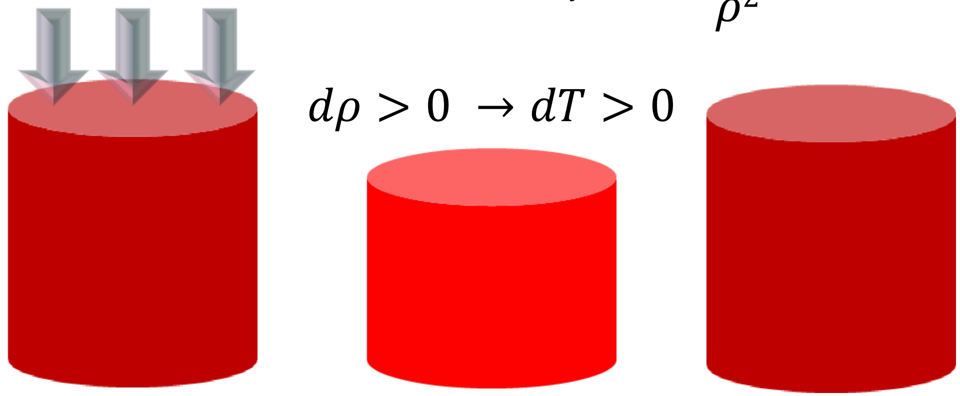


L'origine des oscillations de la courbe de lumière

Cas adiabatique

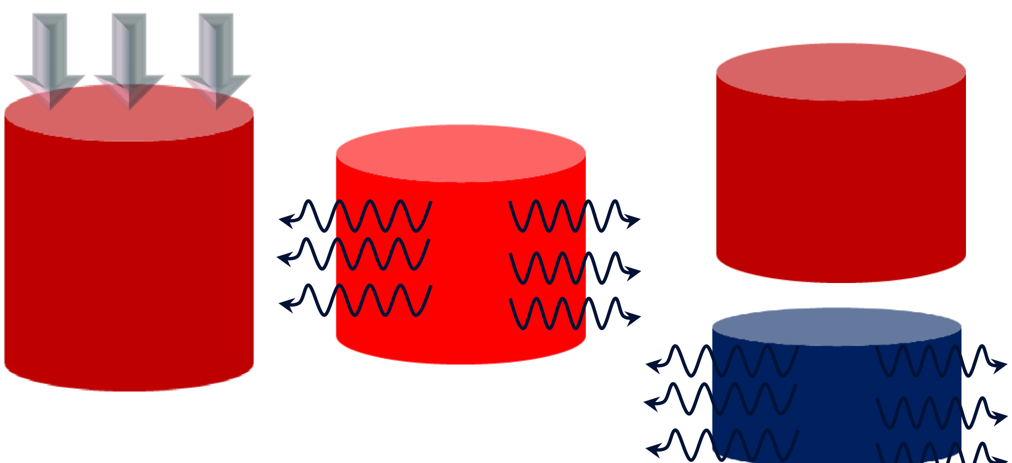
$$de = -pdV \qquad c_v\, dT = \frac{p}{\rho^2}\, d\rho$$

$$d\rho > 0 \ \rightarrow dT > 0$$



Cas radiatif

$$de = -pdV + \delta Q = -pdV \ - [\Lambda(\rho, T)/\rho]\ \mathrm{dt}$$

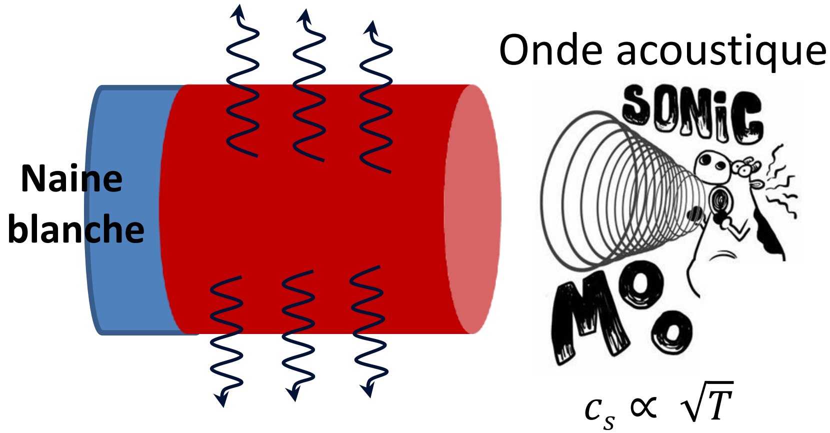


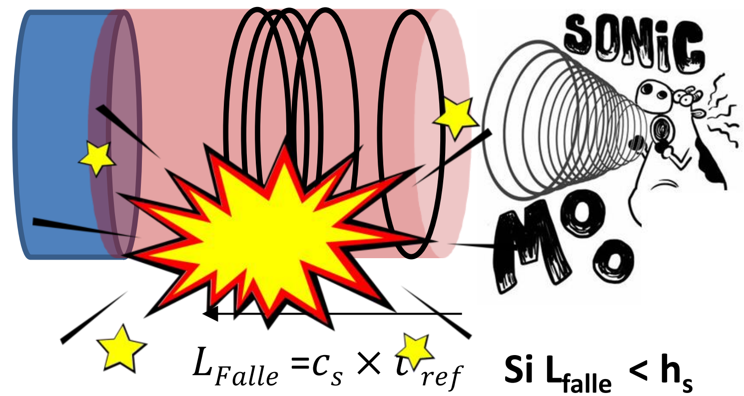
Cas du cyclotron

Cas du rayonnement bremsstrahlung

Instabilité de refroidissement

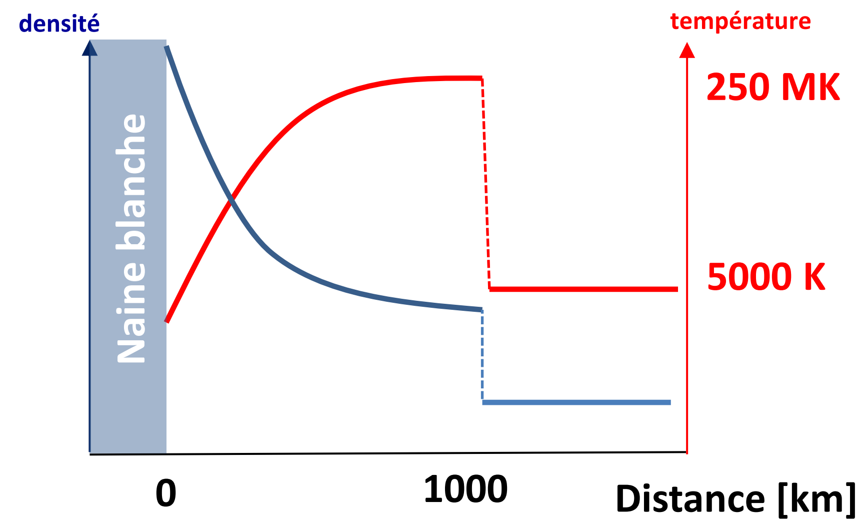
L'origine des oscillations de la courbe de lumière





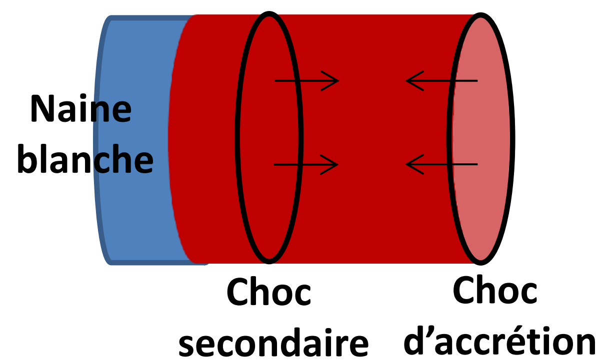
Si $L_{falle} < h_s$

Horizon acoustique

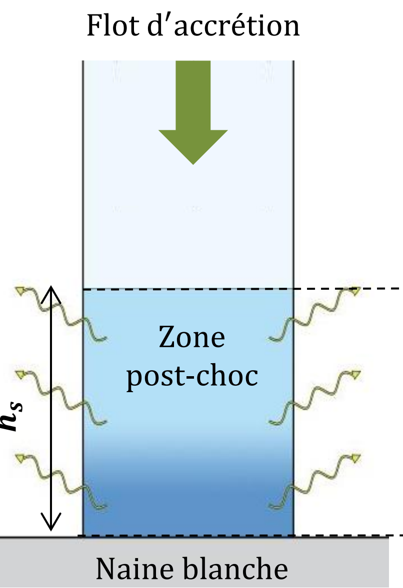


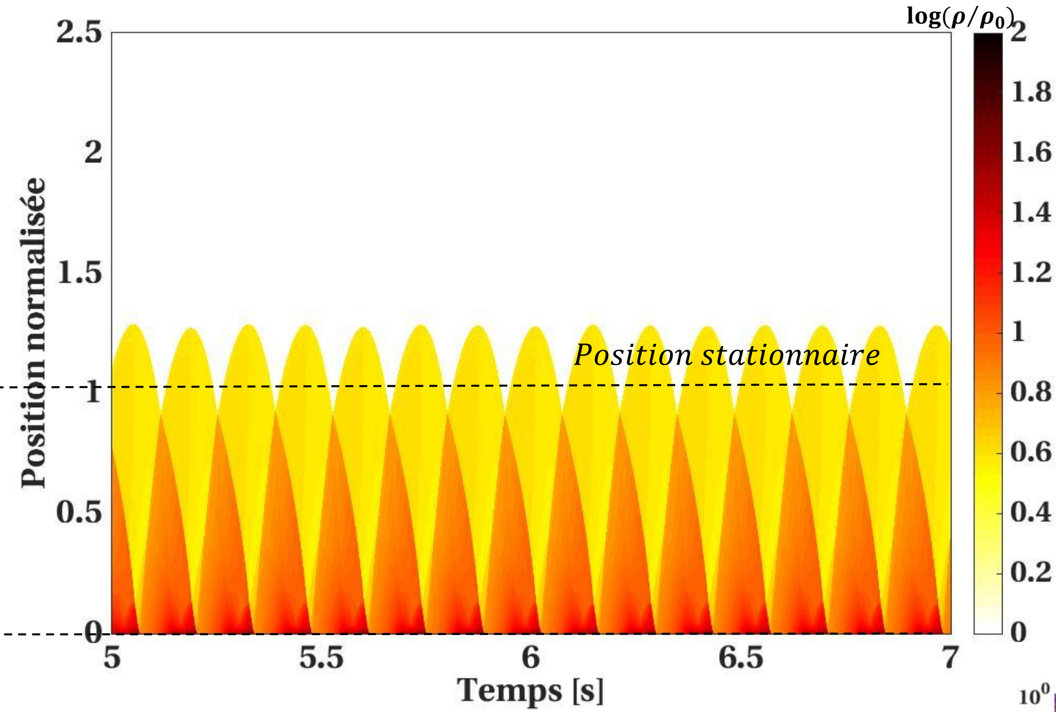
Le plasma redevient supersonique
Création d'un choc secondaire !

Cas du rayonnement bremsstrahlung



Reproduire l'accrétion dans les variables cataclysmiques

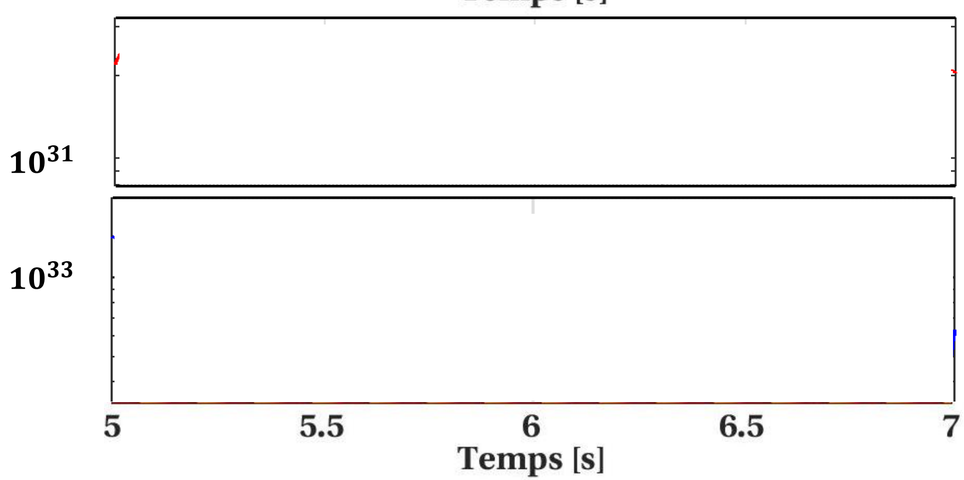




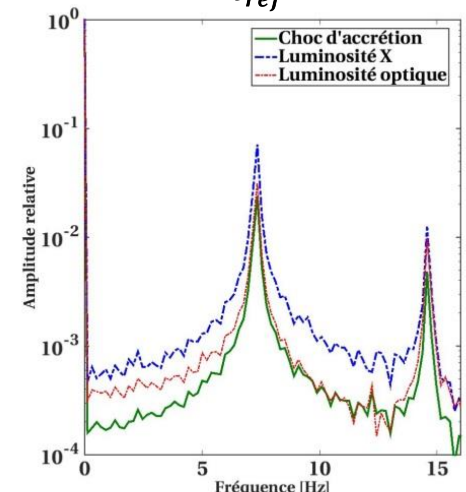
Simulation L. Van Box Som

Luminosité optique

Luminosité X

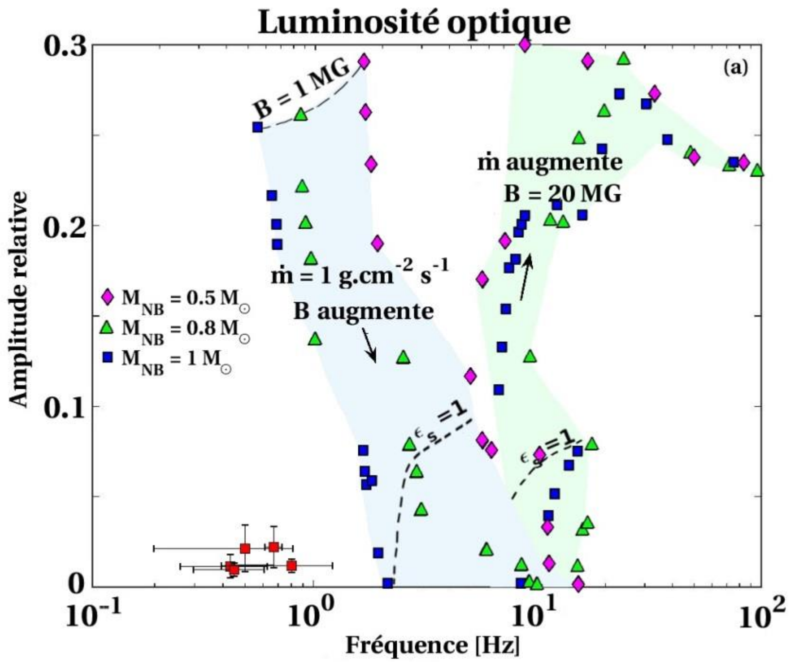


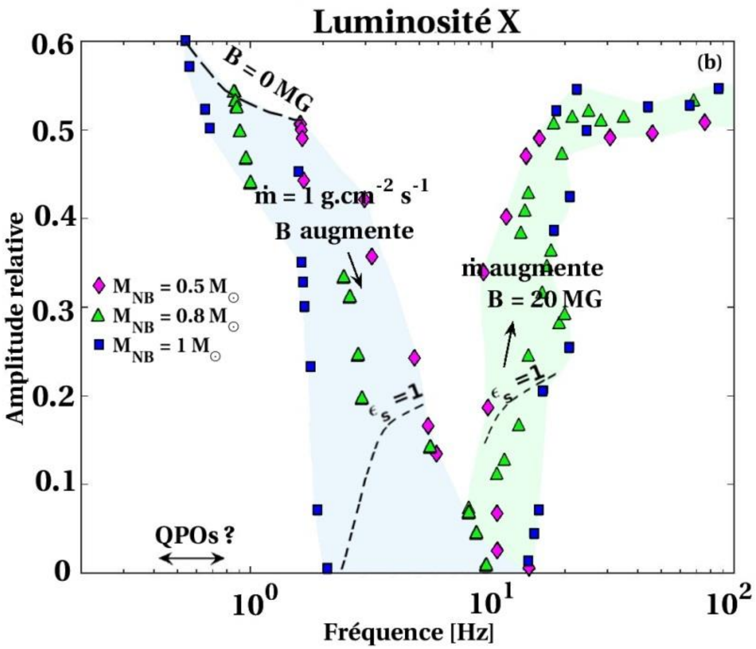
$$f \sim \frac{1}{t_{ref}} \simeq 8 \text{ Hz}$$



Observation 0.5-1 Hz

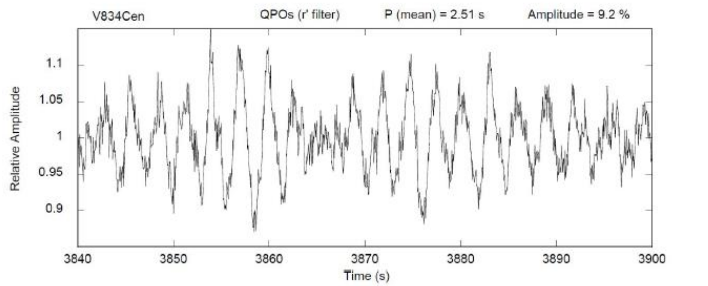
Reproduire l'accrétion dans les variables cataclysmiques magnétiques



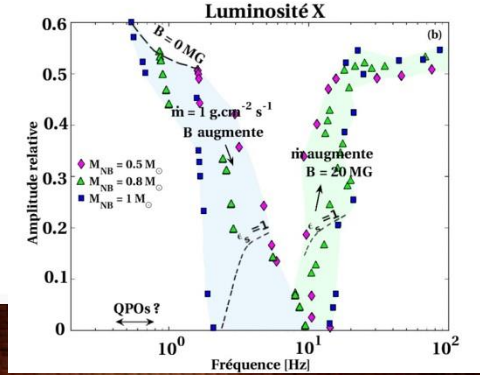


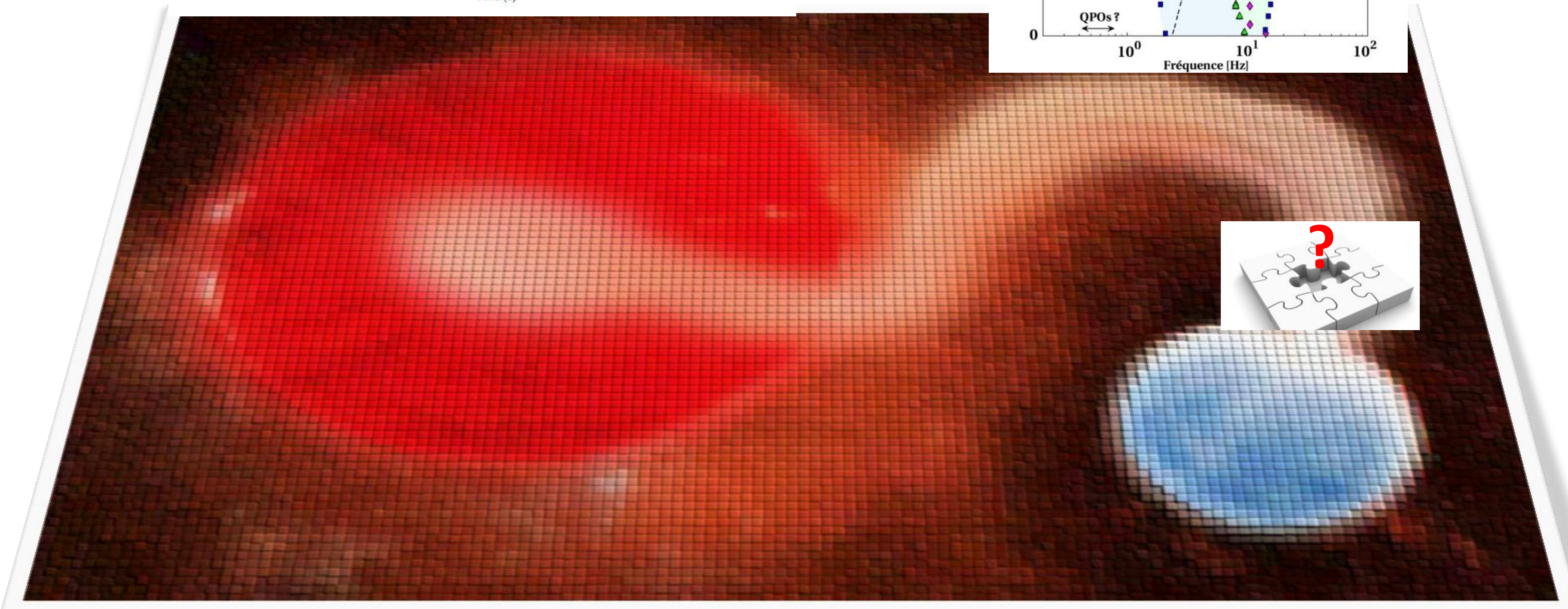
Les variables cataclysmiques magnétiques

Origines des oscillations quasi-périodiques ?

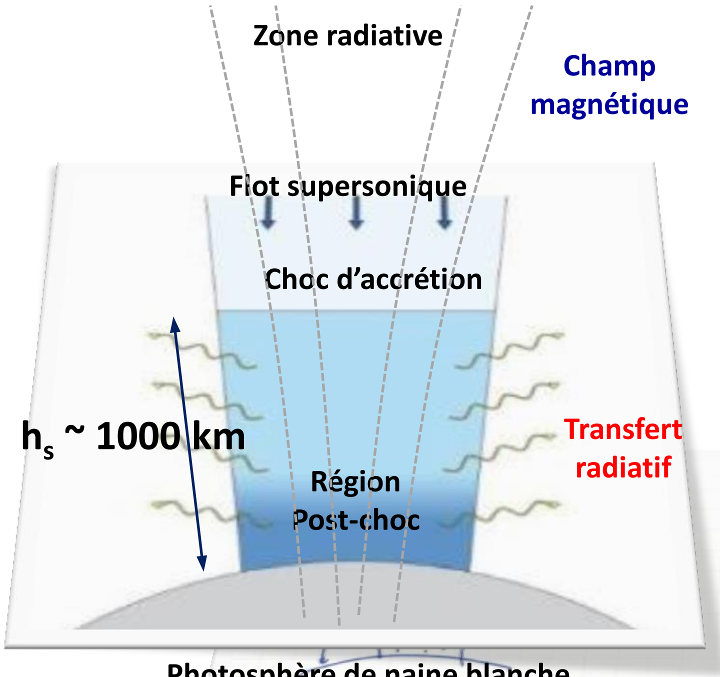


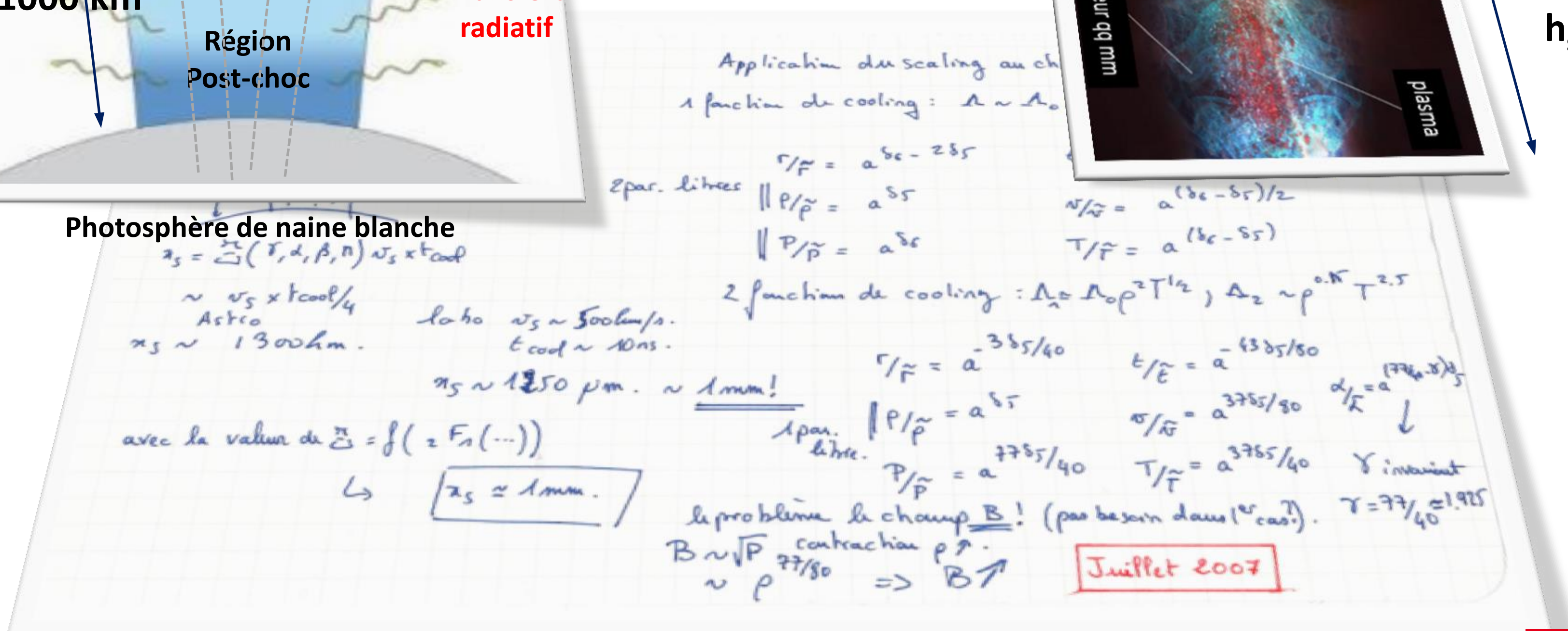
Pourquoi pas de QPO dans le domaine X ?

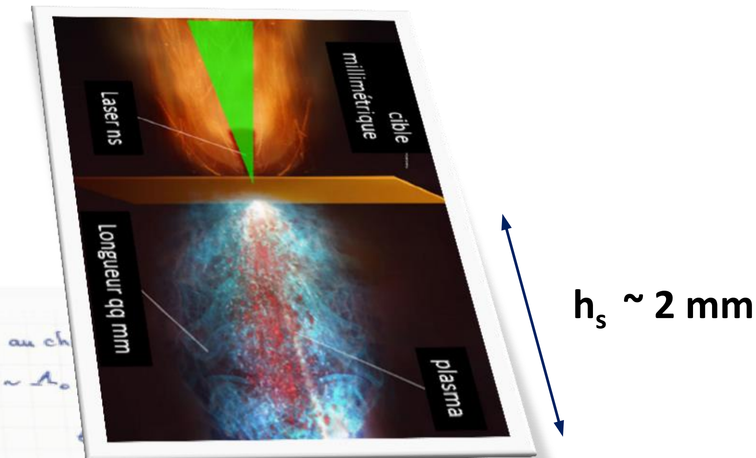




Reproduire l'accrétion dans les variables cataclysmiques magnétiques







Utiliser les lasers de puissance comme des microscopes pour l’astrophysique

Les lois d'échelle des colonnes d'accrétion

Propriétés de similarité de la région de hautes énergies

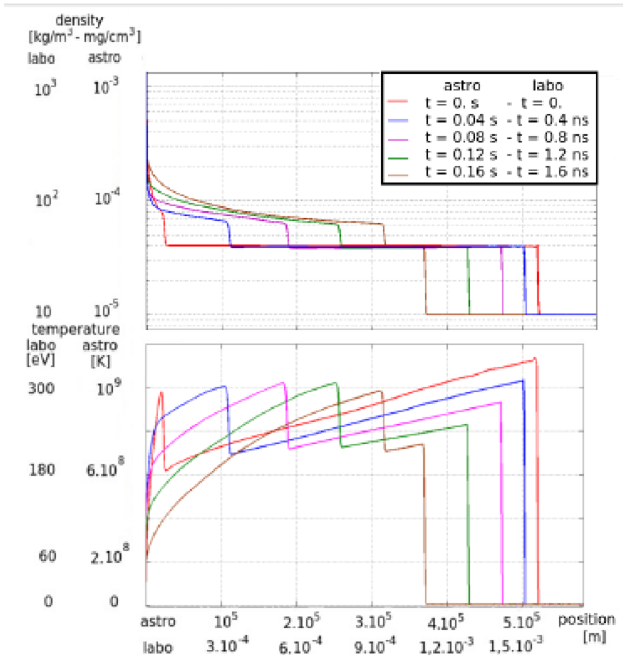
[Falize et al. ApJ, 730, 96 (2011)], [Busschaert et al. NJP 15, 035020 (2013)]

$$\rho_A/\rho_L = a \qquad L_A/L_L = b/a^2 \qquad v_A/v_L = \sqrt{b/a}$$

$$P_A/P_L = b \qquad t_A/t_L = \sqrt{b/a^3} \qquad T_A/T_L = b/a$$

Application des lois d'échelle

	L (cm)	t(s)	V(cm/s)	ρ (g/cc)	T (eV)	B (MG)
Polar	10^7	1	3×10^8	10^{-8}	10^4	10
Labo	0.1	10^{-8}	3×10^7	10^{-2}	120	625



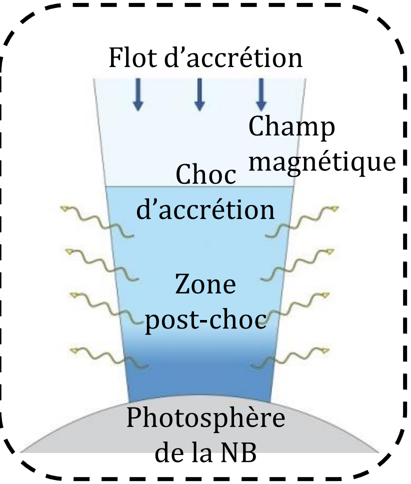
Refroidissement dans la zone post-choc

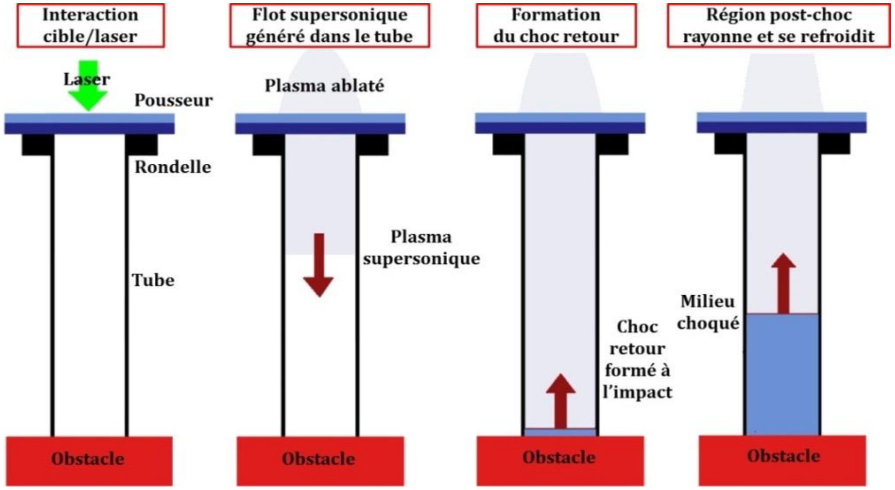
$$\boxed{h_s \approx v_S \times t_{cool}/4} \rightarrow \begin{array}{l} v_S \approx 300\,\mathrm{km.s^{-1}} \\ t_{cool} \approx 10\,\mathrm{ns} \end{array} \rightarrow h_S \approx 800\,\mu\mathrm{m}$$

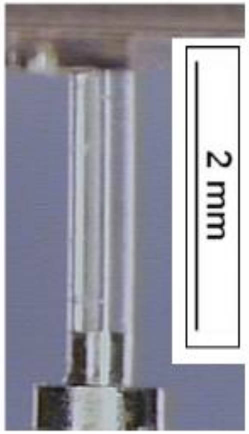
Des lois d'échelle adaptées peuvent être utilisées afin de définir des colonnes d'accrétion à des échelles diagnosticables en laboratoire

Les variables cataclysmiques magnétiques

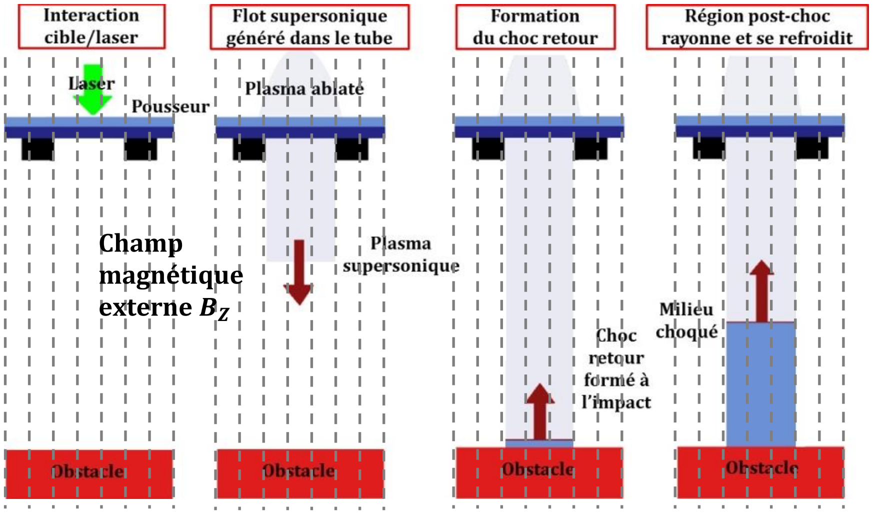
Cible avec tube :

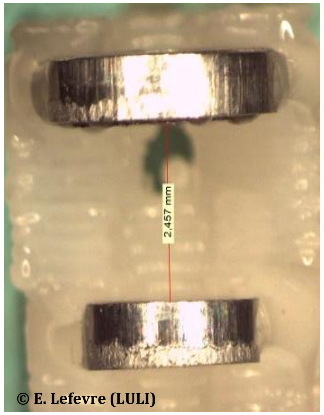






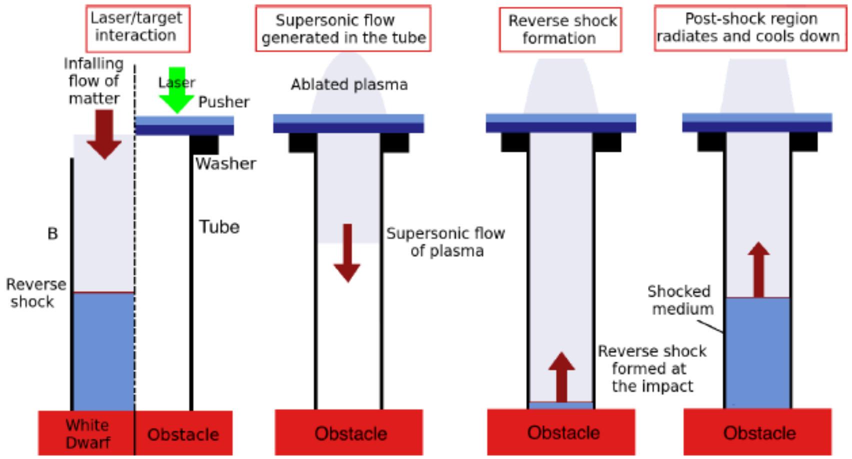
Cible avec champ magnétique :

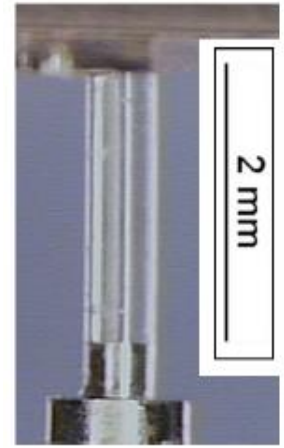


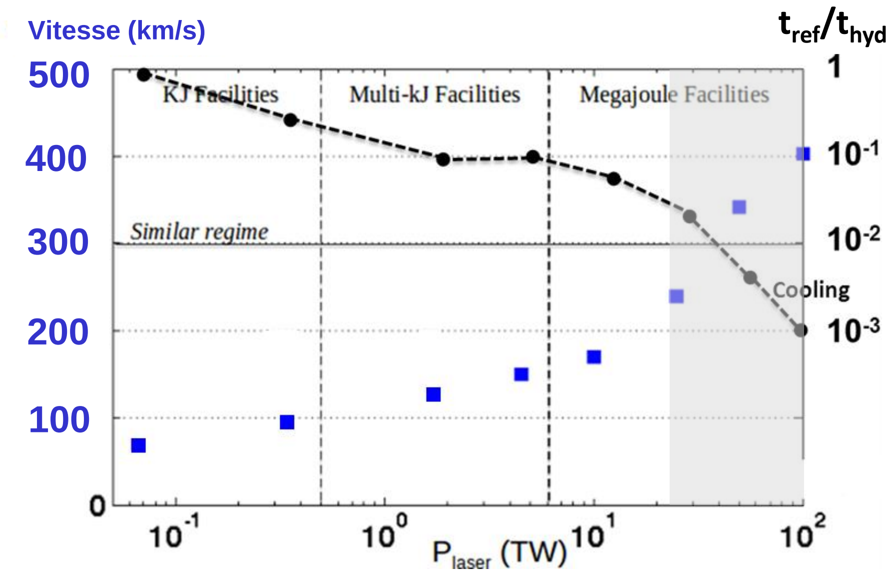


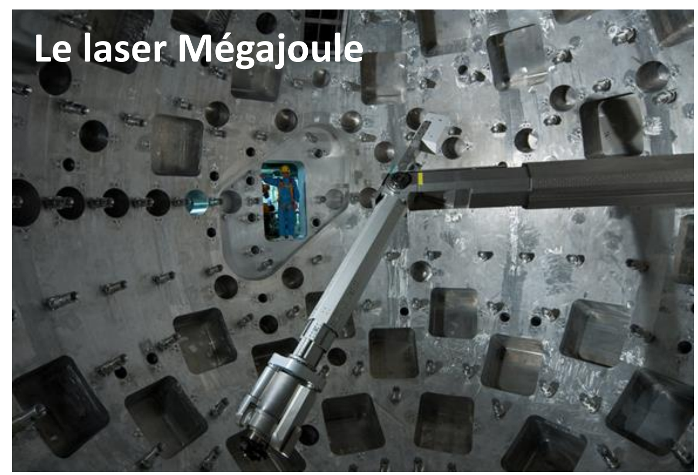
[Albertazzi et al., HPLSE (2018)]

les lasers de puissance : microscopes de l'astrophysique

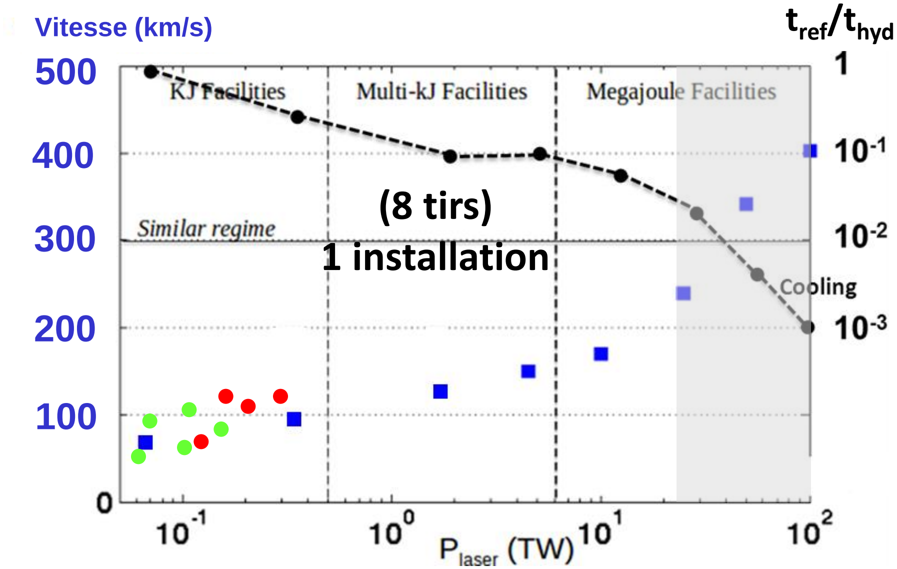


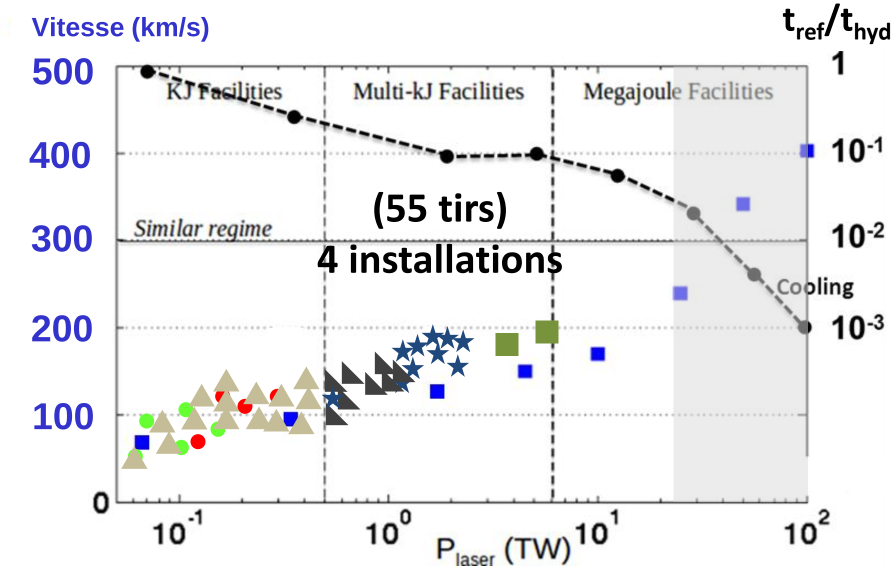






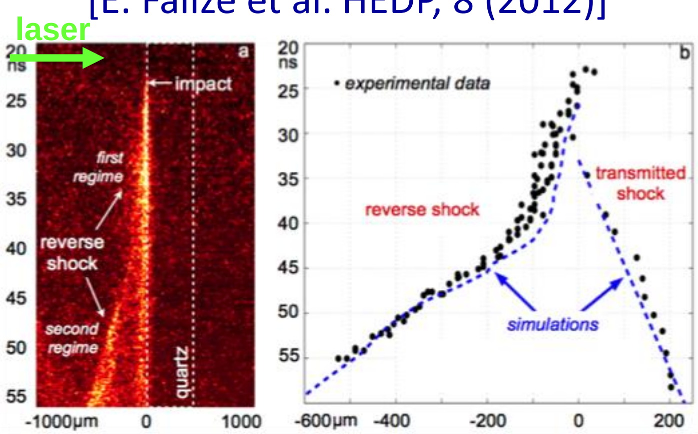
les lasers de puissance : microscopes de l'astrophysique





Expérience LULI2000

[E. Falize et al. HEDP, 8 (2012)]



les lasers de puissance : microscopes de l’astrophysique

nature COMMUNICATIONS

ARTICLE

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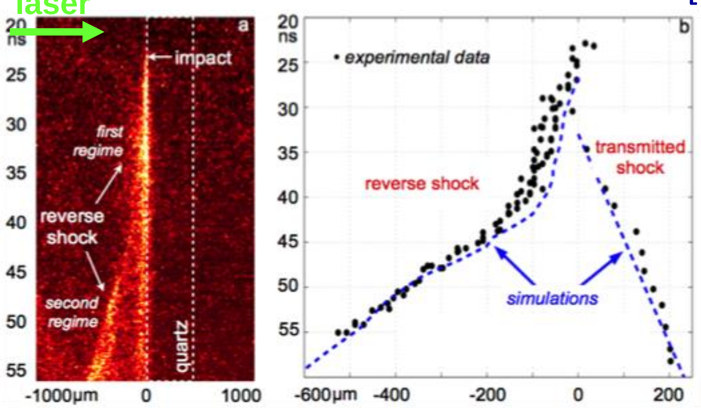
Laboratory analogue of a supersonic accretion column in a binary star system

J.E. Cross[1], G. Gregori[1], J.M. Foster[1,2], P. Graham[2], J.-M. Bonnet-Bidaud[3], C. Busschaert[4], N. Charpentier[4], C.N. Danson[1,2], H.W. Doyle[1,5], R.P. Drake[6], J. Fyrth[2], E.T. Gumbrell[2], M. Koenig[7,8], C. Krauland[6], C.C. Kuranz[6], B. Loupias[4], C. Michaut[9], M. Mouchet[9], S. Patankar[2], J. Skidmore[2], C. Spindloe[10], E.R. Tubman[11], N. Woolsey[11], R. Yurchak[7] & É. Falize[3,4]

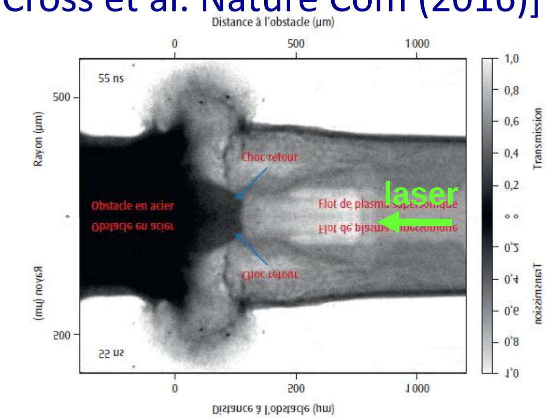
Expérience LULI2000

[E. Falize et al. HEDP, 8 (2012)]

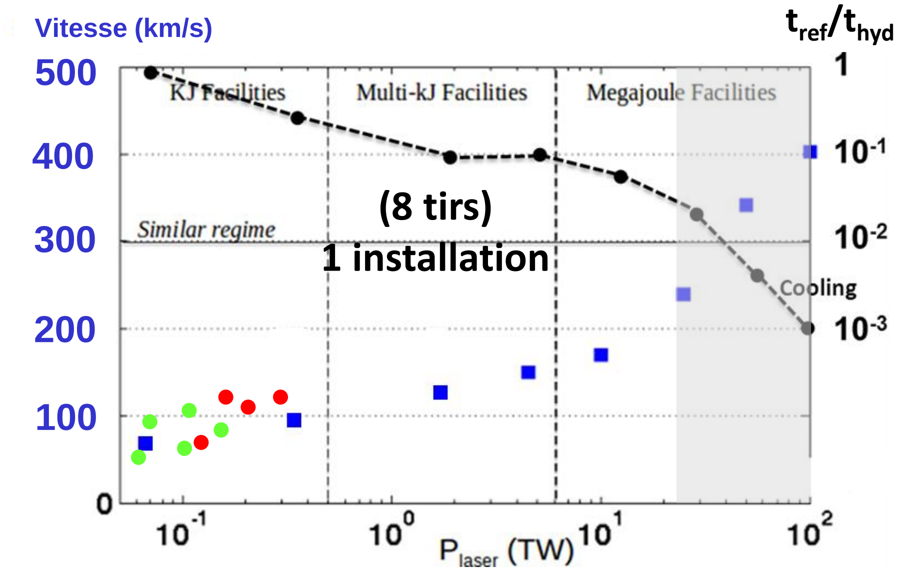


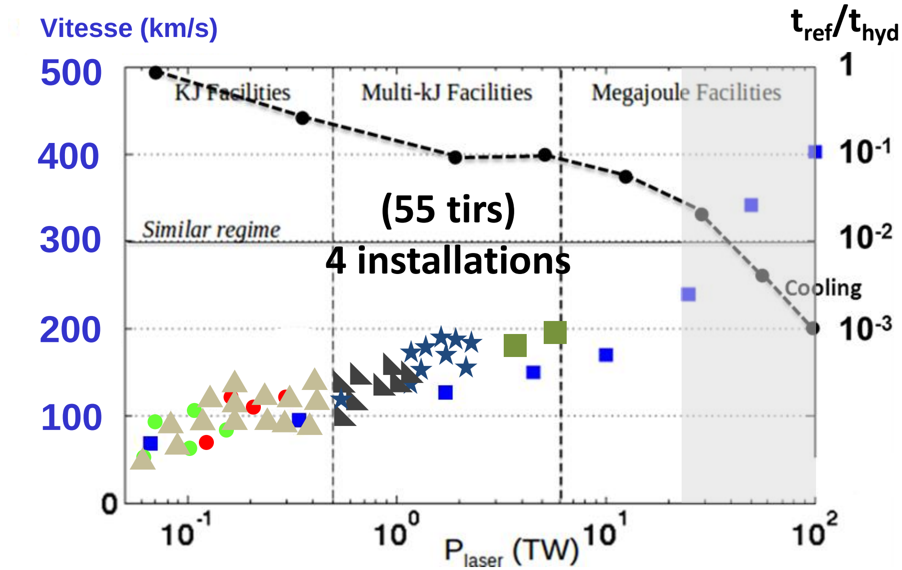
Expérience ORION

[J. Cross et al. Nature Com (2016)]



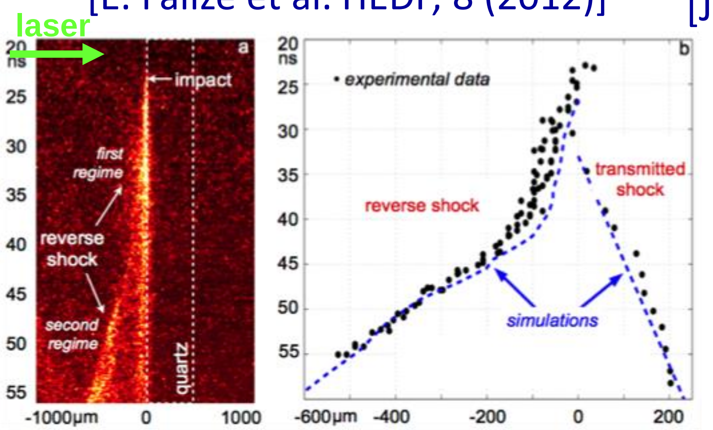
les lasers de puissance : microscopes de l'astrophysique





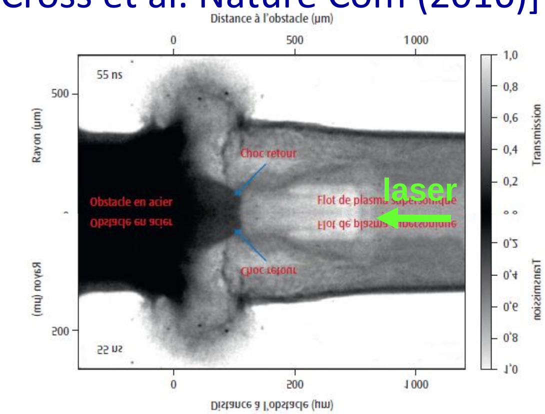
Expérience LULI2000

[E. Falize et al. HEDP, 8 (2012)]



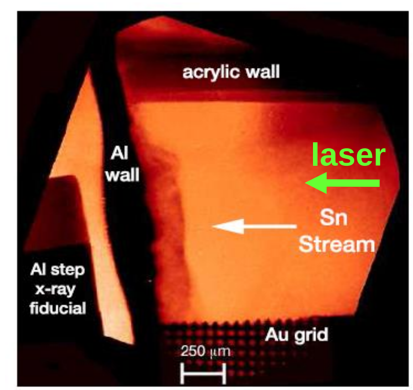
Expérience ORION

[J. Cross et al. Nature Com (2016)]



Expérience OMEGA

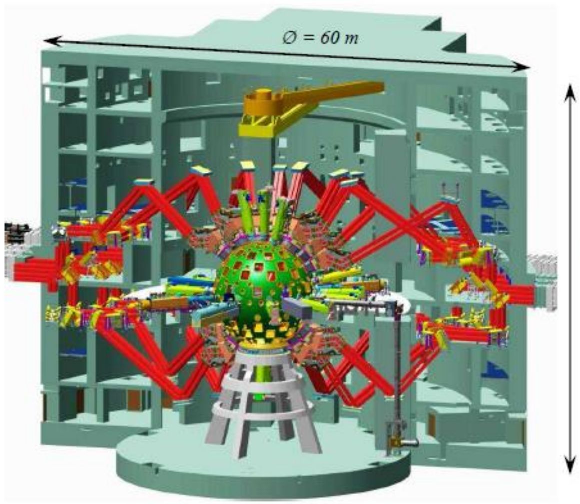
[C. Krauland et al. ApJ, 762 (2013)]



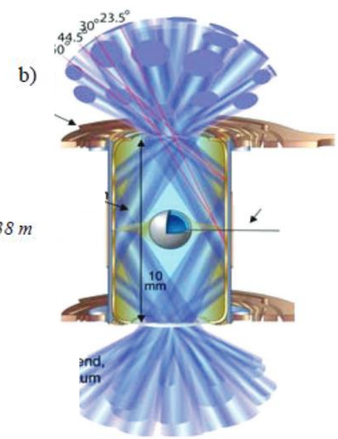
les lasers de puissance : microscopes de l’astrophysique

Configuration des faisceaux laser
sur une installation Mégajoule

Le LMJ



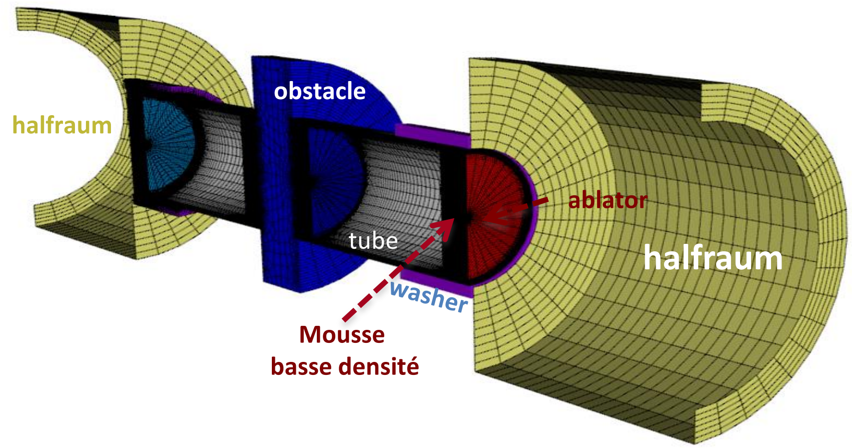
Cible FCI

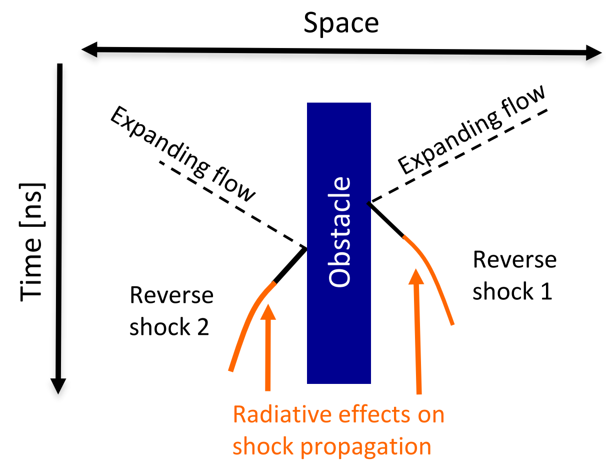


[http://www-lmj.cea.fr/fr/ForUsers.htm]

	L (cm)	t(s)	V(cm/s)	ρ (g/cc)	T (eV)
Polar	10^7	1	3×10^8	10^{-8}	10^4
Labo	0.1	10^{-8}	3×10^7	10^{-2}	120

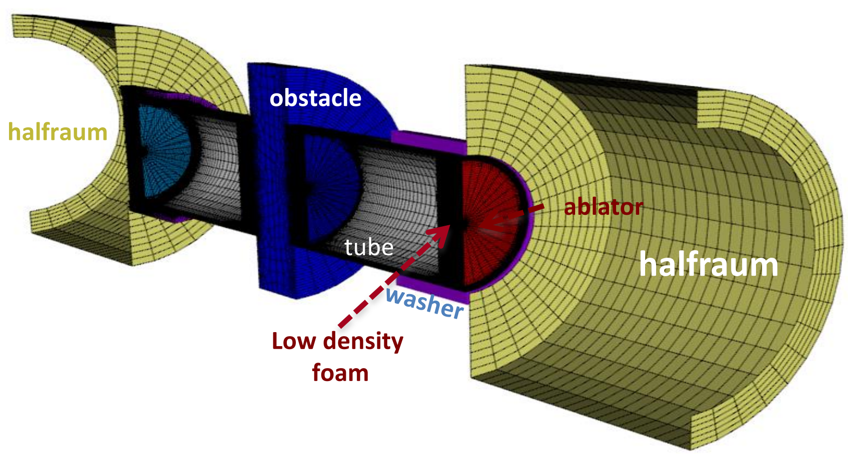
Cible POLAR pour une installation Mégajoule

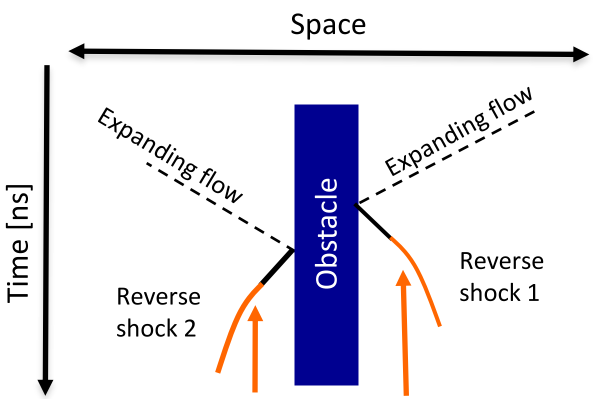




les lasers de puissance : microscopes de l'astrophysique

Cible POLAR pour une installation Mégajoule

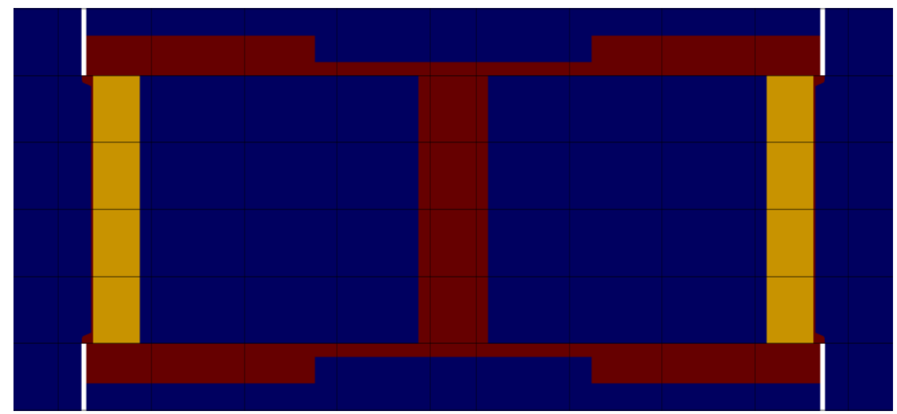




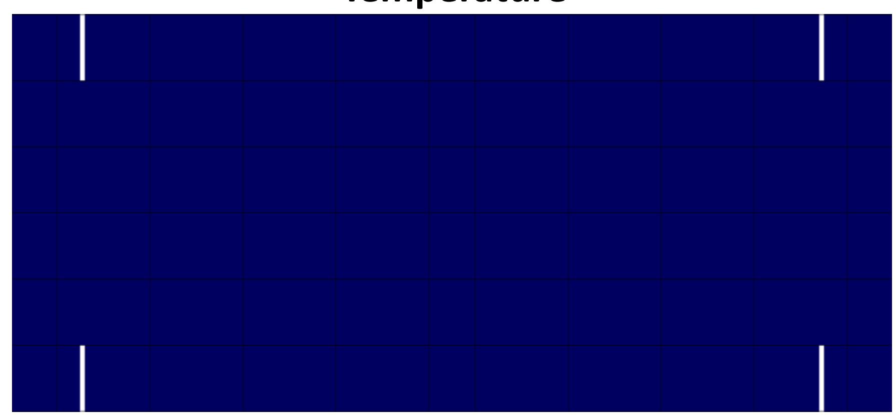
Radiative effects on shock propagation

Simulations 2D hydro-rad avec le code FCI2

Densité

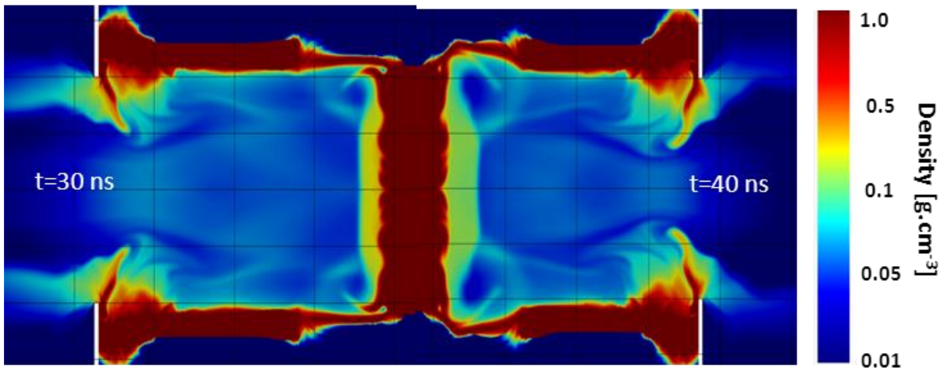


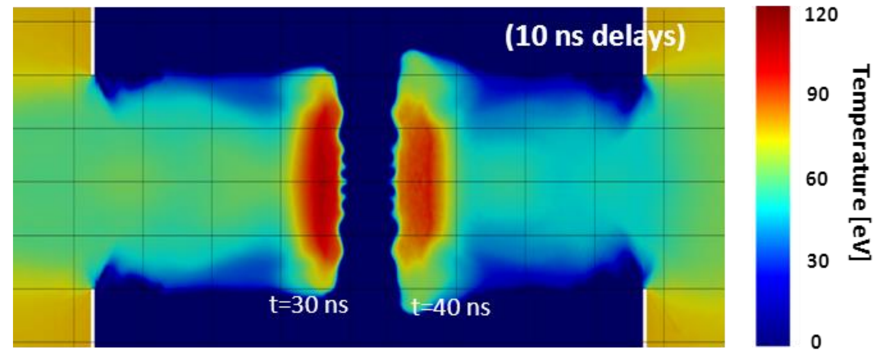
Température



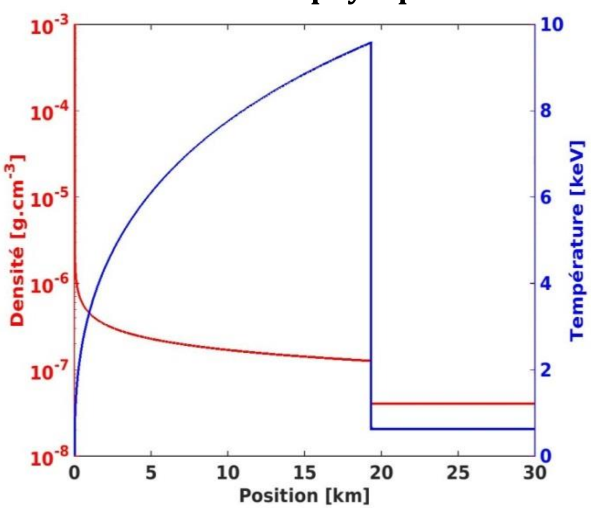
les lasers de puissance : microscopes de l'astrophysique

Zone radiative 0.01 $g.cm^{-3}$ - 120 eV

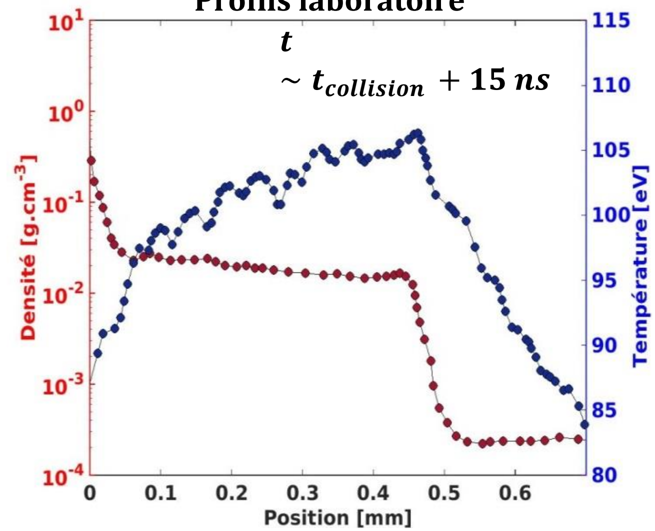




Profils astrophysiques



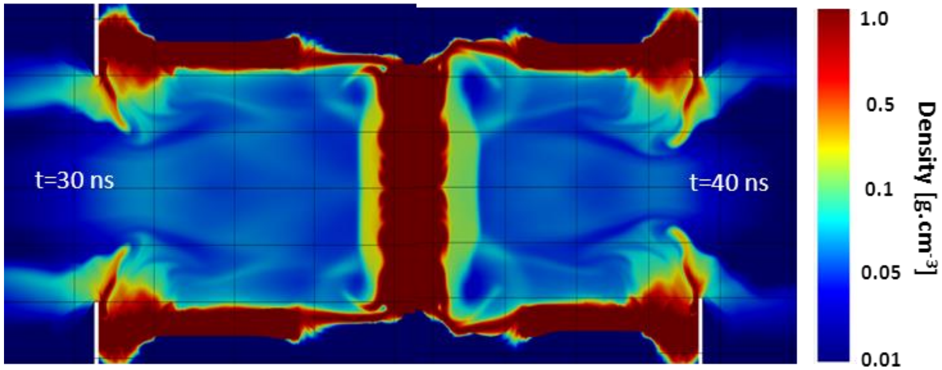
Profils laboratoire

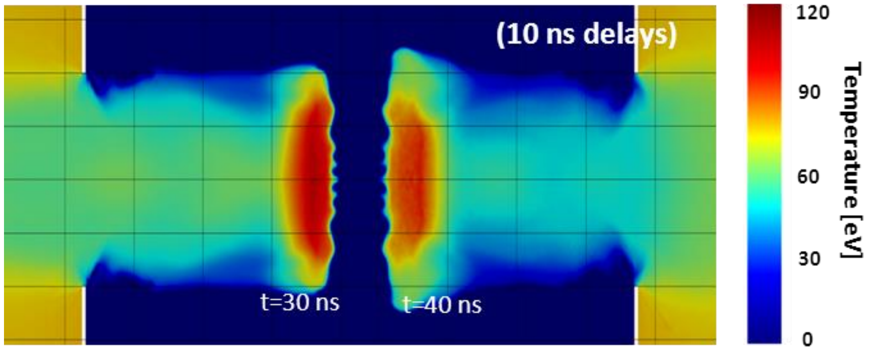


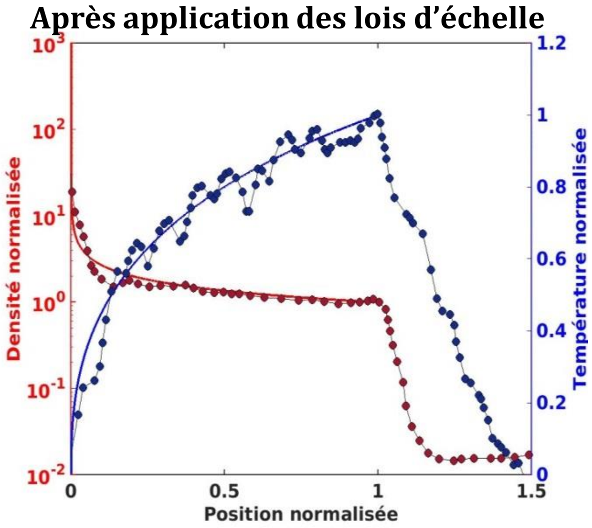
Lucile Van Box Som (thèse 2018)

les lasers de puissance : microscopes de l'astrophysique

Zone radiative 0.01 $g.cm^{-3}$ - 120 eV







Lucile Van Box Som (thèse 2018)

Je possède d'autant mieux le monde
que je suis plus habile à le miniaturiser
G. Bachelard
la poétique de l'espace

Festival d'astronomie de Fleurance
Ferme des étoiles

cea