超新星遗迹粒子加速相关研究

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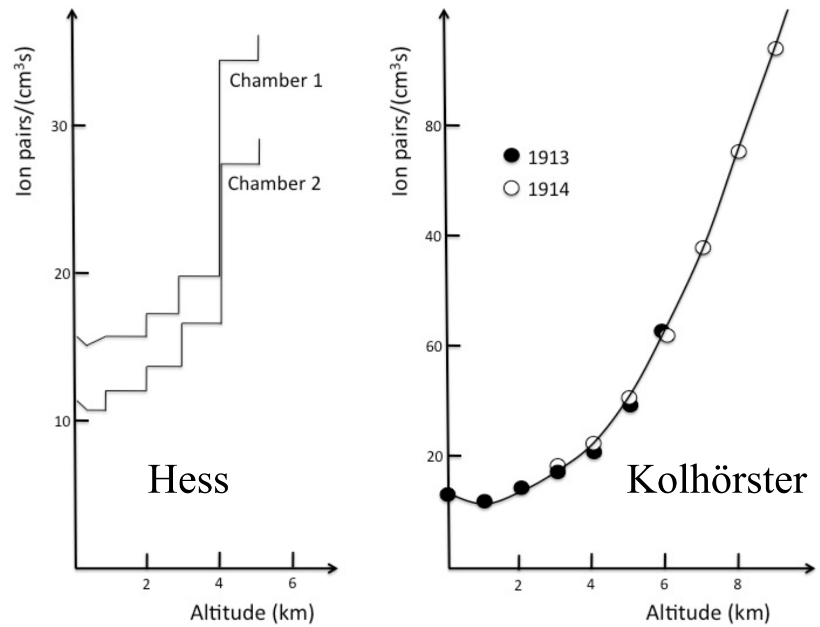
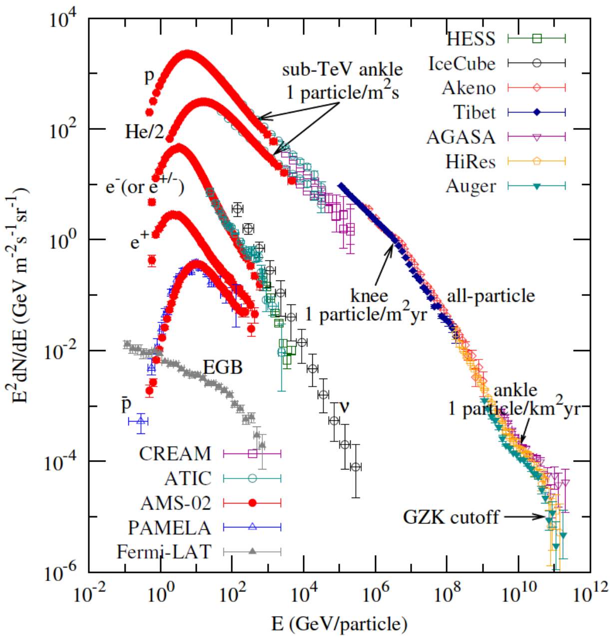
报告内容

- 研究背景
- 近期工作

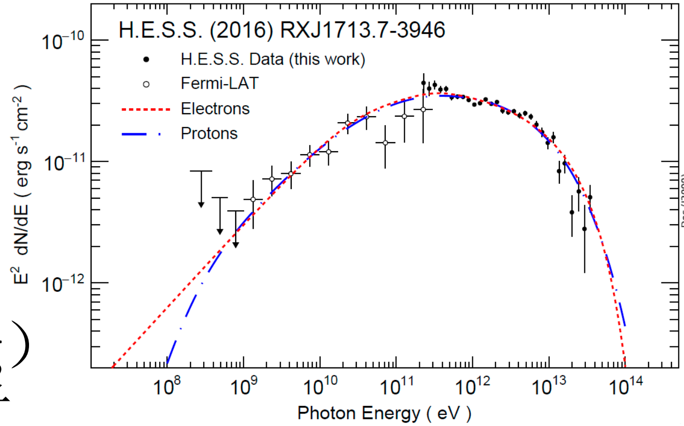
研究背景

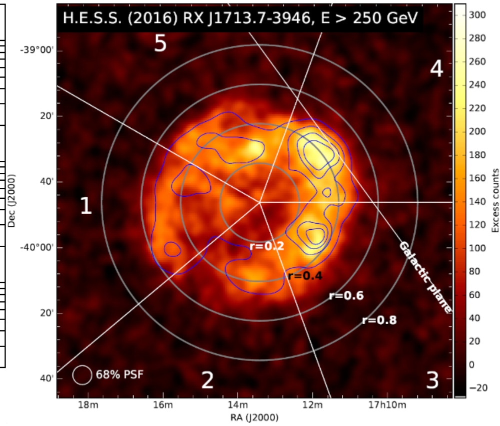
- 1912 年，Victor Hess 通过高空气球实验测量了空气电离度随海拔升高而升高的变化关系，证实了宇宙射线的存在
- **宇宙射线**是相对论性的高能粒子，由 99% 的核子以及 1% 的电子构成。这些核子中 90% 为质子，9% 为氦核，剩余 1% 为更重的核子

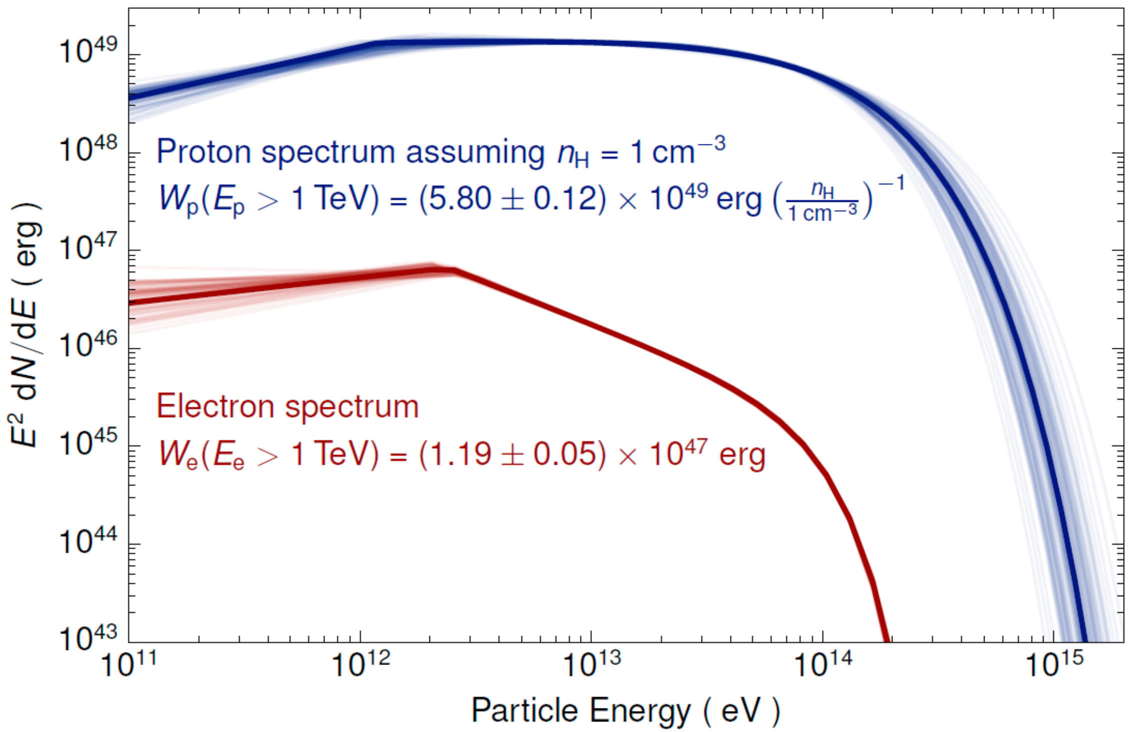




- 超新星爆发被认为是“膝”区（PeV 能量）以下宇宙射线的主要来源，其激波总动能（10^{51} erg）的 10% 足以提供观测到的宇宙射线能量密度（1 eV/cm^3）
- 观测表明，**超新星遗迹**有能力加速带电粒子至亚 PeV 能量
- **扩散激波加速**被认为是最有效的高能粒子天体物理加速机制，而超新星遗迹的大尺度激波正好为这一机制提供平台







- 近年来，一系列高精度的地面以及空间实验极大地推动了对宇宙射线以及超新星遗迹的探测
- 更加精确的观测数据需要更加合理细致的模型加以解释

近期工作

- Anomalous Distributions of Primary Cosmic Rays as Evidence for Time-dependent Particle Acceleration in Supernova Remnants
- Global Constraints on Diffusive Particle Acceleration by Strong Nonrelativistic Shocks

Anomalous Distributions of Primary Cosmic Rays as Evidence for Time-dependent Particle Acceleration in Supernova Remnants

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Anomalous Distributions of Primary Cosmic Rays as Evidence for Time-dependent Particle Acceleration in Supernova Remnants

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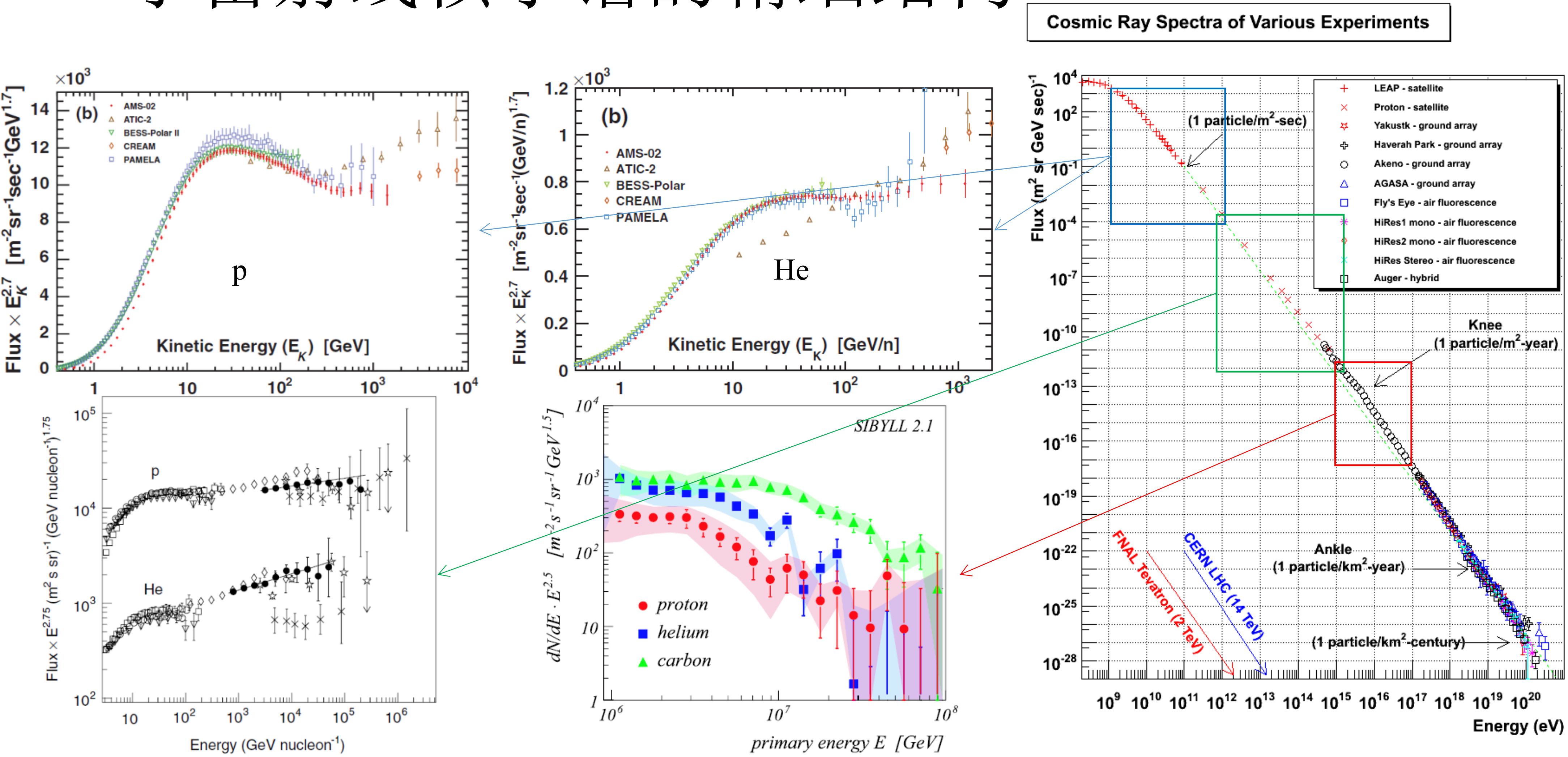
Abstract

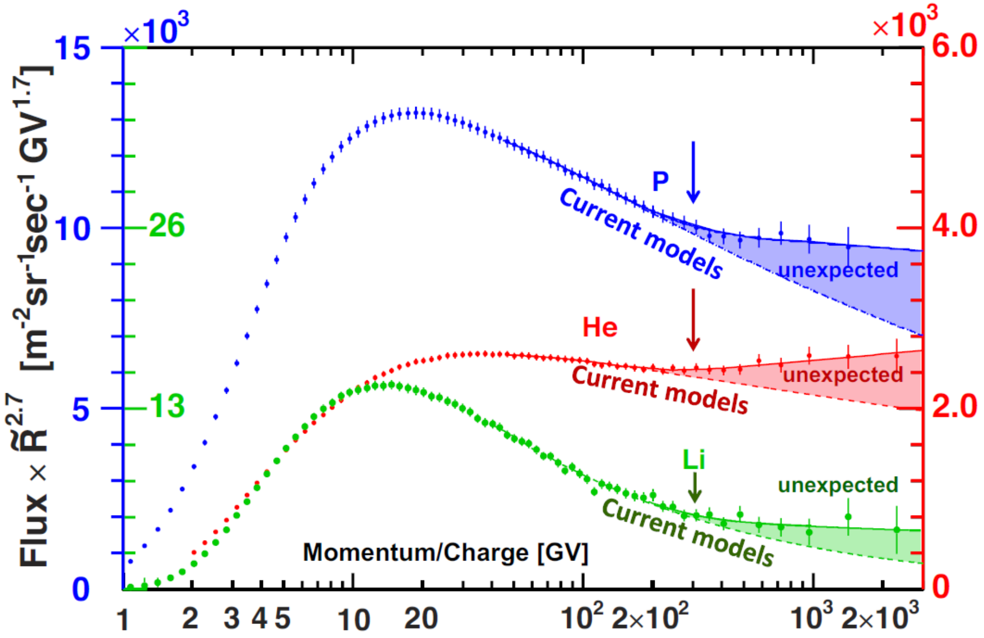
Recent precise measurements of cosmic-ray (CR) spectra show that the energy distribution of protons is softer than those of heavier nuclei, and there are spectral hardenings for all nuclear compositions above ∼200 GV. Models proposed for these anomalies generally assume steady-state solutions of the particle acceleration process. We show that if the diffusion coefficient has a weak dependence on the particle rigidity near shock fronts of supernova remnants (SNRs), time-dependent solutions of the linear diffusive shock acceleration at two stages of SNR evolution can naturally account for these anomalies. The high-energy component of CRs is dominated by acceleration in the free expansion and adiabatic phases with enriched heavy elements and a high shock speed. The low-energy component may be attributed to acceleration by slow shocks propagating in dense molecular clouds with low metallicity in the radiative phase. Instead of a single power-law distribution, the spectra of time-dependent solutions soften gradually with the increase of energy, which may be responsible for the “knee” of CRs.

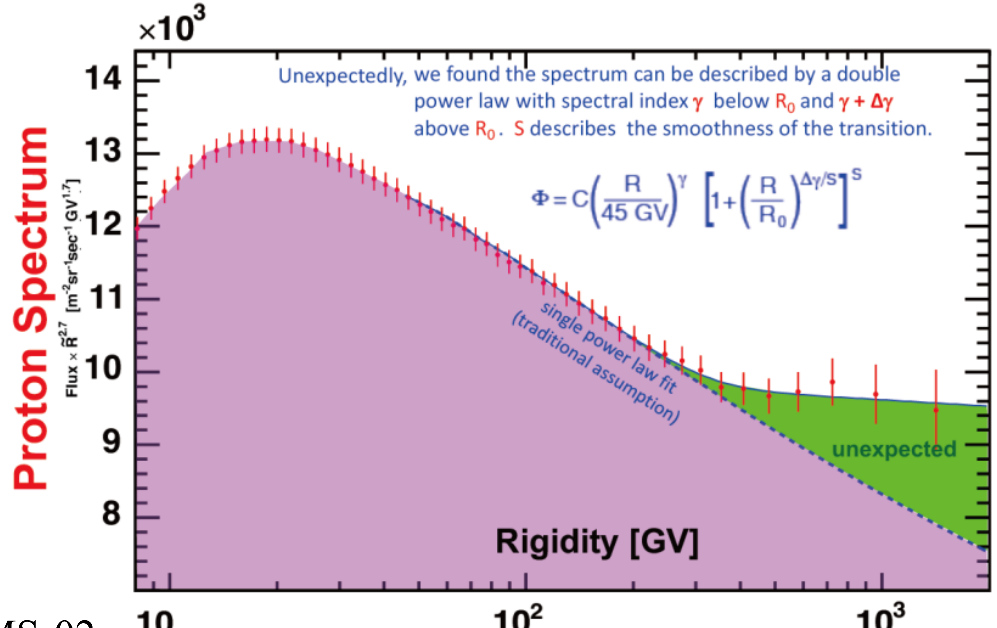
Key words: acceleration of particles – cosmic rays – ISM: supernova remnants – shock waves

Supporting material: data behind figure

宇宙射线核子谱的精细结构







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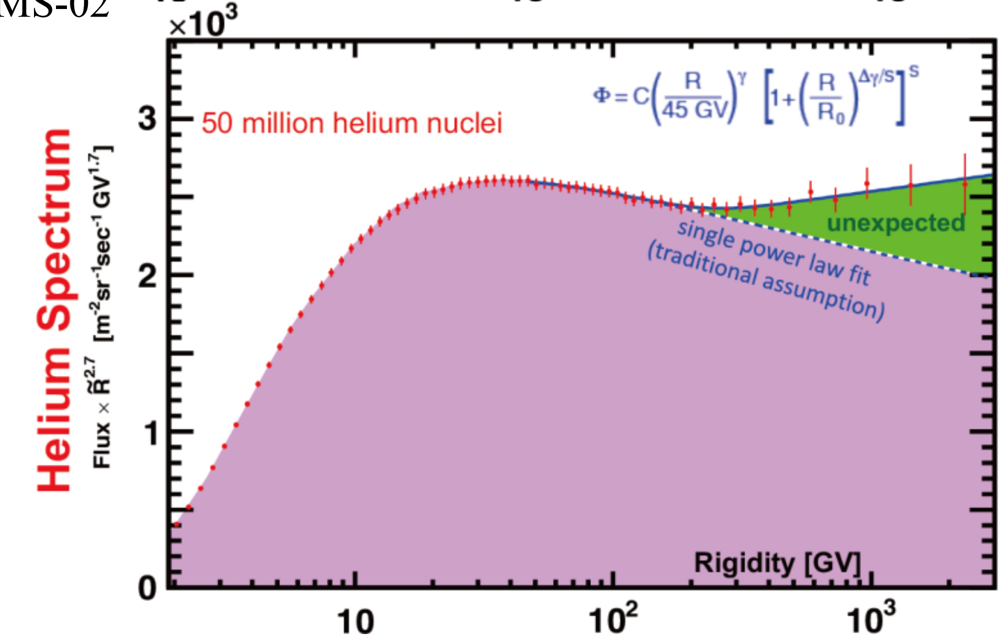
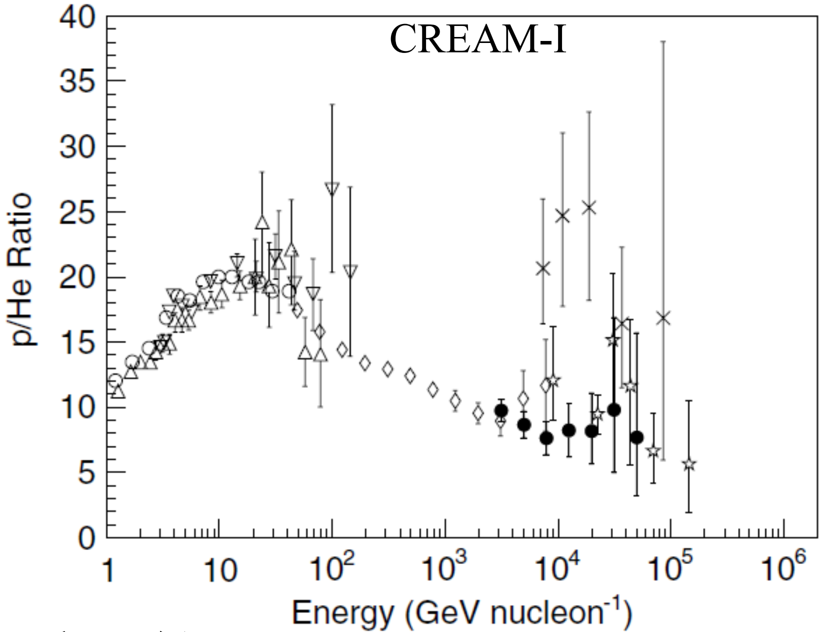
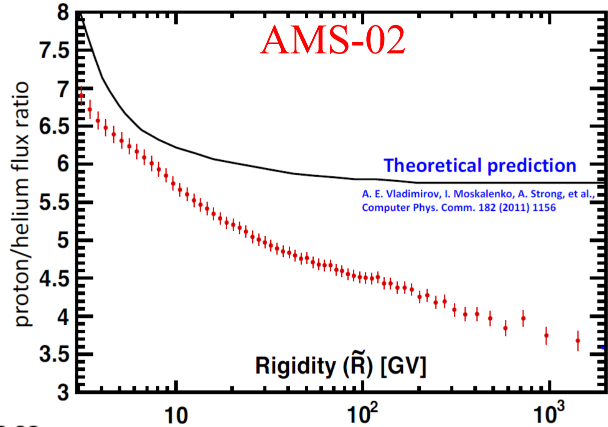
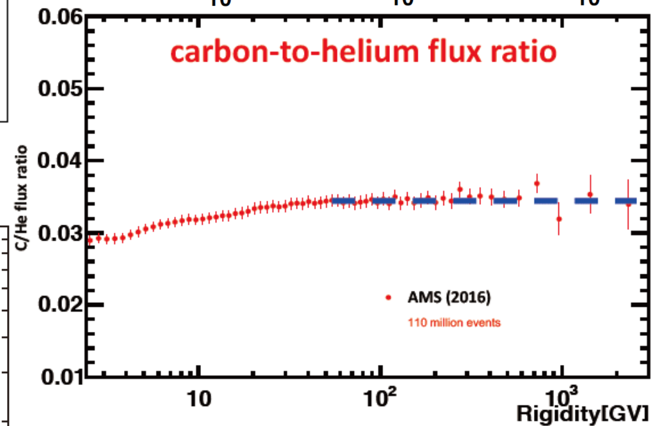


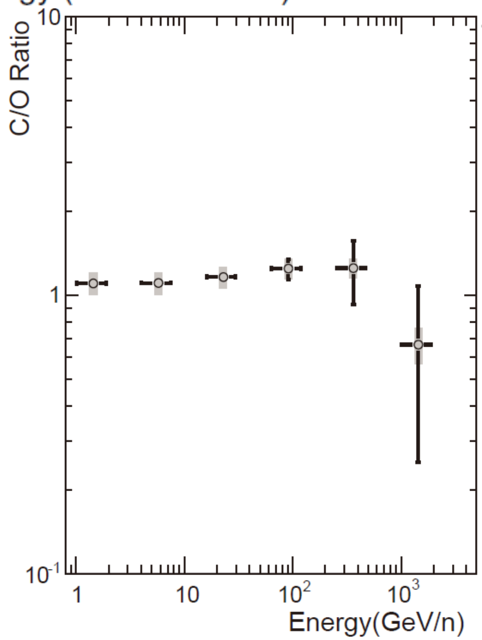
- 200 至 400 GV 处刚度谱普遍拐折变硬

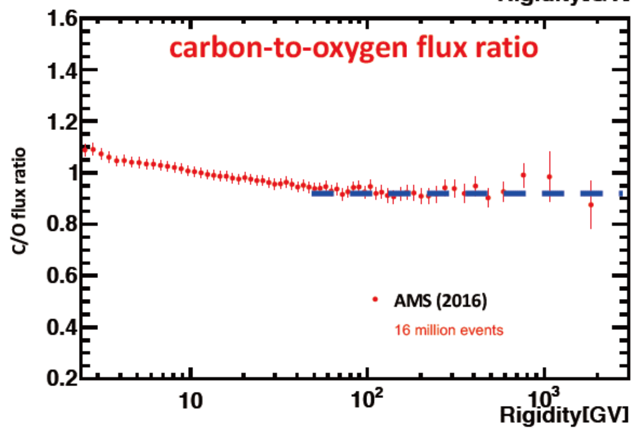






- 45 GV 以上刚度谱中质子软于其它核子，刚度谱**依赖于荷质比**





- 最简单的“稳态加速-漏箱传播”模型给出的高能原初核子刚度谱为简单幂率，并且谱指数不依赖于粒子种类，因而不能解释观测到的精细结构
- 一些修正模型已经被提出，基于改进的稳态加速或者传播模型

✓Malkov et al. 2012, PhRvL——强激波更容易抑制质子的注入

✓Tomassetti 2015, ApJL——双分量模型，其中低能分量可能来自于某个邻近的高质子丰度源

✓Tomassetti 2012, ApJL——空间依赖的传播参数

✓Blasi et al. 2012, PhRvL——湍流的自生长对宇宙射线输运特性的修正

- 加速时标正相关于粒子能量，对于高能粒子加速可能未达稳态

时间依赖的超新星遗迹粒子加速模型

- 双分量近似，表征超新星遗迹的演化，导致能谱（刚度谱）拐折变硬
- 时间依赖的线性扩散激波加速，被加速粒子谱随着能量增加而变软，导致能谱的膝区
- 被加速粒子的注入速度与粒子种类无关，即注入刚度依赖于荷质比，导致刚度谱对荷质比的依赖

时间依赖的线性扩散激波加速

- **一维 Parker 方程**（$p = ZeR$）

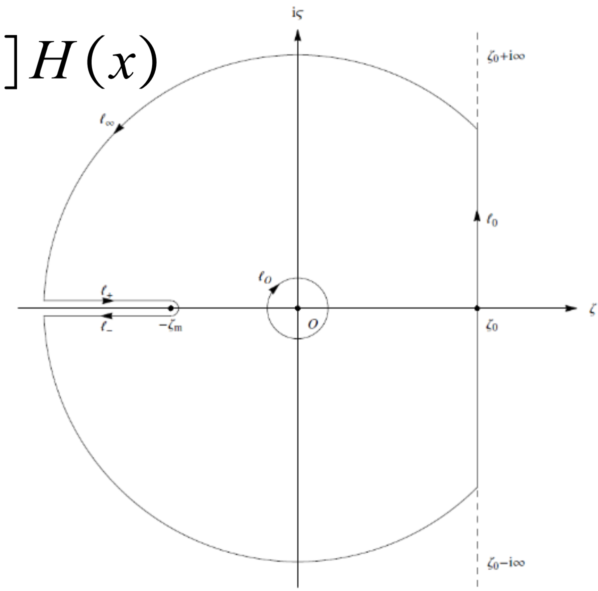
$$\boxed{\frac{\partial f}{\partial t}} - \frac{\partial u}{\partial x}\frac{p}{3}\frac{\partial f}{\partial p} + u\frac{\partial f}{\partial x} = \frac{\partial}{\partial x}\left(\kappa\frac{\partial f}{\partial x}\right) + Q$$

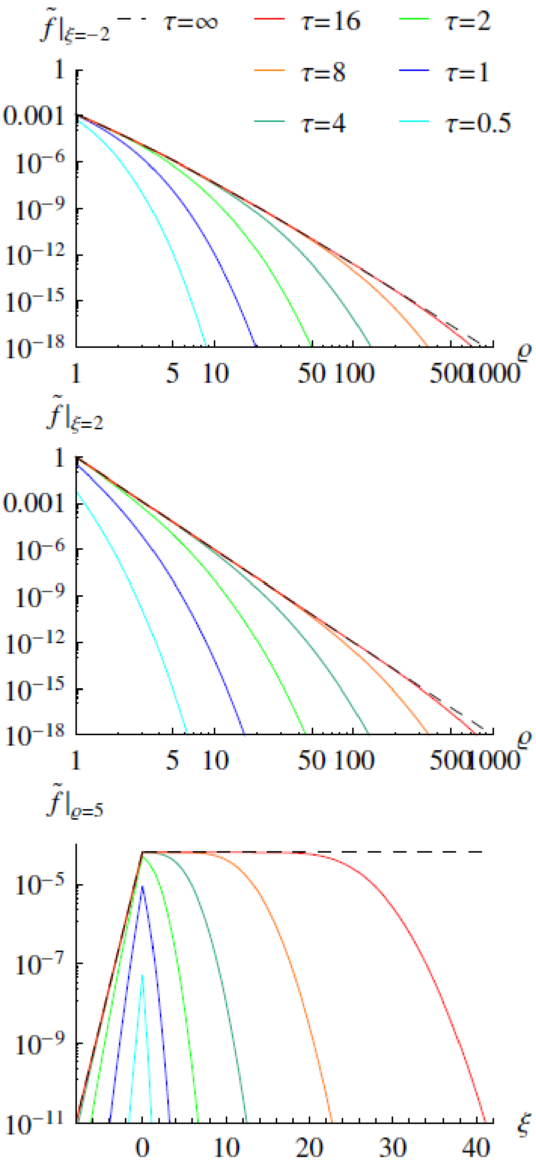
$$u(x,t) = u_1 + (u_2 - u_1)H(x)$$

$$\kappa(p,x,t) = \kappa_1(p) + [\kappa_2(p) - \kappa_1(p)]H(x)$$

$$p^2 Q(p,x,t) = Q_0\delta(p - p_0)\delta(x)H(t)$$

- 我们以拉普拉斯变换写出解的一般积分形式





- 能谱随能量增加逐渐变软，给出解释宇宙射线膝区的可能性
- 能谱随时间增加逐渐变硬而逼近稳态
- 若假设所有粒子都以相同的速度注入，则荷质比大的粒子注入刚度较低，从而刚度谱较软

$$t_{\rm acc} = \frac{4}{u_1 - u_2}\left(\frac{\kappa_1}{u_1} + \frac{\kappa_2}{u_2}\right)$$

$$\tau = \frac{t}{t_{\rm acc}(p_0)}, \quad \varrho = \frac{p}{p_0}, \quad \xi = \frac{x}{\sqrt{\kappa_1(p_0)t_{\rm acc}(p_0)}}$$

$$u_1/u_2 = 2, \quad \kappa_1/\kappa_2 = 5, \quad \kappa \propto p^{1/3}$$

双分量近似

The above analysis is somewhat simplified, and we are left with one surprising observational fact: within the current uncertainties, the gamma-ray emission beyond the shell is energy independent (Sect. 3.3), whereas one would expect that the diffusion length scale is larger for more energetic particles. This

H.E.S.S. Collaboration, Abdalla, H., et al. 2016, arXiv:1609.08671

湍流扩散（Bykov & Toptygin 1993, PhyU）

- **早期阶段（Early stage）**

（T_S = kyr，L_S = 5 pc，$u_1 = 5\times10^3$ km/s）

模型 1：$u_1/u_2=4$，$\kappa_1/\kappa_2=1$，$\kappa\propto R^0$，$v_0=10^4$ km/s

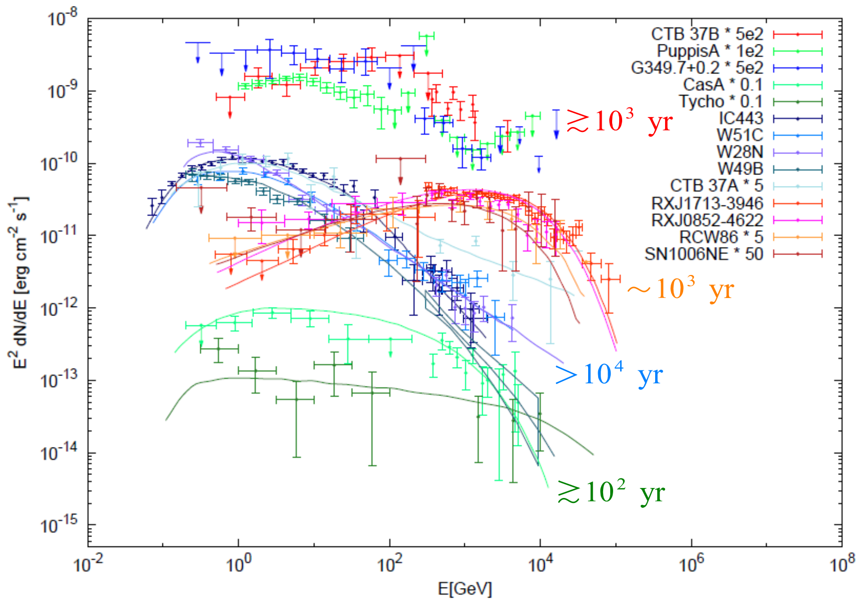
模型 2：$u_1/u_2=4$，$\kappa_1/\kappa_2=16$，$\kappa\propto R^0$，$v_0=10^4$ km/s

- **晚期阶段（Advanced stage）**

（T_S = 100 kyr，L_S = 50 pc，$u_1 = 5\times10^2$ km/s）

模型 1：$u_1/u_2=4$，$\kappa_1/\kappa_2=1$，$\kappa\propto R^0$，$v_0=10^3$ km/s

模型 2：$u_1/u_2=4$，$\kappa_1/\kappa_2=16$，$\kappa\propto R^0$，$v_0=10^3$ km/s



T_S：超新星遗迹寿命

L_S：超新星遗迹尺度

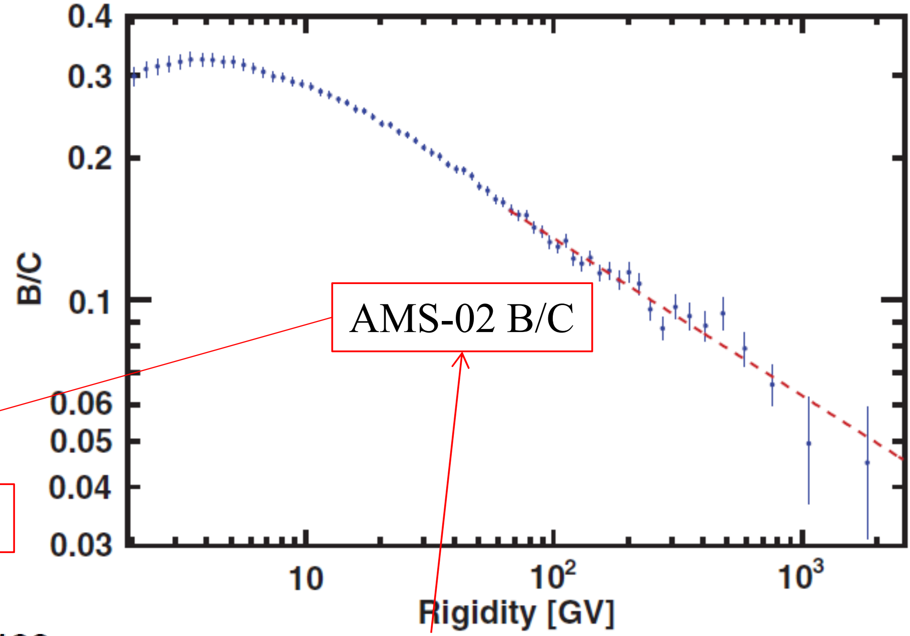
（$L_S \sim T_S u_1$）

- 银河系扩散传播——漏箱近似

$$J_0 = \frac{H_G^2 L_S^2 r_S}{V_G D} \int_{-\infty}^{\infty} \mathrm{d}x \, f|_{t=T_S} v p^2 \frac{\mathrm{d}p}{\mathrm{d}R}$$

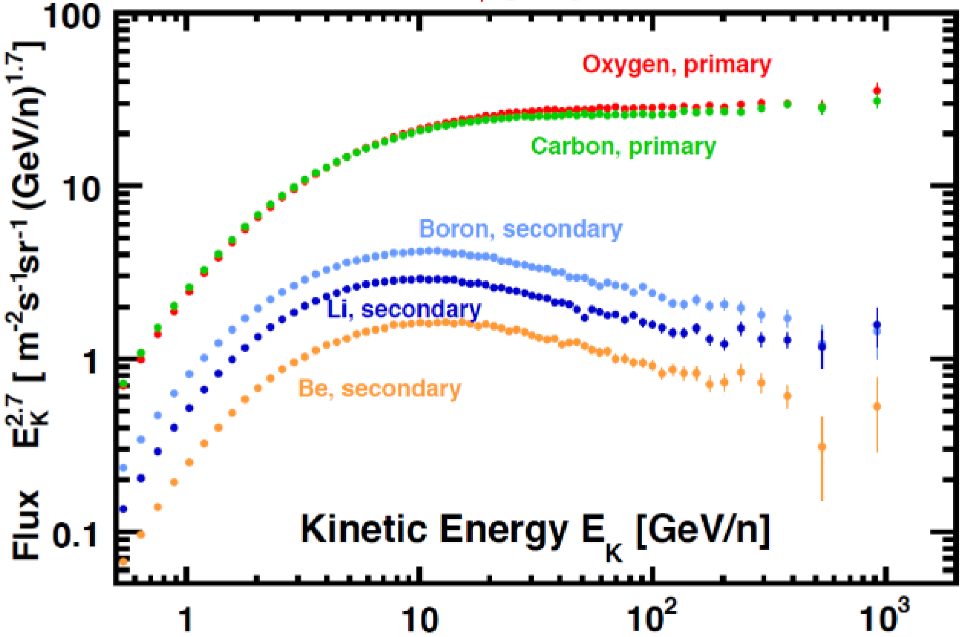
$$D(R) = D_0 \frac{v}{c} \left(\frac{R}{10 \ \mathrm{GV}} \right)^{\frac{1}{3}}, \quad D_0 \sim 10^{29} \ \mathrm{cm}^2 \mathrm{s}^{-1}$$

Kolmogorov 扩散



- 太阳调制——势场近似

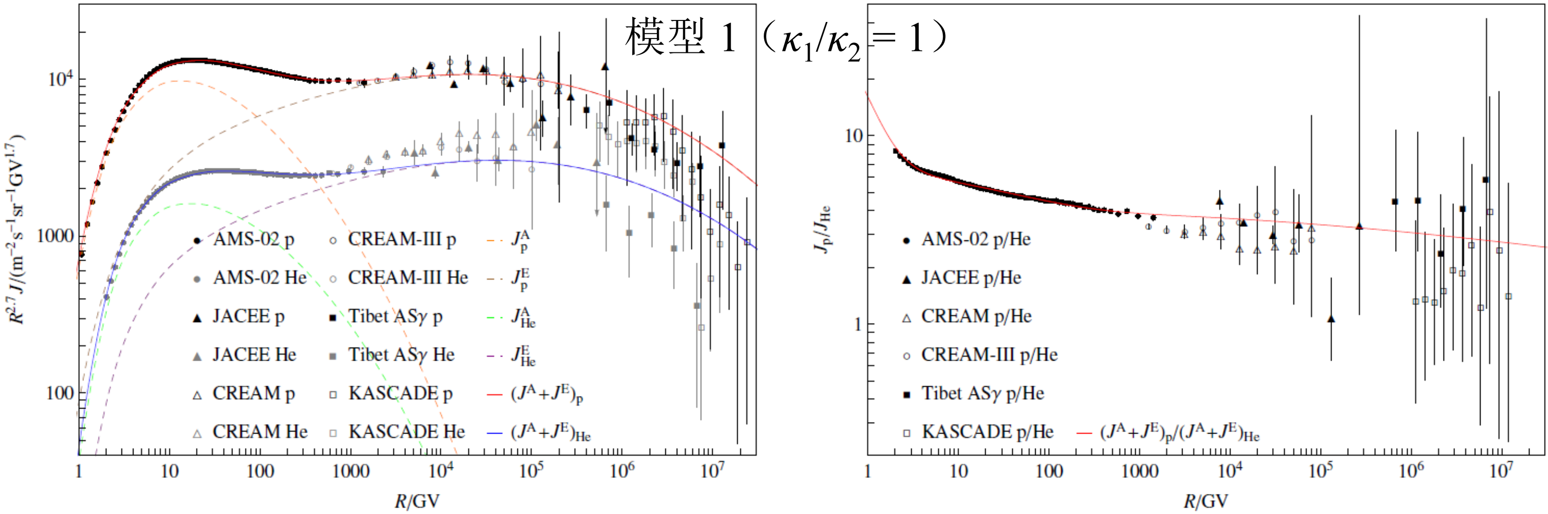
$$J(R) = \frac{vR^2}{v'R'^2} J_0(R'), \quad R' = R^2 + 2R\phi \frac{c}{v} + \phi^2$$



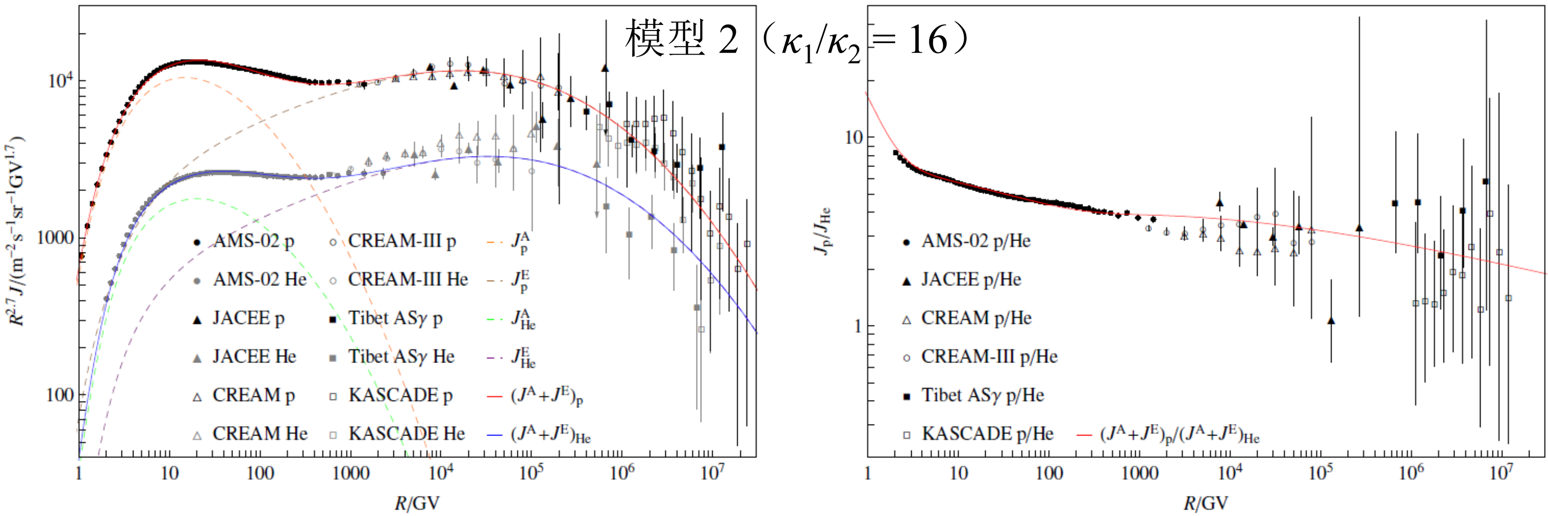
$H_G \sim 0.1$ kpc：银河系厚度
$V_G \sim \mathrm{kpc}^3$：银河系体积
$r_S = 0.03/\mathrm{yr}$：超新星爆发率
$\phi = 0.8$ GV：太阳调制等效势

拟合结果

模型 1（$\kappa_1/\kappa_2 = 1$）



模型 2（$\kappa_1/\kappa_2 = 16$）



Fitting Parameters

$\frac{\kappa_1}{\kappa_2}$	τ_S^E	τ_S^A	$\frac{(Q_0)_p^E}{(Q_0)_{He}^E}$	$\frac{(Q_0)_p^A}{(Q_0)_{He}^A}$	$\frac{(Q_0)_p^E}{(Q_0)_p^A}\left(\frac{10u_1^A}{u_1^E}\right)^2\frac{(\kappa_2 L_S^2)^E}{(\kappa_2 L_S^2)^A}$	$\frac{(Q_0)_p^A}{\mathrm{cm^{-2}s^{-1}sr^{-1}}}\frac{\kappa_2^A}{D_0}\left(\frac{L_S^A}{50\ \mathrm{pc}}\right)^2\left(\frac{u_1^A}{5\times10^7\ \mathrm{cm\ s^{-1}}}\right)^{-2}\left(\frac{V_G}{\mathrm{kpc^3}}\right)^{-1}\left(\frac{H_G}{0.1\ \mathrm{kpc}}\right)^2$
1	9.0	4.7	9.1	18.5	0.2	8.4×10^{-3}
16	10.7	6.3	9.0	17.7	0.3	9.4×10^{-4}

Derived Diffusion Coefficients and Injection Rates

$\frac{\kappa_1}{\kappa_2}$	$\frac{\kappa_2^{E}}{\mathrm{cm^2 s^{-1}}}\left(\frac{u_1^{E}}{5\times10^{8}\ \mathrm{cm\ s^{-1}}}\right)^{-1}\left(\frac{L_S^{E}}{5\ \mathrm{pc}}\right)^{-1}$	$\frac{\kappa_2^{A}}{\mathrm{cm^2 s^{-1}}}\left(\frac{u_1^{A}}{5\times10^{7}\ \mathrm{cm\ s^{-1}}}\right)^{-1}\left(\frac{L_S^{A}}{50\ \mathrm{pc}}\right)^{-1}$	$\frac{(Q_0)_p^{E}}{\mathrm{cm^{-2}\ s^{-1} sr^{-1}}}\frac{T_S^{E}}{\mathrm{kyr}}\left(\frac{L_S^{E}}{5\ \mathrm{pc}}\right)^{2}$	$\frac{(Q_0)_p^{A}}{\mathrm{cm^{-2}\ s^{-1} sr^{-1}}}\frac{T_S^{A}}{100\ \mathrm{kyr}}\left(\frac{L_S^{A}}{50\ \mathrm{pc}}\right)^{2}$
1	3.3×10^{25}	6.4×10^{25}	570	10
16	6.9×10^{24}	1.2×10^{25}	440	8

$$\kappa_2 = \frac{3 T_S u_1^2}{16 \tau_S (4 + \kappa_1/\kappa_2)}$$

$$n \sim \frac{4\pi Q_0}{v_0}, \quad E \sim 2\pi e (Q_0 R_0)_p L_S^2 T_S$$

$$n_p^E \sim 10^{-5}\ \mathrm{cm^{-3}}, \quad n_p^A \sim 10^{-6}\ \mathrm{cm^{-3}}$$

$$E^E \sim 10^{48}\ \mathrm{erg}, \quad E^A \sim 10^{50}\ \mathrm{erg}$$

$$\kappa \sim 0.01 u L_S$$

The relative length scale of the gamma-ray emission measured beyond the shock is rather large, $\Delta r / r_{SNR} \approx 13\%$, for a precursor scenario. This can already be seen in the comparisons

H.E.S.S. Collaboration, Abdalla, H., et al. 2016, arXiv:1609.08671

结论

- 时间依赖的超新星遗迹粒子加速模型能够拟合观测到的原初宇宙射线核子谱精细结构
- 超新星遗迹附近带电粒子的输运行为可能由背景流体的湍流运动主导

Global Constraints on Diffusive Particle Acceleration by Strong Nonrelativistic Shocks

张铁然，刘四明

(草稿...)

自洽扩散激波加速

- 实际的粒子加速应当是与背景流体相互耦合的过程
- 当被加速粒子所携带总能量与背景流体内能相比不可忽略时，应当考虑粒子加速对背景流体的反作用
- 若考虑用超新星遗迹粒子加速解释宇宙射线起源，则至少需要10% 的加速效率，这时试验粒子假设的正确性需要被检验

- 流行的做法是在流体力学方程中添加由加速粒子输运方程所决定的“宇宙射线压强”

$$P_c = 4\pi \int p^2 dp v p N/3$$

- 本质上是一套耦合的非线性微分方程组，严格求解十分困难

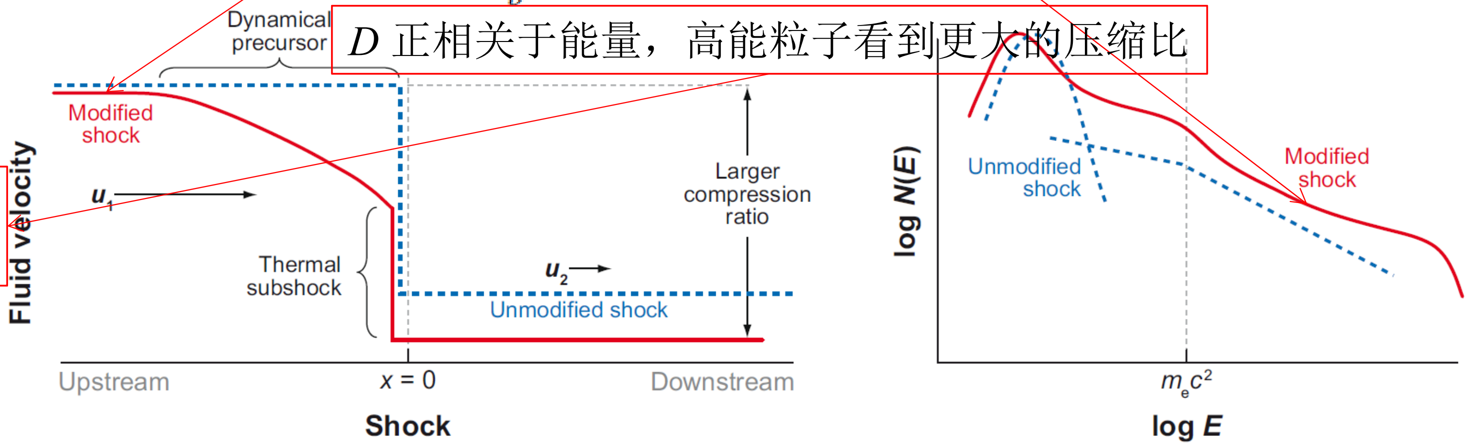
$$\frac{\partial \rho}{\partial t} = -\frac{1}{r^2}\frac{\partial}{\partial r} r^2 u \rho$$

$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial r} - \frac{1}{\rho}\left(\frac{\partial P_g}{\partial r} + \frac{\partial P_c}{\partial r}\right)$$

$$\frac{\partial P_g}{\partial t} = -u\frac{\partial P_g}{\partial r} - \frac{\gamma_g P_g}{r^2}\frac{\partial r^2 u}{\partial r} - (\gamma_g - 1)(w-u)\frac{\partial P_c}{\partial r}$$

$$\frac{\partial N}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r} r^2 D(p,r,t)\frac{\partial N}{\partial r} - w\frac{\partial N}{\partial r} + \frac{\partial N}{\partial p}\frac{p}{3r^2}\frac{\partial r^2 w}{\partial r}$$
$$+ \frac{\eta_f \delta(p-p_f)}{4\pi p_f^2 m}\rho(R_f+0,t)(\dot{R}_f - u(R+0,t))\delta(r-R_f(t))$$
$$+ \frac{\eta_b \delta(p-p_b)}{4\pi p_b^2 m}\rho(R_b-0,t)(u(R_b-0,t) - \dot{R}_b)\delta(r-R_b(t))$$

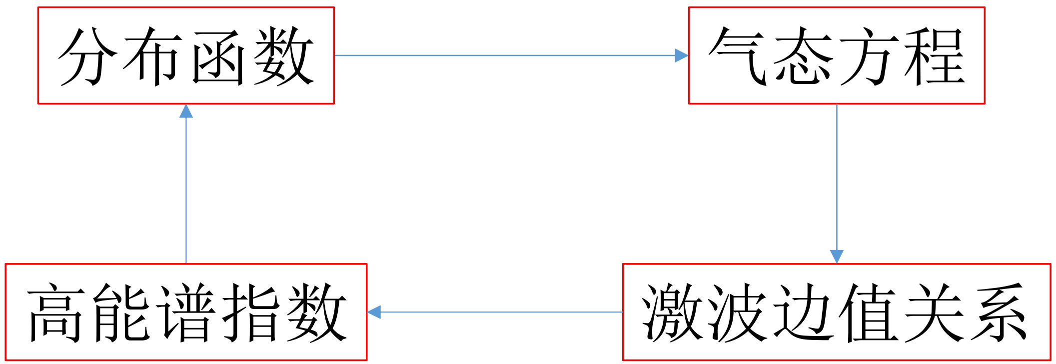
D 正相关于能量，高能粒子看到更大的压缩比



与观测相矛盾（H.E.S.S. Collaboration, Abdalla, H., et al. 2016, arXiv:1609.08671）

问题概观

- 解的渐进形式：低能热分布，高能幂率分布
- 反馈机制



- 存在一个以高能谱指数为未知数的超越方程，给出自洽解

最简化的假设

- 低能 Maxwell 分布，高能稳态扩散激波加速幂率分布

$$f \sim \frac{n}{(2\pi mT)^{3/2}} \begin{cases} e^{-\frac{p^2}{2mT}} & 0 < p < p_{\mathrm{m}} \\ e^{-\frac{p_{\mathrm{m}}^2}{2mT}} \left(\frac{p}{p_{\mathrm{m}}}\right)^{-\alpha} & p_{\mathrm{m}} < p < p_{\mathrm{M}} \\ 0 & p_{\mathrm{M}} < p \end{cases}, \quad \alpha = \frac{3u_1}{u_1 - u_2}$$

- Rankine-Hugoniot 强激波

适用于 dynamical precursor 之外

$$\frac{\alpha}{\alpha - 3} = \frac{u_1}{u_2} = 1 + 2\frac{U(\alpha)}{P(\alpha)}$$

$$U \approx \int_0^{mc} \frac{p^2}{2m} f 4\pi p^2 \mathrm{d}p + \int_{mc}^{p_{\mathrm{M}}} cpf 4\pi p^2 \mathrm{d}p, \quad P \approx \int_0^{mc} \frac{p^2}{3m} f 4\pi p^2 \mathrm{d}p + \int_{mc}^{p_{\mathrm{M}}} \frac{cp}{3} f 4\pi p^2 \mathrm{d}p$$

$$\rho_{\mathrm{t}} = mn\left(\operatorname{erf}\xi_T^{-1} - \frac{\mathrm{e}^{-\xi_T^{-2}}}{\sqrt{\pi}} 2\xi_T^{-1}\right), \quad \rho_{\mathrm{p}} = mn\frac{\mathrm{e}^{-\xi_T^{-2}}}{\sqrt{\pi}} \frac{\xi_{\mathrm{M}}^{3-\alpha} - 1}{3-\alpha} 4\xi_T^{-3}$$

$$U_{\mathrm{t}} = nT\left[\frac{3}{2}\operatorname{erf}\xi_T^{-1} - \frac{\mathrm{e}^{-\xi_T^{-2}}}{\sqrt{\pi}}\left(3\xi_T^{-1} + 2\xi_T^{-3}\right)\right], \quad U_{\mathrm{p}} = nT\frac{\mathrm{e}^{-\xi_T^{-2}}}{\sqrt{\pi}}\left(\frac{\xi_c^{5-\alpha} - 1}{5-\alpha} + \frac{\xi_{\mathrm{M}}^{4-\alpha} - \xi_c^{4-\alpha}}{4-\alpha} 2\xi_c\right) 4\xi_T^{-5}$$

$$P_{\mathrm{t}} = \frac{2}{3} U_{\mathrm{t}}, \quad P_{\mathrm{p}} = nT\frac{\mathrm{e}^{-\xi_T^{-2}}}{\sqrt{\pi}}\left(\frac{\xi_c^{5-\alpha} - 1}{5-\alpha} + \frac{\xi_{\mathrm{M}}^{4-\alpha} - \xi_c^{4-\alpha}}{4-\alpha}\xi_c\right)\frac{8}{3}\xi_T^{-5}$$

$$\xi_T = \frac{\sqrt{2mT}}{p_{\mathrm{m}}}, \quad \xi_c = \frac{mc}{p_{\mathrm{m}}}, \quad \xi_{\mathrm{M}} = \frac{p_{\mathrm{M}}}{p_{\mathrm{m}}}$$

- 下标 t：热成分的贡献；下标 p：幂率成分的贡献

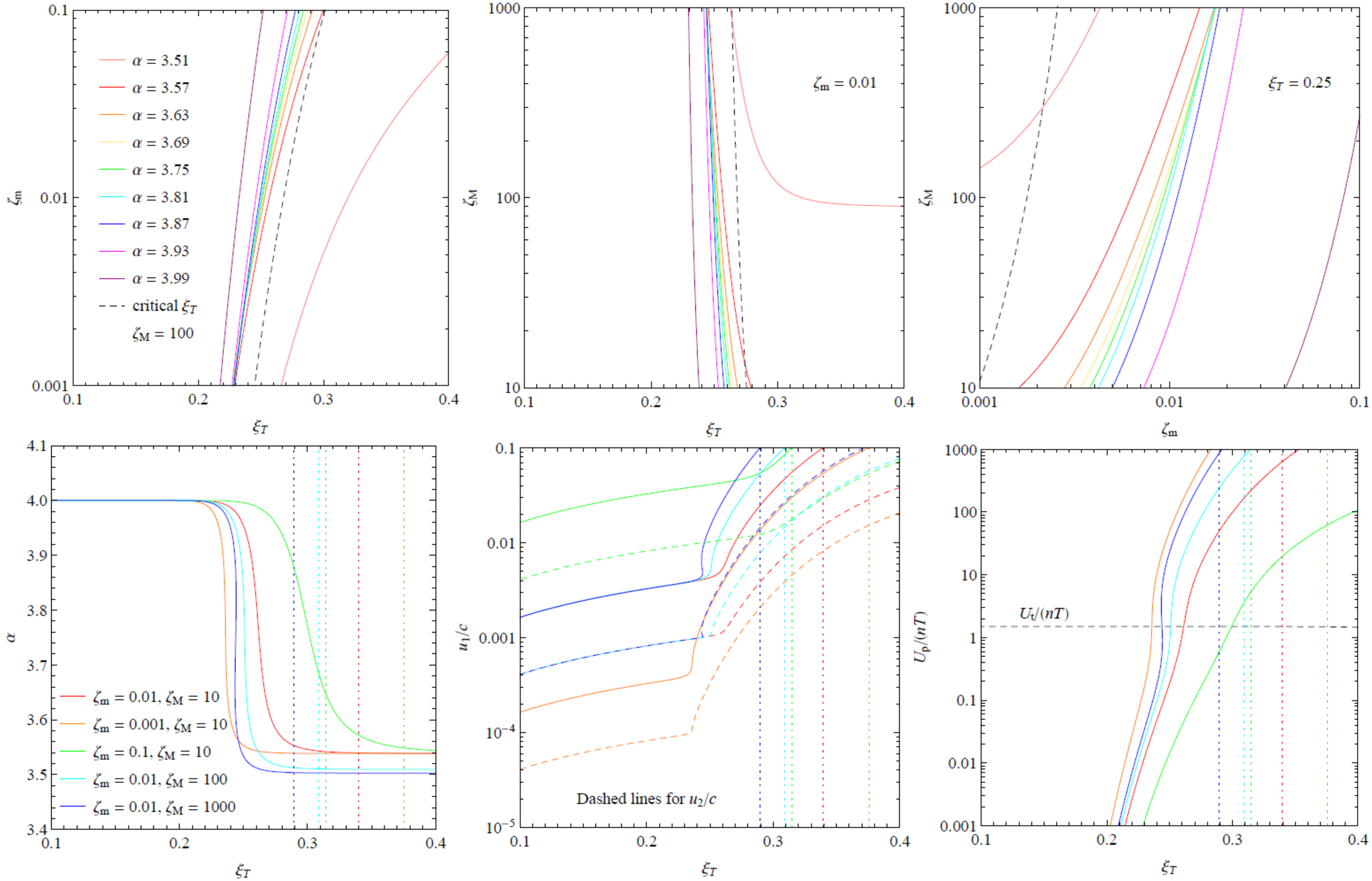
- 临界位置

$$\xi_T^{-2} = -\frac{5}{2}\,\mathrm{W}_{-1}\left\{-\frac{2}{5}\left[\frac{3\sqrt{\pi}/8}{(1+2\ln\zeta_{\mathrm{M}})\xi_c-1}\right]^{\frac{2}{5}}\right\}$$

- 最小谱指数

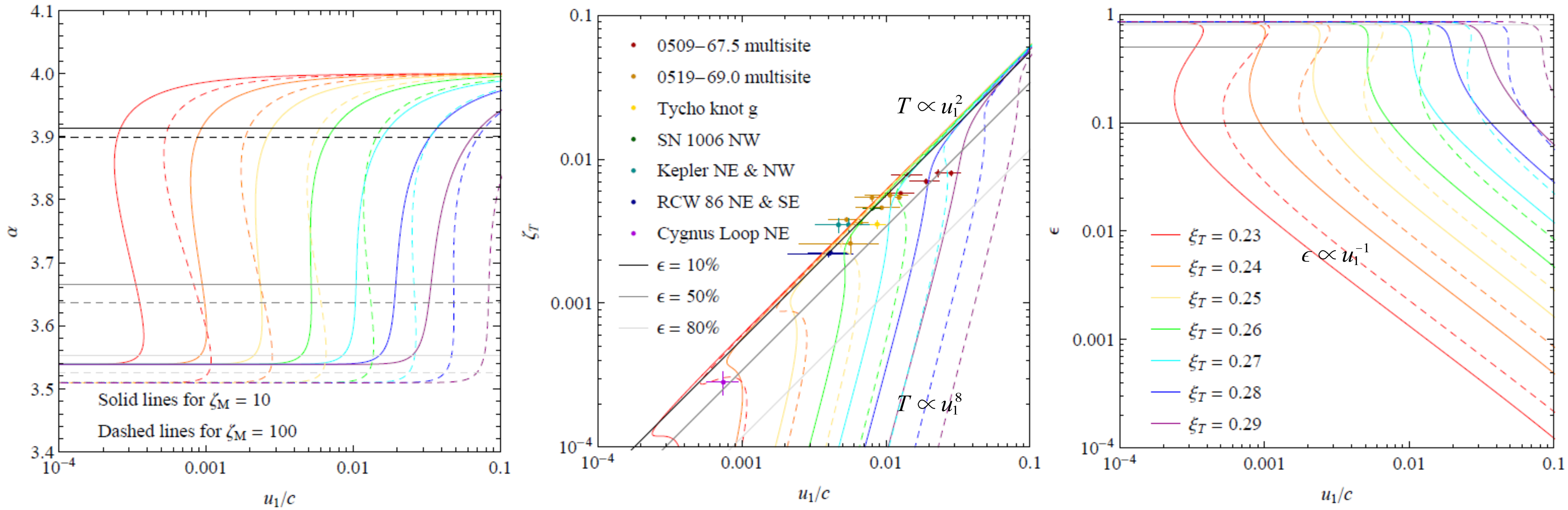
$$\alpha_{\mathrm{m}} \approx \frac{7}{2} + \frac{2\sqrt{\zeta_{\mathrm{M}}}-13/9-\sqrt{\left(2\sqrt{\zeta_{\mathrm{M}}}-13/9\right)^2-4\left(4/27+\sqrt{\zeta_{\mathrm{M}}}\ln\zeta_{\mathrm{M}}\right)/3}}{4\left(4/27+\sqrt{\zeta_{\mathrm{M}}}\ln\zeta_{\mathrm{M}}\right)}$$

$$\zeta_T = \sqrt{\frac{2T}{mc^2}},\quad \zeta_{\mathrm{m}} = \frac{p_{\mathrm{m}}}{mc},\quad \zeta_{\mathrm{M}} = \frac{p_{\mathrm{M}}}{mc}$$



- 超新星遗迹典型参数 $T \sim$ keV，$cp_m \sim 0.01$ GeV，$cp_M \sim 10$ GeV，临界位置 $\xi_T \sim 0.25$

- 超新星遗迹的加速效率大致在 10% 到 50% 之间
- 年老超新星遗迹的 ξ_T 略小于年轻遗迹的



$$\epsilon = \frac{P_p}{\rho_1 u_1^2} = \frac{2}{2+P/U}\frac{P_p}{P}, \quad \eta = \frac{1}{1+\rho_t/\rho_p} \sim e^{-\xi_T^{-2}}\xi_T^{-3}$$

加速效率　注入率

结论

- 激波气体在非相对论性与相对论性之间的转换敏感地依赖于 ξ_T，对于超新星遗迹这种转换发生于 $\xi_T \sim 0.25$
- 年老超新星遗迹的注入率可能小于年轻遗迹的

谢谢