CHALMERS
UNIVERSITY OF TECHNOLOGY

DREAM

Five flavours of hottail formation

O. Embreus and M. Hoppe

Flattop plasma ("ASDEX-like"):

- Core temperature of 5.5 keV
- Pure deuterium plasma with uniform $n_e = 2.6 \times 10^{19}\,\mathrm{m}^{-3}$
- $R_0 = 1.65\,\mathrm{m}$, $a = 0.5\,\mathrm{m}$
- $I_p = 800\,\mathrm{kA}$, $\left[j_{\|}/B = (j_0/B_{\mathrm{min}})(1-(r/a)^4)^{3/2}\right]$
- Elongation $\kappa \in [1, 1.15]$

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Disruption induced by instantaneous deposition of deuterium-argon mixture:

- Uniform density $n_{Ar} = 7.8 \times 10^{18}\,\mathrm{m}^{-3}$, $n_D = 2.6 \times 10^{20}\,\mathrm{m}^{-3}$
- Constant heat diffusion $D = 4000\,\mathrm{m}^2/\mathrm{s}$.

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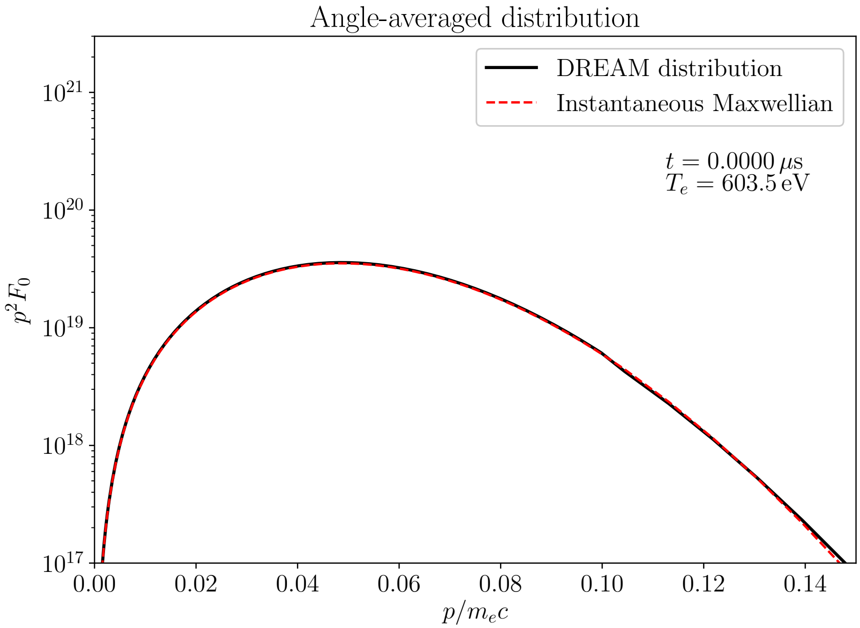
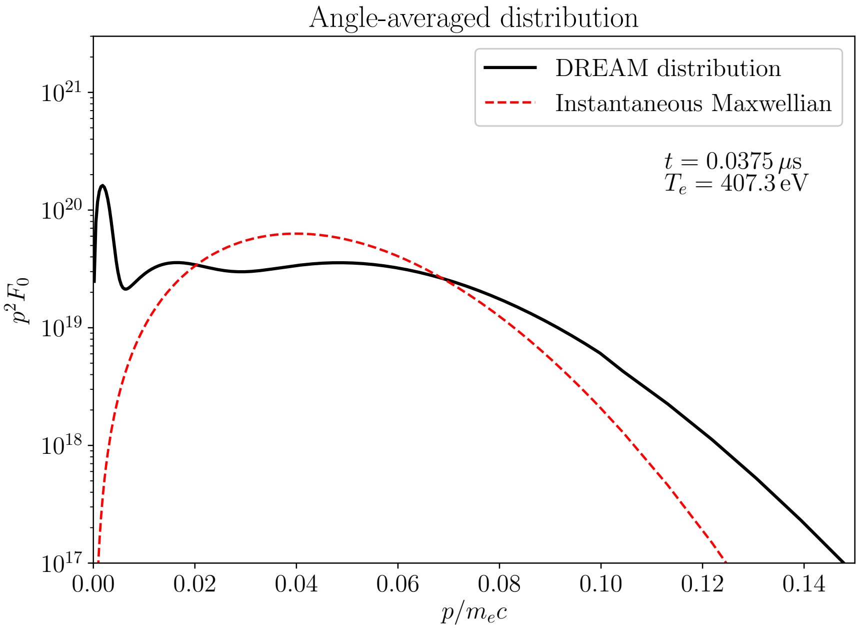
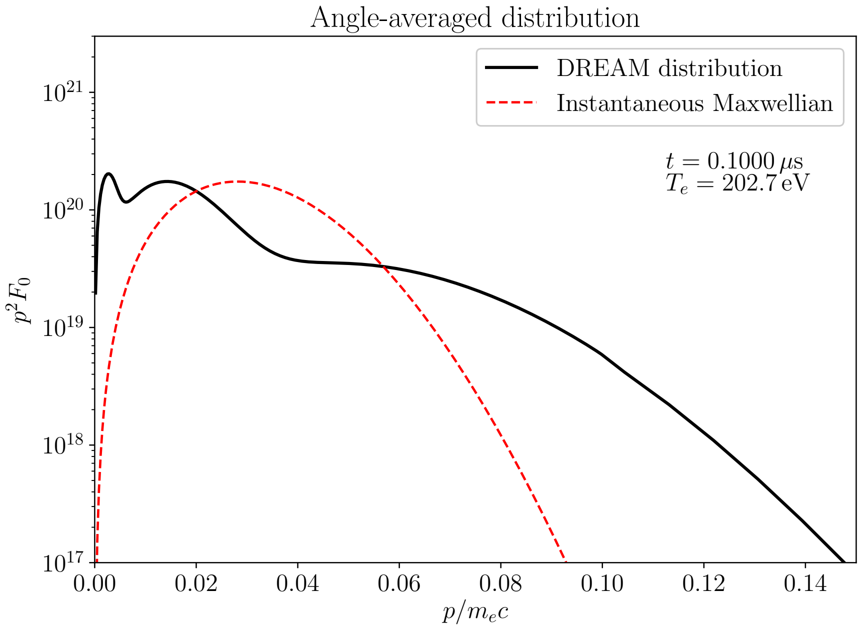
Kinetic electron model:

- Bounce averaged Fokker-Planck equation in zero-orbit-width limit
- Electric field acceleration and relativistic screened test-particle collisions
- Particle source ensuring density conservation
- Evolved self-consistently: Current density; electron and ion temperatures; electric field; ion charge states; poloidal flux

Conventional kinetic hottail model: "FULLY KINETIC"

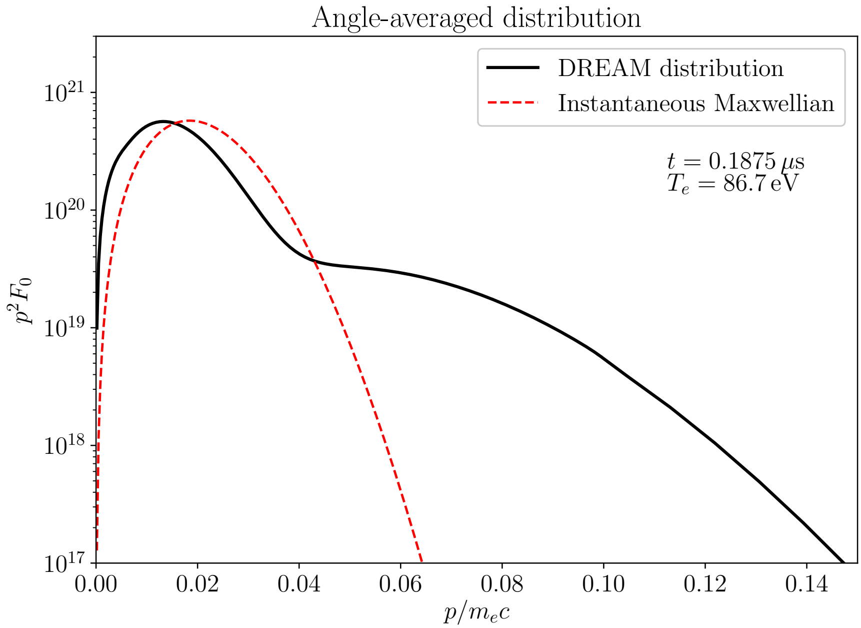



Angle-averaged distribution
DREAM distribution
Instantaneous Maxwellian
$t = 0.0375\,\mu$s
$T_e = 407.3\,$eV
$p^2 F_0$
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
$p/m_e c$

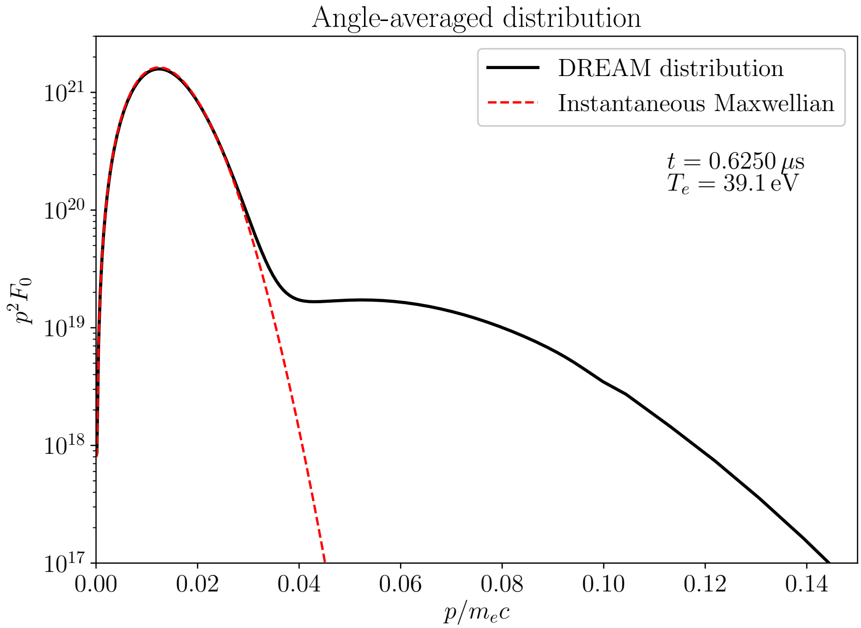


Angle-averaged distribution
DREAM distribution
Instantaneous Maxwellian
$t = 0.1000\,\mu$s
$T_e = 202.7\,$eV
p^2F_0
10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
p/m_ec

Conventional kinetic hottail model: "FULLY KINETIC"



Conventional kinetic hottail model: "FULLY KINETIC"



- Until thermal collapse is well underway, single temperature description not accurate
- Non-linear electron collisions appear needed to describe the dynamics

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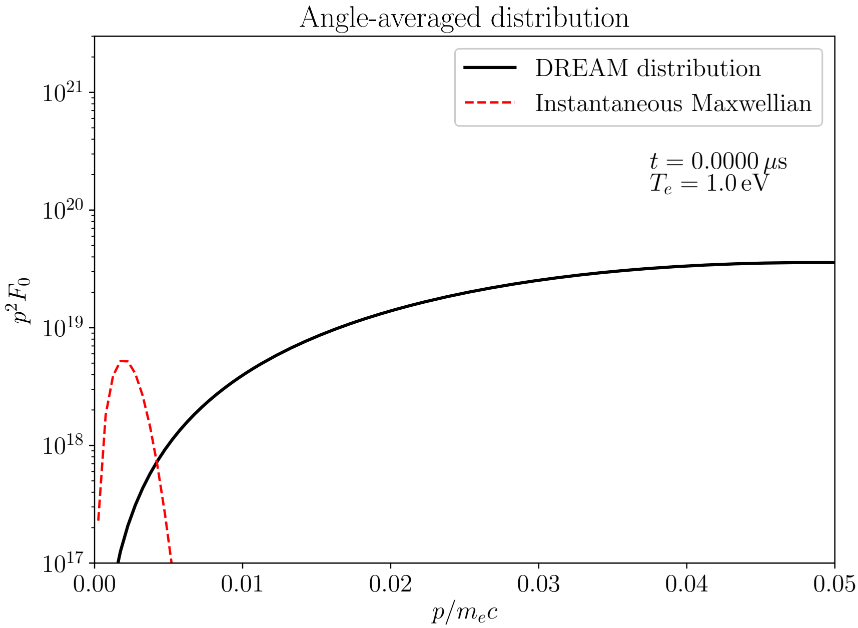
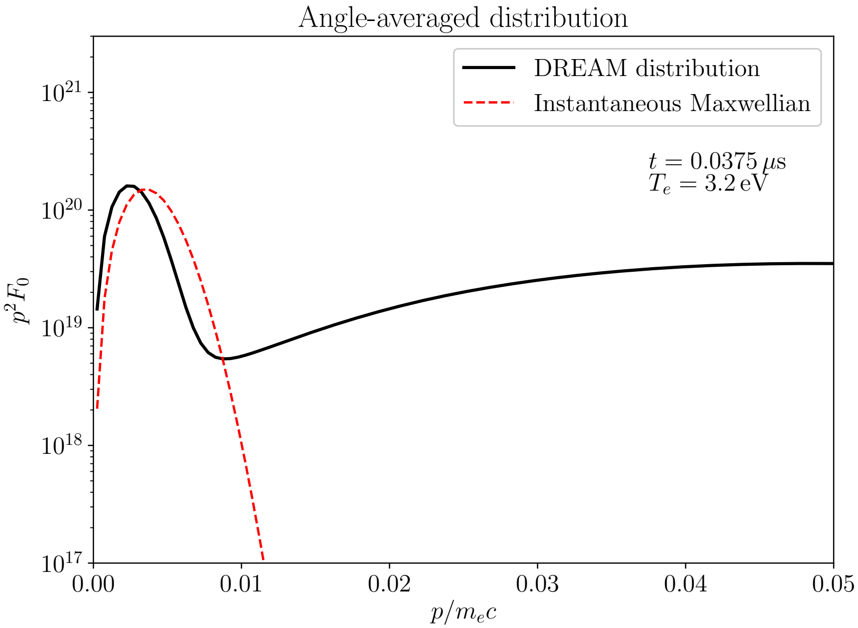
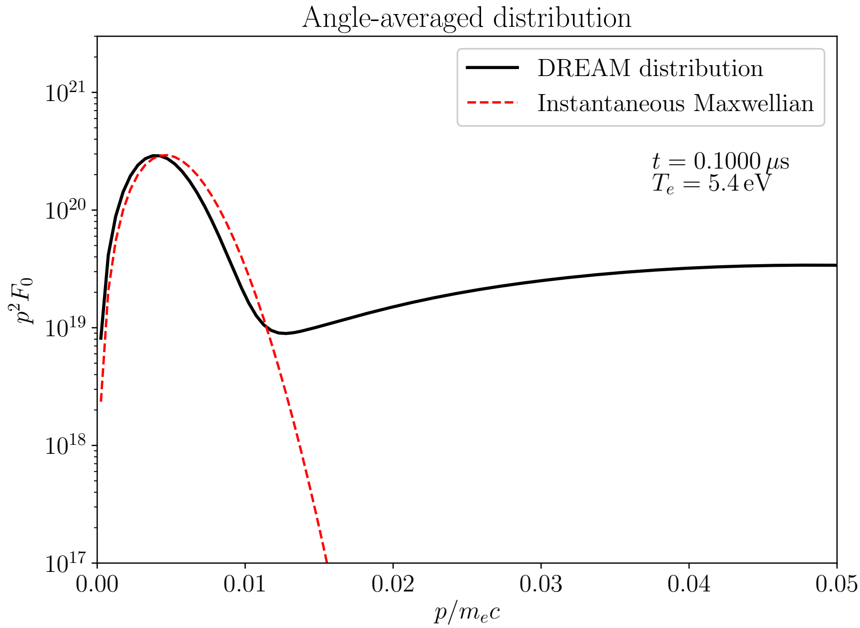
- Non-linear electron collisions appear needed to describe the dynamics

Aleynikov & Breizman (NF 2017) presented an alternative picture:

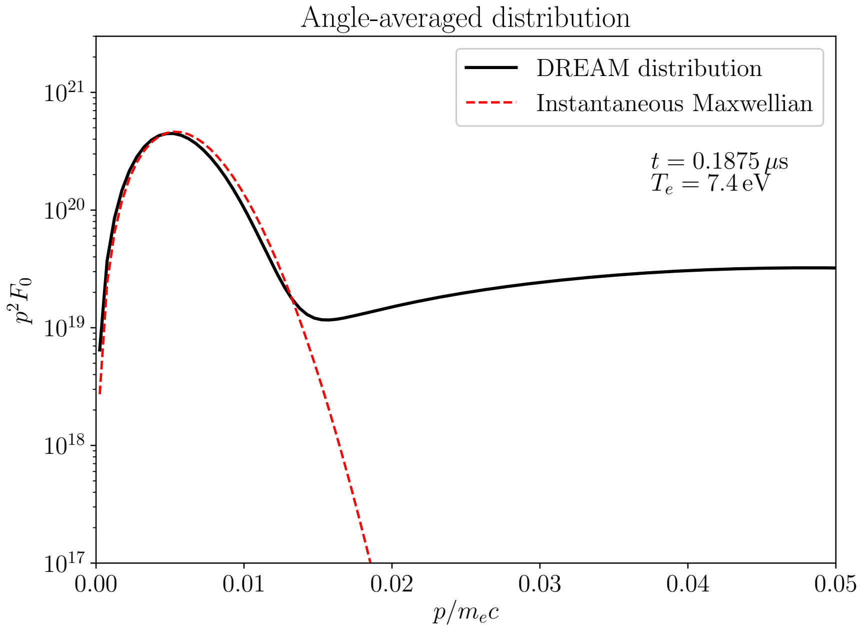
- Self-collisions among newly ionized electrons sufficiently fast to form cold Maxwellian
- Fluid electron density and temperature should represent that of newly ionized electrons (initialized at $n = T = 0$)
- Hot-tails form a second electron population which exchange energy with these *cold* electrons (+ ionize them)
- Energy still approximately conserved – eventually the approaches should end up at $\approx$ same temperature

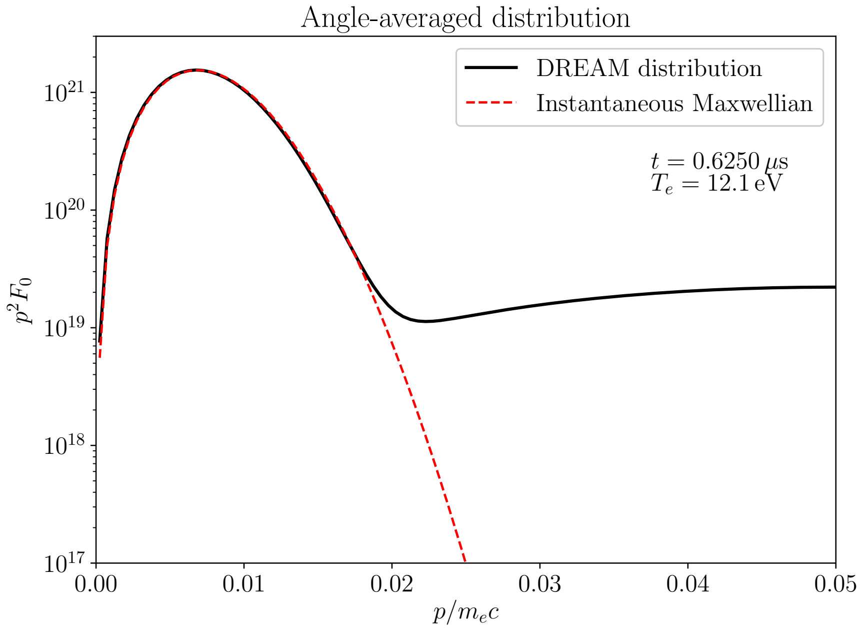

Angle-averaged distribution
DREAM distribution
Instantaneous Maxwellian
$t = 0.0000\,\mu$s
$T_e = 1.0\,$eV
$p^2 F_0$
10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
0.00
0.01
0.02
0.03
0.04
0.05
$p/m_e c$


Angle-averaged distribution
DREAM distribution
Instantaneous Maxwellian
$t = 0.0375\,\mu$s
$T_e = 3.2\,$eV
10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
$p^2 F_0$
0.00
0.01
0.02
0.03
0.04
0.05
$p/m_e c$

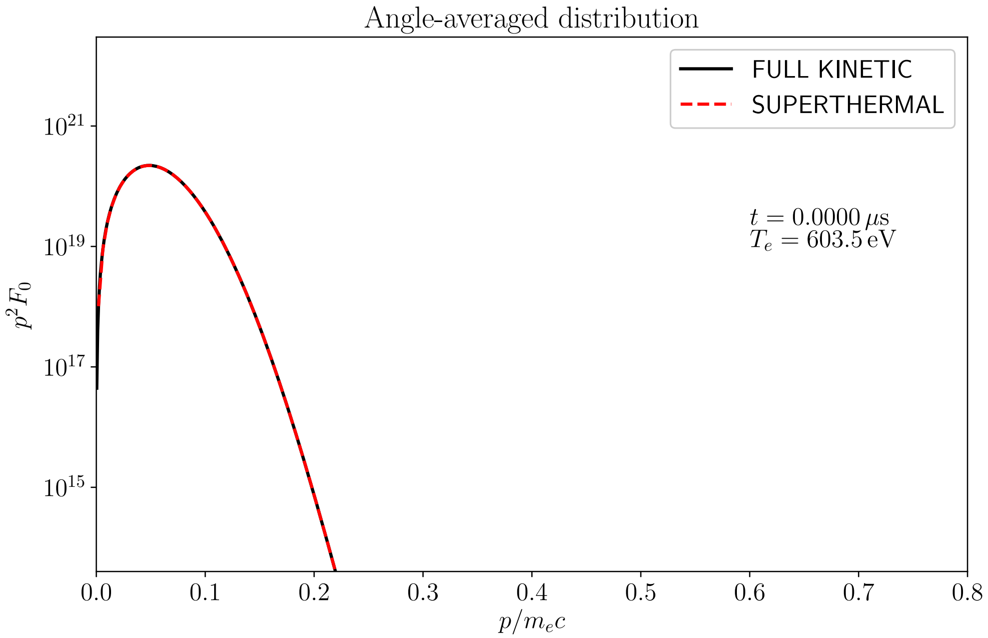

Angle-averaged distribution
DREAM distribution
Instantaneous Maxwellian
$t = 0.1000\,\mu$s
$T_e = 5.4\,$eV
$p^2 F_0$
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
0.00
0.01
0.02
0.03
0.04
0.05
$p/m_e c$

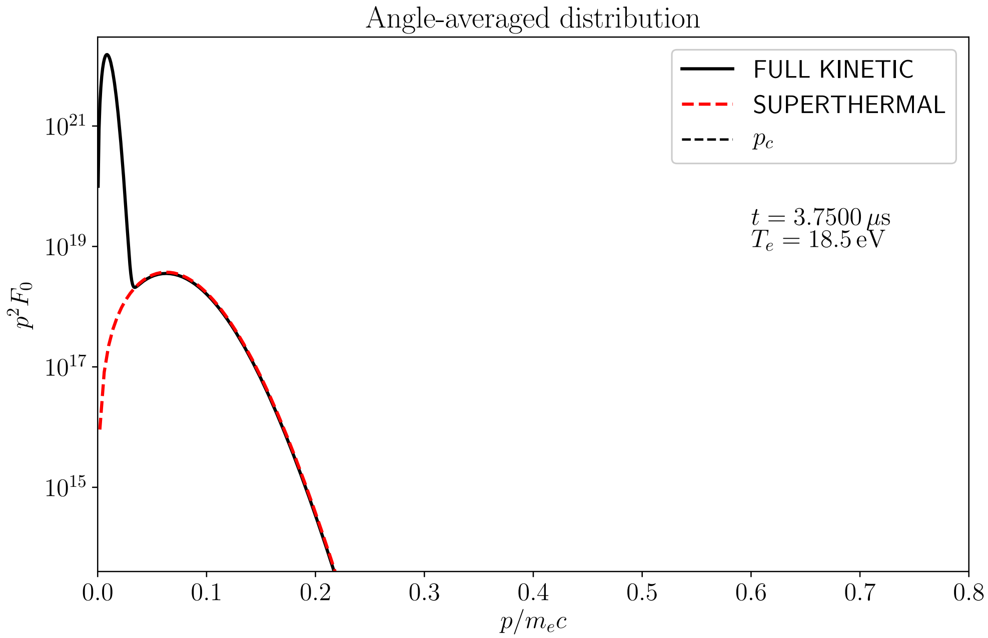
Modified kinetic hottail model: “2-ELECTRON KINETIC”

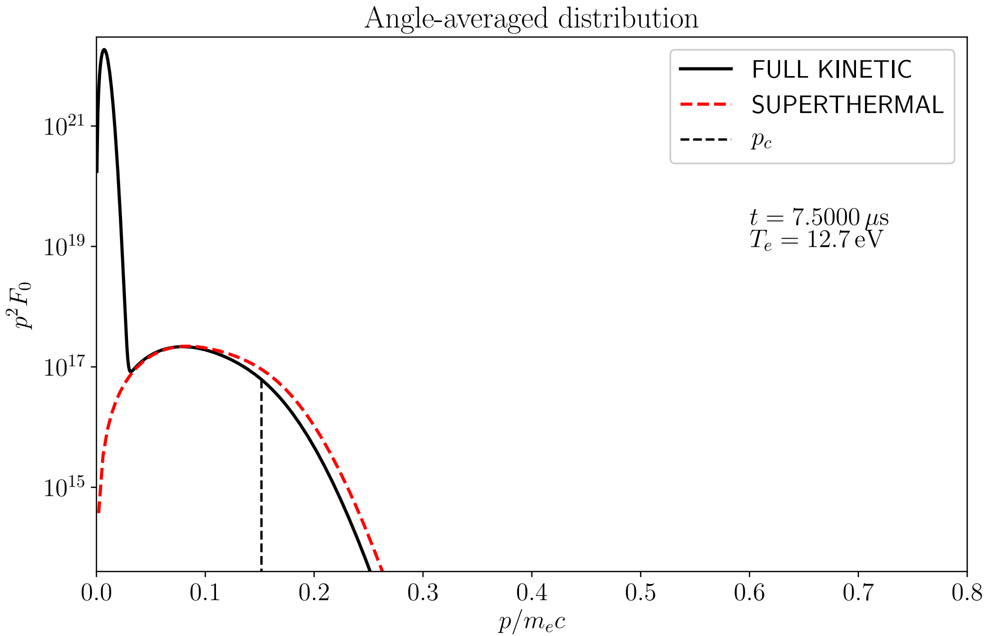



Angle-averaged distribution
DREAM distribution
Instantaneous Maxwellian
$t = 0.6250\,\mu$s
$T_e = 12.1$ eV
10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
$p^2 F_0$
0.00
0.01
0.02
0.03
0.04
0.05
$p/m_e c$

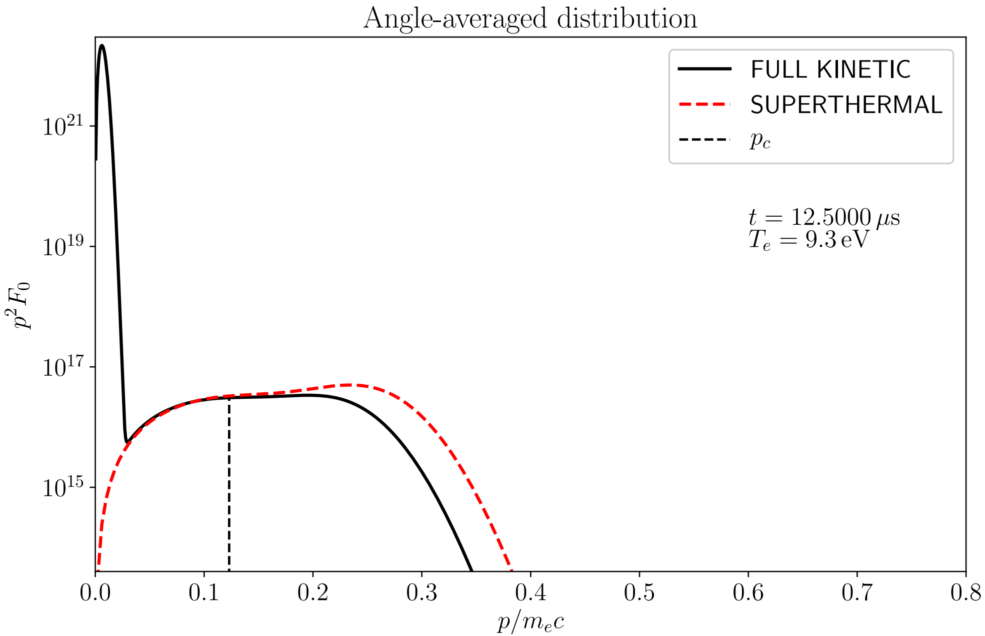
- “cold” population is essentially Maxwellian with $T \ll \langle W \rangle$: replace by fluid!
- Replace collision frequencies by superthermal limit
  - $\nu_s \propto n_{\text{cold}} / v^2 p$
  - $\nu_D \propto n_{\text{cold}} / v p^2$
- Natural particle sink in $p = 0$: join electron flux with n_{cold}
- $n_{\text{cold}} = \sum_i Z_i n_i - \int f_{\text{hot}} \, \mathrm{d}\boldsymbol{p} - n_{\text{RE}}$
- $j_{||} = \sigma(T_{\text{cold}}) E - e \int v_{||} f_{\text{hot}} \, \mathrm{d}\boldsymbol{p} + ecn_{\text{RE}}$

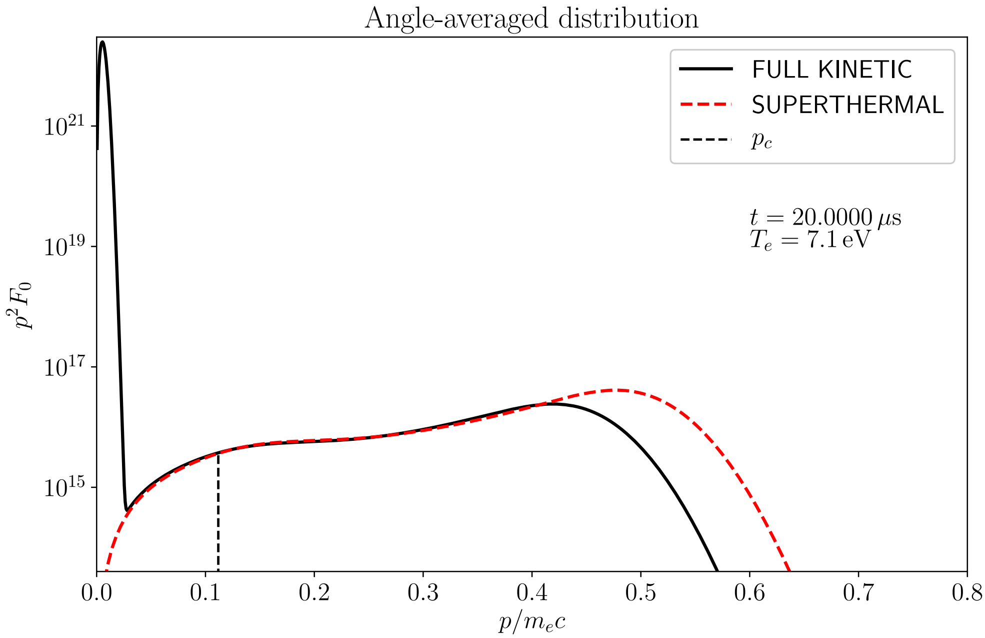

Angle-averaged distribution
FULL KINETIC
SUPERTHERMAL
$t = 0.0000\,\mu$s
$T_e = 603.5\,$eV
10^{21}
10^{19}
10^{17}
10^{15}
$p^2 F_0$
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
$p/m_e c$


Angle-averaged distribution
FULL KINETIC
SUPERTHERMAL
p_c
$t = 3.7500\,\mu$s
$T_e = 18.5\,$eV
10^{21}
10^{19}
10^{17}
10^{15}
$p^2 F_0$
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
$p/m_e c$

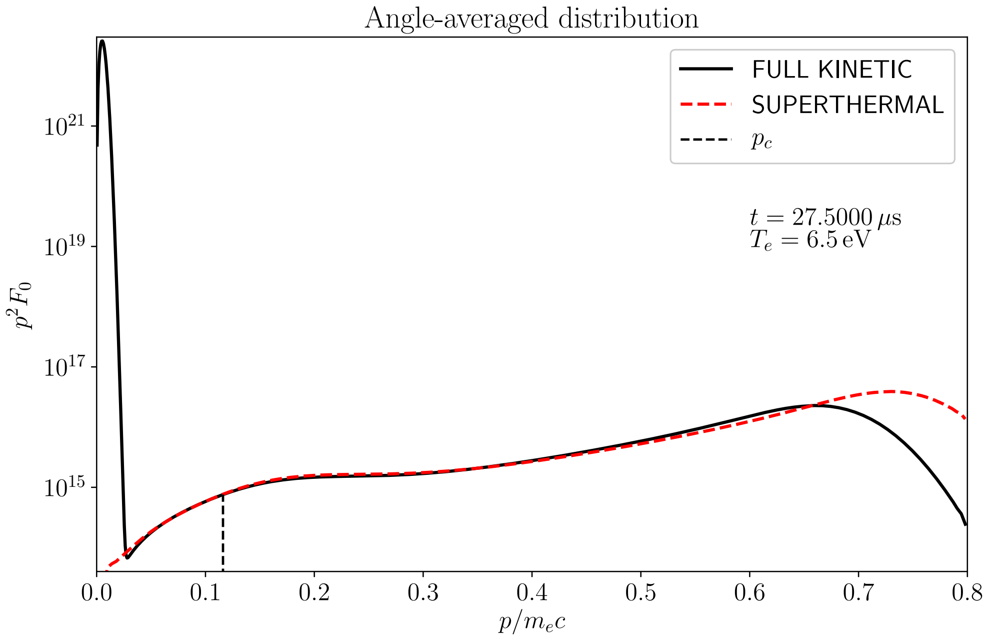

Angle-averaged distribution
FULL KINETIC
SUPERTHERMAL
p_c
$t = 7.5000\,\mu$s
$T_e = 12.7\,$eV
10^{21}
10^{19}
10^{17}
10^{15}
$p^2 F_0$
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
$p/m_e c$

Mixed fluid kinetic hottail model: "SUPERTHERMAL"




Angle-averaged distribution
FULL KINETIC
SUPERTHERMAL
p_c
$t = 20.0000\,\mu$s
$T_e = 7.1\,$eV
$p^2 F_0$
10^{21}
10^{19}
10^{17}
10^{15}
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
$p/m_e c$

Mixed fluid kinetic hottail model: “SUPERTHERMAL”



Approximations used to derive the avalanche growth rate [Rosenbluth & Putvinski 1997] can be applied to model hot tail:

- Asymptotic expansion with the ordering (“strong pitch-angle scattering”)

$$Z_{\text{eff}} = \mathcal{O}(1), \quad E = \mathcal{O}(\delta), \quad \text{[everything else]} = \mathcal{O}(\delta^2)$$

- Leading order equation: $f_0 = f_0(t, r, p)$ (isotropic)

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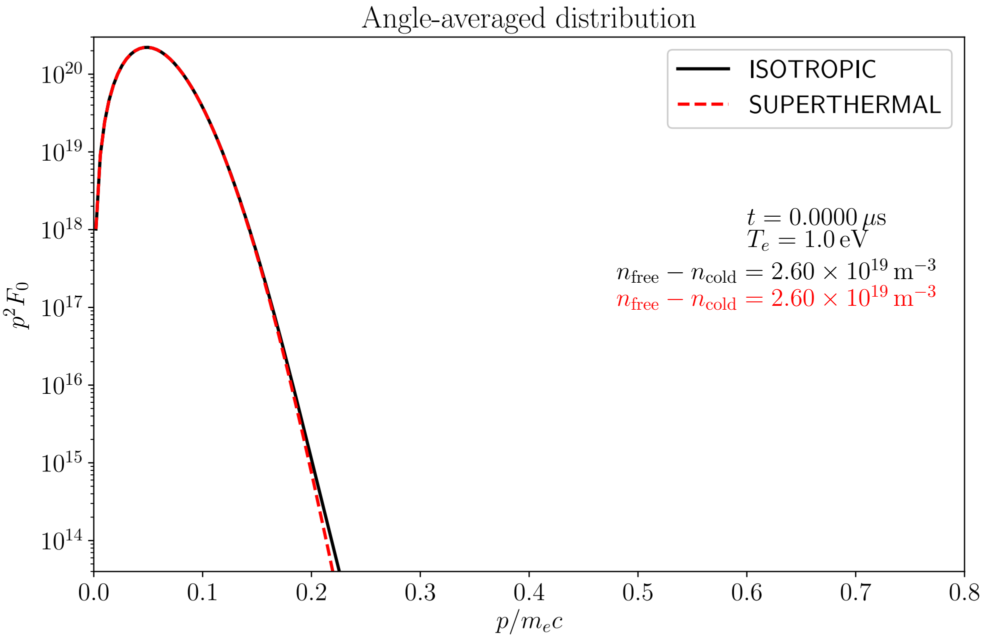
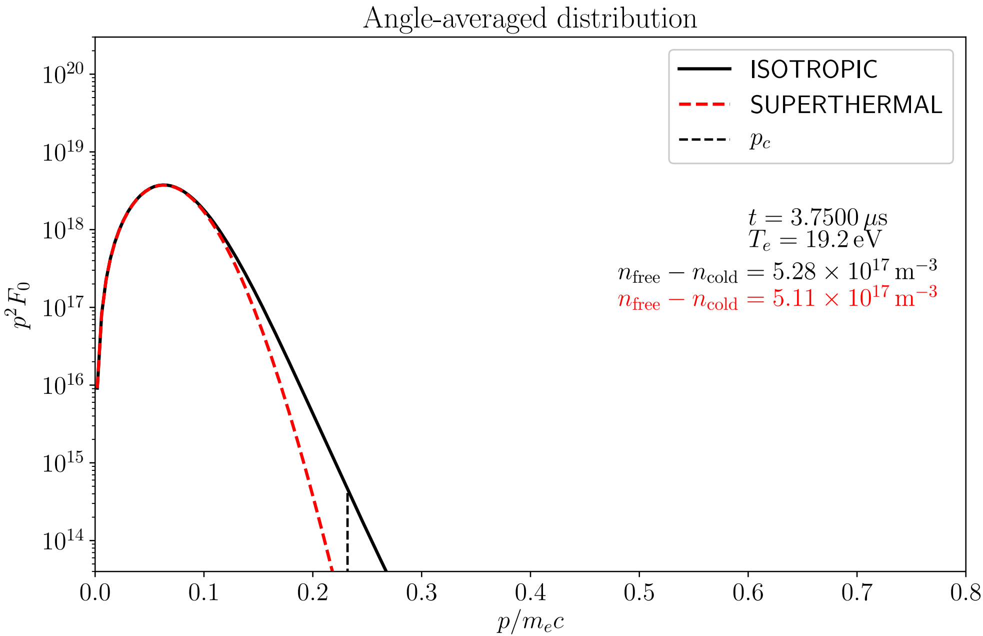
- Leading order equation: $f_0 = f_0(t, r, p)$ (isotropic)
- Next-order equation yields

$$\frac{1}{\mathcal{V}'}\frac{\partial(\mathcal{V}'\{eE_\parallel \boldsymbol{b}\cdot\nabla p^i\}f)}{\partial p^i} \mapsto -\int_0^{1/B_{\max}} \frac{\lambda \mathrm{d}\lambda}{\langle\sqrt{1-\lambda B}\rangle}\frac{(e\langle \boldsymbol{E}\cdot\boldsymbol{B}\rangle)^2}{4}\frac{1}{p^2}\frac{\partial}{\partial p}\left(\frac{p^2}{\nu_D}\frac{\partial f_0}{\partial p}\right)$$

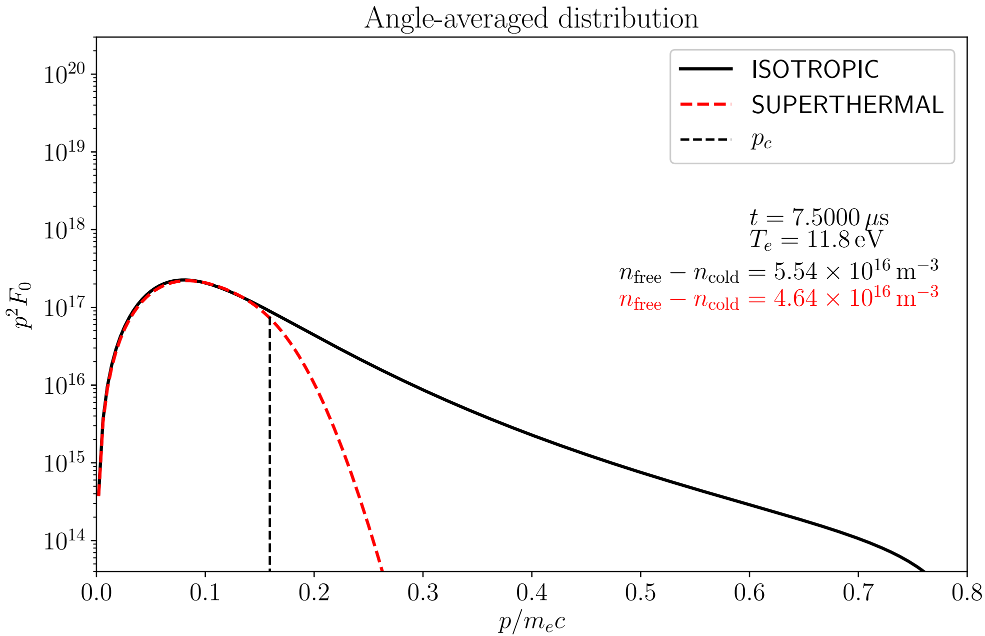
(bounce averaged E-field term becomes 1D energy diffusion term)

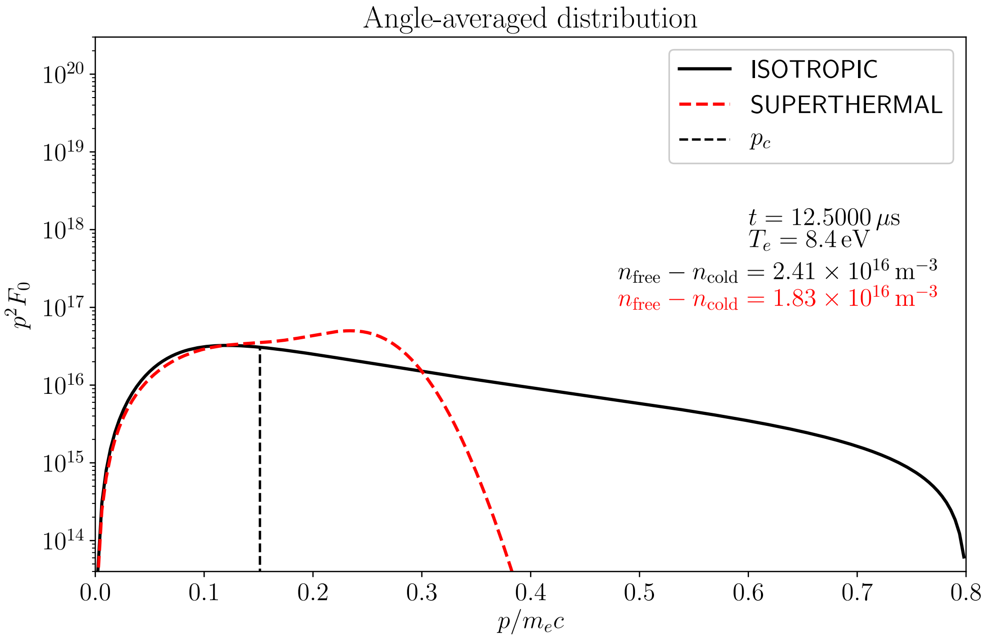


Angle-averaged distribution
ISOTROPIC
SUPERTHERMAL
$t = 0.0000\,\mu$s
$T_e = 1.0\,$eV
$n_{\text{free}} - n_{\text{cold}} = 2.60 \times 10^{19}\,\text{m}^{-3}$
$n_{\text{free}} - n_{\text{cold}} = 2.60 \times 10^{19}\,\text{m}^{-3}$
$p^2 F_0$
$p/m_e c$
10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

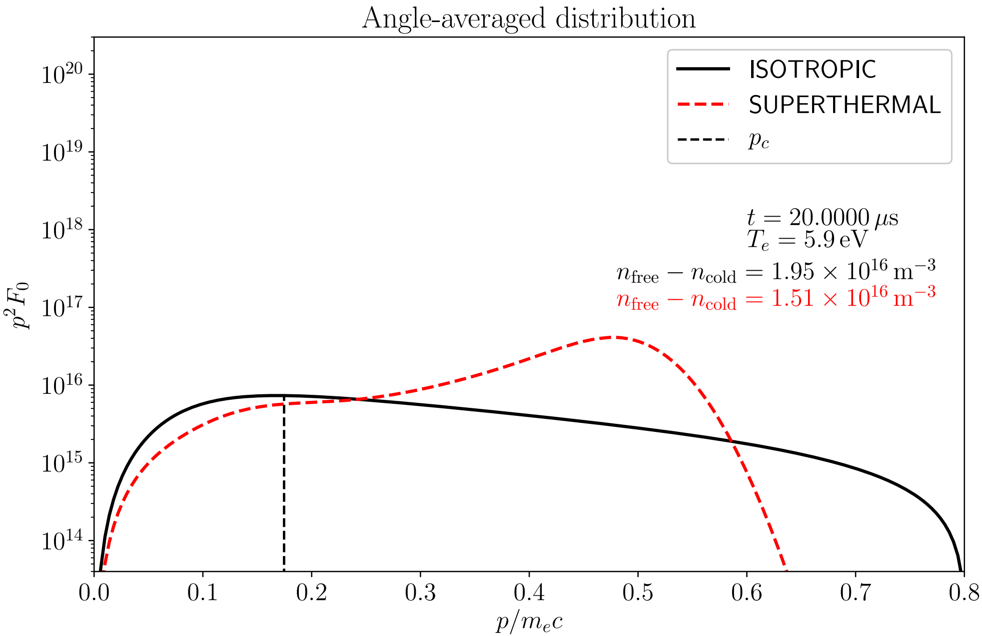

Angle-averaged distribution
ISOTROPIC
SUPERTHERMAL
p_c
$t = 3.7500\,\mu$s
$T_e = 19.2\,$eV
$n_{\rm free} - n_{\rm cold} = 5.28 \times 10^{17}\,$m^{-3}
$n_{\rm free} - n_{\rm cold} = 5.11 \times 10^{17}\,$m^{-3}
$p^2 F_0$
$p/m_e c$
10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

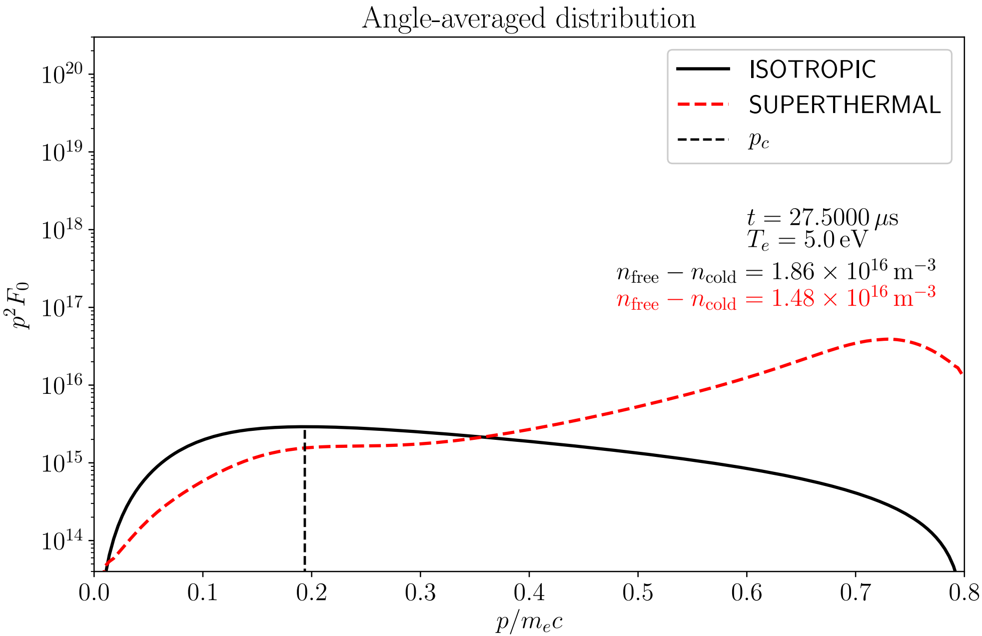
Reduced hottail model: “ISOTROPIC”





Angle-averaged distribution
ISOTROPIC
SUPERTHERMAL
p_c
$t = 12.5000\,\mu s$
$T_e = 8.4\,\mathrm{eV}$
$n_{\mathrm{free}} - n_{\mathrm{cold}} = 2.41 \times 10^{16}\,\mathrm{m}^{-3}$
$n_{\mathrm{free}} - n_{\mathrm{cold}} = 1.83 \times 10^{16}\,\mathrm{m}^{-3}$
$p^2 F_0$
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
$p/m_e c$


Angle-averaged distribution
ISOTROPIC
SUPERTHERMAL
p_c
$t = 20.0000\,\mu$s
$T_e = 5.9\,$eV
$n_{\mathrm{free}} - n_{\mathrm{cold}} = 1.95 \times 10^{16}\,\mathrm{m}^{-3}$
$n_{\mathrm{free}} - n_{\mathrm{cold}} = 1.51 \times 10^{16}\,\mathrm{m}^{-3}$
$p^2 F_0$
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
$p/m_e c$



Angle-averaged distribution
ISOTROPIC
SUPERTHERMAL
p_c
$t = 27.5000\,\mu$s
$T_e = 5.0\,$eV
$n_{\mathrm{free}} - n_{\mathrm{cold}} = 1.86 \times 10^{16}\,\mathrm{m}^{-3}$
$n_{\mathrm{free}} - n_{\mathrm{cold}} = 1.48 \times 10^{16}\,\mathrm{m}^{-3}$
$p^2 F_0$
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
$p/m_e c$

The isotropic equation is essentially

$$\frac{\partial f_0}{\partial t} = \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2\left(p\nu_s f_0 + \frac{k}{\nu_D}\frac{\partial f_0}{\partial p}\right)\right],$$

where

$$\frac{k/\nu_D}{p\nu_s} \propto (E/E_c)^2 v^3 p^2$$

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$$\frac{\partial f_0}{\partial t} = \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2\left(p\nu_s f_0 + \frac{k}{\nu_D}\frac{\partial f_0}{\partial p}\right)\right],$$

where

$$\frac{k/\nu_D}{p\nu_s} \propto (E/E_c)^2 v^3 p^2$$

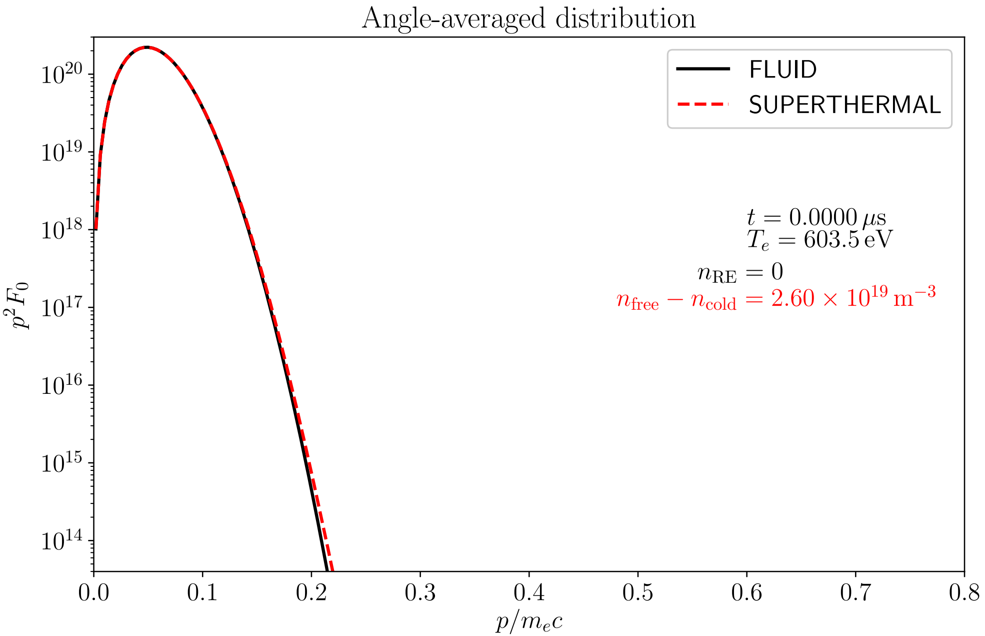
$\Rightarrow$ Sharp transition from ν_s-dominated to E-dominated at $p = p_0$:

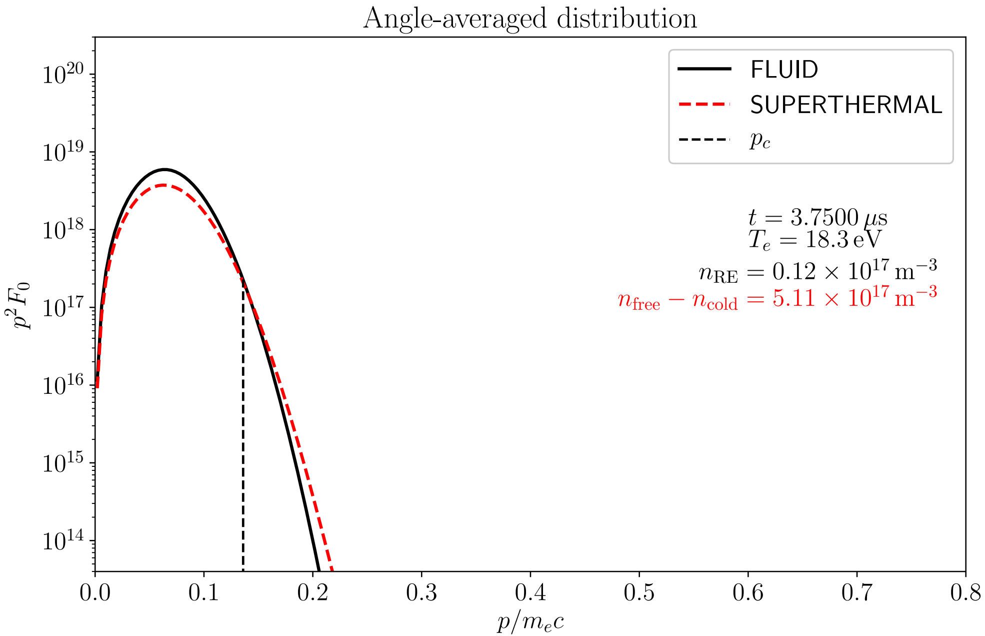
$$p\nu_s f_0 + \frac{k}{\nu_D}\frac{\partial f_0}{\partial p}\bigg|_{p=p_0} = 0$$

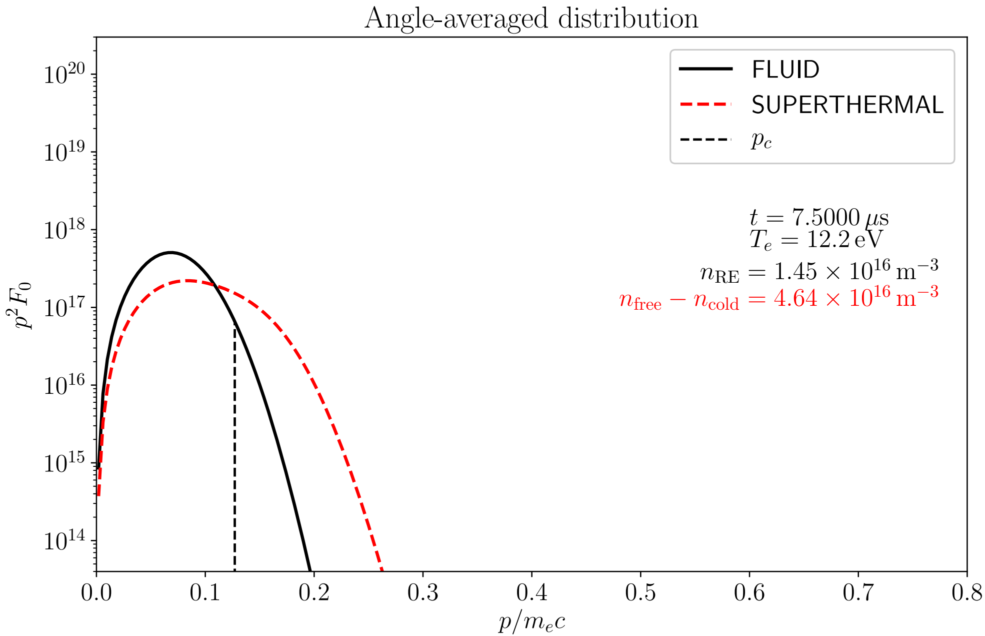
- For $p < p_0$ the equation is [Smith & Verwicthe (2008)]

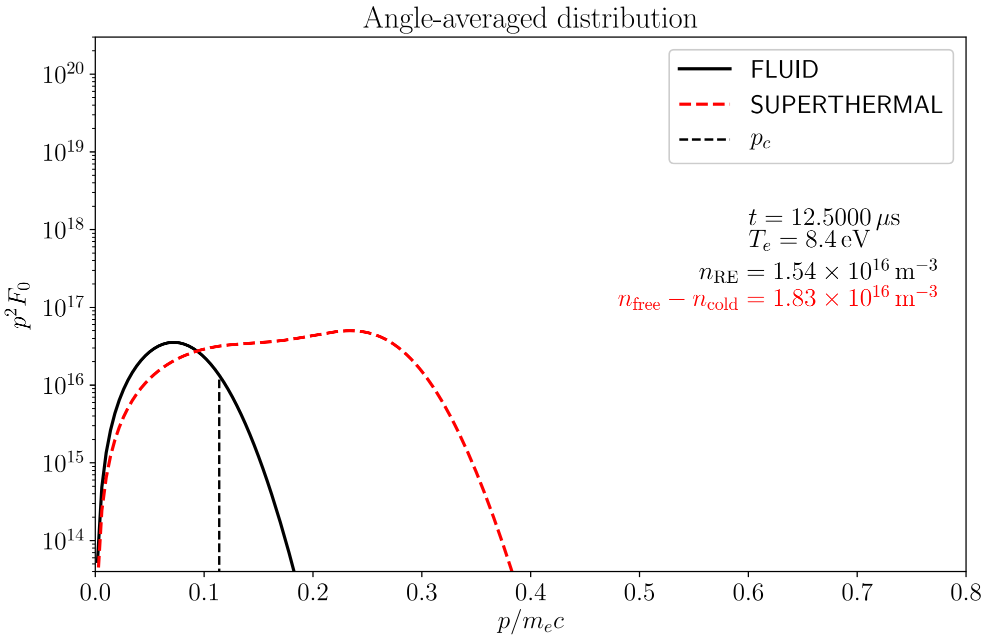
$$\frac{\partial f_0}{\partial t} = \frac{1}{p^2}\frac{\partial p^3 \nu_s f_0}{\partial p}$$

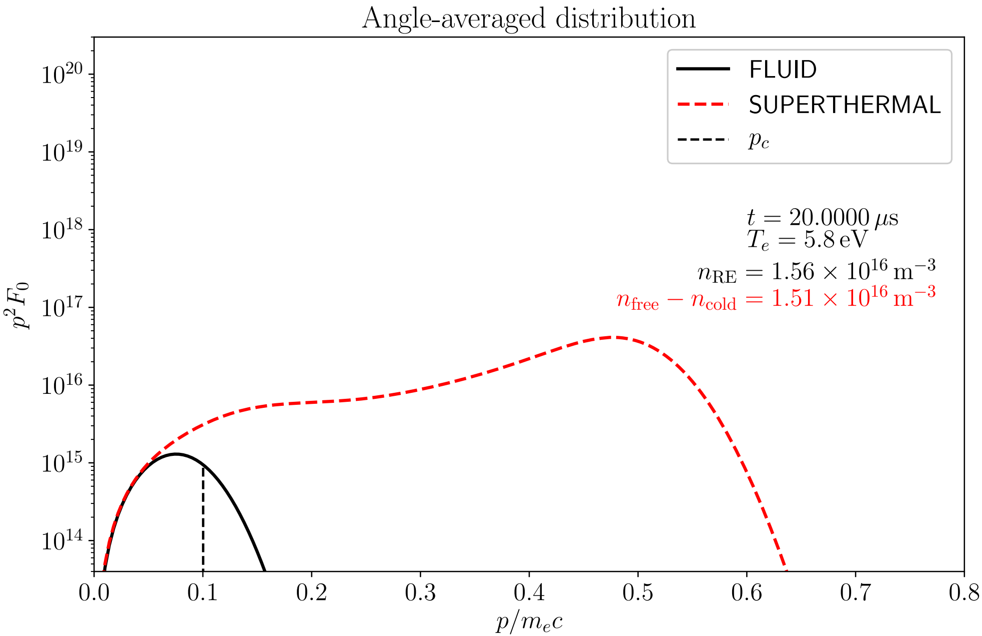
- Analytic solution for f_0, and $\partial n_{\mathrm{RE}}/\partial t = -4\pi p_0^2 \dot{p}_0 f_0(p_0)$

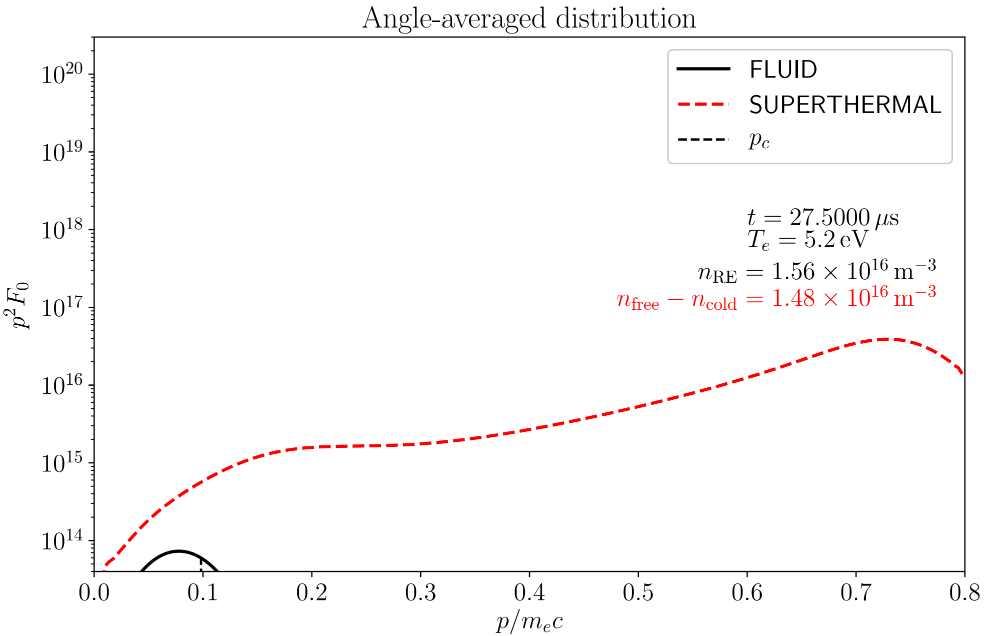

Angle-averaged distribution
FLUID
SUPERTHERMAL
$t = 0.0000\,\mu$s
$T_e = 603.5\,$eV
$n_{\mathrm{RE}} = 0$
$n_{\mathrm{free}} - n_{\mathrm{cold}} = 2.60 \times 10^{19}\,\mathrm{m}^{-3}$
$p^2 F_0$
$p/m_e c$


Angle-averaged distribution
FLUID
SUPERTHERMAL
p_c
$t = 3.7500\,\mu$s
$T_e = 18.3\,$eV
$n_{\rm RE} = 0.12 \times 10^{17}\,\mathrm{m}^{-3}$
$n_{\rm free} - n_{\rm cold} = 5.11 \times 10^{17}\,\mathrm{m}^{-3}$
$p^2 F_0$
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
$p/m_e c$


Angle-averaged distribution
FLUID
SUPERTHERMAL
p_c
$t = 7.5000\,\mu$s
$T_e = 12.2\,$eV
$n_{\mathrm{RE}} = 1.45 \times 10^{16}\,\mathrm{m}^{-3}$
$n_{\mathrm{free}} - n_{\mathrm{cold}} = 4.64 \times 10^{16}\,\mathrm{m}^{-3}$
$p^2 F_0$
$p/m_e c$
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8


Angle-averaged distribution
FLUID
SUPERTHERMAL
p_c
$t = 12.5000\,\mu$s
$T_e = 8.4\,$eV
$n_{\mathrm{RE}} = 1.54 \times 10^{16}\,\mathrm{m}^{-3}$
$n_{\mathrm{free}} - n_{\mathrm{cold}} = 1.83 \times 10^{16}\,\mathrm{m}^{-3}$
$p^2 F_0$
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
$p/m_e c$


Angle-averaged distribution
FLUID
SUPERTHERMAL
p_c
$t = 20.0000\,\mu$s
$T_e = 5.8\,$eV
$n_{\mathrm{RE}} = 1.56 \times 10^{16}\,\mathrm{m}^{-3}$
$n_{\mathrm{free}} - n_{\mathrm{cold}} = 1.51 \times 10^{16}\,\mathrm{m}^{-3}$
$p^2 F_0$
$p/m_e c$
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8


Angle-averaged distribution
FLUID
SUPERTHERMAL
p_c
$t = 27.5000\,\mu$s
$T_e = 5.2\,$eV
$n_{\mathrm{RE}} = 1.56 \times 10^{16}\,\mathrm{m}^{-3}$
$n_{\mathrm{free}} - n_{\mathrm{cold}} = 1.48 \times 10^{16}\,\mathrm{m}^{-3}$
$p^2 F_0$
$p/m_e c$
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

- Ongoing “SUPERTHERMAL FLUID” mode work:
  - Contribution to $j_{||}$ from hot distribution
  - Energy transfer from analytic slowing-down distribution to “cold” electrons
  - Ionization due to slowing-down distribution
- TODO: Screening effects (inelastic collisions) and Smith & Verwichte p_0 formula
- Note: Analytic hot tail model incompatible with fast-electron radial transport

- Resolution
  Nr × Np × Nxi= 15 × 140* × 68*
- Simulation time in illustrated test case:
  - "FULL KINETIC": 4 hours
  - "SUPERTHERMAL": 1 hour 7 min
  - "ISOTROPIC": 1 min 40 sec
  - "FLUID": 25 sec
- Further developments in the works:
  - Q: with e.g. MGI, can the "cold" electrons equilibrate with the hot tail?
  - Stabilize "SUPERTHERMAL" to support quiescent plasma before TQ
  - Future (probably): full non-linear "NORSE" collision operator