Гидродинамическая модель нетеплового излучения пузырей Ферми

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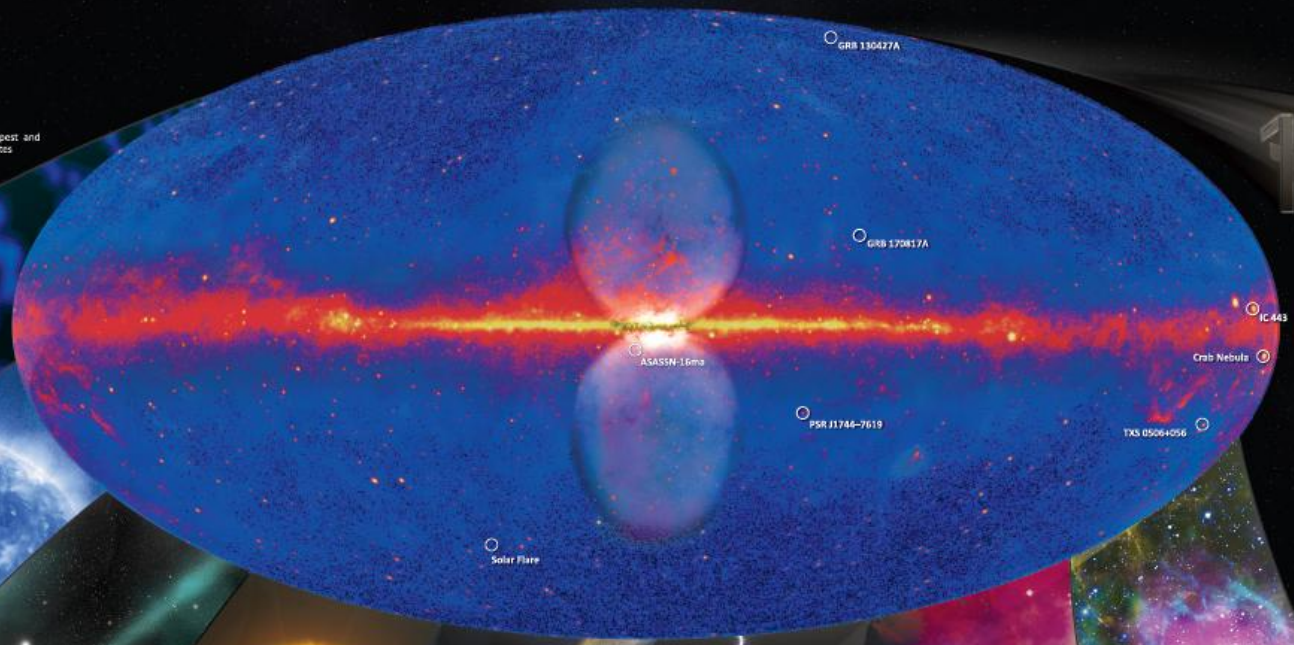
ФИАН

National Aeronautics and Space Administration

Fermi's Decade of Gamma-ray Discoveries



10 years

Fermi 10-year Sky Map

This all-sky view, centered on our Milky Way galaxy, is the deepest and best-resolved portrait of the gamma-ray sky to date. It incorporates observations by NASA's Fermi Gamma-ray Space Telescope from August 2008 to August 2018 at energies greater than 1 billion electron volts (GeV). For comparison, the energy of visible light falls between 2 and 3 electron volts. Lighter shades indicate stronger emission.
NASA/DOE/Fermi LAT Collaboration

GRB 130427A

On April 27, 2013, a blast of light from a dying star in a distant galaxy became the focus of astronomers around the world. The explosion, known as a gamma-ray burst and designated GRB 130427A, was detected by Fermi for about 20 hours. The burst included a 95 GeV gamma ray, the most energetic light yet detected from a GRB.
NASA/DOE/Fermi LAT Collaboration

Solar Flare

Although our Sun is not usually a bright gamma-ray source, solar flares can briefly outshine everything else in the gamma-ray sky. On March 7, 2012, Fermi detected flares erupting on the side of the Sun not visible to the spacecraft. The flares produced accelerated particles that fell onto the side of the Sun facing Earth, resulting in gamma rays Fermi could detect.
NASA/SDO

PSR J1744-7619

Discovered by Einstein@Home, a distributed computing project that analyzes Fermi data using home computers, PSR J1744-7619 is the first gamma-ray millisecond pulsar that has no detectable radio emission.
NASA/DOE/Fermi LAT Collaboration/SSU/A. Simonnet

ASASSN-16ma

Fermi has discovered several novas, outbursts powered by thermonuclear eruptions on white dwarf stars. This was a surprise because novas weren't expected to be powerful enough to produce gamma rays. One event, dubbed ASASSN-16ma, shows that both gamma rays and visible light seem to be produced by the same physical process. *NASA/DOE/Fermi LAT Collaboration*

GRB 170817A

This landmark event represents the first time light was seen from a source that produced gravitational waves. Fermi's detection of GRB 170817A coincided with a signal from merging neutron stars detected by the LIGO and Virgo gravitational-wave observatories. *NSF/LIGO/SSU/A. Simonnet*

TXS 0506+056

Among the nearly 2,000 active galaxies Fermi monitors, TXS 0506+056 stands out as the first one known to have produced a high-energy neutrino. Neutrinos are tiny, ghost-like particles that barely interact with matter and are thought to be produced in the same extreme physical environments as gamma rays. In July 2018, Fermi linked this galaxy to a detection by the Ice Cube Neutrino Observatory at the South Pole.
NASA Goddard/Fermi LAT Collaboration

Crab Nebula

The Crab Nebula, a young supernova remnant containing a pulsar, surprised Fermi astronomers with gamma-ray flares driven by the most energetic particles ever traced to a specific astronomical object. To account for the flares, scientists say electrons near the pulsar must be accelerated to energies a thousand trillion (10^{15}) times greater than visible light.
NASA/CXC/SAO/A. Hester et al.

Fermi Bubbles

Fermi data revealed vast gamma-ray bubbles extending tens of thousands of light-years from the Milky Way's plane. The Fermi Bubbles may be related to past activity of the supermassive black hole at our galaxy's heart.
NASA Goddard

Galactic Center

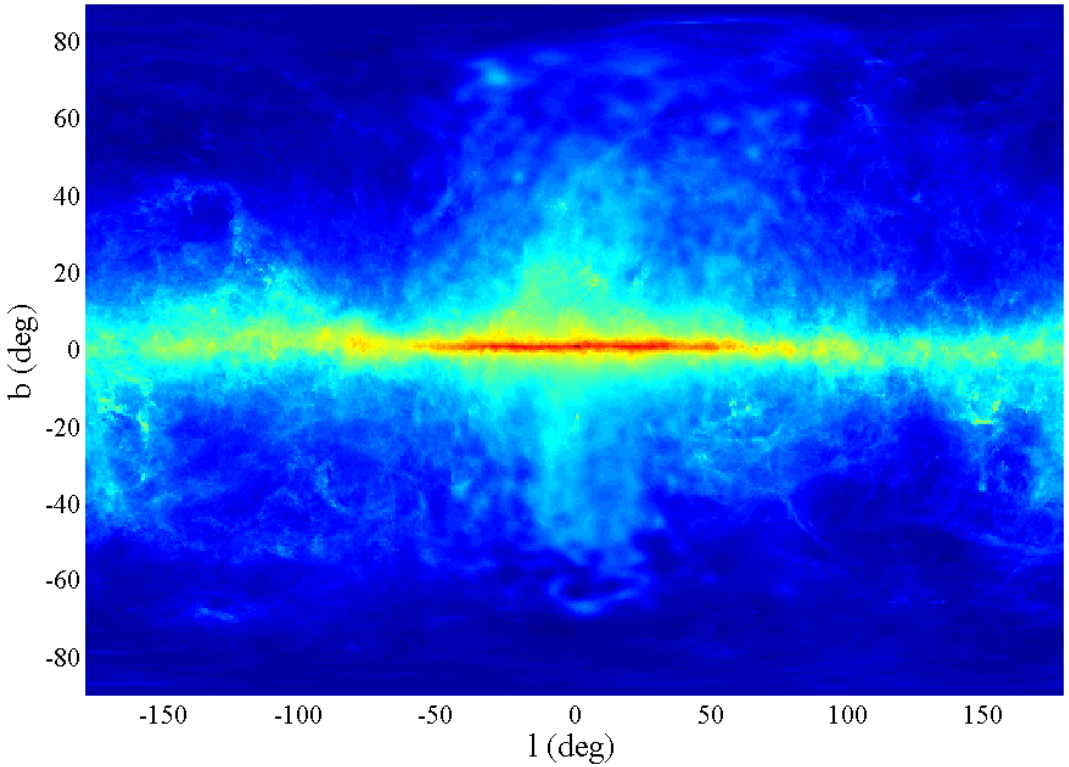
The central region of the Milky Way is brighter in gamma rays than expected. Whether this excess is a collection of undiscovered millisecond pulsars or possibly evidence of annihilation of dark matter particles remains a mystery and will be part of Fermi's ongoing studies.
NASA Goddard/A. Mellinger, CMU; T. Linden, Univ. of Chicago

IC 443, the Jellyfish Nebula

The shock waves of supernova remnants like the Jellyfish Nebula can accelerate protons to near the speed of light. When they slam into nearby gas clouds, gamma rays are produced. Fermi detects this emission, confirming that supernova remnants accelerate high-energy cosmic rays. *NASA/DOE/Fermi LAT Collaboration/WDAG/AURA/NOAO, PI-Calibody/UCLA*

Fermi Bubbles

- Симметричные (относительно плоскости Галактики) структуры
- Высота 8 кпк
- Полная светимость в γ диапазоне
$$F_\gamma = 4 \cdot 10^{37}\ \text{эрг/с}$$
- Также наблюдаются в радио, WMAP, Planck, $20 - 70$ ГГц

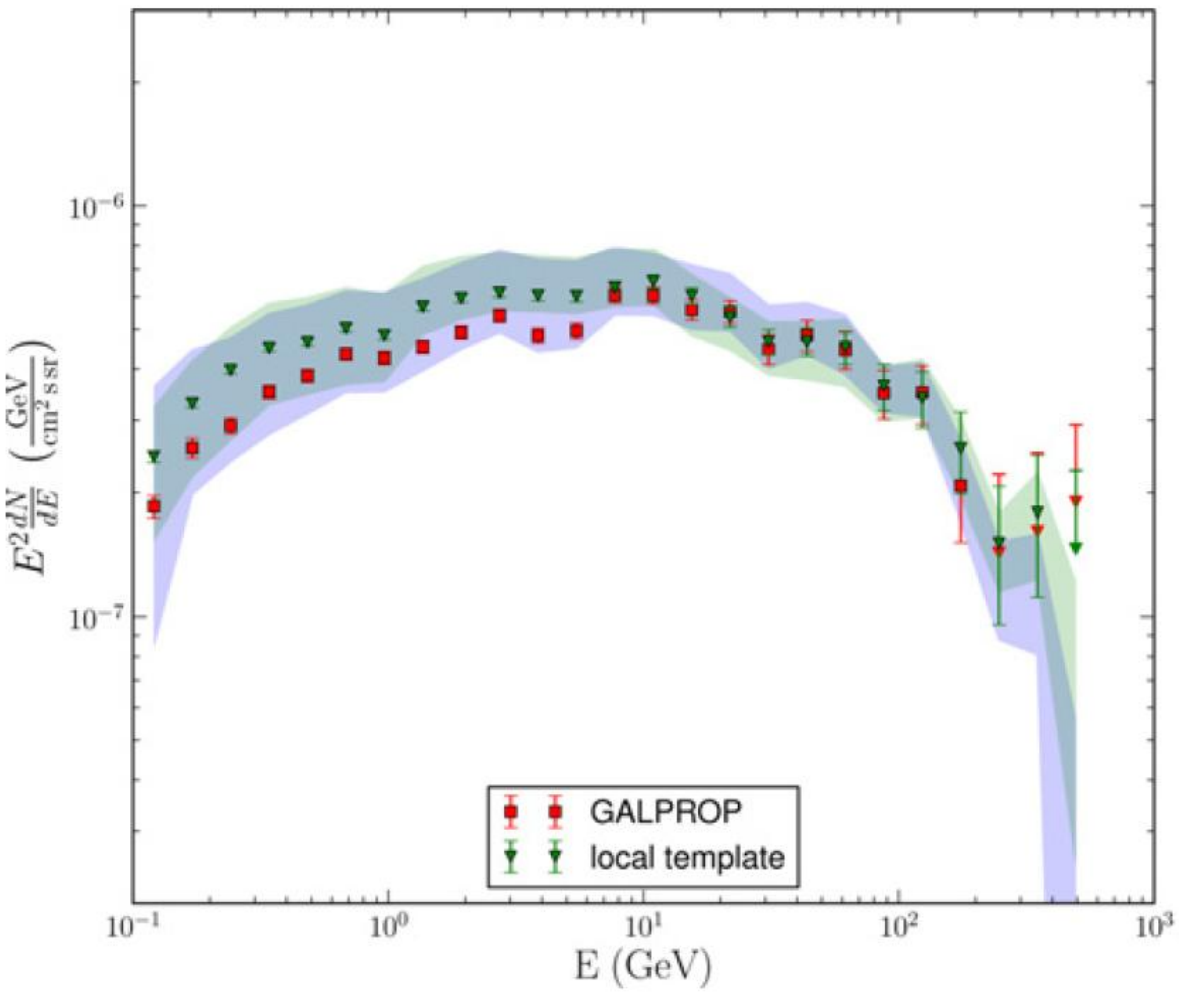


Фон Галактики (без точечных источников), $E_\gamma = 10$ ГэВ

Спектр Fermi Bubbles

1. Спектральный индекс 2
2. Завал спектра на $E_\gamma = 100$ ГэВ

Ackermann 2014



Erosita Bubbles

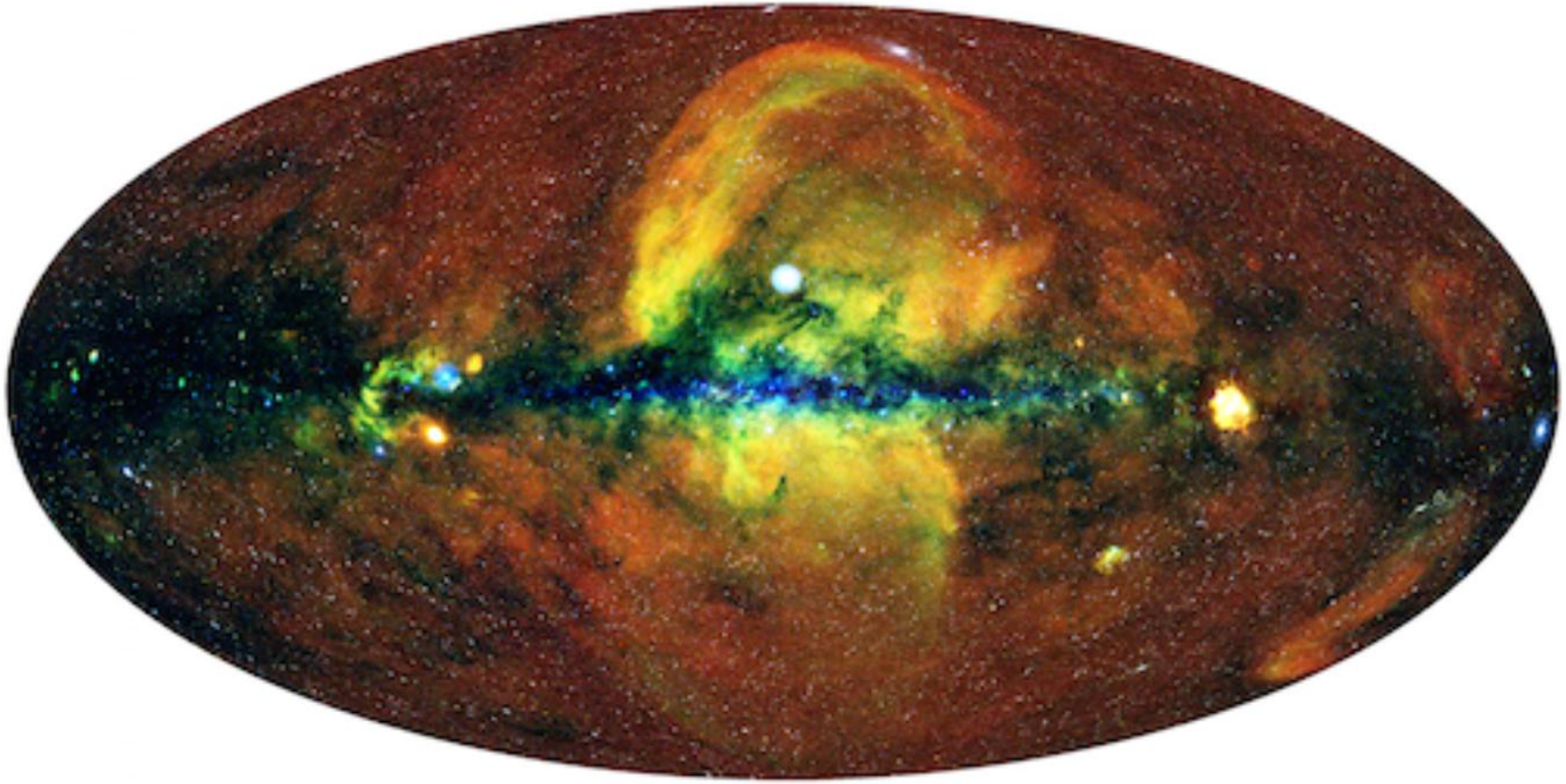
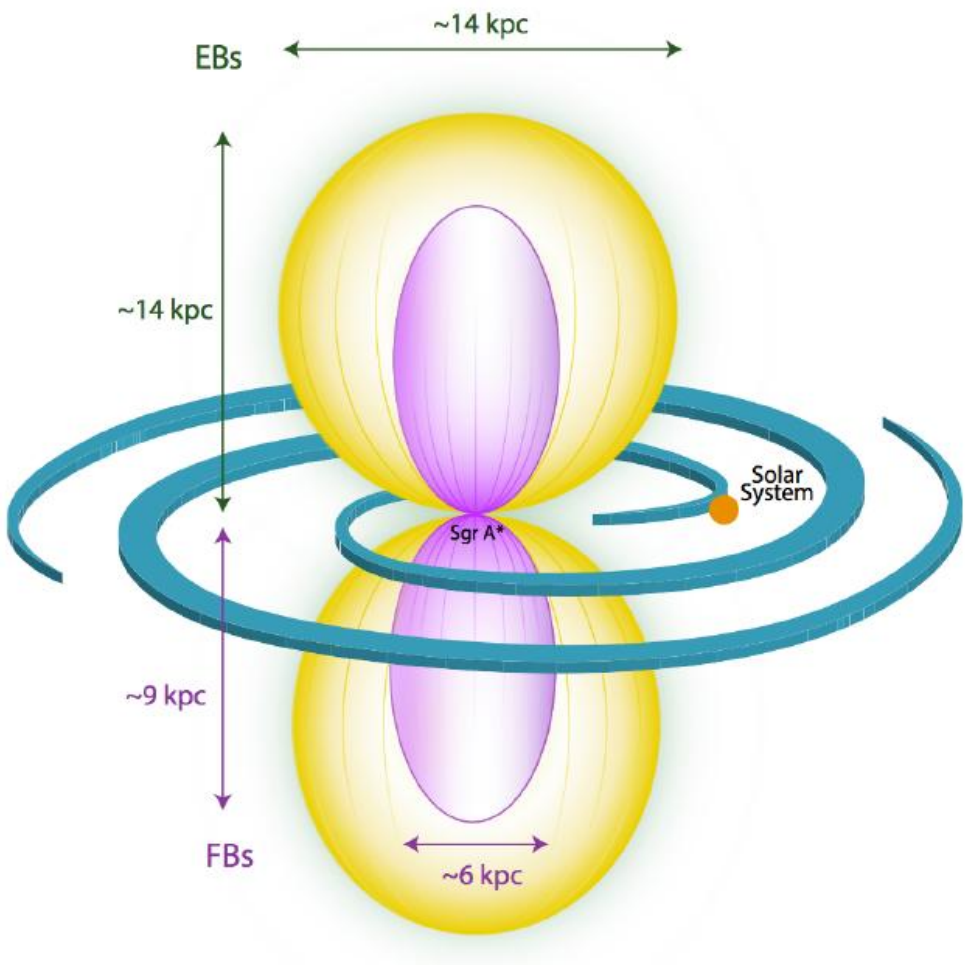


Fig. 1 | The Spektr-RG–eROSITA all-sky map. An RGB map of the first Spektr-RG–eROSITA all-sky survey (red for 0.3–0.6 keV, green for 0.6–1.0 keV, blue for 1.0–2.3 keV) is shown in Galactic

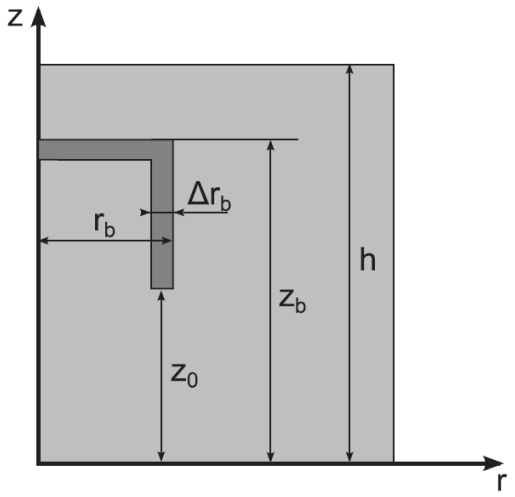
Размеры пузырей



Предыдущие работы

Цикл работ Cheng, Chernyshov, Dogiel, Ko, 2014-2015

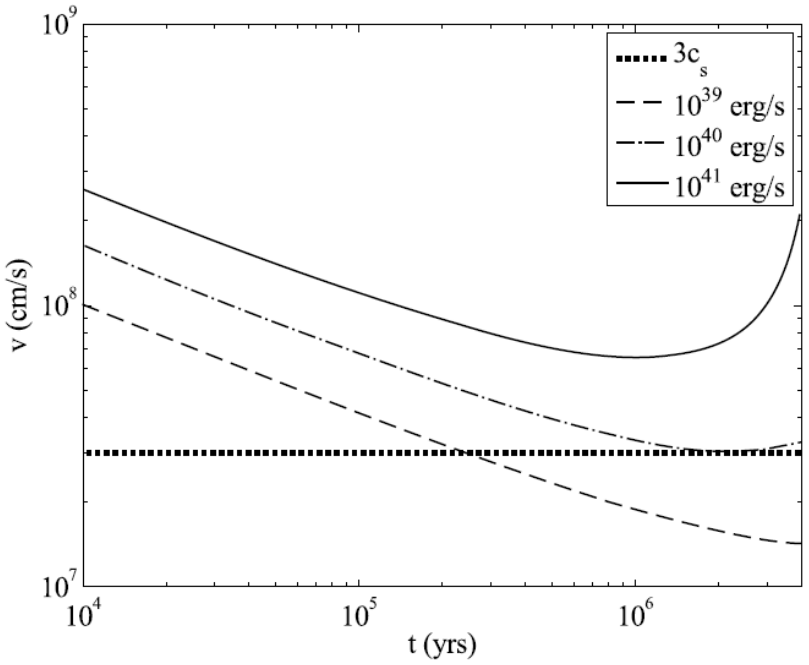
1. Ускорение из фоновой плазмы или доускорение КЛ?
2. Диффузионное уравнение для всего Гало
3. Источники – сверхновые в диске
4. γ-излучение за счет IC
5. Результаты воспроизводят спектры γ и радио излучения
6. Но! Толщина крышки и мощность турбулентности подобраны под данные наблюдений

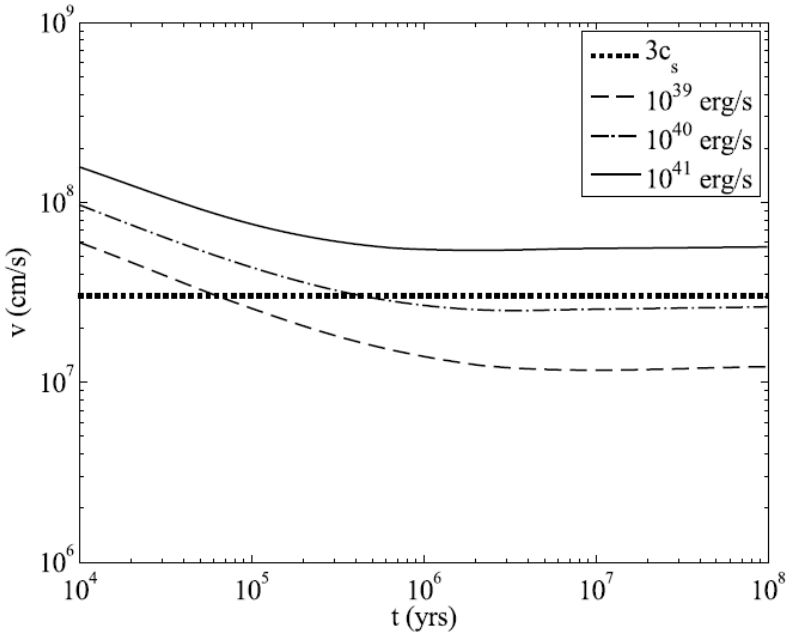


Ko, Breitschwerdt, Chernyshov, Cheng, Dai, Dogiel, 2020

- Исследование ударной волны из центра Галактики
- Источник энергии: поглощение звезд черной дырой (TDE)
- Частота событий: одно в $10^4 - 10^5$ лет
- Энерговыделение в кин. энергию газа $10^{52} - 10^{53}$ эрг, Dai 2018
- Для степенного Гало: УВ замедляется
- Для экспоненциального Гало: УВ ускоряется
- Необходимо $L > 10^{41}$ эрг/с

- $\rho = \rho_0 \exp(-z/H)$





Решение Компанейца, 1960

Введем переменную y (новое время)

$$y(t) = \int_0^t dt \sqrt{\frac{\gamma_g^2 - 1}{2} \cdot \frac{E(t)}{\rho_0 V(t)}},$$

где $E(t) = Lt$, что аналогично

$$\left(\frac{dy}{dt}\right)^2 \cdot V(t) = \frac{\gamma_g^2 - 1}{2} \cdot \frac{E(t)}{\rho_0}.$$

Объем пузыря

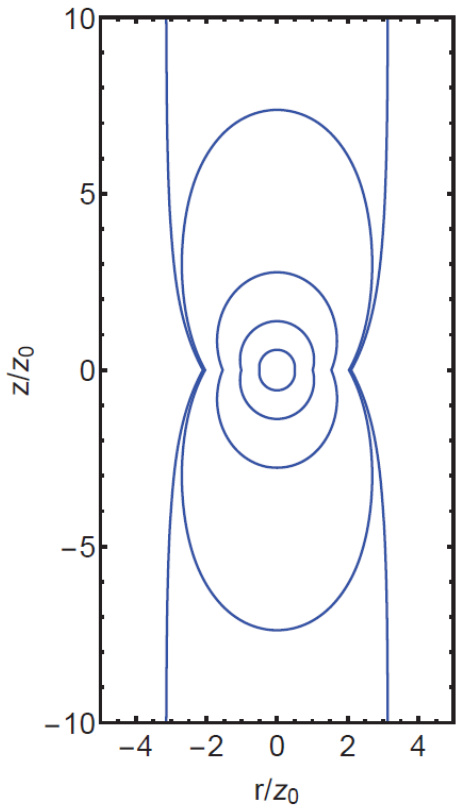
$$V(y) = 2\pi \int_0^{z_u} r^2 dz,$$

верхняя точка

$$z_u(y) = -2H \ln(1 - \frac{y}{2}).$$

Форма ударной волны

$$r(y, z) = 2H \arccos\left(\frac{1}{2} exp(\frac{z}{2H})(1 - \frac{y^2}{4H^2} + exp(-\frac{z}{H}))\right)$$



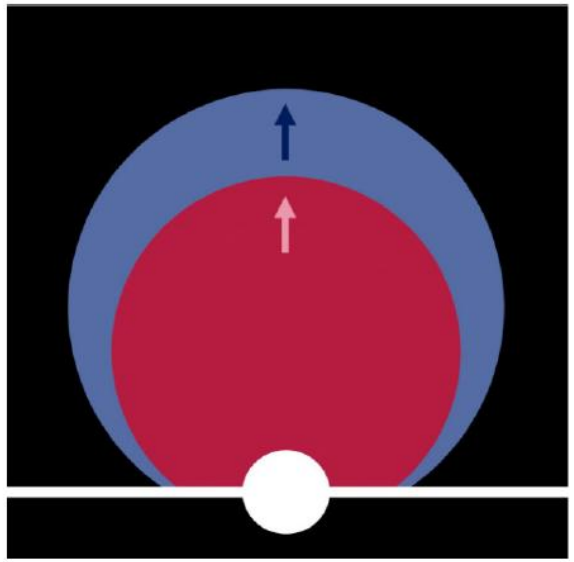
Толщина оболочки $d(t)$

Полная масса оболочки в данный момент времени

$$m(t) = 2\pi \int_0^{z_u} \rho(z) r^2 \, dz.$$

Определим толщину оболочки $d(t)$ соотношением

$$m(t) = d(t) \times \int_{surface} \rho_{in} dS$$



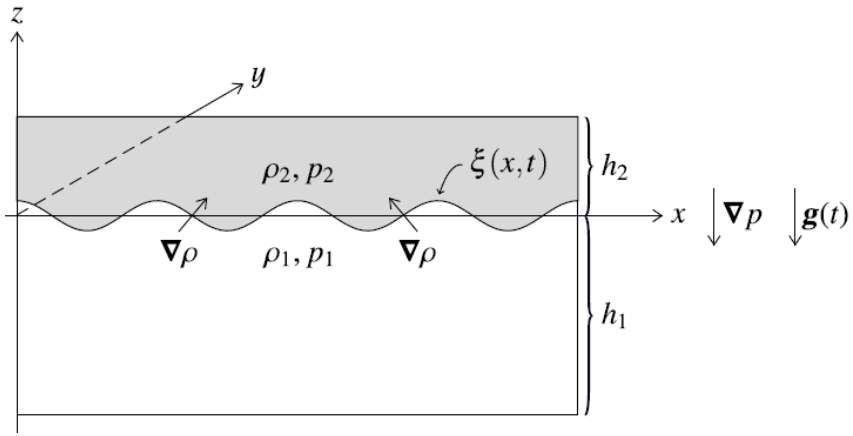
Неустойчивость Релея-Тейлора

Линейная стадия, $kh \gg 1$

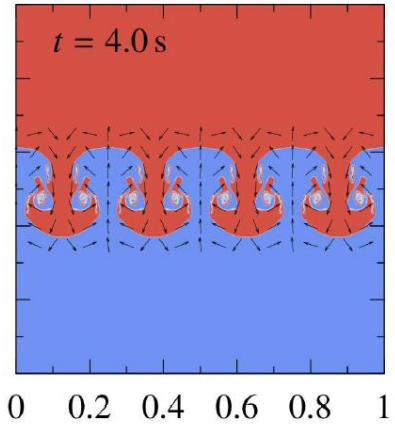
$$\ddot{\eta}(t) = kg(t) \cdot \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} \cdot \eta(t),$$

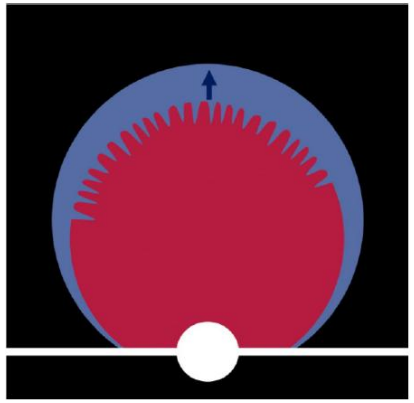
нелинейная стадия

$$\dot{\eta}(t) = 2\sqrt{\alpha g(t) \cdot \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} \cdot \eta(t)}.$$



- E. Fermi, J. von Neumann 1953 (Technical Report no. AECU-2979, Los Alamos Scientific Laboratory); Ristorcelli & Clark 2004; Breitschwerdt 2022
- $\alpha = 0.02 \ - 0.1,$ мы используем $\alpha = 0.04$



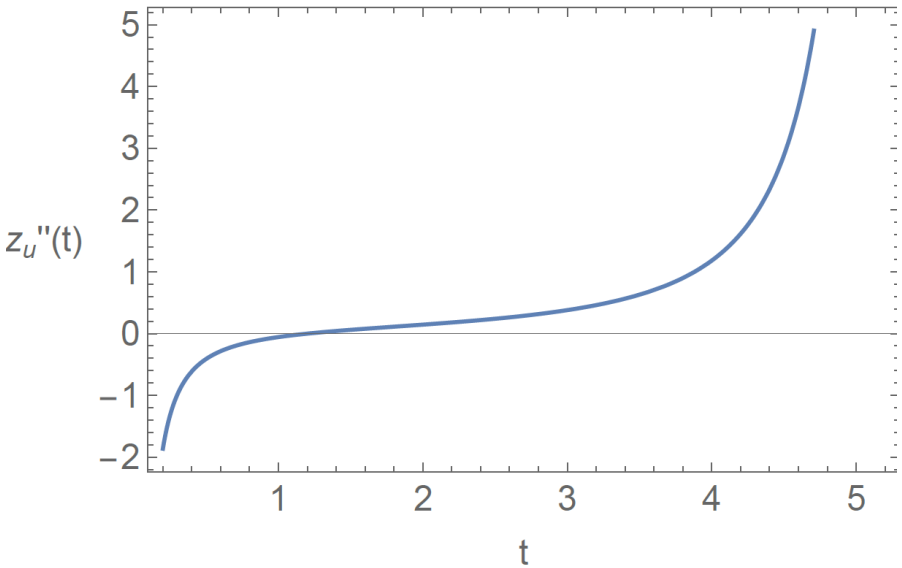


Безразмерные уравнения, Компанеец

Есть три размерных параметра: ρ_0, L, H и один безразмерный: α.

$$\tilde{z} = \frac{z}{H}, \qquad \tilde{t} = \frac{t}{t_0}, \qquad \tilde{m} = \frac{m}{\rho_0 H^3},$$

$$t_0^3 = \frac{2}{\gamma_g^2 - 1} \cdot \frac{\rho_0 H^5}{L}.$$



Переменная y

$$\left(\frac{dy}{dt}\right)^2 \cdot V(y) = t.$$

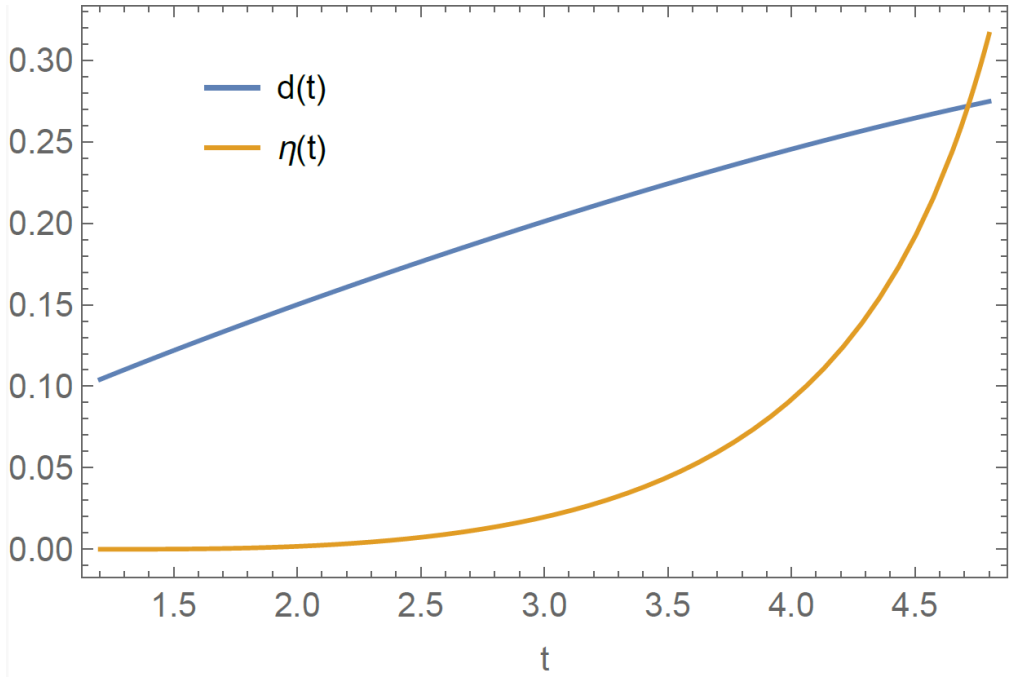
Объем пузыря и верхняя точка

$$V(y) = 2\pi \int_0^{z_u} r^2 dz, \qquad z_u = -2\ln(1 - \frac{y}{2}).$$

Форма ударной волны

$$r(y, z) = 2\arccos\left(\frac{1}{2}e^{z/2}(1 - \frac{y^2}{4} + e^{-z})\right).$$

Безразмерные уравнения, амплитуда РТ



Масса и толщина оболочки

$$m(t) = 2\pi \int_0^{z_u} e^{-z} \cdot r^2 \cdot \, dz.$$

$$m(t) = d(t) \times 16\pi \int_0^{z_u} e^{-z} \cdot r\sqrt{1 + (dr/dz)^2}\, dz.$$

Амплитуда РТ-неустойчивости

$$\dot{\eta}(t) = 2\sqrt{\alpha \ddot{z}_u \eta}.$$

Результаты вычислений

- Считаем только один раз!

$$t_b = 4.715, \qquad y(t_b) = 1.913, \qquad z_u(t_b) = 6.27,$$
$$\eta(t_b) = 0.272, \qquad \dot{\eta}(t_b) = 0.467$$

- Выберем значения

$$H = 1.3 \text{ кпк}, \ \rho_0 = 7 \cdot 10^{-27} \text{ г/см}^3, \ L = 10^{41} \text{ эрг/с}$$

- Тогда единицы времени и скорости

$$t_0 = 1.37\, My, \quad H/t_0 = 10^3 \text{ км/с}$$

- Момент развала оболочки: $d(t) = \eta(t)$
- Момент развала $6.5\ My$, высота пузыря в момент развала $\widetilde{z_u}(t_b)H = 8.1$ кпк
- Толщина оболочки в момент развала всего 0.3 кпк

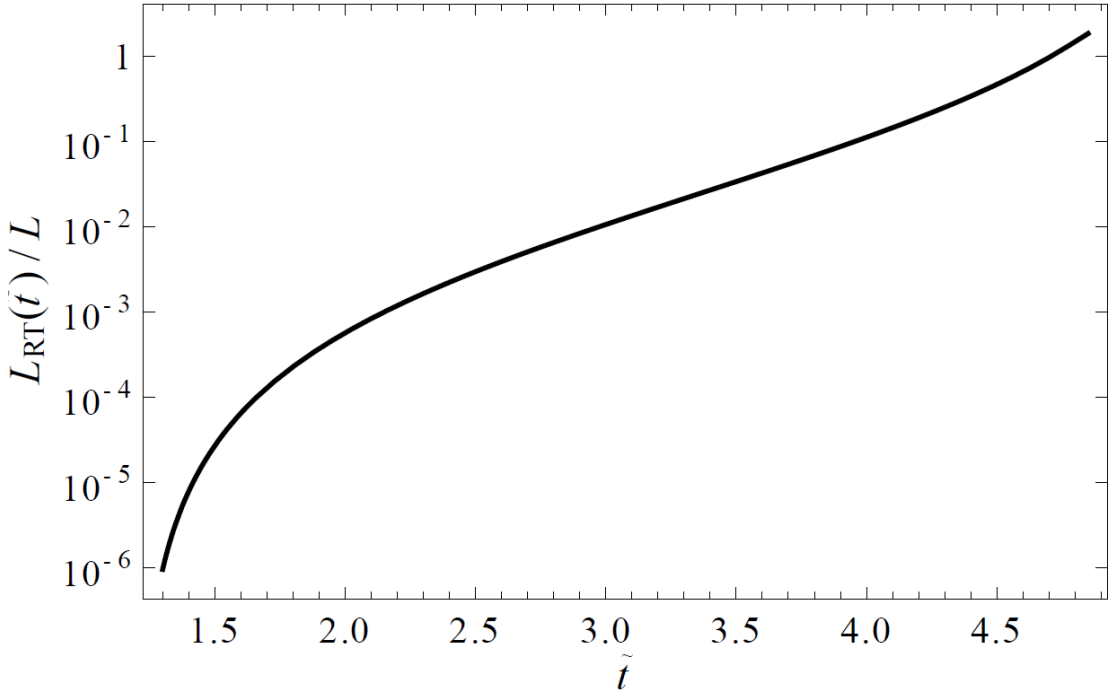
Мощность в турбулентности

- Колмогоров: в единице объема по спектру перекачивается мощность

$$\varepsilon = \rho \times \frac{v_{turb}^3}{l_{turb}}$$

- Оценим $v_{turb} = \dot{\eta}(t)$
- Оценим $l_{turb} = \eta(t)$
- Полная мощность турбулентности во всем пузыре

$$\tilde{W}(t) = V \times \varepsilon = m_{turb} \times \frac{\dot{\eta}^3}{\eta}.$$



Ускорение электронов

- МГД турбулентность, $B_0 \gg \delta B$

$$W(k) \approx \frac{A\rho\dot{\eta}^2}{2}\eta^{2/3}k^{-5/3}$$

- Резонансное рассеяние (QLT)

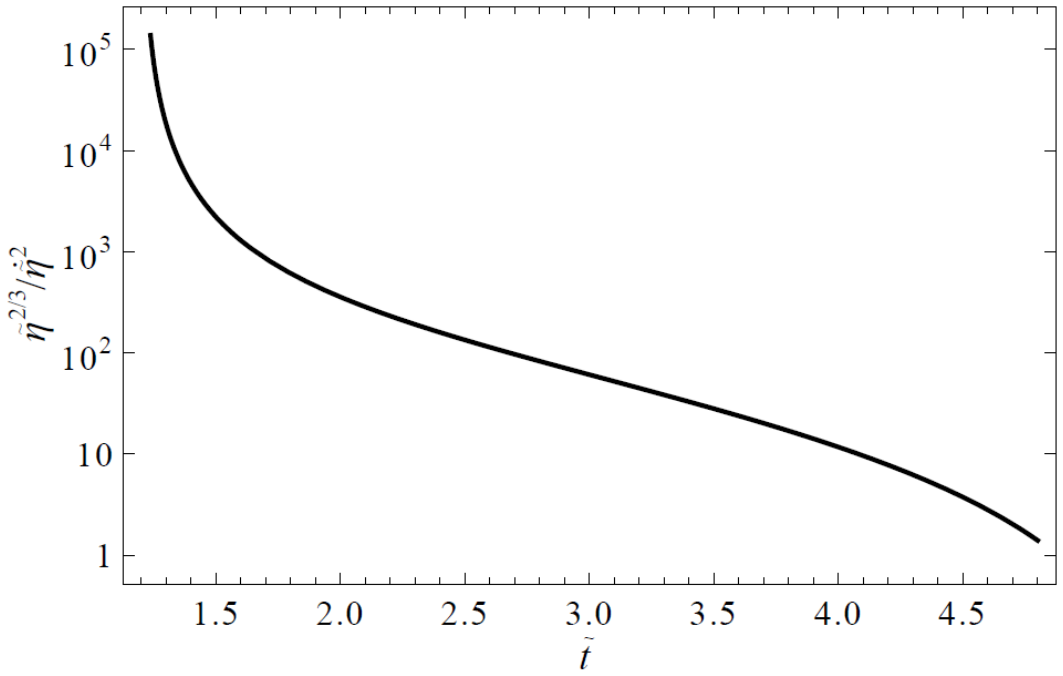
$$\kappa = \frac{4\pi^2 v_{\rm A}^2 k_{\rm res}}{c} \cdot \frac{k_{\rm res} W(k_{\rm res})}{B^2} p^2 \,,$$

- Потери = IC. Оценим максимальную энергию

$$\tau_{acc} = \frac{p^2}{4\kappa} = \tau_{loss} = \frac{m^2c^2}{\sigma_T w p}$$

- Ускорение идет быстрее всего в конце эволюции

$$\tau_{acc} \sim \frac{\eta^{2/3}}{\dot{\eta}^2}$$



Максимальная энергия электронов

$$E_{\max} = mc^2 \left(\frac{A\pi\dot{\eta}^2\Omega^{1/3}}{2\eta^{2/3}c^{1/3}} \cdot \frac{m}{\sigma_T w} \right)^{3/4}$$

Для тех же значений

$$H = 1.3 \text{ кпк}, \ \rho_0 = 7 \cdot 10^{-27} \text{ г/см}^3, \ L = 10^{41} \text{ эрг/с},$$
$$B = 2 \text{ мкГс}, \ w = 1 \text{ эВ/см}^3,$$

$$E_{max} = 190\,\text{ГэВ} \times A^{3/4}$$

Выводы

1. Гидродинамическая модель объясняет ускорение электронов до энергий 1 ТэВ
2. Объяснить структуру Fermi+Erosita bubbles не получается