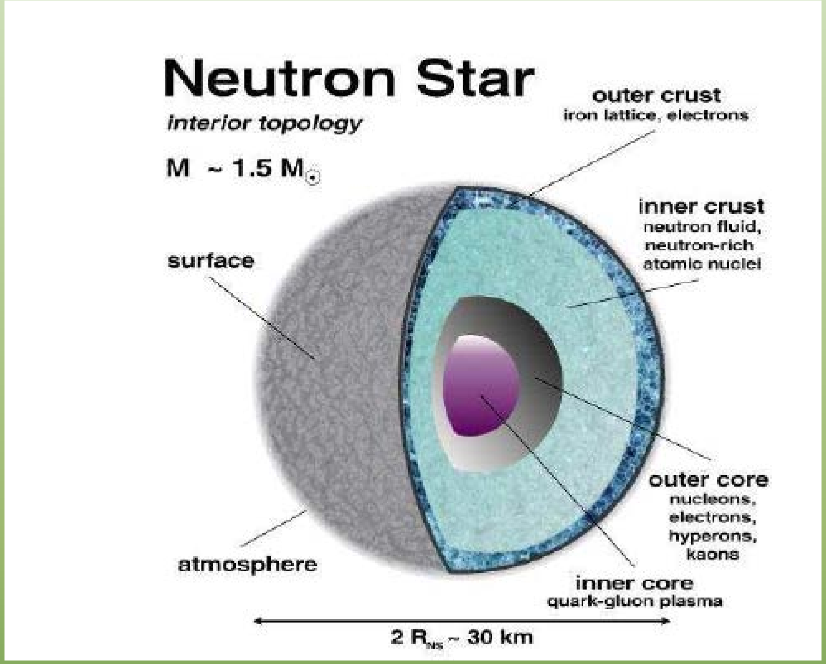
ANISOTROPY IN COSMIC RAYS FROM INTERNAL TRANSITIONS IN NEUTRON STARS

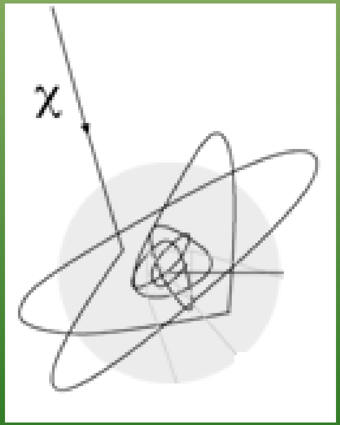
M Ángeles Pérez-García

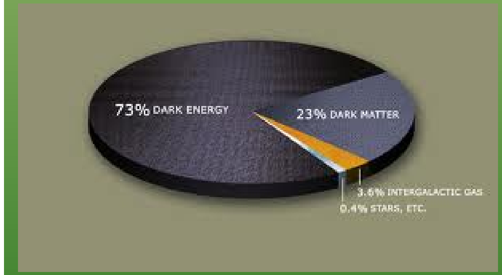
Fundamental Physics Department & IUFFyM,
University of Salamanca, Spain

(in collaboration with)
K. Kotera and J. Silk (@IAP, Paris, France)

Astroparticle source: NS





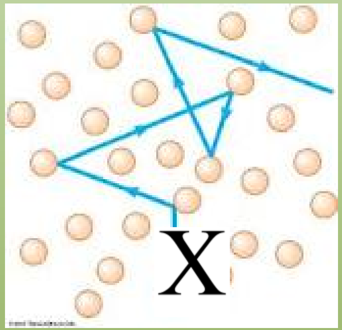


- Neutron stars are among the most dense compact stars.
- Mass ≈1.5 Mo, R ≈ 12 km
- Central densities $\rho \approx 10^{14 \div 15}$ g/cc
- Central temperatures: T≈1 MeV.
- Surface magnetic fields: $B \approx 10^{9}$-10^{15} G
- Efficient accretors: SM matter and Dark matter (DM)

Neutron star efficient DM trap

The efficiency of NS to capture DM is much larger than for the sun:

Magnitude	Sun	Neutron star
Central density [g/cc]	10^2	10^{14}
Mean free path [1/σn] cm	10^{14}	100
Capture rate [s^{-1}]	10^{23}	10^{25}

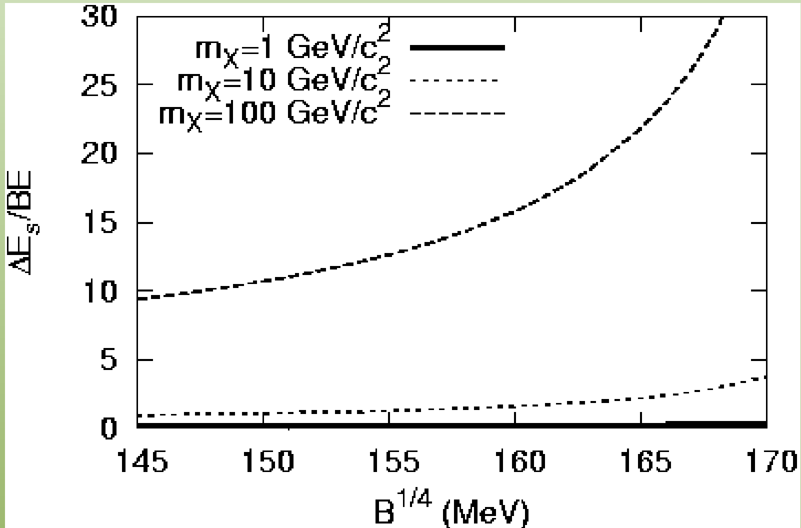


$$F = \frac{3.042 \quad 10^{25}}{m_X\,(GeV)} \rho_{DM} \Big/ \rho_{DM,0} \; (s^{-1})$$

- DM can be accreted from galactic profile by many massive astrophysical objects

[Goldman, Nussinov, Press, Spergel, Kouvaris, Lavallaz, Fairbairn, Silk, Stone, Perez-Garcia..]

Internal engine based on deconfinement of quark matter



Perez-Garcia, arXiv: 1205.2581, Proc. Moriond'12
Perez-Garcia, Silk, PLB 711, 6 (2012)

Mechanism for actual deconfinement not clear:

- Dark matter driven spark seeding
  Perez-Garcia, Silk, Stone PRL 105, 141101 (2010)
- Density raise due to NS spin down
  J. Staff, R. Ouyed, and P. Jaikumar, ApJ 645,L145 (2006).

Prog. Theor. Phys. Vol. 44 (1970), No. 1

Hydrostatic Equilibrium of Hypothetical Quark Stars

Naoki ITOH
Department of Physics, Kyoto University Kyoto

March 24, 1970

Ambartsumyan and Saakyan[1)] initiated the study of the degenerate superdense gas of elementary particles taking into account various hyperons. Afterwards many authors[2)] have investigated hyperon stars further either by adding newly discovered elementary particles or by assuming some interactions between these elementary particles. A primitive and straightforward question then arises: What state occurs at the density higher than hyperon stars? No one can answer this question now, as our knowledge of strong interaction physics is very incomplete.

If a baryon consists of some fundamental particles, it may be possible that unbound fundamental particles will exist in the interior of superdense stars. Ivanenko and

with the mass m. One quantum state can be occupied by less than or equal to q para-fermions. Putting $q=1$, we have the usual fermion case. The ratio of the limiting momentum p_0 to mc, $x\equiv p_0/mc$, is related to the number density of para-fermions, n, by

$$n=q\frac{8\pi m^3c^3}{3h^3}x^3. \quad (1)$$

The pressure is given by

$$P=q\frac{\pi m^4c^5}{3h^3}f(x) \quad (2)$$

with the function

$$f(x)=x(2x^2-3)(x^2+1)^{1/2}+3\sinh^{-1}x. \quad (3)$$

The internal energy of the gas $U_{\rm kin}$ is given by

$$U_{\rm kin}=q\frac{\pi m^4c^5}{3h^3}Vg(x), \quad (4)$$

where

$$g(x)=8x^3\{(x^2+1)^{1/2}-1\}-f(x). \quad (5)$$

We shall consider a quark star consisting of an equal amount of u, d and s-quarks for simplicity. The condition of the charge

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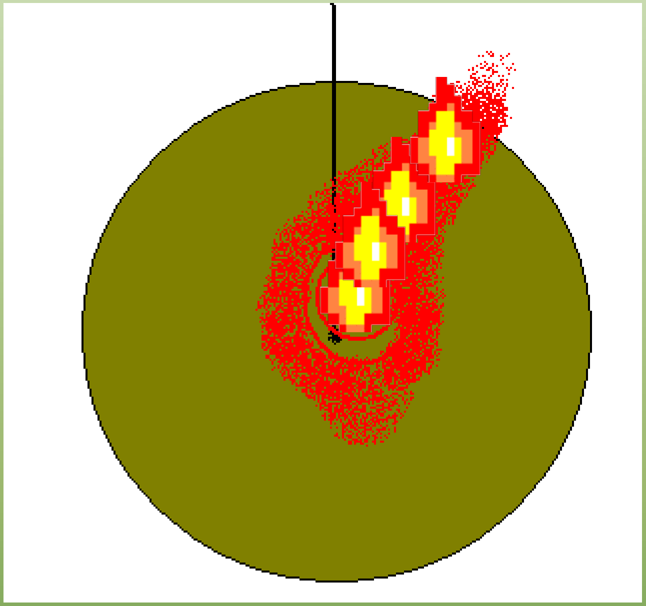
Cosmic separation of phases

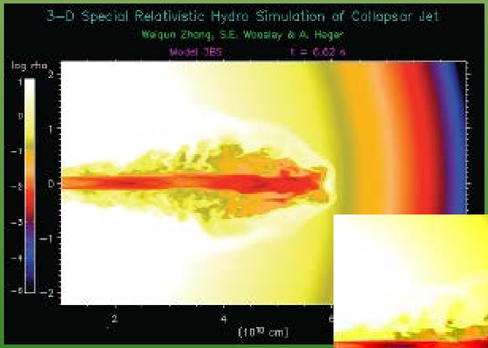
Edward Witten*
Institute for Advanced Study, Princeton, New Jersey 08540
(Received 9 April 1984)

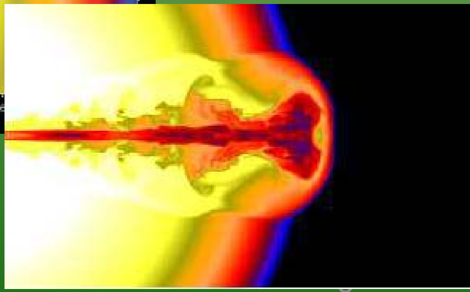
A first-order QCD phase transition that occurred reversibly in the early universe would lead to a surprisingly rich cosmological scenario. Although observable consequences would not necessarily survive, it is at least conceivable that the phase transition would concentrate most of the quark excess in dense, invisible quark nuggets, providing an explanation for the dark matter in terms of QCD effects only. This possibility is viable only if quark matter has energy per baryon less than 938 MeV. Two related issues are considered in appendices: the possibility that neutron stars generate a quark-matter component of cosmic rays, and the possibility that the QCD phase transition may have produced a detectable gravitational signal.

NS transition and astroparticle ejection

- We propose internal phase transitions trigger ejection of novel astroparticles.
- Nuclearites/ strangelets: weakly charged uds matter.
- Ejection may happen also in merger events: NS, BH, QS
- Ejected mass fraction less than ≈10^{-4} Mo
- Relativistic break out assumed to happen with complex dynamics.



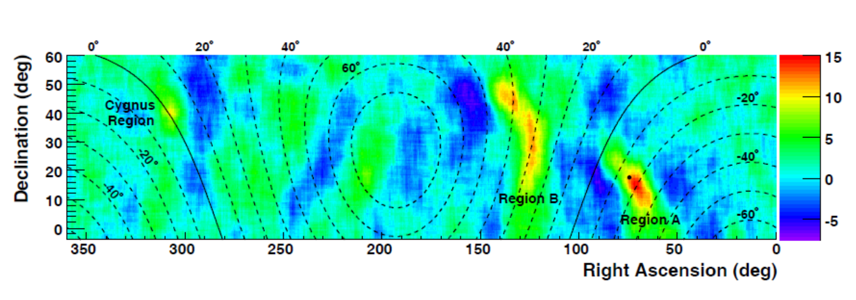


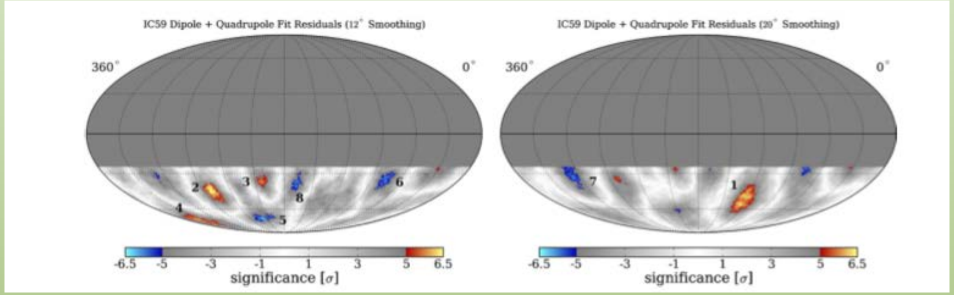


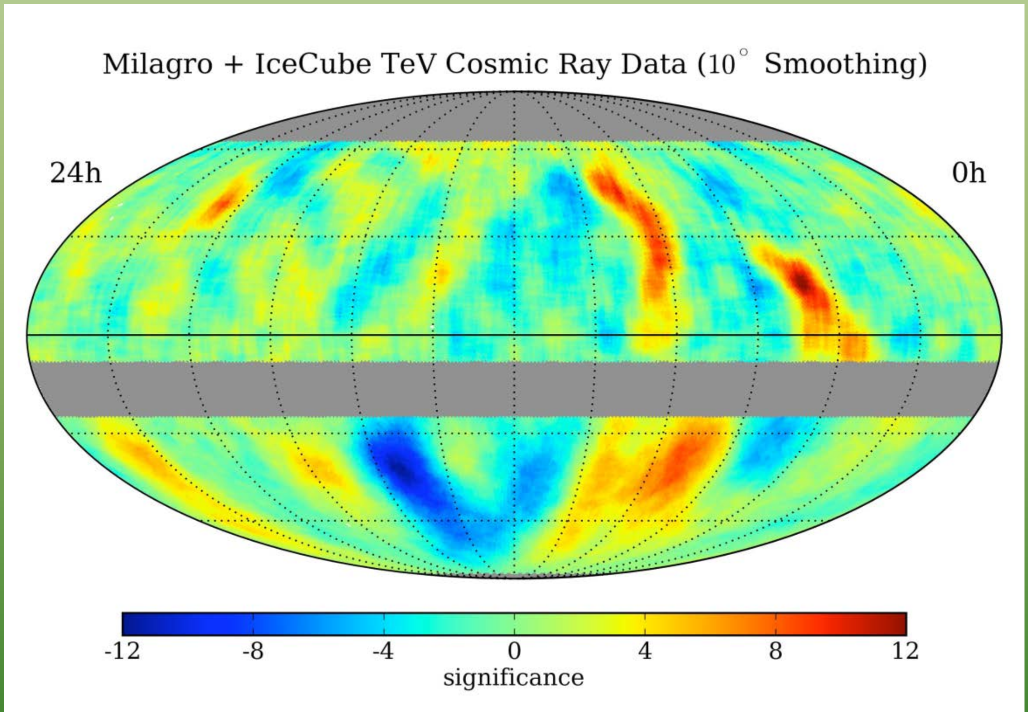
Zhang, Woosley and Heger 2003

Pérez-García, Silk, Stone PRL 105, 141101 (2010)
Pérez-García, Silk PLB 711, 6 (2012)
Pérez-García, Daigne, Silk ApJ 768 145 (2013)

CR anisotropies







Super-Kamiokande,Tibet-III,Milagro, ARGO-YB and IceCube

have reported large and small scale anisotropies with considerable significance in the TeV-PeV range.

Abdo et al, Arxiv: 0801.3827, Phys. Rev. Lett., 101, 221101

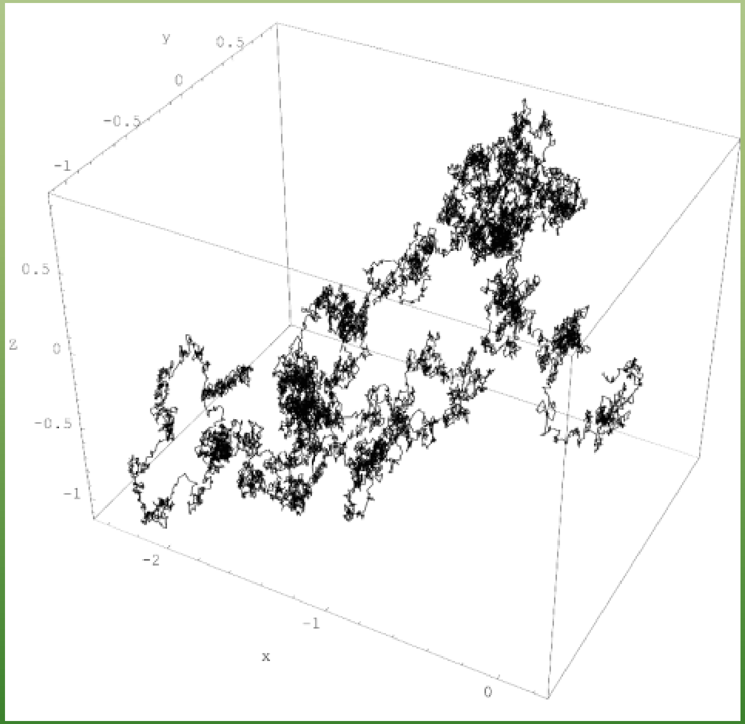
Abbasi et al., ApJ, 740, 16, 2011
Arxiv: 1105.2326

CR anisotropies

Gyroradius of regular CRs seems not to be large in Galactic field.

$$r_g(p) \simeq \frac{p}{eZB} \simeq 1 \left(\frac{p/Z}{10^{15}\,\mathrm{eV}}\right) \left(\frac{B}{\mu\mathrm{G}}\right)^{-1} \mathrm{pc}$$

CRs would perform Random walks

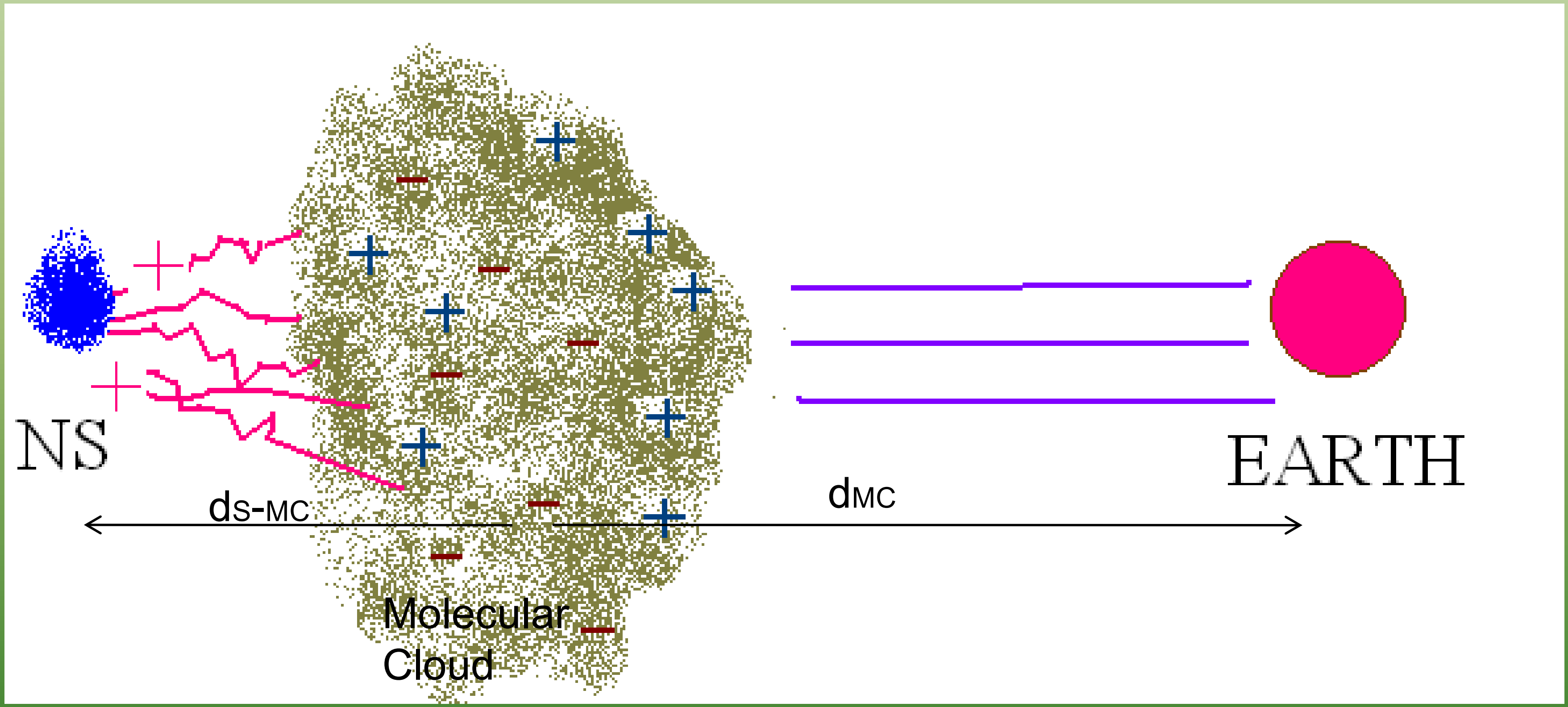


Previous works :

Anisotropy at multiple scales arises from turbulent propagation in the GMF
Giacinti & Sigl, arXiv: 1111.2536

Magnetic mirroring and funneling from nearby source
Drury and Aharonian, Astropart. Phys. 29 420-423 (2008)

Novel Physical scenario



Ejection model

We propose that a novel phase of finite quark matter lumps (i.e. nuclearites, strangelets) could be primaries

Kinetic energies due to gravitational energy conversion

E injected into the expelled outer crust for standard NS mass and radius

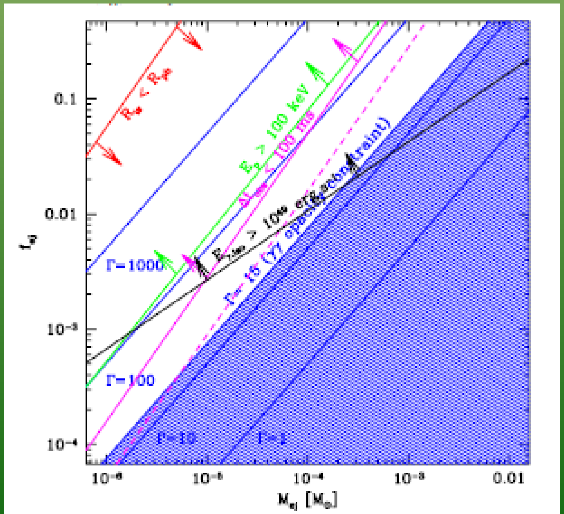
A−lumps could then gain energies of order the typical energy observed in hotspot

$$K \approx 4\times10^{50}\ erg\left(\frac{f_{ej}}{10^{-3}}\right)$$

$$A \leq 10^2 - 10^4$$

$$K \approx 22\ TeV\left(\frac{A}{10^3}\right)\left(\frac{\Gamma}{22}\right)$$

Kotera, Pérez-García, Silk
arXiv:1303.1186



$$\Gamma \approx \frac{K}{M_{ej}} \approx 21\left(\frac{f_{ej}}{10^{-3}}\right)\left(\frac{R_{NS}}{10km}\right)^{-1}\left(\frac{M}{1.5M_\odot}\right)^{2}\left(\frac{M_{ej}}{10^{-5}M_\odot}\right)$$

Perez-Garcia, Daigne, Silk, ApJ 768 145 (2013)

NS transtion to QS

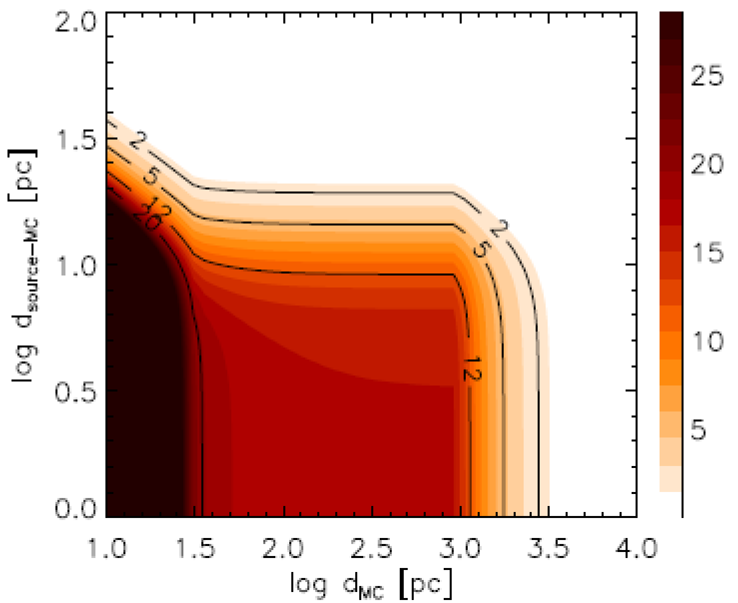


FIG. 1. Particle excess significance σ (Eq. 1), as would be observed by Milagro with 7 years of data, at $E = 20\,\mathrm{TeV}$, as a function of the distance of the MC to the Earth, $d_{\rm MC}$, and the distance between the source and the MC, $d_{\rm s-MC}$, for strangelets with $Z = 1$, $A = 10^3$ and a MC of radius $R_{\rm MC} = 25\,\mathrm{pc}$, source of luminosity $L_{\rm MC} = \eta 10^{40}\,\mathrm{erg/s}$, and an efficiency factor $\eta = 5\times10^{-8}$. The color bar indicates the value of σ, and black lines depict specific numerical values of σ as indicated.

Kotera, Pérez-García, Silk
arXiv:1303.1186

Signal depends on energy and can be parametrized using source characteristics and ejecta.

$$\sigma_{<\Omega} = N_{\rm s,<\Omega}/(N_{\rm iso,<\Omega})^{1/2}$$

$$N_{\rm s,<\Omega} = L_{\rm MC} A(\alpha,\delta) 4\pi d^2_{\rm s-MC} \Omega E^{-1}$$

$$N_{\rm iso,<\Omega} = \dot{E} J_{\rm iso,sr} A(\alpha,\delta)$$

Luminosity in strangelets inside the Molecular cloud a $Z/A \sim 10^{-3}$

$$L_{\rm MC} = E_{\rm MC}/\Delta t \sim 3.5\times10^{40}\,\eta Z^{-1/3}(R_{\rm MC}/25\,\mathrm{pc})^{-2}\,\mathrm{erg/s}$$

$$\sigma(E) = \frac{\eta}{E^{3/2}}\left[1 + \frac{d^4_{\rm s-MC}c^2}{4D^2R^2_{\rm MC}}\right]^{-1} \frac{E_{\rm ej}}{\Delta t} \frac{A(\alpha,\delta)^{1/2}}{4\pi d^2_{\rm MC}\Omega J^{1/2}_{\rm iso,sr}}$$

This requires $\eta \approx 10^{-8}$ as a result of: efficiency in neutralization, rate transition, ejection at source.

Angular extent spots

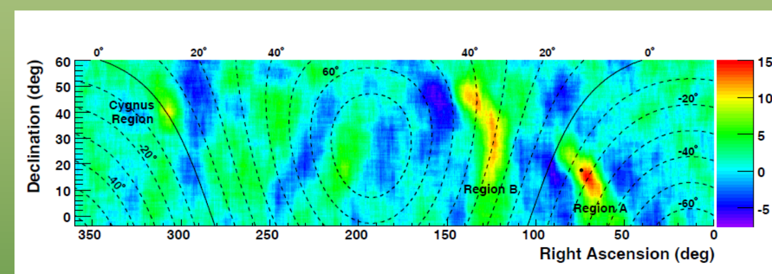
Angular extent depends on the geometry, but typically could be of order 10º.

$$\theta_{\rm MC} \sim 14^\circ\,(R_{\rm MC}/25\,{\rm pc})(d_{\rm MC}/200\,{\rm pc})^{-1}$$

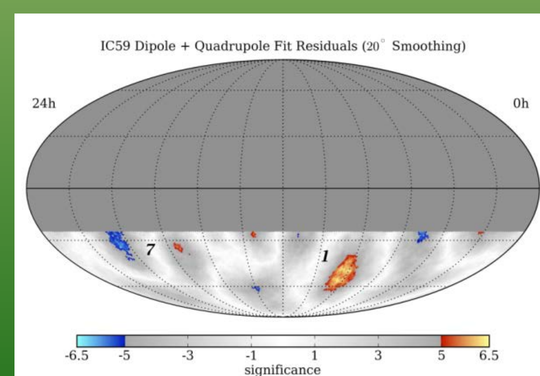
Kotera, Pérez-García, Silk
arXiv:1303.1186

Some regions quoted in released experimental results are in the directions of Molecular clouds:

REGION A -> Taurus MC:



REGION 1 -> Vela MC Ridge:



Conclusions

- We discussed a new mechanism for formation of Cosmic Ray hotspots based on the astroparticle ejection in a NS phase transition

- Energies in the range of short GRBs 10^{49}-10^{52} erg can be injected due to a fraction of gravitational energy conversion in the event.

- Not high Lorentz factors are needed if ejected nuclearite has A= 10^{2}-10^{4} and ejected mass is 10^{-5} solar masses
Rate of transition small 10^{-7} in the galaxy.

- Large signal strength possible if transition happens inside molecular cloud. Angular hotspot extent can match small scales.

NOT ALL NS CONVERT TO QUARK STARS
EFFICIENCY IS LOW

It is expected a low efficiency in the transition of the NS.

Individual sparks probable but percolation effect needed.

Old NS and enhanced DM regions are more likely

The rate would be small as it corresponds to a large delay between the end of the life of massive progenitor and emission of SGRB.

$$\frac{\mathcal{R}_{\rm SGRB}}{\mathcal{R}_{\rm NS\to QS,max}} \simeq (8\times10^{-2}\to 3\times10^{-1})\left(\frac{\langle f_{\rm b}\rangle}{50}\right)\left(\frac{\langle f_{\rm SGRB}\rangle}{0.1}\right)$$

Perez-Garcia, Daigne, Silk, ApJ(2013)