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Plasma Instabilities in Relativistic Shocks

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Nonlinear Processes in Astrophysical Plasmas:
Particle Acceleration, Magnetic Field Amplification, and Radiation Signatures

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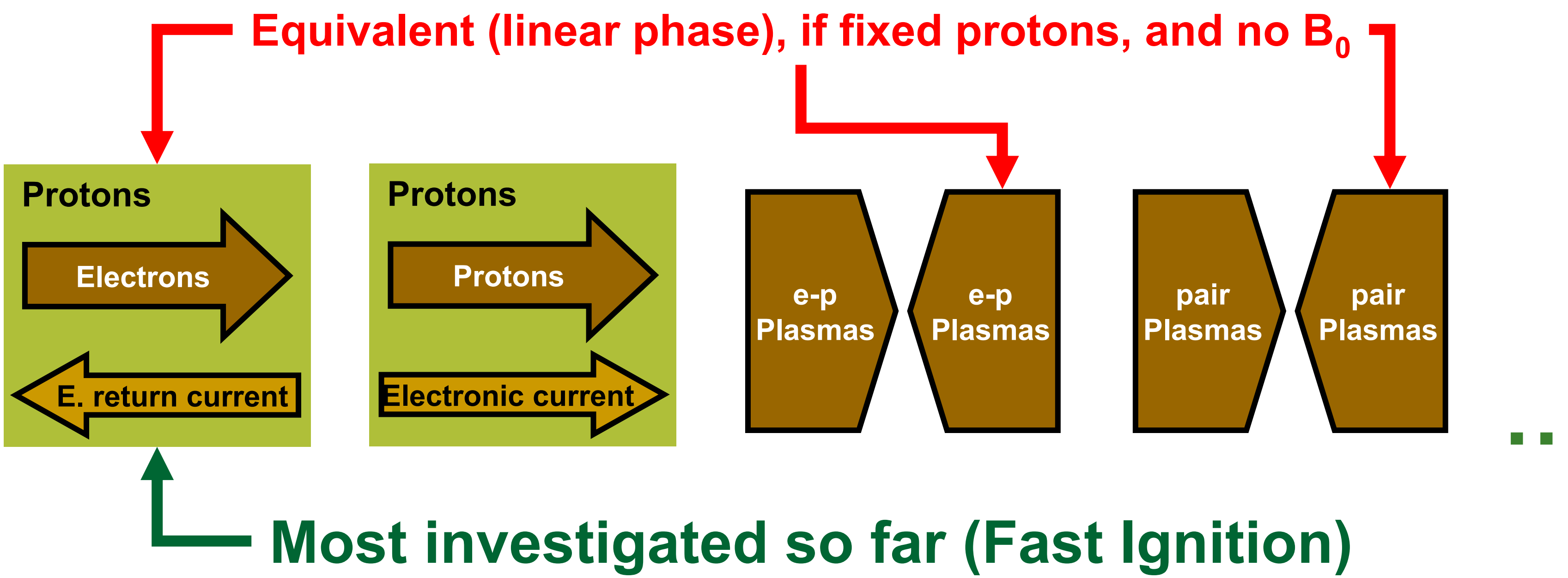
Kavli Institute for Theoretical Physics

Outline

- Kind of system**s** considered
- Formalism
- Electron beam/plasma interaction – No B_0
- Proton beam, B_0 //
- Conclusions

The kind of system considered

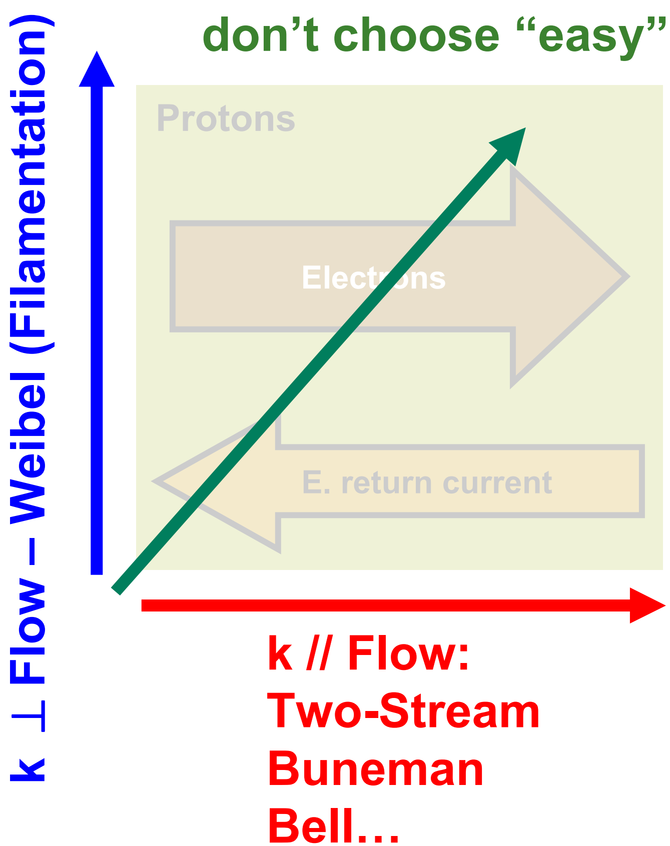
- Infinite beam/plasma system, homogenous, collisionless, current and charge neutral, magnetized or not.
- LINEAR evolution.
- Settings are numerous:



Formalism

Many ways to perturbate the system:

k Oblique – because real word perturbations don't choose "easy" alignment - Σ all orientations



- Vlasov + Maxwell - Linearized
- Perturbation $\propto \exp(i\mathbf{k}.\mathbf{r}-i\omega t)$ with $\mathbf{k}=(k_{//},k_{\perp})$
- Dielectric tensor **T**
- Det(**T**)=0

$$\mathcal{T} = \begin{pmatrix} T_{xx} & T_{xy} & T_{xz} \\ T_{xy}^{*} & T_{yy} & T_{yz} \\ T_{xz}^{*} & T_{yz}^{*} & T_{zz} \end{pmatrix}$$

- Every single unstable mode is recovered

About the dispersion equation

- General form:

$$\det\left|\frac{\omega^2}{c^2}\varepsilon_{ij} + k_i k_j - k^2\delta_{ij}\right| = 0$$

Where,

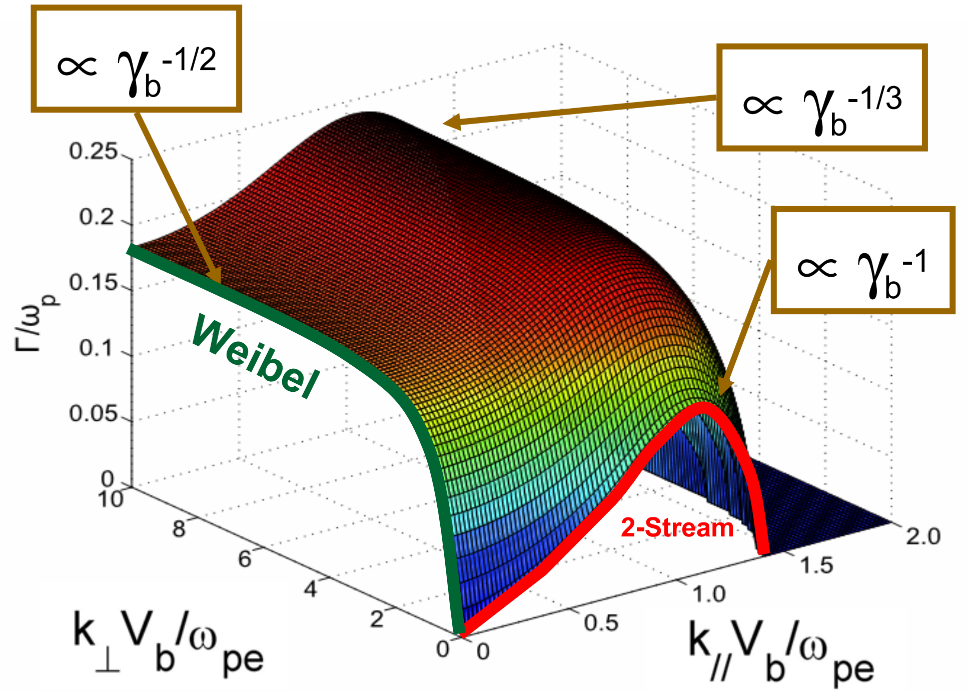
$$\varepsilon_{kl}(\omega,\mathbf{k}) = \delta_{kl} + \sum_{\alpha=b,p}\frac{n_\alpha}{\omega^2}\int\int\int\frac{p_k}{\gamma}\frac{\partial f_\alpha^{(0)}}{\partial p_l}d^3p + \sum_{\alpha=b,p}\frac{n_\alpha}{\omega^2}\int\int\int\frac{p_k p_l}{\gamma^2}\frac{\mathbf{k}\cdot\partial f_\alpha^{(0)}/\partial\mathbf{p}}{\omega - \mathbf{k}\cdot\mathbf{p}/\gamma}d^3p$$

$\gamma(p_x,p_y,p_z)$ couples de 3 directions,
can't separate the integral, 2D not equiv. to 3D

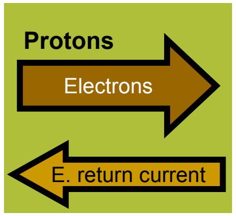
Cold regime (DF Dirac δ's) and no B0

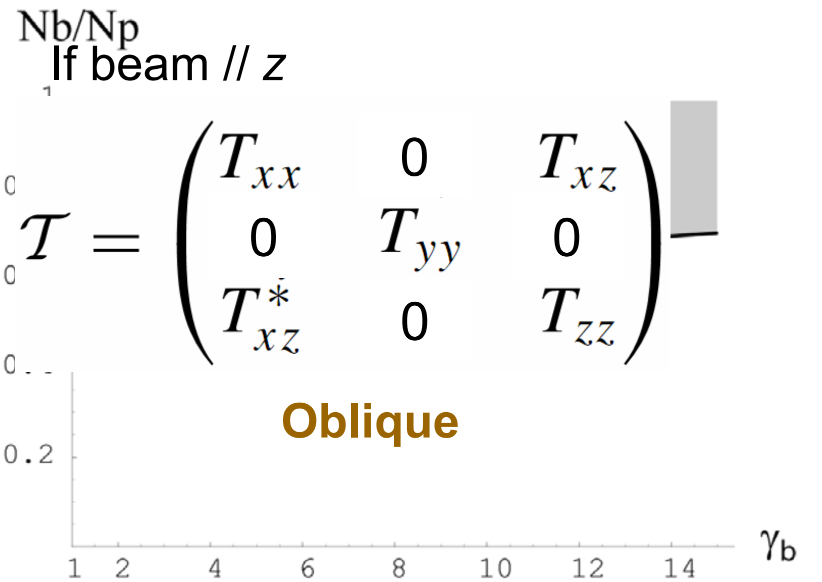
Spectrum (just 1 branch)

Nb /Np=1/9 , Vb=0.9c
From Karmakar, PRE, 2009



Hierarchy





If beam // z

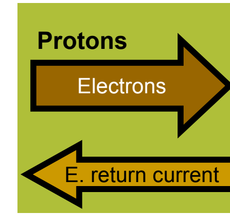
$$\mathcal{T} = \begin{pmatrix} T_{xx} & 0 & T_{xz} \\ 0 & T_{yy} & 0 \\ T_{xz}^* & 0 & T_{zz} \end{pmatrix}$$

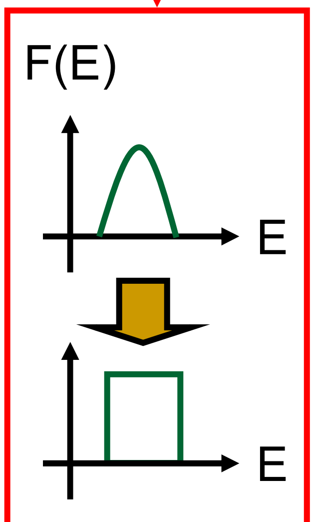
Oblique

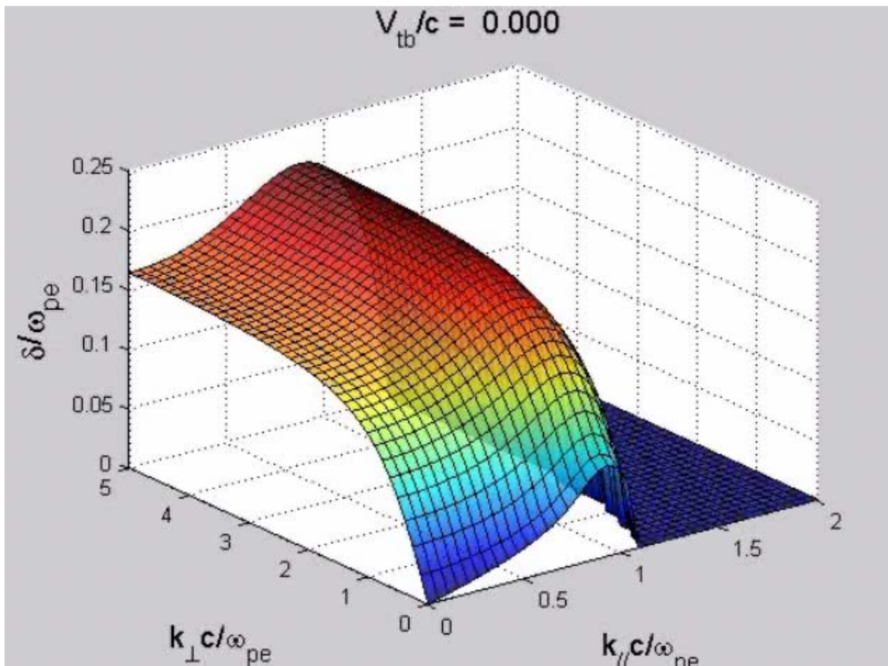
Fainberg, et al, Sov. Phys. JETP 30, 528 (1970).
Califano, et al, Phys. Rev. E 58, 7837 (1998).
Bret, PoP 12, 082704, (2005)

Kinetic effects (still no B_0)

- **Waterbag** calculation (10 s CPU instead of 3 weeks).
  $N_b/N_p = 0.1$, $\gamma_b = 4$



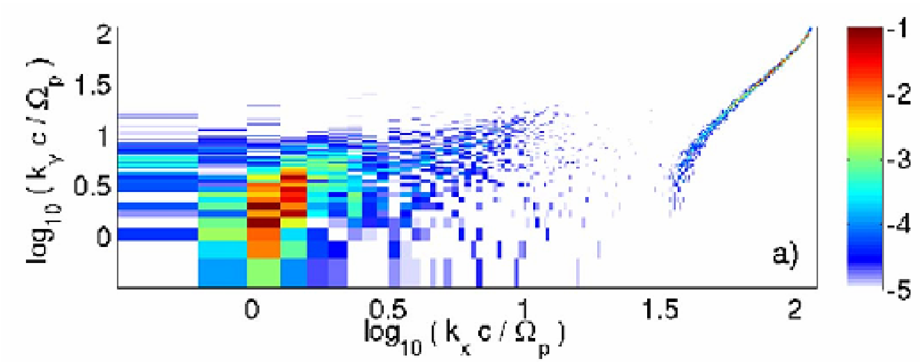




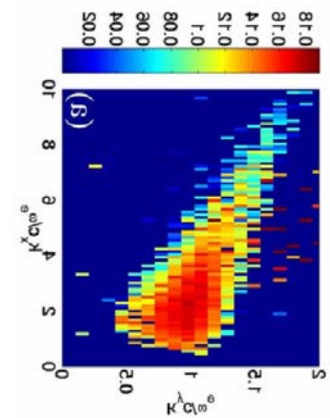
Beam Temp.
first stabilizes Weibel &
modes with $k_\perp >> k_{//}$

L.O. Silva et al., Bull. Am. Phys. Soc. 46, 205 (2001)

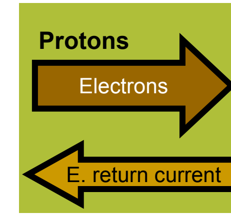
Waterbag model: PIC's confirmations

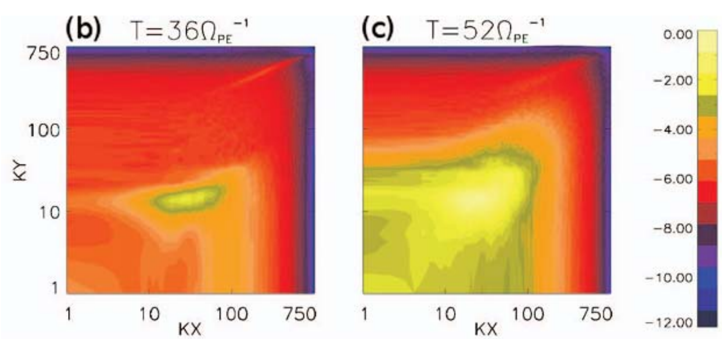


Dieckmann, PoP, 2006

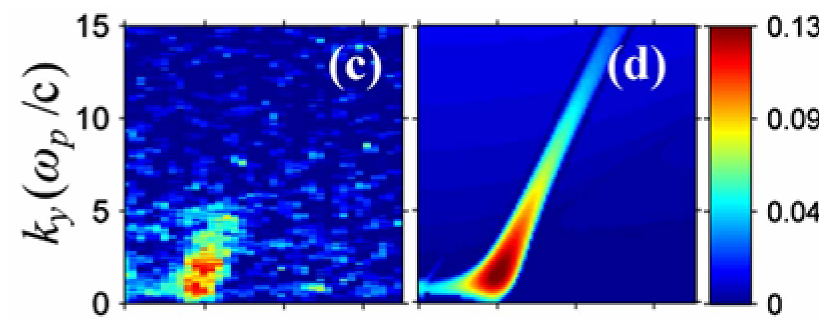


Gremillet, PoP, 2007





Frederiksen, PoP, 2008

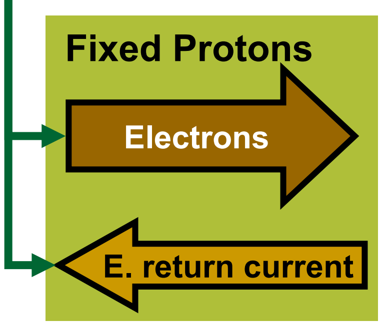


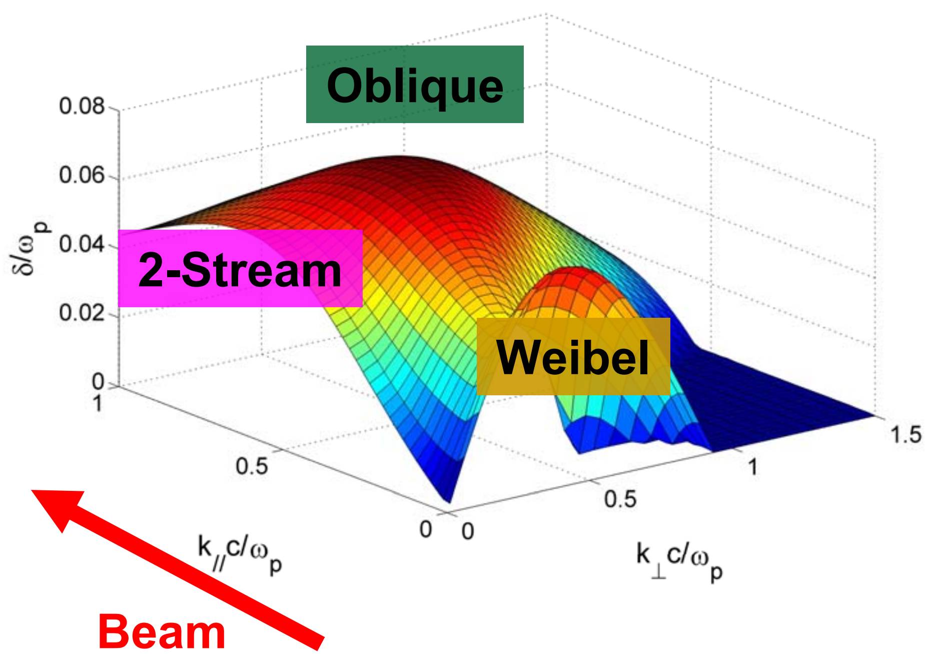
Kong, PoP, 2009

Kinetic regime (still no B_0)

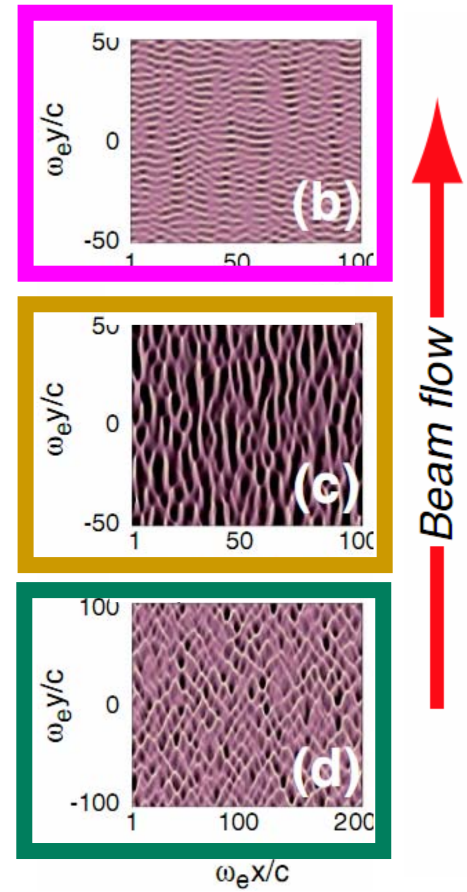
- Typical spectrum and generated patterns

$$f_\alpha^0(\mathbf{p}) = \frac{\mu_\alpha}{4\pi\gamma_\alpha^2 K_2(\mu_\alpha/\gamma_\alpha)} \exp[-\mu_\alpha(\gamma(\mathbf{p}) - \beta_\alpha p_y)]$$





IF dominant…

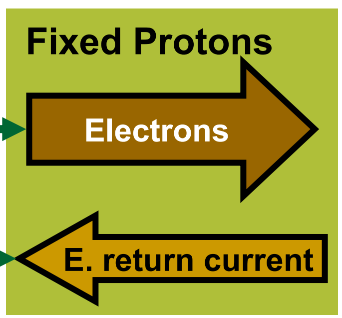


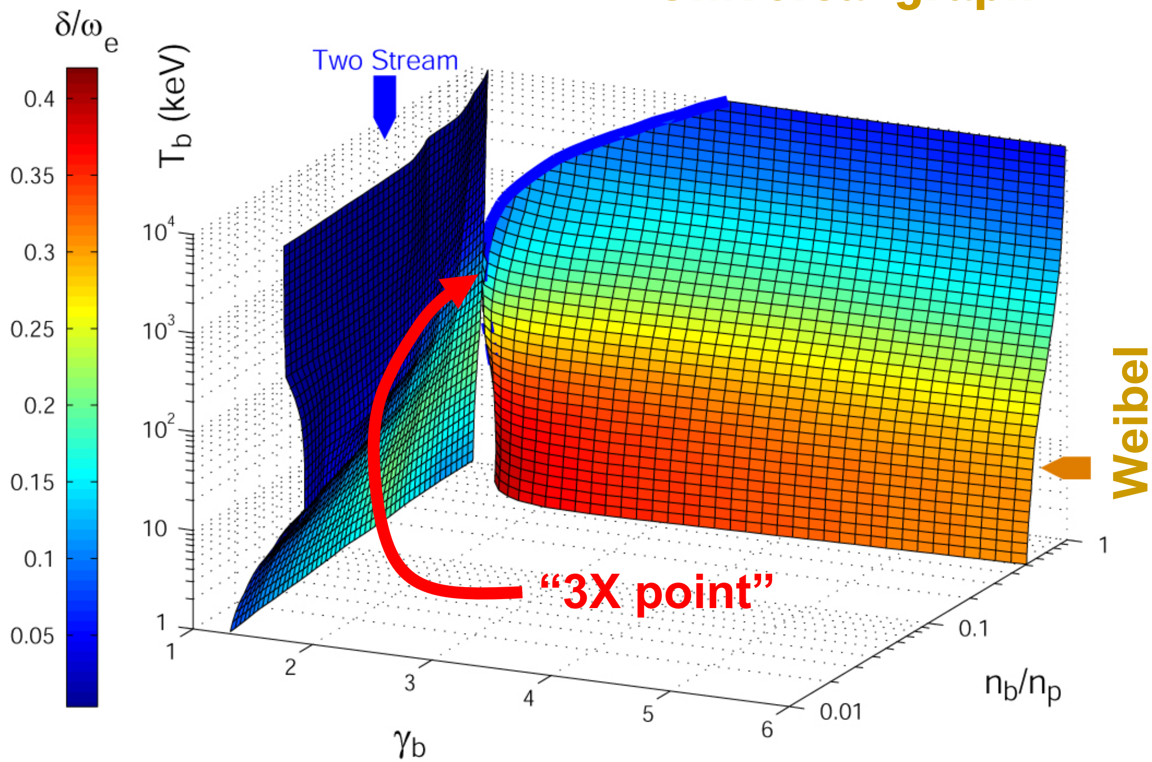
Kinetic regime (still no B_0) – Modes hierarchy

$$f^0_\alpha(\mathbf{p}) = \frac{\mu_\alpha}{4\pi\gamma_\alpha^2 K_2(\mu_\alpha/\gamma_\alpha)} \exp[-\mu_\alpha(\gamma(\mathbf{p}) - \beta_\alpha p_y)]$$

T_plasma: 5 keV

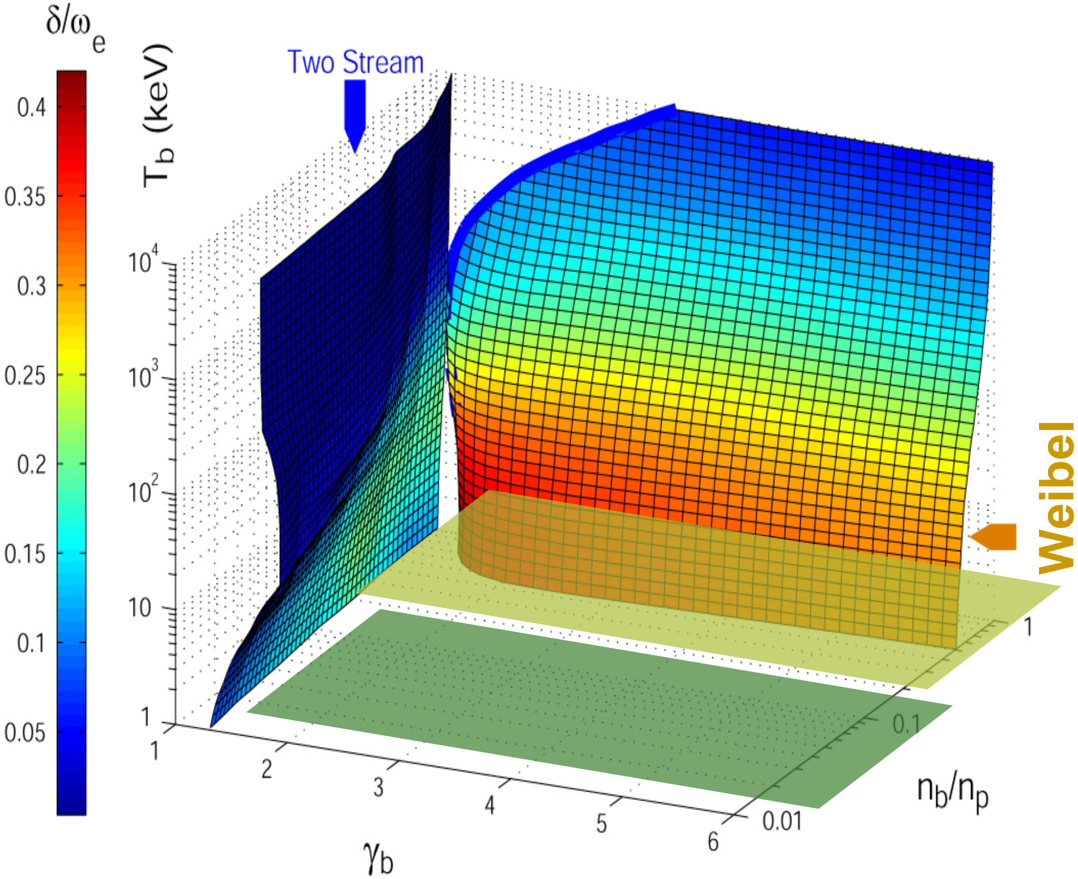
Universal graph





A. Bret et al., PRL 100, 205008 (2008).

Shock physics context

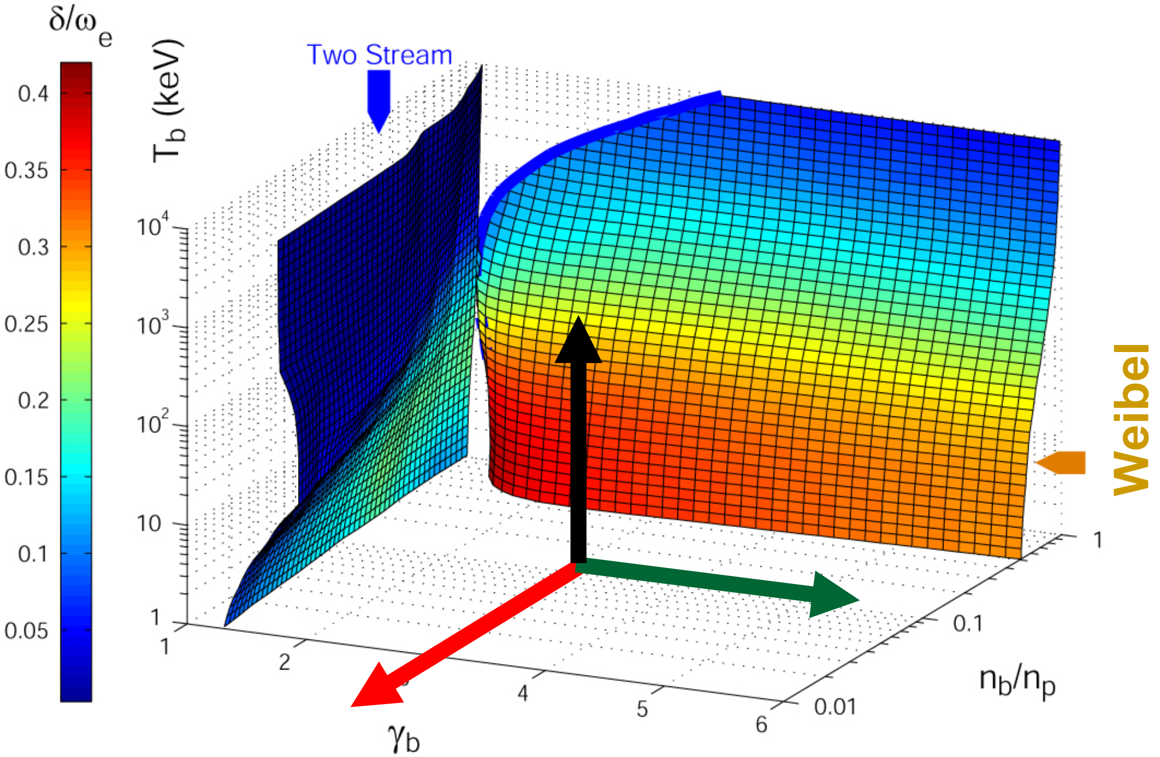


- Shock formation
  - Weibel
  - Oblique
- Particle acceleration
  - Oblique (Sironi, Silva…)

Oblique modes: Growth rate scalings

- Oblique modes govern in the following limits:
  - $N_b/N_p \rightarrow 0$
  - $T_b \rightarrow \infty$
  - $\gamma_b \rightarrow \infty$

Limits are relevant as Oblique modes keep governing



Oblique modes: Growth rate scalings

- Oblique modes similar to Two-stream ones:

Parameters	Two-stream	Oblique
T_b	T_b^{-1}	T_b^{-1}
γ_b	γ_b^{-1}	$\gamma_b^{-1/3}$
n_b/n_p, $\boxed{\text{low } T_b}$	$(n_b/n_p)^{1/3}$	$(n_b/n_p)^{1/3}$
n_b/n_p, $\boxed{\text{large } T_b}$	n_b/n_p	n_b/n_p

Only difference

Fluid

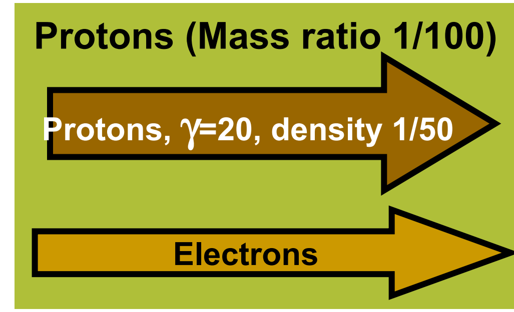
Kinetic

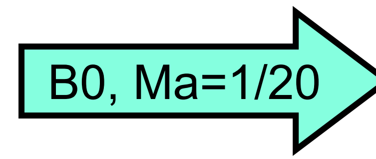
$$\boxed{\frac{T_b}{m_e c^2} > \gamma_b \left(\frac{n_b}{n_p}\right)^{2/3}}$$

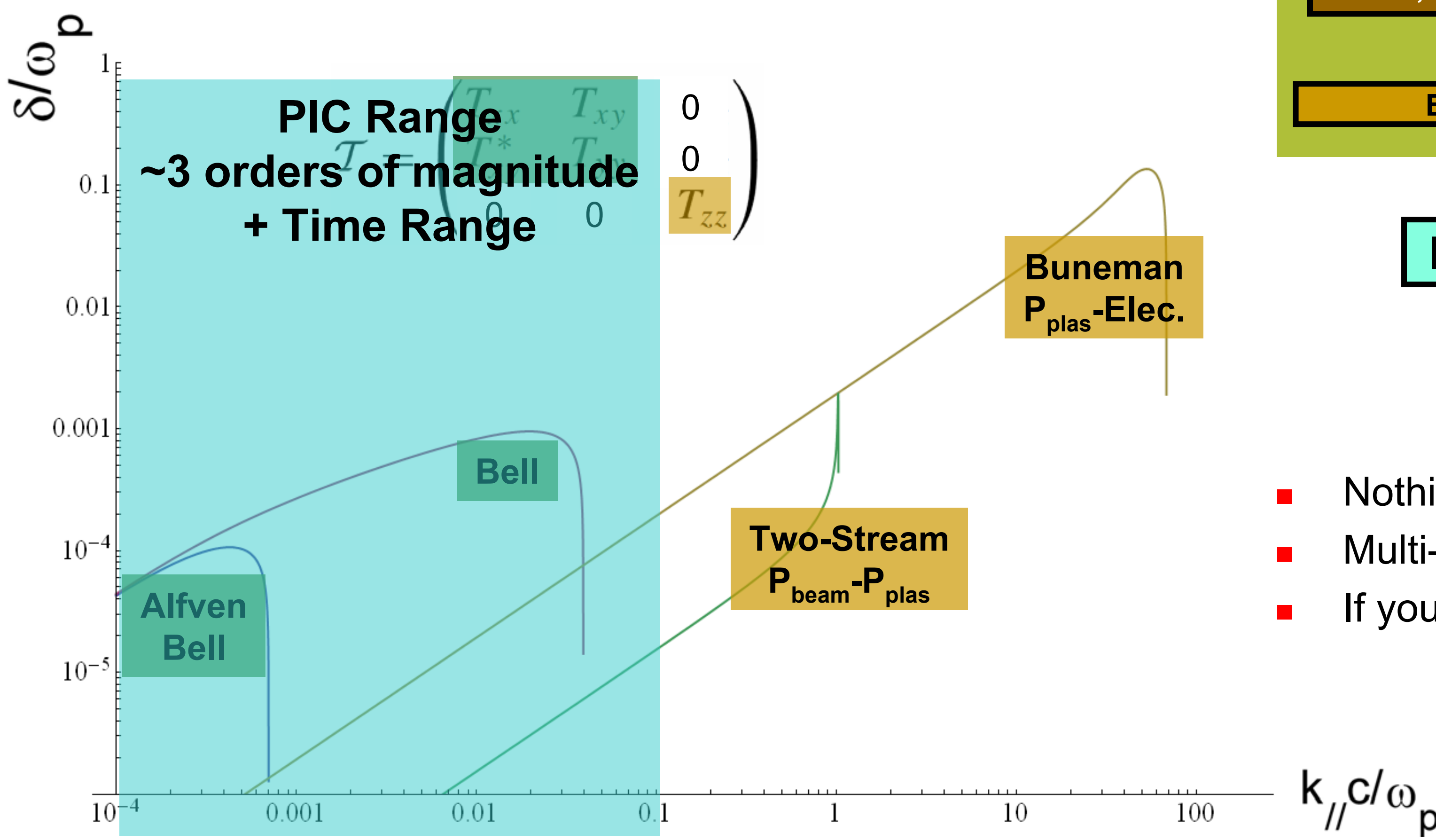
A. Bret, Gremillet L, In Preparation

Proton beam – Magnetized, cold

- Flow aligned **k**'s, // *z*



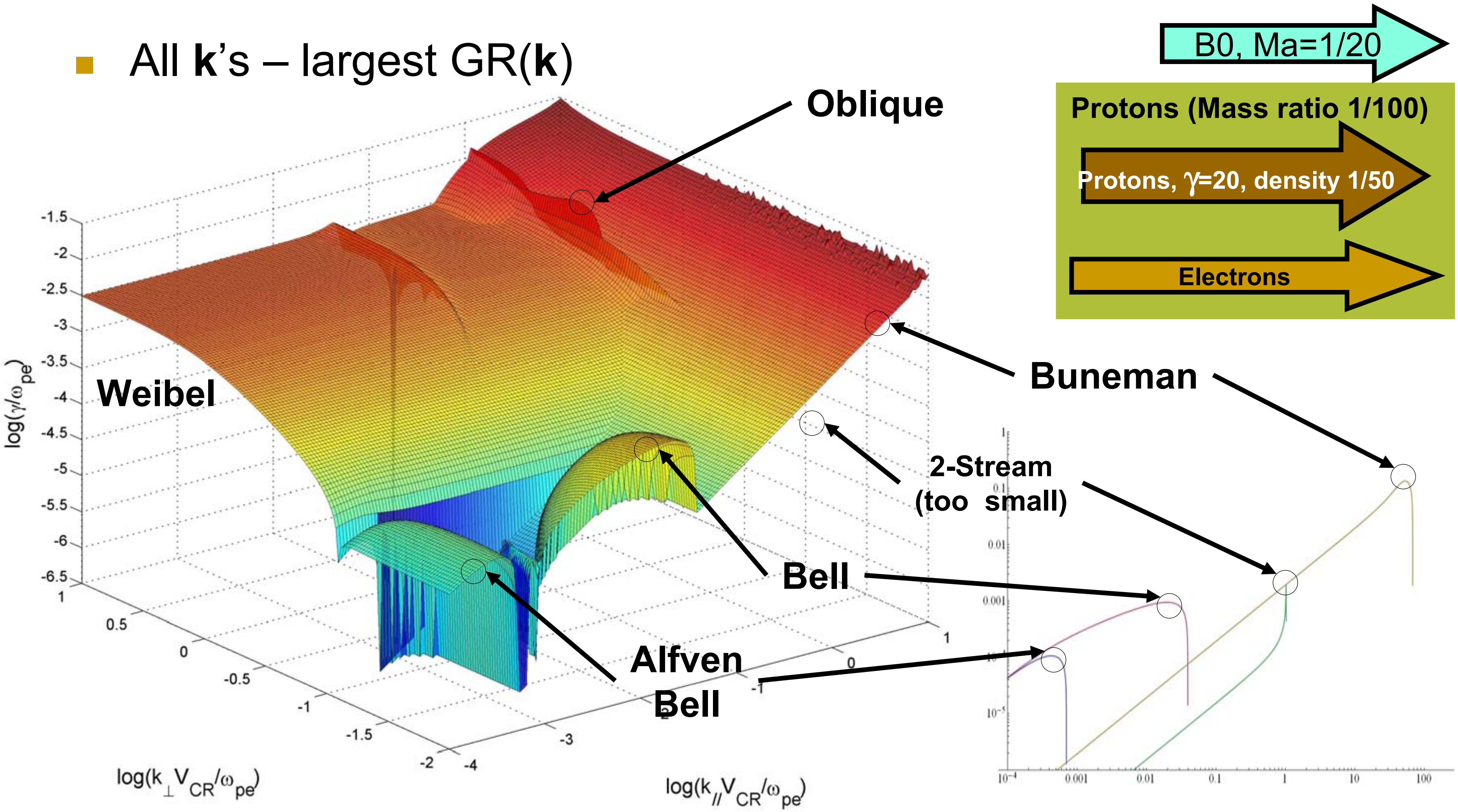




- Nothing more
- Multi-scale (PICs !)
- If you want your insta…

Proton beam – Magnetized, cold

- All **k**'s – largest GR(**k**)



Conclusions

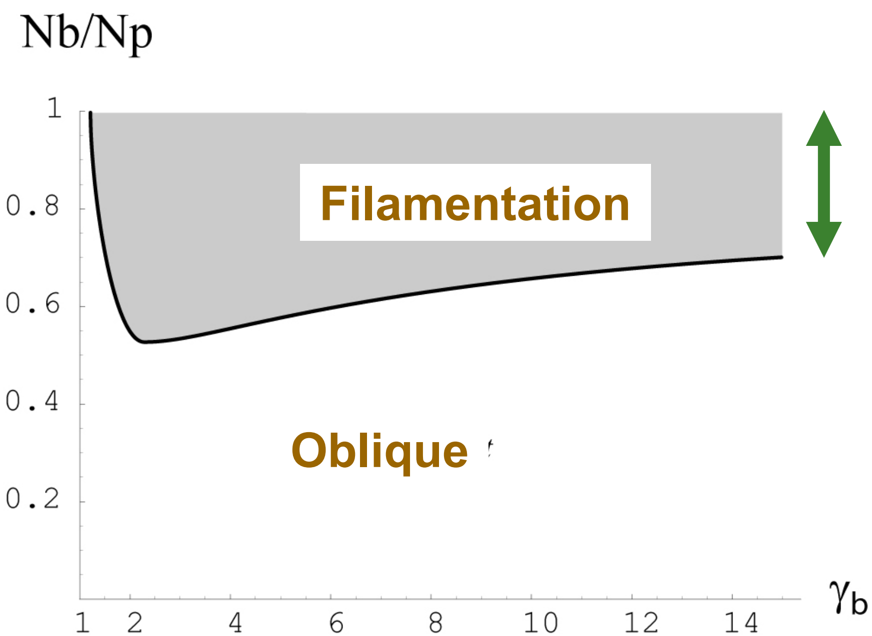
- Beam plasma instabilities are relevant for:
  - Shock Formation (the trigger),
  - Particle acceleration.
- The simplest system (no B_0, fixed ions, e-beam+RC) has been analyzed thoroughly, including in the kinetic regime
- Shock Formation: comparable density shells. Weibel/Oblique dominant.
- Particle Acceleration: Diluted beam regime, Oblique modes.
- System with CR, B_0: rich, multi-scale spectrum.

THANK YOU

Shock Physics: Formation

- Typical scenario: colliding shells.
- PIC scheme: Plasma interact with itself
  -> equal density shells (Fila/Weibel)

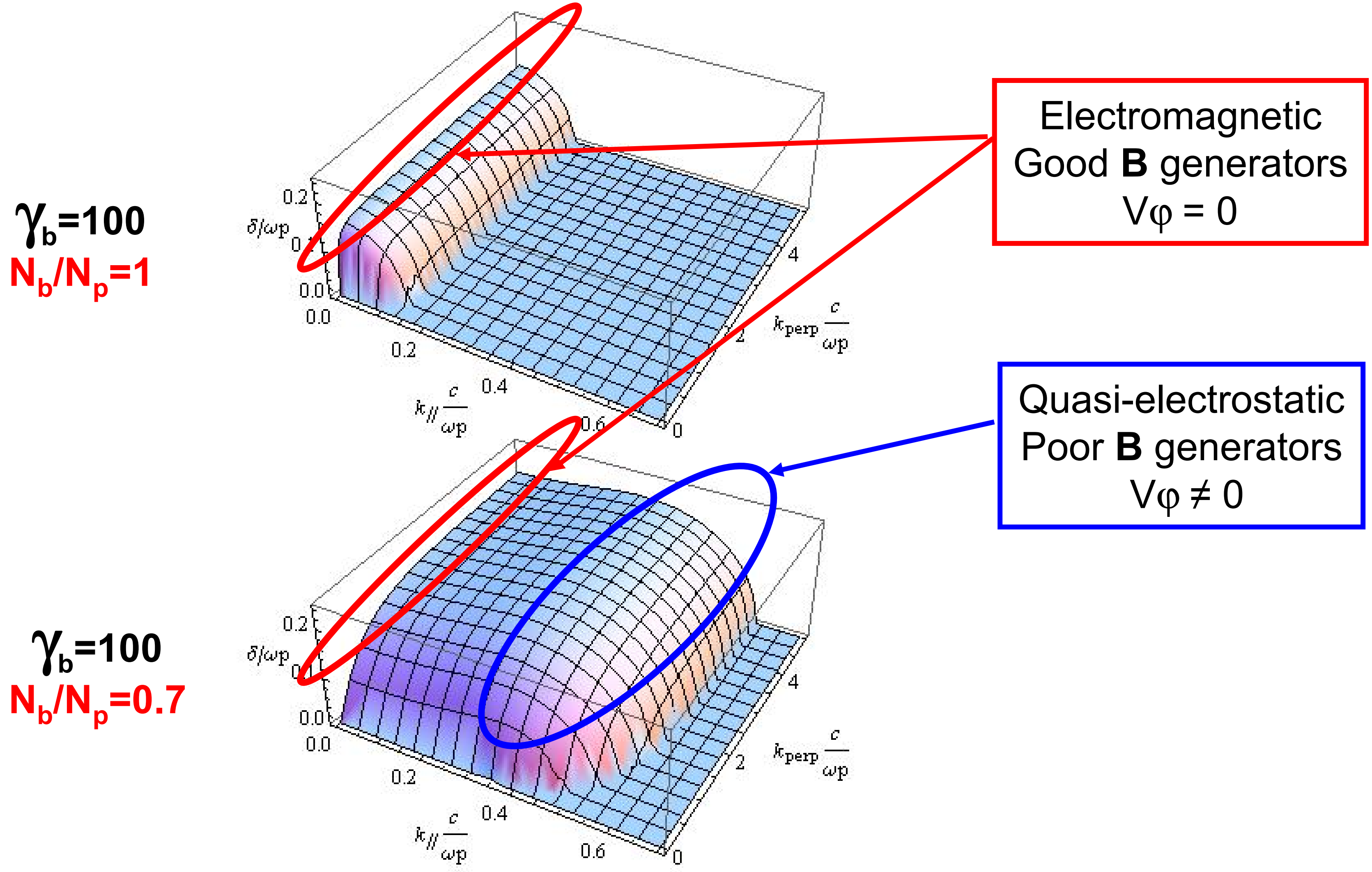
- What if different density shells?
- If un-magnetized, pair plasmas, or e-protons:



$\propto \gamma_b^{-1/3}$

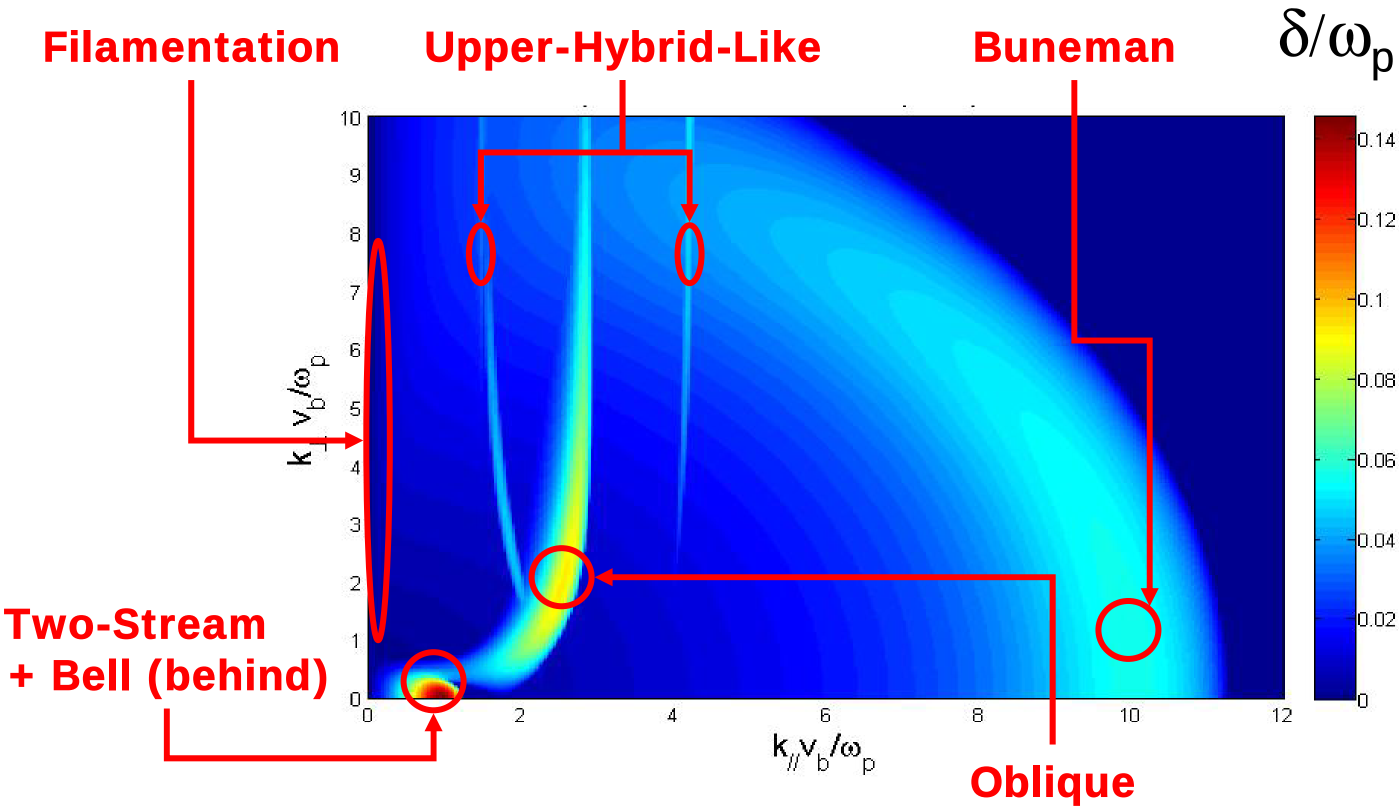
Fila. may not govern high γ_b collisions of slightly ≠ density shells.
Shock Formation?

Shock Physics: Formation



Shock Physics: Particle acceleration

- Relativistic, diluted, e-beam/plasma interaction, **B_0 // Flow**.
- Typical sprectrum:



$N_b/N_p=0.1$
$\gamma_b=2$
$\omega_B=2\omega_p$
$Mp/Me=1836$
$T=0$
$(\omega_B = qB_0/M_ec)$

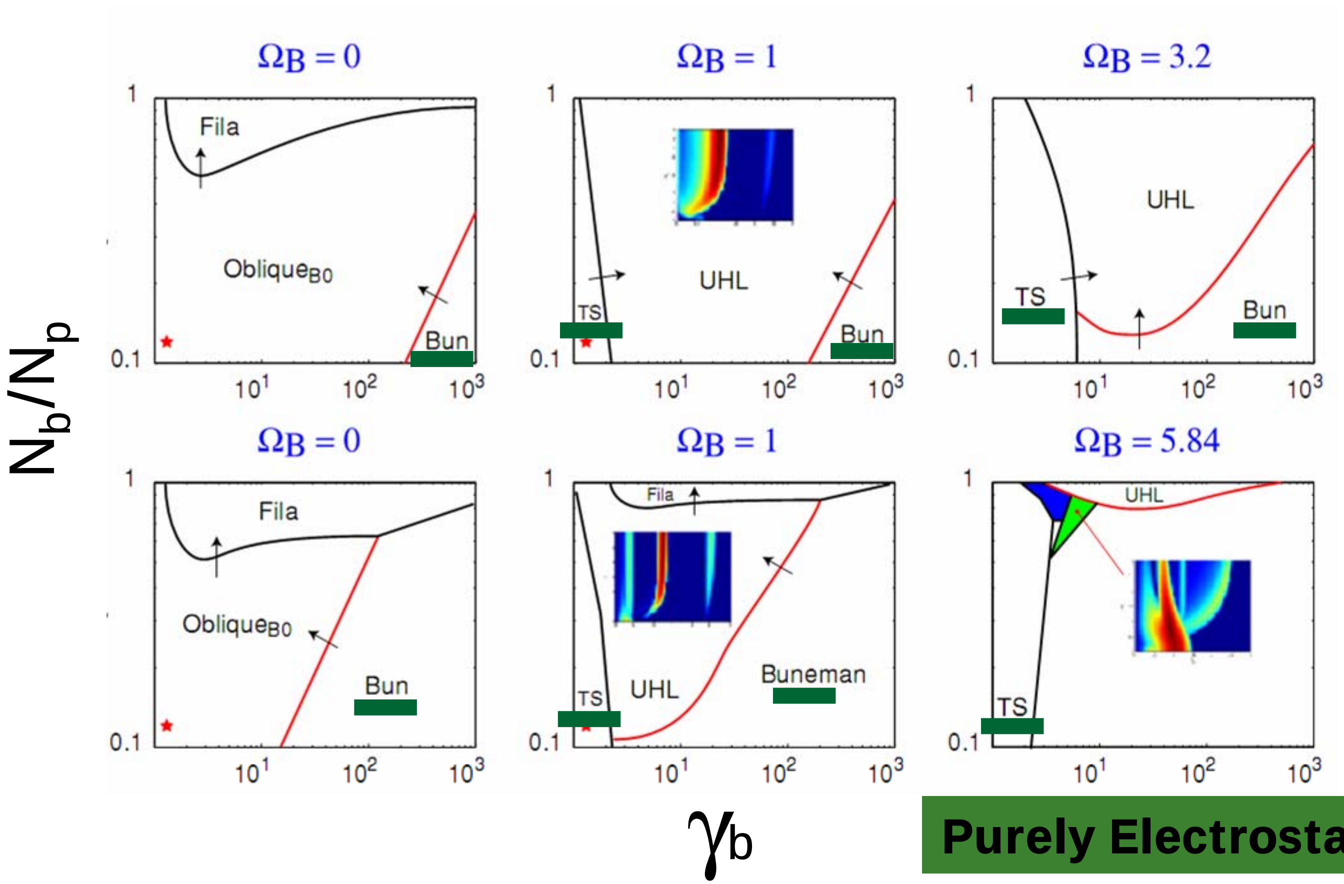
Bret, ApJ, 2009

For a thorough analysis of $B_0 \perp$ Flow case, see:
Lemoine & Pelletier, MNRAS, *In Press* - arXiv:0904.2657

Shock Physics: Particle acceleration

- Consider a relativistic, diluted, e-beam/plasma interaction.
- Dominant mode:

$\Omega_B = \omega_b / \omega_p$



Mp/Me=1836

Mp/Me=100

Purely Electrostatic Instabilities

Bret, ApJ, 2009

Outline of the Talk

- System considered
- Plasma instabilities and relativistic shocks
  - Shock Formation
  - Particle acceleration
- Oblique Modes – Cold and Waterbag results
- Kinetic theory of Oblique Modes
  - Scaling laws for the Growth Rate
- Non-parallel flows
- Conclusions