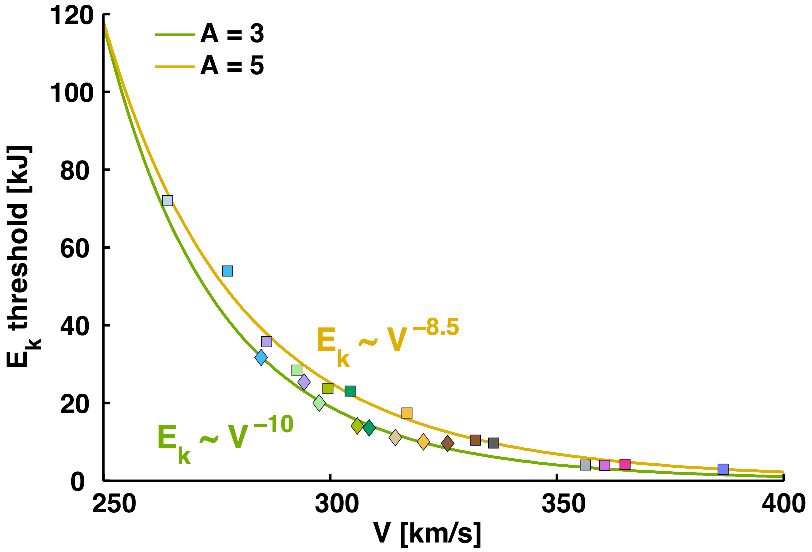
energie atomique • energies alternatives

1D baseline target designs for direct drive shock ignition.



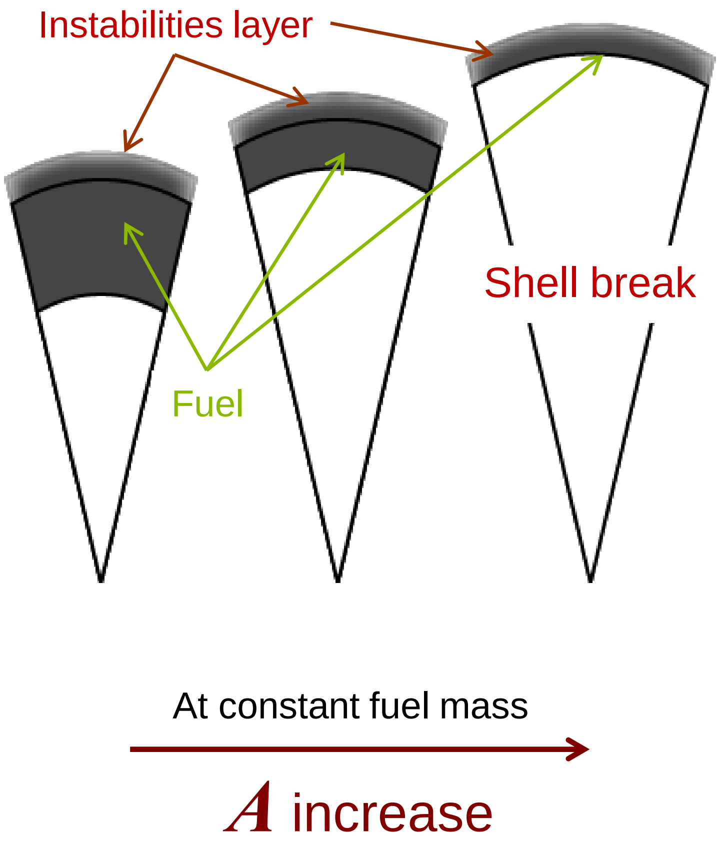
V. Brandon[1], B. Canaud[1], S. Laffite[1]
M. Temporal[2], R. Ramìs[2].

1 – CEA, DAM, DIF - F-91297 Arpajon France
2 - ETSIA, Universidad Politecnica de Madrid, Spain

In direct drive fusion, hydrodynamic stability is a priority.

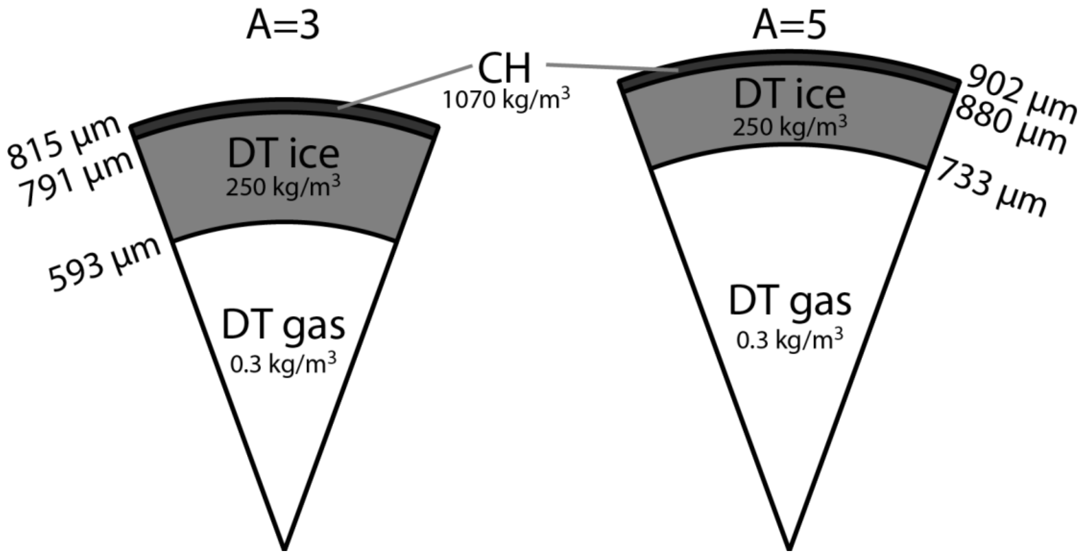
- **With direct laser ablation, shell acceleration is high.**
- **Hydrodynamic instabilities have high amplitude and involve shell breaking.**
- **Instabilities must be limited:**
  - > by reducing implosion velocity.
  - > by increasing shell thickness.
- **Implosion velocity targeted is around 300 km/s.**
- **Initial aspect ratio (IAR) :**

$$A = \frac{R_{fuel}}{\Delta R}$$



Two target designs are considered with different IAR.

- **Initial considerations :**
    - > A = 3 and A = 5.
    - > Fuel : *300 µg DT ice (~25 MJ free).*
    - > CH pusher is used to reinforce laser target coupling.



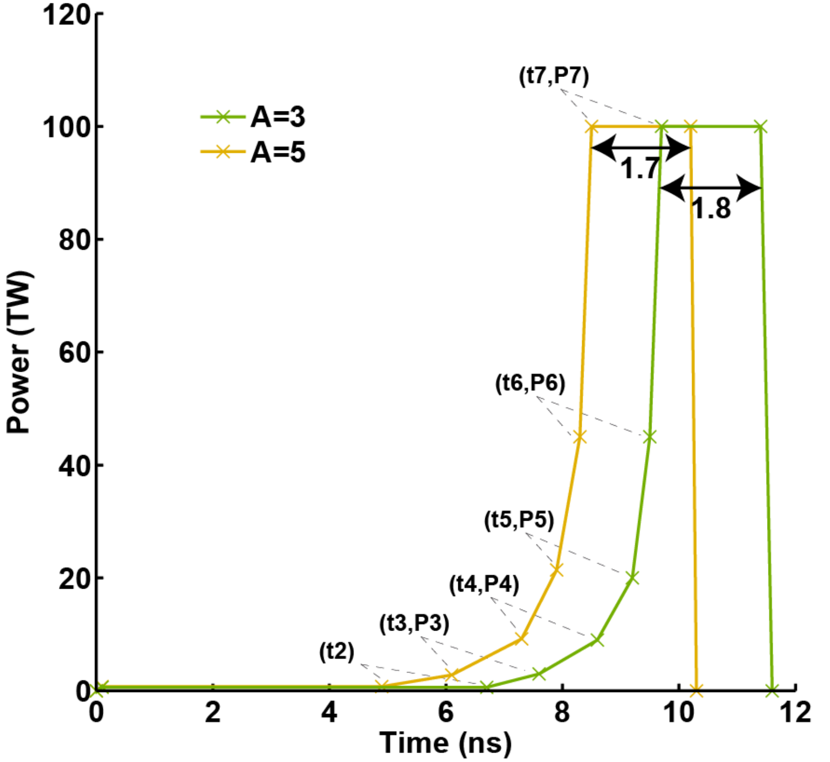
- **Ablator thickness is determined with Lindl** *(Phys. Plasma,1995)* **formulas and an initial ablation pressure (P_a) of 300 GPa :**

$$p_a(\mathrm{Pa}) = 40\,.10^{-3}\left(\frac{I(\mathrm{W/m^2})\,.10^{-4}}{\lambda(\mathrm{m})}\right)^{\frac{2}{3}} \qquad \dot{m}_a(\mathrm{kg/m^2/s}) = 2.6\,.\,10^{-7}\left(\frac{I(\mathrm{W/m^2})\,10^{-4}}{\lambda^4(\mathrm{m})}\right)^{\frac{1}{3}}$$

A pre-optimized laser shape is evaluated with Kidder's law.

- **Kidder's law (1976) leads to an isentropic implosion and is composed by:**
  - > a foot (1st shock).
  - > a ramp (compression).
  - > a drive (implosion velocity).

- **Ablation pressure is fixed to $P_a \sim 300$ GPa *($P_{l\ foot} \sim 1$ TW)* for an adiabatic coefficient : $\alpha \sim 1$.**

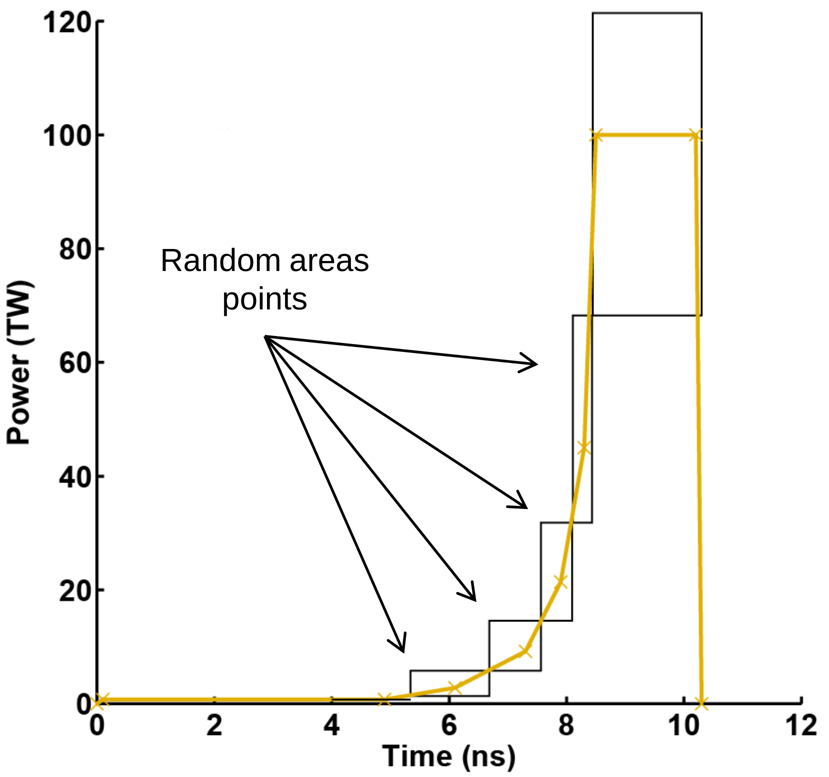


Theses laser shapes are the starting point of the optimization.

In our study, calculations are realized with 1D code.

A Monte Carlo random walk is used to refine optimization

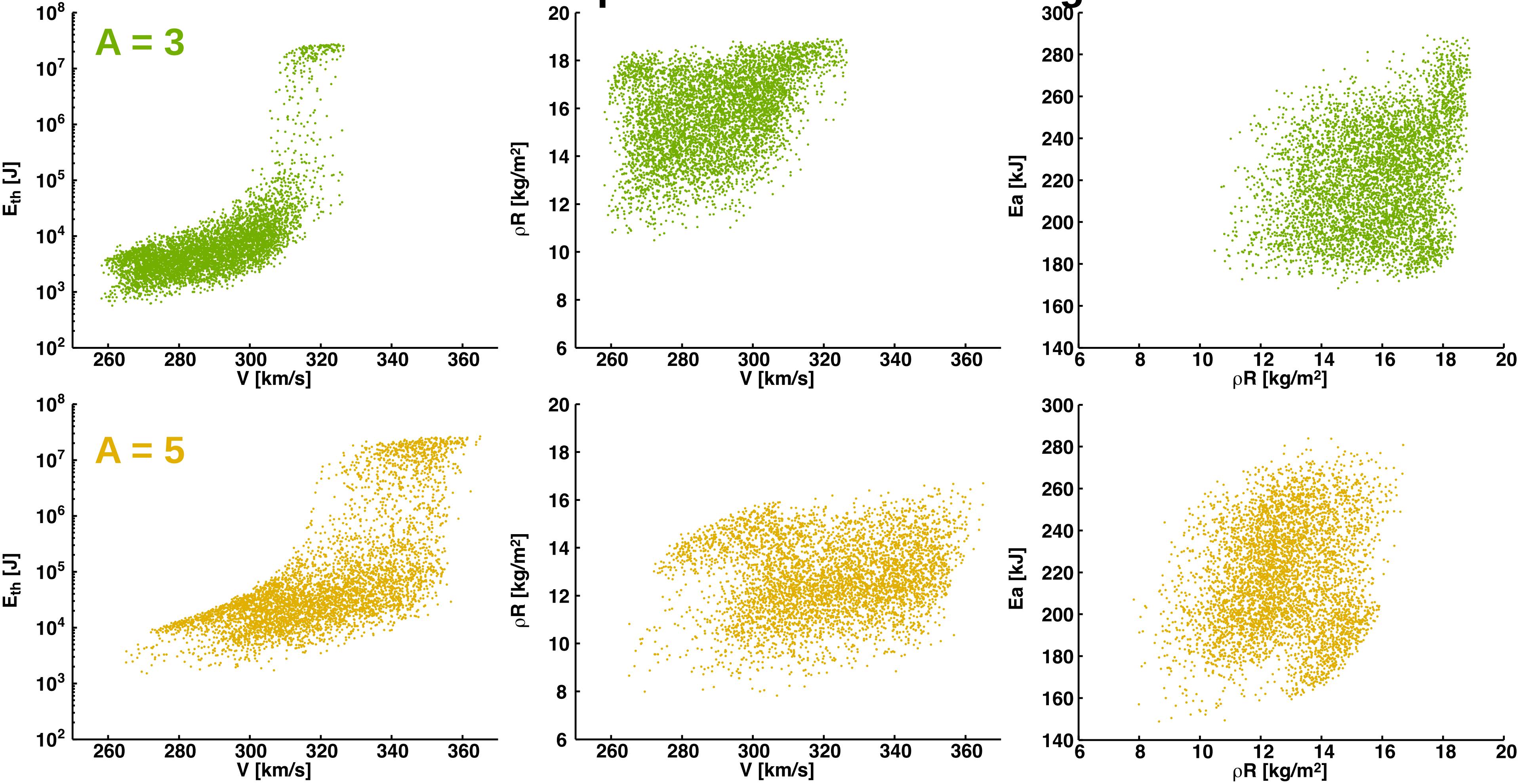
- **Optimization parameters are the laser shape points:**
  - 6 times and 5 laser powers.
  - Constant drive duration.
  - Constant foot power.
- **Each ramp points are selected by random walk:**
  - A new laser pulse shape is slightly modified at each random realization.
    - ***Shock timing is different for each laser pulse shape.***
    - ***Hydrodynamics data (pressure, temperature, density, implosion velocities…) change with each laser pulse shape.***
- **Drive power varies in order to explore large implosion velocity range (250 < V < 370 km/s).**
- **Laser shape robustness could be explore.**



- **Criteria are:**
  - Areal density.
  - Thermonuclear energy.
  - Absorbed energy.

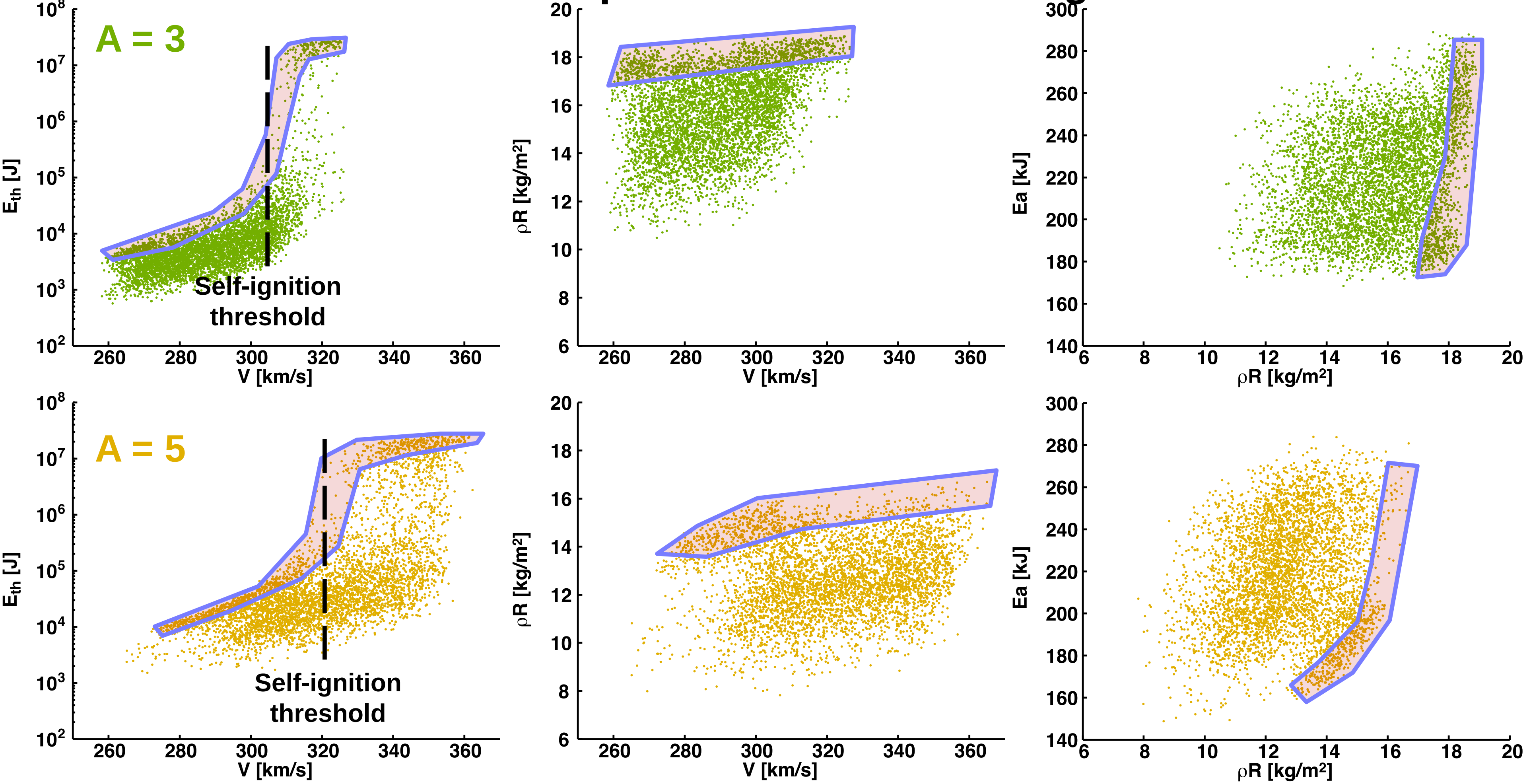
Optimization results.

- **More than 5000 computations for each design have been realized.**



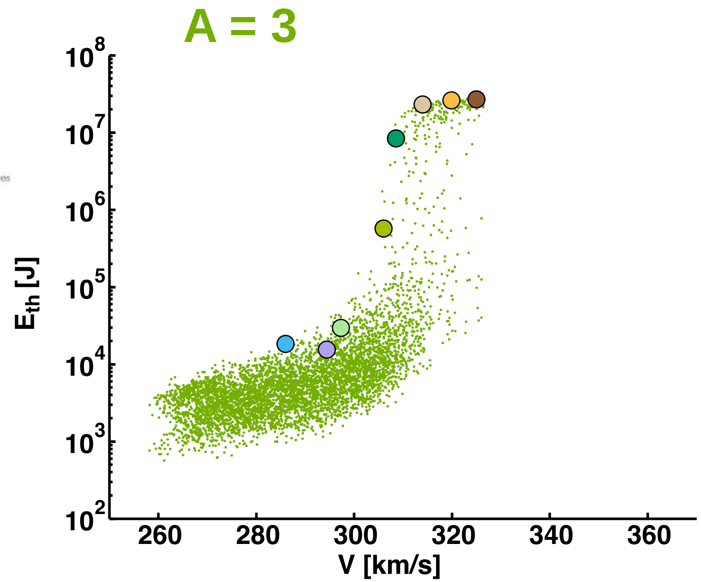
Optimization results.

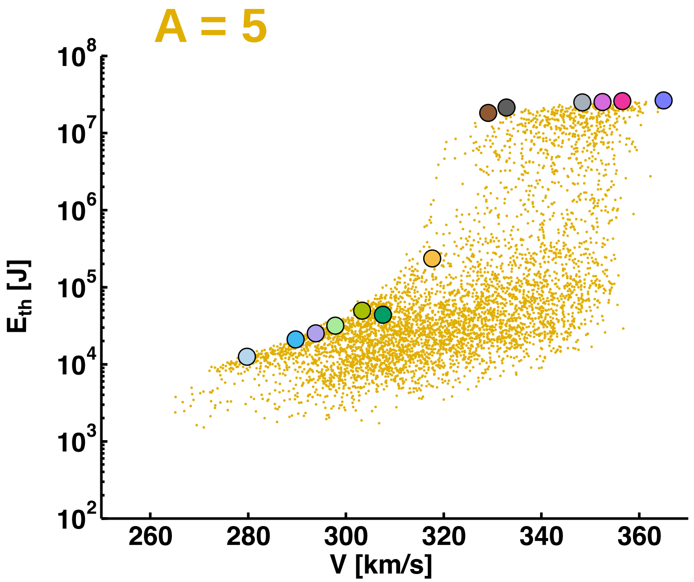
- **More than 5000 computations for each design have been realized.**



- **Self ignition threshold is reached for the two designs :**
  - > A=3 : V_{th}~310 km/s ρR_{max} ~1.85 g/cm^2 180 kJ < E_a < 280 kJ
  - > A=5 : V_{th}~320 km/s ρR_{max} ~1.60 g/cm^2 160 kJ < E_a < 260 kJ

Working points selection:





A=3					A=5				
V (km/s)	P (TW)	Ea (kJ)	ρR (kg/m²)	Eth (kJ)	V (km/s)	P (TW)	Ea (kJ)	ρR (kg/m²)	Eth (kJ)
					280	56	171	14,6	12
286	82	215	18,5	18	289	61	181	15,0	21
294	91	233	18,8	15	294	61	187	15,3	25
298	96	238	18,4	29	298	65	193	15,6	32
306	102	234	18,6	573	303	66	199	15,8	49
308	104	250	18,7	8389	308	69	204	15,9	44
314	110	260	18,2	23032	317	79	219	15,9	234
320	114	272	18,6	26216					
325	119	283	18,9	26915	329	87	226	16,0	18119
					333	86	233	16,4	21411
					348	100	249	16,6	24862
					352	103	264	16,4	25064
					356	108	267	16,6	25695
					365	111	280	16,7	26296

- **An exhaustive catalog of target designs for a wide range of implosion velocity is now available.**
- **Selection is led by:**
  - > **Maximum areal density under threshold.**
  - > **Maximum thermonuclear energy above threshold.**
  - > **Minimum absorbed energy.**

A scaled target catalog is realized.

- **For each working point, we are to going to reach the self ignition threshold in varying fuel mass at constant implosion velocity.**
- **The scale factor f allows to build the scaled targets family:**

$$M = M_0 * f,\ E = E_0 * f,$$

$$r = r_0 * f^{1/3},\ t = t_0 * f^{1/3},$$

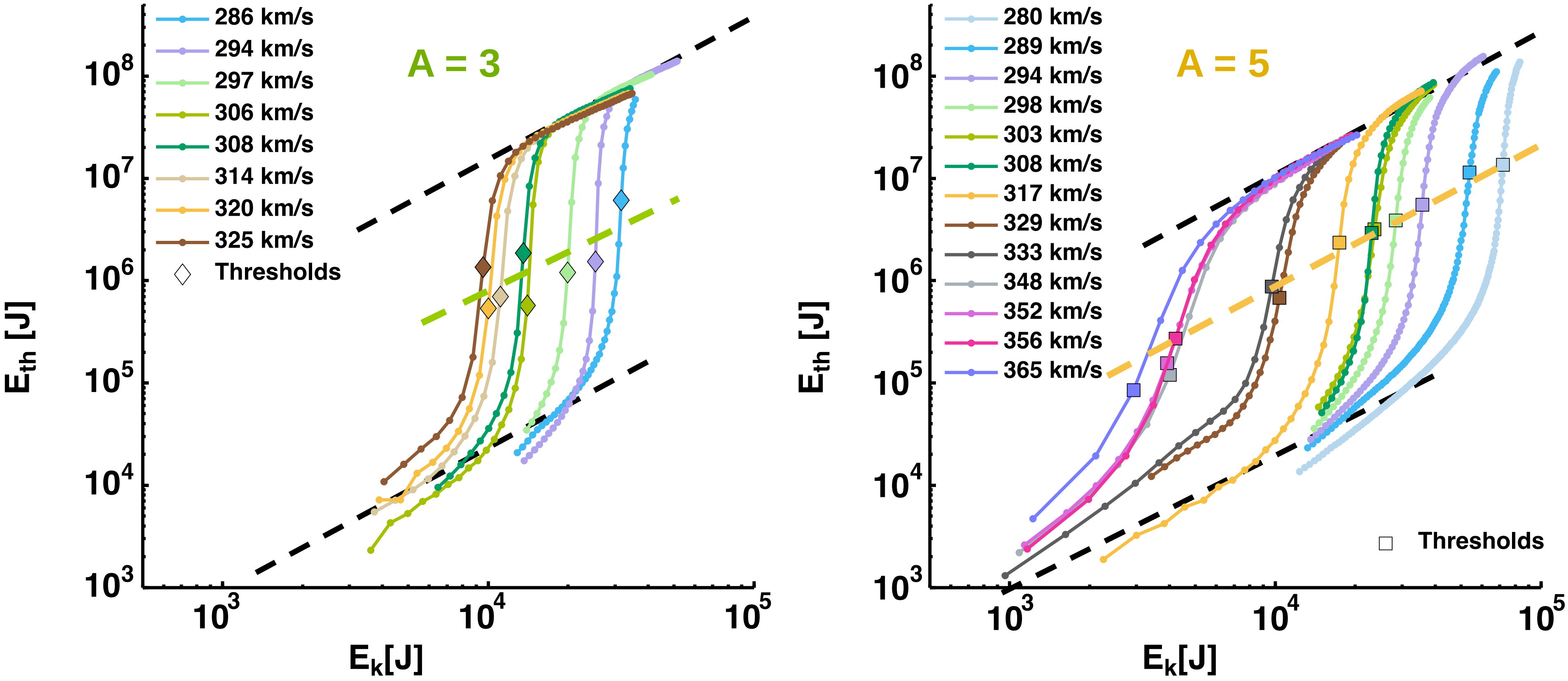
$$P_l = P_{l_0} * f^{2/3},$$

$$V = V_0,\ I = I_0,\ \rho = \rho_0.$$

Kinetic energy will change only with mass, and thus with scale factor.

Scaled target families and thresholds

- **With an elaborate scale factor variation, self ignition threshold is precisely explored.**

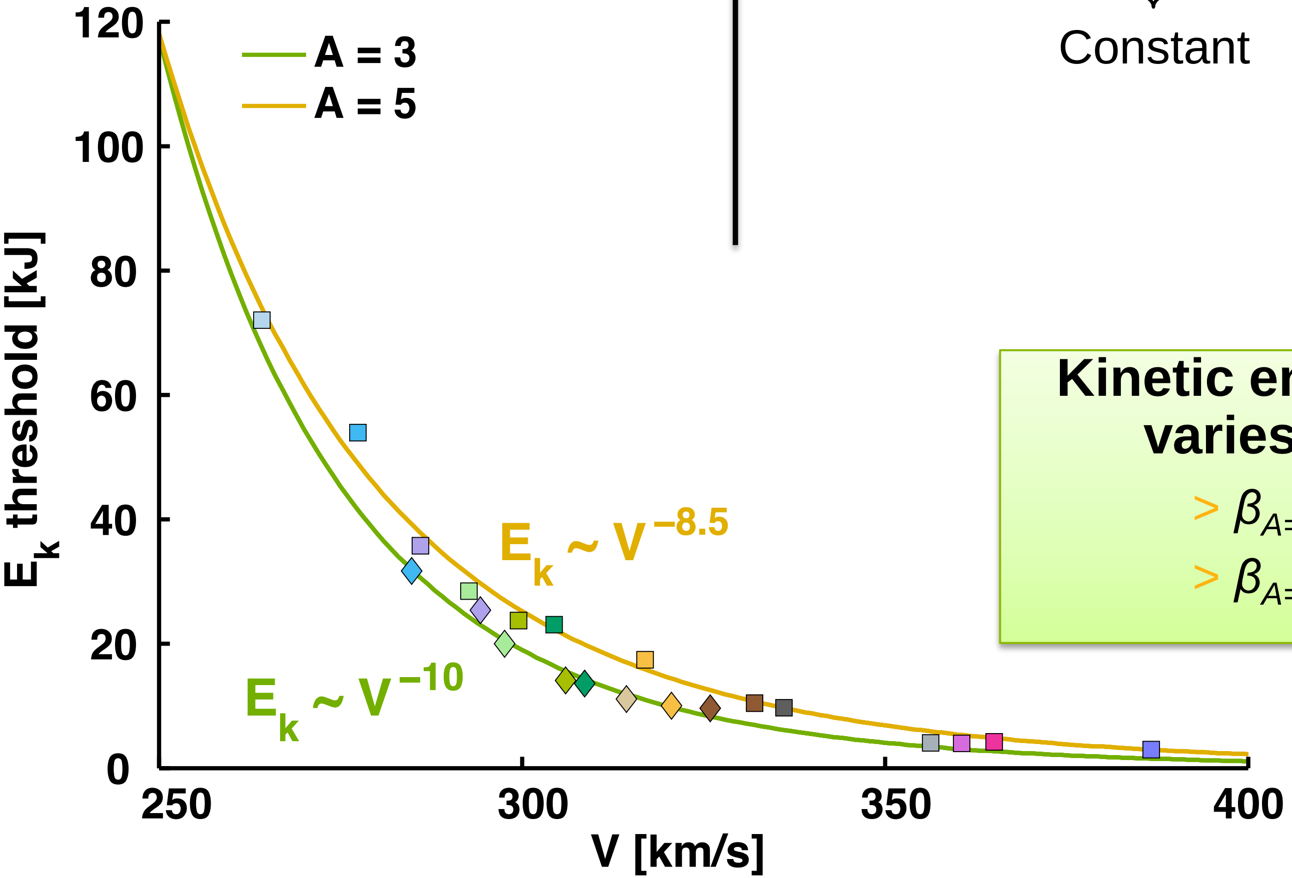


The large implosion velocity range allows to verify the kinetic energy threshold dependence with implosion velocity.

Kinetic energy threshold is varies in $V^{-\beta}$.

- ***Betti et al.*** *(Phys. Plasma 2002)* **in their shell compression model shows :**

$$E_k \approx 2.7(kJ)\alpha_s^3\left(\frac{3\cdot 10^7}{V_i(cm/s)}\right)^{\textcircled{7}}$$



- **Bayer-Juraszek model** *(CEA private comm.)* **suggests :**

$$E_k^{min} = \underbrace{2\pi\left(\frac{3}{5}\right)^5 6^6(a_{hs}a_{sh})^3}_{\text{Constant}}(\rho RT)^3_{hs}\underset{\substack{\downarrow\\ \frac{P_{sh}}{P_{hs}}}}{\varepsilon^2}\underset{\substack{\downarrow\\ \text{Isentrope parameter}\\ \text{of shell at}\\ \text{stagnation}}}{\frac{\alpha_{sh}^3}{\textcircled{v^{10}}}}$$

Kinetic energy threshold varies in $V^{-\beta}$ *with* :

> $\beta_{A=3} = 10$

> $\beta_{A=5} = 8.5$

Pre-conclusion

- **Two new target designs have been realized.**
- **A large implosion velocity range is explored (260 < V < 370).**
- **Kinetic energy threshold is identified.**
- **A large catalog of target design is available**
    - **For a wide implosion velocity range.**
    - **For several fuel mass.**
- **There is three kinds of target designs :**
    - **Designs largely under self ignition threshold.**
    - **Marginally ignited designs (interesting in shock ignition).**
    - **Self ignited designs.**

Two-Plasmon Decay (TPD) is the most sensitive LPI

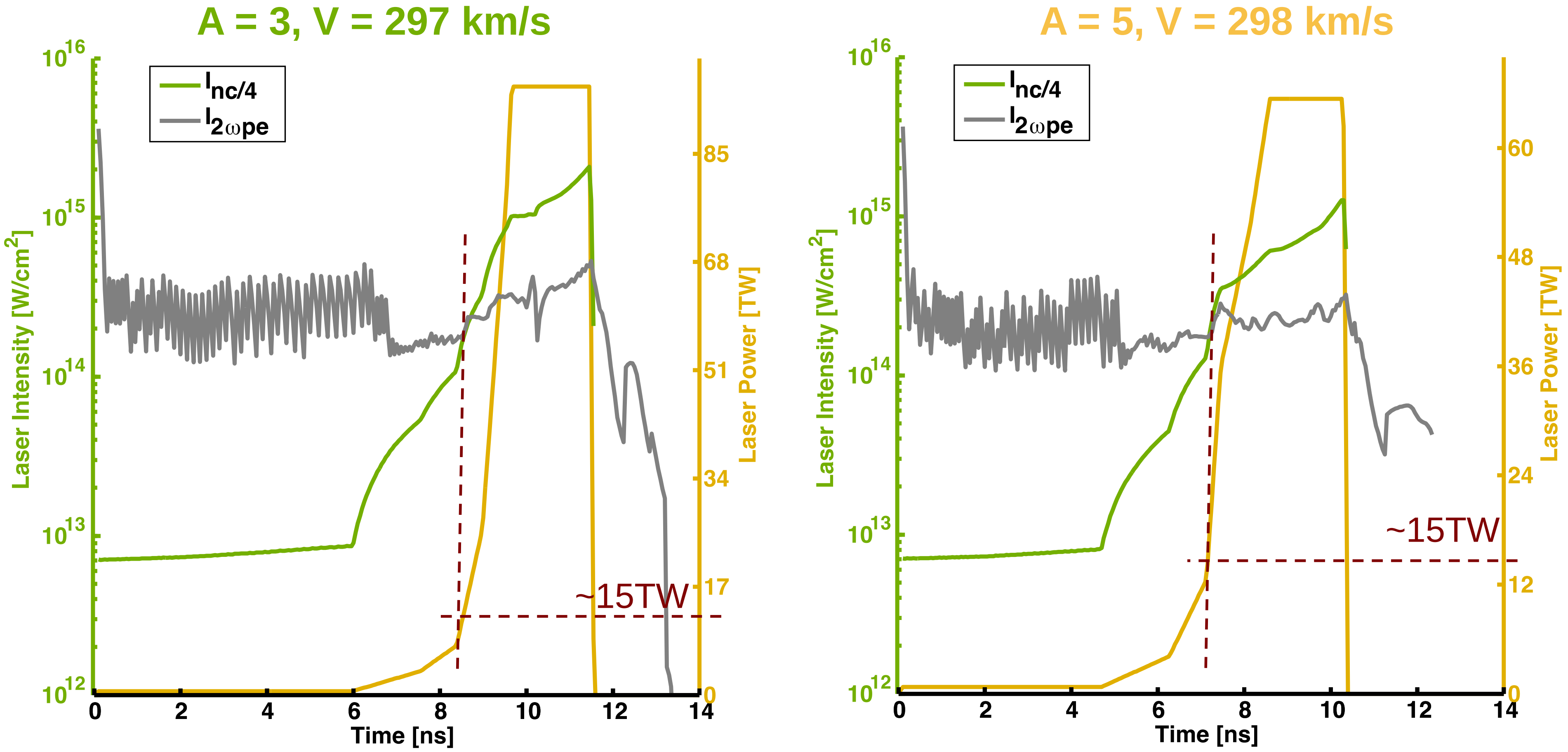
- **TPD produces hot electrons that warm cryogenic fuel.**
- **We must evaluate the TPD threshold intensity in our new designs. TPD are defined at $n_c/4$.**
- **Laser intensity is defined as follow :**

$$I[W/cm^2] = \frac{P_{drive}[W]}{4\pi R^2_{n_c/4}[cm^2]}$$

- **Simon *et al.*** *(Phys. Fluids, 1983)* **have defined the threshold intensity of TPD activation :**

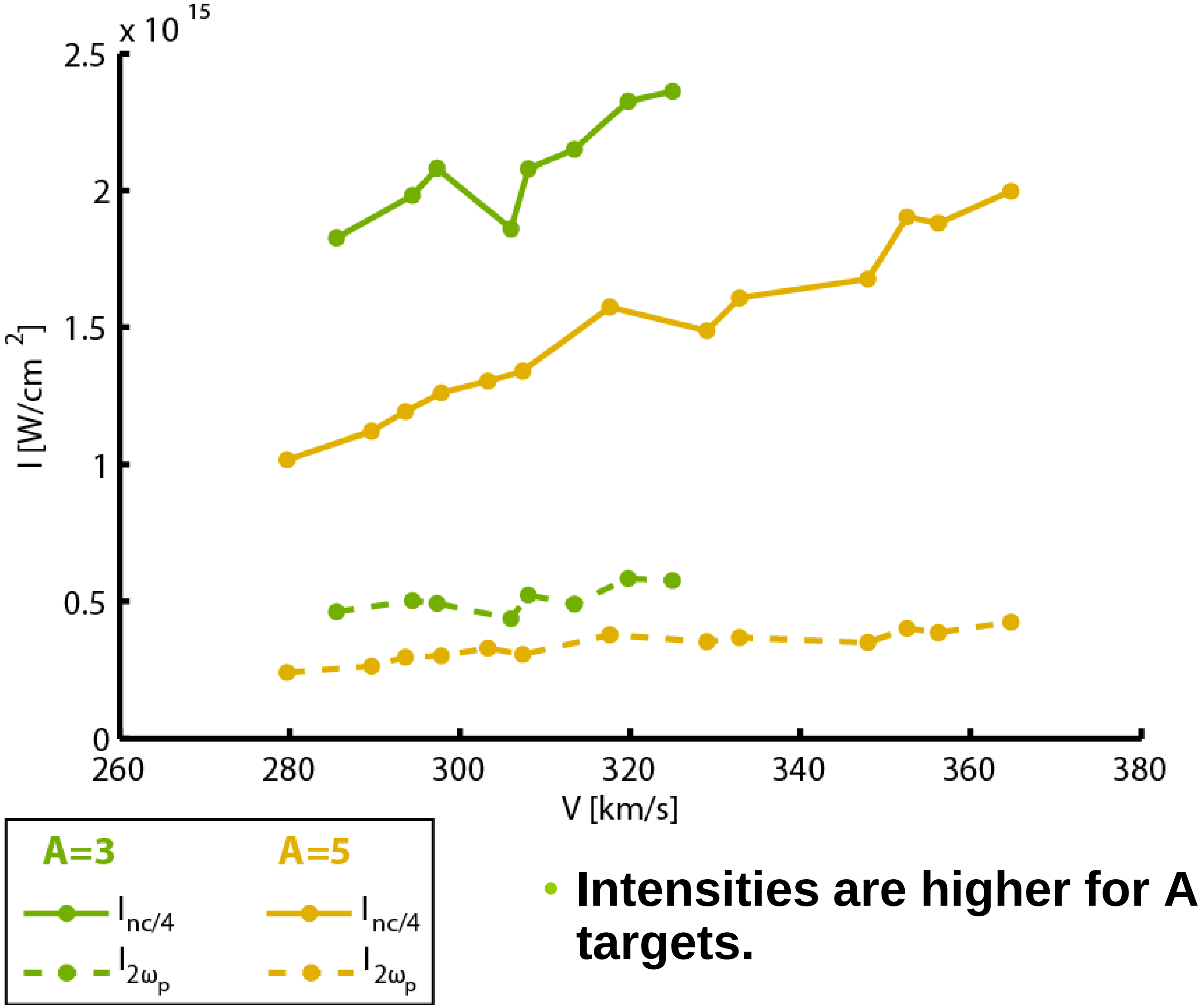
$$\boxed{I_{TPD}[W/cm^2] \approx \frac{80 \cdot 10^{14}\ T_e[keV]}{\lambda[\mu m]\ L[\mu m]}\ \ with\ \ L = -\frac{n_e/n_c}{\nabla(n_e/n_c)}}$$

TPD activation threshold is reached during ramp



In all cases, even if implosion velocity is low, TPD threshold is reached during ramp.

Maximal intensity is proportional to the implosion velocity



- **Intensities are higher for A=3 than A=5 targets.**
- **Trend is globally the same according to the implosion velocity.**

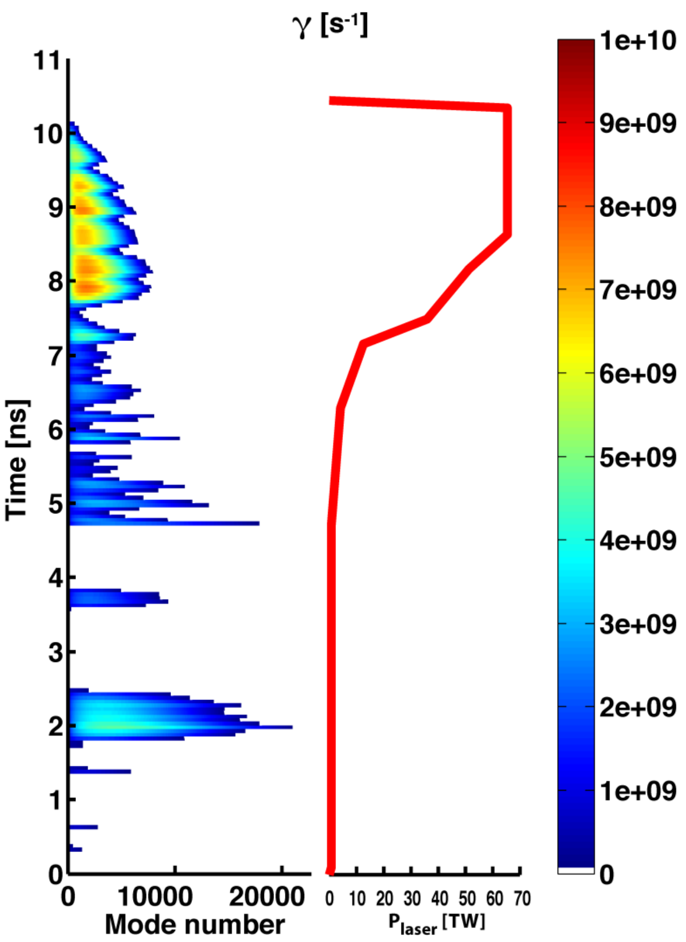
Hydrodynamic stability is evaluated in computing roughness

- **In a first step, Goncharov-Betti model** *(Betti et al.,Phys. Plasma,1998)* **determines the time-resolved RTI growth rate:**

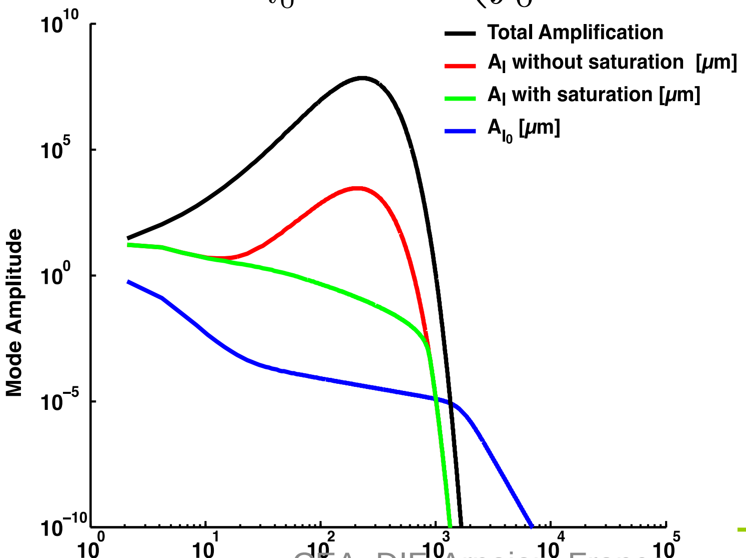
$$\gamma = \sqrt{A_t k g + \delta^2 k^4 L_0^2 V_a^2 + \left(\omega^2 - \frac{1}{\xi_l}\right) k^2 V_a^2} - \delta k^2 L_0 V_a - \beta k V_a$$

- **Then, Haan's model of saturation** *(Haan, Phys. Rev. A, 1989)* **estimates time-resolved e-folding with LLNL-spectrum** *(Marinak et al., Phys. Plasma, 2001)***:**

$$\frac{A_l}{A_{l_0}} = exp\left(\int_0^{t_{stag}} \gamma(t)\,dt\right)$$



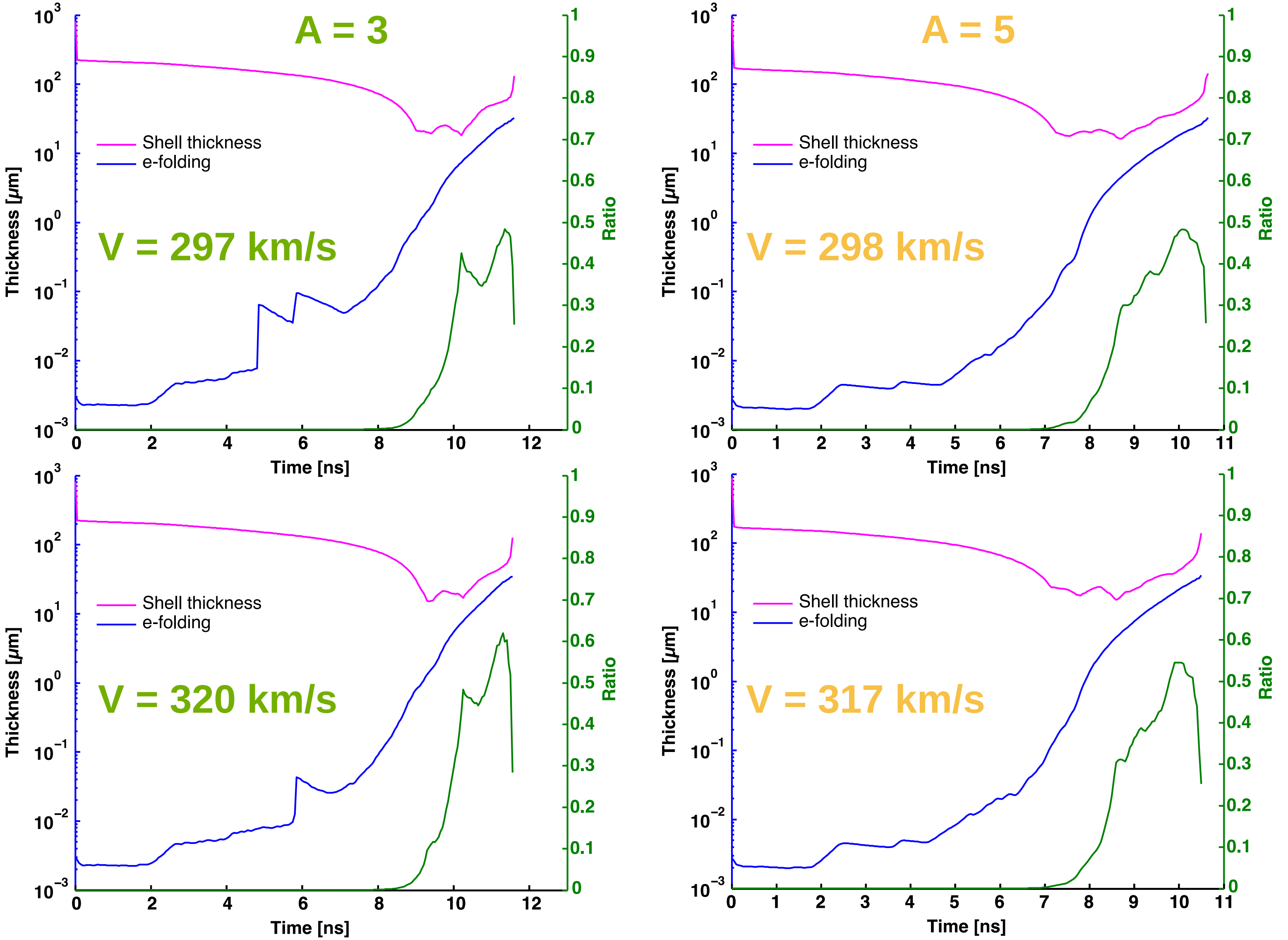
A = 5
V = 298 km/s



E-folding is determined as :

$$\sigma_{rms} = \sqrt{\sum_l A_l^2}$$

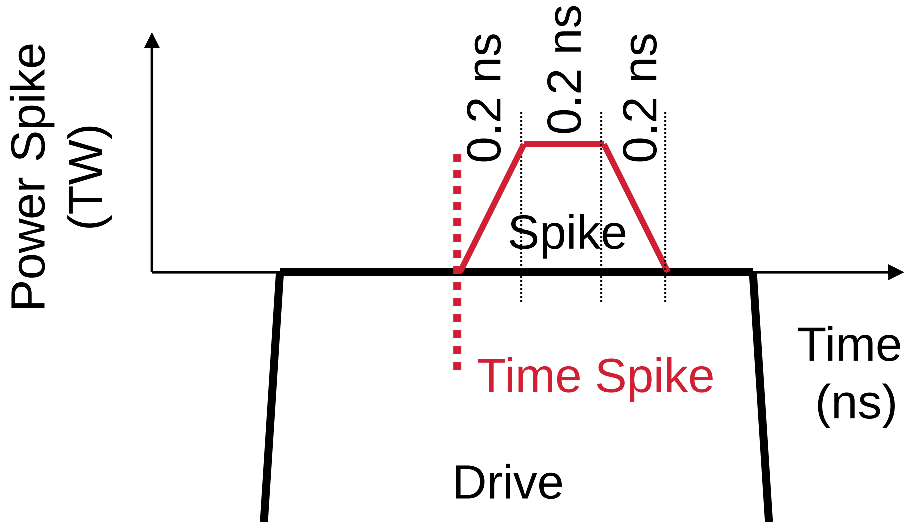
Hydrodynamic stability varies with implosion velocity.



Adiabat shaping will be considered to improve stability

Shock ignition is used on target under threshold to have gain

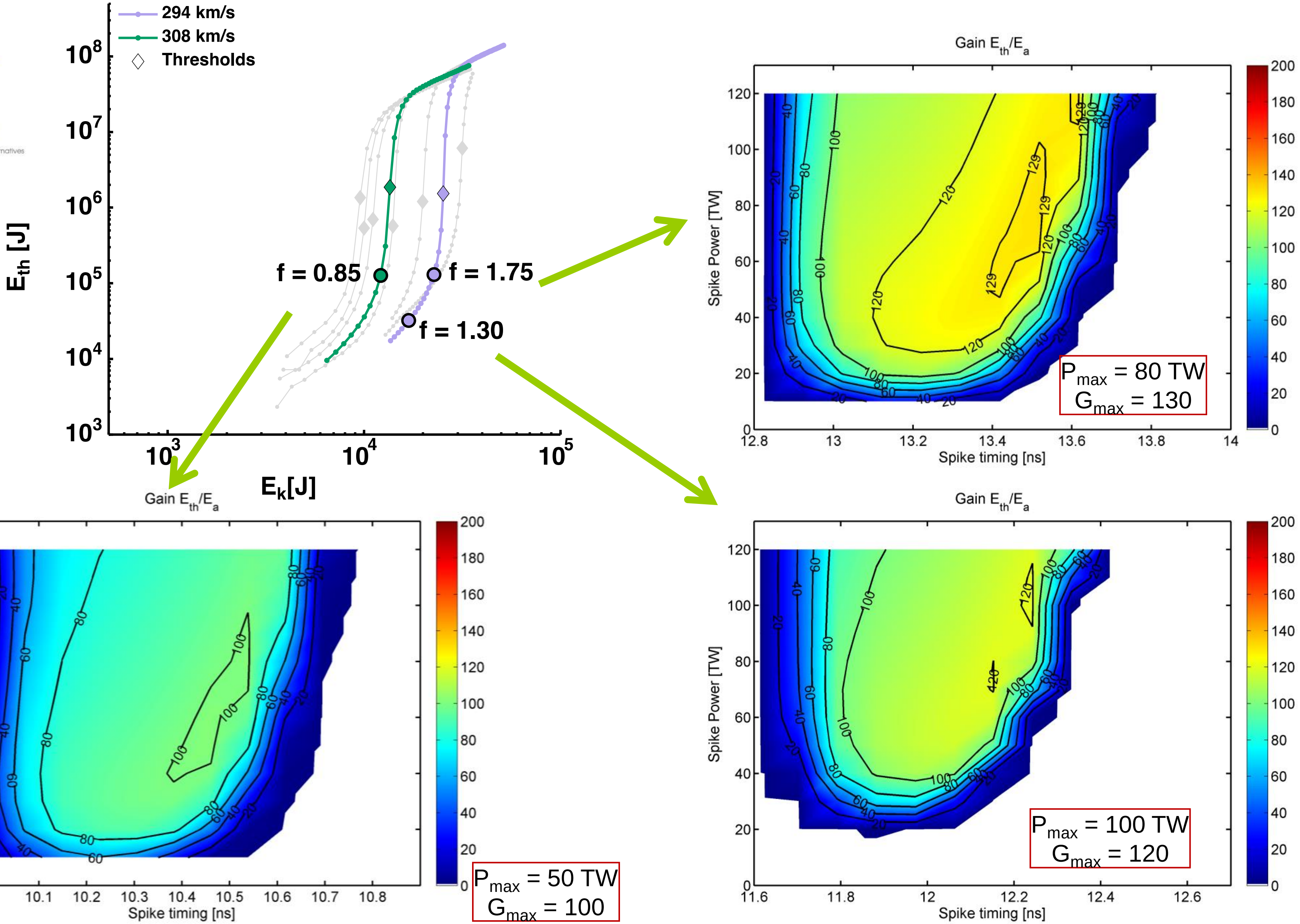
Betti et al. 2007



- **Spike timing and power must adjust to:**
  - Obtain high gains,
  - With limited powers.

Shock ignition results for A=3

A = 3

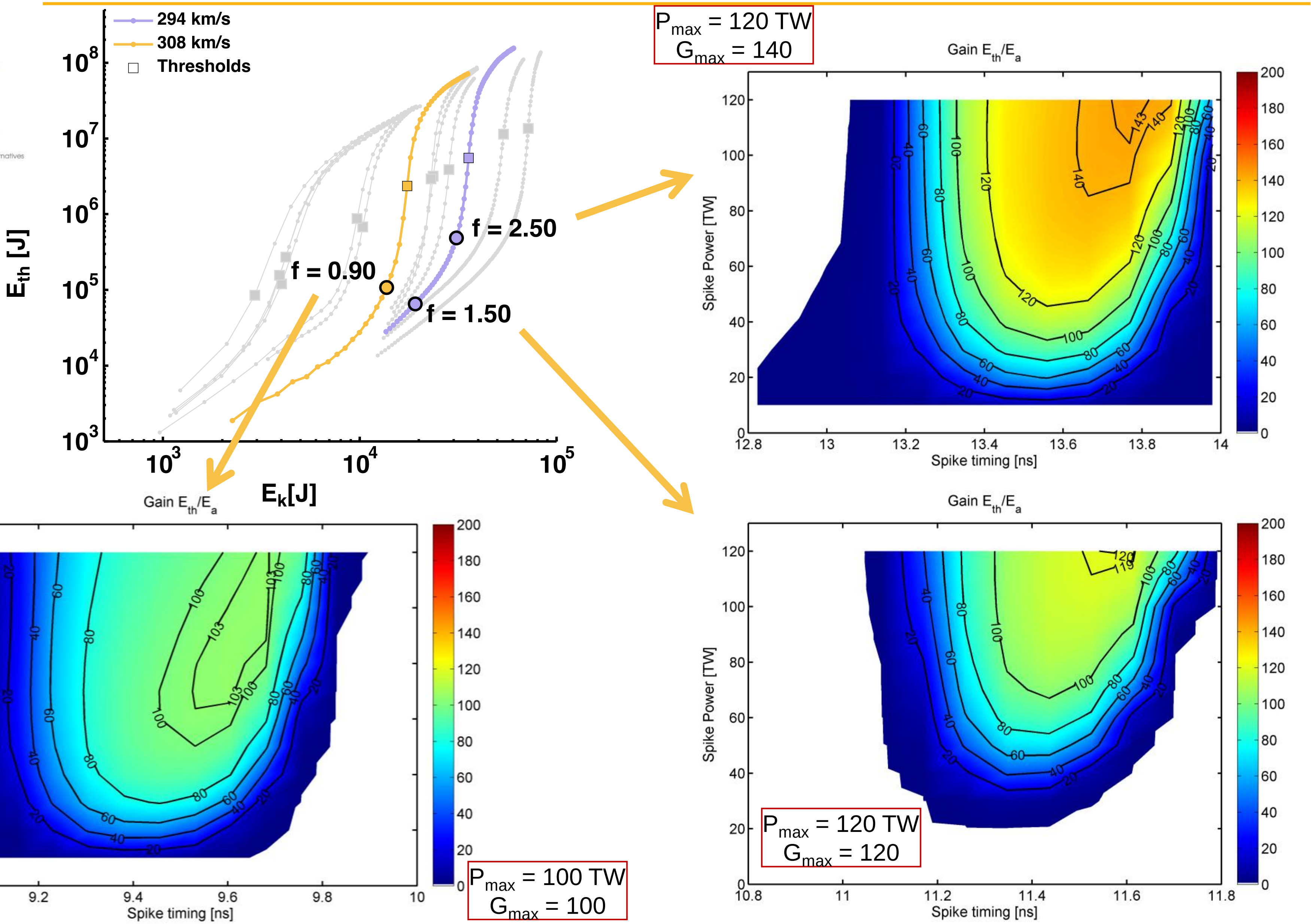


P_{max} = 80 TW
G_{max} = 130

P_{max} = 50 TW
G_{max} = 100

P_{max} = 100 TW
G_{max} = 120

Shock ignition results for A=5



A = 5

P_{max} = 120 TW
G_{max} = 140

P_{max} = 100 TW
G_{max} = 100

P_{max} = 120 TW
G_{max} = 120

Conclusion

- **We define two new direct drive targets…**
- **… optimized by random walk according to implosion velocity, thermonuclear energy, areal density and absorbed energy.**
- **Several working points have been defined for a wide implosion velocity range (260 < V < 370).**
- **Kinetic energy threshold is proportional to $V^{-\beta}$ with $8.5<\beta<10$.**
- **Laser intensity is higher than the TPD threshold during ramp and drive. Hot electrons can not be neglected.**
- **Hydrodynamic stability is principally sensitive to implosion velocity and therefore to the laser power drive. E-folding evaluation shows that half of shell thickness is dominated by RTI. Adiabat shaping must be used.**
- **Shock ignition study reveals that gains are maximum when we choose a point close to the kinetic energy threshold (marginally ignited targets) and at low implosion velocity.**

Thank for your attention.